IPhT

Institut de Physique Théorique de Saclay

Rapport d'activité juin 2007 – mai 2011

Commissariat à l'énergie atomique
et aux énergies alternatives
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Foreword

This report presents an overview of the activities of the Institut de Physique Théorique (IPhT) from June 2007 to May 2011.

Over this four years period, more than 700 papers have been published by IPhT members (permanent researchers, PhDs and PostDocs, long term visitors). All these works are surveyed in the three scientific parts of the report :
– Models and Structures: Mathematical Physics
– Cosmology and Particle Physics
– Statistical Physics, Condensed Matter and Biophysics
Each part starts with an overview that should help the interested reader to find its way to the more technical details. The separation in three main themes is partly artificial, and the same people often contribute to several chapters.

The writing of the scientific part involved all the permanents members of the lab. These individual contributions were collected by a team of "volunteers" and then passed to the three editors who also had the charge to write the overviews. Each level involved a good amount of polishing, and I thank all the participants for their works. The three editors, Didina Serban, Stéphane Lavignac and Olivier Parcollet deserve a special mention.

The last part describes others facets of the IPhT: awards, teaching, external fundings, scientific editing, research administration, organization... My deputies, Anne Capdepon and Olivier Golinelli, dedicated a lot of time to it.

Many things have happened in France and in the world during the last four years, several of them being quite dramatic. Though what happened at IPhT is doomed to be anecdotal in this perspective, the Institute changed at an accelerated pace, and the impact of some of the world scale events can be seen clearly on French research and in particular at IPhT. The following remarks are an attempt to describe and (hopefully) understand the situation of the IPhT today and the stakes for tomorrow.

Expansion

One important trend is expansion. Over the period under review, a single CEA physicist retired, two juniors where hired and one senior moved to IPhT. On the CNRS side, three physicists have retired and one has left academic research, meanwhile four junior physicists were hired, and one senior moved to IPhT. Though the number of permanent members has raised only marginally, the number of students and PostDocs is still progressing very fast. It has increased by a factor of 4 or 5 over the last ten years, and now represents about half of the "crew". Moreover, the number of visitors (from one day visitors to sabbaticals, from trainees to permanents in neighboring institutions spending part of their time at IPhT,...) is also expanding rapidly: having 120 people around is now a common situation.

Concerning the evolution for the next ten years, another important fact will superpose to this expansion. In 2010, new rules for retirements have been adopted by the French chambers. Up to 2009, special agreements "forced" CEA employees to retire at the age of 60. Most physicists of this age argue with reason that they are still able to produce high quality research, and IPhT has always found means to allow them to pursue their work in good material conditions. The new horizon is now the age of 70. Budget forecasts indicate that the number of permanents at IPhT will not increase (an euphemism). A mechanical consequence is a period of about ten years with very few hirings on the CEA side. This is unavoidable, but destabilizes noticeably the age pyramid of the Institute. Arguably, this is partly compensated by fresh blood coming from students, PostDocs and possibly hirings at CNRS.

External fundings

Another trend is the increasing importance of external fundings. Ten years ago, external fundings where totally marginal. In 2011, more than 75% of our PostDocs are paid on external fundings, this is also the situation for invitations and travels. External fundings have become vital for the Institute. They come from a number of sources. Europe is by far our main provider, via Marie Curie programs and European Research Council (ERC) grants. Then comes the French "Agence Nationale de la Recherche" (ANR). Several more targeted sources (fundings for scientific exchanges with specific countries,...) come as complements.

But other sources of funding should take an important role in the near future, via large structures that have come to life in France recently. One of their goals is to make French main research areas more visible from the outside world. They regroup hundreds to thousands of researchers on specific themes. This started a few years ago with the so-called "Réseaux Thématiques de Recherche Avancée". But the major step was the launch in 2010 of the "Grand emprunt de la France : Investissement d'avenir" (a reaction to the financial crisis since 2008) which is deeply reshaping the landscape of French research. Under the flag of "excellence", new structures called Idex, Equipex, Labex (the generic name "*ex" is used in the sequel) are in the process of labeling.

A short aside is in order. It is hard to (over)estimate the impact that these new structures have had or will have on the more traditional entities devoted to science in France, CNRS and CEA to quote only the ones most relevant for the IPhT. In fact the name "external funding" is by opposition to means coming from CEA or CNRS. These two organisms still cover the salaries of permanents of the IPhT. They also provide access to reviews. CEA provides the buildings and working environnement. Some predict that in the short or middle term these will be their sole roles. CEA (mainly) and CNRS still contribute significantly to direct scientific activities (invitations, missions, conferences) but this is steadily decreasing. Obviously, the new structures will sooner or later have a dominant position to orient the scientific policy of the French research. This situation is a source of worry for both CEA employees (36 physicists and 8 persons in the support group) and CNRS members (16 physicists) at IPhT. In the past years, the CNRS has been "re-organized" several times, possibly to adapt to this new situation. In the same period, the CEA has not experienced such "jolts", but its implication in the new structures is a clear sign that important changes are on their way. There will also be consequences on the relations between the IPhT and the University, though it is too early to know exactly which ones. There is definitely room for improvements. Let me just note that IPhT harbors already a few professors (or assistant professors) for part of their research, that several IPhT members have a notable investment in teaching, but that many more would like to teach and lack opportunities.

IPhT is directly involved in two successful Labex. P2IO, "Physique des deux infinis et des origines" covers our activities in particle physics and astrophysics. PALM, "Physique : Atomes, Lumière, Matière" covers our activities in statistical mechanics, condensed matter physics and biophysics. Our activities in mathematical physics participate to the "Fondation mathématique Jacques Hadamard" which was not selected as a Labex in the first round, but which had already received a thorough governmental funding.

The members and/or teams at IPhT have in fact been remarkably successful in garnering all kind of fundings. The most spectacular record is for the highly competitive ERC grants. Four of them began during the period under review, and four more will begin soon, leading to a total of six "starting grants" and two "advanced grants" at IPhT. A ninth ERC laureate spends part of her time at IPhT on an excellentia University/CEA chair. The successes at ANR are also very noticeable. Let us just quote, among the almost twenty ANR contracts at the institute, the three ANR excellentia chairs attributed to three recently recruited members. These successes are obviously the main reason for the important expansion of the Institute, which should go on for another four or five years at least, and more generally for its visibility and attractiveness.

Closer to experiment

A third important trend is to get closer to experiments. This is particularly striking in Cosmology and Particle Physics. The role of the LHC is of course important, but many other present or future instruments (RHIC, Planck, Lisa,...) mobilize IPhT teams. The tendency is also visible in Statistical Mechanics (structural glasses, granular materials,...), Condensed Matter (new materials, heavy fermions, graphene,...) and Biophysics (motors, structure prediction, sequence alignment,...). It is clear enough from this short description that the situation is hardly comparable because experiments in high energy physics and condensed matter have totally different scales (time, cost,...).
To get closer to experiments, the birth of the "*ex" structures could have a significant favorable incidence in the future, because they incorporate theoretical physicists in structures involving a fair majority of instrumentalists and because one of their goals is to allow transverse research.

Coding

Finally, the importance of computer science related activities has raised significantly since the previous report. This goes from web-servers for biophysics to software for condensed matter physics, precision gauge theory computations or cosmology and astroparticles. There is of course a long history of numerical computation and simulation in Physics, but there is a clear shift in the approach. The aim is not simply to have a running code for an individual, a team or a community anymore, but to produce/furnish a real software compliant with software standards. Portability and durability imply a need for clarity, simplicity, readability, generality and modularity of the code. This is getting more and more important in physics, and is probably going to lead to some new specializations in a near future. There is still plenty of room for good physicists inventing good algorithms, because history shows that progress in computing hard problems often (if not always) comes from a better understanding of the physics. But these new creative algorithms have to be implemented respecting professional coding standards and without wasting time in reinventing the standard algorithms. This requires close contacts between physicists and computer scientists. A short term tendency seems to rely for this part on students or PostDocs coming from computer science but with a background in physics.

Excellentia

As the reader will surely have noticed, "excellence" is the buzzword these days, and it is meant to become a label, hence possibly also a Grail, at all scales from individuals to vast geographic areas. It is timely to try to explain the position and situation of the IPhT.

I surely do hope that the review of the external committee will conclude that, averaged over the Institute, the result is indeed excellent. What I know for sure is that people at IPhT (and elsewhere in the other scientific institutions for that matters) do their very best to produce excellent research. The question is more on how much energy we should put in to get excellentia labels. In the near future these labels will clearly bring more money, but will also imply changes in our working habits. So the position of the IPhT, which can clearly not be represented by the position of its director alone, is contrasted. Some of us feel that we have no choice but to enter basically every competition, while some other would accept some cuts (in money, invitations, travels) to preserve the tranquility and comfort they need to work best. There is a spectrum of intermediate positions.

One can interpret some of the changes at the IPhT (and possibly more generally in French research) over the last decade or so, as a metaphor of economic globalization. Some people argue that this passage was totally unavoidable. As the history of real economy shows, even if this is true in average, it does not mean that all other strategies were doomed to failure: in some places original niche strategies have been (even more) successful. In fact, the IPhT had a number of specificities (some would say eccentricities) that made it world famous and could have made it a successful candidate for alternative development models. One could even argue that some of the evolutions developed at the cost of part of our originality. It is nevertheless a fact that in the nineties, the IPhT engaged firmly in a series of important changes, starting with the implementation of a regular review by an international scientific committee and (soon after) of a new, open, hiring procedure. The situation today is clearly very influenced by this move, for obvious reasons. Most of the members of the international scientific committees and of the people hired since 1995 had been exposed early to the American (or close to American) research systems. They find it natural to apply for grants and to build a group of students and PostDocs around them. But the older IPhT philosophy, often based on close collaborations among permanents, is still vivid.

Highlights

Compared to other entities devoted to theoretical physics worldwide, the IPhT is amongst the giants, with more than 50 permanent researchers (36 are CEA employees and 16 are CNRS members). Its basic aim is contribute to a better understanding of the laws of nature, from the largest scales to the smallest ones. This goal can take a variety of incarnations, depending on the field of research and the personality of the researcher. But the IPhT can claim to harbor at least one respected specialist in most of the important physics themes of current interest. This is one of it's notable specificities, maybe one that could be preserved despite the many changes and uncertainties of the future. Among the obvious benefits is the possibility, and even incentive, of cross fertilization among different fields.

The Institute disposes of several task forces of leading experts.

One example is the field of precision perturbative quantum gauge field theory computations. This field is living a revolution that started about a decade ago and still goes on. The LHC makes this activity particularly timely because high precision background subtraction is needed to get at the new physics expected there. The activity at IPhT goes from abstract (but deep) results relating gauge theory and gravity amplitudes to more concrete (but highly tricky) computations of standard model cross sections. The intermediates are numerous, there is impressive mathematics in each, and the flow of ideas if by no means one-way. The output is a mixture of standard publications and practical software. These activities also have close connections with integrable systems – a tradition at IPhT - used to compute the spectrum of supersymmetric gauge theory, and of course with string theory.

String theory is a rather recent direction taken by the IPhT. After several failures to attract seniors, the policy to build a junior group is by now a real success. The group cannot cover all aspects of the subject, but its members have made fundamental contributions to black holes, flux compactifications, ADS/CFT and many more.

Another example of a considerable task force at IPhT is the group studying non-perturbative aspects of QCD, extremely competitive in all aspects of this domain, with the notable exception of lattice computations.

A large human quota is also devoted to physics beyond the standard model, astroparticles and cosmology. At IPhT perhaps more than elsewhere these subjects are close cousins because of the number of cross-collaborations. This activity has benefited from a number of recruitments in the recent past, and its dynamics is an evidence.

Condensed matter physics is also a huge theme that the IPhT integrated to its scientific policy only recently. This resulted in the recruitment of three physicists, all junior at that time. This small group was able to provide a "technology watch" and in particular interact strongly with the other rather large condensed matter physics groups nearby and with other members of the IPhT. This has led to a number of notable contributions. The recent emergence of AdS/CFT methods in condensed matter was a good opportunity to create new contacts within the Institute.

A number of IPhT members also devote a lot of attention to another very important "recent" subject, out of equilibrium statistical physics, either via works on paradigmatic models, or via general exact out-of equilibrium relations, or finally via concrete applications for instance to biology. This activity is also close to complex systems in general, disordered systems and spin glasses. The attention is now focusing on granular materials and structural glasses.

Among the obvious absences of the IPhT, the Institute cannot claim to have a group working on biophysics. However, a number of physicists have a deep interest in biology (and this is a tradition in fact) resulting in a number of important contributions, ranging from "biology-inspired theoretical physics" to "theoretical physics applied to biology" *and* used by biologists.

Other activities can progress significantly by the efforts of a few.

Mathematical physics has seen some of its representatives get closer to pure mathematics, with great success. One can note the works on dynamical systems and quantum chaos but visible contributions to important combinatorial, probabilistic and algebraic geometry problems also come to mind: planar maps, Razumov-Stroganov type conjectures, cluster algebras, Eynard-Orantin equations coming from random matrix theory, quantum gravity.

As shown by work done at the Institute, random geometry can also be a fruitful path to a better understanding of non-unitary quantum field theories, conformal or massive, via logarithmic conformal field theories and super sigma models, with concrete applications in condensed matter.

A fair proportion of the IPhT production made its way in the top 10% or top 1% most cited in Physics over the period 2007-2011. Some papers have had the honor of the front-cover of good journals or have been awarded prizes. This is of course a valuable way of counting merits, but there are others that require more understanding and long term view. Clearly I'm far from having these two qualities on the full spectrum of the activities at IPhT. Needless to say, reading the report gave me the feeling that many remarkable works have been going on in the Institute. But I find it impossible to propose a fair list of highlights for the scientific achievements at IPhT during the last four years. This is probably best left to the judgment of the visiting committee.

Challenges for the future

The first and clearest challenge for the future is the quality and originality of research, either measured by the "excellentia" or by other traits. Though only the future can tell, the reading of this report gives me strong reasons to be confident. I hope other readers will share this view.

Though we are used to attribute human traits to abstract entities, it is excessive to view the good work done at IPhT as a scientific success of the IPhT. My predecessors, with the help of internal and external scientific committees, deserve credit to have hired and brought together good people, creating a general environment propitious to good science. But from then on, whatever is done is done by individuals, or very small groups. So the main challenge is for individuals.

To make good research, one of the important tools today is funding. Again, there are good reasons to be confident, and again, this important challenge is mainly for individuals because this is how funding (especially in theoretical physics) is often targeted.

Research is partly a lonesome activity, and this reinforces the human tendency to attribute our successes to ourselves, and our failures to external circumstances. For this reason and for many others, it is not surprising that the two individual challenges lead to a cascade of challenges for the administration of the IPhT (more globally, of the Direction des Sciences de la Matière, of the CEA,...). Here is a non-exhaustive list.

The main managing tool for a scientific policy is recruitment, either permanent positions or long-term visitors. On this front, the situation is alarming. As already mentioned, the question of permanent positions is relegated to the middle or even the long term. This should incite us to be even more careful in the choice of PostDocs and long term visitors. But by now the money to pay these visitors comes mostly from targeted individual grants. If the needs fit with a grant goals, I'm confident that the grant holder will make clever choices. But a view at the level of the Institute is crucial as well. For instance, what was done about a decade ago for string theory and condensed matter, namely the creation *ex nihilo* of a group, would be totally impossible today. The possibility of creating a biophysics group is an example of an important issue that has to be postponed.

The diversification of financial resources over the last years has mechanically led to an explosion of administrative tasks. The recent hardenings of the implementation of the French employment law have amplified this tendency. The number of things to do, but also their complexity, are at least an order of magnitude higher than it was ten years ago. The situation is critical. The dedication and skill of our administrative group, plus the affectation of more and more time and energy of the deputy directors of the IPhT to these tasks (at the cost of neglecting other important issues) are reaching their limits. The same observations apply probably at higher levels in the CEA.

As already mentioned, the number of people present daily at IPhT well exceeds 100, and we are in an urgent need for a macroscopic raise of the number of offices. It is to be noted that, in the meantime, people not interested in getting funding share the inconveniences with people having funding for a number of visitors. The quality of life, at least if measured by the area per physicist, is deteriorating rapidly. But spatial extension comes with another challenge: the population of the IPhT is not only larger, but also more and more heterogeneous, with people coming from diverse horizons and expecting to spend a limited period in the Institute. A risk of phase separation is emerging, people with the same interests demanding to occupy neighboring offices. At the same time, the new "*ex" structures will sooner or later create an incentive for both permanent and non-permanent people to be more delocalized. Good or bad, these tendencies are new at IPhT and requires some thinking.

There is a slow shift from the old situation, when the IPhT was overwhelmingly populated by permanent researchers, to a situation closer to what is considered as normal abroad, when the IPhT will harvest a much smaller number of permanents with an army of non-permanents (PhD students, PostDocs, ...). This process will take a long time, and is beyond my horizon, but I would like to make two remarks. While obviously many places over the world manage to do top quality research with such a structure, the transition for the IPhT will probably be delicate, and relying plainly on retirements to decide of the future population of permanents is clearly not the right thing to do. Precarity is also an issue, and even if this is naive, I do hope that the non-permanents that will give their best young years to the Institute will do it in a situation, in France and in the world, when this experience will increase significantly their prospects of finding attractive positions, be it in fundamental research or elsewhere.

To summarize, the economy of the future at IPhT will require delicate balances: get fundings for projects but avoid to see our research targeted by fashion; preserve creative thinking without losing sight of stategic management; leave a lot of room for individual initiative, but keep a strong feeling for collective interests; offer to all the members of the Institute – permanent or not – working conditions that allow them to give their best.

The devotion of physicists for physics (at IPhT and elsewhere) is the best guarantee that we shall be able to win the challenges of the future, and I'm already eager to see how the main challenge for our Institute, the one for scientific inventiveness and originality, will be met in the next years.

Michel Bauer

CHAPTER A

Mathematical physics

Introduction

The research in the group of mathematical physics concerns a wide spectrum of topics, ranging from string theory, quantum gravity, matrix models, combinatorics, statistical models on fixed and random geometries, integrability, conformal field theory, quantum field theory in curved spaces, classical and quantum dynamical systems (including effects of noise and non-hermiticity), to number theory. These subjects are deeply interconnected, and they are often using a common ensemble of tools, that gives the group its unity. In many cases, the research reported here is also closely related with the activity of other groups in our Institute.

We start this introduction with topics related to string theory. If one regards the overall research landscape that falls under this designation, one can see that, after the stream of discoveries of the second superstring revolution and of the AdS/CFT correspondence, the field has divided roughly in three distinct subfields, which, although related technically, are guided by three different physical aims.

The first aim is to relate string theory to the real world, trying to obtain both phenomenologically-interesting systems, or systems realizing inflation or de Sitter vacua. A major activity of the IPhT group in this direction is the construction of compactifications on six-dimensional compact manifolds with flux, of heterotic compactifications, and the understanding of the supersymmetry-breaking mechanisms that are proposed to give rise to deSitter vacua in string theory. Topological strings calculate holomorphic quantities in string compactifications, and since topological strings can be related to random matrices, the extensive work done in Saclay on elucidating various aspects of topological strings also falls into this category. A differently-flavored work which falls in the same overall aim is the calculation of string and supergravity amplitudes at higher loop order, and the efforts to establish whether $N = 8$ supergravity is ultraviolet finite.

The second aim, motivated by the fact that string theory is a theory with a remarkable success in describing black holes, is to investigate whether one can solve or deepen our understanding of longstanding problems of quantum gravity. These include the information paradox, the protection of chronology, the physics of cosmological singularities, or the microscopic origin of the black hole entropy. Our group uses a variety of research attack angles here, ranging from the Kerr-CFT correspondence and 2D quantum gravity, to constructing and analyzing supersymmetric and nonsupersymmetric multicenter solutions, and using them to test the the recent conjecture that black holes are ensembles of horizonless microstate solutions, or to see how various black hole indices jump across the walls of marginal stability in the moduli space.

The third aim is to use string theory not as much as a theory to explain the real world, but rather as a mathematical machinery which, via the AdS-CFT correspondence, relates strongly-coupled gauge theories to weakly-coupled string theory. Hence, one can try to use AdS-CFT and string theory as a tool to understand the aspects of the strongly coupled theories that appear in various real-world systems, like the strongly coupled quark-gluon plasma, or condensed-matter systems.

One of the major goals in this area is to use AdS-CFT to describe asymptotically-free gauge theories (like QCD) and for this one needs to understand string theory in AdS when the curvature is larger than the string scale. The only tool for this is integrability, and our group works on the integrable structures that appear in the duality between $\mathcal{N} = 4$ Super-Yang-Mills and string theory in $AdS_5 \times S^5$.

Another important issue tackled in our group is the construction of new gauge-gravity solutions. Those include solutions dual to four-dimensional field theories with less supersymmetry, dual to metastable supersymmetry breaking in three and four dimensions, dual to the deconfinement phase transition in three-dimensional theories, or dual to nonconformal lower-dimensional theories similar to those that appear in describing certain condensed-matter systems.

Yet another research direction concerns string corrections to the AdS-CFT correspondence, and whether this correspondence can be derived directly by using CFT arguments. Besides the activity in our group, many members of the particle physics group in our Institute work on using AdS-CFT to describe strongly-interacting quark-gluon plasmas; this activity is reported in section B.17 on gauge-gravity duality.

Thematically moving away from string theory somewhat, we come to random matrix theory. This is one of the traditional fields of activity of the IPhT, whose members made seminal contributions over the years. Random matrices arise in many areas of physics, mathematics, biology, economics.

One of the main results of the pioneereing works of Wigner, Dyson and Metha had been the control of the leading order in the $1/N$ expansion, where N is the matrix size. Concerning the $1/N$ expansion, the state of the art has been significantly pushed forward at IPhT. The all-order control of various models has been obtained, including models with one or more Hermitian matrices, super-matrices, the so called β-ensembles, the chain of matrices, and the $O(n)$ matrix model. It was also observed that it computes the large size expansion of various crystal–melting models (also called random partitions, or random plane partitions, or random self–avoiding walks). The results on the $1/N$ expansion of the matrix models are deeply related to problems in enumerative geometry and in string theory, where one is interested in counting Riemann surfaces with given characteristics (handles, boundaries). The method of topological recursion allows to count the surfaces of higher topology in terms of number of surfaces with lower topology. It was conjectured that the Gromov-Witten invariants in algebraic geometry should also obey the same topological recursion. This would be an important fact, since it would allow an explicit computation of those invariants.

The matrix models and integrable models allow one to define in a very natural way a quantum version of the Riemannian geometry of surfaces, where the Bethe ansatz equations constitute consistency conditions. Similar properties are investigated in the context of integrability in AdS/CFT. The consequences of the existence of this quantum geometry are still under exploration by the researchers in our group.

As an application of random matrices to economy, a new ensemble of random matrices related to multivariate Student random variables has been introduced, whose density of states fits nicely the density of state of empirical correlation matrices of real–world financial data.

Another, related subject of research is the study of random surfaces, i.e. statistical models of discrete matter (spins, particles) on fluctuating (random) lattices. This problem is attacked from two complementary directions, namely with random matrix tools, but also with purely combinatorial techniques. Exploiting the progress of the random matrix theory, many new results have been obtained for statistical lattice models, like the Ising model and of the $O(n)$ models on random lattices of arbitrary topology. The analysis of the large lattice limits gave rise to new relations with conformal field theories and Liouville gravity.

Discrete random surfaces correspond to combinatorial structures called maps, which are also the object of an active research at IPhT, running along two main directions: the algebraic problem of counting maps (enumeration) and the study of their geometry, naturally described by the graph distance. Exploiting the bijection between maps and appropriate decorated trees and the underlying integrable structure, a number of results have been proven concerning the properties of geodesics in the limit of large random maps.

Random trees are met in many fields of sciences, ranging from social sciences to biology, physics and computer science. In this context a new class of tree–growth models by vertex splitting and attachment has been introduced, motivated by its possible relation with RNA folding.

Still in the framework of Liouville quantum gravity, the famous Knizhnik–Polyakov–Zamolodchikov (KPZ) relation between scaling exponents of a conformal field theory in a Euclidean planar domain and in quantum gravity, has received a renewed attention from IPhT's researchers. A first mathematically rigorous proof of the KPZ relation, twenty years after its discovery, has been given, which uses a probabilistic and geometrical notion of quantum area measure. The relation of this new result with the original derivation has been clarified, using heat kernel and CFT methods and anomaly consistency arguments.

Critical geometrical models on non fluctuating lattices are also of the highest interest, for a variety of reasons. First, they are relevant to probability theory and to our general understanding of critical phenomena. In this direction, the most important is probably the study of interfaces in two-dimensional critical system, which has been pushed forward in 2000 by Schramm's seminal work, leading to an explosion of activity and of results concerning the so called stochastic Loewner–Schramm evolution (SLE). Among the open questions in this area which are investigated at IPhT, one can cite the generalization of SLE to non simply–connected regions and to non–critical systems, the need of concrete physical realizations of SLE, and its link with two dimensional quantum gravity. Other related progress here includes preliminary study of interfaces with branchings and crossings, such as the domain walls in the Potts model - we note here that the corresponding work [t11/054] was recently awarded the Journal of Physics A Best Paper Prize 2011.

Critical geometrical models are also important for a variety of applications, ranging from valence bond descriptions of quantum systems to interacting anyons, coloring problems, and biopolymers. Important progress has been realized in all these areas.

Meanwhile, the intimate link between statistical physics of discrete systems and combinatorics can be used to give a purely combinatorial solution to some statistical problem in physics or, conversely, apply physical methods to combinatorial puzzles. This deep interplay is a guiding principle for the activity of the combinatorics group at IPhT, which takes different directions, in addition to the already mentioned progresses in the area of random surfaces.

A first line of research concerns variations around the Razumov-Stroganov conjecture, recently proved by Sportiello and Cantini, relating some highly constrained enumeration problems (such as fully-packed loops on a square lattice in bijection with alternating sign matrices, or tilings of domains in the plane) to the ground state of some physical integrable model (typically the $O(n)$ dense loop model). A thirty-year old conjecture connecting the alternating sign matrices to the so called descending plane partitions has been proved. Another issue involves the Gessel's conjecture, concerning constrained walks in a subset of a square lattice: a combinatorial formula for a subset of Gessel walks has been given.

The combinatorics of discrete integrable dynamical systems is also under investigation, with connections to newly found mathematical structures such as cluster algebras (a mathematical version of "the theory of everything", with applications ranging from quiver representations and category theory to algebraic geometry and string theory, via Teichmüller space geometry), as well as to Bethe Ansatz solutions of integrable lattice models or spin chains. For instance, one finds that a class of discrete "Hirota-type" integrable evolution equations may be solved in terms of (commutative or non-commutative) weighted path models, thereby allowing to prove deep conjectures such as the positivity of certain cluster algebras.

An important area of research and progress pushed forward by IPhT's members concerns two–dimensional quantum field theories with supersymmetry, more specifically sigma models with super–manifold targets. The study of this topic stems from interest in the phase transitions of non-interacting disordered electronic systems, such as the transition between plateaux in the integer quantum Hall effect, but super–sigma models also play an important role in the study of geometrical problems like percolation and polymers, as well as in the the Green–Schwartz or pure spinor formulation of string theories. These models typically exhibit non-Hermitian "hamiltonians", and present considerable difficulties in non perturbative analyses. In particular, the associated conformal field theories are logarithmic, and involve not fully reducible representations of the Virasoro and fusion algebras.

The progress in this area has been profound, and due in large part to the solution of lattice model discretizations of super target sigma models. These discretizations on the one hand have opened the way to using mathematical tools and concepts developed in the field of associative algebras in the last ten years, uncovering new relations between physics and representation theory. On the other hand, the discretizations, have furthered relations with geometrical models, the lattice analogs of chiral algebras being in most cases diagram algebras such as the Temperley Lieb or the Brauer algebras. The interplay between conformal field theory and loop models (and variants thereof) has thus been particularly fruitful. Major results include the solution of conformal supersphere and superprojective sigma models, the discovery of dualities between sigma and Gross Neveu models in the orthosymplectic case, the solution of the strong coupling CFT associated with $\theta = \pi$ superprojective sigma models, and the construction of a general formalism to tackle boundary logarithmic CFTs using quantum groups at roots of unity. Applications range from edge state properties in the spin quantum Hall effect to the classification of boundary conditions for loop models. The latter have also been the subject of very interesting studies in random matrix theory. Meanwhile of course, geometrical models are a natural tool to define and tackle new types of field theories. Recent work on domain walls and interfaces in the Potts model for instance has yielded promising results for models with branchings, exhibiting new patterns of exponents and other physical features, not seen before.

Another instance of quantum field theory on a curved spacetime is quantum field theory in the de Sitter space. In this context more insight has been gained on the intriguing behavior of the particle decay in this space–time, thanks to the study of the Källen–Lehmann decomposition of the one–loop two point function for a scalar theory.

Another direction of activities in mathematical physics concerns classical and quantum dynamical systems, in clean or noisy systems. On example of classical dynamics concerns some elementary 1D dynamical systems, the interval exchange transformations and their generalizations. In spite of the simplicity of their definition, these transformations can lead to subtle ergodic properties, and represent an active part of the modern mathematical theory of dynamical systems.

Still in 1D, the addition of a multiplicative noise to a simple oscillator can drastically modify its long time behaviour; for instance, it can lead to a certain form of intermittency, which is sensitive to the power spectrum of the noise. Such noisy dynamical systems can be used to describe as diverse physical phenomena as population dynamics in a random medium, or the interplay between disorder and nonlinearity in the 1D Schrödinger equation. The kinematic dynamo problem addresses the instability of the magnetic field in the induction equation driven by a given velocity field, neglecting the feedback of the magnetic field on the flow. In view of several experimental situations in various confined geometries, the choice of a realistic velocity profile is crucial to determine the threshold for this instability. As a first approximation to the situation of a turbulent flow, one can add a stochastic component to the velocity, and observe its effect on the instability threshold .

Various aspects of quantum mechanical systems are also addressed by the members of our group. One is a random matrix model for decoherence of a spin in a complex environment, obtaining non-Markovian behaviours. More fundamental questions in quantum mechanics, namely the interplay between reversibility, locality and causality and their consequences on the quantum formalism are also addressed. The scattering theory for nonlocal potentials is studied, as well as the description of the phenomenon of "echoes" or "antiresonances" within the formalism of Regge trajectories in the complex angular momentum plane. Specific 1-particle scattering systems are studied, namely those for which the corresponding classical flow exhibits a chaotic set of trapped trajectories; there the focus is on the description of the resonances and metastable states in the semiclassical limit. A similar formalism, including the spectral study of a nonselfadjoint "Hamiltonian", is used to describe the propagation of damped waves in chaotic domains. Back to 1D, several methods (exact WKB method, ODM method) are used to study the spectra of certain 1D polynomial potentials, including non self-adjoint, PT-symmetric cases.

Finally, the zeros of Riemann's zeta function, are used to generate a family of "secondary" zeta functions, which are then carefully analyzed. Although the problem seems purely number theoretic, one should keep in mind that these zeros often serve as a "mock spectrum" for a quantized chaotic system.

This chapter contains contribution from a number of permanent researchers (M. Bauer, I. Bena, G. Biroli, J Bros, J. Bouttier, F. David, B. Eynard, P. Di Francesco, B. Duplantier, M. Gaudin, M. Grana, E. Guitter, I. Kostov, K. Mallick, R, Minasian, P. Moussa, S. Nonnenmacher, C. Normand, V. Pasquier, R. Schaeffer, H. Saleur, D. Serban, P. Vanhove, A. Voros, J. Zinn-Justin) and J. L. Jacobsen, in part-time delegation from Université Paris-Sud until 2008. The activity of the group was strengthen by a relatively large number of post-docs (A. Alexandrov, A. Ayyer, S. El-Showk, A. Gainutdinov, S. Giusto, N. Gromov, M. Guică, N. Halmagyi, K. Hosomichi, J. Manschot, B. Poszgay, F. Saueressig, A. Saxena, B. Vercnocke, B. Vicedo) and of PhD students (R. Bondesan, G. Borot, J.-E. Bourgine, C. Candu, J. Dubail, G. Giecold, E. Goi, O. Marchal, D. Marques, S. Massai, N. Orantin, F. Orsi, A. Puhm, C. Ruef, E. Schenck, I. Shenderovich, R. Vasseur, D. Volin).

The activity of the group was partly financed by 2 ERC Starting Grants and a number of ANR projects.

A.1 Flux compactifications

Flux compactifications remains one of the main research directions of string theory. In spite of much recent progress there is a number of outstanding open problems concerned both with the applied side, i.e. relations with particle physics and supersymmetric low energy theories, and conceptual aspects, such as reconciliation with the string dualities and quantum properties.

A.1.1 Generalized geometry and global aspects *(M. Graña, R. Minasian, N. Halmagyi, D. Márques, E. Goi)*

The so-called non-geometric backgrounds do arise when one tries to perform dualities which have global obstructions. Ref. [t08/118] focused on the description of these non-geometric backgrounds from the point of view of generalized geometry (a generalized version of Riemannian geometry that combines the metric and gauge potentials into larger geometric structures). A local generalized geometrical definition of the "non-geometric charges" appearing in effective four-dimensional theories has been proposed using the Courant bracket and some global aspects, such as whether the local non-geometric charges can be gauged away, have been addressed as well. In [t07/134] similar questions have been addressed from the point of view of sigma models on target spaces given by a principal torus fibration, and it was shown how treating the 2-form B as a gerb connection captures the gauging obstructions and the global constraints on the T-duality. It was shown in particular that the obstruction to T-duality lies in the non-Hamiltonian action of the symmetry group. Ref. [t08/252] addressed the global issues, such as quantization of the pure spinors, in topological theories, and discussed the relation to the twisted K-theory classification of D-branes.

Ref. [t09/039] gives the description of flux backgrounds where all the string dualities (perturbative and non-perturbative) are manifest, using the language of exceptional generalized geometry, an extension of generalized complex geometry appropriate for M-theory backgrounds. The kinetic terms as well as the potential arising on the four-dimensional effective theory upon compactification, were encoded in U-duality covariant expressions. Using this U-duality covariant formulation, all the possible fluxes (geometric and non-geometric) arising in compactifications have been classified in [t10/093]. These fluxes correspond to gaugings on the four-dimensional effective theories, and such classification gives the complete dictionary between four-dimensional gauged supergravities and ten-dimensional string theories.

One of the key phenomenologically attractive features of compactifications with fluxes is their potential to give masses to moduli (unphysical four-dimensional massless scalars arising in fluxless compactifications, which correspond mostly to parameters of the internal geometry). In Ref. [t09/328] the set of massless and light fields were identified for particular internal coset-type manifolds, i.e. it was shown that a truncation of the ten-dimensional theory to this subset of modes is consistent. The landscape of supersymmetric and non-supersymmetric vacua (including the possibility of de Sitter vacua) is explored. Ref. [t11/014] performs a systematic study of stabilization of moduli in the presence of U-dual fluxes in compactifications on toroidal geometries, identifying for example regions of parameter space that do not admit complete moduli stabilization.

In [t09/022] discrete families of (flux) backgrounds on internal manifolds of different topologies were constructed by performing certain coordinate dependent O(d,d) transformations. The principal examples of this construction include respectively the family of type IIB compactifications with D5 branes and O5 planes on six-dimensional nilmanifolds, and the heterotic torsional backgrounds. Classes of non-supersymmetric solutions in toroidal compactifications were obtained in [t07/135] from the four-dimensional low-energy theory. One of the interests of these solutions is that if the Standard Model lives on D-branes in such backgrounds, the supersymmetry breaking is communicated to the visible sector (the open strings attached to the D-branes) in the form of soft terms, as expected in the MSSM. The geometrically induced mu-term is computed, and the patterns of soft-terms in each type of breaking are discussed. The effective scalar potential turns out to possess interesting phenomenological properties. Ref. [t10/022] analyzes the conditions for obtaining de Sitter vacua in string theory on the example of IIA compactifications on solvmanifolds with O6/D6 sources. A new treatment of the non-supersymmetric source terms was proposed. While for space-time filling supersymmetric branes, the energy density is minimized by a pullback of a special form given by a pure spinor, in our solution, the combined bulk-brane energy density is extremized by replacing the DBI action by a pullback of a polyform from the bulk, which is no longer pure.

In [t09/327] a generalization of the Courant bracket was shown to arise from the Lagrangian for the two-dimensional sigma model. The central properties of non-geometric backgrounds are intrinsically stringy and as such it was important to understand the origins of the target space algebraic structures from the string worldsheet.

In [t10/245] the space of BPS solutions of II supergravity on the resolved conifold was analyzed. Type II supergravity on conifold backgrounds provided important ways of engineering supergravity duals to four dimensional super Yang-Mills theory and as such are important for understanding the basic holographic dictionary away from the conformal limit. In this work we classified the BPS solutions for massive IIA supergravity and proposed a particular family of solutions to be mirror to a previously known solution of IIB supergravity on the deformed conifold. Particular emphasis was placed on the fact the the space of BPS solutions in the IIB theory has an extra branch not seen in the IIA theory and it was proposed that this missing branch of IIA solution would be non-geometric in nature.

A.1.2 Instanton effects *(F. Saueressig)*

Stringy and non-perturbative effects are important ingredients for building semi-realistic models connecting string theory to four-dimensional low energy physics. In particular, the instanton effects originating from euclidean D- and NS5-branes wrapping submanifolds of the internal space still pose many unanswered questions. A setup where one can hope to understand such effects in detail is type II string theory compactified on a Calabi-Yau threefold (CY). In this case, the low energy physics is captured by a $N = 2, d = 4$ supergravity action and it is conceivable that the constraints coming from string dualities and supersymmetry suffice to determine the perturbative and non-perturbative corrections to the low energy effective action. The non-perturbative duality chains underlying this program together with the exact expression encoding the D(-1)- and D1-instanton corrections arising in the Type IIB string compactification are summarized in the proceedings article [t07/136]. By mirror symmetry, these corrections are equivalent to the A-Type D2-brane instanton corrections arising in the Type IIA compactification on the mirror CY.

Determining the full D2-brane instanton corrections via electric-magnetic duality required a detailed understanding of quaternion-Kähler manifolds without toroidal symmetries. This issue was addressed in two mathematical works [t08/104] and [t08/115] which developed the twistor space description for hyper-Kähler and quaternion-Kähler manifolds, respectively. Instead of working with the rather complicated metric of the quaternion-Kähler manifold itself, this formulation encodes all the relevant geometrical data in holomorphic transition functions which connect the various patches of the twistor space. As its main virtue this construction admits deformations of the transition functions, which explicitly break the symmetries intrinsic to previous projective superspace constructions. This feature together with the close connection to wall-crossing formulas made the formalism tailor-made for capturing non-perturbative corrections as deformations of the classical transition functions.

The work [t08/203] then developed the twistor-space description of the A-type D2-instanton corrections, by formulating the previously known results in the language of contact geometry. Covariantizing the resulting transition functions with respect to electro-magnetic duality and employing mirror symmetry, all D-instanton corrections arising within the type II compactifications were found as a concise sum of dilogarithmic functions. This picture was completed by the explicit construction of the D-instanton corrected type IIA and type IIB twistor spaces in [t09/066] which also led to explicit expressions for the non-perturbative corrections to the classical mirror map.

A.2 Heterotic strings *(R. Minasian, A. Puhm)*

Although the advent of string dualities and flux compactifications has somewhat sidelined heterotic strings, it has remained an active and important research area due to the appealing features of the heterotic compactifications as well as a number of unresolved fundamental questions.

While it has been known for a long time what conditions the internal geometry should satisfy in order to preserve supersymmetry in the presence of non-trivial NS H flux, interesting constructions appeared only recently. Ref. [t10/160] studied the non-linear sigma model realization of a heterotic vacuum with $\mathcal{N} = 2$ space-time supersymmetry. In particular the requirements of (0,2) + (0,4) world-sheet supersymmetry have been examined and it was shown that a geometric vacuum must be described by a principal two-torus bundle over a K3 manifold.

In [t08/185] Narain T-duality was considered on a nontrivially fibered n-torus bundle in the presence of a topologically nontrivial NS H flux. The action of the duality group on the topology and H flux of the corresponding type II and heterotic string backgrounds was determined. Specializing to the case of supersymmetric T^2-fibered torsional string backgrounds with nontrivial H flux, it was proven that the topology change under the T-duality preserves the global tadpole condition in the total space as well as on the base of the torus fibration. Some of these T-dualities exchange half of the field strength of an unbroken U(1) gauge symmetry with the anti-self-dual part of the curvature of a physical circle fibration, and it was verified that such T-dualities indeed exchange the supersymmetry condition for the circle bundle with that of the gauge bundle.

In [t10/159] the heterotic CFT/geometry correspondence was studied for non-rational internal conformal field theories with N=(0,2) supersymmetry through the triality between minimal models, Landau-Ginzburg orbifold theories and sigma models on Calabi-Yau manifolds. This was checked using a counting algorithm that allows to compute the charged massless spectrum of a wide class of SO(10) GUT models. It was found that while untwisted sectors can effectively be treated like in (2,2) models, in twisted sectors non-BPS states contribute to the spectrum.

A.3 Black holes in string theory

String theory is a quantum theory of gravity, and has had several astounding successes in describing properties of black holes. The string theory group is very active in several areas of black hole physics: constructing and counting horizonless black hole microstate geometries, obtaining a microscopic description of Kerr black holes, calculating the moduli-dependance of black hole degeneracies via wall-crossing, and finding the mechanisms by which string theory realizes chronology protection in black hole interactions.

A.3.1 Supersymmetric black hole microstate geometries *(I. Bena, S. Giusto, C. Ruef)*

Recent progress in string theory points to the possibility that black holes should not be thought of as fundamental objects, but rather as statistical ensembles of a huge number of smooth geometries. Establishing this requires the construction and counting of very large classes of solutions that have the same charges, mass and angular momentum as a black hole, but have no horizon. The Saclay team has solved several longstanding and important problems in this direction.

The first is the construction in [t07/075] of the first microstate solution corresponding to a five-dimensional black ring that has a macroscopic horizon. The second is the discovery of the so-called abyss solutions [t07/075]. These are smooth low-curvature horizonless solutions that have a throat whose length can be arbitrarily large. Since this is not allowed by the AdS-CFT correspondence, it must be that quantum effects stop this throat from being arbitrarily large, and thus can destroy a macroscopically large chunk of a smooth low-curvature classical solution. This phenomenon, conjectured first in [t07/075], has been confirmed by a rigorous analysis by a team from University of Amsterdam.

In [t08/033] we investigated a transformation that relates various black hole microstate geometries, and that corresponds to spectral flow in the dual CFT. This transformation can relate smooth solutions with a multi-center Taub-NUT base to solutions where one or several Taub-NUT centers is replaced by two-charge supertubes. Since supertubes can depend on arbitrary functions, this established that the moduli space of smooth horizonless black hole microstate solutions is classically of infinite dimension. This entropy that comes from a supertube in such a background was found in [t08/075] to be parametrically larger than the entropy of a similar supertube in flat space, and this entropy enhancement mechanism can give entropies of the same order as the entropy of a black hole, coming entirely from smooth horizonless configuration.

We have also explored the relation between the description of supertubes using their Born-Infeld action (which is a probe approximation), and using the full supergravity solution, and found that the Born-Infeld description captures the same essential physics as the complete supergravity solution [t08/211]. We have also showed that the charges that give the enhanced entropy of a supertube can be much larger than the asymptotic charges of the solution containing the supertube. Last, but not least, we could show that all the three-charge black hole microstate geometries constructed so far can be embedded in $AdS_3 \times S^3$, and hence can be related to states of the D1-D5 CFT.

To fully establish the entropy enhancement mechanism, we constructed the largest known class of fully-backreacted black hole microstate solutions [t10/081], which contain a round supertube that has an arbitrary density mode, and hence depend on an arbitrary function of one variable. When this function is constant these solutions become usual Denef-type multicenter four-dimensional solutions [t08/211], but when the density is an arbitrary function the four-dimensional interpretation disappears. Since the solutions found in [t10/081] are much more complicated than the ones used to argue that the entropy of smooth supergravity solutions cannot be black-hole-like, our construction reopens this fascinating question.

A.3.2 Microstates from string theory *(S. Giusto)*

The need to develop a systematic method to construct the geometries representing black hole microstates is the motivation behind the work in [t10/006], where string amplitudes for the emission of closed string states from a D1-D5 bound state were computed. These amplitudes provide the large distance expansion of the gravity and RR fields emitted by a system of D-branes, and thus link the gravitational and microscopic description of black holes. In [t10/006] the consistency of the method was tested by reproducing the asymptotic expansion of the known 2-charge microstates.

A.3.3 Kerr/CFT correspondence *(M. Guică)*

The (generalized) Kerr/CFT correspondence is a conjectured duality between an extremal rotating black hole and a CFT, whose central charge is proportional to the angular momentum of the black hole. If shown to be correct, this duality provides an explanation for the microscopic origin of the entropy of all extremal rotating black holes.

In order to better understand this proposed holographic duality, it is useful to embed specific examples in string theory. In [t10/247], we have studied a one-parameter family of extremal non-supersymmetric black hole solutions in supersymmetric compactifications of string/M-theory to five dimensions. The black holes carried electric graviphoton charge Q and $SU(2)$ angular momentum J_L, obeying $Q^3 \leq J_L^2$. We showed that in the maximally charged limit $Q^3 \to J_L^2$, the near-horizon geometry becomes a singular quotient of $AdS_3 \times S^2$, which coincides precisely with the near-horizon geometry of a black string solution to the same theory carrying magnetic charge $P = J_L^{\frac{1}{3}}$.

Oftentimes, the microscopic duals of the black strings are known, and they are CFTs with central charges $c_L = c_R = 6P^3$. In the limit we considered, this central charge agrees with that of the $c_L = 6J_L$ CFT predicted by the Kerr/CFT correspondence. At linear order away from maximality, the CFT is in a thermal state and we have moreover shown that its associated thermal entropy reproduces the linearly sub-maximal Kerr-Newman entropy. Beyond linear order, for general $Q^3 < J_L^2$, one has a finite-temperature quotient of a warped deformation of the magnetic string geometry. The corresponding dual deformation of the magnetic string CFT potentially supplies, for the general case, the $c_L = c_R = 6J_L$ CFT predicted by Kerr/CFT. Near maximality, the deformation can be studied using the known tools of AdS_3/CFT_2.

A.3.4 Background dependence of supersymmetric spectra *(J. Manschot)*

An important problem is the dependence of the quantum-mechanical spectra of supersymmetric theories on parameters which encode the "shape" of the manifolds (or background) on which the theory is considered. Part of the spectrum can become unstable and disappear from the spectrum under variation of these parameters (or vice versa). In supergravity, this part of the spectrum corresponds to multi-center black holes.

Ref. [t10/130] analyses the (stable) spectrum of black hole solutions in $\mathcal{N} = 2$ supergravity with 3 centers as function of parameters of the Calabi-Yau. The main results are that the partition function, which enumerates the number of supersymmetric states is convergent, and the requirement of so-called "rational invariants" as a measure for the number of states. Using these rational invariants, Ref. [t11/080] with B. Pioline and A. Sen gives an elementary understanding using Boltzmann statistics of mathematical wall-crossing formulas. Ref. [t11/080] also applies localization techniques to determine the number of states associated to multi-center black holes, which in this context means that knowledge of collinear black hole solutions is sufficient. This idea is made more precise and applied much more generally in Ref. [t11/082].

A system whose background dependence is very similar to that of supergravity, is $\mathcal{N} = 4$ Yang-Mills on a complex surface S. Refs. [t10/138] and [t11/078] analyse this system for gauge groups $U(2)$ and $U(3)$ in a more mathematical setting. Ref. [t10/138] analysed the modular properties and provided an exact formula (similar to the Rademacher formula) for the number of supersymmetric states. Refs. [t11/078] applies [t10/130] and gives the generating function for rank 3; the generating functions for rank 1 and 2 were derived by Göttsche ('90) and Yoshioka ('94) respectively. The proceedings [t11/081] extend this analysis and address the holomorphic anomaly in this context.

A.3.5 Chronology protection *(I. Bena, B. Vercnocke)*

One of the most puzzling facts to emerge from the study of black holes is the so-called "chronology protection": physical processes cannot create configurations with closed timelike curves (ctc's). Since the presence of these curves is governed by certain coefficients in a given solution, which can easily change by changing charges or angular momenta by a very small amount, it is interesting to understand why these small ctc–inducing changes cannot happen physically.

In [t08/211] we studied the merger of a black ring and a supertube, which for many ranges of charges and angular momenta can naively produce black ring solutions that have closed timelike curves. We have found that in the mergers for which a complete supergravity solution exists (when the supertube and the ring are concentric), chronology is never violated. However, in mergers where the supertube enters the black ring horizon at some azimuthal angle, in order for chronology to be protected the charges brought in by a supertube cannot be simply the charges that appear in its Born-Infeld action, but must depend on the azimuthal angle in a nontrivial way. The confirmation of this prediction awaits the full supergravity solution for the merger.

In [t10/248] chronology protection was studied from the point of view of the stringy exclusion principle. We investigated and proved, using the AdS/CFT correspondence, the one-to-one correspondence between chronology violation/protection in a family of supersymmetric solutions to AdS supergravity in three dimensions and the absence/presence of negative norm states in the spectrum of the dual CFT, through the condensation of type IIB 7-branes.

A.3.6 Multicenter non-BPS black holes *(I. Bena, S. Giusto, C.Ruef)*

It has been known for a few years that in string theory and supergravity there exist a very large number of multi-center supersymmetric solutions. Although the second-order Einstein's equations governing these solutions are nonlinear, supersymmetry allows one to factorize these equations into first order ones, which are relatively straightforward to solve. These solutions generically depend on two coordinates, and their physics has greatly advanced our understanding of supersymmetric black holes.

It has been a longstanding problem to try to obtain multicenter non-supersymmetric solutions, and to see if the interesting physics that the supersymmetric solutions have yielded is just an artifact of supersymmetry, or extends to more generic black hole configurations that are closer to those of the real world. Nevertheless, in the absence of supersymmetry solving the second-order nonlinear Einstein's equations to is highly nontrivial, and solutions that depend on two variables are notoriously difficult to find. The best example of such a solution is the Kerr black hole, which was found almost 50 years after Einstein discovered his equations.

In [t09/020] we have used a certain factorization of Einstein's equations (called the almost-BPS ansatz) for extremal non-BPS solutions to construct the first two-center non-supersymmetric solution that has a nonzero angular momentum. We then extended this work and constructed a nonsupersymmetric solution that has an arbitrary number of aligned centers [t09/113]. We have also used the almost-BPS ansatz to construct the "seed solution" (from which all other solutions can be generated by dualities) for the most general under-spinning four-dimensional extremal black hole in string theory [t09/020].

Using a similar technology, we have constructed a class of non-supersymmetric non-extremal solitonic solutions that have the same mass and charges as a finite-temperature black hole with a macroscopic horizon [t09/130]. There are only 2 other classes of such solitonic solutions known at this point, and their existence and physics supports the fact that the so-called fuzzball proposal applies not only to BPS black holes, but also to non-BPS nonextremal black holes.

In [t09/137] we used the fact that some branes do not feel a force in certain systems (this corresponds to a calibration) to find a new factorization of Einstein's equations into a first-order system of equations that describes non-supersymmetric multicenter solutions. We have found a way to solve these equations linearly, and have given a recipe to construct 11-dimensional and 5-dimensional supergravity solutions using as a base-space any four-dimensional Euclidean electrovac solution to the Einstein-Maxwell equations, and in particular, Israel-Wilson four-dimensional spaces. The solution with an Israel-Wilson base interpolate between the BPS and the almost-BPS solutions, to which they reduce in certain limits.

This construction was extended in [t09/271], where non-BPS solutions were constructed starting from arbitrary elecrovac solutions. This paper contains the largest known class of smooth five-dimensional non-supersymmetric solutions dual to microstates of non-BPS nonextremal black holes, constructed starting from four-dimensional Euclidean Kerr-Newmann-Taub-Bolt solutions.

We have also found in [t11/065] a new non-supersymmetric black ring in Taub-NUT that unlike all the other known black rings in Taub-NUT has two angular momenta. This black ring solution has an Israel-Wilson base space, and is completely regular despite being located at a point where both the metric of the base space and the warp factor are singular: the singularities cancel each other to yield a completely physical warped solution.

A.3.7 Solutions in pure gravity *(S. Giusto, A. Saxena)*

In [t08/297] some recently developed generating techniques were applied to the construction of an exact solution of 5D Einstein gravity representing a neutral black ring in a Taub-NUT space. This solution provides the gravitational description of a system of D0 and D6 branes, and the knowledge of the exact solution allowed us to study the interactions between D0 and D6 branes and their equilibrium configurations in various limits, including the extremal limit in which the thermal excitations of the D0 branes are turned off.

A.4 Structure of gauge theory and string theory amplitudes

Gauge theory and quantum gravity amplitude computations have recently been a tremendous research activity, revealing a surprising connection between amplitudes in quantum gravity, and non-Abelian gauge theories. These connections are between the weakly coupled regimes of these theories whereas the AdS/CFT relation puts in relation a strongly coupled gauge theory with a weakly coupled gravitational theory in curved space. By combining the constrains from unitarity in various dimensions and duality relations in string theory it has been possible to derive a proliferation of new relations and results for previously unknown or seemingly not-calculable amplitudes in field theory, both in gauge theory and supergravity.

A.4.1 Structure of gauge theory amplitudes *(P. Vanhove)*

We have shown that for given tree-level amplitudes of in total n incoming and outgoing particles there exists a minimal basis of amplitudes in which all other color-ordered amplitudes in QCD can be expanded [t09/092], [t10/023]. This is an enormous simplification when the number of particles grows, and, moreover, we have provided a constructive determination of a minimal basis. We showed, as well how to reconstruct generic tree-level amplitudes in gauge and gravity amplitudes from this basis and a momentum kernel function, depending only on the kinematical invariants of the interactions process [t10/145]. The construction used the connection between tree-level gauge theory and gravity amplitudes and the zero slope limit of string theory amplitude. This form of the tree level amplitudes points to striking relations between gauge and gravity amplitudes, that have important implication at the quantum level [t10/045]. By using these relations in the unitarity cuts of one-loop, we have shown that such a reduction implies relations between coefficients of the one-loop amplitudes when expanded in a basis of scalar integral functions [t10/030].

The combined action of gauge (diffeomorphism) invariance and maximal supersymmetry imply remarkable simplifications in the perturbative structure of $N = 8$ supergravity amplitudes. We have showed in [t08/018], and [t08/057] that these imply that all n gravitons one-loop amplitudes can be expressed solely in terms of scalar box integral functions in four dimensions, proving that $\mathcal{N} = 8$ supergravity amplitude satisfy the no-triangle property. Surprisingly we showed [t08/156] that one-loop multiphoton amplitudes with at least eight external photons, satisfy the no-triangle properties in four dimensions as well.

A.4.2 Automorphic properties of string theory in various dimensions *(P. Vanhove)*

In [t10/001], [t10/039] and [t08/100] we analysed the structure of higher-loop interactions in $\mathcal{N} = 8$ supergravity. Using the constrains from supersymetry and non-perturbative dualities we have determined the form of the 1/2, 1/4 and 1/8-BPS coupling to the low-energy effective action in dimensions $3 \leq D \leq 10$ for maximally supersymmetric type II superstring compactified on tori. These coupling satisfy non-renormalisation theorems that we have showed, implying the absence of ultraviolet divergences for $\mathcal{N} = 8$ supergravity in four dimension until seven loops [t10/012]. We showed as well in this work, that the decoupling limit of massive perturbative and non-perturbative string states is singular as a consequence of the non-perturbative dualities.

A.4.3 Perturbative string theory in various dimensions *(P. Vanhove, B. Vercnocke)*

In [t07/126] we have analyzed the structure of the low-energy expansion of one-loop four-graviton amplitude in type II string theory. We have showed that the α' expansion of the analytic contribution only involve polynomials in depth one zeta values, and that the integrand can be expessed in terms of new modular form, now studied by a PhD student of Don Zagier.

In [t09/086] we have determined the complete ultraviolet behaviour of four-gluon multi-loop amplitudes in $\mathcal{N} = 4$ super-Yang-Mills in dimensions $4 \leq D \leq 10$ using the pure spinor formalism. We have showed that non-planar contributions have a milder ultraviolet behavior than the leading planar contributions. In [t08/019] a modified prescription for the integration over the pure spinor cone in the functional integral was provided, in order to resolve the issues in evaluating the D-term type of contributions in amplitudes. An introductory review of scattering amplitudes in string theory appears in [t10/177].

A.4.4 Asymptotically safe quantum gravity *(F. Saueressig)*

Weinberg's asymptotic safety conjecture states that gravity constitutes a consistent and predictive quantum field theory within Wilson's generalized framework of renormalization. The key ingredient in this scenario is a non-Gaussian fixed point of the gravitational renormalization group (RG) flow which controls the UV behavior of the theory and ensures the absence of unphysical divergences. Exploring this intriguing possibility typically relies on functional renormalization group equations (FRGEs), which encode the flow of an entire Lagrangian action on the space of all possible theories. The main evidence supporting the existence of the fixed point thereby originates from approximate non-perturbative solutions of the FRGE.

In [t07/154] we constructed a partial differential equation capturing the RG flow of modified gravity theories of the form $S = \int d^dx\sqrt{g}f(R)$. Based on this equation we showed that certain classes of non-local gravitational interactions monomials, including, e.g., $\int d^dx\sqrt{g}\ln(R)$ and $\int d^dx\sqrt{g}R^{-n}$, popular in cosmological model building, can consistently be decoupled from the flow and are not generated dynamically. Moreover, expanding the $f(R)$-equation in positive powers of the scalar curvature, it was found that the monomials $R^3, R^4, \ldots$ do not give rise to relevant couplings. This result provided first hand evidence that the UV-critical surface of the non-Gaussian fixed point is actually finite-dimensional, backing up the predictivity of the construction.

Building on these results, [t09/012] carried out the first non-perturbative approximation of the gravitational RG flow, which included the square of the Weyl-tensor as a non-scalar curvature term ($R^2 + C^2$-approximation). Notably, the gravitational fixed point known from the $f(R)$-computation remained stable in the presence of the new interaction monomial. Moreover, from the four coupling constants contained in the ansatz only three are associated with relevant directions implying an experimentally testable prediction of asymptotic safety at the four-derivative level. In addition it was demonstrated that asymptotic safety may be able to cure the sickness of perturbative higher-derivative gravity resulting from the occurrence of poltergeists. In [t09/024] the $R^2 + C^2$-computation was supplemented by a free scalar matter field. At the perturbative level, this setting constitutes the prototype of a theory which is perturbatively non-renormalizable at one-loop level: the C^2-interaction is the one-loop counterterm arising from the quantization of the Einstein-Hilbert action in the presence of the scalar. Most remarkably, the non-Gaussian fixed point known from the Einstein-Hilbert plus matter computation, persisted in the presence of the C^2-term, leading to the conclusion that asymptotic safety can also be saved once perturbative counterterms are included.

A.5 Integrability, AdS/CFT correspondence and the exact spectrum of the $\mathcal{N} = 4$ SYM theory

The most prominent example of AdS/CFT correspondence relates the $\mathcal{N} = 4$ super Yang-Mills theory and string theory on $AdS_5 \times S^5$. In the last decade, it became clear that, in the planar limit, the dilatation operator of the $N = 4$ super Yang-Mills theory is equivalent to an integrable super-symmetric spin chain. The problem of finding the complete spectrum of anomalous dimensions (or, equivalently, of quantizing the free strings in the $AdS_5 \times S^5$ background) was therefore reduced to the diagonalization of this long-range spin chain. In the limit of large charges, the spectrum is encoded in a set of Bethe ansatz equations, while for finite charges the energies are determined by the thermodynamic Bethe ansatz equations, alternatively written in the form of a so-called Y-system. The validity of the Bethe ansatz equations and that of the Y-system was established by extracting the anomalous dimensions for various operators and by comparing them with the predictions both from the perturbative gauge theory (weak coupling) and perturbative string theory (strong coupling). Among the most studied examples are the twist-two operator, whose anomalous dimension is related to the so-called cusp anomalous dimension, also known under the name of scaling function. On the string side, the corresponding state is associated with the folded rotating string with angular momentum S in AdS_5 and $J = 2$ in S^5. Another testing example is offered by the Konishi operator, the operator with the lowest charge whose anomalous dimension is not protected by supersymmetry. All the cases studied until now, involving computations up to five loop order in gauge theory and up to two-loop order for strings, confirm that Bethe ansatz equations and the associated Y-system are able to reproduce exactly both the perturbative gauge theory regime and the perturbative string regime. The existence of an integrable model which interpolates between the two perturbative limits confirms the validity of the AdS/CFT conjecture and provides a non-perturbative solution to the spectral problem.

General aspects of integrability, including the contributions of the authors and new results, were reviewed in the habilitation thesis [t10/042] and in the PhD theses [t09/286] and [t09/283] which were published as invited review articles in special numbers of J. Phys A. In [t10/042] the development of the ideas of integrability in the context of AdS/CFT are reviewed. Special emphasis is put on the relation with long-range integrable spin chains, the connection with the Hubbard model, the strong coupling limit of the Bethe ansatz equation. A chapter is devoted to the thermodynamical Bethe ansatz and the Y-system. In [t09/283] the emphasis is put on the formulation of the integral Bethe Ansatz equations as a Riemann-Hilbert problem. Several examples of such equations are solved perturbatively by Wiener-Hopf techniques. In [t09/286] the algebraic curve method is reviewed, together with the method of quantization at one loop proposed by the author together with P. Vieira. Various application concern the determination of the dressing phase at one loop at strong coupling (the so-called Hernandez-Lopez dressing phase), as well as the computation of finite-size corrections for different string solutions.

A.5.1 The BES equation and the scaling function *(N. Gromov, I. Kostov, D. Serban, D. Volin)*

The Bethe ansatz equations determining the cusp anomalous dimension, or the scaling function, were rewritten by Beisert, Eden and Staudacher (BES) as an integral equation for the magnon density. While at weak coupling this equation can be solved straightforwardly order by order in the coupling constant g, its strong coupling limit is non-uniform in the spectral parameter and the $1/g$ expansion is difficult to control. In [t08/007] we have proposed a method to transform the BES equation determining the anomalous dimension of the twist-two operators into a set of difference equations obeyed by the resovent, which are valid for arbitrary coupling constant. These equations can be solved at strong coupling recursively at any order in $1/g$. It was shown that the analyticity properties satisfied by the resolvent are sufficient to fix uniquely the solution and this justified the recursive procedure employed by the Basso, Korchemsky and Kotanski in 2007 to compute the cusp anomalous dimension.

An equation similar to the BES equation, proposed in 2006 by Freyhult, Rej and Staudacher (FRS) fixes the generalized scaling function. The generalized scaling function controls the large S behavior of the dimension of operators with $J \sim \ln S$. The method of the difference equation proposed in [t08/007] was extended to the FRS equation in [t09/044], and solved to the two-loop order at strong coupling. On the other hand, the two-loop generalized scaling function was obtained directly from the Bethe ansatz equations in [t08/094]. Up to a term due to the different order of limits implied by the different procedures, the two results agree. A initial disagreement with the direct string computation by Roiban and Tseytlin 2007 was subsequently corrected by the authors of the string computation. The small J limit was shown by Alday and Maldacena, 2007 to be described by the $O(6)$ sigma model. In [t08/094] the leading logarithmic terms associated with the $O(6)$ sigma model were evaluated for any order in $1/g$.

Inspired by the relation between the FRS equation and the $O(6)$ sigma model put forward by Basso and Korchemsky in 2008, the method of the difference equation was adapted to the generic $O(N)$ sigma model in [t09/081]. An analytical derivation of the mass gap of the $O(N)$ sigma models was given and the large-order behavior of the weak coupling asymptotic expansion for the energy was investigated. It was found that for sufficiently large N the series is sign-oscillating, which is expected from the large N solution of the sigma model, while for $N = 3$ and $N = 4$ the series are of constant positive sign.

The BES equation contains a dressing factor which is not determined by the $PSU(2,2|4)$ symmetry alone, but it is constrained by a crossing-like equation written by Janik in 2006. Beisert, Eden and Staudacher, 2006 wrote down an integral representation for the dressing factor, but a direct verification that this ansatz satisfies the crossing equations was lacking. In [t09/079], a constructive proof was given that the BES dressing phase is the solution of the crossing equation with minimal number of singularities.

A.5.2 Semiclassical limit and the algebraic curve method *(N. Gromov, D. Serban, I. Shenderovich, D. Volin)*

The semiclassical limit of the non-linear sigma model describing strings in $AdS_5 \times S^5$ can be expressed in terms of an algebraic curve with $PSU(2,2|4)$ symmetry. The algebraic curve can also be obtained by taking the continuum limit of the Beisert-Staudacher equations, and it was used as a constraint in fixing the general structure of these equations. A method to compute the string one-loop corrections by quantizing the algebraic curve was proposed in 2007 by Gromov and Vieira. Unlike the Beisert-Staudacher equations, which neglect wrapping interactions in the spin chain and therefore miss a part of the finite-size corrections, the quantization of the algebraic curve captures the exact finite-size corrections at one loop. In [t08/130] a very general, efficient way to compute the fluctuation frequencies is provided, which allows to determine the energy shift for generic multi-cut solutions. The procedure was applied to two-cut solutions, in particular to the giant magnon solution, and allowed to determine the finite-size corrections at subleading order. The latter were then compared to the finite-size corrections from Lüscher-Klassen-Melzer formulas and found to be in perfect agreement. In [t08/017] the formalism was used to compute the leading exponential correction to the quantum energy of the fundamental excitation of the light-cone gauged string in $AdS_5 \times S^5$, which is the giant magnon solution. Two independent ways to obtain this correction are presented: the first approach makes use of the algebraic curve description of the giant magnon. The second relies on the purely field-theoretical Lüscher formulas, which depend on the world-sheet S-matrix. The two approaches agree to all orders in g/Δ, where Δ is the string energy.

The method of the algebraic curve was used in [t11/017] to one-loop quantize the folded string solution for the type IIB superstring in $AdS_5 \times S^5$. Explicit results were obtained for arbitrary values of its Lorentz spin S and R-charge J in terms of integrals of elliptic functions. The leading three coefficients of strong coupling expansion of short operators and in particular the anomalous dimension of the Konishi state were obtained. Unlike in the case of the scaling function, this series is in half-integer powers of the inverse coupling constant $1/g$. The results agree with the values predicted numerically at intermediate coupling from the Y-system approach by Gromov, Kazakov and Vieira in 2009. This helped settle a long-standing controversy about the validity of the Y-system results at strong coupling. The finite size corrections for the large folded rotating string were also obtained in the form of a series in $1/\ln S$. The computation was done both in the algebraic curve formalism and using the Y-system.

The issue of the stability of the semiclassical solutions was addressed in [t08/051]. Highly spinning classical strings on $R \times S^3$ are described by the Landau-Lifshitz model or equivalently by the Heisenberg ferromagnet in the thermodynamic limit and their spectrum can be given in terms of spectral curves. It is a priori not clear whether any given admissible spectral curve can actually be realized as a solution to the discrete Bethe equations, a property which can be referred to as stability. In order to study the issue of stability, the general two-cut solution or elliptic curve was found and explored. It appears that all admissible spectral curves are indeed stable if the branch cuts are positioned in a suitable, non-trivial fashion.

A.5.3 The AdS_4/CFT_3 correspondence *(N. Gromov)*

A new case of AdS/CFT correspondence was discovered recently (O. Aharony, O. Bergman, D. L. Jafferis, and J. Maldacena, 2008), relating the $\mathcal{N} = 6$ super-symmetric Chern-Simons theory in 2+1 dimensions and string theory in the $AdS_4 \times CP^3$ background. This new example bears many resemblances the with AdS_5/CFT_4 case, including the fact that the computation of the spectrum in the planar limit could also be reduced to the diagonalization of an integrable spin chain. Many of the results which were obtained in the AdS_5/CFT_4 context were transposed to this new example. In [t08/128] the algebraic curve with $OSp(2,2|6)$ symmetry was derived. It encodes all classical string solutions at strong t'Hooft coupling and the full two loop spectrum of long single trace gauge invariant operators in the weak coupling regime. This construction can also be used to compute the complete superstring semi-classical spectrum around any classical solution. In [t08/121] a set of Bethe equations yielding the full asymptotic spectrum to all orders in the t'Hooft coupling. These equations interpolate between the 2-loop Bethe ansatz of Minahan and Zarembo and the string algebraic curve determined by N. Gromov and P. Vieira in [t08/128]. The several $SU(2|2)$ symmetries of the theory seem to highly constrain the form of the Bethe equations up to a dressing factor whose form was also also conjectured. In [t08/129], the fluctuation energies around the algebraic curve solution for the folded string were computed, using the results from [t08/128]. A resummation procedure was given, and under this procedure the one-loop scaling function computed from the algebraic curve coincides with the one computed from the Bethe ansatz equations proposed in [t08/121].

A.5.4 Classical integrability of the coset sigma model *(B. Vicedo)*

The classical integrable structure of Z_4-graded supercoset sigma-models, arising in the AdS/CFT correspondence, was studied in [t10/026] and [t09/143]. In [t10/026] the central object is the standard R-matrix of the Z_4-twisted loop algebra. In order to correctly describe the Lax matrix within this formalism, the standard inner product on this twisted loop algebra requires a further twist induced by the Zhukovsky map, which also plays a key role in the AdS/CFT correspondence. The non-ultralocality of the sigma-model can be understood as stemming from this latter twist since it leads to a non skew-symmetric R-matrix.

In [t09/143] the Lax connection of the Green-Schwarz superstring in $AdS_5 \times S^5$ was constructed within the Hamiltonian formalism. The result coincides with that obtained by M. Magro in 2009. It differs in a crucial way from the Bena-Polchinski-Roiban connection by terms proportional to the Hamiltonian constraints. These extra terms ensure that the integrals of motion are all first class, and that the Lax connection is flat in the strong sense.

A.6 Holography and gravity duals *(I. Bena, M. Graña, R. Minasian, N. Halmagyi, G. Giecold, F. Orsi, S. Massai)*

In the low-energy limit, the gauge/gravity correspondence maps a strongly coupled quantum field theory to a weakly coupled classical gravity theory. This map has far-reaching consequences for understanding the nature of string, gravity and gauge theories. It has led to the discovery of new important properties of supersymmetric gauge theories (integrability or dualities).

A.6.1 Supersymmetry breaking in AdS/CFT

One of the main open problems remaining in theoretical physics, if we believe in supersymmetry, is understanding how it is broken. It was shown recently that dynamical supersymmetry breaking in a long-lived meta-stable vacuum is a phenomenologically viable possibility in $\mathcal{N}=1$ supersymmetric QCD.

For theories with a gravity dual, the gauge/gravity correspondence would be at present the tool to study such strongly coupled phenomena. Refs. [t09/237] and [t11/019] are the first steps in a programme developed at IPhT to finding meta-stable vacua in certain $\mathcal{N}=1$ gauge theories whose supersymmetric vacua are well understood on the dual gravity side.

One such metastable vacuum was conjectured by Kachru, Pearson and Verlinde to arise by placing anti D3-branes in the Klebanov-Strassler dual geometry. In [t09/237] we have has succeeded in constructing implicitly the non-supersymmetric solution sourced by these anti-D3 branes, by perturbing around the supersymmetric Klebanov-Strassler solution. The 16-dimensional space of perturbations around the supersymmetric solution at the linearized level was solved, and the candidate meta-stable vacua fully identified within the system. The analysis has shown that the only solution that could correspond to a metastable anti-D3 brane solution must have a certain singularity in the infrared. In general such singularities are excluded in string theory, and if this is so in this construction, this implies that anti D3 branes must source non-normalizable modes, and hence are not dual to vacua where supersymmetry is broken spontaneously.

If so, this would invalidates the KKLT construction of de Sitter vacua in string theory, and would change completely the way string cosmology is done. On the other hand, if this singularity is acceptable, then we have constructed the first-order backreacted solution corresponding to the metastable vacuum of the Klebanov-Strassler theory. This solutions would allow one to find the vacuum expectation values of many physically relevant operators, which would allow one to better use this vacuum for string phenomenology and cosmology model-building purposes.

This construction was extended to M-theory putative duals of metastable vacua of 2+1 dimensional theories, where the supersymmetry breaking objects are anti-M2-branes, and a similar but stronger infrared singularity was found in all candidate metastable solutions [t10/169].

In order to extend the anti-D3 solution to less symmetric setups, a consistent supersymmetric truncation of the ten-dimensional supergravity system was identified in [t10/132], which contains as a subset the system used in [t09/237].

Besides their gauge theory relevance, the solutions with antibranes are also a crucial ingredient in mechanisms to construct viable cosmologies within string theory. In [t10/174], the full analytic form of the attractive potential for D3-branes, (which gives the inflaton potential in these string-cosmology scenarios) was computed.

A.6.2 New solutions dual to supersymmetric four-dimensional theories

In [t08/253], a class of super-conformal beta-deformed $\mathcal{N}=1$ gauge theories dual to string theory on $AdS_5 \times X$ with fluxes, where X is a deformed Sasaki-Einstein manifold. The supergravity backgrounds are explicit examples of Generalized Calabi-Yau manifolds: the cone over X admits an integrable generalized complex structure in terms of which the BPS sector of the gauge theory can be described. The moduli spaces of the deformed toric $\mathcal{N}=1$ gauge theories are studied on a number of examples and are in agreement with the moduli spaces of D3 and D5 static and dual giant probes.

New families of interpolating two-parameter solutions of type IIB supergravity were constructed in [t09/109]. These correspond to D3-D5 systems on non-compact six-dimensional manifolds which are T^2 fibrations over Eguchi-Hanson and multi-center Taub-NUT spaces, respectively. One end of the interpolation corresponds to a solution with only D5 branes and vanishing NS three-form flux. A topology changing transition occurs at the other end, where the internal space becomes a direct product of the four-dimensional surface and the two-torus and the complexified NS-RR three-form flux becomes imaginary self-dual. Depending on the choice of the connections on the torus fibre, the interpolating family has either $\mathcal{N}=2$ or $\mathcal{N}=1$ supersymmetry. In the $\mathcal{N}=2$ case it can be shown that the solutions are regular.

A.7 Enlarging the scope of the AdS/CFT correspondence

Recently AdS/CFT has found applications far removed from its original setting in string theory including AdS/QCD, AdS/CMT and entirely non-string-theoretic models such as Vasiliev gravity. This suggests that AdS/CFT, as a tool to study strongly coupled theories, has much wider applicability than initially appreciated.

A.7.1 Fundamental issues *(S. El-Showk)*

In two dimensions scale invariance combined with unitarity (and some other constraints) imply conformal invariance. While it is often naively thought that this also holds in other dimensions counter-examples have been known to experts for some time. In [t11/068] we examine the interesting case of free YM in $d \neq 4$ and find that it admits a non-unitary conformal extension given by inclusion of the ghost and anti-ghost field. More precisely the theory contains a unitary sector (the physical fields) but conformal symmetry does not commute with BRST so a physical field may be a descendent of a ghost. Unfortunately the combination of BRST, anti-BRST and conformal symmetry does not generate a finite dimensional algebra and it is thus not clear that this structure can be extended beyond the free theory. Interestingly, however, combining only BRST or anti-BRST with conformal symmetry does generate a closed sub-algebra of $OSp(d,2|2)$.

In order to isolate essential features of the AdS/CFT duality, and denude them of their stringy origins, in [t11/069] we exploit the conformal bootstrap construction of CFTs to determine which (strongly) coupled CFTs might admit AdS duals. Constrained only by conformal invariance we find (independently of any underlying microscopic model) necessary conditions for a sector of the CFT to admit a natural description in terms of a dual bulk theory and compare our finding to known examples in order to extract the general principles underlying the duality. This approach also highlights the qualitatively different nature of perturbative and non-perturbative bulk states in the CFT, with the former admitting a natural bulk description while the latter seem to live most naturally in the CFT (as they are manifestly holographic).

A.7.2 Stringy corrections *(R. Minasian)*

Stringy corrections in AdS/CFT generally fall into the category of either α' effects or string loop effects, corresponding to $1/\lambda$ and $1/N$ corrections, respectively, in the dual field theory. While $\alpha'^3 R^4$ corrections have been well studied, at least in the context of $\mathcal{N} = 4$ super-Yang-Mills, less is known about the $1/N^2$ corrections arising from closed string loops. In [t10/161], $\mathrm{AdS}_5 \times X_5$ compactifications of the IIB string were considered, and the closed string loop correction to the anomaly coefficients a and c in the dual field theory were computed. For $T^{1,1}$ reductions, the string loop correction yields $c - a = 1/24$, which is the contribution to $c - a$ of a free $\mathcal{N} = 2$ hypermultiplet. The paper also started the study of reductions to lower dimensional AdS theories as well as the investigation of the nature of T-duality with higher derivatives.

A.7.3 New solutions duals to two-dimensional theories *(G. Giecold, N. Halmagyi)*

In [t09/326] we constructed a family of holographic RG flows from eleven-dimensional supergravity on the seven-sphere. An important technical tool we used was a particular truncation of maximally supersymmetric $SO(8)$-gauged supergravity in four dimensions. The space of AdS_4 solutions within this truncation have been known for some time but it had been an outstanding problem to classify the domain wall solutions which interpolate between them. We found new BPS flow solutions which interpolate between all the BPS critical points in this truncation and gave a three-dimensional field theory interpretation. The generic flow in this class preserves just two supercharges and due to this minimal amount of supersymmetry, the gravity techniques we developed were crucial in understanding the phase structure of the field theories. A key structure of this family of flows is a certain universality in that the generic flows in this family all terminate at the same point in the IR, demonstrating that one particular AdS_4 solution is an attractive basin in the space of BPS solutions.

There exists some incertitude in the literature about the nature of the deconfining phase transition in 2+1 dimensional gauge theories - whether this transition is first-order or Kosterlitz-Thouless. Given that there exists a Klebanov-Strassler-like supergravity solution dual to a confining 2+1 dimensional gauge theory, we have constructed the black hole solution dual to the deconfined high-temperature phase of this theory [t09/221], and argued that the physics of this solution indicates that the phase transition is not Kosterlitz-Thouless.

A.7.4 AdS/CFT for condensed matter applications *(N. Halmagyi)*

With a view towards studying quantum field theories of interest to condensed matter physics, we have studied gravitational systems dual to field theories which are not Lorentz invariant. One crucial issue in applying holographic techniques to such field theories is establishing that the gravitational background dual to the ground state of field theory is stable. In the work [t10/246] we performed a detailed analysis of the spectrum around a particular non-BPS AdS_4 background found from eleven-dimensional supergravity on the seven-sphere. The background had been proposed in the literature as the ground state of the first string embedding of a so-called holographic super-conductor. We computed a family of modes which violate the Breitenlohner-Freedman bound thus rendering this solution unstable.

In the work [t11/066] we have used four dimensional gauged supergravity to classify gravity solutions to certain non-relativistic quantum field theories. The field theories in question, while not possessing Lorentz invariance do preserve a particular scaling symmetry. The total symmetry groups of these solutions are known as Schrödinger or Lifshitz symmetries. We found several infinite classes of solutions to four dimensional gauged supergravity with these symmetries, some of which are known to admit embeddings into string theory.

A.8 Topological recursion

In many problems of enumerative geometry, one is interested in counting geometrical objects with given topologies. For instance in string theory, one wishes to “count” Riemann surfaces with a given number of handles and given number of boundaries, with a certain weight. Random matrices can also be rephrased into the problem of counting discrete surfaces (for instance triangulations) of given topologies. In many of these problems it was found, or sometimes only observed or conjectured, that there is a universal relationship between counting functions of different topologies. The topological recursion is a recursion which allows to count surfaces of higher topologies, in terms of number of surfaces of lower topologies. In some sense it says that every surface can be decomposed into a pair of pants and a lower topology surface (see figure). Eventually, the topological recursion allows to count objects of all possible topologies, by knowing only how to count objects with the lowest topology, i.e. the disc and cylinder. We wrote a review on this subject [t08/189].

A.8.1 Topological recursion and matrix models *(B. Eynard, N. Orantin, G. Borot, O. Marchal)*

Initially, the problem in random matrices, was to find all the coefficients of the large size expansion of a random matrix problem. It was found that those coefficients could be computed recursively: each new coefficients can be computed from the previous. Eventually, this shows that all the coefficients are fully determined by the knowledge of the first one. The first coefficient, called the initial data, or also called the spectral curve, is not determined by this recursion, it has to be determined by another method, depending on the problem under consideration.

This led us to define, for every initial data (i.e. for any spectral curve), a sequence of coefficients determined by this recursion. They are sometimes called symplectic invariants of the spectral curve. This is a mathematical axiomatical definition. Its interest comes from the fact that the sequence of coefficients defined this way, have lots of applications in physics and mathematics, and also they have many nice geometrical properties: first they are invariant under symplectic transformations of the spectral curve, whence their name, and they have nice modular transformations, they obey the so-called special geometry, and they encode an integrable system.

Many of our efforts in the past few years focused on studying the mathematical properties of the symplectic invariants and topological recursion.

For instance in [t09/015], we try to understand the integrable structure of those invariants, and we show that they satisfy some determinantal formulae, which are typical of integrable systems. In [t08/164] we study the modular properties of those invariants, and we show that they transform in a way opposite to θ–functions. This shows, that if we multiply them by a θ–function, we get some modular invariants.

In [t09/196], we try to understand the geometric origin of the topological recursion. In some sense, the symplectic invariants should count some number of surfaces living in a certain space, and obeying certain symmetry properties (although it is not so clear which space and which symmetry properties in general). The recursion consists in observing that a surface can be cut into pieces, and thus the number of surfaces can be obtained by adding and multiplying the numbers of elementary pieces, this is what the topological recursion does. Imagine that we can start from one boundary (which has the shape of a circle) of the surface, and propagate it at constant velocity parallel to itself into the surface. At the beginning, the boundary is a circle, and sweeps a cylinder. But necessarily, at some time, the boundary cannot remain a circle, it gets pinched. We cut the surface at that time, and remove the cylinder swept. The remaining piece of the surface has in general a smaller topology, and thus we get a recursion on the topology of the surfaces we count (see fig.A.1).

In [t11/045], we found a new formula, expressing the symplectic invariants, in terms of counting Riemann surfaces with a weight given by some topological characteristic classes. This leads to associate to any spectral curve a certain characteristic class in the moduli space of Riemann surfaces. This characteristic class is very simply computed as the Laplace transform of the spectral curve. The implications of that formula are still to be understood. We could show so far, that the formula introduced in [t11/045] reproduces famous formulae as special cases, for instance the famous ELSV (Ekedahl–Lando–Shapiro–Vainshtein) formula (in other words, the characteristic class of the Lambert spectral curve is the Hodge class), or the Mariño–Vafa formula (the characteristic class of the framed vertex spectral curve is the product of 3 Hodge classes) are special cases of it. This formula also shows that mirror symmetry is very closely related to Laplace transform.

A.8.2 CFT approach to matrix models *(I. Kostov, N. Orantin)*

The CFT description of the matrix models [t98/112] can be used to obtain in a closed form the genus expansion of the observables. The saddle point of a large N matrix integral defines a complex curve. In [t10/283] the genus expansion is obtained in terms of a CFT associated with this curve. To each branch point of the Riemann surface one associates an operator which

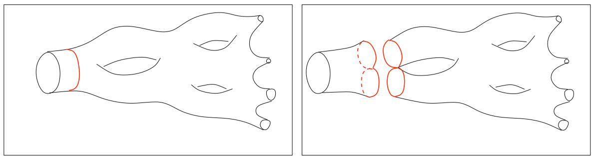


Figure A.1: Topological recursion: we start from one boundary (which has the shape of a circle) of the surface, and propagate it at constant velocity parallel to itself into the surface. At the beginning, the boundary is a circle, and sweeps a cylinder. But necessarily, at some time, the boundary cannot remain a circle, it gets pinched. We cut the surface at that time, and remove the cylinder swept. The remaining piece of the surface has in general a smaller topology, and thus we get a recursion on the topology of the surfaces we count.

represents a twist field dressed by the modes of the twisted boson. The partition function of the matrix model is computed as a correlation function of such dressed twist fields. The method is tested on the simplest example of the Hermitian matrix model, where the classical solution is described by a hyperelliptic Riemann surface.

Another powerful method to compute the genus expansion is the topological recursion, which also can be formulated entirely in terms of the complex curve. It is interesting and important to understand the relation between the two methods. It is shown [t10/125] that although the two approaches lead to different graph expansions for the higher genus terms, the final results are identical. Moreover, the diagrams of the CFT approach can be obtained by assembling graphs from the graph expansion that stems from the topological recursion.

A.8.3 Quantization of Riemann surfaces *(B. Eynard, N. Orantin, G. Borot, O. Marchal)*

The random matrix model which is solved by the topological recursion, is a model of a random matrix which possesses the hermitian symmetry. Other ensembles of matrices can be defined with other symmetries. They are often called Wigner's ensembles classified by a number β, which is $\beta = 1$ for hermitian symmetry, $\beta = 2$ for symplectic symmetry, and $\beta = 1/2$ for orthogonal symmetry, but it can be defined for every other values of β.

The method which led to the topological recursion for $\beta = 1$, can be extended to every value of β, with very little changes [t09/175], [t10/154]. In fact, the topological recursion itself doesn't change, which shows that it is a very universal object. The only thing which changes is the initial data, the spectral curve.

For $\beta = 1$, the spectral curve is a curve in the (x, y) plane, it is usually given by an equation $f(x, y) = 0$ for a certain analytical function f, and the ingredients involved in the formulation of the topological recursion, are geometric properties of that curve: the notion of genus, cycles, matrix of periods, holomorphic and meromorphic forms, form–cycle duality, Riemann bilinear identity, all of them introduced more than 150 years ago by Riemann and the other founders of the Riemannian geometry of surfaces.

For $\beta \neq 1$, we see that the topological recursion doesn't change, provided that we redefine all those geometric notions. The spectral curve can still be written with a function $f(x, y)$ but now x and y are some quantum variables, they don't commute, they satisfy $yx - xy = \hbar$ where $\hbar$ is proportional to $\beta - 1$. If we appropriately redefine the notions of genus, cycles, matrix of periods, holomorphic and meromorphic forms, we find that the topological recursion is unchanged. Also, with those definitions, all the nice properties of Riemannian geometry remain unchanged, like the Riemann bilinear identity, or the form–cycle duality. This allows to define in a very natural way, a "quantum" Riemannian geometry of surfaces. Moreover, unexpectedly, we found that the very definition of those geometrical object, implies a Bethe ansatz as a consistency condition. In some sense, the Bethe ansatz is the condition that the integral of a differential meromorphic form along a cycle, depends only on the homology class of the cycle, and not on the precise locus of the cycle on the surface. The Bethe ansatz is the condition that cohomology is well defined. This is what we do in [t09/175, t10/154]. The consequences of that geometry are still under exploration.

A.8.4 Topological recursion, algebraic geometry and topological strings *(B. Eynard, A. Alexandrov, N. Orantin, G. Borot, O. Marchal)*

An important application of the topological recursion concerns algebraic geometry and topological string theory.

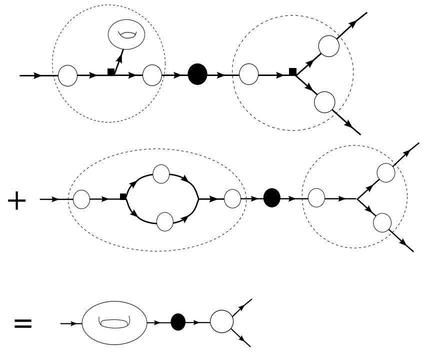


Figure A.2: An example of the correspondence between the graph expansions in the topological recursion and CFT approaches.

Topological string theory, is the low energy limit of string theory, where all the strings are in some sense frozen to their lowest possible energy states, but there can be many such lowest states, which can not be deformed into one–another, because the compactification Calabi–Yau space has a non-trivial topology.

In string theory in general, one is interested in counting in how many ways a string can propagate from a given initial state to a given final state. Topological string theory thus consists in counting, up to conformal deformations, how many surfaces with given boundaries and topology, can be embedded in a target space. This number is usually an integer, or in fact a rational number because surfaces with symmetries are counted quotiented by their symmetry order, and is called Gromov-Witten invariants by mathematicians in algebraic geometry.

In 2007, it was conjectured by M. Mariño and al (BKMP conjecture), that, if the target space has an additional toric symmetry, then its Gromov–Witten invariants should satisfy the topological recursion. They checked this conjecture on many examples, but a full general proof is still missing and has become an important challenge among algebraic geometers. Only very few cases, involving the simplest target spaces, have been proved. This would be an important fact, since this would allow an explicit computation of those invariants.

In [t07/104], we proved that the Gromov–Witten invariants of a point (the simplest possible target space) indeed satisfy the topological recursion. This was not the first proof, but it was the first one using matrix models. In [t09/055] and [t09/101], we were the first to prove the next simplest case, called the Bouchard-Mariño conjecture. In [t09/055], we used a matrix model, and in [t09/101], we provided a direct algebraic proof, using the so called "cut and join equations". Later, another case of the BKMP conjecture, for the target space $\mathbb{C}^3$, was proved independently by Chen, and Zhou, using the same ideas we had introduced in [t09/101]. Since then, we found another much simpler proof for $\mathbb{C}^3$ in [t11/045], using only basic algebraic manipulations, and the already proved case of the point. We hope that the ideas introduced in [t11/045] will allow to prove the conjecture for more complicated geometries.

Beside, we made another attempt to prove the BKMP conjecture for general target spaces, using a matrix model. In [t10/029], we showed that Gromov–Witten invariants can be formulated as a random matrix problem. This had been long expected in principle since the famous works of Dijkgraaf and Vafa, and here we exhibited an explicit matrix model, which works for every geometry, i.e. every toric 3-dimensional Calabi–Yau space. This matrix model does satisfy the topological recursion, but the difficulty in proving the BKMP conjecture, was to identify the initial data of the recursion, i.e. the spectral curve. In order to prove the BKMP conjecture, one has to prove that the spectral curve arising from the matrix model, is the same as the spectral curve conjectured by BKMP, which is the "mirror" of the target space, issued from mirror symmetry. The matrix model's spectral curve can be computed as the curve which extremizes the matrix model's energy. In [t10/099] we proved that the mirror curve is indeed an extremum of the matrix model's energy, which confirms BKMP conjecture. Unfortunately, the matrix model's energy can have many other local extrema, and we couldn't prove that the mirror curve is indeed the absolute extremum, we could only prove that it is one among possible local extrema, and thus our computation is not

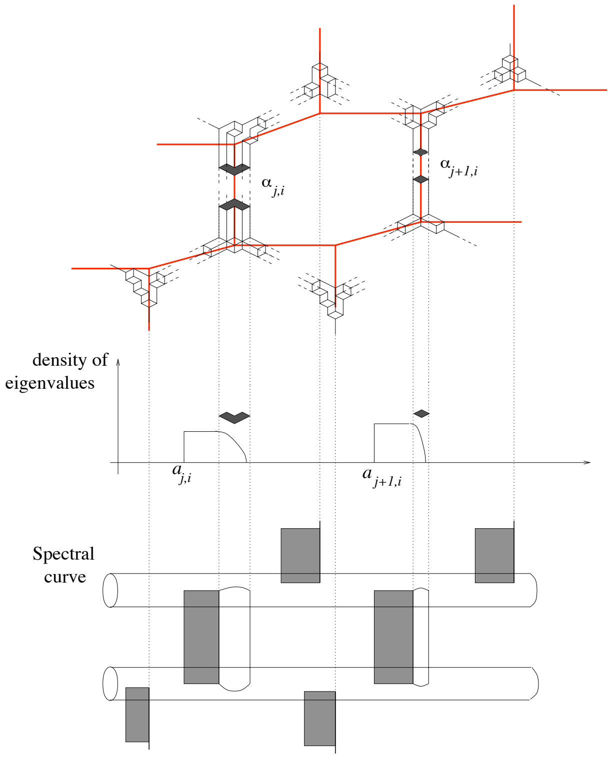
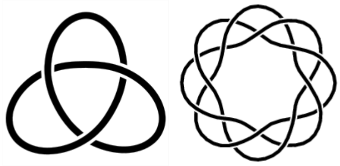


Figure A.3: The Gromov–Witten invariants can be computed by the topological vertex formula, i.e. by counting 3d partitions, glued along the edges of a graph encoding the geometry of the target space. The eigenvalues of the matrix model are the positions of boxes across horizontal slices (i.e. cutting vertical edges). The matrix model's spectral curve is the analytical continuation of the limiting density of those eigenvalues in the large size limit. It is thus a surface made of several sheets (each sheet is represented by a horizontal cylinder, there are as many sheets as the number of horizontal slices of the graph), glued along cuts (represented by vertical cylinders). It also has poles corresponding to the "frozen" boxes (accumulations of poles are represented by grey strips). Thanks to the symplectic invariance property of the topological recursion, the poles don't contribute, and can be ignored. After subtracting the poles, the spectral curve is an algebraic curve, which can be seen as the thickening of the graph, known as the mirror curve.

yet a mathematical proof of BKMP.

In [t08/164], we use the symplectic invariants defined from the topological recursion, to propose a candidate for the full non–perturbative topological string partition function. The main reason for our proposal, is that it is modular invariant (which we prove in [t08/164]). In topological strings, Bersahdsky, Cecotti, Ooguri and Vafa have found the famous "holomorhic anomaly equation", which says that the perturbative part of the string theory partition function is not modular invariant, but modular invariance can be recovered by adding some non–analytical terms. This was not fully satisfactory, because, according to the expected duality between string theory and conformal field theory (AdS/CFT correspondence), the partition function should be analytical. We show in [t08/164], that modular invariance can also be restored non–perturbatively without breaking analyticity. Our partition function also has the background property invariance (a perturbative expansion can only be defined near a background, but string theory should eventually be independent of the choice of background), and satisfies many properties expected for a string theory.

Finally, in [t11/134], we consider another application of the topological recursion to knot theory. Gopakumar and Vafa suggested that the invariants (Homfly colored polynomials) of a knot can be computed in terms of topological strings in a certain target space. In [t11/134], we show that the topological recursion can also apply to knot theory. Starting from the Chern–Simons matrix models, we can write a matrix model to compute the knot invariants of "torus knots"



(knots which can be drawn on a torus). Our computation proves that the spectral curve associated to a torus knot is a symplectic transformation of the unknot, thus confirming the Gopakumar-Vafa hypothesis.

A.9 Random matrices

Random matrix theory is interested in the statistics of eigenvalues of a random matrix, particularly in the limit of large random matrices. The leading order has been known since the pioneering works of Wigner, Dyson and Mehta. One of the questions we address is understanding the subleading corrections to those laws, to all orders. Other subjects of research concern the relation between matrix models and tau functions and integrability, as well as the relation with quantum gravity in two dimensions and the relation with non-critical string theory.

A.9.1 Large random matrices *(M. Bergère, G. Borot, P. Desrosiers, B. Eynard, O. Marchal, N. Orantin)*

In [t08/026], we show how to compute the large size expansion to all subleading orders for various matrix models with hermitian symmetry, including the so-called one-matrix and multi-matrix models. We show that to all orders in the size, there are quasi-periodic oscillations, and we compute them exactly to all orders. Those oscillations are due to some tunneling effects describing eigenvalues jumping from one region with large probability to another.

We have generalized the results known for matrices with Hermitian symmetry to other symmetries. In [t09/163] we compute the large size expansion of super-matrices containing both a bosonic and a fermionic part. We show that the large N expansion is again given by the same topological recursion as for hermitian symmetry, and in some sense super-matrices are just an analytical continuation of ordinary hermitian matrices, except that fermionic eigenvalues are counted with a negative multiplicity. This also leads to an interesting supersymmetry formula which exchanges the roles of bosonic and fermionic variables.

Another ensemble of random matrices which was studied is the so-called β–ensemble described in section (A.8.3). The hermitian symmetry $\beta = 1$ has a self–dual property, which allows to integrate over the angular part very easily. But for other values of β, there is no efficient known formula to compute integrals over angular parts of random matrices. In [t08/081] we find some new recursion relations among angular integrals, and we find some new formulae which we hope could lead to a better understanding of those cases. Our observation is that in the n-dimensional space, when $n-1$ vectors are chosen orthogonal, then there is only one possibility of chosing the n^{th} vector so that it is orthogonal to the other $n-1$. This gives a relationship between the angular part of matrices of dimension n and $n-1$.

In [t10/154], [t09/175], [t08/140] we find a systematic way to compute the large size expansion of the statistical distribution of eigenvalues of all β one-matrix ensembles. The method is a generalization of the topological recursion, and yields a bonus.

The probability distribution of the largest eigenvalue of a random matrix is universal; it is the same for every random matrix model (under reasonable assumptions) and it depends only on the symmetry group. This probability distribution is called the Tracy-Widom law. In [t10/137], [t10/166], [t10/187] we compute the asymptotic expansion of the Tracy-Widom law for all β symmetry groups and we relate it to the topological recursion; in other words we provide a geometric interpretation to the Tracy-Widom law.

It has been long observed and conjectured that the Wigner's ensemble β and $4/\beta$ are closely related. This duality is carefully proved in [t08/013] using relations among Jack polynomials, and using a matrix Fourier transform.

A.9.2 Matrix models and tau functions *(A. Alexandrov, O. Marchal)*

Random partitions is a popular subject of modern mathematical physics. They appear in such diverse areas as 2d Yang-Mills and 3d Chern-Simons theory, instanton calculus of supersymmetric gauge theories in different dimensions and Hurwitz-Hodge-Gromov-Witten theory. Of course, sums over partitions/representations play an increasing role in string theory, so all aforementioned theories can be described by particular string models. In [t10/074] we derive exact matrix integral representations for different sums over partitions. The characteristic feature of all obtained matrix models is the presence of logarithmic (or, vice versa, exponential) terms in the potential. The Toda lattice integrability of the basic sums over partitions can be easily derived from the matrix model representation.

Since the early nineties, when the spectacular Witten conjecture was proved by Kontsevich, the Kontsevich-Witten tau-function, that is the partition function of two-dimensional topological gravity, became an inevitable part of mathematical physics. In [t10/146] we constructed a simple cut-and-join operator representation for the Kontsevich-Witten tau-function. Our derivation is based on the Virasoro constraints. Possible applications of the obtained representation are discussed.

Hurwitz numbers count the ramified coverings of a Riemann surface. Their calculation is obviously important in string theory and from time to time it attracts certain attention. In [t11/100] we have investigated integrable properties of different generating functions of generalized Hurwitz numbers. The functions with simple integrability of Toda and KP type are singled out.

There exist many definitions of a tau function and integrable system. One of them, is the notion of isomonodromic tau function, introduced by Miwa-Jimbo, which associates a tau function to a linear system of differential equations, based on the WKB asymptotics. The definition of Miwa-Jimbo applies only to non-degenerate systems (when the eigenvalues of the limitting system are all distinct). But the so-called 2-matrix model (introduced for instance in order to study the Ising model on a random lattice)is degenerate. In [t08/196], in collaboration with M. Bertola, a generalization of the Jimbo-Miwa construction was proposed in order to prove that the 2-matrix model is indeed an isomonodromic tau function.

A.9.3 Scattering of folded strings in two-dimensional Minkowski space *(I. Kostov)*

According to a conjecture, advanced by Maldacena and based on the matrix model for the Euclidean black hole, the Lorentzian black hole metric is generated by condensation of long folded strings. Maldacena showed that the reflection of a long folded string from the Liouville potential is given by the boundary two-point function function in a certain limit. The amplitude for a state containing two long folded strings to come from and go back to infinity is computed in [t07/188]. The computation is done both in the worldsheet theory and in the dual matrix model, the matrix quantum mechanics. The matrix model description allows to evaluate the amplitudes involving any number of long strings, which are given by the mixed trace corelators in an effective two-matrix model.

A.9.4 The Student ensemble of correlation matrices: eigenvalue spectrum and Kullback-Leibler entropy *(G. Biroli)*

In collaboration with J.-P. Bouchaud and M-Potters and motivated by the analysis of financial data we studied in [t08/027] a new ensemble of random correlation matrices related to multivariate Student (or more generally elliptic) random variables. We established the exact density of states of empirical correlation matrices that generalizes the Marcenko-Pastur result. The comparison between the theoretical density of states in the Student case and empirical financial data is surprisingly good, even if we were still able to detect systematic deviations. Finally, we computed explicitely the Kullback-Leibler entropies of empirical Student matrices, which are found to be independent of the true correlation matrix, as in the Gaussian case. We provide numerically exact values for these Kullback-Leibler entropies.

A.10 Random geometries

Statistical models can be considered not only on lattices which are regular, but also on random lattices with a fixed topology (they can be drawn on a surface, for example a plane, a sphere, a torus, etc.). They were initially introduced in connection with quantum gravity, but they appear now in various problems in physics, ranging from string theory to crystal growth, or in biology to describe fluctuating membranes.

The Ising model on a random surface, introduced by Kazakov in 1986, is the simplest model of gravity coupled to matter. Another example studied is the $O(n)$ model, introduced by Kostov in 1988, which is a model of self-avoiding loops on a random lattice. This model was used to study boundary critical phenomena in random geometry. One possible formulation of the statistical models on random graphs is in terms of random matrices, since the Feynman graphs for matrix integrals generate random surfaces of arbitrary topology. Another formulation, of combinatorial nature, is given in terms of random maps.

Statistical models can be also considered on random trees. Random trees arise in many branches of science, ranging from the social sciences through biology, physics and computer science to pure mathematics. In physics, random trees often occur in the context of statistical mechanics or quantum field theory, and fall into one universality class, called *generic random trees*. Another large class of random trees arises in *growth processes* (for instance branched polymer growing in a solution), and in many important real world cases one can observe the structure of the growing tree but only guess the rules which govern the growth (social networks, the internet, citation networks, etc.).

A.10.1 Statistical models on random lattices *(M. Bergère, G. Borot, B. Eynard, N. Orantin, A. Prats-Ferrer)*

In [t07/118], we compute the probability of Ising model configurations with fixed given spin signs on the boundaries of the surface, with an arbitrary number of boundaries, and an arbitrary topology.

In [t08/072], we compute the probabilities for any topologies of another statistical model called "chain of matrices", which is an extension of the Ising model where spins can have L different values from 1 to L, and can randomly change by unit jumps. We prove that those probabilities are computed by the topological recursion.

In [t09/160], we study another statistical model called $O(n)$ model. We found a method to compute the probability of such random loops in various configurations, in all topologies. The computation of probabilities on the plane were already known, and in [t09/160] we compute them in all other topologies, and the answer is again given by the same topological recursion already found in many other models. This shows that the topological recursion is a very universal tool. We conjecture that many other statistical models are also solved by the same topological recursion, for instance the Potts model.

It is also particularly interesting to study what happens for very large lattices. Physicists have understood in the 80's that the limit of large lattices is described by a conformal field theory coupled to gravity, but this is still not yet considered proved to the mathematics community. In [t09/015], [t09/116], we establish rigorously some of the results implied by conformal field theory.

Another interesting problem in statistical physics concerns crystal meltings, also called 3D partitions. The problem consists in randomly piling cubic boxes in the corner of a room, and ask what is the typical surface, in the limit of a large room with a large number of boxes. The typical shape was described in the famous works of Okounkov in 2003, but what about fluctuations around the typical shape?

In [t08/056], [t09/050], we show that this problem can be mapped to a random matrix model, We show how the statistics of the eigenvalues of a random matrix, are related to the statistics of the height of the cubes in the room. This allows to prove that corrections to the typical shape, to all orders in powers of the size of the room, are computed by the topological recursion. This also gives an explanation of why the statistical behaviors observed in crystal melting are the same as the universal laws of random matrices.

A.10.2 Geometrical critical phenomena, matrix models and 2D gravity *(J.-E. Bourgine, K. Hosomichi, I.K. Kostov)*

The boundary critical phenomena appear in a large number of fields, ranging from solid state physics to string theory. The situation becomes more interesting when the degrees of freedom on the boundary have less symmetry than those in the bulk. In this case one speaks of surface anisotropy. The most studied example of such boundary behavior are the D-branes in string theory. Another example is given by the ferromagnets with surface anisotropy, which can have a rich pattern of surface transitions. A good laboratory for studying such phenomena is the $O(n)$ loop model with $-2 < n < 2$. In the loop gas formulation of the anisotropic boundary conditions, the boundary conditions are introduced by changing the Boltzmann weights of the loops that touch the boundary [t06/155]. The problem was formulated on a fluctuating lattice in [t07/036]. An exact solution was obtained for the dense phase of the loop gas. The interpretation of the solution based on the boundary 2D quantum gravity confirms the spectrum of the boundary operators conjectured in [t09/186]. A matrix model formulation of the anisotropic boundary conditions was presented in [t08/193]. It was shown that in the rational points of the $O(n)$ model the anisotropic boundary conditions correspond to "alternating height" boundary conditions in the RSOS models. The bound-

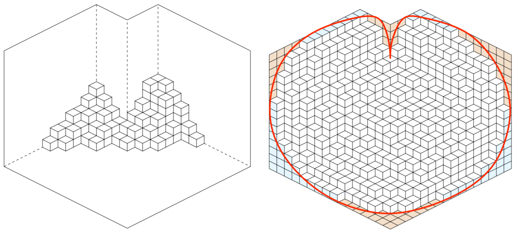


Figure A.4: A 3D partition, is a piling of boxes in the corner of a room (the room itself may have corners). It is also a model for crystal melting. When the number of boxes is large, one observes a limit shape separating a “liquid” region from a “frozen” region. The limit shape was found by Kenyon-Okounkov and Sheffield in 2003. Here, we recover the limit shape using a matrix model, and we also find all corrections to the limit shape, as an asymptotic expansion in the size of the domain.

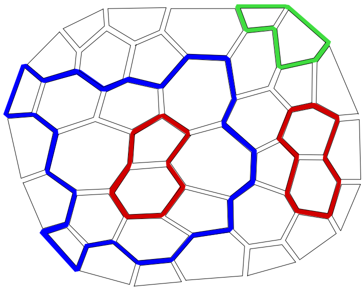


Figure A.5: A loop configuration for the $O(n)$ loop gas with anisotropic boundary conditions. The loops that touch the boundary (in blue and green) have fugacities n_1 or n_2 depending on their color ($n_1 + n_2 = n$).

ary correlation functions involving two different anisotropic boundary conditions were computed in [t09/041].

The solution for the dilute phase of the loop gas was obtained in [t09/186] using the correspondence with a matrix model. In this, more complicated, case the boundary coupling constants should be tuned to obtained a conformal boundary condition. The key result is the analytic expression for the boundary two-point correlator for any value of the bulk and boundary coupling constants. The solution leads to the same boundary phase diagram and the boundary critical exponents as those obtained in [t09/073]. Moreover, the solution allows to study the bulk and the boundary deformations away from the anisotropic special transitions. In particular it shows how the anisotropic special boundary conditions are deformed by the bulk thermal flow towards the dense phase.

A.10.3 Distance statistics in random maps *(J. Bouttier, E. Guitter)*

Discrete models for fluctuating surfaces appear in various domains of physics, ranging from the study of biological membranes to string theory. Such discrete random surfaces correspond to combinatorial structures called *maps*, which are the subject of an active field of research with deep algebraic and probabilistic aspects. Algebraic aspects arise when one addresses the fundamental problem of *enumeration*: how many maps (*i.e.* of given size or topology) do exist? Probabilistic aspects are related to refined questions about the *geometry* of random maps.

The enumeration problem has a long history, starting with Tutte's seminal series of papers in the 1960's, and punctuated with decisive contributions from physicists, namely matrix integrals and related methods.

In [t10/258], we present an introduction to these methods aimed at both physicists and combinatorists. The resulting counting formulas often take a remarkably simple form: this led people to look for alternate elementary derivations of these formulas, which are found in the form of *bijections* between maps and suitable trees. It was then realized that these bijections give access to further geometrical information on maps.

From the random geometry point of view, a natural observable is the *graph distance*. A salient question is the existence of scaling limits for the distance in large random maps, which should then correspond to models of continuous random surfaces. Of particular interest is the so-called *Brownian map* which describes the generic scaling limit of random planar maps in the universality class of so-called pure gravity, like maps with prescribed face degrees, for instance planar triangulations or planar quadrangulations. The Brownian map was shown to have the topology of the two-dimensional sphere but it has nevertheless a number of surprising geometrical properties, which place it half-way between a tree-like object and a smooth surface. A number of these properties were discovered and characterized quantitatively in the last four years by computing a number of laws for the distance statistics in maps.

Our analysis of the distance statistics in maps relies on three steps: (1) the aforementionned *bijective coding* of the maps by decorated trees, the so-called mobiles; (2) the exact derivation of a number of mobile generating functions, thanks to some underlying *integrable structure*; (3) and finally the analysis of the hereby obtained map enumeration results in the *scaling limit* of large maps and properly scaled distances. In [t07/163], attention is paid to the statistics of *geodesics* in maps. There it is shown that all the geodesics connecting two given points on the map remain close to each other so that they become identical in the scaling limit. This generic property fails however for a few "exceptional" endpoints which can be linked by (at most three) truly distinct geodesics. The distance-dependent distribution of these exceptional points was obtained. The most advanced result in the field of distance statistics is the computation in [t08/078] of the distance-dependent *three-point function* of planar maps, which gives the joint law for the distances between three random points on the map. A remarkable phenomenon of "confluence" of geodesics was discovered, which states that, in the scaling limit, the two geodesic paths leading from two arbitrary points to a given third one merge into a common geodesic before reaching this point. A precise quantitative study of the shape of geodesic triangles can be found in [t08/182] (see Figs.A.6 and A.7). The phenomenon of confluence reveals some underlying tree-like structure of the Brownian map. Heuristically, it was claimed that large maps can be viewed as made of a large component, the "mother universe" with attached small components, the "baby universes" arranged into tree-like structures. This picture is made more precise in [t10/020] where we explore the geometry of "minimal neck baby universes" (minbus) and derive a number of distance-dependent characterizations of these minbus (distance-dependent two-point function inside a minbu, law for the distance from a random point to the mother universe, etc).

All the results above deal with maps having the topology of the sphere but several extensions were obtained for more involved geometries. In [t09/138], we consider maps with a boundary and give explicit formulas for the bulk-boundary and boundary-boundary distance-dependent correlators in various encountered scaling regimes (small, dense or critical boundary). The critical boundary regime is characterized by a one-parameter family of scaling functions interpolating between the Brownian map and the Brownian Continuum Random Tree. We also address the question of the bulk-loop distance statistics in the context of maps equipped with a self-avoiding loop. Another natural extension consists in having maps of higher genus. A first characterization of their geometry is given in [t10/024] where a number of distance-dependent universal scaling functions are computed exactly, characterizing the distance statistics of large toroidal maps (probability distribution of the length of the shortest *non-contractible* loop passing via a random point - law for the distance between two random points).

Finally, in [t10/135], we return to the discrete setting and provide a novel viewpoint on the integrable structure at work in step (2) above. We show that the basic geometric observable, the distance-dependent two-point function, appears within the continued fraction expansion of the simplest "global" quantity, namely the generating function for maps with a boundary. This unexpected connection to the fundamental problem of map enumeration explains combinatorially the existence of general exact formulas for the two-point function.

A.10.4 Random tree growth by vertex splitting *(F. David)*

Motivated by our previous study of tree growth models by attachment processes (together with P. Di Francesco, E. Guitter, IPhT, and T. Jonsson, University of Iceland), and by our proposal of tree growth models for RNA folding, we have introduced and studied a new and general class of tree growth models by splitting and attachment processes ([t08/135], work with M. Dukes, T. Jonsson and S. Stefansson from the Univer-

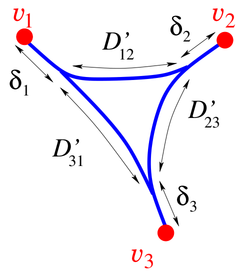


Figure A.6: A schematic picture of the phenomenon of confluence of geodesics in the Brownian map: if v_1, v_2 and v_3 are typical random points, the geodesics connecting them pairwise have common parts of non-zero length δ_1, δ_2 and δ_3. A "geodesic triangle" is thus characterized by a total of six lengths, whose law can be computed explicitly [t08/182].

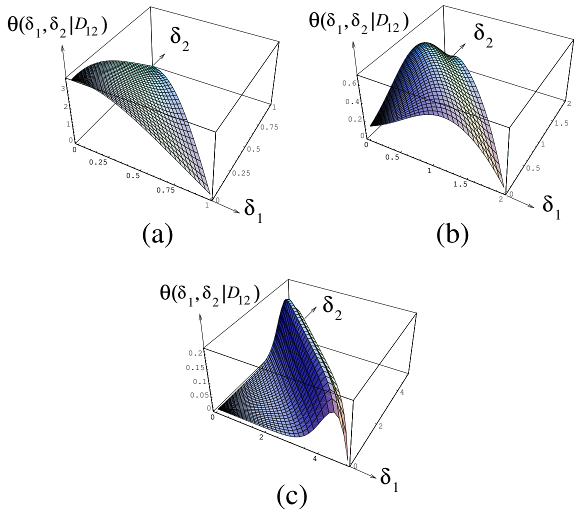


Figure A.7: Plots of the conditional probability density for (δ_1,δ_2) given the value of $D_{12} = D'_{12} + \delta_1 + \delta_2$ (see notations in Fig.A.6), here for (a) $D_{12} = 1.0$, (b) 2.0 and (c) 5.0.

sity of Iceland). This class of models is a vast generalisation (with some simplifications) of the RNA model of [t07/068], such that at each time step the tree is separated into two components by splitting a vertex and then connecting the two pieces by inserting a new link between the daughter vertices. Besides its interest for our physical questions, this model generalises also growth and fragmentation models considered in the mathematical litterature, such as the preferential attachment model and Ford's alpha-model for phylogenetic trees (in particular generalizations of Aldous models). A mean field theory as been developed for the vertex degree distribution. It is proven that this mean field theory is exact (no fluctuation corrections) in some special cases. The predictions of mean field theory have been checked to agree with extensive numerical simulations in general. Exact results are obtained for various correlation functions and mass distribution functions. In particular explicit formulas are given for the intrinsic Hausdorff dimension of the tree. It is shown that this dimension can vary from one to infinity, depending on the parameters of the growth process (splitting rates) for the model.

A.11 Liouville quantum gravity and KPZ

There is a close relationship between the behavior of critical systems in random geometries and that on regular lattice, discovered by Knizhnik, Polyakov and Zamolodchikov (KPZ). This relationship involves quantum gravity in two dimensions, which can be seen in terms of a conformal field theory with a component describing the matter degrees of freedom, and a Liouville component, which takes into account the fluctuations of the underlying lattice. The KPZ relation links the critical exponents in the fixed and the fluctuation geometries. Renewed interest to this subject comes from the relation of

Schramm-Loewner evolution (SLE) with conformal field theory and quantum gravity. In this context, it became possible to derive results already known to physicists in a mathematically rigorous way.

A.11.1 Rigorous proof of the KPZ relation *(B. Duplantier)*

(Critical) Liouville quantum gravity is a way to produce a "random geometry" from the two-dimensional Gaussian (massless) free field (GFF). One replaces the Euclidean area measure dz on a smooth planar domain D with a random measure $\mu_\gamma = e^{\gamma h(z)}dz$, where $\gamma \in [0,2)$ is a fixed constant and h is an instance of the zero or free boundary GFF on D. Since h is not defined as a function but as a distribution on D, one has to use a regularization procedure: in the joint work [t08/047] with Scott Sheffield (MIT), the quantum area measure μ_γ is constructed as the limit $\mu_\gamma = \lim_{\varepsilon\to 0} \mu_{\gamma,\varepsilon}$ of the regularized quantities $\mu_{\gamma,\varepsilon} := \varepsilon^{\gamma^2/2} e^{\gamma h_\varepsilon(z)}dz$, where $h_\varepsilon(z)$ is the mean value of h on the circle of radius ε centered at z. One interprets μ_γ as the area measure of a random surface $\mathcal{S} := (D,h)$ conformally parameterized by D (Fig.A.8). A quantum boundary length measure on boundary arcs of D is similarly constructed.

Consider now planar d-dimensional *fractal* sets and the scaling properties of their *Euclidean* or analogously *quantum measures*: • If one rescales the domain D via the map $z \to bz$, $b \in \mathbb{C}$ (so that its Euclidean area is multiplied by $|b|^2$) then the d-dimensional Euclidean fractal measure of a fractal $X \subset D$ is multiplied by $|b|^d = |b|^{2-2x}$, where x (the so-called *Euclidean scaling weight*) is defined by $d := 2 - 2x (\leq 2)$. • If X is a fractal subset of a random surface $\mathcal{S}$, and one rescales $\mathcal{S}$ so that its μ_γ-quantum area increases by a factor of $|b|^2$, then the quantum fractal measure of X is multiplied by $|b|^{2-2\Delta}$, where Δ is the analogous *quantum scaling weight* (Fig. A.8).

The celebrated Knizhnik-Polyakov-Zamolodchikov (KPZ) relation (1988) then states that x and Δ are related by $x = \left(1-\gamma^2/4\right)\Delta + \gamma^2\Delta^2/4$.

Twenty years after its discovery, the article [t08/047] with S. Sheffield gives the first rigorous proof of the KPZ relation. We also prove its extension to the boundary case. It rests in particular on the following Brownian property of the GFF: for fixed z, the circle average $h_\varepsilon(z)$ is standard Brownian motion in time $t := -\log\varepsilon$. Owing to the use of the regularized conformal factor $e^{\gamma h_\varepsilon(z)}$ in $\mu_{\gamma,\varepsilon}$ in constructing the Liouville measure μ_γ above, this allows seeing the KPZ relation as being in essence a Brownian *exponential martingale* property. This in addition places the KPZ formula in a much broader context than the original conformal field theory (CFT) approach: it is valid for any fractal set sampled independently of the Gaussian free field, and for any $\gamma < 2$ chosen independently from the fractal, in contrast with the initial KPZ scheme where $\gamma = \gamma(c)$ is fixed by the value of the central charge c associated with the critical fractal considered. The complete probabilistic proof of KPZ requires working with the limit measure μ_γ (or its boundary analog) and is given in the mathematical article [t08/047]; the essentials for physics are given in the Letter [t09/033] with S. Sheffield, and developed in the Les Houches Seminar lecture [t09/290] and the ICMP09 plenary lecture [t09/291].

Another issue is the definition of Liouville quantum gravity for $\gamma > 2$. In the usual CFT approach $\gamma(c) \leq 2$ with $c \leq 1$. The answer is given by *duality*. The corresponding random surface is a treelike foam of Liouville quantum bubbles of dual parameter $\gamma' = 4/\gamma$, $\gamma < 2$, ("baby universes") connected to each other at "pinch points" and rooted at a "principal bubble" parameterized by the domain D. As anticiped by Klebanov in 1992, a *non-standard* KPZ relation exists for $\gamma > 2$, which is dual to the usual relation. A probabilistic derivation of this dual KPZ relation is given in [t09/033], using the same Brownian perspective on the GFF (see also the two extended lectures [t09/290] and [t09/291]). A complete proof requires constructing the quantum area limit measure for $\gamma > 2$.

A.11.2 Derivation of the geometrical KPZ relations *(M. Bauer, F. David)*

Motivated by the recent derivation by B. Duplantier and S. Sheffield of the KPZ relations by probabilistic methods in a 2D geometric setting [t08/047], we have studied in [t08/159] the relation between this approach and the original derivation of the KPZ relations (by conformal field theory methods) in 2D quantum gravity. Indeed the new formulation applies when comparing the dimensions of fractal (deterministic or random) sets in a random measure given by an (a priori given) exponential of a free field theory (Liouville theory), while the old one applies to correlations functions of some CFT in a random Riemannian metric, and provides a justification of the Liouville theory as an effective field theory. In particular their domain of applicability are in fact somehow different (but overlap-

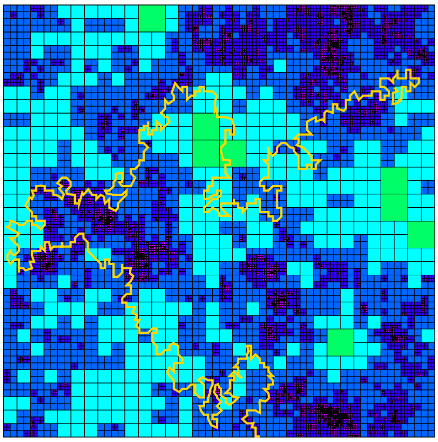


Figure A.8: A quantum gravity dyadic decomposition of the torus, where all Euclidean squares have similar small quantum areas δ. A random fractal X (here a self-avoiding walk) intersects these quantum squares with a probability scaling as δ^{Δ}.

ping).

We have given a derivation of the geometrical KPZ relations, by heat kernel and CFT methods, and using anomaly consistency arguments. This approach provides a covariant way (w.r.t. the diffeomorphisms) to define neighborhoods of fractals in 2D quantum gravity, via a quantum diffusion process. This shows that both formulations of the KPZ relations can be incorporated in a common general framework, within the realm of conformal field theory.

A.11.3 SLE, KPZ and Liouville quantum gravity *(B. Duplantier)*

Schramm-Loewner evolution (SLE) is a stochastic process, depending on a real parameter κ, which describes the *universal continuous scaling limit* of 2D critical curves such as, *e.g.*, percolation ($\kappa = 6$), self-avoiding walks ($\kappa = 8/3$) and Ising model interfaces ($\kappa = 3$). Its invention by Schramm in 1999 is on par with Wiener's 1923 mathematical construction of universal continuous Brownian motion. Critical phenomena in the plane (including SLE) are well-known to be related to conformal field theory (CFT), a fact anticipated in the so-called Coulomb gas approach to critical 2D statistical models. Liouville quantum gravity, itself a CFT, can be heuristically coupled to other CFT's via KPZ, and this has been used to predict properties of critical curves and SLE.

However, in the joint work [t10/223] with S. Sheffield, we provide the first *rigorous* connection between SLE and Liouville quantum gravity. We show that when two boundary arcs of a Liouville quantum gravity random surface are conformally welded to each other (in a quantum length-preserving way) the resulting interface is an SLE (Fig. A.9). In particular, this rigorously establishes the relation between Liouville and SLE parameters: $\gamma = \sqrt{\kappa}$ for $\kappa \leq 4$ and $\gamma = 4/\sqrt{\kappa}$ for $\kappa > 4$. This corresponds precisely to the famous relation between the Liouville parameter and the central charge in the Liouville-CFT correspondence, $\gamma(c) = \left(\sqrt{25-c} - \sqrt{1-c}\right)/\sqrt{6} \leq 2$ with $c = \frac{1}{4}(6-\kappa)(6-16/\kappa) \leq 1$. A second *dual* solution is found as $\gamma' = 4/\gamma > 2$, which corresponds to the non-standard Liouville quantum gravity mentioned in section A.11.1 above, where the quantum measure develops atoms with localized area.

We also develop in [t10/223] a theory of *quantum fractal measures* (consistent with the KPZ relation) and analyze their evolution under conformal welding via the introduction of explicit SLE related *exponential martingales*; the latter play the (now mathematically rigorous) role of the so-called "quantum gravity dressing" of conformal operators in a CFT coupled to Liouville gravity. As an application, we construct *quantum* length and boundary intersection measures *on* the SLE curve itself. This for instance allows calculating the SLE quantum length contained in any domain D (Fig. A.9).

A.12 Geometrical models and applications

Statistical models in two dimensions can be defined not only in terms of local Boltzmann weights, but also in terms of non-local objects, which are loops, clusters, interfaces or walls. In

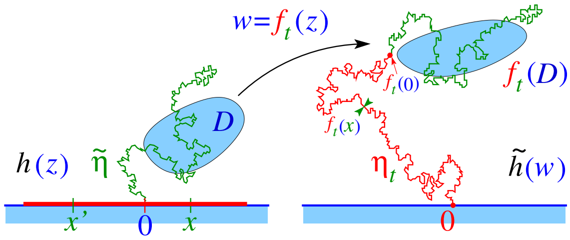


Figure A.9: Conformal welding map f_t: the quantum gravity boundary lengths associated with the GFF γh are equal for any pair of real segments $[0, x]$ and $[x', 0]$ such that $f_t(x) = f_t(x')$, and the zipped-up curve η_t is an SLE_κ with $\kappa = \gamma^2$.

particular, this point of view offers a fruitful connection with SLE and with fractal properties of various statistical mechanics objects.

A.12.1 Interfaces in 2D statistical mechanics *(M. Bauer, D. Bernard)*

Since Schramm's breakthrough in 2000, the study of interfaces in two-dimensional critical system has been a very active field, leading to fruitful contacts between probabilists and conformal field theorists. Many results that would have been considered as out of reach before 2000 are now elementary exercises in stochastic calculus exploiting the Schramm-Loewner equation. A celebrated example is Schramm's formula. Suppose that due to boundary conditions an interface in a critical system connects two boundary points of a simply connected region and take a point in the bulk. Schramm's formula, which gives the probability that the point in the bulk lies on the left or on the right of the interface, can be derived on a single sheet of paper.

However, as usual after a rapid progress, new deep questions have arisen for which there is no clue yet. In such cases, one has to rely on special properties of particular models to get some hints on a possible general structure.

Among the open questions, we shall stress three. As we shall see, they are somehow related. The first is the generalization of SLE to non-simply connected regions. The second is the interpretation of SLE in terms of concrete models. The third is the generalization of SLE to non-critical systems.

Non simply connected regions have moduli. The simplest illustration is a region with the topology of an annulus. Such a region is conformally equivalent to a region limited by two concentric circles, one with radius one and the other with radius $R > 1$, and R is the moduli in that case: two regions with a different R are conformally inequivalent. Non simply connected domains do not have so many symmetries. Annuli, for instance, have only rigid rotations. Most of the time, there are no symmetries at all.

To contrast with the simply connected case, remember that Riemann's theorem asserts that any two simply connected regions are conformally equivalent and moreover that these regions have enough symmetries to allow either 3 boundaries points or 1 bulk and 1 boundary point to be chosen at convenience. The first case is relevant for *chordal* SLE (an interface connecting two boundary points) or *dipolar* SLE (an interface connecting a boundary point to a boundary segment) while the second case is relevant for *radial* SLE (an interface connecting a boundary point to a bulk point). Schramm used Riemann's theorem to show that conformally invariant measures on random curves in simply connected regions depend on a single parameter, denoted by κ.

The arguments used by Schramm to derive SLE in simply connected regions are insufficient for non simply connected regions. The best one can do at the moment is to use peculiar properties of certain models to fix the ambiguities left by general arguments. These peculiar properties also turn out to make it possible to compute explicitly some features encoded in the relevant Schramm-Loewner equation.

For instance, the level lines of the Gaussian free field are known to be related to $\mathrm{SLE}_{\kappa=4}$. In [t10/056] we have shown how this relation allows to define chordal SLE_4 processes in annuli, describing traces that are anchored on one of the two boundary components. The precise nature of the processes depends on the conformally invariant boundary conditions imposed on the second boundary component. Extensions of Schramm's formula to doubly connected domains are given for the standard Dirichlet and Neumann conditions and a relation to first-exit problems for Brownian bridges is established. For the free field compactified at the self-dual radius, the extended symmetry leads to a class of conformally invariant boundary conditions parametrized by elements of $SU(2)$. It is shown how to extend SLE_4 to this setting. This allows for a derivation of new passage probabilities *à la* Schramm that interpolate continuously from Dirichlet to Neumann boundary conditions.

Turning to the second theme, to oversimplify a little bit, one can say that the interpretation of chordal SLE in terms of statistical mechanics models is rather good. The interpretation of radial SLE is already less clear, but the worst case is dipolar SLE. To take only one example, we note that $\mathrm{SLE}_{\kappa=8/3}$ is believed to describe self avoiding walks. This can be supported by numerics for the chordal and radial cases, but the meaning of the boundary conditions at the end of the hitting segment for dipolar $\mathrm{SLE}_{8/3}$ in terms of self avoiding walks is totally unknown. Recall that dipolar SLE describes interfaces that join a boundary point to a boundary arc in a simply connected region. The central question analyzed in [t08/152] is the following: what is the effect on an interface in dipolar SLE when it is conditioned to hit a certain sub-arc of the initial selected boundary arc. This question is rather natural if one aims at understanding better dipolar SLE. We obtained a complete description of the corresponding interface measure, via several tricks, both from the probabilistic approach and from the conformal field theory approach. We could show that $\mathrm{SLE}_{\kappa=2}$, which describes the continuum limits of loop erased random walks, is characterized as being the only case for which dipolar SLE conditioned to stop on an interval coincides with dipolar SLE on that interval. We illustrated this property by computing a new bulk passage probability for dipolar SLE_2. This characterization should be compared to the analogous characterization of $\mathrm{SLE}_{8/3}$, which is the only case for which chordal SLE conditioned to avoid a hull is chordal SLE in the region obtained by cutting the hull from the initial region.

Looking at interfaces out of the critical point is also a natural question. Let L be the typical size of the system and a be the lattice spacing. When the correlation length is finite in terms of a, the description is not two complicated and has been understood some time ago. Oversimplifying again, there is an average position of the interface, whose length is of order L, the fluctuations are transverse and of order $L^{1/2}$, they are typically of the random walk type with short range correlations. When L is sent to $+\infty$, there is a Brownian continuum limit if the transverse direction is rescaled appropriately.
The case when the correlation length is a finite fraction of L, and a is sent to 0, is much more complicated. Conformal invariance is lost, and the interface measures in different simply connected regions are not related by pure kinematics, as is the case at the critical point. However, for a given domain, say the upper-half plane or a strip, it is still possible to describe the interface via a (chordal or dipolar) Loewner evolution. As usual, this evolution involves a random source term. For SLE, this random source term is a Brownian motion (with a scale $\sqrt{\kappa}$ to be precise). But out of the critical point the statistics of this random source term becomes extremely complicated. One of the issues is whether perturbation theory around the critical measure will apply or not. Of course, formally it does as shown by a naive field theory representation where the deviation to the critical temperature is obtained by perturbing with an appropriate operator. In probability theory, such perturbations are related to would-be martingales, which cannot be computed or even characterized explicitly for general κ. When the perturbed theory is a free field theory, the situation is much better. This was used in [t07/204] and [t09/132] for $\kappa = 2$ and $\kappa = 4$. The first case describes loop-erased random walks in the dipolar geometry when the underlying random walk is penalized by its number of steps. The field theory is that of massive symplectic fermions. The second case describes level lines of the massive Gaussian free field in the chordal geometry. One is led to an implicit description of the martingale deforming the interface measure in terms of certain functional determinants. They involve space-dependent mass terms that are a kind of substitute for a dependence upon conformal transformations. In the loop-erased random walk case, a hitting probability can be computed explicitly for constant mass, allowing to retrieve the statistics of the Loewner source term from an independent perspective. In the case of $\kappa = 4$ we could show that the statistics of the full Gaussian field factorizes as a product of the statistics of the interface and the statistics of the Gaussian free field in each of the regions delimited by the interface.

A.12.2 Multifractal harmonic measure and winding of random 2D interfaces *(B. Duplantier)*

In [t08/044], the multifractal behaviour of conformally invariant curves in two dimensions is revisited with I.A. Binder (Toronto). The mixed multifractal spectrum associated with both the harmonic measure and winding (monodromy) near such critical curves, originally obtained via quantum gravity methods with the same co-author in 2002 [t02/124], is here rederived by Coulomb gas-CFT methods only. The results also extend to the general case of multiple paths in a star configuration. Consider a random conformal path $\mathcal{S}$, part of a critical scaling curve in a 2D statistical system, *e.g.*, the trace of a Schramm-Loewner evolution (SLE) (Fig. A.10).

The harmonic measure $\omega(z)$ of a ball centered on the path and passing through a point z is the probability that a Brownian motion started away from the path $\mathcal{S}$ first hits $\mathcal{S}$ inside that ball. Electrostatically, one can consider $\mathcal{S}$ as an equipotential, and define $\omega(z)$ as the portion of electric charge induced on $\mathcal{S}$ inside the ball and the winding $\vartheta(z)$ as the rotation angle of the Green line (*i.e.*, electrostatic field line) reaching z from infinity.

To extract the asymptotic geometrical harmonic measure and rotation properties of random paths, we resort to a Coulomb gas formalism that generalizes that by Bettelheim *et al.* in 2006. We introduce *chiral vertex operators*, with different holomorphic and anti-holomorphic parts, and perform the analysis of their short-distance *scaling* and *monodromy* properties in operator product expansions with path-creating operators. Their CFT transformation rules under the uniformizing Riemann map $w(z)$ of the complex plane slit by the random path(s) yield the desired information about the harmonic measure $\omega(z)$ and rotation $\vartheta(z)$, via their local correspondence to the conformal map's derivative $w'(z)$, namely $\omega(z) \sim |zw'(z)|$ and $\vartheta(z) \sim -\arg w'(z)$. The multifractal moments $\omega^n(z)e^{-p\,\vartheta(z)}$ for arbitrary powers n and p are thus found to typically scale as $|z|^{x(n,p)}$ for $z \to 0$, with explicit exponents $x(n,p)$. By double Legendre transform they give access to the mixed multifractal spectrum $f(\alpha,\lambda)$, *i.e.*, to the fractal dimension of the subset of points on the path where the typical behavior of the complex quantity $\omega(z)e^{i\vartheta(z)}$ is $|z|^{\alpha+i\lambda}$ for $z \to 0$. This is also generalized to multiple random paths in a star configuration, where the harmonic measure and winding exhibit multiple multifractal behaviours in the various sectors of the conformally invariant star. Together with our previous approach via quantum gravity [t02/124], this provides two different derivations of these multifractal spectra. A third, mathematically rigorous, proof has been obtained by the same authors by working directly with the Schramm-Loewner evolution, and will be the subject of a forthcoming publication.

A.12.3 Domain walls and interfaces - again *(J. Dubail, J.L. Jacobsen, H. Saleur)*

While most of the activity in the field has concentrated on geometrical loop models, there are many other situations of interest, involving branchings and intersections, whose description either in terms of field theory or in terms of SLE is more complicated, or even unknown to this day. An old example of this was the arboreal gas which was found in [t05/025] to be described by a supersphere sigma model and an effective non compact target at criticality. In the last few years, we proposed a solution of what is probably the simplest problem in this family, the statistics of domain walls in the Q-state Potts model ([t11/054] and [t11/055]). This solution involves in particular a clean definition of the concept of domain walls (which can be "thin" or "thick") for Q generic, and gives rise to exponents in the Kac table which had not been seen before in a geometrical setting, raising the challenge for a direct field theoretic understanding. This will probably require a thorough algebraic reformulation, generalizing in particular the Temperley Lieb algebra to a new object which encodes both physical spin clusters and Fortuin Kasteleyn clusters.

A.12.4 Boundary loop models *(J. Dubail, J.L. Jacobsen, H. Saleur)*

While loop models have been by now very well studied in the bulk, their properties near the boundary present a wealth of behaviors which had been largely unnoticed until quite recently. In a series of works dating back to [t06/155], Jacobsen and Saleur discovered in this context new types of conformal boundary conditions (dubbed now JS) using ideas from the field of associative algebras (boundary Temperley Lieb or blob algebras [t94/188]). These boundary conditions were later studied formally in the context of matrix models, but they also offer more concrete applications. In [t09/281] for instance, the special transition in the two dimensional $O(n)$ model with coupling anisotropy breaking the symmetry down to $O(n_1) \times O(n-n_1)$ was thus solved, and the full phase diagram mapped out. Another application to the coloring problem by Jacobsen and Saleur where a different number of colors in the bulk and the boundary are allowed was discussed in [t09/068].

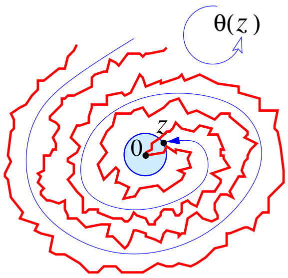


Figure A.10: A random conformal path $\mathcal{S}$; $\omega(z)$ is the harmonic measure in the ball centered at $0 \in \mathcal{S}$ and passing through z ; $\vartheta(z)$ is the (possibly indefinite) winding angle of the Green line reaching the ball when $z \to 0$.

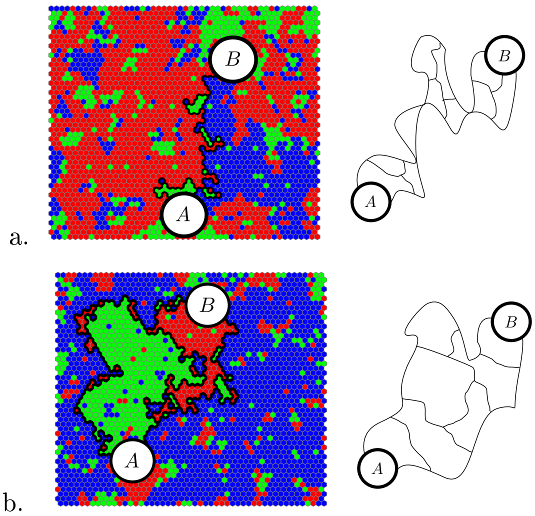


Figure A.11: The two different types of DW, here shown in the bulk case (geometry of the infinite plane). A *thin* DW corresponds to the interface between two clusters of different colours (a), while for a *thick* DW the two clusters have the same colour. An illustration for the $Q = 3$ Potts model is given (left) as well as a schematic picture for non-integer Q (right).

A.12.5 Valence bonds and entanglement *(J.L. Jacobsen, H. Saleur)*

Loop models and loop diagrams are also related to quantum spin problems via the concept of valence bonds. This is particularly useful in the analysis of entanglement in disordered systems as discussed for instance by Koo, Haas and Saleur in [t07/143]. It also provides a convenient intuitive grasp of entanglement in general, by relating it with various statistical features of valence bonds connecting subsystems. The valence bond entanglement entropy in the XXX spin chain for instance was studied numerically in details, and found to be remarkably similar numerically to the usual Von Neumann entanglement entropy. In [t08/109], Jacobsen and Saleur solved in closed form the problem of valence bond entropy for the ground state of the XXZ spin chain, and showed that it did in fact behave differently (albeit not by much for the isotropic case) from the Von Neumann result. The resulting combinatorial problem exhibits as often remarkable properties.

A.12.6 Interacting anyons *(Y. Ikhlef, J.L. Jacobsen, H. Saleur)*

Temperley Lieb algebras have been revisited in the recent past in the context of topological quantum computers and anyons. It has been argued in particular that hamiltonians expressed in terms of Temperley Lieb generators described interacting anyons, and their critical properties could be related with occurrences of non abelian statistics. In [t09/072], we revisited the phase diagram of the anyonic spin chains, and, using in particular geometrical representations and earlier results on the antiferromagnetic Potts model, demonstrated the existence of a new integrable point, described by a new conformal field theory they solved independently in [t09/282]. While challenged for two years, our claim is now accepted in the literature, and should lead to a better understanding of certain plateaux in the fractional quantum Hall effect.

A.12.7 Random tilings *(J.L. Jacobsen)*

Although many models of random tilings of the plane have been solved in the past, new examples keep being motivated by applications in physics and mathematics. In a recent experiment by M.O. Blunt *et al.*, a two-dimensional molecular network of para-terphenyl-3,5,3',5'-tetracorboxylic acid was adsorbed onto graphite. The rod-like molecules arrange as a dimer covering of the hexagonal lattice—a priori a well-known tiling problem. However, the experimentally measured value of the stiffness constant in the corresponding Gaussian free field theory turns out to be 1.66 ± 0.08 times larger than the theoretical prediction. In [t09/336] we have related this effect to an interaction between neighbouring dimers of the same spatial orientation. They showed how to map the interacting tiling problem to a Coulomb gas model and derived the corresponding critical exponents. In particular, they predicted that a Kosterlitz-Thouless transition would be observed if the experimental compound could be cooled to a temperature $T \simeq 110$K.

A.12.8 Lattice models of biopolymers *(J.L. Jacobsen)*

Lattice models of loops, and Hamiltonian walks in particular, have often been proposed as toy models of globular proteins. In [t08/306] we proposed an efficient algorithm providing unbiased sampling of three-dimensional Hamiltonian walks, based on earlier work by Mansfield. In particular the universal scaling function for the end-to-end distance was obtained with great accuracy. In [t10/277] we generalised the algorithm to study two walks of equal length that jointly fill the cubic lattice. As in [t08/306] strong evidence for the ergodicity of the algorithm was provided by a companion enumerative study [t07/228].

The issue of polymer mixing has recently gained renewed interest in the area of physical biology. One outstanding question is to understand the organisation and segregation of chromosomes within simple bacteria, including during duplication. In these applications one typically has two polymer chains confined to a bar-shaped geometry, akin to that of a rod-shaped cell. In [t10/277] we have given convincing numerical evidence that if each chain is modelled by a Hamiltonian walk, the two chains will segregate spatially.

A.12.9 Colouring and flow problems *(J.L. Jacobsen)*

Graphs colourings and related problems have a long history at the fronteer between mathematics, computer science, and theoretical physics. The number of colourings can be expressed as the so-called chromatic polynomial, which occurs as the zero-temperature limit of the antiferromagnetic Potts model. Computing this polynomial is #P-hard, meaning that the computational effort grows exponentially in the size of the graph. In [t10/276] we described a new type of algorithm for computing the chromatic polynomial of a planar graph. It combines the transfer matrix principle with a graph-theoretical construction known as tree decomposition. Roughly speaking, this means that time evolves recursively instead of linearly. The algorithm improves the running time from $\exp(\mathrm{c}\,N)$ to $\exp(\mathrm{c}\,N^{\alpha})$ with an exponent α which is $\simeq 0.3$ on average and it is $1/2$ in the worst case.

The chromatic polynomial on the triangular lattice was shown to be an integrable model by Baxter (1986). In [t10/278] we have found a 79-term series expansions for the bulk, surface and corner free energies in the non-critical phase. These series permitted him to conjecture exact product formulae for the surface and corner energies for the first time.

For planar graphs, proper vertex Q-colourings are dual to nowhere-zero integer Q-flows, but this equivalence breaks down for non-planar graphs. In [t10/279] in collaboration with Salas we studied the flow polynomial on a certain class of non-planar graphs. In 1954 W.T. Tutte conjectured that any (bridgeless) graphs has a $Q = 5$ flow. A main result of [t10/279] is that this conjecture is "almost false": there exists graphs whose flow polynomial has real roots arbitrarily close to $Q = 5$. On a deeper level, [t10/279] demonstrates the relevance of representation theory in the study of the Q-state Potts model in dimensions higher than two.

A.13 Loop models, integrability and combinatorics

The relationship between statistical physics and combinatorics has undergone tremendous developments in the recent years. Beyond mere counting of configurations, both ideas and techniques of statistical physics have been successfully applied to solving notoriously hard combinatorial problems. Loop models with quantum symmetries have provided a new framework relating standard combinatorial objects such as plane partitions and alternating sign matrices. Integrability gives new ways of thinking about combinatorial problems, that involve other branches of mathematics as well, such as probability theory, algebraic geometry and representation theory.

A.13.1 Loop gas, combinatorics, and quantum algebra *(P. Di Francesco)*

As part of a long-standing collaboration with P. Zinn-Justin (LPTHE, Jussieu), we have been studying two-dimensional statistical lattice models known as "loop gases" which may be viewed as contour maps of some random 3D landscape. One main motivation was to better understand the rationale behind the Razumov-Stroganov conjecture (2001), identifying a surprising connection between probabilities of configurations of two loop models in very different geometries.

Some aspects of this relation have been the subject of intense work from the combinatorial community. This correspondence is indeed related to the so-called Alternating Sign Matrix conjecture, proved independently in the mid 90s by Zeilberger and Kuperberg, and establishing the identity between the total number of (i) Alternating Sign Matrices (ASMs) of size $n \times n$, namely matrices with entries $0, 1, -1$ such that ± 1 alternate along rows and columns, possibly separated by any number of 0s, and with row and column sums all equal to 1 and (ii) Totally Symmetric Self-Complementary Plane Partitions (TSSCPPs), namely rhombus tilings of a $2n \times 2n \times 2n$ hexagon of triangular lattice, by means of the three elementary rhombi obtained by gluing two elementary triangles along an edge. Kuperberg extended the counting to include ASMs with various symmetries, in relation to plane partitions with various symmetries. His original method relies on a bijection between ASMs and configurations of the 6 Vertex model on an $n \times n$ grid of square lattice, and variations thereof.

With the Razumov-Stroganov conjecture, now proved in a purely combinatorial way by Cantini and Sportiello (2010), yet another physical statistical model was introduced into the game: a dense loop model on a semi-infinite cylinder of square lattice with fixed perimeter $2n$.

Our chief weapon is integrability, allowing for exact solutions. In [t07/224], we use methods borrowed from quantum integrable systems to compute certain correlations of the loop gas in a semi-infinite strip, as illustrated in Fig.A.12. In particular, we find the relevant solutions of the quantum Knizhnik-Zamolodchikov equation satisfied by the groundstate of the model, via multiresidue integral representations, and the extensive use of representations of the Temperley-Lieb algebra.

As a by-product, we get a closed expression for the sum of the un-normalized configuration probabilities in the groundstate of the dense loop gas for strip width N, identified in various limits of the parameters of the model with partition functions for: (i) the Vertically Symmetric Alternating sign Matrices (VSASMs) of size $N + 1 = 2n + 1$ for even N and (ii) the Cyclically Symmetric Transpose Complementary Plane Partitions (CSTCPP) of size $N - 1$, represented in Fig.A.13 for odd and even sizes.

The original ASM conjecture formulated by Mills, Robbins and Rumsey in 1983 concerned yet another combinatorial object called Descending Plane Partitions (DPPs), and established a connection between multiply refined counting thereof and ASMs. The counting of DPPs was done by Andrews in the late 70s, but the above connection with ASMs, whose counting is the same, remains mysterious, in particular no natural bijection between the objects is known to this day. The Mills-Robbins-Rumsey conjecture remained open for 28 years, and our paper [t11/048] finally gives its complete proof. We first use the Kuperberg connection of ASMs to the 6 Vertex model to actually compute the partition function of the homogeneous 6 Vertex model as a simple determinant. Next, we use the reformulation of DPP in terms of non-intersecting lattice paths, to express the partition function as another determinant. Finally we connect the two by use of the generating functions for the matrix elements within the determinants, also identified as the transfer matrix for 1+1-dimensional Lorentzian triangulations in infinite size. We may summarize the essence of this proof as yet another triumph of quantum integrability: (i) that of the 6 Vertex model, allowing for rephrasing the partition function in determinantal terms (ii) that of non-intersecting lattice paths, also expressible as free fermions (iii) that of Lorentzian gravity in 1+1 dimension, via commutation of transfer matrices (Di Francesco, Guitter, Kristjansen, 1999).

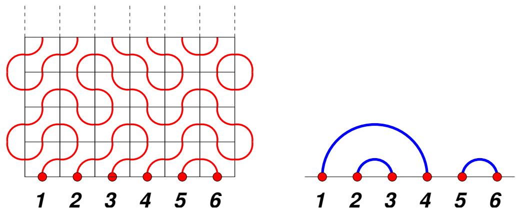


Figure A.12: A typical configuration of the dense loop gas on a semi-infinite strip, and the correlation function this configuration contributes to, namely the non-crossing pattern of connections of the $2N = 6$ loop ends of the boundary.

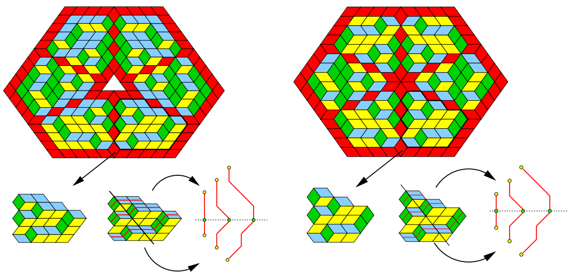


Figure A.13: Typical configurations of the CSTCPP for respectively odd ($N = 5$) and even ($N = 4$) sizes. The odd size includes a central triangular hole of size $2 \times 2 \times 2$.

A.13.2 Combinatorics of alternating sign matrices and of Gessel's conjecture *(A. Ayyer)*

As explained in Section A.13.1, alternating sign matrices are related to fully packed loops (FPLs) and to the Razumov- Stroganov conjecture, now the Cantini-Sportiello theorem. In [t08/247] (with D. Zeilberger) we attempt to prove the conjecture using a bijectional approach. We have been unsuccessful but we believe the techniques we present can be used to give an alternative proof of the conjecture.

Alternating sign matrices are known to be equinumerous with descending plane partitions, a class of plane partitions introduced by George Andrews in 1979. Mills, Robbins and Rumsey noticed startling numerical coincidences between refined enumeration of these two structures in 1983. However, there is no known bijection between these objects. In [t09/156] a bijection is proven between a natural subset of descending plane partitions and permutations using the ascent statistic.

Totally symmetric self-complementary plane partitions (TSSCPPs) are yet another class of plane partitions known to be enumerated by the alternating sign matrix numbers. Once again, Mills, Robbins and Rumsey noticed startling numerical coincidences between refined enumeration of TSSCPPs and alternating sign matrices in 1986. No bijection is known between any of these three objects. In [t11/105] (with R. Cori and D. Gouyou-Beauchamps) we find a natural bijection between subclasses of these using monotone triangles. Since alternating sign matrices are natural generalizations of permutations, there is a notion of pattern-avoidance for these too. We show that those alternating sign matrices in bijection are those which, in a very precise sense, avoid the pattern 312.

In 2001 Ira Gessel conjectured a formula for the number of walks in the first quadrant of $\mathbb{Z}^2$, built out of $2n$ steps in the directions $(1,1),(1,0),(-1,0),(-1,-1)$, starting and ending at the origin. In a remarkable tour de force, Gessel's original conjecture has been finally proven in 2008 using computer algebra techniques by M. Kauers, C. Koutschan, and D. Zeilberger. To give a simpler proof of Gessel's conjecture, in [t09/025] we interpret walks in the first quadrant with the above–mentioned steps as a generalization of Dyck words with two sets of letters. Using this language, we give a formal expression for the number of walks in the steps above beginning and ending at the origin. We give an explicit formula for a restricted class of such words using a correspondance between such words and Dyck paths. Finally we remark on another combinatorial problem in which the same formula appears and argue for the existence of a bijection.

A.13.3 Limit shapes in tiling/dimer systems *(P. Di Francesco)*

Geometrically constrained statistical models defy the general principles in that the constraints make them very dependent on their boundary conditions. A large class of such models are dimer models, namely the compact covering of fixed bipartite graphs with dimers, i.e. mutually excluding pairs of neighboring vertices. Dimers have received much attention recently from a new approach to their thermodynamics using hydrodynamic equations (Wilson, Propp, Kenyon, Okounkov, Reshetikhin), establishing in particular the existence of "frozen" regions of ordered dimers separated from disordered regions with nontrivial entropy via "arctic curves". The frozen regions are clearly induced by the shape of the boundary, to which the arctic curve is tangent.

In [t09/234], we investigate the case of partially free boundaries on dimer models. We use the formulation of dimer models on the hexagonal lattice via non-intersecting lattice paths, and study their asymptotics via saddle-point techniques. In this case, the dimer configurations are in bijection with rhombus tilings of corresponding domains of the triangular lattice (in the same spirit as for Plane Partitions), and lattice paths are easily obtained by following successions of two types of rhombi throughout the configuration. They can also be interpreted as views in perspective of 3D piles of unit cubes in domains made of the intersection of several positive octants of the 3D space.

A.13.4 Discrete integrable systems, quantum spin chains and cluster algebras *(P. Di Francesco)*

This work is a new collaboration with Rinat Kedem (University of Illinois, Urbana-Champaign) aimed at better understanding the combinatorics of discrete integrable systems. The latter may be viewed as dynamical systems in discrete time, with sufficiently many conserved quantities.

Examples arise from the study of completeness of the Bethe Ansatz solution to integrable quantum spin chains with the symmetry of some Lie group, where it is shown that the state counting amounts to representation-theoretic statements on fusion coefficients, also expressed via non-linear recursion relations between characters of some special modules (Kirillov-Reshetikhin, 1988), called Q or T-systems (the latter include an extra spectral parameter, related to the quantum parameter of the spin chain, and are connected to the so-called Y-systems arising from Thermodynamic Bethe Ansatz solutions to quantum spin chains). In [t07/210] we give a proof of the so-called combinatorial Kirillov-Reshetikhin conjecture by use of generating functions for generalized characters.

More generally, we have investigated the full spectrum of solutions of Q and T systems, viewed as discrete dynamical systems, in terms of their initial data. In [t08/255], we first established a connection between Q and T-systems and a mathematical structure known as Cluster Algebras, introduced in 2000 by Fomin and Zelevinsky. A cluster algebra describes the evolution of a data vector attached to each vertex of an infinite Cayley tree, subject to specific "mutations" along the edges of the tree, governed by a skew-symmetric "exchange" matrix often represented as a quiver, also mutated across edges. The defining axioms for mutations are such that they guarantee the Laurent property, namely that any mutated data can be expressed as a Laurent polynomial of the data at any other vertex of the tree. Fomin and Zelevinsky put forward the conjecture (still open to this day) that the coefficients of these Laurent polynomials are non-negative integers. It is a challenge to find a combinatorial/statistical physics interpretation for these.

The structure of cluster algebra appears in many different mathematical and physical contexts, such as: Somos sequences (non-linear recursion relations), quiver representation theory (category theory), surgery of Teichmüller space and triangulations (geometry), total positivity of Grassmannians (linear algebra), network theory and non-intersecting lattice paths, wall-crossing for Donaldson-Thomas invariants (algebraic geometry and string theory).

Our systems are very special in the cluster algebra world: they turn out to be integrable, i.e. to have sufficiently many conserved quantities to be amenable to exact solutions in terms of initial data. In [t08/256], we show that the solutions of the Q-system for the A_r Lie algebra may be expressed in terms of partition functions for discrete paths or families of discrete non-intersecting paths on suitable target graphs, with step weights that are positive Laurent monomials of the initial data, thereby proving the Fomin-Zelevinsky positivity conjecture for these particular cluster algebra mutations. We found a remarkable formulation for the cluster mutations in terms of local rearrangements of (possibly branching) continued fractions, whose

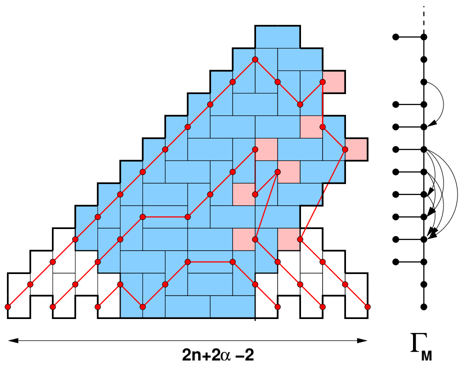


Figure A.14: A typical configurations of dominos and defects covering a domain whose shape is determined by the initial data of the Q-system. We have also represented the underlying non-intersecting paths and the target graph on which they are travelled, also determined by the initial data.

shape is determined by initial data. We also provided an alternative combinatorial interpretation of the solutions as partition functions for domino tilings of deformed Aztec diamonds of the square lattice using standard 2×1 and 1×2 dominos, as well as "defects" (see Fig.A.14).

More exact results were obtained in [t09/233], [t09/235], [t10/231] on the T-system as well, by reformulating the former in terms of electrical networks, namely weighted non-intersected lattice paths on graphs obtained by gluing elementary "electrical" chips, in the same spirit as the canonical decomposition of totally positive GL_n matrices into products of elementary upper and lower triangular matrices.

The simplicity of our solution allowed for an immediate extension to the case of non-commutative variables, this time in the form of discrete path partition functions with non-commutative step weights multiplied in the order in which the steps are taken. In particular we proved a conjecture by Kontsevich [t09/236] related to wall-crossing for non-commutative Donaldson-Thomas invariants. More generally, we designed a framework for a non-commutative version of the Q-system [t10/119], [t10/232], based on the theory of quasi-determinants of Gelfand-Retakh. It involves a non-commutative generalization of multiply branching continued fractions and their local rearrangements. The corresponding non-commutative Q-systems include as a special case the so-called quantum Q-systems, associated to quantum cluster algebras. The latter were defined in 2005 by Berenstein and Zelevinsky as a natural quantization of the notion of cluster algebra, and bears connections to the questions of positivity of Lusztig's canonical bases of quantum enveloping algebras. Finally, in [t11/047] we introduced a quantum version of the T-sytsem for $sl(2)$ based on the associated quantum cluster algebra, and constructed its solutions for arbitrary initial data in terms of non-commutative networks. In particular, this solution allowed us to prove the quantum version of the Fomin-Zelevinsky positivity conjecture for the associated quantum cluster algebra.

A.13.5 Labelled positive paths and matchings *(B. Duplantier)*

In the joint work [t09/036] with O. Bernardi (Orsay) and P. Nadeau (Vienna), we study the partition function of a three-dimensional *freely-jointed chain* (FJC) of n steps, anchored at a plane in a half-space (a model of interest to biological physicists for describing the micromanipulation of DNA chains). This problem is found to require a combinatorial treatment. Of particular interest is the n-dimensional polytope Π_n in $\mathbb{R}^n$ consisting of all points $(x_1,\dots,x_n)\in[-1,1]^n$ such that $\sum_{i=1}^j x_i \geq 0$ for all $j=1\dots n$, whose volume gives the partition function of the FJC (at zero tensile force).

It is shown in [t09/036] that a collection of n-dimensional subpolytopes partitioning the polytope Π_n is in bijection with a set of so-called *well-labelled positive paths*. A well-labelled positive path of size n is made of a sequence $p_1,p_2,\dots,p_{n-1}$ of discrete steps $\{-1,0,+1\}$ such that $\sum_{i=1}^j p_i \geq 0$ for all $j=1\dots n-1$, together with a permutation $\{\sigma_1,\sigma_2,\dots,\sigma_n\}$ of $\{1,\dots,n\}$ such that $p_i=-1$ implies $\sigma_i<\sigma_{i+1}$, while $p_i=1$ implies $\sigma_i>\sigma_{i+1}$. The generating functions of those paths and their Motzkin counterparts are evaluated by coupled recursions. We also establish a bijection between well-labelled positive paths of size n, labelled binary trees, and matchings (i.e. fixed-point free involutions) on $\{1, \ldots, 2n\}$. This proves in particular that the number of well-labelled positive paths is $(2n-1)!! \equiv (2n-1) \cdot (2n-3) \cdots 3 \cdot 1$. Given that the volume of each subpolytope is $1/n!$, our results prove combinatorially that the volume of Π_n, *i.e.*, the partition function of the original FJC, is $\frac{(2n-1)!!}{n!}$. By specializing our bijection, we prove a series of other combinatorial results, such as the number of permutations of size n such that each prefix has no more ascents than descents being $[(n-1)!!]^2$ if n is even and $n!!\,(n-2)!!$ otherwise. The complete study of the FJC partition function with a non-vanishing tensile force will be the subject of a forthcoming publication.

A.14 Sigma models on supermanifold targets: structures and applications

Two dimensional non-linear sigma models with super-manifold target spaces have emerged in a wide variety of systems, and their study has become increasingly relevant for some of the most challenging problems of modern physics.

In condensed matter, super-manifold target spaces arise mostly in the supersymmetric approach to non-interacting disordered systems. The transition between plateaux in the integer (2+1 dimensional) quantum Hall effect is for instance believed to be related to the sigma model (1+1 dimensional) U(1,1|2)/U(1|1) × U(1|1) at $\theta = \pi$, a conformal field theory which has not yet been understood, despite decades of work. Other super sigma models arise in the description of similar phase transitions belonging to different universality classes. Of particular recent interest is the transition between plateaux in the 'spin quantum Hall effect' (Class C) observed in dirty $d + id$ superconductors (see below). Supermanifold targets also arise in the study of geometrical problems, such as percolation, polymers etc.

In string theory, super-group and super-coset targets play an important role in the Green-Schwarz or pure spinor type formulation, where supersymmetries act geometrically as isometries of an underlying space-time (target space) supermanifold. Important examples arise in the context of the AdS/CFT dualities between supersymmetric gauge theories and closed strings. For instance, it has been known for a few years that string theory on $AdS_3 \times S^3$ could be quantized if it were possible to construct conformal quantum field theories with a PSL(2|2) target space.

In addition to such concrete applications, there exists a number of fundamental reasons to be interested in particular in *conformal* σ-models with target space (internal) supersymmetry. Being non-unitary, the relevant conformal field theory models exhibit rather unusual features such as the occurrence of reducible but indecomposable representations and the existence of logarithmic singularities (on the world-sheet). The resulting issues of non semi-simplicity have profound mathematical connections. On the other hand, the special properties of Lie supergroups allow for constructions which are not possible for ordinary groups. For instance, there exist several families of supergroup σ-models which admit a new kind of marginal deformations that are not of current-current type. The solution of these models is one of the most tantalizing modern problems in the field.

A.14.1 Conformal sigma models on supergroups: lines of CFT *(C. Candu, J.L. Jacobsen, H. Saleur)*

The simplest conformal σ-model is probably the supersphere sigma model, that is the coset $Osp(2n+2|2n)/Osp(2n+1|2n)$. The case $n = 0$ is nothing but the ordinary $O(2)$ sigma model (the free boson), which pretty much guarantees vanishing of the beta function to all orders, and the existence of a line of conformal field theories with properties depending on the sigma model coupling g_σ^2. Like for all the other super sigma models, non-unitarity precludes the use of standard techniques to calculate the spectrum and the correlation functions. To make progress, Candu and Saleur in [t07/166] and [t07/167] first obtained a lattice regularization of the CFT based on an orthosymplectic superspin chain. They then performed a decomposition of the Hilbert space in terms of representations of the *osp* algebra and its centralizer, which in this case turns out to be (a quotient of) the Brauer algebra. Because the algebras involved are not semi-simple, this decomposition is complicated, involves various types of indecomposable modules, and relies in part on some very recent results in the theory of cellular and quasi-hereditary algebras. On the other hand, there is a growing expectation - justified in part by results from Read and Saleur in the previous period [t06/136, t06/154] - that the resulting 'bimodule' structure is essentially independent of the size of the lattice, and identical with the one of the continuum limit. Using this idea, Candu and Saleur were able to conjecture the full structure of the boundary CFT (with Neumann boundary conditions), including the structure of the Virasoro modules, and the exact dependence of the conformal weights on the coupling constant. They were also able to conjecture a *duality* between the super sphere sigma model and the orthosymplectic Gross Neveu model. Part of these results were later proved in works by Schomerus and collaborators.

Later, Candu, Saleur and collaborators in Hamburg performed in [t09/193] a similar analysis for the superprojective sigma model $CP^{n-1|n}$ which, this time, gives rise to a line of CFTs at central charge $c = -2$, the $n = 0$ case being nothing but the symplectic fermion theory. On top of the algebraic analysis, they also performed perturbative expansions at weak coupling and minisuperspace analysis, and concluded to the absence of duality with the Gross Neveu model, for yet unknown reasons. They also investigated in details the role played by the topological angle and the boundary, with potential applications to the study of edge states in topological insulators (see below).

Meanwhile, the conformal sigma models can be interpreted in terms of geometrical models of statistical mechanics. The most striking consequence is that, if one takes dense polymers (corresponding to packed self avoiding walks, forced to occupy a non vanishing fraction of the available space) and allows for 6 legs crossings, a new universality class is obtained, with exponents varying continuously [t09/194].

A.14.2 $CP^{n+m-1|n}$ models at $\theta = \pi$: strong coupling physics *(R. Bondesan, J. Dubail, J.L. Jacobsen, H. Saleur)*

While models such as the supersphere sigma model can be at least partly understood using perturbation theory, there are many other cases - and the model expected to describe the critical properties at the transition between plateaux in the integer quantum Hall effect is of this type - where the interesting physics occurs only at strong coupling. The simplest example in this context is provided by the (more general) σ-models on superprojective spaces $CP^{n+m-1|n} = U(n+m|n)/[U(1) \times U(n+m-1|n)]$ at $\theta = \pi$, in particular the models $CP^{n|n}$ which are expected to flow to CFTs with vanishing central charges. In previous work, Read and Saleur had managed to find the spectrum of exponents for these theories in the bulk [t01/197]. In the recent work [t11/056], Bondesan, Jacobsen and Saleur managed to solve the strong coupling CFT in the presence of boundaries. This is particularly interesting as it gives a way of understanding the spectrum for different values of the topological angle $\theta = \pi$ modulo 2π. Indeed, while bulk sigma models are expected to only be sensitive to the value of θ up to multiples of 2π, in the presence of boundaries, the exact value of θ matters. In fact, this value is what makes the difference between the different plateaux transitions in the Hall effect. It corresponds, physically, to the existence of additional *edge states* on the boundary of the sample. In [t11/056], the surprising result was obtained that for $CP^{n|n}$ and $\theta > \pi$ ($\theta = 3\pi, 5\pi$ etc) the exponents are in fact irrational. Their values result from an extremely technical analysis based on loop models, which will be described partly below. The interesting point is that these exponents have an immediate translation in terms of transport properties for the class C disordered systems. In a paper with I. Gruzberg and H. Obuse, Bondesan Jacobsen and Saleur have analyzed transport in the corresponding Chalker Codington disordered network model, and found remarkable agreement with their analytical predictions.

A.14.3 RG flows in super Gross Neveu models *(B. Pozsgay, H. Saleur)*

The challenge of sigma models with supertargets goes beyond the study of their conformal limits. Like their ordinary cousins, models such as the orthosymplectic (orthogonal) Gross Neveu model for instance appear formally integrable, and attempts have been made over the years to write their S matrices and analyze their physical properties. Considerable difficulties are however encountered, once again due to non unitarity - typically, in the case of supergroups, probability is only conserved with respect to a non positive metric. Put it otherwise, events with negative probabilities have to formally be included. In [t09/195] Poszgay and Saleur investigated the particular case of the $OSp(2|2)$ Gross Neveu and supersphere sigma models, and attempted to connect the S matrices with a thermodynamic Bethe ansatz. We uncovered fascinating duality properties, relating for instance the ground state energy of these theories with the one of ordinary theories - namely the $SO(4)$ sigma and Gross Neveu models respectively - generalizing earlier observations for the $OSp(4|2)$ case. They also studied the possibility of finding an integrable flow *into* the Gross Neveu model, which could then originate at the non trivial Nishimori critical point of the random bond (strongly) disordered Ising model.

Unfortunately, they concluded that such flows did not have a non trivial origin, showing that the Nishimori point is inaccessible by integrable techniques.

A.14.4 Sigma models and loop models *(J. Dubail, J.L. Jacobsen, H. Saleur)*

It is increasingly clear that the properties of the sigma models of interest in condensed matter physics are profoundly related with those of loop models. This correspondence comes formally from the diagrammatic representation of centralizer algebras going back at least to Brauer (1937). Physically, it finds it origin in the network models à la Chalker Coddington, and ultimately, in the properties of trajectories of random electrons in two dimensions. In a series of articles dating back to [t06/155], Jacobsen and Saleur have focussed on the role of boundary conditions in loop models, uncovering very complex structures with many potential applications. In [t09/071] and [t09/073], they have solved the more general problem of loop models on annuli subject to different boundary conditions on the left and right hand sides. This is profoundly related to the study of centralizers of spin chains with higher spin representations at the extremities (and thus, to the physics of edge states, see above). The technology to solve this problem relies largely on representation theory of the two boundary Temperley Lieb algebra, which was pioneered by Saleur [t94/188], and has drawn ever more attention from the mathematics community.

A.14.5 Logarithmic CFT *(J. Dubail, A. Gainutdinov, J.L. Jacobsen, H. Saleur, R. Vasseur)*

The CFTs associated with the sigma models are all logarithmic - which in essence means that the representations of their chiral algebra (Virasoro etc) come in different varieties, some of them being only indecomposable instead of irreducible. This has profound consequences, and makes the abstract study of these CFTs proverbially difficult. The parallel drawn in [t06/136] by Read and Saleur with non semi simple Lie algebras and their centralizers has grown to become one of the main tools in the field. Recently, Vasseur Jacobsen and Saleur [t10/021] were able to push this relationship to measure indecomposability parameters (parametrizing Jordan cells of the L_0 generator) in the case of polymers and percolation. Our result profoundly affected the status quo in the literature, and opened the way to a better understanding of LCFTs at vanishing central charge in particular. The analysis was generalized further in [t11/057] to several families of LCFTs. As a result, the relationship between lattice and continuum limit algebras appears ever deeper. Moreover, all the tools are now ready to tackle the case of *bulk* LCFTs, which is technically considerably more difficult, as the usual relationship between boundary and bulk CFTs does not appear to generalize in any simple way to the logarithmic case. Saleur and coworkers have many preliminary results in this direction, which will be their main focus in the year to come.

The mathematical structures unraveled by the analysis of lattice models are of interest in their own right. In particular, the emergence of the "full" or "Lusztig" quantum group at root of unity to describe $(1,p)$ logarithmic theories with central charge $c = 1 - 6\frac{(p-1)^2}{p}$ suggests to study fusion in LCFT exactly using the same principles as in the lattice, Temperley Lieb based analysis, pioneered by Read and Saleur in [t06/136]. A. Gainutdinov and coworkers explored various aspects of this idea, and built in particular the full fusion algebra of the $(1,p)$ models in [t11/086].

A.15 Quantum field theory on curved spaces

A.15.1 Field quantization in curved space *(R. Schaeffer)*

In curved spaces it naturally occurs that a given coordinate set covers only part of the whole space. In this case, the remainder is classically not accessible. The question then is to determine to which extend this next world can weight up the events in our accessible space. Quantum effects connect the two. Depending on the physical description of the system one considers, however, this next world may be from inexistent up to determinant for the occurrence of events here below; violently antagonist views of our world indeed? vain antagonism, just a gage choice? General Relativity indeed tells us that the description of a physical state is to be independent of the coordinate system choice.

The resolution of this dilemma requires to go beyond the Feynman rule, that in Minkowski space selects the unique vacuum where elementary excitations are solely positive energy states. Several examples show such a move is necessary [t07/121] in de Sitter space to preserve the de Sitter invariance under a change of coordinates; more generally to insure a given physical state indeed yields equivalent expectation values of observables whatever the coordinate representation, as required by Einstein's principle. The step to insure the latter is to pin down [t08/277, t09/297] the most general quantization allowed in curved space. Lifting the Feynman rule then unravels a vast area of new possibilities with potentially unexpected consequences, still under exploration.

A.15.2 From star–triangle integrals on Lobatchevski space to Källen-Lehmann representations of perturbative two-point functions in the de Sitter universe *(J. Bros, M. Gaudin, V. Pasquier)*

In collaboration with H. Epstein and U. Moschella [t09/269], we produce a seemingly undiscovered formula for a certain integral $h(\kappa, \nu, \lambda)$ of the product of three generalized Legendre functions of the first kind with respective parameters κ, ν, λ. Such Legendre-type functions have an interesting interpretation as being the two-point functions of free Quantum Field Theories (QFT) with three different masses κ, ν, λ on the ($d-$dimensional) de Sitter spacetime, while the integration manifold for this triplet is the Lobatchevskian submanifold of the complexified de Sitter hyperboloid.
Two types of comments are relevant:

1) *from the viewpoint of mathematics:* a blending of geometrical ideas and analytic methods is used for computing the quantity $h(\kappa, \nu, \lambda)$ on the basis of a generalized "star-triangle identity". The latter involves the integration on triangles on the asymptotic cone of the de Sitter hyperboloid, which is implemented (thanks to a beautiful geometrical identification) in an old work by one of us (M.G) on Clebsch-Gordan coefficients.

2) *from the viewpoint of QFT on the de Sitter universe:* $h(\kappa, \nu, \lambda)$ turns out to provide the Källen-Lehmann weight $\rho_{\nu,\lambda}(\kappa)$ of the bubble diagram of two massive fields with given masses ν and λ, expressed as a linear superposition of free-field two-point functions with mass κ. Thereby, this computation allows one to generalize the study of "particle decay in de Sitter space-time" as given by first-order perturbation theory in a Lagrangian interacting quantum field theory: in a previous work by one of us (J.B.) and H. Epstein and U. Moschella (see [t08/272] and a short version of it reported in the previous "rapport d'activité de l'IPhT: 2005-2007") the case of a disintegration in two equal mass particles (i.e. $\nu = \lambda$) has been treated completely, thanks to the computation of $h(\kappa, \nu, \nu)$ which was much simpler. In that special case, a complete analysis of the lifetime of a de Sitter particle is given in [t08/272], including the extension to cases of masses κ in the complementary series of the de Sitter group and the proof that the lifetime of a de Sitter particle is independent of its velocity when it is of the order of the de Sitter radius.

Then, thanks to the general computation of $h(\kappa, \nu, \lambda)$ given in [t09/269], all the aspects of the analysis of [t08/272] can be transported to the case of disintegration in two particles with unequal masses.

A.16 Generalized interval exchange maps *(P. Moussa)*

Following previous papers [t03/033, t04/046], in collaboration with S. Marmi and J.-C. Yoccoz, we have obtained new results in the study of interval exchange maps. Such maps are interesting examples of mathematical dynamical systems, since they generalise rotations on a 2D torus to similar transformations on Riemann surfaces of higher genus. They are also associated with rational pseudo-integrable billard maps. The study of interval exchange maps is itself a chapter of ergodic theory of dynamical systems.

When the exchange is realised through a translation, the exchange maps is said to be standard. In [t08/112] the authors have considered affine interval exchange maps, including a further linear rescaling. They show that almost all such maps have wandering intervals, which implies that they are not conjugated, but only topologically semiconjugated to a standard exchange map. In [t10/234] the analysis is extended to generalized exchange maps, where the transformations are deformations of translations with some regularity properties. Among such transformations, we characterize those which are conjugated to standard maps: within the manifold of all possible deformations, they form a submanifold of specified codimension.

A.17 Stochastic dynamical systems *(K. Mallick)*

Randomness in the external conditions entails the parameters of a system to fluctuate and can therefore be modeled as multiplicative noise in the dynamical equations. Our aim in the following works was to investigate how the interplay of noise and nonlinearity in a system far from equilibrium can drastically alter the properties of the dynamics both qualitatively and quantitatively and induce some unusual phenomena.

A.17.1 Dynamical systems subject to general noise

A noise acting on a dynamical system can drastically modify an instability process. In particular, a multiplicative noise can lead to a new type of intermittency, called On–Off intermittency, in which quiet and laminar (off) phases randomly follow bursting (on) phases. This intermittency has been identified in various experiments. Most theoretical works consider white or Ornstein-Uhlenbeck noises. However, in realistic situations, the noise is far from being white. In [t07/170] we discuss the dependence of the intermittency on the Power Spectrum Density (PSD) of the noise. We derive analytical results for some particular types of noises and perform a cumulant expansion for an arbitrary PSD. We show that the intermittent regime is controlled by the ratio between the departure from the threshold and the value of the PSD at zero frequency. Our results are in agreement with numerical simulations (joint work with F. Petrélis, ENS Paris and S. Aumaître, CEA)

In [t07/212, t09/049] we use an effective Markovian description to study the long-time behavior of a nonlinear second-order Langevin equation subject to a Gaussian noise with *arbitrary spectrum* (provided the spectrum decays algebraically at high frequencies). We analytically compute the probability distribution function in phase space in the long time limit. This leads to scaling formulae for the growth of the amplitude, of the momentum, and of the energy transfer. In particular, we show that the scaling exponents depend on both the stiffness of the confining potential at infinity, and the smoothness of the random excitation: the smoother the noise (which corresponds to a faster decay of the power spectrum at high frequencies) the less efficient the energy transfer from the bath to the oscillator. At large times the system reaches a nonequilibrium steady state in which physical observables do not grow anymore; the crossover from power-law growth to this steady state occurs when the rate of energy dissipation by friction matches that of energy absorption from the random environment.

A.17.2 Diffusion and multiplication in a random medium

In [t10/191], we investigate the evolution of a population of non-interacting particles which undergo diffusion and multiplication. Diffusion is assumed to be homogeneous, while multiplication proceeds with space dependent rates, reflecting the nonhomogeneous distribution of nutrients. The latter distribution defines a landscape, which is assumed to be a stationary and quenched random variable with zero average (so that the population size would remain constant if the distribution were homogeneous). The fluctuations drastically affect the behavior of the population size, and different statistical properties of this landscape lead to a number of laws for the growth of the population. We show that in most cases, the total population increases faster than exponential. This behavior is due to two features of the noise, namely its multiplicative nature, and its unboundedness. Another striking feature is the huge difference between typical and average behaviors. In order to determine the average growth law, one has to consider all possible realizations of the random landscape, and the average is dominated by rare configurations in which extremal statistics play an important role. We have performed asymptotically exact calculations in the situation where the landscape is described by a Brownian noise. There, the determination of the average population growth reduces to calculating a first passage exponential functional of the Brownian motion, which can be done exactly. More general cases are analyzed through heuristical predictions. (joint work with P. Krapivsky, Boston University).

A.17.3 Localization in the non-linear Schrödinger equation

In [t08/133] we consider the problem of the one-dimensional Anderson localization for the nonlinear Schrödinger equation (NLS). The basic question is to investigate whether Anderson localization can survive the effects of nonlinearities. This problem is relevant for experiments in nonlinear optics (e.g. disordered photonic lattices). We show that the asymptotic growth of the moments of a stationary wave function for NLS (and of its derivative), can be determined knowing the corresponding growth rates for the linear Schrödinger equation. Using a mapping to a Langevin equation, we compute the latter rates (and in particular the behavior of high order cumulants). Finally, a resummation procedure is used to deduce the results for the nonlinear Schrödinger equation, in particular and the localization length of the stationary states (joint work with S. Fishman and A. Iomin, Technion, Israel).

A.18 (Magneto-)hydrodynamical instabilities *(Ch. Normand)*

Axisymmetric flows, ubiquitous in Nature, are the source of various instabilities in fluid dynamics. Helical flows in a conducting fluid are at the origin of growing magnetic fields (dynamo effect); this effect is studied both for steady and for time dependent flows. Centrifugally stable circular Couette flows can become unstable when they take place in a stably stratified fluid, the onset conditions are studied for an inviscid flow.

A.18.1 Energetic stability of cylindrical dynamos

In [t08/032] a cylindrical dynamo problem is studied through a Galerkin expansion of the magnetic field components. Thresholds for the energy instability of the system are estimated, in the form of lower bounds for the critical magnetic Reynolds numbers R_m^E for different azimuthal modes m. The value of R_m^E for the most unstable modes (axisymmetric and antisymmetric) are found to be close to each other, so that one may expect mode coupling through the feedback on the velocity field. This mechanism could explain the eventual growth of the axisymmetric mode, which is otherwise excluded by the usual modal stability analysis.

A.18.2 Helical dynamos driven by stochastic flows

Investigating the role of turbulence on dynamo action implies to solve the full MHD equations, which can be done numerically only in very specific situations. A simplified problem is to determine how the onset of dynamo driven by steady flows is modified by the addition of time-dependent fluctuations, with a temporal behavior modelled by a periodic or a stochastic function.

Refs. [t10/079], [t11/052] study the generation of magnetic field by a helical flow made of a mean steady flow plus a random fluctuating flow. The steady flow and the fluctuations are both solid body screw motions with constant pitches, respectively $\bar{\Gamma}$ and $\widetilde{\Gamma}$, and the time dependence of the fluctuation is a Gaussian white noise. The threshold shift induced by fluctuations of small amplitude is calculated analytically for different values of $\widetilde{\mu} = m + k\widetilde{\Gamma}$ and $\bar{\mu} = m + k\bar{\Gamma}$, m and k being the axial and azimuthal wavenumbers of the growing magnetic field. A steady flow is optimized for dynamo action when the dynamo threshold R_c is minimum. For helical flows it occurs when the pitch of the magnetic helical lines, $|m/k|$, and the pitch of the flow satisfy the condition of spatial resonance $\bar{\mu} \approx 0$. We find that, for small enough values of $\bar{\mu}$, the threshold R_c can be lowered by the addition of the small random fluctuating flow, provided $\tilde{\mu}$ belongs to an appropriate interval near 0. The conclusion is that optimized fluctuations are beneficial to dynamo action driven by helical flows.

Ref. [t11/052] also considers a purely fluctuating flow, with temporal fluctuations modelled by a colored noise, and investigate the influence of the correlation time on the dynamo onset.

A.18.3 Strato-rotational instability

The strato-rotational instability (SRI) occurring in stably stratified rotating flows is a possible source of turbulence in Keplerian accretion disks and in oceans. In the laboratory, SRI was detected in experiments on a circular Couette flow (CCF) between two concentric cylinders of radii R_1 and R_2 rotating at angular velocities Ω_1 and Ω_2, respectively. In the small gap limit $R_1/R_2 = \eta \to 1$, the modified Rayleigh criterion for SRI in inviscid fluids, $\Omega_1/\Omega_2 = \mu < 1$, is unable to account for the fact that unstable modes were experimentally observed only when $\mu < \eta$. In numerical simulations of viscous CCF, SRI was found when $\mu < \mu^*$, with μ^* being either larger or smaller than η.

Ref. [t09/185] analyses the influence of finite gap effects on the stability criterion. The inviscid dispersion relation is derived analytically for non axisymmetric perturbations and the exact value of the growth rate is computed for three representative values of η. For a given value of μ, unstable modes are found on a bounded interval of axial wavenumbers. As μ increases, the interval becomes narrower and shifts towards higher wavenumbers values. Wavenumbers observed in experiments and computations fall inside the interval predicted by the theory provided $\mu < \mu_s$, with values $\mu_s \geq \eta$ when $\eta \to 1$ and $\mu_s < \eta$ when $\eta \to 0$, in agreement with the stability limits found in the available data. It is concluded that viscous damping of the modes with large wavenumbers is responsible for the disappearance of SRI when $\mu > \mu_s$.

A.19 Dynamics of quantum decoherence and random matrix models *(F. David)*

The study of decoherence and dissipation in open quantum system is an established subject, of crucial importance in condensed matter physics, atomic and quantum physics, quantum information, and especially for a proper understanding of the quantum formalism and of the quantum measurement processes. Random matrix methods have been used since a long time, as a way to model the complicated dynamics and couplings between a simple quantum system and the external environment. Most established results are valid in the so-called Markovian regime, where the dynamics of the environment is fast, so that quantum memory effects can be neglected.

Motivated by the search of a better understanding of the general regime, we have proposed and solved a simple but very general quantum model of an SU(2) spin interacting with a large external system with N states [t10/134]. The coupling is described by a random hamiltonian in a new general gaussian SU(2)×U(N) random matrix ensemble. The model is solved in the large N limit, for any value of the spin j and for any choice of the coupling matrix element distributions in the different possible angular momentum channels l (and provided that the internal dynamics of the spin is slow). Besides its mathematical interest as a non-trivial random matrix model, this model allows to study and illustrate in a simple framework various important quantum phenomena: the decoherence dynamics, the conditions of emergence of classical degrees of freedom and of the classical phase space for the spin, the general properties of quantum diffusion in phase space. The large time evolution for the spin is shown to be non-Markovian in general, the Markov property emerging in some very specific cases, both for the dynamics of the external system and the coupling, but also for the initial conditions.

A.20 Quantum formalism *(F. David)*

The role of causal reversibility, together with causality and locality, is stressed in the justification of the quantum formalism in [t11/035]. Firstly, in the algebraic quantum formalism, starting from the general notion of states and observables, it is shown that reversibility implies that the observables of a quantum theory form a real C*-algebra. Not so well known GNS-like theorems from the '60-'70 imply that it can be represented as an algebra of operators on a real Hilbert space. The restriction to standard complex C*-algebras and complex Hilbert spaces is recalled to come from the constraints of locality and separability. Secondly, in the quantum logic formalism, it is discussed which axioms (existence of an orthocomplementation and the covering property) derive from reversibility. Here again, assuming locality ensures that the lattice of propositions can be represented as projectors on a complex Hilbert space, and leads to the standard representation of the quantum formalism.

A.21 Scattering theory with nonlocal potentials and complex angular momentum theory *(J. Bros)*

In [t10/142], we have established the meromorphy properties of the partial scattering amplitude $T(\lambda, k)$ associated with physically relevant classes of *nonlocal potentials*, in domains of the space $\mathbf{C}^2$ of the complex angular momentum λ and complex momentum k (the square root of the energy). In these domains, the general expression of T as a quotient $\Theta(\lambda, k)/\sigma(\lambda, k)$ of two holomorphic functions is obtained by using the Fredholm–Smithies theory for complex k, at first for $\lambda = \ell$ integer, and in a second step for λ complex (with $\Re e\lambda > -1/2$). This allows to define the polar manifold of T by solving $\sigma(\lambda, k) = 0$.

We then justify the Watson resummation of the partial wave amplitudes in an angular sector of the λ–plane, in terms of the various connected components of this polar manifold. While integrating the standard notion of interpolation of resonances in the upper half–plane of λ (due to Regge), this unified representation of the singularities of T also provides an attractive possible description of the "echoes" (or "antiresonances") in the lower half–plane of λ. Such a possibility, which is forbidden in the case of local potentials, represents an enriching alternative to the standard Breit–Wigner hard–sphere picture of these echoes. (collab. with E. De Micheli and G.A. Viano).

A.22 Nonhermitian quantum chaos *(S. Nonnenmacher, E. Schenck)*

Several types of quantum systems lead to consider effective nonselfadjoint "Hamiltonians" of the form $H = H_0 - i\epsilon H_1$, with H_0, H_1 hermitian, and $\hbar \leq \epsilon \ll 1$. The first example is the scattering of a particle by a localized potential ("scatterer"). The original Hamiltonian, H_0, admits (complex valued) resonances below the continuous spectrum; the latter can be obtained as eigenvalues of an operator of the above form, obtained by "deforming" H_0. Our aim is to understand the semiclassical distribution of the eigenvalues of H, using the underlying classical dynamics. We focussed on scattering systems for which the set of (classical) trapped trajectories is fractal, and hosts a chaotic dynamics. For such systems, no separation of variables, or normal form, are possible, so the resonance spectrum is not explicit.

A.22.1 Resonances for chaotic scattering systems

In [t07/106], [t09/052] we give a sufficient condition for the presence of a gap in the resonance spectrum (that is, a resonance free strip below the real axis). This condition is expressed by the negativity a certain *topological pressure* associated with the classical flow on the trapped set. In two dimensions, this criterium amounts to an upper bound on the Hausdorff dimension of the trapped set. A resonance gap implies strong dispersive properties for the associated quantum or wave system. (collab. with M. Zworski)

We developed in [t10/055] a new method to analyze these resonances. The idea is to extract them from an auxiliary *quantum monodromy operator*, which quantizes the Poincaré map for the flow. This monodromy operator has similar properties with the *open quantum maps* used as a toy model for chaotic scattering systems. In [t11/143] we used this method to show that the resonances in the case of $N \geq 3$ convex hard obstacles satisfy *fractal Weyl upper bounds* in the high energy limit. (collab. with J. Sjöstrand and M. Zworski)

We are also interested in the "shape" of the associated metastable states for such systems. We have shown in [t07/106] that their phase space distribution can be described by a certain family of probability measures, invariant w.r.to the classical flow up to a global decay. Yet, it remains unclear whether quantum mechanics will "select" certain of these measures, as is the case for closed chaotic systems. This question could be partially answered only for a very specific open quantum map in [t08/111]: we showed all the metastable modes of near-minimal decay rate semiclassically have the same phase space distribution, but this uniqueness breaks down in the "bulk" of the spectrum. (collab. with J. Keating, M. Novaes and M. Sieber).

The review article [t11/144] on spectral aspects of open chaotic systems summarizes the recent advances described above (and some others).

A.22.2 Damped quantum systems

The second class of systems consists in damped waves propagating on a compact domain (or manifold): H_0 is the free motion, while $H_1 \geq 0$ represents the damping. The spectrum of H lies in a strip below the real axis. One is interested in the distribution of the imaginary parts of the eigenvalues (quantum decay rates). We have concentrated on situations where the classical dynamics is chaotic (e.g. a manifold of negative curvature), and the damping function is nonhomogeneous. The distribution of the decay rates is then peaked near a "typical" value, given by the phase space average of the damping. In [t08/055] we estimated the width of this distribution for a toy model of damped quantum maps, and established a condition for a spectral gap in terms of a certain topological pressure of the classical flow. In [t09/131] the same condition is proved by Schenck in the case of damped waves on a manifold of negative curvature, and from there one shows that the energy of the waves decays exponentially. In the framework of damped quantum maps, upper bounds for the density of quantum decay rates *away* from the typical value are established in [t09/013]: these bounds have the form of fractal Weyl laws (namely, fractional powers of $\hbar^{-1}$), and the powers correspond to large deviation functions for the classical chaotic dynamics.

A.23 Quantization and resummation methods in quantum mechanics *(J. Zinn-Justin)*

A.23.1 Multi-instantons and exact quantization

The articles [t07/225], [t09/307], [t09/308], [t10/035], [t10/036] are all different applications of ideas developed by the author in the eighties and inferred from multi-instanton considerations in the quantum mechanics of potentials with degenerate classical minima. There a generalization of the exact form of the Bohr–Sommerfeld quantization equation was conjectured, which was later partially proved. More recently, this generalized quantization condition was reformulated in the context of the so called exact WKB expansion, allowing the calculation of many terms of the semiclassical expansion and systematic numerical checks of the conjecture. In the recent publications a number of applications to other potentials like $x^2 + gx^N$ for a number of values of N, including non-Hermitian PT symmetric potentials, are studied (collab. with U.D. Jentschura, M. Lubasch, A. Surzhykov).

A.23.2 Order–dependent mapping and the spectrum of $V(x) = x^2 + i\sqrt{g}x^3$

The article [t10/034] contains an analysis of several summation methods for divergent series and, in particular, elaborates on an original method introduced by Seznec and Zinn-Justin, called Order–Dependent Mapping (ODM). The articles [t10/236] and [t10/238] apply the ODM method to a detailed study of the ground state energy of the non-Hermitian Hamiltonian corresponding to the potential $x^2+i\sqrt{g}x^3$ with $g>0$. This Hamiltonian is PT symmetric, that is, it is invariant under a simultaneous transformation $x \mapsto -x$ and complex conjugation. In 1992, Bessis and Zinn-Justin had conjectured that the spectrum of such a Hamiltonian is real. This problem has then generated much interest, in particular because it appears in some integrable models. The conjecture has since been proven as well as the Borel and Padé summability of the perturbative expansion. However, interesting problems remained concerning level crossing (complex PT symmetric Hamiltonians do not experience level repulsion) and the precise relation with another PT symmetric Hamiltonian with potential $ivx+ix^3$, v real. In [t10/236] it is shown that the ODM method applied to the expansion in powers of g allows a precise numerical determination of the coefficients of the large g expansion. In [t10/238] the large g expansion is used to determine the small v expansion. The location of the first level crossing is determined, and shown to correspond to a spontaneous breaking of the PT symmetry (collab. with U.D. Jentschura).

A.24 Zeta functions over zeros of zeta functions *(A. Voros)*

The survey monograph [t09/085] covers the properties of several kinds of zeta functions built over the zeros $\{\rho\}$ of the Riemann zeta function $\zeta(x)=\sum_{k=1}^{\infty} k^{-x}$ (or more generally, over the zeros of L-functions, Dedekind and Selberg zeta functions).

Those second-generation zeta functions, called "superzeta functions" for brevity, are mainly:

$$\sum_{\rho}(\rho+t-1/2)^{-s}, \qquad \sum_{\rho}\left[\rho(1-\rho)+t^2-1/4\right]^{-s/2}$$

(summing over all the zeros; if restricted to the upper half-plane zeros instead, the leftmost sum yields a superzeta function "of the third kind", which is more singular but also described in the book).

Similar in structure to the Hurwitz zeta function $\zeta(s,t)=\sum_{n=0}^{\infty}(n+t)^{-s}$, the superzeta functions have surprisingly many explicit, yet largely overlooked properties, which are surveyed in an accessible and synthetic manner, to be ultimately compiled in some twenty tables. No book whatsoever had previously addressed this topic in analytic number theory. Concretely, this handbook should serve users of symmetric sums over the Riemann zeros or their generalizations. More generally, it aims at reviving the interest of number theorists and complex analysts toward those somewhat neglected functions, on the 150th anniversary of Riemann's work on the zeta function named after him.

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CHAPTER B

Cosmology and particle physics

Introduction

The research activities of the Particle Physics and Cosmology group of the IPhT cover a broad range of topics in theoretical cosmology, astroparticle physics, particle physics beyond the Standard Model, quantum chromodynamics and nuclear physics.

Cosmology is a very active research topic at the IPhT and our activities in this field range from studies of the early Universe (e.g., inflationary scenarios) to works on the large-scale structures observed in the present Universe.

A first major topic of modern cosmology is the generation during an early inflationary era of the primordial fluctuations that seeded the large-scale structures (such as galaxies) that we observe today. In particular, while the simplest single-field scenarios predict almost-Gaussian initial fluctuations, alternative models (e.g., multifield inflation) can give rise to significant non-Gaussianities. This topic of "primordial non-Gaussianities" has become a very active subject in the community, with the upcoming increasingly precise observations (e.g., the current Planck mission), as it gives a sensitive probe of early Universe physics. On a first side, we have computed the nonlinear contributions to higher-order correlations that arise in single-field models, and we have for instance uncovered new contributions to the four-point function. On a second side, we have studied the non-Gaussianities generated in multifield models, including both gravity and non-gravity induced couplings.

Another important probe of the early Universe would be the detection of gravitational waves generated by primordial phase transitions. We have developed analytical models to evaluate the stochastic background of gravitational waves generated by the collision of broken phase bubbles and by the associated magnetohydrodynamical turbulence. We have thus shown that the space interferometer LISA could detect this background for electroweak symmetry breaking scenarios leading to a strongly first order phase transition.

A related topic is the possible generation of magnetic seeds in the primordial Universe, which could explain the ubiquitous magnetic fields that we observe today on cosmological scales. We have built a detailed model for the evolution of magnetic fields in the primordial plasma and obtained new constraints on generation mechanisms. We have also considered its impact on the Cosmic Microwave Background (CMB) anisotropies.

A second important subject of current cosmology is the study of the CMB anisotropies. In relation with the upcoming Planck data and the study of "primordial non-Gaussianities", it has become necessary to go beyond linear order, to keep pace with observational precision and to distinguish primordial signals from late-time nonlinear effects. We have performed a series of works to study such effects and we have computed the main contributions at second order to the CMB fluctuations, as well as the full second-order bispectrum, by a consistent implementation of the Boltzmann equation. This is a long-term project that aims at building a CMB code up to second order, which will be quite valuable for the community. On the other hand, we have also computed secondary effects, due for instance to the time dependence of the potentials along the line of sight and to lensing distortions.

A third major topic is the study of the formation of large-scale structures. Indeed, from the distribution of galaxies and clusters we can obtain complementary constraints on the background cosmology (such as the behavior of the dark energy component) and primordial fluctuations. This again requires precise predictions, up to 1% on weakly nonlinear scales, which has led to a recent surge of activity in perturbation theory, motivated by the development of dedicated wide field surveys. Indeed, it is possible to improve over the standard perturbative approach by implementing resummation schemes, which provide better controlled and more accurate predictions. Several approaches have been proposed and developed at the IPhT, and can already be applied to non-Gaussian initial conditions or combined to phenomenological models to cover the highly nonlinear regime. This is again a long-term project that aims at building accurate and fast methods, in order to reach the accuracy required by future observations (e.g., Euclid).

On a more theoretical side, we have also performed a series of works to study a simplified toy model, the "adhesion model", where exact or well-controlled results can be derived, to shed light on the nonlinear aspects of the dynamics and the behavior of such resummations. In particular, we have been able to explain the different behaviors found in the Eulerian and Lagrangian frameworks.

In relation with the topic of primordial non-Gaussianities, we have also studied in detail the signature of this primordial signal in the low-redshift large-scale structures, using both analytical tools and numerical simulations. In particular, we have estimated the constraints that can be obtained on scale-dependent non-Gaussianities, which had not been much studied yet.

A fourth important subject is the understanding of the dark energy component, which is one of the major puzzles of theoretical physics. This is a very active topic in the community, which has led to the development of major observational projects, such as the future space mission Euclid. We have studied quintessence models with a vanishing sound speed, where the dark energy component clusters and can affect the formation of large-scale structures. More generally, we have estimated the constraints on the dark energy equation of state that can be derived from the CMB.

Finally, in the field of weak lensing, which is a long-held topic at the IPhT, we have presented the first computation up to second order of the cosmic shear, including all relativistic effects and without relying on small-angle approximations. We have also estimated the sensitivity of weak lensing observables on primordial non-Gaussianities.

The cosmology section of this chapter gathers contributions from 8 permanent researchers, F. Bernardeau, C. Caprini, P. Valageas, F. Vernizzi, who specialize on cosmology, and P. Brax, J. Bros, V. Pasquier, G. Servant, who also contribute to other chapters; and 3 postdocs, C. Bonvin (who left in September 2010), Z. Huang (who arrived in October 2010), E. Sefusatti (who arrived in January 2009). The group also has 1 current PhD student, N. van de Rijt.

Particle physics beyond the Standard Model is a very active research subject in Saclay, where many of its aspects are studied, from electroweak symmetry breaking to astroparticle physics. These activities take place in a particularly rich experimental context: the Large Hadron Collider (LHC) at CERN has started to explore the terascale and is going to shed light on fundamental questions regarding the building blocks of matter and their relative interactions; neutrino and flavour physics experiments are providing us with complementary information about the flavour structure of the physics relevant at high energies; a variety of astroparticle physics experiments are constraining the properties of dark matter and may help us, in conjunction with the LHC, to identify its nature; and finally, cosmological observations are delivering more and more accurate information about cosmological parameters.

An important part of our research activities in physics beyond the Standard Model aims at identifying the dynamics of electroweak symmetry breaking through its signatures at the LHC. Since the top quark has a large Yukawa coupling to the Higgs boson, top physics is a privileged place where to look for such signatures. For instance, a generic prediction of models in which the Higgs boson arises as a pseudo-Goldstone boson is the existence of fermionic partners of the top quark, whose production at the LHC has been studied in detail. Model-independent approaches based on effective field theories were developed in order to interpret the anomalously large forward-backward asymmetry in $t\bar{t}$ production measured at the Tevatron, and to assess the sensivity of top quark collider observables to new physics. Simulations of specific observables like four-top production were also performed. Deviations from the standard Higgs mechanism can also be probed in the Higgs sector itself, and this was demonstrated for double Higgs production, or by searching for spin-1 resonances of the electroweak gauge bosons, which are characteristic of many alternative scenarios of electroweak symmetry breaking.

Another very active line of research at the IPhT is the physics of flavour and CP violation, in which indirect signals of physics beyond the Standard Model may appear. A first question of interest is the origin of the quark and lepton mass and mixing patterns, which could be related to the mechanism that suppresses new physics contribution to flavour- and CP-violating observables. The disparity between the large lepton mixing and the small CKM mixing angles in the quark sector, for instance, could be explained by discrete flavour symmetries, and this has been addressed both in the context of Grand Unification and of strong electroweak symmetry breaking scenarios. The efficiency of the flavour symmetry and wave function renormalization approaches in suppressing supersymmetric flavour violation were compared. We also pursued the study of the implications of massive neutrinos, within the supersymmetric seesaw mechanism, for the baryon asymmetry of the Universe and for flavour- and CP-violating processes. In particular, a connection between leptogenesis and CP violation at low energy was found in some Grand Unified models. Finally, the possibility of observing new fermions generically present in low-scale flavour gauge theories has been studied.

A traditionally strong activity in Saclay is the study of supersymmetric models and their phenomenology. Supersymmetry breaking and its mediation to the observable sector has been investigated in the framework of gauge-mediated supersymmetry breaking. It was demonstrated that radiative corrections can stabilize the supersymmetry breaking vacuum while allowing for sizable gaugino masses, thus evading a well-known problem of gauge mediation. Also, unconventional superpartner spectra with well-defined gaugino mass ratios were shown to arise in the presence of an underlying Grand Unified Theory. Various aspects of non-minimal supersymmetric models and string compactifications were studied, such as four-fermion interactions arising in intersecting D-brane models, or the occurrence of singlet extensions of the minimal supersymmetric standard model in heterotic orbifolds.

A much strengthened line of research at the IPhT in the last few years is the one in the domain of astroparticle physics and particle cosmology, i.e. at the intersection between particle physics beyond the Standard Model and cosmology or astrophysics. In this line lie the works performed on the electroweak phase transition, dark matter, dark energy and inflation models.

The dynamics of the electroweak phase transition in the early Universe is very sensitive to the actual mechanism of electroweak symmetry breaking. It is well known that it cannot be first order within the Standard Model, as successful electroweak baryogenesis would require, but the situation can be different in alternative scenarios. We have studied the dynamics of electroweak bubble nucleation when the Higgs boson emerges as a composite bound state from a strongly interacting sector, and showed that the associated signal in gravity waves can be large. From a model-independent perspective, we have studied the hydrodynamics of bubble growth in a first-order phase transition, which is relevant both for electroweak baryogenesis and for the size of the gravity wave signal resulting from bubble collisions.

Dark matter constitutes most of the matter content of the Universe, as a number of cosmological and astrophysical observations now confirm. However, little is known about its nature and it has not been directly detected yet. Many new particle candidates for dark matter, coming from various extensions of the Standard Model, have been identified and studied over the last decade. Within this broad context, the research performed at the IPhT has moved along two main axes. The first one is the exploration of dark matter phenomenology in specific models. This includes the investigation of Minimal Dark Matter, a new model proposed by us a few years ago, whose predictions for direct and indirect dark matter experiments have been precisely computed; and the study of new dark matter candidates from Grand Unified Theories, warped extra dimensions and from a strongly-interacting electroweak symmetry breaking sector. The second axis is the model-independent analysis of recent cosmic ray observations in terms of dark matter and the identification of the corresponding constraints. It was shown in particular that the lack of associated signals impose very strong restrictions on dark matter interpretations of charged cosmic ray data.

With the advent of the era of precision cosmology, there has been a renewed interest in particle physics models for the early Universe, and the IPhT has actively participated in this effort over the past four years. We have studied a certain number of inflationary models and their consequences for preheating and the formation of cosmic strings. We have also analysed possible inflationary scenarios within the Intriligator–Seiberg–Shih framework of metastable supersymmetry breaking. The accelerated expansion of the Universe may be due to cosmologically coupled scalar fields, such as chameleons. Motivated by this, we investigated the possibility of observing scalar field models coupled to matter in laboratory experiments, and our work prompted a large body of experimental activity. Following our original work in 2002 and 2004, we have also studied the modification of the growth of structures induced by the presence of a cosmologically coupled scalar field.

The beyond the Standard Model section of this chapter gathers contributions from 7 permanent researchers: P. Brax, M. Chemtob (emeritus), M. Cirelli, C. Grojean, S. Lavignac, C. Savoy (emeritus), G. Servant; 5 postdocs: M. Frigerio (2005-2009), F. Iocco (2008-2009), J.-M. No (2009-2011), A. Sil (2006-2009), G. Zaharijas (2009-2011); and 6 PhD students, E. Cluzel, C. Delaunay, P. Hosteins, S. Mariadassou, P. Panci and J. Parmentier, who defended their theses in September 2011, October 2008, September 2007, December 2011, March 2011 and July 2011, respectively.

The study of strong interactions is a very active and diverse activity at the IPhT. Our activities cover a broad spectrum of research topics, ranging from nuclear physics to studies of quantum chromo-dynamics in the context of searches of new physics at the LHC.

A major thread of research in our group is the study of amplitudes in gauge theories, mostly QCD but also supersymmetric variants such as the $N = 4$ supersymmetric Yang-Mills theory that can be employed as a laboratory for studying new approaches. A common theme in these studies is the use of hidden symmetries and structures satisfied by these amplitudes, that can be employed to bypass the standard computation techniques in terms of Feynman diagrams. In recent years, this has led to a breadth of new methods for efficiently computing amplitudes in QCD (typically, amplitudes with many externals legs, possibly up to NLO). Our activity on this subject ranges from the study of formal aspects of these symmetries, the development of new on-shell techniques for computing one-loop amplitudes, and the implementation thereof in a form that can be directly used in phenomenological studies.

Another related area of study is the development of new jet algorithms. These are important tools in the experimental study of QCD at high energy colliders such as the LHC in order to make the contact between perturbatively calculable cross-sections, in terms of quarks and gluons, and actual measurements that see only hadrons. Any suitable jet algorithm must be infrared and collinear safe. In addition, the very large particle multiplicity in final states at the LHC (especially in heavy ion collisions) renders crucial the clustering efficiency of these algorithms. We have played a central role in developing new jet algorithms, such as the k_t and anti-k_t algorithms, that are now used by the major collaborations at the LHC.

An important domain of research at the IPhT is the study of the Color Glass Condensate, an effective theory for the study of hadronic and nuclear wave functions in the high energy regime, where gluon saturation effects become important. These effects are crucial for instance in a first principles study of nucleus-nucleus collisions at high energy. Our activity here covers both formal aspects that aim at developing the formalism and justifying its applicability to high energy collisions (e.g. via factorization theorems that relate various types of reactions), and phenomenological studies whose goal is to confront the predictions of the Color Glass Condensate effective theory to experimental results at HERA, RHIC or the LHC.

There has been in the last four years some activity on central diffractive production in hadronic collisions at high energy at the TEVATRON or at the LHC, which is a very clean production channel for new particles such as the Higgs, since they can be measured with almost no background.

The last four years have seen the appearance of new domains of application of the AdS/CFT correspondence (and more generally gauge-gravity dualities). While these ideas were so far employed in order to study formal properties of gauge theory amplitudes, these techniques have now made an incursion into the territory of the phenomenology of quark-gluon matter at high temperature, such as the matter produced in heavy ion collisions. All these studies deal with QCD-like theories rather than QCD itself, but it is believed that some of their properties at strong coupling are rather close to those of QCD. Thanks to these techniques, we have studied at strong coupling questions such as the parton picture, the energy loss of a heavy quark in a plasma, the properties of meson bound states in hot matter, and the viscosity of the quark-gluon plasma.

In heavy ion collisions at high energy, the experimental results for bulk observables suggest that the quark-gluon matter produced in these collisions can be described as an almost frictionless fluids in expansion and can be modelled using relativistic hydrodynamics. An important observation is that the final anisotropy of the momentum of the observed particles can be related via the hydrodynamical evolution to the initial shape anisotropies of the system. Our group has played a major role in developing practical methods for measuring the parameters that quantify these anisotropies in the experimental results. A major result has also been the realization that event-by-event shape fluctuations are an essential ingredient in interpreting these results. Our team has also worked on some more formal aspects of relativistic hydrodynamics, by obtaining exact solutions in some special cases.

During the last four years, there have also been some work on quantum field theories at finite temperature. This activity has covered several topics: the behavior of heavy quarks in the quark-gluon plasma, the exact renormalization group and its applications, random matrices applied to the study of confinement, and lattice studies of SU(3) gauge theory in three dimensions.

Another domain of study of the strong interactions group at the IPhT is that of cold baryonic matter at high density. The equation of nuclear matter in this regime is poorly known, and could possibly undergo a number of phase transitions, and it is of central importance in the physics of compact stars. This problem has been addressed by various methods: hidden local symmetry, holographic methods and gauge-gravity dualities, and topological arguments.

Theoretical nuclear physics has mainly concerned two areas in the period covered by this report: the theory of fusion and fission reactions, and the mathematical foundations of the nuclear density functional.

The strong interactions section of this chapter contains contributions from 13 permanent researchers: J.-P. Blaizot, P. Brax, R. Britto, F. Gelis, B. Giraud, E. Iancu, G. Korchemsky, D. Kosower, A. Morel, J.-Y. Ollitrault, R. Peschanski,

M. Rho, G. Soyez; and from 11 postdocs: J. Albacete, E. Avsar, S. Badger, G. Diana,Y. Hatta, H. Johansson, M. S. Kugeratski, T. Lappi, M. Luzum, C. Marquet, E. Mirabella. During this four year period, 3 students have obtained their PhD in the strong interaction group: G. Beuf, C. Gombeaud, C. Vergu, and 3 students have started a PhD: J. Laidet, L. Palhares, Z. Peng.

B.1 Physics of the early universe

B.1.1 Primordial non-Gaussianities *(F. Bernardeau, F. Vernizzi)*

The observation of primordial non-Gaussianities would be of dramatic importance for our understanding of the inflationary era, as a detection (or a tight upper bound) could constrain or rule out many inflationary models.

First, within the standard single-field inflationary model, which is still consistent with current data, it has become important to study cosmological perturbations beyond linear order to extract information from the observations, which are getting increasingly precise. This subject of research has become popular under the name of "primordial non-Gaussianities". In particular, a large effort of the community has been devoted to the study of higher-order correlations in the cosmological perturbations, which provide information about interactions taking place during inflation. Using the so-called "in-in" (or Schwinger-Keldysh) formalism, in collaboration with Seery and Sloth we have studied the four-point function generated during inflation from exchange of gravitons [t08/251]. This was the first worked-out example of calculation of an exchange diagram in the cosmological context. This contribution to the four-point function had been previously overlooked in the literature and it is of the same order as the one coming from purely scalar gravitational interactions.

Second, it is known that alternative models of inflation with multiple fields can produce large primordial non-Gaussianities. One mechanism is through self couplings of the fields in isocurvature directions. In [t10/038] a short review of this mechanism is given emphasizing the difference of amplitude to be expected between gravity and non-gravity induced couplings. In [t10/114], exact mathematical results are given regarding the amplitude evolution of induced bispectra, in case of non-gravity couplings, for different inflationary backgrounds.

B.1.2 Nonlinear perturbations *(F. Vernizzi)*

In [t10/244] we have reviewed, by invitation of Classical and Quantum Gravity, the covariant approach to cosmological perturbations developed in collaboration with David Langlois in a series of papers published from 2005 to 2008.

B.1.3 Scalar tachyons in the de Sitter universe *(J. Bros)*

In collaboration with H. Epstein and U. Moschella [t10/237], we provide a construction of a class of local and de Sitter covariant tachyonic quantum fields, namely fields which satisfy a de Sitterian Klein-Gordon (K-G) equation with discrete negative values of the squared-mass parameter and which have no Minkowskian counterpart. Technically, the construction goes through a primitive (Krein-type) space S with indefinite-metric, on which the field only satisfies an "anomalous" non-homogeneous K-G equation. Then it is in a de Sitter invariant "physical subspace of states" with positive squared-norm and finite codimension in S that the true K-G equation is restored. This phenomenon (which carries some reminiscence of the Gupta-Bleuler construction of QED) turns out to disappear in the Minkowskian limit (i.e.the infinite radius limit of the de Sitter hyperboloid or the vanishing cosmological constant), but it might very well be present in a de Sitter modelization of the early universe with a very tiny radius.

B.1.4 A new lattice code to study preheating *(Z. Huang)*

In [t11/075] we present a new lattice code, "HLattice", that studies the dynamics of scalar fields and gravity in the early universe. It differs from previous publicly available codes in three aspects: (i) a much higher accuracy is achieved with a modified 6th-order symplectic integrator; (ii) the backreaction from gravity to the dynamics of scalar fields is consistently included; (iii) it includes a new method to separate gravity waves from the total metric perturbations. We explain that the traditional way to calculate gravity waves suffers from a lattice effect that mixes the scalar modes and tensor modes. Thus, some of the earlier results may be insufficiently accurate or even wrong by an order of magnitude.

B.1.5 Gravitational waves from primordial phase transitions *(C. Caprini, G. Servant)*

First order phase transitions in the early universe can give rise to a stochastic background of gravitational waves (GW). Three main processes lead to the production of the GW signal: the collision of the broken phase bubbles, the magnetohydrodynamical (MHD) turbulence in the plasma stirred by the bubble collisions, and the magnetic fields amplified by the MHD turbulence. In [t07/142, t09/011, t09/121, t10/072] analytical methods have been developed to predict the main features of the GW power spectrum, starting from a description of the source which we tried to make as simple and as model independent as possible. In particular, [t07/142] analyzes GW production by bubble collisions, providing a model for the bubble velocity power spectrum based on a statistical description that is suitable for both detonations and deflagrations. Then, [t09/011] compares the analytical results with the GW spectra derived from numerical simulations of bubble collisions, establishing that the structure of the unequal time correlation of the GW source and its continuity in time are fundamental for a correct determination of the peak position of the GW spectrum. In [t09/121], a detailed model of the MHD turbulence generated by bubble collisions is proposed, accounting for the fact that turbulence and magnetic fields act as sources of GW for many Hubble times after the phase transition is completed, modeling the initial stirring phase preceding the Kolmogorov cascade, and using a realistic power spectrum for the MHD turbulence. The main conclusion of these works is that the GW signal from a first order phase transition occurring at electroweak symmetry breaking falls into the sensitivity range of the space interferometer LISA if the phase transition lasts for about one hundredth of the Hubble time and the energy density of the turbulent motions is about twenty percent of the total energy density in the universe at the phase transition time.

The advantage of building an analytical model for the GW source is that the main features of the resulting GW spectrum, such as the peak frequency, the amplitude, and the slopes both at low and high wavenumbers, can be predicted by general arguments based on the characteristics of the source: in particular, the structure of its space and time correlation. The resulting spectrum depends on a few parameters describing the source, and can then be applied to different specific models of the phase transition. For example, in [t10/120] the picture developed in the aforementioned analysis is applied to a hypothetical first order QCD phase transition: the amplitude and the spectral shape of the GW are predicted, demonstrating that the signal is potentially interesting for detection via pulsar timing arrays.

B.1.6 Cosmic magnetic fields *(C. Bonvin, C. Caprini)*

The observational evidence of large-scale magnetic fields in matter structures covers nowadays an impressive range of length scales and redshifts: from galaxies to high-redshift quasars, from clusters and superclusters to low-density filamentary regions. However, the origin of these fields remains an open problem. One of the possible explanations is that they have been generated in the primordial universe: primordial magnetogenesis mechanisms have in fact the advantage of providing magnetic seeds filling the entire universe, which goes in the right direction to explain both the ubiquity of the observed fields and the uniformity of the measured amplitudes. If a primordial magnetic field is present in the early universe, observables such as the CMB or Nucleosynthesis can be used to infer limits on its intensity or make predictions on its possible detection. Very stringent upper bounds on the magnetic field intensity have been derived using gravitational waves at Nucleosynthesis, which strongly challenge some of the proposed generation mechanisms occurring before Nucleosynthesis, such as primordial phase transitions [t09/169, t11/064]. A detailed modeling of the magnetic field evolution in the primordial plasma has been developed both for helical and non-helical fields to render these bounds more precise and realistic [t09/169, t09/121]. Magnetogenesis mechanisms operating after Nucleosynthesis, mainly based on charge separation, are mostly inefficient, since they rely on the presence of vorticity in the primordial plasma, which is small and difficult to generate: for example, it cannot be transferred from the metric to the matter fluids at linear order purely by gravitational interactions [t07/156]. Therefore, the general picture that can be inferred is that a primordial magnetic field generated by a non-causal process, such as inflation, and with a red spectrum, seems to be favored as a seed for the magnetic fields observed today in structures.

The most convincing way to establish whether such a field is present in the primordial universe, would be to detect its trace in the CMB. Therefore, it is important to predict all the effects that a magnetic field would have on the CMB anisotropies. For example, in [t10/071] the shape of the scalar temperature anisotropy induced by a magnetic field at low multipoles is analyzed in connection with the right initial conditions for the field and the metric perturbations. Moreover, a magnetic field would generate non-Gaussianities in the CMB: in [t09/031] the CMB bispectrum of the scalar temperature anisotropy is derived, and used to infer upper bounds on the magnetic field intensity through the WMAP bounds on $f_{\rm NL}$.

B.1.7 DBI cosmic strings *(P. Brax, C. Caprini)*

In [t08/155], we study cosmic string configurations in a model that extends the standard

Abelian-Higgs one with a non-linear Dirac-Born-Infeld (DBI) action for the kinetic term. The profile of the cosmic strings is studied numerically and it is demonstrated that the core is narrower than that of Abelian-Higgs strings. Moreover, it is found that the corresponding action is smaller than in the standard case suggesting that the formation of DBI-cosmic strings could be favored in brane models. The string solutions are non-pathological everywhere in parameter space, and DBI cosmic strings are no longer BPS: rather they have positive binding energy, suggesting that, when they meet, two DBI strings will not bind with the corresponding formation of a junction. Hence, a network of DBI strings is likely to behave as a network of standard cosmic strings.

B.2 CMB physics beyond linear order

In order to constrain the primordial non-Gaussianities discussed in Sect. B.1.1 from observations of the CMB (or other probes), we must first be able to predict with a good accuracy the contributions to observed non-Gaussianities that arise from late-time nonlinear effects. These may take place during the recombination era as well as during the late matter and dark energy dominated eras.

B.2.1 Recombination era *(F. Bernardeau)*

In a series of papers [t08/162, t09/244, t10/032, t10/195] written in collaboration with J.-Ph. Uzan and C. Pitrou, we have explored the physics of mode couplings during the recombination era and how they can lead to a significant bispectrum in the CMB temperature field. This is a work program that has been actively pursued by several teams and that aims at characterizing the intrinsic temperature and polarization bispectra to be expected in CMB observations. These mode couplings can be viewed as a background signal against which mode couplings effects originating from the inflationary era can be compared.

In our first paper, [t08/162], we identified the leading mechanism at play at small angular scales. We found it to be due to mode couplings in the sub-horizon gravitational potential dominated by the CDM component. In fact, those coupling effects take place very early - even before equality - and we explain how their effects can be computed through the response function of the photon anisotropies computed at linear order. Using this approach, we can also estimate the amplitude of the CMB bispectrum on small scales, although it is not possible to compute the CMB bispectrum in all configurations. To be able to do so, we derived and implemented the set of equations consistently describing the evolution of the second-order temperature fluctuations, e.g. including the second-order effects contained in the Boltzmann equation. These investigations culminated in [t10/032], where we presented the resulting shape of the bispectrum. There are two companion papers. One, [t09/244], stresses that at second order the photon energy distribution is actually non-thermal; there is therefore a difference between the bolometric temperature and the occupation number temperature whose statistical properties are slightly different. We also present in [t10/195] a detailed mathematical derivation of how the flat sky approximation can be used through controllable expansions, including the case of bispectra computations.

B.2.2 Late-time effects *(F. Vernizzi)*

As explained above, in order to interpret higher-order correlations in the cosmological data, it is important to develop theoretical tools that allow us to disentangle a primordial cosmological signal from late-time physics due to gravitational interactions. In this context, in collaboration with Boubekeur, Creminelli, D'Amico, and Noreña, we have calculated the three-point function in the CMB anisotropies generated during the post-inflationary evolution, for low multipoles and in a matter dominated universe [t09/201]. In this particular limit the calculation can be performed almost analytically and checked by physical arguments. The generated three-point function is dominated by lensing, a contribution that was overlooked in the literature, but it is below Planck sensitivity.

B.3 Formation of large-scale structures

B.3.1 Resummation schemes *(F. Bernardeau, E. Sefusatti, P. Valageas)*

The growth of large-scale structures in the Universe through the amplification of small primordial fluctuations by gravitational instability is a key ingredient of modern cosmology. This process can be used to constrain cosmological parameters as well as the initial conditions. In particular, some observational probes (e.g., baryon acoustic oscillations) focus on weakly nonlinear scales and require theoretical predictions for the matter power spectrum and bispectrum (i.e. the low-order correlation functions) with an accuracy of 1%. This has led to a renewed interest in perturbation theory, since these scales are within the reach of perturbative approaches. Indeed, in addition to the standard perturbation theory it is useful to build resummation schemes that can provide increasingly accurate analytical methods and avoid the use of costly numerical simulations. Several of these approaches are being developed in IPhT.

The Gamma-expansion approach ("RPT")

In the framework of Eulerian perturbation theories we have extended exact results found by Crocce and Scoccimarro to a whole family of objects: the multi-point propagators. These quantities describe how a given mode is changed by an infinitesimal variation of the amplitude of one or a finite number of modes in the initial conditions. In [t08/161], we have shown that spectra at any order can be reconstructed from the knowledge of those objects, by "glueing" them together. This is the essence of the Γ-method (or "RPT" for "renormalized perturbation theory") and this is the motivation for extensive studies of the multi-point propagators. In the same paper, we have also shown that the UV (i.e. short wave-mode) behavior of these objects can indeed be explicitly computed through the resummation of a whole class of diagrams. This approach proves very general. In [t10/090] we describe how it can be implemented in case of non-Gaussian initial conditions, explaining how the Γ-expansion is modified and giving the explicit expressions of the multi-point propagators in their UV limit.

Path-integral formulation and "large-N" expansions

In addition to the "RPT" approach discussed above, many resummation schemes have been proposed in the literature and in [t07/162] we have tested several methods ("large-N" expansions, "RPT", running with a high-k cutoff) by using the simpler Zeldovich dynamics as a benchmark. We find that most methods (except for "RPT") fail to recover the relaxation of the matter power spectrum on highly nonlinear scales, as one goes to high orders. We also explain how "RPT" is based on the approximation of a wide separation of scales and describes the transport of small-scale density fluctuations by larger-scale velocity modes ("sweeping effect"), rather than a true relaxation due to small-scale interactions.

Next, in [t08/016] we have described how two "large-N" resummation schemes can be used to obtain the matter power spectrum and bispectrum (as well as higher-order correlations), for both the Zeldovich and the actual gravitational dynamics.

Eulerian versus Lagrangian propagators

A key quantity that arises in most resummation schemes is the propagator, or response function, that describes how fluctuations propagate with time. In the usual Eulerian framework, this propagator shows a fast decay that is governed by the "sweeping effect" described above. In order to go beyond this effect, we have investigated in [t08/160] the propagators that arise in a Lagrangian framework, since the latter are insensitive to this "sweeping effect". Applying the "RPT" approach, in the reformulation of [t07/162], we find that this leads to a Lagrangian propagator that no longer decays in the nonlinear regime. In order to better understand this difference, we have studied in [t09/216] the Eulerian and Lagrangian propagators associated with the one-dimensional "adhesion model", based on the Burgers dynamics, where many exact results can be derived. We show that the Eulerian propagators can be expressed in terms of the one-point velocity probability distribution, and exhibit a strong exponential decay, while the Lagrangian propagators can be written in terms of the halo mass function and only show a power-law decay, which is related to the the low-mass tail of the mass function. This explains these qualitatively different behaviors and suggests that Lagrangian propagators are much more sensitive probes of small-scale relaxation.

B.3.2 Combined models *(P. Valageas)*

The approaches described in Sect. B.3.1, which are based on the fluid approximation and perturbative expansions, cannot go beyond shell crossing (where the velocity field becomes multivalued) and handle highly nonlinear processes. Using the Zedovich dynamics as a benchmark, and a closely related "sticky model", we compare in [t10/170] the amplitude of perturbative and non-perturbative terms (which we can compute exactly at all orders for these two simpler dynamics). We find that for the standard ΛCDM initial conditions the potential of perturbative schemes is greater at higher redshift, since one can go up to order 66 of perturbation theory at $z = 3$, and to order 9 at $z - 0$, before non-perturbative contributions become dominant. This further motivates the study of resummation schemes, especially at $z > 1$.

For practical purposes, it is useful to obtain unified models that can describe all scales.

We have described in [t10/171] how to combine (resummed) perturbation theories with phenomenological halo models. In particular, we have shown that the halo-model contributions contain counterterms that had been missed in previous works and ensure a physically meaningful and accurate behavior.

B.3.3 Burgers dynamics as a toy model *(F. Bernardeau, P. Valageas)*

Perturbative approaches only offer a partial understanding of the nonlinear gravitational dynamics while it can be difficult to distinguish intermediate physical processes from the results of numerical simulations. In order to go beyond these limitations it is useful to investigate simpler toy models that can be fully understood and where exact results can be derived. They can also serve as benchmarks for general approximation schemes. This motivates the study of the "adhesion model", which goes beyond the Zeldovich dynamics by making particles cluster after collisions instead of escaping to infinity and thus includes some fully nonperturbative shell crossing effects. This is also known as the Burgers dynamics in the fluid dynamics context.

Thus, we have undertaken a series of works to study the Burgers dynamics, paying attention to issues that arise in the cosmological context. In [t08/199], we derive many exact properties of the one-dimensional Burgers dynamics for the case of initial velocity fields that are also Brownian motions. In particular, we note that both the "stable-clustering ansatz" and the "Press-Schechter" mass function, that are widely used in the cosmological context, happen to be exact in this case. As a by-product, we have also derived new results for a ballistic aggregation process in [t08/201].

Next, in [t09/179] we study the case of white-noise one-dimensional initial velocity field, deriving again exact expressions such as the density power spectrum and halo mass function. We also discuss the generalization to other initial conditions and higher dimensions through a multifractal formalism.

Then, using an asymptotic method that we had developed in previous works on the gravitational dynamics, we derive in [t09/180] the asymptotic velocity and density probability distributions of this Burgers dynamics in the quasi-linear regime and for rare-event tails (including high-mass nonlinear shocks). This applies to random Gaussian initial conditions in arbitrary dimension, with power-law initial power-spectra, which is the case of interest for both the "adhesion model" in cosmology and the "decaying Burgers turbulence" in fluid dynamics.

In dimension two and higher, the Burgers dynamics can be quite complex and the velocity field does not fully define the matter distribution. More precisely, one must add to the Euler equation a continuity equation and several choices are possible (that coincide outside of the shock manifold). In [t09/250] we discuss in detail how a "geometrical Burgers dynamics", which can be built from the initial fields through geometrical constructions, provides an elegant model but differs from using the usual continuity equation. In particular, this leads to both halo mergings and fragmentations in dimension greater or equal to two, a property that was sometimes overlooked in the literature.

Finally, in [t10/173] we present a numerical study of this "geometrical Burgers dynamics" in both one and two dimensions. We introduce a new algorithm, based on exact geometrical constructions, that provides the exact dynamics for each initial condition. Focusing again on random Gaussian initial conditions, with power-law initial spectra, we find that many statistical indicators show the same qualitative properties as those observed for 3D gravitational clustering. In particular, the mass functions obey to a large extent the usual "Press-Schechter" like scaling. These results again suggest that this "geometrical Burgers dynamics" provides a useful tool to understand gravitational clustering.

B.3.4 Phenomenological models for halo mass functions and bias *(P. Valageas)*

Two quantities that are closely related to observational studies of galaxies and clusters of galaxies are the halo mass function and correlation (or "bias"). Most popular models for these two statistics involve several free parameters that need be fitted to numerical simulations and lessen their predictive power. We have presented in [t09/181] a simpler model that requires fewer free parameters, while remaining in good agreement with simulations, and which should be more robust. We also point out the impact of halo motions on their two-point correlation. Next, we have extended this approach to non-Gaussian initial conditions in [t09/182], and to halos defined by arbitrary density thresholds in [t10/172].

B.3.5 Reconstruction of the large-scale velocity field *(F. Bernardeau)*

It has been shown that, in a large range of dynamical regimes, the Monge-Ampère-Kantorovitch (MAK) reconstruction method can be used to recover the initial position of observed galaxies, and consequently their present-day 3D velocity. Such observations would be very important for characterizing the large-scale structure of the universe. These results were obtained however in ideal cases where biasing, finite volume effects were absent. In [t07/123] we extensively study the uncertainty in the mass-to-light assignment due to incompleteness (missing luminous mass tracers), and the poorly determined relation between mass and luminosity. We eventually show that, in the context of observational data, it is possible to build a relatively unbiased estimator of Ω_m using MAK.

B.4 Observation of primordial non-Gaussianities in large-scale structures *(E. Sefusatti, P. Valageas)*

Primordial non-Gaussianities may also be observed through their impact on large-scale structures, which provide a complementary probe to the CMB studied in Sect. B.2. Again, this requires accurate predictions and detailed studies of perturbation theory, especially since primordial non-Gaussianities are usually greater on large quasi-linear scales. In [t09/054] we have derived the expressions for the one-loop contributions in cosmological, Eulerian, perturbation theory to the matter bispectrum and to the galaxy bispectrum, in presence of non-Gaussian initial conditions. In particular, we describe the peculiar dependence on scale and shape of the triangular configurations of these various contributions to the bispectra.

Next, we have presented a detailed comparison with numerical simulations in [t10/141]. We find that one-loop perturbation theory provides quite accurate predictions at redshifts $z > 1$, and still provides a significant improvement over tree-level computations at $z = 0$.

Although the primordial non-Gaussian parameter $f_{\rm NL}$ is often taken to be constant, it has been shown to be scale-dependent in several models of inflation with a variable speed of sound. In [t09/321], we perform a Fisher matrix analysis of the bispectra of the temperature and polarization of the CMB and derive the expected constraints on the parameter $n_{\rm NG}$ that quantifies the running of $f_{\rm NL}(k)$ for current and future CMB missions such as WMAP, Planck and CMBPol. On the other hand, we find that large-scale structure observations should achieve results comparable to or even better than those from the CMB, while showing some complementarity due to the different distribution of the non-Gaussian signal over the relevant range of scales.

We have reviewed in [t10/140] the theoretical and observational problems associated with studies of primordial non-Gaussianity through bispectrum measurements in the CMB and sarge-scale structures. In particular, we describe current results and future prospects for the detection of a non-vanishing primordial component and its relation with different inflationary models.

From the observational point of view, we have studied in [t09/183] optimized estimators to probe primordial non-Gaussianities, through the observation of the CMB or the distribution of galaxy clusters, and their cross-correlations. In particular, they compress the data associated with three-point correlations into one-point estimators that retain the sensitivity to primordial non-Gaussianities and some scale dependence.

B.5 Dark energy

B.5.1 Building quintessence models *(F. Vernizzi)*

Dark energy is the cosmological component responsible for the current acceleration of the Universe. It is usually assumed to be smooth on cosmological scales. For instance, standard quintessence based on a minimally coupled canonical scalar field propagates fluctuations at the speed of light, maintaining them homogeneous within a Hubble patch. However, there are theoretical motivations to consider quintessence models based on a scalar field with zero sound speed. These models can be constructed using an effective field theory approach and have the advantage to be stable also when the equation of state of dark energy is less than -1, that is, $P/\rho < -1$ [t09/202].

B.5.2 Impact on large-scale structures *(C. Caprini, E. Sefusatti, F. Vernizzi)*

A dark energy component with zero sound speed would alter the evolution of structures not only by changing the background evolution of the Universe but also by actively participating to gravitational clustering. This is most evident in the regime where structures become nonlinear. In collaboration with Creminelli, D'Amico, Noreña, and Senatore, we have studied this regime using the spherical collapse model [t09/199], showing that quintessence contributes to the total halo mass by a fraction that increases at low redshifts and is proportional to the ratio between quintessence and dark matter energy densities. The nonlinear regime of structure formation has been further studied using Eulerian perturbation theory in [t11/007]. In particular, we show that the reduced bispectrum receives sensible modifications in the clustering case, similar to those found in the spherical collapse model, that can potentially be used to detect or rule out the model.

From the observational point of view, we investigate in [t08/015] the power of next-generation CMB and large-scale structure surveys in constraining the nature of dark energy through the cross-correlation of the Integrated Sachs Wolfe effect and the galaxy distribution. We demonstrate that a survey which covers more than 35% of the sky, with a median redshift higher than 0.8, and which detects more than a few galaxies per squared arcmin, can detect the correlated signal at a level of more than 4 sigma. The constraints that such a survey can put on the nature of dark energy (through different parametrizations of its equation of state) are then computed with a standard Fisher matrix analysis.

B.5.3 Large-scale structure growth in modified gravity models *(F. Bernardeau, P. Brax)*

In [t11/099] we explore the mode-coupling structure and amplitude in a class of modified gravity models. This class of models corresponds to dilaton induced modified gravity that takes advantage of the chameleon mechanism to pass the GR tests within the solar system. We show that the dilaton field introduces a whole new series of coupling terms (of any order) that can be significant on scales of observational interest. We show that the amplitude of these effects for bispectra could be detectable - it is at few percents level - offering a way to discriminate among different dark energy models through large-scale structure observations.

B.5.4 Time drift of cosmological redshifts and its variance *(F. Bernardeau)*

In the context of the ELTs (Extremely Large Telescope) scientific case, it has been claimed that it could be possible to measure the equation of state of the universe (hence to constrain the dark energy component) from the measurement of the time drift of redshifts of absorption clouds (along the line of sight of quasars). This method may however suffer from large systematics. In [t08/022] we explore the effects of peculiar acceleration and how it compares to the Hubble acceleration.

B.5.5 Stars within the Chaplygin gas *(V. Pasquier)*

A simple model for the dark energy is the Chaplygin gas, characterized by an equation of state of the form $p \propto -1/\rho$. In [t08/188] we have studied static solutions of the Tolman-Oppenheimer-Volkoff equations for spherically symmetric objects (stars) living in a space filled with this Chaplygin gas. Two cases were considered. In the normal case all solutions (excluding the de Sitter one) realize a three-dimensional spheroidal geometry. The second case arises when the modulus of the pressure exceeds the energy density (the phantom Chaplygin gas). There is no more equator and all solutions have the geometry of a truncated spheroid with the same type of singularity.

B.6 Weak lensing

B.6.1 Second-order effects in the cosmic shear *(F. Bernardeau, C. Bonvin, F. Vernizzi)*

As for CMB observations, it is important to obtain accurate predictions for weak lensing observables in order to put constraints on cosmology and primordial initial conditions. We have studied in [t09/200] the cosmic shear, i.e. the collective effect of gravitational lensing distortions on galaxy shapes due to the foreground gravitational matter field. In particular, we have computed the reduced cosmic shear up to second order in the gravitational potential without relying on the small-angle or thin-lens approximations. This leads to new couplings in addition to the standard non-linear terms.

B.6.2 Sensitivity to primordial non-Gaussianities *(E. Sefusatti)*

In [t11/051] we quantitatively evaluate the impact of primordial non-Gaussianity onto weak lensing auto- and cross-correlation power spectra. We show that it is strongly suppressed by projection effects. More generally, we point out that the clustering of biased tracers of the three-dimensional density field is generically more sensitive to non-Gaussianity than observables constructed from projected density fields.

B.7 Collider signatures of new physics

B.7.1 The top quark as a window on new physics *(C. Grojean, G. Servant)*

The top quark being the heaviest of all the elementary fermions of the Standard Model (SM), it is expected to play a special role in electroweak symmetry breaking. It has been among the central physics topics at the Tevatron and it will remain so at the LHC during this decade. In theories beyond the SM that provide a mechanism for mass generation, new physics must have a large coupling to the top quark. It is therefore natural to use top quark observables to test the mechanism responsible for electroweak symmetry breaking and more generally to search for physics beyond the SM. For instance, the problem of the quantum stability of the weak scale together with current electroweak data provide a plausible motivation for considering a light Higgs emerging as a pseudo-Goldstone boson from a strongly-coupled sector. On the other hand, this approach also suggests that SM fermion masses should arise via mixing of elementary fermions with composite fermions of the strong sector. In this context, the top quark is mainly a composite object while the other light SM quarks are mainly elementary. A natural prediction is then the existence of light ($\lesssim 1\,\text{TeV}$) fermionic composite partners of the third generation fermions, in particular the top quark. At the LHC, composite quarks can be pair-produced with a large QCD cross section. They can also be singly produced. Prospects at the LHC for their discovery are very promising, as shown in collaboration with R. Contino. In [t07/149], we studied the pair production and detection at the LHC of the top partners with electric charge $Q = 5/3$ ($T_{5/3}$) and $Q = -1/3$ (B), that are predicted in models where the Higgs is a pseudo-Goldstone boson. The exotic $T_{5/3}$ fermion, in particular, is the distinct prediction of a Left-Right custodial parity invariance of the electroweak symmetry breaking sector. Both kinds of new fermions decay to Wt, leading to a $t\bar{t}WW$ final state. We focussed on the golden channel with two same-sign leptons, and showed that a discovery could come with less than 100 pb^{-1} (less than 20 fb^{-1}) of integrated luminosity for masses $M = 500\,\text{GeV}$ ($M = 1\,\text{TeV}$). In the case of the $T_{5/3}$, we presented a simple strategy for its reconstruction in the fully hadronic decay chain. Our analysis also directly applies to the search of 4th generation b' quarks and is being pursued by ATLAS and CMS.

We have also developped some model-independent approaches based on low-energy effective field theory. In [t10/302], we used top quark pair production as a probe of *top-philic* non-resonant new physics. Following a low-energy effective field theory approach, we calculated several key observables in top quark pair production at hadron colliders (*e.g.* total cross section, $t\bar{t}$ invariant mass distribution, forward-backward asymmetry, spin correlations) including the interference of the Standard Model with dimension-six operators. We determined the LHC reach in probing new physics after having taken into account the Tevatron constraints. In particular, we showed that the gluon fusion process $gg \to t\bar{t}$ which remains largely unconstrained at the Tevatron is affected by only one *top-philic* dimension-six operator, the chromomagnetic moment of the top quark. This operator can be further constrained by the LHC data as soon as a precision of about 20% is reached for the total $t\bar{t}$ cross section. In [t11/128], we also presented the effective field theory approach to same-sign top pair production, in relation with the $t\bar{t}$ forward-backward asymmetry. While our approach is general and model independent, it is particularly relevant to models of Higgs and top compositeness.

With ATLAS PhD student Léa Gauthier from SPP, we worked on the first detailed simulation of four-top production at the LHC [t10/301], [t10/305]. Four-top production is a spectacular final state and a sensitive probe of new physics that is relatively unconstrained by precision measurements at LEP or resonance searches at the Tevatron. Examples are models where the top quark is composite or where a new heavy particle couples strongly or exclusively to top quarks. A study of four-top production was also done for a multi-TeV e^+e^- collider such as CLIC in [t10/300].

B.7.2 Composite Higgs physics *(C. Delaunay, C. Grojean)*

Notwithstanding its simplicity, the appeal of the SM Higgs picture comes from its successful agreement with electroweak precision data, provided that the Higgs boson is rather light. In this regard, being an elementary scalar is not a virtue but rather a flaw because of the quadratic divergences destabilizing the Higgs mass. It is thus tantalizing to consider the Higgs boson as a composite bound state emerging from a strongly-interacting sector. In order to maintain a good agreement with electroweak data, it is sufficient that a mass gap separates the

Higgs resonance from the other resonances of the strong sector. Such a mass gap can naturally follow from dynamics if the strongly-interacting sector possesses a global symmetry, G, spontaneously broken at a scale f to a subgroup H, such that the coset G/H contains a fourth Nambu–Goldstone bosons that can be identified with the Higgs boson. In these models, the physics of the Higgs boson is determined by two additional parameters that depend on the global symmetries of the strong sector at the origin of the breaking of the electroweak symmetry, as shown in our previous work JHEP 0706 (2007) 045. In [t10/304], we have analyzed how the searches for the Higgs boson are affected by its underlying dynamics and we have evaluated the discovery potential of the Higgs boson at the LHC. This analysis offers a promising way to probe deviations away from the SM. However, such deviations might have various origins. One distinctive and genuine signature of the strong dynamics responsible for the electroweak symmetry breaking is the growth with energy of the scattering amplitudes among the Goldstone bosons of the SM, i.e., the longitudinally polarized vector bosons as well as the Higgs boson itself. In [t10/031], we studied the enhancement of the double Higgs production by vector boson fusion in pp collisions.

The composite Higgs models have a natural flavour structure that easily explains the fermion mass spectrum without generating troublesome flavour changing neutral currents. This structure automatically explains the alignment of the masses and mixing angles in the quark sector. However, the large mixing in the neutrino sector requires additional flavour symmetries. In [t08/271], we presented, in the context of models of strong electroweak symmetry breaking, a simple model of lepton masses and mixing based on the A_4 non-abelian discrete symmetry with no tree-level lepton flavour violation and small loop-induced lepton flavour amplitudes.

The composite Higgs models are a continuous interpolation between the SM and Higgsless models, i.e., models where the longitudinal WW scattering amplitudes are unitarized via the exchange of spin-1 resonances. An introduction to Higgsless models has been presented in [t07/217] and various alternative approaches to explain the dynamics of the electroweak symmetry breaking have been reviewed in [t07/218] and [t09/295]. Most of the alternative models are characterized by the existence of massive spin-1 degrees of freedom, some of them carrying an electric charge. In [t11/131], we studied the discovery prospect of such a W' at the LHC through its decays to 2 jets, $W\gamma$ and WZ. In particular, we show that the decay channel $W' \to W\gamma$, which is strongly suppressed in gauge models, could indicate a composite nature of this heavy resonance and could thus provide valuable information about the true dynamics of the breaking of the electroweak symmetry.

C. Grojean has also edited several school and workshop proceedings [t07/122], [t08/276], [t09/294], [t10/305], [t10/306], [t10/307].

B.8 Flavour physics and neutrinos

B.8.1 Flavour models *(C. Grojean, M. Frigerio, J. Parmentier, C. Savoy)*

Notwithstanding our fair knowledge of the quark flavour parameters (their masses, mixing angles and the CKM phase) and the strong experimental constraints on the leptonic ones, we have no cogent explanation for their origin yet. The quest for a theory of flavour that would both provide a rationale for the measured parameters and yield testable predictions is an active field of research.

In [t09/293], the results of the current generation of flavour physics experiments were summarised and confronted with the theoretical predictions, which have greatly improved in the past decade.

Some features of the quark and lepton mass and mixing patterns suggest possible underlying flavour symmetries. In collaboration with E. Ma [t07/110], it was shown that the smallness of the 1-3 lepton mixing angle and of the ratio between the solar and atmospheric neutrino mass squared differences can be understood as the departure from a common limit where they both vanish. We found that the simplest flavour symmetry that can correlate the values of these two parameters is the discrete group Q_8, the smallest non-abelian subgroup of $SU(2)$. As a consequence, a lower bound on the 1-3 mixing is predicted and will be tested soon experimentally.

An important issue in flavour physics is the disparity between the large lepton mixing angles and the small CKM mixing in the quark sector. This problem is particularly severe in the context of Grand Unification, where leptons and quarks belong to the same multiplets. In collaboration with F. Bazzocchi and S. Morisi [t08/126], we demonstrated that it is nonetheless possible to unify all SM fermions into a unique $(\mathbf{16}, \mathbf{3})$ representation of the $SO(10) \times A_4$ group, where $SO(10)$ is the unified gauge group and A_4

is the group of even permutations of four objects, acting as a flavour symmetry. Our analysis shows that tri-bi-maximal lepton mixing (that is, $\tan^2\theta_{23} = 1$, $\tan^2\theta_{12} = 0.5$, $\tan^2\theta_{13} = 0$) as well as hierarchical quark and charged lepton masses can be both explained in this framework and share a related origin. This represents a significant step towards a flavour theory compatible with Grand Unification.

In collaboration with E. Dudas, G. von Gersdorff and S. Pokorski [t10/243], we compared the theoretical and experimental predictions of two classes of models addressing the fermion mass hierarchies and the flavour changing neutral current (FCNC) problem in supersymmetry: Froggatt–Nielsen $U(1)$ gauged flavour models and Nelson–Strassler/extra-dimensional models with hierarchical quark and lepton wave functions. We showed that, while both approaches lead to identical predictions for the fermion mass matrices, the second class of models yields a stronger suppression of FCNC effects. Moreover, although at first sight the Froggatt–Nielsen setup is more constrained due to anomaly cancelation, imposing the unification of gauge couplings in the extra-dimensional case generates conditions which precisely match the mixed anomaly constraints in the Froggatt–Nielsen scenario. Finally, we provided an economical extra-dimensional realisation of the hierarchical wave function scenario in which the leptonic FCNC effects can be efficiently suppressed due to the strong coupling (CFT) origin of the electron mass.

Many flavour models have been proposed to explain the pattern of quark and lepton masses and mixing angles, but they are testable only if the flavour symmetry is broken at relatively low energies. The intrinsic parity violation by the flavour charges associated with the light quarks and leptons requires anomaly cancellation by new heavy fermions. In [t11/122], benchmark supersymmetric flavour models have been built and studied to argue that: *i)* the flavour symmetry breaking should be about three orders of magnitude above the higgsino mass, which is also enough to efficiently suppress flavour and CP violations from higher-dimensional effective operators; *ii)* new fermions with exotic decays into lighter particles are typically required at scales of the order of the higgsino mass. The heavy quarks would be more easily produced at the LHC and could perhaps be identified by their decay into an energetic lepton and two jets. Actually, the (non-supersymmetric) minimal extension of the Standard Model to such a flavour theory requires the new fermions to be quasi-stable, which makes the observation of the new quarks stopped at the detector even easier.

B.8.2 Leptogenesis and lepton flavour violation *(M. Frigerio, P. Hosteins, S. Lavignac)*

One of the challenges extensions of the Standard Model have to face is to generate dynamically the observed baryon asymmetry of the Universe. Among the proposed mechanisms, leptogenesis is a very attractive one since it just requires the addition of the heavy fields that are needed to generate the small neutrinos masses via the seesaw mechanism. The requirement that leptogenesis generates the observed cosmological baryon asymmetry thus represents a non-trivial constraint on theories that include these ingredients, such as Grand Unified Theories based on the $SO(10)$ gauge group. In collaboration with A. Abada and F.-X. Josse-Michaux [t08/069], we performed a detailed quantitative study of leptogenesis in $SO(10)$ models with a left-right symmetric seesaw mechanism, in which neutrino masses arise from the exchange of both heavy right-handed neutrinos and a heavy $SU(2)_L$ triplet. We solved numerically the flavour-dependent Boltzmann equations including the contribution of the next-to-lightest right-handed neutrino, and found that successful leptogenesis is indeed possible in these models, while it is difficult to achieve in $SO(10)$ models with a type I seesaw mechanism.

In [t08/070], in collaboration with A. Romanino, we investigated a particularly predictive leptogenesis scenario, which is realized in $SO(10)$ models with matter fields lying both in **16** and in **10** representations. In this scenario, neutrino masses originate from a triplet seesaw mechanism, and the relevant CP asymmetry is directly related to the light neutrino mass parameters. In particular, the CP violation needed for leptogenesis is provided by the phases of the lepton mixing (PMNS) matrix, which can in principle be measured experimentally. This is to be contrasted with most leptogenesis scenarios, in which the CP asymmetry depends on unknown high-energy parameters and is unconnected to low-energy CP violation. Successful leptogenesis in this scenario requires a rather large value of the yet unknown mixing angle θ_{13}.

In a subsequent paper written in collaboration with L. Calibbi and A. Romanino [t09/158], we studied flavour changing processes in the same $SO(10)$ scenario. We showed that the raditively-induced flavour violating effects are controlled by purely low-energy flavour parameters (namely the CKM and PMNS matrices, together with the neutrino and up quark masses), while their overall size also depends on high-energy parameters. Requiring successful leptogenesis constrains the latter to vary within a small range, yielding predictions for flavour violating processes. In particular, $\mu \to e\gamma$ lies within the reach of the MEG experiment if the superpartner spectrum is accessible at the LHC, and the agreement between the theoretical prediction for the indirect CP violation parameter in the kaon system ϵ_K and its measured value can be improved.

B.9 Supersymmetry and string phenomenology

B.9.1 Supersymmetry breaking and its mediation *(S. Lavignac, J. Parmentier)*

If supersymmetry is discovered at the LHC, an important question will be to identify the mechanism responsible for its breaking and mediation to the observable sector. The ratios of gaugino masses will provide useful information: they are predicted to be in the same ratios as the gauge couplings squared in the most popular schemes, minimal gauge mediation and minimal supergravity. Any deviation from this proportionality relation would signal a non-minimal mediation mechanism. In [t08/110], [t10/097], in collaboration with E. Dudas, we studied gauge mediation scenarios in which the dominant contribution to messenger masses comes from their couplings to the Higgs fields responsible for the breaking of an underlying grand unified gauge group. This results in a non-standard superpartner spectrum whose features are mainly determined by the unified gauge group and the messenger representations. Explicit examples include spectra with an unusually light bino, which can even be the lightest supersymmetric particle (LSP), as well as spectra with a gluino or wino NLSP and a gravitino LSP, which lead to specific signatures at the LHC. A complete, viable model with an explicit supersymmetry breaking sector of the Intriligator–Seiberg–Shih type coupled to the messenger fields was constructed.

Gauge mediation is an attractive mechanism for transmitting supersymmetry breaking to the observable sector, since it automatically solves the supersymmetric flavour problem. However, explicit models often have difficulties in generating large enough gaugino masses. More specifically, Komargodski and Shih proved that renormalizable models in which supersymmetry is broken à la O'Raifeartaigh yield vanishing gaugino masses at the leading order, unless there is an instability of the supersymmetry breaking flat direction in the messenger direction. This problem can be cured if quantum corrections lift the flat direction in such a way that the supersymmetry breaking minimum (with zero messenger vacuum expectation values) becomes metastable. In collaboration with E. Dudas [t10/175], we studied under which conditions they can promote it to the ground state of the theory, thus allowing for sizeable gaugino masses without metastability. We found that, in a large class of renormalizable O'Raifeartaigh models coupled to messenger fields, the required condition is the suppression (typically by a one-loop factor) of the messenger couplings to the goldstino superfield.

B.9.2 Non-minimal supersymmetric extensions of the Standard Model *(M. Chemtob, S. Lavignac)*

The Higgs sector of the Minimal Supersymmetric Standard Model suffers from a fine-tuning problem associated with the large radiative corrections needed to satisfy the lower bound on the Higgs boson mass from the LEP experiment, $m_H > 114.4\,\text{GeV}$. An elegant solution to this problem is to realize the Higgs boson as the pseudo-Goldstone boson of a spontaneously broken approximate global symmetry, so as to maintain radiative corrections to the Higgs potential under control. In collaboration with A. Kaminska [t10/094], we studied a supersymmetric model in which the lightest Higgs boson arises as the pseudo-Goldstone boson of a global $SU(3)$ symmetry. A notable difference with previous models is that soft terms arise from gauge-mediated supersymmetry breaking, which in turn provides a mechanism to break the global $SU(3)$ symmetry, namely through the (calculable) tadpole of a gauge singlet field.

In the next-to-minimal supersymmetric standard model (NMSSM), the so-called μ-problem is solved by trading the bilinear Higgs bosons term $\mu H_u H_d$ for the trilinear coupling $H_u H_d S$ involving an extra singlet field S. An economical explanation of neutrino masses also becomes available in the generalization of the NMSSM including the lepton number violating trilinear couplings $L_i H_u S$. However, the full model with the attendant soft supersymmetry breaking couplings suffers from the presence of scalar field directions along which the effective potential is unbounded from below, as well as of tachyonic modes and charge and colour breaking minima. These instabilities impose constraints on the parameters of the lepton number violating interactions. We have explored their implications for the mass spectrum of the model through a detailed study of the mass matrices for the boson and fermion modes in the regular electroweak symmetry breaking vacuum [t07/113].

B.9.3 Phenomenology of string models *(M. Chemtob, P. Hosteins)*

Progress in the understanding of the role of D-branes in type II superstring theories has led (among other things) to the construction of models with stable multiple brane setups compatible with TeV string scale. In particular, Standard Model-like solutions were built with four stacks of intersecting D6-branes on a toroidal orientifold. A crucial feature of these models is the presence of massless fermions localized at points of the internal space where brane pairs intersect. These open string modes interact through tree-level exchange of massive (virtual) open string modes, leading to effective local four-fermion operators. We evaluated the chirality-conserving contact interactions of quarks and leptons by means of an approximate subtraction procedure aimed at removing the string massless and massive (Kaluza–Klein) momentum modes, so as to retain only the string Regge and winding modes [t08/145]. The signatures of these contact interactions at high-energy colliders and in flavour physics depend on two free parameters, the string and compactification scales. Useful constraints are derived from their contributions to the Bhabha scattering differential cross section, to neutral meson (K^0-$\bar{K}^0$, B^0-$\bar{B}^0$, D^0-$\bar{D}^0$) mixing and to lepton flavour violating three-body leptonic decays of the μ and τ leptons.

Heterotic string model building has received a vigorous stimulus in recent years through the focus on anisotropic type string compactifications, yielding effective unified gauge theories in five or six spacetime dimensions with matter modes distributed in the bulk or near fixed branes. Attempts to implement this scheme for the Z_{6-II} orbifold with two Wilson lines gave access to a fertile mini-landscape of vacua realizing extensions of the Minimal Supersymmetric Standard Model (MSSM) with decoupled exotic modes. In [t09/154], we searched for extensions of the MSSM with extra singlets and/or extra $U(1)$'s. The string theory selection rules were used to constrain the dependence of the effective superpotential on the various scalar field directions parameterizing the moduli space of vacua. Instead of a statistical vacuum number counting, we choose three representative Pati-Salam unified string models on which we performed an automated selection of vacuum solutions satisfying the D-term flatness and approximate F-term flatness conditions. The main purpose was to establish an existence proof for supersymmetric vacua in which suppressed bilinear terms for the electroweak Higgs doublets coexist with unsuppressed trilinear couplings to suitable massless singlet modes.

B.10 The electroweak phase transition

B.10.1 The nature of the electroweak phase transition and its cosmological imprints *(C. Delaunay, C. Grojean, G. Servant)*

We have very limited information about the dynamics of the electroweak phase transition in the early Universe. It is known that it cannot be first order within the Standard Model, since LEP data constrains the Higgs mass to be too large to generate an important bump in the thermal potential. The situation could be different, however, if the Higgs boson self-interactions were not the ones posited in the SM. In [t07/141], we studied the dynamics of electroweak bubble nucleation when the Higgs boson emerges from a strongly interacting sector as a composite bound state.

Another interesting cosmological consequence of new strong dynamics at the TeV scale is a period of supercooling in the early Universe followed by a strong first-order phase transition. This has barely been explored and we have investigated in [t11/129] how this opens new avenues for addressing major cosmological puzzles such as the genesis of dark matter and the origin of the matter-antimatter asymmetry. We have outlined the very peculiar cosmological properties characterizing some models of strong dynamics at the TeV scale. In particular, we motivated the mechanism of cold baryogenesis in this context [t11/130]. A large signal in gravity waves in the milli-hertz range would be a smoking-gun signature of this near-conformal dynamics at the TeV scale. A gravity wave detector such as LISA would be a completely independent window on the electroweak scale, and could complement the information provided by the LHC.

In collaboration with C. Caprini, we also worked on analytical derivations of the spectrum of gravitational waves due to bubble collisions and to the induced magneto-hydrodynamical turbulence. This work is described in the cosmology section of this report.

B.10.2 Bubble growth in first-order phase transitions *(J.-M. No, G. Servant)*

In [t10/299], we studied the hydrodynamics of bubble growth in first-order phase transitions. This is very relevant for electroweak baryogenesis, as the baryon asymmetry depends sensitively on the bubble wall velocity, as well as for predicting the size of the gravity wave signal resulting from bubble collisions, which depends on both the bubble wall velocity and the plasma fluid velocity. We performed this study in different bubble expansion regimes, namely deflagrations, detonations, hybrids (steady states) and runaway solutions (accelerating wall), without relying on a specific particle physics model. We computed the efficiency of the vacuum energy transfer to the bubble wall and to the plasma in all regimes. We clarified the condition determining the runaway regime and stressed that in most models of strong first-order phase transitions this would modify the expectations for the gravity wave signal.

Following this study, we pointed out in [t10/176] that for the expansion regime of deflagrations (small, subsonic wall velocities), in addition to the friction of the plasma on the bubble wall, another effect can contribute to counterbalancing the pressure difference on the wall that drives the expansion, namely the fact that the compression front ahead of the bubble wall for deflagrations heats up the plasma in front of the wall, which diminishes the pressure difference on the wall. In particular, it was found that due to the presence of this effect, deflagrations may be achieved even for very small or vanishing friction, contrary to usual expectations. This may have important implications for electroweak baryogenesis scenarios, for which a small relative velocity between the wall and the plasma in front (usually assumed to be the wall velocity) is needed, since it allows to estimate in some cases a subsonic wall velocity without the need to know the precise value of the friction. Finally, we showed in [t11/032] that in the case of deflagrations or hybrids, also due to the existence of a compression front ahead of the bubble wall, the relative velocity between the wall and the plasma in front is in general smaller than the wall velocity, and this effect is larger for stronger phase transitions. Therefore it may be possible to have a small relative velocity between the wall and the plasma in front while the bubble expands with a relatively large velocity, opening the possibility of sizable gravitational wave background signals in scenarios where electroweak baryogenesis is possible.

B.11 Dark matter

B.11.1 Dark matter phenomenology and model-building *(M. Cirelli, F. Iocco, P. Panci, G. Servant)*

Dark matter constitutes most of the matter content of the Universe, as a number of cosmological and astrophysical observations now confirm. However, little is known about its nature and it has not been directly detected yet. There are many new particle candidates that might constitute dark matter, coming from different theories beyond the Standard Model, and this has been an incredibly rich and varied area of research in the last twenty years.

Until a few years ago, most studies concentrated on supersymmetric candidates. However, in the last decade, a plethora of new candidates have been studied as it has been realized that most standard Model extensions attempting to solve the hierarchy problem contain weakly-interacting dark matter candidates in their spectrum. Non-supersymmetric dark matter candidates have been reviewed in [t10/303], emphasizing the connection with new physics at the electroweak scale, in particular in the context of new constructions suggested in the last decade, such as Little Higgs or composite Higgs models.

We continued the investigation of Minimal Dark Matter, a new model proposed a few years ago by us. In contrast with the usual, more elaborated approaches to dark matter pursued in the context of theories beyond the Standard Model, an extra matter multiplet is simply added on top of the Standard Model. We found that a proper assignment of the gauge quantum numbers automatically ensures that one of these candidates is stable (the fermionic quintuplet with zero hypercharge). This theory is so simple that it allows to fully compute the dark matter phenomenology (interactions with nucleons in underground experiments, annihilation products, etc.), leading to precise predictions for the next generation of dark matter experiments. The study of this phenomenology has been the topic of [t07/052], which focuses on the relic abundance production in the early Universe (and, in passing, describes the formalism for the so-called Sommerfeld enhancement that became later of wide interest in the community) and of [t08/034], which focuses on predicting the fluxes of positrons, antiprotons and gamma rays from the annihilations of Minimal Dark Matter particles in the galactic halo. Our work on Minimal Dark Matter has been collected in an invited review [t09/010].

In the framework of more general analyses of dark matter phenomenology, we analysed in [t09/027] (in collaboration with C. Bräuninger, a master student) another interesting possible signal of dark matter indirect detection: fluxes of anti-deuterium synthetized in galactic annihilations. The study focussed on the "very heavy Dark Matter" scenarios individuated by the recent data, and found promising perspectives especially for primary annihilation channels into quarks. In [t09/082], we also studied the implications of dark matter annihilations on star evolution. We investigated the possible observable modifications to the characteristic lifetime of early stars in case they are powered by dark matter annihilations, and found that the effects would be detectable only for extreme regimes.

With a number of international collaborators, we embarked in 2010 on a systematic, model-indepedent compilation of results useful for indirect dark matter detection, both in terms of formulae and in terms of numerical functions/tables that can be adapted to compute virtually any dark matter signature. The results have led to [t10/025], a publication that hopefully will prove useful for many researchers in the community.

B.11.2 Dark matter and Grand Unification *(M. Frigerio)*

The cosmological and astrophysical evidence for dark matter can be accounted for by a new, stable particle with the appropriate annihilation cross section, typically a weakly interacting particle with a mass in the TeV range. It turns out that the addition of such a state to the Standard Model makes it possible for gauge couplings to unify without low-energy supersymmetry. The dark matter particle should be a fermion isotriplet with zero hypercharge, $T \equiv (T^+, T^0, T^-)$, that could be seen in future direct detection experiments. In collaboration with T. Hambye, we showed in [t09/285] that this candidate is uniquely selected if we require that *i)* its stability is ensured by the grand unified symmetry, and *ii)* the addition of this state to the Standard Model leads to gauge coupling unification above the scale corresponding to the experimental lower bound on the proton lifetime, $M_{\rm GUT} > 10^{15}$ GeV.

B.11.3 Extra-dimensional dark matter *(G. Servant)*

For a Weakly Interacting Massive Particle (WIMP) to be a viable dark matter candidate, it should be stable. In supersymmetry, this occurs because of a new discrete symmetry: R-parity. In Little Higgs models, the underlying symmetry is a the so-called T-parity. In extra-dimensional models, this is Kaluza–Klein (KK) parity. However, KK parity is a good symmetry only in specific extra-dimensional models, those with flat extra dimensions. On the other hand, most of the interesting phenomenology (as far as addressing the hierarchy problem is concerned) arises in the context of warped extra dimensions (Randall–Sundrum models). In this context, KK parity is broken by the Anti-de-Sitter geometry and there is no stable Kaluza–Klein state. In [t07/153], we made the first attempt to implement a Kaluza–Klein parity in warped compactifications by gluing two identical slices of 5D AdS in either the UV or the IR region. Model-building issues as well as phenomenological properties were discussed. Collider signals of the warped KK parity are different from either the conventional warped extra dimension without KK parity, in which the new particles are not necessarily pair produced, or the KK parity in flat universal extra dimensions, where each KK level is nearly degenerate in mass. Dark matter and collider properties of a TeV mass KK Z gauge boson as the Lightest Kaluza–Klein particle were discussed. Phenomenology at the LHC of extra-dimensional dark matter was reviewed in the book chapter [t10/058].

B.11.4 A top quark - dark matter connection *(G. Servant)*

In [t09/315], we explored the possibility that the top quark has important couplings to dark matter. If the dark matter particle arises as part of the dynamics of electroweak symmetry breaking, it is natural to expect it to have large couplings to the most massive states of the Standard Model, in particular to the top quark, and suppressed couplings to the light SM degrees of freedom. If this is the case, dark matter will couple at the loop level both to photons and to the Higgs boson, and the Higgs boson could be copiously produced in the galaxy in association with a photon from dark matter annihilations or decays. The resulting photon spectrum possesses a line whose energy reflects the mass of the Higgs and of the WIMP and does not arise if dark matter is a scalar or a Majorana fermion, thus providing information about the WIMP spin and statistics. Indirect detection of WIMPs annihilating or decaying in our galaxy into high energy gamma rays could potentially be our first indication that WIMPs are electroweakly active particles, and our first non-gravitational glimpse of dark matter thanks to telescopes such as FERMI. This implies that the Fermi/GLAST satellite and ground-based Air Cherenkov telescopes could probe the Higgs boson and complement information obtained at the LHC. We have illustrated this phenomenon in a case in which the WIMP is composed of Dirac fermions annihilating via a massive vector resonance (Z') which couples strongly to the top quark, serving as a portal between dark matter and the Standard Model. Our setup arises naturally in models in which the top quark acquires its mass through a large mixing with composite states in a new strongly interacting sector.

B.11.5 Dark matter interpretation of cosmic ray data *(M. Cirelli, F. Iocco, P. Panci, G. Zaharijas)*

During the summer of 2008, the PAMELA satellite announced preliminary data on the positron flux in cosmic rays, showing confirmation of an excess over the expected background that previous experiments had already exposed. Soon after, we compared in [t08/163] the fluxes from Minimal Dark Matter annihilations predicted in [t08/034] with these data. We found a remarkably good agreement and were able to determine the set of astrophysical parameters giving the best fit. Then we started a model-independent interpretation of the data in charged cosmic rays (positrons, but also antiprotons from the PAMELA satellite, and electrons + positrons from ATIC, FERMI, HESS and other experiments), with the goal of identifying the dark matter models that are capable of explaining the observed signals while remaining compatible with searches in all other channels. We found that the PAMELA results alone, if due to dark matter annihilations, individuate quite unusual dark matter properties: either a very heavy particle (above 10 TeV) or a lighter one annihilating mainly into leptonic channels such as e^+e^-. Adding the balloon datasets in the analysis leaves us with the second possibility only [t08/139].

No claim of a dark matter signal in cosmic ray data can be supported without a critical inspection of the associated effects that it should entail. This led us to investigate the constraints on the dark matter interpretations discussed above, coming from: *i)* gamma rays and synchrotron radiation from the galactic center and from dwarf satellite galaxies [t08/184]; *ii)* the flux of gamma rays produced by inverse Compton scattering of energetic positrons on the low-energy ambient photons in the galactic halo [t09/030], [t09/187] (a signal that has the advantage of being less sensitive to astrophysical details than the gamma rays from the galactic center); *iii)* the flux of isotropic, and therefore extragalactic, gamma rays [t10/229]; *iv)* the cosmological evolution of the Universe [t09/046], [t09/065], based on the fact that dark matter annihilations during the epoch of galaxy formation would inject charged particles and energy, producing reionization and heating of the primordial gas which can exceed current measurements of the optical depth of the Universe, and modifying the spectra of the Cosmic Microwave Background (CMB). The bottom line of all these analyses is that the lack of associated signals impose very stringent constraints on the dark matter interpretations of charged cosmic ray data, a result which is now agreed upon by most of the community.

In [t10/229], [t10/230], the FERMI collaboration has looked at possible anisotropies in the arrival direction of leptons (electrons and positrons) which could betray their origin from a local astrophysical source (as opposed to a smoothly distributed dark matter): bounds are found and some bright sources can be excluded. G. Zaharijas, a member of the FERMI collaboration, is the corresponding author for [t10/229]. These works have been presented at a large number of meetings, often in the form of more general reviews on the status of dark matter indirect detection, as in [t09/178], [t10/098].

In [t10/062], we examined a class of dark matter models often advertised as being able to explain the cosmic ray excesses, namely models with multistate dark matter coupled to light hidden sector bosons. A detailed calculation showed that these models actually suffer from several tensions with the gamma ray constraints and in reproducing the cosmological abundance of dark matter. They can therefore only very marginally be considered viable.

B.11.6 Neutrino cosmology *(M. Cirelli)*

Neutrinos have an important impact on cosmology at various stages, most notably because their streaming on cosmological distances in the early Universe helped shaping the distribution of the galactic structures that we observe today. Recent experiments and satellites have made it possible to observe such effects with increasingly good precision, making it possible to constrain both the sum of neutrino masses and the total number of neutrinos (the latter is meant to include the three neutrinos of the Standard Model, plus any exotic light weakly interacting particle that behaves like a neutrino). We worked on several of these aspects in the past and closely follow the recent developments. We presented several reviews on this topic [t08/200], [t10/167].

B.12 Particle physics models for the early Universe

B.12.1 Inflation *(P. Brax, E. Cluzel, S. Mariadassou)*

In the last four years, we have studied a certain number of inflationary models and their consequences for preheating and the formation of cosmic strings. We investigated the KKLT scenario of supersymmetry breaking [t07/176] and its coupling to inflation. In particular, we have realised the first fully gauge invariant setting accommodating both KKLT stabilisation of the moduli and inflation [t07/178]. In these generalised racetrack models, a generic prediction is that the spectral index is low like in small field inflation [t07/180]. We have also studied the possible formation of cosmic strings at the end of inflation in these scenarios [t08/227], [t08/228]. Cosmic strings may also result from the presence of extra $U(1)$'s in models extending the usual Abelian Higgs model to non-linear actions of the DBI type [t08/155]. The preheating phase of inflationary models is crucial and may lead to the non-perturbative creation of gravity waves and black holes. With Jean-Francois Dufaux, we have considered preheating for small field inflation [t10/205]. We have found that tachyonic and resonance preheatings are both crucial. Although not detectable with future experiments, gravity waves are also copiously produced. Finally, we have studied the creation of particles when two branes cross each other in DBI inflation [t09/265]. This leads to an abrupt jump in the power spectrum of primordial fluctuations like in Starobinsky's model for Cosmic Microwave Background (CMB) features [t11/112].

B.12.2 Supersymmetry breaking and inflation *(P. Brax, C. Savoy, A. Sil)*

A remarkable property of a class of asymptotically free supersymmetric QCD-like theories is duality: in the strongly-coupled regime they are described by the metastable potential of a dual supersymmetric theory. This has recently been put forward by Intriligator, Seiberg and Shih as a natural framework for supersymmetry breaking. We suggested a somewhat analogous description for the sector responsible for (hybrid) inflation, such that the reheating temperature and the measured inflation parameters are related to the gauge coupling and mass parameter of a supersymmetric QCD theory. We identified the R-symmetries of the inflationary and supersymmetry breaking sectors, assumed to be described by two independent supersymmetric QCD theories that are only coupled through supergravity. Then, fixing the inflation parameters from CMB data, we derived the supersymmetry breaking scale and obtained a rationale for the Universe to be stuck in the metastable supersymmetry breaking vacuum after inflation [t07/117], [t08/230], [t09/213].

B.12.3 Dark energy and modified gravity *(P. Brax)*

In 2007, we started studying the possible observation of scalar field models coupled to matter in laboratory experiments [t07/092]. We have focussed on three types of experiments where our work prompted a large body of experimental work. In particular, we have analysed the optical [t07/175] and Casimir consequences [t07/177] of chameleon models which may lead to the acceleration of the Universe while being screened in gravitational tests of fifth forces and equivalence principle violation. In optics, chameleons may be produced via the Primakoff effect in a magnetic field. This may happen in optical cavities and is being looked for by experiments such as CHASE at Fermilab or BMV in Toulouse. Scalar fields may induce a new force in Casimir experiments. In particular, this force could be screened when the material in between the Casimir plates in dense enough while present in vacuum. We have been awarded a grant to carry out this experiment in Amsterdam under the supervision of D. Iannuzzi [t10/215]. Finally, the CAST experiment may see back-converted X-ray photons from chameleons created in the solar tachocline [t10/214]. This project will be one of the CAST objectives starting from 2011. Other possibilities such as atomic precision tests [t10/206] and afterglow experiments [t10/209] have been envisaged. We also applied the Eotwash constraints to $f(R)$ models and deduced strong constraints on the equation of state of dark energy [t08/229].

We have also studied chameleons with field dependent couplings [t10/211]. Using path integral methods, we have calculated the coupling of scalar fields to photons in scalar-tensor theories [t10/207]. We have studied shift symmetric dark energy models in supergravity [t09/211] and the coupling of inflation to dark energy [t08/235].

We have thoroughly studied the coupling of dark energy to the Standard Model and the consequences for accelerator physics. We have shown that the coupling to the Higgs sector is sensitive to high energies and to the UV completion of both the Higgs and the dark energy sectors. This implies that the creation of Higgs particles via WW fusion may be influenced by the presence of a dark energy sector [t09/212], [t09/209].

We have studied a possible application of the AdS/CFT setup in a cosmological context and linked the acceleration of the Universe with the conformal anomaly in this case [t10/210].

Following our original work in 2002 and 2004, we have studied the modification of the growth of structures induced by the presence of a cosmologically coupled scalar field (such as a chameleon) [t10/105]. We have considered the linear regime [t10/205], the second order perturbation theory and the bispectrum [t11/099], and finally the non-linear stages both analytically with the spherical collapse model [t10/213] and numerically with large N-body simulations [t11/113]. These efforts are particularly worthwhile for dilatonic models [t10/212] where local tests of gravity imply that modified gravity occurs on galaxy cluster scales. We are extending our work to galileon models and also to CMB precision tests which will be soon available thanks to the Planck satellite.

Finally, we have given lectures on dark energy [t09/264].

B.13 Gauge theory amplitudes

B.13.1 Symmetries of scattering amplitudes in gauge theories *(G. Korchemsky)*

Gauge theories have been and will remain the corner stone of all models unifying the elementary particles. The Large Hadron Collider (LHC) experiment will probably provide evidence for new physics at the multi-TeV energy frontier. In order to exploit fully the potential of the LHC, new approaches to the study of multiparticle scattering processes in the underlying gauge theories need to be developed. This is of crucial importance for the efficient evaluation of the significant background of Standard Model physics, against which the signals for new physics have to be assessed.

Until recently, the standard approach to computing scattering processes in gauge theories relied on a perturbative Feynman diagram expansion. While this procedure is very well understood, the complexity of the calculation grows so rapidly with increasing the number of particles that it seriously challenges our ability, especially beyond the leading order, to compute background processes to the accuracy required by the LHC physics. This calls for developing a new technique for computing various observables in gauge theories.

In the past few years several remarkable developments took place. They concern a special type of gauge theory, the maximally supersymmetric $\mathcal{N} = 4$ Yang-Mills theory ($\mathcal{N} = 4$ SYM), the first example of an ultraviolet finite quantum field theory. As a consequence, it exhibits conformal symmetry at the quantum level – a very unusual feature for four-dimensional quantum field theory. Although the $\mathcal{N} = 4$ SYM Lagrangian differs from that of QCD, the two gauge theories share many common features and progress in understanding the properties and in developing new calculation methods for $\mathcal{N} = 4$ SYM can have direct relevance for QCD and for the Standard Model. For example, tree-level gluon amplitudes are the same in all gauge theories, and thus new results for $\mathcal{N} = 4$ SYM can be immediately applied to the calculation of multi-jet event background at LHC.

Dual superconformal symmetry

The scattering amplitudes in maximally supersymmetric $\mathcal{N} = 4$ SYM theory have a number of remarkable properties both at weak and at strong coupling. Defined as matrix elements of the S-matrix between asymptotic on-shell states, they inherit the symmetries of the underlying gauge theory. In addition, trying to understand the properties of the scattering amplitudes, one can discover new dynamical symmetries of the $\mathcal{N} = 4$ theory. In a series of papers, we argued that the planar scattering amplitudes in $\mathcal{N} = 4$ SYM theory have a hidden symmetry that we called the dual superconformal symmetry. It appears on top of all well-known symmetries of the scattering amplitudes (supersymmetry, conformal symmetry, etc.) and is not related (not in an obvious way, at least) to an invariance of the Lagrangian of the theory (see [t09/076, t09/102, t10/013]). At strong coupling, the same symmetry also emerges in the AdS/CFT description of scattering amplitudes, from invariance of the string sigma model on an

$AdS_5 \times S^5$ background under a combined bosonic and fermionic T-duality. It is even more intriguing that the dual conformal symmetry is also present in QCD but only in the Regge limit (see [t09/284]). It worth mentioning that it is in this limit that QCD is believed to admit a dual description in terms of a (still mysterious) hadronic string. In close analogy with $\mathcal{N} = 4$ SYM, we expect that dual conformal symmetry provides yet another glimpse into the QCD/string duality.

Scattering amplitudes / Wilson loops / Corrrelation function duality

Based on the previous QCD findings and on strong coupling analysis of scattering amplitudes within AdS/CFT correspondence by Alday-Maldacena, we have previously demonstrated that MHV scattering amplitudes in planar $\mathcal{N} = 4$ theory are related to Wilson loops evaluated on closed polygon-like contours in a "dual" Minkowski space-time, consisting of light-like segments defined by the on-shell gluon momenta.

We have argued in [t10/091, t10/092, t10/139] that the duality between MHV amplitudes and light-like Wilson loops can be extended to include the duality to the correlation functions of conformal primary operators located at the vertices of the same polygon-like contour. One of the consequences of this relation is that the dual conformal symmetry of the MHV amplitudes can be derived from the conventional conformal symmetry of the light-like Wilson loops and the correlation functions. To verify the duality, we studied in [t10/091, t10/092, t10/139] the correlation functions of half-BPS protected operators in $\mathcal{N} = 4$ super-Yang-Mills theory in the limit where the positions of the adjacent operators become light-like separated. We computed the loop corrections by means of Lagrangian insertions and showed, in a number of examples at one and two loops, that the logarithm of the correlation function coincides with twice the logarithm of the matching MHV gluon scattering amplitude.

In a recent development (see [t11/034, t11/036, t11/037]), we further extended the duality between MHV amplitudes and the light-cone limit of correlation functions to generic non-MHV amplitudes in planar $\mathcal{N} = 4$ SYM theory. We considered the natural generalization of the bosonic correlation functions to super-correlators of stress-tensor multiplets and showed, in a number of examples, that their light-cone limit exactly reproduces the square of the matching super-amplitudes. We found that the super-correlators computed at Born level can be effectively used to compute various scattering amplitudes in planar $\mathcal{N} = 4$ SYM theory: If all points of the super-correlator form a light-like polygon, the correlator is dual to the tree-level amplitude. If a subset of points are not on the polygon but are integrated over, they become Lagrangian insertions generating the loop corrections to the correlator. In this case the duality with amplitudes holds at the level of the integrand. We build up the superspace formalism needed to formulate the duality and present the explicit example of the NMHV tree amplitude as the dual of the lowest nilpotent level in the correlator.

Cusp anomalous dimension

The cusp anomalous dimension is a ubiquitous quantity in $\mathcal{N} = 4$ Yang-Mills theory, and it is one of the best investigated observables in the AdS/CFT correspondence. In application to the scattering amplitudes, the cusp anomalous dimension controls the structure of leading infrared singularities. In planar $\mathcal{N} = 4$ SYM theory, perturbative expansion of the cusp anomalous dimension at weak coupling has a finite radius of convergence while at strong coupling it admits an expansion in inverse powers of the 't Hooft coupling which is given by a non-Borel summable asymptotic series. In [t08/220], we studied the cusp anomalous dimension in the transition regime from strong to weak coupling. We argued that the transition is driven by non-perturbative, exponentially suppressed corrections. To compute these corrections, we revisited the calculation of the cusp anomalous dimension in planar $\mathcal{N} = 4$ SYM theory and extended the previous analysis by taking into account nonperturbative effects. We demonstrated that the scale parameterizing nonperturbative corrections coincides with the mass gap of the two-dimensional bosonic O(6) sigma model embedded into the $AdS_5 \times S^5$ string theory. This result is in perfect agreement with the prediction coming from the string theory consideration.

B.13.2 New techniques for scattering amplitudes *(R. Britto, E. Mirabella)*

On-shell techniques for one-loop amplitudes

We have been finding and developing new techniques for computing scattering amplitudes in QCD, especially in processes with many final states, and through next-to-leading-order in the coupling constant. These new techniques, in which all intermediate quantities are on-shell and gauge invariant, are efficient and yield expressions for amplitudes in their most compact forms. Our methods, summarized in [t10/257], have been used to obtain certain gluon amplitudes for the first time, at tree level and one-loop order. Each of these computations represents an improvement in general methodology that can be applied to broad classes of amplitudes. One strength of this approach, compared with more traditional methods, is that it applies to amplitudes with an arbitrary number of particles. By any technique, but especially traditional ones, the complexity of a computation increases rapidly with the number of external particles. The reason that my approach can generalize is that it is mainly independent of the features of individual integrals.

This research follows two principal lines. First, we have been developing these techniques for one-loop amplitudes with a view towards efficient, automatic, algorithmic computation. The framework of these calculations overlaps a great deal with that of D. Kosower. Our particular specialty is in deriving compact analytic expressions. Therefore, we have been working with symbolic computation (Mathematica) to implement these techniques and learn how to get the best results as efficiently as possible. At the same time, we aim to develop a numerical counterpart to this analytic algorithm and measure its efficiency against other methods.

Extensions to more general amplitudes

Second, we have been widening the realm of applicability of the techniques for calculating loop amplitudes. They are fully developed for one-loop amplitudes where all the virtual particles are massless, which is sufficient for most QCD background processes at the LHC. However, in a general theory where the virtual particles might have significant masses, one-loop amplitudes have additional components which are much more difficult to determine by on-shell methods. One of these additional components are the so-called tadpole integral contributions. The on-shell approach to one-loop amplitudes is to use "unitarity cuts", which are operations restricting certain chosen propagators to their mass shells, combined with knowledge of a complete set of "master integrals" which are known explicitly and form a linear basis for any Feynman integral. If at least two propagators are cut in this fashion, the result is a singularity of the amplitude associated with a certain momentum channel. If only one propagator is cut, there is no physical momentum channel to serve as a point of reference. This is the problem with the "tadpole" integral contributions, which are the integrals with only one propagator remaining in the denominator. We have outlined two proposals for computing these tadpole contributions. First, in a joint publication with B. Feng [t09/332], we found that it is possible to add one more (unphysical) propagator in a formal sense, cut it along with the existing propagator, use our previous methods for traditional cuts, and finally decouple the effects of the unphysical propagator. Second, in a joint publication with E. Mirabella [t10/254], we studied the meaning of the single-cut integral in itself. Not only does it lack a simple interpretation in terms of external kinematics, but moreover it typically diverges and picks up contributions from functions other than the master integrals. Nevertheless, we found that divergences could be regularized, and that with a careful, though difficult treatment, not only can tadpole contributions be determined, but in principle every other kind of contribution can be identified uniquely as well in this cut. We are continuing to study the implementation of single cuts in physical scattering processes.

B.13.3 NLO amplitudes *(D. Kosower)*

BlackHat software library

The primary activity in NLO QCD was within the BlackHat collaboration, developing and applying the BlackHat software library. This library uses on-shell methods – unitarity and on-shell recursion – to compute one-loop amplitudes numerically. The basic idea behind on-shell methods is to use only information about physical states in calculations of amplitudes, and to turn general properties — factorization, unitarity, and the existence of a representation based on Feynman integrals — into tools for performing calculations. These on-shell methods have provided a means of breaking the long-standing bottleneck to NLO calculations of processes with several jets in the final state, that of computing higher-multiplicity one-loop amplitudes in QCD. The basic ideas and approach to a numerical implementation of the on-shell methods were reported in [t08/054]. Calculations of several one-loop amplitudes were reported in various conference proceedings [t08/117, t08/123]. Several physics applications followed: the computation of the NLO cross section for W+3-jet production at both the Tevatron and the LHC, reported in refs. [t09/019, t09/078, t09/136]; the NLO prediction for Z, γ^*+3-jet cross sections at the Tevatron [t10/040, t10/065, t09/268]; and a landmark result, the NLO prediction for the production of W+4-jet production at the LHC [t10/111]. The W+4-jet process is an important background to top-pair production as well as the discovery of new physics beyond the Standard Model. We have also pointed out the typical left-handed polarization of both $W^{\pm}$ at *large* transverse momentum, an effect distinct from the well-known polarization at small transverse momentum, and one that should be useful in distinguishing 'prompt' Ws from those arising in decays of heavy states [t09/268, t11/040]. Other related work by S. Badger included a new technique for computing rational terms in QCD amplitudes [t08/106] and its application to an unexpected simplicity in QED and gravity amplitudes [t08/156].

$\mathcal{N} = 4$ maximally supersymmetric Yang–Mills theory

Calculations in the $\mathcal{N} = 4$ maximally supersymmetric Yang–Mills theory are important as a simple laboratory for developing techniques for QCD, and also important in their own right for deepening our understanding of the AdS/CFT duality between strings (strong coupling) and this gauge theory (weak coupling). With a variety of collaborators, I computed two two-loop six-point amplitudes in the $\mathcal{N} = 4$ theory, the MHV [t08/045] and NMHV ones [t08/045]. The former was crucial in establishing the connection with a Wilson-loop calculation, and in confirming the existence of a 'remainder' function beyond the simple exponentiation hypothesis of Bern, Dixon and Smirnov. The latter furnishes additional such functions, targets for any attempt to link weak and strong coupling. Other work in this area, by H. Johansson and collaborators, included the computation of the complete four-loop amplitude, including non-planar terms [t10/075]; the observation that a novel structure for the kinematic terms paralleling color coefficients in gauge theories, extends to loop amplitudes, thereby extending the notion of gravity amplitudes as a 'double copy' of gauge-theory amplitudes and hinting at new structures underlying the latter [t10/044, t10/086]; and a review of unitarity and other modern techniques for higher-loop amplitudes [t11/029].

New approach to parton showers

A third subject is that of developing a new approach to parton showers, based on the use of $2 \to 3$ branching antennæ instead of the usual $1 \to 2$ collinear splitting functions. This allows one to preserve masslessness at all stages of the shower [t07/107]; offers an understanding of the effect of finite terms neglected in previous approaches [t07/107]; and opens the way to new approaches to matching to finite-order matrix elements [t10/196].

B.13.4 SUSY particle production *(E. Mirabella)*

Pair production of squark and gluino is the most important discovery channel of TeV-scale supersymmetry at the LHC. An extremely interesting and challenging ongoing project is the computation the electroweak contributions to these processes. These contributions, together with the known QCD corrections, complete the NLO analysis.

Electroweak corrections include $\mathcal{O}(\alpha_s\alpha)$, $\mathcal{O}(\alpha^2)$ and $\mathcal{O}(\alpha_s^2\alpha)$ contributions. The latter are the more involved ones, *e.g.* they include the full set of one-loop QCD graphs interfering with the tree-level electroweak diagrams. In order to obtain UV finite results, the MSSM has to be completely renormalized at next-to-leading order, properly taking care of different regularization schemes in the presence of supersymmetry. The soft and collinear divergences are cancelled by real photon and real gluon emission. Owing to their complexity, we regularized and isolated these divergences using both phase space slicing and dipole subtraction methods, with mass regularization as well as dimensional regularization. The impact of the electroweak contributions on the total cross section is at the level of several percent and can be even more significant in the kinematical distributions. The latest results on this project concern squark–squark [t10/007] and sbottom–anti-sbottom pair production [t11/021].

We have computed the NLO electroweak contributions to the *semi-inclusive bottom-Higgs production* [t10/284]. This process is an important discovery channel for supersymmetric Higgs boson for large values of $\tan\beta$.

B.14 Jet algorithms *(G. Soyez)*

Jets — seen in a first approximation as a proxy for the hard partons produced in hadronic collisions — are common objects, present in a large number of analyses and understanding them better has therefore the potential of translating immediately into improved analyses *e.g.* for new-physics searches.

B.14.1 Optimal jet radius

In order to compare the behavior of different jet definitions, we had done a Monte-Carlo study of the mass reconstruction of a resonance decaying into two jets, showing that optimizing the radius used in the jet reconstruction could lead to a significant improvement. In this work, it has been shown that the results of these simulations can be understood analytically. This is one of the few analytic results constraining the parameters of the jet definitions.

B.14.2 Jets in heavy ion collisions

The study of jets in heavy-ion collisions, where the contribution from the Underlying Event — *i.e.* the soft background produced together with the hard probes — spoils their efficient reconstruction, the reconstruction of jets is particularly challenging. Developing around the idea that the background contribution can be subtracted using jet-area-based methods, we have made in [t10/298] an extensive study of different reconstruction scenarios showing that a decent resolution is achievable and suggesting various techniques to improve it further.

Still in the context of heavy-ion collisions, we have addressed concerns in [t11/126] about the recent measurements of the dijet asymmetry at the LHC. While this observable is certainly affected by in-medium quenching effects, the (intra-event) fluctuations of the soft background also affects the dijet asymmetry. This means that a quantitative statement about the nature of quenching effects is hard to make without further constraints on the background fluctuations.

Finally, we have performed in [t11/125] a computation of the ratio between the inclusive jet cross-section computed with the same algorithm but 2 different radii at NLO in perturbative QCD, and shown that this observable can have rather large non-perturbative corrections that could also be estimated analytically. This observable can be measured at RHIC (both in pp and $AuAu$ collisions) as well as at the LHC.

B.14.3 FastJet package

The FastJet package (see *www.fastjet.fr*) — a package that implements a series of jet-clustering algorithms and related tools such as jet areas — has now become the common interface to jet clustering: it is used both by the LHC experiments in their respective analysis softwares and by the theorists studying jet physics. This has triggered many discussions, in particular with the LHC experimentalists, even more so since the anti-k_t algorithm, that we have introduced in 2008, has been adopted as the default jet-clustering algorithm at the LHC. As a consequence, new features are regularly added: we have released FastJet v2.4.2 in February 2010, v2.4.3 in April 2011, and v3.0 shall be available soon.

B.15 Color Glass Condensate

At high energy, a hadron or nucleus becomes a dense system of weakly-coupled gluons. However, the weakness of the coupling 'constant' is compensated by the large gluon density, leading to an important non-linear effect known as gluon saturation. The theoretical study of such a system requires resummations of the naive perturbation theory, which are best handled by an effective theory based on QCD known as the Color Glass Condensate (CGC). The general ideas of this approach are confirmed, at least qualitatively, by the existing experimental data in electron-proton collisions and in nucleus-nucleus collisions. We have written recently a review on the subject [t10/066].

B.15.1 Angular ordering in the evolution towards saturation *(E. Iancu)*

Another effect which is neglected by the standard evolution equation for the CGC, the 'JIMWLK equation', but which may be important for the distribution of particles in the final state, is the angular ordering of the successive gluon emissions, related to quantum coherence in the process of radiation. This ordering is correctly accounted for by the linear CCFM equation, which however misses the non-linear physics of gluon saturation. In Refs. [t09/173, t09/174] we provided a heuristic generalization of the CCFM equation which includes saturation via an absorptive boundary condition. We have also considered the effects of a running coupling and performed detailed numerical studies of the evolution of the gluon distribution, as described by this new equation.

B.15.2 BFKL physics in hadron-hadron collisions *(C. Marquet)*

A model was developed to describe diffractive events in hadron-hadron collisions where a rapidity gap is surrounded by two jets [t09/095]. The hard color-singlet object exchanged in the t-channel and responsible for the rapidity gap is described by the pQCD Balitsky-Fadin-Kuraev-Lipatov Pomeron, including corrections due to next-to-leading logarithms. The model is able to reproduce all Tevatron data, and allows to estimate the jet-gap-jet cross section at the LHC.

B.15.3 Geometric scaling *(E. Iancu, R. Peschanski)*

Geometric scaling in Mueller-Navelet jets

The CGC approach is well suited for the calculation of observables involving large separations in rapidity, like forward jets. In particular, we have predicted that the Mueller-Navelet jets — a pair of forward-backward jets — should be sensitive to gluon saturation at the LHC energies and in particular exhibit the phenomenon of geometric scaling [t08/084], originally observed in deep inelastic scattering at HERA. The Mueller-Navelet jets are about to be measured at the LHC, so our prediction should be soon confronted with the data.

Scaling in HERA data

In [t08/062], using the "Quality Factor" (QF) method, we analyze the scaling properties of deep-inelastic processes at HERA and fixed target experiments for x<0.01. We look for scaling formulae of the form $\sigma(\tau)$, where $\tau(\log Q^2, Y)$ is a scaling variable suggested by the asymptotic properties of QCD evolution equations with rapidity Y. We consider four cases: "Fixed Coupling", corresponding to the original geometric scaling proposal and motivated by the asymptotic properties of the Balitsky-Kovchegov (BK) equation with fixed QCD coupling constant, two versions "Running Coupling I,II" of the scaling suggested by the BK equation with running coupling, and "Diffusive Scaling" suggested by the QCD evolution equation with Pomeron loops. The Quality Factors, quantifying the phenomenological validity of the candidate scaling variables, are fitted on the total and DVCS cross-section data from HERA and predictions are made for the elastic vector-meson and for the diffractive cross-sections at fixed small x_pom or β. The first three scaling formulae have comparably good QF while the fourth one is disfavored. Adjusting initial conditions gives a significant improvement of the "Running Coupling II" scaling.

QCD Traveling Waves

In [t09/298], we identify the nonlinear evolution equation in impact-parameter space for the "Supercritical Pomeron" in Reggeon Field Theory as a 2-dimensional stochastic Fisher and Kolmogorov-Petrovski-Piscounov equation. It exactly preserves unitarity and leads in its radial form to an high energy traveling wave solution corresponding to an "universal" behavior" of the impact-parameter front profile of the elastic amplitude; Its rapidity dependence and form depend only on one parameter, the noise strength, independently of the initial conditions and of the non-linear terms restoring unitarity. Theoretical predictions are presented for the three typical different regimes corresponding to zero, weak and strong noise, respectively. They have phenomenological implications for total and differential hadronic cross-sections at colliders.

In [t09/302], we define a mapping of the QCD Balitsky-Kovchegov equation in the diffusive approximation with noise and a generalized coupling allowing a common treatment of the fixed and running QCD couplings. It corresponds to the extension of the stochastic Fisher and Kolmogorov-Petrovski-Piscounov equation to the radial wave propagation in a medium with negative-gradient absorption responsible for anomalous diffusion, noninteger dimension, and damped noise fluctuations.

In the paper [t08/060], using the relation of a set of nonlinear Langevin equations with reaction-diffusion processes, we note the existence of a maximal strength of the noise for the stochastic traveling wave solutions of these equations. Its determination is obtained using the field-theoretical analysis of branching-annihilation random walks near the directed percolation transition. We study its consequence for the stochastic Fisher-Kolmogorov-Petrovsky-Piscounov equation. For the related Langevin equation modeling the Quantum Chromodynamic nonlinear evolution of the gluon density with rapidity, the physical maximal-noise limit may appear before the directed percolation transition, due to a shift in the traveling-wave speed. In this regime, an exact solution is known from a coalescence process. Universality and other open problems and applications are discussed in the outlook.

B.15.4 Global fits to HERA data *(J. Albacete)*

In [t10/197], we demonstrated that the running coupling BK equation provides a very good description of the inclusive structure functions in electron-proton collisions at small-x from HERA, including the latest high precision data from the combined analysis from the H1 and ZEUS collaborations. We also showed that the heavy quark contribution to inclusive cross sections can be well accommodated in the dipole model approach.

B.15.5 Gluon saturation in forward observables *(J. Albacete, C. Marquet)*

In [t10/073], we considered the forward dihadron azimuthal correlations in d+Au collisions at RHIC. We studied the observed suppression of the away-side peak in two-pions correlations at forward rapidities, showing that such an effect can be well described in the framework of the Color Glass Condensate.

In [t10/010], we studied the single inclusive hadron production in p+p and d+Au collisions at RHIC. Here we presented a phenomenological analysis of available data in terms of the hybrid formalism for forward production and unintegrated gluon distributions evolved according to the running coupling BK equation. With this set up we provided a very good quantitative description of the observed suppression of nuclear modification factors in the forward region, thus providing additional evidence for the importance of non-linear, saturation effects in this kinematic region.

B.15.6 CGC calculations for the Electron Ion Collider

Future high-energy electron-ion colliders have been proposed (the EIC and LHeC) to, among other things, investigate non-linear parton evolution in QCD. In this context, CGC calculations for several deep inelastic scattering observables have been performed.

Diffractive structure functions *(T. Lappi, C. Marquet)*

In [t08/089], we have computed diffractive structure functions for both protons and nuclei in the framework of Color Glass Condensate models with impact parameter dependence. These models have previously been shown to provide good agreement with inclusive F_2 measurements and exclusive vector meson measurements at HERA. For nuclei, they provide good (parameter free) agreement with the inclusive F_2 data. We have demonstrated the good agreement of our computations with HERA measurements on inclusive diffraction. We also extended our analysis to nuclei and predicted the pattern of enhancement and suppression of the diffractive structures functions that can be measured at an Electron Ion Collider. We showed that the impact parameter dependence crucially affects our analysis, in particular for large invariant masses at fixed Q^2.

Semi-inclusive DIS *(C. Marquet)*

Semi-inclusive hadron production in deep inelastic scattering (SIDIS) was addressed [t09/097]. It was shown that at small Bjorken x, this process provides a direct probe of the unintegrated gluon distribution. In particular, even at large values of photon virtualities, one is sensitive to the saturation regime of the target wave function, if the transverse momentum of the produced hadron is of order of the saturation momentum.

Diffractive vector meson production off nuclei *(C. Marquet)*

The crucial differences between coherent diffraction (when the nucleus doesn't break-up) which dominates at small momentum transfer, and incoherent diffraction (when the nucleus scatters inelastically) which dominates at large momentum transfer, have been investigated using the McLerran-Venugopalan model for the CGC wave function [t10/028].

B.15.7 Saturation scale from Wilson line correlators *(T. Lappi)*

In the color glass condensate framework the saturation scale measured in deep inelastic scattering of high energy hadrons and nuclei can be determined from the correlator of Wilson lines in the hadron wavefunction. These same Wilson lines give the initial condition of the classical field computation of the initial gluon multiplicity and energy density in a heavy ion collision. In [t07/146], the Wilson line correlator in both adjoint and fundamental representations is computed using exactly the same numerical procedure that has been used to calculate gluon production in a heavy ion collision.

B.15.8 Factorization in the saturated regime *(F. Gelis, T. Lappi)*

In the collision of two hadrons or nuclei at high energy, in a regime where non linear effects such as saturation are relevant, the standard DGLAP or BFKL factorization frameworks fail to resum all the leading logarithmic contributions. In a series of three papers [t08/068, t08/116, t08/232], we have proven that one can still factorize all the leading logs of the collision energy in the Color Glass Condensate framework, provided one considers sufficiently inclusive observables. In this factorization, that in a sense generalizes the BFKL resummation by including all the non-linear corrections that arise in the high gluon density regime, the projectiles are described by functionals that represent their color charge content and evolve with the factorization scale according to the JIMWLK equation.

B.15.9 Multiplicity in nucleus-nucleus collisions *(J. Albacete, J.-P. Blaizot, F. Gelis, T. Lappi)*

Semi-analytical results

In [t08/261], we show that a special choice of light-cone gauge can greatly simplify the calculation of the classical color field created in the initial stages of nucleus-nucleus collisions. Within this gauge, we can in particular construct explicitly the conserved color current and calculate exactly the gauge field immediately after the collision. This field is used as a boundary condition in an iterative solution of the Yang-Mills equations in the forward light-cone. In leading order, which corresponds to a linearization of the Yang-Mills equation in the forward light-cone, we obtain a simple formula for the spectrum of gluons produced in nucleus-nucleus collisions. This formula reproduces exactly the known formula for proton-nucleus collisions, where k_t-factorization is recovered, while the latter property apparently breaks down in the case of nucleus-nucleus collisions

In [t10/296], we study the gluon distribution in nucleus-nucleus collisions in the framework of the Color-Glass-Condensate. Approximate analytical solutions are compared to numerical solutions of the non-linear Yang-Mills equations. We find that the full numerical solution can be well approximated by taking the full initial condition of the fields in Coulomb gauge and using a linearized solution for the time evolution. We also compare kt-factorized approximations to the full solution.

Multiplicity estimate for the LHC

In [t07/219], we have estimated the multiplicity of gluons expected in nucleus-nucleus collisions at the energy of the LHC, based on the CGC framework. The color charge distributions of the colliding nuclei were evolved to the appropriate collision with the BK equation, with a simplistic implementation of running coupling effects. One word of caution is in order here: this framework strictly speaking describes what happens at very short times after the collision, but not the subsequent fragmentation that may occur later in the evolution. This multiplicity is therefore a lower bound of the final value, that should perhaps be increased if fragmentation is significant in the final state.

Complete multiplicity distribution

In [t09/063], we have extended the previous study by a calculation of all the higher moments of the multiplicity distribution. We have found there that this distribution is approximately a negative binomial distribution, a fact that had been observed in hadronic collisions at high energy. To our knowledge, this is the first derivation of such a distribution in a framework that can be derived from QCD. Moreover, our study makes a prediction for the dependence of the two parameters that characterize the negative binomial distribution (the number of sources, and the mean number of produced gluons per source) as a function of the collision energy and its impact parameter.

Effect of initial geometry fluctuations

In [t10/313], we devised a model for initial gluon production in ultra-relativistic nucleus-nucleus collisions at RHIC and the LHC based on the use of unintegrated gluon distributions evolved according to the running coupling BK evolution and kt-factorization. Moreover, Monte Carlo techniques were employed to describe the fluctuations in the collision geometry. Our predictions agree very well with the data on total multiplicities measured in the first Pb+Pb collisions at the LHC, and also describe successfully existing RHIC data.

B.15.10 Two gluon correlations at large rapidity *(F. Gelis, T. Lappi)*

In [t09/124], we have analyzed the long range rapidity correlations observed in the STAR experiment at RHIC. Our goal was to extract properties of the two particle correlation matrix, accounting for the analysis method of the STAR experiment. We found a surprisingly large correlation strength for central collisions of gold nuclei at highest RHIC energies. We argued that such correlations cannot be the result of impact parameter fluctuations.

In [t09/164], we have applied the above factorization results in a semi–quantitative study of the double inclusive gluon spectrum. In this paper, we have shown that the CGC framework leads to a long-range rapidity correlation between pairs of produced gluons, that reflects the fact that QCD evolution in rapidity is significant only over rapidity intervals of order $1/\alpha_s$. Such correlations had in fact been observed experimentally at RHIC, and this study has since then become the standard explanation of this long range correlation.

Later, we have made this analysis more quantitative in [t10/067], where we calculated the actual dependence of the correlation strength with the rapidity separation between the two gluons (in the previous work, we had made approximations that amounted to neglect this dependence). In fact, the real strength of the CGC is not that it predicts a long range correlation (any sensible model of hadronic collisions should have such correlations), but that it provides a way to perform a first principles calculation of the deviation from a flat correlation.

Finally, we have argued in [t10/149] that similar correlations may also exist in proton-proton collisions, provided one triggers on events that have an exceptionally large multiplicity. There is ongoing speculation that this effect may contribute to the 2-hadron correlations observed recently at the LHC by the CMS experiment.

B.15.11 Schwinger mechanism *(F. Gelis, T. Lappi)*

In [t09/104], we have developed a new method for deriving the (well-known) Schwinger mechanism of pair production by an electrical field. This derivation establishes a connection between the Schwinger mechanism and particle production in the CGC framework at 1-loop order. As a by-product, we obtained not only the mean number of pairs produced by the electrical field, but also all the higher moments – and we could conclude from this that the distribution of the produced pairs is a coherent Bose-Einstein distribution.

B.15.12 Thermal equilibration *(F. Gelis, T. Epelbaum)*

An outstanding problem in the application of the CGC framework to the description of heavy-ion collisions is that of the thermalization of the gluonic system produced in these collisions. Immediately after the collision, this system of gluons is in a coherent state very far out-of-equilibrium, but experimental measurements tend to favor a rather quick thermal equilibration.

In [t09/165], we made a first attempt to relate the CGC framework to a Boltzmann equation. However, this has remained so far a formal exercise and was not pursued as a practical way to study thermalization due to the technical complexity of this Boltzmann equation.

A much more promising effort in this direction is to resum a family of higher order corrections to the CGC picture, that is known to give secular divergences if considered at fixed order. These divergences are closely related to instabilities and chaos in the classical Yang-Mills equations, and to the known fact that they have positive Lyapunov exponents. We have developed a resummation procedure that collects the terms that have the most divergent behavior at every loop order, and we have shown that the outcome of this resummation is well behaved at any time. In [t10/148], we took this resummation further in the simpler case of a scalar field theory, and implemented it numerically in order to investigate its effect on the thermalization of the system. We have shown that it leads to a rapid decay of the initial coherent state, and to the relaxation of the pressure in the system to its equilibrium value.

B.15.13 Collisional meson dissociation *(C. Marquet)*

A 4-point function was computed which allows to estimate the survival probability of a meson propagating in the presence of cold or hot QCD matter [t08/226]. It was found that this probability decreases proportionally to the inverse medium length instead of the exponential law usually assumed in phenomenological studies. This will be relevant when considering the production of high-p_T heavy mesons in nucleus-nucleus collisions, as these can be produced within the medium and their in-medium dissociation will contribute to the strong suppression observed in heavy-ion collisions.

B.16 Central diffractive processes *(R. Peschanski)*

In [t08/001], we propose a new set of measurements which can be performed at the LHC using roman pot detectors. This new method is based on exploiting excitation curves to measure kinematical properties of produced particles. We illustrate it in the case of central diffractive W pair production.

In [t08/278], central diffractive production of heavy states (massive dijets, Higgs boson) is studied in the exclusive mode using a new Hybrid Pomeron Model (HPM). Built from Hybrid Pomerons defined by the combination of one hard and one soft color exchanges, the model describes well the centrally produced diffractive dijet data at the Tevatron. Predictions for the Higgs boson and dijet exclusive production at the LHC are presented.

In [t08/071], exploiting the idea that the fast partons of an energetic projectile can be treated as sources of color radiation interpreted as wee partons, it is shown that the recently observed property of extended limiting fragmentation implies a scaling law for the rapidity distribution of fast partons. This leads to a picture of a self-similar process where, for fixed total rapidity Y, the sources merge with probability varying as 1/y.

B.17 Gauge-gravity duality

In heavy ion experiments at RHIC, it has been observed that the quark-gluon plasma created in these collisions behaves like an almost perfect fluid, which could be explained if one assumes that it is a system with strong coupling. This might be explained by the fact that the matter produced in the collision is rapidly expanding and thus becomes dilute and potentially strongly coupled.

These findings raised the question of the theoretical tools at our disposal for studying such a strongly coupled form of matter. Such techniques had emerged a bit earlier in string theory, in the context of the gauge/string duality also known as the AdS/CFT correspondence. In this description, a gauge field theory with conformal symmetry and strong coupling — the $\mathcal{N} = 4$ supersymmetric Yang–Mills (SYM) theory — is conjectured to be equivalent ("dual") to a string theory that lives in a ten-dimensional space-time and has weak coupling (thus it reduces to classical gravity).

This approach has been used for qualitative studies of a strongly-coupled quark-gluon plasma, since QCD itself becomes nearly conformal in the deconfined phase at finite temperature. To obtain the "dual" of a finite-temperature plasma, one must insert a black hole in the target space-time of the string theory. Using this approach, we have studied the propagation of 'hard probes' (partons or jets with high energy and momentum) through a strongly-coupled plasma, with results to be detailed in what follows.

B.17.1 Parton picture at strong coupling *(E. Iancu)*

The observation at RHIC of a strong energy loss by partons (quarks and gluons) propagating through the quark-gluon plasma — a phenomenon known as 'jet quenching' — raised the question about the partonic structure of hadronic system at strong coupling. Conceptually, the most direct way to probe the structure of a hadron at a hard resolution scale is to perform deep inelastic scattering (DIS), i.e. to scatter a virtual photon off that hadron. In a series of 4 publications, we have studied the analogous problem at strong coupling, using the AdS/CFT correspondence, for three different types of hadronic targets: a glueball in [t07/191], a finite-temperature plasma in [t07/192, t08/085], and a nucleus in [t09/171]. These studies allowed us to deduce a picture for the parton structure in a (conformal) gauge theory at strong coupling: via successive branching, the partons with relatively high energy dissociate into new partons with lower energies, until an equilibrium (or 'saturation') state is reached in which all the partons carry low fractions of the total energy ('low x') - the highest possible value of x being fixed by energy conservation.

This scenario bears some similarity with the phenomenon of gluon saturation at weak coupling, thus suggesting the universality of this phenomenon, from weak to strong coupling. However, unlike what happens at weak coupling, where most of the hadron energy is carried by the pointlike valence quarks, at strong coupling there are no such constituents: all the partons are soft and the hadron looks more like a jelly. A striking consequence of this picture is the absence of hard jets in the final state of a hypothetical collision at strong coupling. The final state would rather consist in an isotropic distribution of soft matter, as produced via successive parton branching.

B.17.2 Langevin dynamics and jet quenching at strong coupling *(E. Iancu)*

On the basis of the above mentioned parton picture, we have clarified the mechanism for energy loss and momentum broadening for a heavy quark immersed in a strongly-coupled plasma [t09/056]. Unlike at weak coupling, where the quark looses its energy predominantly via multiple scattering off the medium constituents, at strong coupling it does so via medium-induced parton branching. This mechanism is encoded in a Langevin equation that we have derived from AdS/CFT. Our construction has also interesting formal consequences: it establishes a 'duality' between the phenomenon of jet quenching in a gauge theory at strong coupling and the Unruh effect in the supergravity theory (the semi-classical limit of the string theory).

B.17.3 Heavy quark energy loss at strong coupling *(C. Marquet)*

It was shown that, on the gravity side of the correspondence, energy loss is not due to a space-time event horizon, but rather to a string world-sheet horizon [t08/066]. On the gauge-theory side, this horizon corresponds to the plasma saturation scale that screens long-wave length fluctuations out of the quantum wave function of the quark, which then loses the energy that those fluctuations carry into the medium. This understanding in terms of a partonic picture allowed to extend the existing gravity calculations to estimate the thermalization time of a heavy quark produced in a strongly-coupled SYM plasma [t08/223], as well as to infer the rate of energy loss of a heavy quark in a finite-length plasma. The path length dependence of the energy loss was found to be stronger in the strong-coupling regime (proportional to the third power of the path length) compared to the weak-coupling regime (proportional to the square of the path length). In the prospect of phenomenological studies, this important result has been incorporated inside a jet-quenching calculation [t09/122]. It was shown that modeling the non-perturbative physics using the length-cubed law, instead of the length-squared law as in standard calculations, improves the description of the experimental data obtained in Au+Au collisions at RHIC.

B.17.4 A lattice test of the strong coupling hypothesis *(E. Iancu)*

In Ref. [t09/172] we proposed a lattice test of the strength of the coupling in QCD at finite temperature. This consists in the lattice calculation of the expectation value of a special 'twist-two' operator which is orthogonal to the energy-momentum tensor in the sense of the renormalization group. This operator has a negative anomalous dimension, so at strong coupling its expectation value should be strongly suppressed in the continuum limit.

B.17.5 Mesons in a strongly coupled plasma *(E. Iancu)*

In Ref. [t09/339] we have studied mesons (quark-antiquark bound states) in a plasma at finite temperature and strong coupling. We have computed the corresponding spectral functions and their contribution to the absorption of a virtual photon by the plasma. Interestingly, the meson dispersion relations become *space-like* in the high momentum limit, showing that their binding energy grows as fast as the kinetic energy when increasing the meson momentum.

B.17.6 Radiation at strong coupling: the quest for string fluctuations *(E. Iancu)*

Very recently, we considered a conceptual problem which deals with the foundations of AdS/CFT, namely the importance of string fluctuations. A central assumption prevailing since the original papers by Maldacena and Witten is that string fluctuations are irrelevant in the strong coupling limit. In Refs. [t10/289, t11/118] we showed via explicit examples that this is not always the case. By working in the supergravity approximation, which ignores these fluctuations, we found that the AdS/CFT predictions for observables like the radiation by accelerated sources in the vacuum of the $\mathcal{N} = 4$ SYM theory at strong coupling are incompatible with quantum mechanics. For instance, the energy distribution produced by an accelerated heavy quark, that we have exactly computed (in the supergravity approximation) for an arbitrary quark motion [t11/118], exhibits the same space-time pattern as the corresponding classical distribution: the radiation propagates at the speed of light without quantum broadening. We have then identified a class of string fluctuations which do not decouple at strong coupling and which could restore the agreement between the results of the string theory and our general physical expectations [t10/289].

B.17.7 Viscosity of the QGP *(R. Peschanski)*

In [t07/189], we focus on challenging problems of QGP hydrodynamics, such as viscosity and thermalization, in terms of gravitational duals of both the static and relativistically evolving plasma. We show how a Black Hole geometry arises naturally from the dual properties of a nearly perfect fluid and explore the lessons and prospects one may draw for actual heavy ion collisions from the Gauge/Gravity duality approach.

B.17.8 Early time dynamics *(R. Peschanski)*

In [t09/126], we study the boost-invariant dynamics of a strongly-coupled conformal plasma in the regime of early proper-time using the AdS/CFT correspondence. It is shown, in contrast with the late-time expansion, that a scaling solution does not exist. The boundary dynamics in this regime depends on initial conditions encoded in the bulk behavior of a Fefferman-Graham metric coefficient at initial proper-time. The relation between the early-time expansion of the energy density and initial conditions in the bulk of AdS is provided. As a general result it is proven that a singularity of some metric coefficient in Fefferman-Graham frame exists at all times. Requiring that this singularity at $\tau = 0$ is a mere coordinate singularity without the curvature blow-up gives constraints on the possible boundary dynamics. Using a simple Pade resummation for solutions satisfying the regularity constraint, the features of a transition to local equilibrium, and thus to the hydrodynamical late-time regime, have been observed.

B.17.9 High energy bounds on N=4 SYM amplitudes *(R. Peschanski)*

In [t09/299], we study the high-energy behavior of colorless dipole elastic scattering amplitudes in N=4 SYM gauge theory through the Wilson loop correlator formalism and Euclidean to Minkowskian analytic continuation. The purely elastic behavior obtained at large impact-parameter L, through duality from disconnected AdS_5 minimal surfaces beyond the Gross-Ooguri transition point, is combined with unitarity and analyticity constraints in the central region. In this way we obtain an absolute bound on the high-energy behavior of the forward scattering amplitude due to the graviton interaction between minimal surfaces in the bulk. The dominant "Pomeron" intercept is bounded by alpha less than or equal to 11/7 using the AdS/CFT constraint of a weak gravitational field in the bulk. Assuming the elastic eikonal approximation in a larger impact-parameter range gives alpha between 4/3 and 11/7. The actual intercept becomes 4/3 if one assumes the elastic eikonal approximation within its maximally allowed range L larger than expY/3, where Y is the total rapidity. Subleading AdS/CFT contributions at large impact-parameter due to the other d=10 supergravity fields are obtained. A divergence in the real part of the tachyonic KK scalar is cured by analyticity but signals the need for a theoretical completion of the AdS/CFT scheme.

B.17.10 Brane cosmology *(R. Peschanski, P. Brax)*

In [t10/239], we introduce a duality relation between two distinct branes, a cosmological brane with macroscopic matter and a holographic brane with microscopic gauge fields. Using brane-world cosmology with a single brane in a 5-dimensional AdS5 background, we find an explicit time-dependent holographic correspondence between the bulk metric surrounding the cosmological brane and the N=4 gauge field theory living on the boundary of the Z2-symmetric mirror bulk, identified with the holographic brane. We then relate the cosmic acceleration on the cosmological brane to the conformal anomaly of the gauge theory on the holographic brane. This leads to a dual microscopic interpretation of the number of e-foldings of the cosmological eras on the cosmological brane.

B.17.11 Hadrons in AdS/QCD models *(C. Marquet)*

On the application of the AdS/CFT dictionary to model confining gauge theories at zero temperature, it was noticed that the additional freedom at disposal to break conformal invariance can always be used to reproduce all 2- and 3-point functions. Therefore it was investigated if 4-point functions could be reproduced as well, this was done using electromagnetic properties of hadrons. In particular the Compton scattering amplitude of a spin-less target was calculated within the popular soft-wall model [t10/005], and serious limitations have been pointed out.

B.18 Relativistic hydrodynamics

Experiments at RHIC (Brookhaven) have shown that the matter produced in a nucleus-nucleus collision behaves like a fluid. In this picture, particles are emitted independently, with some probability distribution determined by the fluid profile. This distribution is not azimuthally symmetric: one usually defines anisotropic flows, v_n, as the Fourier coefficients of this probability distribution $v_n \equiv |\langle e^{in\varphi}\rangle|$, where φ is the azimuthal angle, n is a positive integer, and angular brackets denote an average value.

B.18.1 Flow extraction methods *(J-Y. Ollitrault)*

v_n can be inferred from azimuthal correlations between outgoing particles. One difficulty is to separate correlations stemming from collective effects from other, "nonflow" correlations. In addition, the flow pattern is expected to fluctuate event by event: another difficulty is to estimate the magnitude of these flow fluctuations. In the last decade, we have developed a series of methods (the cumulant method and the Lee-Yang zeroes method) which suppress nonflow correlations and are now widely used. They were used in particular in the first analysis by the ALICE experiment at LHC [arXiv:1011.3914]. However, most analyses at RHIC used an older method, the event-plane method. This method gives results which always lie above estimates from 4-particle cumulants, and below estimates from 2-particle cumulants. We explain this difference in [t09/047] (see also [t09/084]), by calculating the sensitivity of the event-plane method to nonflow effects and flow fluctuations. We show that the result from the event-plane method is a well-defined interpolation between 2-particle and 4-particle cumulants, which does not give any independent information. In another paper [t08/020], we show that the Lee-Yang-zeroes method can be seen as a slightly modified event-plane method.

B.18.2 The four lowest harmonics *(J-Y. Ollitrault)*

In November 2010, the ALICE collaboration published the first measurement of elliptic flow (v_2), the largest flow harmonic, in Pb-Pb collisions at the LHC [arXiv:1011.3914]. A few days later, Matt Luzum showed [t10/182] that these results were compatible with his earlier prediction using viscous hydrodynamics. Shortly before the LHC started operating, several groups independently raised the possibility that elliptic flow might even be present in *proton-proton* collisions at large multiplicities. In [t10/151], we estimated the magnitude of v_2 in pp collisions using a partonic model of the proton based on QCD evolution. Our result is that azimuthal correlations from the parton evolution are likely to be larger than correlations expected from elliptic flow. We also finished an ongoing work pertaining to the interpretation of RHIC data: we showed in [t09/112] that the shear viscosity of QCD can be extracted by comparing the measured centrality dependence of v_2 with viscous hydrodynamic calculations. The uncertainty remains large, and is dominated by uncertainties on the initial density profile in the transverse plane.

Quadrangular flow, v_4, has been measured by several collaborations at RHIC, but results were poorly understood. Back in 2005, we had shown that ideal hydrodynamics predicts $v_4 = \frac{1}{2}(v_2)^2$, but data are consistently above this value. Our recent breakthrough was to recognize the importance of v_2 fluctuations [t09/152] (see also [t09/106, t09/245]), which explain most of the deviation (there is a residual unexplained discrepancy for central collisions). We have also computed v_4 for the first time using viscous hydrodynamics [t10/060]. In viscous hydrodynamics, one needs to convert the fluid into particles at the end of the calculation, and there is some arbitrariness in this procedure. We have shown that the procedure used by everyone so far fails badly for v_4 [t10/059], although it works well for v_2.

A breakthrough was made in 2010 by Alver and Roland from MIT [arXiv:1003.0194], who realized that several patterns seen in azimuthal correlations, known as *ridge* and *shoulders*, can be interpreted simply as anisotropic flow in the third harmonic, v_3. Together with Alver, we made the first quantitative prediction for v_3 using viscous hydrodynamics [t10/095], and we showed that this observable is more sensitive to viscosity than elliptic flow. Our prediction is in quantitative agreement with values inferred from STAR correlation data.

The last sizable harmonic, which is smaller than the previous three, is v_1. The possibility that initial fluctuations followed by collective flow generate a nonzero v_1 at midrapidity was first raised by Teaney and Yan [arXiv:1010.1876]. We have made a quantitative prediction for this v_1 using ideal hydrodynamics with fluctuating initial conditions [t11/039]. We had extracted v_1 from published STAR correlation data [t10/185], and these measured values are in excellent agreement with our hydrodynamic calculation. We have also proposed a specific method to analyze this v_1 more accurately (also in [t10/185]).

B.18.3 Long-range correlations *(J-Y. Ollitrault)*

Collective flow produces azimuthal correlations between particles, even if they are separated by a large rapidity gap. An important achievement of our group is the recent recognition [t10/184] that *all* the azimuthal patterns of these long range correlations can in fact be explained by collective flow, provided all four harmonics are taken into account. We have proposed new flow observables which can be constructed by correlating up to five particles in the first three Fourier harmonics, and made quantitative prediction for these observables [t11/110].

B.18.4 HBT interferometry *(J-Y. Ollitrault)*

In [t09/018] (see also [t09/099]), we have studied another class of observables, namely, Bose-Einstein correlations between identical pions. These correlations are usually said to be sensitive probes of thermalization and flow. There was, however, a longstanding discrepancy between hydrodynamics and experimental data from RHIC known as the "HBT puzzle". We have calculated these correlations using a relativistic Boltzmann equation in which one can tune the mean free path and vary the degree of thermalization. We found that for realistic values of the mean free path, most of the HBT puzzle is automatically solved. Similar findings were reported independently by Pratt [arXiv:0811.3363] and other groups.

B.18.5 Exact solutions *(R. Peschanski)*

In [t07/100], we have proposed a generalization of the Bjorken in-out Ansatz for fluid trajectories which, when applied to the (1+1)-dimensional hydrodynamic equations, generates a one-parameter family of analytic solutions interpolating between the boost-invariant Bjorken picture and the non boost-invariant one by Landau. This parameter characterizes the proper-time scale when the fluid velocities approach the in-out Ansatz.

In [t08/144], using the formalism of the Khalatnikov potential, we have derived exact general formulae for the entropy flow dS/dy, where y is the rapidity, as a function of temperature for the (1+1)-d relativistic hydrodynamics of a perfect fluid. We studied in particular flows dominated by a sufficiently long hydrodynamic evolution, and provided an explicit analytical solution for dS/dy.

In [t10/033], looking for the underlying hydrodynamic mechanisms determining the elliptic flow, we have showed that for an expanding relativistic perfect fluid the transverse flow may derive from a solvable hydrodynamic potential, provided that the entropy is transversally conserved and the corresponding expansion "quasi-stationary". Exact solutions for the velocity flow coefficient v_2 and the temperature dependence of the spatial and momentum anisotropy were obtained and were shown to be in agreement with the elliptic flow features of heavy-ion collisions.

In [t10/210], we have presented a general solution of relativistic (1+1)-dimensional hydrodynamics for a perfect fluid flowing along the longitudinal direction as a function of time, uniformly in transverse space. The Khalatnikov potential is expressed as a linear combination of two generating functions with polynomial coefficients of 2 variables. These polynomials define an infinite-dimensional basis of solutions. The kinematics of the (1+1)-dimensional flow can be reconstructed from the potential.

In [t10/242], the possibility that particle production in high-energy collisions is a result of two asymmetric hydrodynamic flows is investigated, using the Khalatnikov form of the (1+1)-dimensional approximation of hydrodynamic equations. The general solution is discussed and applied to the physically appealing "generalized in-out cascade" where the space-time and energy-momentum rapidities are equal at initial temperature but boost-invariance is not imposed. It is demonstrated that the two-bump structure of the entropy density, characteristic of the asymmetric input, changes easily into a single broad maximum compatible with data on particle production in symmetric processes. A possible microscopic QCD interpretation of asymmetric hydrodynamics was proposed.

B.19 QFT at finite temperature

B.19.1 Heavy quarks in a quark-gluon plasma *(J.-P. Blaizot)*

Real and imaginary-time $Q\overline{Q}$ correlators

In [t07/213], we investigate the behavior of a pair of heavy fermions, denoted by Q and $\bar{Q}$, in a hot/dense medium. Although we have in mind the situation where Q and $\bar{Q}$ denote heavy quarks, our treatment will be limited to simplified models, which bear only some general similarities with QCD. We study in particular the limiting case where the mass of the heavy fermions is infinite. Then a number of results can be derived exactly: a Schrodinger equation can be established for the correlator of the heavy quarks; the interaction effects exponentiate, leading to a simple instantaneous effective potential for this Schrodinger equation. We consider simple models for the medium in which the $Q\bar{Q}$ pair propagates. In the case where the medium is a plasma of photons and light charged fermions, an imaginary part develops in this effective potential. We discuss the physical interpretation of this imaginary part in terms of the collisions between the heavy particles and the light fermions of the medium; the same collisions also determine the damping rate of the heavy fermions. Finally we study the connection between the real-time propagator of the heavy fermion pair and its Euclidean counterpart, and show that the real part of the potential entering the Schrodinger equation for the real-time propagator is the free energy calculated in the imaginary-time formalism.

A path integral for heavy quarks in a hot plasma

In [t10/295], we propose a model for the propagation of a heavy-quark in a hot plasma, to be viewed as a first step towards a full description of the dynamics of heavy quark systems in a quark-gluon plasma, including bound state formation. The heavy quark is treated as a non relativistic particle interacting with a fluctuating field, whose correlator is determined by a hard thermal loop approximation. This approximation, which concerns only the medium in which the heavy quark propagates, is the only one that is made, and it can be improved. The dynamics of the heavy quark is given exactly by a quantum mechanical path integral that is calculated in this paper in the Euclidean space-time using numerical Monte Carlo techniques. The spectral function of the heavy quark in the medium is then reconstructed using a Maximum Entropy Method. The path integral is also evaluated exactly in the case where the mass of the heavy quark is infinite; one then recovers known results concerning the complex optical potential that controls the long time behavior of the heavy quark. The heavy quark correlator and its spectral function are also calculated semi-analytically at the one-loop order, which allows for a detailed description of the coupling between the heavy quark and the plasma collective modes.

B.19.2 Exact renormalization group *(J.-P. Blaizot)*

Solutions of renormalization group flow equations with full momentum dependence

In [t09/257], we demonstrate the power of a recently-proposed approximation scheme for the non-perturbative renormalization group that gives access to correlation functions over their full momentum range. We solve numerically the leading-order flow equations obtained within this scheme, and compute the two-point functions of the O(N) theories at criticality, in two and three dimensions. Excellent results are obtained for both universal and non-universal quantities at modest numerical cost.

Exact renormalization group and Φ-derivable approximations

In [t10/292], we show that the so-called Φ-derivable approximations can be combined with the exact renormalization group to provide efficient non-perturbative approximation schemes. On the one hand, the Φ-derivable approximations allow for a simple truncation of the infinite hierarchy of the renormalization group flow equations. On the other hand, the flow equations turn the non linear equations that derive from the Φ-derivable approximations into an initial value problem, offering new practical ways to solve these equations.

Pressure of a hot scalar theory within the non-perturbative renormalization group

In [t10/294], we apply to the calculation of the pressure of a hot scalar field theory a method that has been recently developed to solve the Non-Perturbative Renormalization Group. This method yields an accurate determination of the momentum dependence of n-point functions over the entire momentum range, from the low momentum, possibly critical, region up to the perturbative, high momentum region. It has therefore the potential to account well for the contributions of modes of all wavelengths to the thermodynamical functions, as well as for the effects of the mixing of quasiparticles with multi-particle states. We compare the thermodynamical functions obtained with this method to those of the so-called Local Potential Approximation, and we find extremely small corrections. This result points to the robustness of the quasiparticle picture in this system. It also demonstrates the stability of the overall approximation scheme, and this up to the largest values of the coupling constant that can be used in a scalar theory in 3+1 dimensions. This is in sharp contrast to perturbation theory which shows no sign of convergence, up to the highest orders that have been recently calculated.

B.19.3 Random matrices *(J.-P. Blaizot)*

Large N_c confinement and turbulence

In [t08/260], we suggest that the transition that occurs at large N_c in the eigenvalue distribution of a Wilson loop may have a turbulent origin. We arrived at this conclusion by studying the complex-valued inviscid Burgers-Hopf equation that corresponds to the Makeenko-Migdal loop equation, and we demonstrate the appearance of a shock in the spectral flow of the Wilson loop eigenvalues. This picture supplements that of the Durhuus-Olesen transition with a particular realization of disorder. The critical behavior at the formation of the shock allows us to infer exponents that have been measured recently in lattice simulations by Narayanan and Neuberger in d=2 and d=3. Our analysis leads us to speculate that the universal behavior observed in these lattice simulations might be a generic feature of confinement, also in d=4 Yang-Mills theory.

Universal shocks in random matrix theory

In [t09/259], we link the appearance of universal kernels in random matrix ensembles to the phenomenon of shock formation in some fluid dynamical equations. Such equations are derived from Dyson's random walks after a proper rescaling of the time. In the case of the Gaussian Unitary Ensemble, on which we focus in this letter, we show that the orthogonal polynomials, and their Cauchy transforms, evolve according to a viscid Burgers equation with an effective "spectral viscosity" $\nu_s = 1/2N$, where N is the size of the matrices. We relate the edge of the spectrum of eigenvalues to the shock that naturally appears in the Burgers equation for appropriate initial conditions, thereby obtaining a new perspective on universality.

B.19.4 Lattice QCD *(R. Lacaze, A. Morel)*

Eigenvalues and eigenvectors of the staggered Dirac operator

In [t08/052], we examine the eigenvalues and eigenvectors of the staggered Dirac operator on thermal ensembles created in QCD at finite temperature with two flavours of dynamical staggered quarks. We make a numerical analysis of the cumulative distribution of eigenvalues. In particular we see that across the phase transition a gap opens in the spectrum, with a clear crossover from low to high temperature behaviour evidenced by an increase in the lowest eigenvalue by three order of magnitude in the neighbourhood of T_c. To obtain additional insight on the gap formation, we analyse the localization properties of the eigenvectors using the inverse participation ratio (IPR) and the localization function. For finite volume lattices in the low-temperature phase the eigenvectors are extended, but generic field configurations in the high temperature phase give rise to localized eigenstates. We examine measures of the stability of such localization and find that at finite volumes localization occurs through Mott's mechanism of the formation of mobility edges. However, the band gap between the localized and extended states seem to scale to zero in the limit of large volume.

Screening correlators with chiral fermions

In [t08/053], we study screening correlators of quark-antiquark composites at $T = 2T_c$, where T_c is the QCD phase transition temperature, using overlap quarks in the quenched approximation of lattice QCD. As the lattice spacing is changed from $1/4T$ to $a = 1/6T$ and $1/8T$, we find that screening correlators change little, in contrast with the situation for other types of lattice fermions. All correlators are close to the ideal gas prediction at small separations. The long distance falloff is clearly exponential, showing that a parametrization by a single screening length is possible at distances $z \geq 1/T$. The correlator corresponding to the thermal vector is close to the ideal gas value at all distances, whereas that for the thermal scalar deviates at large distances. This is examined through the screening lengths and momentum space correlators. There is strong evidence that the screening transfer matrix does not have reflection positivity.

Three dimensional finite temperature SU(3) gauge theory

Three-dimensional $SU(3)$ gauge theory shares with QCD the existence of a transition between a low temperature sector where the gauge degrees of freedom are confined inside glueballs, and, above a critical temperature T_c, a phase where they behave as interacting fields asymptotically free at large distances. This non perturbative phenomenon is a consequence of the IR singularities of the perturbative expansion, in which fermionic matter fields do not participate. Lattice simulations of $SU(3)$ gauge theory in 3 dimensions without quarks have been performed. Compared with QCD, the effect of the IR (UV) singularities is even stronger (weaker) and the computational effort much lighter, while the lessons drawn should be relevant to the realistic situation. In the large T/T_c region, the pressure P and the energy and entropy densities of the gluon plasma have been measured for various lattice sizes and $T/T_c < 15$ [t08/214]. The extrapolation to $T/T_c = \infty$ of P/T^3 for the largest lattices is close to the Stefan-Boltzmann law. For the same model, the correlation length between Polyakov loops have been measured inside the confined phase and compared with the prediction of the bosonic string model [t09/280]. Good agreement is found for $T/T_c < 0.7$, As the critical temperature is approached, the two values are not expected to agree anymore since the two models belong to different universality classes. More precise estimates of the correlation length close to T_c are in progress.

B.19.5 Boundary effective theory *(F. Gelis)*

Calculations at finite temperature that involve large field amplitudes become non perturbative, even if the coupling constant is small. In [t09/167], we have proposed a new way of reorganizing the perturbative expansion, dubbed the "Boundary Effective Theory" (BET), that is better behaved in these circumstances because its building blocks are classical fields. In [t11/137], we have used the BET in order to compute the effective potential in a scalar field theory at finite temperature. In this paper, we have shown that this effective theory leads to an effective potential that smoothly interpolates between the well-known 1-loop result for small fields and a result at large field that deviates significantly from the classical action (due to large non-linear corrections).

B.20 Cold baryonic matter at high density and compact stars *(M. Rho)*

Baryonic matter at high density is a very poorly understood strongly correlated system relevant to compact stars stable against gravitational collapse. It cannot be accessed by lattice QCD because of the sign problem, there are no established model-independent theoretical tools, and at present no useful experimental data are available. We address this problem relying on the following three strategies [t10/017]: (i) hidden local symmetry, (ii) large N_c and (iii) topology. Hidden local symmetry can be considered – bottom-up – as emergent from current algebras or as reduced – top-down – from string theory via holography. In both cases, topology figures in the structure of baryons as solitons, i.e., skyrmions or instantons, in large N_c effective Lagrangians. We present a variety of predictions obtained in the approach that can impact on the QCD phase structure, with hitherto unanticipated features of nuclear forces and nuclear structure at high density, and on the equation of state (EoS) for compact stars.

B.20.1 Half-skyrmion matter

It has been discovered that when solitons constructed from hidden local symmetry Lagrangian valid at large N_c, gauge-equivalent to nonlinear sigma model extended to the scale corresponding to the vector-meson mass, are put on an FCC crystal lattice so as to simulate dense baryonic matter, there is a phase transition from a skyrmion matter in FCC to a half-skyrmion matter in CC at a density above that of nuclear matter. This half-skyrmion matter is characterized by vanishing quark condensate ($\langle\bar{q}q\rangle = 0$) but non-zero pion decay constant. As such, it is not a chiral-symmetry restored state. It resembles the deconfined quantum critical phase in condensed matter in which half-skyrmions become relevant degrees of freedom. There are no well-defined order parameters here, so the process does not belong to the familiar Ginzburg-Landau-Wilson paradigm. This phase gives several novel predictions [t09/242] such as strong binding of anti-kaons in nuclear matter, possibly leading to the formation of dense kaonic nuclei and precocious kaon condensation in neutron-star matter. It also predicts a drastic modification in nuclear tensor forces which will surely affect the nuclear symmetry energy at a high density relevant to compact stars [t10/068]. These features could be tested at FAIR and JPARC.

B.20.2 Dilatons and the repulsive core

Implementing the trace anomaly of QCD to hidden local symmetric theories requires the presence of dilatons associated with broken conformal symmetry of QCD. Such a theory that combines hidden local symmetry and broken conformal symmetry was constructed in [t08/010, t09/023]. Driving the matter described by such a Lagrangian to chiral restoration at high density can be effectuated by what is called "dilaton limit (DL)" that leads to Weinberg's mended symmetry. It was found [t11/026] that as one approaches the DL, the vector mesons ρ and ω decouple from the baryons. As a consequence, the famous hard-core repulsion present at short internuclear distances – confirmed in lattice QCD in matter-free space – gets suppressed at high density, a prediction which has not yet been made in the literature. Furthermore, the nuclear symmetry energy which is proportional to the square of the ρNN coupling will also get suppressed. This mechanism was suggested as a means to understand the recently discovered 1.97 solar-mass star – the largest so far measured with certainty – PSRJ1614-2230.

B.20.3 Holographic dual QCD

The recent development on gravity-gauge duality has led to a low-energy effective theory that is built with an infinite tower of hidden local gauge fields. The holographic dual model that is closest to QCD is the Sakai-Sugimoto D4/D8-$\overline{\text{D8}}$ brane model. This model does not, however, have the ultraviolet completion corresponding to QCD, so is unlikely to work at very short distances, but it gives a fairly good description of those meson properties that can be well approximated by large N_c or, in the lattice language, in the quenched approximation. In [t07/017, t07/064], baryons that correspond to Witten's baryon vertex were constructed in terms of the instantons of the 5D YM action of Sakai and Sugimoto, and the effective action comprised of baryons and mesons in 5D so constructed was found to be in surprisingly good agreement with data, in fact better than the previous skyrmion model.

One of the most notable results of this description is that the vector (ρ,ω) dominance in hadron interactions, first proposed in 1960's by Sakurai, which has worked very well in the meson sector but failed badly in the baryonic sector, is recovered for *both* mesons *and* baryons in terms of the infinite tower of 4D vector mesons [t07/140]. It has been shown that the infinite-tower structure can be captured in the nucleon form factors by a simple formula with two parameters determined in the meson sector of the Sakai-Sugimoto model, giving a surprisingly good agreement with experimental form factors [t11/025]. Together with other developments involving many-nucleon systems, this indicates a very important role that is played by the infinite tower inherited from the bulk gravity sector.

In [t09/176], instanton baryons were put on an FCC crystal lattice in a way analogous to skyrmions to describe dense baryonic matter. Thanks to the infinite tower structure of HLS fields, this approach comes out to be a lot more powerful than the skyrmion approach. It was found that the instantons in FCC crystal fractionize at a density close to the half-skyrmion density into half-instantons in BCC, in the form of dyons in a salt configuration. This lends support to the half-skyrmion structure with the vanishing quark condensate discovered previously.

Describing dense hadronic matter in holographic QCD without exploiting crystal structure that agrees with nature turns out to be extremely difficult. Identifying the $U(1)$ RN charge in the bulk with baryonic density of the boundary sector – which is often done by string theorists – gives a result that is totally at odds with nature. An alternative model with a D4/D6 structure with a compact D6 baryon vertex was tried [t11/141] but it also failed.

B.20.4 Neutron stars and black holes

The possibility of kaon condensation in compact-star matter [t07/139] has implications on black-hole formations and hugely enhanced entropy in the Universe. This aspect was discussed in light of a possible connection to the "cosmological natural selection" [t08/037].

The recent discovery of the 1.97 solar-mass object PSRJ1614-2230 was claimed to "rule out" the possible softening associated with kaon condensation invoked for black-hole formation. It was shown in [t11/024] that this claim is unfounded, that it is possible to have a three-layer compact-star structure consisting of nucleon matter, kaon condensed matter and quark matter that can accommodate $\sim 2M_\odot$ stars with a radius $\sim$ 10 km and a central density of $\sim$ 10 times the nuclear matter density, all consistent with the observation.

B.21 Theoretical nuclear physics *(B. Giraud)*

B.21.1 Theory of fusion and fission

Our work in this area is about practical questions, such as the irradiation of thick materials, the synthesis of super-heavy elements by fusion of heavy ions, the use of the complex scaling method to predict resonances [t10/084, t09/090, t08/154, t08/095].

B.21.2 Theory of density functionals

This part of our activities deal with more formal mathematical methods, for a rigorous foundation of the nuclear density functional theory, including the important role played by nuclear symmetries and the necessary influence of concavity upon calculations of masses, densities and energy surfaces [t07/172, t08/014, t07/171, t10/057, t09/091, t09/207, t09/206, t07/174, t07/173].

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CHAPTER C

Statistical physics and condensed matter

Introduction

The *Statistical Mechanics and Condensed Matter Theory* group has a large spectrum of activities, which are presented hereafter in three parts: *Classical Statistical Physics, Condensed Matter Physics, and BioPhysics.* The first part is concerned with classical systems, where quantum effects play no role (e.g. glass physics); the second part is devoted to quantum systems : bulk condensed matter physics (e.g. spin liquids, high-temperature superconductors or heavy fermions) and mesoscopic physics (e.g. graphene, quantum impurities); finally, the last part is devoted to the interface between physics and biology.

In this introduction, we first present a very brief summary of the various activities, which are detailed in the following subsections. This section is clearly non-exhaustive and should only be used a guide for the reader of this chapter.

Statistical physics

Out of equilibrium systems are at the core of the research on classical statistical mechanics at IPhT. Indeed, while the conceptual framework for the theory of *equilibrium* systems is quite well-established in statistical mechanics (with e.g. the notion of statistical ensembles, thermodynamics, free energy), it has no equivalent for *non-equilibrium systems.* As a result, even simple questions remain unanswered, e.g. how to characterize forced steady states far from equilibrium (and far from linear response regime) and compute their physical properties ? How to generalize the notion of entropy or free energy in these regimes ? How to characterize the glass transition and its slow dynamics ?

In the recent years, new fluctuations theorems and relations like Jarzynski's equality have started to address these issues and some works have been devoted to this direction (section C.1). A complementary direction of research strongly developed at IPhT consists in studying exactly solvable models of out-of-equilibrium phenomena, in order to explore these fundamental issues in concrete and solvable cases.

Hopefully, these models will play an analogous role to the Ising model in the elaboration of the theory of equilibrium phase transitions. For example, results have been obtained in reaction-diffusion models, on the asymmetric simple exclusion process model (ASEP), on the ABC model, or in "directed Ising" models, which are Ising models with a non conserved dynamics (section C.2).

Various aspects of stochastic processes have been studied, including the study of the statistics of excursions (i.e. the intervals between consecutive zeros), of several stochastic processes, the maximal entropy random walk on an arbitrary graph, and new applications of stochastic Markov process to sample systems with complex energy landscapes in Monte Carlo methods (section C.3).

In glasses, spin glasses, granular systems and some other disordered systems, the relaxation times towards equilibrium becomes so large below some critical temperature that the systems never reach equilibrium and exhibits genuinely non-equilibrium phenomena, like aging. Several fundamental questions are raised with the experiments of various glassy systems: How to characterize the glass transition? What is the order parameter? Understanding these issues is an important activity in the Institute.

In the field of glasses, for the first time, a qualitative thermodynamic difference between the high temperature and deeply supercooled equilibrium glass forming liquid has been explicitly shown, leading to a renewed discussion of the random first order theory, and several other approaches, like "mode coupling theory". Again, these general ideas and methods are carefully tested in several minimal solvable models, like the spiral model or kinetically constrained models, which have been studied with a combination of mathematical and numerical approaches (section C.4). Granular media and jamming is a related subject, studied in a fruitful collaboration with experimentalists of the neighbouring laboratory, the "Service de l'Etat Condensé" (SPEC), (Cf section C.5).

Understanding the nature of the spin glass phases and of the transition from the high temperature disordered phase has long been a very active subject at the IPhT. Several new results have been obtained during the period of the report, e.g. on the nature of the spin glass phase in low dimensions, on the distribution of relaxation time in the Sherrington-Kirkpatrick model, on large random correlations in individual mean field sample, on the existence of a static spin glass phase on soft scalar spin version of the random field Ising model (section C.6). Besides, phase transition and non-equilibrium dynamics of disordered systems in the presence of frozen disorder have also been studied using renormalization techniques (section C.7).

Finally, the tools and methods elaborated to study statistical physics systems also have important applications to other fields in soft condensed matter physics. The activity of IPhT has strongly expanded in two of these directions with the recent hirings of two permanent researchers. The first direction is concerned with (hard) optimization problem, like e.g. the boolean satisfiability problem (section C.8). The second direction is the study of various networks, their structure, their evolution, and more recently their spatial aspects. Networks are fundamental in theoretical epidemiology where transportation and mobility networks are the key ingredient in the spread of infectious diseases. The problem is then to understand the coupling between the movement of individuals and the spread of the disease, both processes having their own spatial and temporal scales. In geography and urbanism, networks are also a key ingredient in understanding the structure and the evolution of cities (section C.9).

Condensed matter physics

In strongly correlated quantum systems, the effect of the interactions between the electrons or the atoms deeply challenge the standard paradigms of theoretical condensed matter physics. Standard concepts and methods, such as Fermi liquid theory, Density Functional Theory (band theory), or Landau's symmetry breaking view on phase transitions fail to account for a large number of remarkable phenomena observed in experiments and due to collective behaviors of fermions (or bosons). The fractional quantum hall effect, or the high-temperature superconductivity are two famous and spectacular examples but many other important experimental discoveries had a major impact : metal-insulator transitions, zero-temperature continuous phase transitions in metals and magnets, breakdown of the Fermi-liquid behavior in cuprates and in heavy fermions compounds, exotic orders (charge, spin, orbital) in transition metal oxides, interaction and quantum effects in low-dimensional geometries (artificially structured nanoscale materials: dots, wires, graphene).

The research activity in condensed matter at the IPhT aims at understanding the basic mechanisms involved in new states of matter, new phase transitions, or, more generally, new phenomena that have been (or which could be) observed in real systems. While the study of strongly correlated *materials* (bulk condensed matter systems) remain the main activity at the IPhT condensed matter theory group, new subjects are slowly developing (e.g. graphene, effect of interaction in mesoscopic physics, ultra-cold atoms).

Heavy fermions compounds continue to challenge the theorists with their non-Fermi liquid regime, or their quantum phase transitions. For example, the heavy fermion compound URu_2Si_2 and its mysterious "Hidden Order" phase, has received a renewed attention recently with new experiments. A new "modulated spin liquid" theory has recently been proposed for it, in the context of a selective Mott picture of this class of compounds (section C.10). Besides, recent experiments on ^3He bi-layers made in the Saunders' group in London mimic the heavy fermions physics, with one localized layer (playing the role of the localized f electrons) and one delocalized one (playing the role of conduction electrons). These experiments have therefore been studied with similar theoretical tools (section C.10).

High temperature superconductivity remains a central mystery of strongly correlated physics, in spite of the large body of available experimental data, including several new recent experiments. Besides, the discovery of a new family of iron-based superconductors (the pnictides) in 2008 has driven an intense experimental and theoretical activity. Both of these compounds have been studied at IPhT (section C.11). For the normal phase of the cuprates, a new picture of a selective Mott transition in momentum space in the Brillouin zone was proposed based on a series of approximate solutions of microscopic models using cluster dynamical mean field methods. Roughly speaking, the nodal regions remain metallic while the antinodal ones become insulating, in agreement with the phenomenology. Besides, using the first implementation of dynamical mean field theory methods within FLAPW electronic structure methods, the degree of correlation of one iron-based superconductor, which was the subject of strong debates, was investigated.

Frustrated spin systems and dimer models have also been studied at IPhT (section

C.12). They are typically toy models for various materials, e.g. some insulators or the normal phase of high-temperature superconductors in the RVB point of view. They can exhibit non-standard phases, like e.g. spin liquids, dimer phase.

The study of interaction effects in ultra-cold atomic gases of bosons and fermions has been an emerging field in the recent years, at the frontier of quantum optics and condensed matter physics. These experiments have raised hope to understand fundamental issues of strongly correlated systems by creating artificial solids with ultra-cold atoms embedded in optical lattices, in spite of their current severe limitation in temperature (they are actually very hot). In the recent years, the IPhT has had some activity in this emerging field (section C.13): polarized superfluids of the Sarma type were shown to be stable at high enough interaction; a detailed discussion of the recent experimental realization of fermionic Mott transition in ultra-cold gases, in the ETH group in Zürich, including detailed comparison with ab-initio microscopic computation was provided.

Motivated by the new ultra-cold atom and mesoscopic experiments, the out-of-equilibrium dynamics of quantum open or closed systems have been a subject of renewed interest. Several works have been devoted to this issue (cf section C.16).

Mesoscopic systems and nanosystems constitute another direction of research at IPhT. Quantum impurity models, out of equilibrium transport and various aspects of nanotubes have been studied (section C.18). Graphene has received a lot of attention recently, due e.g. to the Dirac character of its low-energy excitations. Still, many important questions concerning the effects of disorder, of the substrate and of interactions remain unanswered. Several works have been devoted to these questions by C. Bena (regular visitor from Orsay), using the spatial variations of local density of states in order to establish both the nature of disorder in graphene, to retrieve information about the chirality of the quasiparticles and the form of the quasiparticle wavefunction; some of these predictions have been confirmed by recent scanning tunneling microscopy experiments.

Various aspects of the Anderson localisation problem have been studied (section C.19), including in the many-body case using e.g. exact renormalization methods.

Finally, most of the condensed matter systems studied at IPhT are in strong correlation regime, in which perturbative or conventional mean-field calculations are well known to be inappropriate. More elaborate theoretical tools or ideas need to be employed or developed to tackle these problems: (conformal) field theory, renormalization group, new approximation technique or innovative algorithms. At IPhT, a strong effort is devoted to these methodological developments. For example, a new bosonization technique in dimension greater than one was proposed (cf section C.20), which may also provide a new perspective on the (in)famous sign problem of Quantum Monte Carlo algorithms; an efficient algorithm for solving multiple quantum impurity models and (cluster) dynamical mean field methods has been developed and is now routinely used in several groups worldwide (cf section C.11); quantum entanglement properties have been studied in various systems (section C.17), inspiring new ways to probe the nature of the many-body wave functions of critical one-dimensional systems, e.g. spin chains; some connection with 2d quantum systems have also be explored (section C.17); the use of integrability to compute physical quantities (e.g. current) in out-of-equilibrium steady states has been carefully investigated in some model systems (cf section C.18).

Biophysics

Soft Condensed Matter, Biological Systems and Interdisciplinary Physics is slowly developing at IPhT. The group has enlarged its spectrum beyond that of biopolymers and electrostatics in biological systems to include molecular motors, epidemiology, spatial networks, etc. In addition, the group has started to deal with questions of direct interest to real biological systems and is providing WebServers for protein structure alignment and for RNA pseudoknot predictions.

Biophysics as it is done at the IPhT, is at the crossroads of Soft Condensed Matter theory , Disordered Systems and non-equilibrium Statistical Physics.

Soft Matter theory enters biophysics through polymer theory, in the study of biopolymers, their melting transitions, their response to external forces, etc. , and through Coulombic systems, in the study of the solvation of proteins, of the water and ions distribution, etc.

Biopolymers such as DNA, RNA and proteins, have a chemical sequence dependence which can be modeled, to a first approximation, as a quenched random sequence. In addition to the melting transition, random RNA undergoes a freezing transition, of the same type as those studied in Disordered Systems.

Finally, molecular motors, the dynamics of actin filaments, and also the kinetics of protein folding all involve the use of methods and concepts of non-equilibrium Statistical Physics.

One of the main characteristics of this group is the utilization of the most sophisticated techniques of statistical physics, such as field theory, matrix field theory, path integrals, the Bethe Ansatz, stochastic equations, etc.. In addition to these sophisticated analytic works, elaborate numerical calculations are also performed in order to determine folding pathways of proteins or to predict RNA secondary structures.

Finally, two WebServers have been set up. One, entitled Mistral, allows multiple structure alignment of protein structures. By aligning protein structures, one can look for structurally conserved motifs in proteins, and this in turn can be used to determine the function of proteins or their evolution. The other server, TT2NE, predicts secondary structures of RNA with pseudoknots, from their chemical sequence. This is an important information, since loops and pseudoknots are known to embed the binding sites of RNA.

C.1 Fluctuation theorems and related identities

C.1.1 Fluctuation theorems and work identities *(K. Mallick)*

During the last decade, many exact relations for non-equilibrium processes have been derived. The Jarzynski equality is one of these remarkable results. This relation implies that the statistical properties of the work performed on a system in contact with a heat reservoir at constant temperature during a *non-equilibrium* process are related to the free energy difference between two *equilibrium* states of that system.

In [t10/217], we study non-equilibrium work relations for a space-dependent field with stochastic dynamics (Model A). Jarzynski's equality is obtained through symmetries of the dynamical action in the path integral representation. We derive a set of exact identities that generalize the fluctuation-dissipation relations to non-stationary and far-from-equilibrium situations and argue that these identities are prone to experimental verification. Furthermore, we show that a well-studied invariance of the Langevin equation under supersymmetry, which is known to be broken when the external potential is time-dependent, can be partially restored by adding to the action a term which is precisely Jarzynski's work. The work identities can then be retrieved as consequences of the associated Ward-Takahashi identities.

In [t11/012], we prove a generalized fluctuation-dissipation relation that is valid for a system perturbed in the vicinity of a non-equilibrium steady-state and obeying a discrete Markov dynamics. We derive this relation using a generalized form of the Sasa relation (which is an extension of Jarzynski's identity to non-equilibrium states) that we derive by studying the time-reversed Markov chain. We explain how this generalized fluctuation-dissipation relation can be understood in terms of trajectory entropy excess. The results are illustrated on a simple pedagogical example of a molecular motor.

In [t09/255], we derive Fluctuation Relations for quantum Markovian dynamical systems. Many works on quantum fluctuation relations, including the pioneering ones, consider only closed systems (i.e. unitary evolution) prepared in a Gibbs state and isolated from their environment during their evolution which is thus unitary. In our work, we use the Lindblad master equation which is an effective model for a non-equilibrium open quantum system, widely used in Quantum Optics. The Lindbladian evolution is a non-unitary dynamics for the density matrix of the open system. By investigating the general properties of the Lindblad equation under time-reversal, we prove a quantum analog of Jarzynski's relation. Besides, we show that, in the vicinity of a quantum non-equilibrium steady state, this identity implies a generalized quantum fluctuation-dissipation theorem. Then, we prove a generic relation amongst correlation functions, a kind of book-keeping formula which yields the quantum analog of Crooks' relations. In the special case of conservative Hamiltonian dynamics (closed system), the relations we obtain are identical to previously known quantum work theorems. In particular, we show that for a closed system, the generalized fluctuation-dissipation theorem reduces to the celebrated Callen-Welton-Kubo formula.

Recent developments in Non-Equilibrium Statistical Mechanics with emphasis on the work identities and on the Gallavotti-Cohen symmetry in Markovian systems were reviewed in [t09/322]. A series of lectures on this topic was also given at the IPhT, in May-June 2009. The lecture notes are available at [t09/249].

C.1.2 Maximization of the Shannon entropy of dynamical trajectories *(C. Monthus)*

In [t11/050], we discuss the simplest generalization of statistical physics to non-equilibrium steady states: the principle is to maximize the Shannon entropy associated with the probability distribution of dynamical trajectories in the presence of constraints, including the macroscopic current of interest, via the method of Lagrange multipliers. This approach yields Gibbs distribution for dynamical trajectories, and the Gallavotti-Cohen symmetry is automatically satisfied.

C.1.3 A meaningful expansion around detailed balance *(B. Wynants)*

In [t11/042], we consider Markovian dynamics modeling open mesoscopic systems which are driven away from detailed balance by a nonconservative force. A systematic expansion is obtained of the stationary distribution around an equilibrium reference, in orders of the nonequilibrium forcing. The first order around equilibrium has been known since the work of McLennan (1959), and involves the transient irreversible entropy flux. The expansion generalizes the McLennan formula to higher orders, complementing the entropy flux with the dynamical activity. In that way nonlinear response around equilibrium can be meaningfully discussed in terms of two main quantities only, the entropy flux and the dynamical activity. The expansion makes mathematical sense as shown in the simplest cases from exponential ergodicity.

C.1.4 The modified Sutherland–Einstein relation for diffusive nonequilibria *(B. Wynants)*

There remains a useful relation between diffusion and mobility for a Langevin particle in a periodic medium subject to nonconservative forces. The usual fluctuation-dissipation relation easily gets modified and the mobility matrix is no longer proportional to the diffusion matrix, with a correction term depending explicitly on the (nonequilibrium) forces. In [t11/043], we discuss this correction by considering various simple examples and we visualize the various dependencies on the applied forcing and on the time by means of simulations. For example, in all cases the diffusion depends on the external forcing more strongly than does the mobility. We also give an explicit decomposition of the symmetrized mobility matrix as the difference between two positive matrices, one involving the diffusion matrix, the other force–force correlations.

C.1.5 Monotone return to steady nonequilibrium *(B. Wynants)*

In [t11/154], we propose and analyze a new candidate Lyapunov function for relaxation towards general nonequilibrium steady states. The proposed functional is obtained from the large time asymptotics of time-symmetric fluctuations. For driven Markov jump or diffusion processes it measures an excess in dynamical activity rates. We present numerical evidence and we report on a rigorous argument for its monotonous time-dependence close to the steady nonequilibrium or in general after a long enough time. This is in contrast with the behavior of approximate Lyapunov functions based on entropy production that when driven far from equilibrium often keep exhibiting temporal oscillations even close to stationarity.

C.2 Exactly solvable models out of equilibrium

C.2.1 Some exactly solvable models out of equilibrium *(K. Mallick)*

Statistical physics of systems far from equilibrium does not have yet definite theoretical foundations. Universal properties of non-equilibrium statistical physics are successfully explored through the investigation of stochastic processes, that are governed by simple dynamical rules at the microscopic level but that display a rich macroscopic behavior.

The ballistic aggregation model is one of the simplest interacting particles processes of non-equilibrium statistical mechanics and as such has attracted a lot of attention in the past decades. It represents a sticky gas of N particles with random initial positions and velocities, moving deterministically, and forming aggregates when they collide. In [t08/209], we investigate the long time behavior of the one-dimensional ballistic aggregation model and obtain a closed formula for the stationary measure of the system. In particular, we identify universal properties which are independent of the initial position and velocity distributions of the particles, study cluster distributions and derive exact results for extreme value statistics (because of correlations these distributions do not belong to the Gumbel-Fréchet-Weibull universality classes). This model generates dynamically many different scales and can be viewed as one of the simplest exactly solvable model of N-body dissipative dynamics

In [t09/157], we consider a non-equilibrium reaction-diffusion model on a finite one dimensional lattice with bulk and boundary dynamics inspired by Glauber dynamics of the Ising model. We show that the model has a rich algebraic structure that we use to calculate its properties. In particular, we show that the Markov dynamics for a system of a given size can be embedded in the dynamics of systems of higher sizes. This remark leads us to devise a technique we call the *transfer matrix Ansatz* that allows us to determine the steady state distribution and correlation functions. Furthermore, we show that the disorder variables satisfy very simple properties and we give a conjecture for the characteristic polynomial of Markov matrices. Lastly, we compare the transfer matrix Ansatz used here with the matrix product representation of the steady state of one-dimensional stochastic models. In [t09/252], we prove that the transfer matrix Ansatz method also applies to the simple exclusion process with open boundaries.

In the field of non-equilibrium statistical mechanics, the Asymmetric Simple Exclusion Process (ASEP) has reached the status of a paradigm. The ASEP is a discrete lattice-gas model of interacting particles in which particles hop while satisfy an exclusion constraint. A natural generalization of the ASEP is to consider models with different types (or colors) of particles. Such systems, called multispecies asymmetric exclusion process, arise naturally in the studies of shocks or by applying the coupling technique in probability theory. The description of the steady-state of such models was a long-standing open problem that we have studied in a series of papers. In [t08/134], we construct the stationary measure of the N species totally asymmetric exclusion process in a matrix product formulation; we make the connection between the matrix product formulation and queuing theory: this allows us to interpret the operators that appear in the Matrix Ansatz as matrices acting on the (infinite) space of queue lengths. In [t08/213], we generalize the matrix approach to the Partially asymmetric process for which no mapping to queuing theory was available: the matrix Ansatz is found by taking tensor products of quadratic algebras and we give a purely algebraic proof of the stationarity of the invariant measure. Besides, the matrix algebra is re-interpreted in terms of the action of a transfer matrix Finally, in [t11/046], we construct a general transfer matrix Ansatz between multi-species exclusion processes with different numbers of species and analyze recursive combinatorial structures within the set of these different models, which can be encoded in a Hasse diagram. We prove that the Matrix Ansatz is in fact a mapping that intertwines Markov Matrices of different stochastic systems and this allows us to construct non only the stationary state but also full sectors of the spectrum i.e., relaxation states.

C.2.2 Large deviations of the current in the exclusion process *(K. Mallick)*

An important physical quantity in the ASEP is the statistics of the current in the stationary regime (this current corresponds to a local height variable in the corresponding random interface model). In particular, large deviations, that are expected to play an essential role in non-equilibrium statistical physics, are a very relevant quantity to measure, to compute numerically and, if possible, to calculate analytically.

For the exclusion process on a periodic ring, the large deviation function of the current was determined by Derrida and Lebowitz in 1999, but only for the particular case of the *totally* asymmetric exclusion process (TASEP). This result was derived using the Bethe equations which, for the TASEP, can be solved explicitly thanks to a decoupling property that reduces them to a one variable polynomial equation plus a self-consistency condition. In the general case, when jumps on both directions are allowed, the Bethe equations do not decouple and the problem remained unsolved for almost ten years. The general case is important to understand how non-equilibrium behavior builds itself up starting from the equilibrium (i.e. detailed-balance) case. In [t07/181], we overcame this technical barrier by using a functional reformulation of the Bethe Ansatz that maps it into a purely algebraic problem of polynomial factorization: this allowed us to calculate the first two cumulants of the current (K. Mallick and S. Prolhac).

In [t08/236], we studied the weakly asymmetric limit and obtained the complete large deviation function at dominant order w.r.t. to the size of the system. Previously, T. Bodineau and B. Derrida used the continuous (hydrodynamic) limit of model and applied Jona-Lasinio's macroscopic fluctuation theory; they predicted a non-equilibrium phase transition with respect to a fugacity parameter, conjugate to the current variable. The exact calculation of [t08/236] confirms the existence of this transition, which corresponds to a breaking of analyticity in the large deviation function, emphasizing again the importance of this observable in systems far from equilibrium (K. Mallick and S. Prolhac).

In [t08/198], Sylvain Prolhac was able to determine the expression of the third order cumulant (skewness) for an arbitrary value of the asymmetry parameter. The skewness measures the non-Gaussian character of the probability distribution and its non-vanishing is a sign of the non-equilibrium character of the statistics. Finally, the complete problem of the current's statistics in the exclusion process on a ring was entirely solved by S. Prolhac in [t10/106]. There, a combinatorial expression for all the cumulants in all the cases was derived. In the thermodynamic limit, three different scaling regimes can be observed for the current fluctuations, depending on how the asymmetry scales with the size L of the system: the Edwards-Wilkinson phase, the Kardar-Parisi-Zhang universality class, and an intermediate regime (with asymmetry $\gg 1/L$ and $\ll 1/\sqrt{L}$) for which no large scale continuous description is yet known.

These recent results on the exclusion process have been reviewed in the STAPHYS Proceedings [t11/096] and in the Lecture Notes [t10/064].

The analytical study of the fluctuations of the current fluctuations in the original totally asymmetric exclusion process (TASEP) on a finite one-dimensional lattice with open boundaries (i.e., in contact with two reservoirs at different potentials) is a very challenging problem. This question naturally arose in this field at the time when the first exact solutions of the ASEP were found but it has remained unsolved and vexing since then. This is far from being a purely academic problem: it is important because in presence of reservoirs, the ASEP model becomes a rather realistic description of 1d transport and it can be related to real experimental situations (quantum dots). Only the mean value and the variance of the current had been calculated in the beginning of the 90's. In the weakly asymmetric regime, progress was made using a macroscopic additivity principle. In [t11/096], we have found a formula for the generating function of the cumulants of the current in the open TASEP, which is related to the large deviation function by Laplace transform. This formula is of combinatorial nature and it is valid for all system sizes and for all values of the chemical potentials of the reservoir. All previously known cases are retrieved as special limits and the behavior of the large deviation function in the phase diagram can be precisely analyzed (A. Lazarescu and K. Mallick).

C.2.3 Algebraic properties of a disordered asymmetric Glauber model *(A. Ayyer)*

In [t11/108] we study a system of spins on a finite one-dimensional lattice, with one open and one closed boundary. The dynamical rules are chosen to be an asymmetric version of Glauber dynamics. For this model, we prove an explicit formula for the characteristic polynomial of the transition matrix of the associated Markov chain. We also analyzed two special cases of the model, which resemble a ferromagnetic and antiferromagnetic Ising chains.

C.2.4 On some classes of open two-species exclusion processes *(A. Ayyer)*

In [t10/133] (with J. L. Lebowitz and E. R. Speer) we consider a totally asymmetric exclusion process with two species on a finite one-dimensional lattice with open boundaries. This model generalizes previous work in which second class particles can neither enter nor leave the system. For certain classes of rates we compute the currents and phase diagram, and in some other classes, we obtain some monotonicity properties. We also analyze a simple example where there is a shock in which the densities of all three species are discontinuous.

C.2.5 The spectrum of an asymmetric annihilation process *(A. Ayyer)*

In an earlier work with Kirone Mallick [t09/157] on the asymmetric annihilation process, we had conjectured an explicit formula for the characteristic polynomial of the transition matrix of the associated Markov chain. In [t10/100] (with Volker Strehl), we prove that conjecture by generalizing the model using the Hadamard transform (a kind of discrete Fourier transform).

C.2.6 Phase diagram of the ABC model on an interval *(A. Ayyer)*

The three species asymmetric ABC model was initially defined on a ring by Evans, Kafri, Koduvely, and Mukamel, and the weakly asymmetric version was later studied by Clincy, Derrida, and Evans. In [t09/070] (with E. A. Carlen, J. L. Lebowitz P. K. Mohanty D. Mukamel and E.R. Speer) the latter model is studied on a one-dimensional lattice of N sites with closed (zero flux) boundaries. In this geometry the local particle conserving dynamics satisfies detailed balance with respect to a canonical Gibbs measure with long range asymmetric pair interactions. This generalizes results for the ring case, where detailed balance holds, and in fact the steady state measure is known only for the case of equal densities of the different species: in the latter case the stationary states of the system on a ring and on an interval are the same. We prove that in the N to infinity limit the scaled density profiles are given by (pieces of) the periodic trajectory of a particle moving in a quartic confining potential. We further prove uniqueness of the profiles, i.e., the existence of a single phase, in all regions of the parameter space (of average densities and temperature) except at low temperature with all densities equal; in this case a continuum of phases, differing by translation, coexist. The results for the equal density case apply also to the system on the ring, and there extend results of Clincy et al.

C.2.7 Non equilibrium stationary states and phase transitions in directed Ising models *(C. Godrèche)*

The studies of the Katz-Lebowitz-Spohn model, of the Simple Exclusion Process, or of the Zero Range Process, among others, showed that imposing a bias on a reversible stochastic process leading to equilibrium changes its properties drastically. The process, which is no longer reversible, reaches a stationary state in the long-time regime, whose description is far more difficult than its equilibrium counterpart.

A similar question can be posed for the kinetic Ising model with non conserved dynamics. The idea is that each spin is influenced by only a subset of its nearest neighbors and therefore the asymmetry of the dynamics violates the reversibility of the process. We shall name these models "directed Ising models". The questions posed are: what are the consequences of imposing a bias on the model? Are the dynamical properties changed? Is the stationary state of a different nature? The two papers [t09/309] and [t11/098], are devoted to these questions.

In the first one, [t09/309], the nonequilibrium properties of directed Ising models with non-conserved dynamics, in which each spin is influenced by only a subset of its nearest neighbors, is studied. We treat the following models: (i) the one-dimensional chain; (ii) the two-dimensional square lattice; (iii) the two-dimensional triangular lattice and (iv) the three-dimensional cubic lattice.

We raise and answer the question: (a) under what conditions is the stationary state described by the equilibrium Boltzmann-Gibbs distribution? We show that, for models (i), (ii) and (iii), in which each spin "sees" only half of its neighbors, there is a unique set of transition rates, namely with exponential dependence in the local field, for which this is the case. For model (iv), we find that any rates satisfying the constraints required for the stationary measure to be Gibbsian should satisfy detailed balance, ruling out the possibility of directed dynamics. We finally show that directed models on lattices of coordination number $z \geq 8$ with exponential rates cannot accommodate a Gibbsian stationary state. We conjecture that this property extends to any form of the rates. We are thus led to the conclusion that directed models with Gibbsian stationary states only exist in dimensions one and two.

We then raise the question: (b) do directed Ising models, augmented by Glauber dynamics, exhibit a phase transition to a ferromagnetic state? For the models considered above, the answers are open problems, with the exception of the simple cases (i) and (ii). For Cayley trees, where each spin sees only the spins further from the root, we show that there is a phase transition provided the branching ratio, q, satisfies $q \geq 3$. In the second one [t11/098], the study by Glauber of the time-dependent statistics of the Ising chain is extended to the case where each spin is influenced unequally by its nearest neighbors. The asymmetry of the dynamics implies the failure of the detailed balance condition. The functional form of the rate at which an individual spin changes its state is constrained by the global balance condition with respect to the equilibrium measure of the Ising chain. The local magnetization, the equal time and two-time correlation functions and the linear response to an external magnetic field obey linear equations which are solved explicitly. The behavior of these quantities and the relation between the correlation and response functions are analyzed both in the stationary state and in the zero-temperature scaling regime. In the stationary state, a transition between two behaviors of the correlation function occurs when the amplitude of the asymmetry crosses a critical value, with the consequence that the limit fluctuation-dissipation ratio decays continuously from the value 1, for the equilibrium state in the absence of asymmetry, to 0 for this critical value. At zero temperature, under asymmetric dynamics, the system loses its critical character, yet keeping many of the characteristic features of a coarsening system.

C.3 Stochastic processes

C.3.1 Longest excursion of stochastic processes in nonequilibrium systems *(C. Godrèche)*

In [t09/310], we consider the excursions, i.e., the intervals between consecutive zeros, of stochastic processes that arise in a variety of nonequilibrium systems and study the temporal growth of the longest one $l_{max}(t)$ up to time t. For smooth processes, we find a universal linear growth $< l_{max}(t) >\sim Qt$ with a model dependent amplitude Q. In contrast, for non smooth processes with a persistence exponent theta, we show that $< l_{max}(t) >$ has a linear growth if $\theta < \theta_c$ while $< l_{max}(t) >\sim t^{1-\psi}$ if $\theta > \theta_c$. The amplitude Q and the exponent θ_c are novel quantities associated with nonequilibrium dynamics. This behavior is obtained by exact analytical calculations for renewal and multiplicative processes and numerical simulations for other systems such as the Ising model under coarsening dynamics as well as the diffusion equation with random initial conditions.

C.3.2 Random walk and related stochastic processes *(J.M. Luck)*

We have introduced maximal entropy random walk (MERW) on an arbitrary graph. Our initial motivation was to provide a faithful discretization of the Feynman path integral, where

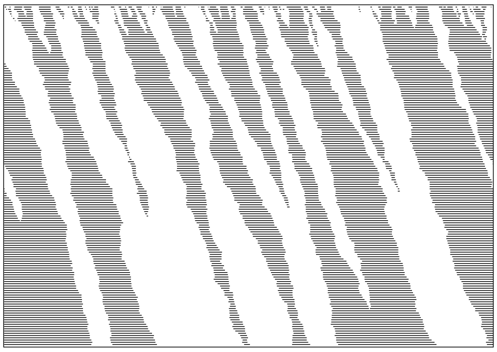

Figure C.1: Space-time representation of the zero-temperature biased coarsening of the directed Ising chain with periodic boundary conditions

all paths of given length and endpoints would be equally probable. MERW can be alternatively defined as the discrete-time random walk which maximizes the entropy production rate. Its construction is germane to that of Shannon-Parry measures known in ergodic theory. The corresponding hopping probabilities are determined by the Perron-Frobenius eigenvalue and eigenvector of the adjacency matrix of the graph. MERW coincides with Pólya's usual random walk on graphs where all the nodes have the same degree. It may however exhibit unexpected localization features. In the case of a regular lattice with a weak bond dilution, the stationary probability of finding a particle performing MERW localizes in the largest nearly spherical "Lifshitz region" of the lattice which is free of defects [t08/165, t10/051].

An imaginary exponential functional of Brownian motion has been scrutinized. This random complex integral shows up naturally as a tool in the study of the binary annihilation process, within the Doi-Peliti formalism for reaction-diffusion systems, once every spatial dependence has been neglected. The main emphasis has been put on the complementarity between the usual Langevin approach and another approach based on the similitude with Kesten variables and one-dimensional disordered systems [t11/005].

C.3.3 Do solids flow? *(G. Biroli)*

In collaboration with J. Kurchan and F. Sausset [t10/110], we showed that solidity is only a time-scale dependent notion: equilibrium states of matter that break spontaneously translation invariance, e.g. crystals, flow if even an infinitesimal stress is applied. However, they do so in a way inherently different from ordinary liquids since their viscosity diverges for vanishing shear stress with an essential singularity. We found an ultra-slow decrease of the shear stress as a function of the shear rate, which explains the apparent yield stress identified in rheological flow curves. Finally, we suggested that an alternating shear of frequency ω and amplitude γ should lead to a dynamic phase transition line in the (ω,γ) plane, from a "flowing" to a "non-flowing" phase.

C.3.4 Slow annealing through critical points: the Kibble-Zurek mechanism revisited *(G. Biroli)*

In collaboration with L. Cugliandolo and A. Sicilia [t10/109], we revisited the Kibble-Zurek mechanism introduced to explain the dynamics of phase ordering systems during an infinitely slow annealing across a second order phase transition. We elucidated the time and cooling rate dependence of the typical growing length and we used it to predict the number of topological defects left over in the symmetry broken phase as a function of time, both close and far from the critical region. Our results extend the Kibble-Zurek mechanism and reveal its limitations.

C.3.5 First passage in infinite paraboloidal domains *(P. Krapivsky)*

First passage and diffusion problems naturally appear in numerous phenomena in physics, chemistry and biology. In many models, one considers a particle confined in a domain and absorbed whenever it hits the boundaries. The survival probability of such a particle is a function of the confining domain. A particle enclosed in a finite volume will decay exponentially. When the domain is infinite, more interesting algebraic decay can occur, depending on the geometric properties of the enclosure. In [t10/194], Paul Krapivsky and Sid Redner investigate the first passage problem in generalized paraboloidal domains, of arbitrary dimension, defined by the equation $y = a(x_1^2 + \ldots + x_{d-1}^2)^{p/2}$ where $p > 1$. By using an extreme statistics argument (also known as a Lifshitz tail argument), the authors show that when a particle is inside the paraboloid, its survival property $S(t)$ generically decays as a stretched exponential, $\ln S \sim -t^{(p-1)/(p+1)}$, independent of the spatial dimension. This also allows them to determine the average hitting time. However, when the particle is outside the paraboloid and is absorbed when hitting it, dimensionality matters but the exponent p characterizing the paraboloid is irrelevant: For $d = 2$, we have $S(t) \sim t^{-1/4}$ and for $d = 3$, $S(t) \sim (\ln t)^{-1}$. In higher dimensions, the particle survives with finite probability. The authors also investigate the situation where the interior of the paraboloid is initially uniformly filled with non-interacting diffusing particles that are absorbed by the boundary and calculate the time dependence of the distance between the apex and the particle closest to the apex. These studies shed a new light on the interplay between diffusion processes, first passage times and geometry.

C.3.6 Zero-temperature dynamics in the 3d Ising-Glauber model *(P. Krapivsky)*

The aim of studies in coarsening dynamics is to understand how ordered phases that are thermodynamically favored below the critical temperature in systems with short-ranged interactions can be formed dynamically. An archetypal example is the Ising model endowed with Glauber dynamics, where domains consist of spins that all point up or point down. When such an Ising model, initially in the high temperature phase, is quenched at the final temperature $T = 0$, energy raising spin flips are forbidden. In that case, the possibility exists that the model falls into a local minimum, *i.e.*, a state whose energy is lower than any other state that differs by one spin-flip. At zero temperature, the system may not be able to escape from such a local minimum state and thus will never reach the true ground state. A one dimensional system of finite size L ultimately reaches complete alignment -the ground state. In two dimensions, the ground state is reached with probability $p < 1$ (p is roughly $2/3$) and with probability $1 - p$ the system may end up in a state that consists of an even number of straight strips. In greater than two dimensions, the probability of reaching the ground state decays very rapidly with L (the typical size of the system) and, in practice, the ground state is never reached. In [t10/192], P. Krapivsky et al. consider the case of the 3d Glauber-Ising model on a periodic cubic lattice and show that typical metastable states can be viewed as the discrete analogs of minimal surfaces. Such long-time states are not static and do not consist in isolated configurations. Rather, they form a connected iso-energy set within which the system wanders forever by flipping *'blinker'* spins *ad infinitum* with no energy cost. The authors investigate the topology of a typical metastable domain and find that its genus g grows algebraically with system size: $\langle g \rangle \sim L^\gamma$ with $\gamma \sim 1.7$. Because of the blinker states, the energy relaxation is extremely slow, with characteristic time that grows exponentially with system size.

C.3.7 A light impurity in an equilibrium gas *(P. Krapivsky)*

In [t10/193], P. Krapivsky and L. D'Alessio investigate the evolution of a light impurity particle in a Lorentz gas where the background atoms are in thermal equilibrium. This problem, reminiscent of Fermi's model for cosmic rays acceleration, is a natural generalization of the standard Lorentz gas is which scatters are assumed to be immobile. The behavior of the light particle is analyzed using the Boltzmann equation framework. The authors show that in the long time limit, the collision term of the Boltzmann equation simplifies allowing them to reduce the integro-differential Lorentz-Boltzmann equation to a partial differential equation. By studying the resulting equation, the authors calculate the average particle displacement and show that it grows linearly with time and proportionally to the thermal velocity of the background atoms -the density of the gas, the size of atoms and the details of the interaction between the particle and the atoms do not affect the asymptotic. The thermal motion of the background atoms causes the average particle speed to grow as $t^{\lambda/(2(d-1)+\lambda)}$ where λ characterizes the divergence of interaction potential at short distances r (the interaction behaves as $r^{-\lambda}$) and d is the dimension. The authors also calculate the universal scaling laws for the velocity and position distributions. Generically, these distributions are not Gaussian. The theoretical predictions are in perfect agreement with numerical simulations.

C.3.8 Accelerated sampling of Boltzmann distributions *(H. Orland)*

The sampling of Boltzmann distributions by stochastic Markov processes, can be strongly limited by the crossing time of high (free) energy barriers. As a result, the system may stay trapped in metastable states, and the relaxation time to the equilibrium Boltzmann distribution may be very large compared to the available computational time. In [t08/285], we show how, by a simple modification of the Hamiltonian, one can dramatically decrease the relaxation time of the system, while retaining the same equilibrium distribution. The idea is to decrease the relaxation time to equilibrium by increasing the gap of the Hamiltonian.This is done by adding to the Hamiltonian a term proportional to the projector to its ground state. The method is illustrated on the case of the one-dimensional double-well potential.

C.3.9 Accelerated stochastic sampling of discrete statistical systems *(H. Orland)*

We propose in [t10/260] a method to reduce the relaxation time towards equilibrium in stochastic sampling of complex energy landscapes in statistical systems with discrete degrees of freedom by generalizing the platform previously developed for continuous systems. The method starts from a master equation. The master equation is transformed into an imaginary-time Schrödinger equation. The Hamiltonian of the Schrödinger equation is modified by adding a projector to its known ground state. We show how this transformation decreases the relaxation time and propose a way to use it to accelerate simulated annealing for optimization problems. We implement our method in a simplified kinetic Monte Carlo scheme and show an acceleration by an order of magnitude in simulated annealing of the symmetric traveling salesman problem. Comparisons of simulated annealing are made with the exchange Monte Carlo algorithm for the three-dimensional Ising spin glass. Our implementation can be seen as a step toward accelerating the stochastic sampling of generic systems with complex landscapes and long equilibration times.

C.4 Glass physics

C.4.1 A theoretical perspective on the glass transition and nonequilibrium phenomena in disordered materials *(G. Biroli)*

In collaboration with L. Berthier we wrote a review, to be published on Review of Modern Physics, [t10/273] that provides a theoretical perspective on the glass transition in molecular liquids at thermal equilibrium, on the spatially heterogeneous and aging dynamics of disordered materials, and on the rheology of soft glassy materials.

C.4.2 Dynamical heterogeneity in glasses, colloids and granular materials *(G. Biroli)*

In collaboration with L. Berthier, J.-P. Bouchaud, L. Cipelletti, W. van Saarloos we edited a book [t11/106] on dynamical heterogeneity that will be published in July 2011 by Oxford University Press. It provides a broad and up-to-date overview of the current understanding of dynamic heterogeneity in glasses, colloids, and granular media. The book contains formal chapters about recent theoretical developments and very phenomenological ones concerned with more practical and experimental aspects. Such a broad scope would have been difficult to cover by a single author. We have therefore mustered different scientists, who have all made important contributions to the field. In collaboration with L. Berthier, J.-P. Bouchaud and R. Jack we wrote a chapter [t10/268] of the book in which we review the recent progress and the open questions about the characterization of dynamic heterogeneity in glassy materials.

C.4.3 Lattice models and the glass transition *(G. Biroli)*

In order to gain a deeper understanding of the glass transition we have studied several lattice models. In collaboration with C. Toninelli, we rigorously proved in [t07/128] that the spiral model has an ideal glass phase transition and obtained the corresponding critical properties, thus confirming the previous results obtained with D.S. Fisher. In collaboration with F. Sausset, G. Tarjus and C. Toninelli [t09/227] we studied Kinetically constrained models (KCMs) on hyperbolic lattices obtained by regular tilings of the hyperbolic plane. We showed that for generic tilings there exists a dynamical glass transition, which has a mixed character: it is discontinuous but characterized by a diverging correlation length, similarly to what happens on

Bethe lattices and random graphs of constant connectivity. In collaboration with R. Darst and D. Reichman, we introduced [t09/225] a new lattice glass model whose dynamical rules are based on thermodynamic considerations, as opposed to the purely kinetic ones of KCMs. We showed by numerical simulations that it is a qualitatively good model of glass-formers, in particular it displays violations of the Stokes-Einstein relation and the growth of various length scales associated with dynamical heterogeneity.

C.4.4 Theory of the glass transition: random first order transition *(G. Biroli)*

In collaboration with J.-P. Bouchaud et al. we showed [t08/151] for the first time a qualitative thermodynamic difference between the high temperature and deeply supercooled equilibrium glass-forming liquid: the influence of boundary conditions propagates into the bulk over larger and larger length scales upon cooling. The increase of this length scale is a clear signature of the emergence of some hidden static order, as it was expected within the random first-order transition theory (RFOT) of the glass transition. In collaboration with J.-P. Bouchaud, we reviewed the RFOT picture for glasses [t09/239]: the basic arguments and the intuition bolstering the theory, the pros and cons that support or undermine it, the directions, both theoretical and experimental, where progress is needed to ascertain the status of RFOT. Finally, we compared RFOT to other recent theories, including elastic models, Frustration Limited Domains or Kinetically Constrained models. Recently, in collaboration with C. Cammarota, G. Tarjus and M. Tarzia, we developed [t10/121] the first renormalization group (RG) analysis of RFOT. We used a Migdal-Kadanoff real space method applied directly on the replica field theory. Within this approximation we found that along the RG flow the properties associated with metastable glassy states, such as the configurational entropy, are only defined up to a characteristic length scale that diverges as one approaches the ideal glass transition. The critical exponents characterizing the vicinity of the transition are the usual ones associated with a first-order discontinuity fixed point.

C.4.5 Theory of the glass transition: mode coupling theory *(G. Biroli)*

In collaboration with A. Billoire, J.-P. Bouchaud and T. Sarlat, we studied numerically a disordered spin model, the fully connected Random Orthogonal Model, for which the predictions of the Mode Coupling Theory (MCT) of the glass transition hold exactly. Our conclusion [t09/094] is that the quantitative predictions of MCT are exceedingly difficult to test even for models for which MCT is exact because of strong pre-asymptotic effects. Furthermore, we found that naive finite size scaling is violated at the MCT transition. In collaboration with A. Andreanov and J.-P. Bouchaud, we derived MCT as a Landau theory [t09/228], thus clarifying the universality of MCT predictions; in particular the square root singularity of the order parameter, the scaling function in the β regime and the functional relation between the exponents defining the α and β timescales. In collaboration with J.-P. Bouchaud, A. Lefèvre and M. Tarzia, we developed [t09/229] a theory of non-linear responses of super-cooled liquids based on MCT. We obtained the frequency and temperature dependence of the non-linear response in the α and β-regimes. Our results demonstrate that supercooled liquids are characterized by responses to external perturbations that become increasingly non-linear as the glass transition is approached.

C.4.6 Dynamical heterogeneity in supercooled liquids *(G. Biroli)*

In collaboration with experimentalists of SPEC/CEA we showed in [t10/280] the first evidences of growing spatial correlations at the glass transition from nonlinear response experiments. Experimental results on non-linear dielectric susceptibility were obtained and compared to theoretical results obtained previously, see [t09/229]. In collaboration with R. Candelier et al. we identified [t09/224] by numerical simulations of a two dimensional glass forming liquid the pattern of microscopic dynamical relaxation: On short timescales, bursts of irreversible particle motion, called cage jumps, aggregate into clusters. On larger time scales, clusters aggregate both spatially and temporally into avalanches. This propagation of mobility, or dynamic facilitation, takes place along the soft regions of the systems. Our results characterize the way in which dynamical heterogeneity evolves in moderately supercooled liquids and reveal that it is astonishingly similar to the one found for dense glassy granular media.

C.4.7 Glassy dynamics as a melting process *(L. Zdeborova)*

The following properties are in the present literature associated with the behavior of supercooled glass-forming liquids: faster than exponential growth of the relaxation time, dynamical heterogeneities, growing point-to-set correlation length, crossover from mean field behavior to activated dynamics. In [t11/071] we argue that these properties are also present in a much simpler situation, namely the melting of the bulk of an ordered phase beyond a first order phase transition point. We discuss in detail the analogies and the differences between the glass and the bulk melting transitions. In [t11/072] we push this analogy even further and show that for a class of Ising spin models undergoing a first order transition - namely p-spin models on the so-called Nishimori line - the melting dynamics can be exactly mapped to the equilibrium dynamics. In this mapping the dynamical -or mode-coupling- glass transition corresponds to the spinodal point, while the Kauzmann transition corresponds to the first order phase transition itself. Both in mean field and finite dimensional models this mapping provides an exact realization of the random first order theory scenario for the glass transition.

C.4.8 Aging is - almost - like equilibrium *(A. Lefèvre)*

Mean field models have played a key role in understanding the slowing down of dynamics in glassy systems. However, there remained a few incertainties in the solution of the resulting dynamical equations. Indeed, the decay of the slow, aging part, of the relaxation of two points correlations was only characterized through undetermined scaling functions - the so-called time re-parametrization invariance. In collaboration with A. Andreanov, we focused on the regime separating the equilibrium part of the relaxation and the aging one, and showed that it in fact includes all relevant information about ageing dynamics. We showed that knowing the relaxation of the energy is enough for characterizing the whole dynamics of all correlation functions, which in particular lead to a conjecture about the stretched exponential decay of correlators at long times. Making one step further, in [t09/267], we showed that slow dynamics below and above the ideal glass transition are identical provided the distance to the low energy metabassins are identified. In other words, at a given energy, dynamics probe the same regions of the energy landscape, be they above or below the critical point. This strong results makes it possible to fully characterize - within mean field models - the crossover from ageing to equilibrium when ageing is interrupted and to compute the asymptotic behaviour of the crossover time scale. It also provides natural scaling conjectures for the growing of a dynamic correlation length in the glassy phase, as a function of the age of the sample.

C.5 Granular media and the jamming transition

C.5.1 Jamming transition of granular materials and relationship with glassy dynamics *(G. Biroli)*

In collaboration with the experimental group of Olivier Dauchot in SPEC/CEA, we studied several aspects of the Jamming transition of granular materials. We identified [t09/230, t08/030] from experiments the pattern of microscopic dynamical relaxation and their relationship with dynamical heterogeneities. We found results very similar to the ones obtained for supercooled liquids [t09/224]. Moreover we studied their evolution approaching the jamming transition in [t09/223]. Our main finding is that dynamical facilitation becomes less conserved and play a lesser role for structural relaxation approaching the transition. In [t10/275, t08/030] we studied whether the dynamics of granular media in the jammed, glassy region can be described in terms of “modes”, as proposed in the literature. Analyzing experimental results obtained by the Saclay group, we found that the description in terms of modes is questionable. Modes cannot even be precisely defined close to the jamming transition because the system is not stable enough and instead it displays frequent “cracks”. The statistical analysis performed in [t10/275] is corroborated by the analysis [t10/282] of the super-diffusive motion detected close to the transition. This corresponds to a genuine Levy flight, but with “jump” size very small compared to the diameter of the grains. These jumps are random in time, but correlated in space, and can be interpreted as micro-crack events at all scales.

C.5.2 Slow dynamics of a granular column *(J.-M. Luck)*

The study of the slow orientational dynamics of a column of interacting grains has been completed with the exploration of the full parameter space of the model. The resulting four dynamical regimes (ballistic, logarithmic, activated, and glassy) have been characterized by means of the distribution of the jamming time of zero-temperature dynamics, and of the statistics of attractors reached by the latter, in perspective with the Edwards hypothesis. Shape effects are most pronounced in the cases of strong and weak frustration, and essentially disappear around a mean-field point [t10/082]. Two reviews on these and related matters have appeared in popular journals [t08/113, t09/064].

C.6 Spin glasses

C.6.1 The nature of the spin glass phase in low dimension *(C. De Dominicis)*

One of the most debated point in spin-glass theory has to do with the fact that there are two, apparently, unrelated approaches to look at the problem: In infinite dimensions, almost all experts agree: Parisi's replica approach exactly solves the problem posed by the SK model. In low dimension ($2 \leq d \leq 8$) the droplet theory put forward by Fisher and Huse and by Bray and Moore offers an other way, with the concept of scale dependent coupling. And for the last authors a proposal to keep the Parisi approach down to 6 dimensions and the droplet one at and below $d = 6$. Here we will be essentially using the tools of replica calculus (mostly via replica Furrier transforms), and we will construct the free energy as a stationary functional of the field $Q_{a,b} \equiv \overline{< S_a S_b >}$. We try to keep track of the $Q_{a,b}$ matrix, when deriving components of the Hessian (second functional derivative) whose eigenvalues are the "masses" of the $Q_{a,b}$ propagators. Keeping in mind that stability requires nonnegative (masses) eigenvalues.

We [t09/279] write the overlap matrix $Q_{a,b}$ as $Q_{a,b} = \delta_{a,b} + q(1-\delta_{a,b}) + \delta Q_{a,b}$. The original SK solution is given by $\delta Q_{a,b} = 0$. Here we expand in powers of $\delta Q_{a,b}$ and we keep up to 4th order in δQ (the lowest order accepting solutions with full replica symmetry breaking (FRSB) ansatz). The surprise is that the FRSB solution exists only for $0.549.. \leq T < T_c = 1$ Besides, the $Q(x)$ obtained does not vanish with x (as in the exact Parisi solution). If we work in zero magnetic field ($q = 0$) and $Q_{a,b} = \delta_{a,b} + \delta Q_{a,b}$ now $Q(x)$ vanishes with x, but the FRSB solution exists only for $0.915.. \leq T < T_c = 1$ and thus cannot be used to study the system close to $T = 0$.

We now work [t09/272] with two fields: The Ising field σ_a and a constraint field λ_a that will force the spins σ_a to remain close to ± 1. The (doubly) stationary free energy (with respect to both, fields and correlations) is then organized according to the number of loops. The simplest contribution is given by a two loop diagram. However, it turns out that at low enough T the constraint becomes ineffective and a FRSB solution exists only for $0.783.. \leq T < T_c = 1$. Perhaps it would be worth going one more step in the loop expansion e.g. by keeping *all* graphs with a single loop of spin field propagators, to test how the constraint is then taken into account.

In [t10/274] and [t11/101], the structure of the Hessian of the SK model is investigated near zero T. The eigenvalues of the Hessian are the masses of the bare propagators in the expansion around the mean field solution of Parisi. In the $T \ll 1$ limit, two regions can identified:
i) for x close to zero (x is the overlap variable, in $Q(x)$) the spectrum of the Hessian remains non trivial and maintains the FRSB structure found at higher T,
ii) for $T \ll x \leq 1$, as $T \to 0$ the components of the Hessian become insensitive to changes of the overlaps, the bands, typical of the FRSB, collapse. In this region most eigenvalues vanish, except longitudinal masses that remains positive.

In the $T \to 0$ limit, the width of the (inner) first region shrinks to zero and in the (outer) other region positive and null eigenvalues survive. In the last work a way of computing multiple spin averages (e.g. $< S_a S_b S_c S_d >$) is detailed, exhibiting for example the difference or differential equations giving birth to multispin averages of the free energy itself.

C.6.2 Finite size scaling in the SK model *(A. Billoire)*

In collaboration with T. Aspelmeier, E. Marinari and M. Moore [t07/147] we argue that when the number of spins N in the SK model is finite, the Parisi scheme can be terminated after K replica-symmetry breaking steps, where $K(N) \propto N^{1/6}$. We have checked this idea by Monte Carlo simulations: we expect the typical number of peaks and features R in the (non-bond averaged) Parisi overlap function $P_J(q)$ to be of order $2K(N)$, and our counting (for samples of size N up to 4096 spins) gives results which are consistent with our arguments. We can estimate the leading finite size correction for any thermodynamic quantity by finding its K dependence in the Parisi scheme and then replacing K by $K(N)$. Our predictions of how the Edwards-Anderson order parameter and the internal energy of the system approach their thermodynamic limit compare well with the results of our Monte Carlo simulations. The N-dependence of the sample-to-sample fluctuations of thermodynamic quantities can also be obtained; the total internal energy should have sample-to-sample fluctuations of order $N^{1/6}$, which is again consistent with the results of our numerical simulations.

C.6.3 Distribution of relaxation time in the SK model *(A. Billoire)*

In [t10/157] numerical data on the probability distribution of the equilibrium relaxation time of the Sherrington-Kirkpatrick model are presented, for several values of the system size N and temperature T. The whole distribution scales with the scaling variable $N^{1/3}(T_c - T)$ strengthening the belief that indeed $E(\ln\tau(N)) \propto N^{1/3}$ in the spin glass phase.

In [t10/179] using results of a Monte Carlo simulation of the Sherrington-Kirkpatrick model, we try to characterize the slow disorder samples, namely we analyze visually the correlation between the relaxation time for a given disorder sample J with several observables of the system for the same disorder sample. For temperatures below T_c but not too low, fast samples (small relaxation times) are clearly correlated with a small value of the largest eigenvalue of the coupling matrix, a large value of the site averaged local field probability distribution at the origin, or a small value of the squared overlap $< q^2 >$. Within our limited data, the correlation remains as the system size increases but becomes less clear as the temperature is decreased (the correlation with $< q^2 >$ is more robust). There is a strong correlation between the values of the relaxation time for two distinct values of the temperature, but this correlation decreases as the system size is increased. This may indicate the onset of temperature chaos.

C.6.4 Large random correlations in individual mean field spin glass sample *(A. Billoire)*

In collaboration with I. Kondor, J. Lukic and E. Marinari [t10/158] we argue that complex systems must possess long range correlations and illustrate this idea on the example of the mean field spin glass model. Defined on the complete graph, this model has no genuine concept of distance, but the long range character of correlations is translated into a broad distribution of the spin-spin correlation coefficients for almost all realizations of the random couplings. When we sample the whole phase space we find that this distribution is so broad indeed that at low temperatures it essentially becomes uniform, with all possible correlation values appearing with the same probability. The distribution of correlations inside a single phase space valley is also studied and found to be much narrower.

C.6.5 Spin glass phase in random field Ising model, possible or not *(L. Zdeborova)*

Krzakala, Ricci-Tersenghi and Zdeborova have recently closed a twenty years open question by proving that the random field Ising model with non-negative interactions and arbitrary external magnetic field on an arbitrary lattice does not have a static spin glass phase. In [t11/070] we generalize this proof to a soft scalar spin version of the Ising model: the Ginzburg-Landau model with random magnetic field and random temperature-parameter. We do so by proving that the spin glass susceptibility cannot diverge unless the ferromagnetic susceptibility does. In [t11/073] we investigate in detail the phase diagrams of the p-body $\pm J$ Ising model with and without random fields on random graphs with fixed connectivity. One of our most interesting findings is that a thermodynamic spin glass phase is present in the three-body purely ferromagnetic model in random fields.

C.7 Other disordered systems

C.7.1 Phase transitions of random systems *(T. Garel and C. Monthus)*

In the presence of frozen disorder, phase transitions are governed by the renormalization of probability distributions (in contrast to pure systems where only a few coupling constants are relevant). It is thus instructive to study these transitions on diamond lattices where exact renormalization for the relevant probability distributions can be written: this approach has been applied to disordered polymers [t07/130] and to random ferromagnets [t07/152]. It is also useful to obtain exact results on the Cayley tree [t09/028].

C.7.2 Disorder-dominated phases of random systems *(T. Garel and C. Monthus)*

In the low-temperature disorder-dominated phases of various random models (directed polymer, ferromagnetic random Potts model, Ising spin-glasses), the free-energy cost $F(L)$ of an excitation of length L presents fluctuations that grow as a power-law $\Delta F(L) \sim L^{\omega}$ with the so-called droplet exponent $\omega > 0$. The tails of the probability distribution $\Pi(x)$ of the rescaled free-energy cost $x = (F_L - \bar{F_L})/L^{\omega}$ are governed by two exponents (η_-, η_+) defined by $\ln \Pi(x \to \pm\infty) \sim -|x|^{\eta_{\pm}}$. We have proposed simple relations between these tail exponents (η_-, η_+) and the droplet exponent ω [t07/133]. For the statistics of global observables in disordered systems, like the distribution of the ground state energy over the samples, we have similarly proposed to analyse the matching between typical fluctuations and large deviations to obtain relations between exponents [t10/009].

C.7.3 Random walks in random media *(T. Garel and C. Monthus)*

For random walks in random media, we have extended the strong disorder renormalization approach to the two-dimensional case [t10/002]. For the statistics of first-passage times, we have also studied the exact renormalization of the associated backwards master equations [t10/004]. The response to a small external force is found to be anomalous [t10/102].

C.7.4 Non-equilibrium dynamics of disordered systems *(T. Garel and C. Monthus)*

For the dynamics of many-body disordered systems, we have introduced a strong disorder renormalization procedure in configuration space [t08/048, t08/092]. In particular, we have described in [t08/122] how to construct explicitly the valleys separated by the highest dynamical barriers. In [t09/208], we have introduced an eigenvalue method to compute the largest relaxation time of finite systems. For the non-equilibrium dynamics of polymers and interfaces in random media, we have proposed a conjecture for the barrier exponent ψ governing the slow activated dynamics [t08/004]. For driven interfaces in random media, we find an anomalous zero-velocity phase at small external force [t08/148].

C.8 Hard optimization problems *(L. Zdeborova)*

The Boolean satisfiability problem is a benchmark of hard optimization problem in computer science. In [t11/067] we study the adversarial satisfiability problem, where the adversary can choose whether variables are negated in clauses or not in order to make the resulting formula unsatisfiable. This is one case of a general class of adversarial optimization problems that often arise in practice and are algorithmically much harder than the standard optimization problems. We use the cavity method to compute large deviations of the entropy in the random satisfiability problem with respect to the negation-configurations.

C.9 Networks, theoretical epidemiology, quantitative urbanism

C.9.1 Spatial networks *(M. Barthélemy)*

Complex systems are very often organized under the form of networks where nodes and edges are embedded in space. Transportation and mobility networks, Internet, mobile phone networks, power grids, social and contact networks, neural networks, are all examples where space is relevant and where topology alone does not contain all the information. Characterizing and understanding the structure and the evolution of spatial networks is thus crucial for many different fields ranging from urbanism to epidemiology. An important consequence of space on networks is that there is a cost associated to the length of edges which in turn has dramatic effects on the topological structure of these networks. We will expose thoroughly the current state of our understanding of how the spatial constraints affect the structure and properties of these networks. We will review the most recent empirical observations and the most important models of spatial networks. We will also discuss various processes which take place on these spatial networks, such as phase transitions, random walks, synchronization, navigation, resilience, and disease spread.[t11/027]

C.9.2 Fluctuation effects in metapopulation models: percolation and pandemic threshold *(M. Barthélemy, C. Godrèche, J.-M. Luck)*

Metapopulation models provide the theoretical framework for describing disease spread between different populations connected by a network. In particular, these models are at the basis of most simulations of pandemic spread. They are usually studied at the mean-field level by neglecting fluctuations. Here we include fluctuations in the models by adopting fully stochastic descriptions of the corresponding processes. This level of description allows to address analytically, in the SIS and SIR cases, problems such as the existence and the calculation of an effective threshold for the spread of a disease at a global level. We show that the possibility of the spread at the global level is described in terms of (bond) percolation on the network. This mapping enables us to give an estimate (lower bound) for the pandemic threshold in the SIR case for all values of the model parameters and for all possible networks.[t10/049]

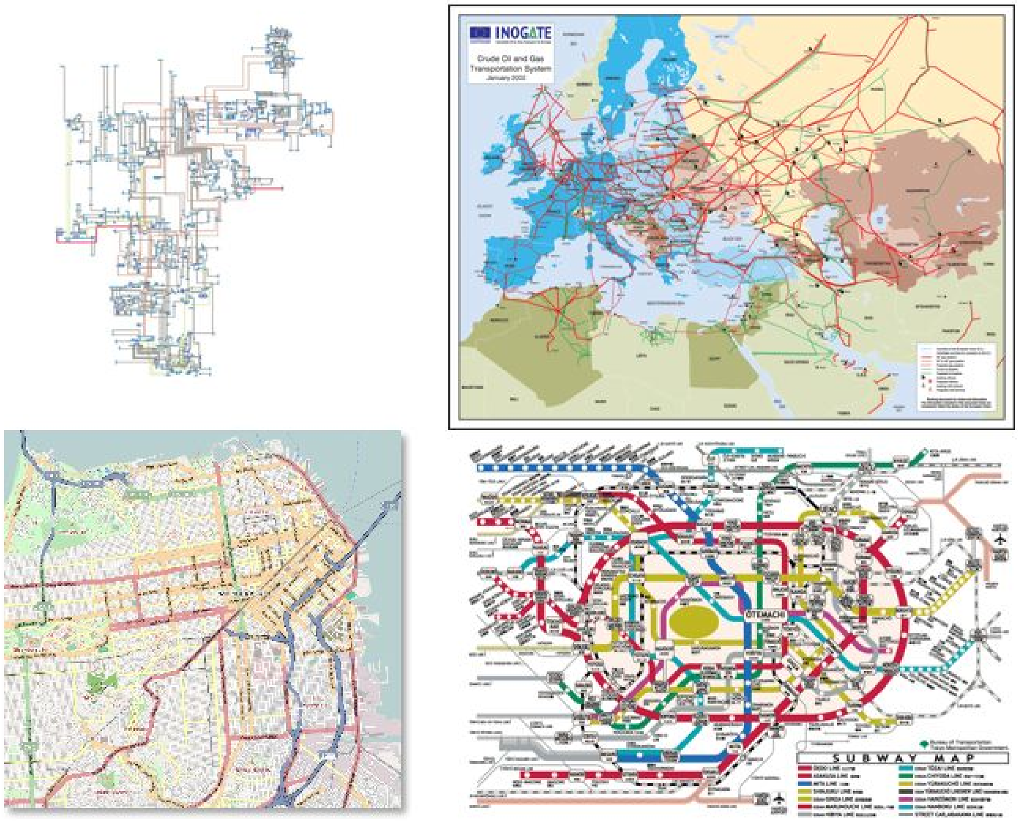

Figure C.2: Example of spatial networks. (A) Manhattan power grid. (B) European pipelines. (C) Roads and streets in San Francisco, (D) Tokyo subway.

C.9.3 Disentangling collective trends from local dynamics *(M. Barthélemy)*

A single social phenomenon (such as crime, unemployment or birth rate) can be observed through temporal series corresponding to units at different levels (cities, regions, countries...). Units at a given local level may follow a collective trend imposed by external conditions, but also may display fluctuations of purely local origin. The local behavior is usually computed as the difference between the local data and a global average (e.g. a national average), a view point which can be very misleading. We propose here a method for separating the local dynamics from the global trend in a collection of correlated time series. We take an independent component analysis approach in which we do not assume a small unbiased local contribution in contrast with previously proposed methods. We first test our method on synthetic series generated by correlated random walkers. We then consider crime rate series (in the US and France) and the evolution of obesity rate in the US, which are two important examples of societal measures. For crime rates, the separation between global and local policies is a major subject of debate. For the US, we observe large fluctuations in the transition period of mid-70's during which crime rates increased significantly, whereas since the 80's, the state crime rates are governed by external factors and the importance of local specificities being decreasing. In the case of obesity, our method shows that external factors dominate the evolution of obesity since 2000, and that different states can have different dynamical behavior even if their obesity prevalence is similar.[t09/251]

C.9.4 Structure of urban movements: polycentric activity and entangled hierarchical flows *(M. Barthélemy)*

The spatial arrangement of urban hubs and centers and how individuals interact with these centers is a crucial problem with many applications ranging from urban planning to epidemiology. We utilize here in an unprecedented manner the large scale, real-time 'Oyster' card database of individual person movements in the London subway to reveal the structure and organization of the city. We show that patterns of intra-urban movement are strongly heterogeneous in terms of volume, but not in terms of distance travelled, and that there is a polycentric structure composed of large flows organized around a limited number of activity centers. For smaller flows, the pattern of connections becomes richer and more complex and is not strictly hierarchical since it mixes different levels consisting of different orders of magnitude. This new understanding can shed light on the impact of new urban projects on the evolution of the polycentric configuration of a city and the dense structure of its centers and it provides an initial approach to modeling flows in an urban system.[t10/113]

C.9.5 Fluctuations, records, and leaders in growing network models *(C. Godrèche, H. Grandclaude, J.-M. Luck)*

Growing networks have become increasingly popular. They provide a natural explanation for the two most salient features observed in real networks, either natural or man-made: small-world effect (the diameter of the network grows very slowly with the number of nodes, typically logarithmically) and scalefreeness (the degrees of nodes have a broad distribution, falling off as a power law). In simple growing network models with preferential attachment, a new node enters at each time step, and attaches to one earlier node according to some stochastic rules. The network thus obtained is a random tree, and its size (number of nodes) is nothing but its age (the time elapsed since it started to grow). Bianconi and Barabási (BB) have introduced a very fruitful model, where the attachment probability to a given node depends on two ingredients: a dynamical one (its degree at the attachment time) and an intrinsic one (its quality or fitness, modeled as quenched disorder). The relative importance of these two effects is measured by a temperature. The most salient feature of the BB model is that it may have, depending on disorder, a condensation transition at some finite temperature. The earlier Barabási-Albert (BA) model is recovered at infinite temperature, while a novel phenomenon takes place in the low-temperature condensed phase, as some nodes attract a finite fraction of all the connections.

We have devoted several works to the study of fluctuations in various models of growing networks, including the BA and BB models. Our main motivation was to aim at a better understanding of the dynamics in the condensed phase, where the most important part is played by high-degree nodes. We have thus paid special attention to the leader, i.e., the node whose degree is the largest at a given time. More specifically, we have performed a systematic investigation of finite-size effects on the distribution of the node degrees. These effects have been shown to exhibit different behaviors in three regimes in the size-degree plane: stationarity, finite-size scaling, large deviations [t09/100]. The zero-temperature limit of the BB model has also been explored in depth. In this limit, the record node (the node whose fitness is the best at the current time) attracts all the new connections, until it is outdone by a fitter node. This observation led us to introduce a novel stochastic growth model, the record-driven growth process. Many features of the latter can be analyzed by exact methods, based on the statistics of records. To give one example, any record node has a chance $\omega = 0.624329988...$ to eventually become the leader of the network, where ω is the Golomb-Dickman constant which arises in various problems of combinatorics, including random permutations [t08/142]. More generally, we have investigated leaders and lead changes in growing networks, by exploring many quantities concerning either the leader at a given time (its age, the distribution of its degree, the number of co-leaders if any) or the whole history of lead changes (numbers of lead changes and of distinct leaders). For the BB model, irrespectively of the existence of a condensation transition, new leaders appear endlessly at any temperature, albeit extremely slowly, on a doubly logarithmic time scale, so that "the leader of today is the record of old". This analysis also provides a novel picture for the dynamics in the condensed phase. The latter is characterized by an infinite hierarchy of condensates, whose relative sizes are non-self-averaging and keep fluctuating forever [t09/184, t10/078].

C.10 Heavy fermion physics

C.10.1 The modulated spin liquid in URu_2Si_2 *(C. Pépin)*

In [t10/288], we get involved in the study of URu_2Si_2, a heavy fermion compound which represents one of the oldest mystery in condensed matter physics, and which has received a renewed attention recently, due to a body of new and creative experimental work. The pure compound shows a pronounced second order phase transition at $T_0 = 17K$ towards a mysterious ordered phase dubbed "Hidden Order" (HO). The amount of entropy lost at the transition is large, of the order of $0.3RLn2$. There is a large amount of evidence that the transition is not of magnetic character and that a large number of carriers do disappear at T_0. Moreover, recent studies show a striking similarity between the hidden order phase and a large moment anti-ferromagnetic phase which is revealed under a small amount of uni-axial pressure. In our work, we exploit this remarkable similarity between the two phases, and we suggest a Resonant Valence Bond (RVB) spin liquid as a strong candidate for the hidden order, modulated in the dual lattice. This order parameter has the particularity to be very hard to detect, as all the spin liquid phases, besides the fact that, since it breaks the Z_4 symmetry of the lattice, it leads to a pronounced second order phase transition at T_0 [instead of a cross-over]. The Modulated Spin Liquid shows strong similarities with a corresponding antiferromagnetic phase, and can be considered as the "RVB-parent" of the antiferromagnet. We intend to investigate further the properties of this interesting new candidate, and in particular, in the near future to construct a realistic model for the dynamic spin susceptibility, in order to the able to address the extensive neutron scattering results already available.

C.10.2 Kondo breakdown in ^{3}He bi-layers *(A. Benlagra, C. Pépin)*

In [t08/179], [t08/180] and [t10/286], we apply our newly developed model of the Kondo breakdown, originally conceived for heavy fermions, to a recent experiment by the group of J. Saunders in London [M. Neumann *et al.*, Science, **317** 1356 (2007)]. In this experiment a Quantum Critical Point (QCP) of unknown nature is revealed through specific heat and NMR measurements in 3He bi-layers. Atoms of ^{3}He are deposed on a substrate made of two layers of ^{4}He itself deposed on graphite. As the coverage of the two last layers is slowly varied, one observes, at a critical coverage of 9.2 nm^{-1} a sudden increase of the static susceptibility. At a bit bigger coverage, of $n_c = 10$ nm^{-1} the effective mass is shown to increase by a factor of 20. The critical coverage n_c is consequently identified as the quantum critical coverage of the system. In our papers we address this experiments by mapping the two layers system onto an Anderson lattice with inter-layer Coulomb repulsion between the ^{3}He fermions. We make the assumption that the experimentally revealed QCP corresponds to a Mott localization of the atoms on the second layer, while the ones in the first layer have already localized at lower doping. Applying our Eliashberg theory of the Kondo breakdown, we were able to quantitatively account for the variation of the effective mass, and of the transition temperature as a function of the coverage. We reproduce as well the variation of the activation gap with coverage, although we are short of a factor of 10, for the quantitative value of the gap.

C.10.3 Kondo breakdown and selective Mott transition in heavy fermions *(A. Benlagra, K.-S. Kim, C. Pépin)*

The breakdown of the Landau theory of the Fermi liquids, experimentally observed in heavy fermion compounds still remains a mystery for the theoretician: The resistivity is linear (or quasi-linear) in temperature for many compounds around zero temperature phase transitions and the specific heat coefficient doesn't saturate (as it should do in a well behaved Fermi liquid). For a very long time, we have looked for a QCP of magnetic nature to explain the unusual properties of these materials, but none of the magnetic QCP for itinerant electrons provided a strong enough violation of the Fermi liquid theory to explain the experiments. New experimental observations and band structure studies showed recently that the compound Yb Rh_2 Si_2 doped with a small amount of Ge had more valence fluctuation that one would expect for a true heavy Fermi compound. This incited us to look for a new type of QCP, not directly associated to magnetic transitions. We found one, in the Kondo-Heisenberg lattice, for which the effective hybridization between the two type of electrons, the localized spinons and the conduction electron band goes to zero at zero temperature. At this fixed point, the Fermi surface volume changes abruptly while the spinon Fermi surface gets completely "hot". Moreover, this QCP has a multi-scale character, with above a small energy scale E^*, a marginal Fermi liquid regime, including a resistivity in T LogT in 3 dimensions, and logarithmically divergent specific heat variation. This very interesting QCP, that we called the "Kondo breakdown" is the first effective field theory which leads to a regime quasi-linear in temperature for the resistivity in 3 D.

In addition we found that a phase with an hybridization modulated in space, analogous to the Fulde Ferell Larkin Ovshinikov superconductor can occur. It's again the first evidence for such a phase in heavy fermion compounds.

In a series of eight papers [t08/267, t08/268, t08/178, t09/026, t08/269, t09/275, t10/019, t10/287] we explore the testability of our theory for various experimental probes. the main idea underlying those tests is that the Kondo breakdown model is a good model for transport properties whereas it misses the effect of magnetism in the system. We consider the proximity to the selective Mott transition, as the main provider for scattering events, so that this mechanism dominates the transport. The system has the peculiarity that it has two types of electrons, ones at the brink of localization [the f-electrons] and ones very localized [the c-electrons]. Critical scattering of the c- electrons through the lattice of f-electrons gets a backscattering component and hence a mechanism to decay the current. The various transport and thermodynamic probes that we have examined count a study of the Wiedemann-Franz ratio, one of the Grüneysen ratio, as well as a quite systematic study of prediction of the Seebeck coefficient and the thermopower. In both those cases, we found that the model can bring some qualitative predictions.

C.11 High temperature superconductors and Mott transition

C.11.1 Cuprate superconductors *(M. Ferrero, O. Parcollet)*

One of our directions of research consists in developing systematic *hybrid* methods to solve microscopic models of strongly correlated systems, like e.g. the Hubbard model, or the 3 bands model of cuprates. Indeed, direct numerical approaches like Quantum Monte Carlo have failed to solve these models because e.g. of the famous sign problem (in contrast to their bosonic analogues). New hybrid methods are therefore emerging, mixing analytical and physical insights with innovative algorithms in order to bypass this major difficulty, and making the traditional distinction between "numerical experiment" and "theory" largely obsolete.

Roughly speaking, one can distinguish two strategies: in the *top-to-bottom* strategy, one starts from high temperature (or high doping) regions where the physics is simpler, and progresses towards lower temperature. This follows in spirit the Renormalization Group idea : start from high energy physics, and let progressively the low energy degrees of freedom emerge; in the *bottom-to-top* strategy, one tries to understand the zero temperature ground state, its quantum properties, and then deduce the finite temperature properties from there. Dynamical Mean Field Theory (DMFT) and its extensions implement the first strategy, while DMRG and extensions are an example of the second one.

Cluster DMFT methods are technically a systematic expansion of the two-particle irreducible Luttinger-Ward-Baym-Kadanoff functional around the atomic limit. Physically, DMFT can also be seen as a quantum generalization of the classic Weiss mean field for the Mott transition, mapping a lattice problem onto an effective quantum impurity problem (Anderson model) in a self-consistent bath. Its cluster extensions then map the lattice model onto N such coupled impurities (in their bath). The cluster size N is the control parameter : it interpolates from the mean field ($N = 1$) to the exact solution of the lattice model ($N \to \infty$), and determines the resolution in momentum space of the method. Cluster methods open a route to a controlled solution of the many-body models, starting from high temperature or doping, where DMFT is only weakly corrected. Physically, this strategy is well-suited for many strongly correlated materials since they have many different possible instabilities at low temperature, while their intermediate temperature properties can be expected to be more universal. Cluster methods exist in various forms. For example, in the so-called Dynamical Cluster Approximation version, the Brillouin zone is tiled with a finite number of patches, on which the electronic self-energy is approximated by a function of frequency only (constant in momentum). The bigger the cluster is, the more refined the resolution, as illustrated on Fig. C.3.

Our work has followed two complementary directions. First, in [t08/192, t09/114], using a *minimal* two sites cluster approach (the left picture on Fig. C.3), we proposed a very simplified description of the normal phase of cuprates in terms of a selective Mott transition in momentum space, where the nodal regions stay metallic while the antinodal regions become insulating. Second, we confirmed this picture by comparing systematically the solution for various cluster sizes, up to the largest cluster doable with reasonable resources (16 sites), e.g. those represented on Fig. C.3 [t09/105, t09/129, t10/122] (the cluster size is limited in practice by the resurgence of the sign problem). Those calculations were made accessible by huge recent progress in algorithms, including our new continuous time quantum Monte Carlo "CT-AUX" algorithm designed for cluster problems, which is now used by several groups worldwide [t08/086]. Finally, the consequences of this physical picture for $c-$axis optical conductivity were also investigated, in collaboration with the group of D.

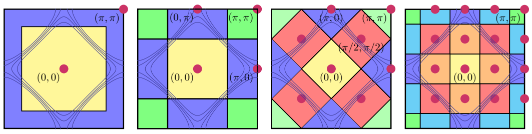

Figure C.3: *The momentum resolution in the Brillouin zone for some Cluster DMFT methods with 2,4,8, and 16 patches, from [t10/122].*

Basov (San Diego, USA) [t10/259]. The consequences of this idea in the superconducting phase is currently under investigation, following the first results obtained with small clusters in [t07/084].

C.11.2 Iron-based superconductors *(M. Ferrero, O. Parcollet)*

In 2009, the question of the degree of correlation of the new iron-based (pnictides) superconductors was strongly debated, in particular in the DMFT community. Therefore, in [t09/115], we studied the strength of electronic correlations in one of the iron-based (pnictides) superconductors, using the first implementation of an ab-initio approach combining the local density approximation (LDA) and Dynamical Mean Field Theory in the framework of the full-potential linear augmented plane waves (FLAPW) method. Our findings support the physical picture of a metal with intermediate correlations.

C.11.3 Effect of crystal field splitting on the Mott transition *(M. Ferrero, O. Parcollet)*

In [t08/035], we investigated the effect of the crystal-field splitting on the Mott metal-insulator transition in correlated materials such as transition-metal oxides. At large values of the splitting, a transition from a two-band to a one-band metal, as the on-site repulsion increases, is followed by a standard Mott transition for the remaining band. At small values of the splitting, a direct transition from a two-band metal to a Mott insulator with partial orbital polarization is found.

C.12 Antiferromagnets and spin liquids

C.12.1 Classical frustrated spin systems *(G. Misguich)*

In [t08/206] we explored the phase diagram of a two-dimensionnal classical spin-like model which captures the physics of non-collinear antiferromagnets. In such systems the order parameter is not a simple vector but a matrix in $O(3)$. At finite temperature the magnetic ordering is forbidden by the Mermin-Wagner theorem but the chirality degrees of freedom associated to the two connected components ($\sim SO(3)$) of $O(3)$ gives rise to a finite temperature transition (discrete symmetry breaking). Using Monte-Carlo simulations (Wang-Landau) we explained that the particular attraction between the chirality domain walls and the Z_2 vortices associated to $SO(3)$ is a mechanism which favors the first-order nature of the chiral transition in frustrated spin systems.

In [t11/103] we introduced some classical spin structures which respect all the lattice symmetries *modulo global* 0(3) *spin transformations*, cf Fig. C.4. Dubbed "regular magnetic orders" (RMO), they are defined as spin configurations for which any lattice symmetry (translations, etc.) can be absorbed by a global spin rotation in $O(3)$. We show how to construct these states for any given lattice using simple group theory arguments. From a physical point of view, we showed that RMO are ground-states of many frustrated Heisenberg models, including those for which the energy minimization cannot be done analytically.

C.12.2 Quantum dimer models *(G. Misguich)*

Heisenberg models offer accurate descriptions of many antiferromagnetic insulators but in several cases, quantum fluctuations drive the system to phases without any magnetic order, even at $T = 0$. Those phases, so called "spin-liquids", are not easily described directly in terms of the spin degrees of freedom but they can be qualitatively understood through simplified models where the basic degrees of freedom are *pairs* of spins coupled in a singlet state, also called valence-bond, or *dimer*. A quantum dimer model (QDM) describes the dynamics of these (short-ranged) singlet pairings. In collaboration with F. Mila (Lausanne), we investigated the liquid phase of the QDM on the triangular lattice [t07/159]. There, we proposed some variational approximation to describe the gapped Z_2 vortex excitations (dubbed "visons") which caracterize this phase.

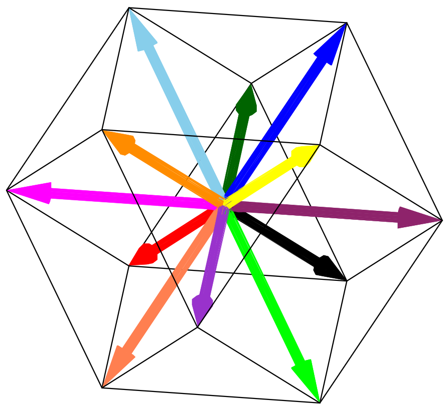

Figure C.4: Spin directions of a twelve-sublattice "cuboc" state on a kagome network

C.12.3 Quantum spin liquids *(G. Misguich)*

[t07/161], [t08/250] and [t11/018] correspond to three book chapters (one in collaboration with C. Lhuillier) on quantum spin liquids and fractionalization in quantum antiferromagnets.

C.12.4 The valence bond glass phase *(G. Biroli)*

In collaboration with M. Tarzia [t08/150] we showed that a new glassy phase can emerge in presence of strong magnetic frustration and quantum fluctuations. It is a Valence Bond Glass. We studied its properties solving the Hubbard-Heisenberg model on a Bethe lattice within the large N limit introduced by Affleck and Marston. This new quantum glassy phase has no electronic or spin gap (although a pseudo-gap is observed), it is characterized by long-range critical valence bond correlations and is not related to any magnetic ordering. This phase was recently found in experiments by Mclaughlin *et al.* in double Perovskite Ba_2YMoO_6.

C.12.5 Dimers on the cubic lattice *(G. Misguich, V. Pasquier)*

[t08/079] is the continuation of a previous work [t06/197] concerning a phase transition in a three-dimensional classical dimer model on the cubic lattice. Each dimer occupies two sites in such a way that each site is covered by one and only one dimer. In addition to this hard-core constraint, an energy equal to -1 times the number of square plaquettes with two parallel dimers is associated to each configuration. At low temperature the plaquette interaction favors a regular (crystalline) arrangements of dimers. At high temperature the dimers are no longer ordered but their correlations decay algebraically with distance. The later phase has been dubbed "Coulomb phase". The precise nature of the transition between the crystal and the Coulomb phase has not yet been fully elucidated and this work presents a detailed numerical analysis of the correlation functions at the transition.

C.12.6 Vacancy localization in the square dimer model *(J. Bouttier, E. Guitter)*

In [t07/070], we study the classical dimer model on a square lattice with a single vacancy by developing a graph-theoretic classification of the set of all configurations which extends the spanning tree formulation of close-packed dimers. With this formalism, we can address the question of the possible motion of the vacancy induced by dimer slidings. We find a probability $57/4 - 10\sqrt{2}$ for the vacancy to be strictly jammed in an infinite system. More generally, the size distribution of the domain accessible to the vacancy is characterized by a power law decay with exponent 9/8. On a finite system, the probability that a vacancy in the bulk can reach the boundary falls off as a power law of the system size with exponent 1/4. The resultant weak localization of vacancies still allows for unbounded diffusion, characterized by a diffusion exponent that we relate to that of diffusion on spanning trees.

C.13 Ultra-cold atomic gases

C.13.1 Fermionic Mott transition *(M. Ferrero, O. Parcollet)*

In [t08/191], we performed a theoretical study of a fermionic gas with two hyperfine states confined to an optical lattice, in order to discuss the realization of the fermionic Mott transition in recent experiments (Joerdens *et al.*, 2008). We derived a generic state diagram as a function of interaction strength, particle number, and confining potential. We discussed the central density, the double occupancy and their derivatives as probes for the Mott state.

C.13.2 Polarized superfluidity in the attractive Hubbard model with population imbalance *(M. Ferrero, O. Parcollet)*

In [t08/190], we studied a two-component Fermi system with attractive interactions and different populations of the two species in a cubic lattice. For an intermediate coupling we found a uniformly polarized superfluid which is stable down to very low temperatures. The momentum distribution of this phase closely resembles that of the *Sarma* phase, characterized by two Fermi surfaces. This phase is shown to be stabilized by a potential energy gain, as in a BCS superfluid, in contrast to the unpolarized BEC which is stabilized by kinetic energy.

C.14 Graphene

C.14.1 Graphene fundamental physics *(C. Bena)*

Graphene has been studied extensively in the recent years, especially after it became possible to fabricate it through exfoliation. Its most fascinating aspect is the existence of the linearly-dispersing gapless excitations in the vicinity of the Dirac points. Over the past few years we have focused on analyzing both the fundamental physics of graphene, as well as on making predictions for the local density of states measurable in STM experiments in graphene, and on making connection to these experiments. Concerning the fundamental aspects, together with G. Montambaux, in [t11/079] we have addressed some subtle fundamental issues arising in the tight-binding study of graphene, as well as of other systems that have a crystalline structure with more than one atom per unit cell, for which the choice of tight-binding basis is not unique. Also in [t08/300], we have analyzed the real-space free Green's function matrix, and its analytical expansions at low-energy, carefully incorporating the discrete lattice structure of graphene and the form of the atomic-orbital wave function, and we have computed the real-space Green's function in the presence of an impurity.

C.14.2 Effects of impurity scattering in graphene on the local density of states *(C. Bena)*

We have shown that the analysis of the local density of states (LDOS) measurable in STM experiments can be used to establish both the nature of the impurities, as well as the form of the full Hamiltonian of the system (and not only the band structure). Thus in [t07/226] we showed that the chirality of quasiparticles gives rise to a peculiar signature in the Friedel oscillations generated in the presence of an impurity, and we predicted that this signature can be extracted from the Fourier transform of the local density of states. These prediction were confirmed by the groups of P. Mallet, J. Y. Veuillen (Grenoble) and of K. Kern, I. Brihuega (Stuttgart) [t11/077]. Also, with the experimental group of L. Simon (Mulhouse) in [t08/298] we showed that it is possible to analyze the real-space LDOS to retrieve information about the position and nature of impurities in graphene. In [t09/330] we calculated the LDOS in graphene in the quantum Hall regime and showed that it can be used to understand the form of the quasiparticle wavefunction, as well as the nature of disorder in graphene.

C.14.3 Modified graphene and graphene-related materials *(C. Bena)*

With the experimental group of L. Simon (Mulhouse), in [t10/249] we have observed a "new" type of ordering in monolayer graphene with intercalated small gold clusters between the top monolayer graphene and the buffer layer of epitaxial graphene. In this system we have found a strong pattern of standing waves at high energies, with period twice that of the atomic lattice. A detailed analysis of the standing wave patterns using Fourier transform scanning tunneling spectroscopy suggested that this phenomenon can arise from a strong modification of the band structure of graphene and (or) from the formation of charge density waves. Subsequently, in [t10/251] we have studied modified graphene in the presence of a next-to-nearest-neighbor coupling and a third-nearest-neighbor coupling. We have shown that extra Dirac points, as well as hybrid points (the electrons have a linear dispersion along one direction and a quadratic dispersion along the perpendicular direction) may appear in the spectrum when large values of the third nearest neighbor coupling are considered. This in turn yields a lowering of the energy of the Van Hove singularities in the graphene density of states.

C.15 Bosonic systems

C.15.1 Super-solidity in He^4 *(G. Biroli)*

The possibility of the existence of super-solids was discussed by Leggett and Andreev and Lifshitz forty years ago. The first experimental evidences found by Kim and Chan in 2005 triggered a lot of new activity, especially because their results could not be explained by the theories developed in the past. It is by now clear that disorder plays a crucial role: perfect crystals of He^4 are not super-solid. In collaboration with J-P. Bouchaud [t08/029] we have put forward a theory of super-solidity based on quantum plasticity induced by dislocations. Recent experiments have shown that dislocations play an important role, although more results are needed to obtain a clear picture. Another possibility put forward by Prokofiev *et al.* is that, at least in some experimental samples, the He^4 solid is a glass and not a crystal. In collaboration with C. Chamon and F. Zamponi [t09/232] we introduced a model of interacting bosons in three dimensions that displays this phase unambiguously and that can be analyzed exactly based on a mapping between quantum Hamiltonians and classical Fokker-Planck operators. This provides a proof that this state of matter, the super-glass, can indeed exist (our work was selected for a presentation on the APS journal). Later on, in collaboration with B. Clark, L. Foini and F. Zamponi [t10/272], we investigated whether glassiness enhances superfluidity. Using an upper bound on the superfluid fraction derived by Leggett we found that this is not the case. Our results suggest that the experimental observations of large superfluid fractions in He^4 after a rapid quench correspond to samples evolving far from equilibrium, instead of being in a stable glass phase.

C.15.2 Bose Einstein condensation of magnons *(G. Misguich)*

$TlCuCl_3$ is an antiferromagnetic insulator with a non-magnetic ground-state (spin singlet). The elementary excitations (magnons) have a gap that can be reduced by an external magnetic field. When the gap closes, the magnons *condense*. This is the onset of magnetic long-ranged order (perpendicular to the applied field). In [t07/160] we extended our previous calculations (based on a self-consistent Hartree-Fock calculation and a realistic dispersion relation of the magnons) to compare the computed magnetization curves with those measured experimentally in the group of H. Tanaka in Tokyo.

C.16 Out of equilibrium dynamics of quantum systems

C.16.1 Quantum out of equilibrium dynamics *(B. Sciolla, G. Biroli)*

Significant advances in the field of ultra cold atoms have allowed one to engineer macroscopic quantum many-body systems in almost perfect isolation from the environment and probe their out of equilibrium dynamics. In collaboration with B. Sciolla [t10/123] we exactly solved the off-equilibrium dynamics of the infinite dimensional Bose Hubbard Model after a quantum quench, which corresponds to a sudden change of the repulsive interaction. This protocol and this model are both relevant for experiments. For integer filling, we found a dynamical transition separating regimes of small and large quantum quenches starting from the superfluid state. This transition is very similar to the one found for the fermionic Hubbard model by mean field approximations. On a different front, motivated by the studies of quantum non-equilibrium dynamics induced by an external drive, we studied the driven dynamics of quantum coarsening. In collaboration with C. Aron and L. Cugliandolo [t09/231, t10/270] we analyzed models of M-component rotors coupled to two electronic reservoirs at different chemical potentials that generate a current threading through the system. In the large M limit we derived the dynamical phase diagram as a function of temperature, strength of quantum fluctuations, voltage and coupling to the leads. We showed that the slow relaxation in the ordering phase is universal. Our results should apply to generic driven quantum coarsening. Finally, we studied the symmetries of the generating functionals related to the dynamics of quantum and classical systems. This allows a more deeper understanding of fluctuation-dissipation relations and fluctuation theorems out of equilibrium. The part on classical dynamics has already been published in [t10/269].

C.16.2 Thermalization of isolated quantum systems *(G. Biroli)*

The thermalization for isolated quantum systems after a sudden parameter change, a so-called quantum quench, is a question that recently received a lot of attention because of experiments in cold atoms. In collaboration with C. Kollath and A. Lauchli [t09/226] we investigated the pre-requisites for thermalization focusing on the statistical properties of the time-averaged density matrix and of the expectation values of observables in the final eigenstates. We found that eigenstates, which are rare compared to the typical ones sampled by the microcanonical distribution, are responsible for the absence of thermalization of some infinite integrable models and play an important role for some non-integrable systems of finite size, such as the Bose-Hubbard model. We clarified the so called Eigenstate Thermalization Hypothesis and discussed two alternative scenarios for thermalization. Moreover, in [t10/115] we analyzed the statistical properties of the energy levels of the extended one dimensional Bose Hubbard model and related them to thermalization and the absence thereof found in previous DMRG analyses.

C.16.3 Quantum phase space Brownian motion, a simple open system *(M. Bauer, D. Bernard)*

The study of open quantum systems is already quite old, but recent advances in quantum manipulations of simple systems (photons, electrons, Q-bits) coupled to an environment have led to a revival of interest. On a more mathematical side, these systems lead naturally in certain limits to quantum versions of the standard classical stochastic calculus. A missing ingredient at the moment are stopping times.

In [t11/136] we present a detailed study of a simple quantum stochastic process, the quantum phase space Brownian motion, which we obtain as the Markovian limit of a simple model of an open quantum system: an harmonic oscillator coupled linearly to a reservoir of harmonic oscillators, in such a way that the total number operator is conserved. Taking a continuous frequency distribution for the reservoir and going to a long time/small coupling limit leads to drastic simplifications. This physical description of the process allows us to specify and to construct the dilation of the quantum dynamical maps, including conditional quantum expectations. The quantum phase space Brownian motion possesses many properties similar to those of the classical Brownian motion, notably its increments are independent and identically distributed. Possible applications to dissipative phenomena in the quantum Hall effect are suggested. We also briefly mention a proposal for the notion of quantum stopping time and illustrate it on a discrete time quantum evolution.

C.17 Quantum entanglement

C.17.1 Entanglement of two disjoint intervals in a spin chain *(V. Pasquier)*

In collaboration with Shunsuke Furukawa and Jun'ichi Shiraishi [t08/187] we have studied the generic scaling properties of the mutual information between two disjoint intervals, in a class of one-dimensional quantum critical systems described by the c=1 bosonic field theory.[1]

A numerical analysis of a spin-chain model reveals that the mutual information is scale-invariant and depends directly on the boson radius. The results have been interpreted in terms of correlation functions of branch-point twist fields. This study has provided a new way to determine the boson radius, and furthermore has demonstrated the power of the mutual information to extract more refined information of conformal field theory than the central charge.

C.17.2 Entanglement in Rokhsar-Kivelson wave-functions and Shannon entropy of spin chains *(J.-M. Stéphan, G. Misguich, V. Pasquier)*

The scaling of entanglement in two-dimensional (2d) quantum systems (massive or critical) is an important theoretical question but the calculations (numerical or analytical) are usually difficult – if not impossible – for a generic many-body Hamiltonian. In [t09/089] (collaboration with S. Furukawa) it was realized that the calculations simplify dramatically for a specific family of wave-functions, dubbed "Rokhsar-Kivelson". Such a 2d *quantum* state $|\psi\rangle$ is constructed from a 2d *classical* model of statistical mechanics (ex: Ising, vertex or hard-core dimer models) and the weight $\psi(c)$ of a classical configuration c is simply the (square root of) classical Boltzmann weight $\psi(c) = \exp(-\frac{1}{2}E(c))$. In some appropriate geometry, the entanglement entropy of a half-infinite cylinder is then nothing but the Shannon entropy $S = -\sum_i p_i \ln(p_i)$ associated

[1] The mutual information $I_{A,B}$ of two subsystems A and B is defined as $I_{A,B} = S_A + S_B - S_{A\cup B}$ where S_Ω is the entanglement (Von-Neumann) entropy of the subsystem Ω.

to the (classical) probabilities p_i to observe a configuration i at the frontier between the upper and lower half-infinite cylinders. These p_i can in turn be obtained from the dominant eigenvector of the classical transfer matrix. This allowed to study the scaling of the entanglement in some RK states for relatively large 2d systems. The dominant term is proportional to the length of the boundary between the two subsystems but we identified a sub-leading and universal constant to the entropy, which depends on the compactification radius for critical states corresponding to a free boson. The 2d Ising universality class was investigated in [t10/117].

In the picture above, the eigenvector of the transfer matrix can be viewed as a 1d wavefunction. Then, the findings above lead us to consider its Shannon entropy (and Rényi generalization) as a new probe for 1d quantum systems. In [t10/225] the limit $n = \infty$ or the Rényi entropy was related to an entanglement measure in the case of the XXZ chain. In [t11/102] we found a phase transition as a function of the of the Rényi parameter n, which was explained in CFT terms as a boundary phase transition and illustrated numerically on the XXZ and $J_1 - J_2$ chains.

C.17.3 Fidelity in critical spin chains *(J. Dubail, J.-M. Stéphan, H. Saleur)*

In recent years, it has been understood that entanglement measures are useful tools for the understanding and characterization of new and exotic phases of matter, especially when the study of local order parameters alone proves insufficient. Among these measures, the entanglement entropy, defined through a bipartition of the quantum system, is the most established. In [t10/265] we introduce another quantity which we call "bipartite fidelity" for a generic quantum system. It is defined as the overlap between its ground-state wave function, and the ground-state one would obtain if the interactions between two complementary subsystems were switched off. Although it is not strictly speaking an entanglement measure, we show that it enjoys several nice properties that are similar to the entanglement entropy. In particular, it allows generically to detect quantum phase transition, and admits a universal scaling form $\sim (c/8)\ln L$ at one-dimensional quantum critical points. L is a typical size of the smallest subsystem and c is the central charge of the underlying conformal field theory, describing the system at long distances. We will also briefly discuss other potential applications, for example to topologically ordered wave functions. In a related work [t08/246], Campos-Venuti, Saleur and Zanardi have studied the overlap of ground state wave functions of XXZ hamiltonians with different values of the anisotropy parameter, and suggested deep relations between the corresponding fidelity and entanglement.

C.17.4 Entanglement spectrum in one-dimensional systems *(A. Lefèvre)*

Recent years have seen growing interest in studying quantum entanglement spectra. At quantum critical points, they display remarkable scaling properties, which encode useful information about correlations and the underlying symmetries. In addition, they are at the core of algorithms using matrix product states such as DMRG, which compute truncated spectra in order to generate various observables. In [t08/265], we derived universal part of the continuous spectrum of the reduced density matrix in one dimension, using a conformal field theory method introduced by Calabrese and Cardy. The outcome of our calculation is perfectly in line with exact and numerical results obtained for XX and XXZ chains. Although this approach cannot provide the degeneracy of eigenvalues, it predict accurately the gaps beetween them. Our results have been since widely used in order to interpret numerical results from DMRG and design precise convergence tests.

C.18 One-dimensional systems, quantum impurities and nanosystems

C.18.1 Transport out of equilbrium in the IRLM *(E. Boulat, H. Saleur)*

Since 1995 ([t95/178]), Saleur and coworkers had proposed a strategy to compute out of equilibrium transport properties in interacting quantum impurity problems by combining the Bethe ansatz with a scattering description of the (open) systems. While in reasonable agreement with experiments, their results had remained the subject of some controversy, in part because of the underlying integrability, which describes transport in terms of quasiparticles very different from the physical electrons. In the last few years, N. Andrei and collaborators had made this criticism more acute in their (inconclusive) study of the interacting resonant level model (IRLM). In a series of works with E. Boulat and P. Schmitteckert, Saleur has revisited the issue. After extending the logic pioneered in [t95/178] to the IRLM in [t07/061], they managed to calculate the current out of equilibrium analytically *and* numerically in [t08/244]. The numerical calculation is intricate, and relies on a sophisticated adaptation of the time dependent DMRG technique. Since the results of [t08/244] only hold in the universal field theoretic limit, simulations have moreover to be performed in a wide range of values of microscopic parameters, in order to identify and validate the scaling region. The outcome entirely supported the analytical results, hence validating the approach pioneered in [t95/178]. It was, in fact, one of the very first times where non equilibrium transport in the presence of interactions could be convincingly tackled both numerically and analytically.

One of the fascinating features of this type of quantum dot problem is the presence of quaisparticles with a charge different from the electron charge. This cannot be seen directly when studying the current, but becomes observable when considering the zero temperature shot noise, where, in the Poissonian limit, the Fano factor (noise/current) gives directly the charge of the carriers. In [t10/116], Branschaedel, Boulat, Saleur and Schmitteckert on the one hand managed to calculate the shot noise in closed form for the IRLM, on the other hand, managed to also determine this shot noise numerically, finding again excellent agreement between the two approaches. The numerical calculation of the noise itself is of course considerably difficult, and relies on a straightforward evaluation of time integral of two point functions of the current, together with a delicate analysis of the finite size effect, as described in [t11/053]. Once again, the results are a first, and justify the astounding CPU time (above 2 million hours) spent on the project by the Karlsruhe Institute. Meanwhile, Saleur and coworkers have kept working [t07/202] on the determination of the full counting statistics, and have just managed to calculate it analytically for the problem of edge states tunneling in the fractional quantum Hall effect and the IRLM. The corresponding work will be published soon, and exhibits many relevant features, including a verification of the Galavotti-Cohen identities.

C.18.2 Friedel oscillations in the Kondo effect *(H. Saleur)*

The *length* dependence of Kondo physics is much less well understood than the temperature dependence. It is generally expected that physical quantities exhibit a crossover at a length scale roughly the inverse of the Kondo temperature but this crossover has never been observed experimentally and has sometimes been questioned theoretically. One way of observing this length scale is through the density oscillations around a magnetic impurity. This idea has become particularly timely due to possibility of scanning tunneling microscopy of magnetic ions on metallic surfaces.

Surprisingly, the literature on the subject of charge oscillations in the Kondo problem was almost silent for many years. The origin is probably the idea of "spin-charge" separation, which suggest that at low energy, all the physics is in the spin sector, the charge sector being unaffected. This is not correct, but for slightly subtle reasons. The issue was fully clarified by Affleck, Borda and Saleur in [t08/108] who properly identified the way to calculate the charge density in the scaling limit, performed perturbative analysis in the UV and IR, and also carried out numerical renormalization group calculations.

C.18.3 Effects of interactions in carbon nanotubes *(C. Bena)*

The physics of one-dimensional systems such as carbon nanotubes is believed to be dominated by interactions, which lead to very strongly correlated states of matter deemed Luttinger liquids. The main goal of our research in this field is to theoretically understand and model quantities measurable in transport experiments, such as the conductance and the noise, as well as the local density of states measurable in an STM experiment. In particular, over the past years we have tried to understand how these quantities, in particular the high-frequency non-symmetrized noise, are affected by the interplay between the strong electronic interactions and the presence of metallic leads. Thus, with I. Safi (LPS Orsay) and A. Crepieux (CPT Marseille), we have computed the non-symmetrized finite-frequency noise in both FQHE edge states [t07/077] and in nanotubes [t08/153]. We were among the first to study the effects of the interactions on the asymmetry in the finite-frequency non-symmetrized noise, and we predicted that the fractionalization of charge in nanotubes can be tested by such a measurement. Furthermore, in [t09/331], we have shown that the apparently non-interacting features observed by the group of N. Mason (Urbana Champaign) in STM experiments performed with a superconducting tip do not rule out the existence of strong interactions in carbon nanotubes.

C.18.4 Carbon nanotubes in contact with superconductors *(C. Bena)*

Together with K. Le Hur (Yale) and S. Vishveshwara (UIUC) [t07/227], we have analyzed the density of states of a nanotube in contact with a superconducting substrate and we have found that an unconventional double-gap situation can arise in the two bands for nanotubes of large radius: due to the interactions in the nanotube, the appearance of a BCS gap in one band of the nanotube stabilizes superconductivity in the second band. Also, in collaboration to the Quantronics group in SPEC CEA Saclay, we have analyzed experimentally and theoretically carbon nanotubes connected to superconducting electrodes. These can carry a supercurrent mainly transmitted by discrete entangled electron-hole states confined to the nanotube, called Andreev bound states (ABS). In [t10/127] we have made the first tunneling spectroscopy of individually resolved ABS. Also, by analyzing the evolution of the ABS spectrum with a gate voltage and with magnetic flux, we have shown that the ABS arise from the discrete electronic levels of the molecule and that they reveal detailed information about the energies of these levels, their relative spin orientation and the coupling to the leads.

C.19 Anderson localization

C.19.1 Anderson model on Bethe lattices: density of states, localization properties and isolated eigenvalue *(G. Biroli)*

In collaboration with G. Semerjian and M. Tarzia [t10/271], we revisited the Anderson localization problem on Bethe lattices, putting in contact various aspects which have been previously only discussed separately. For the case of connectivity 3 we compute by the cavity method the density of states and the evolution of the mobility edge with disorder. Furthermore, we show that below a certain critical value of the disorder the smallest eigenvalue remains delocalized and separated by all the other (localized) ones by a gap. We also study the evolution of the mobility edge at the center of the band with the connectivity, and discuss the large connectivity limit.

C.19.2 Anderson localization transitions *(T. Garel, C. Monthus)*

We have studied various aspects of Anderson localization transitions. On the Cayley tree, Anderson localization can be analyzed in terms of traveling waves and presents interesting analogies with the directed polymer model [t08/186, t11/020]. In dimension $d = 2, 3$, we have used the exact Aoki renormalization procedure [t09/088]. An essential property of Anderson localization transitions is the multifractality of eigenfunctions, as well as the multifractality of two-point Landauer transmission that we have studied in various geometries [t09/051, t09/087, t09/155]. We have shown how some general properties of multifractal spectra could be obtained within a real-space renormalization analysis: in [t09/177], we have analyzed the physical origin of the exact symmetry of the multifractal spectrum in relation with the Gallavotti-Cohen fluctuation relations of large deviation functions that are well-known in the field of non-equilibrium dynamics; in [t10/069], we have explained the statistics of critical Inverse Participation Ratios in terms of the traveling-wave solutions of some appropriate renormalization procedure. In [t10/136], we have developed a strong disorder perturbation theory to better understand the strong multifractality regime; finally in [t11/049], we have analyzed the exact renormalization of the Dyson hierarchical model for Anderson localization. Besides these studies of electron localization, we have also characterized the localization properties of phonons in random systems [t10/080, t11/010].

C.19.3 Many body localization *(T. Garel, C. Monthus)*

The problem of many body localization can be seen as an Anderson localization problem in configuration space. For a one-dimensional lattice model of interacting fermions with disorder, we have applied an exact renormalization procedure in configuration space to analyze the finite-disorder critical point [t10/043].

C.19.4 Spectral features and localization properties of simple quantum systems *(J.-M. Luck)*

The fluctuations of the quantum conductance through a one-dimensional disordered system consisting of independent scattering units has been investigated, in the regime where the lengths of the elementary units and their transmission probabilities are drawn independently, according to broad distributions. This models e.g. the Anderson localization problem for an electron in the presence of a non-stationary random potential whose fluctuations grow with distance. Four different phases have been characterized, depending on the values of the Lévy indices of both distributions: usual localization, underlocalization, superlocalization, and fluctuating localization [t07/112].

We have analyzed the tight-binding electronic spectra of various graphs with spherical topology, including the five Platonic solids, the fullerene, and two families of polyhedra. The effect of a quantized radial magnetic field and that of a radial electric field in the presence of strong spin-orbit interactions have been studied in parallel on the same structures. Most of these spectra have been obtained analytically in closed form. They exhibit a rich pattern of degeneracies. This work has also revealed an unexpected correspondence between the magnetic and electric problems at a special point [t08/003, t08/024].

The persistent currents and the magnetization of a multiply connected mesoscopic system have been explored in detail. The sample consists of two unequal clean metallic rings sharing a contact point, in a magnetic field. Many novel features with respect to the single-ring geometry have been underlined, including the pattern of twofold and threefold degeneracies, the key rôle of length and flux commensurability, and in the case of commensurate ring lengths the occurrence of infinitely many idle levels which do not carry any current [t08/202].

We have investigated the dynamical behavior of a quantum particle in low-dimensional systems which are exceptions to the common wisdom on localization, in the sense that the localization length diverges at some isolated special energies. Two well-known one-dimensional examples have been dealt with in parallel: the chain with off-diagonal disorder and the random-dimer model. The mean density profile of the particle becomes critical in the long-time regime. The quantum motion exhibits a peculiar kind of anomalous diffusion that we have dubbed bi-fractality [t11/009].

C.20 Bosonization in any dimensions and the Monte Carlo sign fermion problem *(C. Pépin)*

In [t09/276, t10/015, t10/018], we derive a new bosonization method for a system of interacting fermions, working in any dimension. The method starts with a Hubbard-Stratonovich decomposition of the quartic interaction into a carefully chosen set of bosonic modes. The resulting field theory is quadratic in the fermionic degrees of freedom. We then write the equation of motion of the fermions self-consistently interacting with the bosonic field. Lastly this equation of motion is re-exponentiated into the partition function, using a technique standard in the physics of stochastic equation : the Bechhi-Rouet-Stora-Tyupkin (BRST) technique. It involves extending the space of variables to a supersymmetric version of it, with two additional supersymmetric parameters θ and $\bar{\theta}$, which effectively reduce the dimension by two units. The resulting lagrangian is a ψ^4-field theory of non commutative but periodic in imaginary time [hence bosonic] fields ψ. We have started testing this new bosonization onto the old problem of re-summing the non analyticities of the Landau Fermi liquid theory, and just recently got a result [unpublished].

Meanwhile, we got interested in determining whether our new method of treating interacting fermions could be useful into bringing some new light into the long standing Monte Carlo sign fermion problem. The statistical errors in Quantum Monte Carlo (QMC) simulations are well known to diverge for fermions in interaction. In these simulation techniques one evaluates the average $\langle A \rangle = Z^{-1} \sum_c A(c)p(c)$ where $p(c)$ is the probability of a specific configuration c, while $Z = \sum_c p(c)$. This technique is very well suited to the evaluation of statistical averages, as soon as $p(c)$ is positive. But in the case of a system of interacting fermions, $p(c)$ is given by a fermionic determinant, and can become negative for certain configurations of the internal field ϕ, where ϕ is, for example a Hubbard-Stratonovich field introduced above. Our idea is to circumvent this problem within our bosonization method. Instead of re-exponentiating the equations of motion like in the analytic part, we want to invert them numerically, after regularizing them. The trick here is that since the we have now written the equations of motion for a bosonic field [representing a particle-hole pair], a regularization is now possible, which eliminates the poles, hence all possibility of a singularity. Our solution is indeed positive for any configuration of the field [absence of sign problem], and the (QMC) codes converge quickly. We are currently checking the convergence to the correct value, in the limit of large number of sites.

C.21 Open source libraries for strongly correlated systems *(O. Parcollet)*

We participate to the development of open sources libraries for strongly correlated systems within the project ALPS 2.0 (Algorithms and

Libraries for Physics Simulations) [t11/084].

C.22 Polymers and polyelectrolytes

The functionalization of surfaces by the adsorption or grafting of polymers or polyelectrolytes is one of the most versatile and efficient techniques to produce biomaterials or biosensors.

In the realm of the microelectronic industry, one of the big challenges is to find affordable ways of generating high-density ordered nano-structures that can be transferred to a silicon substrate, in order to produce low cost microchips. This can be done by adsorbing and ordering lamellar phases of block copolymers on nano-patterned surfaces.

For both cases described above, the self-consistent field theory is used to predict the phase diagrams, the polymer concentration, the ion profiles and other properties as a function of the physical parameters. This should allow a better control of the properties of the surface.

C.22.1 Block copolymer at nano-patterned surfaces *(H. Orland)*

In [t10/262], we present numerical calculations of lamellar phases of block copolymers at patterned surfaces. We model symmetric diblock copolymer films forming lamellar phases and the effect of geometrical and chemical surface patterning on the alignment and orientation of lamellar phases. The calculations are done within self-consistent field theory (SCFT), where the semi-implicit relaxation scheme is used to solve the diffusion equation. Two specific set-ups, motivated by recent experiments, are investigated. In the first, the film is placed on top of a surface imprinted with long chemical stripes. The stripes interact more favorably with one of the two blocks and induce a perpendicular orientation in a large range of system parameters. However, the system is found to be sensitive to its initial conditions, and sometimes gets trapped into a metastable mixed state composed of domains in parallel and perpendicular orientations. In a second set-up, we study the film structure and orientation when it is pressed against a hard grooved mold. The mold surface prefers one of the two components and this set-up is found to be superior for inducing a perfect perpendicular lamellar orientation for a wide range of system parameters.

C.22.2 Organization of block copolymers using NanoImprint lithography: comparison of theory and experiments *(H. Orland)*

In [t11/090], we present NanoImprint lithography experiments and modeling of thin films of block copolymers (BCP). The NanoImprint technique is found to be an efficient tool not only to align lamellar phases perpendicularly to the substrate, but also to get rid of in-plane defects over distances much larger than the natural lamellar periodicity. The modeling relies on self-consistent field calculations done in two- and three-dimensions, and is found to be in good agreement with the experiments. It also offers some insight on the NanoImprint lithography setup and on the conditions required to perfectly ordered BCP lamellae.

C.23 Coulombic systems

Electrostatics is one of the main driving forces in biological systems. In particular, the organization of ions and water around charged biomolecules substantially determines their in- and out-of-equilibrium biochemical properties. The mean-field Poisson-Boltzmann theory has been successfully applied to biological systems. However, it lacks two important ingredients: i) the discreteness of water, which in first approximation can be viewed as permanent dipoles, and ii) the finite size of ions and of water molecules. The works in this section deal with including these two effects, namely dipolar water and finite sizes of ions and water, by suitably modifying the Poisson-Boltzmann equations. This generalized theory is applied to the solvation of proteins or small molecules in water.

C.23.1 Incorporating dipolar solvents with variable density in Poisson-Boltzmann electrostatics *(M. Bon, H. Orland)*

We describe a new way to calculate the electrostatic properties of macromolecules that goes beyond the classical Poisson-Boltzmann treatment with only a small extra CPU cost. The solvent region is no longer modeled as a homogeneous dielectric media but rather as an assembly of self-orienting interacting dipoles of variable density. The method effectively unifies both the Poisson-centric view and the Langevin Dipole model. The model results in a variable dielectric constant $\varepsilon(r)$ in the solvent region and also in a variable solvent density $\rho(r)$ that depends on the nature of the closest exposed solute atoms. The model was calibrated using small molecules and ions solvation data with only two adjustable parameters, namely the size and dipolar moment of the solvent. Hydrophobicity scales derived from the solvent density profiles agree very well with independently derived hydrophobicity scales, both at the atomic or residue level. Dimerization interfaces in homodimeric proteins or lipid-binding regions in membrane proteins clearly appear as poorly solvated patches on the solute accessible surface. Comparison of the thermally averaged solvent density of this model with the one derived from molecular dynamics simulations shows qualitative agreement on a coarse-grained level. Because this calculation is much more rapid than that from molecular dynamics, applications of a density-profile-based solvation energy to the identification of the true structure among a set of decoys become computationally feasible. Various possible improvements of the model are discussed, as well as extensions of the formalism to treat mixtures of dipolar solvents of different sizes.[t08/286]

C.23.2 Solvation of ion pairs: the Poisson-Langevin model *(H. Orland)*

Salt bridges play an important role in protein stability and protein-protein interactions. We have computed the electrostatics free energies of analogues of charged amino acid sidechains using two different implicit solvent models, the Poisson-Boltzmann (PB) model and our own Poisson-Langevin (PL) model, and compared their values to results from explicit solvent free energy calculations. A systematic difference is observed between the PB and explicit results, which we attribute to the basic assumption of PB that water density is constant. In contrast, the PL results match remarkably well with the explicit solvent results. We attribute this success to the ability of the PL model to give a realistic picture of the dielectric response of water to the presence of charged molecules.[t09/333]

C.23.3 Computing ion solvation free energies using the dipolar Poisson model *(H. Orland)*

A new continuum model is presented for computing the solvation free energies of cations in water. It combines in a single formalism based on statistical thermodynamics the Poisson model for electrostatics with the Langevin dipole model to account for nonuniform water dipole distribution around the ions. An excellent match between experimental and computed solvation free energies is obtained for 10 monovalent and divalent ions.[t09/312]

C.23.4 Beyond the Poisson-Boltzmann model: modeling biomolecule-water and water-water interactions *(H. Orland)*

We present an extension to the Poisson-Boltzmann model in which the solvent is modeled as an assembly of self-orienting dipoles of variable densities. Interactions between these dipoles are included implicitly using a Yukawa potential field. This model leads to a set of equations whose solutions give the dipole densities; we use the latter to study the organization of water around biomolecules. The computed water density profiles resemble those derived from molecular dynamics simulations. We also derive an excess free energy that discriminates correct from incorrect conformations of proteins.[t09/311]

C.24 Physics of DNA: theoretical and experimental investigations

DNA, the carrier of genetic information, is embedded in polymerized nucleic acids, and as a result, many topics of the molecular biology of gene raise fundamental issues of polymer physics, for instance in DNA condensation, in the interaction of DNA with surfaces, in DNA hybridization and in DNA translocation through membranes.

C.24.1 Aggregation and adsorption at the air-water interface of bacteriophage phi X174 single-stranded DNA *(J.-L. Sikorav)*

Chromosomal DNA molecules are in condensed states in cells, corresponding to a chain conformation much denser than that of a random coil state. A central issue in molecular biology is to understand the consequences of DNA condensation on fundamental processes such as DNA replication or gene expression. We have discovered a coupling between the processes of DNA condensation (here an aggregation in the bulk of the solution) and DNA adsorption at the air-water interface, thus establishing a link between the previously disconnected fields of DNA condensation and of surface science of DNA.[t08/305]

C.24.2 DNA adsorption at liquid/solid interfaces *(J.-L. Sikorav)*

We have characterized DNA adsorption at a liquid/solid interface by X-ray reflectivity.

Monodisperse double-stranded DNA molecules were adsorbed on a positively charged surface, obtained through chemical grafting of a homogeneous organic monomolecular on an oxide-free monocrystalline Si(111) wafer. The adsorbed DNA is found to incrust into the soft monolayer. The surface coverage is very high, and the adsorbed layer is expected to display 2D nematic ordering. This system is promising for the development of nucleic acid chip hybridization technologies.[t08/304]

C.24.3 Mechanism of thermal renaturation and hybridization of nucleic acids: Kramers' process and universality in Watson-Crick base pairing *(H. Orland, J.-L. Sikorav)*

The hybridization of complementary single-strands nucleic acids is involved in essential biological processes (such as genetic recombination) and is the most important tool of biotechnologies (through Polymerase Chain Reaction or PCR, DNA chips . . .). The understanding of its mechanism is therefore a subject of fundamental and applied interest. Yet, more than fifty years after their discovery, hybridization reactions remain poorly understood. They have been described in two types of experimental conditions: initially in simple homogeneous systems, and later in a variety of heterogeneous systems, in which the reacting chains undergo a phase separation (such as an aggregation or an adsorption) concomitant with the reaction. We have investigated the mechanism of hybridization in simple, homogeneous conditions, where the rate of the reaction is known to increase as a power law of the average degree of polymerization of the reacting single-strands. We have found that the reaction is not diffusion controlled (as believed earlier), but instead is an activated process that can be described with Kramers' rate theory. The reacting single-strands are in universal good solvent conditions. The length dependence of the rate results from a thermodynamic excluded volume effect. The scaling exponent is determined by an equilibrium monomer contact probability, which involves a critical exponent described by des Cloizeaux. The predicted value for this exponent (0.52 ± 0.01) agrees closely with the experimental results (0.51 ± 0.01). The rate of the hybridization can be considerably increased in heterogeneous systems, up to one million fold, and our work should contribute to clarify the mechanisms involved.[t08/284]

C.24.4 A model for polymer translocation *(K. Mallick)*

In [t10/063], we investigate a model of chaperone-assisted polymer translocation through a nanopore in a membrane. Translocation is driven by irreversible random sequential absorption of chaperone proteins that bind to the polymer on one side of the membrane. The proteins are larger than the pore and hence the backward motion of the polymer is inhibited. This mechanism rectifies Brownian fluctuations and results in an effective force that drags the polymer in a preferred direction. The translocated polymer undergoes an effective biased random walk and we compute the corresponding diffusion constant. Our methods allow us to determine the large deviation function which, in addition to velocity and diffusion constant, contains the entire statistics of the translocated length.

C.25 Statistical physics of homopolymeric RNA

Thermodynamic experiments, such as melting or pulling on RNA, allow to measure, or at least assess, some physical parameters necessary to parametrize their free energy function. In this section, we present some work on the thermodynamics of homo-RNA, in particular the determination of the loop exponents.

C.25.1 Impact of loop statistics on the thermodynamics of RNA folding *(H. Orland)*

Loops are abundant in native RNA structures and proliferate close to the unfolding transition. By including a statistical weight l^{-c} for loops of length l in the recursion relation for the partition function, we show that the heat capacity depends sensitively on the presence and value of the exponent c, even for a short explicit tRNA sequence. For long homo-RNA we analytically calculate the critical temperature and critical exponents which exhibit a non-universal dependence on c. [t08/049]

C.25.2 Secondary structure formation of homopolymeric single-stranded nucleic acids including force and loop entropy: implications for DNA hybridization *(H. Orland)*

Loops are essential secondary structure elements in folded DNA and RNA molecules and proliferate close to the melting transition. Using a theory for nucleic acid secondary structures that accounts for the logarithmic entropy $-c \log m$

for a loop of length m, we study homopolymeric single-stranded nucleic acid chains under external force and varying temperature. In the thermodynamic limit of a long strand, the chain displays a phase transition between a low temperature / low force compact (folded) structure and a high temperature / high force molten (unfolded) structure. The influence of c on phase diagrams, critical exponents, melting, and force extension curves is derived analytically. For vanishing pulling force, only for the limited range of loop exponents $2 < c < 2.479$ a melting transition is possible; for $c \leq 2$ the chain is always in the folded phase and for $2.479 < c$ always in the unfolded phase. A force induced melting transition with singular behavior is possible for all loop exponents $c < 2.479$ and can be observed experimentally by single molecule force spectroscopy. These findings have implications for the hybridization or denaturation of double stranded nucleic acids. The Poland-Scheraga model for nucleic acid duplex melting does not allow base pairing between nucleotides on the same strand in denatured regions of the double strand. If the sequence allows these intra-strand base pairs, we show that for a realistic loop exponent $c \approx 2.1$ pronounced secondary structures appear inside the single strands. This leads to a lower melting temperature of the duplex than predicted by the Poland-Scheraga model. Further, these secondary structures renormalize the effective loop exponent $\hat{c}$, which characterizes the weight of a denatured region of the double strand, and thus affect universal aspects of the duplex melting transition.[t11/092]

C.26 Statistical physics of random RNA

Random RNA is studied, in particular in order to shed some light on the expected glass transition at low temperature.

F. David has been interested in the problem of the secondary structure of long RNA strands (m-RNA for instance) and the role of base disorder on the secondary structure. Unlike protein folding, which exhibits a strong interdependence between secondary and tertiary structure, RNA folding may be studied at the level of secondary structures due to a clear separation of energy scales. Since the pioneering work of Bundschuh and Hwa, several authors have studied the statistical physics of RNA secondary structures for random sequences, in particular at IPhT. It is commonly believed that these systems undergo a freezing transition upon lowering the temperature.

The nature of the freezing transition and the properties of the low temperature/strong disorder glassy phase was still poorly understood, even at the level of statics. In particular topological constraints (planarity) induce frustration and compete with long range forces. This is therefore a difficult and fascinating problem at the interface between the physics (and the mathematics) of disordered systems, and quantitative biology.

C.26.1 Field theory for random RNA *(F. David)*

The program initiated by F. David and Kay Wiese (École Normale Supérieure) in 2005 (to formulate a systematic and consistent field theory for Random RNA folding) has been achieved. This program is based on an ensemble of new tools: formulation of the model in terms of random walks in an auxiliary $D = 3$ dimensional space, introduction of random-matrix-like auxiliary fields to implement topological constraints, and the use of a multilocal operator product expansion to analyse the UV and IR divergences of the model.

In a long and thorough article the definition of the model is detailed. This field theory is shown to be renormalizable to all orders in perturbation theory in $D = 2 + \epsilon$. This establishes the consistency of the calculation at first order in ϵ of Lässig-Wiese. Moreover the renormalizability allows to work in the new (and simpler) scheme of open polymers, which was already used by F.D. and K.W. to study denaturation of random RNA under tension. The scaling exponents of the model at the freezing transition are computed for the first time at 2-loop order. Exact scaling identities between exponents are proven. The systematic treatment of the denaturation transition of random RNA is also presented for the first time, as well as 2 loop calculations for the critical exponents for this transition. Finally the relevance of the model and of these calculations for the understanding of the low temperature glassy phase of random RNA is discussed.[t09/074]

C.26.2 A growth model for random RNA *(F. David)*

Together with C. Hagendorf and K. J. Wiese (École Normale Supérieure), F. David has introduced a new non perturbative formulation of random RNA folding based on hierarchical approximations. This hierarchical model is shown to be equivalent to a tree-growth model with some special properties, and also to some fragmentation model. Both models can be solved analytically, giving access to exact scaling exponents and fractal dimensions, to scaling functions for large molecules, and to the corrections to scaling (which is new for these kind of models). These results are checked by numerical simulations of up to 6500 bases. The equivalence of RNA models with growth/fragmentation models should be helpful in understanding more general tree-growth processes.[t07/068]

C.27 Pseudoknot prediction in biological RNA

In the last fifteen years, it has been recognized that RNA is a major actor in the biology of the cell, not only as an information carrier, but also because of its enzymatic and regulatory action. The biological activity of RNA is closely related to its folded structure.

The simplicity of the RNA secondary structure problem makes the enumeration of secondary structures a classic combinatorics problem. This aspect has been tackled by random matrix theory, and in the case of random RNA, by simplified hierarchichal models.

For real RNA biological data, a classification of RNA pseudoknots according to their genus is proposed. With this classification, it is shown that RNA of size smaller than 500 bases have very low genus (< 3) and this allows to generate efficient algorithms for the prediction of RNA structures.

C.27.1 Prediction of RNA secondary structures with pseudoknots *(M. Bon, H. Orland)*

We present a new algorithm to predict RNA secondary structures with pseudoknots. The method is based on a classification of RNA structures according to their topological genus. The algorithm utilizes a simplified parametrization of the free energies for pair stacking, loop penalties, etc. and in addition a free energy penalty proportional to the topological genus of the pairing graph. Our method can take into account all pseudoknot topologies and achieves high success rates compared to state-of-the-art methods. This shows that the genus is a promising concept to classify pseudoknots.[t10/261]

C.27.2 TT2NE: a novel algorithm to predict RNA secondary structures with pseudoknots *(M. Bon, H. Orland)*

We present TT2NE, a new algorithm to predict RNA secondary structures with pseudoknots. The method is based on a classification of RNA structures according to their topological genus. TT2NE guarantees to find the minimum free energy structure irrespectively of pseudoknot topology. This unique proficiency is obtained at the expense of the maximum length of sequence that can be treated but comparison with state-of-the-art algorithms shows that TT2NE is a very powerful tool within its limits. Analysis of TT2NE's wrong predictions sheds light on the need to study how sterical constraints limit the range of pseudoknotted structures that can be formed from a given sequence. An implementation of TT2NE on a public server can be found at http://ipht.cea.fr/rna/tt2ne.php. [t11/089]

C.27.3 Random matrix theory and RNA folding *(H. Orland)*

In this article we review a series of recent applications of random matrix theory (RMT) to the problem of RNA folding. The intimate connection between these two fields of study lies in their common diagrammatic description: all secondary structures of an RNA molecule are represented by planar diagrams which are naturally interpreted as the Feynman diagrams of a suitable large-N matrix model. As a consequence, all subleading 1/N corrections of the matrix model correspond to diagrams that are not planar, and that can be mapped into folded configurations of the RNA molecule including pseudoknots. Moreover, the standard topological expansion of the matrix model induces an elegant classification of all possible RNA pseudoknots, according to their topological genus. The RMT-based statistical description of the RNA-folding problem has been extended also to the folding of a generic homopolymer with saturating interaction. While reviewing several known findings, we extend previous results about the asymptotic distribution of pseudoknots of a phantom homopolymer chain in the limit of large chain length.[t11/088]

C.28 Dynamics of protein folding

This section addresses the problem of the determination of transition paths in protein folding. The question can be formulated as follows: which are the paths connecting a denatured state of a protein to its native state? This problem is studied with the use of path integrals, which sum the possible trajectories of the protein in conformation space, weighted by their correct action. This path-integral is then evaluated by the saddle-point method, which exhibits the dominant path. Fluctuations can be computed and the method is illustrated on various examples, both with classical or quantum force fields.

C.28.1 Dominant reaction pathways in high dimensional systems *(H. Orland)*

This paper is devoted to the development of a theoretical and computational framework to efficiently sample the statistically significant thermally activated reaction pathways, in multi-dimensional systems obeying Langevin dynamics. We show how to obtain the set of most probable reaction pathways and compute the corrections due to quadratic thermal fluctuations around such trajectories. We discuss how to obtain predictions for the evolution of arbitrary observables and how to generate conformations which are representative of the transition state ensemble. We present an illustrative implementation of our method by studying the diffusion of a point particle in a 2-dimensional funneled external potential.[t08/283]

C.28.2 Kramers theory for conformational transitions of macromolecules *(H. Orland)*

We consider the application of Kramers theory to the microscopic calculation of rates of conformational transitions of macromolecules. The main difficulty in such an approach is to locate the transition state in a huge configuration space. We present a method which identifies the transition state along the most probable reaction pathway. It is then possible to microscopically compute the activation energy, the damping coefficient, the eigenfrequencies at the transition state and obtain the rate, without any a-priori choice of a reaction coordinate. Our theoretical results are tested against the results of Molecular Dynamics simulations for transitions in a 2-dimensional double well and for the cis-trans isomerization of a linear molecule.[t08/282]

C.28.3 Stochastic dynamics and dominant protein folding pathways *(H. Orland)*

We present the results of a recently developed theoretical framework denominated Dominant Reaction Pathways (DRP), to study thermally activated reactions in multi-dimensional systems. In particular, we focus on application to the protein folding reaction. By applying the saddle-point approximation to the stochastic path integral generated by the Langevin equation, we derive a least-action principle, which allows us to rigorously determine directly the most probable reaction pathways, bypassing the long-standing computational problems associated with the decoupling of time-scales in the problem. We show the results of number validation studies, in which the accuracy of the DRP approach was assessed, studying molecular transitions. In all cases, the DRP predictions are found to be consistent with the MD results, but extremely less computationally expensive.[t08/287]

C.28.4 Simulating stochastic dynamics using large time steps *(H. Orland)*

We present a novel approach to investigate the long-time stochastic dynamics of multi-dimensional classical systems, in contact with a heat-bath. When the potential energy landscape is rugged, the kinetics displays a decoupling of short and long time scales and both Molecular Dynamics (MD) or Monte Carlo (MC) simulations are generally inefficient. Using a field theoretic approach, we perform analytically the average over the short-time stochastic fluctuations. This way, we obtain an effective theory, which generates the same long-time dynamics of the original theory, but has a lower time resolution power. Such an approach is used to develop an improved version of the MC algorithm, which is particularly suitable to investigate the dynamics of rare conformational transitions. In the specific case of molecular systems at room temperature, we show that elementary integration time steps used to simulate the effective theory can be chosen a factor ~ 100 larger than those used in the original theory. Our results are illustrated and tested on a simple system, characterized by a rugged energy landscape.[t09/306]

C.28.5 Dominant reaction pathways in protein folding: a direct validation against molecular dynamics simulations *(H. Orland)*

The dominant reaction pathway (DRP) is an algorithm to microscopically compute the most probable reaction pathways in the overdamped Langevin dynamics without investing computational time in simulating the local thermal motion in the metastable configurations. In order to test the accuracy of such a method, we investigate the dynamics of the folding of a beta hairpin within a model that accounts for both native and non-native interactions. We compare the most probable folding pathways calculated with the DRP method with the folding trajectories obtained directly from molecular dynamics simulations. We find that the two approaches give consistent results.[t09/305]

C.28.6 Dominant folding pathways of a peptide chain, from ab-initio quantum-mechanical simulations *(H. Orland)*

Using the Dominant Reaction Pathways method, we perform an ab-initio quantum-mechanical simulation of a conformational transition of a peptide chain. The method we propose makes it possible to investigate the out-of-equilibrium dynamics of these systems, without resorting to an empirical representation of the molecular force field. It also allows to study rare transitions involving rearrangements in the electronic structure. By comparing the results of the ab-initio simulation with those obtained employing a standard force field, we discuss its capability to describe the non-equilibrium dynamics of conformational transitions.[t10/124]

C.28.7 Fluctuations in the ensemble of reaction pathways *(H. Orland)*

The dominant reaction pathway (DRP) is a rigorous framework to microscopically compute the most probable trajectories, in non-equilibrium transitions. In the low-temperature regime, such dominant pathways encode the information about the reaction mechanism and can be used to estimate non-equilibrium averages of arbitrary observables. On the other hand, at sufficiently high temperatures, the stochastic fluctuations around the dominant paths become important and have to be taken into account. In this work, we develop a technique to systematically include the effects of such stochastic fluctuations, to order $k_B T$. This method is used to compute the probability for a transition to take place through a specific reaction channel and to evaluate the reaction rate.[t10/264]

C.28.8 Generating transition paths by Langevin bridges *(H. Orland)*

We propose a novel stochastic method to generate paths conditioned to start in an initial state and end in a given final state during a certain time t_f . These paths are weighted with a probability given by the overdamped Langevin dynamics. We show that these paths can be exactly generated by a non-local stochastic differential equation. In the limit of short times, we show that this complicated non-solvable equation can be simplified into an approximate local stochastic differential equation. For longer times, the paths generated by this approximate equation do not satisfy the correct statistics, but this can be corrected by an adequate reweighting of the trajectories. In all cases, the paths are statistically independent and provide a representative sample of transition paths. The method is illustrated on the one-dimensional quartic oscillator.[t11/091]

C.29 Molecular motors and dynamics of actin filaments

C.29.1 Molecular spiders *(K. Mallick)*

In recent years, chemists have constructed spectacular synthetic molecular systems which can move on surfaces and tracks. One such object is a multi-pedal molecular spider whose legs are short single-stranded segments of DNA. These spiders can move on a surface covered with single-stranded DNA segments, called substrates. The substrate DNA is complementary to the leg DNA. The motion proceeds as legs bind to the surface DNA through the Watson-Crick mechanism, then dissociate, then rebind again, etc. More precisely, a bond on the substrate with an attached leg is first cleaved, and the leg then dissociates from the affected substrate (which we shall call product). After that the leg can rebind to the new substrate or to the product.

In [t07/182], we establish different mappings between various models of spiders and simple exclusion processes. This allows us to classify different type of models and to select exactly solvable cases as templates. For spiders with simple gait and varying number of legs, this allows us to compute the diffusion coefficient and, when the hopping is biased, their velocity.

C.29.2 Fluctuation relations and molecular motors *(K. Mallick)*

Motor proteins are nano-machines that convert chemical energy into mechanical work and motion. Important examples include kinesin, myosin, and RNA polymerase. Despite a number of theoretical models, understanding the mechanochemical transduction mechanisms behind these motors remains a significant challenge: indeed, such systems are far from equilibrium and display large fluctuations. Thus, the usual framework of equilibrium statistical mechanics can not be applied.

In [t07/183], we investigate theoretically the violations of Einstein and Onsager relations, and the efficiency for a single processive motor operating far from equilibrium using an extension of the discrete two-state motor model. With the aid of the Fluctuation Theorem, we analyze the general features of these violations and this efficiency and link them to mechanochemical couplings of motors. In particular, an analysis of the experimental data of kinesin using our framework leads to interesting predictions that may serve as a guide for future experiments. In [t08/210], we study a flashing ratchet model with switching between two continuous potentials. We show that this model exhibits the Gallavotti-Cohen symmetry relation, provided that the dynamics is described in terms of a chemical and a mechanical variable. The symmetry is obeyed by the generating function of the mechano-chemical currents. This function, which contains all the long time properties of the currents, can be determined exactly in some simple cases. We review the relations between models of molecular motors and fluctuation theorems in [t09/246].

C.29.3 Dynamics of filament growth and instabilities *(K. Mallick)*

A large number of structural elements of cells are made of fibers. Well studied examples of these fibers are microtubules and actin filaments. Microtubules are able to undergo rapid dynamic transitions between growth (polymerization) and decay (depolymerization) in a process called dynamic instability. Actin filaments are able to undergo treadmilling-like motion. These dynamic features of microtubules and actin filaments play an essential role in cellular biology. For instance, the treadmilling of actin filaments occurs in filopodia, lamellipodia, flagella and stereocilia. Actin growth dynamics is also important in acrosome reactions, where sperm fuses with egg. During cell division, the movements of chromosomes are coupled to the elongation and shortening of the microtubules to which they bind.

In [t08/207], we study the stochastic dynamics of growth and shrinkage of single actin filaments or microtubules taking into account insertion, removal, and ATP/GTP hydrolysis of subunits. The resulting phase diagram contains three different phases: a rapidly growing phase, an intermediate phase and a bound phase. We analyze all these phases, with an emphasis on the bound phase. We also discuss how hydrolysis affects force-velocity curves. The bound phase shows features of dynamic instability, which we characterize in terms of the time needed for the ATP/GTP cap to disappear as well as the time needed for the filament to reach a length of zero (i.e. to collapse) for the first time. We obtain exact expressions for all these quantities, which we test using Monte Carlo simulations. In [t09/247], we extend this approach in two ways by including the dynamics of both ends and by comparing two possible mechanisms of ATP hydrolysis. Our emphasis is mainly on two possible limiting models for the mechanism of hydrolysis within a single filament, namely the vectorial or the random model. We propose a set of experiments to test the nature of the precise mechanism of hydrolysis within actin filaments. In [t10/218], we develop a model to describe the force generated by an array of well-separated parallel biofilaments, such as actin filaments. The N filaments are assumed to only be coupled through mechanical contact with a movable barrier. We calculate the filament density distribution and the force-velocity relation with a mean-field approach combined with simulations. We identify two regimes: a non-condensed regime at low force in which filaments are spread out spatially, and a condensed regime at high force in which filaments accumulate near the barrier. We confirm that in this model, the stall force is equal to N times the stall force of a single filament. However, surprisingly, for large N, we find that the velocity approaches zero at forces significantly lower than the stall force.

C.30 Bioinformatics

Bioinformatics provide tools to analyze and organize biological data. Two of the emblematic problems of bioinformatics are studied in this section, namely sequence alignment and structure alignment. In both cases, sophisticated methods from statistical physics are used to propose a solution to these problems. The algorithm for structural alignment is then used to study and classify knots in proteins.

C.30.1 Bernoulli matching model and sequence alignment *(K. Mallick)*

The goal of a sequence alignment problem is to find similarities in patterns in different sequences. Sequence alignment is one of the most useful quantitative methods of evolutionary molecular biology. A classic alignment problem deals with the search of the Longest Common Subsequence (LCS) in two random sequences. Finding analytically the statistics of LCS of a pair of sequences randomly drawn from the alphabet of c letters is a challenging problem in computational evolutionary biology. The exact asymptotic results for the distribution of LCS have been derived recently in in a simpler, yet nontrivial, variant called the Bernoulli Matching model.

In [t07/169], we apply the Bethe ansatz technique to the Bernoulli Matching model via an exact mapping to the 5-vertex model on a square lattice. Considering the terrace-like representation of the sequence alignment problem, we reproduce by the Bethe ansatz the results for the averaged length of the Longest Common Subsequence in Bernoulli approximation. In addition, we compute the average number of nucleation centers of the terraces.

C.30.2 MISTRAL: a tool for energy-based multiple structural alignment of proteins *(H. Orland)*

The steady growth of the number of available protein structures has constantly motivated the development of new algorithms for detecting structural correspondences in proteins. Detecting structural equivalences in two or more proteins is computationally demanding as it typically entails the exploration of the combinatorial space of all possible amino acid pairings in the parent proteins. The search is often aided by the introduction of various constraints such as considering protein fragments, rather than single amino acids, and/or seeking only sequential correspondences in the given proteins. An additional challenge is represented by the difficulty of associating to a given alignment, a reliable a priori measure of its statistical significance. Results: Here, we present and discuss MISTRAL (Multiple STRuctural ALignment), a novel strategy for multiple protein alignment based on the minimization of an energy function over the low-dimensional space of the relative rotations and translations of the molecules. The energy minimization avoids combinatorial searches and returns pairwise alignment scores for which a reliable a priori statistical significance can be given.[t09/313]

C.30.3 Knotted vs. unknotted proteins: evidence of knot-promoting loops *(H. Orland)*

Knotted proteins, because of their ability to fold reversibly in the same topologically entangled conformation, are the object of an increasing number of experimental and theoretical studies. The aim of the present investigation is to assess, on the basis of presently available structural data, the extent to which knotted proteins are isolated instances in sequence or structure space, and to use comparative schemes to understand whether specific protein segments can be associated to the occurrence of a knot in the native state. A significant sequence homology is found among a sizable group of knotted and unknotted proteins. In this family, knotted members occupy a primary sub-branch of the phylogenetic tree and differ from unknotted ones only by additional loop segments. These “knot-promoting” loops, whose virtual bridging eliminates the knot, are found in various types of knotted proteins. Valuable insight into how knots form, or are encoded, in proteins could be obtained by targeting these regions in future computational studies or excision experiments.[t10/263]

C.30.4 Mistral WebServer *(H. Orland)*

http://ipht.cea.fr/protein.php

C.30.5 TT2NE WebServer *(H. Orland)*

http://ipht.cea.fr/tt2ne.php

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[t11/098] C. Godrèche. *Dynamics of the directed Ising chain.* (2011), arXiv:1102.0141.

[t11/101] A. Crisanti and C. De Dominicis. *Stability of the Parisi solution for the Sherrington–Kirkpatrick model near T = 0. J. Phys. A*, 44, 15006, (2011), arXiv:1101.5233v1.

[t11/102] J.M. Stéphan, G. Misguich, and V. Pasquier. *Phase transition in the Rényi-Shannon entropy of Luttinger liquids.* (2011), arXiv:1104.2544.

[t11/103] L. Messio, C. Lhuillier, and G. Misguich. *Lattice symmetries and regular states in classical frustrated antiferromagnets.* (2011), arXiv:1101.1212.

[t11/106] Berthier L., Biroli G., Bouchaud J.-P., Cipelletti L., and van Saarloos W., editors. *Dynamical Heterogeneities in Glasses, Colloids, and Granular Media.* Oxford University Press, USA, (2011).

[t11/108] A. Ayyer. *Algebraic Properties of a Disordered Asymmetric Glauber Model. J. Stat. Mech.*, 1102, P02034, (2011), arXiv:1012.0875.

[t11/136] M. Bauer and D. Bernard. *Quantum Stochastic Processes: A Case Study.* (2011), arXiv:1101.3472.

[t11/154] C. Maes, K. Netocny, and B. Wynants. *Monotone return to steady nonequilibrium. Phys. Rev. Lett. (to appear)*, (2011), arXiv:1102.3028.

CHAPTER D

Appendices

D.1 Awards

Jean-Paul BLAIZOT
J. Hans D. Jensen prize awarded by Ruprecht-Karls University (Heidelberg). February 2009.

Claude GODRÈCHE
Chevalier des palmes académiques. September 2009.

Ivan KOSTOV
Servant prize awarded by the Academy of Sciences. September 2007.

Matt LUZUM
2011 Dissertation in Nuclear Physics Award for his thesis, awarded by the American Physical Society. November 2010.

Ruben MINASIAN
Recipient of a *Friedrich Wilhelm Bessel Research Award* after having been nominated for this award by the German scientist Prof. Dr. Stefan Theisen, Max-Planck-Institut fuer Gravitationsphysik, Golm/Potsdam. November 2007.

Cécile MONTHUS
Gustave Ribaud prize awarded by the Academy of Sciences. September 2007.

Olivier PARCOLLET
Ernest Déchelle prize awarded by the Academy of Sciences. November 2009.

Hubert SALEUR
Silver medal of CNRS. May 2011.

Jean ZINN-JUSTIN
Academy of Science. March 2011.

D.2 Summary of publications

All the data given here consider only publications signed with IPhT among the institutions, and published in reviews indexed in the ISI-Web of Science database.

They have been etablished by the IST, the office of the CEA in charge of this domain, in May 2011. Consequently, these data concern the full calendar years from 2007 to 2010, and not 2011.

Note that the year corresponds to the date of the publication in the review, but not the date of submission of the manuscript, or the publication as preprint on ArXiv.org.

Year	2007	2008	2009	2010	Total
Nb of publications	166	186	191	186	729

We give below the total number of publications on 2007–2010 for journals with at least 5 publications.

Journal of High Energy Physics	95
Physical Review D	71
Physical Review Letters	53
Physical Review B	45
Journal of Statistical Mechanics	42
Nuclear Physics A	41
Journal of Physics A-Mathematical and Theoretical	40
Nuclear Physics B	40
Journal of Cosmology and Astroparticle Physics	28
Physical Review E	27
Physics Letters B	21
Physical Review C	17
Acta Physica Polonica B	13
EPL	13
Journal of Statistical Physics	13
Nuclear Physics B-Proceedings Supplements	10
Journal of Physics G-Nuclear and Particle Physics	9
European Physical Journal B	8
Astronomy & Astrophysics	6
Communications in Mathematical Physics	6
Journal of Chemical Physics	6
European Physical Journal C	6
Classical and Quantum Gravity	5
Progress of Theoretical Physics Supplement	5
Other journals	109

D.3 Fundings and grants

European Research Council ERC (FP7)

Person	Type	Topic	Dates
I. Bena	ERC Starting Grant	String-QCD-BH: String Theory, QCD and Black Holes	01/01/2010–31/12/2014
M. Graña	ERC Starting Grant	OberservableString: The Low Energy Limit of String Theory and the Observable World	01/02/2011–31/01/2016
D. Kosower	ERC Advanced Grant	MM-PGT: Modern Methods for Perturbative Gauge Theories	01/01/2009–31/12/2013
G. Servant	ERC Starting Grant	Cosmo@LHC: Cosmology at the CERN Large Hadron Collider	01/07/2008-30/06/2013

Individual Marie-Curie Fellowships (FP6, FP7)

Person	Type	Topic	Dates
C. Bena	Intra-European Fellowship, FP6	TSINANO : Transport in Strongly Interacting Nanosystems	06/11/2006–05/11/2008
I. Bena	International Reinte -gration Grant, FP6	String Theory, QCD and Black Holes	01/09/2007–31/08/2009
M. Frigerio	European Individual Fellowships, FP7	BEYOND NEUTRINO MASS : From neutrino mass phenomenology to the particle physics theory beyond the Standard Model and related signatures in cosmology and colliders	01/09/2007–31/08/2009
J. Lopez Albacete	Intra-European Fellowship, FP7	HICLHC : Heavy Ion Collisions at the LHC : Strong coupling techniques for high density QCD	01/06/2009–30/05/2011
C. Marquet	Outgoing International Fellowship, FP6	Study of newly-discovered matter in very energetic collisions of hadrons or heavy ions	01/06/2007–31/05/2010
E. Sefusatti	Intra-European Fellowship, FP7	AGILE : Perturbative Approaches to Gravitational Instability and Lensing in Cosmology	05/01/2010–04/01/2012

Marie Curie Initial Training Networks (ITN), International Research Staff Exchange Scheme (IRSES) and Research Training Networks (RTN)

Local Contact	**Topic**	**Partners**	**Dates**
P. Brax C. Caprini M. Cirelli C. Savoy F. Vernizzi	UniverseNet : The origin of our universe: Seeking links between fundamental physics and cosmology	Coord. : Subir Sarkar (Oxford University) Part. : Lancaster King's College London IFAE Barcelona Bonn LMU Munchen Niels Bohr Institute Copenhagen CERN Helsinki Ioannina INFN Italy APC Paris Warsaw Seoul University	2008-2010
R. Britto D. Kosower G. Soyez (Part)	LHCPhenoNet : Advanced Particle Phenomenology in the LHC era	Coord. : German Rodrigo (Instituto de Fisica Corpuscular , Valencia)	01/01/2011-31/12/2013
F. David (Part 13)	ENRAGE : European Network on Random GEometry	Coord. : R. Loll, Utrecht University Part 2 : Barcelona Univ Part 3 : Bielefeld Univ Part 4 : Herio-Watt Univ Part 5 : Iceland Univ Part 6 : ICL, UK Part 7 : Krakow Univ Part 8 : Leipzig Univ Part 9 : Copenhagen Univ Part 10 : NRD, Athens Part 11 : Univ Paris-Sud Part 12 : Oxford Univ	01/09/2005-31/08/2009
B. Duplantier (Part.)	CASIMIR, New Trends and Applications of the Casimir Effect	Coord. : A. Lambrecht, LKB	01/01/2008-12/31/2012
I. Kostov (Part 3)	UNIFY : Unification of Fundamental Forces and Applications	Coord : M. S. Costa, Univ. de Porto Part 2 : Univ. de Berlin Part 4 : Perimeter Institute, Part 5 : C.N. Yang Institute for Theoretical Physics, Part 6 : Univ. de Tokyo	01/06/2011-31/05/2015

J.-M. Normand	PRACE : Partnership for Advanced Computing in Europe	Austria: JKU Bulgaria: NCSA Cyprus: CaSToRC Czech Republic: VSB Finland: CSC France: GENCI Germany: GCS Greece: GRNET Ireland: ICHEC Italy: CINECA The Netherlands: NCF Norway: SIGMA - UNINETT Poland: PSNC Portugal: FCTUC Serbia: IPB Spain: BSC Sweden: SNIC Switzerland: ETH Zurich Turkey: UYBHM UK: EPSRC	2008-2012
C. Savoy (Part 2)	QUEST : The Quest For Unification: Theory Confronts Experiments followed by UNILHC : Unification in the LHC era	Coord. : I. Antoniadis (Ecole Polytechnique, Palaiseau) Part 3 : Bonn University Part 4 : AUTH, Greece Part 5 : INFN, Italy Part 6 : ICTP, Italy Part 7 : IST, Portugal Part 8 : UAM, Spain Part 9 : UVEG, Spain Part 10 : UOXF.DR, UK Part 11 : Warsaw Univ. Part 12 : CERN,Geneva	01/10/2004-30/09/2008 01/10/2009-30/09/2013

P. Vanhove (Part.)	ForcesUniverse : Constituents, Fundamental Forces and Symmetries of the Universe	Coord. : Dieter Luest , Ludwig-Maximilians-Universität München Part 3 : Munich, Max-Planck Part 4 : Barcelona, Spain Part 5 : IHES, France Part 6 : LPT ENS, France Part 7 : IST, Portugal Part 8 : Nordisk Institut for Teoretisk Fysik Part 9 : Trinity College, Ireland Part 10 : INFN, Italy Part 11 : Turin, Italy Part 12 : Louvain, Belgium Part 13 : Imperial College, Angleterre Part 14 : Université de Neuchatel, Suisse Part 15: Université de Patras, Grece Part 16 : INR, Bulgarie Part 17: Université d'Utrecht, Hollande Part 18: University d'Iceland, Iceland Part 19: Université de Padou, Italie Part 20: Université de Milan, Italie Part 21: Université de Bruxelles, Belgique Part 22: Université d'Edinbourg, Ecosse Part 23 : ETH, Suisse Part 24: Université de Craiova, Roumanie Part 25: Université de Groningen, Hollande	01/11/2004 - 30/10/2008

National grants

ANR stands for "Agence nationale de la recherche" since 2005.

ANR Chaire d'excellence

Person	**Acronym : Topic**	**Dates**
R. Britto	HSPQCD : Hard Scattering in Precision QCD	15/12/2009–14/11/2012
G. Soyez	Jets4LHC : Developing new jet algorithms Optimising their parameters for LHC physics	31/12/2010–30/12/2013
F. Vernizzi	CMBSecond : Cosmic Microwave Background Anisotropies at Second Order	01/12/2009–30/11/2013

ANR JCJC - Jeune chercheur, jeune chercheuse (Young researcher)

Local contact	**Acronym : Topic**	**Coordinator**	**Dates**
I. Bena	String-QCD-BH : String Theory, QCD and Black Holes	I. Bena	22/07/2008–31/12/2013
S. Lavignac	NEUPAC : Propriétés non standard des neutrinos et leur impact en astrophysique et en cosmologie	C. Volpe (IPN, Orsay)	05/12/2005–04/12/2008

S. Nonnenmacher	RESOCHAOQUAN : Résonances et décohérence en chaos quantique	S. Nonnenmacher	30/11/2005–29/05/2009
S. Nonnenmacher	METHCHAOS : Méthodes spectrales en chaos classique et quantique	C. Guillarmou (ENS, Paris)	01/11/2009–31/10/2013
G. Servant	DARKPHYS : Matière noire et énergie noire : un défi pour la physique des particules	G. Servant	06/11/2006–06/11/2010

ANR "Blanc"

Local contact	**Acronym : Topic**	**Coordinator**	**Dates**
M. Bauer	SLE : Outils probabilistes et invariance conforme en théorie des champs : SLE et autres processus de croissance	D. Bernard (ENS Paris)	06/11/2006–01/11/2010
F. Bernardeau	NLDyn : Dynamique gravitationnelle non linéaire en cosmologie	F. Bernardeau	05/11/2007–04/11/2010
G. Biroli	DynHet : Quantative characterisation of dynamic heterogeneities in glassy materials : models, simulations and new experiments	F. Ladieu (CEA/SPEC)	08/11/2007–07/01/2011
G. Biroli	FAMOUS : Far from equilibrium phenomena in quantum systems	L. Cugliandolo (UPMC)	01/10/2009–30/09/2012
B. Eynard	GranMA : Large Random Matrices	A. Guionnet (ENS Lyon)	01/01/2009–31/12/2011
T. Garel C. Monthus	POLINTBIO : Polymères, Interfaces et Systèmes Désordonnés : entre Mathématiques, Physique et Biologie	G. Giacomin (Math Paris 7)	2005–2008
E. Iancu	De RHIC à LHC : Interactions fortes dans le régime de haute énergie : de RHIC à LHC	E. Iancu	06/11/2006–01/11/2010
D. Kosower	QCD@LHC : QCD, torseurs et le LHC	D. Kosower	06/12/2005–06/12/2008
S. Lavignac	TH-EXP@TEV : Confronting theory with experiments at the Terascale	S. Lavignac	20/12/2010–19/11/2014
R. Minasian	BHTSV : Structure of vacuum, topological strings and black holes	R. Minasian	06/11/2006–06/11/2009
J.-Y. Ollitrault	hadron@LHC : Hadron phenomenology in proton-proton and nucleus-nucleus collisions at the LHC	J.-Y. Ollitrault	01/01/2009–31/12/2012
C. Pépin	ECCE : Extreme conditions correlated electrons	D. Braithwaite (CEA Grenoble)	06/11/2006–06/11/2009
H. Saleur	INT-AdS/CFT : Structures intégrables et la conjecture AdS/CFT : chaînes de spin et modèles sigma non-linéaires sypersymétriques	H. Saleur	06/11/2006–06/11/2008
H. Saleur	DIME : Disorder, interactions, transport in low dimensions : exact methods and results	H. Saleur	20/12/2010–19/12/2014
C. Savoy	Phys@col&cos : Physique au-delà du modèle standard : implications pour les collisionneurs et la cosmologie	A. Djouadi (Paris 11)	01/12/2005–01/12/2008

ANR “Systèmes complexes et modélisation mathématique"

Local contact	Acronym : Topic	Coordinator	Dates
M. Barthélémy	Dyxi : Dynamiques Citadines Collectives : Hétérogénéités Spatiales et Individuelles	J.-P. Nadal (ENS&EHESS)	2009-2012

RTRA

RTRA stands for "Réseau thématique de recherche avancée -Triangle de la Physique du Plateau de Saclay" since 2007.

Person	Topic	Dates
J.-M. Luck	Invitation Y. Avishai	2007
G. Biroli	Meeting "Dynamical heterogeneities in glasses, colloids and granular media, Leiden (Pays-Bas)"	2007-2008
G. Biroli A. Lefèvre	Beg-Rohu school	2008
H. Orland	Invitation D. Andelman	2008
V. Pasquier, D. Serban	Les Houches summer school	2008
O. Parcollet	Aspen conference "Correlated Behavior and Quantum Criticality in Heavy Fermion and Related Systems "	2008-2009
D. Serban	15th Itzykson Meeting "New Trends In Quantum Integrability"	2009-2010
V. Pasquier, D. Serban	Conference “Physics in the Plane”, Les Houches	2010
C. Godrèche	16th Itzkykson Meeting "Extremes and Records"	2010-2011
L. Zdeborova	starting/installation grant, DySpaN "Dynamics on sparse networks"	2011-2014

Other national and international programs

CEFIPRA stands for Indo French Centre for the Promotion of Advanced Research.
COFECUB stands for "Comité Français d'Evaluation de la Coopération Universitaire et Scientifique avec le Brésil".
ECO-NET stands for "Programmes de collaboration avec l'Europe de l'est et l'ex-URSS".
ESF stands for European Science Foundation.
GDR stands for "Groupement de recherche" of CNRS.
GDRI stands for "Groupe de recherche international" of CNRS.
GRAM stands for "Gravitation, Références, Astronomie, Métrologie" of CNRS.
PEPS stands for "Projets Exploratoires Pluridisciplinaire" of CNRS.
PHC stands for "Partenariats Hubert Curien du ministères des Affaires étrangères et européennes, avec le soutien du ministère de l'Enseignement supérieur et de la Recherche".
PICS stands for "Projet International de Coopération Scientifique" of CNRS.
PNCGC stands for "Programme National de Cosmologie et Galaxies" of CNRS.
P2I stands for "Groupement d'intérêt scientifique Physique des deux infinis".

Program	Theme	Partner	Contact	Dates
ESF	HOLOGRAV "Holographic methods in strongly coupled systems""	University of Southampton, UK CERN ENS	I. Bena G. Korchemsky D. Kosower I. Kostov R. Peschanski D. Serban	2009-2014

PICS	Aspects of String Theory with fluxes	England	I. Bena M. Graña M. Petrini (coord.)	2010-2012
P2I	Matière Noire et Nouvelle Physique: une attaque sur plusieurs fronts		F. Bernardeau	2008-2010
PNCG	Calculs de précision pour grands relevés cosmologiques		F. Bernardeau	2011
PHC Sakura	Precision calculations for cosmological large-scale structure observations	RESCEU, University of Tokyo	F. Bernardeau	2011–2012
CNRS-USA Programme d'échange	Fluctuations et longueur de corrélation dynamiques dans les systemes vitreux	USA	G. Biroli	2007-2008
PHC Pessoa	The Early Universe and Dark Energy	Université de Lisbonne	P. Brax	2010
GRAM	Progress on Old and New Themes in Cosmology (conference PONT Avignon 2011)		P. Brax	2011
P2I	Des micro interactions élémentaires aux macro structures cosmiques et retour	IAP Paris	M. Cirelli	2008-2010
PNCG	Progress on Old and New Themes in Cosmology (conference PONT Avignon 2011)		M. Cirelli	2011
PEPS	Decaying Dark Matter, matière noire asymétrique et effet de l'annihilation de matière noire sur la formation de galaxies		P. Serpico (coord. LAPTh Annecy) M. Cirelli F. Iocco G. Servant G. Zaharijas	2010-2011
PHC Jules Verne	Physical Applications of Random Graph Theory	University of Iceland	F. David	2006–2007
PICS	Systemes intégrables discrets, algébres d'amas et positivité	USA	P. Di Francesco	2011
Echange France - MIT	The Mathematics of Liouville Quantum Gravity	MIT-France Seed Fund	B. Duplantier	01/01/2011-08/31/2012
PEPS	SLE & Quantum Gravity		B. Duplantier	05/01/2010-31/12/2010
COFECUB ECOS-SUD	Generalizing Geometry in String Theory : its phenomenological implications	Argentine	M. Graña R. Minasian M. Petrini (coord.)	2008–2012
Echange France - MIT	Generalizing geometry in string theory	MIT-France Seed Fund	M. Graña R. Minasian (coord.)	2006-2007

CNRS-USA Programme d'échange	Nouvelles approches au probleme de la brisure de symétrie électrofaire	Cornell, UC Davis	C. Grojean	2006-2008
PHC Amadeus	Du RHIC au LHC sur une supercorde	Vienna University of technology (Autriche)	E. Iancu	2009–2010
COFECUB Capes	Théories effectives et techniques non-perturbatives pour des systèmes de quarks et de gluons	Brasil	E. Iancu	2009–2013
CNRS - PICS	Symétries cachées des amplitudes de diffusion dans les théories de Yang-Mills	Russie	G. Korchemsky	2010
ECO-NET	Intégrales de Feynman à deux boucles et au-delà	Skobeltsyn Inst. Nucl. Phys., Lomonosov Moscow State Univ.; Chelkowski Inst. Phys., Univ. Silesia, Pologne	D. Kosower	2006–2008
Echange France - MIT	Perturbative amplitudes in gauge theory and quantum gravity	MIT	D. Kosower - P. Vanhove	2008–2009
PHC Sakura	Matrix Models and String Theory	Institut Riken de Kyoto (Japan)	I. Kostov	2006–2007
PHC Rila	Géométrie aléatoire, gravité quantique et théories conformes	Institut de recherche nucléaire et de l'énergie nucléaire, Sofia (Bulgarie)	I. Kostov	2007–2008
GDRI	French-Russian network in Theoretical and Mathematical Physics	Académie des Sciences Russe	I. Kostov J.-M. Maillet (coord.) V. Terras (coord.)	2008-2012
PHC Proteus	Physics from the grand unification scale to LHC energies	Slovenia	S. Lavignac	2010–2011
GDR	Quantum Dynamics		S. Nonnenmacher (coord.) - S.De Bièvre (Lille) - Alain Joye (Grenoble)	2009–2012
COFECUB USP	Les premiers instants d'une collision d'ions lourds ultra-relativistes	Brasil	J.-Y. Ollitrault	2008–2011

CEFIPRA	Hot and dense matter in quantum chromodynamics	LPT Orsay; TIFR Mumbai; VECC Kolkata	J.-Y. Ollitrault	2005–2007
CEFIPRA	Extreme QCD in the LHC era	TIFR Mumbai	J.-Y. Ollitrault	2011–2013
PHC Polonium	QGP and Strings	Jagellonian University (Pologne)	R. Peschanski	2008–2009
ESF	Interdisciplinary Statistical and Field Theory Approaches to Nanophysics and Low Dimensional Systems (INSTANS)		H. Saleur	01/05/2005 - 30/04/2010
COFECUB Capes	La frontière des hautes énergies: exploration des nouveaux modèles de la physique des particules au collisionneur LHC du CERN et aux expériences avec des neutrinos	Brasil	C. Savoy	2007-2009
Coopération scientifique et universitaire	Hidden structures of gauge and quantum gravity amplitudes	Institut Niels Bohr, Copenhague	P. Vanhove	2010
ESF	"L'Univers quasi-Gaussian"		F. Vernizzi	2009

D.4 Habilitation thesis - Habilitation à diriger des recherches

BENA Iosif

Black Holes, Black Rings and their Microstates (Trous noirs, anneaux noirs et leur microétats) [t09/347],
Université Pierre et Marie Curie - Paris 6, Spécialité : Physique, 16/06/2009.

NONNENMACHER Stéphane

A few aspects of quantum chaos (Quelques aspects de chaos quantique) [t09/127],
Université Paris-Sud 11, Spécialité : Mathématiques (option Physique Mathématique), 05/06/2009.

PÉPIN Catherine

Quantum critical points in strongly correlated electron compounds (Points critiques quantiques dans les composés à fortes corrélations électroniques) [t08/315],
Université Pierre et Marie Curie - Paris 6, Spécialité : Physique Théorique, 06/11/2008.

SERBAN Didina

Integrability and the AdS/CFT correspondence (Intégrabilité et correspondance AdS/CFT) [t10/042],
Université Paris-Sud 11, Spécialité : Physique Théorique, 29/05/2009.

VALAGEAS Patrick

Formation of large-scale structures in cosmology: gravitational dynamics (Formation des structures de grande échelle en cosmologie: dynamique gravitationnelle) [t10/203],
Université Paris Diderot - Paris 7, Spécialité : Astrophysique, 03/12/2010.

VANHOVE Pierre

Non-renormalisation theorems in string theory (Théorèmes de non-renormalisation en théorie des cordes) [t07/063],
Université Pierre et Marie Curie - Paris 6, Spécialité : Physique Théorique, 26/10/2007.

D.5 Doctoral schools - Écoles doctorales

IPhT is affiliated to 3 "écoles doctorales":

ED 107 École doctorale de physique de la région parisienne.

ED 447 (alias EDX) École doctorale de l'École polytechnique.

ED 517 PNC - Particules, Noyaux et Cosmos (formerly ED 381: Constituants élémentaires et systèmes complexes).

D.6 PhD defenses

Between June 2007 and May 2011, 21 PhD theses have been defensed at IPhT:

Hosteins Pierre
Neutrino masses and physics beyond the standard model (Masse des neutrinos et physique au-delà du modèle standard) [t07/200],
supervised by S. Lavignac, Université Paris-Sud 11, ED 381, 10/09/2007.

Orantin Nicolas
From matrix model's topological expansion to topological string theories: counting surfaces with algebraic geometry (Du développement topologique des modèles de matrices à la théorie des cordes topologiques : combinatoire de surfaces par la géométrie algébrique) [t07/119],
supervised by B. Eynard, Université Pierre et Marie Curie - Paris 6, ED 107, 13/09/2007.

Ikhlef Yacine
Exact results on two-dimensional loop models (Résultats exacts sur les modèles de boucles en deux dimensions) [t07/216],
supervised by H. Saleur and J. Jacobsen, Université Paris-Sud 11, ED 107, 27/09/2007.

Andreanov Alexei
Glass transition: a mean-field theory (Transition vitreuse: théorie de champ moyen) [t07/201],
supervised by G. Biroli and J.-P. Bouchaud (CEA-Spec), École Polytechnique, ED 447, 09/10/2007.

Vergu Cristian
Twistors, strings and supersymmetric gauge theories (Twisteurs, cordes et théories de jauge supersymétriques) [t08/120],
supervised by D. Kosower, Université Pierre et Marie Curie - Paris 6, ED 107, 15/07/2008.

Delaunay Cédric
Electroweak symmetry breaking: origin and consequences (Brisure de symétrie électrofaible : origine et conséquences) [t08/238],
supervised by C. Grojean, Université Paris-Sud 11, ED 107, 02/10/2008.

Candu Constantin
Discretisation of conformal sigma models on superspheres and projective superspaces (Discrétisation des modèles sigma invariants conformes sur des supersphères et superespaces projectifs) [t08/237],
supervised by H. Saleur, Université Pierre et Marie Curie - Paris 6, ED 107, 31/10/2008.

Michel Yann
Properties of extremal black holes in supergravity and string theory (Aspect des trous noirs extrémaux en supergravité et en théorie des cordes),
supervised by P. Vanhove and B. Pioline, Université Pierre et Marie Curie - Paris 6, ED 107, 01/12/2008.

Beuf Guillaume
Contributions to the study of strong interactions at high energy and high density (Contributions à l'étude des interactions fortes à haute énergie et haute densité) [t09/314],
supervised by R. Peschanski, Université Pierre et Marie Curie - Paris 6, ED 107, 26/06/2009.

Bon Michaël
Prediction of secondary structures of RNA with pseudoknots (Prédiction de structures secondaires d'ARN avec pseudo-noeuds) [t09/256],
supervised by H. Orland, École Polytechnique, ED 447, 21/09/2009.

Prolhac Sylvain
Exact results for the asymmetric simple exclusion process (Méthodes exactes pour le modèle d'exclusion asymétrique) [t09/161],
supervised by K. Mallick, Université Pierre et Marie Curie - Paris 6, ED 107, 23/09/2009.

Volin Dmytro
Quantum integrability and functional equations (Intégrabilité quantique et équations fonctionnelles) [t09/283],
supervised by I. Kostov and D. Serban, Université Paris-Sud 11, ED 107, 25/09/2009.

Benlagra Adel
Quantum criticality in ^{3}He bi layers and heavy fermion compounds (Criticalité quantique dans les bi-couches d' ^{3}He et les composés à fermions lourds) [t09/274],
supervised by C. Pépin, Université Paris-Sud 11, ED 107, 09/11/2009.

Sarlat Thomas
A finite dimensional model for the glass transition (Un modèle de dimension finie pour la transition vitreuse) [t09/296],
supervised by A. Billoire, Université Pierre et Marie Curie - Paris 6, ED 107, 13/11/2009.

Schenck Emmanuel
Open quantum systems and semiclassical methods (Systèmes quantiques ouverts et méthodes semi-classiques) [t09/266],
supervised by S. Nonnenmacher and A. Voros, Université Pierre et Marie Curie - Paris 6, ED 107, 17/11/2009.

Ruef Clément
Black holes in string theory: towards an understanding of quantum gravity (Trous noirs en théorie des cordes : vers une compréhension de la gravité quantique) [t10/083],
supervised by I. Bena, Université Paris-Sud 11, ED 107, 18/06/2010.

Bourgine Jean-Émile
Matrix models and boundary problems in Liouville gravity (Modèles de matrices et problèmes de bord dans la gravité de Liouville) [t10/168],
supervised by I. Kostov, Université Paris-Sud 11, ED 107, 18/06/2010.

Gombeaud Clément
Thermalization in ultrarelativistic heavy ion collisions (Thermalisation dans les collisions d'ions lourds ultrarelativistes) [t10/199],
supervised by J.-Y. Ollitrault, Université Pierre et Marie Curie - Paris 6, ED 107, 02/07/2010.

Dubail Jérôme
Boundary conditions in some non-unitary conformal field theories (Conditions aux bords dans des théories conformes non unitaires) [t10/198],
supervised by H. Saleur and J. Jacobsen, Université Paris-Sud 11, ED 107, 07/09/2010.

Messio Laura
Ground states and excitations of frustrated magnetic systems, from the classical limit to the quantum case (Etats fondamentaux et excitations de systèmes magnétiques frustrés, du classique au quantique) [t10/144],
supervised by G. Misguich and C. Lhuillier (LPTMC-UPMC), Université Pierre et Marie Curie - Paris 6, ED 389, 14/09/2010.

Marchal Olivier
(Aspects géométriques et intégrables des modèles de matrices aléatoires) [t10/200],
supervised by B. Eynard and J. Harnad (Montreal), Université Paris Diderot - Paris 7, ED 107, 20/12/2010.

D.7 Current PhD students

In May 2011, IPhT has 21 PhD students:

Parmentier Jeanne
Phenomenological aspects of supersymmetry breaking (Aspects phénoménologiques de la brisure de supersymétrie),
supervised by S. Lavignac and E. Dudas (X-CPhT), 2007–11/07/2011.

Borot Gaëtan
Some problems in enumerative geometry, random matrices, integrability, studied via geometry on Riemann surfaces (Quelques problèmes de géométrie énumérative, de matrices aléatoires, d'intégrabilité, étudiés via la géométrie des surfaces de Riemann),
supervised by B. Eynard, 2008–23/06/2011.

Cluzel Émeline
Inflation in string cosmology (Inflation en cosmologie des cordes),
supervised by P. Brax and J. Martin (IAP), 2008–22/09/2011.

Giecold Grégory
Gauge/String duality and field theories at strong coupling (Correspondance AdS/CFT, ses extensions et applications aux théories de champs à fort couplage),
supervised by I. Bena and E. Iancu, 2008–17/06/2011.

Goi Enrico
Aspects of supersymmetry breaking in type IIA superstring theory: vacua and deformations (Quelques aspects de la brisure de supersymétrie en théorie des cordes de type IIA: vides et déformations),
supervised by R. Minasian, 2008–21/09/2011.

Grandclaude Hélène
Dynamics of out-of-equilibrium networks (Dynamique des réseaux hors-équilibre),
supervised by C. Godrèche, 2008–2011.

Mariadassou Sophie
Preheating after small field inflation (Phase de préchauffement après l'inflation à petit champ),
supervised by P. Brax, 2008–2011.

Orsi Francesco
Flux Compactifications in String Theory (Compactifications avec flux en théorie des cordes),
supervised by M. Grana, 2008–2011.

Stephan Jean-Marie
Entanglement in low-dimensional quantum systems (Intrication dans des systèmes quantiques à basse dimension),
supervised by V. Pasquier, 2008–2011.

Bondesan Roberto
Supersymmetric field theory and statistical mechanics models (Théorie de champs supersymétrique et mécanique statistique),
supervised by H. Saleur and J. Jacobsen, 2009–2012.

Peng Zongren
Topics in N=4 Yang-Mills theory (Sujets dans la théorie de Yang-Mills N=4),
supervised by D. Kosower, 2009–2012.

Sciolla Bruno
Out-of-equilibrium quantum dynamics for cold atoms (Dynamique quantique hors-équilibre pour atomes froids),
supervised by G. Biroli, 2009–2012.

Shenderovich Igor
Integrable structures in gauge theories and supersymmetric string theories (Structures intégrables dans les théories de jauge et dans les théories des cordes supersymétriques),
supervised by I. Kostov and D. Serban, 2009–2012.

Van de Rijt Nicolas
Signatures of the primordial universe in large scale surveys (Signatures de l'univers primordial dans les grands relevés cosmologiques),
supervised by F. Bernardeau and F. Vernizzi, 2009–2012.

Laidet Julien
QCD's evolution equations in saturated regime (Équations d'évolution en QCD en régime saturé),
supervised by F. Gelis and E. Iancu, 2010–2013.

Lazarescu Alexandre
Finite size results for the open asymmetric exclusion process (Le processus d'exclusion asymétrique ouvert: quelques résultats en taille finie),
supervised by K. Mallick, 2010–2013.

Massai Stefano
Non-supersymmetric compactifications of string theory (Compactifications non supersymétriques de la théorie des cordes),
supervised by M. Grana, 2010–2013.

Puhm Andrea
Black holes in string theory (Trous noirs en théorie de cordes),
supervised by I. Bena, 2010–2013.

Tourkine Piotr
UV completeness of quantum gravity theories (Complétude ultraviolette des théories de gravité quantique),
supervised by P. Vanhove, 2010–2013.

Vasseur Romain
Field Theory and non-interacting fermionic systems with quenched disorder (Théorie des champs et systèmes d'électrons libres désordonnés),
supervised by H. Saleur and J. Jacobsen, 2010–2013.

D.8 Postdocs

Name	Supervisor	Origin	Financial Support	Dates
ALBACETE LOPEZ Javier	E. Iancu	ECT, Trento	Marie Curie IEF	june-09 may-12
ALEXANDROV Alexander	B. Eynard	Imperial College	ANR	oct-09 sept-11
ALMEIDA Leandro	R. Britto	Univ. New York	ANR	sept-10 sept-12
AVSAR Emil	E. Iancu	Univ. De Lunds	ANR	dec-07 oct-09
AYYER Arvind	K. Mallick	Rutgers Univ.	CEA	oct-08 sept-10
BADGER Simon	D. Kosower	Univ. Durham	ANR	oct-06 sept-08
BENA Cristina	H. Saleur	Rutgers Univ.	Marie Curie IEF	oct-06 oct-08
BON Michael	H. Orland	IPhT	CEA	mar-11 feb-12
BONVIN Camille	F. Bernardeau	Dep. Physique théorique, Genève	CEA P2I	oct-08 sept-10
BOWICK Marc John	E. Guitter	Univ. Syracuse	EGIDE	jan-07 jul-07
CAMMAROTA Chiara	G. Biroli	Univ. Rome	ANR - CNRS - CEA	nov-09 nov-12
CAPRINI Chiara	P. Brax	Univ. Geneve	ANR	oct-07 permanent
CHESTERMAN Michael	P. Vanhove	Karlstad University	CEA	oct-05 sept-07
CIRELLI Marco	C. Savoy	Yale Univ.	EGIDE - CEA	sept-06 permanent
DIANA Giovani	D. Kosower	INFN Milan	ERC	dec-10 nov-12
DE SANDES KIMURA Horoshi	C. Savoy	Univ. Sao Paulo	COFECUB	oct-10 mar-12
DESROSIERS Patrick	B. Eynard	Melbourne Univ.	CEA	sept-07 feb-08
EL-SHOWK Sheer	I. Bena	Univ. Amsterdam	RUBICON - ERC	sept-09 sept-13
FERRERO Michel	O. Parcollet	CPHT, Polytechnique	ANR	oct-08 sept-09
FRIGERIO Michele	S. Lavignac	Univ. of California	Marie Curie EIF	sept-07 aug-09
GAYNUTDINOV Azat	H. Saleur	Inst. Lebedev, Moscow	CEA - Marie Curie	sept-09 oct-13
GIUSTO Stefano	I. Bena	Univ. Toronto	CEA	sept-07 aug-09
GROMOV Nikolay	H. Saleur	ENS Paris	ANR	nov-07 nov-08
GUICA Monica-Maria	I. Bena	LPTHE Jussieu	ANR	sept-10 aug-11
HALMAGYI Nick	I. Bena	Univ. Chicago	ANR	sept-08 aug-11
HATTA Yoshitaka	E. Iancu	RIKEN BNL Research Center	CEA	oct-06 jan-08
HIDALGO Irene	S. Lavignac	Orsay	ANR	nov-07 feb-08
HOSOMICHI Kazuo	I. Kostov	Univ. Toronto	CEA	oct-05 sept-07
HUANG Zhiqi	F. Vernizzi	Univ. Toronto	ANR - Eurotalents	oct-10 sept-13
IOCCO Fabio	M. Cirelli	INAF, Observatoire, Florence	CEA P2I	nov-08 oct-09
JOHANSSON Henrik	D. Kosower	UCLA - Los Angeles	ERC	oct-09 oct-12
KASHANI-POOR Amir-Kian	R. Minasian	Univ. Amsterdam	ANR	oct-08 oct-09
KIM Ki-Seok	C. Pepin	KIAS Seoul	ANR	sept-07 aug-08

KUGERATSKI SOUSA Maria	E. Iancu	Univ. Sao Paulo	COFECUB	june-07 june-08
KYTOLA Kalle	F. David	Univ. of Helsinki	Marie Curie RTN	nov-06 nov-07
LAPPI Tuomas	F. Gelis	Brookhaven National Laboratory, Upton	CEA	oct-07 dec-09
LUZUM Matt	J.-Y. Ollitrault	Univ. Washington Seattle	ANR - ERC	oct-09 sept-12
MANSCHOT Ian	I. Bena	Rutgers Univ.	ANR - CEA	sept-09 sept-11
MARQUET Cyrille		IPhT	Marie Curie OIF	sept-07 aug-10
MARQUES Diego	M. Grana	Univ. De La Plata, Argentine	ERC	apr-11 may-12
MIRABELLA Edouardo	R. Britto	Max Planck Inst.	ERC	oct-09 sept-11
NO Jose Miguel	S. Lavignac	IFT, Madrid	CEA - Eurotalents	oct-09 sept-11
PORTUGAL Licinio	E. Iancu	Univ. Rio de Janeiro	COFECUB	sept-06 dec-07
RAY Tirtha Sankar	S. Lavignac	Saha Inst. Of Nuclear Physics	ITN - CEA	jul-10 june-12
SAUERESSIG Frank	R. Minasian	Utrecht Univ.	ANR	sept-07 sept-08
SAUSSET Francois	G.Biroli	Univ. Pierre et Marie Curie	bourse	nov-08 oct-09
SAXENA Ashish	I. Bena	Univ. Toronto	Marie Curie IRG	sept-07 feb-08
SEFUSATTI Emiliano	F. Bernardeau	Fermi National Accelerator Lab.	ANR - Marie Curie IEF	jan-09 jan-12
SIL Arunansu	C. Savoy	Univ of Delaware	Marie Curie ITN	oct-06 sept-09
TARZIA Marco	G. Biroli	Univ. Orsay	CNRS	dec-07 nov-08
TRIENDL Hagen	I. Bena	Univ. Hambourg	ANR	oct-10 sept-12
VERCNOCKE Bert	I. Bena	Univ. Leuwen	ERC	oct-10 sept-12
VICEDO Benoit	H. Saleur	Univ. Cambridge	ANR	sept-08 aug-10
WYNANTS Bram	H. Orland	Univ. Leuwen	CEA	oct-10 sept-11
ZAHARIJAS-SEFUSATTI Gabrijela	G. Servant	Univ. Stockholm	ANR - CEA - P2I	nov-09 oct-11
ZAMPONI Francesco	G. Biroli	LPT, Paris	CEA	sept-06 aug-07

D.9 Internships

Supervisor	Student	Level	Dates
P. Vanhove	Valentin Assassi	Ecole Centrale Paris	01/09/2010-31/12/2010
B. Eynard	Antoine Baker	Ecole Normale Supérieure	20/02/2007- 27/07/2007
E. Sefusatti	Nicolas Bonne	Polytechnique	06/04/2011-29/06/2011
C. Caprini	Simon Bonnefoy	Univ. Montpellier	04/03/2011-15/06/2011
B. Eynard	Guillaume Boudarham	Univ. Pierre et Marie Curie	15/01/2007-05/03/2007
M. Cirelli	Carolin Braüninger	Univ. Tubingen	13/10/2008-14/04/2009
E. Iancu	Clémentine Broutin	Polytechnique	10/04/2007-06/07/2007
R. Britto	Xavier Busch	Polytechnique	13/10/2008-13/04/2009
F. Bernardeau	Sandrine Codis	ENS Paris	10/01/2011-04/03/2011
G. Soyez	Stéphane Dartois	ENS Lyon	20/04/2011-01/08/2011
K. Mallick	Alban Debacker	ESPCI Paris Tech	01/07/2009-31/07/2009
F. Gelis	Thomas Epelbaum	ENSTA Paris	06/04/2010-06/08/2010
F. Gelis	Thomas Epelbaum	M2 physique théorique	01/01/2011-28/02/2011
S. Nonnenmacher	Quentin Gendron	ENS Cachan	02/06/2009-31/07/2009
P. Brax	Sophie Grezes-Rueff	Univ. Orsay	07/05/2007-20/06/2007
J. Bros	Emmanuel Jolibois	ENS Paris	06/02/2008-14/03/2008
G. Korchemsky	Andrey Lokhov	Polytechnique	12/04/2010-23/07/2010
G. Korchemsky	Andrey Lokhov	Polytechnique	10/01/2011-04/03/2011
L. Zdeborova	Jared Lolli	ENS Paris	01/02/2011-30/06/2011
M. Barthelemy	Jacopo Nespolo	Univ. Paris VI	12/01/2010-05/03/2010
R. Britto	Adrien Nicolas	Polytechnique	12/04/2010-31/07/2010
I. Kostov	Amael Obliger	Univ. Paris 7	17/01/2011-20/05/2011
J.-P. Blaizot	Leticia Palhares	PhD, Rio de Janeiro	01/09/2010-31/08/2011
M. Cirelli	Paolo Panci	PhD, Univ. L'Aquila, Italy	15/01/2009-15/07/2009
G. Misguich	Thiago Penteado Sabetta	Polytechnique	10/01/2011-09/05/2011
C. Pépin	Adam Rançon	ENS Paris	05/01/2009-26/04/2009
P. Brax	Benoît Schmauch	Polytechnique	11/04/2011-01/07/2011
I. Kostov	Igor Shenderovich	Univ. St Petersburg	01/04/2009-30/09/2009
G. Misguich	Jean-Marie Stephan	M2 physique quantique	01/12/2007-30/04/2008
P. Valageas	Julien Vandeportal	M2 physique chimie Montpellier	10/02/2007-10/07/2007
C. Cataldi	Célia Zaffanella	Lycée Gustave Eiffel	02/10/2007-31/10/2009

D.10 IPhT lectures

These courses take place Friday morning at IPhT. Most of them are part of the PhD program of the ED 107 "École doctorale de physique de la région parisienne". They are mainly intended for PhD students, but they are open for everybody. More details are given on the IPhT web site.

Viennot Xavier (LaBRI, Bordeaux)
Eléments de combinatoire algébrique; 12 h; Sep 2007.

Bernardeau Francis (IPhT)
Cosmologie et fluctuations primordiales; 12 h; Nov 2007.

Fayet Pierre (LPT, ENS Paris)
Le modèle standard supersymétrique; 12 h; Jan 2008.

Biroli Giulio (IPhT)
Transition vitreuse et systèmes hors d'équilibre; 12 h; Mar 2008.

Douçot Benoît (LPTHE, Paris 6-7)
Cohérence quantique de systèmes macroscopiques; 12 h; May 2008.

Wiegmann Paul (Chicago Univ.)
Hydrodynamic instabilities in quantum liquids; 6 h; Sep 2008.

Saleur Hubert (IPhT)
Théorie des champs à basse dimension : introduction et applications; 16 h; Oct 2008.

Deruelle Nathalie (APC, Paris 7)
Les trous noirs en relativité générale; 12 h; Jan 2009.

Bauer Michel (IPhT and LPT-ENS Paris)
Probabilités et processus stochastiques, pour les physiciens (et les curieux); 12 h; Mar 2009.

Mallick Kirone (IPhT)
Développements récents en mécanique statistique loin de l'équilibre; 8 h; May 2009.

Houdayer Jérôme (IPhT)
Ondelettes et analyse numérique; 10 h; Jun 2009.

Nonnenmacher Stéphane (IPhT)
Chaotic dynamical systems; 12 h; Sep 2009.

Parcollet Olivier (IPhT)
Quantum many body problem: selected topics; 10 h; Nov 2009.

Barthélemy Marc (IPhT)
Dynamical processes on complex networks; 8 h; Jan 2010.

Petrini Michela (LPTHE, Paris 6)
The AdS/CFT correspondence; 10 h; Mar 2010.

Shifman Mikhai (Minnesota Univ. and Chaire Blaise Pascal) and
Yung Alexei V. (PNPI, S. Petersburg)
Dynamics of supersymmetric gauge theories; 12 h; May 2010.

Peschanski Robi (IPhT) and
Janik Romuald (Jagellonian Univ., Krakow)
The dynamics of quark-gluon plasma and AdS/CFT correspondence; 8 h; Nov 2010.

Britto Ruth (IPhT)
Introduction to scattering amplitudes; 8 h; Jan 2011.

Durrer Ruth (Geneva Univ.)
Cosmology and the cosmic microwave background; 12 h; Mar 2011.

Kempe Julia (LRI, Paris 11)
Quantum algorithms and information; 6 h; Apr 2011.

Zia Royce (Virginia Tech.)
Exploring nonequilibrium statistical mechanics with driven diffusive systems; 6 h; May 2011.

D.11 Teaching in university or "grandes écoles"

In french universities, the undergraduate studies ("License") last three years, L1, L2 and L3; the master lasts two years, M1 and M2; finally, the PhD lasts generally three years.

Bauer Michel M1; École normale supérieure
Introduction to quantum field theory; 30 h/year; 2007–2011.

Bauer Michel M2; École normale supérieure
Probability and stochastic processes for physicists; 45 h/year; 2011–.

Bernardeau Francis L3; École polytechnique
General physics, special relativity and quantum physics; 64 h/year; 2008–2011.

Biroli Giulio M1; École polytechnique
Quantum mechanics and statistical physics; 72 h; 2011.

Blaizot Jean-Paul graduate; University of Tokyo
Quantum fields at finite temperature: from tera to nano Kelvin; 15 h; 2009.

Blaizot Jean-Paul graduate; University of Nanjing (China)
Quantum fields at finite temperature: from tera to nano Kelvin; 15 h; 2011.

Bouttier Jérémie L3; ESPCI
Mathematical methods for physicists; 24 h/year; since 2009.

Britto Ruth M1/M2; EPFL Lausanne
Constructing scattering amplitudes; 14 h; 2010.

David François M2; ENS Paris
Introduction to statistical field theory; 40 h/year; 2007 – 2011.

David François M2; Perimeter Institute, Waterloo, Canada
Perimeter scholar international program; quantum field theory II; 20 h/year; 2009, 2010.

Di Francesco Philippe Graduate; Univ. Illinois, Urbana-Champaign
Integrable combinatorics; 45 h; 2009.

Duplantier Bertrand M1; École polytechnique
Physics of polymers and biological membranes; 36 h; 2008.

Duplantier Bertrand M2; EPFL, Lausanne
The polymer physics of DNA; 16 h; 2009.

Gelis François M2; Université Paris-Sud 11, M2 NPAC
Introduction to the physics of heavy ion collisions; 6 h/year; 2008 – 2011.

Grojean Christophe M2; EPFL Lausanne
Introduction to SM; 39 h; 2011.

Kosower David PhD; Weizmann Institute, Israel
On-shell methods in gauge field theory; 12 h; 2010.

Lavignac Stéphane M2; ENS
Exercises in gauge theory of electroweak interactions; 12 h/year; 2008 – 2011.

Mallick Kirone L3; ESPCI
Méthodes mathématiques pour la physique; 22 h; 2007.

Minasian Ruben M2; ENS Paris
Geometrical methods of theoretical physics; 39 h/year; 2007 – 2011.

Ollitrault Jean-Yves L3, M1; École polytechnique
Quantum physics, statistical mechanics, particle physics; 64 h/year; 2007 – 2011.

Soyez Grégory M2; ENS
Exercises in quantum chromodynamics; 8 h; 2011.

Vanhove Pierre PhD; IHES
Perturbative quantum gravity; 20 h; 2011.

Zdeborova Lenka M1, M2, PhD; Tokyo Institute of Technology, Japan
Statistical physics on random graphs; 9 h; 2010.

Zdeborova Lenka M1; ESPCI, Paris
Tutorials in statistical physics; 16 h/year; 2007, 2008.

D.12 Teaching in summer schools

Bauer Michel *A short introduction to critical interfaces in 2d;*
4 h; in *School on stochastic geometry, the stochastic Loewner evolution, and non-equilibrium growth processes*; Trieste; July 2008.

Bauer Michel *A short introduction to critical interfaces in 2d;*
4 h; in *Modern applications of conformal invariance, topical school in statistical physics*; Nancy; March 2011.

Biroli Giulio *Statistical dynamics;*
13.5 h; in *Beg Rohu summer school 2010*; Beg Rohu; Aug 2010.

Britto Ruth *Scattering amplitudes in gauge theories;*
14 h; in *Dutch research school of theoretical physics*; Driebergen, NL; Feb 2010.

Britto Ruth *Multi-leg amplitudes;*
3 h; in *Spring course of the international graduate school Bielefeld-Paris-Helsinki*; Orsay; Mar 2010.

Britto Ruth *Recursive construction of amplitudes;*
6 h; in *Summer school on the structure of local quantum fields*; Les Houches; Jun 2010.

Cirelli Marco *Dark matter;*
2 h; in *Universenet summer school and meeting*; Barcelona, Spain; Sep 2009.

Cirelli Marco *Hoping to indirectly detect dark matter with cosmic rays;*
3 h; in *Carpathian summer school of physics*; Sinaia, Romania; Jun 2010.

Cirelli Marco *Dark matter indirect detection;*
1 h; in *Universenet summer school and meeting*; Lecce, Italy; Sep 2010.

David François *Quantum field theory and renormalisation group;*
20 h; in *Summer school of mathematical physics*; Shanghai institute of advanced studies, Shanghai, China; Aug 2009.

Di Francesco Philippe *Integrable combinatorics: from loop gas to orbital varieties and beyond;*
3 h; in *Random trees 2007*; Univ. Reykjavik, Iceland, ; Aug 2007.

Di Francesco Philippe *Combinatorics;*
3 h; in *European network ENIGMA school "Quantum integrability"*; La Londe les Maures, France; Oct 2007.

Di Francesco Philippe *Integrable combinatorics;*
15 h; in *Oberwolfach seminar "Enumerative combinatorics and integrable models of statistical mechanics"*; Mathematisches Forschungsinstitut Oberwolfach; Nov 2007.

Di Francesco Philippe *Integrable models of statistical physics and enumerative combinatorics;*
13 h; in *Combinatorics and statistical mechanics*; Erwin Schrödinger international institute for mathematical physics, Vienna, Austria; Jul 2008.

Di Francesco Philippe *Integrable combinatorics;*
16 h; in *Semester "Statistical physics, combinatorics and probability: from discrete to continuous models"*; Institut Henri Poincaré, Paris; fall 2009.

Di Francesco Philippe *Master class: cluster algebras;*
4 h; in *Center for quantum geometry of moduli spaces*; Aarhus Univ., Denmark; Jun 2010.

Di Francesco Philippe *Integrable combinatorics;*
6 h; in *Clay mathematics institute 2010 summer school "Probability and statistical physics in two and more dimensions"*; Buzios, Brazil; Jul 2010.

Duplantier Bertrand *A rigorous perspective on Liouville quantum gravity and the KPZ relation;*
1.5 h; in *Exact methods in low-dimensional statistical physics and quantum computing*; Les Houches; Jul 2008.

Eynard Bertrand *Symplectic invariants of spectral curves and their applications to enumerative geometry;*
6 h; in *From integrable structures to topological strings and back*; Sissa, Trieste; Sep 2008.

Eynard Bertrand *Symplectic invariants of spectral curves and their applications to enumerative geometry;*
5 h; in *A new recursion from random matrices and topological string theory*; IPMU Tokyo; Dec 2008.

Eynard Bertrand *Enumeration of maps;*
5 h; in *Statcomb school on embedded random graphs*; IHP, Paris; Autumn 2009.

Eynard Bertrand *Matrix models for topological strings;*
5 h; in *Trimester matrix models and geometry CAMGSD thematic period*; IST Lisbon; Autumn 2009.

Eynard Bertrand *From matrix models to algebraic geometry;*
4 h; in *From matrix models to algebraic geometry*; Northeastern, Boston; Oct 2010.

Gelis François *Gluon saturation from DIS to nucleus-nucleus collisions;*
3 h; in *School on QCD, low-x physics, saturation and diffraction*; Copanello, Italy; Jul 2007.

Gelis François *Pre-equilibrium dynamics in heavy ion collisions;*
6 h; in *Advanced school on QGP*; Indian institute of technology, Mumbai, India; Jul 2007.

Gelis François *Quantum chromo-dynamics at finite temperature;*
4.5 h; in *2nd Rio-Saclay meeting*; CBPF, Rio de Janeiro, Brazil; Sep 2007.

Gelis François *Gluon saturation from DIS to AA collisions;*
6 h; in *Hadronic collisions at the LHC and QCD at high density*; Les Houches, France; Apr 2008.

Gelis François *Color glass condensate and initial stages of heavy-ion collisions;*
3 h; in *Nuclear astrophysics and heavy ion collisions*; Dubna, Russia; Jul 2008.

Gelis François *Initial conditions in AA collisions;*
3 h; in *Initial conditions in heavy ion collisions collisions*; Goa, India; Sep 2008.

Gelis François *Introduction to perturbative QCD;*
3 h; in *Aspects of perturbative QCD*; Orsay, France; Mar 2010.

Grojean Christophe *Alternate electroweak scenarios;*
3h45; in *From string to LHC*; Fireflies Ashram, Bangalore, India; Dec 2007.

Grojean Christophe *Beyond the Higgs: new ideas on electroweak symmetry breaking;*
6 h; in *Third graduate school in physics at colliders: from twistors to Monte Carlos*; Turin, Italy; Jan 2008.

Grojean Christophe *Beyond the Higgs: new ideas on electroweak symmetry breaking;*
3 h; in *IPM international school and workshop on electroweak physics*; Teheran, Iran; May 2008.

Grojean Christophe *Beyond the Higgs: new ideas on electroweak symmetry breaking;*
4h30; in *Ecole de Gif 2008*; Ecole Polytechnique, France; Sep 2008.

Grojean Christophe *Beyond the standard model at the LHC: new ideas on electroweak symmetry breaking;*
2 h; in *VII latin american symposium on high energy physics (SILAFAE) + IX Argentine symposium of particles and fields (SAPyC)*; Bariloche, Argentina; Jan 2009.

Grojean Christophe *Electroweak symmetry breaking: to Higgs or not to Higgs ;*
3 h; in *CERN academic training*; CERN, Switzerland; Feb 2009.

Grojean Christophe *Beyond the Higgs;*
4 h; in *Ecole de physique des particules et cosmologie*; Oran, Algeria; May 2009.

Grojean Christophe *Beyond the standard model: the LHC reach;*
4h30; in *The XIV LNF spring school "Bruno Touschek" in nuclear, subnuclear and astroparticle physics*; Frascati, Italy; May 2009.

Grojean Christophe *Beyond the standard model;*
5 h; in *Fourth graduate school in physics at colliders: on the eve of the LHC*; Turin, Italy; Jul 2009.

Grojean Christophe *Extra dimensions for TeV physics;*
4h30; in *Parma international school of theoretical physics*; Parma, Italy; Sep 2009.

Grojean Christophe *New physics at the LHC;*
2 h; in *Particle, astrophysics and cosmology winter school*; Sesimbra, Portugal; Dec 2009.

Grojean Christophe *Electroweak symmetry breaking;*
1h30; in *PSI summerschool on particle physics: Gearing up for LHC physics*; Zuoz, Switzerland; Aug 2010.

Grojean Christophe *Beyond the standard model;*
4 h; in *German particle physics school*; Maria Laach, Germany; Sep 2010.

Grojean Christophe *Electroweak symmetry breaking;*
2 h; in *Second school on the LHC physics*; Islamabad, Pakistan; May 2010.

Iancu Edmond *Non-linear evolution in QCD at high energies;*
4.5 h; in *Summer School on high-energy QCD, low-x physics, saturation and diffraction*; Copannello, Italy; Jul 2007.

Iancu Edmond *High-energy QCD : the color glass condensate;*
3 h; in *2nd Rio-Saclay meeting*; CBPF, Rio de Janeiro, Bresil; Sep 2007.

Iancu Edmond *Gluon saturation and the color glass condensate;*
6 h; in *Winter school on hadronic collisions at the LHC and QCD at high density*; Les Houches; Mar 2008.

Iancu Edmond *Partons and jets in a strongly-coupled plasma from AdS/CFT;*
4.5 h; in *48th Cracow school of theoretical physics: aspects of duality*; Zakopane, Poland; Jun 2008.

Iancu Edmond *High energy scattering : from weak to strong coupling;*
3 h; in *First high energy physics school*; Magurele, Roumanie; Oct 2008.

Kosower David *On-shell methods in gauge field theory;*
4.5 h; in *String theory - from theory to experiment*; Weizmann Institute, Israel; Apr 2008.

Kosower David *On-shell methods in gauge theory;*
4.5 h; in *Taiwan Summer Institute*; Chi-Tou, Taiwan; Aug 2008.

Kostov Ivan *Boundary loop models and 2D quantum gravity;*
3 h; in *Exact methods in low-dimensional statistical physics and quantum computing*; Les Houches; Jul 2008.

Lavignac Stéphane *Physics beyond the standard model;*
3 h; in *France-Asia particle physics school (FAPPS)*; Les Houches; Sep 2008.

Lavignac Stéphane *Supersymmetry;*
6 h; Univ. Catholique de Louvain-la-Neuve, Belgium; Dec 2008.

Mallick Kirone *Bethe ansatz and applications to non-equilibrium statistical mechanics;*
5 h; Tata Institute, Mumbhai, India; Mar 2007.

Mallick Kirone *Exact results for the exclusion process;*
6 h; in *ALEA (School of combinatorics and probabilities)*; CIRM Marseille; Apr 2010.

Misguich Grégoire *Quantum spin liquids and fractionalization [t07/161];*
2 h; in *Highly frustrated magnetism*; Trieste ICTP, Italy ; Aug 2007.

Misguich Grégoire *Quantum spin liquids [t08/250];*
2 h; in *Exact methods in low-dimensional statistical physics and quantum computing*; Les Houches; Jul 2008.

Nonnenmacher Stéphane *Entropy of chaotic eigenstates;*
2 h; in *Spectrum and dynamics*; CRM, Montreal, Canada ; Apr 2008.

Ollitrault Jean-Yves *Relativistic hydrodynamics;*
4 h; in *Advanced school on quark-gluon plasma*; IIT Mumbai, India; Jul 2007.

Ollitrault Jean-Yves *Relativistic hydrodynamics;*
3 h; in *Hadronic collisions at the LHC and QCD at high density*; Les Houches; Mar 2008.

Schaeffer Richard *Dark energy, dark matter, dark baryons;*
6 h; in *Theoretical physics and mathematics school*; Ubu, Brazil; Feb 2010.

Servant Géraldine *Introduction to cosmology;*
2 h; in *French physics teachers programme*; CERN; Apr 2008.

Servant Géraldine *Cosmology and the particle accelerator connection;*
1 h; in *4th CERN-Fermilab hadron collider physics summer school*; CERN; Jun 2009.

Servant Géraldine *Introduction to cosmology;*
2 h; in *International physics teachers programme*; CERN; Jul 2010.

Servant Géraldine *Cosmological consequences of new physics at the TeV scale;*
1 h; in *The Standard Model and beyond-cosmology*; Corfu; Sep 2010.

Servant Géraldine *Cosmological and astroparticle aspects of physics beyond the Standard Model;*
3 h; in *Annual particle physics retreat*; Mainz University; Sep 2010.

Soyez Grégory *Phenomenology of hadronic colliders;*
9 h; in *BND school 2010 (Belgian-Dutch-German graduate school in particle physics)*; Ostend (Belgium); Sep 2010.

Vanhove Pierre *Non renormalisation theorems in type II superstrings;*
2 h; in *String theory and the real world, from particle physics to astrophysics*; Les Houches; Jul 2007.

Vanhove Pierre *Introductory lectures on pure spinor formalism;*
3 h; in *Fundamental aspects of superstring theory*; KITP, Santa Barbara, California; Jan 2009.

Zdeborova Lenka *Probing the energy landscape of random optimization problem;*
2 h; in *Statistical physics of complexity, optimization and biological information*; Les Houches; Mar 2010.

D.13 Weekly seminars

Monday	11:00	Mathematical Physics
	14:00	Statistical Physics
Tuesday	11:00	General Seminar
Wednesday	14:15	Particle Physics and Cosmology
Thursday	11:00	Condensed Matter Theory
	16:00	PhD seminar
Friday	10:00	IPhT lectures
	14:15	Matrices, Strings & Random Geometries

Usually, seminars take place in the IPhT seminar room (Claude Itzykson room), which can contain up to 50 persons. For bigger events, we can use in the same building an amphitheater for 150 persons (Amphi Claude Bloch).

IPhT also organizes a condensed matter theory seminar in common with the LPS (Orsay).

D.14 Claude Itzykson meetings

The Claude Itzykson meetings are the main scientific events at IPhT. Created to honour the memory of Claude Itzykson and in particular his deep and true love for physics, they have become a tradition. Every year in June, scientists from all over the world (mainly but not only physicists) meet for a few days to cover the main recent advances on a targeted theme. Two important features are the insistence on pedagogical seminars and the opportunity given to young researchers as well as established experts to give a talk.

Integrability in Gauge and String Theory
12th Claude Itzykson Meeting, June 18–22, 2007

Organizers: V. Kazakov (LPTENS), I. Kostov, D. Serban.

G. Arutyunov	:	Zamolodchikov-Faddeev algebra for $AdS_5 \times S^5$ superstring
N. Beisert	:	Symmetries related to AdS/CFT integrability
N. Berkovits	:	New limit of the $AdS_5 \times S^5$ sigma model
N. Dorey	:	Singularities of the magnon S-matrix
B. Eden	:	The BES equation and its strong coupling limit
S. Frolov	:	
N. Gromov	:	Integrability in $AdS_5 \times S^5$ string theory: general 1-loop results
R. Hernandez	:	Magnon kinematics in planar N=4 Yang-Mills
R. Janik	:	Wrapping interactions and virtual corrections
G. Korchemsky	:	Anomalous dimensions of high-spin operators beyond the leading order
D. Kosower	:	From weak to strong coupling at maximal supersymmetry
C. Kristjansen	:	The strong coupling limit of the scaling function from the quantum string Bethe ansatz
L. Lipatov	:	BFKL and double-logarithmic resummation for the multi-loop anomalous dimensions in N=4 SUSY
J. Maldacena	:	Worldsheets and spin chains with boundary
A. Migdal	:	Ancient history of conformal field theory
J. Minahan	:	Two loop results for the near flat sigma model
A. Rej	:	Exact results for twist operators in planar N=4 SYM
R. Roiban	:	Probing the higher loop dilatation operator of N=4 SYM
K. Sakai	:	Origin of dressing phase in N=4 Super Yang-Mills
H. Saleur	:	Associative-algebraic approach to logarithmic conformal field theories
S. Schafer-Nameki	:	Quantum integrability in the pure spinor formalism
V. Schomerus	:	Sigma models on superspaces
G. Semenoff	:	Finite size giant magnon redux
E. Sokatchev	:	Conformal properties of N=4 SYM amplitudes
M. Staudacher	:	Transcendentality, dressing, nesting and wrapping in AdS/CFT
J. Teschner	:	Warm-up for solving noncompact sigma models: the Sinh-Gordon model
A. Tseytiln	:	Quantum string corrections in $AdS_5 \times S^5$
A. Zabrodin	:	Hirota equation for supersymmetric spin chains
K. Zarembo	:	Worldsheet scattering in $AdS_5 \times S^5$

Puzzles of Growth
13th Claude Itzykson Meeting, June 9–11, 2008

Organizers: M. Bauer, D. Bernard (LPTENS), Z. Burda (Univ. Jagiellonski, Krakow), F. David, A. Lefèvre.

E. Ben Jacob	:	The Mathematical skills of bacteria
F. Camia	:	Scaling limits of 2D percolation
S. Dorogovtsev	:	Transition from finite- to infinite-dimensional trees
F. David	:	
M. Drmota	:	Large random planar graphs

B. Duplantier	: Quantum gravity and brownian large deviations
E. Guitter	: The three-point function of planar quadrangulations
W. Janke	: Percolating excitations - a geometrical view of phase transitions
T. Kennedy	: Testing for SLE using the driving process
K. Kytölä	: Some CFT fusions from SLE local martingales
A. Middleton	: Exploring the effects of disorder on geometry
A. Okounkov	: Noncommutative geometry of planar dimers
S. Redner	: Cutting corners
H. Saleur	: Boundary loop models
R. Santachiara	: Interfaces in lattice Z(N) models
S. Smirnov	: Ising lattice universality
W. Werner	: Are frontiers symmetric?

Recent Advances in String Theory
14th Claude Itzykson Meeting, June 17–19, 2009

Organizers: I. Bena, M. Graña, R. Minasian, P. Vanhove.

O. Aharoni	: On d=3 Yang-Mills Chern-Simons theories with "fractional branes" and their gravity duals
N. Arkani-Hamed	: Holography and the S-Matrix
K. Becker	: Torsional heterotic geometries
N. Berkovits	: Spin chains from the topological $AdS_5 \times S^5$ string
Z. Bern	: Harmony of scattering amplitudes: from N=4 super-Yang-Mills theory to N=8 supergravity
J. de Boer	: Quantum aspects of black holes
R. Emparan	: Blackfolds
M. Green	: Supersymmetric string and field theory scattering amplitudes
S. Hartnoll	: Quantum bosons for holographic superconductors
J. Heckman	: The point of E8 in F-theory GUTs
S. Kachru	: Gauge/gravity duality and particle physics
N. Lambert	: Coupling M2-branes to background fields
J. Louis	: Compactifictions and generalized geometries
M. Marino	: Nonperturbative aspects of the topological string
S. Mathur	: Lessons from the information paradox
L. McAllister	: Inflation in string theory
J. McGreevy	: Holographic descriptions of quantum liquids
J. Polchinski	: Holography from CFT
A. Sen	: Black hole hair removal
T. Weigand	: Type IIB GUT vacua and their F-theory uplift

New Trends In Quantum Integrability
15th Claude Itzykson Meeting, June 21–23, 2010

Organizers: D. Lebedev (ITEP Moscow), V. Pasquier, R. Santachiara (LPTMS Orsay), D. Serban.

L. Cantini	: The Razumov-Stroganov correspondence
S. Derkachov	: Factorization of R-matrix, Baxter Q-operators and SOV
P. Dorey	: The boundary staircase
L. Faddeev	: Definition and use of quantum dilogarithm
V. Fateev	: Differential equations for the correlation functions, elliptic conformal blocks and AGT conjecture
A. Gerasimov	: A quantum field theory model of Archimedean geometry
V. Kazakov	: Y-system for the exact spectrum of AdS/CFT
R. Kedem	: Proofs of positivity using integrable models
G. Korchemsky	: Integrability of the N=4 scattering amplitudes
A. Lascoux	: Deformation of Kazhdan-Lusztig and Macdonald bases

S. Lukyanov	: Quantum Sine(h)-Gordon model and classical integrable equations
J.-M. Maillet	: Correlation functions of quantum integrable models : the Bethe ansatz viewpoint
C. Meneghelli	: A shortcut to the Q operator
V. Petkova	: Topological defects in Liouville CFT
S. Prolhac	: Fluctuations of the current in the asymmetric simple exclusion process
S. Shatashvili	: SUSY vacua and quantum integrability
J. Shiraishi	: Macdonald polynomials and quantum algebras
F. Smirnov	: One-point functions for sine-Gordon model at finite temperature
J. Teschner	: From modular duality to Langlands duality
A. Voros	: Exact solvability of the 1D polynomial Schrödinger equation (a survey)
D. Zagier	: Quantum modular forms
K. Zarembo	: Integrability in the AdS3/CFT2 correspondence

Extremes and Records
16th Claude Itzykson Meeting, June 14–17, 2011

Organizers: C. Godrèche, S. N. Majumdar (LPTMS) and G. Schehr (LPTMS).

J.-M. Azais	: Rice method for the extremes of gaussian random fields
E. Bertin	: Renormalization group approach to the statistics of extreme values and sums
J.-P. Bouchaud	: Correlations of extremes – copula, what copula ?
Z. Burda	: Universal behavior of eigenvalues of the product of random gaussian matrices near the edge
T. Burkhardt	: Extreme value statistics of random acceleration and related processes
A. Comtet	: Distribution of the ground state energy in a one dimensional random potential
B. Derrida	: Statistics at the tip of a branching random walk and simple models of evolution with selection
Y. Fyodorov	: Fluctuation properties of 1/f noise: from statistical mechanics to random matrices, Riemann-zeta function, and Burgers turbulence
J. Krug	: Records statistics in time series with drift: theory and applications
P. Le Doussal	: Exact results for the directed polymer and KPZ growth from the Bethe ansatz
S. Nechaev	: Statistics of noncoding RNAs: alignment and secondary structure prediction
Z. Racz	: Order statistics of $1/f^{\alpha}$ signals
S. Redner	: Dynamics of predatory random walkers
A. Rosso	: Anomalous dynamics: extremes for non-Markovian processes
C. Tracy	: The distributions of random matrix theory and their applications
C. Tracy	: Turbulent liquid crystals, KPZ universality, and the asymmetric simple exclusion process
M. Vrac	: Statistical extreme value theory: applications in downscaling of precipitation
P. Yiou	: Climate extreme events: an overview of physical and statistical challenges

D.15 Organization of workshops and conferences

Stéphane LAVIGNAC
École de Gif, (French summer school on particle physics); since 2001.

Jean-Marc LUCK
Rencontres de physique statistique, Paris; every January.

Stéphane NONNENMACHER
Spectral problems in mathematical physics, (monthly seminar at IHP), Paris; 2007.

Edmond IANCU
QCD, low X physics, saturation and diffraction, school, Copanello, Italy; Jul 1–14, 2007.

Pierre VANHOVE
String theory and the real world: from particle physics to astrophysics, summer school, Les Houches; Jul 2–27, 2007.

Iosif BENA
37th Paris Summer Institute on Black Holes, Black Rings and Modular Forms, Paris; Aug 13–24, 2007.

Edmond IANCU, Robi PESCHANSKI
Low X meeting, Helsinki; Aug 29 – Sep 1, 2007.

Bertrand DUPLANTIER, Vincent PASQUIER
Séminaire Poincaré, Paris; Dec 8, 2007; Jan 31, 2009; Nov 21, 2009; Jun 5, 2010; Dec 4 & 18, 2010.

Kirone MALLICK, Robi PESCHANSKI, Laure SAUBOY
Forum de la théorie, Saclay; Feb 7–8, 2008.

Cécile MONTHUS
Disorder and localization phenomena, from theory to applications, Paris; Mar 17–19, 2008.

François GÉLIS, Edmond IANCU, Jean-Yves OLLITRAULT
Hadronic collisions at the LHC and QCD at high density, school, Les Houches; Mar 25 – Apr 4, 2008.

Philippe BRAX, Marco CIRELLI, Géraldine SERVANT
Progress on old and new themes in cosmology (PONT), Avignon; Apr 21-25, 2008.

Philippe DI FRANCESCO, Bertrand DUPLANTIER
Statistical-mechanics and quantum-field theory methods in combinatorial enumeration, Cambridge, UK; Apr 21–25, 2008.

Iosif BENA
Gravitational scattering, black holes and the information paradox, workshop, Paris; May 26–28, 2008.

Michel BAUER, François DAVID, Alexandre LEFÈVRE
On growth and shapes, Enrage topical school, Paris; Jun 2–6, 2008.

Stéphane NONNENMACHER
Mathematical aspects of quantum chaos, Montreal; Jun 2–7, 2008.

Giulio BIROLI, Alexandre LEFÈVRE
Manifolds in random media, random matrices and extreme value statistics, summer school, Beg Rohu; Jun 16–28, 2008.

Pierre VANHOVE
Theory and particle physics: the LHC perspective and beyond, summer school, Cargèse; Jun 16–28, 2008.

David KOSOWER, Pierre VANHOVE
Wonders of gauge theory and supergravity, Paris and Saclay; Jun 23–28, 2008.

Vincent PASQUIER, Didina SERBAN
Exact methods in low-dimensional statistical physics and quantum computing, Les Houches; Jun 30 – Aug 1, 2008.

Olivier PARCOLLET
Frontiers in strongly correlated systems, Aspen; Jul 27 – Sep 7, 2008.

Giulio BIROLI
Dynamical heterogeneities in glasses, colloids and granular media, Leiden; Aug 25 – Sep 5, 2008.

Stéphane LAVIGNAC
NNN08 Next generation nucleon decay and neutrino detectors, Paris; Sep 11–13, 2008.

Olivier PARCOLLET
Quantum coherence and many-body correlations: from mesoscopic to macroscopic scales, Saclay; Oct 22–23, 2008.

Marco CIRELLI, Christophe GROJEAN
Physics of electroweak symmetry breaking and the LHC, workshop, Saclay; Oct 27–29, 2008; Mar 2–3, 2009.

Stéphane NONNENMACHER
Resonances in physics and mathematics, Marseille; Jan 19–23, 2009.

Stéphane Nonnenmacher
Quantum chaos, winter school, Bordeaux; Jan 26–30, 2009.

Jean-Paul Blaizot
Phases of strongly interacting matter, school, Orsay; Mar 9–13, 2009.

François Gélis, Edmond Iancu, Jean-Yves Ollitrault
Quantum field theory in extreme environments, Saclay; Apr 23–25, 2009.

Marco Cirelli
TANGO in PARIS: Testing astroparticle with the new GeV/TeV observations: positrons and electrons, identifying the sources, Paris; May 4–6, 2009.

Giulio Biroli, Alexandre Lefèvre
Quantum physics out of equilibrium, summer school, Beg-Rohu; Jun 15–27, 2009.

Catherine Pépin
Emergent quantum phenomena from the nano to the macro world, Cargèse; Jul 6–19, 2009.

Catherine Pépin
Correlated behavior and quantum criticality in heavy fermion and related systems, Aspen; Aug 9 – Sep 13, 2009.

Jérémie Bouttier
Statistical physics, combinatorics and probability: from discrete to continuous models, trimester at IHP, Paris; Sep 7 – Dec 18, 2009.

Ivan Kostov, Didina Serban
Facets of integrability, Saclay and Paris; Nov 5–7, 2009.

Grégoire Misguich
Novel physics on the kagome network, Orsay; Jan 18–20, 2010.

Vincent Pasquier, Didina Serban
Physics in the plane: From condensed matter to string theory, Les Houches; Feb 28 – Mar 5, 2010.

Henri Orland, Pierre Vanhove
Rencontres IHÉS-IPhT, IHÉS; Mar 18, 2010.

Philippe Brax, Stéphane Lavignac, Laure Sauboy
GDR Terascale, Saclay; Mar 29–31, 2010.

Christophe Grojean, Géraldine Servant
Planck 2010: from the Planck scale to the electroweak scale, CERN; May 31 – Jun 4, 2010.

Francis Bernardeau, Emiliano Sefusatti, Filippo Vernizzi
The almost gaussian universe: a workshop on the observable effects of primordial non-gaussianity, Saclay; Jun 9–11, 2010.

Pierre Vanhove
String theory: formal developments and applications, summer school Cargèse; Jun 21 – Jul 3, 2010.

Edmond Iancu, Robi Peschanski
Low X meeting, Kavala, Greece; Jun 23–27, 2010.

Mariana Grana
String phenomenology, Paris; Jul 5–9, 2010.

Francis Bernardeau, Filippo Vernizzi
Xème école de cosmologie, Cargèse; Jul 5–10, 2010.

Marco Cirelli, Gabrijela Zaharijas
TeV particle astrophysics, Paris; Jul 19–23, 2010.

Henri Orland, Philippe Di Francesco
Statphys24, Cairns, Australia; Jul 19–23, 2010.

Christophe Grojean, Géraldine Servant
Physics at TeV colliders - from Tevatron to LHC, Cargèse; Jul 19–31, 2010.

Marco Cirelli
ICHEP – International conference on high energy physics, Paris; Jul 22–28, 2010.

Iosif Bena
ICHEP Track 12 – Beyond quantum field theory approaches (including string theories), Paris; Jul 22–28, 2010.

Giulio Biroli, Alexandre Lefèvre
Concepts and methods of statistical mechanics, summer school, Beg Rohu; Aug 23 – Sep 4, 2010.

Marco Cirelli
Cosmic rays for particle and astroparticle physics (ICATPP), Como, Italy; Oct 7–8, 2010.

Marco Cirelli
ECFA study of physics and detectors for a linear collider, Geneva; Oct, 2010.

Enrico Goi, Francesco Orsi
Strings, cosmology and gravity student conference (SCGSC), Paris; Nov 3–5, 2010.

Marco Cirelli
Dark matter all around, Paris; Dec 13-17, 2010.

Edmond Iancu
Excited QCD 2011, Les Houches; Feb 20–25, 2011.

Philippe Brax, Chiara Caprini, Marco Cirelli, Géraldine Servant
Progress on old and new themes in cosmology (PONT), Avignon; Apr 18–22, 2011.

Stéphane Nonnenmacher
Spectral gap in dynamical systems, number theory and PDEs, Peyresq, France; May 30 – Jun 3, 2011.

D.16 Research administration

Who	Assignment	Institution
A. Billoire	Coordinator of call projects in mathematics, physics, and communication technologies (2007 – 2011)	Région Rhône-Alpes
F. Bernardeau	Chairman of the AERES evaluation committee (2009)	LUTH
	Scientific committee (CSTS)	Irfu/SAP
	Scientific committee (since 2008)	Cargèse School
F. David	Comité de programmation scientifique (until end 2009)	Institut Henri Poincaré, Paris
	Peer review evaluation panel, Starting grants (since 2007)	European Research Council (ERC)
	AERES evaluation committee (2008)	Institut Jean Lamour and the laboratories UMR 7040, 7555, 7556, 7570 & 7584 (Nancy)
	AERES evaluation committee (2008)	Fédération Dynamique des Systèmes Complexes (UPMC, Paris)
	AERES evaluation committee (2011)	Institut Non-Linéaire de Nice (INLN) and the Federation Wolfgang Döblin (CNRS - Univ. Nice Sophia Antipolis)
	In charge of the "Intergroupe des théoriciens"	French Physical Society
B. Duplantier	Scientific committee	IHÉS
	Selection committee	Univ. Diderot-Paris 7, Univ. Versailles-Saint Quentin
O. Golinelli	Comité d'évaluation (2009–2011)	GENCI – Grand équipement national de calcul intensif
C. Grojean	Scientific committee (2007–2009)	Service de Physique des Particules, CEA Saclay (IRFU/SPP)
	International Detector Advisory Group (2008–2012)	International Linear Collider
	Commission consultative de spécialistes (2010–2014)	Univ. Paris XI
S. Lavignac	Selection committee (2007–2008, 2011)	Université Pierre et Marie Curie - Paris 6
J.-M. Luck	Bureau de l'axe B & Comité de la vie scientifique	RTRA Triangle de la physique.
	Elected member (up to 2008)	Section 02 of the national committee of CNRS.
	Commission consultative de spécialistes (2010–2014)	Sections 29 & 34, Univ. Paris XI (Orsay)
S. Nonnenmacher	Selection committee (2009)	ENS Paris
J.-M. Normand	Work package "Future Petaflop/s computer technologies beyond 2010" (co-leader), Work package "Petaflop/s systems for 2009/2010" (2008–2010)	Partnership for advanced computing in Europe (PRACE), Preparatory phase
	Work package "Future technologies" (2010–2011)	PRACE, 1st implementation phase
J.-Y. Ollitrault	Board of directors (since 2009)	ECT* Trento

H. Orland	Vice-president	IUPAP (International Union of Pure and Applied Physics)
	Chair	Statistical physics Commission (C3) of the IUPAP
O. Parcollet	Comité thématique CT5 (2009–2011)	GENCI – Grand équipement national de calcul intensif
G. Servant	Scientific committee (since 2008)	Institut d'Etudes Scientifiques de Cargèse
P. Vanhove	Founding member (2009)	Institute for Physics and Mathematics of the Universe
	LHC safety commitee for the Autorité de Sûreté Nucléaire (2008)	LHC
	Elected member (2008 – 2012)	CNRS national committee, section 02 (Théories physiques: méthodes, modéles et applications)
	Coordinator of the IPhT sub-node for the European Network Forces Universes (2005 – 2009)	Europe

D.17 IPhT and high performance computing

CEA computers

CEA has shared supercomputer resources, which are among the largest in France and even Europe. They are managed by the CCRT (Centre de Calcul Recherche et Technologie, Research and Technology Computing Centre). The Physics Division of CEA, DSM, contributes about 25% to CCRT. Scientific projects requiring large computer resources are submitted to a scientific committee, which distributes computer time. Since created in 1994, the head of this committee is the head of our Institute. The secretary of the committee is also a physicist of our Institute, Olivier Golinelli.

National computers

Several members of the IPhT are involved in the scientific evaluation of applications for computing time at the GENCI (Grand Équipement National de Calcul Intensif, the organization that manages the main computer centers of the French public research): Olivier Parcollet is a member of the Thematic Committee CT5, "Theoretical physics and plasma physics"; Olivier Golinelli represents the CEA in the Evaluation Committee.

European computers

Building a world-class pan-European High Performance Computing (HPC) Service was a challenge involving governments, funding agencies, centres capable to host and manage the supercomputers, and the scientific and industrial user communities with leading edge applications. This has to be done in a quickly evolving context. An HPC Infrastructure has two unique characteristics: supercomputers serve all scientific disciplines and leading edge supercomputers (Tier-0 systems) have a three year depreciation cycle. This requires a periodic renewal of the systems and a continuous upgrade of the infrastructure. Furthermore, technologies change continuously, novel architectures and system designs will be created and the science focus changes as results are obtained and new directions are explored.

The Partnership for Advanced Computing in Europe Research Infrastructure (PRACE RI, www.prace-ri.eu) has been founded in April 2010 with its seat in Brussels. Four nations (France, Germany, Italy and Spain) have agreed to provide 400 million Euro to implement Tier-0 systems with a combined computing power in the multi Petaflop/s (one quadrillion operations per second) range over the next 5 years. This funding is complemented by up to 70 million Euros from the European Commission (EC) which is supporting the Preparation and Implementation of this infrastructure. Presently, PRACE has two Tier-0 systems: the 1 Petaflop/s IBM BlueGene/P (JUGENE) of the Gauss Centre for Supercomputing (GSC) hosted by FZJ, Jülich, Germany and the 1.6 Petaflop/s Bull Bullx cluster (CURIE), funded by GENCI and installed at CEA CCRT, Bruyères-le-Châtel, France, which will reach its full performance in the second half of 2011. In the third quarter of 2011, the GCS partner HPC Center of University Stuttgart will deploy the first installation step of a 1 Petaflop/s Cray system (Hermit), followed by a 4-5 Petaflop/s second step in 2013. The fourth system Tier-0 system, a 3 Petaflop/s IBM (SuperMUC), will be available in mid 2012 at the GCS partner LRZ-Garching, Munich, Germany. The Spanish and the Italian systems are planned for later (respectively at BSC Barcelona and CINECA Bologna). To keep pace with the needs of the user communities and technical developments, systems within the PRACE RI are expected to reach capabilities of at least one Exaflops/s (one quintillion) in less than a decade. Access for European researchers and their collaborators is determined based on proposals submitted in response to Calls for Proposals (www.prace-ri.eu/hpc-access). These are issued twice a year and are evaluated by leading scientists and engineers in a peer-review process governed by a PRACE Scientific Steering Committee. Users will be supported by experts in porting, scaling, and optimizing applications to novel, highly parallel computer architectures. An in-depth training program accompanies the PRACE offering teaching scientists and students how to best exploit the unprecedented capabilities of the systems. PRACE RI has presently 21 European members. Within PRACE activities, France is represented by GENCI with its three main components, CEA (CCRT at Bruyères-le-Châtel), CNRS (IDRIS at Orsay) and the University (CINES at Montpellier), in addition, INRIA recently join.

Jean-Marie Normand has been deeply involved in the PRACE Preparatory Phase period (January 2008 until June 2010), especially in two among the eight Work packages (WP): in WP7 “Petaflop/s systems for 2009/2010”, for recommendations about the first systems to be deployed and in WP8 “Future Petaflop/s computer technologies beyond 2010". At the request of Prof. Dr. Dr. Thomas Lippert, Head of Jülich Supercomputing Centre and Director of Institute for Advanced Simulation, J.-M. Normand led the WP8, defining and setting up the collaborative work, organizing several Technology survey meetings and completing successfully a selection process of prototypes funded by the EC. Within the PRACE 1st Implementation Phase (www.prace-project.eu) Period (July 2010 up to now), J.-M. Normand actively contributes to WP9 "Future Technologies" (now led by Herbert Hubert, LRZ Garching, Germany). The objectives are (i) the assessment of emerging hardware and software technologies for multi-Petascale systems, (ii) the evaluation of future programming paradigms and (iii) the evaluation of energy efficient HPC solutions. Since 2008, J.-M. Normand contributes within GENCI to the coordination of PRACE activities at the French level, strengthening the collaboration among the three components CCRT, IDRIS and CINES. A PRACE Second Implementation Phase 2 year project, PRACE-2IP, will be launched on September 1st, 2011, dedicated mainly to the integration of the already existing organization DEISA with PRACE RI.

Since December 2010, Jean-Marie Normand is appointed as "CEA's International Expert" in the field "Mathematics, Informatics, Software and Systems Technologies" with speciality "System and Network".

Focusing his activity on energy efficiency, energy consumption and high computing density, J.-M. Normand sent a long document to the CEA Direction (General Administrator, High Commissioner, Strategy and Programme Director) in January 2011. Coping with a continuously increasing demand of strategic computing power, this document underlines that these main issues are a unique opportunity for Europe to become an actor in the design and construction of high performance energy efficient (green) computing systems. Indeed, the CEA, with mainly DRT-LETI and LIST, DAM-DSSI and DSM-INAC-SPINTEC, the Europe with several strong industrial positions in HPC and above all in embedded computing, have many assets to carry on such an ambitious challenge. A CEA programme meeting of the Strategic Orientation Committee (COMOS) took place in April 2011 on these topics with the main presentation given by J.-M. Normand. Discussions continue, especially with the High Commissioner Cabinet, the Strategy and Programme Direction and mainly the DRT-LETI and LIST.

D.18 Scientific editing

Who	Role	Journal
I. Bena	Advisory panel	Journal of Physics A
F. Bernardeau	Editorial Board	Report on Progress in Physics journal (IOP publications)
F. Bernardeau, C. Grojean	Co-editor	Particle physics and cosmology: the fabric of spacetime, Proceedings of the LXXXVI Les Houches Summer School (2007).
G. Biroli, P. Di Francesco, B. Eynard, C. Godrèche, D. Serban	Editors	JSTAT (Journal of statistical mechanics: theory and experiment)
B. Duplantier	Editor	Nuclear Physics B [FS]
	Editor	Journal of Statistical Physics
	Editor	La gazette des mathématiciens (SMF)
	Executive Committee	Annales Henri Poincaré
	Editor-in-Chief	*Poincaré Seminar Series* in Progress in Mathematical Physics, Birkhäuser Science [t08/239, t10/222, t10/224]
C. Grojean	Co-editor	New physics at the LHC: a Les Houches report. Physics at TeV Colliders 2007, New physics working group; Les Houches [t08/276]
	Co-editor	New Physics at the LHC: a Les Houches report: Physics at TeV Colliders 2009; Les Houches [t10/305]
	Co-editor	From the LHC to future colliders, Eur. Phys. Journal C66 525–583, [t09/294]
R. Guida	Editor	Scholarpedia
J.-M. Luck	Editorial Board	Journal of Statistical Physics
	Advisory Panel	Journal of Physics A
S. Nonnenmacher	co-editor	Nonlinearity (2004-2012)
	co-editor	European Physical Journal B (2007-2010)
H. Orland	Editor	Physics Reports (Elsevier)
V. Pasquier, D. Serban	Co-editors	Les Houches Summer School Proceedings, July 2008, [t08/289]
P. Vanhove	Co-editor	Theory and Particle Physics: the LHC perspective and beyond [Nucl. Phys. B Proc. Suppl. 192-193 (2009)]
	Co-editor	String Theory and the real World: From Particle Physics to Astrophysics - Les Houches Summer School Proceedings Volume 87, 2008
	Co-editor	Strings and Branes: The present paradigm for gauge interactions and cosmology [Nucl. Phys. B Proc. Suppl. 171 (2007)]

D.19 Internal organization

D.19.1 Affiliation, direction

The IPhT (Institut de physique théorique) named SPhT (Service de physique théorique until mid 2007) is an institute of DSM (Direction des sciences de la matière), the Physics division of CEA (Commissariat à l'énergie atomique). IPhT is also affiliated with the national research center, CNRS, under the reference URA 2306.

The Head of the institute was Henri Orland from 2004 to 2010, and Michel Bauer since January 2011. The head is assisted by two deputies, Anne Capdepon, and Olivier Golinelli (who replaced Jean-Yves Ollitrault in 2009)

The institute is informally divided into three groups:
Models and structures: mathematical physics,
Cosmology and particle physics,
Statistical physics and condensed matter physics.

D.19.2 Committees

Evaluation

Our activity is reviewed on a regular basis by an evaluation committee *(Conseil scientifique extérieur)*. The present report is meant to serve as a written basis for the evaluation of the period extending from June 2007 to May 2011. The visit of the Institute by the committee is planed on Nov 21–22, 2011. The members are:

Leon Balents (KITP, Santa Barbara, USA), Edmund Bertschinger (MIT, Cambridge, USA), Alain Comtet (LPTMS, Université Paris-Sud, France), Vladimir Fateev (LPTA,Université Montpellier II, France), Jean-François Joanny (Institut Curie, Paris, France), Dieter Lüst (Ludwig-Maximilians Universität, München, Germany), Giuseppe Marchesini (Dipartimento di Fisica, Università Milano-Bicocca, Italy), David Mukamel (Department of Physics of Complex Systems, Weizmann Institute of Science, Israel) Graham Ross (Department of Physics, University of Oxford, UK), George Sterman (C.N. Yang Institute for Theoretical Physics, Stony Brook, USA), Martin Zirnbauer (Institut für Theoretische Physik, Universität zu Köln, Germany).

Local scientific committee *(Conseil scientifique)*

A local scientific committee is elected every second year among the permanent physicists of the institute. It assists the Head of the institute with scientific decisions, in particular hirings. The minutes of meetings can be downloaded from the intranet webpage.

Apart from the head and his deputies, the members were:

in 2007, Michel Bauer, Giulio Biroli (secretary), Philippe Brax, Bertrand Eynard, Edmond Iancu, Hubert Saleur;

in 2008–2009, Alain Billoire , David Kosower, Stéphane Lavignac, Stéphane Nonnenmacher (secretary), Vincent Pasquier;

in 2010–2011, François Gélis, Stéphane Lavignac (secretary), Ruben Minasian, Henri Orland, Olivier Parcollet, Didina Serban.

Institute committee *(Conseil de laboratoire)*

The Institute committee is in charge of practical matters. It aims at facilitating everyday life. It consists in average of eight members, who are elected for two years: three permanent physicists, two administrative staff, one emeritus physicist, one PhD student, and one postdoc. It normally meets three times per year. The minutes of meetings can be downloaded from the intranet webpage.

Apart from the head and his deputies, the members were:

in 2007, François David, Bertrand Duplantier, Michele Frigerio, André Morel, Nicolas Orantin, Olivier Parcollet, Laure Sauboy (secretary);

in 2008–2009, Iosif Bena, Patrick Berthelot, Jérémie Bouttier, Catherine Cataldi, Michele Frigerio, Riccardo Guida, Clément Ruef (secretary), Alexandre Thaumoux;

in 2010–2011, Iosif Bena, Camille Bonvin replaced by Javier Lopez-Albacete and Jose-Miguel No, Jérémie Bouttier, Chiara Caprini, Émeline Cluzel, Laurent Sengmanivanh (secretary), Alexandre Thaumoux.

D.19.3 Support

Administrative secretaries

The Institute has three secretaries, for a total of roughly 100 people (short term visitors are not included in this estimate). The name "secretaries" is historical but misleading, and is used only as a shortcut for the endless list of little and big things they do for the welfare of the Institute. Nowadays, the name "assistants" would be more appropriate. They are multitalented, with sharp skills.

Sylvie Zaffanella is the Secretary of the Head of the Institute. She is also in charge of human resources management, equipment purchase, and travel (to conferences, etc.). Most of our accounting is managed by a different institute, the IRAMIS, for historical reasons. However, CNRS money is managed locally by Sylvie. using a dedicated software, XLAB.

Catherine Cataldi is in charge of PhD students, postdocs, and long-term (> 1 month) visitors.

Laure Sauboy has the responsibility of short-term visitors, whose number is continuously increasing. She also keeps track of fundings and grants (Marie-Curie, ANR, etc.).

The secretaries also help for the organization of conferences and meetings.

As a byproduct of the expansion of the IPhT, due mainly to non-permanent members, the workload of the secretaries has reached (or crossed) the limits of what is acceptable, with consequences for them, but also for our visitors.

Library and electronic resources

Our local library owns as many as 11000 books. It is shared with the neighbouring Condensed Matter Physics Department (SPEC). It has undergone a profound mutation due to the spread of electronic publishing. In 2007 we still received paper versions of 120 journals, but in 2011 this number has dropped by one order of magnitude or almost. This mutation will continue during the next few years.

The support of the library is now provided solely by Bruno Savelli. He is in charge of maintaining the library, and of repair works. We try however to maintain the quality of our book fund: the library is still an important working tool for the researchers. The choice of acquisitions is carried out by the physicists who select the new books, decide how to organize the themes and which of the stolen/lost books should be bought again. This process is coordinated by Riccardo Guida.

We maintain a local repository of our publications, which is fed by physicists since November 2007, when our library manager, Marc Gingold, retired.

The computer team

The management of the computer system is shared with the IRAMIS (Institut Rayonnement Matière de Saclay). The group is composed of 8 people, under the direction of Jean-Louis Greco (IRAMIS).

The local team at Orme des Merisiers, which is mostly in charge of Unix and Linux machines, is composed of 4 people: Pascale Beurtey (IRAMIS) is in charge of the team. She joined the group in 2007, and replaced Anne Capdepon. Philippe Caresmel (IRAMIS) was hired in July 2007 to replace Olivier Croquin, who left in March. Similarly, Laurent Sengmanivanh (IPhT) was be hired in November 2007 to replace Christian Perez, who left in April. Finally, Patrick Berthelot (IPhT) is in charge of maintaining local Windows machines and the wireless network.

A committee composed of physicists (currently: Jérémie Bouttier, Anne Capdepon, François David, François Gélis, Jérôme Houdayer, Grégoire Misguich (secretary) and Lenka Zdeborova) and the local computer team decides the future orientations of our computer system, makes purchase decisions and informs the physicists about changes. The minutes of this committee can be downloaded from our intranet webpage.

Miscellanea

Loïc Bervas, who was until 2007 our scientific secretary, now cumulates a number of scattered but important functions. To list only the main ones, he takes care of orders and inventories (standard furnitures, computers, consumables and so on) of the IPhT; he also helps extracting from the main CEA databases (and putting in human readable form) the incomes and expenses of the IPhT, especially those related to external fundings.

D.20 Permanent members of IPhT

Support

Patrick Berthelot
Loïc Bervas
Anne Capdepon
Catherine Cataldi
Laure Sauboy
Bruno Savelli
Laurent Sengmanivanh (since 2007)
Alexandre Thaumoux (2008 – 2011)
Sylvie Zaffanella

Physicists, CEA

Marc Barthélemy (since 2009)
Michel Bauer
Iosif Bena
Francis Bernardeau
Alain Billoire
Giulio Biroli
Jérémie Bouttier
Philippe Brax
Ruth Britto (since 2008)
Philippe Di Francesco
Bertrand Duplantier
Bertrand Eynard
François Gelis
Claude Godrèche
Olivier Golinelli
Mariana Graña
Christophe Grojean (at CERN since 2006)
Riccardo Guida
Emmanuel Guitter
David Kosower
Jean-Marc Luck
Kirone Mallick
Grégoire Misguich
Stéphane Nonnenmacher
Jean-Marie Normand
Henri Orland
Olivier Parcollet
Vincent Pasquier
Catherine Pépin
Hubert Saleur
Didina Serban
Géraldine Servant (at CERN since 2006)
Jean-Louis Sikorav
Patrick Valageas
Pierre Vanhove
Filippo Vernizzi (since 2008)
André Voros (until 2008)

Physicists, CNRS

Michel Bergère (until 2010)
Jean-Paul Blaizot
Chiara Caprini (since 2008)
Marco Cirelli (since 2007, at CERN since 2009)
François David
Thomas Garel
Jérôme Houdayer
Edmond Iancu
Gregory Korchemsky (since 2008)
Ivan Kostov
Stéphane Lavignac
Alexandre Lefèvre (until 2010)
Ruben Minasian
Cécile Monthus
Christiane Normand
Jean-Yves Ollitrault
Carlos Savoy (until 2008)
Gregory Soyez (since 2010)
Lenka Zdeborova (since 2010)

Conseillers scientifiques CEA, Emerita CNRS and Association "Pour la science"

Roger Balian
Michel Bergère (since 2010)
Jacques Bros
Marc Chemtob (since 2007)
Henri Cornille (until 2008)
Cirano De Dominicis
Bertrand Giraud
André Morel
Pierre Moussa
Robi Peschanski
Mannque Rho
Georges Ripka
Carlos Savoy (since 2008)
Richard Schaeffer
Edgar Soulié
André Voros (since 2008)
Jean Zinn-Justin