The reactor antineutrino anomaly & experimental status of anomalies beyond 3 flavors

G. Mention

CEA Saclay / Irfu / SPP

Rencontres IPhT-SPP, 24 janvier 2012

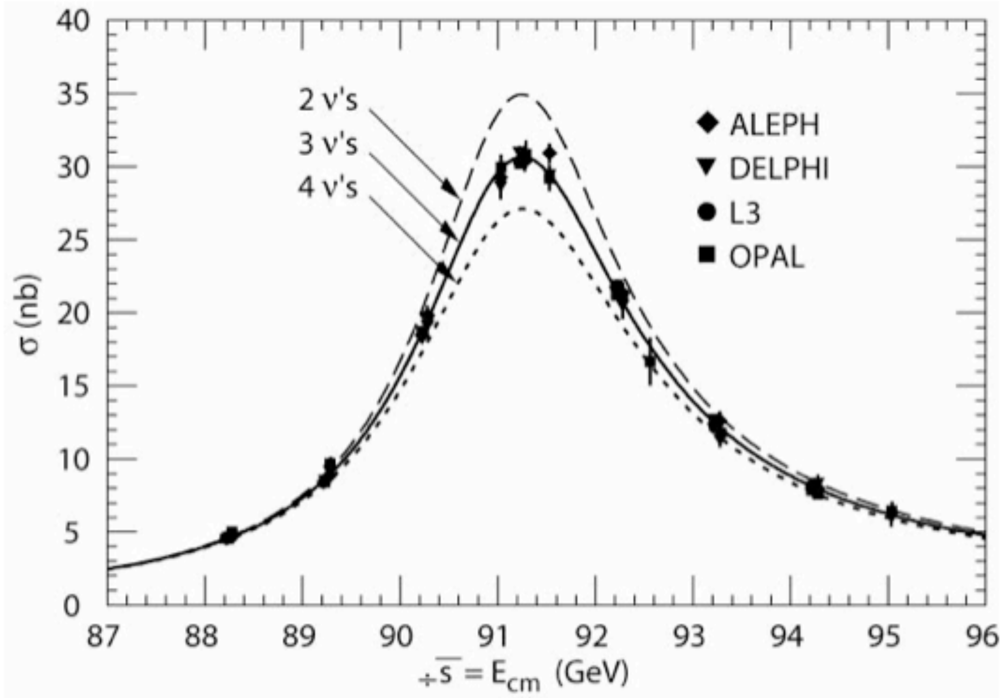
- **List of anomalies:**
  - LSND
  - MB ν , anti- ν
  - Gallium
  - Reactors
- **Outlooks**

Neutrino oscillations: 3 active ν

Large Electron-Positron collider data: exactly 3 active, light ν flavors

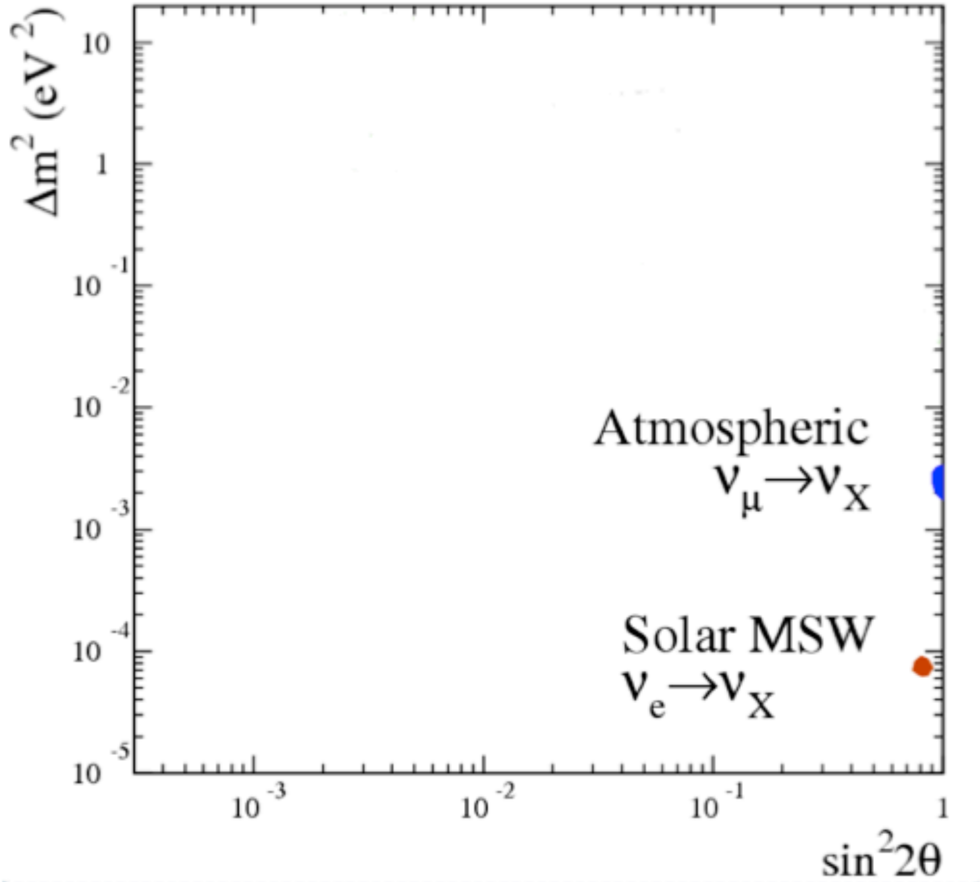
We also know of 3 ν's: ν_e, ν_μ, ν_τ

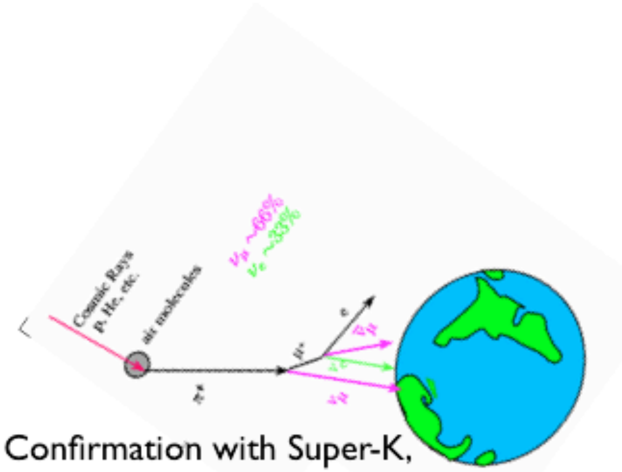
3 ν's require two independent sets of Δm^2 mixing



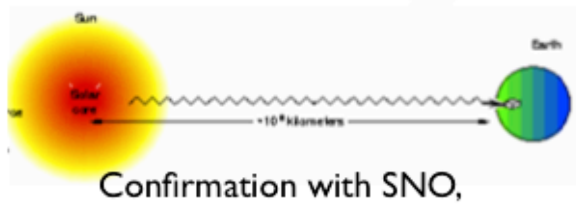
Neutrino oscillations

This is observed and confirmed!



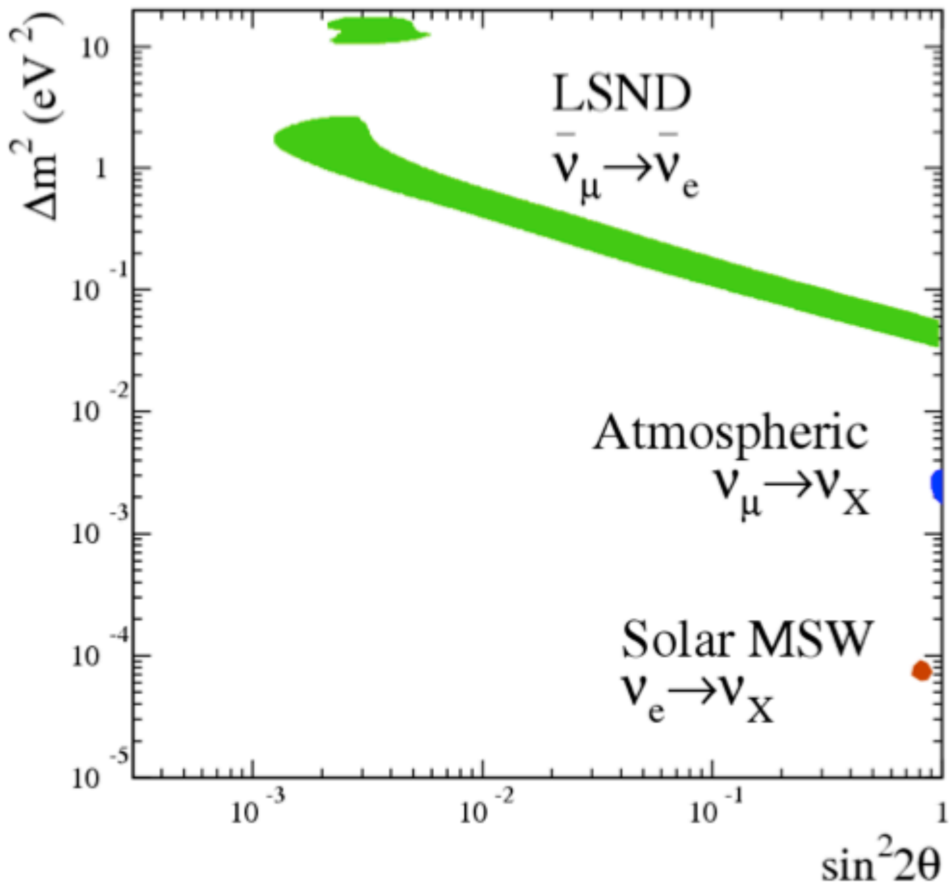


Confirmation with Super-K, K2K and MINOS data



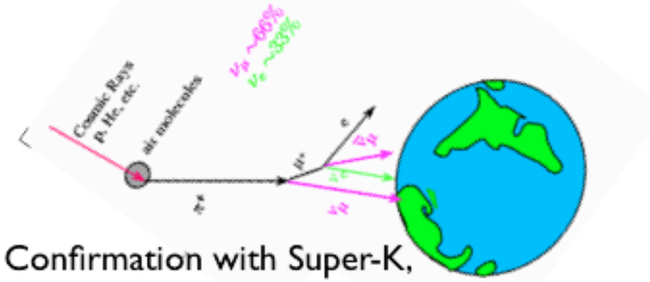
Confirmation with SNO, Kamland data

However…

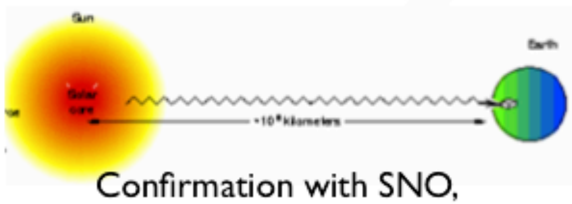


Evidence for high Δm^2 mixing from LSND experiment

some hints from cosmology and reactor data as well



Confirmation with Super-K, K2K and MINOS data



Confirmation with SNO, Kamland data

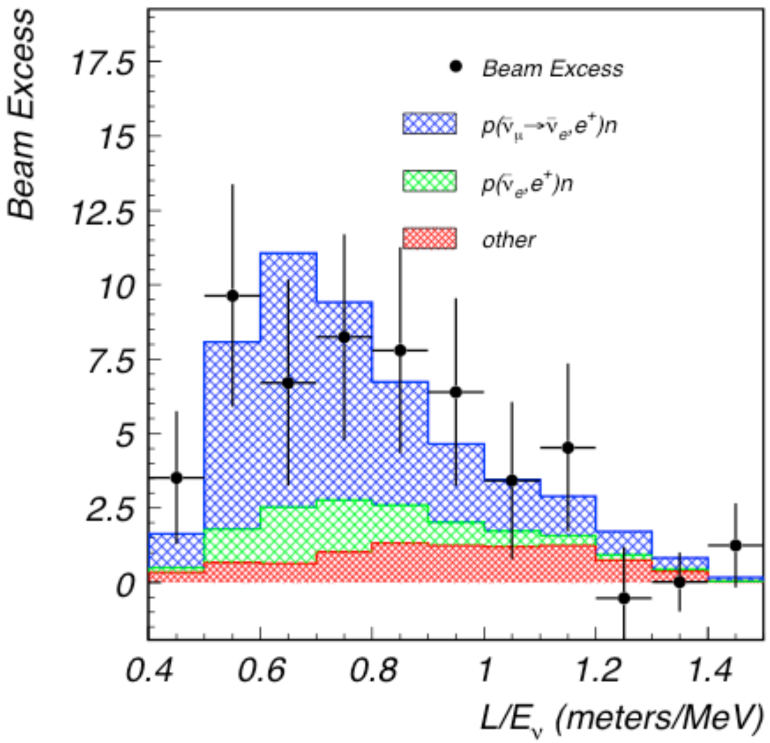
LSND [LSND, PRL 75 (1995) 2650; PRC 54 (1996) 2685; PRL 77 (1996) 3082; PRD 64 (2001) 112007]

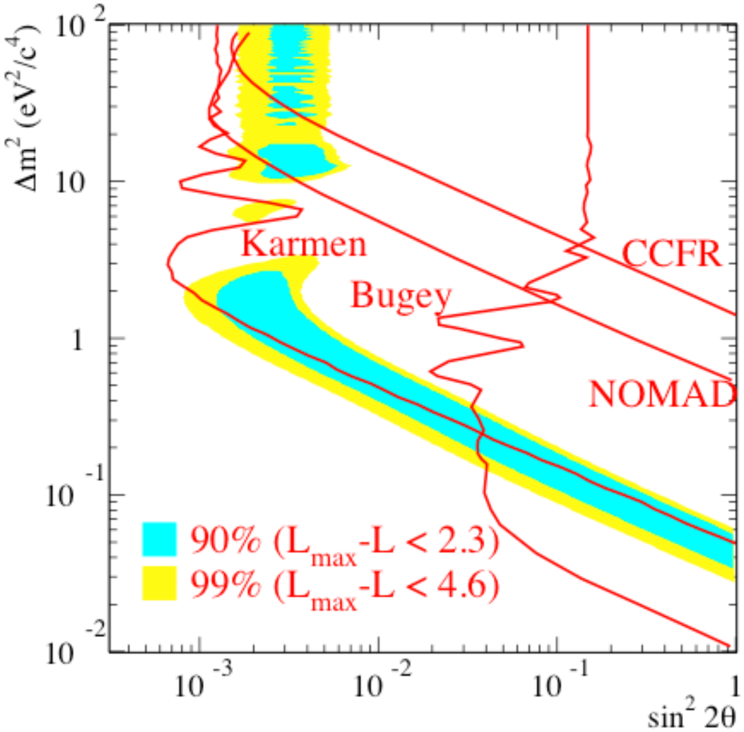
Channel: anti-$\nu_{\mu} \rightarrow$ anti-ν_{e}

Baseline: L ~ 30 m

Energy range: 20 MeV < E < 200 MEV

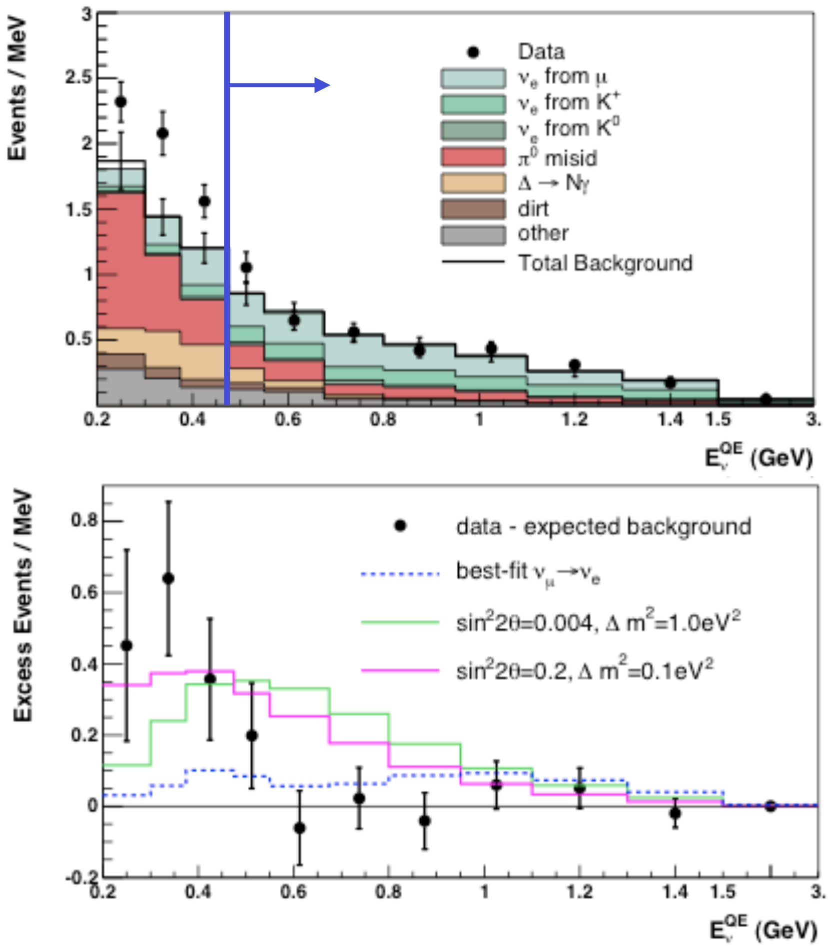
Highly controversial!



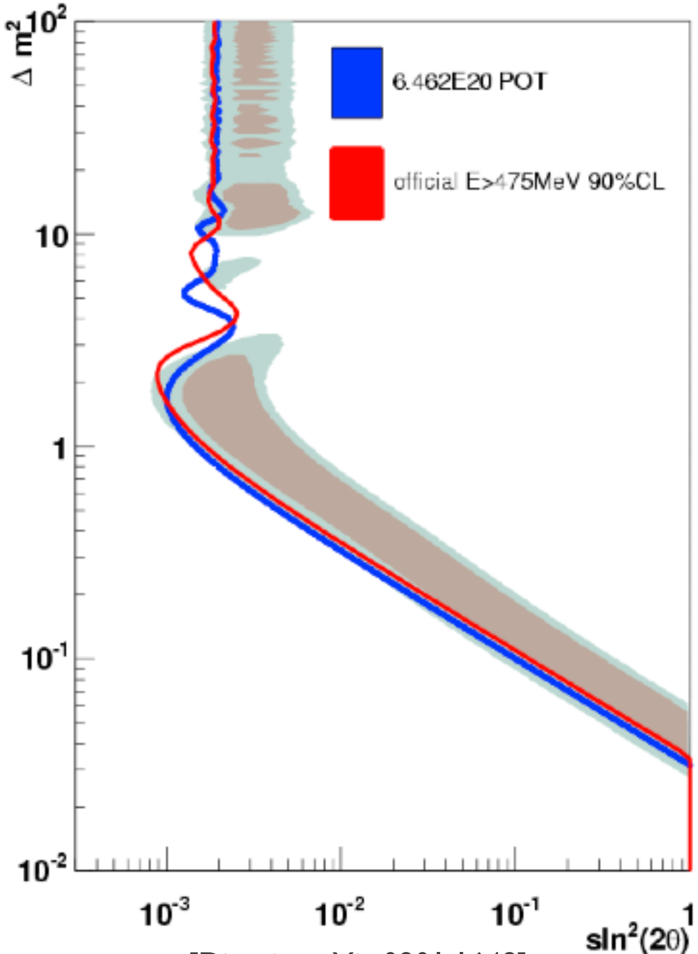


$$\Delta m^2_{LSND} \gtrsim 0.2\,\mathrm{eV}^2 \quad (\gg \Delta m^2_{ATM} \gg \Delta m^2_{SOL})$$

Channel: $\nu_\mu \rightarrow \nu_e$
Baseline: L ~ 541 m
Energy range: 475 MeV < E < 3 GeV



[MiniBooNE, PRL 102 (2009) 101802, arXiv:0812.2243]

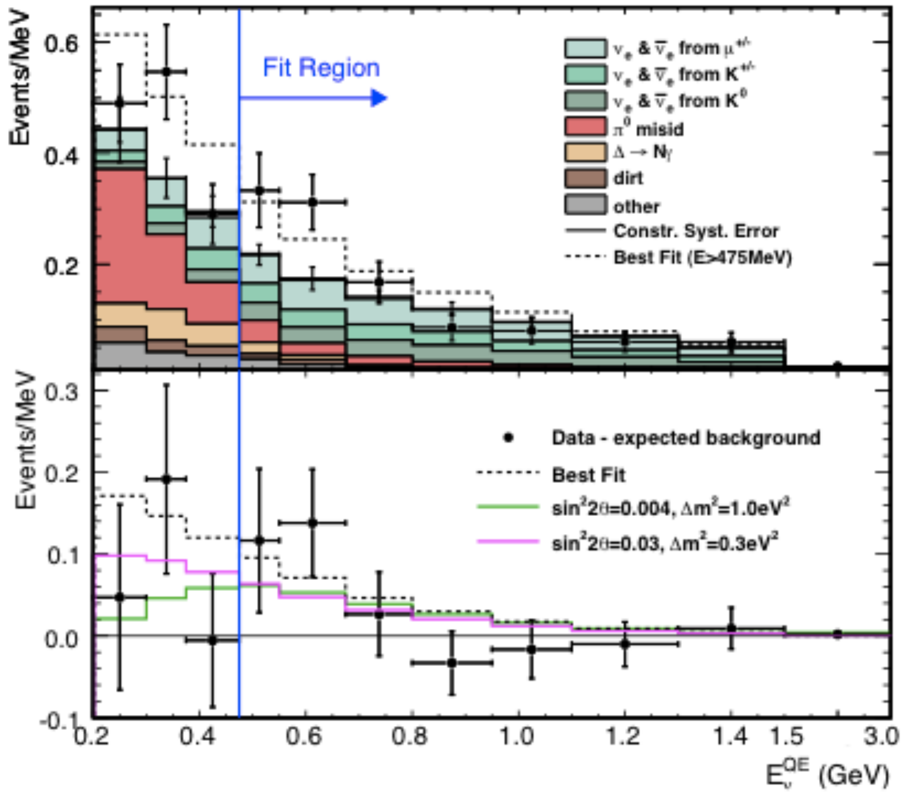


[Djurcic, arXiv:0901.1648]

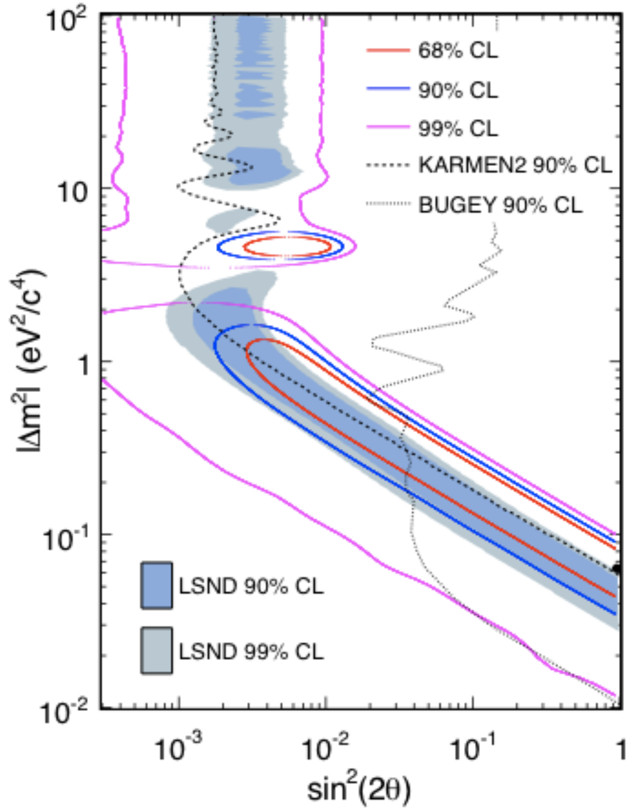
But => Low-Energy Anomaly!

MB anti- ν [PRL 103 (2009) 111801; PRL 105 (2010) 181801]

Channel: anti- $\nu_{\mu} \rightarrow$ anti- ν_{e}
Baseline: L ~ 541 m
Energy range: 475 MeV < E < 3 GeV



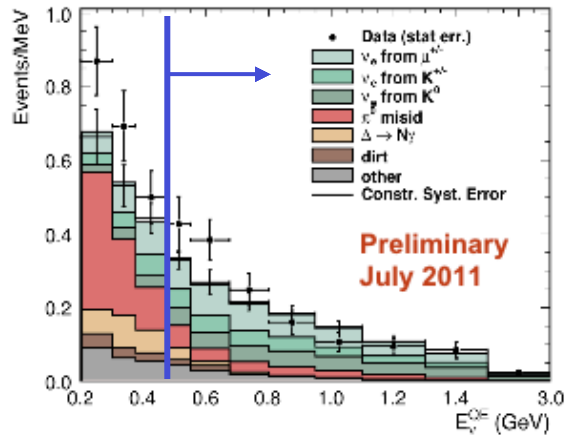
[MiniBooNE, PRL 105 (2010) 181801, arXiv:1007.1150]

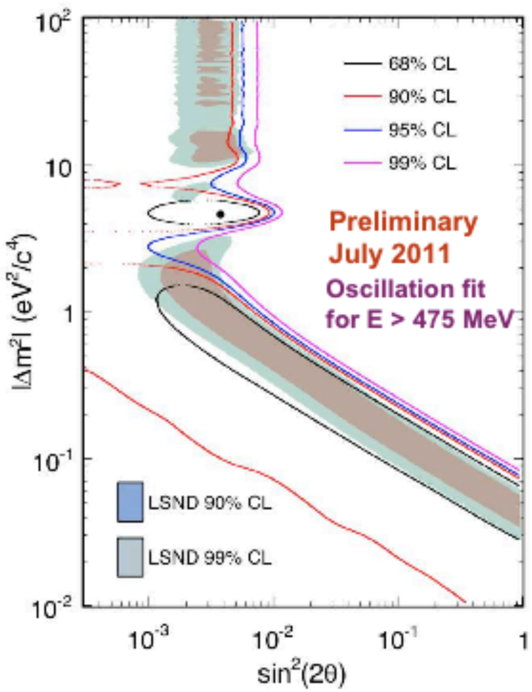


Agreement with LSND anti- $\nu_{\mu} \rightarrow$ anti- ν_{e} signal! … ? …

Similar L/E but different L and E, different backgrounds, beam,…

- Updated result from previous publication
  - 5.66E20 ⇒ 8.58E20 protons-on-target (x1.5)
  - Reduced systematic uncertainties especially backgrounds from beam K^+ decays
- For E > 475 MeV (>200 MeV), oscillations favored over background only (null) hypothesis at the 91.1% CL (97.6% CL)
  - Consistent with LSND but less strong than previous result (99.4%)
  - Best fit: χ^2 prob. = 35.5% (51%)
    Null: χ^2prob. = 14.9% (10%)
- Low energy excess now more prominent for antineutrino running than previous result
  - For E< 475 MeV, excess = 38.6 ± 18.5 (For all energies, excess = 57.7 ± 28.5)
  - Neutrino and antineutrino results are now more similar.
- MiniBooNE will continue running through spring 2012 (at least) towards the request of 15E20 pot (~x2 from this update)
  - Full data set will probe LSND signal at the 2-3 sigma level





Based on Giunti & Laveder, PRD82, 053005 (2010)

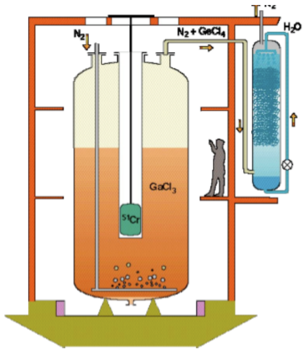
Radiochemical experiments Gallex (left) & Sage (right)

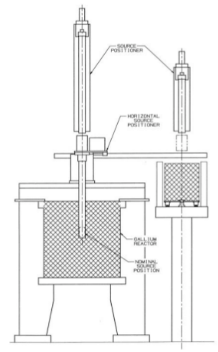
GALLEX ($GaCl_3$) and SAGE (liquid Ga) were radiochemical experiments, counting the conversion rate of ^{71}Ga to ^{71}Ge by (solar) neutrino capture [cannot detect anti-ν_e]

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$

GALLEX

30.3 tons of Gallium
in an aqueous solution :
$GaCl_3$ + HCl



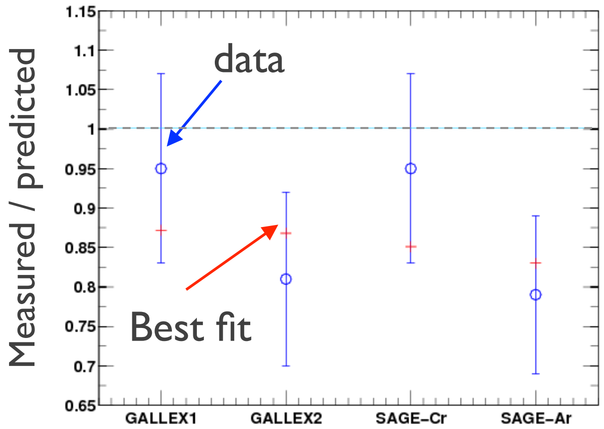


SAGE

30 to 57 tons of
Gallium (metal)
In 10 tanks

Calibration Data

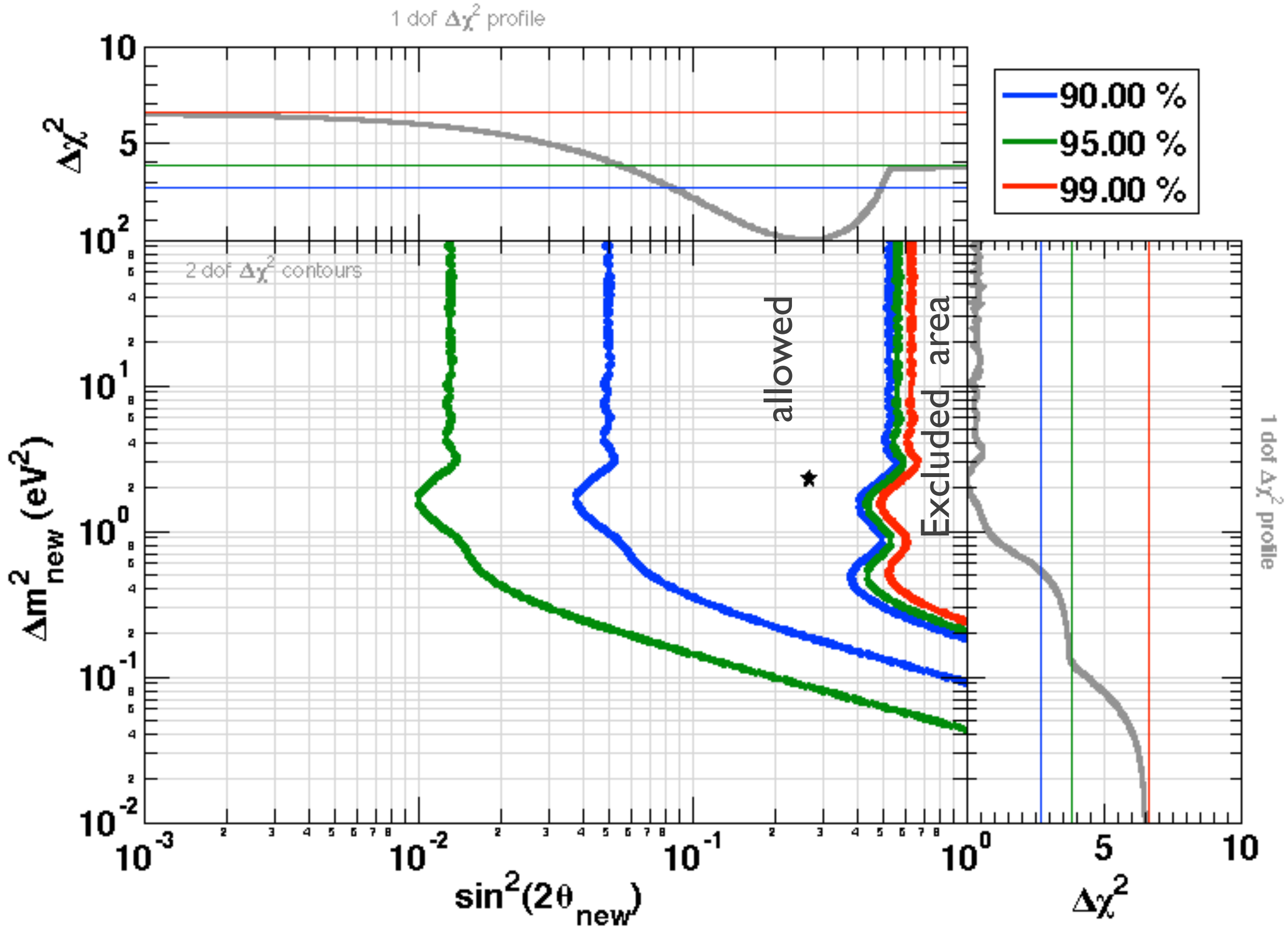
- 2 runs at GALLEX with a ^{51}Cr source (720 keV n_e emitter)
- 1 run at SAGE with a ^{51}Cr source
- 1 run at SAGE with a ^{37}Ar source (810 keV n_e emitter)



All observed a **deficit** of neutrino interactions **compared** to the **expected activity:**

R = meas./pred. rates = 0.86 ± 0.06(1 σ)

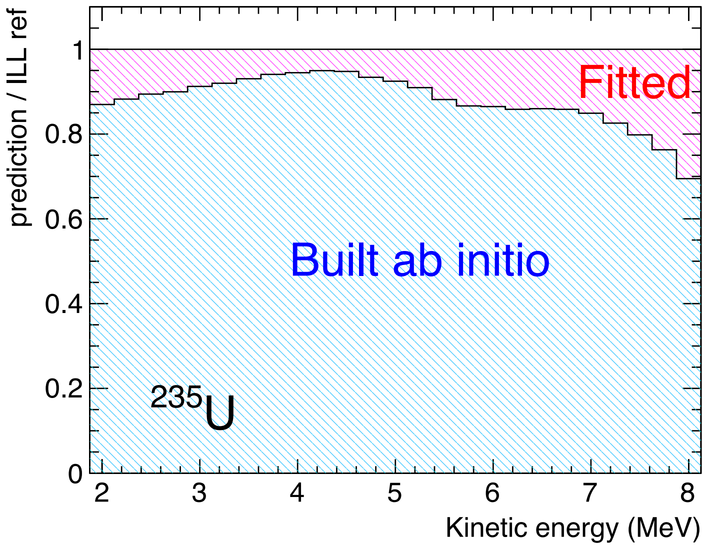
The Gallium anomaly

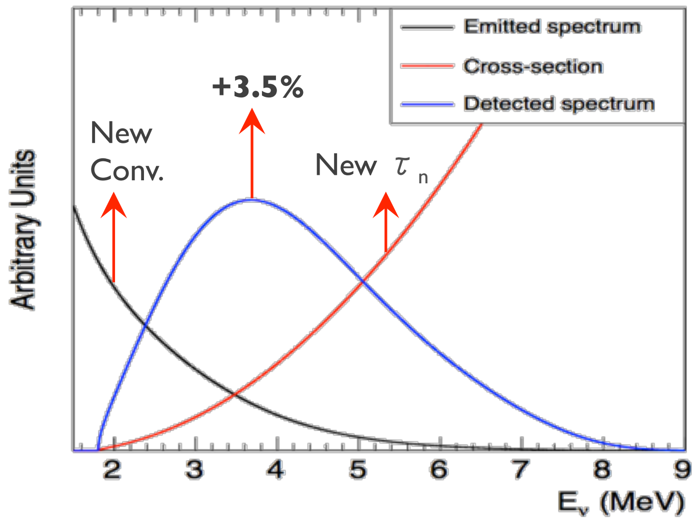


- Effect reported in C. Giunti & M. Laveder in PRD82 053005 (2010)
- Significance reduced by additional correlations in our analysis
- No-oscillation hypothesis disfavored at 97.7% C.L.

Revised reactor neutrino spectra & VSBL reactor ν anomaly

[T. Mueller *et al.*, PRC83, 054615 (2011)]





- Triggered by evaluation for DC far detector phase
- Improved conversion from β to ν spectra
  - Anchored to experimental ILL BILL-spectra of fission products
  - Conversion of individual β branch level; residuals fitted as in original ILL conversion
  - Off-equilibrium effects included
- Improved (& increased) neutron life time measurement; also improved weak magnetism and radiative corrections inclusion

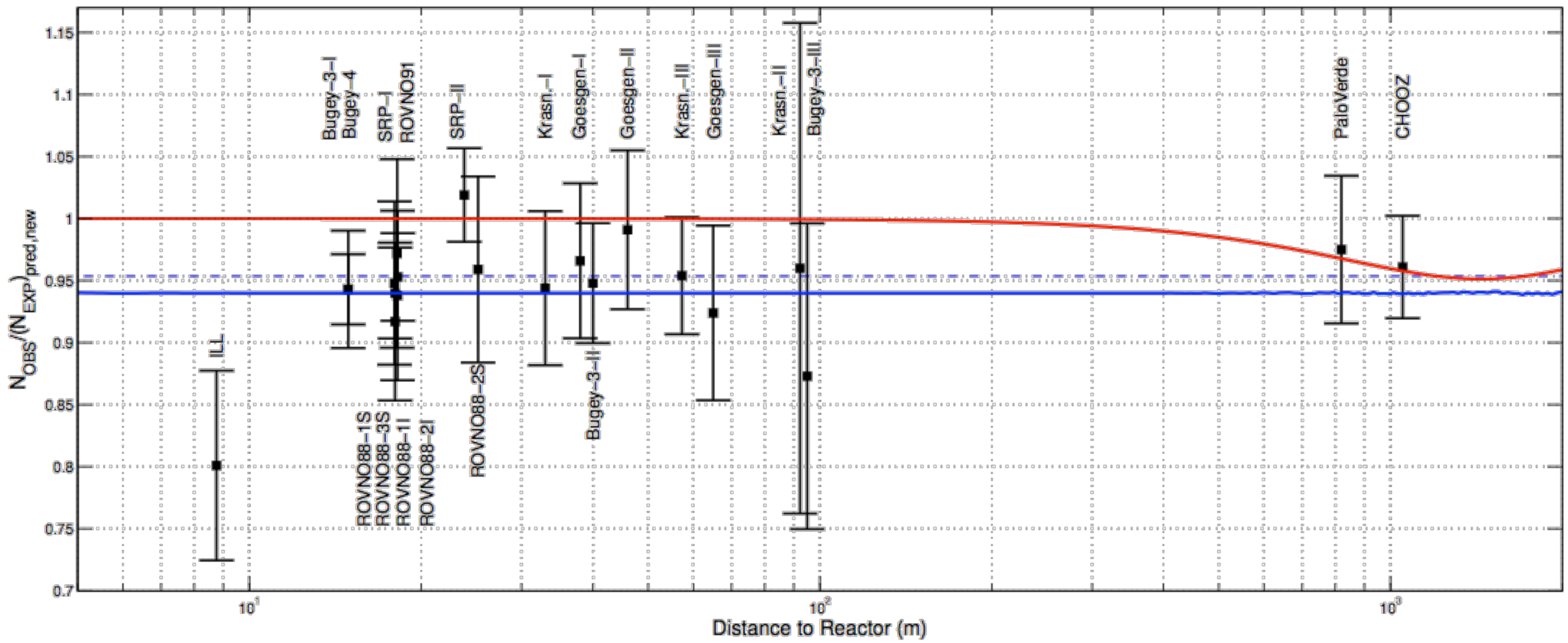
$$\sigma_f^{pred} = \int_0^\infty S_{tot}(E_\nu)\sigma_{\mathrm{V-A}}(E_\nu)dE_\nu = \sum_k f_k \sigma_{f,k}^{pred}$$

	old [3]	new	
$\sigma^{pred}_{f,^{235}U}$	6.39±1.9%	6.61±2.11%	**+3.4%**
$\sigma^{pred}_{f,^{239}Pu}$	4.19±2.4%	4.34±2.45%	**+3.6%**
$\sigma^{pred}_{f,^{238}U}$	9.21±10%	10.10±8.15%	**+9.6%**
$\sigma^{pred}_{f,^{241}Pu}$	5.73±2.1%	5.97±2.15%	**+4.2%**

Independently confirmed by P. Huber: arXiv:1106.0687 although some difference in shape.

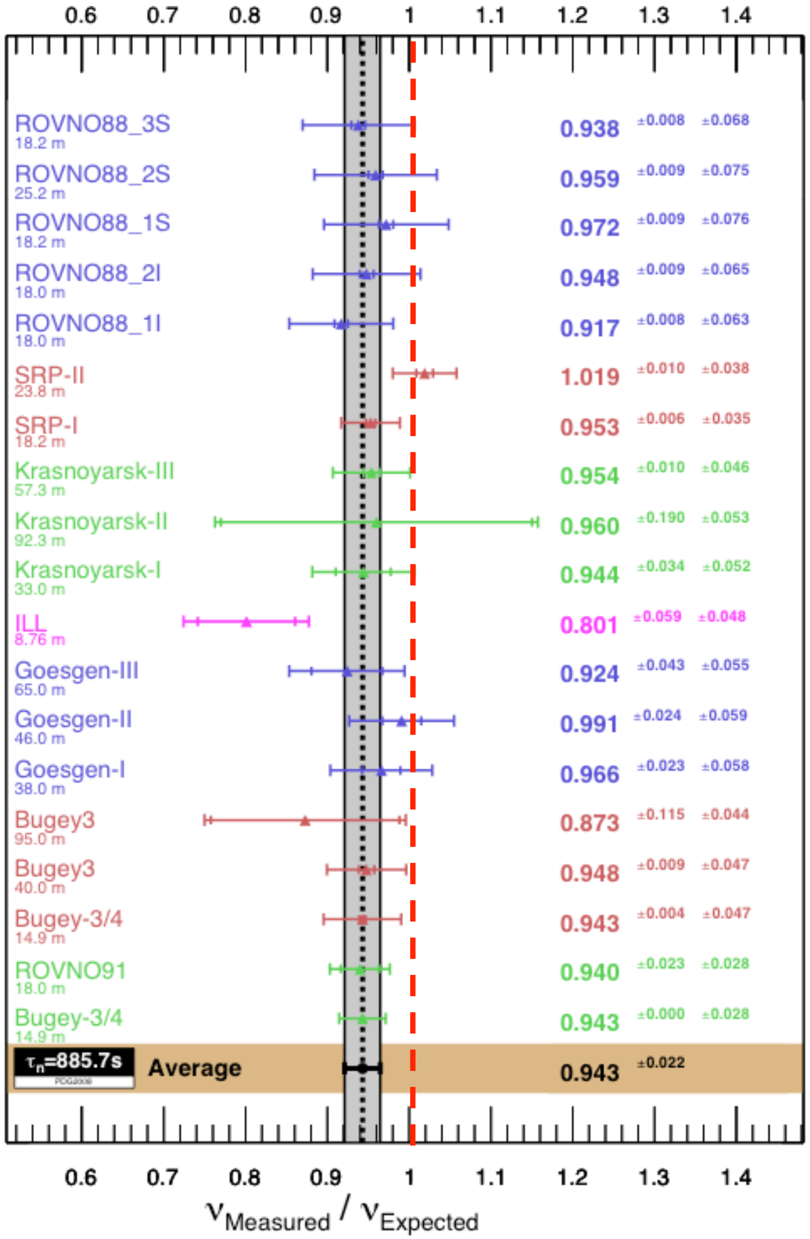
Implications for SBL reactor experiments: [G. Mention et al., PRD83, 073006 (2011)]

The reactor antineutrino anomaly



#	result	techno	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He+H$_2$0	888.7	0.538	0.328	0.078	0.056	0.987	0.943	3.0	3.0	15
2	ROVNO91	^{3}He+H$_2$0	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.943	5.0	5.0	15
4	Bugey-3-II	Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.948	5.1	5.0	40
5	Bugey-3-III	Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.873	14.1	5.0	95
6	Goesgen-I	^{3}He+LS	897	0.6198	0.274	0.074	0.042	1.018	0.966	6.5	6.0	38
7	Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.991	6.5	6.0	45
8	Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.924	7.6	6.0	65
9	ILL	^{3}He+LS	889	$\simeq$1	<0.01	<0.01	<0.01	0.832	0.801	9.5	6.0	9
10	Krasn. I	^{3}He+PE	899	$\simeq$1	<0.01	<0.01	<0.01	1.013	0.944	5.1	4.1	33
11	Krasn. II	^{3}He+PE	899	$\simeq$1	<0.01	<0.01	<0.01	1.031	0.960	20.3	4.1	92
12	Krasn. II	^{3}He+PE	899	$\simeq$1	<0.01	<0.01	<0.01	0.989	0.954	4.1	4.1	57
13	SRP I	Gd-LS	887	$\simeq$1	<0.01	<0.01	<0.01	0.987	0.953	3.7	3.7	18
14	SRP II	Gd-LS	887	$\simeq$1	<0.01	<0.01	<0.01	1.055	1.019	3.8	3.7	24
15	ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.8	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.8	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18

The reactor anti-neutrino anomaly



$$\chi^2 = \left(r - \overrightarrow{\mathrm{R}}\right)^T W^{-1} \left(r - \overrightarrow{\mathrm{R}}\right)$$

Weights: $W = \Sigma^2_{\mathrm{unc.}} + \Sigma_{cor.} C\, \Sigma_{cor.}$

with $\Sigma^2_{\mathrm{unc.}} = \Sigma^2_{\mathrm{tot.}} - \Sigma^2_{\mathrm{cor.}}$

The synthesis of published experiments at reactor-detector distances ≤ 100 m leads to a ratio R of observed event rate to predicted rate of

μ = 0.976 ± 0.024 (**OLD flux**)

With our **NEW flux** evaluation, this ratio shifts to

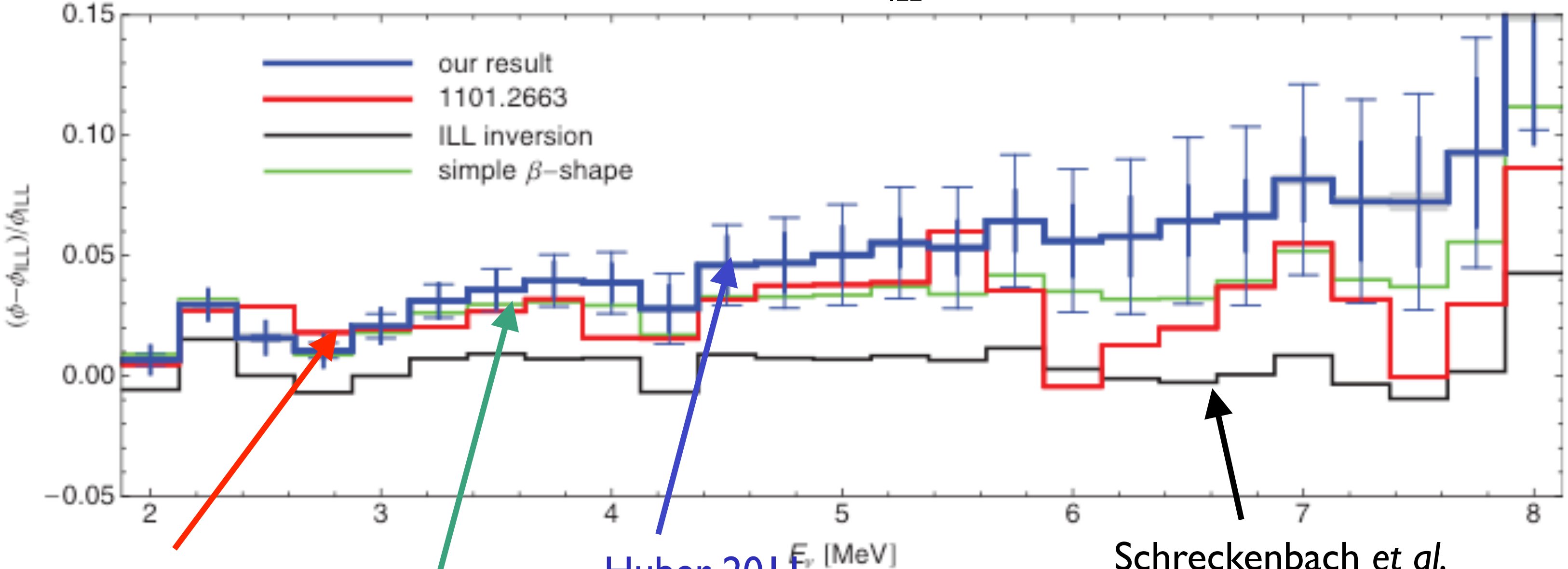
μ = **0.943 ± 0.023**,

leading to a deviation from unity at 98.6% C.L.

χ^2_{min} = 19.6/18

arXiv:1106.0687, PRC 84, 024617 (2011)

Relative difference to old spectrum U235 (ϕ_{ILL})



Mueller *et al.* 2011

Full New Nucl. Data Bases
+ 5 effective β -decay
branches

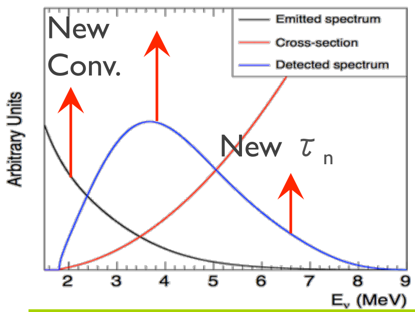
same corrections
as in Muller *et al.*

Huber 2011

New Nucl. Data Bases in Z
distribution of nuclei
+ 30 effective β -decay
branches

Schreckenbach *et al.*

Old Nucl. Data Bases in Z
distribution of nuclei
+ 30 effective β -decay
branches



New Huber's prediction => + 1.25% on anti-ν spectrum prediction

New τ_n PDG 2011 : 881.4 s [PDG 2010 885.7 s] => +0.5% on cross section.

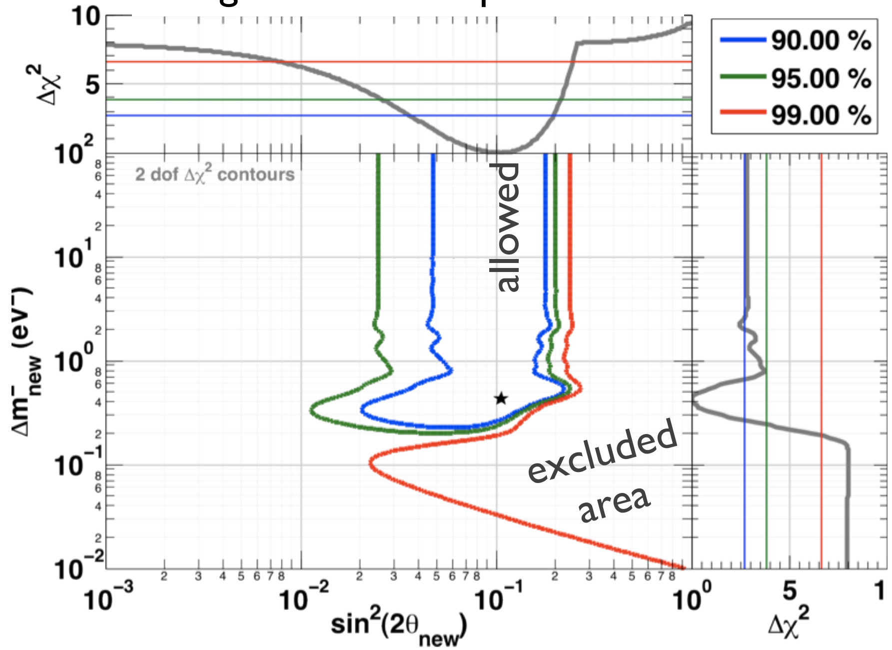
The reactor antineutrino anomaly

- Combine all rate measurements, no spectral-shape information
- Fit to anti-ν_e disappearance hypothesis

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_{\rm new} & \sin\theta_{\rm new} \\ -\sin\theta_{\rm new} & \cos\theta_{\rm new} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{\rm new} \end{pmatrix}$$

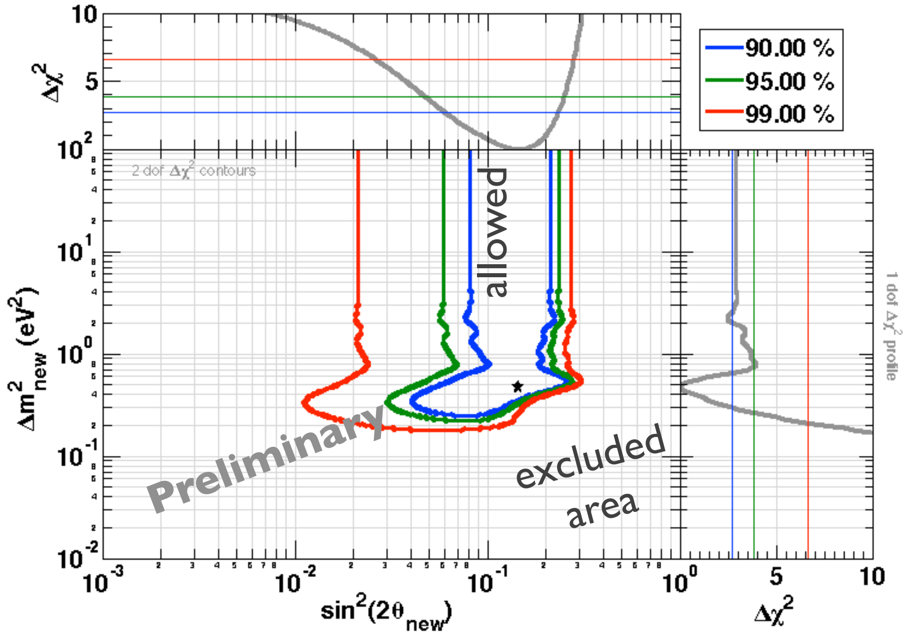
$$P_{\nu_e\to\nu_e}(L,E) = |\langle \nu_e(L)|\,\nu_e(L=0)\rangle|^2 = 1 - \sin^2(2\theta_{\rm new})\sin^2\left(\frac{\Delta m^2_{\rm new} L}{E}\right)$$

using Mueller *et al.* prediction



Absence of oscillations disfavored at **98.6%** C.L.

using Huber prediction

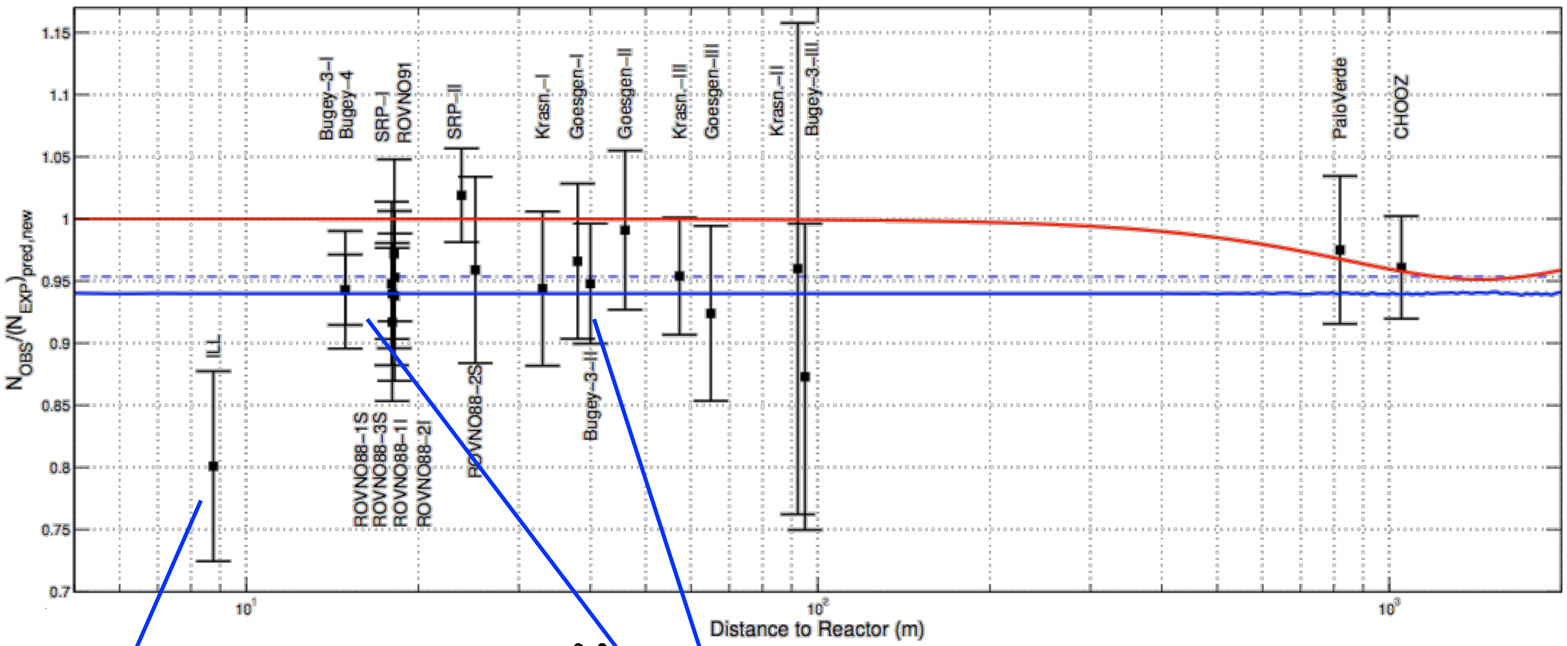


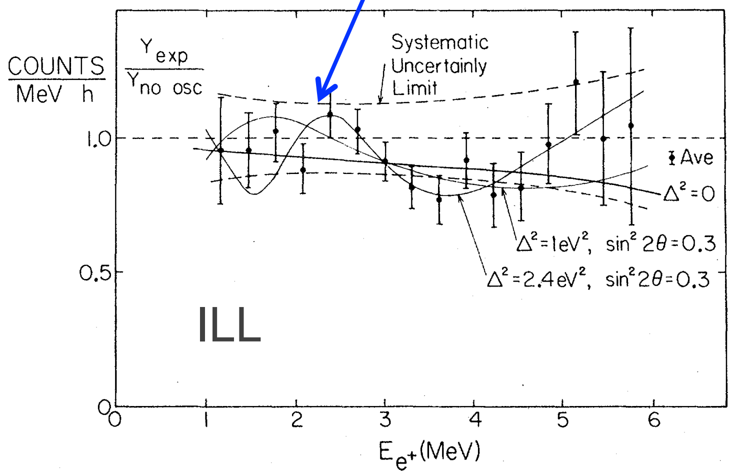
Absence of oscillations disfavored at **99.7%** C.L.

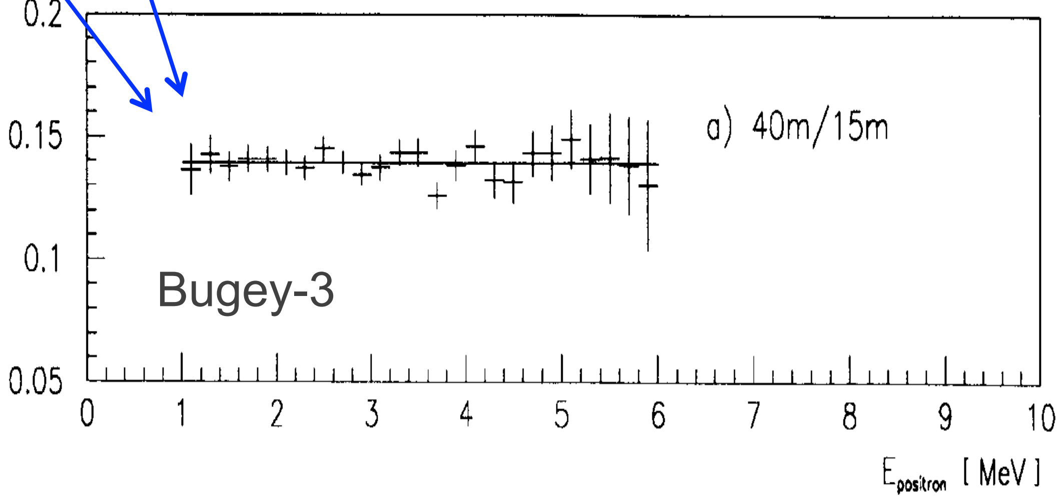
Implications for SBL reactor experiments:

The reactor antineutrino anomaly

[G. Mention et al., PRD83, 073006 (2011)]



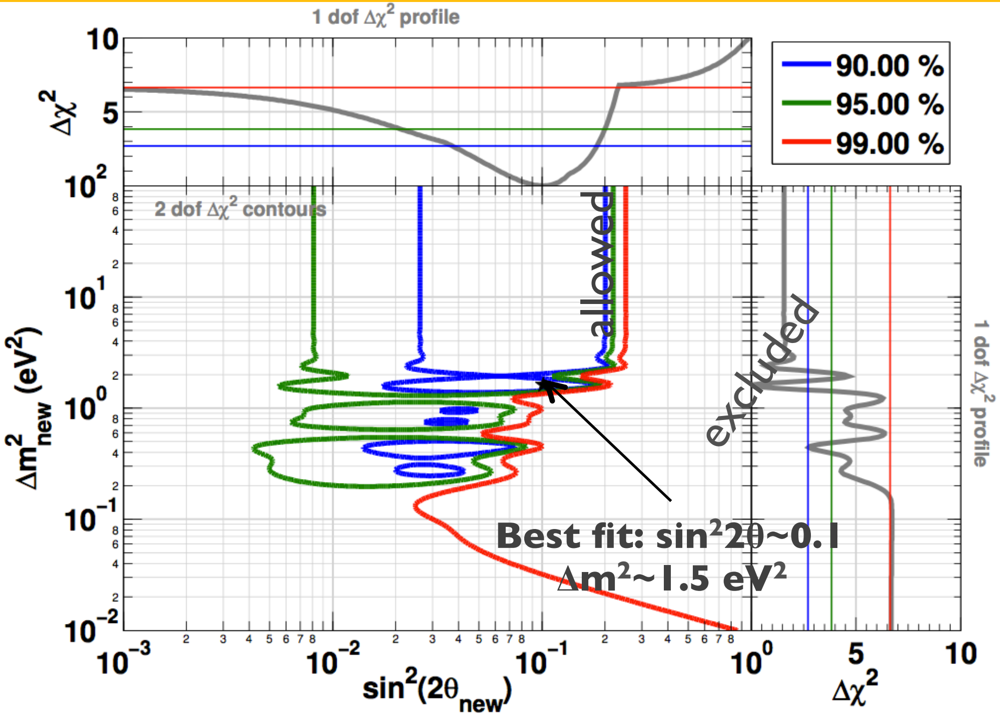


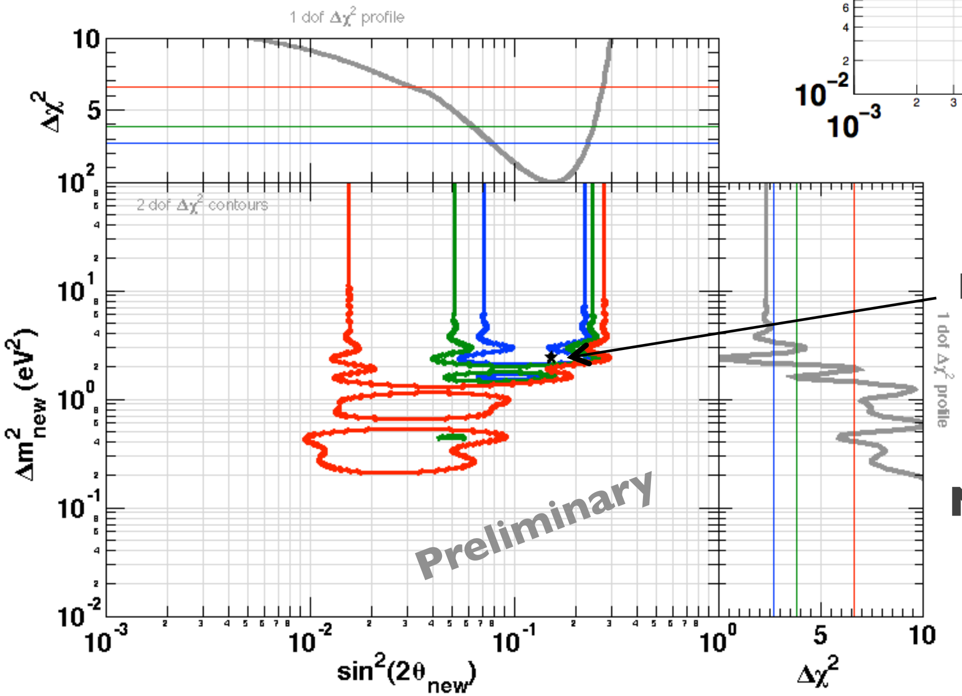


Combined Reactor Rate+Shape contours

using Mueller *et al.* prediction

No oscillation disfavored at 96.5%





Best fit: sin²2θ~0.15
Δm²~2.4 eV²

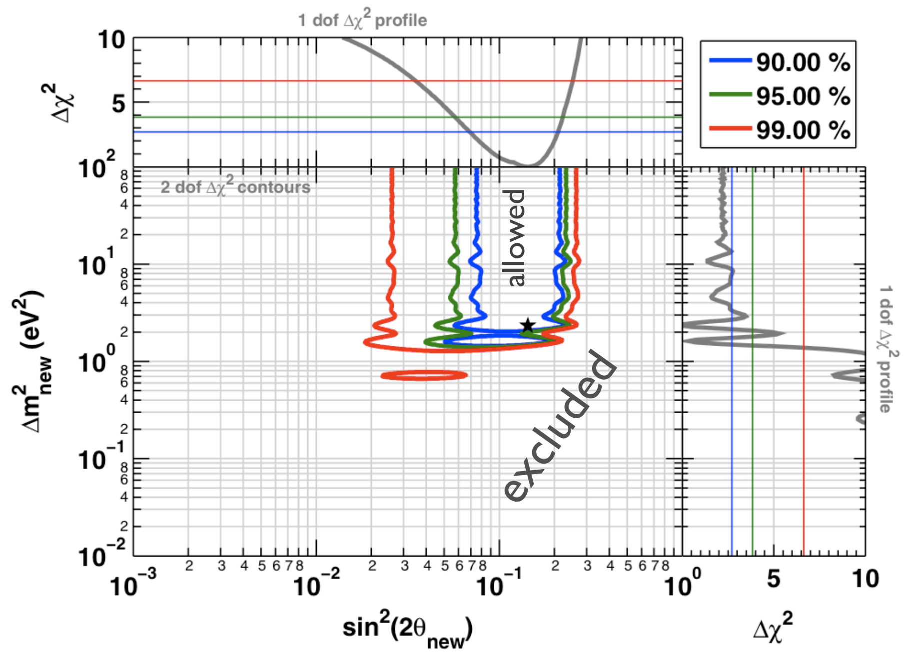
using Huber prediction

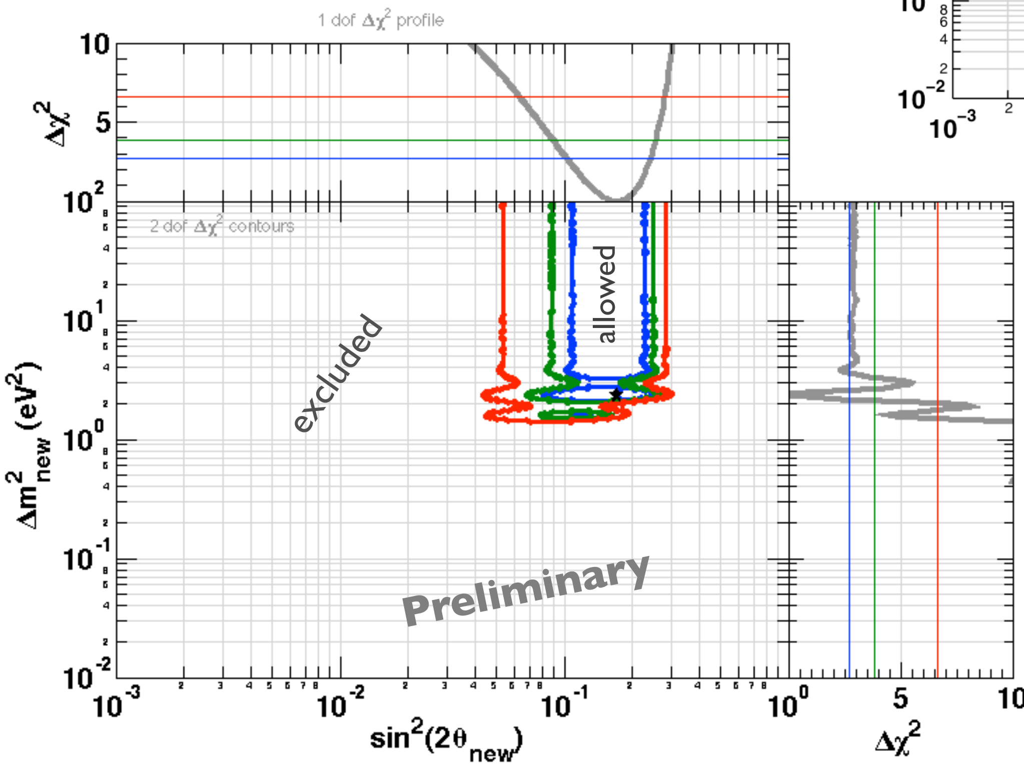
No oscillation disfavored at 99.6%

Putting it together: reactor (rates + shape) + Gallium

using Mueller *et al.* prediction

The no-oscillation hypothesis is disfavored at 99.8% CL





using Huber prediction

The no-oscillation hypothesis is disfavored at 99.97% CL

Putting all together

From C. Giunti, NuFact11, August 2011

ν_μ & anti-ν_μ disappearance $\sin^2(2\theta_{\mu\mu}) = 4\,|U_{\mu 4}|^2 \left(1 - |U_{\mu 4}|^2\right) \simeq 4\,|U_{\mu 4}|^2$

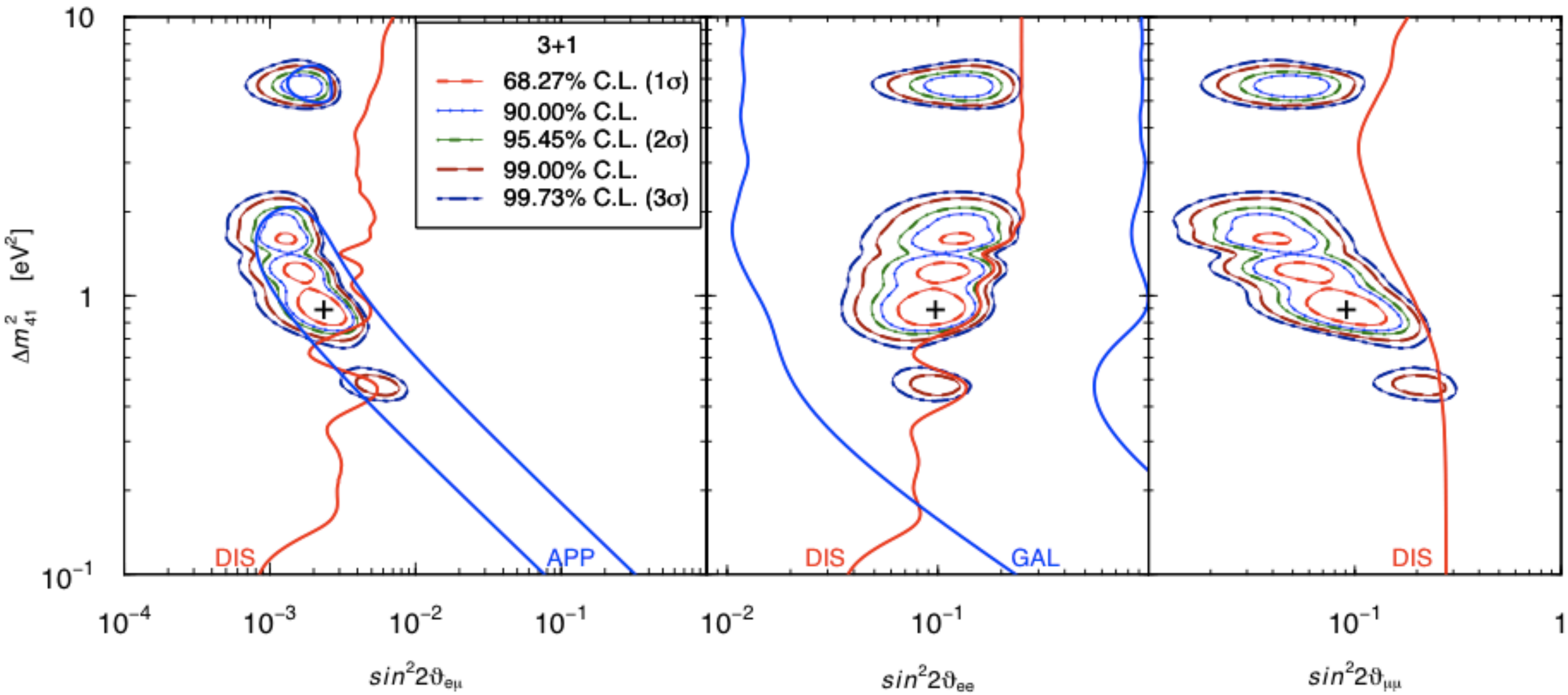
ATM constraint on $|U_{\mu 4}|^2$ [Maltoni, Schwetz, PRD 76 (2007) 093005, arXiv:0705.0107]

anti-ν_e disappearance $\sin^2(2\theta_{ee}) = 4\,|U_{e4}|^2 \left(1 - |U_{e4}|^2\right) \simeq 4\,|U_{e4}|^2$

New Reactor anti-ν_e fluxes [Mueller et al., arXiv:1101.2663], [Mention et al., arXiv:1101.2755]

(anti-)ν_μ ➛ (anti-)ν_e appearance

LSND (anti-ν) & MB (ν & anti-ν) $\sin^2(2\theta_{e\mu}) = 4\,|U_{e4}|^2\,|U_{\mu 4}|^2 \approx \frac{1}{4}\sin^2(2\theta_{ee})\sin^2(2\theta_{\mu\mu})$

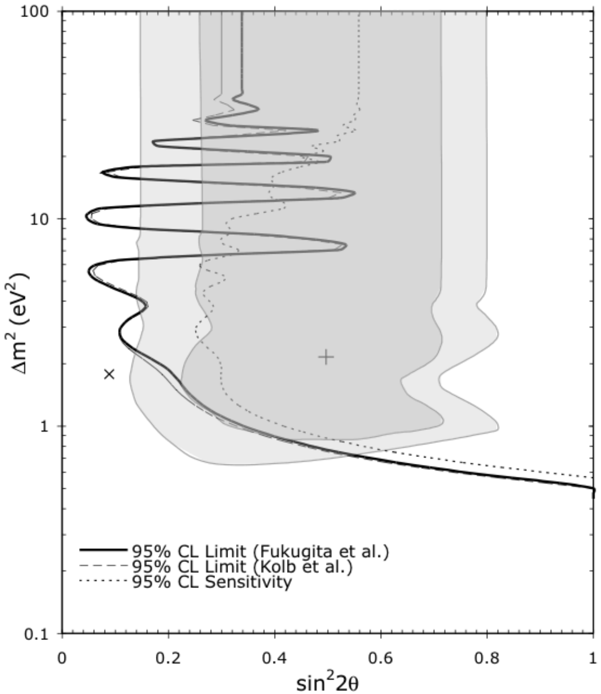


ν_e cross section in KARMEN & LSND

[Conrad and Shaevitz, 1106.5552v2 [hep- ex]]

ν_e cross section on ^{12}C measured in KARMEN (17.7m) & LSND (29.8m)

=> An oscillation would change the measured ν_e-Carbon cross section since assumed flux would be wrong
– Comparing the LSND and KARMEN measured cross sections restricts possible ν_e disappearance.



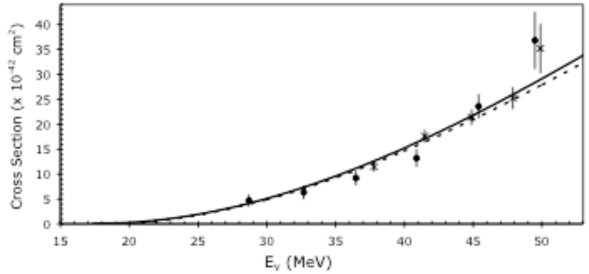


FIG. 2: The KARMEN (points) and LSND (crosses) measured cross sections with statistical errors for $\nu_e + {}^{12}\mathrm{C} \rightarrow {}^{12}\mathrm{N}_{gs} + e^-$ compared to the theoretical prediction of Fukugita, *et al.* (solid line), based on the EPT model, and Kolbe, *et al.* (dashed line), based on the CRPA model.

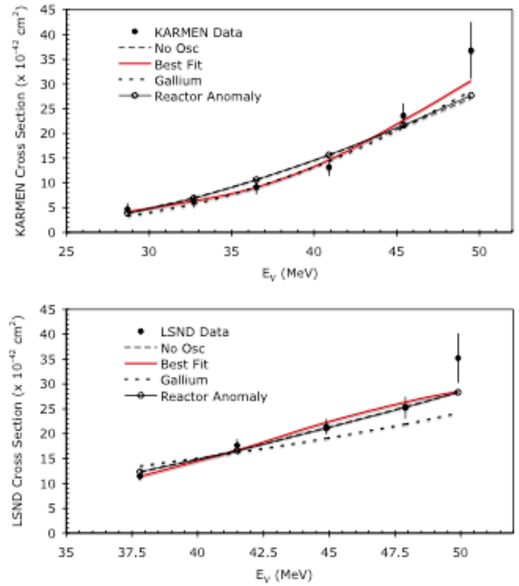


FIG. 3: Comparisons of the data to various oscillation predictions for the KARMEN (top) and LSND (bottom) data using the Fukugita prediction, as described in the text.

Summary about anomalies

Agreement between anomalies:

- LSND and MiniBooNE anti-ν_μ ➛ anti-ν_e
- Gallium anomaly and Reactor antineutrino anomaly

Two experimental tensions among the anomalies:

- [LSND & MiniBooNE anti-ν_μ ➛ anti-ν_e] vs. MiniBooNE ν_μ ➛ ν_e
- [LSND & MiniBooNE anti-ν_μ ➛ anti-ν e] vs. anti-ν_e & anti-ν_μ disappearance limits

[+ Furher info from Cosmology pointing toward sterile neutrino, not addressed here.]

A white paper on this topic will come out soon reviewing the current status about sterile neutrino oscillations.

Despite tensions, there are a number of results and hints that suggest that there may be oscillations to sterile neutrinos with $\Delta m^2 \sim 1$ eV^2

Further running and new experiments are being planned to address this possibility

⇒ Establishing the existence of sterile neutrinos would be a major result!
⇒ These are certainly exciting times for neutrino physics!

Outlooks

Reactor Anomaly: **Nucifer**, small scintillator detector at L = 7m
[Lasserre, talk at EPS-HEP 2011], **SCRAAM** (USA) @ 24 m.

MiniBooNE is continuing to take antineutrino data with anti-ν

ICARUS planned to be moved @ **CERN-PS**: L~1km E~1GeV
[C. Rubbia et al. Proposal, CERN-SPSC-2011-012] looking @ ν_μ & ν_e

MicroBooNE will test the MiniBooNE low-energy anomaly by measuring $\pi^0 \to 2\gamma$ background

Gallium Anomaly: new **"SAGE-2"** Gallium source experiments with 2 spherical shells [Gavrin et al, arXiv:1006.2103]

Possible experiment at a small-size **fast neutron reactor** [Yasuda, arXiv:1107.4766]

ν_e and anti-ν_e radioactive source experiments with low-threshold detectors (MCi ^{51}Cr, ^{37}Ar, [A. Ianni et al., Eur. Phys. J. C8, 609-617 (1999)] or kCi ^{144}Ce [M. Cribier et al., PRL 107 (2011) 201801]).

KATRIN, single β decay.

IceCube, (TeV scale atm. ν resonant matter effect)

Solar and KamLAND, A. Palazzo (complete θ_{13}, θ_{14} degeneracy)

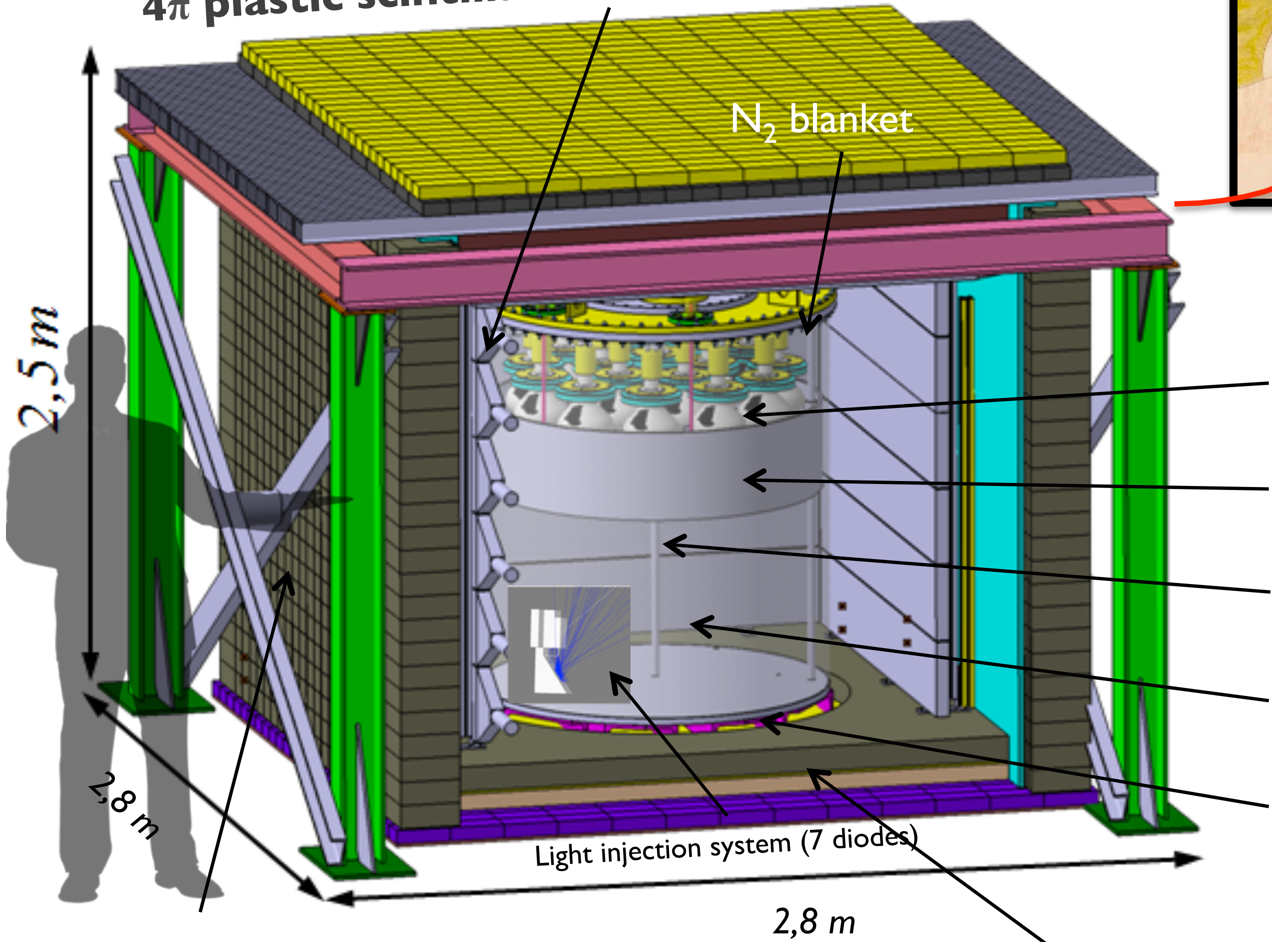
Nucifer

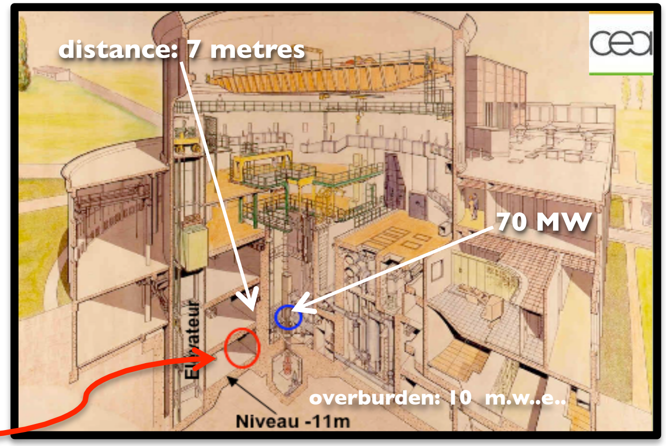
First goal: Non Proliferation

Thermal Power Measurement

Fuel Composition Measurement U/Pu

4π plastic scintillator Muon Veto (30 PMTs)





Osiris research reactor
CEA-Saclay (600 ν/d)
CEA – IN2P3 coll.

16 x 8' PMTs low background

25 cm acrylics buffer

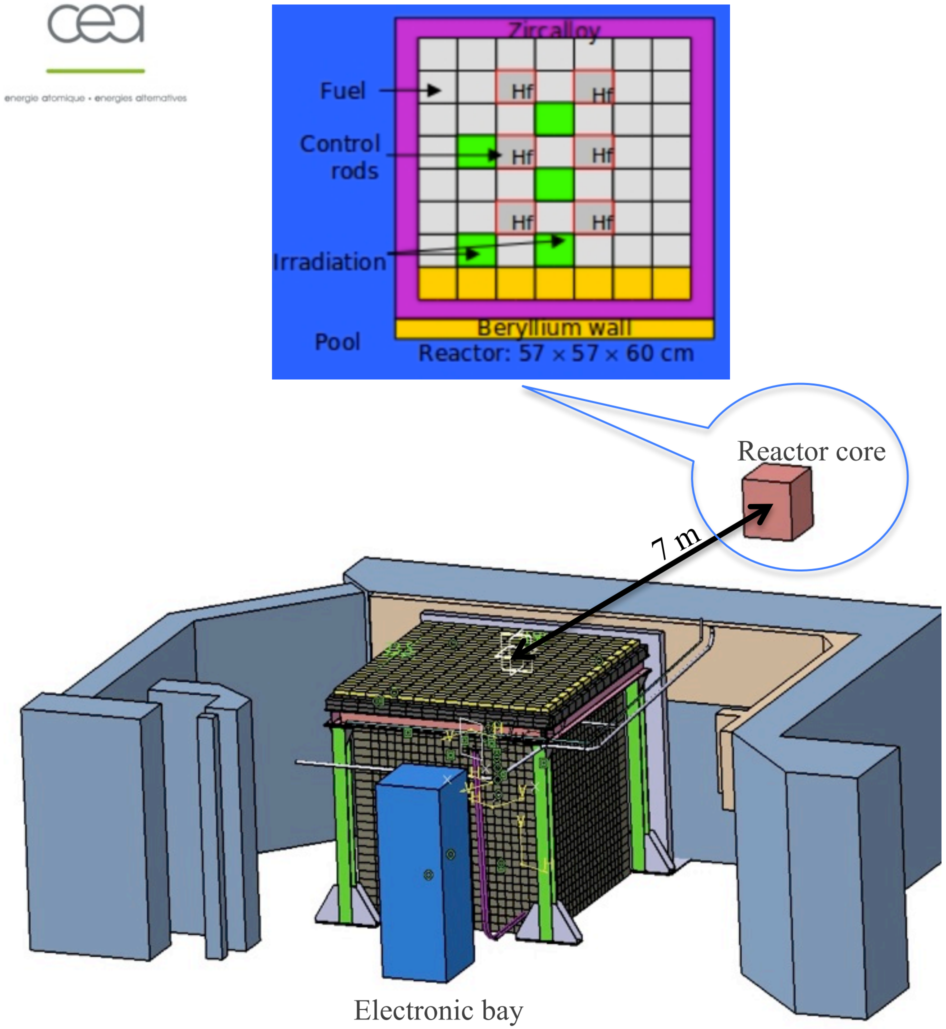
Calibration pipe

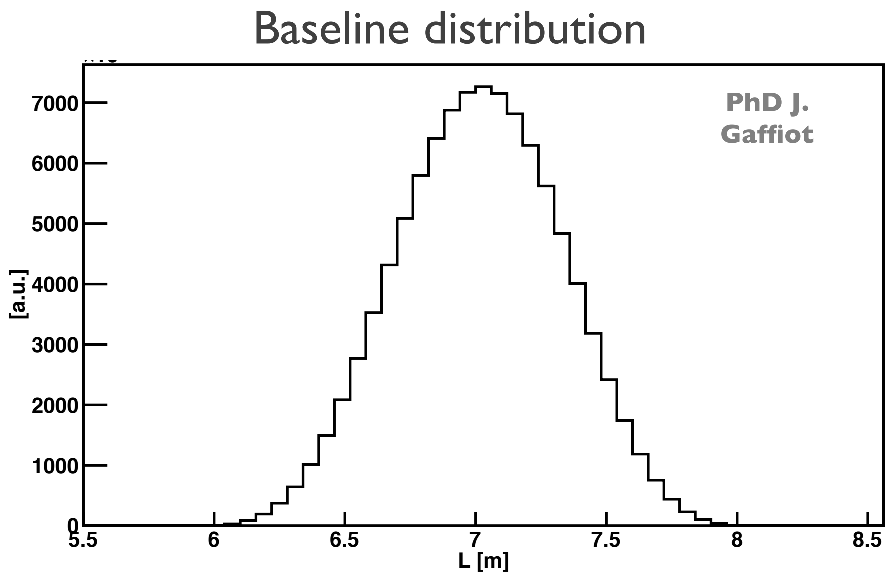
Target: 0.85 m^3 Gd-LS (0.5%)

Stainless steel double containment vessel coated with white Teflon inside

The nuclear core compactness

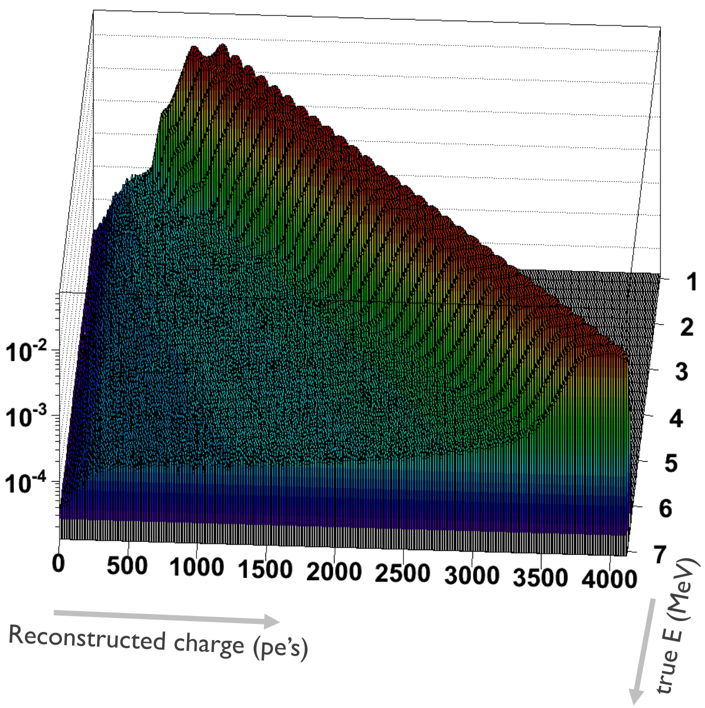
- **Core Size: 57x57x60 cm**
- **Detector Size : 1.2x0.7m (850l)**
- **baseline distribution**
  - <L>=7.0 m
  - variance : 0.3 m
  - eV^2 oscillations are not washed out

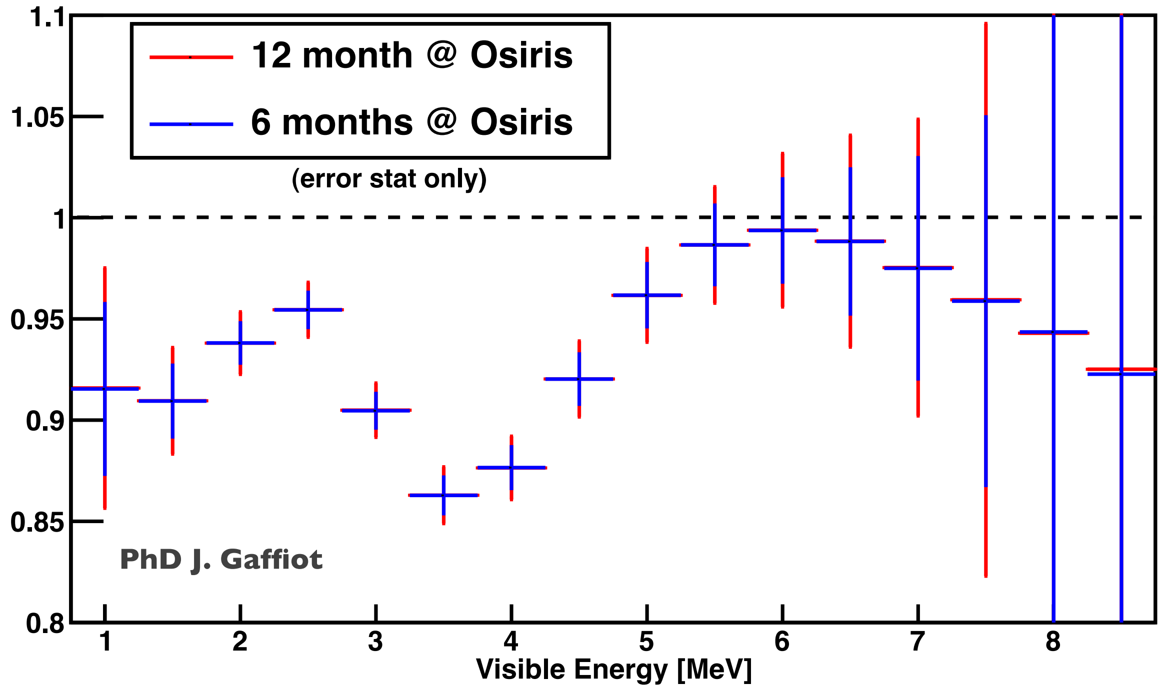




Nucifer attempt testing the anomaly

- Folding the Nucifer Geant4 Monte Carlo detector response
  - Energy resolution from Geant4 simulation (not fully tuned yet)
  - Statistical error bars for 12 & 24 months of data at Osiris
  - $\Delta m^2 = 2.4\ eV^2$ & $\sin^2(2\theta)=0.15$
  - No backgrounds. Thus to be taken with a grain of salt …



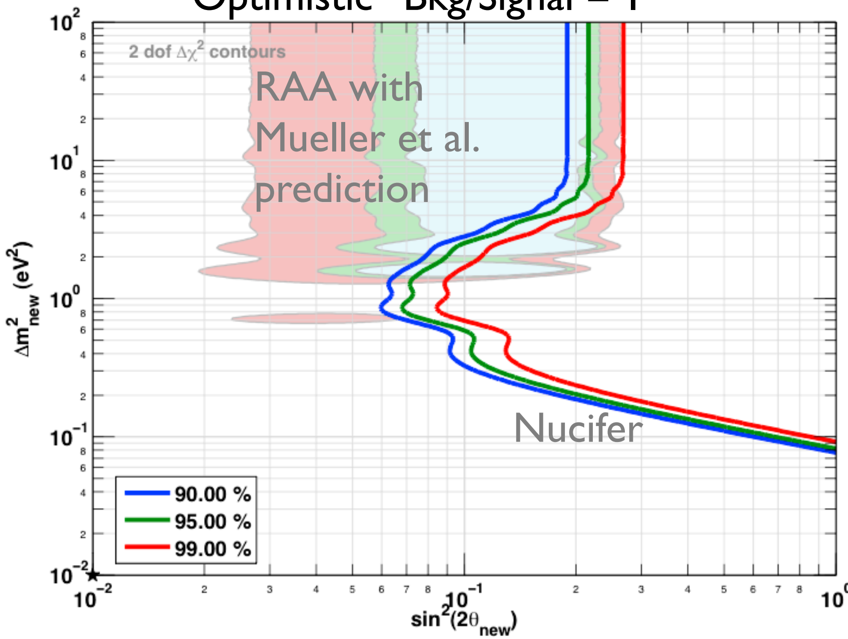


Nucifer potential on Reactor Antineutrino Anomaly

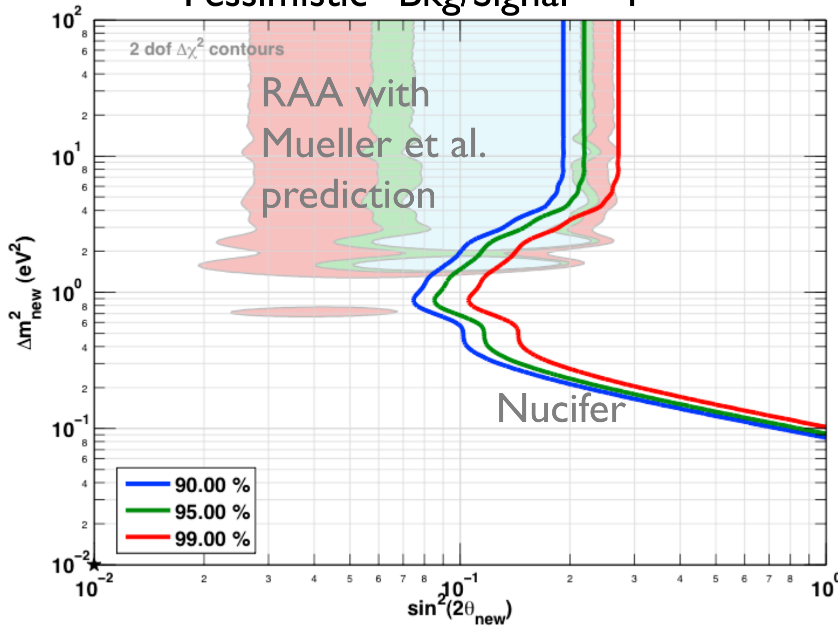
Nucifer detector is installed @ Osiris.
About to start [waiting now for safety authorization to start the filling].

Sensitivity contours with 1 year of data taking
Dependent on background estimations and rejection capabilities.
Nucifer is not an optimized detector for such a measurement BUT can be the first to bring information on this anomaly after ILL exp. in 1981.
2 typical example cases:

"Optimistic" Bkg/Signal = 1



"Pessimistic" Bkg/Signal = 4



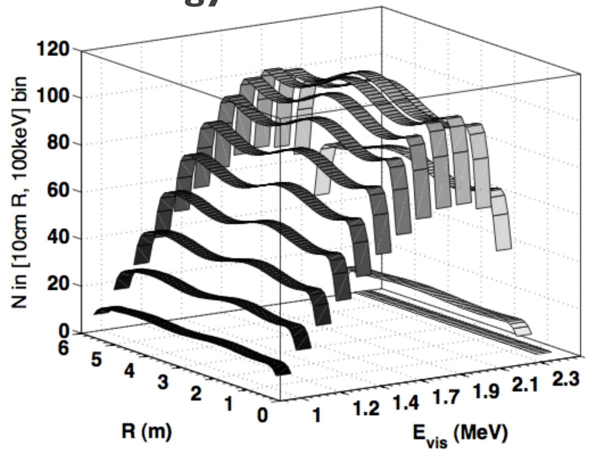
RAA (Reac. Anti ν Anomaly) contours
using Mueller *et. al* prediction, here.

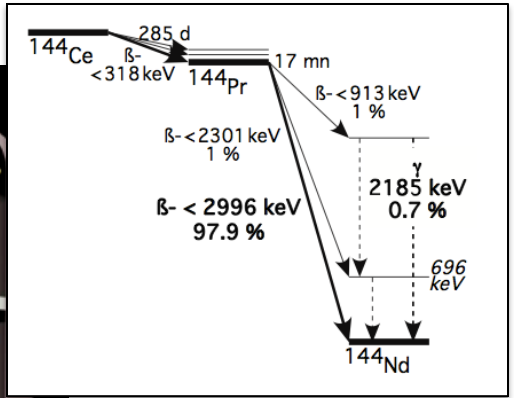
kCi Experiment Concept

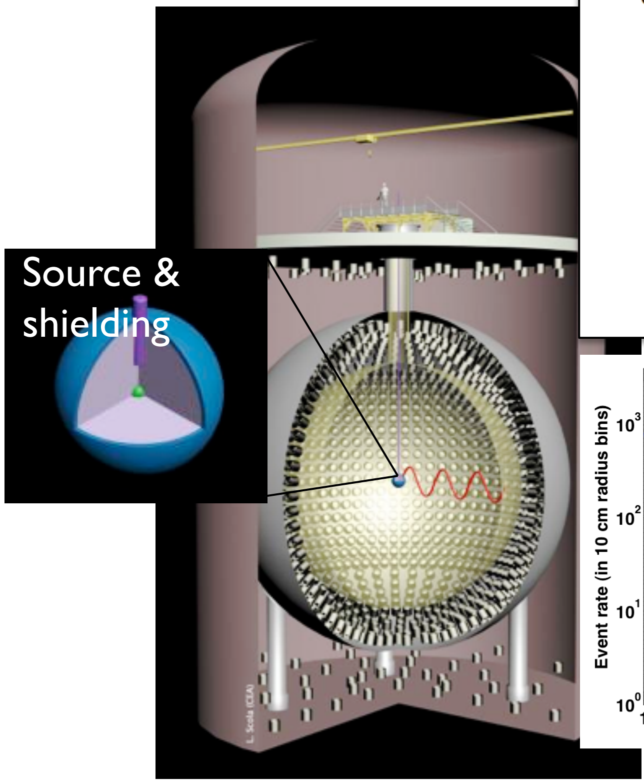
- A strong 50 kCi ^{144}Ce anti-ν_e source in the middle of a large liquid scintillator detector
- Anti-ν_e detection (40,000 evts/yr)
- A good resolution in position (15 cm)
- Almost background free thanks to anti-ν_e coincidences
- Lifetime ~ 1 yr (285 d)
- Compactness of the source (<5cm)
- W and Cu shield

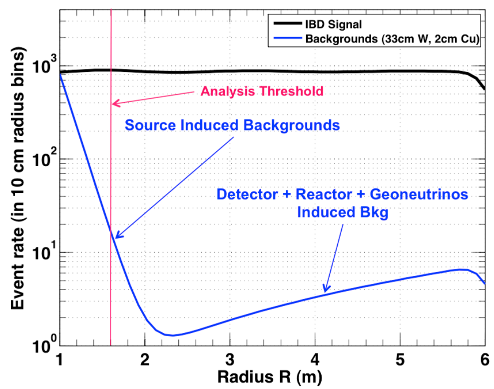
[M. Cribier *et al.*, arXiv: [hep-ex] (2011) PRL 107 (2011) 201801]

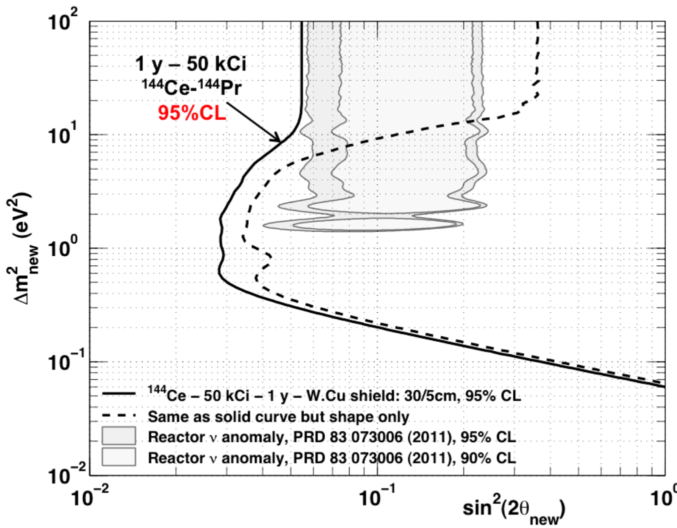
Real oscillation pattern vs. both **radius & energy**











STEREO Experiment Concept

Proposal under study

Reactor experiment @ ILL

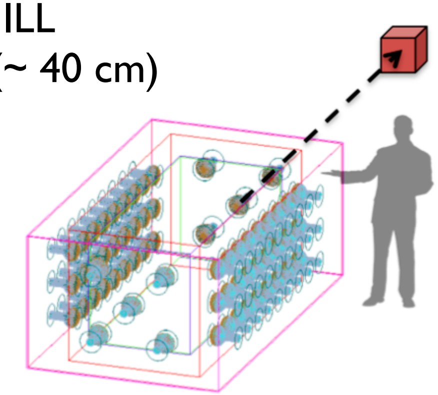
Compact reactor core (~ 40 cm)

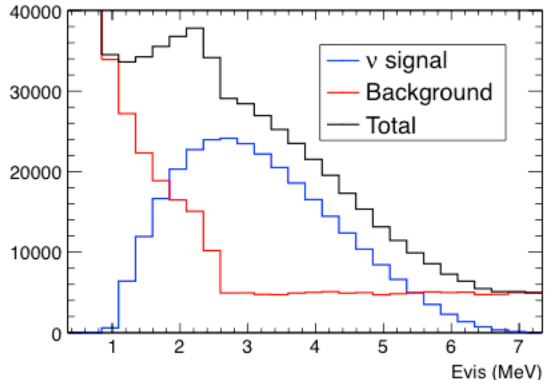
Detector Liq. Scint.

1m x 1m x 2m

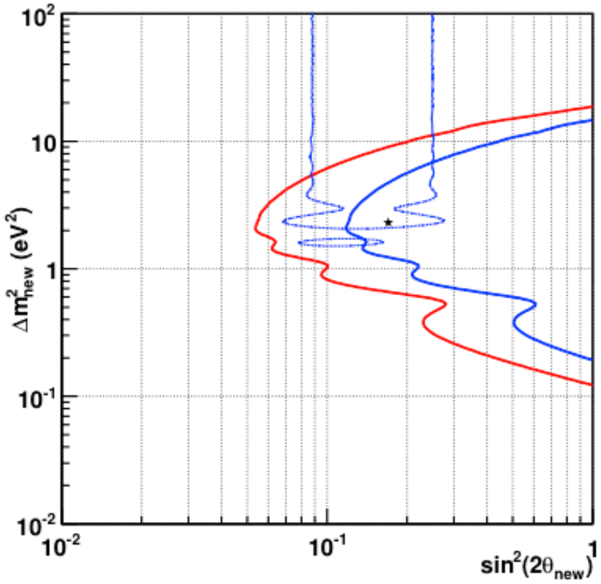
64 PMTs

Goal: focus on shape distorsion





Shape only contours



Able to see oscillations impact in L and E

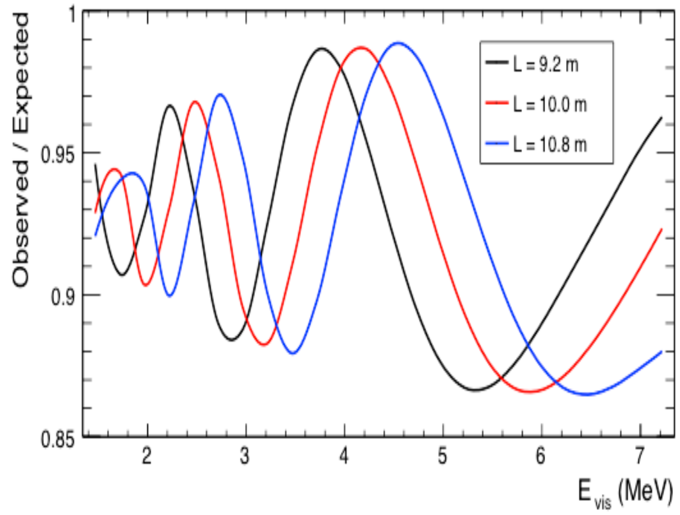
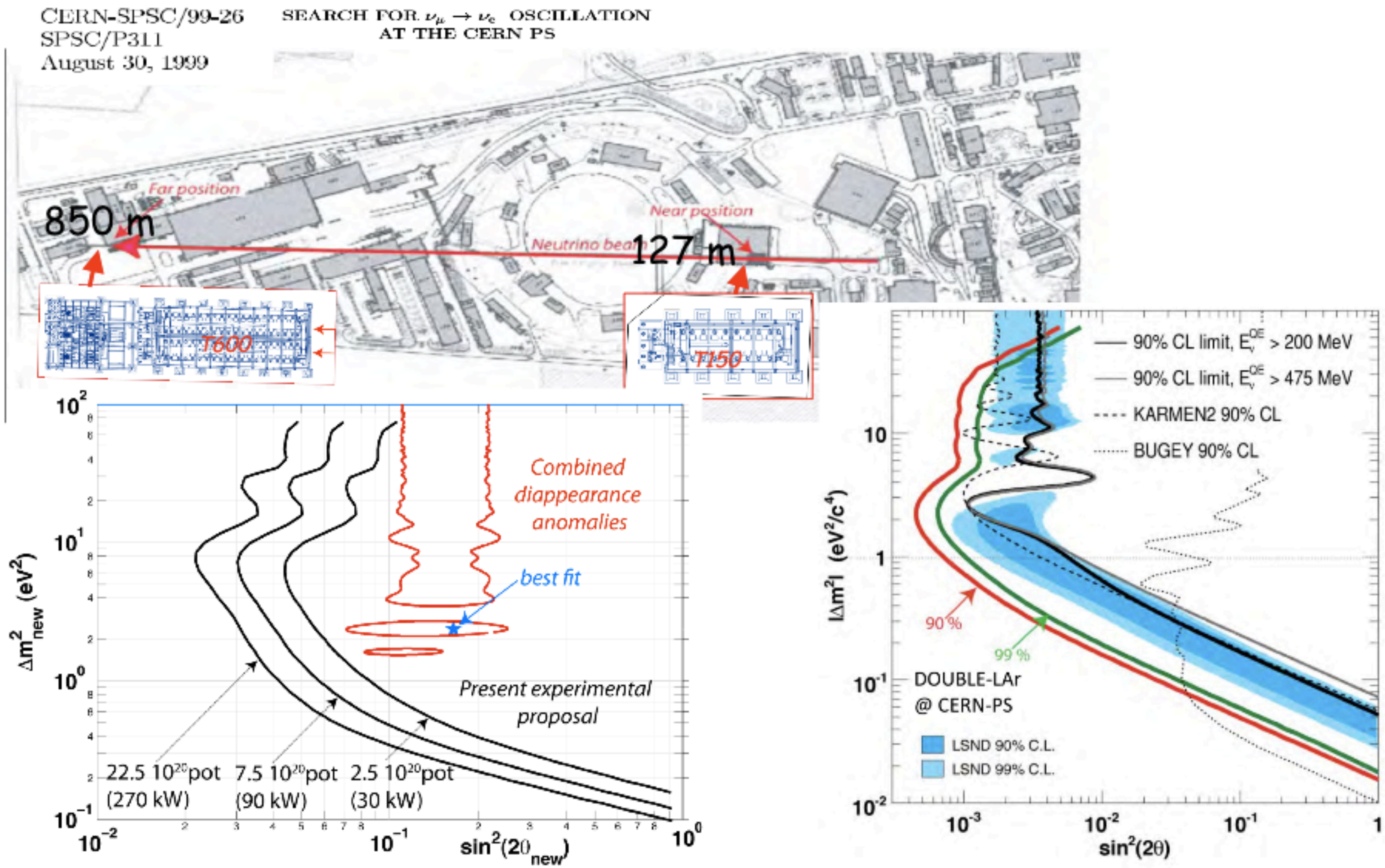


Figure 20. On the left : ILL contour at 95% C.L. (solid red curve) and 5 σ level (solid blue curve). The dotted blue curve shows the contour of the reactor anomaly at 95% C.L.

ICARUS @ CERN-PS: Low Energy (~1GeV) 2 Detector Experiment (C. Rubbia)



Testing the RAA with MCi radioactive ν_e sources