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The Double Chooz reactor neutrino experiment

Rencontres IPhT-SPP

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on behalf of the Double Chooz Collaboration

The Double Chooz collaboration

Brazil
- CBPF
- UNICAMP
- UFABC

France
- APC
- CEA/DSM/IRFU:
  - SPP
  - SPhN
  - SEDI
  - SIS
  - SENAC
- CNRS/IN2P3:
  - Subatech
  - IPHC
- ULB (Belgium)

Germany
- EKU Tübingen
- MPIK Heidelberg
- TU München
- RWTH Aachen
- U. Hamburg

Japan
- Tohoku U.
- Tokyo Inst. Tech.
- Tokyo Metro. U.
- Niigata U.
- Kobe U.
- Tohoku Gakuin U.
- Hiroshima Inst Tech.

Russia
- INR RAS
- IPC RAS
- RRC Kurchatov

Spain
- CIEMAT-Madrid

UK
- Sussex

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- U. Alabama
- ANL
- U. Chicago
- Columbia U.
- UCDavis
- Drexel U.
- IIT
- KSU
- LLNL
- MIT
- U. Notre Dame
- Sandia National Laboratories
- U. Tennessee

Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)

Web Site: www.doublechooz.org/

Contents of this talk

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- Double Chooz
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- Data analysis
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  - Background studies
  - Oscillation fit results
- Prospects
- What about RENO and Daya bay?

Mixing, oscillation and θ_{13}

- Neutrinos mixing and oscillation parametrization

  with $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$

flavor (interaction) — mixing matrix U_{PMNS} — **mass (propagation)**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_t\end{pmatrix} = \begin{pmatrix}1&&\\&c_{23}&s_{23}\\&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&&e^{-i\delta}s_{13}\\&1&\\-e^{i\delta}s_{13}&&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&\\-s_{12}&c_{12}&\\&&1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

measured
$\sin^2(2\theta_{23}) \sim 1$

Unknown!
Limit (from CHOOZ) :
$\sin^2 2\theta_{13} < 0.15$ at 90 % C.L.
for $\Delta m_{31}^2 = 2.5\ 10^{-3}\ eV^2$

(+ indication of a non-zero θ_{13} from the T2K experiment)

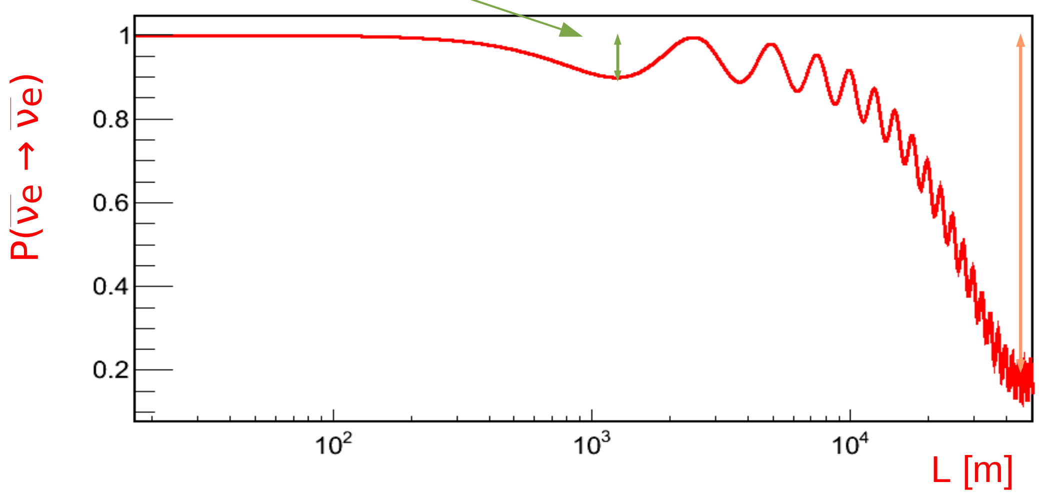
measured
$\sin^2(2\theta_{12}) \sim 0.8$

- Why measuring θ_{13}?
  - > Fundamental unknown physics parameter
  - > Necessary step before the search for CP violation in the leptonic sector (δ_{CP} scaled by $\sin^2 2\theta_{13}$)

Antineutrino disappearance at reactor

- $\overline{\nu}_e$ emitted through β-decay of fission products in N4-REP Chooz B 2 x 4.25 GW_{th} reactor core
  - > **Pure, intense** and **MeV** source
- **Disappearance experiment**
  - > Survival probability:

$$P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{31}^2\, L/E) - \cos^4(\theta_{13}) \sin^2(2\theta_{12}) \sin^2(1.27\, \Delta m_{21}^2\, L/E)$$



with:
- $\sin^2(2\theta_{13}) = 0{,}1$
- $\sin^2(2\theta_{12}) = 0{,}8$
- $\Delta m_{31}^2 = 2{,}5\ 10^{-3}\ eV^2$
- $\Delta m_{21}^2 = 8\ 10^{-5}\ eV^2$
- $E_\nu = 3$ MeV

- Choice of L/E: **clean measurement of one parameter, $\sin^2 2\theta_{13}$**

→ Simplified survival probability: $P(\overline{\nu}_e \rightarrow \overline{\nu}_e) \sim 1 - \sin^2(2\theta_{13}) \sin^2(1.27\, \Delta m_{31}^2\, L/E)$

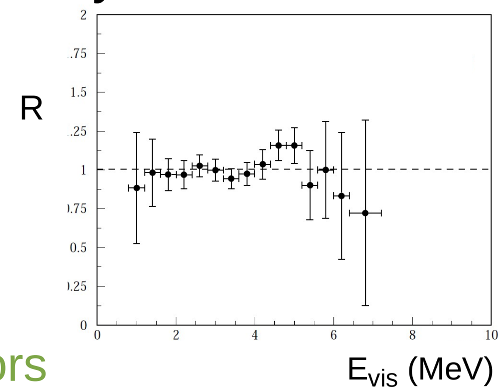
The Double Chooz experiment

From CHOOZ to Double Chooz

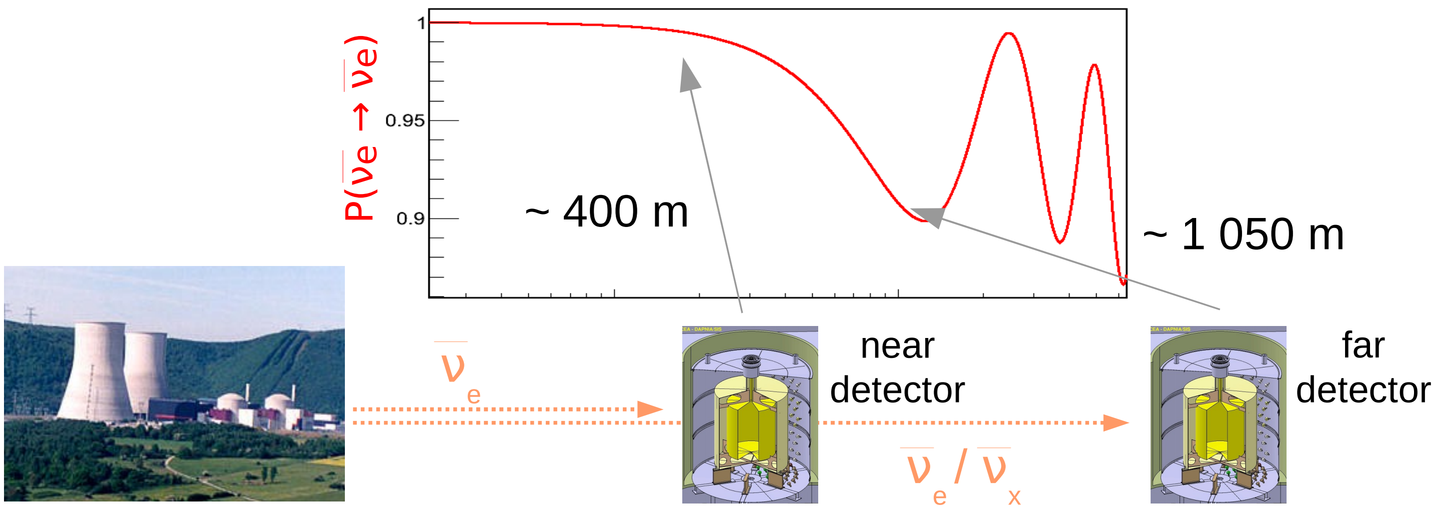
- Former experiment **CHOOZ** limited by stat. and syst.:

  R = 1.01 ± 2.8 % (stat) ± 2.7 % (syst)

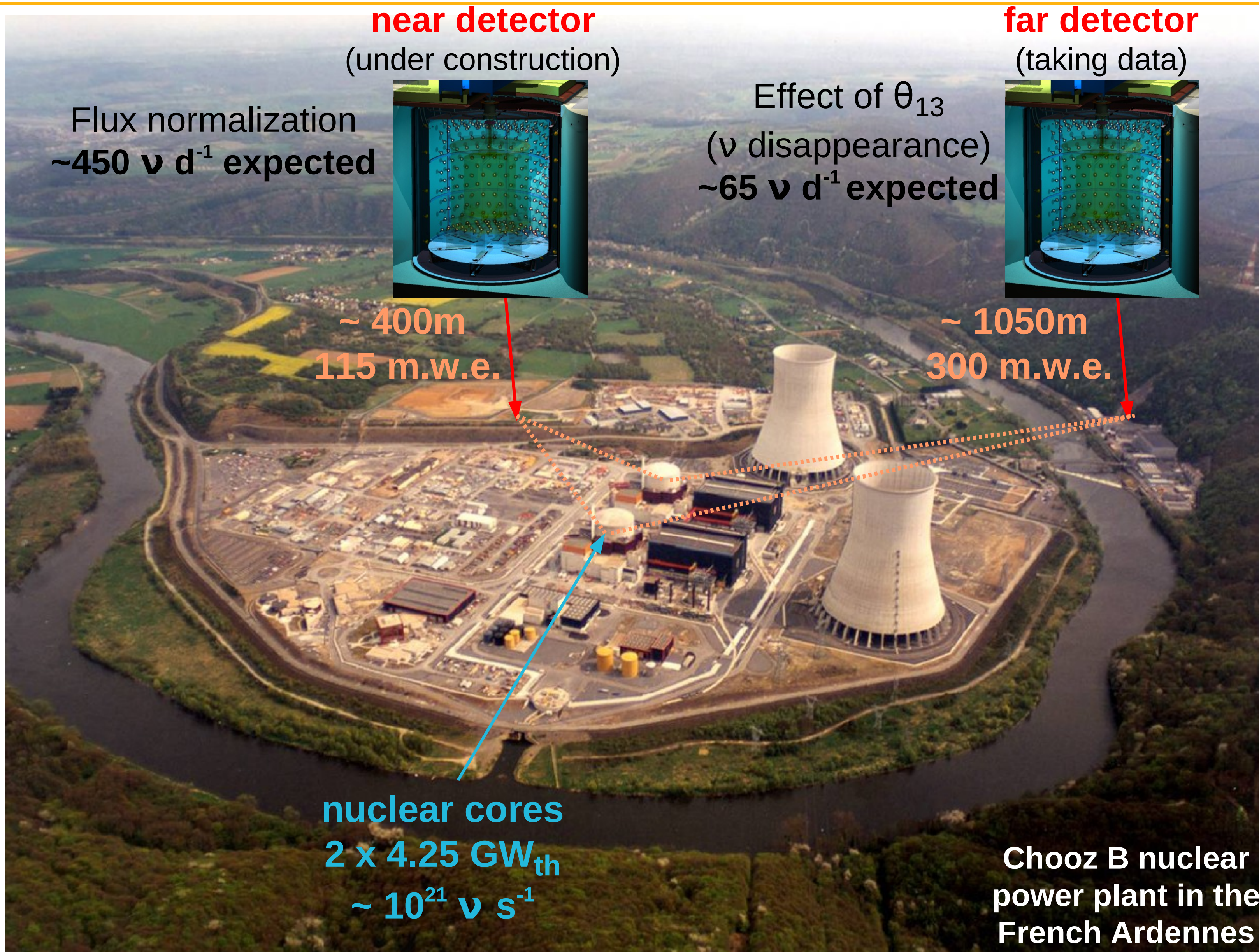
  where $R = N_{\nu\ obs} / N_{\nu\ exp\ w/o\ oscillation}$ ($R \neq 1$ if oscillation)



- **Double Chooz concept:**
  > relative measurement btw 2 identical detectors
  (cancel systematic uncertainties on ν flux and detector response)
  > bigger target volumes, longer data taking
  (work on liquid scintillator and material compatibility)

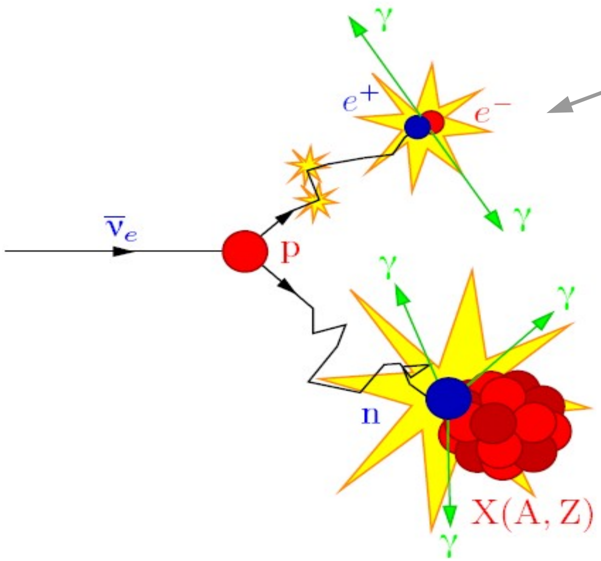


Experimental site



- Inverse β-decay in scintillator:
  (~20% PXE, 80% dodecane, 0.1% dissolved Gd + wavelength shifters)

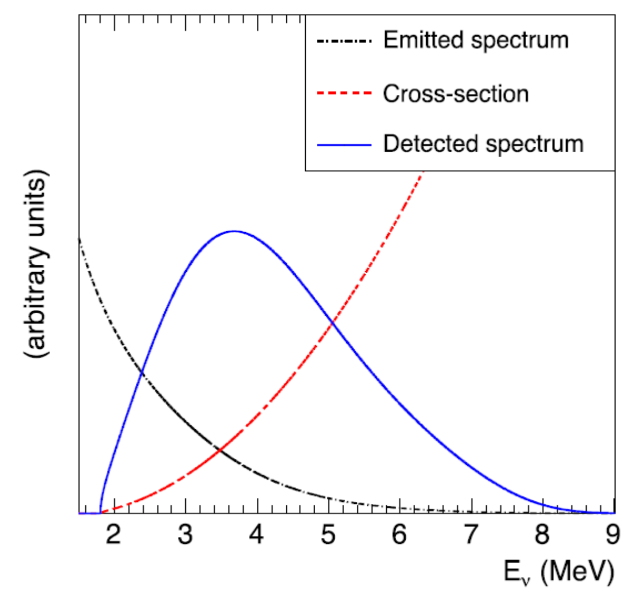
$$\bar{\nu}_e + p \rightarrow n + e^+$$



Prompt signal ~ [1-8] MeV = e^+ energy loss + e^+e^- annihilation

→ $E_{vis} = E_{e+} + m_e \sim E_{\nu_e} - \Delta + m_e$

Delayed signal ~ 8 MeV = n-capture on Gd → cascade γ



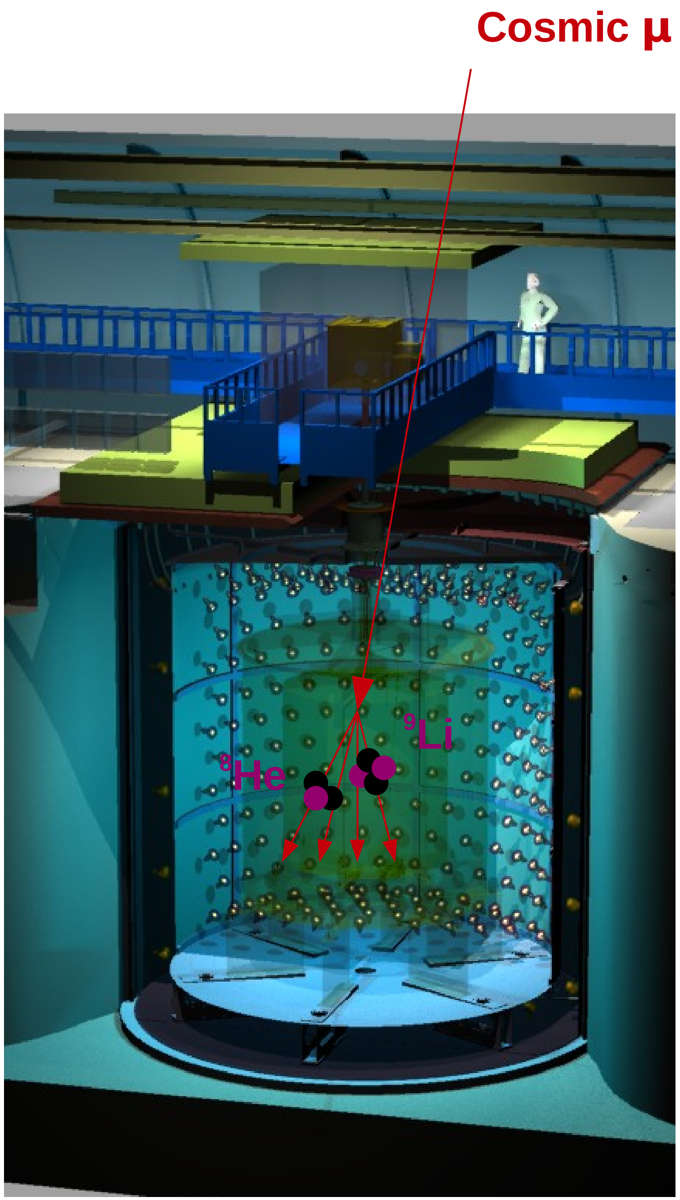
→ **Correlated signals** (time and space)

ΔT ~ 30 µs and **ΔR < 1 m**

seen by photomultipliers (PMT)

Expected backgrounds

- **Correlated background**
  - β-n decaying isotopes **^{9}Li and ^{8}He** μ-produced by spallation processes
    - \> Perfectly mimic the ν signal
    - \> Cannot be vetoed $t_{1/2}$ = 178 ms
    - \> 1.4 ± 0.5 d^{-1} expected



Expected backgrounds

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  - β-n decaying isotopes **^{9}Li and ^{8}He** μ-produced by spallation processes
    - > Perfectly mimic the ν signal
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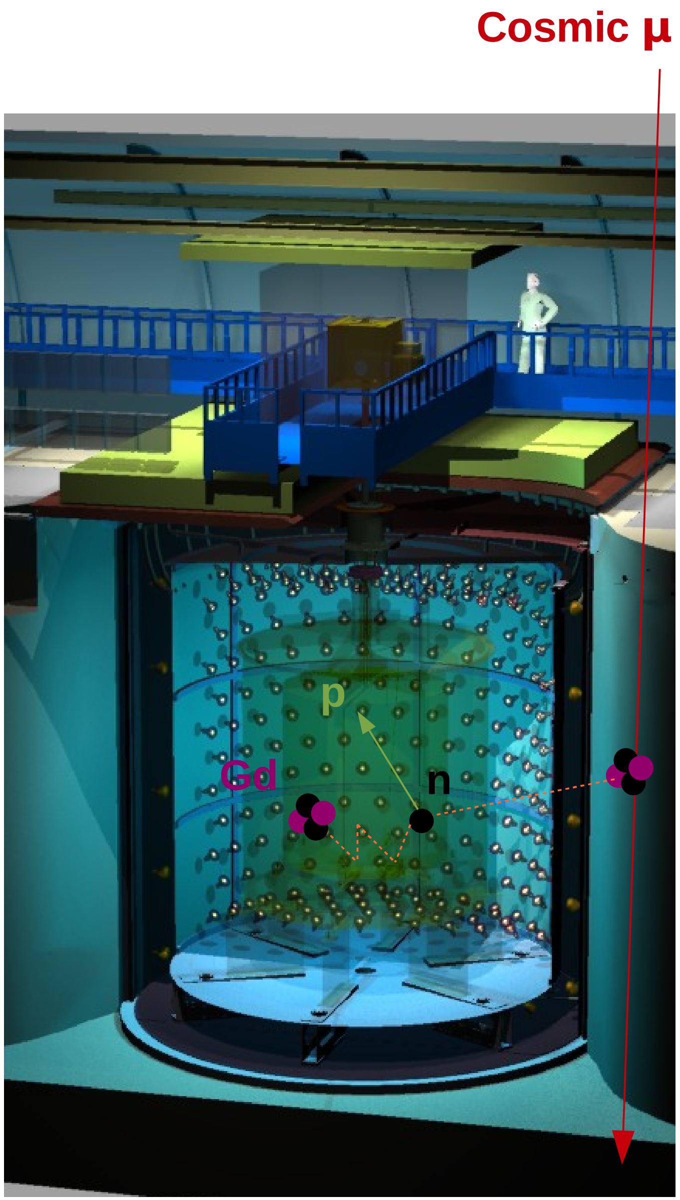
  - μ-induced **fast neutrons**
    - > Prompt signal = recoil proton
    - > Delayed signal = n-capture on Gd
    - > 0.2 ± 0.2 d^{-1} expected



Expected backgrounds

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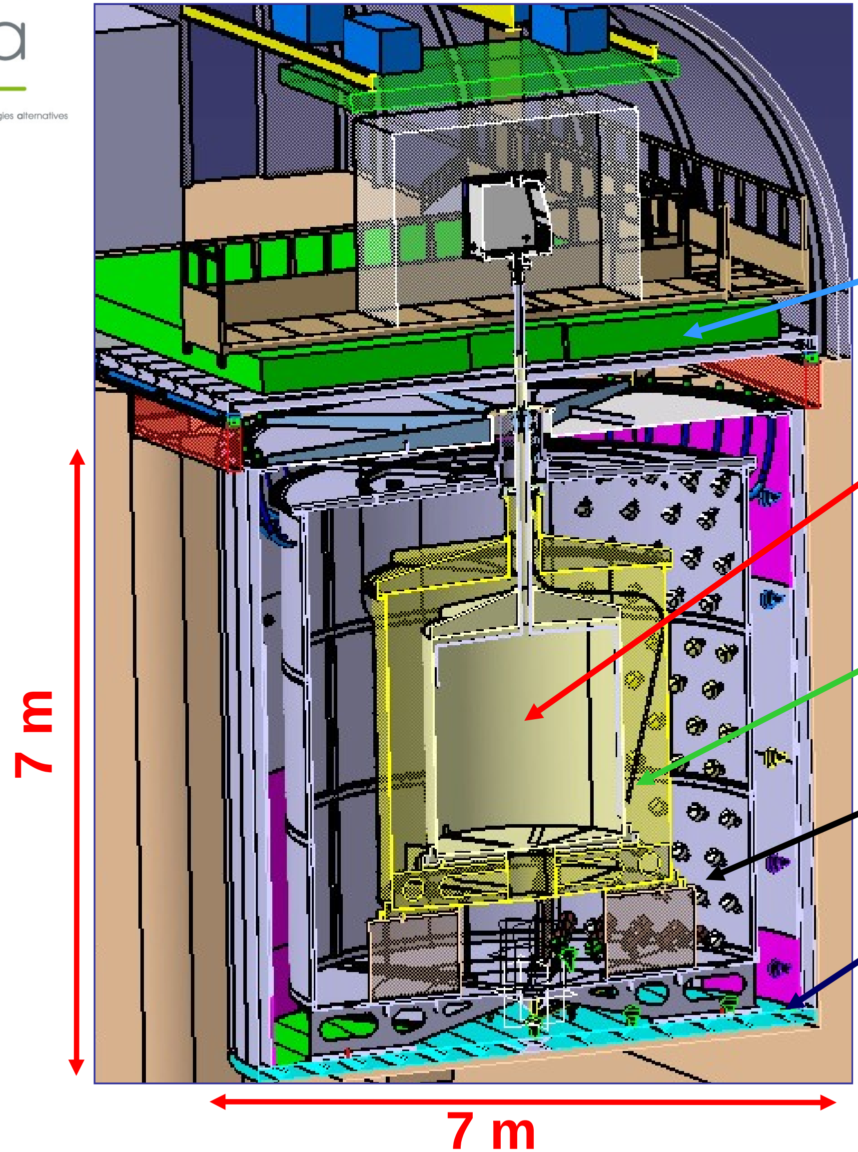
  - β-n decaying isotopes **^{9}Li and ^{8}He** μ-produced by spallation processes
    - > Perfectly mimic the ν signal
    - > Cannot be vetoed $t_{1/2}$ = 178 ms
    - > 1.4 ± 0.5 d^{-1} expected
  - μ-induced **fast neutrons**
    - > Prompt signal = recoil proton
    - > Delayed signal = n-capture on Gd
    - > 0.2 ± 0.2 d^{-1} expected
- **Accidental backgrounds**
    - > Prompt = **radioactivity γ** emitted from a PMT (for instance)
    - > Delayed = μ-induced **fast neutron** captured on a Gd nucleus
    - > 2.0 ± 0.9 d^{-1} expected

The Double Chooz detector



Design:

- Neutrinos detection
- Protection against backgrounds (internal and external)

Outer Veto: 82 m² of 400 mm thick plastic scintillator strips

ν-Target: 10.3 m³ liquid scintillator doped at 0.1 % in Gd, in a 8 mm thick acrylic vessel

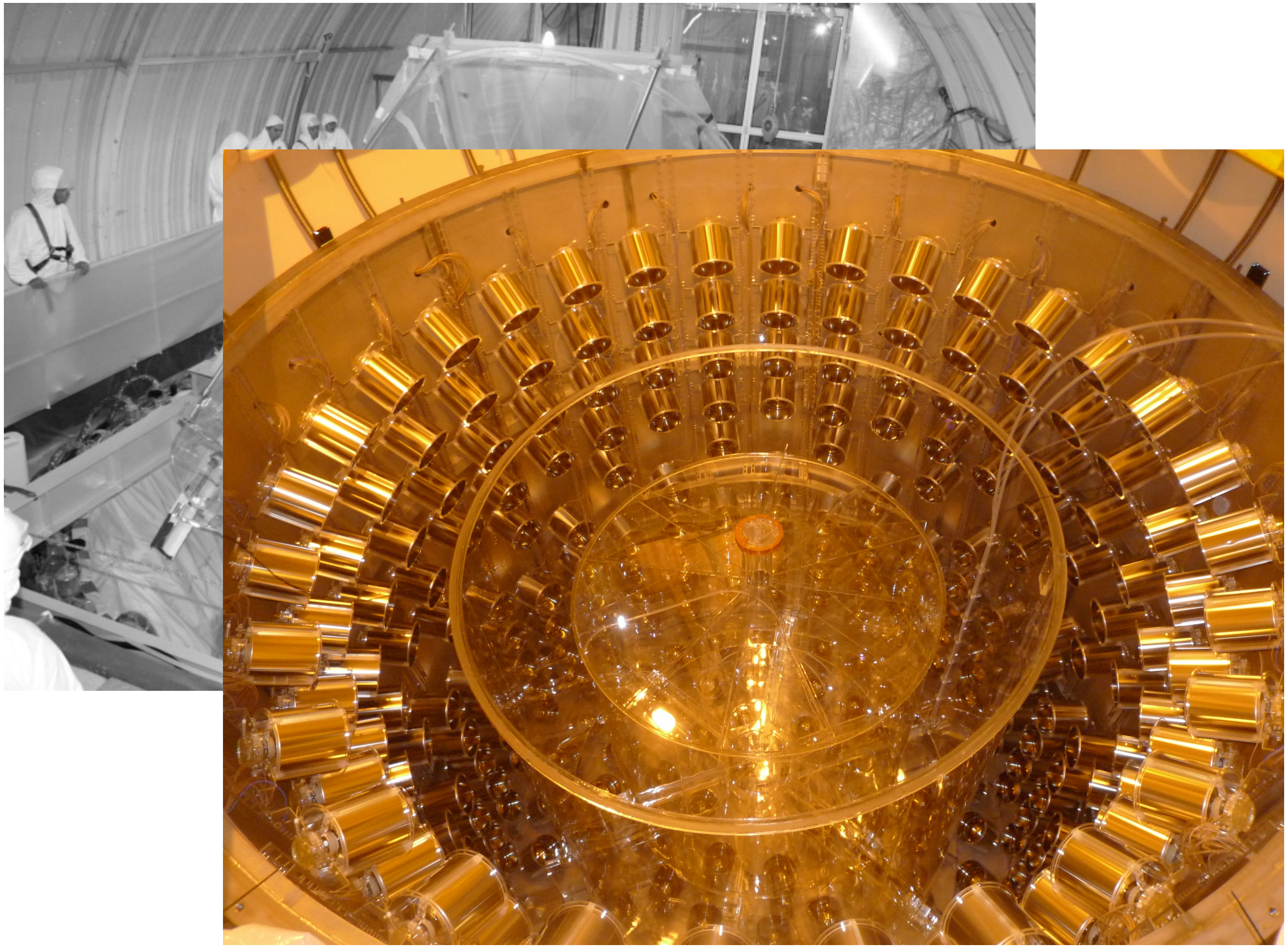
γ-catcher: 22.3 m³ liquid scintillator in a 12 mm thick acrylic vessel

Buffer: 110 m³ mineral oil in a 3 mm stainless steel vessel, seen by 390 PMT

Inner Veto + steel shielding: 90 m³ of liquid scintillator, seen by 80 PMT

The Double Chooz detector

The Double Chooz detector



The Double Chooz detector

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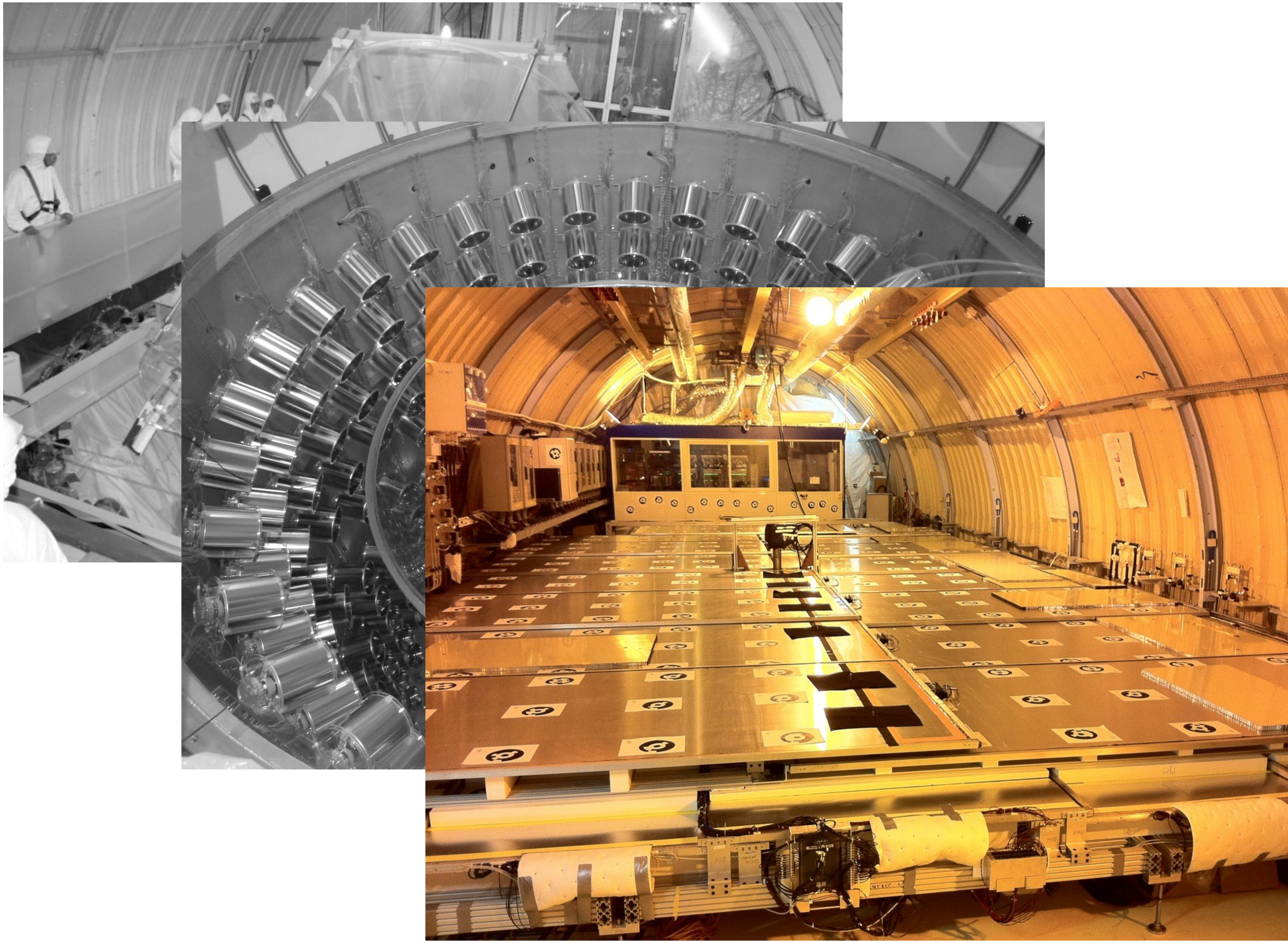
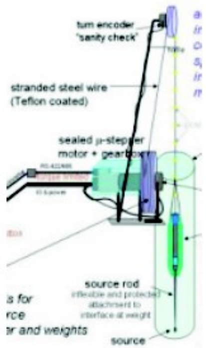


Calibration

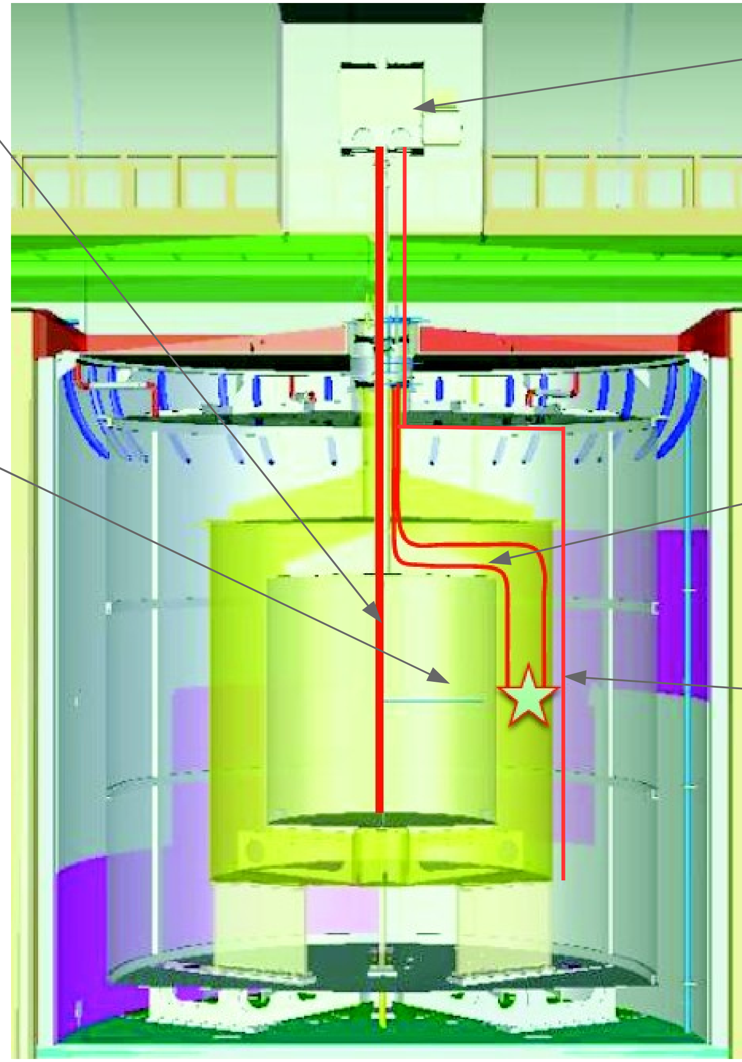
Z-axis system



+ articulated arm
(not installed yet)

+ Lasers
(UV and green)

+ Light injectors
(inner detector + inner veto)



Glove Box

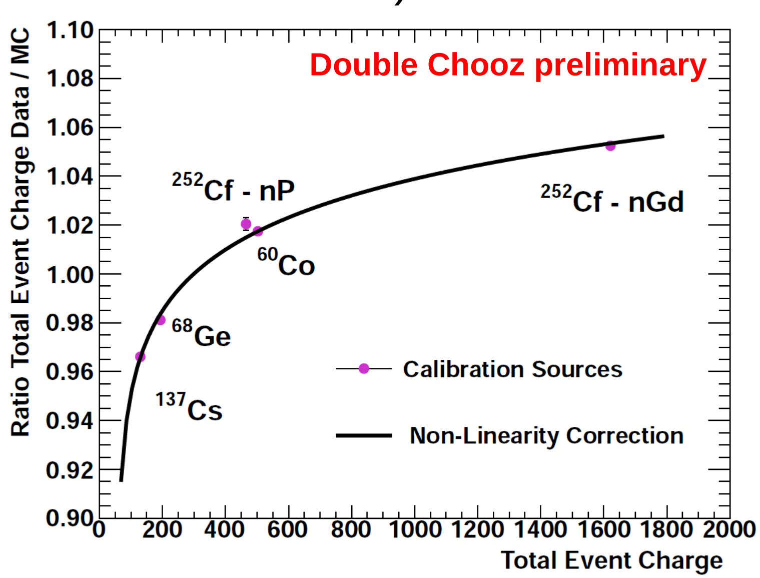
Tube for radioactive sources (in GC)

Tube for radioactive sources (in Buffer)

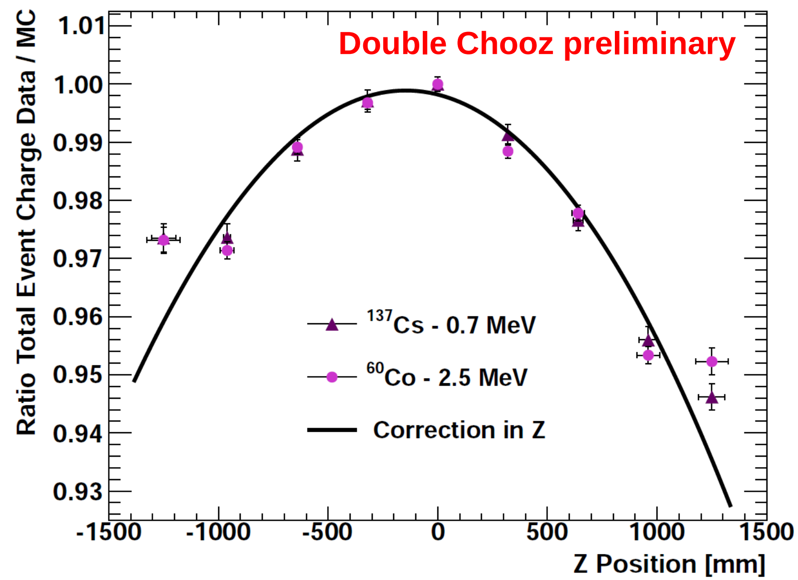
(radioactive sources ^{68}Ge, ^{137}Cs, ^{60}Co, ^{252}Cf)

Calibration

- **Charge correction:** calibrate non-linearity (charge reconstruction and electronics effects)

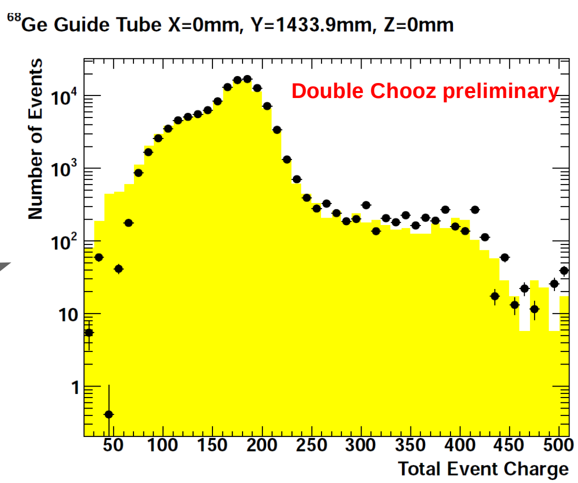


- **Z correction:** calibrate the Z-bias (geometrical effect)



→ **Empirical energy correction function:** removes MC and data discrepancies

→ ^{68}Ge source in a calibration tube: **correction works well, spectrum well modeled**



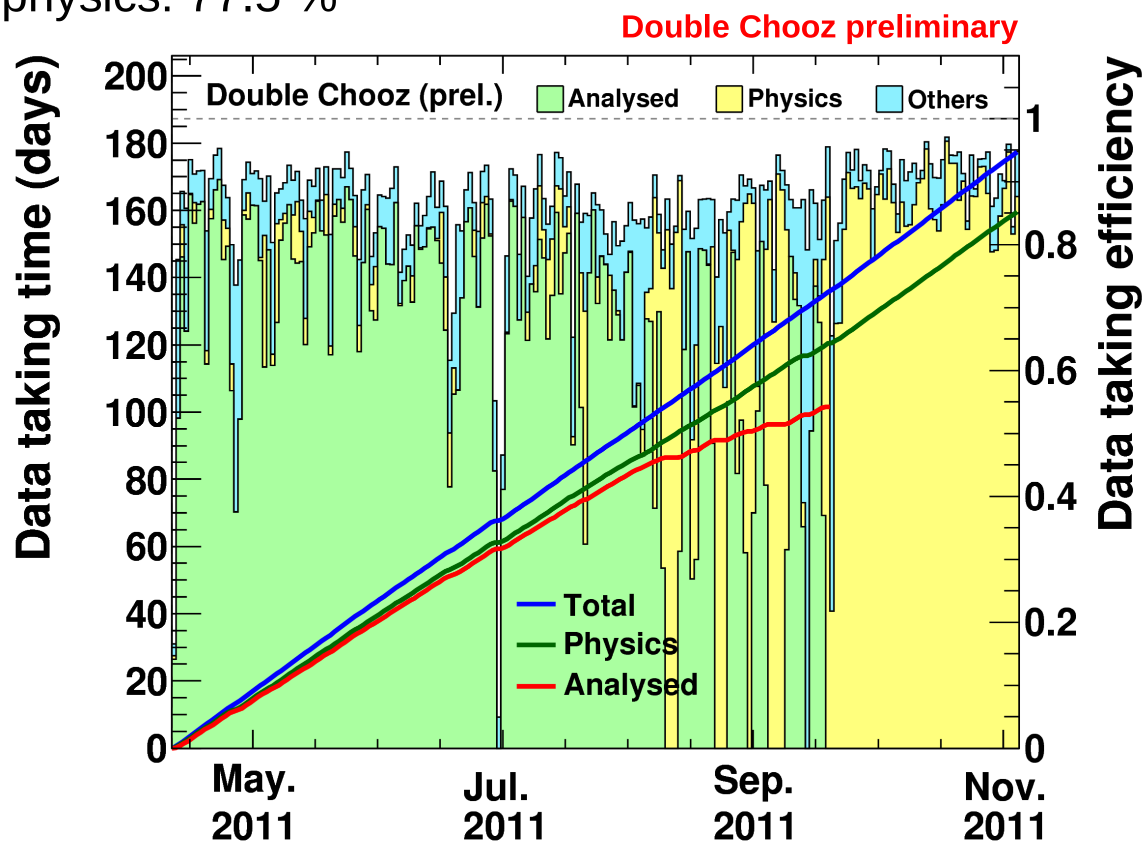
Double Chooz data analysis

Neutrino search

Data Taking Efficiency

- Analysis performed on **102 days of physics** runs, including 16 days of one reactor OFF (+ 1 day of two reactors OFF), with **far detector only**

- Average data taking efficiency
  - in total: 86.2 %
  - in physics: 77.5 %



Neutrino search – An unexpected background...

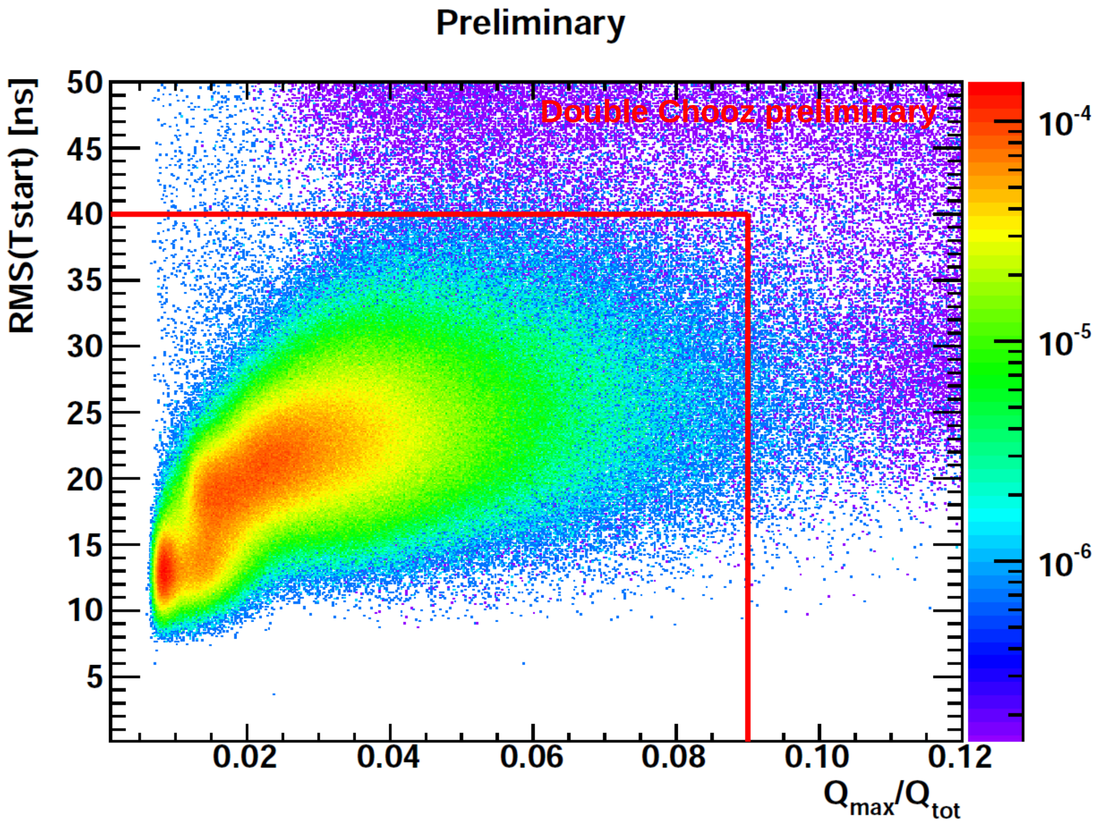
- Called "**Light-Noise**"
- **Parasitic light** emitted by some PMT bases
  - > 15 were turned off
  - > Offline rejection cuts based on anisotropic light collection

- PMT sees its own light
  → Qmax/Qtot cut

(ν signals should be homogeneously spread across the PMTs)

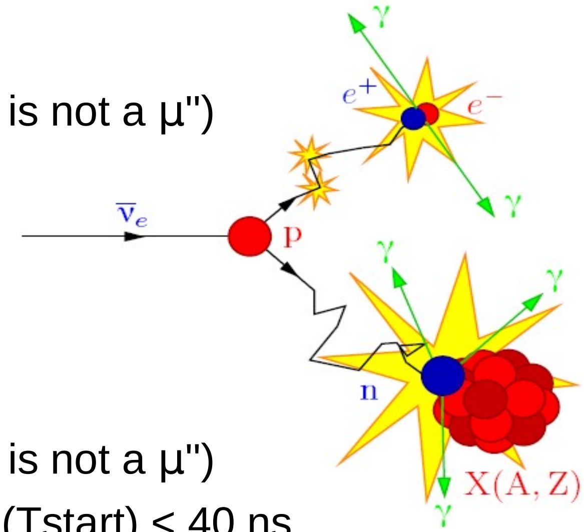
- Large dispersion of start time of PMT signals
  → RMS(Tstart) cut

(ν signals should have small spread in arrival times)



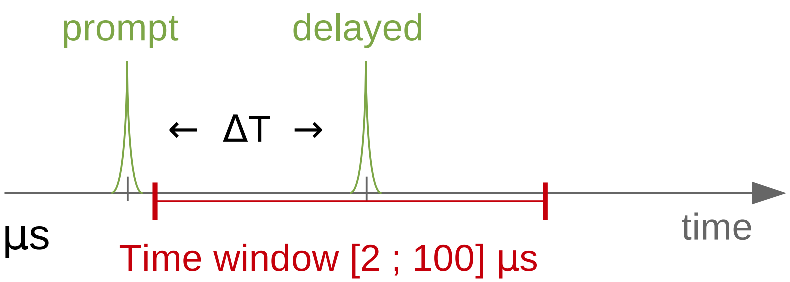
Neutrino search – Analysis cuts

- **Prompt event:**
  - No Inner Veto Energy Deposition (*i.e.*, "event is not a μ")
  - Light-Noise cuts: Qmax/Qtot < 0.09 and RMS(Tstart) < 40 ns
  - Energy in [0.7 ; 12] MeV



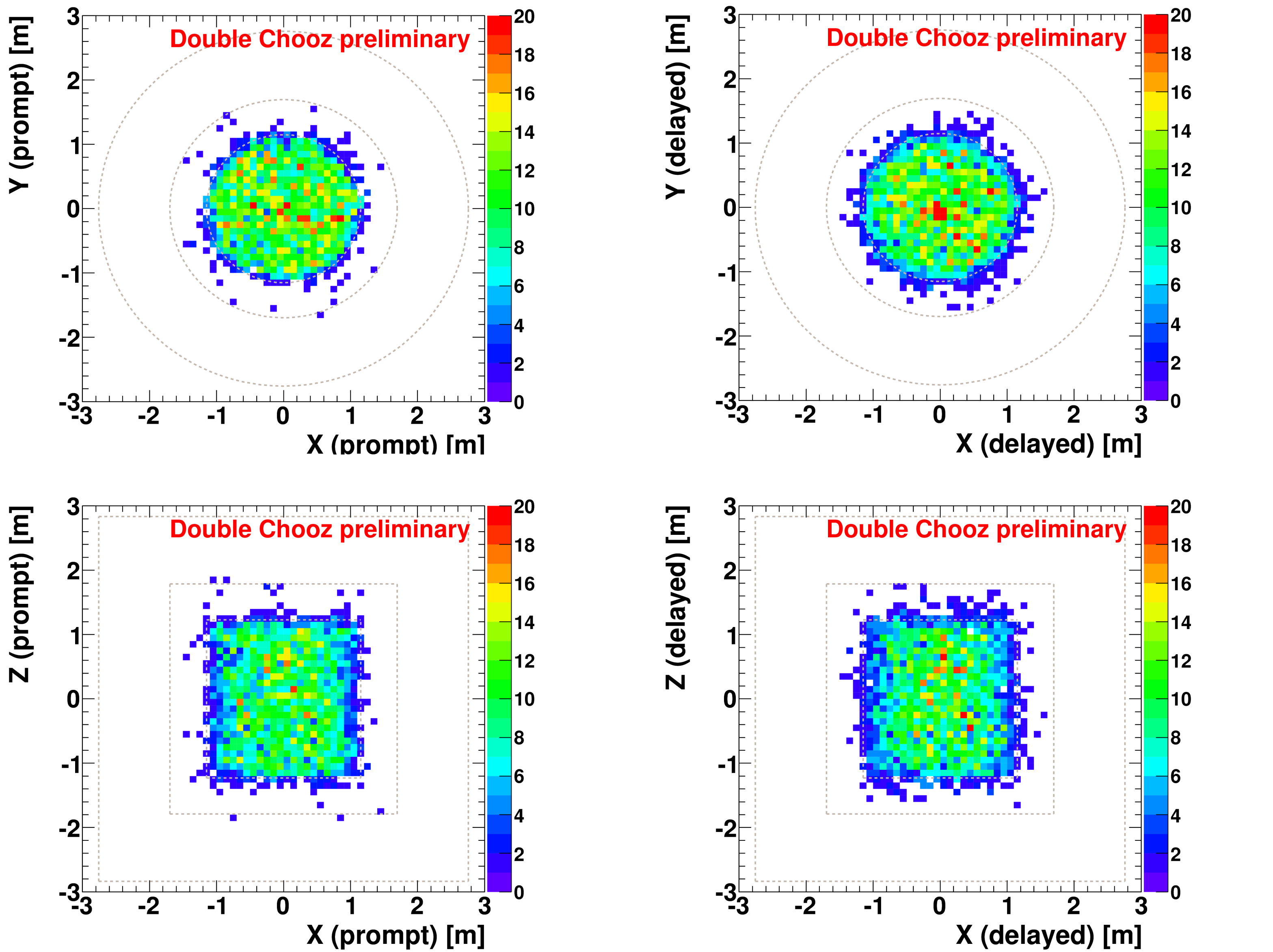
- **Delayed event:**
  - No Inner Veto Energy Deposition (*i.e.*, "event is not a μ")
  - Light-Noise cuts: Qmax/Qtot < 0.06 and RMS(Tstart) < 40 ns
  - Energy in [6 ; 12] MeV

- **Coincidence:**
  - No space coincidence cut applied
  - Time coincidence: 2 μs < ΔT < 100 μs

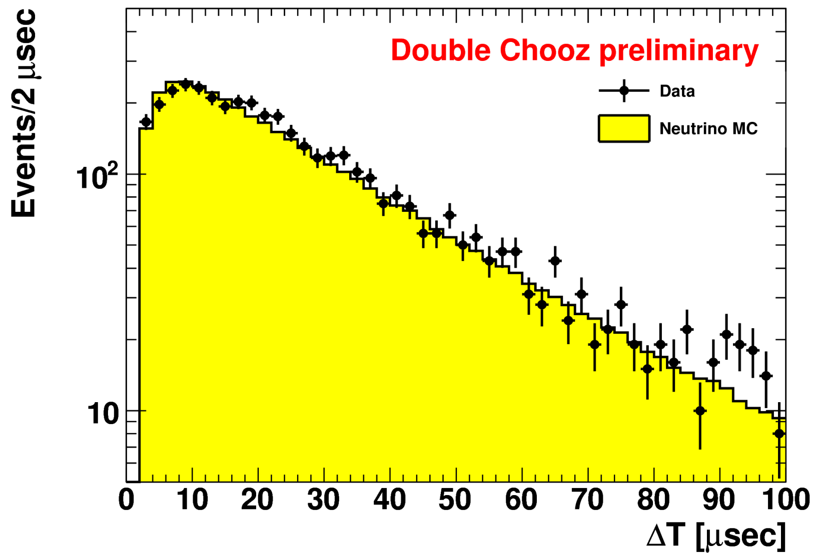


- **Multiplicity:**
  - No valid trigger in the 100 μs preceding the prompt
  - Time window from 2 μs to 100 μs following the prompt can only contain one valid trigger: the delayed event
  - No valid trigger in the time window 100 μs through 400 μs after prompt

Neutrino search – Vertices distributions



Neutrino search – ΔT and ΔR distributions

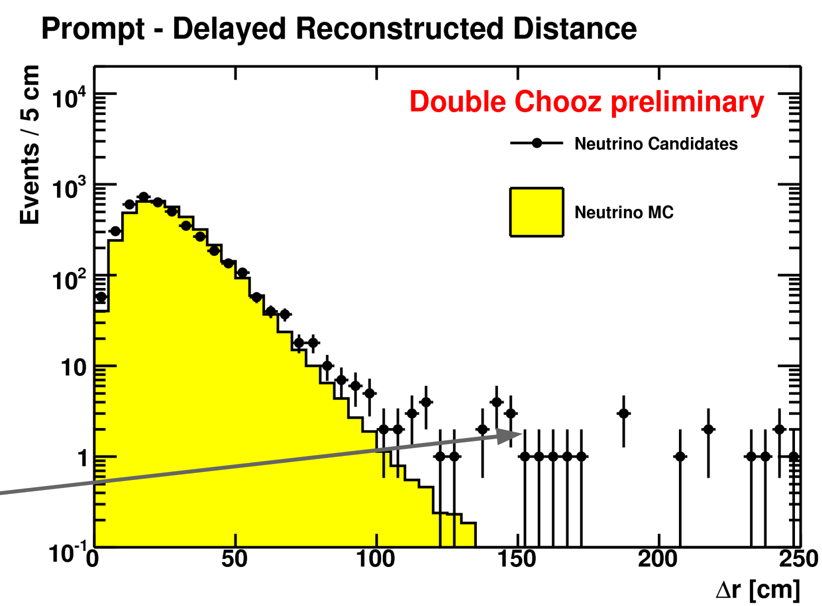


- keV neutrons thermalize within a few μs
- Then they get captured on Gd with **τ ≃ 27 μs**

- ΔR: 3D distance between prompt and delayed vertices
- Low level of accidental background: ΔR cut is not needed

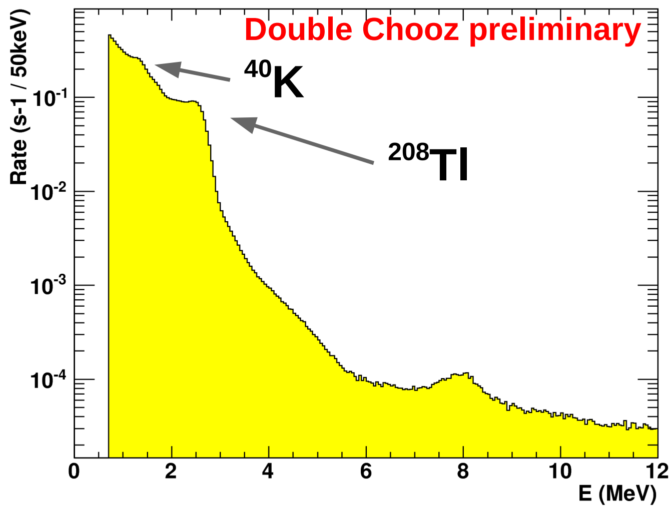
Few background events passed the selection cuts

(called "accidental coincidences")

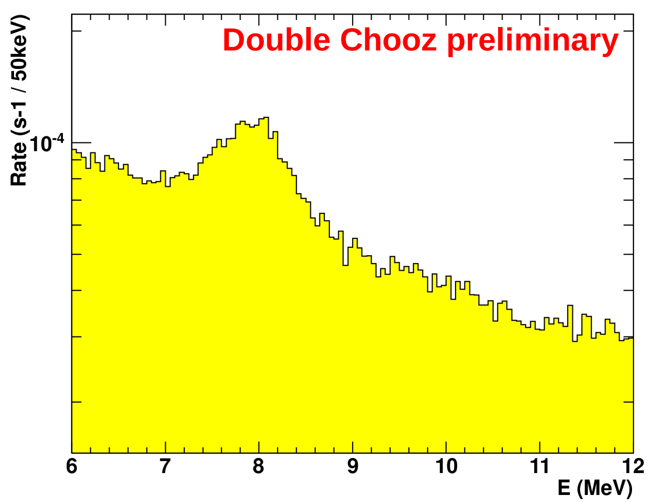


Double Chooz data analysis
Backgrounds studies

Backgrounds studies – Singles

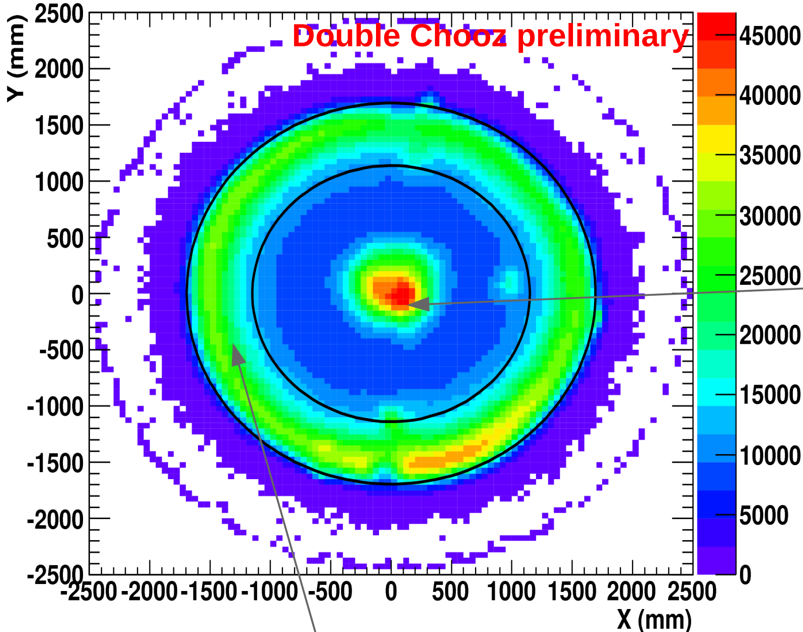


- **[0.7 ; 3] MeV: radioactivity**
- In Double Chooz Proposal: 10 Hz
  - Measured: **7.625 ± 0.001 Hz**

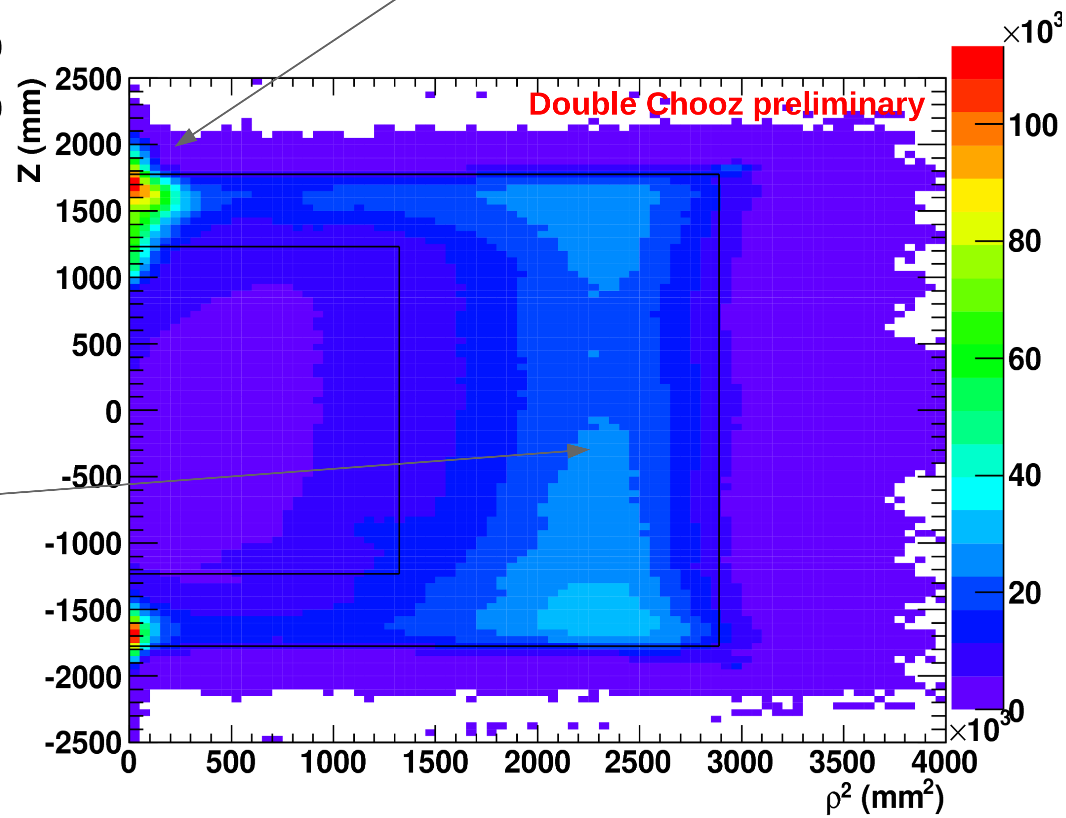


- **[6 ; 12] MeV: thermal neutrons**
- In Double Chooz Proposal: 100 h^{-1}
  - Measured: **20 h^{-1}**

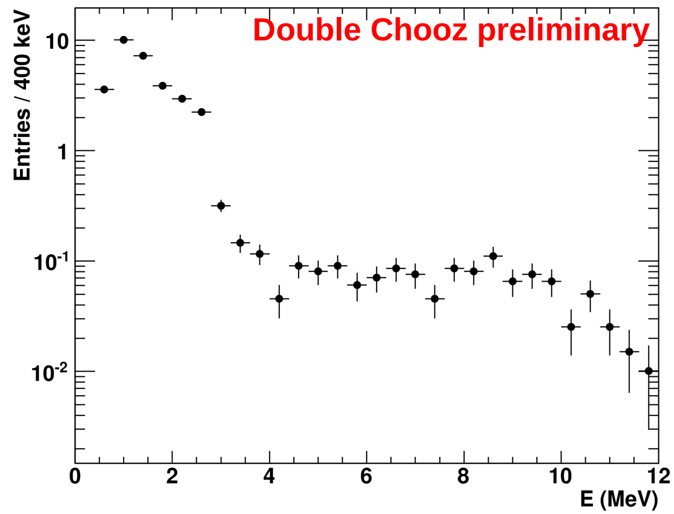
Backgrounds studies – Singles

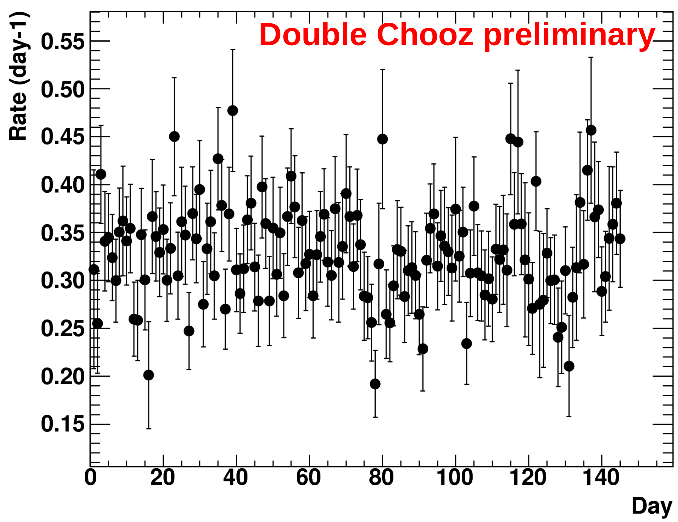


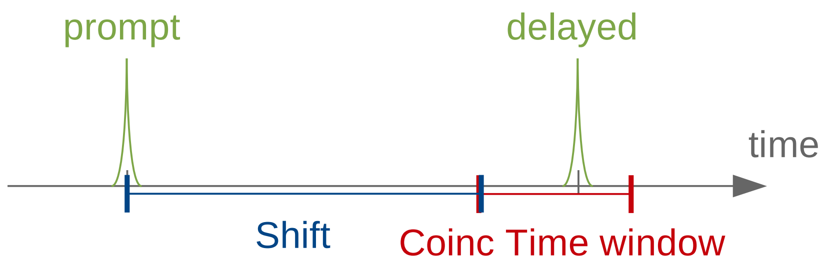
Radioactivity from outside (chimney)



Radioactivity from PMT

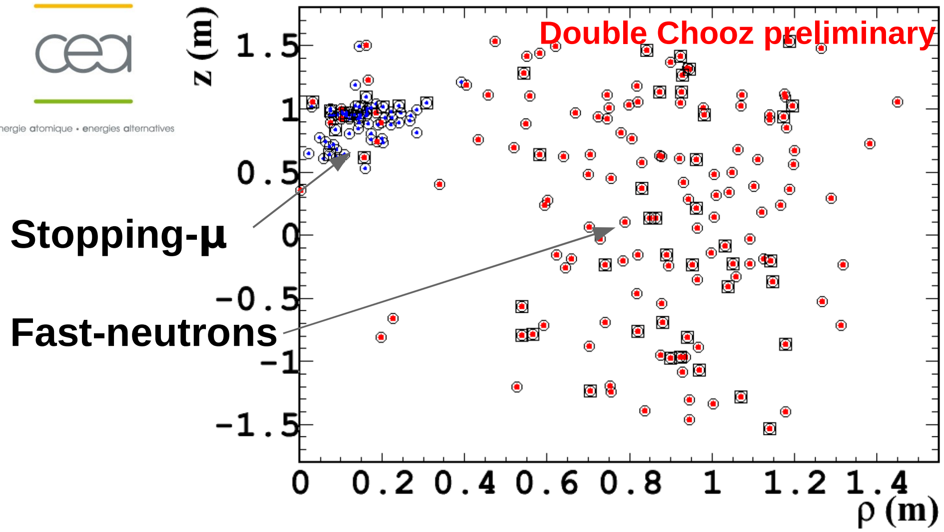


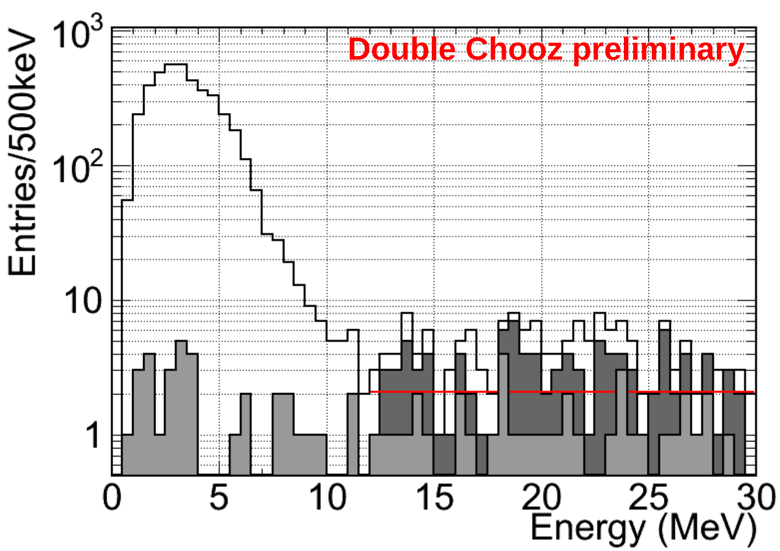




- **Accidentals search:** same as neutrinos, but different coincidence window (delayed event 1 ms after the prompt: **uncorrelated**)
- Spectrum compatible with Singles one
- **Rate:**
  - Measured: **0.33 ± 0.03 d^{-1}**
  - 5 times lower than in the proposal!
  - Stable in time

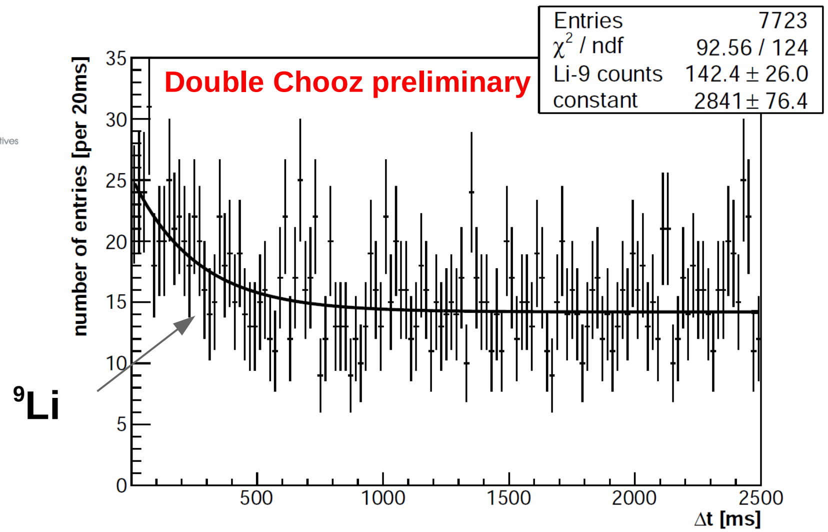
Backgrounds studies – Fast-neutrons

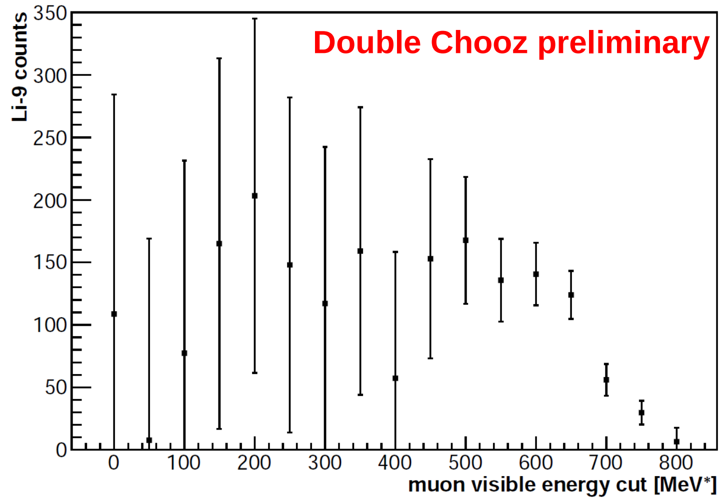




- **Fast-neutrons search:** same as neutrinos, but with upper energy bound at 30 MeV
- Two populations:
  - **Fast-neutrons**
  - **Stopping-muons**
- **Rate:**
  - Extrapolation from high energies to lower ones
  - Measured: **0.83 ± 0.38 d^{-1}**
- **Spectrum:**
  - **Flat**

    (+ stopping-μ shape uncertainty)

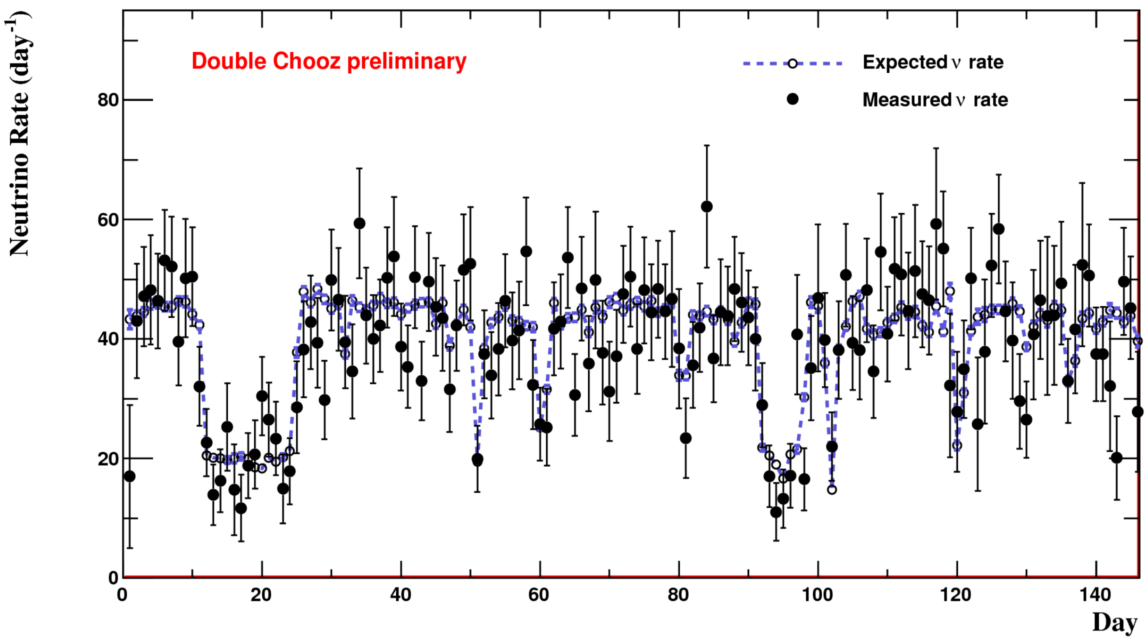


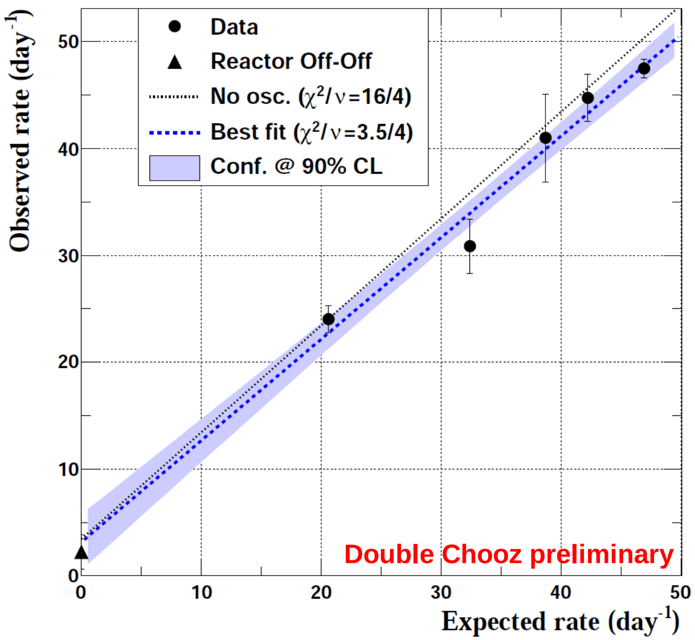


- **^{9}Li search:**
  - Statistical
  - Search for a triple delayed coincidence btw a showering-μ (E > 600 MeV) and a ν-like coincidence
- ΔT btw showering-μ and prompt event is given by the ^{9}Li life time
- **Rate:**
  - Estimated: **2.3 ± 1.2 d^{-1}**
- **Spectrum:**
  - **From nuclear database**

Results

	# of events	Rate (d^{-1})	σ (d^{-1})
Neutrino candidates	4121	42.6	0.7
Accidentals	32.0	0.33	0.03
^{9}Li	227.3	2.3	1.2
Fast-neutrons	69.2	0.83	0.38

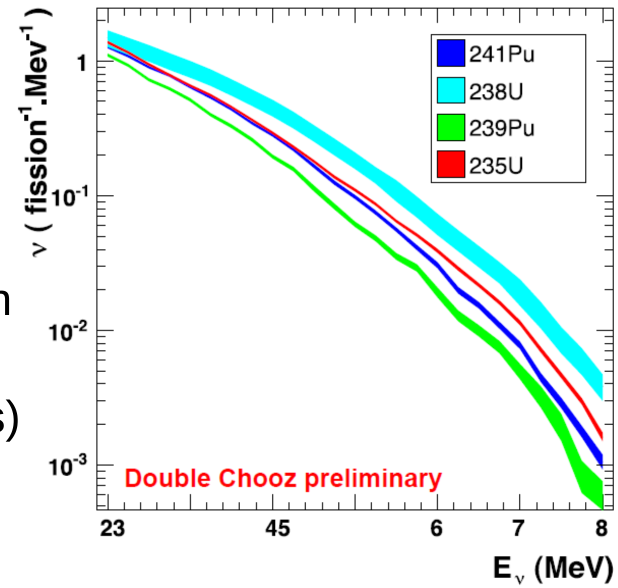




Oscillation fit

Reactor antineutrino flux prediction

- **One detector phase** → need flux prediction
  - > $N_\nu^{exp}(E,t) = N_p\, \varepsilon / 4\pi L^2 \times P_{th}(t) / \langle E_f \rangle \times \langle \sigma_f \rangle$
  - – N_p: number of target protons
  - – ε: detector efficiency
  - – L: distance reactor-detector
  - – $P_{th}(t)$: thermal power (from EDF)
  - – $\langle E_f \rangle = \Sigma\, \alpha_k(t) \langle E_f \rangle_k$: mean energy per fission with k = ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu, and $\alpha_k(t)$: fractional fission rate (from simulations)
  - – $\langle \sigma_f \rangle$: mean cross-section per fission
    - → $\langle \sigma_f \rangle = \int dE\, S_k(E)\, \sigma_{IBD}(E)$
    - → $\langle \sigma_f \rangle = \langle \sigma_f \rangle^{Bugey4} + \Sigma\, [\alpha_k^{DC}(t) - \alpha_k^{Bugey4}(t)] \langle \sigma_f \rangle_k$



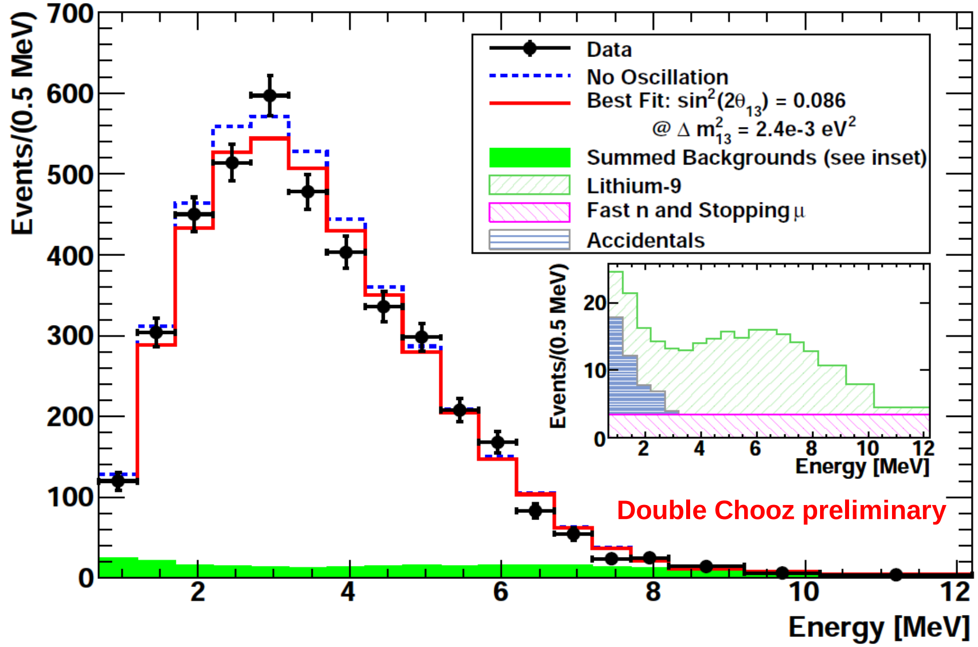
- Use of **Bugey4 flux** measurement ("anchor point") after **correction** for differences in **core composition** (same as CHOOZ)

- **Two detectors phase** → near detector data

Oscillation fit strategy and results

$$\chi^2 = \left(N_i - \sum_R^{\text{Reactors}} N_i^{\nu,R*}\right) \times \left(M_{ij}^{\text{Reactors}} + M_{ij}^{\text{detector}} + M_{ij}^{\text{stat}} + \sum_b^{\text{bkgnds.}} M_{ij}^{b}\right)^{-1} \times \left(N_j - \sum_R^{\text{Reactors}} N_j^{\nu,R*}\right)^{T}$$

- Covariance matrices: uncertainties for:
  - > ν-signal from reactors,
  - > detector response,
  - > signal and backgrounds stats,
  - > backgrounds spectral shape
- Fit using two types of information:
  - > **Rate** (number of events)
  - > **Shape** (spectra)



→ R = 0.944 ± 0.016 (stat) ± 0.040 (syst)

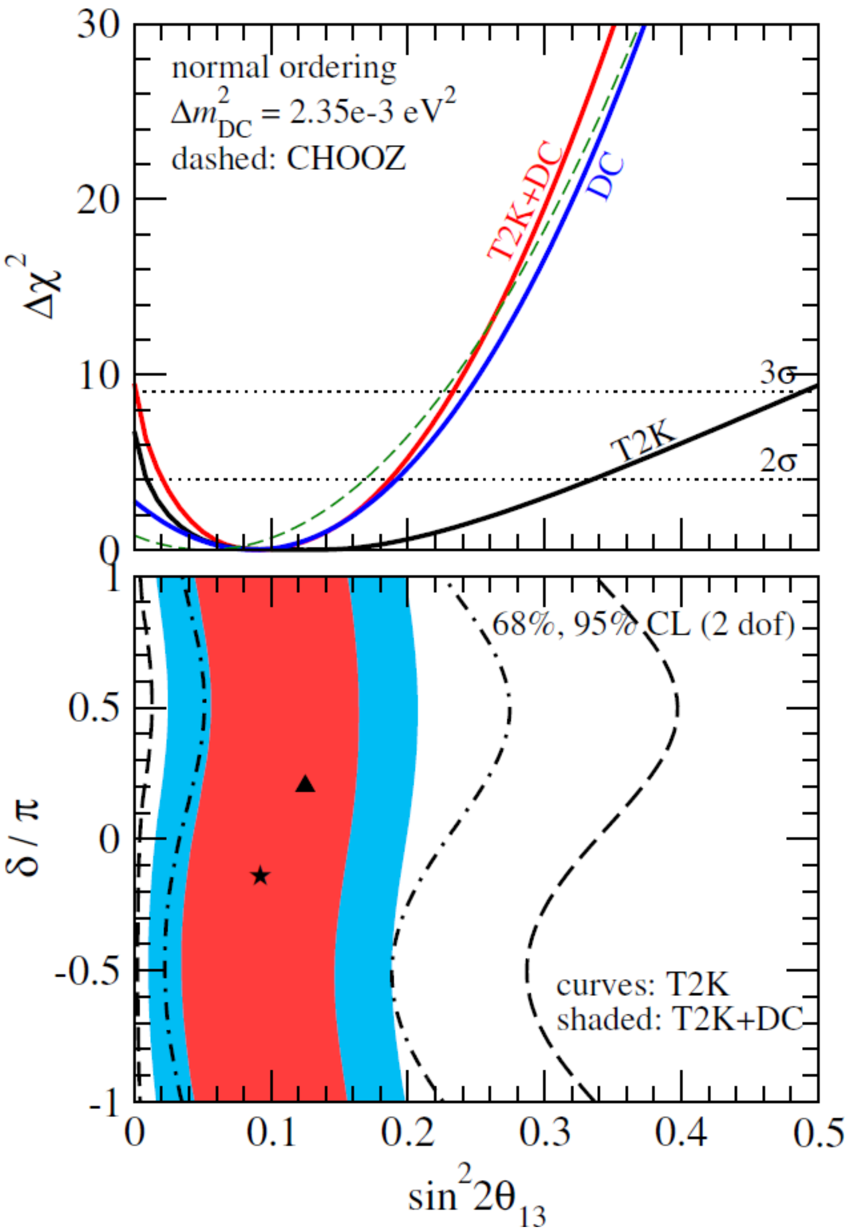
ie **$\sin^2 2\theta_{13}$ = 0.086 ± 0.041 (stat) ± 0.030 (syst)**

or 0.015 < $\sin^2 2\theta_{13}$ < 0.160 at 90 % CL

Combined results on θ_{13}

- Double Chooz and T2K results are consistent

- **θ_{13} = 0 is excluded at 3σ** from T2K+Double Chooz

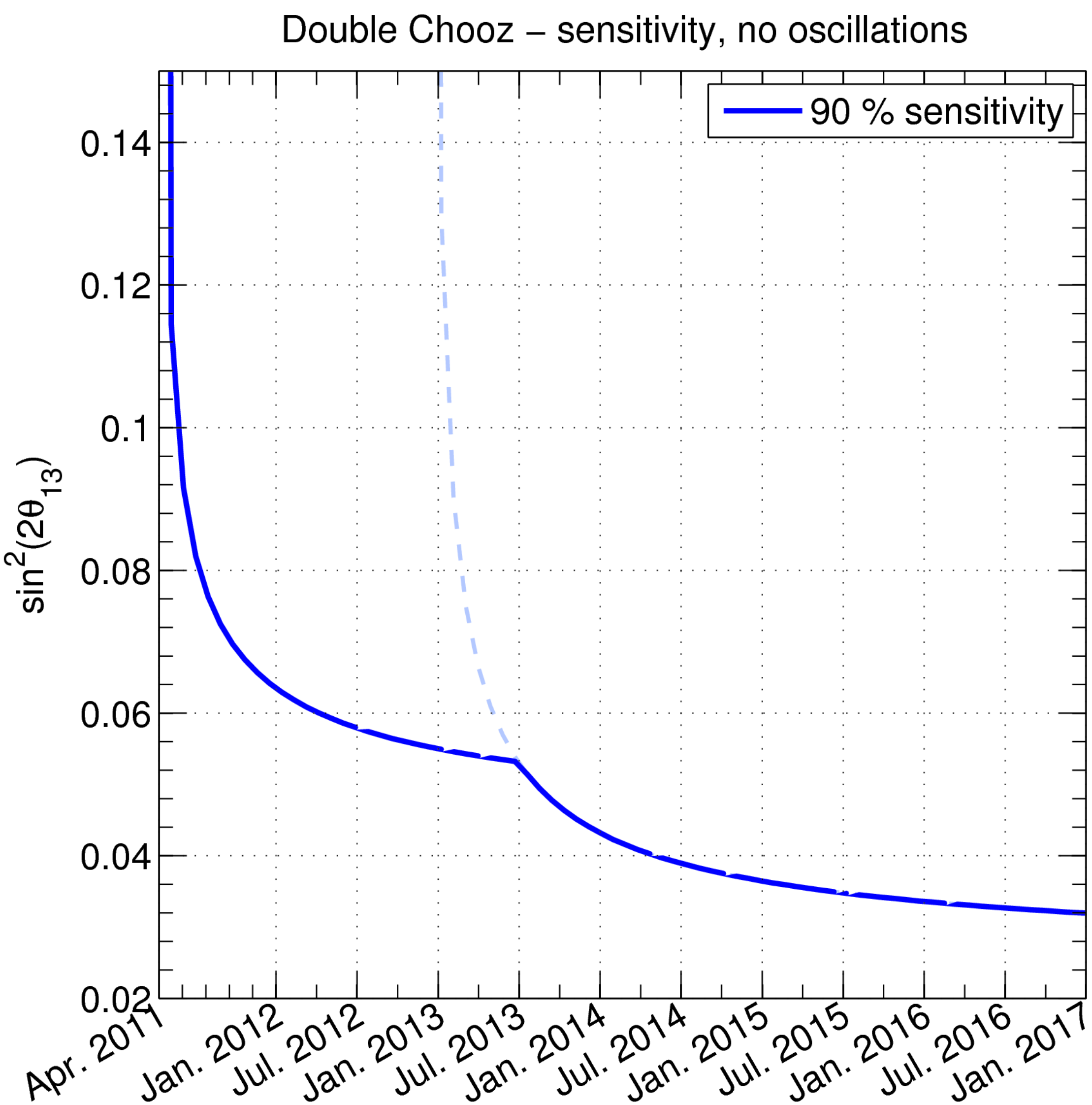


What's next?

Prospects

- First Double Chooz results can be improved by a better **understanding** of the **^{9}Li background** and the **detector**
- Analyzed more data and take advantage of one reactor OFF and two reactors OFF periods
- Near detector expected in **2013**
  - Relative comparison of both detectors, lower systematic errors

Prospects



Double Chooz – sensitivity, no oscillations
90 % sensitivity
$\sin^2(2\theta_{13})$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
Apr. 2011
Jan. 2012
Jul. 2012
Jan. 2013
Jul. 2013
Jan. 2014
Jul. 2014
Jan. 2015
Jul. 2015
Jan. 2016
Jul. 2016
Jan. 2017

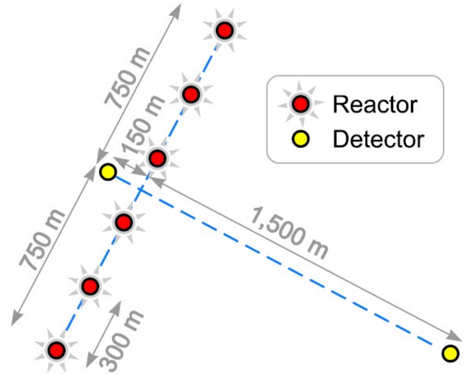
What about the two other reactor neutrino experiments?

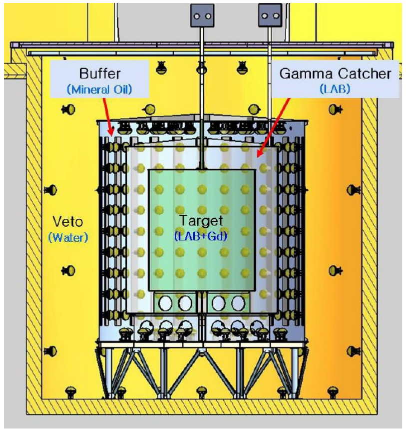
- **Two** 16 tons **identical detectors** close to (290 m and 1,380 m) the **6 x 2.73 GW$_{th}$** YongGwang nuclear plant in **South Korea**
  - > Double Chooz concept

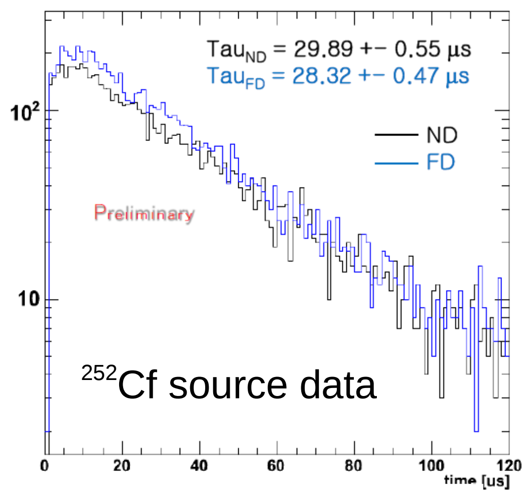
- Both detectors constructed from end of 2009 until July 2011

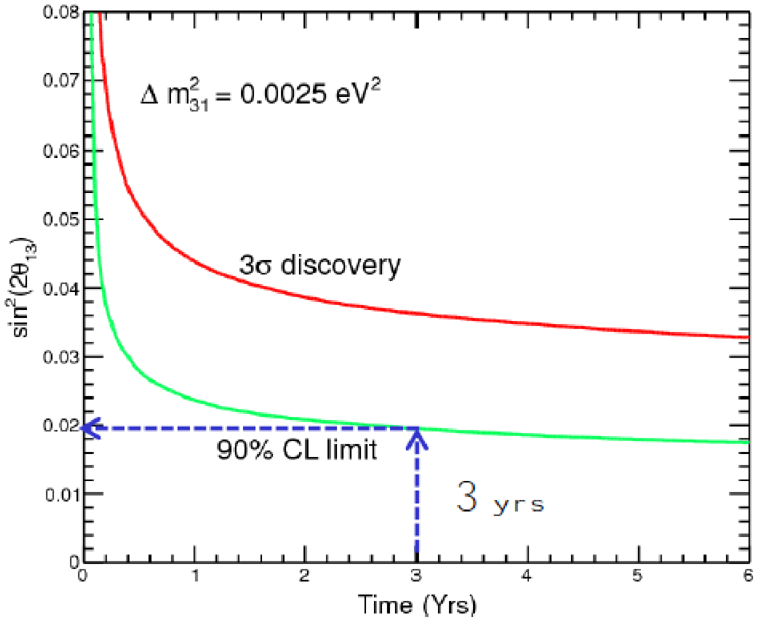
- Commissioning: July 2011

- **Start of data taking: August 1st 2011** (DAQ efficiency > 90 %)







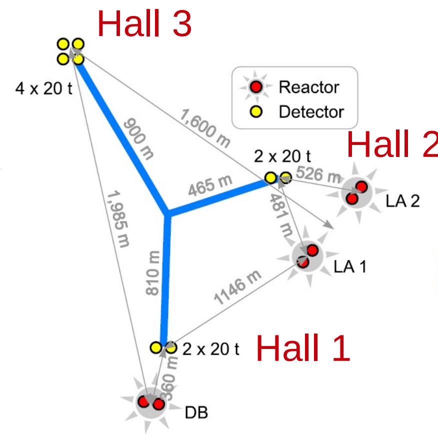


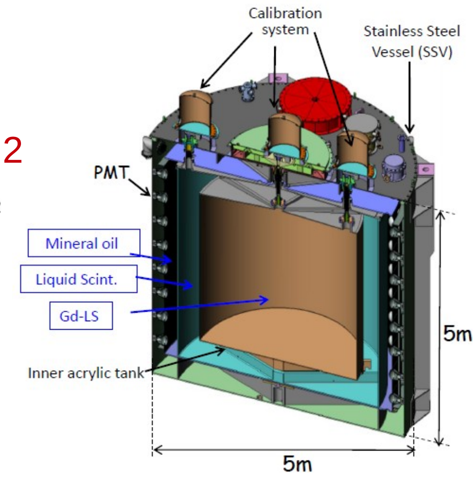
Goal: $\sin^2 2\theta_{13}$ value or new limit available for Neutrino 2012 @ Kyoto, June 2012

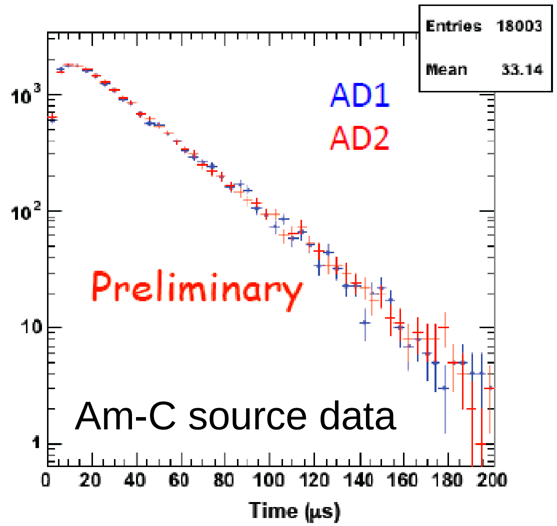
Discovery potential: $\sin^2 2\theta_{13} \sim 0.05$ for March 2012

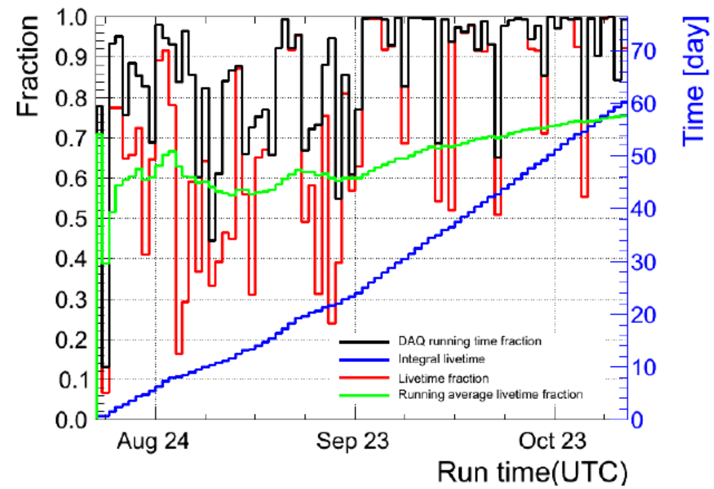
Info from LowNu Conference Talks (Nov. 2011, Seoul)

- **Eight** 20 tons **identical detectors** close to the **6 x 2.9 GW$_{th}$** Shenzen nuclear plant in **China**
  - Two near site with two detectors
  - For at far site
- **Hall 1 takes data since Aug, 2011**
- Hall 2 installation underway
- Hall 3 soon ready for installation
  - > **4 detectors finished**, #5 and 6 nearly finished, #7 and 8 for Spring 2012
- Full experiment running: **Summer 2012**
- **Expected sensitivity** after 3 years of data taking: **$\sin^2 2\theta_{13} < 0.01$ @ 90 % C.L.**









Thank you very much for your attention!

Any questions?

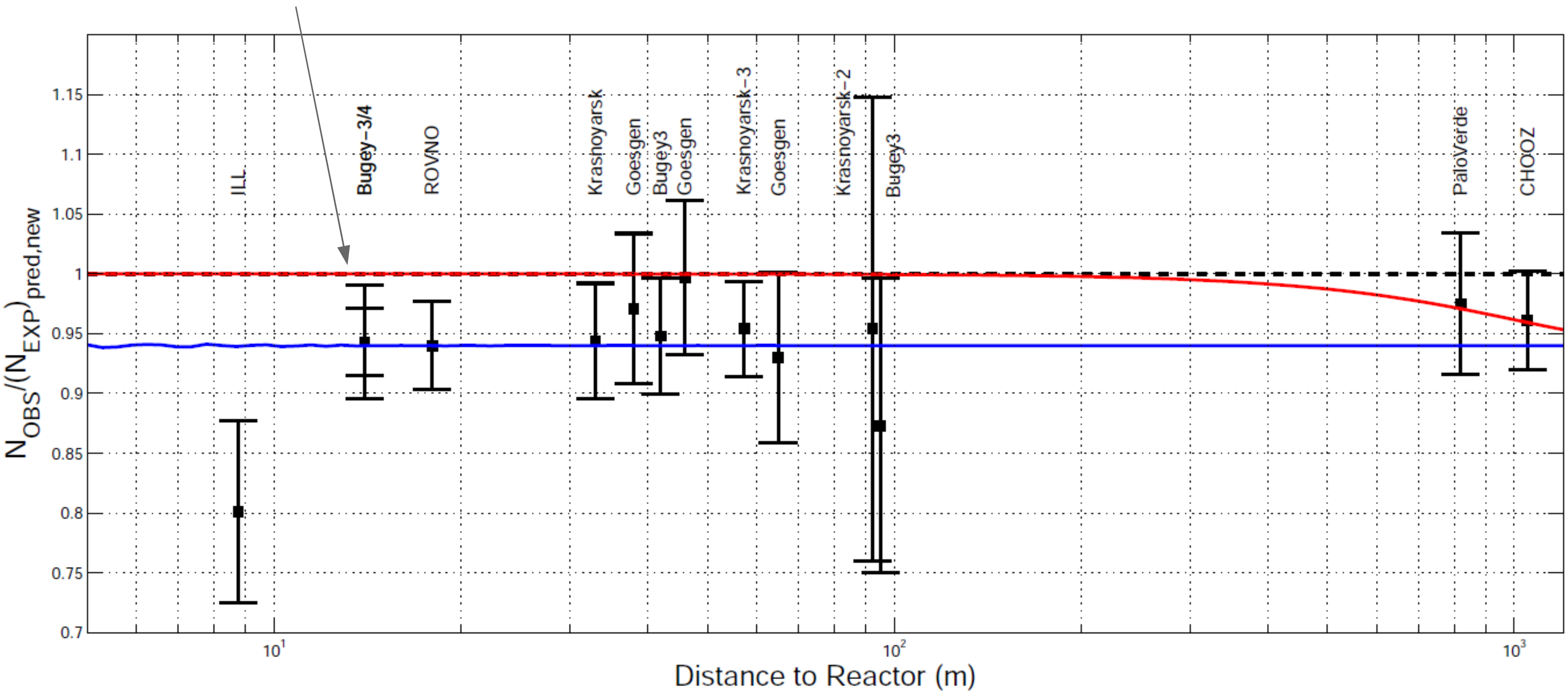
References:

- **CHOOZ final paper**, *Search for neutrino oscillation on a long base-line at the CHOOZ nuclear power station*, M. Apollonio *et al.*, **arXiv:hep-ex/0301017v1 13 Jan 2003**
- **Double Chooz proposal**, *Double Chooz: A Search for the Neutrino Mixing Angle θ13*, F. Ardellier *et al.*, **arXiv:hep-ex/0606025v4 30 Oct 2006**
- **Double Chooz first physics paper**, *Indication of the disappearance of reactor e in the Double Chooz experiment*, Y. Abe *et al.*, **arXiv:hep-ex/1112.6353v1 29 Dec 2011**
- **RENO proposal and TDR**, *RENO: An Experiment for Neutrino Oscillation Parameter θ_{13} Using Reactor Neutrinos at YongGwang*, J. K. Ahn *et al.*, **arXiv:hep-ex/1003.1391v1 6 Mar 2010**
- **Daya Bay proposal**, *A Precision Measurement of the Neutrino Mixing Angle θ_{13} using Reactor Antineutrinos at Daya Bay*, Daya Bay Collaboration, **arXiv:hep-ex/0701029v1 15 Jan 2007**
- **New reactor antineutrino flux,** *Improved Predictions of Reactor Antineutrino Spectra,* Th. A. Mueller *et al.*, **arXiv:hep-ex/1101.2663v1 13 Jan 2011**

Backup slides

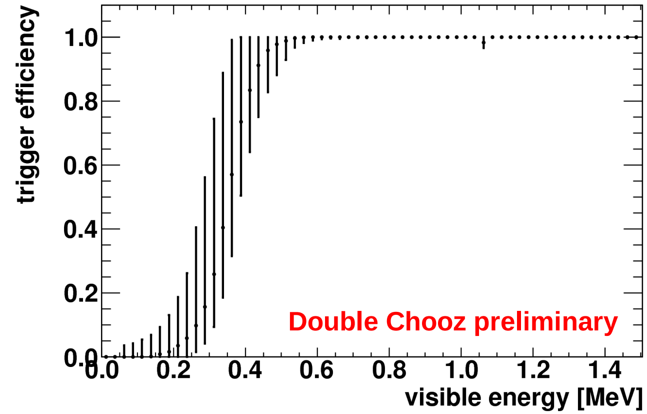
Bugey4 anchor point and reactor ν_e anomaly

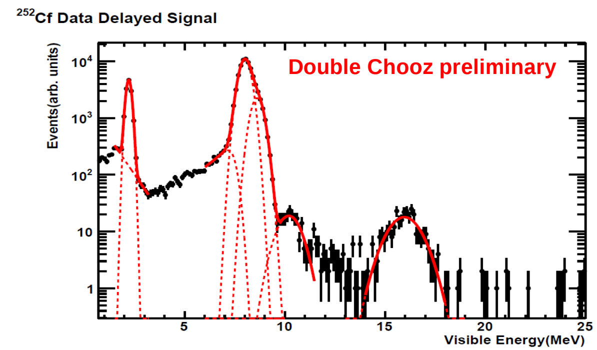
- Possible **short baseline oscillation** (*cf.* Reactor Neutrino Anomaly, G. Mention *et al.*,), Double Chooz phase I normalized to the Bugey4 measurement, and uses the reference electron spectra from ILL irradiation experiment
  - > accounting for differences in core inventories (btw Double Chooz and Bugey4)
  - > taking into account long-lived fission products (off-equilibrium effects)
- Bugey4: most precise measurement of the IBD cross section per fission

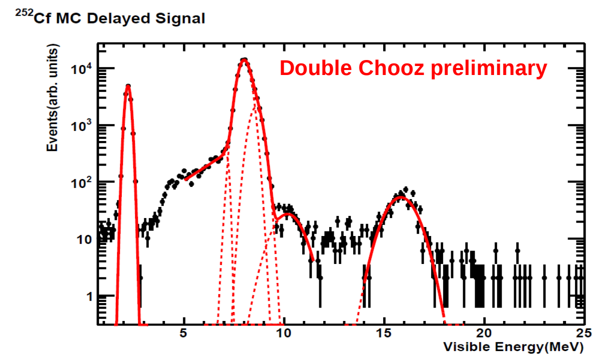


Efficiencies

- **E_{prompt} and trigger efficiency**
  - trigger threshold at 350 keV
  - trigger efficiency: **(100 + 0 – 0.4) %** for E > 700 keV
- **6 MeV cut efficiency**
  - calibration with ^{252}Cf source in ν-target, along the Z-axis
  - computation of GD/(H+Gd) capture rate: (86.0 ± 0.5) %
    - 2 % correction between data and MC
    - **(94.5 ± 0.5) %**
- **ΔT efficiency**
  - Simulation and ^{252}Cf in good agreement
  - **(96.5 ± 0.5) %**







Detector and reactor systematics

Detector (in %)		Reactor (in %)	
Energy response	1.7	Bugey4 measurement	1.4
E_{delay} containement	0.6	Fuel composition	0.9
Gd fraction	0.6	Thermal power	0.5
ΔT	0.5	Reference spectra	0.5
Spill in/out	0.4	Energy per fission	0.2
Trigger efficiency	0.4	IBD cross section	0.2
Target H	0.3	Baseline	0.2
Total	**2.1**	**Total**	**1.8**