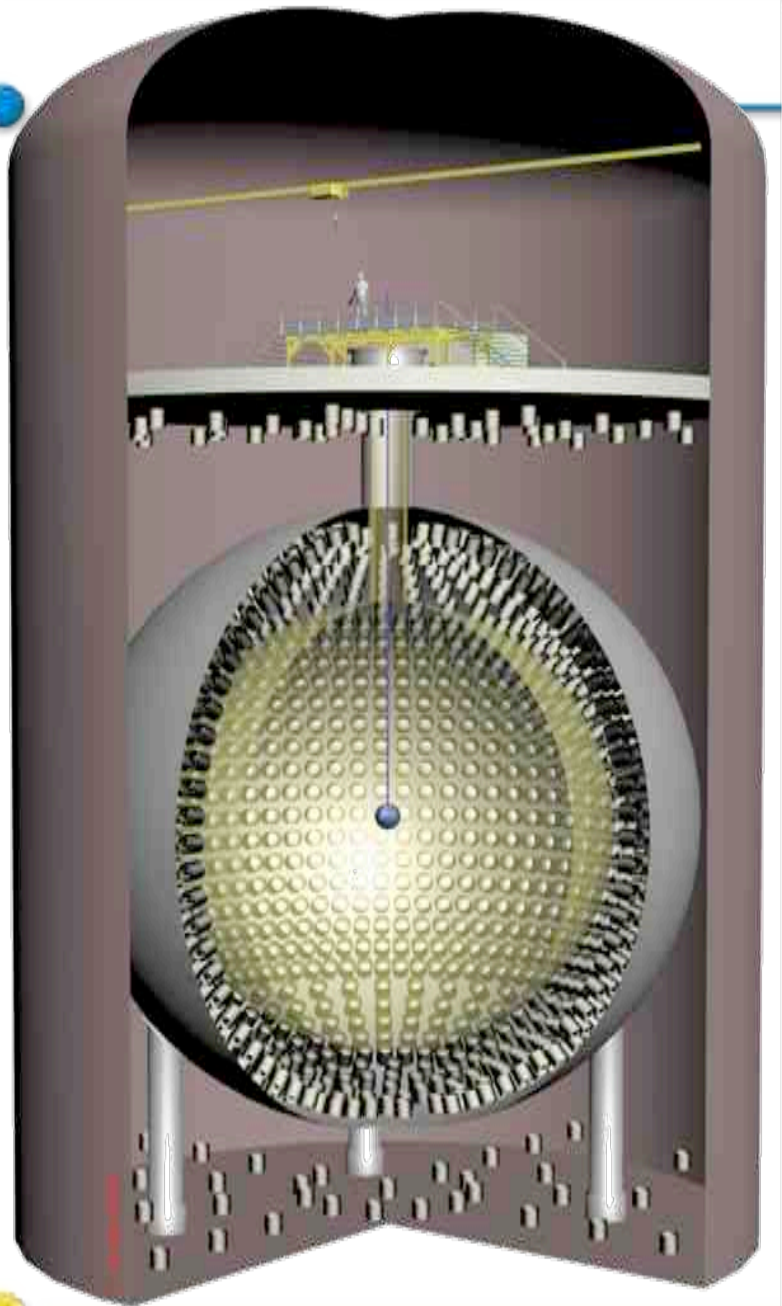


Search for a 4^{th} neutrino (sterile) with an intense antineutrino source at the center of a KamLAND-like detector

Th. Lasserre
(CEA-Saclay, Irfu)

The Reactor Antineutrino Anomaly

G. Mention, M. Fechner, T. Lasserre,*
M. Cribier, Th. Mueller D. Lhuillier, A. Letourneau,

CEA / Irfu

Phys. Rev. D 83, 073006 (2011), arXiv:1101.2755
based on Phys. Rev. C83 054615 (2011)

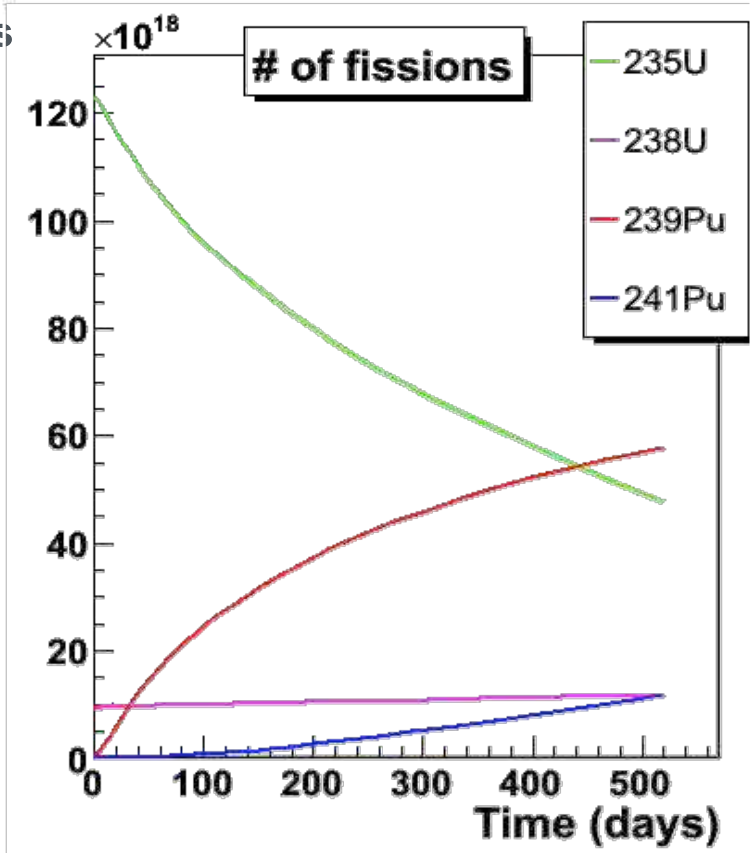
Reactor Neutrino Overview

- **Electron antineutrinos emitted through Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**

- **Nuclear reactors** : $1\ \mathrm{GW_{th}} \Leftrightarrow 2\ 10^{20}\ \bar{\nu}/\mathrm{s}$

- **Neutrino Luminosity** : $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$

  γ: reactor constant
  k : fuel evolution correction up to 10%



- **Common Detection Principle**
  - Inverse Beta-Decay reaction ($\sigma_{\text{V-A}}$)

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

  - Threshold 1.8 MeV. E_ν extend to 10 MeV

- **Measure anti-ν_e of interaction rate**

$$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\mathrm{th}}}{\langle E_f\rangle}N_p\varepsilon\sigma_f \longrightarrow \sigma_f^{\text{meas.}} = \frac{4\pi R^2 n_\nu^{\text{meas.}}}{N_p\varepsilon}\frac{\langle E_f\rangle}{P_{\mathrm{th}}}$$

$$\updownarrow$$

- Comparison of σ_f to prediction

$$\sigma_f^{\text{pred.}} = \int_0^\infty \phi_f^{\text{pred.}}(E_\nu)\sigma_{\text{V-A}}(E_\nu)\mathrm{d}E_\nu$$

New Reactor Antineutrino Spectra

- **Accurate e^- measurements, ILL reactor (1980-89):**
  - Irradiation of ^{235}U, ^{239}Pu, ^{241}Pu foils in intense n_{th} flux from the ILL core
  - High resolution magn. spectrometer, normalization uncertainty of 1.8%

- **Thousands of β-branches involved…**

- **From electron to neutrino spectra: need a conversion**

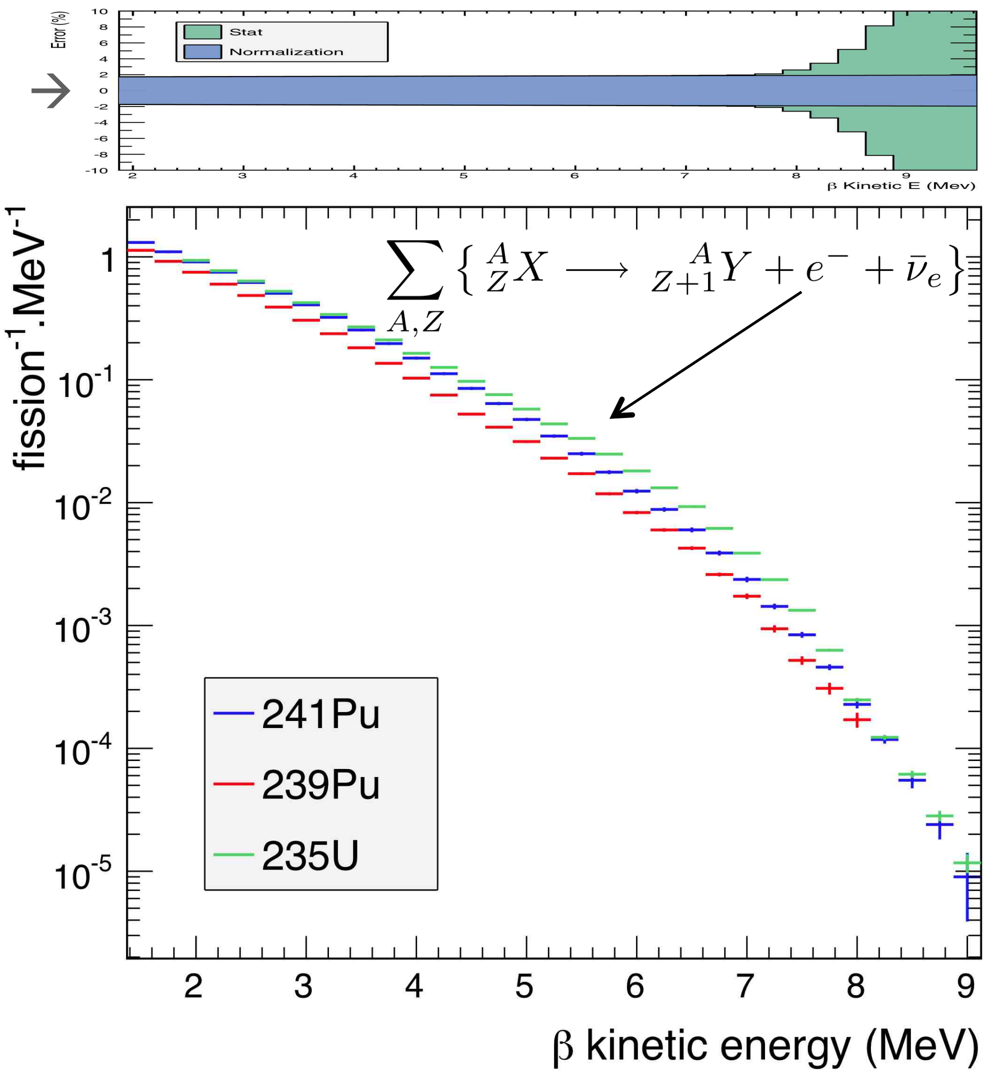
  - **Old Method:**
    - Fit integral e^- spectrum with a sum of 30 effective β-branches
    - Conversion of the effective branches to ν spectra
    - Effective correction on the ν-spectra ($A_{C,W}$)

  - **New Method (Phys. Rev. C83, 054615, 2011)**
    - Conversion with "true" distribution of β-branches reproducing >90% of ILL e^- data + five effective branches to the remaining 10%
    - **Net 3% upward shift in energy-averaged neutrino fluxes with respect to old ν-spectrum for ^{235}U, ^{239}Pu, ^{241}Pu**
    - Confirmed by an independent study: Phys. Rev. C 84, 024617 (2011)

The ILL electron Data Anchorage

Unique reference to be met by any other measurement or calculation

uncertainty →



- Accurate e⁻ measurements @ ILL' (1980-89):
  - High resolution magn. spectrometer
  - Intense and pure thermal n spectrum from the core
  - Extensive use of reference internal conversion electron lines → Normalization (1.8%)

Computing the expected rate/spectrum

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

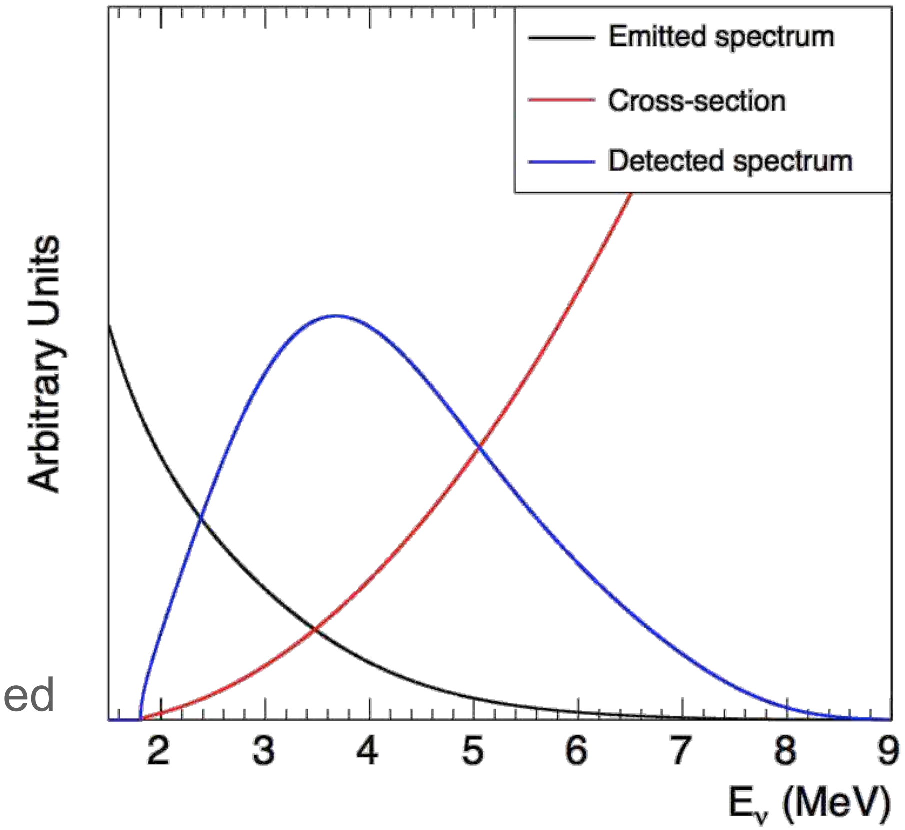
- **Inverse Beta Decay:** $\bar{\nu}_e + p \rightarrow e^+ + n$

- **V-A cross section**

$$\sigma_{\mathrm{V-A}}(E_e) = \kappa\, p_e E_e (1 + \delta_{rec} + \delta_{wm} + \delta_{rad})$$

- **The pre-factor κ ($cm^2\ MeV^{-2}$)**

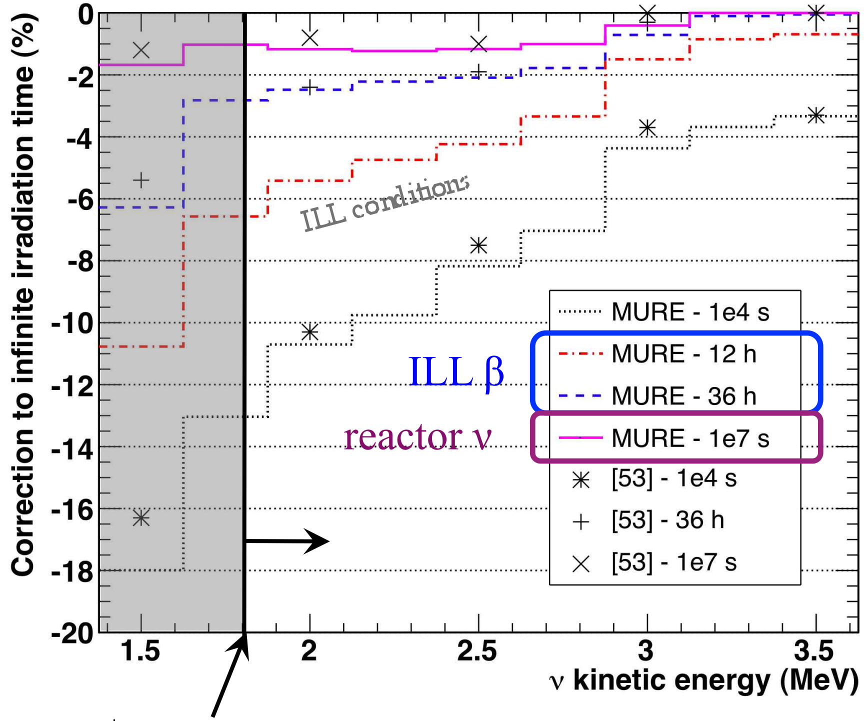
- *Can* be related to neutron life time
- PDG 2010 τ_n : κ = 0.956 10^{-42}
- Evolution in 2011 κ=0.961 10^{-42}
  <τ_n> revision +0.5% → not yet included



Off-Equilibrium Effects

- **10% of fission products have a β-decay life-time long enough to keep accumulating after several days**
  - ILL electron reference spectra : 12 hours to 1.8 days irradiation time
  - Neutrino reactor experiments irradiation time >> months

- **Correction included by default in our new reference model**
- Not included before CHOOZ
- Relative change of ν-spectrum w.r.t. infinite irradiation time



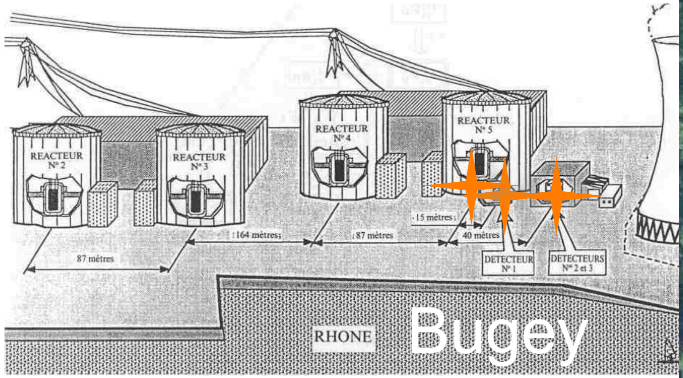
$\bar{\nu}_e + p \longrightarrow e^+ + n$ reaction threshold

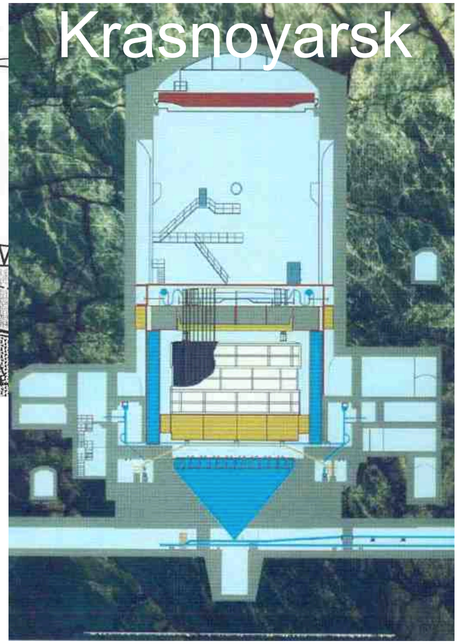
The New Cross Section Per Fission

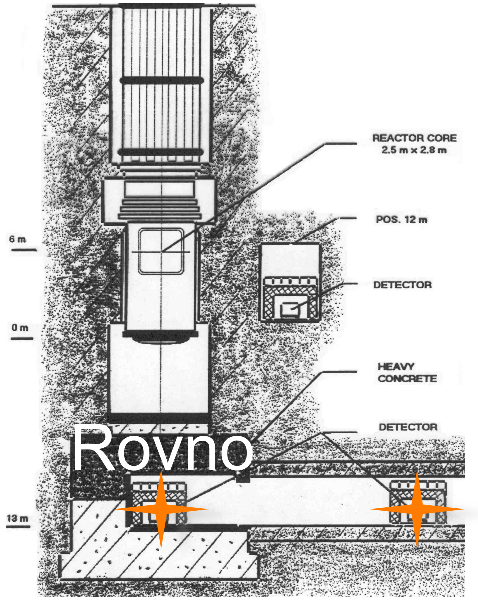
- ν-flux: ^{235}U +2.5%, ^{239}Pu +3.1%, ^{241}Pu +3.7%, ^{238}U +9.8% (σ_f^{pred} ↗)
- Off-equilibrium corrections included (σ_f^{pred} ↗)
- Neutron lifetime decrease by a few % (σ_f^{pred} ↗) $\sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n$
- Negligible evolution of the phase space factor (σ_f^{pred} →)
- Negligible evolution of the energy per fission per isotope (σ_f^{pred} →)
- Burnup dependence: $\sigma_f^{pred} = \sum_k f_k \sigma_{f,k}^{pred}$ (σ_f^{pred} →)
- New Results:

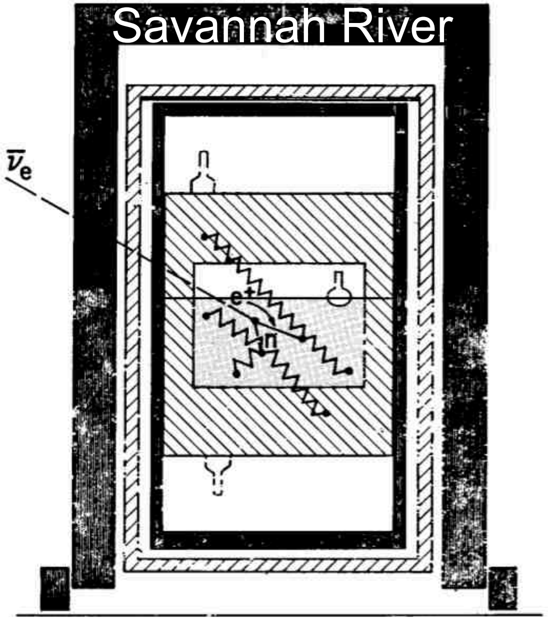
	old [3]	new	new/old
$\sigma_{f,^{235}U}^{pred}$	6.39±1.9%	6.61±2.11%	+3.4%
$\sigma_{f,^{239}Pu}^{pred}$	4.19±2.4%	4.34±2.45%	+3.6%
$\sigma_{f,^{238}U}^{pred}$	9.21±10%	10.10±8.15%	+9.6%
$\sigma_{f,^{241}Pu}^{pred}$	5.73±2.1%	5.97±2.15%	+4.2%

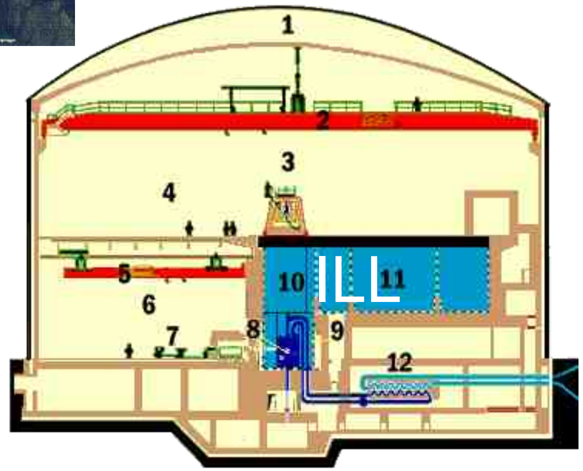
19 Experimental Results below 100m











Measured cross sections are taken at their face values

19 Experimental Results Revisited (L<100m)

Technology Baseline

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He+H_2O	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	^{3}He+H_2O	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	0.946	4.8	4.8	15
4	Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
5	Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.876	14.1	4.8	95
6	Goesgen-I	^{3}He+LS	897	0.620	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	0.992	6.5	6.0	45
8	Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.925	7.6	6.0	65
9	ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.802	9.5	6.0	9
10	Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.936	5.8	4.9	33
11	Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.953	20.3	4.9	92
12	Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.947	4.9	4.9	57
13	SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.952	3.7	3.7	18
14	SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.018	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
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18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.2	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

19 Experimental Results Revisited (L<100m)

Neutron lifetime, normalized to 885.7 s in our study (PDG2010)

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Averaged Fuel Composition

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OBSERVED/PREDICTED ratios: OLD & NEW (this work)

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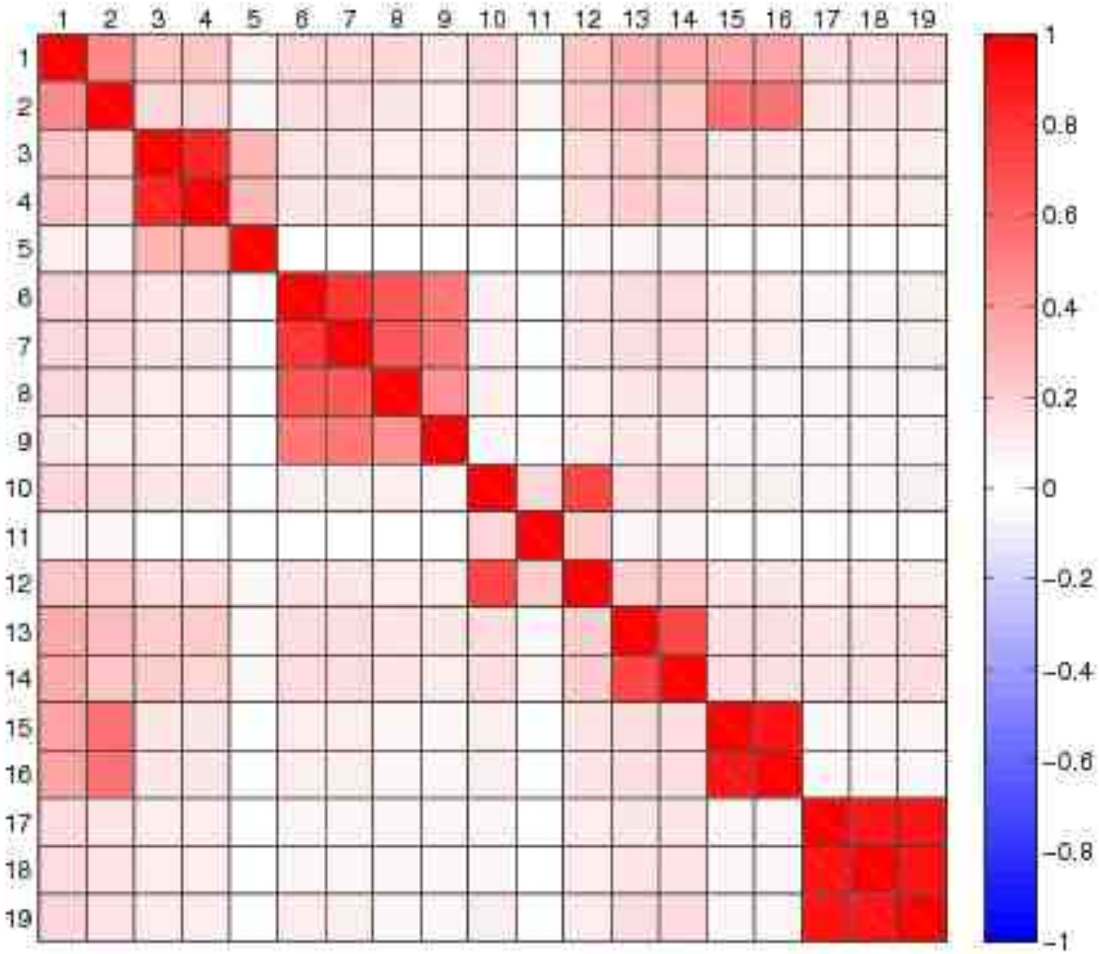
Experiments correlation matrix

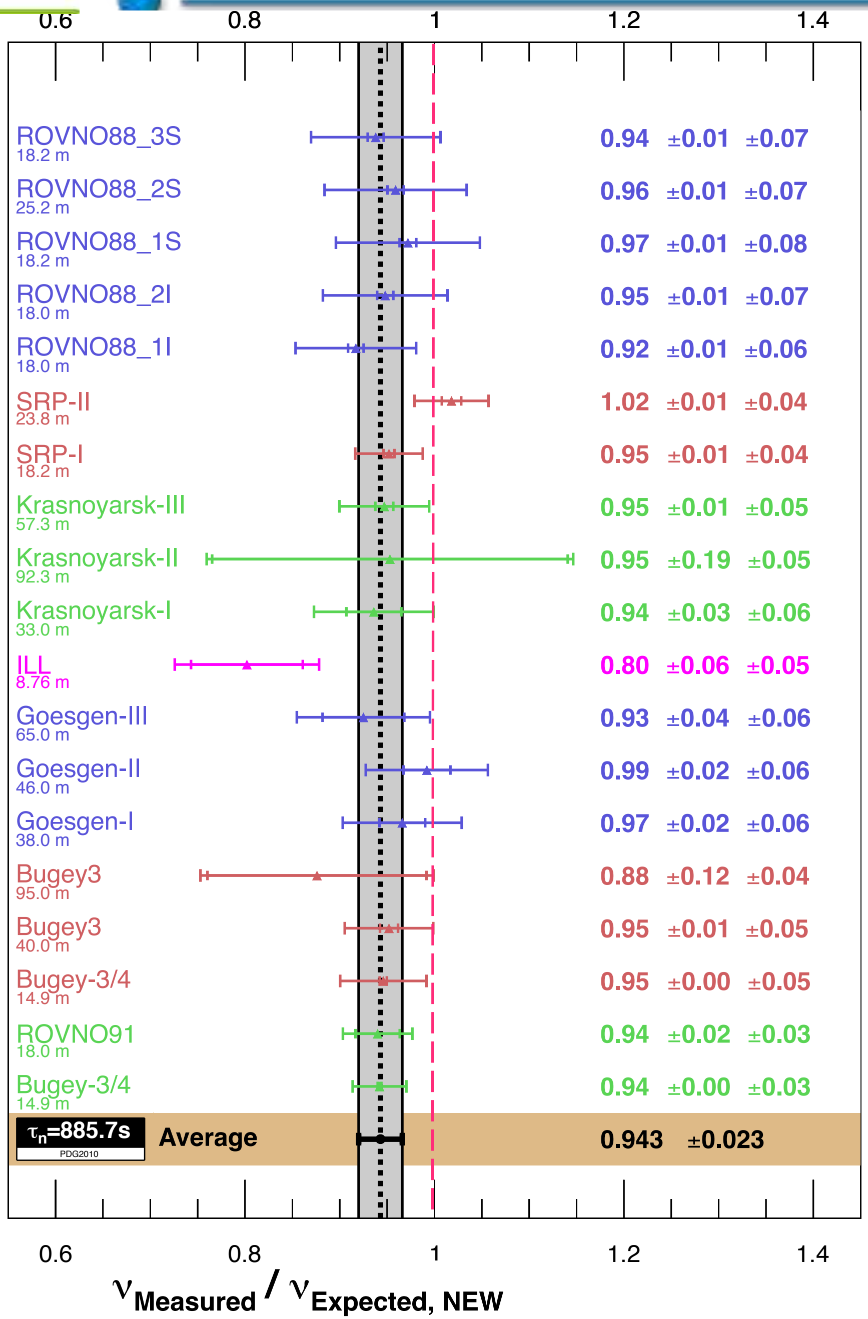
$\vec{R}$	$\Sigma_{tot.}$ (in %)	$\Sigma_{cor.}$ (in %)
▪ Bugey-4 15m	3.0	3.0
▪ Rovno91 18m	3.9	3.0
▪ Bugey-3 15m	5.0	5.0
▪ Bugey-3 40m	5.1	5.0
▪ Bugey-3 92m	14.1	5.0
▪ Goesgen 38m	6.5	6.0
▪ Goesgen 45m	7.6	6.0
▪ Goesgen 65m	9.5	6.0
▪ ILL 9m	5.1	4.1
▪ Krasno 33m	5.1	4.1
▪ Krasno 92m	20.3	4.1
▪ Krasno 57m	4.1	4.1
▪ SRP I 18m	3.7	3.7
▪ SRP II 25m	3.8	3.7
▪ Rovno88 1I 18m	6.9	6.9
▪ Rovno88 2I 18 m	6.9	6.9
▪ Rovno88 1S 18m	7.8	7.2
▪ Rovno88 2S 25m	7.8	7.2
▪ Rovno88 3S 18m	7.2	7.2

C (correlation matrix on Ratios)



- Main pink color comes from the 2% systematic on ILL β-spectra normalization uncertainty
- The experiment block correlations come from identical detector, technology or neutrino source

The reactor antineutrino anomaly



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

- **Best fit for N_{obs}/N_{exp}: μ = 0.943**
- **Uncertainty : 0.023**
- Straight-Line χ^2 = 19.6/19
- **Deviation from unity**
  - Naïve Gaussian : 99.3% C.L.
  - Toy MC: 98.6% C.L. (10^6 trials)
- **No hidden covariance**
  - 18% of Toy MC have χ^2_{min}<19.6

The reactor neutrino anomaly (rate only)

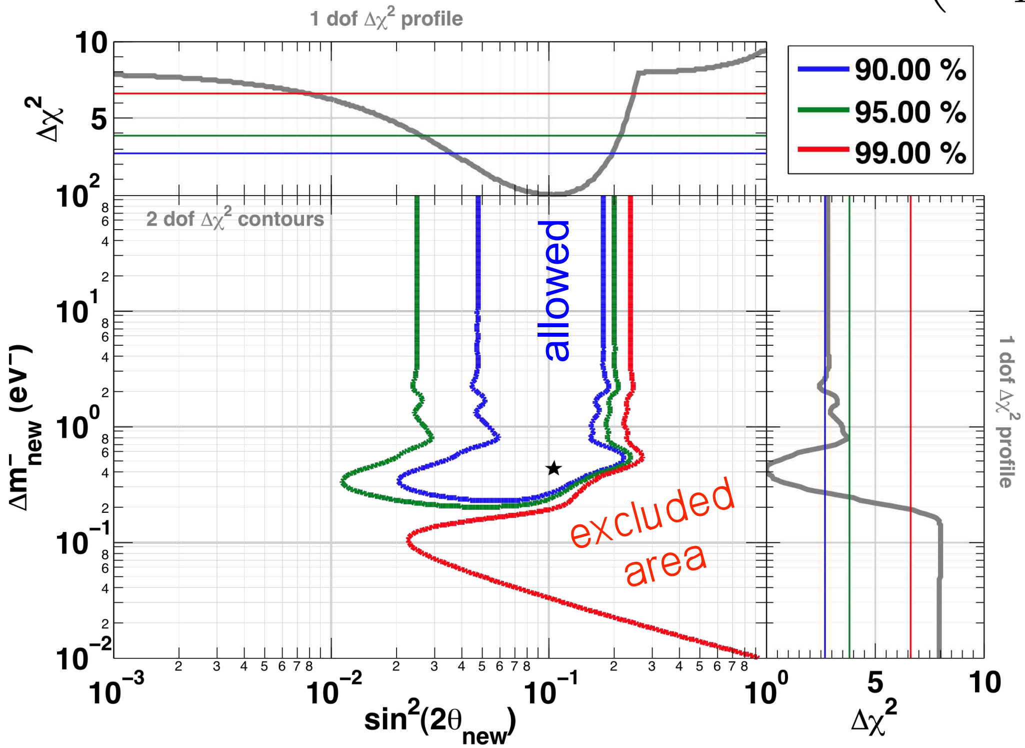
- **18/19 Reactor-SBE : 6% deficit wrt the new prediction (CL: 98.6%)**
  - 3%: Reevaluation of Neutrino Emitted Fluxes
  - 3%: Reevaluation of IDB cross section parameters, neutron lifetime, accounting for off eq. effect
- **Three alternatives:**
  - Improved but still incorrect reactor neutrino flux prediction
  - Bias in **all** short-baseline experiments near reactors …
  - New physics at short baselines
    - **Mixing with a sterile ν : a 4^{th} oscillation mode**
    → new parameters : θ_{new} and Δm^2_{new}

The 4th neutrino hypothesis

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

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

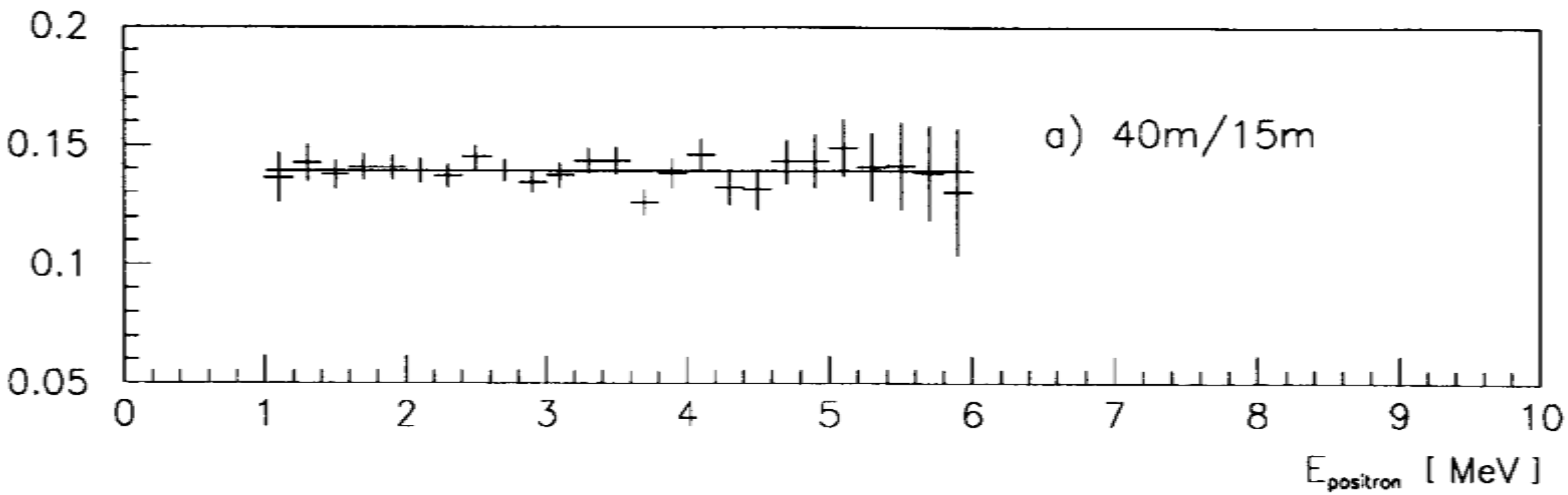
$$P_{\nu_e\to\nu_e}(L,E) = |\langle \nu_e(L)|\, \nu_e(L=0)\rangle|^2 = 1 - \sin^2(2\theta_{\rm new})\sin^2\left(\frac{\Delta m^2_{\rm new} L}{E}\right)$$



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

Spectral shape analysis of Bugey-3

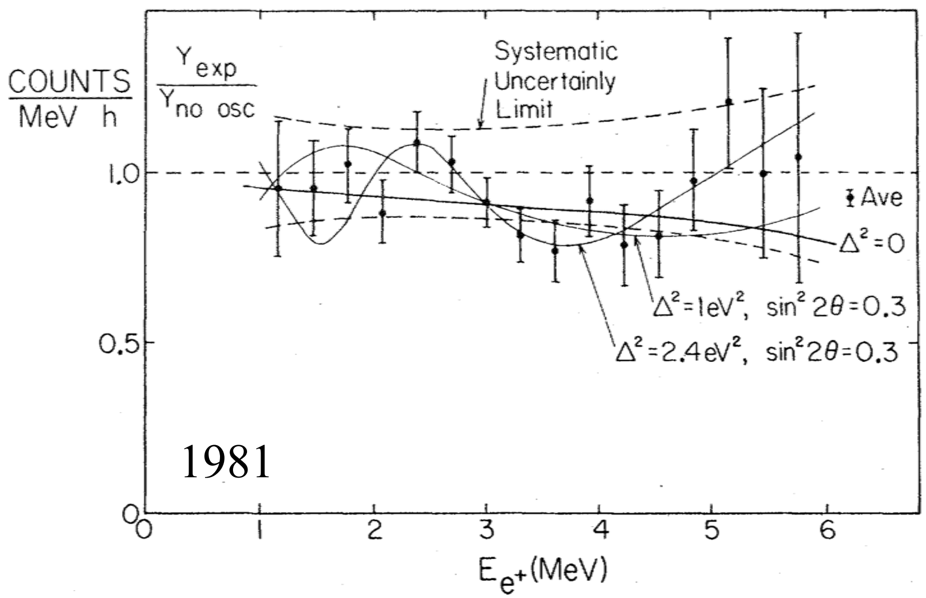
- Bugey-3 spectral measurements at 15 m, 40 m, 90 m
- **No-oscillation results :** robust since it <u>does not rely</u> on reactor spectra
- **Best constraint from high statistics R=15m/40m ratio**



→ **constraint included in our analysis**

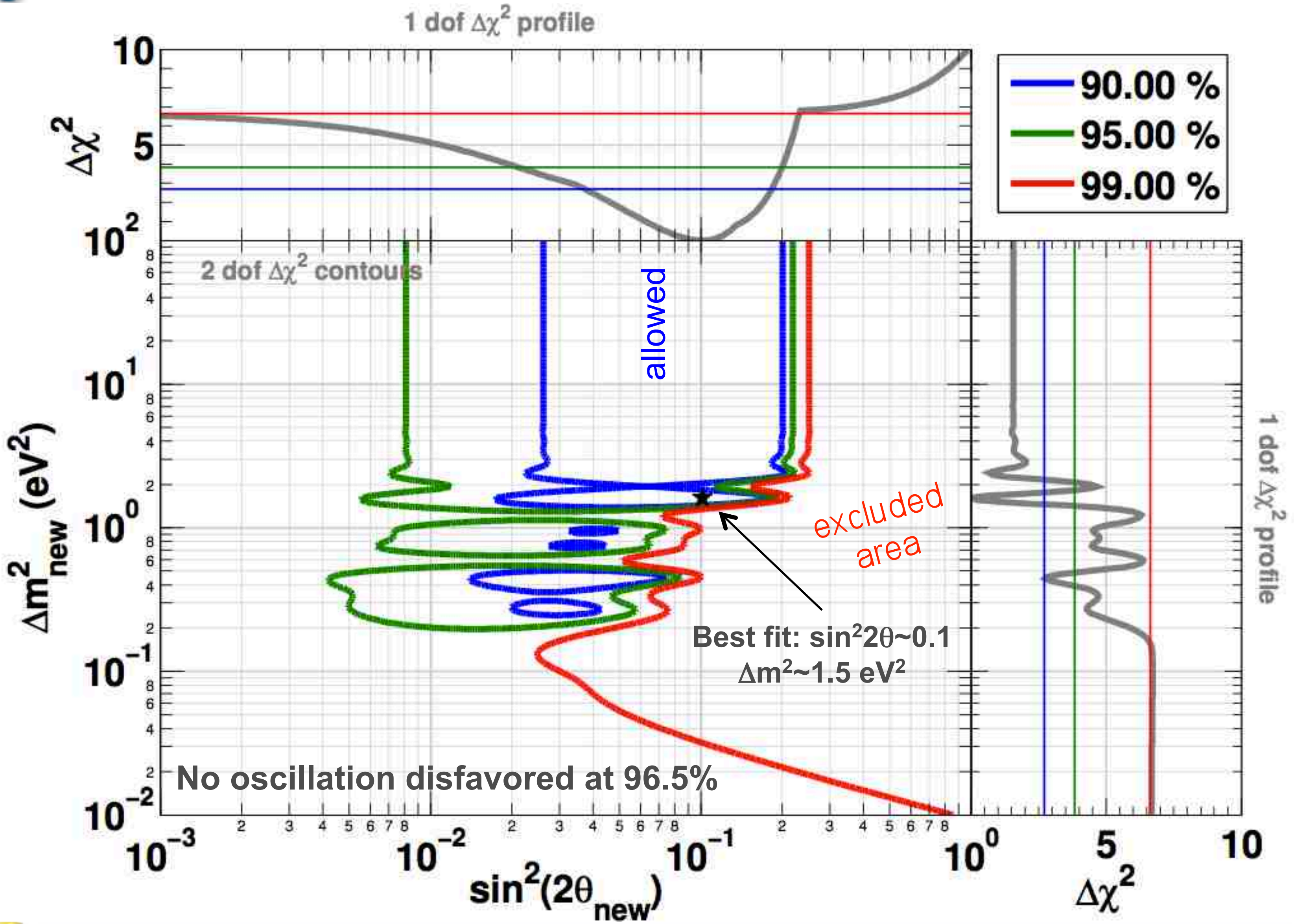
The 1981 ILL neutrino experiment

- Reactor at ILL with **almost pure ^{235}U**, with **compact core**
- Detector **8.76 m** from core (possible bias not excluded)
- Reanalysis in 1995 by part of the collaboration to account for overestimation of flux at ILL reactor by 10%... Affects the rate only



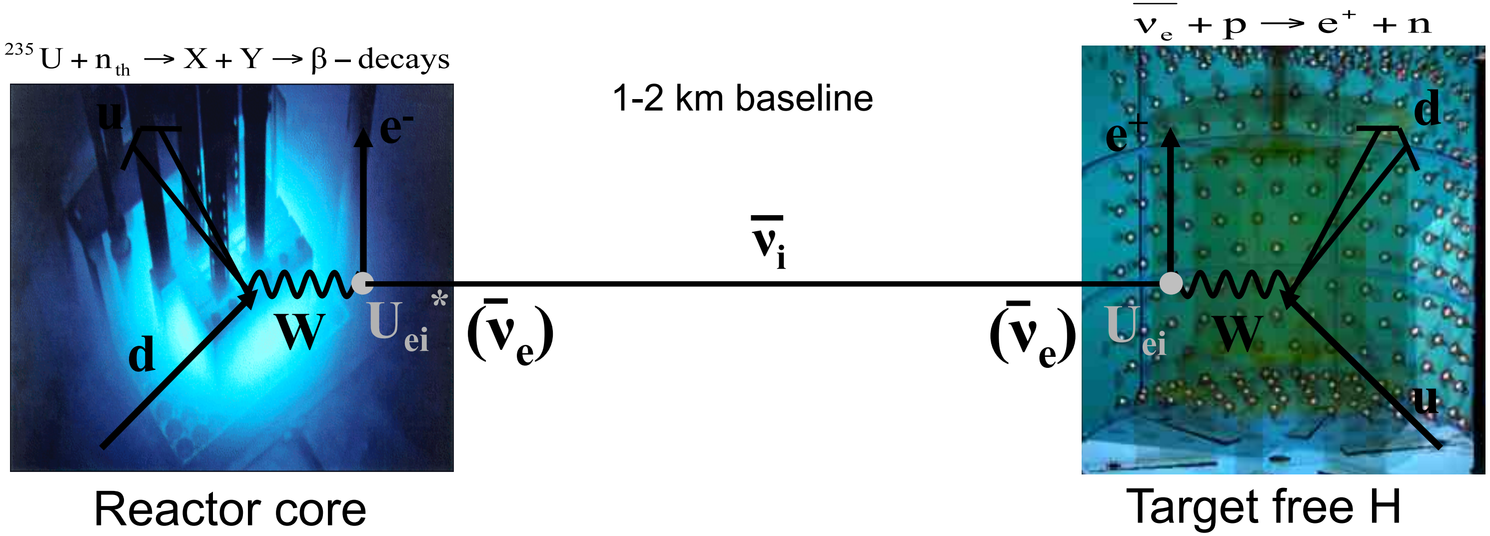
- Large errors, but a striking pattern is seen by eye ?

Combined Reactor Rate+Shape contours



Implication for θ_{13}

Reactor Neutrino Oscillation Physics (θ_{13})



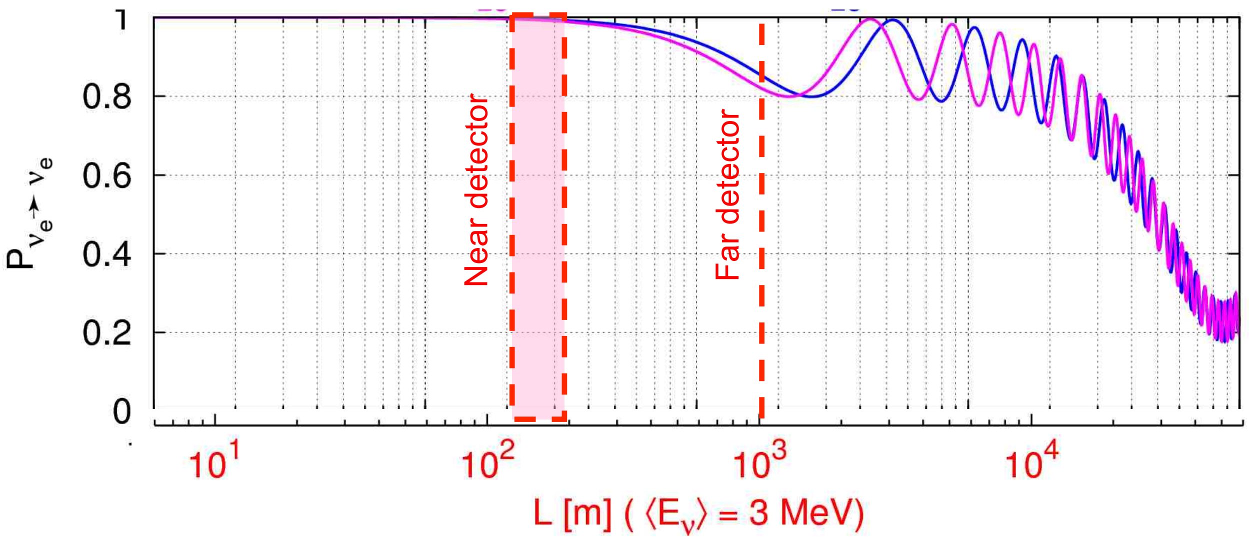
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2(2\theta_{13}) \left[\sin\left(1.27 \frac{\Delta m^2_{atm}\,(eV^2)\,L\,(m)}{E\,(MeV)}\right) + O\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right) \right]$$

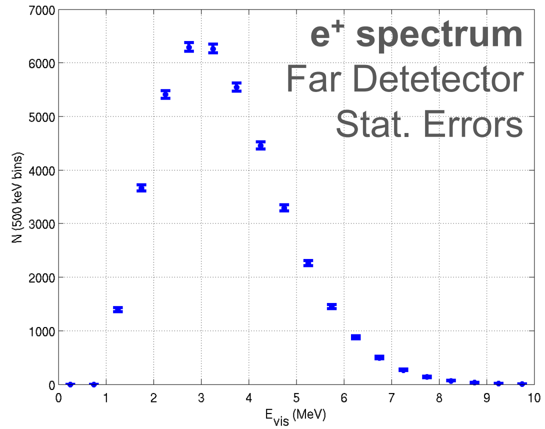
- **Straightforward oscillation formula** : weak dependence on Δm_{sol}^2
- MeV electron antineutrinos : only **disappearance** experiments
- $\sin^2(2\theta_{13})$ measurement **independent of δ-CP**
- $\sin^2(2\theta_{13})$ measurement **independent of sign(Δm^2_{13})**

} **'clean'** information on θ_{13}

The concept from Lev Mikaelyan (Kurchatov, 2000)

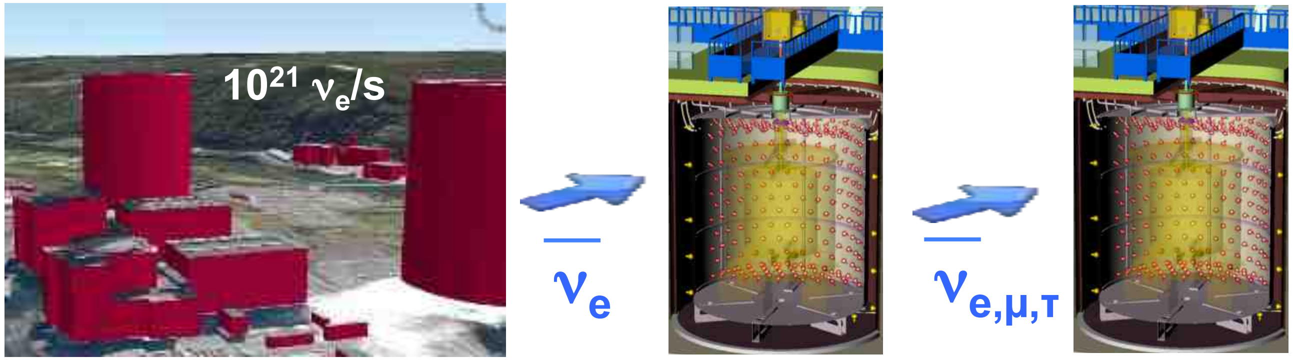
$$P(\nu_e \rightarrow \nu_e) = 1-\sin^2(2\theta_{13})\sin^2(\Delta m^2_{31}L/4E)$$





Δm^2_{atm}= 3.0 10^{-3} eV^2

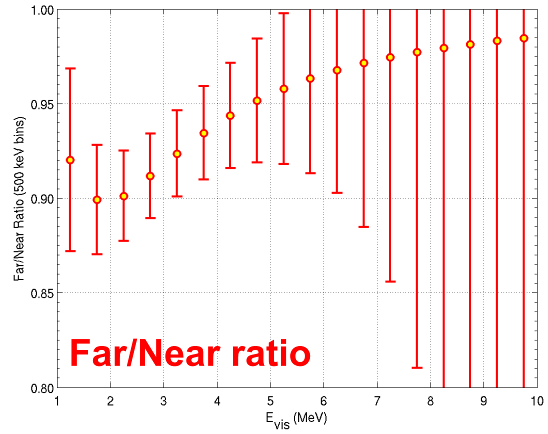
$\sin^2(2\theta_{13})$=0.12

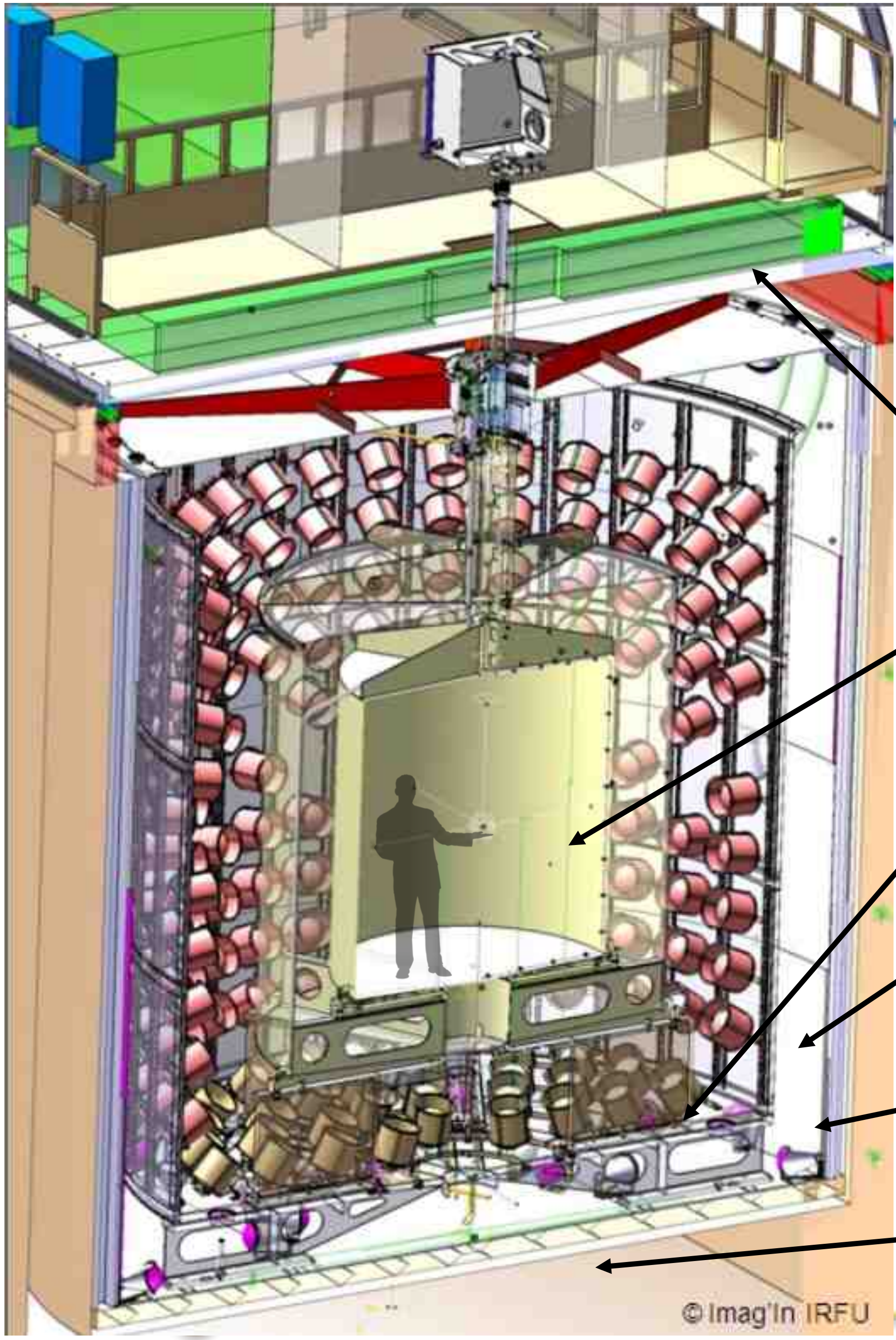


Chooz Nuclear Power Station
2 cores of 4.3 GW_{th} each

Near detector
400 m

Far detector
1050 m





Similar Detector Designs

New 4-region large detector concept from Double Chooz Coll. (2003)

http://bama.ua.edu/~busenitz/rnu2003_talks/lasserre1.doc
http://bama.ua.edu/~busenitz/rnu2003_talks/suekane1.pdf

Outer Veto: plastic scintillator strips (400 mm)

ν-Target: 10,3 m^3 scintillator doped with 1g/l of Gd compound in an acryclic vessel (8 mm)

γ-Catcher: 22,3 m^3 scintillator in an acrylic vessel (12 mm)

Buffer: 110 m^3 of mineral oil in a stainless steel vessel (3 mm) viewed by 390 PMTs

Inner Veto: 90m^3 of scintillator in a steel vessel equipped with 78 PMTs

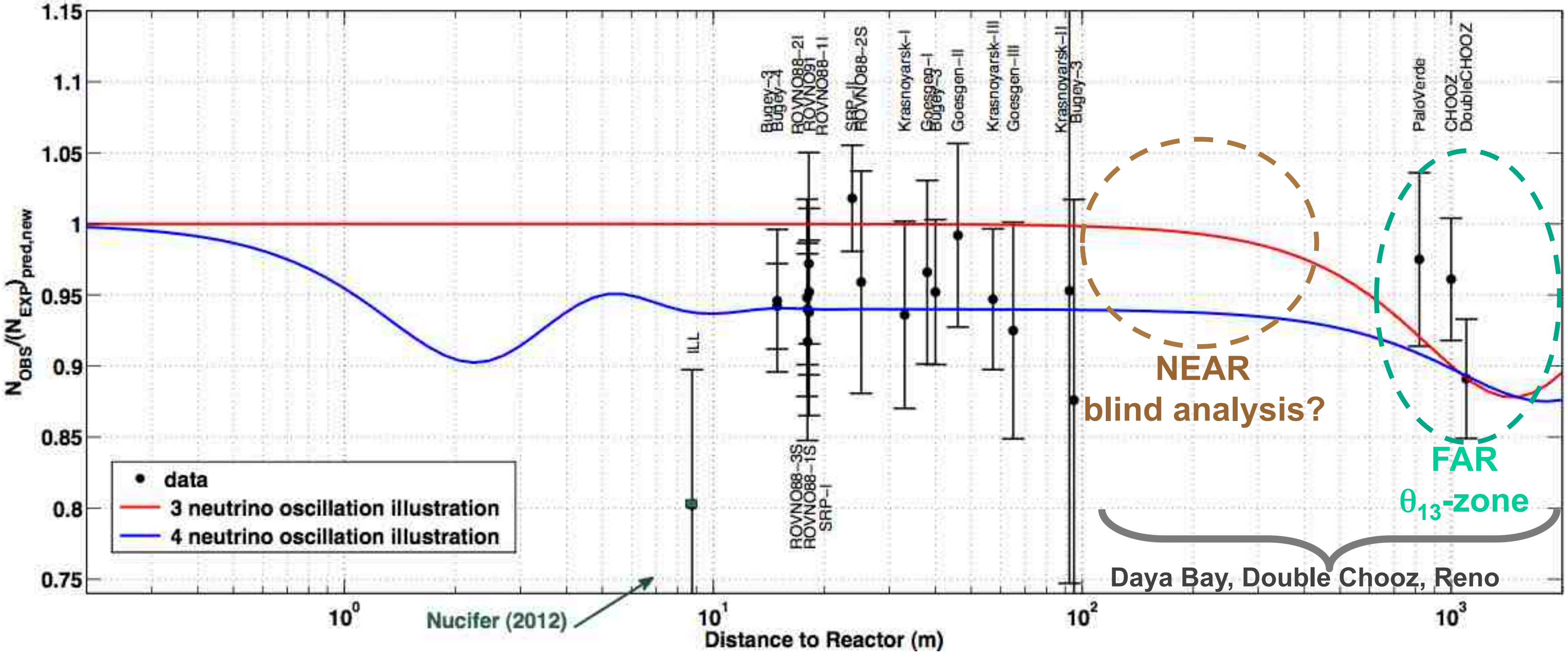
Veto Vessel (10mm) & Steel Shielding (150 mm)

Implication for θ_{13} at 1-2 km baselines

- **The choice of normalization is crucial for reactor experiments looking for θ_{13} <u>without near detector</u>**

  $\sigma_f^{pred,new}$: new prediction of the antineutrino fluxes

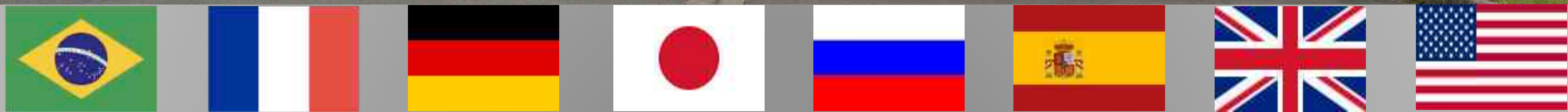
  σ_f^{ano} or σ_f^{bugey} : experimental cross section → CHOOZ & Double Chooz Far



- **A deficit observed at 1-2 km can either be induced by θ_{13} induced oscillation BUT also by other explanations (experimental, biased-ϕ, …)**

Double Chooz Sites (France)

Double Chooz Collaboration



Brazil
CBPF
UNICAMP
UFABC

France
APC
CEA/DSM/IRFU:
SPP
SPhN
SEDI
SIS
SENAC
CNRS/IN2P3:
Subatech & IPHC

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

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

Russia
INR RAS
IPC RAS
RRC
Kurchatov

Spain
CIEMAT-Madrid

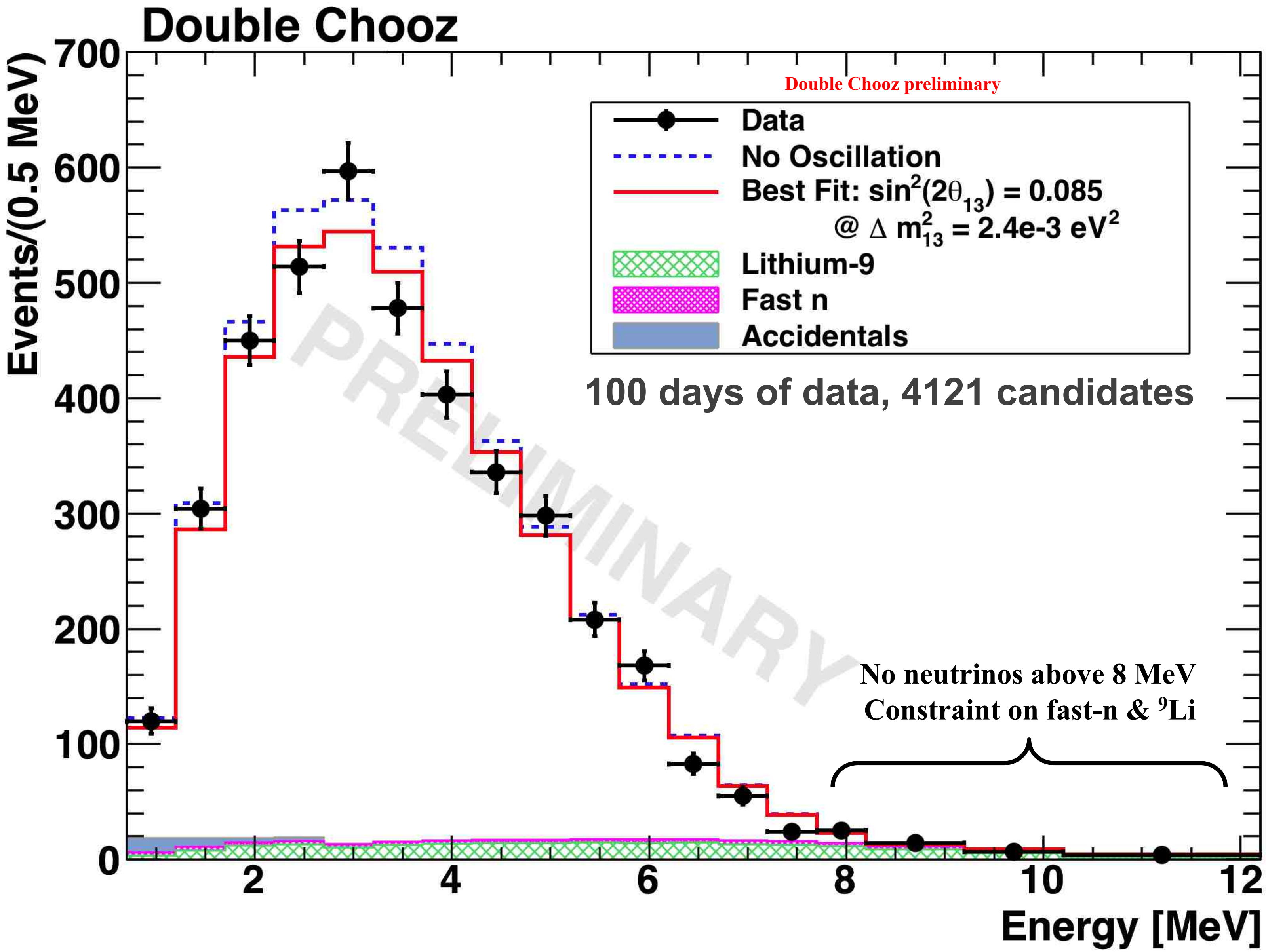
UK
Sussex

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

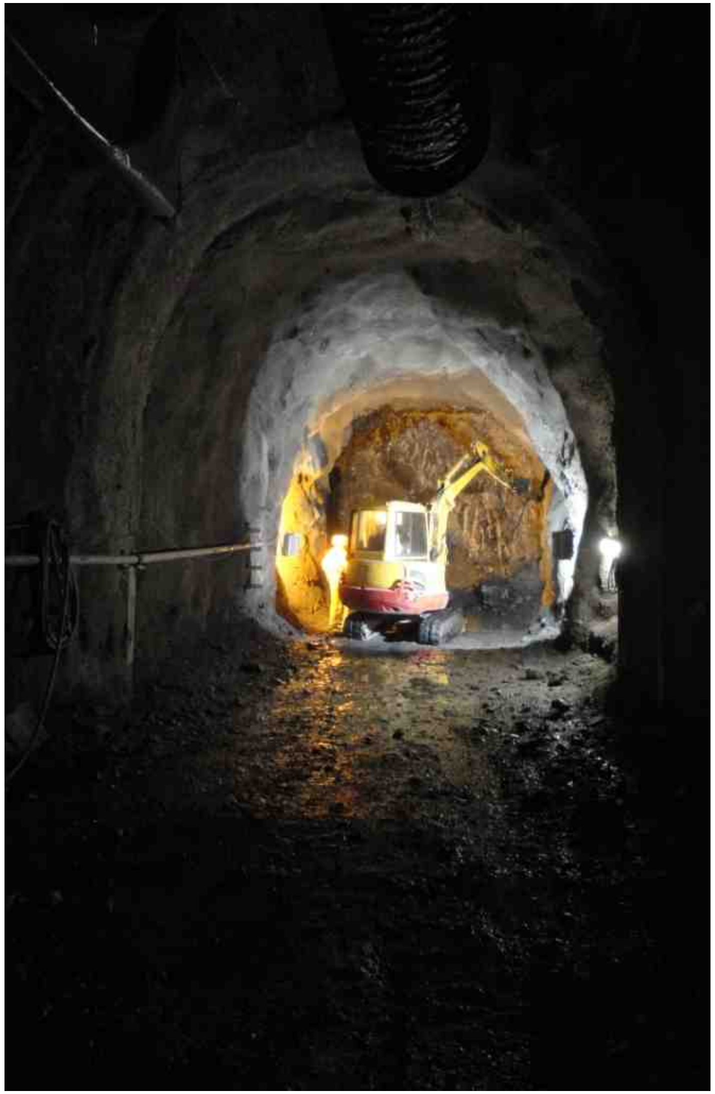
Spokesperson: H. de Kerret (IN2P3)
Project Manager: Ch. Veyssière (CEA-Saclay)
Analysis Coordinator : Th. Lasserre (CEA-Saclay)

Web Site: www.doublechooz.org/

First Double Chooz Results



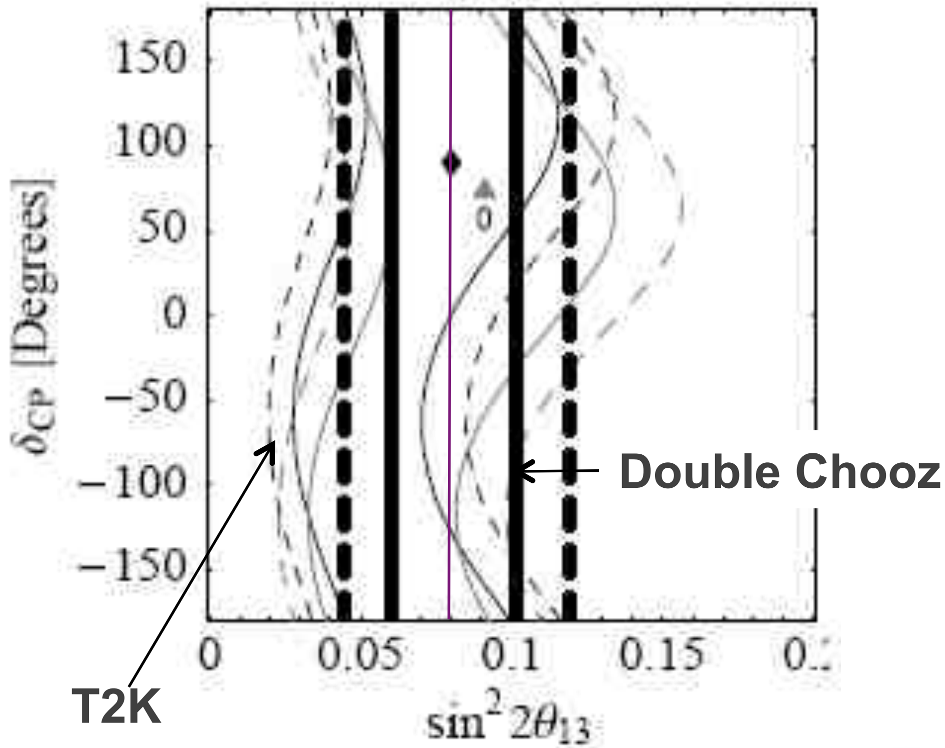
Next: Near Detector at 400 m from 2013



Towards a precise determination of θ_{13}

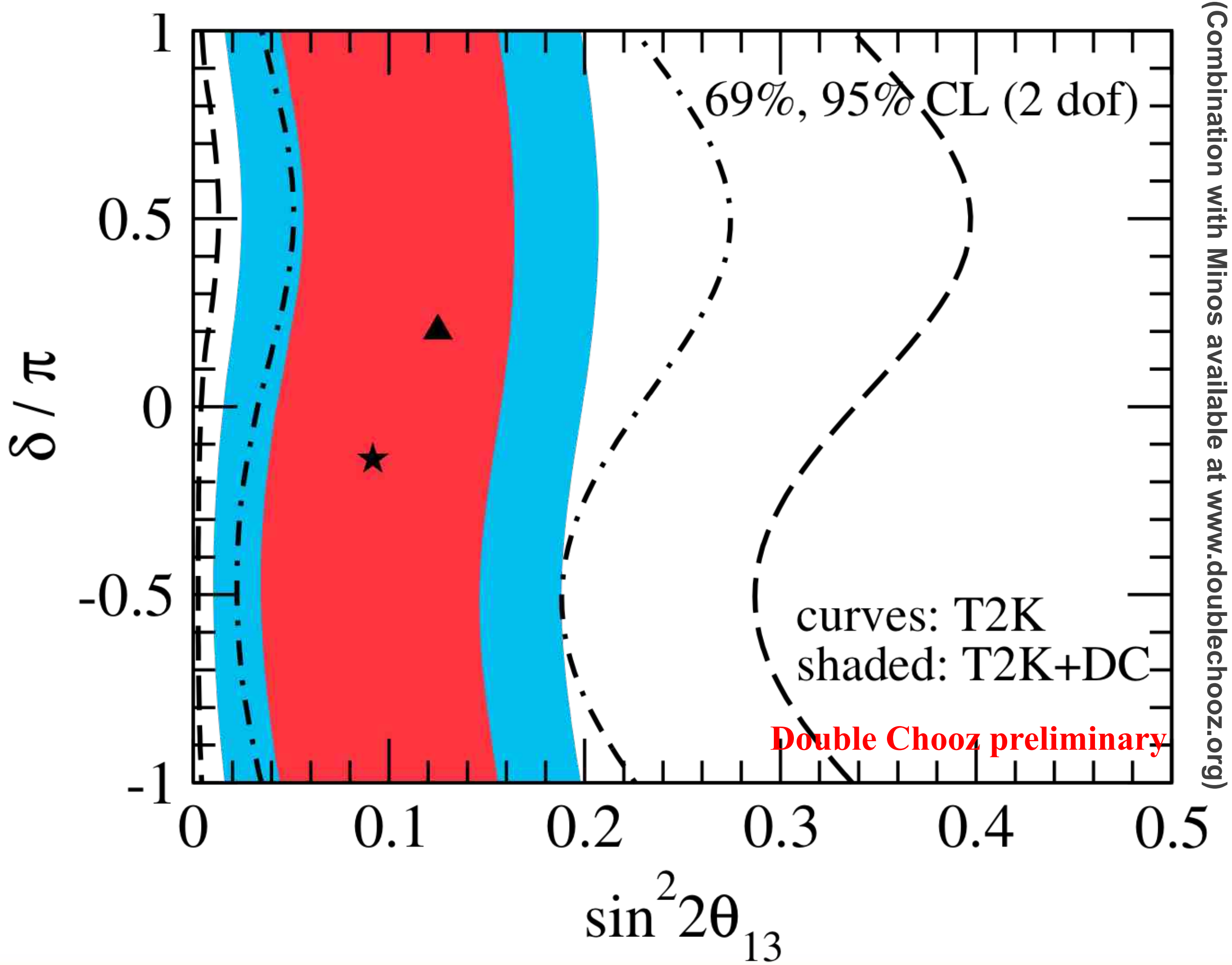
- 2 Reactors (Bkg Measurement)
- Comprehensive Calibration Devices
- Simple Site Configuration

Simulation: $\sin^2 2\theta_{13} = 0.08$



Double Chooz / T2K Synergy

$\theta_{13}>0$ at a 3σ CL



(Combination with Minos available at www.doublechooz.org)

The Gallium Neutrino Anomaly

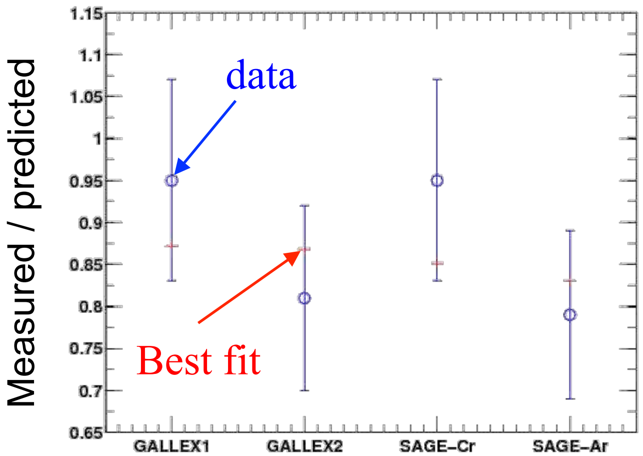
Based on PRD82 053005 (2010)

C. Giunti & M. Laveder

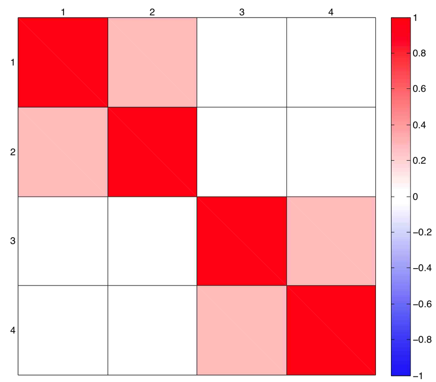
The Gallium anomaly

- **4 calibration runs with intense MCi neutrino sources:**
  - 2 runs at Gallex with a ^{51}Cr source (750 keV ν_e emitter)
  - 1 run at SAGE with a ^{51}Cr source
  - 1 run at SAGE with a ^{37}Ar source (810 keV ν_e emitter)
  - **All observed a deficit of neutrino interactions compared to the expected activity. Hint of mixing with sterile neutrino?**

- **Our analysis for Gallex & Sage:**
  - Monte Carlo computing mean path lengths of neutrinos in Gallium tanks
  - **NEW** : Correlate the 2 Gallex runs together & the 2 SAGE runs together



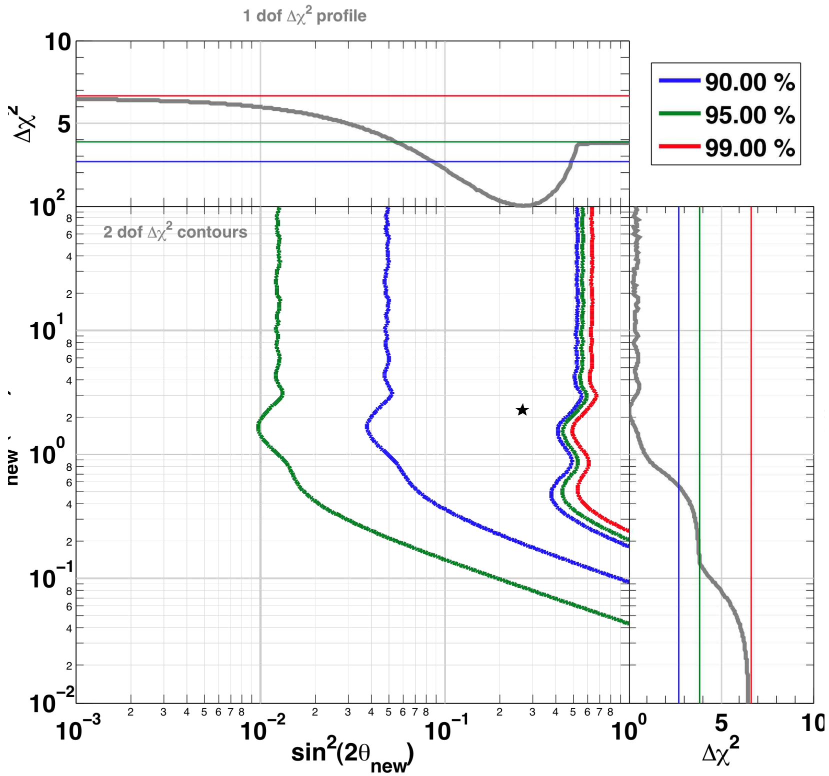
- Gallex-I
- Gallex-II
- Sage-Cr
- Sage-Ar

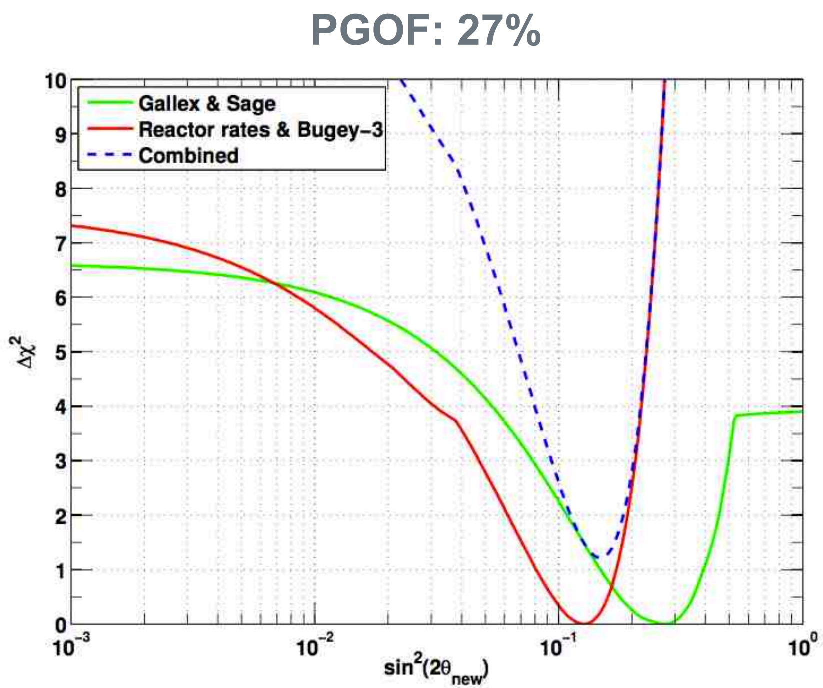


correlation matrix

The Gallium anomaly

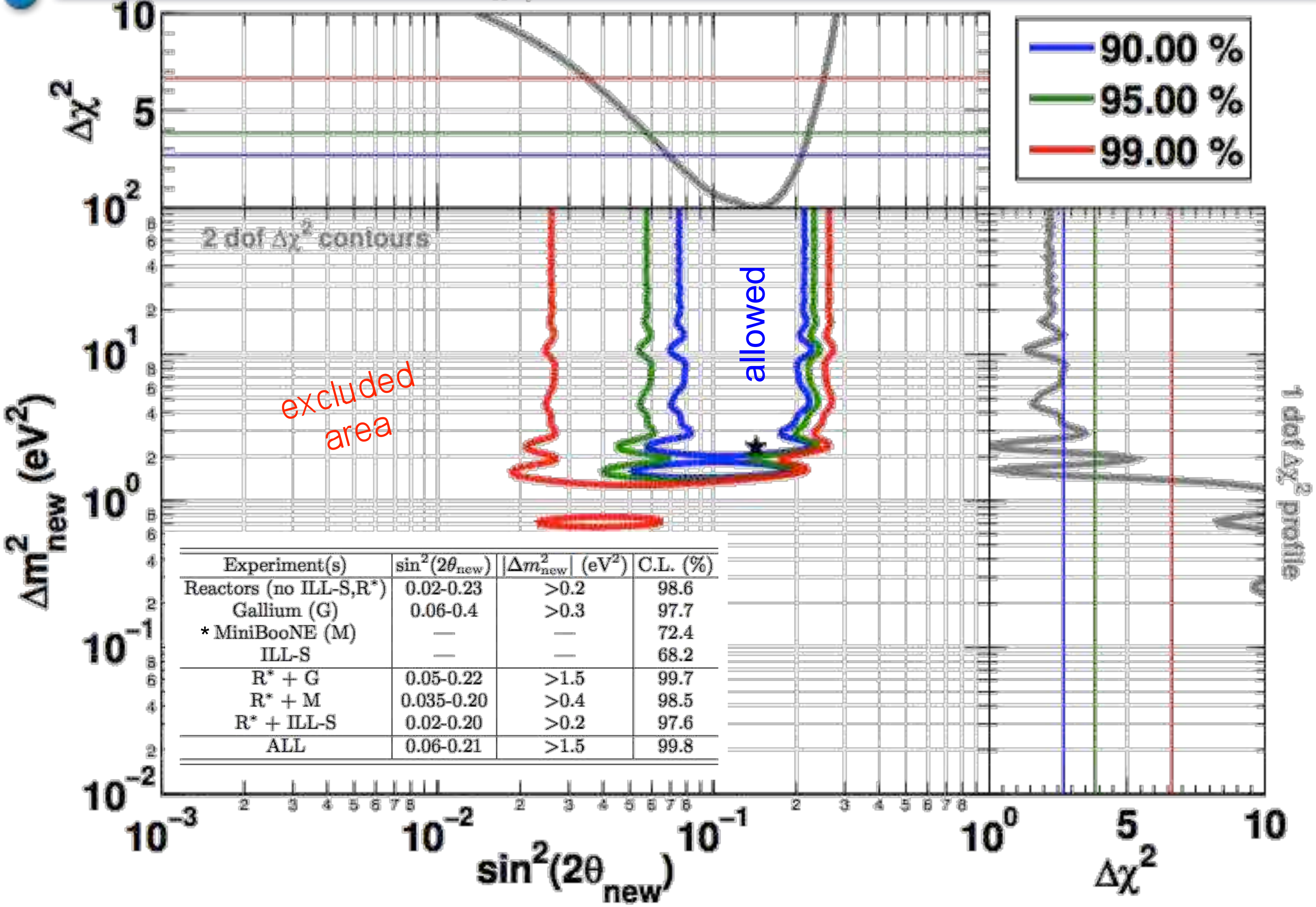
- **Effect reported in C. Giunti & M. Laveder in PRD82 053005 (2010)**





- Significance reduced by additional correlations in our analysis
- No-oscillation hypothesis disfavored at 97.7% C.L.
- No significant tension between neutrino and antineutrino anomalies

Combination: reactor rates + shape + Gallium



Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
* MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

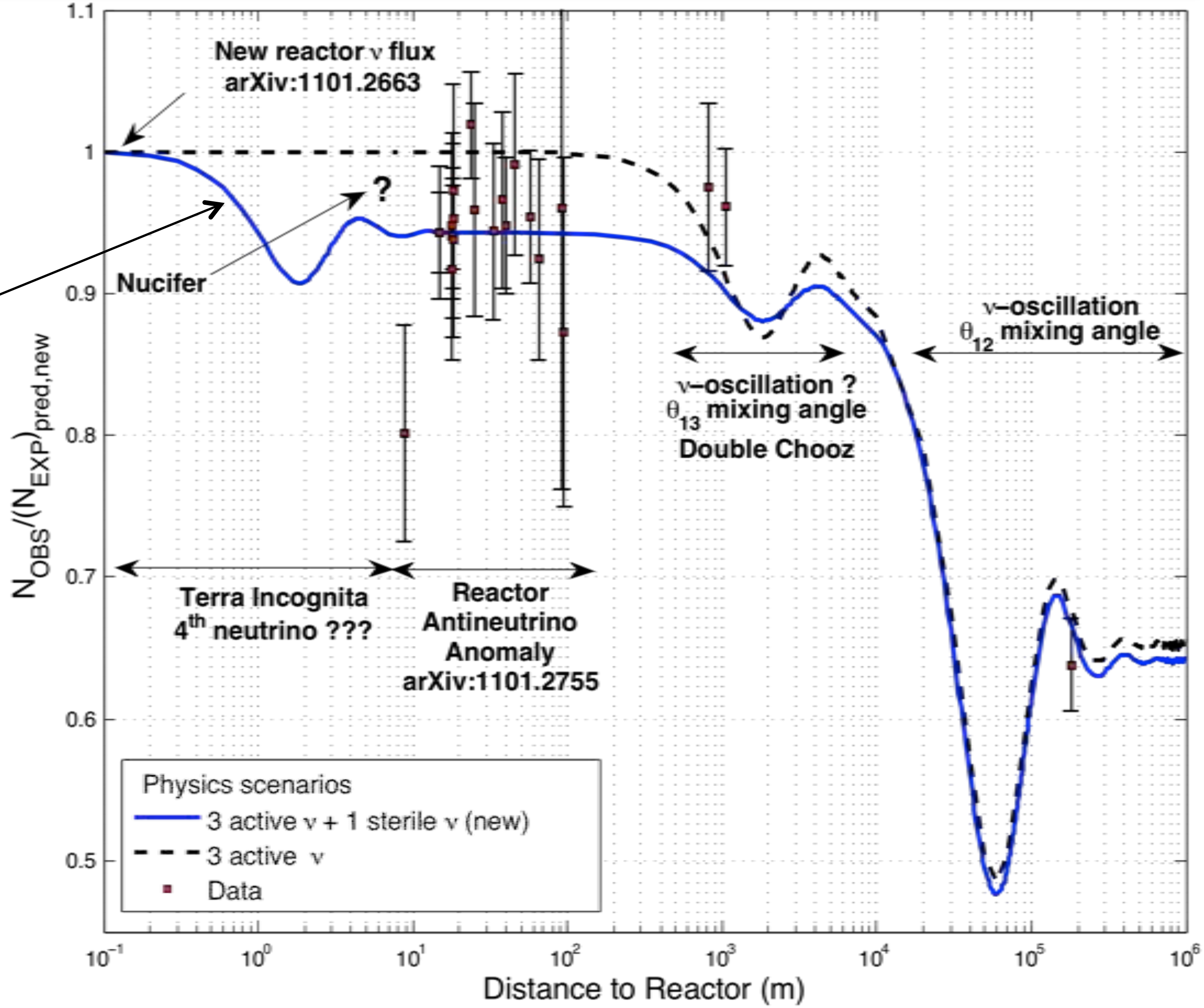
The no-oscillation hypothesis is disfavored at 99.8% CL

* Miniboone re-analysis of : C. Giunti, M. Laveder, Phys. Rev. D82 (2010) 053005

Need for new experimental inputs !

$$L_{optim} = \frac{L_{osc}[\mathrm{m}]}{2}$$

$$= 1.24 \frac{E_{\overline{\nu}_e}[\mathrm{MeV}]}{\Delta m^2_{\mathrm{new}}[\mathrm{eV}^2]}$$

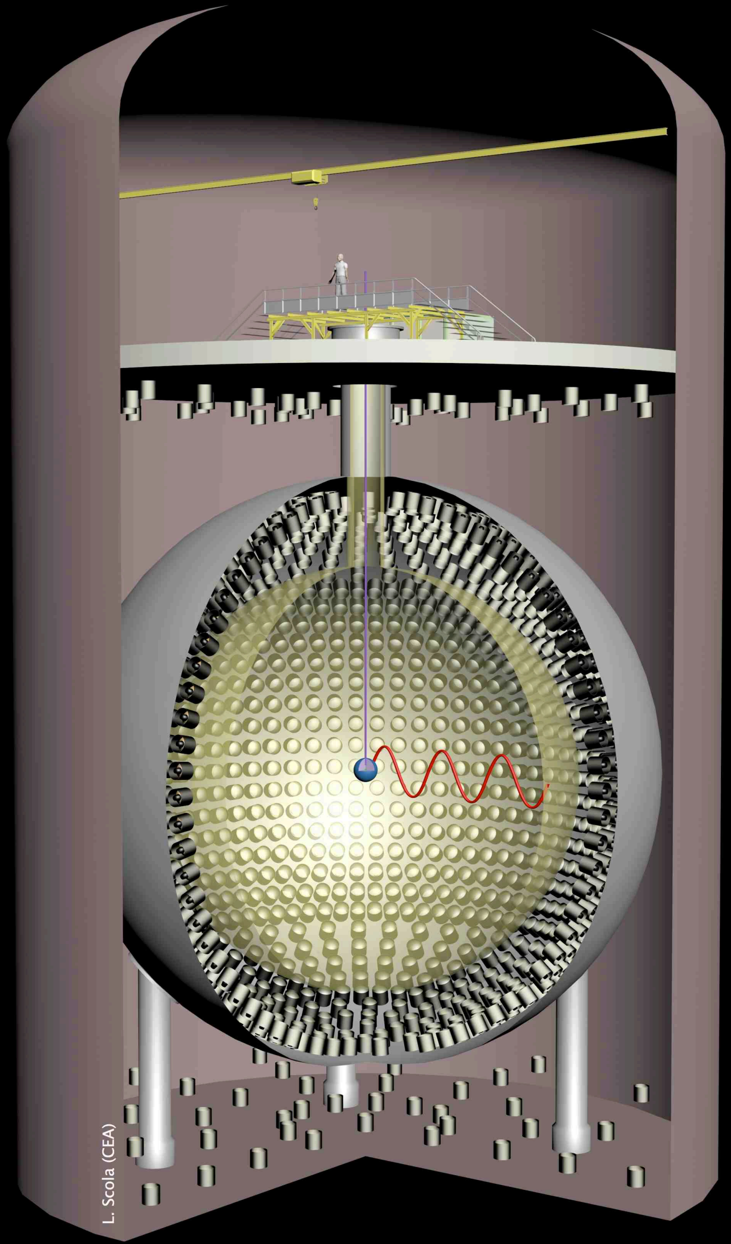


A proposed search for a fourth neutrino with a PBq anti-neutrino source

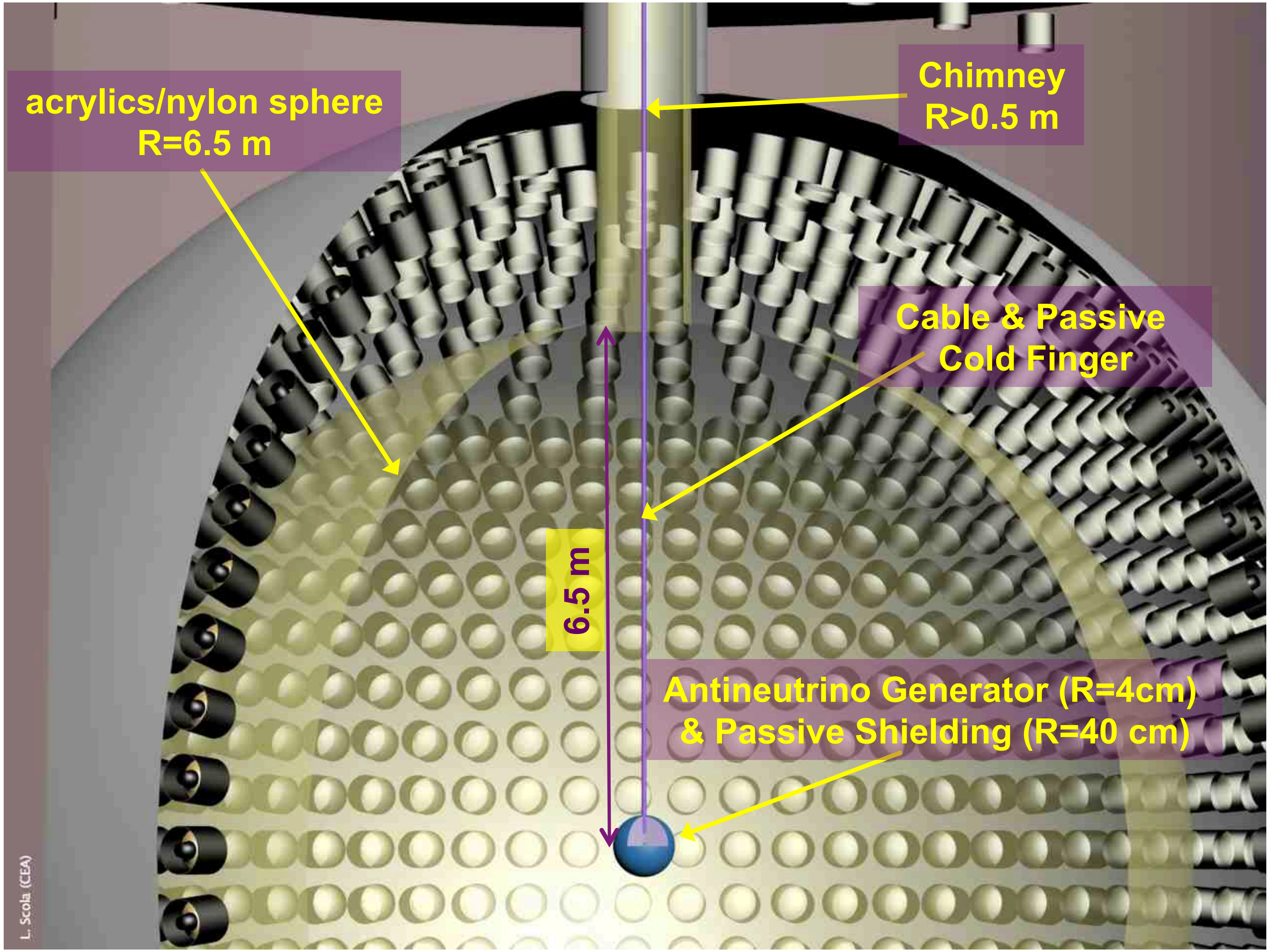
M. Cribier, M. Fechner, T. Lasserre,*
D. Lhuillier, A. Letourneau, G. Mention
D. Franco, S. Schoenert, V. Kornoukhov

Phys. Rev. Lett. 107, 201801 (2011)
arXiv:1107.2335

The Concept



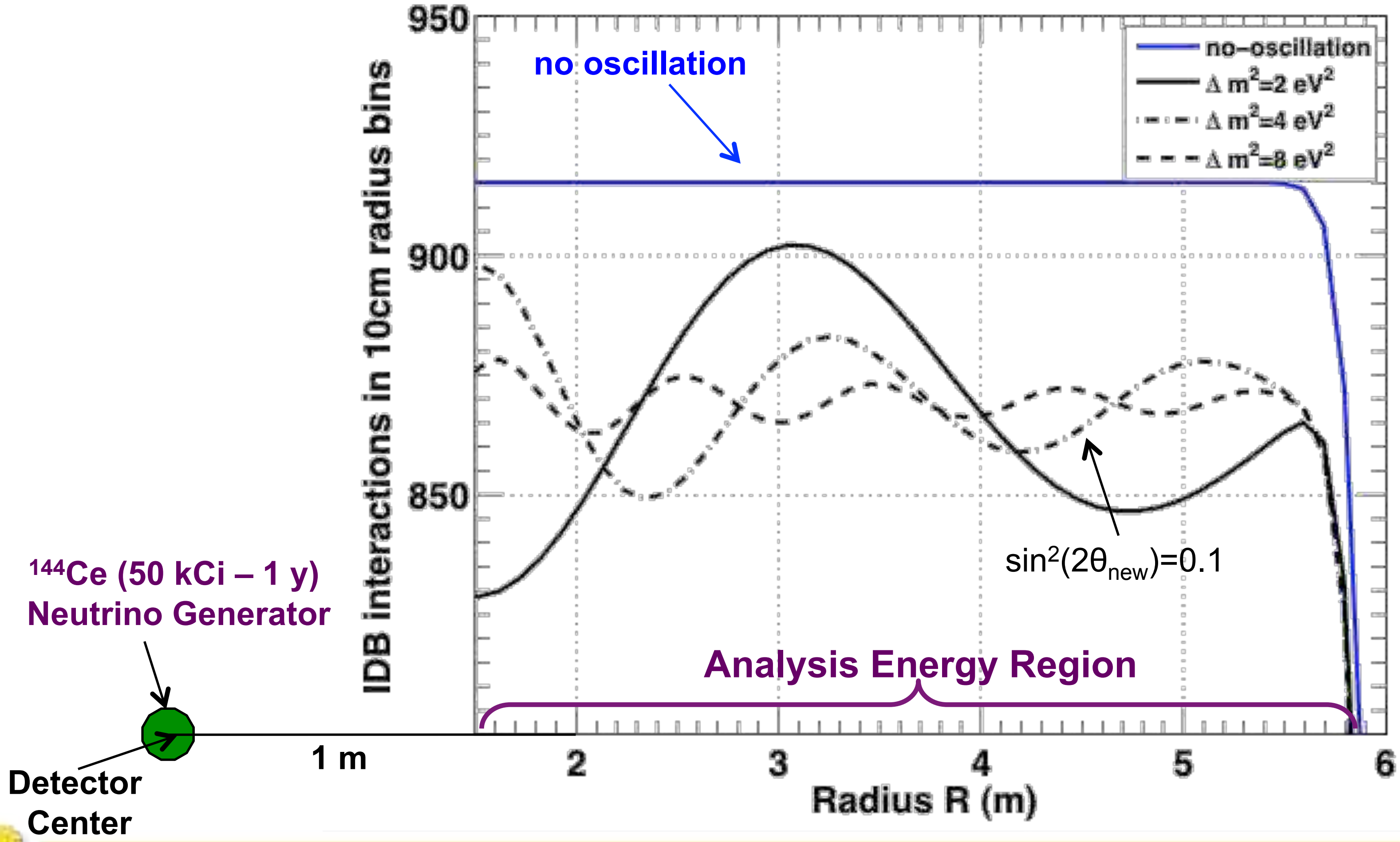
The Concept



acrylics/nylon sphere
R=6.5 m
Chimney
R>0.5 m
Cable & Passive
Cold Finger
6.5 m
Antineutrino Generator (R=4cm)
& Passive Shielding (R=40 cm)
L. Scola (CEA)

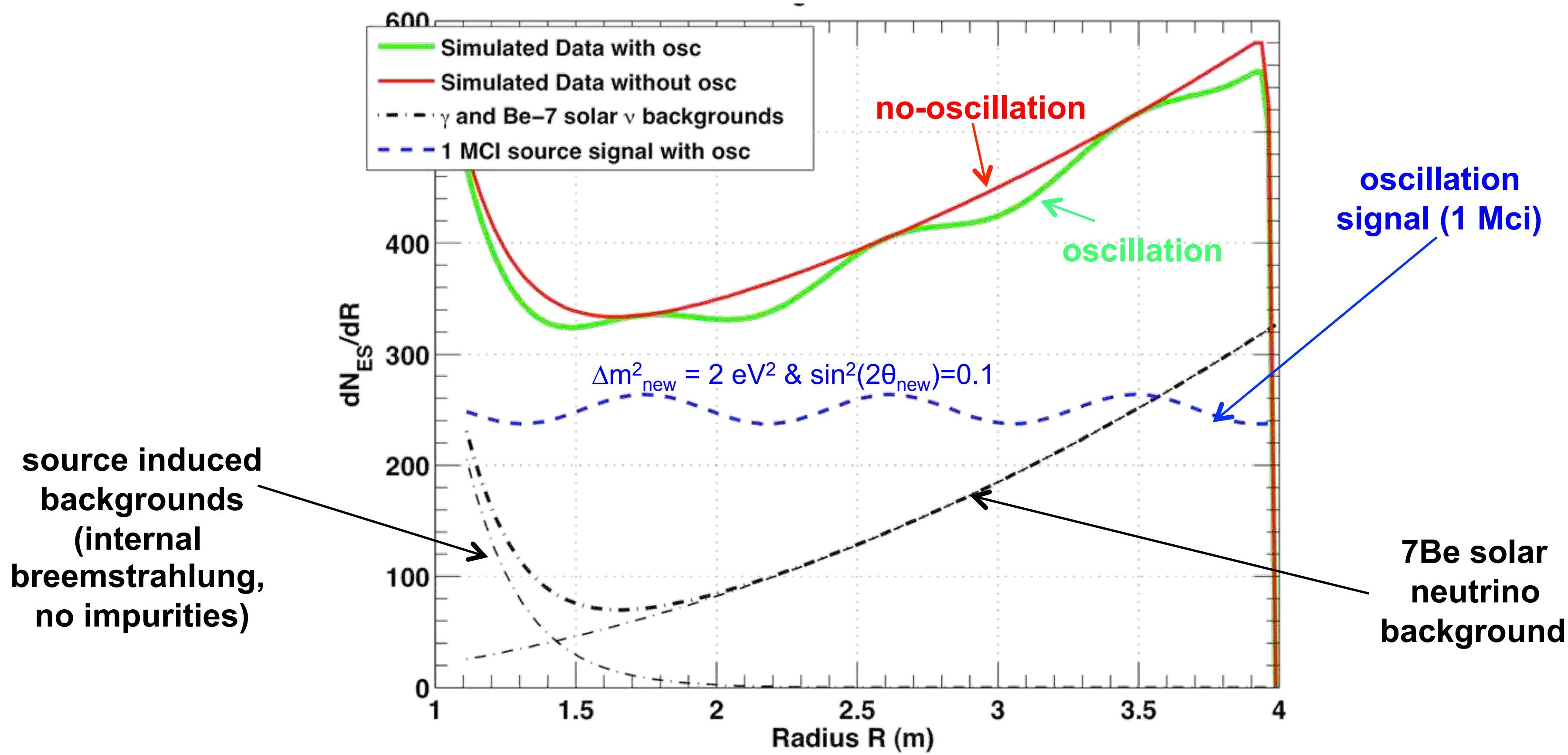
A Unambiguous Proof of $\nu_e \rightarrow \nu_s$ Oscillation

$$\frac{dN}{dR}(R,t) \propto \frac{A(t)}{\cancel{4\pi R^2}} \times \langle\sigma\rangle \times N_p \times \cancel{4\pi R^2} \times P_{ee}\left(\frac{\Delta m^2 R}{\langle E \rangle}\right)$$



Why not a neutrino source ?

- A strong ^{37}Ar **1 Mci** ν source <u>at the center</u> of a large LS detector
- Elastic scattering on e^- (few 10000 evts, 150 days, E>250 keV)
- Ultimate Backgrounds: ^{7}Be Solar Neutrinos !



ν source Need >5 Mci ^{37}Ar source – Feasibility in question

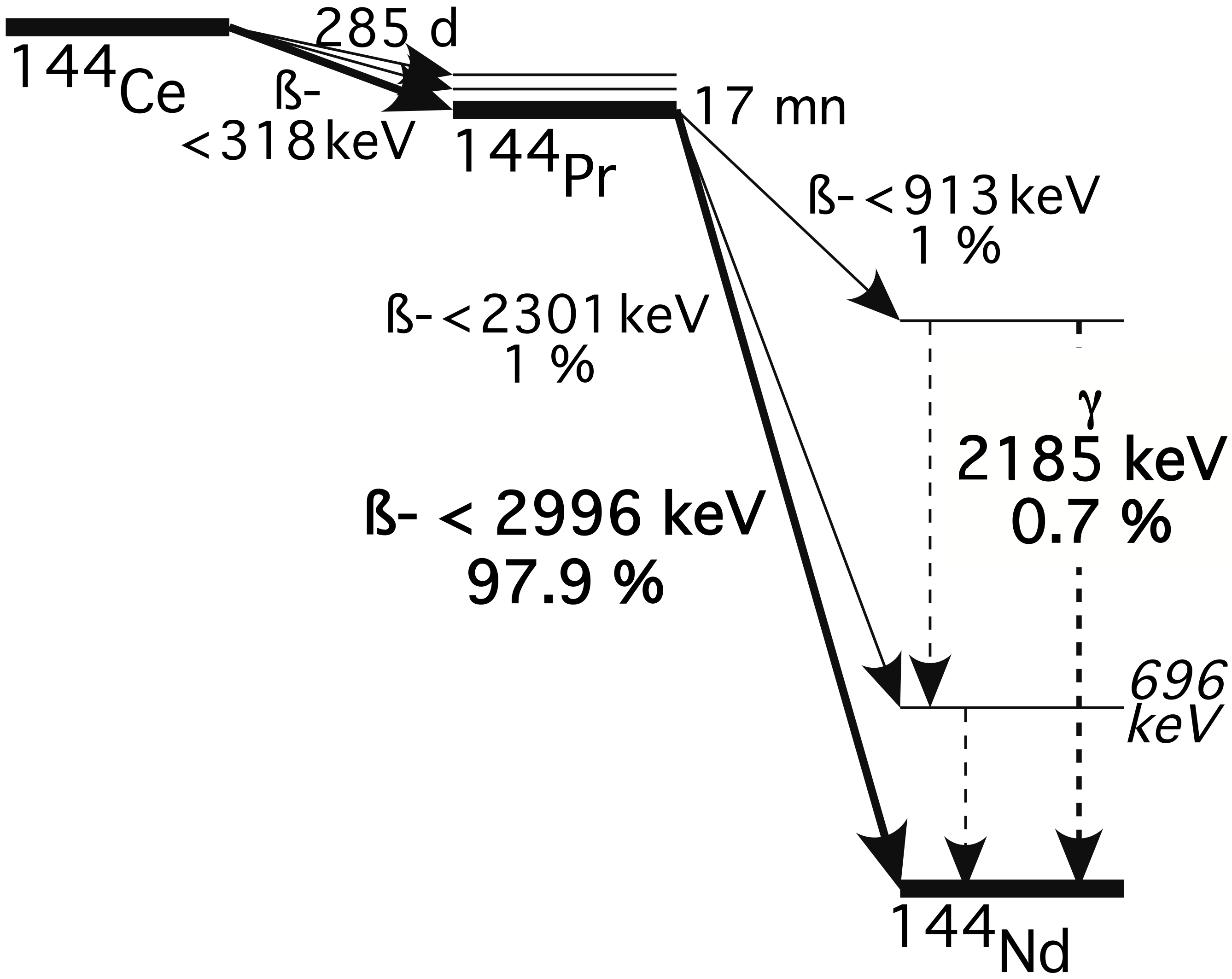
Nuclear Spent Fuel Induced anti-ν_e

- **Antineutrino detection via the inverse beta-decay**
  - High cross section (10^{-43} cm^2) → **from MCi to kCi !**
  - Antineutrino must have **E_ν>1.8 MeV**
  - Long Lifetime for production, transport and measurement

- **ν Source must involve a long-lived low-Q nucleus that decays to a short-lived high-Q nucleus**
  - ^{90}Sr-^{90}Y , **^{144}Ce-^{144}Pr** , ^{106}Ru-^{106}Rb , ^{42}Ar-^{42}K

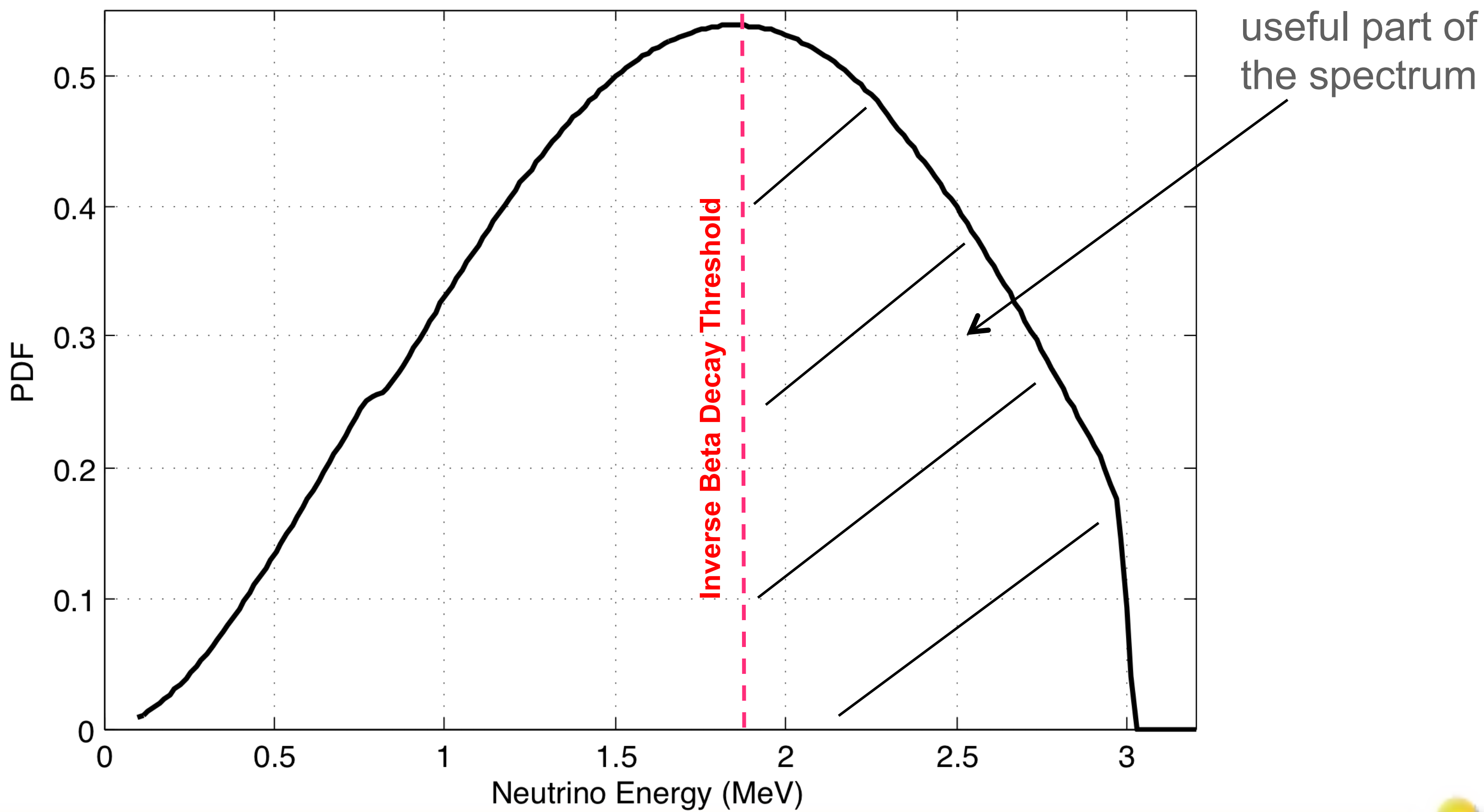
- Detection : anti-ν_e + p → e^+ + n (KamLAND, Double Chooz)
  e^+-n delayed coincidence → **background free experiment**

Best Candidate: ^{144}Ce-^{144}Pr



Neutrino Signal of ^{144}Pr (50 kCi)

- Antineutrino emitter : ^{144}Pr (Half-life : 0.78 y)
- 48.75 % of antineutrinos emitted above IBD threshold



The Cerium Compact Source

- 50 kCi source (1.85 PBq)
- **Assuming a spent fuel cooling time of 3 years**
  - **Composition** (material in form of CeO_2)
    - ^{144}Ce: 0.010%
    - ^{142}Ce: 49.995%
    - ^{140}Ce: 49.995%
  - $\rho(\mathbf{CeO_2})$ = 6.7 g/cm^3 → R_{source} = 3.8 cm
  - 15 g ^{144}Ce → about 1.5 kg of CeO_2
  - Heat release = 380 Watt → Passive Cooling Only
- **Suitable for meter scale neutrino oscillation length search**

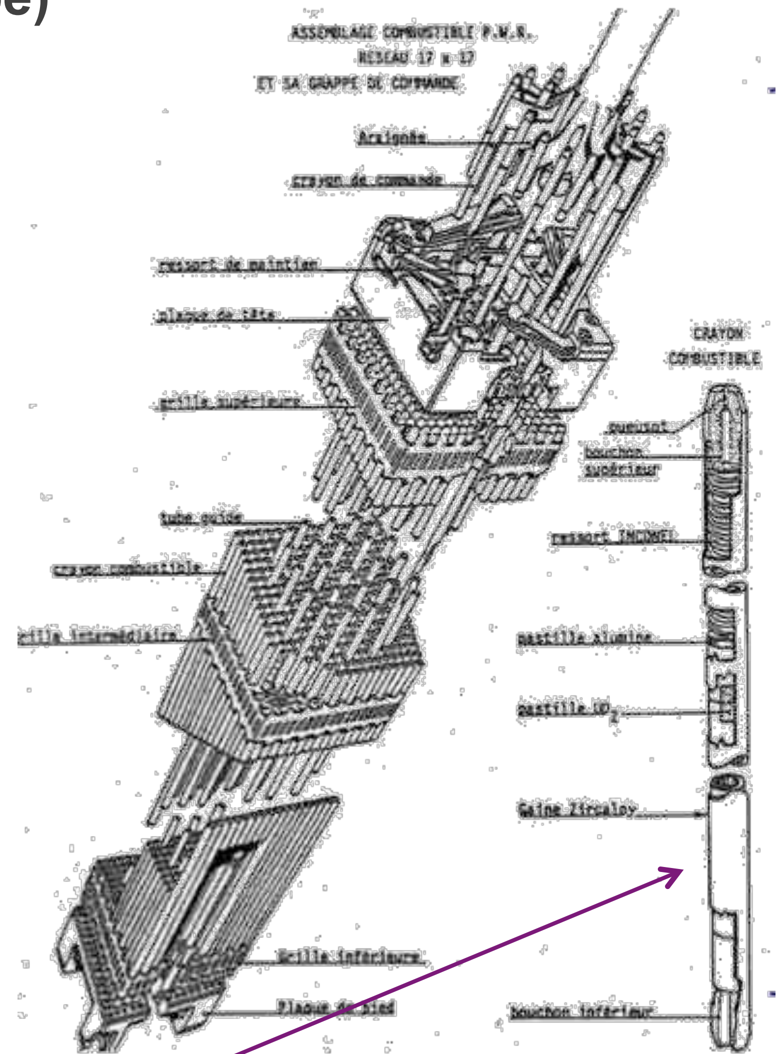
Nuclear Spent Fuel

- **Fuel in N4-reactors (EDF N4-Type)**
  - 120 tons of UO_2
  - $^{235}U \approx 3.45\%$: 3.60 tons

- **205 fuel assembly**
  - 264 rods per assembly
  - 272 "pellets" per rods

- **1 ton of** VVR-440 **spent fuel**
  - Burnup of 40 GW*days/t
  - Fission Products: 44 kg
  - 15 kg of Rare Earth (RE)
    - Ce~25% → ~4 kg

- **15 g of ^{144}Ce = 1.5 kg of Ce**
  → 400 kg spent fuel need
  → 1 fuel assembly needed !



^{144}Ce-^{144}Pr: Production

~ 400 kg of Spent Nuclear Fuel

⇓

Purex process (removal of U, Np and Pu)

⇓

Evaporation

⇓

Concentration of Ce with oxalate precipitation
(REE and TPE concentrate)

⇓

Extraction procedure

(recovery of light REE: La, **Ce**, Pr, Nd (partly))

⇓

Chromatography purification (recovery of 15 g Ce)

⇓

precipitation : **CeO_2**

Existing Facility in Russia (Mayak)

^{144}Ce-^{144}Pr: Purification

- **Technology & Productivity:**
  - Complexing agent displacement chromatography
  - 10 ÷12 kg of Rare Earth per cycle
  - Content of Ce element ~ 25%

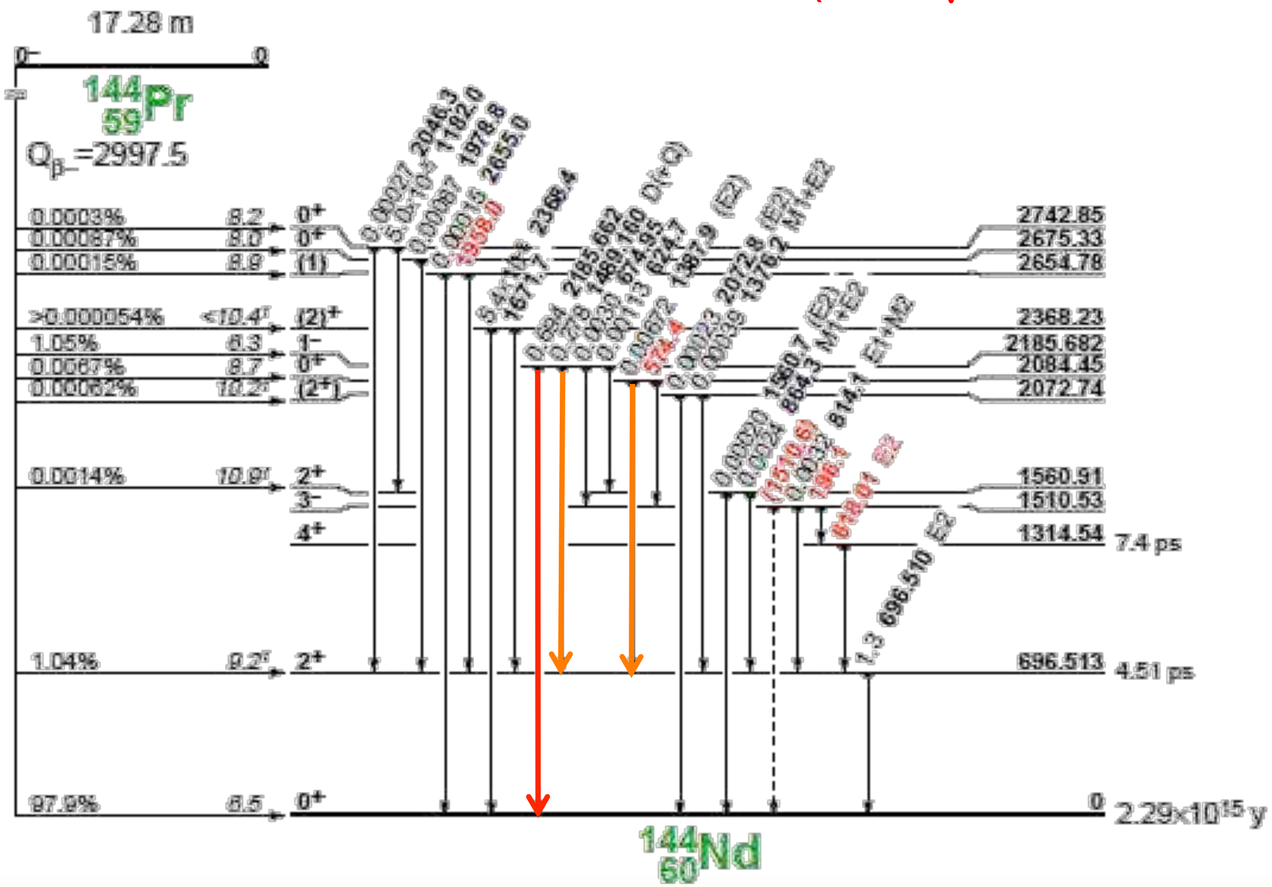
- Ratio of $^{144}Ce/Ce$ element is strongly depended on:
  - Cooling time
  - Fuel burning
  - 1:100 for 3 years old fuel

- **Purification**
  - Content of any others RE (γ-*emitters*) in *Ce* $\leq 10^{-9}$
  - Content of Pu and any TPE (*n emitters*) in Ce $\leq 10^{-10}$

Existing Chromatography Facility (Mayak)

Gamma Backgrounds of ^{144}Ce-^{144}Pr (i)

- γ rays produced by the decay through excited states of ^{144}Pr
  - Intensity γ>1 MeV
    - 1380 keV – 0.007 %
    - 1489 keV – 0.3 %
  - Intensity γ>2 MeV
    - 2185 keV – 0.7 %
      (10^{10} γ/sec for 50 kCi source)

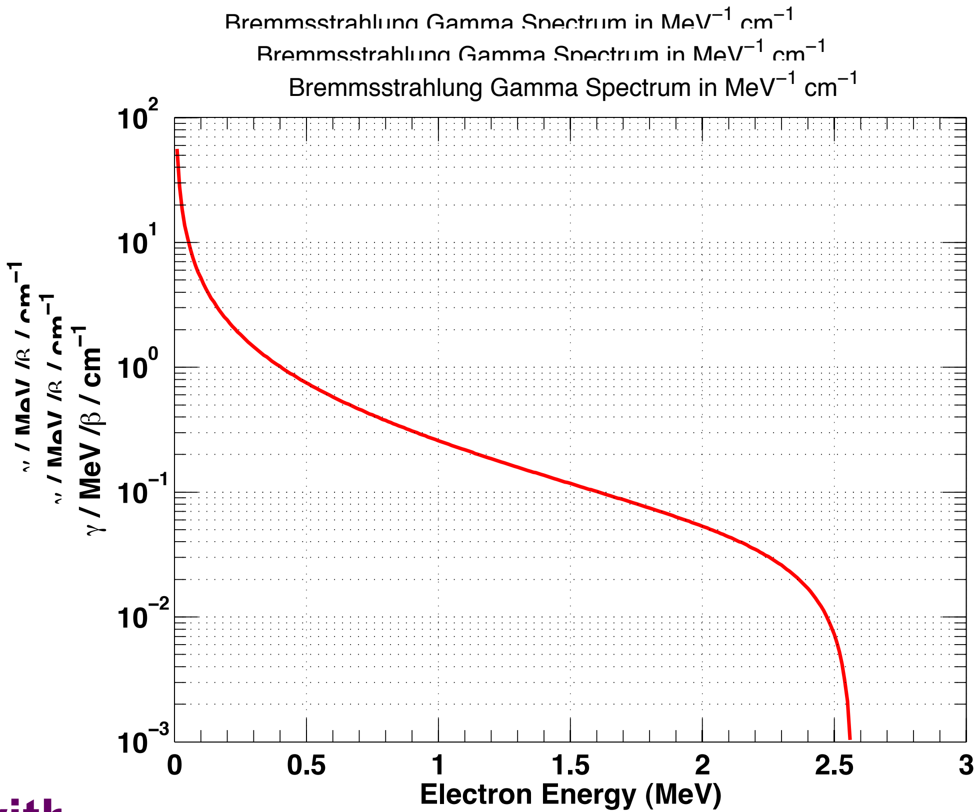


Gamma Backgrounds of ^{144}Ce-^{144}Pr (ii)

- ^{144}Ce Electron – Nucleus Bremsstrahlung in the cerium →emission of gamma photons

- **Bremsstrahlung Modelization Thick Cerium Target**
  - Semi-analytical approach using Koch & Motz (1959)
  - Full GEANT4 Simulation

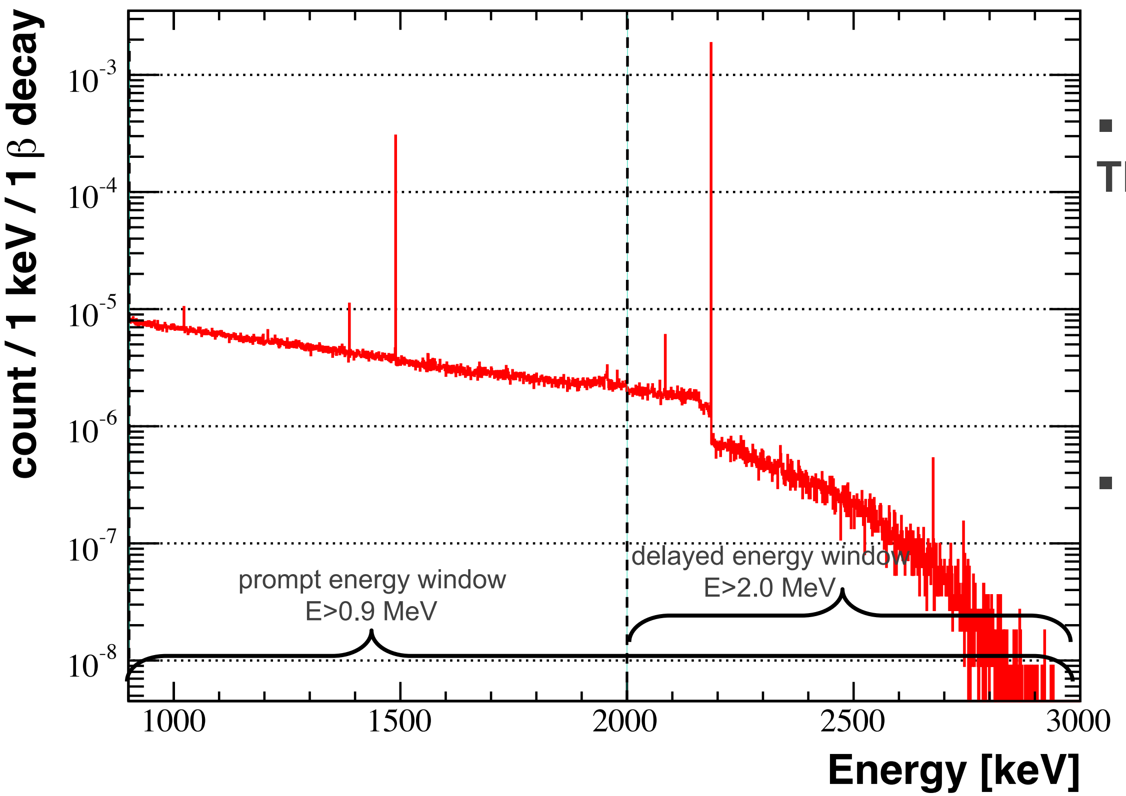
- **#photons escaping the Ce**
  - E>0.9 MeV : 6.5 10^{-3} /decay
  - E>2.0 MeV : 10^{-4} /decay



- **Background less Critical with respect to γ rays produced by the decay through excited states of ^{144}Pr**

Gamma Backgrounds of ^{144}Ce-^{144}Pr (ii)

- ^{144}Ce Electron – Nucleus Bremsstrahlung in the cerium
→emission of gamma photons



- **Bremsstrahlung Modelization in Thick Cerium Target**
  - Semi-analytical approach using Koch & Motz (1959)
  - GEANT4 Simulation (Franco)

- **#photons escaping the Ce**
  - E>0.9 MeV : <6.5 10^{-3} /decay
  - E>2.0 MeV : <10^{-4} /decay

- **Background less Critical with respect to γ rays produced by the decay through excited states of ^{144}Pr**

Neutron Background: ^{244}Cm

- 18.1 y half-life

- in Spent Fuel 5 g of ^{244}Cm for 100 g of ^{144}Ce

- **Spontaneous fission**
  - branching fraction: 1.3 10^{-6}
  - 3.5 MBq for 1.85 Pbq ^{144}Ce

- **Mayak Facility in Russia**
  - Rare Earth Recovery Chain
  - Content of Pu and any Trans-Plutonians (*n emitters*) in Ce ≤ 10^{-10}

  →Bkg < 3 10^{-4} Bq …

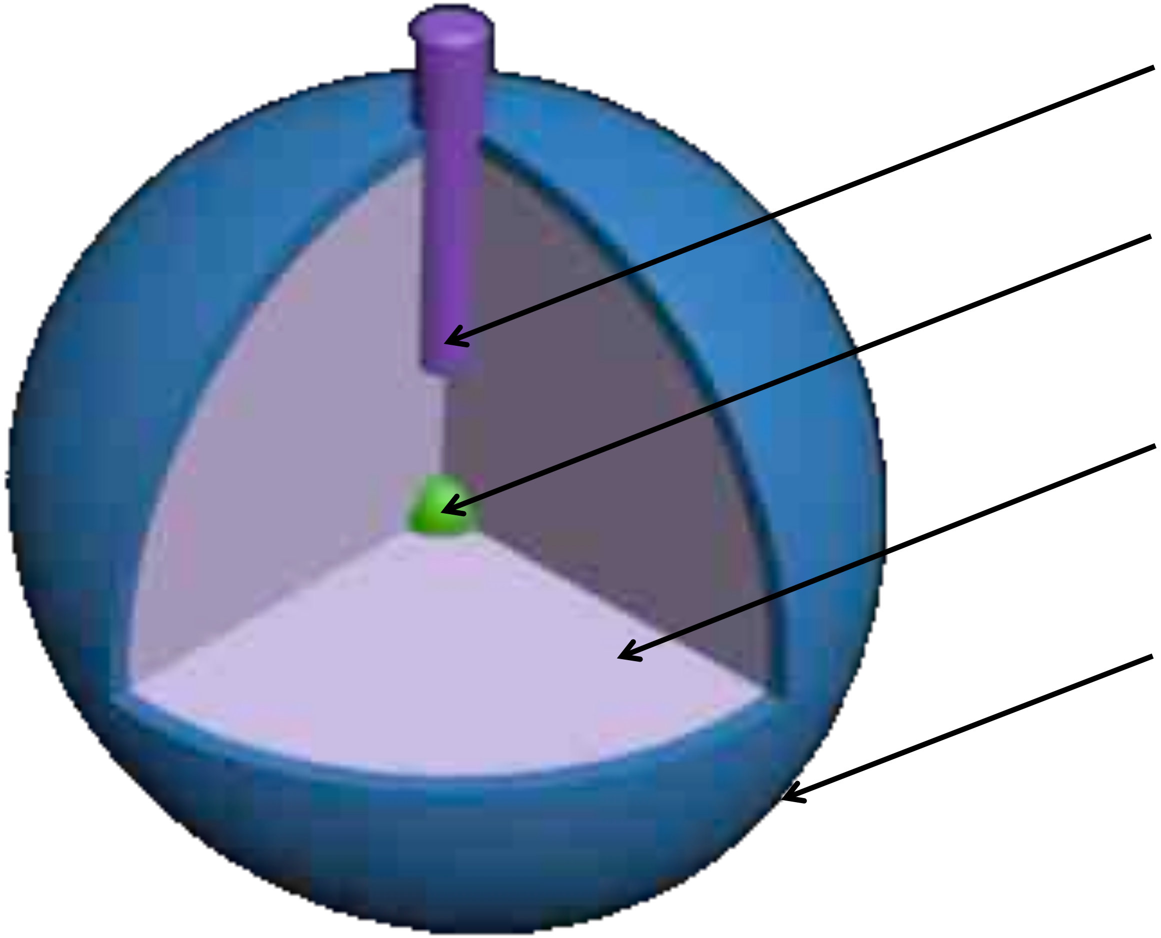
- Different w.r.t with http://arxiv.org/pdf/1109.6036 estimation

Isotope	Half-life (α - decay), years	Half-life (spontaneous fission), years	Yield of isotope, g/ton, cooling time of spent nuclear fuel - 3 years
Plutonium			
^{238}Pu	87.34	$4.77\cdot10^{10}$	75
^{239}Pu	$2.41\cdot10^{4}$	$7.8\cdot10^{15}$	$5.5\cdot10^{3}$
^{240}Pu	$6.57\cdot10^{3}$	$1.15\cdot10^{11}$	$1.98\cdot10^{3}$
^{241}Pu	14.4	$>3\cdot10^{15}$	$1.25\cdot10^{3}$
^{242}Pu	$3.75\cdot10^{5}$	$6.84\cdot10^{10}$	$3.7\cdot10^{2}$
Americium			
^{241}Am	433	~ 10^{14}	240
^{242m}Am	152	$8.8\cdot10^{11}$	0.26
^{243}Am	$7.37\cdot10^{3}$	$3.35\cdot10^{13}$	70
Curium			
^{242}Cm	162.8 days	~ $6.1\cdot10^{6}$	~ $4\cdot10^{-3}$
^{243}Cm	28.5	$5.37\cdot10^{11}$	~ 0.15
^{244}Cm	18.11	$1.37\cdot10^{7}$	21.3
^{245}Cm	$8.5\cdot10^{3}$	$1.39\cdot10^{12}$	~ 1
^{246}Cm	$4.7\cdot10^{3}$	$1.8\cdot10^{7}$	~ 0.1
^{248}Cm	$3.4\cdot10^{5}$	$4.1\cdot10^{6}$	$1.7\cdot10^{-5}$
Californium			
^{250}Cf	13.1	$1.7\cdot10^{4}$	$2.2\cdot10^{-6}$
^{252}Cf	2.638	85.38	$4.0\cdot10^{-8}$

Thanks to V. Kornoukhov

The Shielding (as in PRL 107, 201801, 2011)

Designed to shield gamma rays only



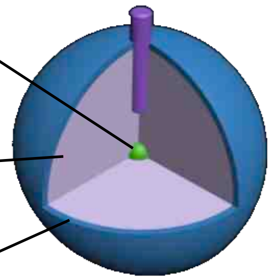
mass ≈ 3.7 tons
diameter ≈ 82 cm

Shielding For Gamma Ray Attenuation

- GEANT4 simulation of the 50 kCi Ce source + shielding

(D. Franco)

Name	Radius	Material	Density
Source	R < 4 cm	CeO_2 ^{144}Ce: 0.010% ^{142}Ce: 49.995% ^{140}Ce: 49.995%	7.65 g/cm^3
Densimet	4 cm < R < 37 cm	W: 98.50% Fe: 0.75% Ni: 0.75%	18.8 g/cm^3 (λ_D = 1.25 cm for 2.185 MeV γ)
Copper	37 cm < R < 39 cm	Cu	8.94 g/cm^3
Scintillator	39 cm < R < 300 cm	C_9H_{12}	0.882 g/cm^3



- γ suppression factor S for one ^{144}Pr beta decay:
  33 cm Densimet : **S_D=2.10^{-13}** & 2 cm Copper : **S_C=0.66**

- Total rate in LS is 260 Hz (160 Hz for E>900 keV)

- **After 1 m of LS: 3 Hz for E>900 keV & 0.75 Hz for E>2 MeV**

50 kCi ^{144}Ce-^{144}Pr Source Background

- **Expected Signal : 40 000 evts/year → 1 mHz**

- **Inverse Beta Decay Delayed Coincidence Signature**
  - Cuts: E_{prompt} > 0.9 MeV, $E_{delayed}$ > 2.0 MeV, Δt<772 µs
  - A cut on ΔV<10 m^3 could further decrease backgrounds

- Any of the ^{144}Pr exited states photons, or Bremsstrahlung photons or shielding backgrounds can account for either the prompt or delayed event, depending on their energy

- After 1 m of LS
  - R_{prompt} = 2.5 Hz $R_{delayed}$ = 0.6 Hz → **R_{acc} = 1 mHz (S/B=1)**

- **After 1.5 m of LS → R_{acc} = 2 10^{-2} mHz (S/B=100)**

- **Note: 3 cm W leads → Source backgrounds divided by 10**

The Shielding Intrinsic Background

- Background induced by intrinsic contamination in **Densimet (W)**

- The contamination in measured by the GERDA collaboration:
  - ^{238}U: 180±20 mBq/kg — ^{232}Th: 70±20 mBq/kg
  - ^{60}Co: 7±2 mBq/kg — ^{40}K: <57mBq/kg

- GEANT4 simulation: Isotopes generated uniformly in the W volume

(D. Franco)

Isotope	Rate [Hz]	Rate E > 900 keV [Hz]	Rate E > 900 Hz R > 139 cm [Hz]
^{238}U	12.6 ± 2.1	5.3 ± 0.9	(7.4 ± 1.2)x10^{-2}
^{232}Th	6.2 ± 1.8	2.6 ± 0.7	(6.0 ± 1.7)x10^{-2}
^{60}Co	0.8 ± 0.2	0.4 ± 0.1	(3.3 ± 0.9)x10^{-3}
^{40}K	< 0.44	< 0.23	< 2.5x10^{-3}
^{137}Cs	< 0.01	0	0
Total	**19.6 ± 2.8**	**8.3 ± 1.2**	**(13.7 ± 2.1)x10^{-2}**

1 order magnitude less than the ^{144}Pr induced background

Other Backgrounds

- **Detector Backgrounds**
  - Accidentals, Fast neutrons, μ-induced isotopes ^{9}Li & ^{8}He
  - Measured in situ in KamLAND and Borexino:
    - 0.14±0.02 counts/ day/100 tons
    - We increase it to 10 counts/day/100 tons in our simulation

- **Geologic neutrinos**
  - Decay of radioactive isotopes of uranium or thorium in Earth
  - Few events per year in 100 ton in KamLAND and Borexino

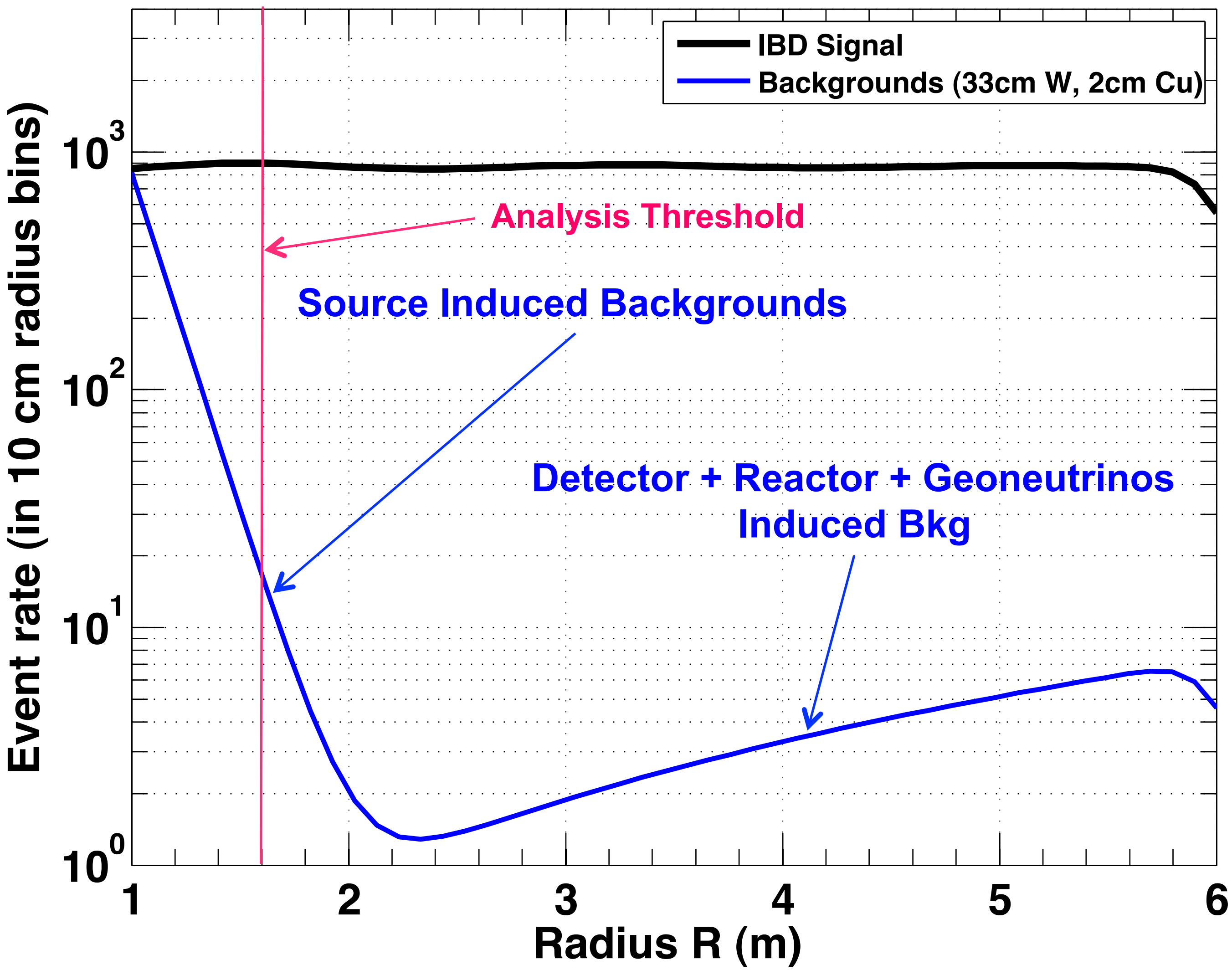
- **Reactor neutrinos**
  - Decays of the fission products in the nuclear cores
  - Measured in KamLAND : 10 events per 100 ton (E<3 MeV)

- **Our Simulation: Detector + Geoneutrinos + Reactors**

→ 20 events per 100 ton per year

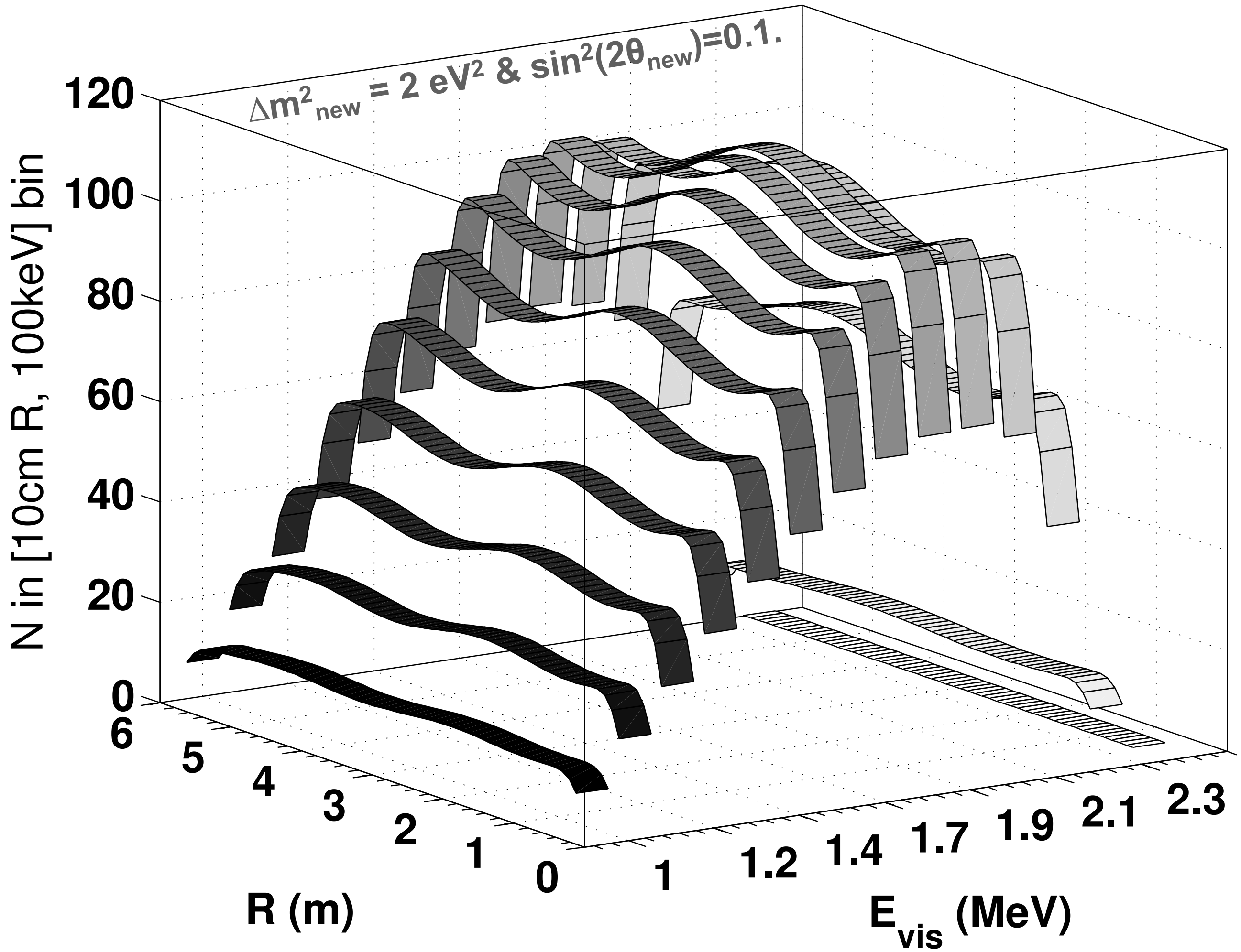
→ Scales with R^2 in concentric ΔR bins

Background Summary



A Neutrino Picture in the (R,E) Plane !

$$\frac{d^2N(R,E_\nu)}{dRdE_\nu} = \mathcal{A}_0 \cdot n \cdot \sigma(E_\nu) \cdot \mathcal{S}(E_\nu) \cdot \mathcal{P}(R,E_\nu) \int_0^{t_e} e^{-t/\tau} dt,$$



Expected Sensitivity

- **Inputs:**
  - 50 kCi ^{144}Ce-^{144}Pr source running for 1 yr
    (decrease in the source activity over 1 year : 66%)
  - 33 cm W + 2 cm Cu Shield
  - Using events between 1.5 and 6 m → background free

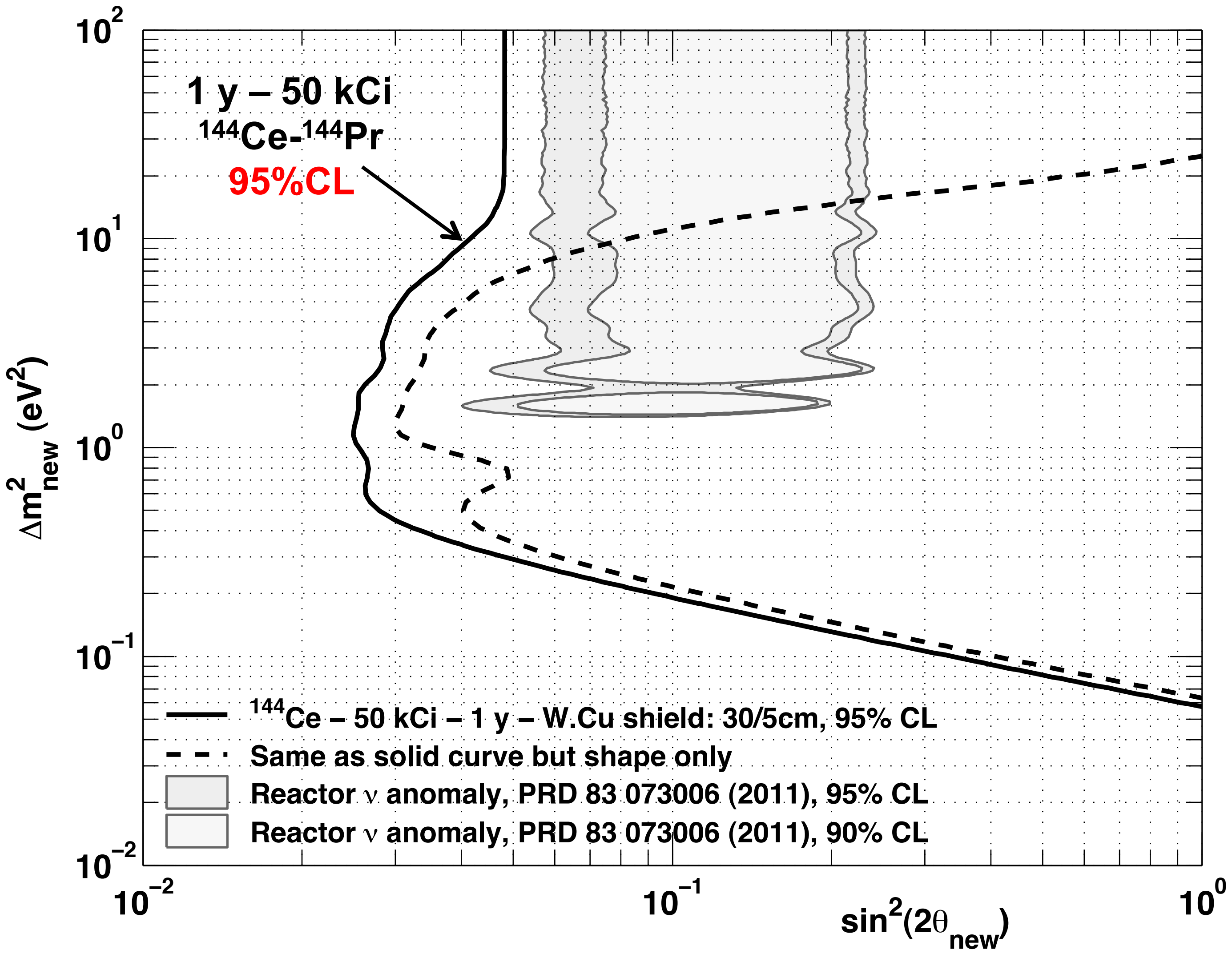
- **Detector Parameters:**
  - 15 cm vertex resolution & 5% energy resolution

- **χ^2 analysis using R (i) & E (j) information:**

$$\chi^2 = \sum_i \sum_j \frac{[N_{\rm obs}^{i,j} - (1+\alpha)N_{\rm exp}^{i,j}]^2}{N_{\rm exp}^{i,j}(1+\sigma_b^2 N_{\rm exp}^{i,j})} + \left(\frac{\alpha}{\sigma_N}\right)^2$$

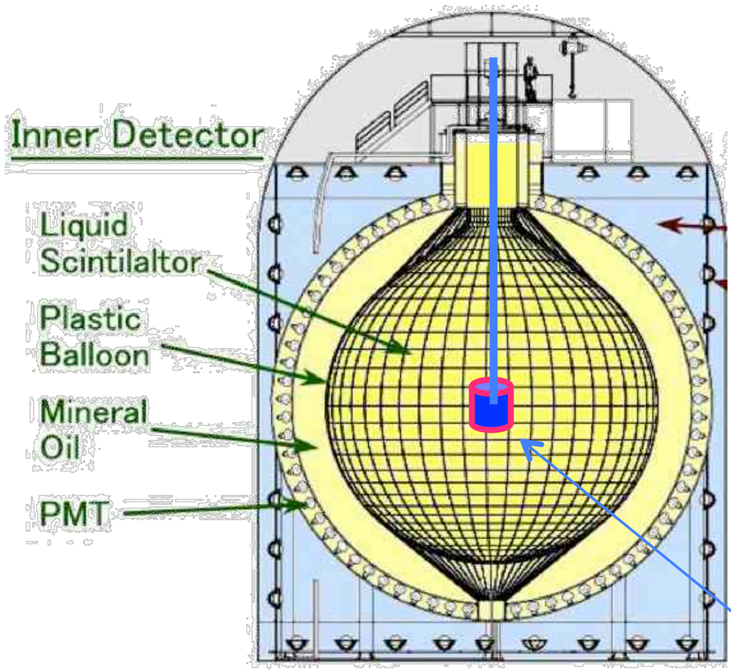
  - **σ_N** : Normalization error of 1% for the source activity uncertainty
  - **σ_b** : Fully uncorrelated systematic error of 2% for:
    - fiducial volume uncertainty (1%) in a calibrated detector
    - analysis detection efficiencies uncertainties (sub-%)

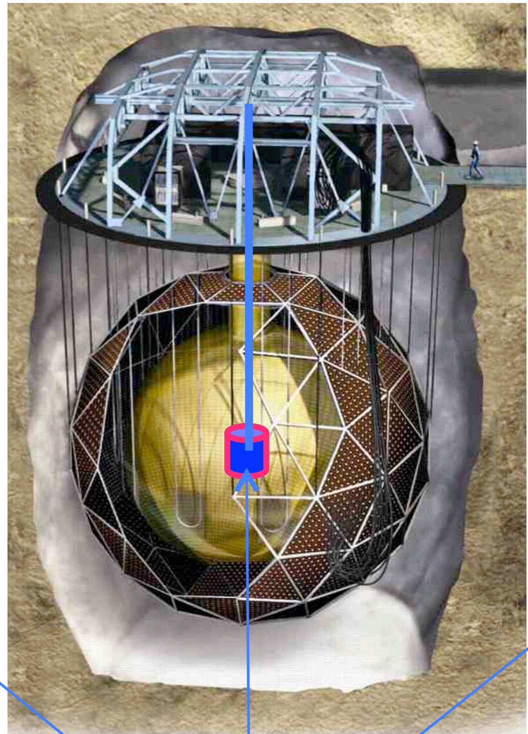
Decisive Test Of the Reactor Anomaly



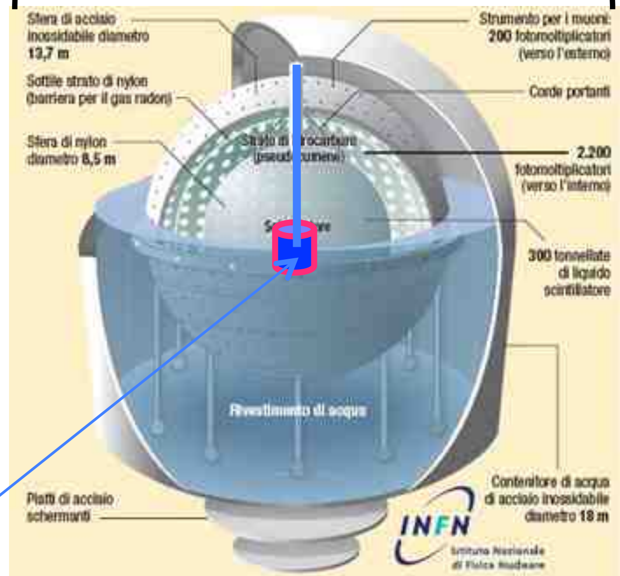
^{144}Ce-^{144}Pr Proposal

3 Suitable Detectors (may necessitate some upgrades)





+ internal initiative
by Borexino Collaboration



a 50 kCi ^{144}Ce-^{144}Pr source

Another recent proposal : a 500 kCi ^{144}Ce-^{144}Pr source in Daya Bay
(D.A. Dwyer et al., http://arxiv.org/pdf/1109.6036 **)**

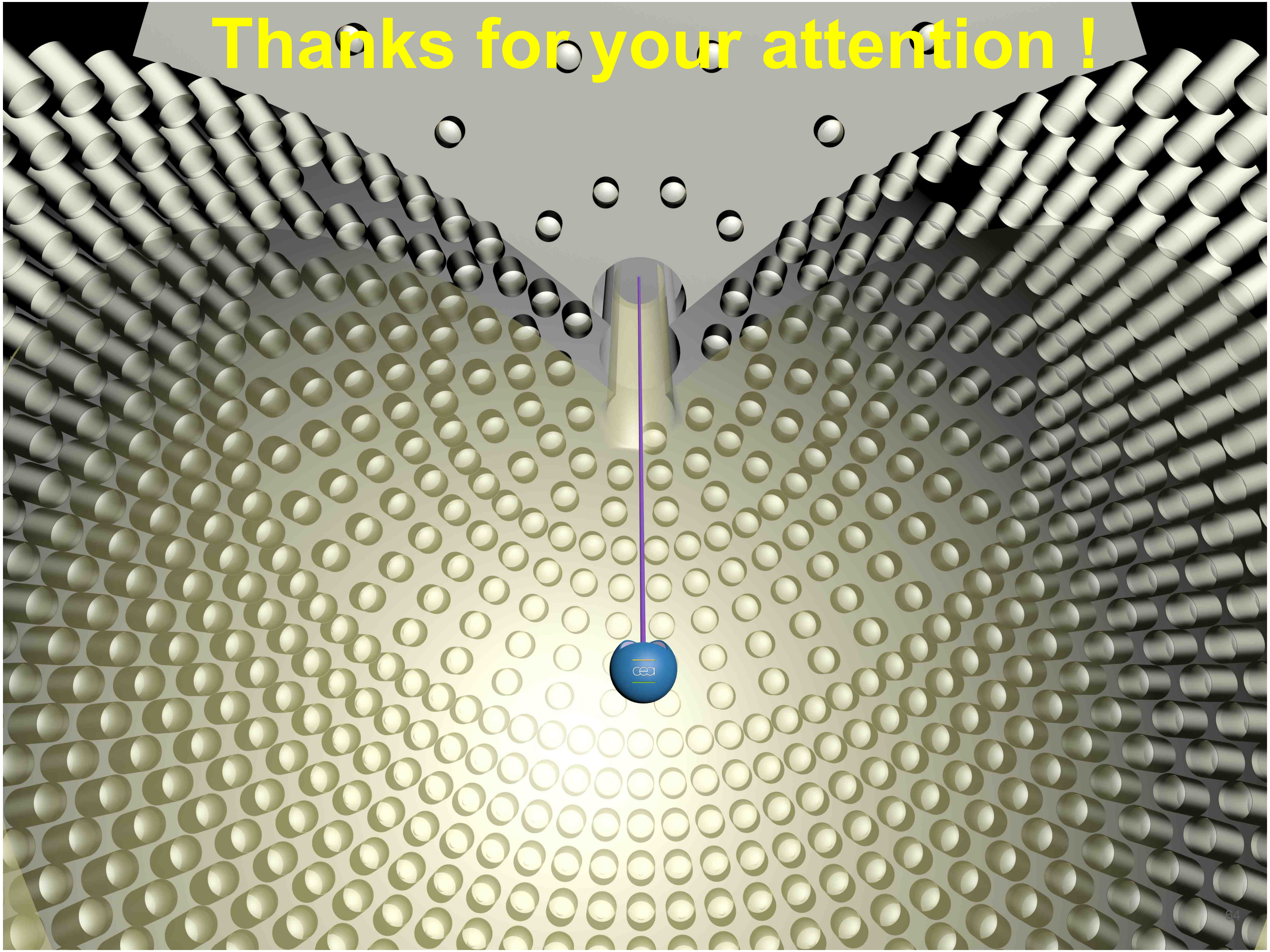
Conclusion and perspectives

- **Reactor Antineutrino Anomaly + Gallium Anomaly**
  - Phys. Rev. C83 054615 (2011) & Phys. Rev. D 83, 073006 (2011)
  - Still some unknown in reactor neutrino spectra
  - 4^{th} ν hypothesis ($\Delta m^2 \approx eV^2$): no-oscillation disfavored at 3σ

- Other Anomalies : LSND & Cosmology
  - **A strong physics case : New experiments are needed !**
  - Already several project (CERN, Fermilab, Sources, Reactors, …)

- **A proposed search for a 4^{th} neutrino with a 50 kCi anti-ν source**
  - **15 g of ^{144}Ce-^{144}Pr encapsulated in a W/Cu shield deployed in a large liquid scintillator detector (PRL 107, 201801, 2011)**
  - The best discovery potential testing the reactor antineutrino anomaly range of parameters
  - **KamLAND** would be perfectly suited for such an experiment!

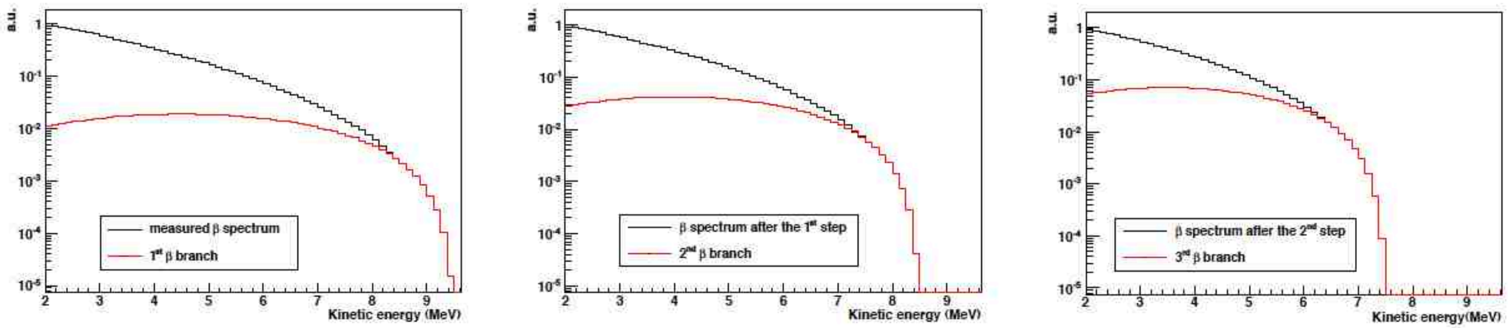
Thanks for your attention !



Backup

ILL data: conversion to ν spectra

- Fit e^- spectrum with a sum of 30 effective branches
- Conversion of the effective branches to ν spectra

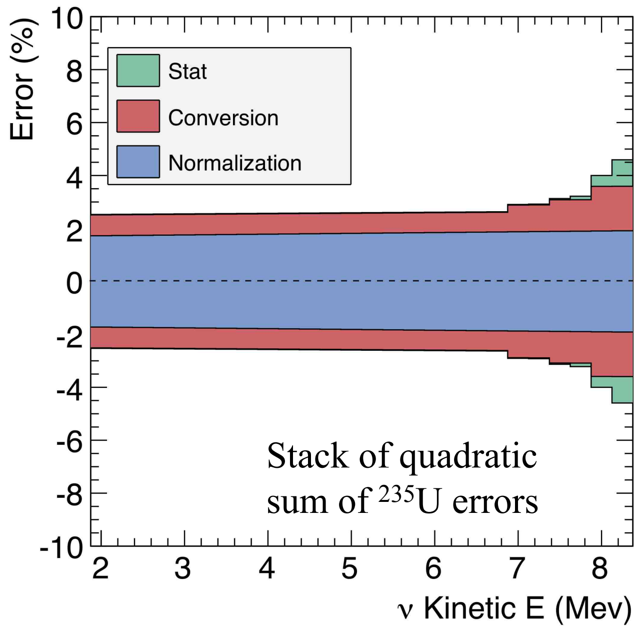


- **All theory included in these effective branches but:**
  - What Z? : Mean fit on nuclear data *Z=f(E0)*

$$Z(E_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

  - What A_{CW}? : effective correction on the ν-spectra

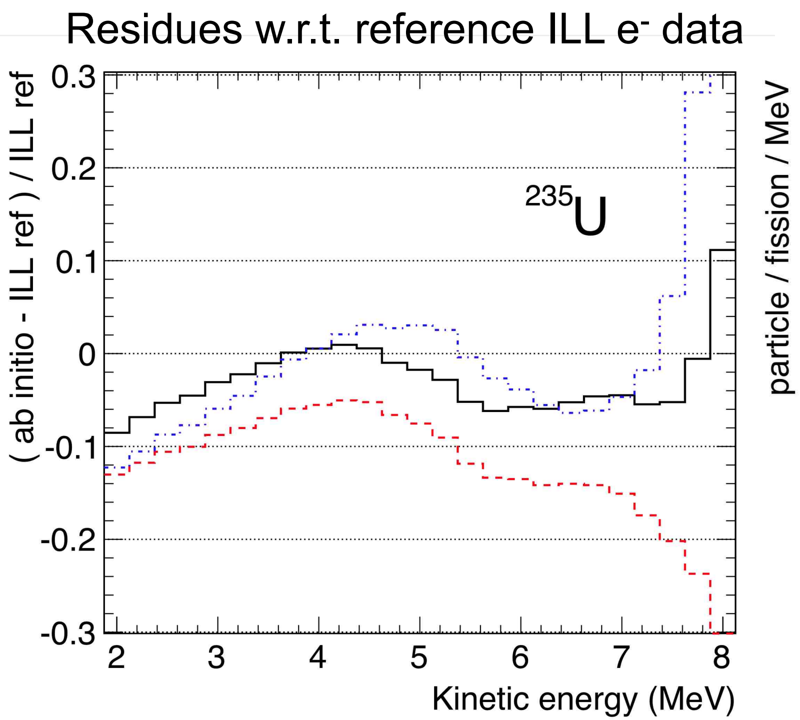
$$DN_n^{C,W}(E_n) \approx 0.65 \times (E_n - 4\text{MeV}) \quad \%$$

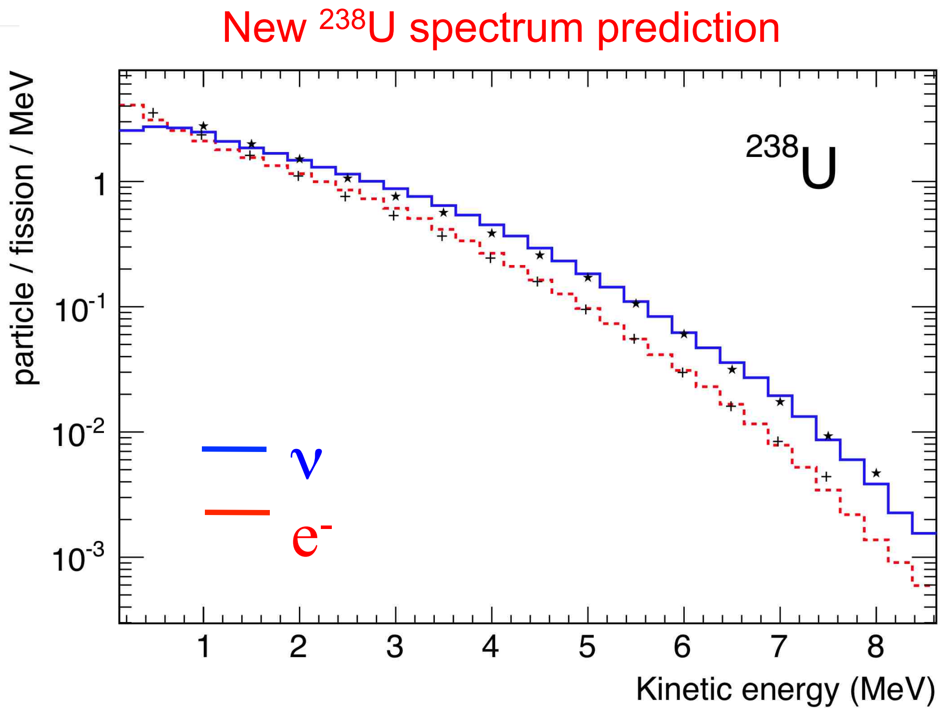


- **Conversion error from envelop of numerical studies**

The Full *Ab Initio* Attempt (electron data)

- MURE evolution code: core composition and off equilibrium effects
- BESTIOLE code: build up database of ~800 nuclei and 10000 β-branches

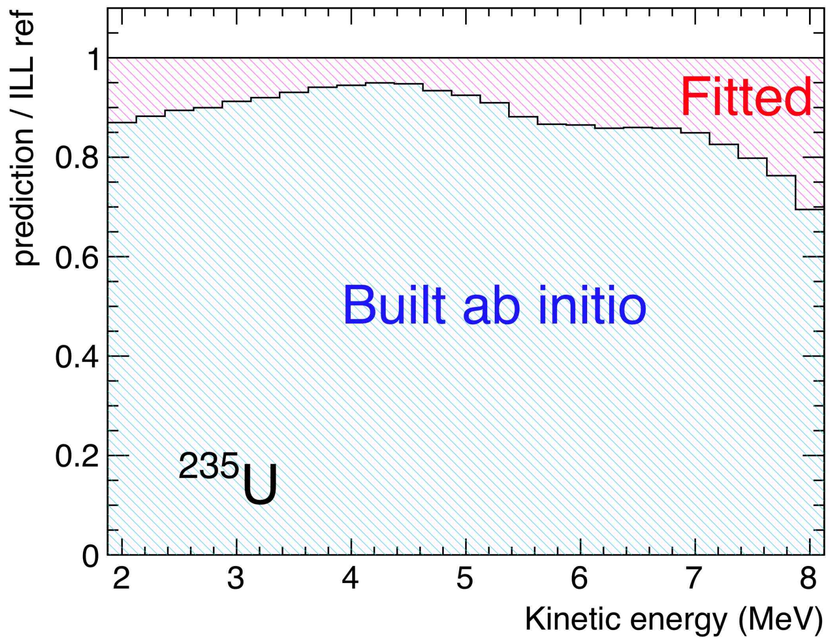


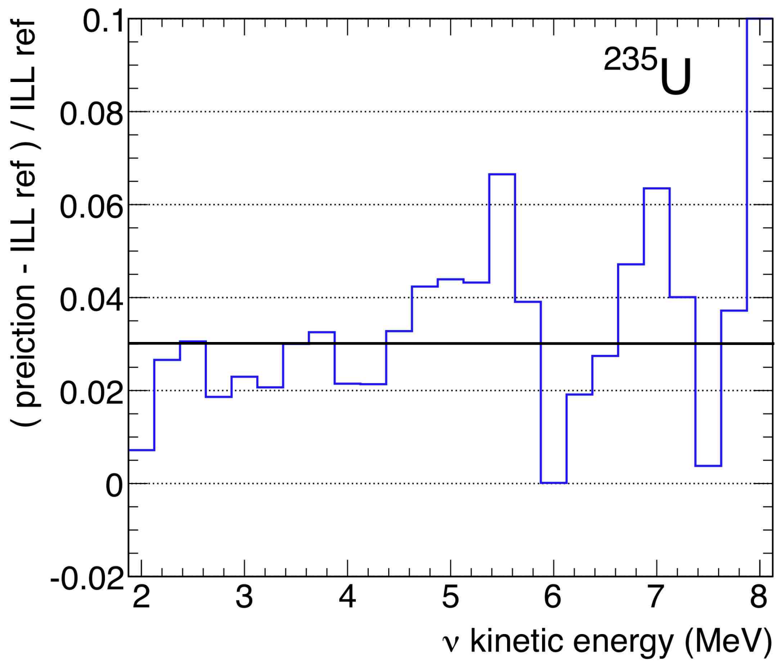


→ 95+/-5% of the spectrum reproduced but still not meeting required precision
→ Useful estimate of ^{238}U spectrum which couldn't be measured @ ILL
→ Measurement at FRMII ongoing (N. Haag & K Schreckenbach)

The New Mixed Conversion Approach

1. **SAME** ILL e- data Anchorage
2. Ab-Initio: “true” distribution of β-branches reproduces >90% of ILL e^- data.
3. Old-procedure: five effective anchorage-branches to the remaining 10%.



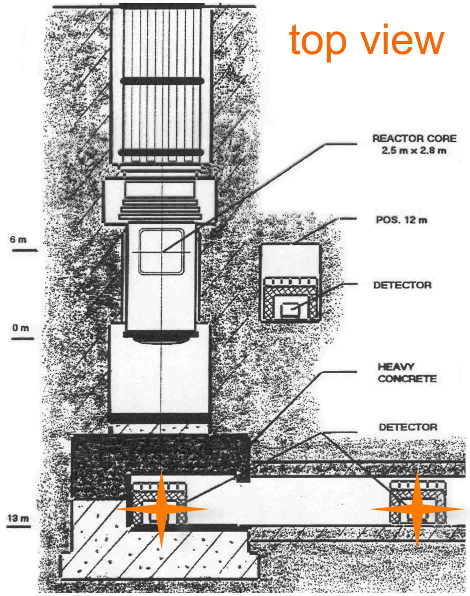


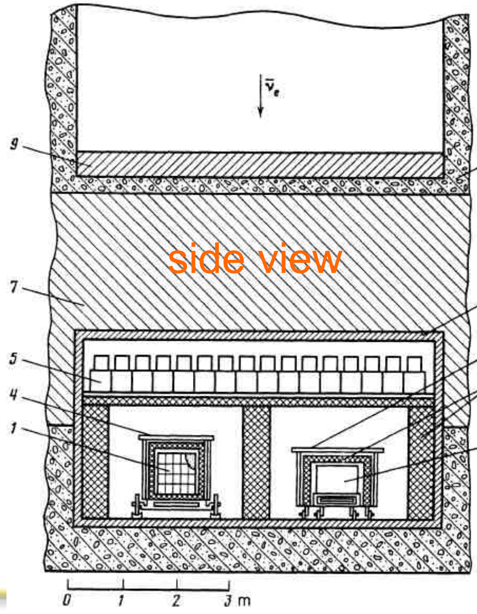
- **+3% normalization shift with respect to old ν spectrum**
- **Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)**
- **Stringent Test Performed – Origin of the bias identified**

ROVNO-88 (5 measurements, Sov Phys JETP67, 1988)

- Rovno, Russia, VVER, 1983-1986
- **Technology**
  - Integral detector with PE target containing ^{3}He counters, only neutrons are detected
  - Liquid Scintillator detector
- **Baselines**
  - 18 m & 25 m
- **Typical fuel composition:**

  60.7% ^{235}U, 27.7% ^{239}Pu, 7.4% ^{238}U, 4.2% ^{241}Pu,
- **Uncertainties:**
  - statistics: < 0.9%
  - systematics: 7- 8%
- **Correlated with:**
  - Rovno91 (integral measurement only),
  - Bugey-4
  - with each other

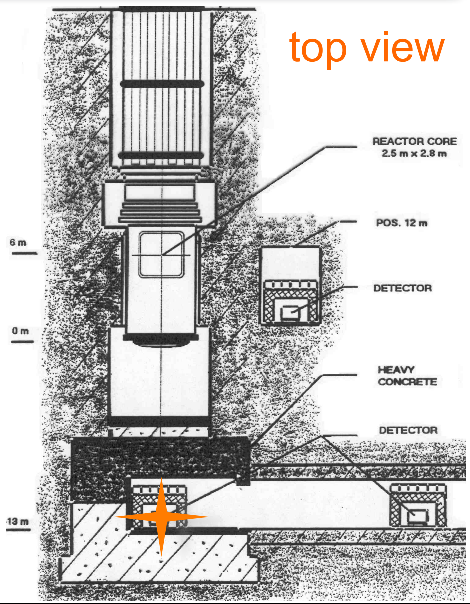


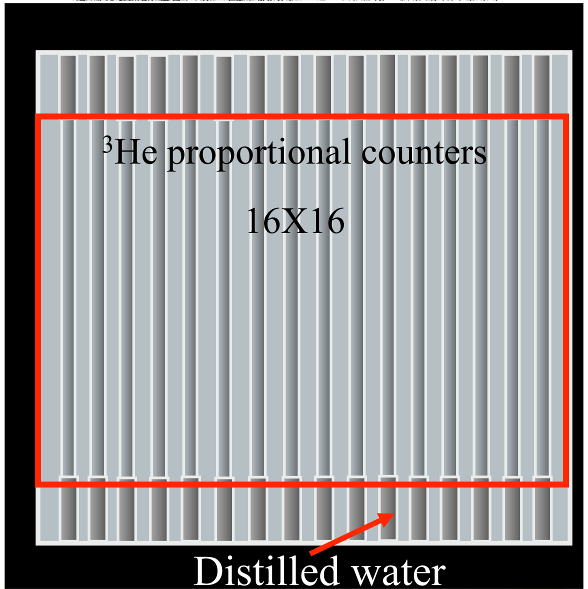


ROVNO-91 (JETP Lett., 54, 1991, 253)

- Rovno, Russia, VVER, late 80's
- **Technology:**
  - **Upgraded** integral detector : **water target** containing ^{3}He counters, only neutrons are detected
- **Baselines**
  - 18 m
- **Fuel composition:**

  61.4% ^{235}U, 27.4% ^{239}Pu, 7.4% ^{238}U, 3.8% ^{241}Pu
- **Uncertainties:**
  - statistics: <1%
  - systematics: 3.8%
- **Correlated with:**
  - Bugey-4 (same detector)
  - Rovno-88

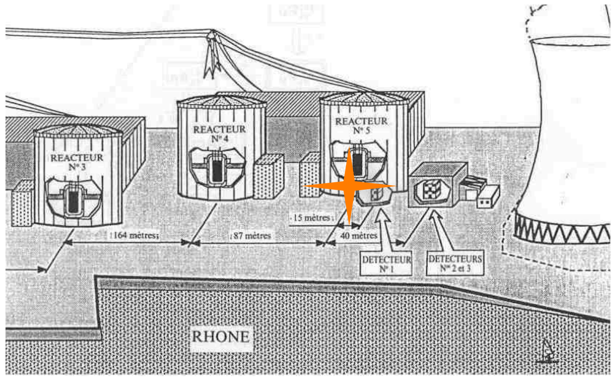


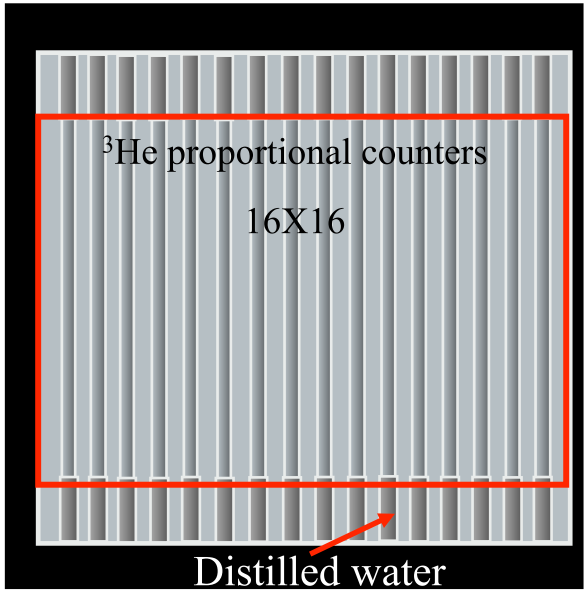


Bugey-4 (Phys. Lett. B338, 383, 1994)

- Bugey, France, PWR, early 1990s
- **Technology:**
  - Integral detector : water target containing ^{3}He counters, only neutrons are detected
- **Baseline**
  - **15 m**
- **Fuel composition:**

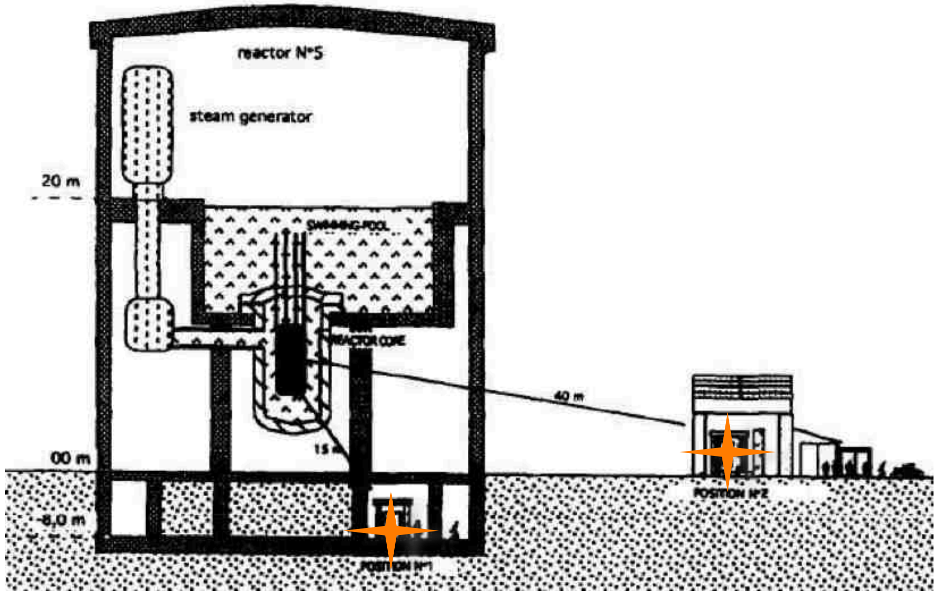
  53.8% ^{235}U, 32.8% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- **Uncertainties:**
  - statistics: 0.04%
  - systematics: 3% (most precise exp.)
- **Correlated with:**
  - ROVNO-91 (same detector)
  - ROVNO-88 (50% arb.)
- ***Experimental cross section used to normalize the CHOOZ experiment result***

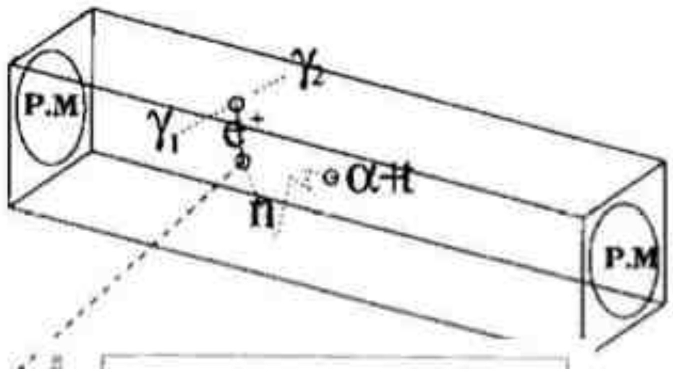




Bugey-3 (3 measurements, Nucl Phys B434, 504, 1995)

- Bugey, France, PWR, 80's
- **Technology**
  - ^{6}Li-LS segmented
- **Fuel composition typical of PWR**
  53.8% ^{235}U, 32.8%
  ^{239}Pu, 7.8% ^{238}U 5.6% ^{241}Pu
- **Baselines**
  - 14 m, 42 m and 95 m:
- **Uncertainties:**
  - statistics: 0.4%, 1.0%, 13.2%
  - systematics: 5.0%
- **Correlated with**
  - each other
- ***Stringent shape distortion analysis disfavoring sub-eV^2 oscillations***

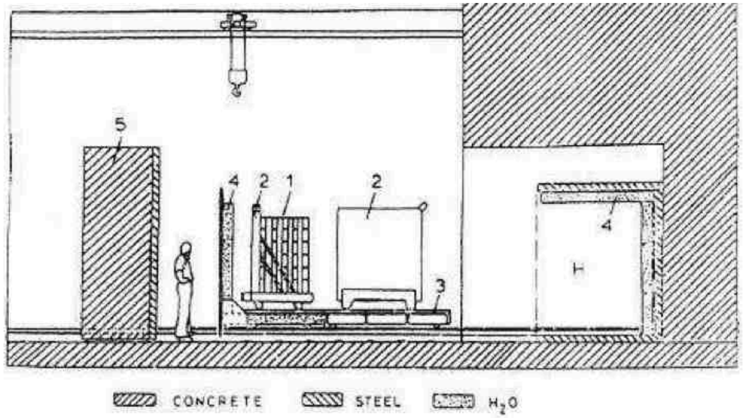


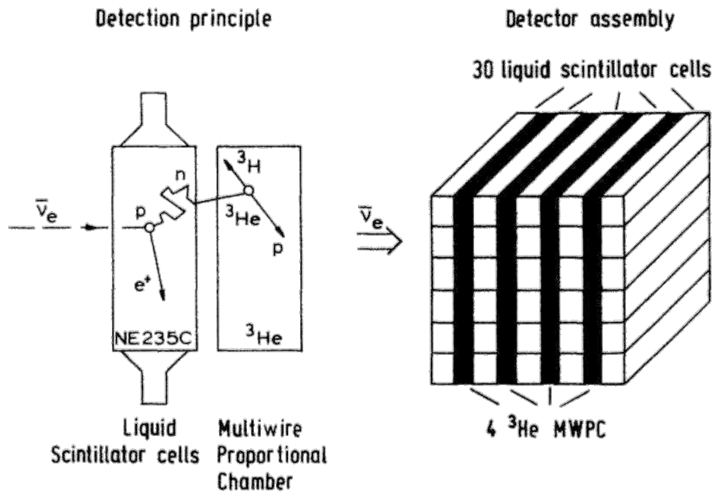


Goesgen (3 measurements, Phys Rev D34, 2621, 1986)

- Gösgen PWR, Switzerland, 1981-1984
- **Technology:**
  - liquid scintillator segmented detector + ^{3}He counters for neutron capture
- **Baselines:**
  - 37.9m, 45.9m, 64.7m
- **3 fuel compositions. Typical:**

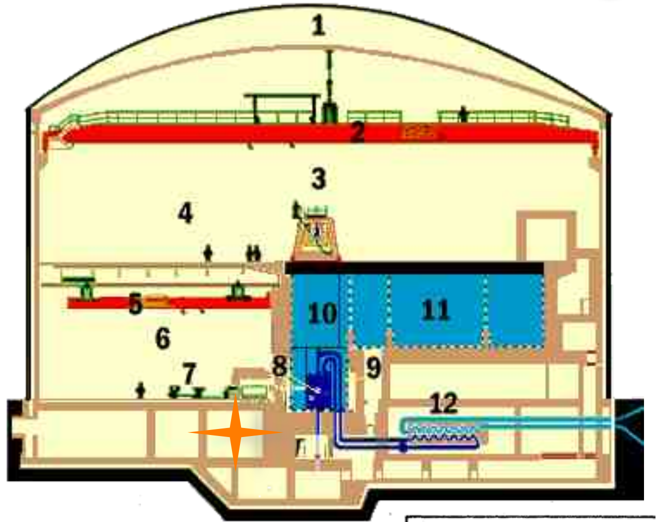
  61.9% ^{235}U, 27.2% ^{239}Pu, 6.7% ^{238}U, 4.2% ^{241}Pu
- **Uncertainties:**
  - statistics: 2.4%, 2.4%, 4.7%
  - systematics: 6.0%
- **Correlated with**
  - ILL (same detector)
  - each other

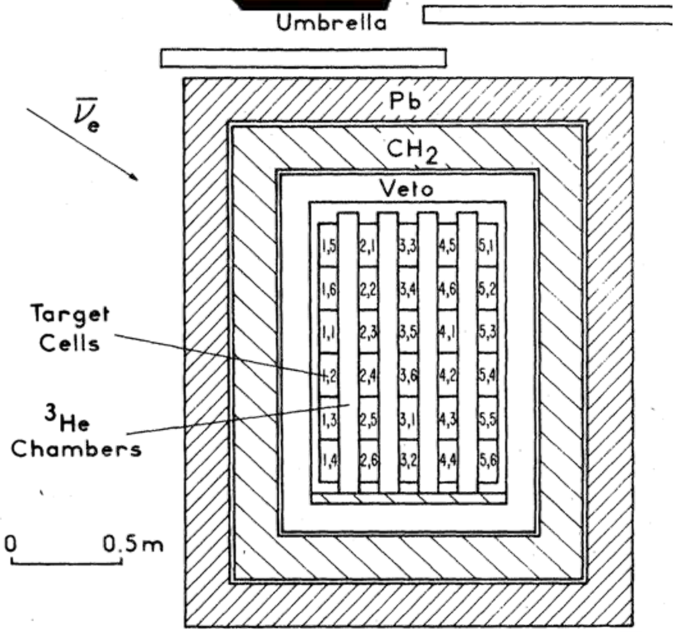




ILL-ν (Phys Rev D24, 1981, 1097)

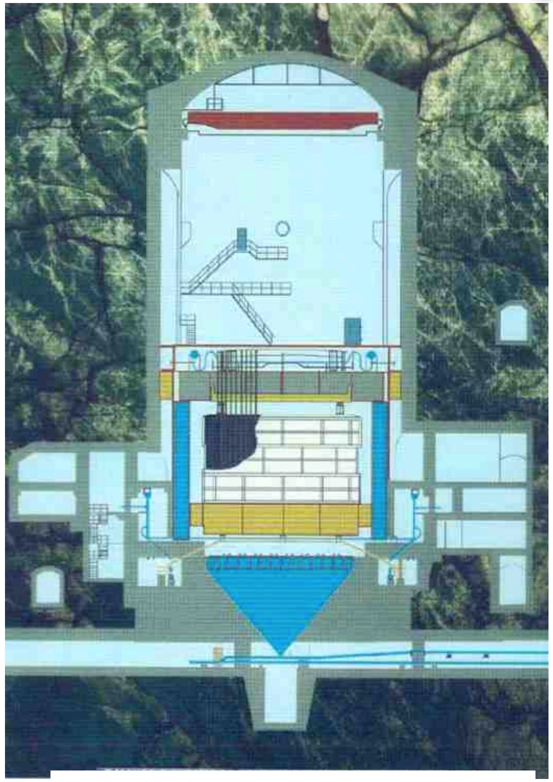
- ILL, Research Reactor, Grenoble, 80-81
- **Technology:**
  - Liquid scintillator segmented detector + ^{3}He counters for neutron capture
- **Baselines**
  - 8.76 (15) m
- **Fuel composition:**
  - almost pure ^{235}U
- **Uncertainties:**
  - statistics: 3.5%
  - systematics: 8.9%
- **Correlated with:**
  - Goesgen
- ***Data reanalyzed in 1995 by sub-group of collaboration to correct +10% upward shift in reactor power (underestimated for 10 y)***

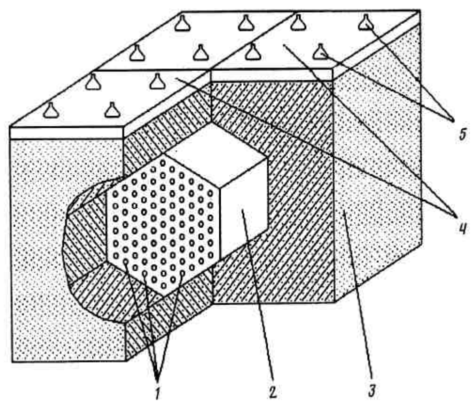




Krasnoyarsk (3 measurements, G.S. Vidyakin et al., JETP. 93, 1987)

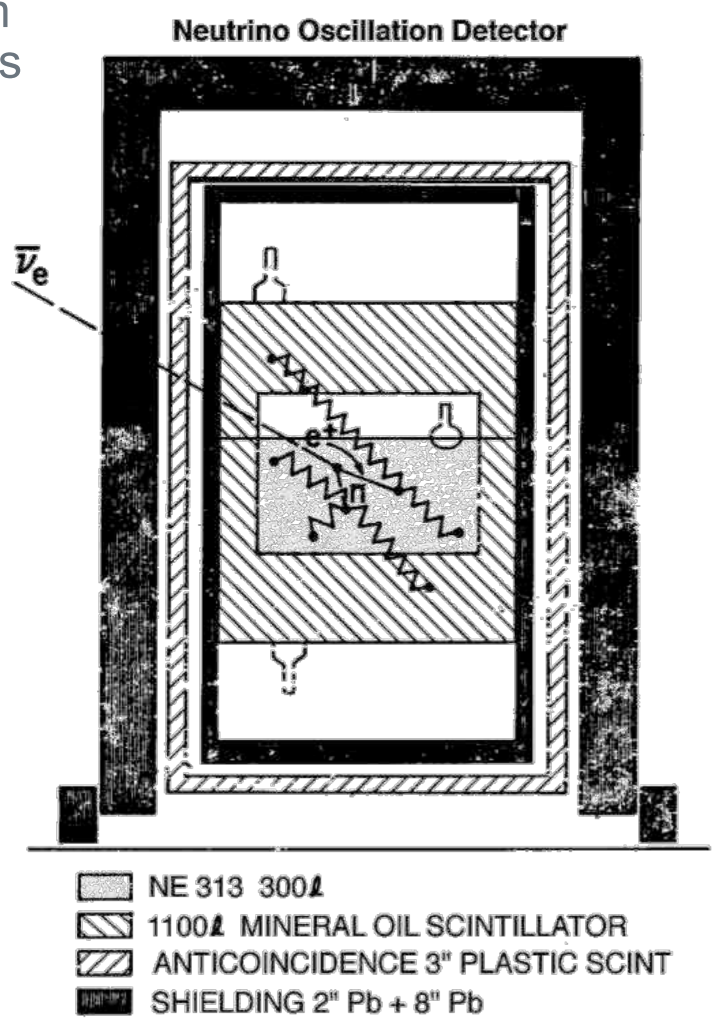
- Krasnoyarsk research reactor, Russia
- **Technology:**
  - Integral detector filled with PE+ ^{3}He counters
- **Baselines:**
  - 33 m, 92 m from 2 reactors (1987)
  - 57.3 m from 2 reactors (1994)
- **Fuel composition:**
  - mainly ^{235}U
- **Uncertainties (33 m, 57 m, 92 m)**:
  - statistics: 3.6%, 1%, 19.9%
  - systematics: 4.8% to 5.5% (corr)
- **Correlated with:**
  - each other





Savannah River Plant (2 measurements, PRD53, 6054, 1996)

- Savannah River, USA, long standing program initiated by F. Reines. Only the last two results are included in our work.
- **Technology:**
  - Liquid scintillator doped with 0.5% Gd
- **Baseline**
  - 18.2 m and 23.8 m
- **Fuel composition:**
  - Difference with pure ^{235}U below 1.5%
- **Uncertainties:**
  - statistics: 0.6% and 1.0%: 3.7%
  - systematics:
- **Correlated with:**
  - each other,
  - but the two results are is slight tension



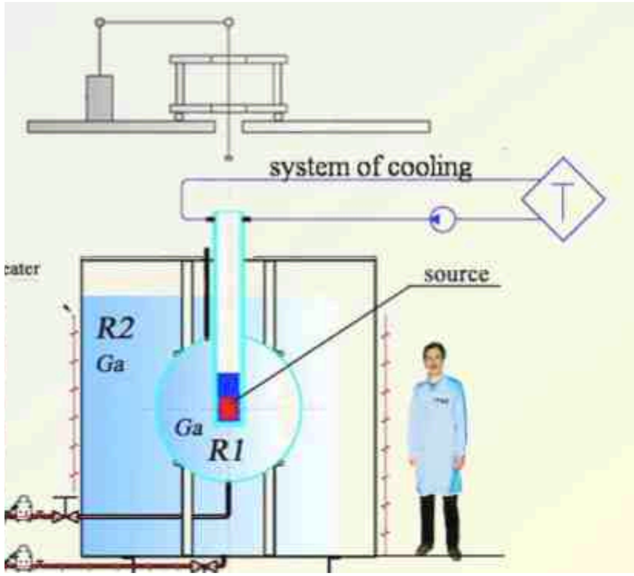
The Baksan Proposal (arxiv:1006.2103)

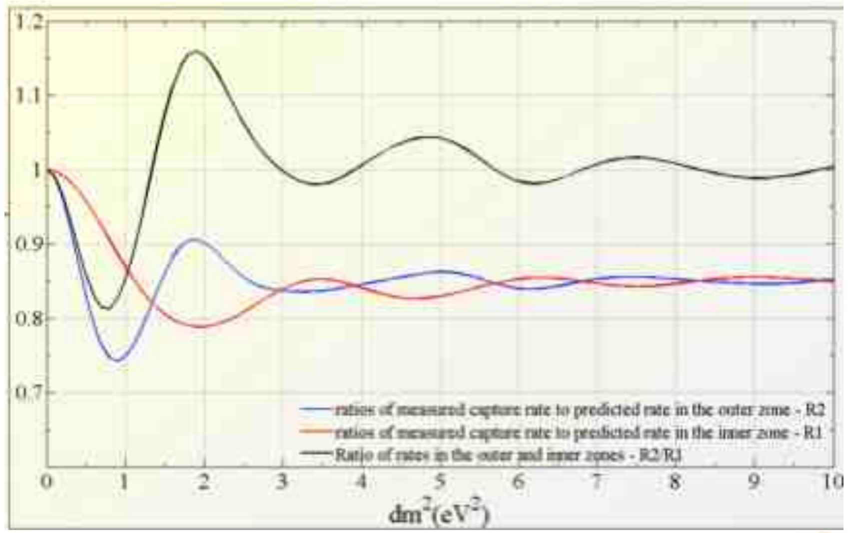
- New Gallium Experiment (well known technology)
  - Zone 1 : 8 t
  - Zone 2 : 42 t

- Source
  - ^{51}Cr - 3 Mci
  - 50 days irradiation in research reactor SM3

- Well known Backgounds
  - Solar neutrinos

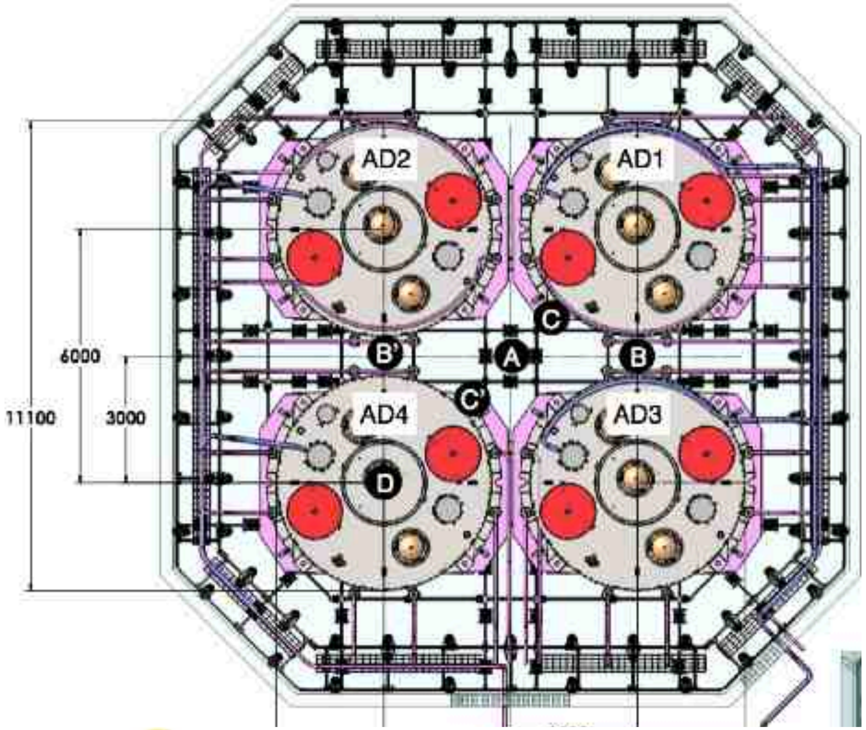
- Partial sensitivity to the reactor anomaly

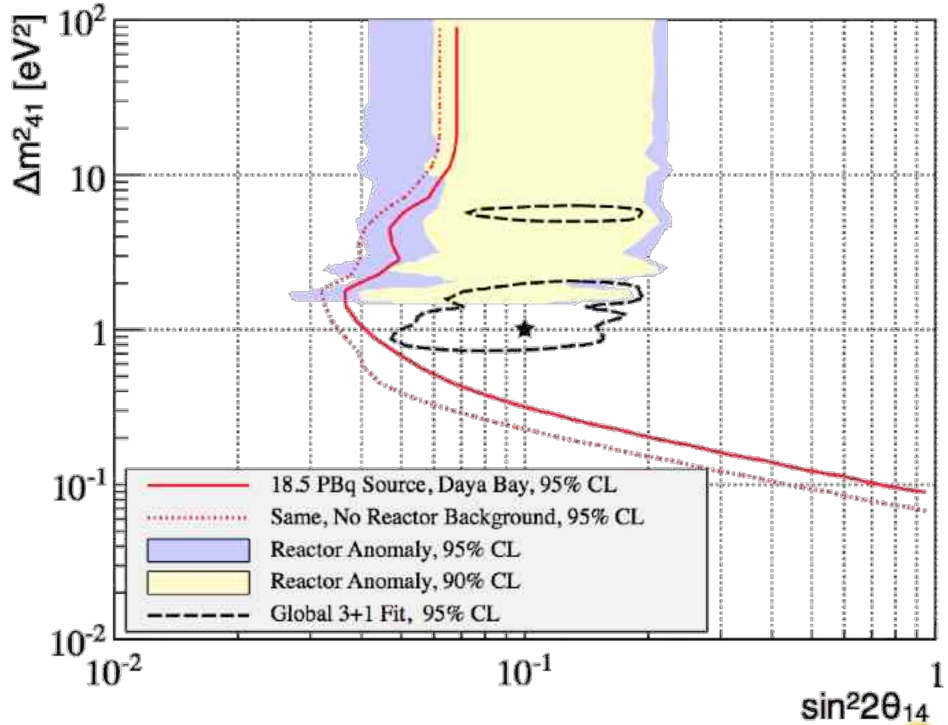




The Daya Bay Proposal

- D. Dwyer et al. Arxiv:1109.6036
- Proposal based on M. Cribier et al., Arxiv:1107.2335
- 500 kCi ^{144}Ce-^{144}Pr source in the Daya Bay FD Pool





The Borexino Proposal

- Significant Effort
- Sources
  - ^{51}Cr - >5 MCi
  - ^{90}Sr – Spent Fuel
  - ^{144}Ce – Spent Fuel
- Gallex ^{51}Cr still available in Saclay
- 3 Locations
  - A – Pit
  - B – Water Buffer
  - C – Center