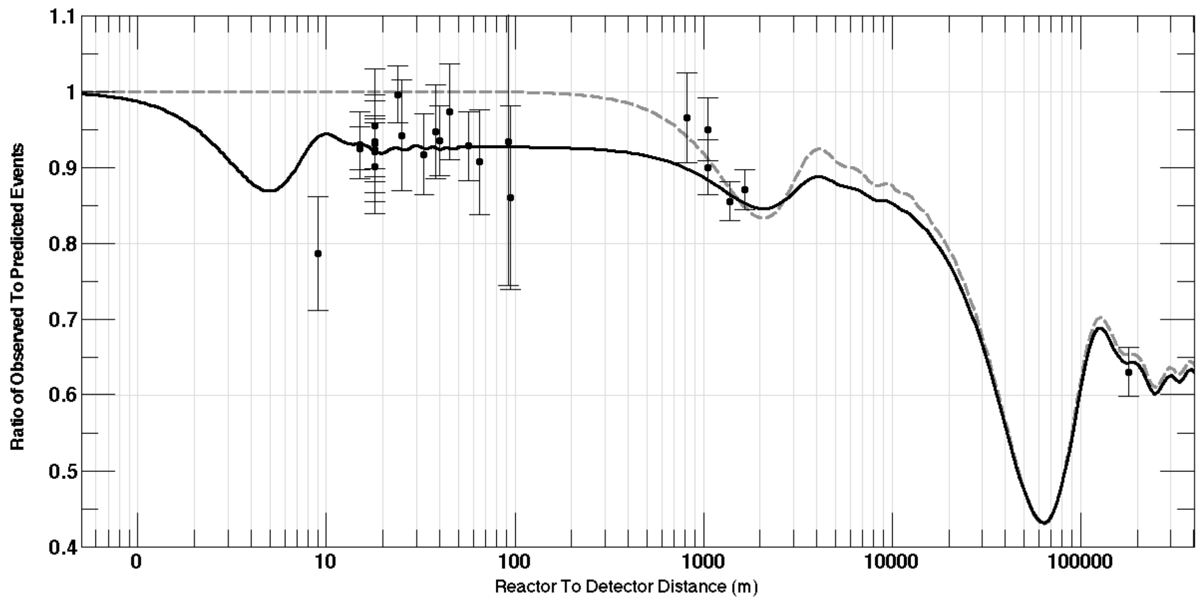
Reactor Neutrino Spectra, IBD Cross Section, and 4^{th} Neutrino

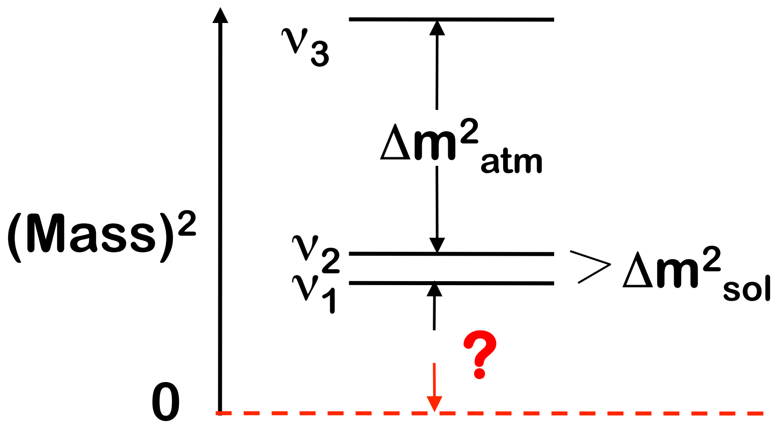
Neutrino Geoscience 2013, Takayama



Th. Lasserre
(CEA-Saclay)

Neutrino Physics: open questions

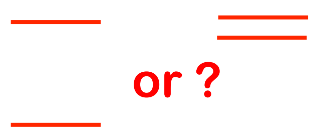
- What are the masses of the mass eigenstates ν_i?



} ν flavor change

} β decay, $\beta\beta0\nu$ decay, cosmology

- Is the spectral pattern



ν behavior in matter, $\beta\beta0\nu$, osc.

- Is there any conserved Lepton Number (Dirac or Majorana neutrino) ? $\beta\beta0\nu$

- Precise measurements of the leptonic mixing matrix?
- Do the behavior of ν violate CP?
- Is leptonic ~~CP~~ responsible for the matter-antimatter asymmetry?

} ν flavor change

- **Are there additional (sterile) neutrino states** ν flavor change, Cosmology

Reactor Neutrino Fluxes (Emitted)

Reactor Neutrinos: Overview

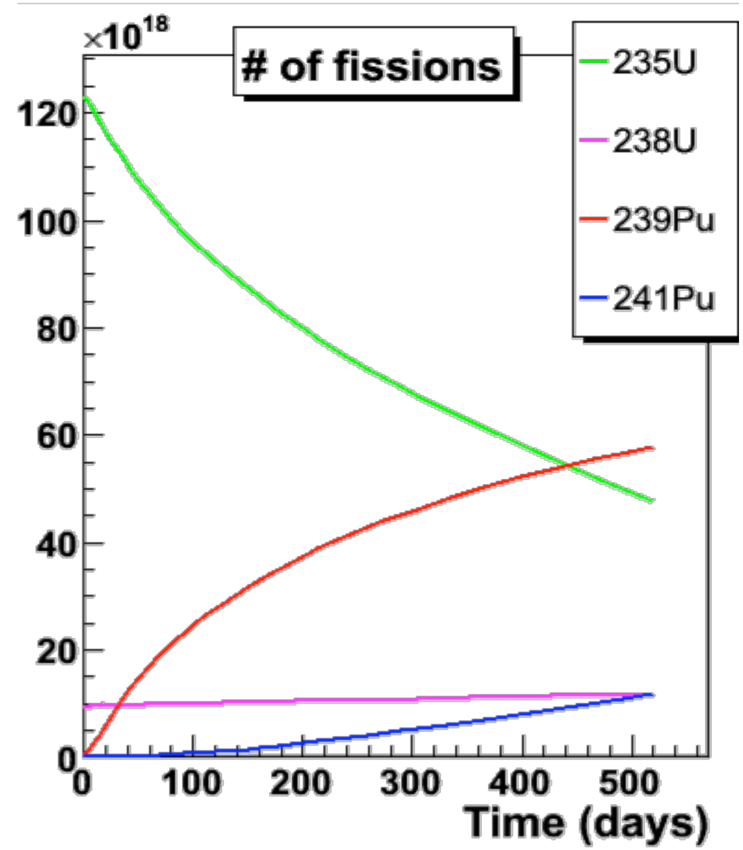
- **Electron antineutrinos emitted through Decays of Fission Products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu**
- **Nuclear reactors** : $1\ \mathrm{GW_{th}} \Leftrightarrow 2\ 10^{20}\ \bar{\nu}/\mathrm{s}$
- **Neutrino Luminosity** : $N_{\bar{\nu}} = \gamma(1+k)P_{\mathrm{th}}$

  γ: reactor constant
  k : fuel evolution correction (<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**

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

$$\updownarrow$$

  - Comparison of σ_f to prediction

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

New Reactor Neutrino Spectra

- **Accurate e^- measurements, ILL reactor (1980-89):**
  - Irradiation of ^{235}U, ^{239}Pu, ^{241}Pu foils in intense n_{th} flux at 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**

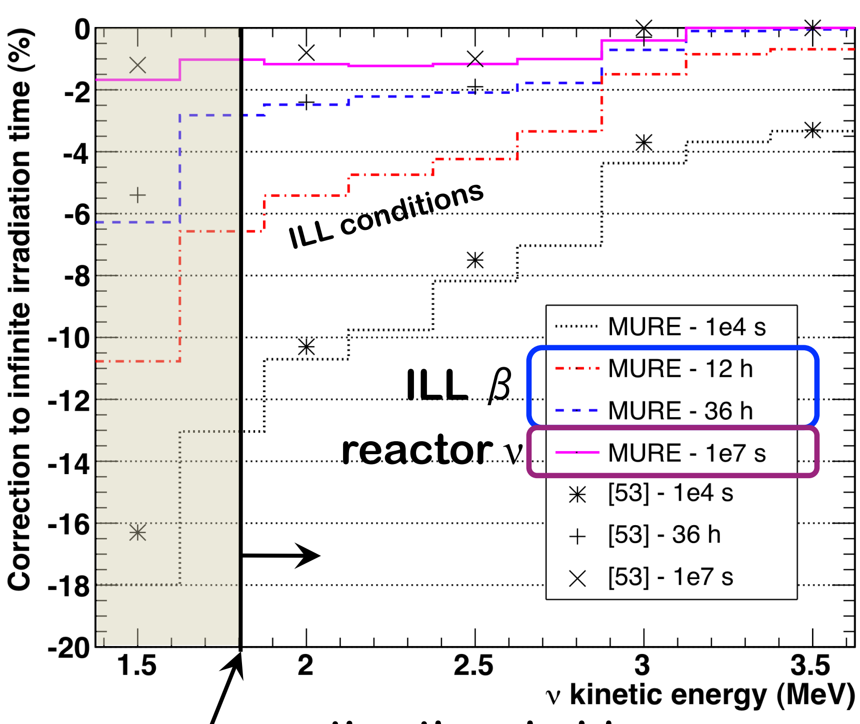
  - **Old Method:**
    - Fit integral e^- spectrum with a sum of 30 effective β-branches
    - Conversion of the effective branches to ν spectra
    - Effective correction on the ν-spectra ($A_{C,W}$)

  - **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 3.5% upward shift in energy-averaged neutrino fluxes with respect to old ν-spectrum for ^{235}U, ^{239}Pu, ^{241}Pu
    - Confirmed and improved by Phys. Rev. C 84, 024617 (2011)

Off-Equilibrium Correction

- **10% of fission products have a β-decay life-time long enough to keep accumulating after several days**
  - ILL electron data: 12 hours to 1.8 <u>days</u> irradiation time

  Whereas
  - Neutrino reactor experiments irradiation time >> 1 <u>month</u>



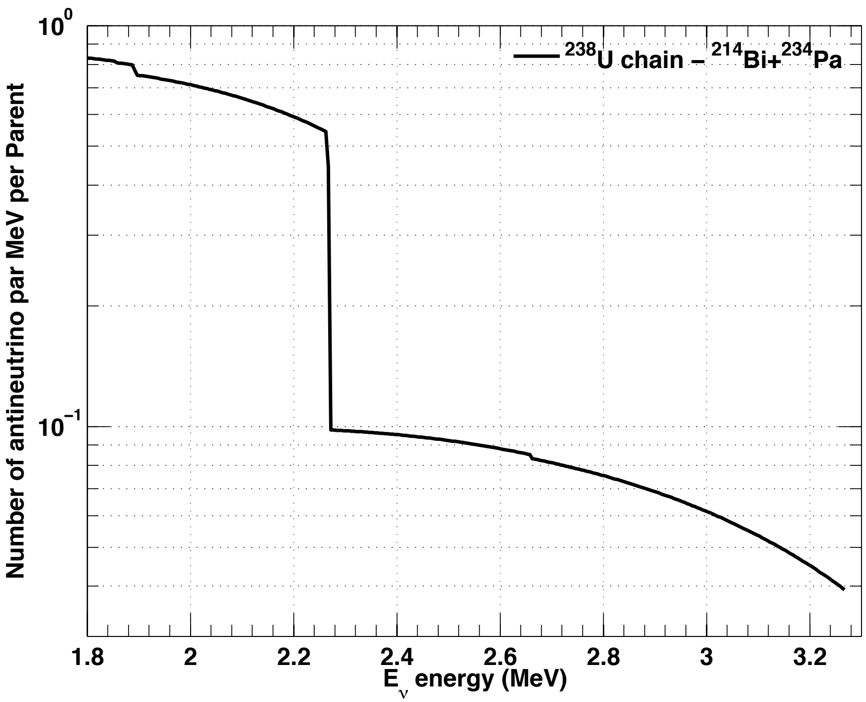
$\bar{\nu}_e + p \longrightarrow e^+ + n$

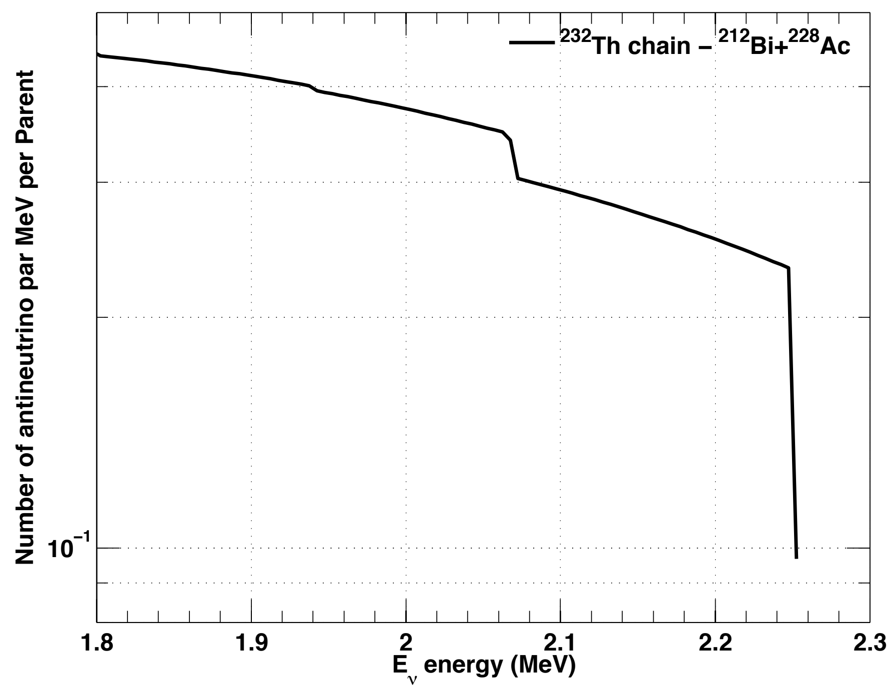
- About 20 isotopes with $t_{1/2}$ > 12 h with Q>1.8 MeV
- Extra upward shift of the reactor neutrino fluxes
  - Computed accounting for fuel history
  - About +1%

Geo Neutrino Fluxes (Emitted)

Geonu fluxes: ab initio computation

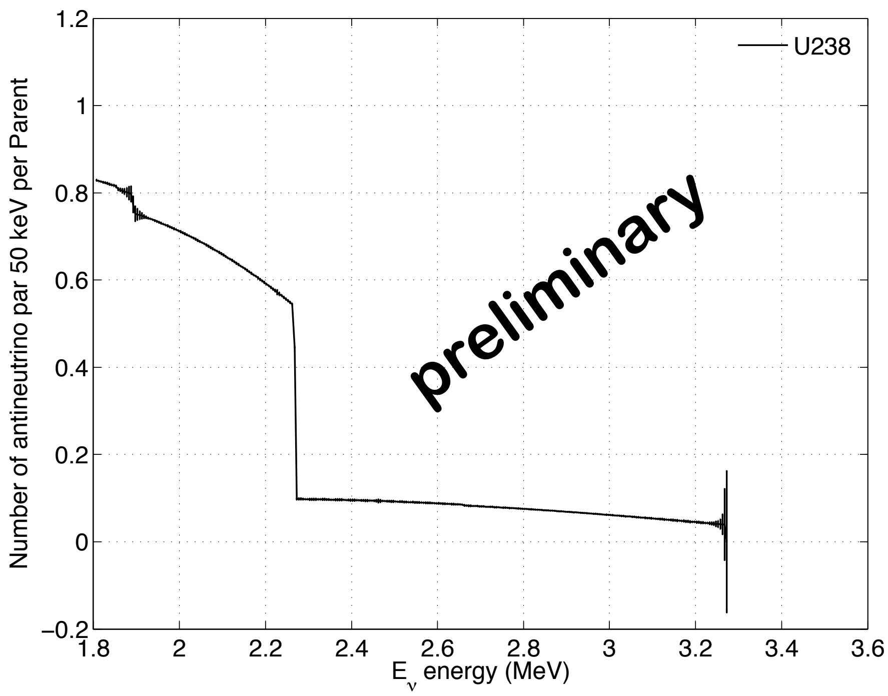
- Apply the work done for reactor neutrino spectra to geoneutrinos
  - Cross check with previous spectrum computation
  - Provide an spectrum error budget
  - Work in progress by S. Dye, T.L, and T. Mueller
  - Focus on E>1.806 MeV

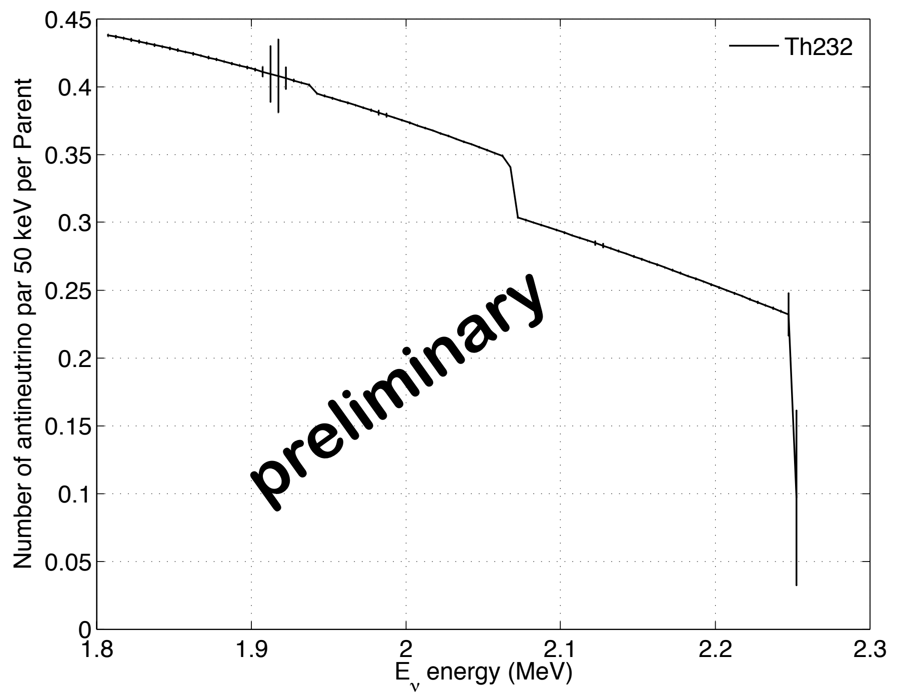




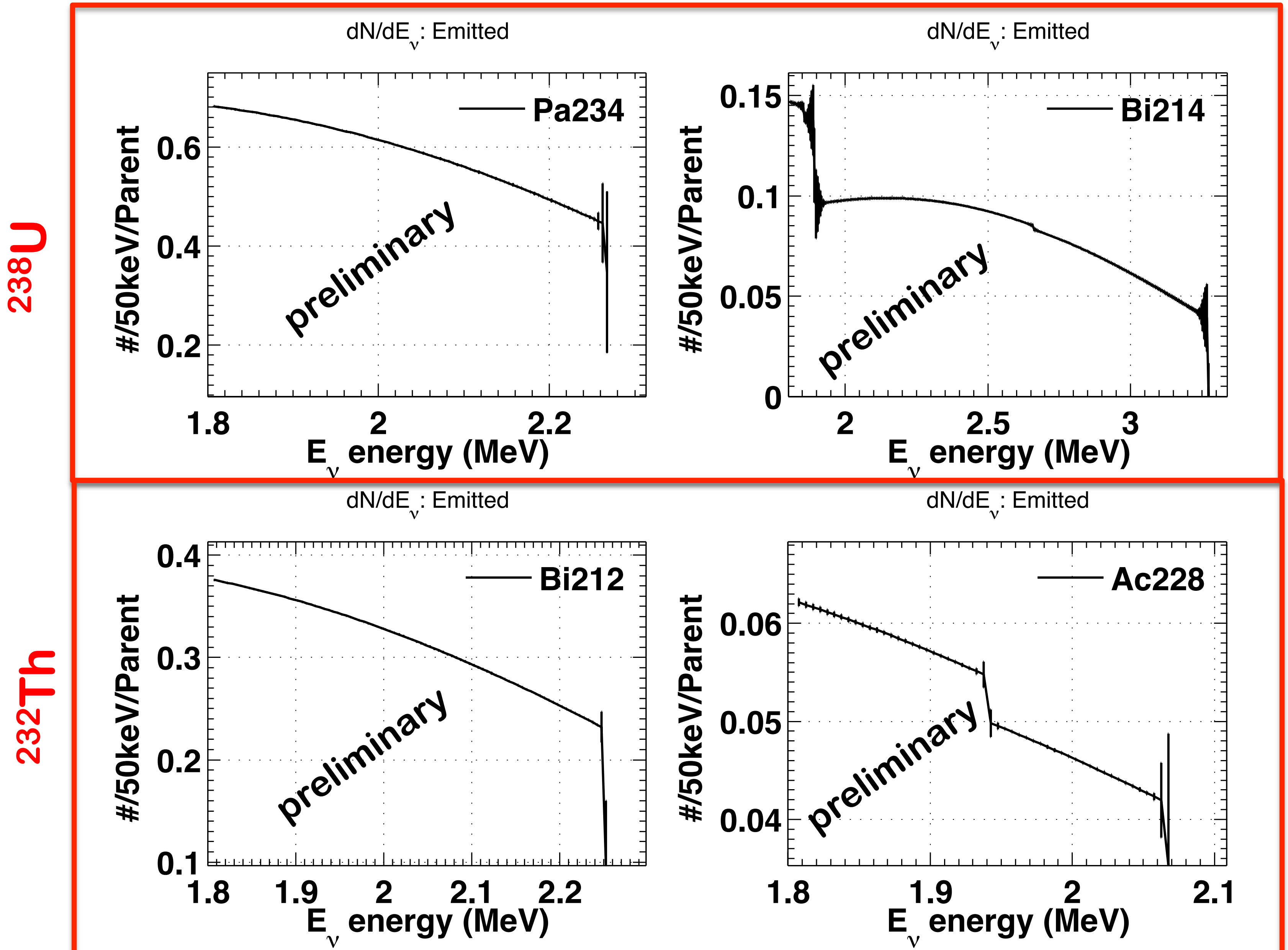
Geonu fluxes: Uncertainties

- Propagation of the errors quoted in nuclear databases
  - End Points
  - Branching Ratios
  - Error on Fermi theory correction not yet fully implemented





^{232}Th & ^{238}U above 1.806 MeV



Reactor & Geo Neutrino Rates (Detected)

(anti-)Neutrino Detection: IBD

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

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

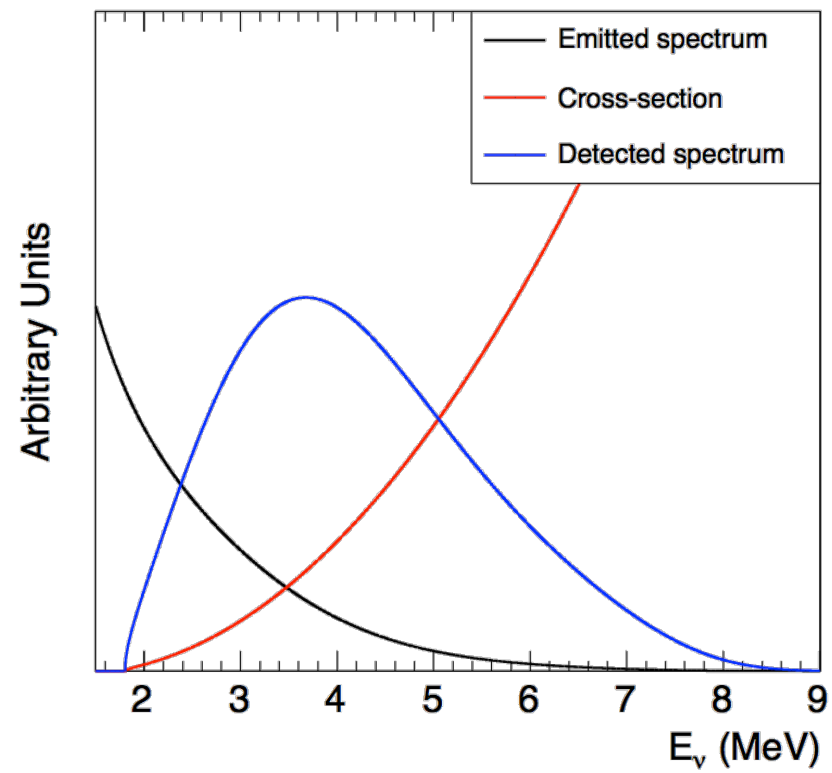
- **V-A cross section**

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

- **Outgoing e+ and incoming ν energies are related by**

$$E_\nu = E_e + \Delta + \frac{E_e(E_e+\Delta)}{M} + \frac{1}{2}\frac{(\Delta^2 - m_e^2)}{M}$$

- **Pre-factor κ (cm^2 MeV^{-2})**
  - neutron mean life (τ_n)
  - Axial/Vector coupling constant ratio (g_A/g_V)



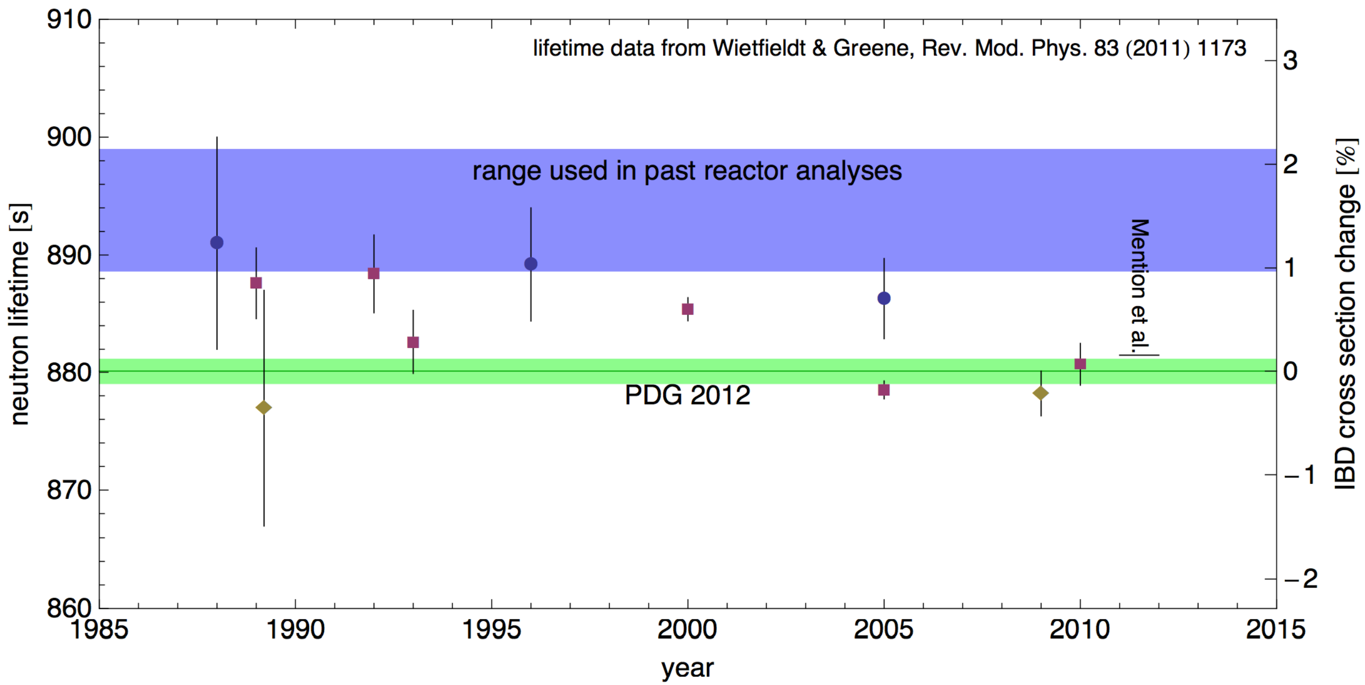
IBD Cross Section Prefactor: τ_n

- **The IDB cross section can be normalized to the β -decay of the free neutrons (τ_n):**

$$\kappa = \frac{2\pi^2}{m_e^5 f^R \tau_n}$$

- **f_R = 1.71465(15) the phase-space factor for β-decay of the free neutron, including outer radiative corrections**

- **τ_n measured values constantly decreased over the last 30 years**



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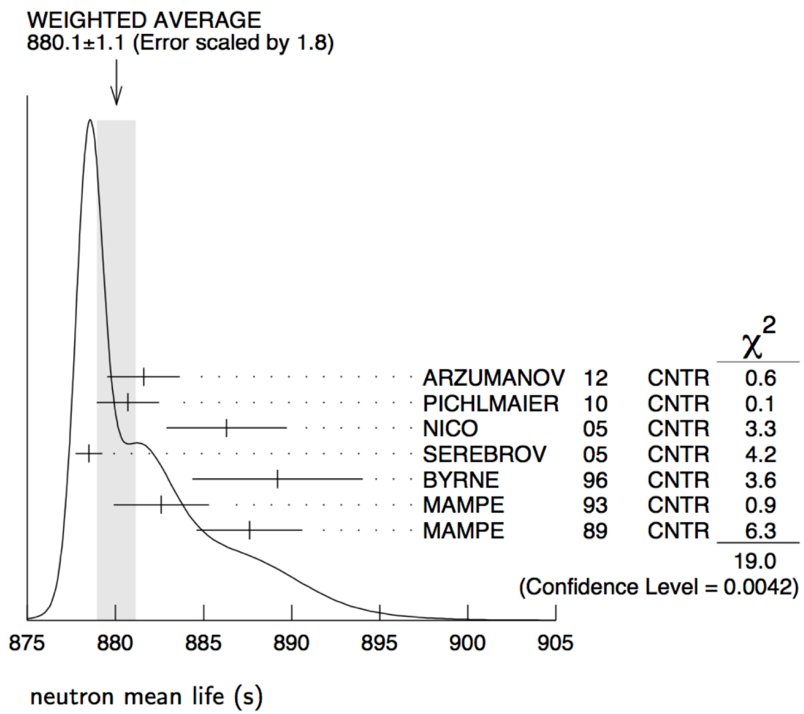
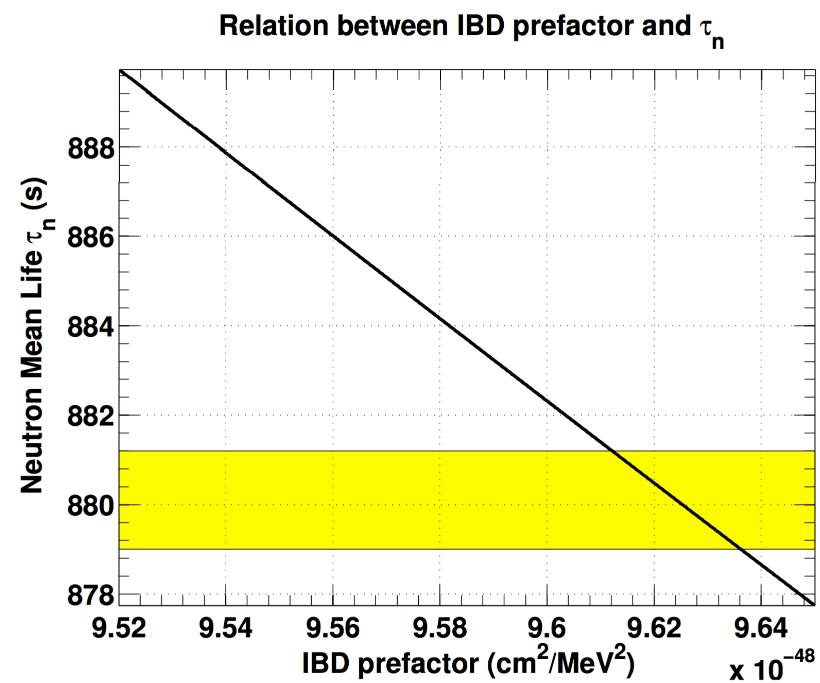
IBD Cross Section Prefactor: τ_n

- The new world average settled to τ_n =880.1±1.1 s (PDG 2012)

→ $\kappa = 9.624 \pm 0.012\ 10^{-48}\ \mathrm{cm^2/MeV^2}$





IBD Cross Section Prefactor: g_A/g_V

- But the IDB cross section can also be normalized with $\lambda = g_A/g_V$

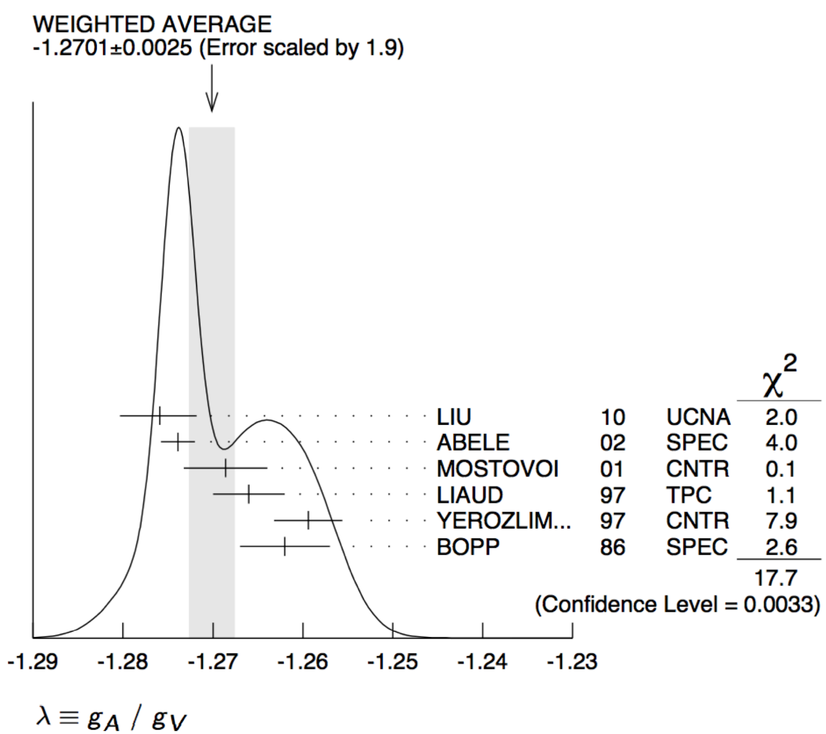
$$\kappa = \frac{G_F^2 cos^2\theta_C}{\pi}(1+\Delta^R_{\mathrm{inner}})(1+3\lambda^2)$$

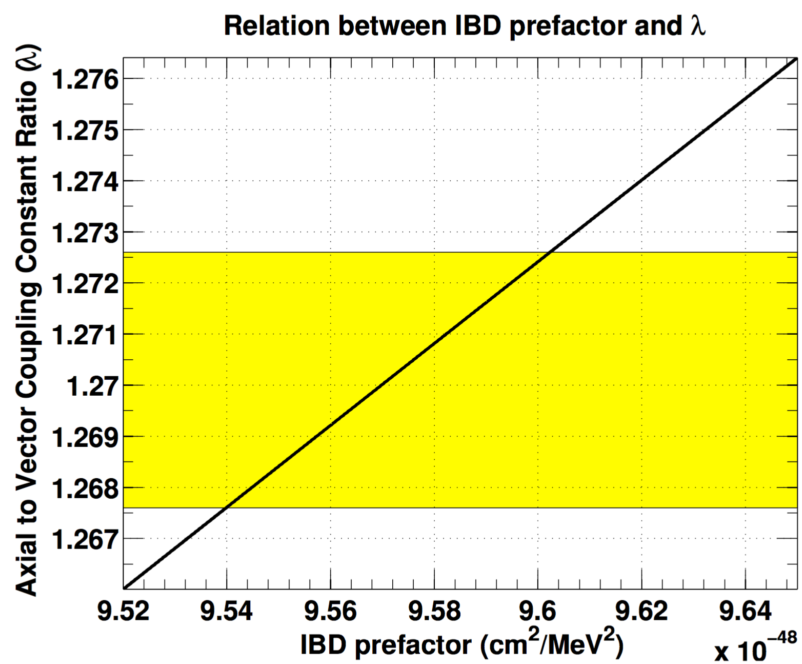
- G_F is the Fermi constant
- θ_C the Cabibbo angle ($\cos\theta_C = 0.9743$)
- $\Delta_{Rinner} = 0.024$ the inner radiative corrections
- $\lambda = 1.2701 \pm 0.0025$ the form factor ratio of the axial to vector coupling constant

IBD Cross Section Prefactor: g_A/g_V

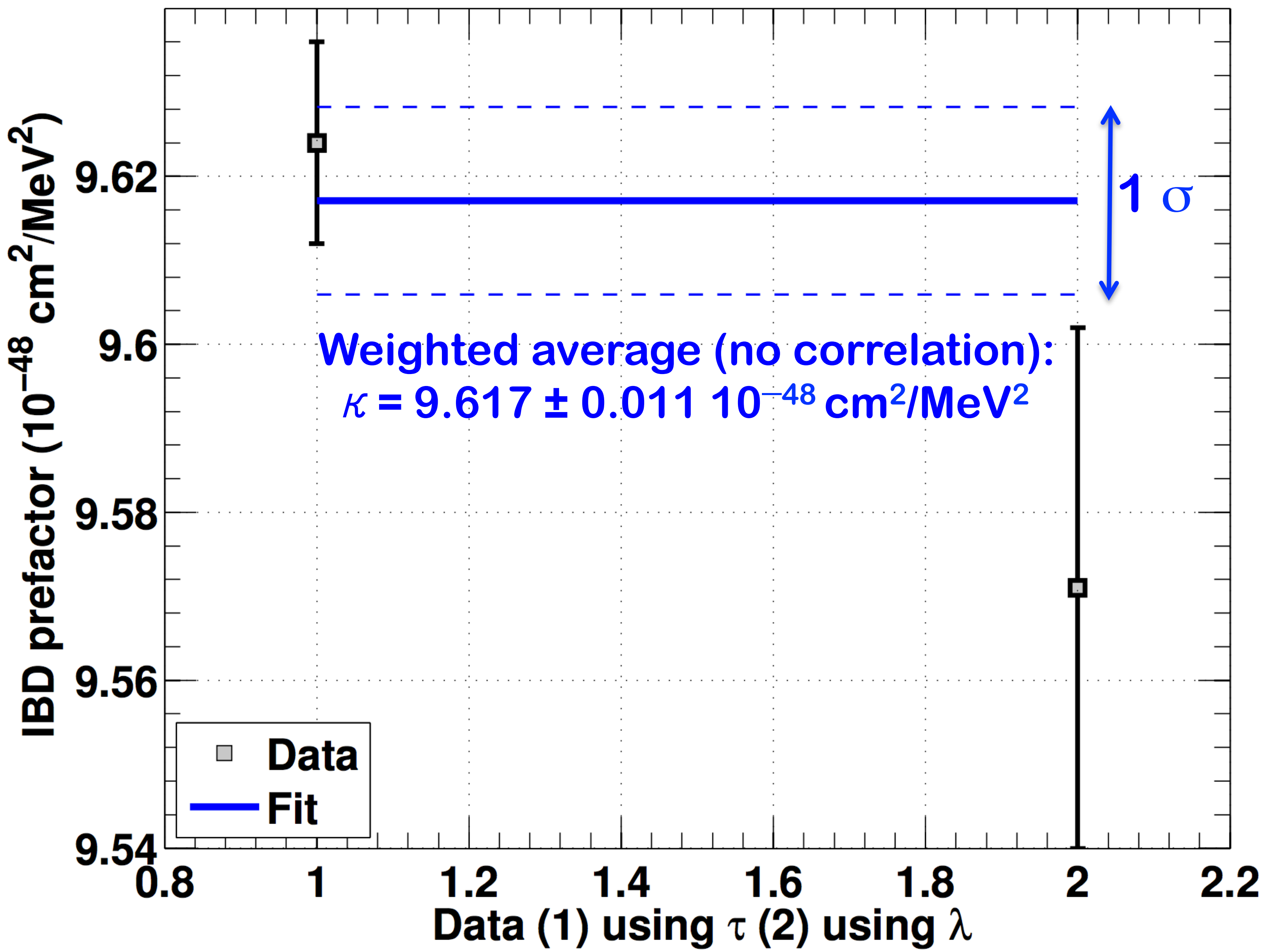
- The latest world average is 1.2701 ± 0.0025 (PDG 2012)

→ κ = 9.571 ± 0.031 10^{-48} cm^2/MeV^2



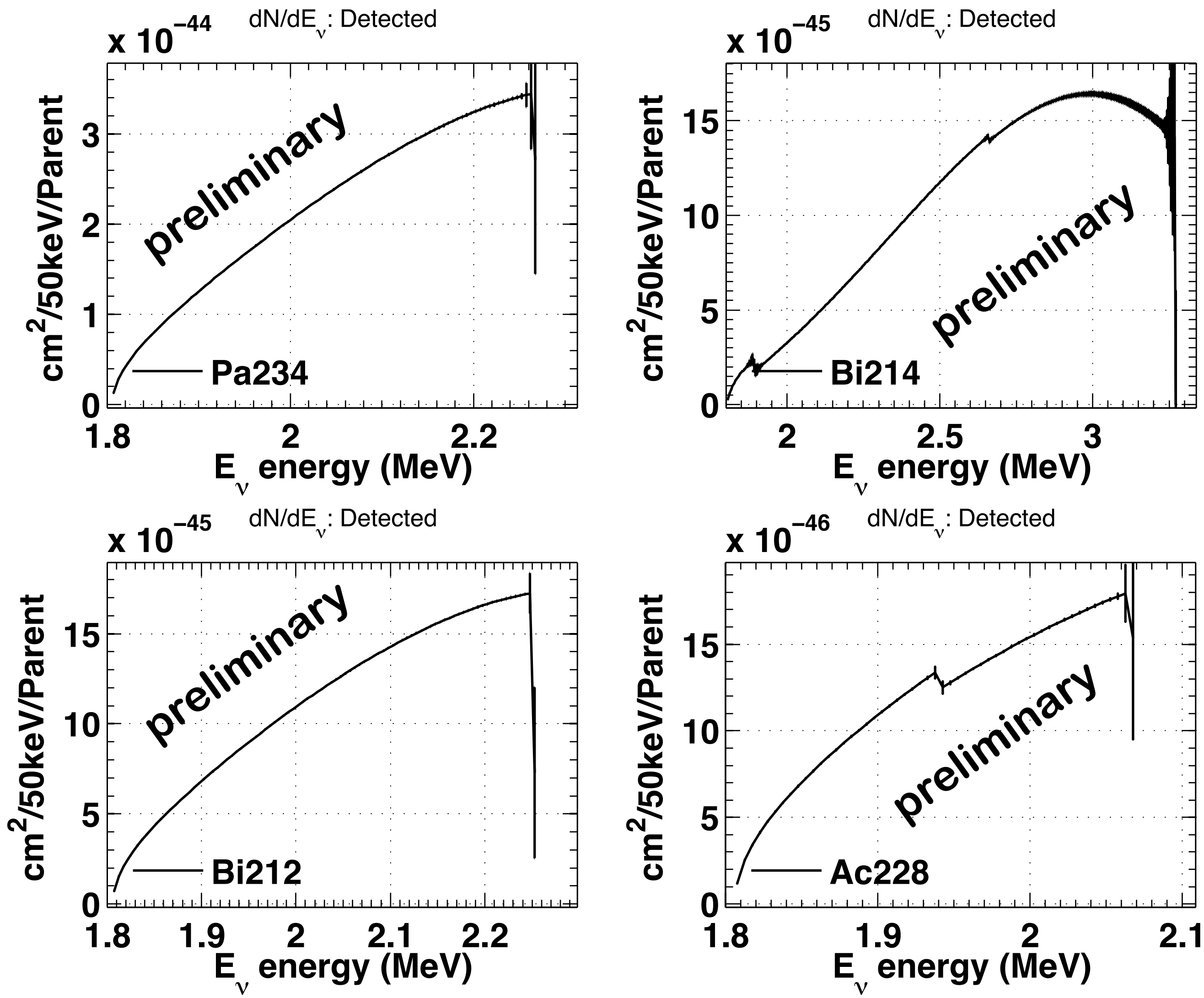


IBD: New Prefactor Prescription?



Application to Geoneutrinos

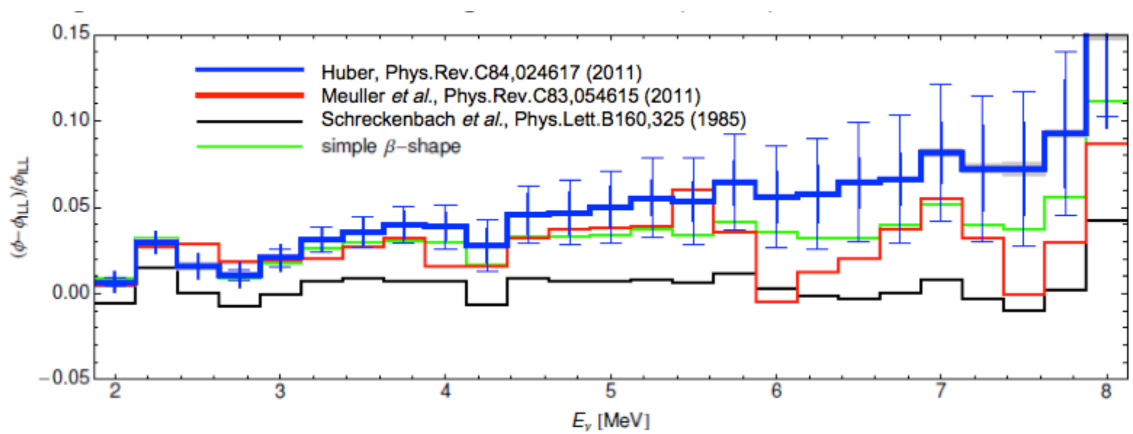
Include both Emission and Detection Uncertainties



Reactor Anomaly

Reactor Anomaly – 2012 Update –

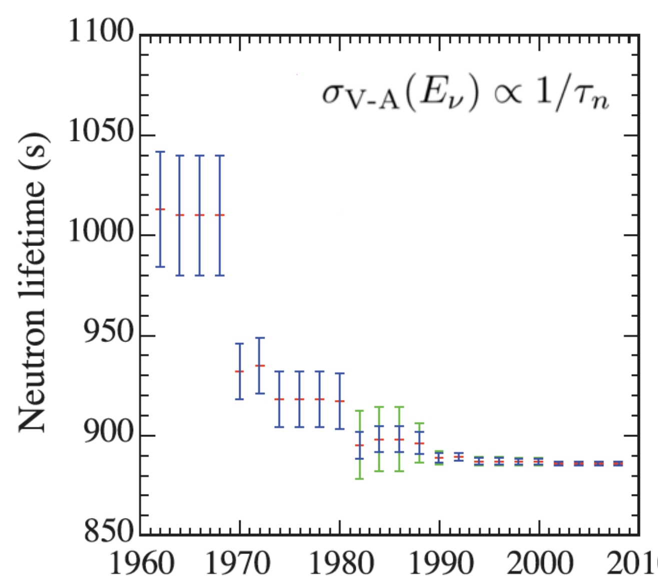
i) $\nu_{emission}$: Improved reactor neutrino spectra → <u>+3.5%</u>



PRC83, 054615 (2011)

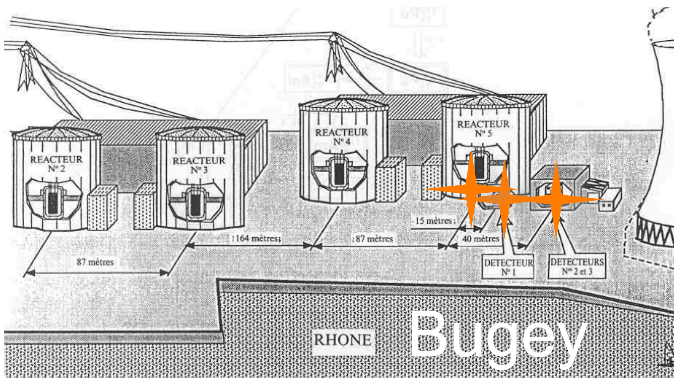
PRC84, 024617 (2011)

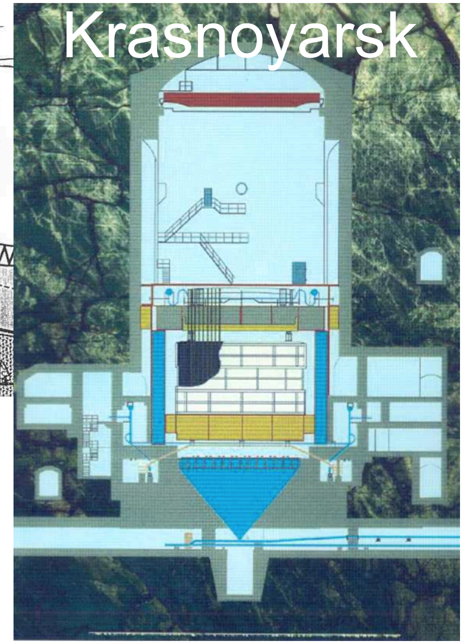
ii) $\nu_{detection}$: Reevaluation of σ_{IBD} → <u>+1%</u>
Evolution of the neutron life time with $\kappa = 9.610\ 10^{-48}\ \mathrm{cm^2/MeV^2}$

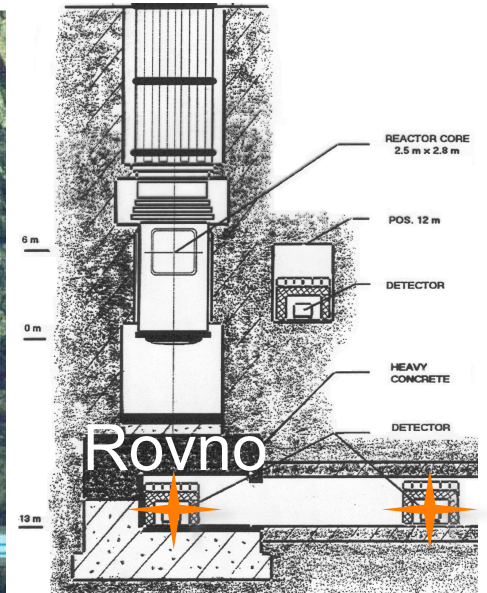


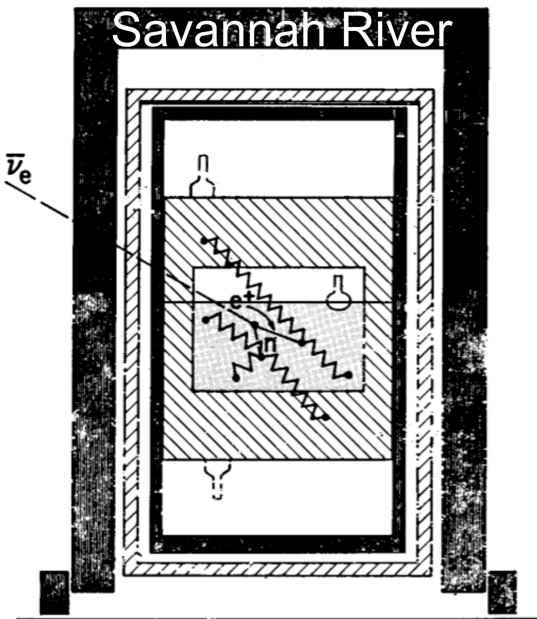
iii) $\nu_{detection}$: Accounting for long-lived isotopes accumulating in reactors → <u>+1%</u>

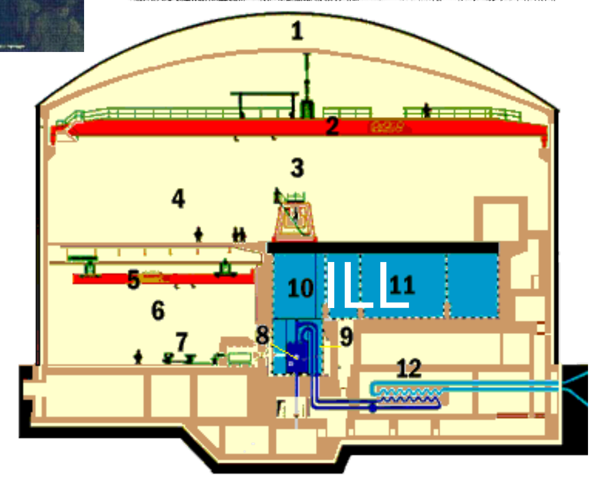
19 Experimental Results below 100m









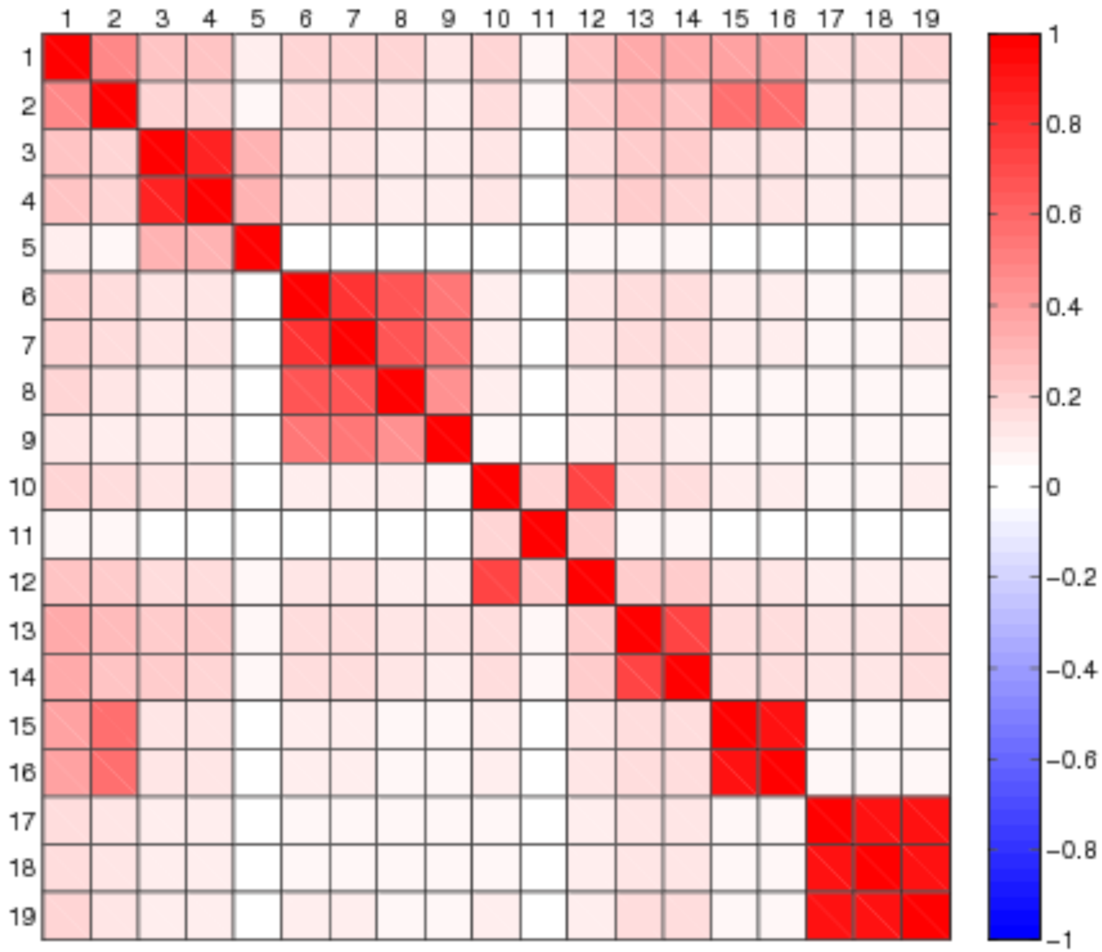


Measured cross sections / fission taken at their face values

But 19 correlated results…

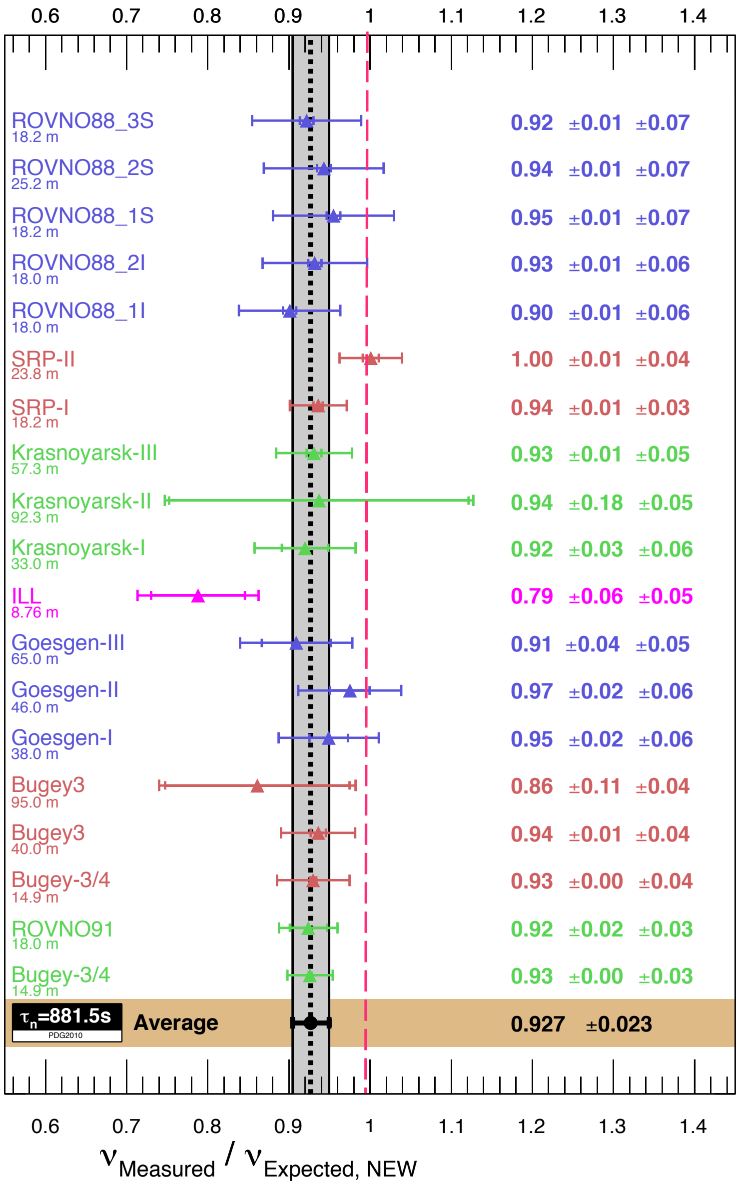
$\vec{R}$	$\Sigma_{tot.}$ (in %)	$\Sigma_{cor.}$ (in %)
Bugey-4 15m	3.0	3.0
Rovno91 18m	3.9	3.0
Bugey-3 15m	5.0	5.0
Bugey-3 40m	5.1	5.0
Bugey-3 92m	14.1	5.0
Goesgen 38m	6.5	6.0
Goesgen 45m	7.6	6.0
Goesgen 65m	9.5	6.0
ILL 9m	5.1	4.1
Krasno 33m	5.1	4.1
Krasno 92m	20.3	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7	3.7
SRP II 25m	3.8	3.7
Rovno88 1I 18m	6.9	6.9
Rovno88 2I 18m	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 1.8% systematic on ILL β-spectra normalization uncertainty
- The experiment block correlations come from identical detector, technology or neutrino source

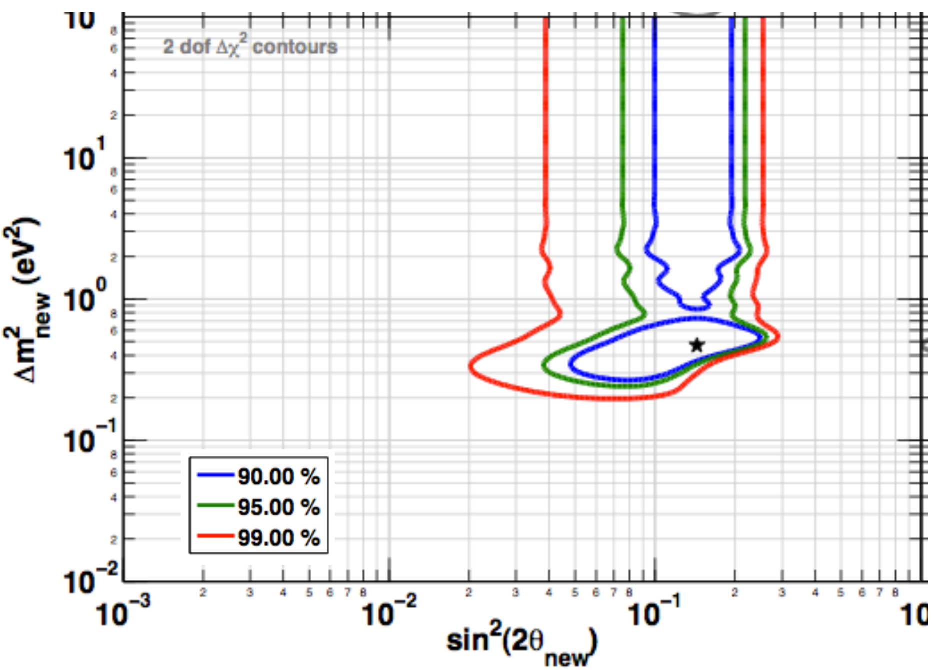
The reactor anomaly



- 19 experiments reanalyzed
- 7% deficit wrt the new prediction
  - ≈3%: reevaluation of emitted flux
  - ≈3%: reevaluation of
    - IDB cross section parameters
    - Neutron lifetime
    - Accounting for off eq. effect
- 99.7 % C.L. deviation from unity
- Artifact or new physics?

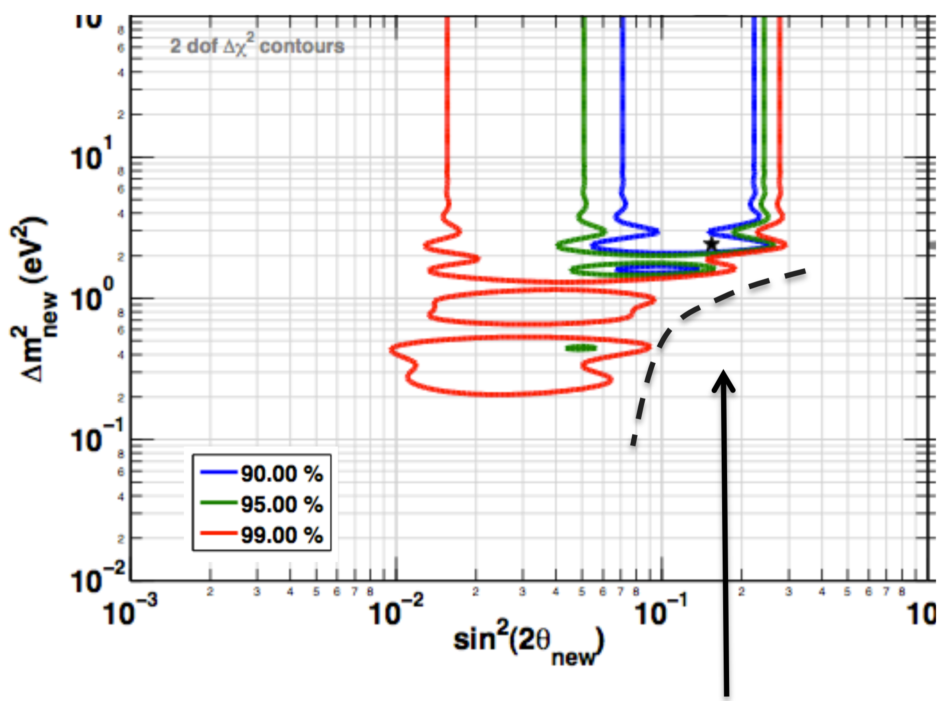
The 4^{th} neutrino hypothesis

Rate Only Analysis



- Best Fit at $\Delta m^2_{new} \approx$ few 0.1 eV^2

Rate + Shape Analysis

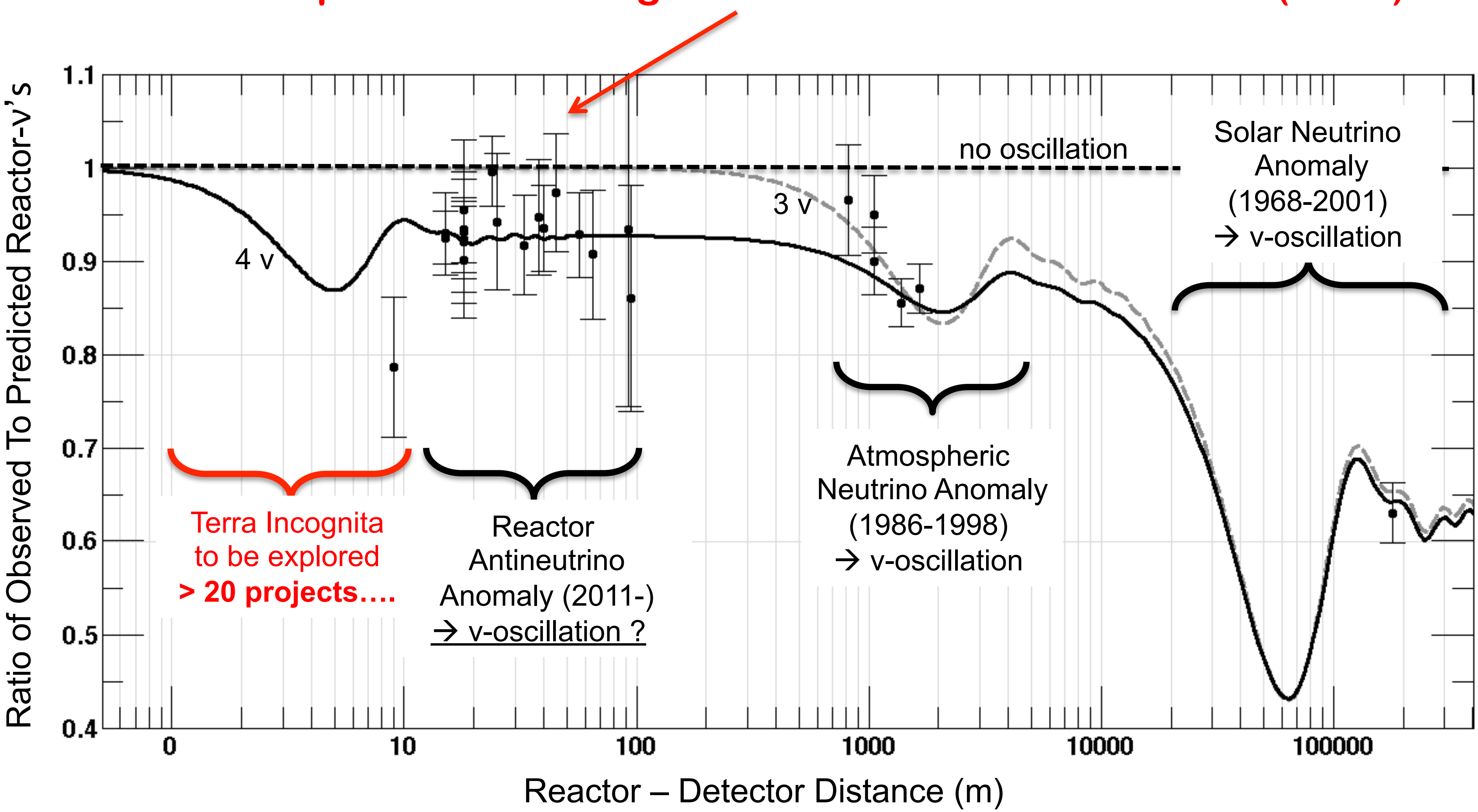


- Bugey-3 40m/15m $E_{spectrum}$ ratio
→ No energy spectrum distortion
→ large PWR core extension

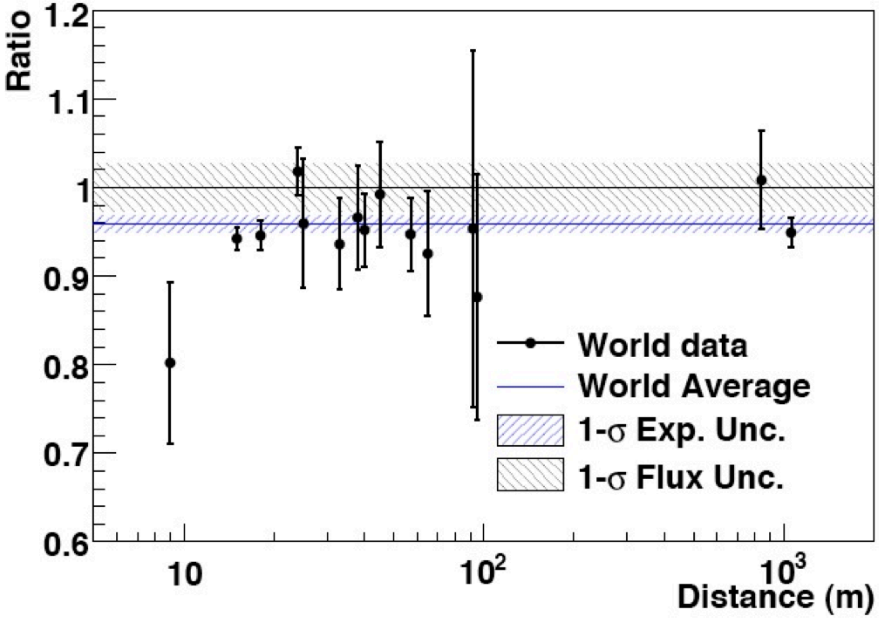
- Best Fit at $\Delta m^2_{new} > 1$ eV^2

The Reactor Anomaly

- **Observed/predicted averaged event ratio: R=0.927±0.023 (3.0 σ)**

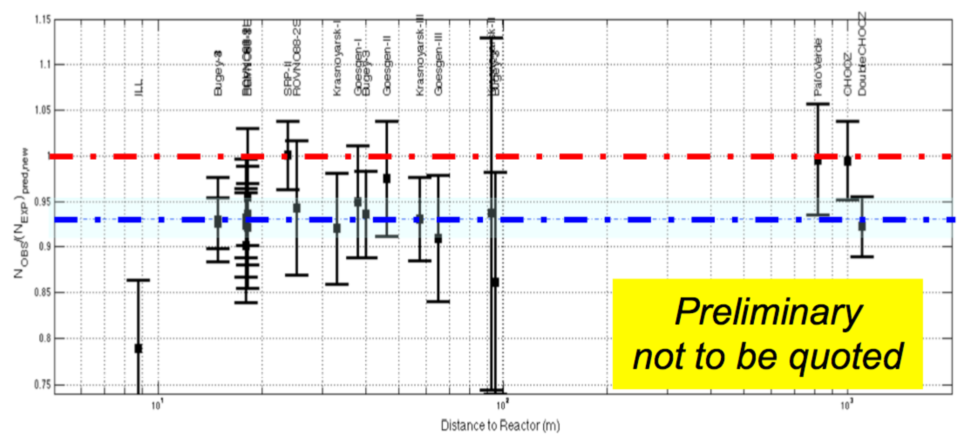


C. Zhang, X. Qian & P. Vogel RAA Reanalysis (arXiv:1303.0900v1)



- New reanalysis of old 19 reactors antineutrinos experiments adding :
  - $sin^2(2\theta_{13})$ = 0.089±0.011
  - allow to use Chooz, Palo Verde, Double Chooz (Gd & Hyd. datas)
  - => *R = 0.959±0.009(stat.) ±0.027(react.flux) : 1.4 σ effect*

- First quick comments from Saclay's group
  - which IBD cross-section used ?
  - which neutrino flux ? P. Huber's ?
  - wrong error used by authors in RAA
    - 0.027 instead of 0.023
    - taken wrongly as fully correlated
    - only ILL data is fully correlated
  - Saclay preliminary similar reanalysis : ≈ 0.93 ± 0.022 *: > 3 σ effect*
  - short written answer in preparation



Sterile Neutrinos

Anomalies & 4th Neutrino

Anomaly	Source	Type	Sensitivity to Oscillation	Channel	Significance
LSND	Decay-at-Rest	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	Total Rate, Energy	CC	3.8 σ
MiniBoone	Short baseline	$\nu_\mu \rightarrow \nu_e$	Total Rate, Energy	CC	3.8 σ
Gallium	Electron Capture	ν_e dis.	Total Rate	CC	2.7 σ
Reactor	Beta-decay	$\bar{\nu}_e$ dis.	Total Rate, Energy	CC	3.0 σ
Cosmology	Big-Bang	All	Number of ν, N_{eff}	CC	≈2 σ

→ **could be interpreted by an existing eV^2 4th neutrino state…**

Sterile Neutrinos

A sterile neutrino is a lepton with no ordinary electroweak interaction except those induced by mixing.

Active neutrinos:

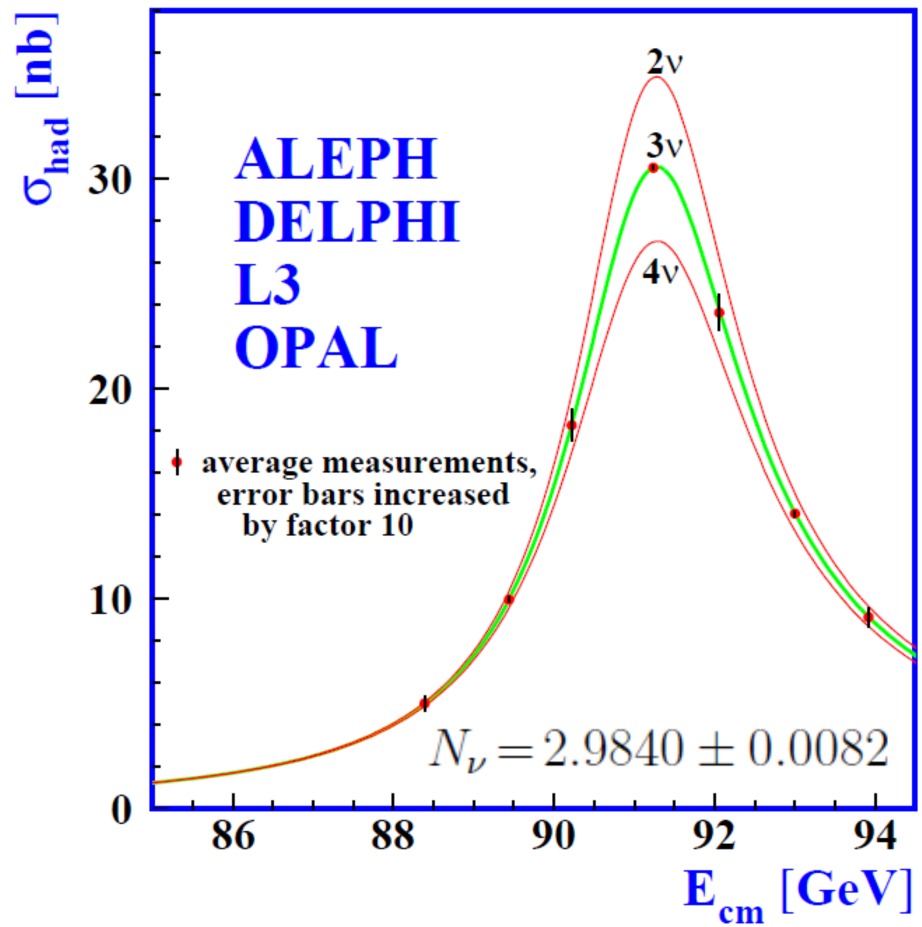
- LEP Invisible Z^0 Width is consistent with only three light active neutrinos
- 2 independent Δm^2

Sterile Neutrino(s)?

- Oscillation with $\Delta m^2 >> \Delta m^2_{atm}, \Delta m^2_{sol}$

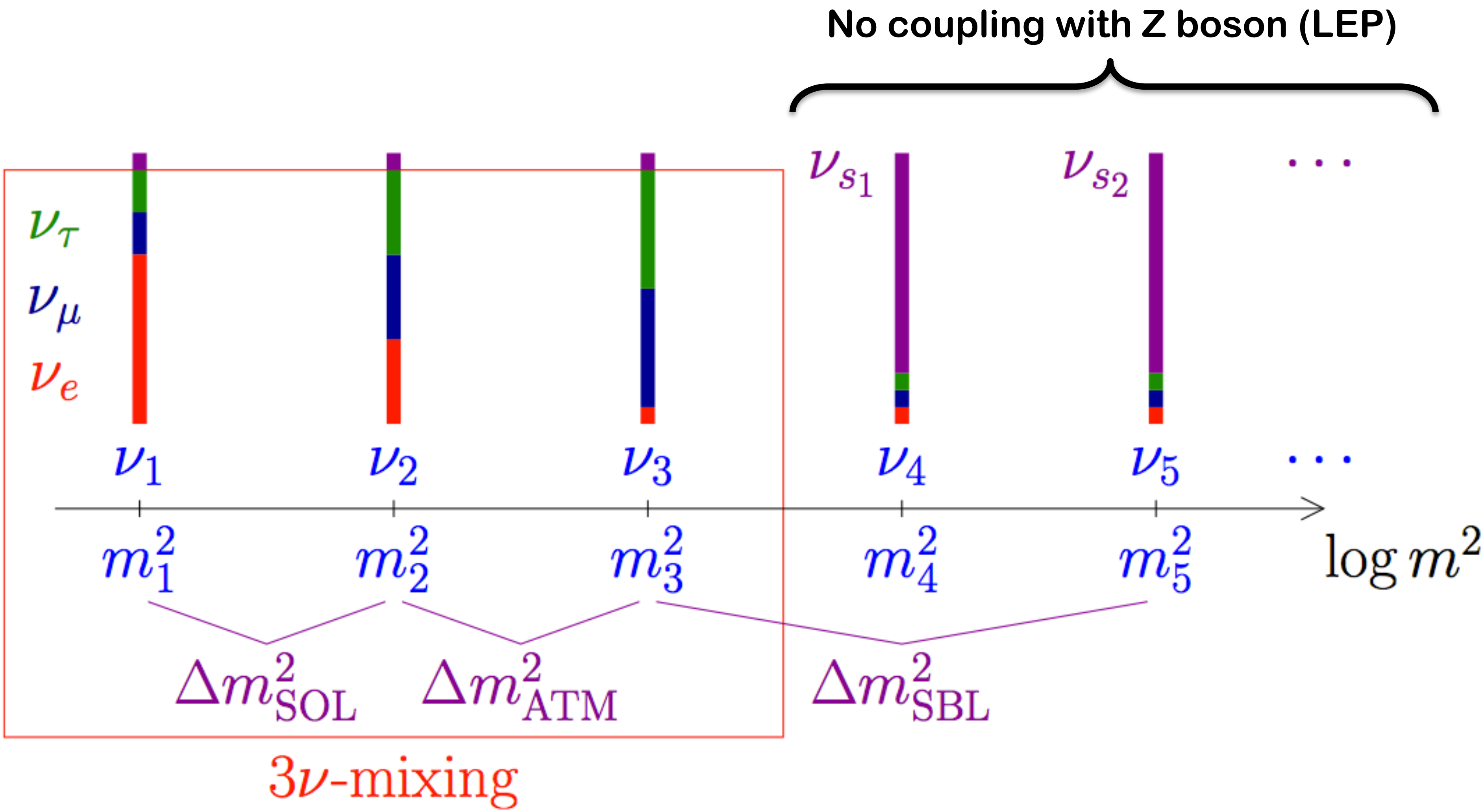
  → 4^{th} sterile ν

Phys.Rept. 427, 257 (2006)



Adding Sterile Neutrinos

Introduce a light ν_R in SM, No SM interactions mixing with active ν' s



Testing RAA & GAA with Intense EC or β emitters

Testing $\overset{(-)}{\nu}_e$ disappearance anomalies

- GA & RAA arise from comparisons between data and event prediction → Need a conclusive technique
- Input from Sterile Neutrino Fits
  - $\Delta m^2 \approx 0.1\text{-}10\ eV^2$ → $L_{osc}(m)=2.5\frac{E(MeV)}{\Delta m^2(eV^2)} \approx 2-10\ m$
  - $\sin^2(2\theta_{new}) \approx 0.1$
- Experimental Specifications
  - Search for L, E, L/E pattern (shape only)
  - Complement with a rate analysis (direct test of RAA+GA)
  - $\Delta m^2 \approx eV^2$: compact source <1m & good vertex resolution (<1m)
  - $\sin^2(2\theta_{new})$: experiment with few % stat. syst. uncertainties

Oscillometry inside a ν-detector

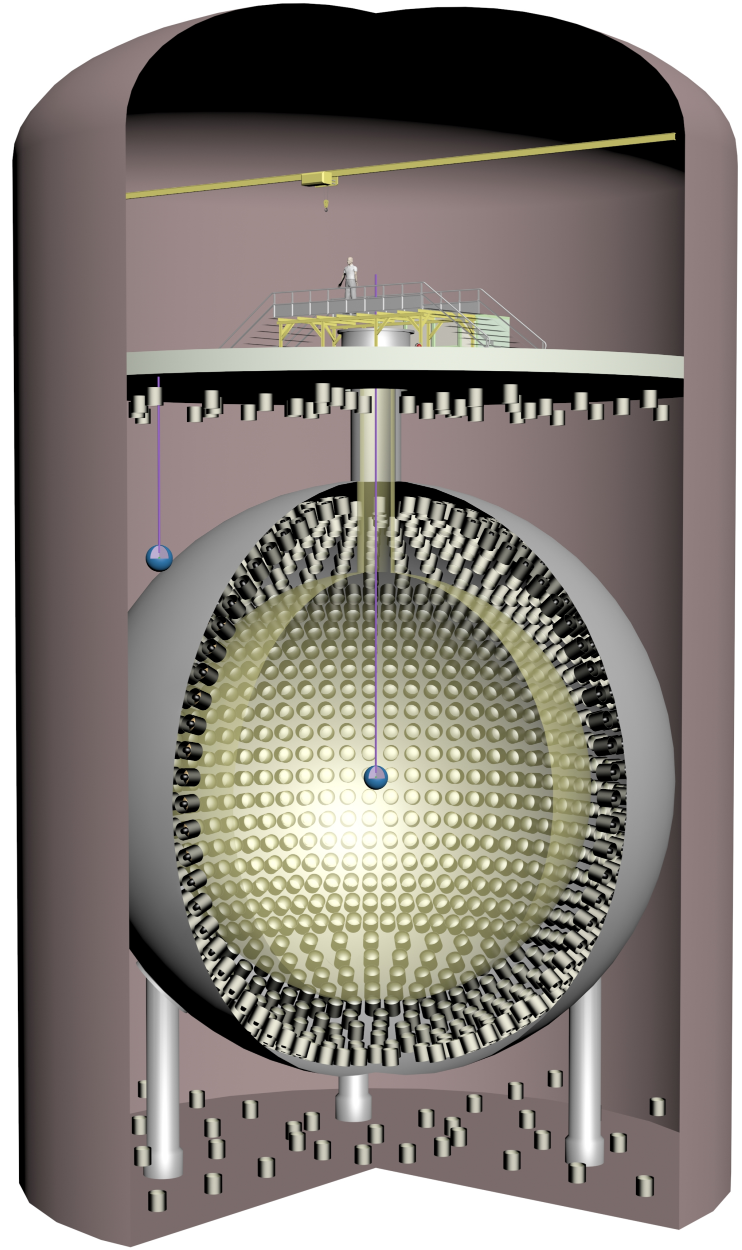
- **Place the ν-emitter inside or close to existing detectors**
  - **Very short Baseline (few m)**
  - **Low Background**

i) ν-source at center

- $$\frac{dN_\nu}{dR} \propto \left[1 - \sin^2(2\theta)\,\sin^2\left(1.27\frac{\Delta m^2 R}{\langle E\rangle}\right)\right]$$

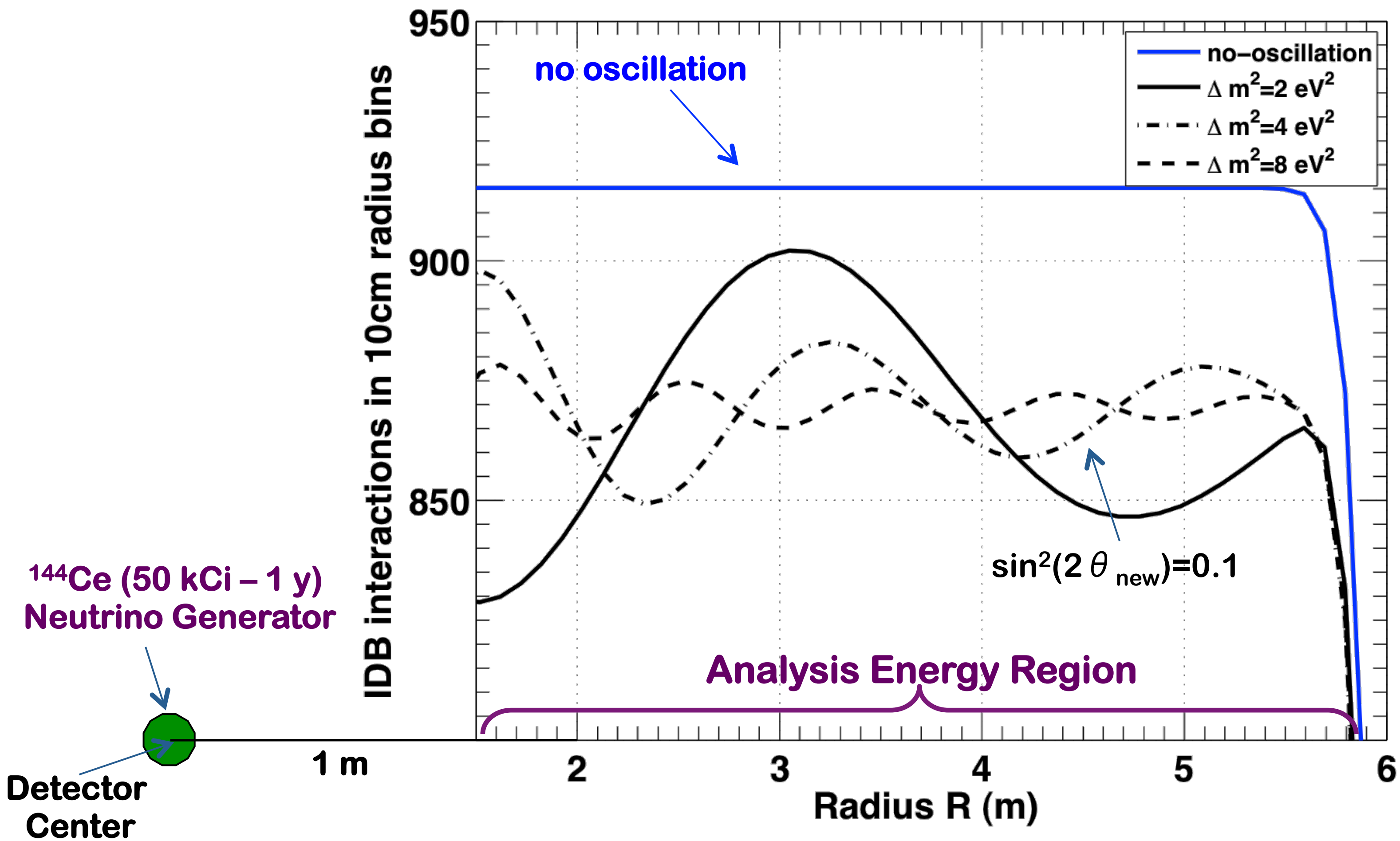
ii) ν-source Outside LS

  - **Specific oscillation pattern analytically computable**



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

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

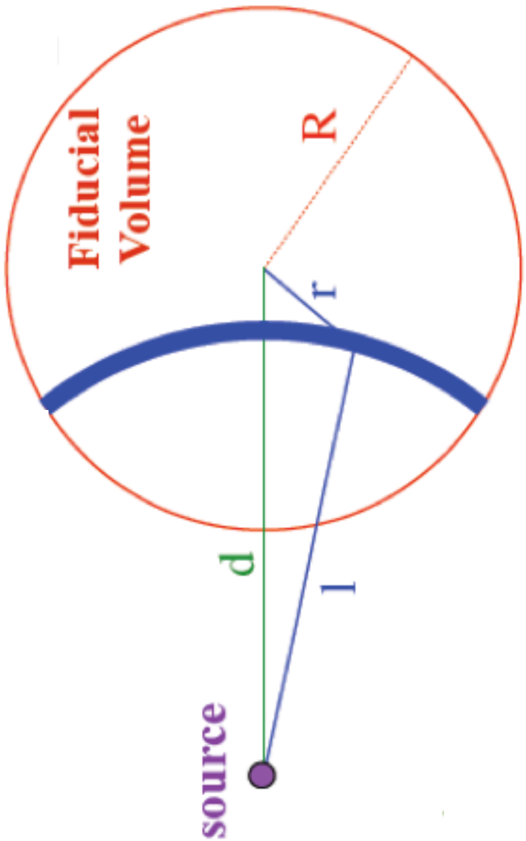


ν generator proposals

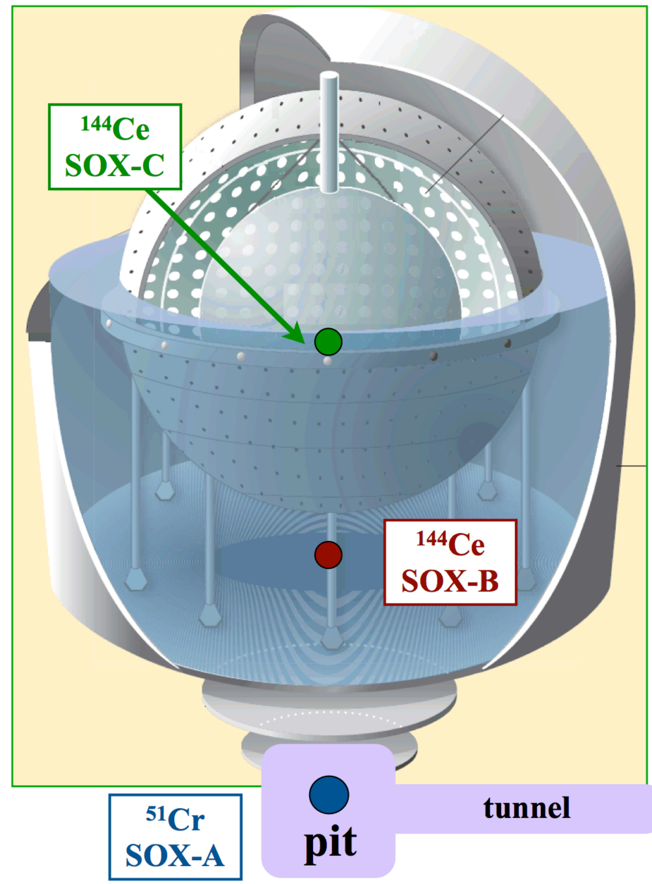
Type	channel	Background	Source	Production	Activity (Mci)		Proposal
ν_e	$\nu_e e \rightarrow \nu_e e$ Compton edge 5% E_{res} 15cm R_{res}	radioactivity (managable) Solar ν (irreducible) ν-Source (out ok but in ?)	^{51}Cr 0.75 MeV $t_{1/2}$=26d	n_{th} irradiation in Reactor	in	>3	Sage LENS
					out	>10	SOX* SNO+
			^{37}Ar 0.8 MeV $t_{1/2}$=35d	n_{fast} irradiation in Reactor (breeder)	in	>1	-
					out	5	Ricochet (NC)
$\bar{\nu}_e$	$\bar{\nu}_e p \rightarrow e^+ n$ E_{th}=1.8 MeV (e^+,n) coincidence 5% E_{res} 15cm R_{res}	reactor ν & ν-Source → Background free!	^{144}Ce E<3MeV $t_{1/2}$=285d	spent nuclear fuel reprocessing	in	0.075	CeLAND* SOX
					out	0.5	Daya-Bay
			^{90}Sr ^{106}Rh		-	-	-
			^{42}Ar	?	-	-	-

$^{51}Cr/^{144}Ce$ Source in Borexino (SOX)

- Existing Tunnel → source at 8.25 m from the LS target



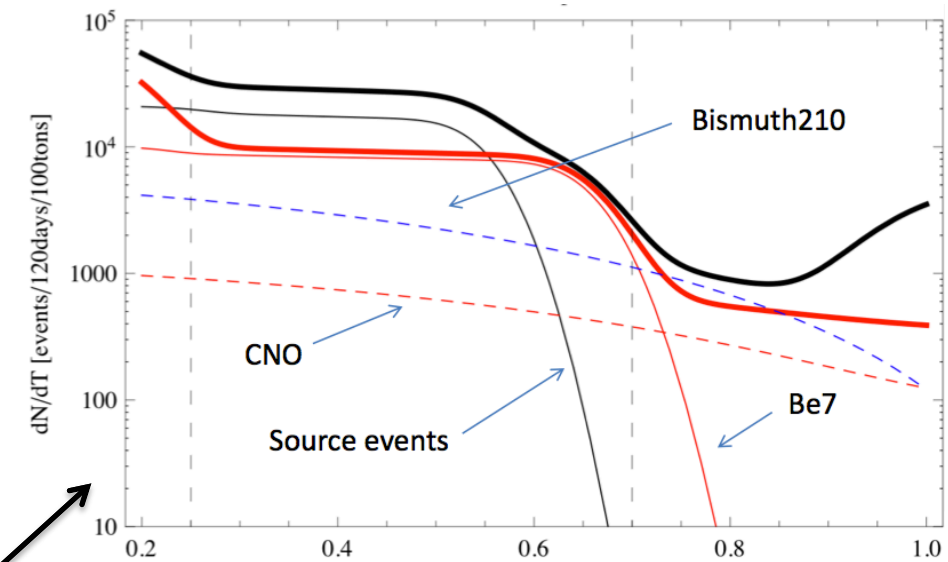
Eur. Phys. J C8, 1999

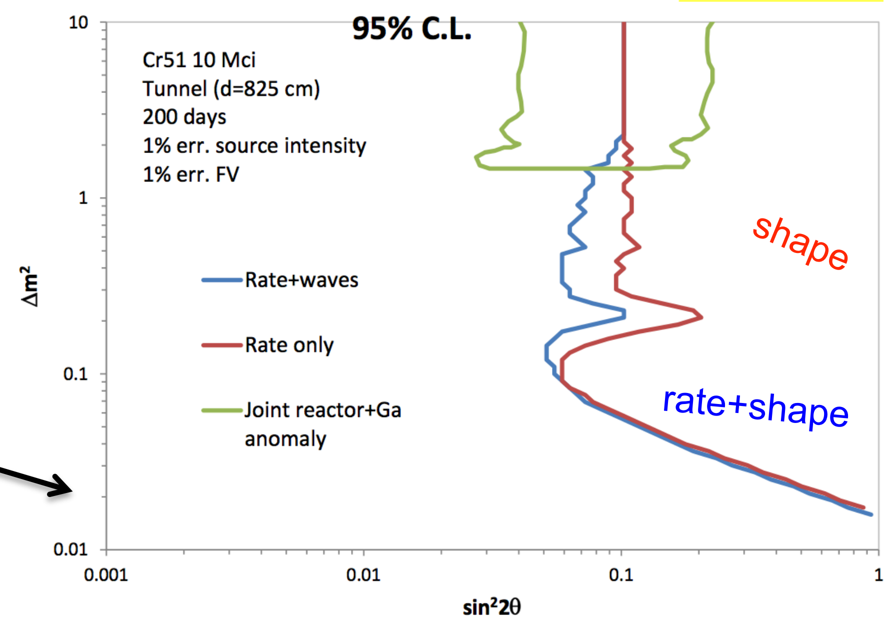


- Observable: ν_e events as a function of distance (l)

^{51}Cr Source underneath Borexino

- **10 MCi ^{51}Cr**
  - Re-use Gallex 36 kg of enriched chromium (38%)
  - But need add. enriched ^{50}Cr
- **Reactors (Petten, Ludmila, US)**
  - $n_{th} \approx 10^{15}$ n/cm²/sec
  - Space to accommodate ^{50}Cr
- **Detection as ^{7}Be solar ν**
  - Well known background in 0.25-0.7 MeV: solar ν's & ^{210}Bi
  - 1% fiducial volume error
- **R+S Oscillometry analysis**
- **ERC Funding**





CeLAND:
75 kCi ^{144}Ce-^{144}Pr in KamLAND

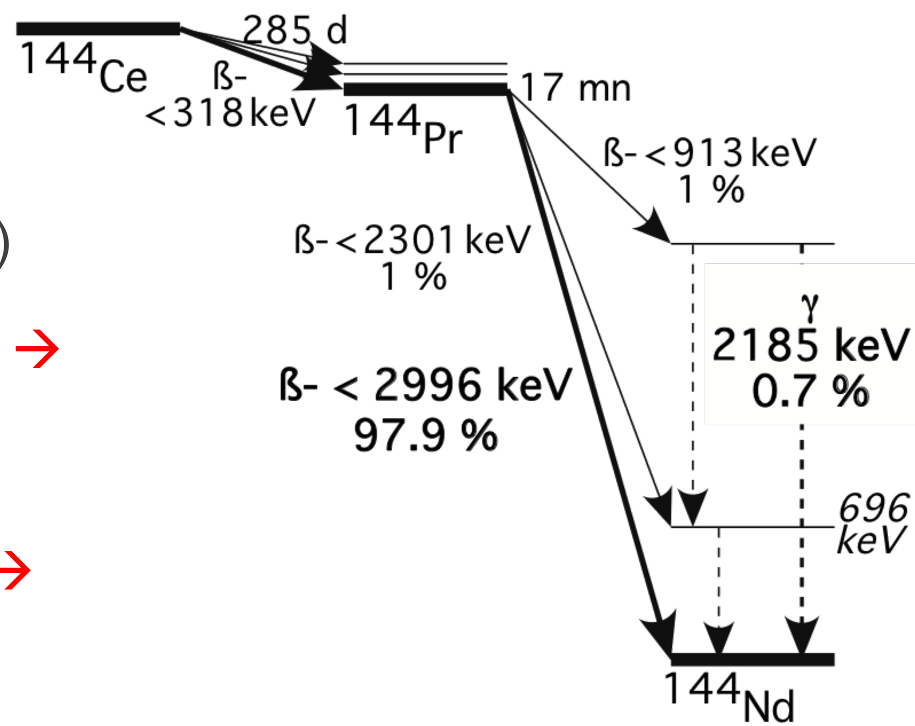
Phys. Rev. Lett. 107, 201801 (2011)

Antineutrino Source: ^{144}Ce-^{144}Pr

(ITEP N°90 1994, PRL 107, 201801, 2011)

erc

- 1st Trick: $\bar{\nu}_e$ source detected via $\bar{\nu}_e + p \rightarrow e^+ + n$ (Thr=1.8 MeV)
  - High IBD cross section → 10-100 kCi activity
  - (e^+,n) detected in coincidence → Background free
- 2nd Trick: ^{144}Ce-^{144}Pr
  - Abundant fission product (5%)
  - ^{144}Ce: long-lived & low-Q_β → Enough time to produce, transport, use
  - ^{144}Pr: short-lived & high-Q_β → $\bar{\nu}_e$-emitter above threshold

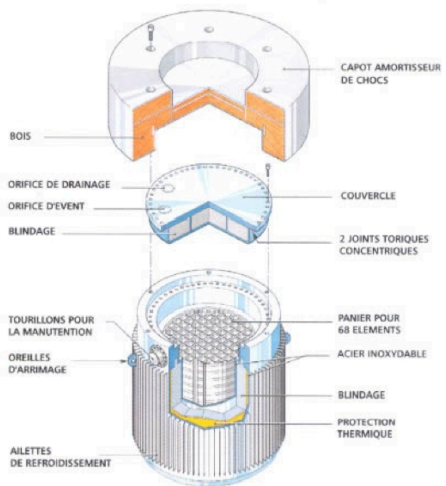


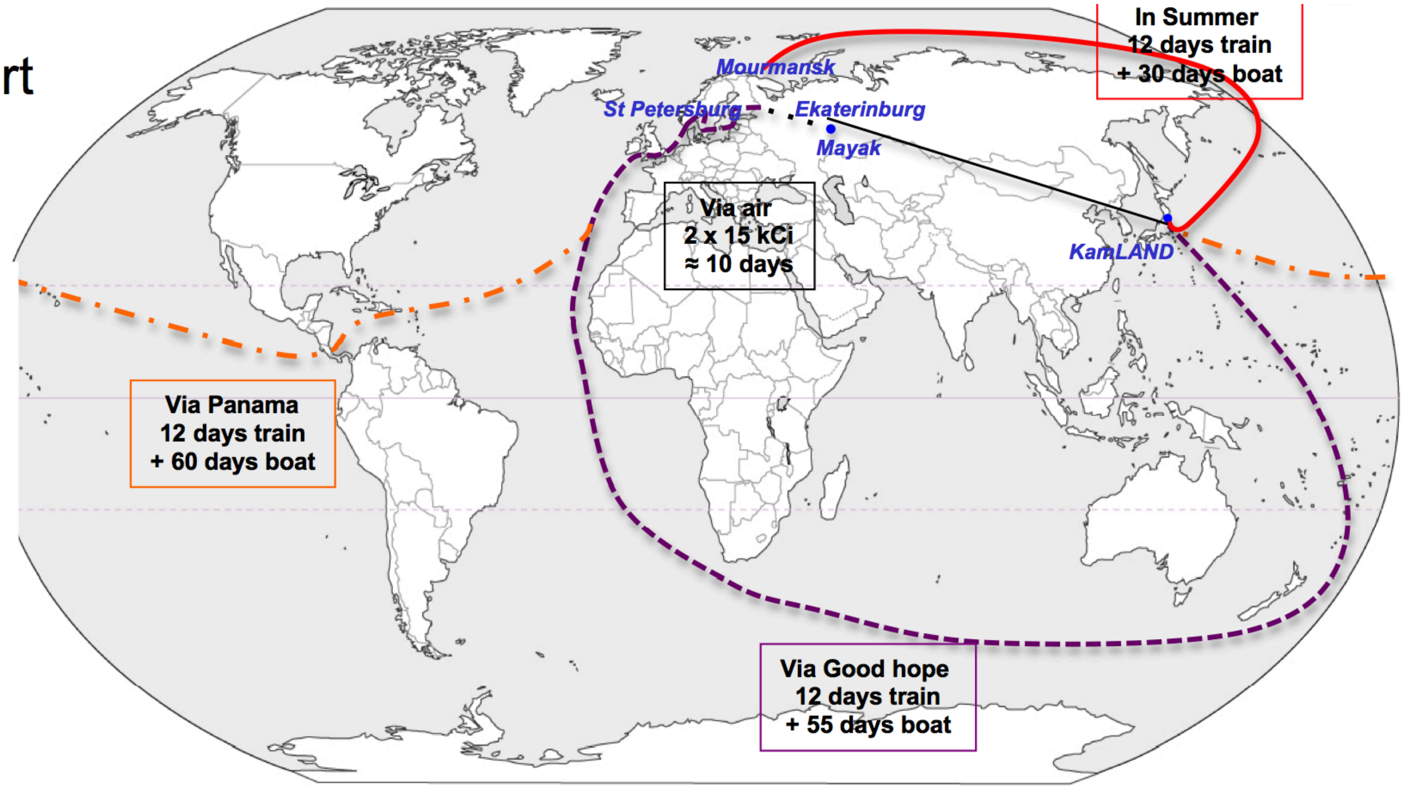
^{144}Ce Production at PA Mayak: 2014

75 kCi (2.77 PBq), 4 kg of Ce0$_2$ (ρ= 4 g/cm^3), 600 W

^{144}Ce Source Transportation: 2014/15

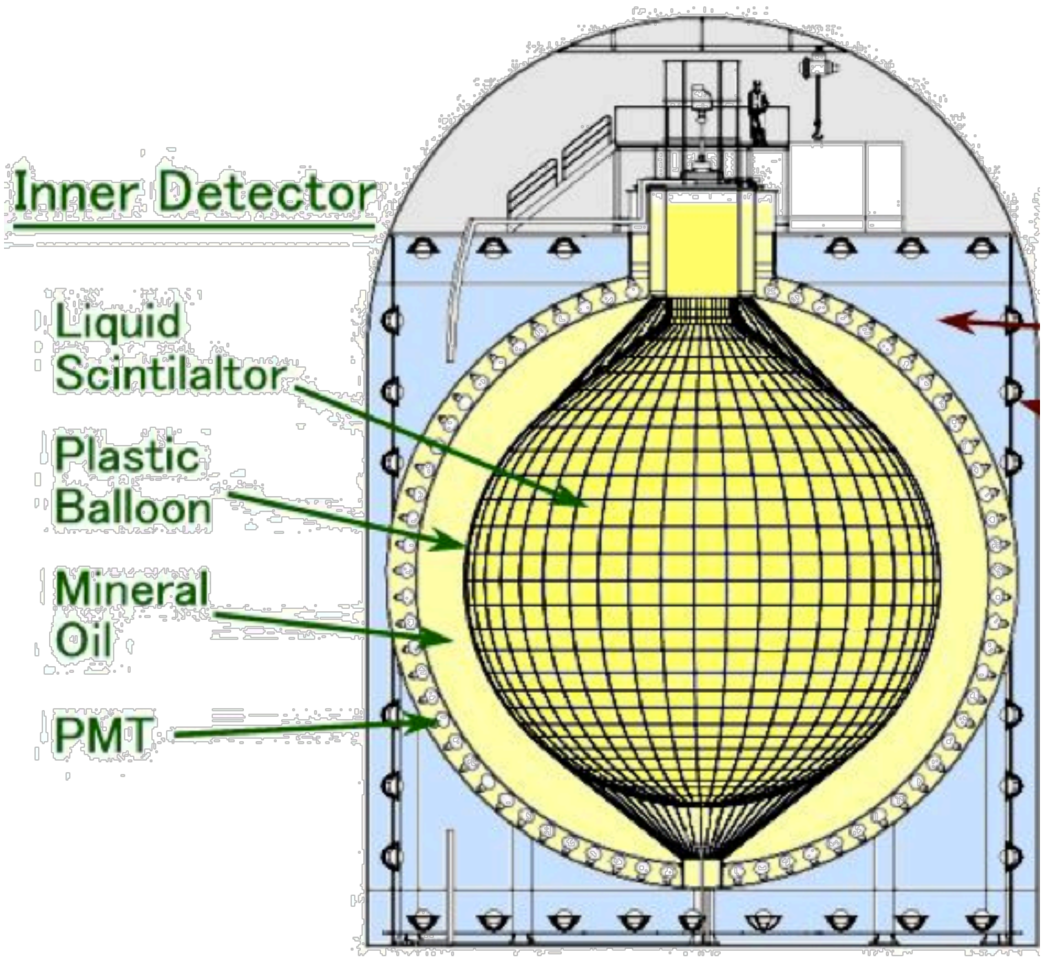
- Certified transport container
  - 23 tons !





- Severe constraints based on regulation issued by IAEA
  - nothing impossible, but long, bureaucratic and costly
  - by air limit for each radioisotope : 16.2 kCi for ^{144}Ce, 2.4 MCi for ^{51}Cr
  - by boat : only limited number of harbours agreed for radioactive materials

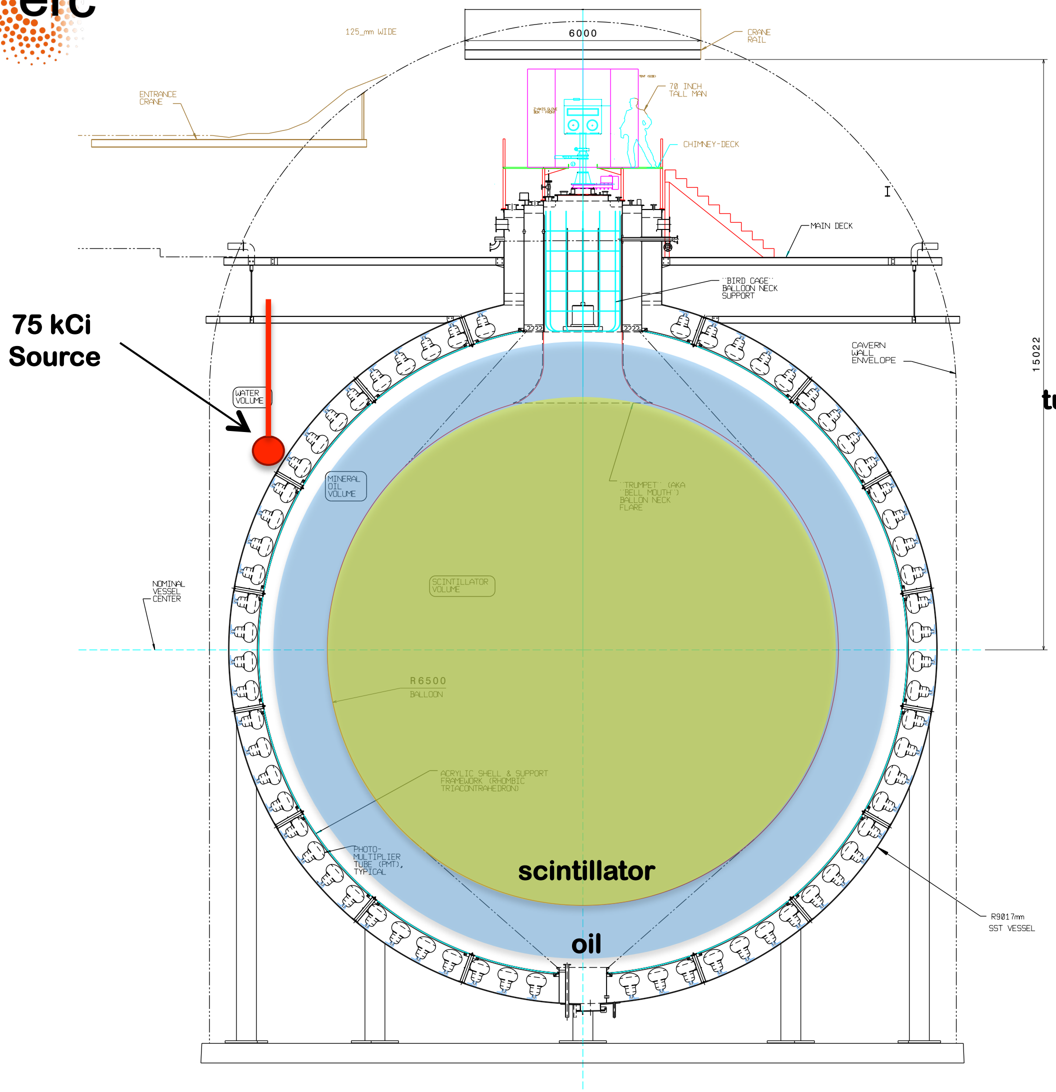
CeLAND: ^{144}Ce in KamLAND



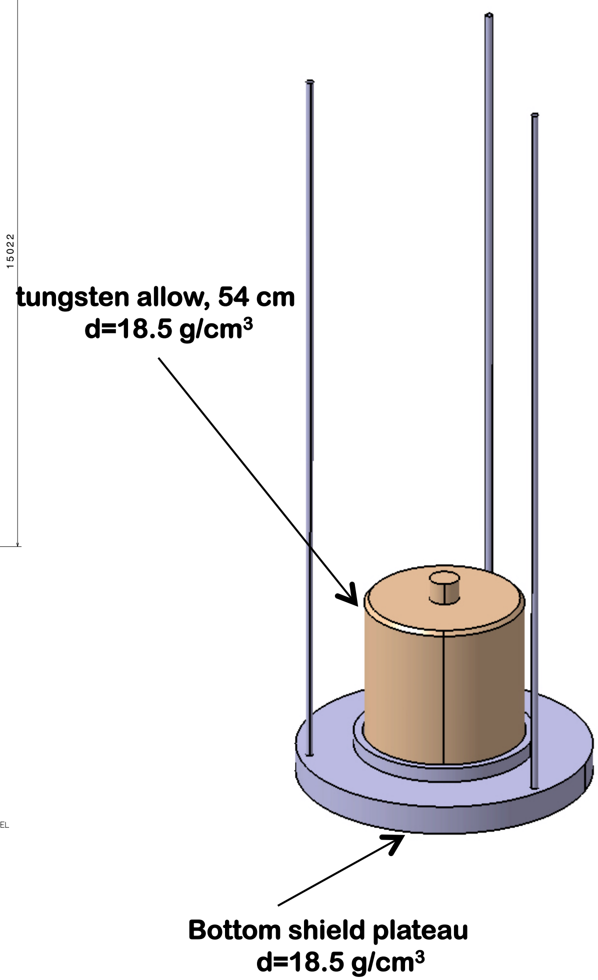
- **A great existing underground detector**

  1000 tons of PC +mineral oil
- **But several constraints**
  - Full of extra pure mineral oil
  - Avoid contaminations
- **The entrance hole**
  - 55 cm in diameter
  - Complex operations to insert the source
- **Hanging suspension**
  - **Phase 1: OD Water**
  - **Phase 2: ID Oil**

CELAND phase 1 in KamLAND



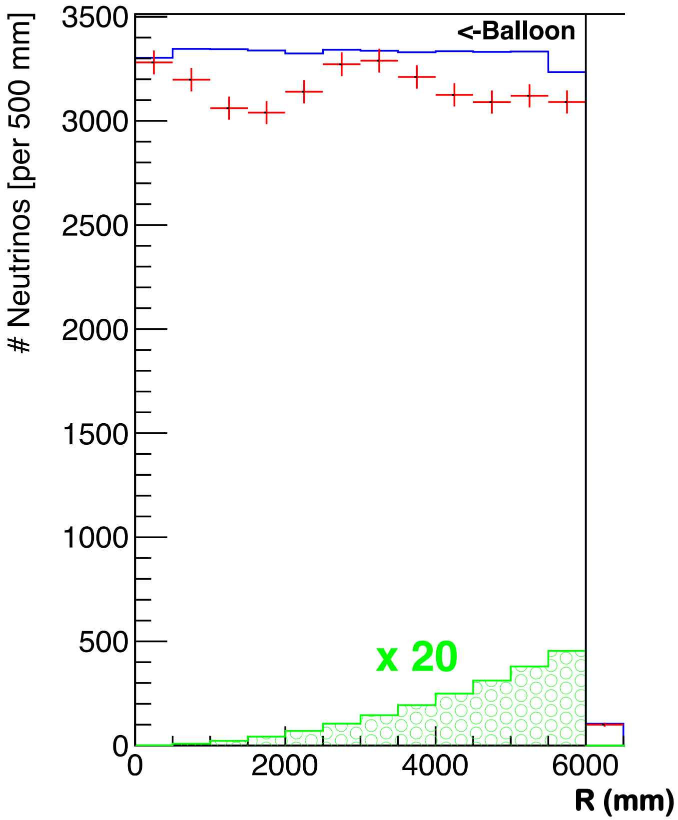
Source @2.5 m away from LS
75 kCi & 6-18 months of data taking



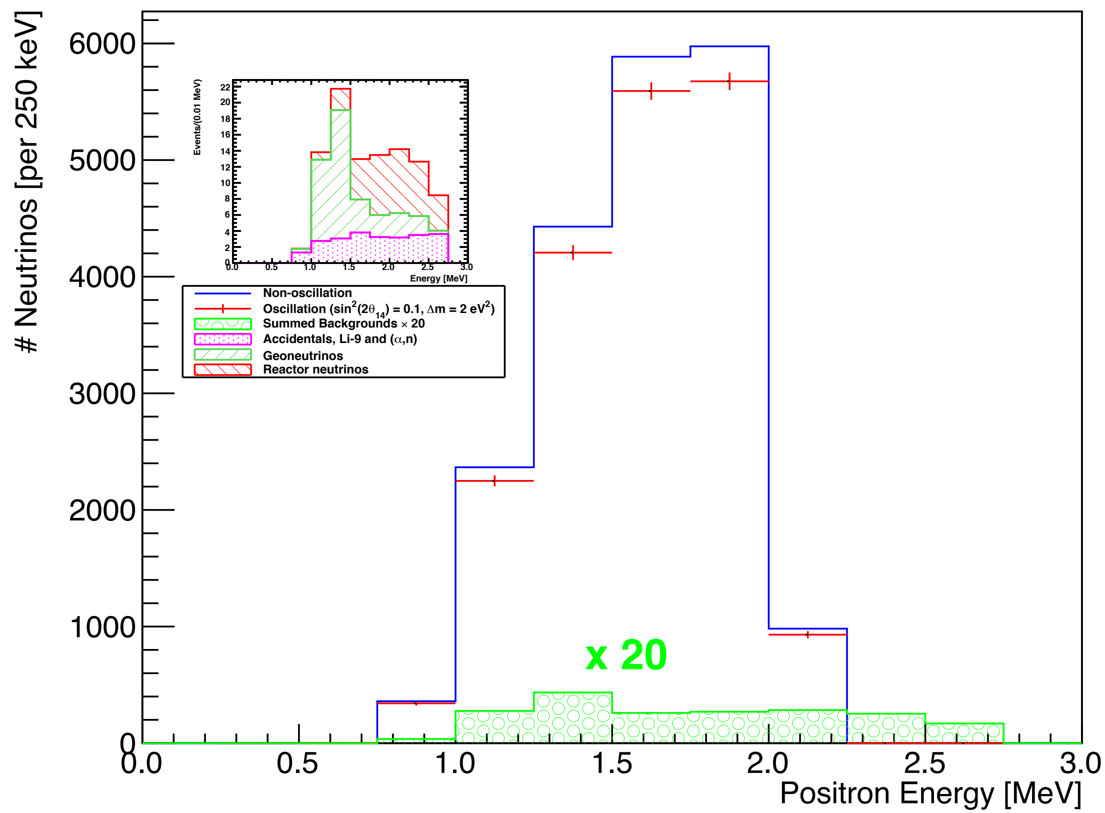
Phase 1: signal/backgrounds

75 kCi Source @2.5 m away from LS
9.3 m from the detector center

Spatial event distribution



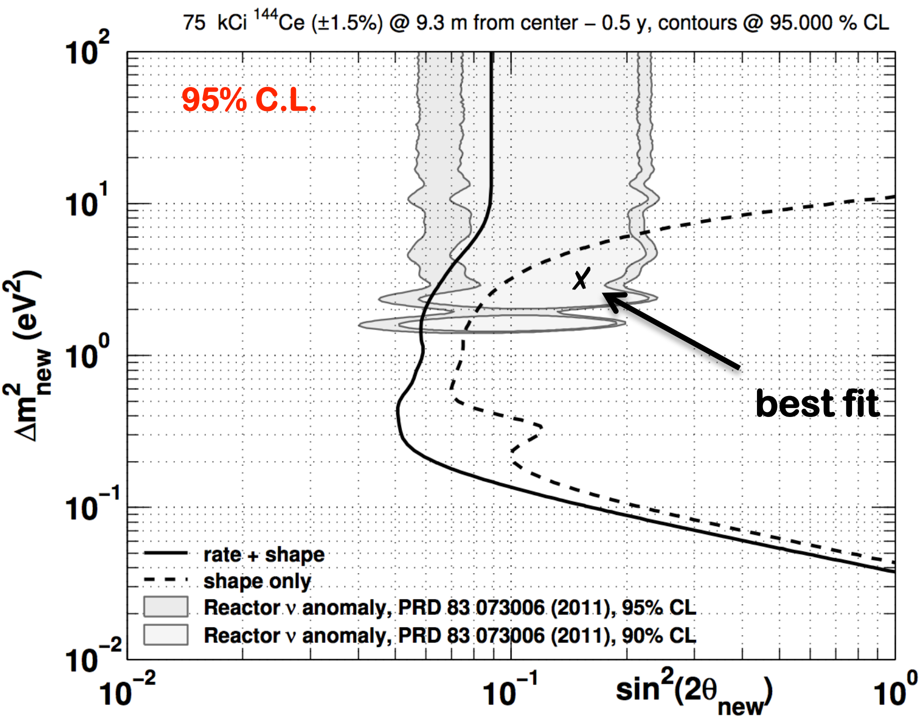
Energy Spectrum



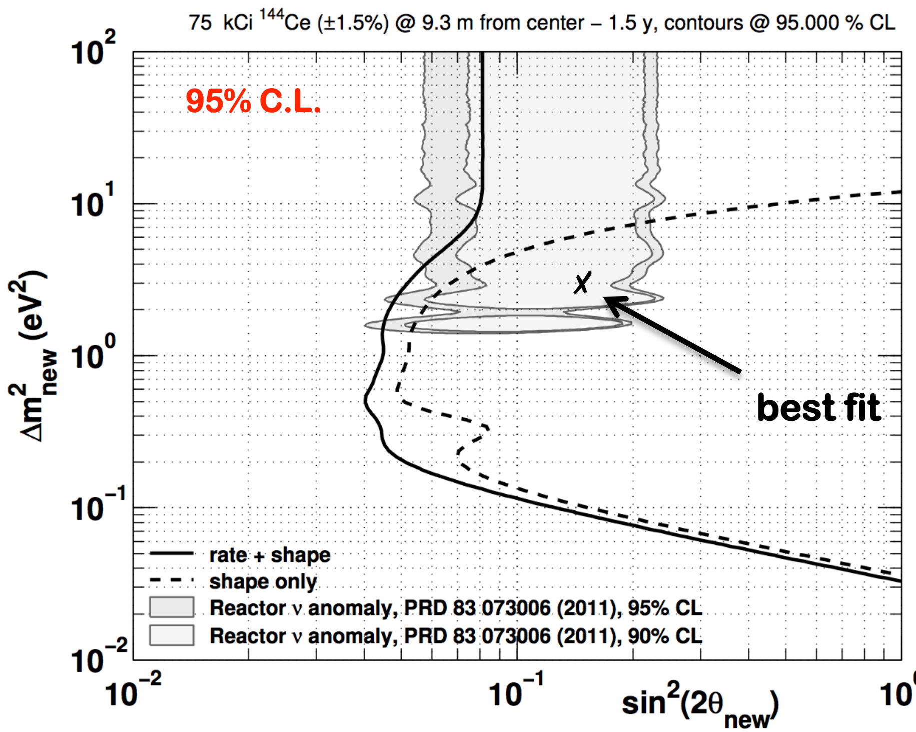
CeLAND phase 1 sensitivity

75 kCi ^{144}Ce-^{144}Pr – 9.3 m from detector center

0.5 year of data (10 kevts)

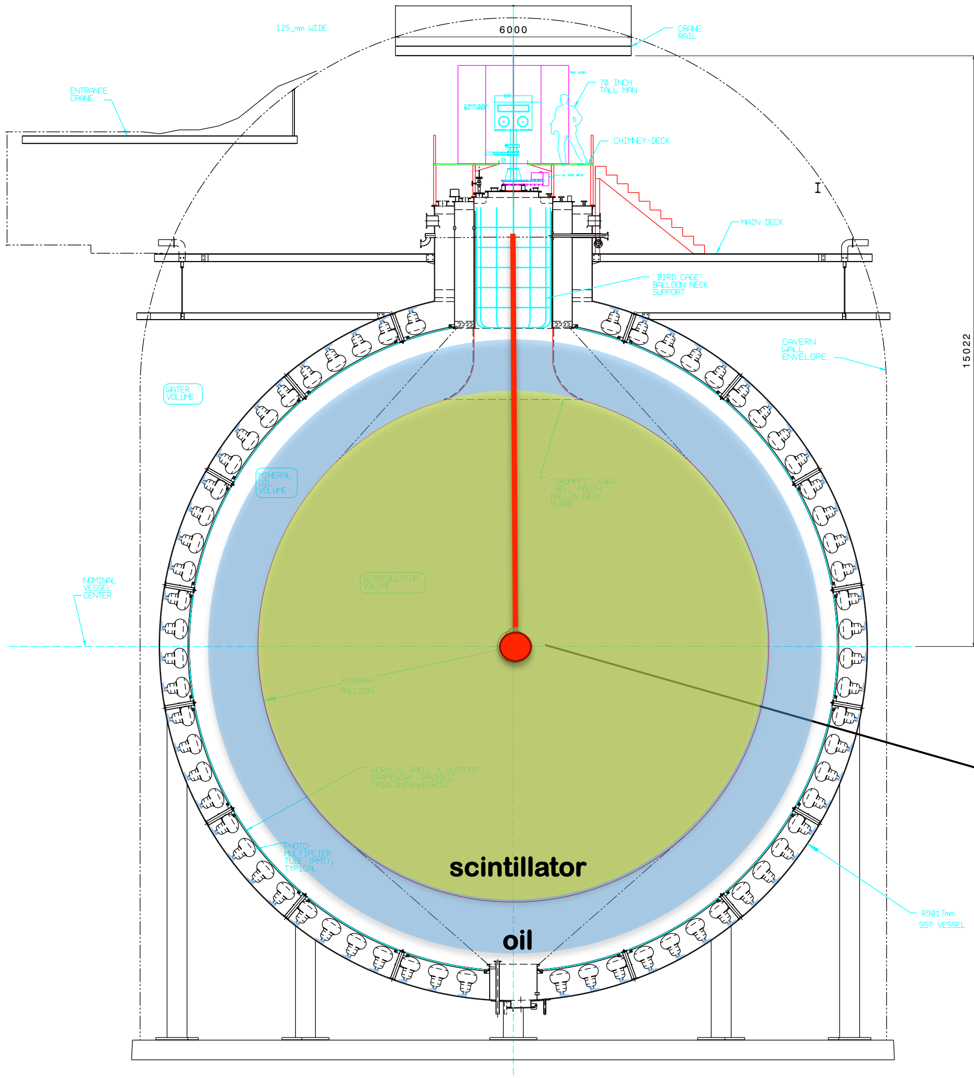


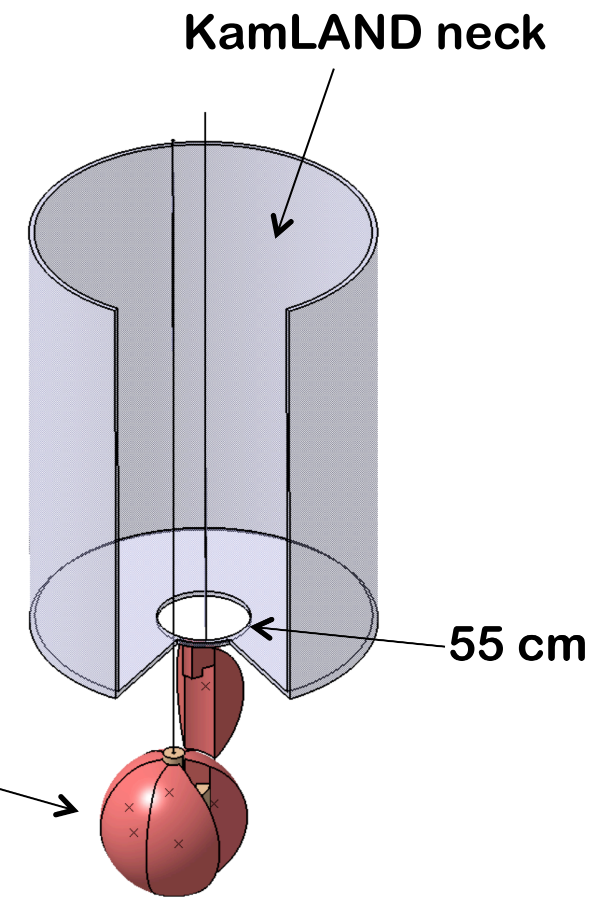
1.5 year of data (20 kevts)



CELAND phase 2 in KamLAND

Relocate the ^{144}Ce source: 75 kCi leads to 50 kCi after 6 months



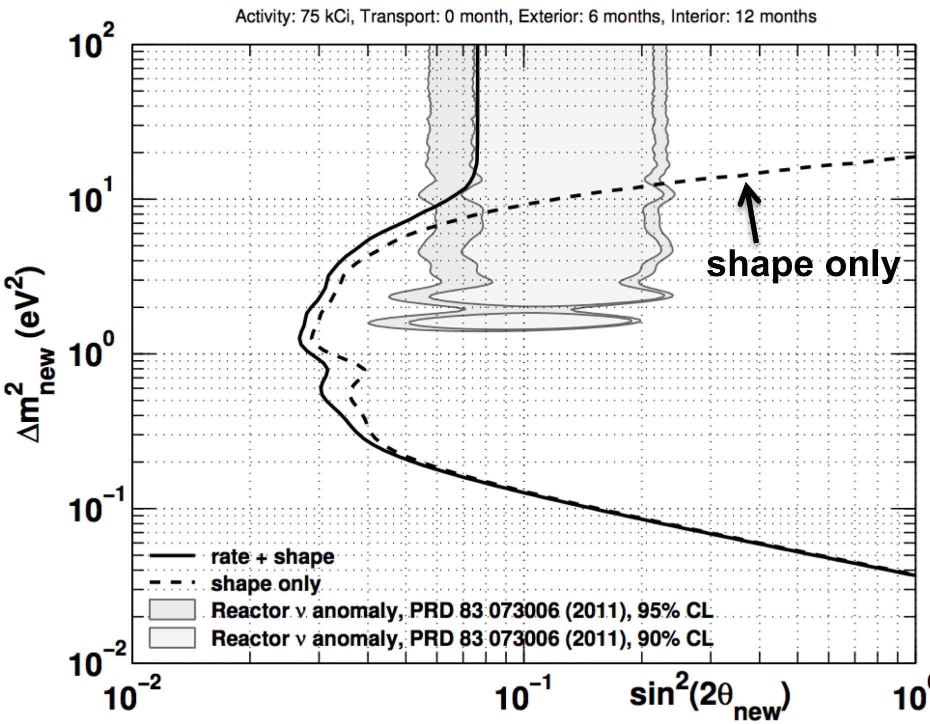


40 cm W-alloy, d=18.5 g/cm^3

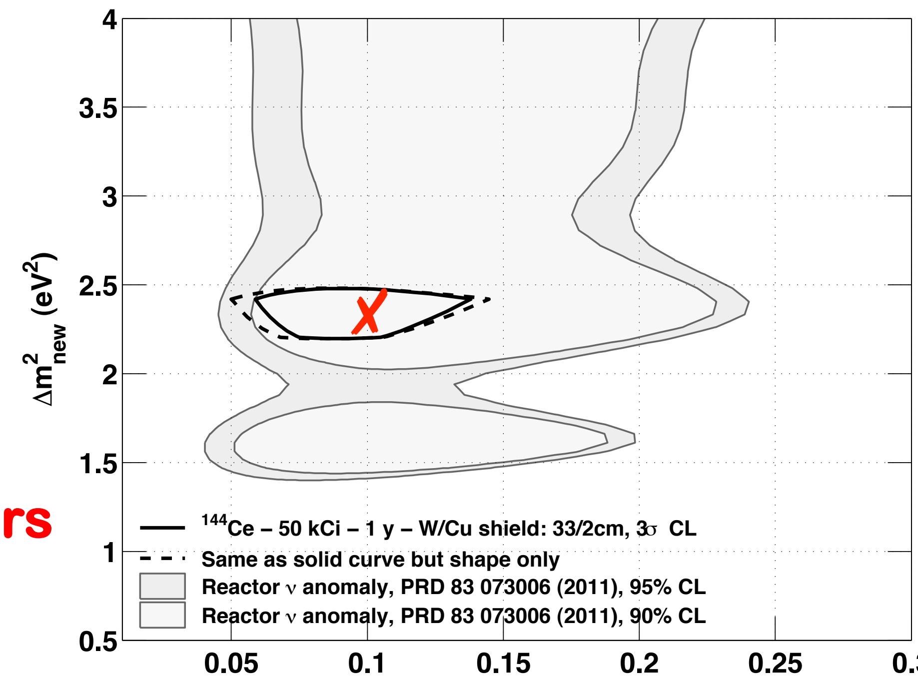
γ-attenuation (2 MeV) : 10^{-13}

CELAND Phase 2: Sensitivity

75 kCi 6 months + 50 kCi 1 year (10+50 kevts)



95% C.L. exclusion

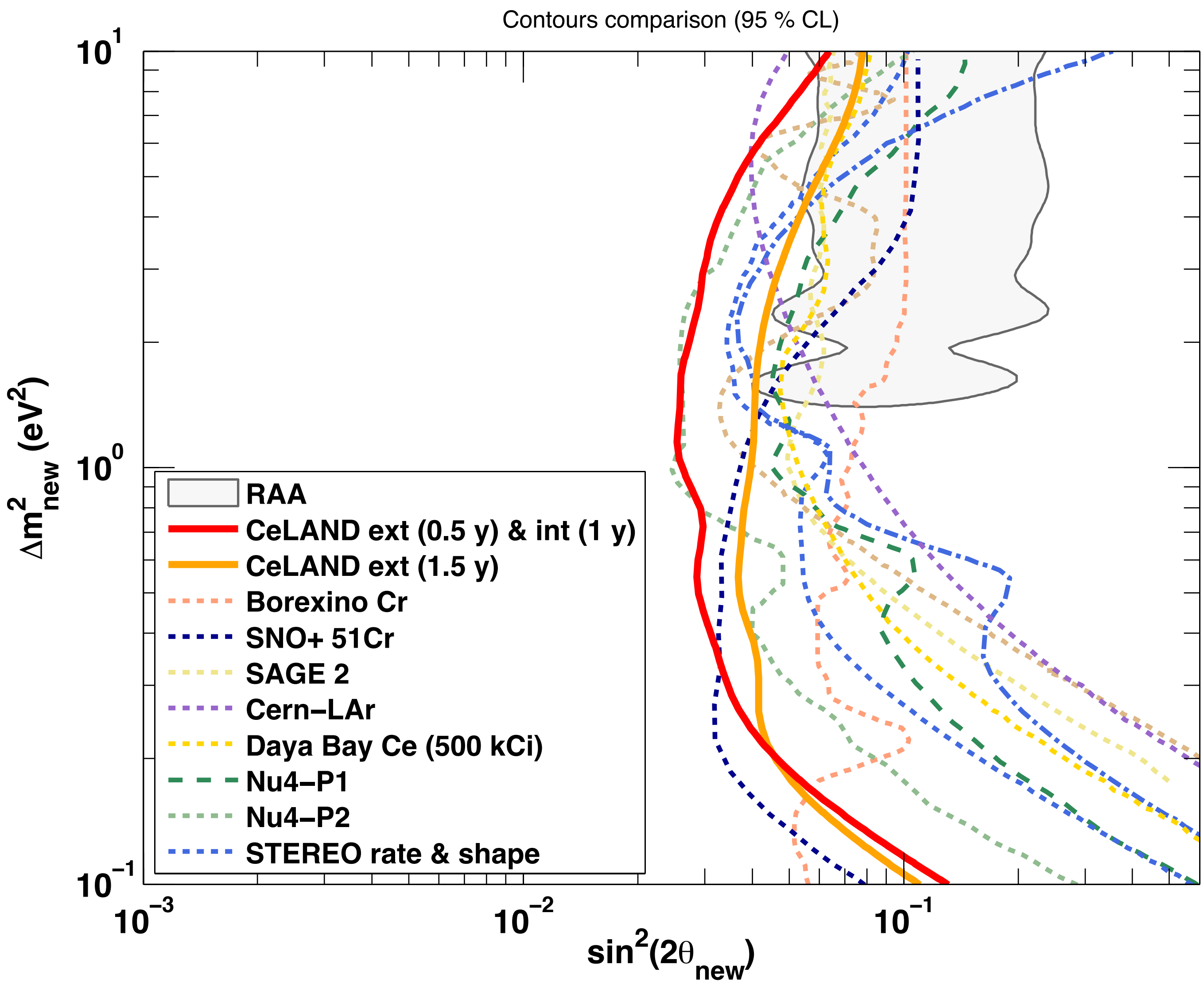


3 σ measurement contours

Many Projects: Overview

Experiment Type	Appearance / Disappearance	Oscillation Channel	Projects
Reactor	Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$	Nucifer, Stéréo, Scraam, Neutrino-4, DANSS, Poséidon, MARS, …
Radioactive Source	Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$ $\nu_e \to \nu_e$	CeLAND, SOX (Cr & Ce), Sage2, SNO+, LENS-s
Cyclotron	Disappearance	$\bar{\nu}_e \to \bar{\nu}_e$	IsoDAR
Pion / Kaon Decay-at-Rest	Apparition & Disappearance	$\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_e \to \nu_e$	OscSNS, CLEAR, DAEδALUS, KDAR
Pion Decay-in-Flight (Beam)	Appearance & Disappearance	$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$ $\nu_\mu \to \nu_\mu$ $\nu_e \to \nu_e$	MINOS+, MicroBooNE, LAr1kton+MicroBooNE, Icarus/Nessie@CERN
Low-E Neutrino Factory	Appearance & Disappearance	$\nu_e \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_\mu$ $\nu_\mu \to \nu_\mu$ $\bar{\nu}_e \to \bar{\nu}_e$	νSTORM@Fermilab

Proposal sensitivities



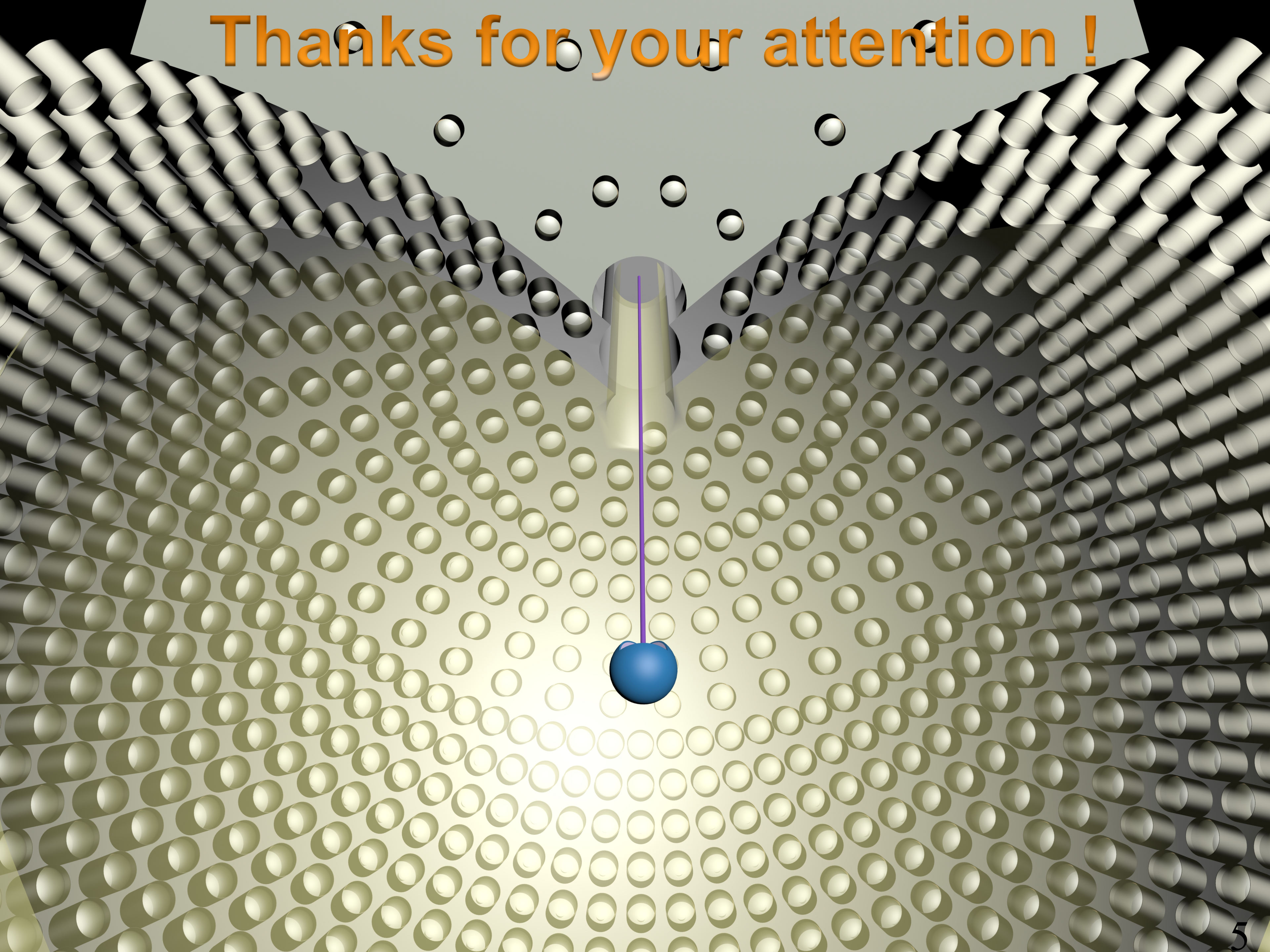
Th. Lasserre – ν–geoscience 2013

Conclusions

- Reactor Neutrino Spectra
  - Modern evaluation : +3.5%
  - Accounting for long-lived isotopes in reactors: +1%
- Revision of the IBD cross section
  - New prefactor proposed : $\kappa = 9.617 \pm 0.011\ 10^{-48}\ \mathrm{cm^2/MeV^2}$

→ Led to the discovery of the Reactor Anomaly in 2011

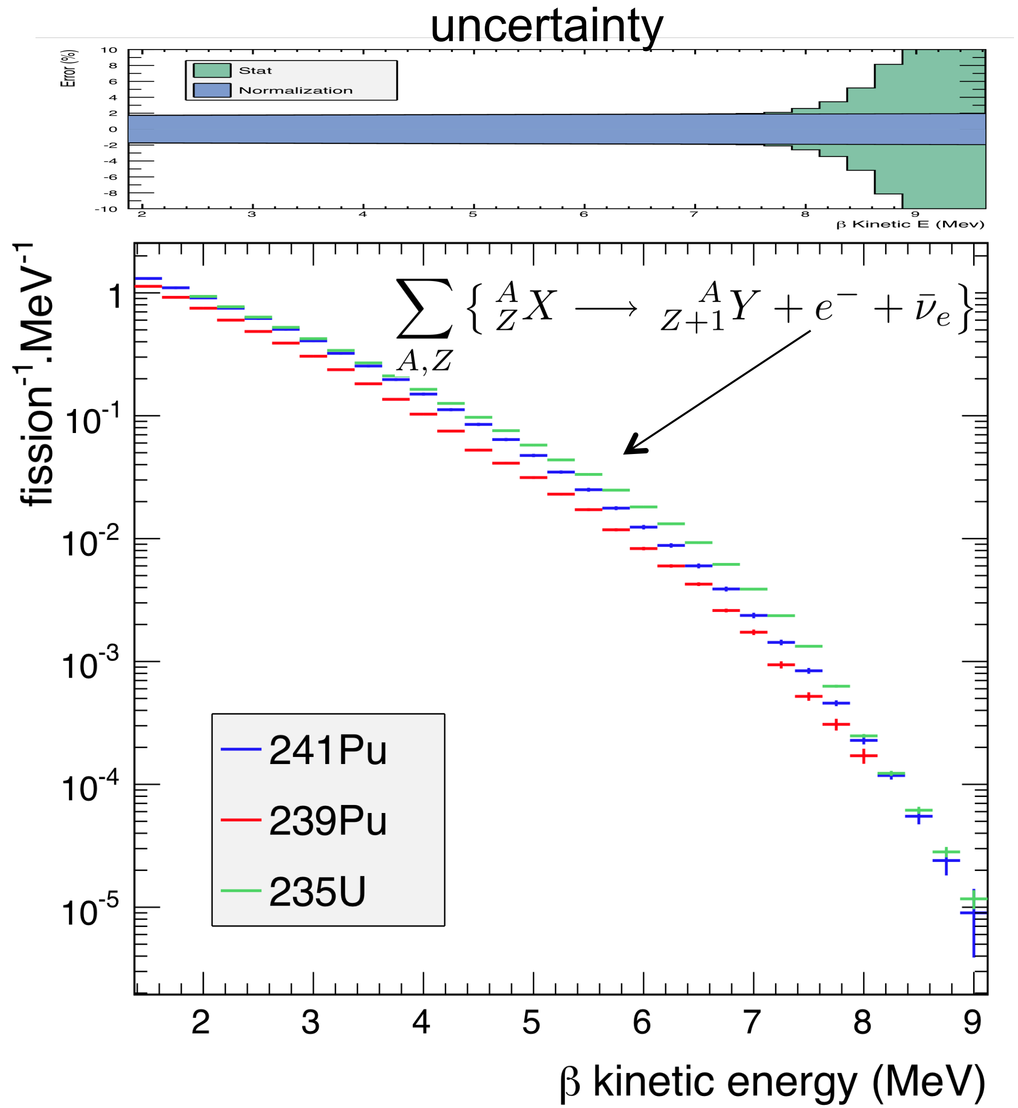
- Set of anomalies calling for clarification
  - sterile neutrino (then a bit less geoneutrinos…)
- Need for new short baseline experiments (20 projects)
  - Need to Test the Beam related anomalies
    - Icarus/Nessie at CERN
  - Need to Test the Gallium and Reactor Anomalies
    - CeLAND /Sox/SBL Reactor Experiments → No Geo-ν for 1 y…


Thanks for your attention !

ILL Electron Data Anchorage

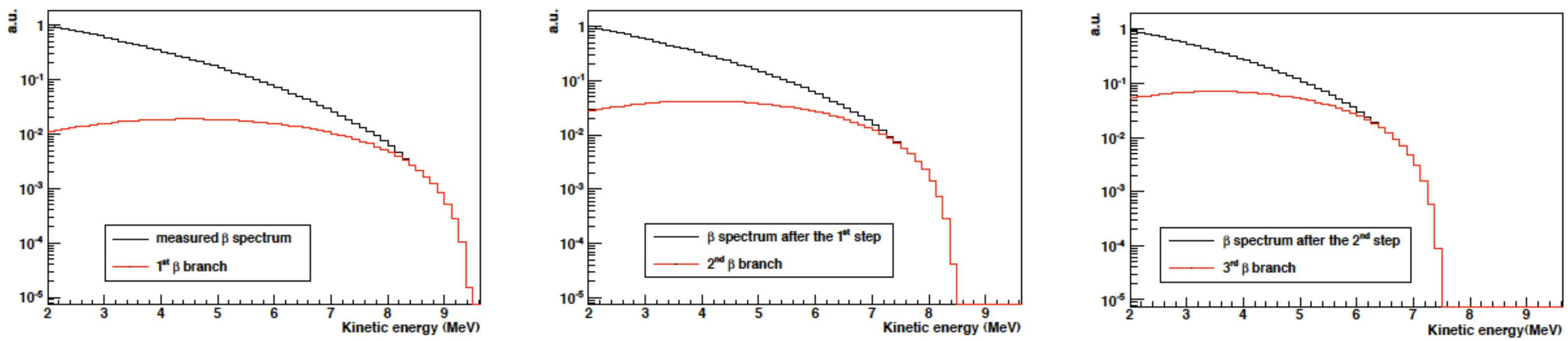
Unique reference to be met by any other measurement or calculation

- **Accurate e⁻ measurements ILL research reactor (1980-89):**
- **High resolution magnetic spectrometer**
- **Intense and pure thermal neutron spectrum from the core**
- **Extensive use of reference internal conversion electron lines**
- **Normalization uncertainty:**
  - **1.8%**
  - **common to all absolute reactor neutrino experiment**



ILL data: conversion to neutrino spectra

- Fit e^- spectrum with a sum of 30 effective branches (Z_i,Q_i)
- Conversion of the effective branches to ν spectra



- All theory included in these effective branches but:

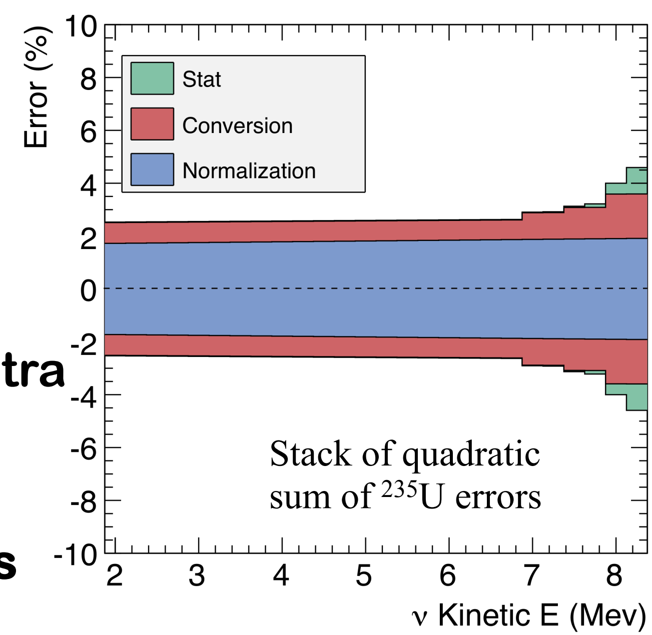
  - Which Z? : Mean fit on nuclear data *Z=f(E₀)*

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

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

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

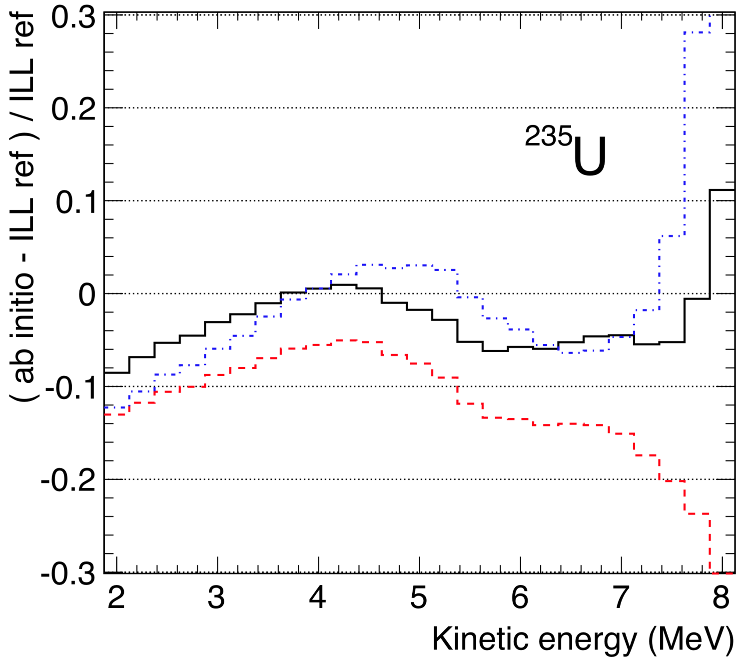
- Conversion error from envelop of numerical studies



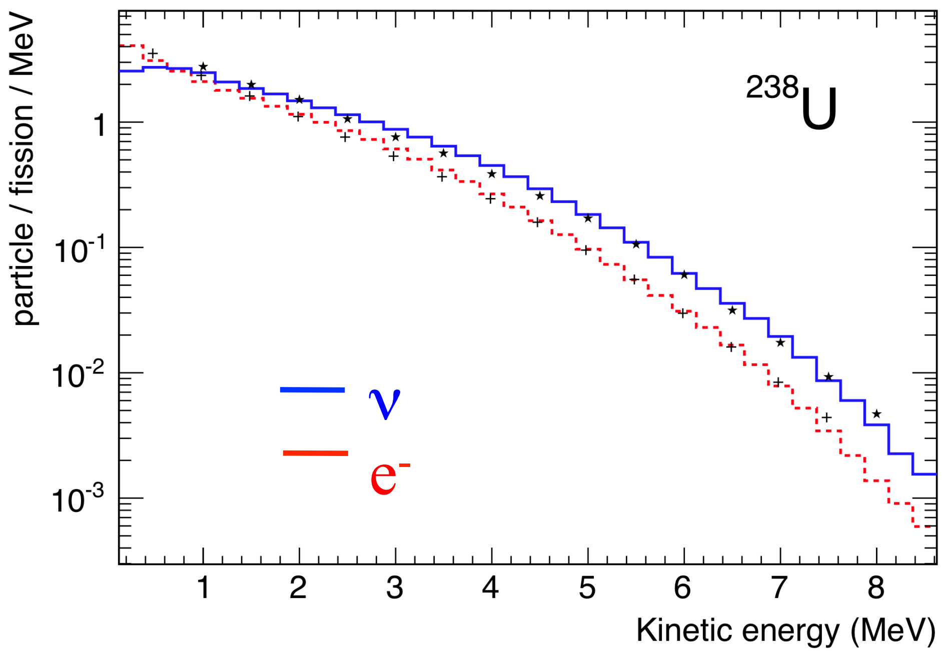
Ab Initio β Spectrum Computation

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

Residues w.r.t. reference ILL e^- data



New ^{238}U spectrum prediction



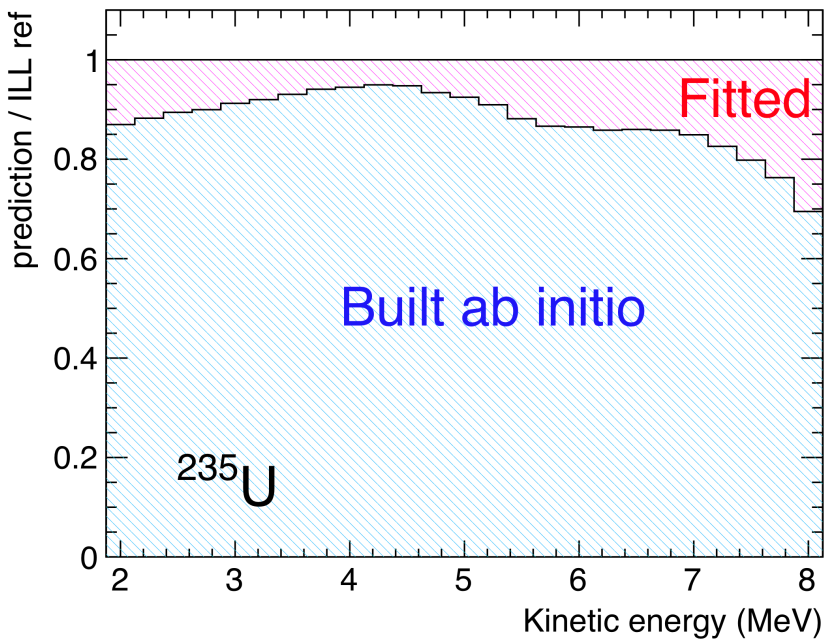
→ 95+/-5% of the spectrum reproduced (electrons)

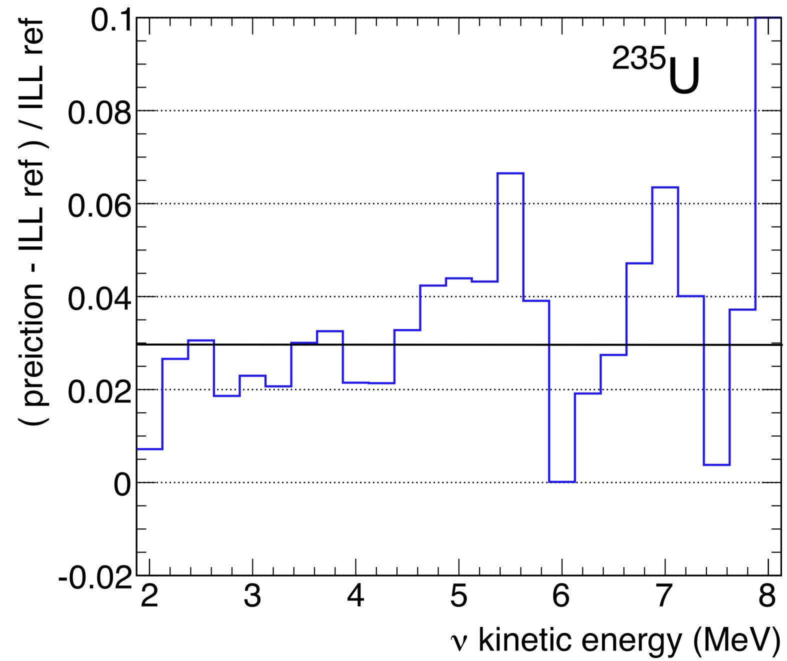
→ Useful estimate of ^{238}U spectrum which couldn't be measured atILL

New Mixed Conversion Approach

Phys. Rev. C83, 054615, 2011

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

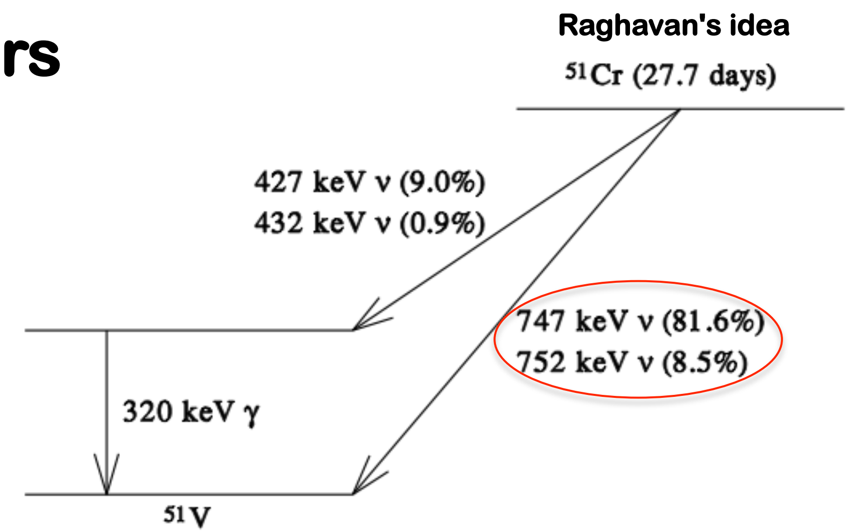


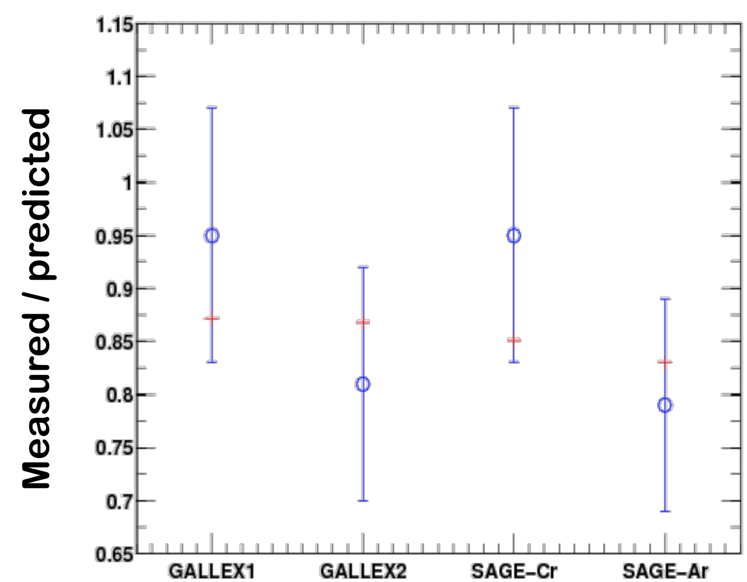


- **+3.5 % normalization shift with respect to old ν spectrum**
- **Similar result for 3 fission isotopes: ^{235}U, ^{239}Pu, ^{241}Pu**
- **Origin of the bias: implementation of β-decay 2nd order corrections**
- **Confirmed and improved by Phys. Rev. C 84, 024617 (2011)**

The Gallium Neutrino Anomaly

- **Test of solar neutrino detectors GALLEX and SAGE (ν_e's)**
  - **E ≈ MeV, Baseline range ≈ few m**
- **4 calibration runs ≈1-2 MCi EC ν_e emitters**
  - Gallex
    - ^{51}Cr source (750 keV)
  - Sage
    - ^{51}Cr & ^{37}Ar (810 keV)
- **Deficit observed**
  - $R_{obs/pred}$=0.86±0.05 ($\sigma_{Bahcall}$)
  - $R_{obs/pred}$=0.76±0.085 (σ_{Haxton})

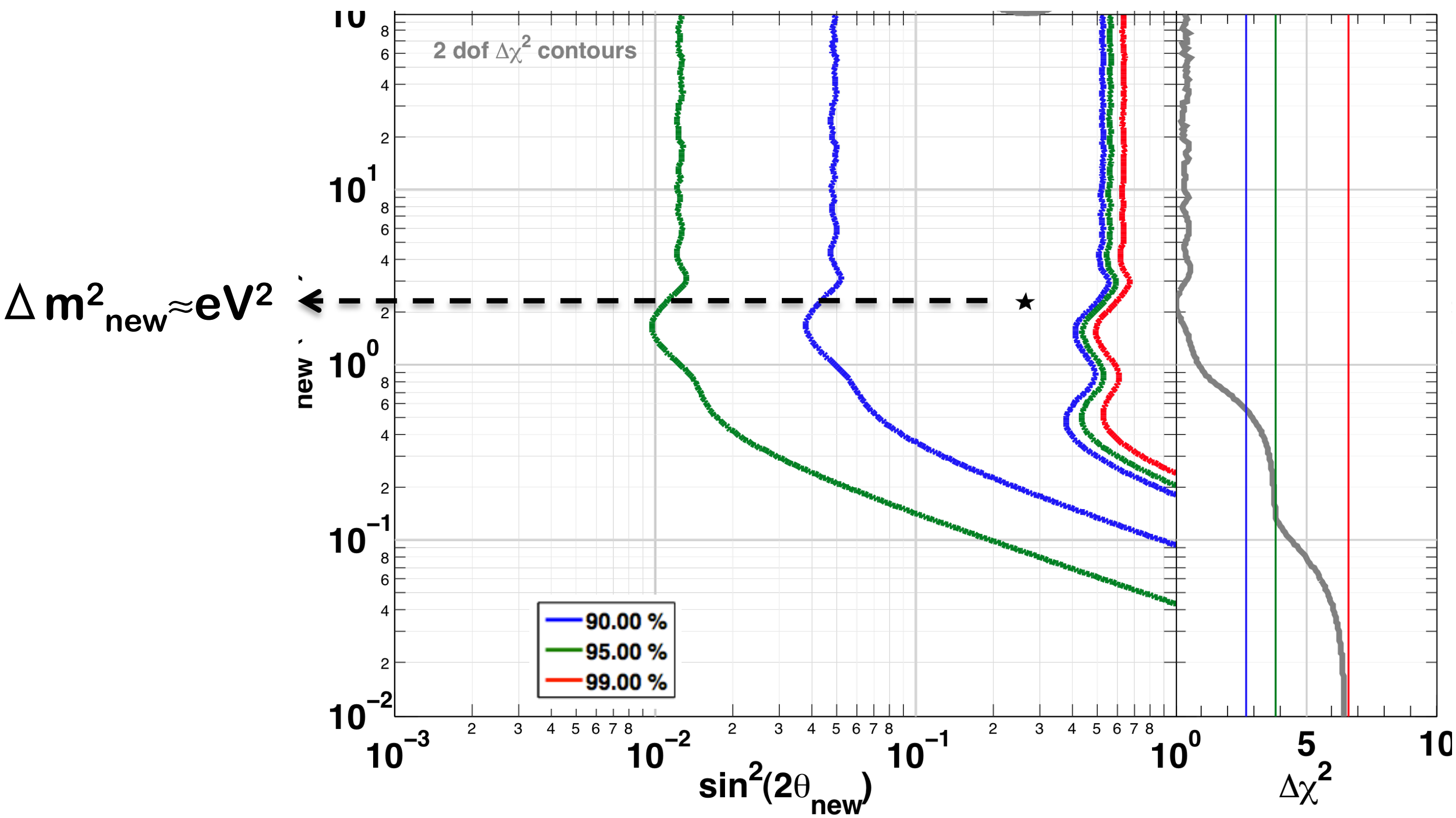




The Gallium Neutrino Anomaly

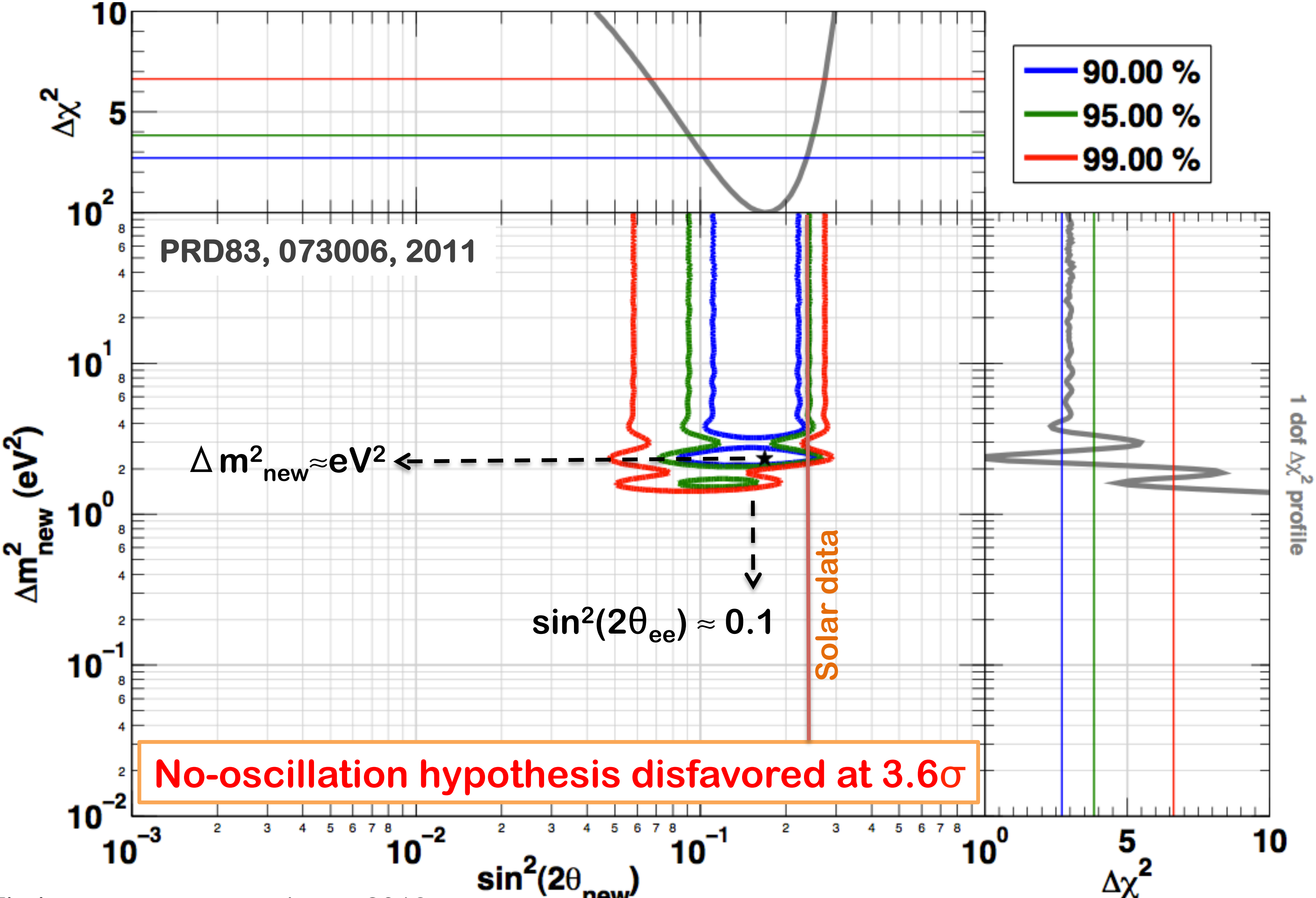
Fit to ν_e disappearance hypothesis (3+1)

$$\begin{pmatrix} \nu_e \\ \nu_s \end{pmatrix} = \begin{pmatrix} \cos\theta_{new} & \sin\theta_{new} \\ -\sin\theta_{new} & \cos\theta_{new} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_{new} \end{pmatrix}, \quad P_{ee} = 1 - \sin^2(2\theta_{new})\sin^2\left(\frac{\Delta m^2_{new} L}{E}\right)$$



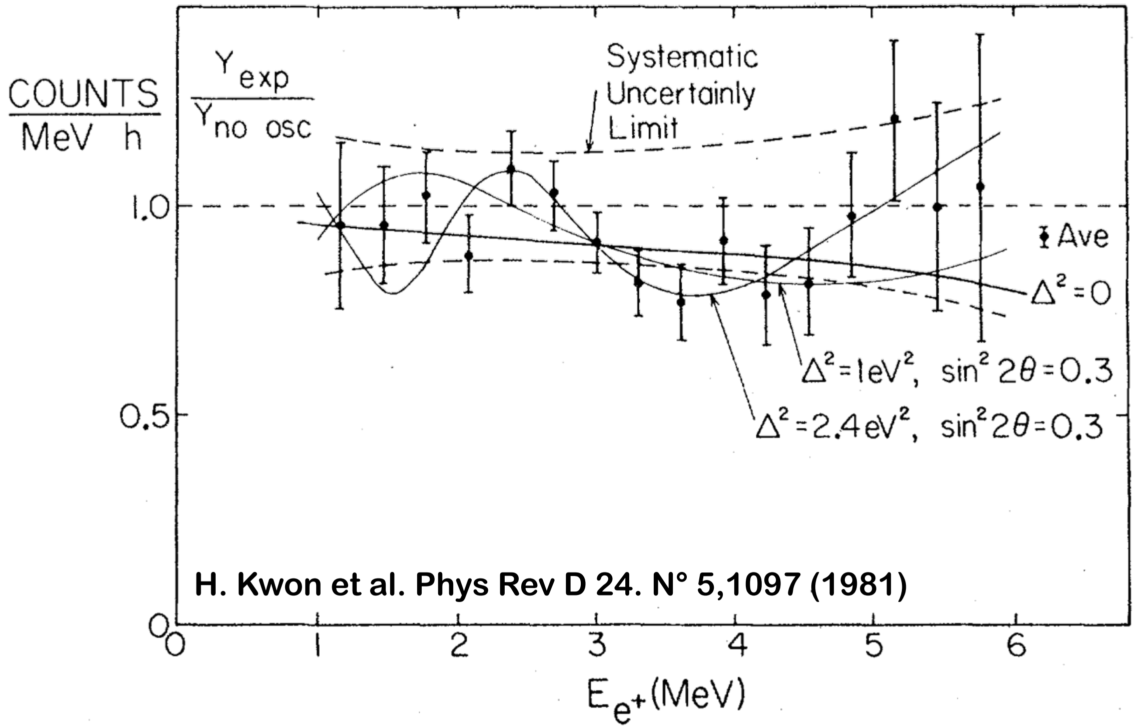
No-oscillation hypothesis disfavored at 2.7σ (PRC 83 065504,2011)

Gallium & Reactor: ν_e disappearance



Puzzling 1981 ILL ν-experiment

- Reactor at ILL with **almost pure** ^{235}U, with **compact core**
- **Detector 8.8 m from a COMPACT core**
- Reanalysis in 1995 to account for overestimation of flux at ILL reactor by 10%... Affects the rate only but **20% deficit**!



H. Kwon et al. Phys Rev D 24. N° 5,1097 (1981)

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