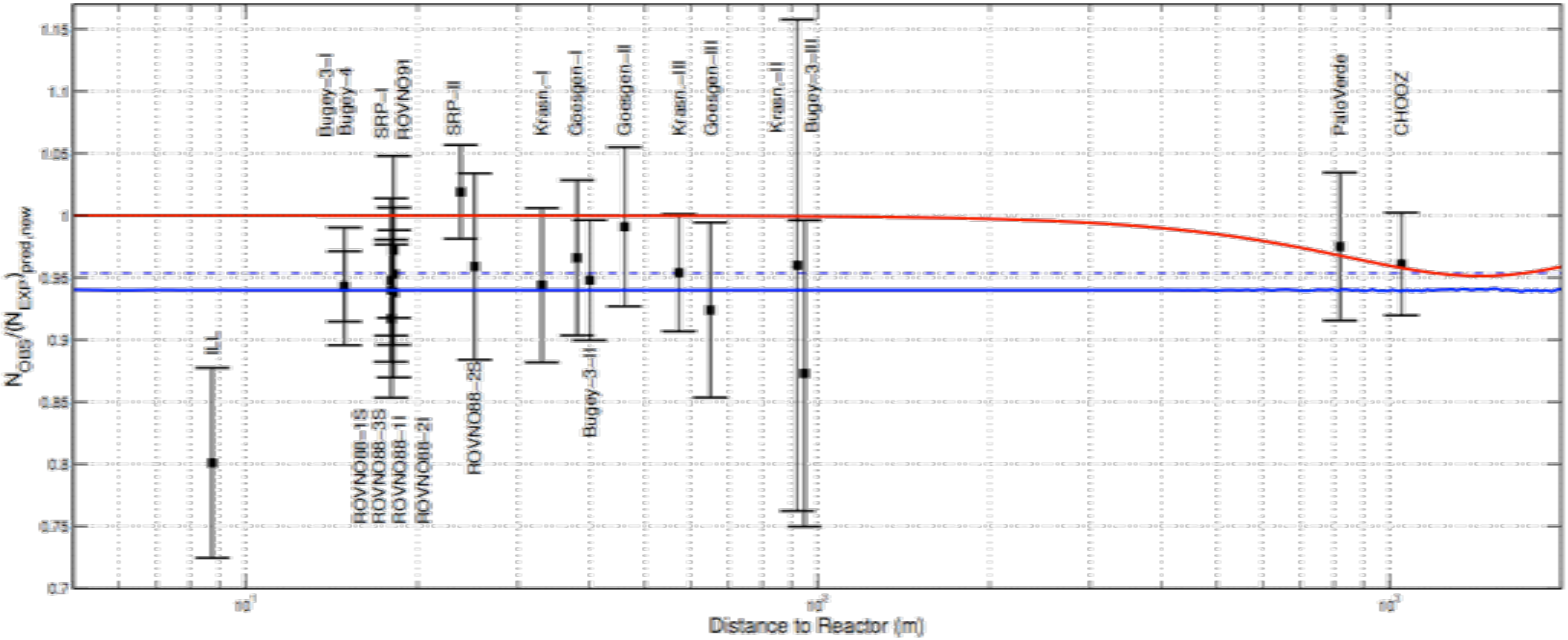
The Reactor Antineutrino Anomaly and implications



Th. Lasserre (CEA-Saclay, Irfu APC & SPP)

New Reactor Antineutrino Spectra

T.A. Mueller, D. Lhuillier, M. Fallot, A. Letourneau, S. Cormon, M. Fechner, L. Giot, T. Lasserre, J. Martino, G. Mention, A. Porta, F. Yermia.*

CEA / Irfu & IN2P3 / Subatech

arXiv:1101.2663 [hep-ex], accepted for publication in PRC
* corresponding author

ν spectrum emitted by a reactor

The prediction of reactor ν spectrum is the dominant source of systematic error for single detector reactor neutrino experiments

Reactor data

Thermal power, $\delta P_{th} \leq 1\%$

Reactor evolution codes

Fraction of fissions from isotope k, δa_k=few % but large anti-correl @ fixed P_{th}

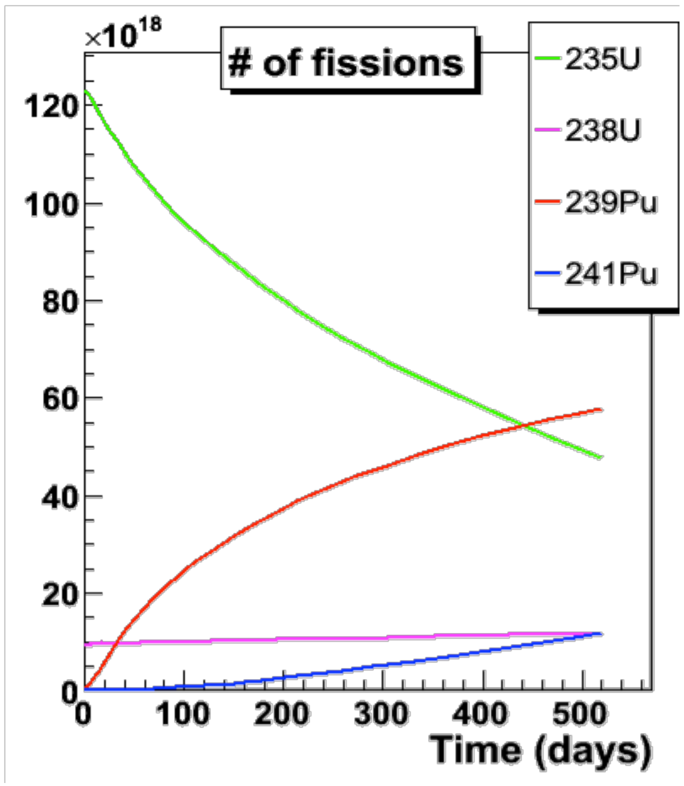
$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E)$$

Nuclear databases

E released per fissions of isotope k, $\delta E_k \approx 0.3\%$

ν spectrum per fission
This work !

$k = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$



The guts of $S_k(E)$

Sum of all fission products' activities

$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

Sum of all β-branch of each fission product

$$S_{fp}(E) = \sum_{b=1}^{N_b} BR_{fp}^b \times S_{fp}^b(Z_{fp}, A_{fp}, E_{0fp}^b, E)$$

Theory of β-decay

$$S_{fp}^b = \underbrace{K_{fp}^b}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E_{0fp}^b)^2}_{\text{Phase space}} \times \underbrace{C_{fp}^b(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta_{fp}^b(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

$$\delta_{fp}^b(Z_{fp}, A_{fp}, E) = \delta_{QED}(E) + A_C(Z_{fp}, A_{fp}) \times E + A_W \times E$$

Complementary approaches to compute the ν flux

Ab initio

Integral measurements

Sum of all fission products' activities

fission product inventory (t)

fission rates (t)

- Fission Yields (JEFF, ENDF, JENDL)
- Life time

Sum of all β-branches of each fission product

Build total spectrum from sum of β-branches

Reference spectrum per isotope

Theory of β-decay

- Complete β-decays schemes (ENSDF)
- β-strength (Greenwood et al.)
- Total β spectrum per nucleus (Rudstam et al.)
- Masses (Q_b)
- Nuclear models …

- ILL electron data

Full ab-inito

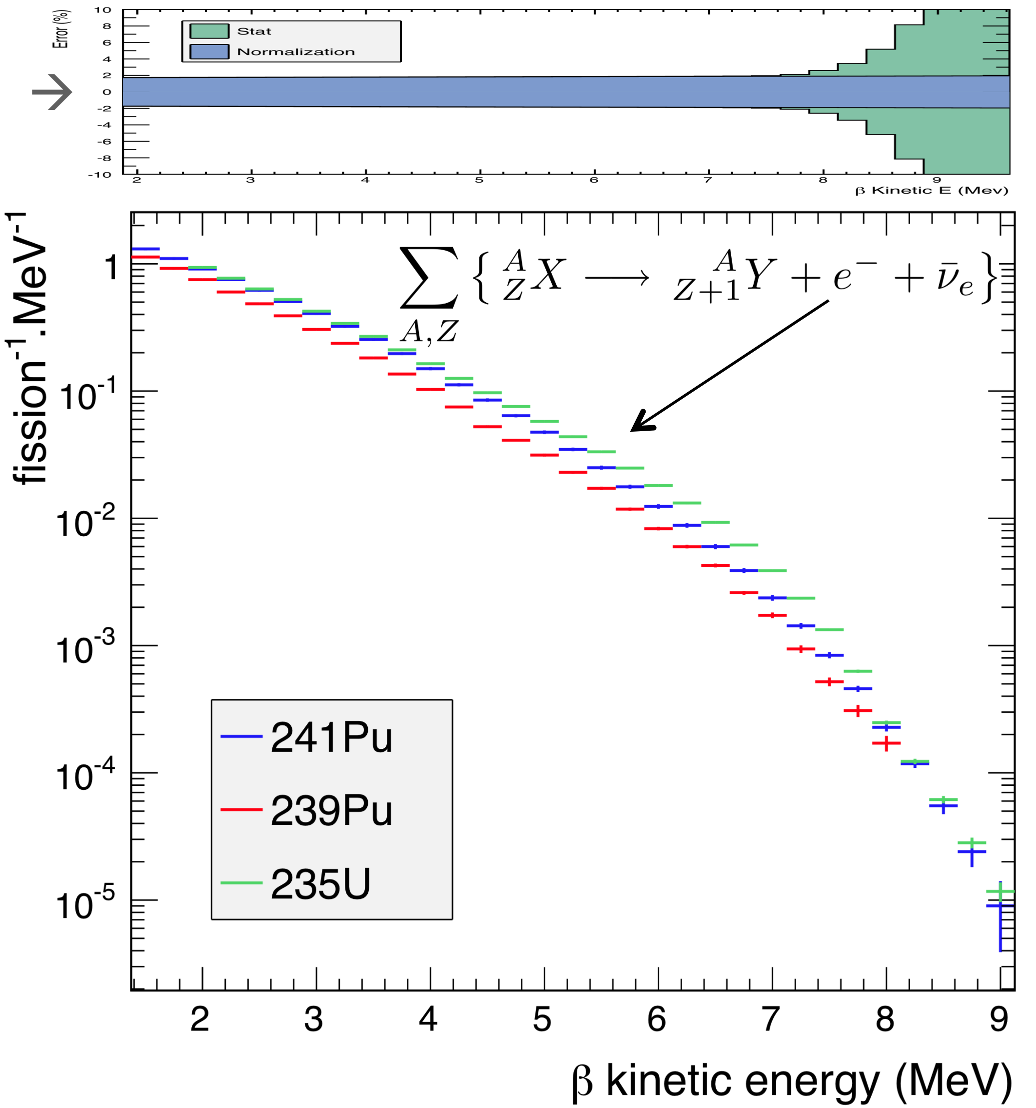
Our mixed approach

Effective

The ILL electron Data Anchorage

Unique reference to be met by any other measurement or calculation

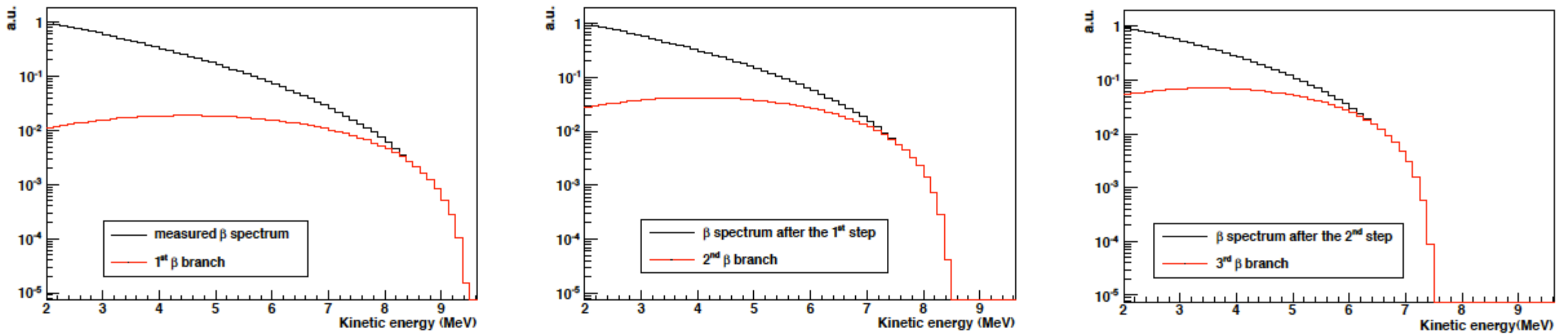
uncertainty →



- 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%)

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:**

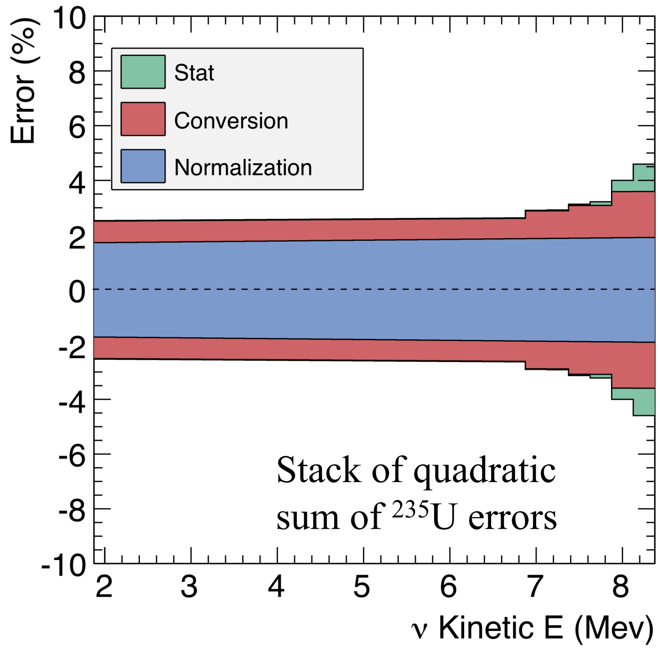
  - What Z? : Mean fit on nuclear data *Z=f(E0)*

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

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

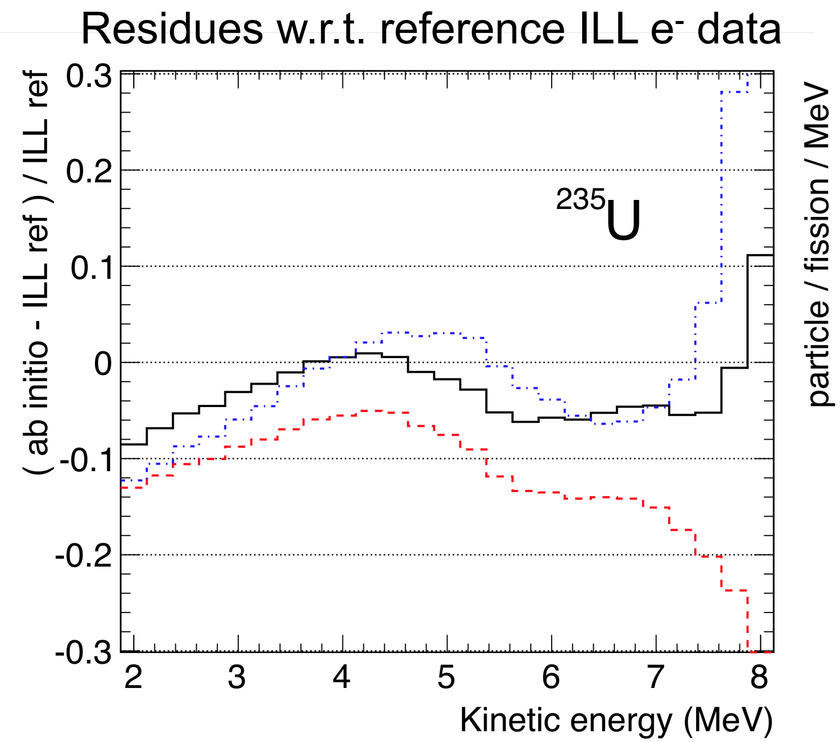
$$DN_n^{C,W}(E_n) \approx 0.65 \times (E_n - 4\text{MeV}) \quad \%$$

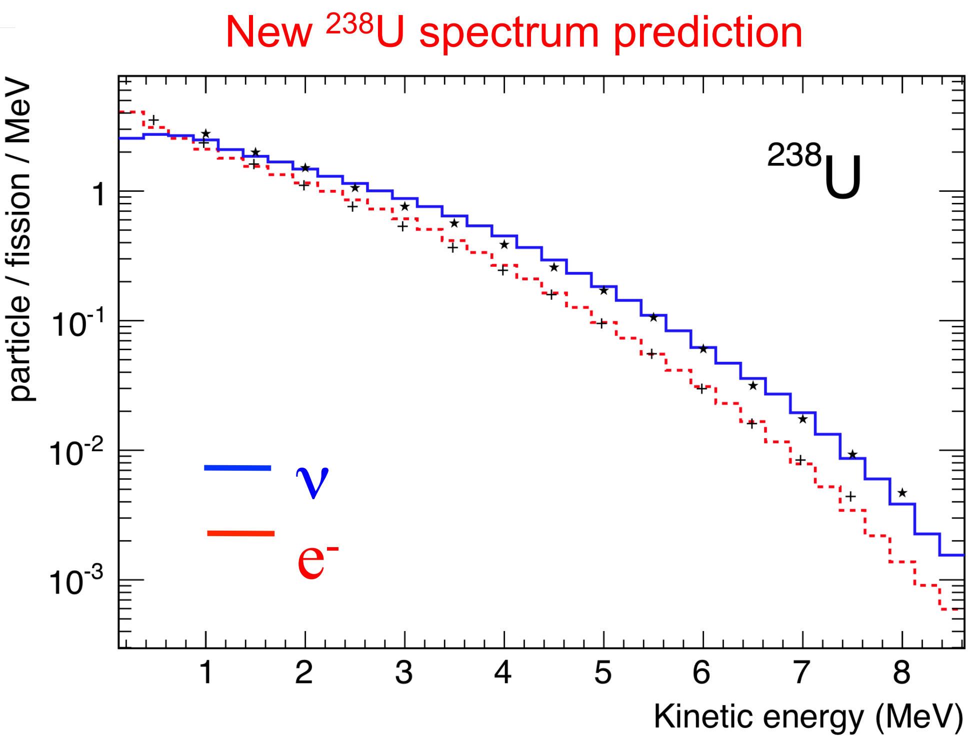
- **Conversion error from envelop of numerical studies**



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

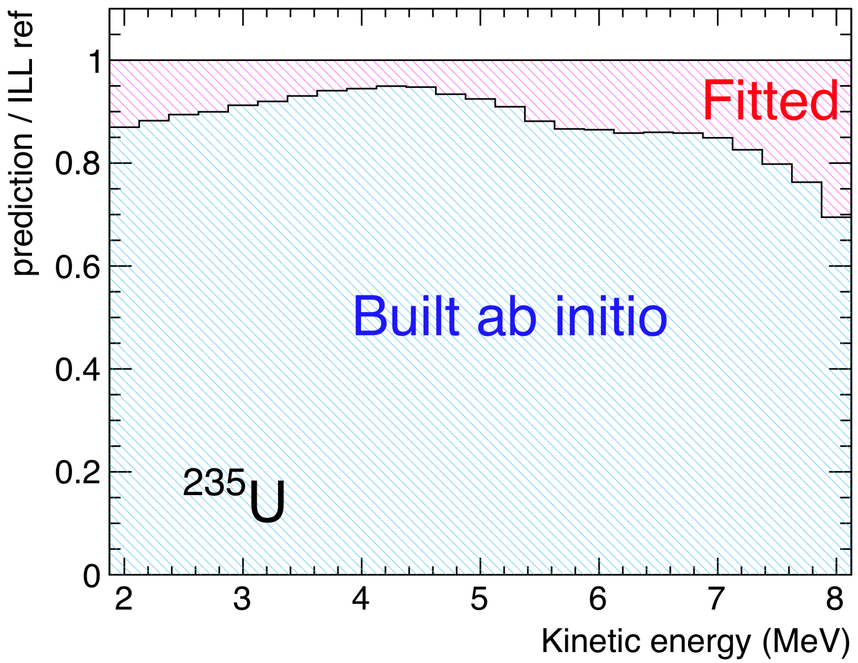


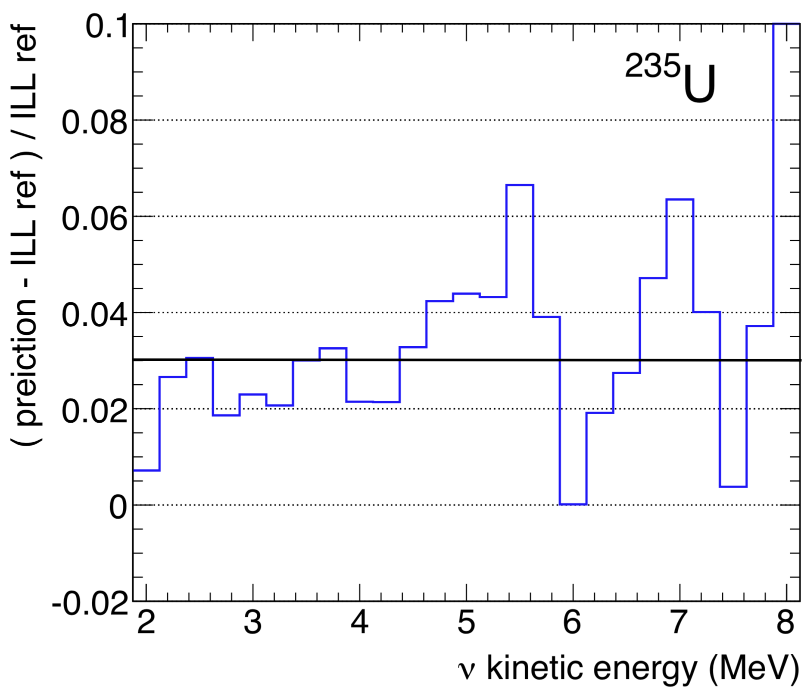


→ 95+/-5% of the spectrum reproduced but still not meeting required precision
→ Useful estimate of ^{238}U spectrum which couldn't be measured @ ILL
→ Measurement at FRMII ongoing (N. Haag & K Schreckenbach)

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**

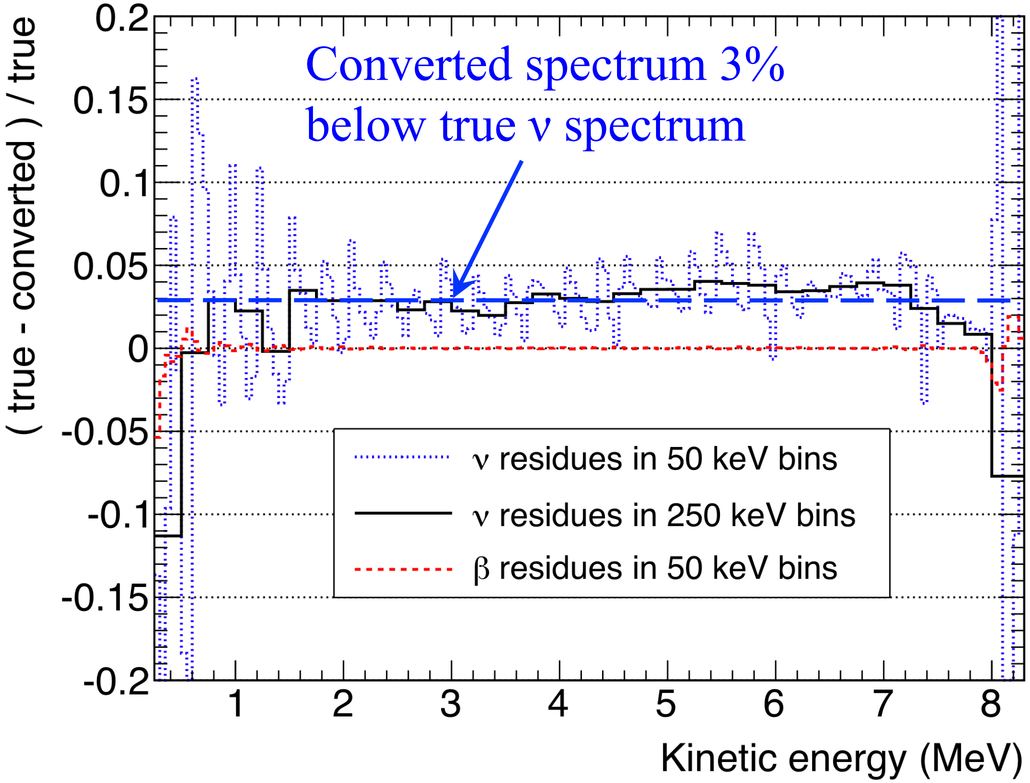
Consistency Check

1. Define "true" e^- and n spectra **from reduced set** of **well-known branches** from ENSDF nuclei data base.

2. Apply exact same **OLD** conversion procedure to true e^- spectrum.

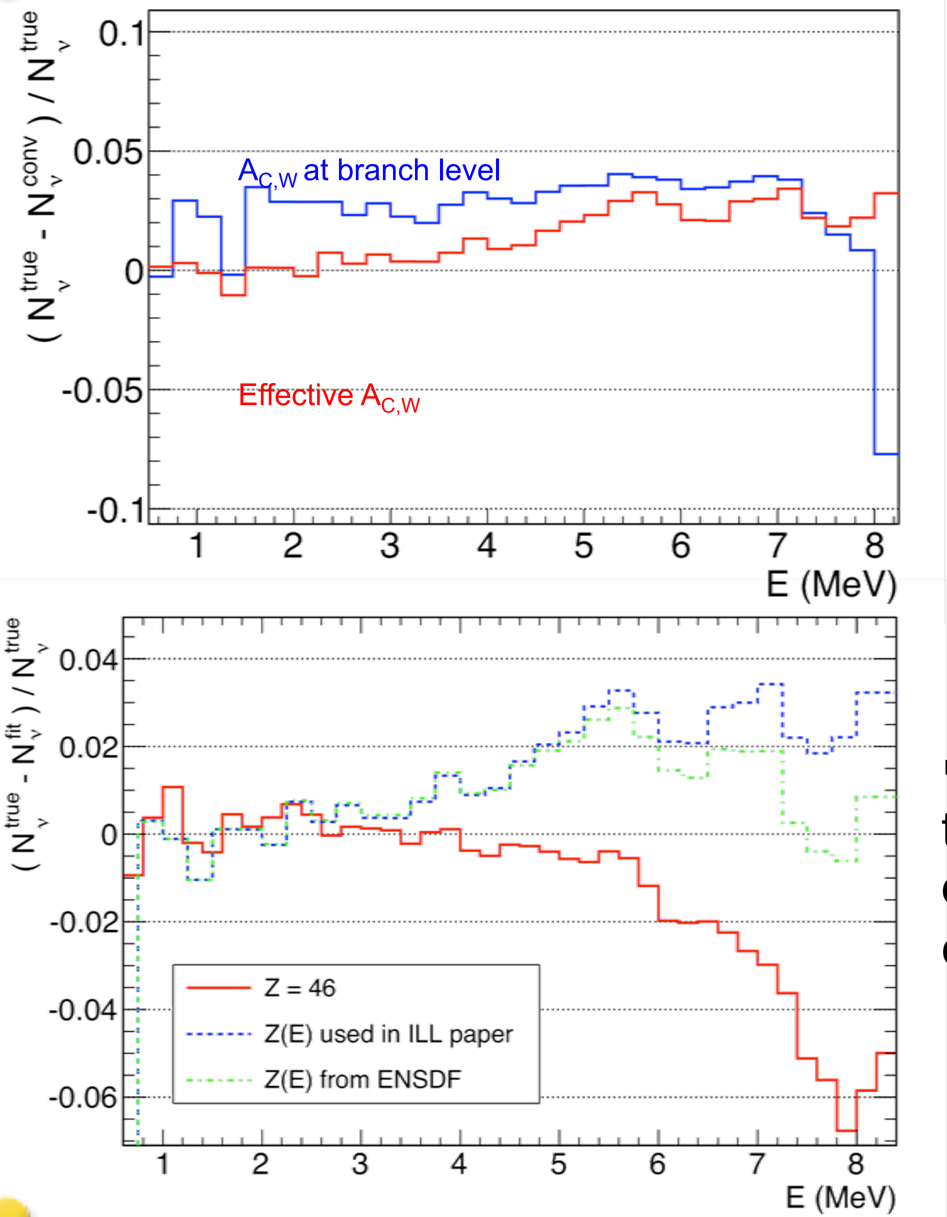
3. Compare the converted n spectrum to the true one.

4. This technique gives a 3% bias compared to the true ν spectrum



→ **OLD** effective conversion method biases the predicted ν spectrum at the level of -3% in normalization

Origin of the 3% shift



- **E <4 MeV**: deviation from effective linear $A_{C,W}$ correction of ILL data

$$\Delta N_\nu^{C,W}(E_\nu) \approx 0.65 \times (E_\nu - 4\,MeV) \quad \%$$

- **E >4 MeV**: mean fit of $Z(E_0)$ doesn't take into account the very large dispersion of Z around the mean curve

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

Off-Equilibrium Effects

MURE evolution code (IN2P3/Subatech)

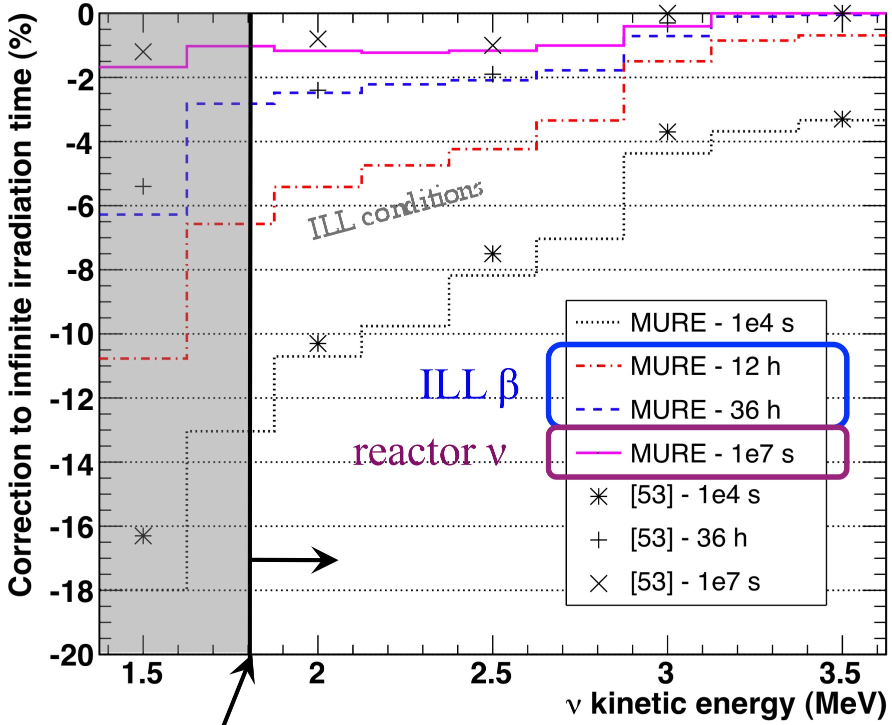
- ILL electron reference spectra : 12 hours to 1.8 days irradiation time
- Neutrino reactor experiments irradiation time >> months
- **BUT 10% of fission products have a β-decay life-time long enough to keep accumulating after several days**

  → need a correction through simulation

  → Not included prior to the CHOOZ experiment

Relative change of ν spectrum w.r.t. infinite irradiation time

Correction included by default in our new reference model



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

The Reactor Antineutrino Anomaly

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arXiv:1101.2755 [hep-ex], accepted for publication in PRD
* corresponding author

V-A IBD Cross Section

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

- **Theoretical predictions: our results agree with**
  - Vogel 1984 (Phys Rev D29 p1918). **Fayans 1985 (Sov J Nucl Phys 42)**
  - Vogel-Beacom 1999: "supersedes" Vogel 84 (Phys Prev D60 053003)
  - Strumia-Vissani Phys. Lett. B564 (2003) 42-54

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

- **The pre-factor κ** (two pseudo-independent approaches)

$$\kappa = \frac{G_F^2 cos^2(\theta_C)}{\pi}(1 + \Delta_{inner}^R)(1 + 3\lambda^2) = \frac{2\pi^2}{m_e^5 f^R \tau_n} \qquad \lambda = |\frac{g_A}{g_V}|$$

- **κ ran down over the history,** from 0.914 10^{-42} cm^2 in 1981
  - Vogel-Beacom 1999 : κ = 0.952 10^{-42} cm^2
  - **Our work is based on 2010 PDG τ_n : κ = 0.956 10^{-42} cm^2**
  - **But we anticipate 2011 κ=0.961 10^{-42} cm^2 (<τ_n> revision +0.5%)**

Reactor Electron Antineutrino Detection

- **Inverse Beta Decay:** $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Threshold: 1.806 MeV
- **Anti-ν_e interaction rate** $n_\nu = \frac{1}{4\pi R^2} \frac{P_{\text{th}}}{\langle E_f \rangle} N_p \varepsilon \sigma_f$
- **Experimental cross section per fission:** σ_f

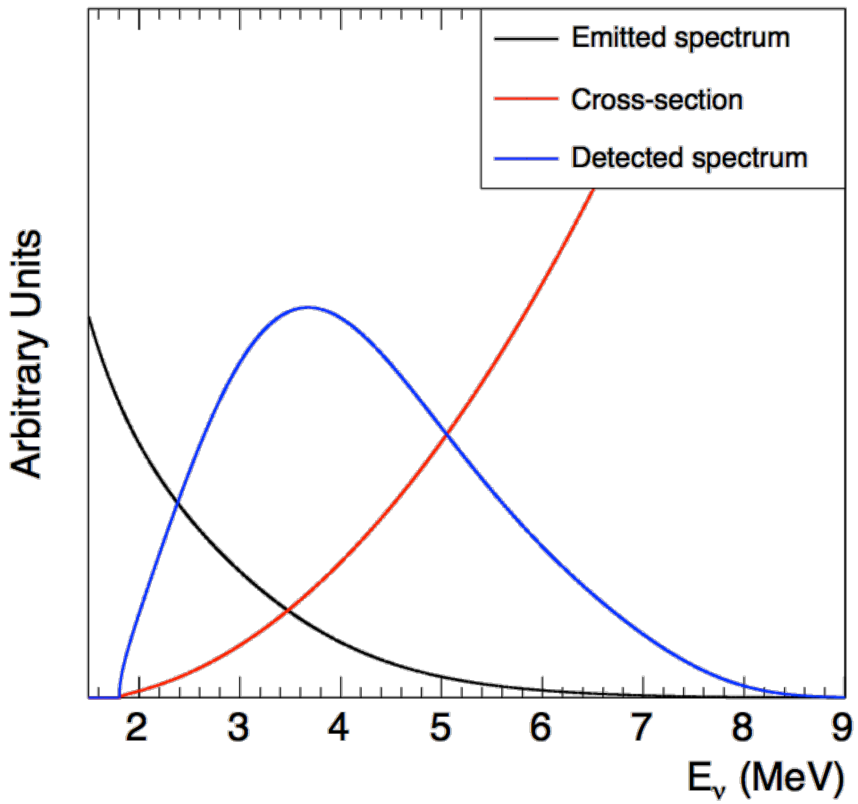
$$\sigma_f^{\text{meas.}} = \frac{4\pi R^2 n_\nu^{\text{meas.}}}{N_p \varepsilon} \frac{\langle E_f \rangle}{P_{\text{th}}}$$

- **Predicted cross section per fission:** σ_{pred}

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

Computing the expected rate/spectrum

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



- **Bugey-4 Benchmark**
  - Phys Lett B 338(1994) 383
  - τ_n = 887.4 s
  - “old” spectra (30 effective branches)
  - no off-equilibrium corrections

10^{-43} cm^2/ fission	^{235}U	^{239}Pu	^{241}Pu
BUGEY-4	6.39±1.9%	4.18±2.4%	5.76±2.1%
This work	6.39±1.8%	4.19±2.3%	5.73±1.9%

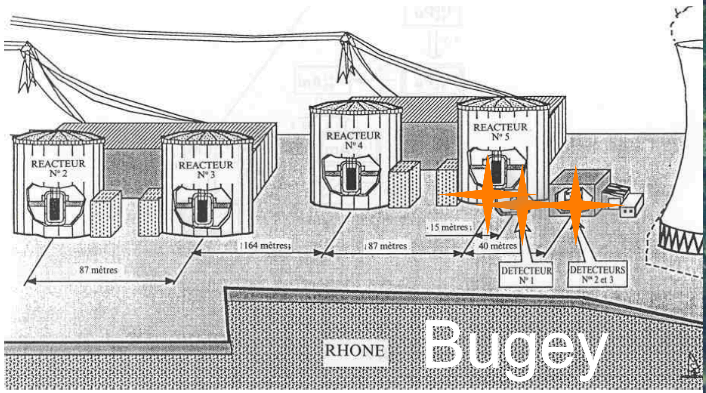
- **Final agreement to better than 0.1% on best known ^{235}U**

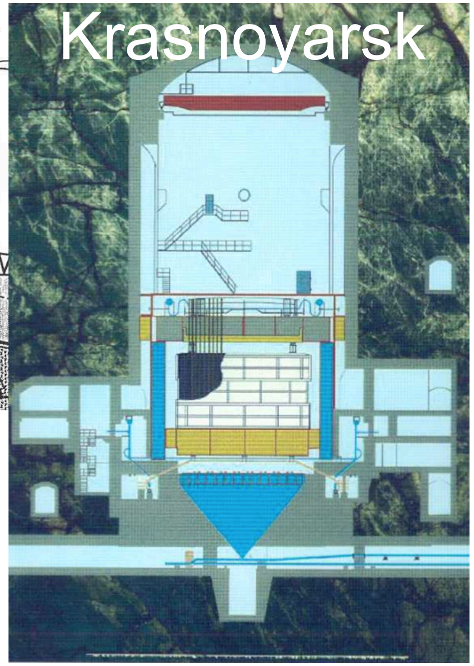
The New Cross Section Per Fission

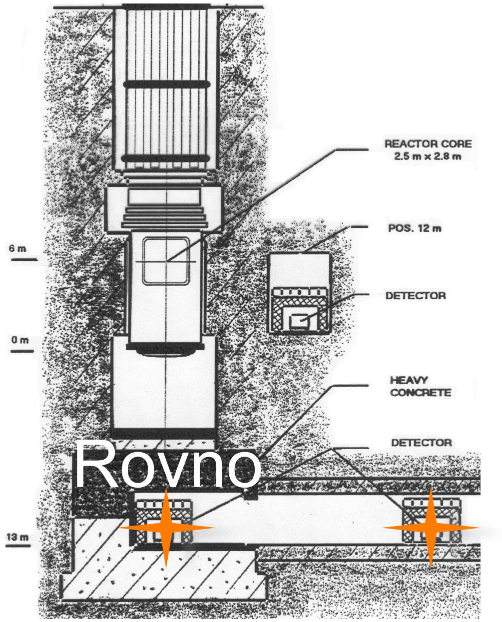
- ν-flux: ^{235}U +2.5%, ^{239}Pu +3.1%, ^{241}Pu +3.7%, ^{238}U +9.8% (σ_f^{pred} ↗)
- Off-equilibrium corrections now included (σ_f^{pred} ↗)
- Neutron lifetime decrease by a few % (σ_f^{pred} ↗) $\sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n$
- Slight evolution of the phase space factor (σ_f^{pred} →)
- Slight 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:

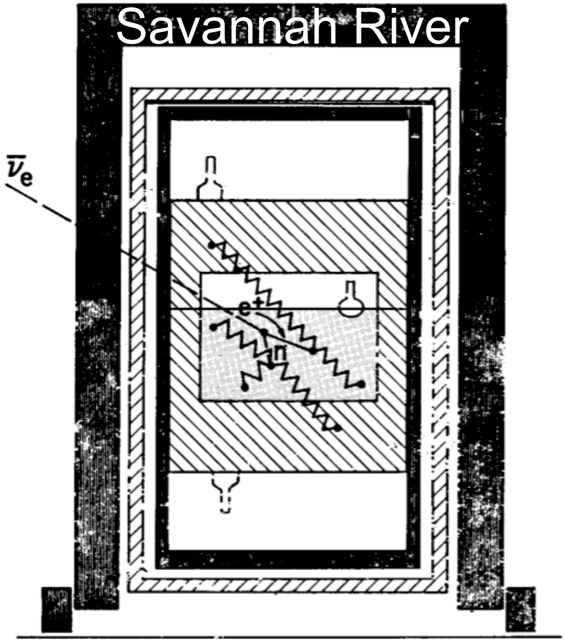
	old [3]	new	new/old
$\sigma_{f,^{235}U}^{pred}$	6.39±1.9%	6.61±2.11%	+3.4%
$\sigma_{f,^{239}Pu}^{pred}$	4.19±2.4%	4.34±2.45%	+3.6%
$\sigma_{f,^{238}U}^{pred}$	9.21±10%	10.10±8.15%	+9.6%
$\sigma_{f,^{241}Pu}^{pred}$	5.73±2.1%	5.97±2.15%	+4.2%

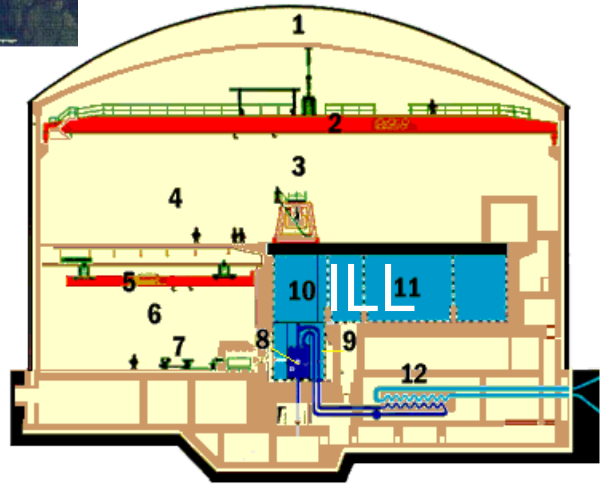
19 Experimental Results below 100m









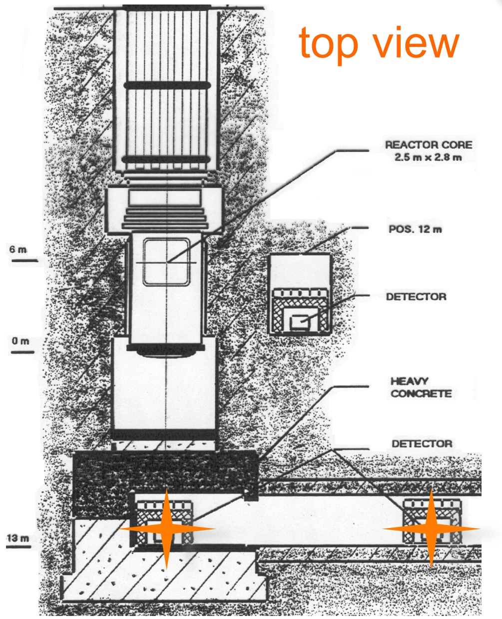


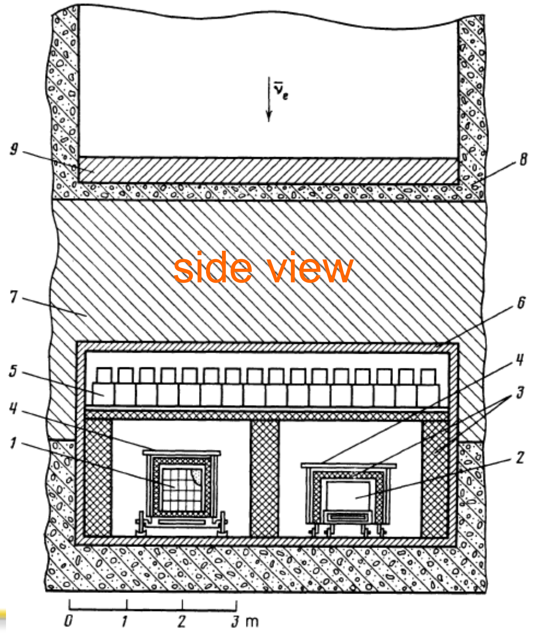
Measured cross sections are taken at their face values

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:**
  - Bugey-4
  - Rovno91 (integral measurement only),
  - with each other



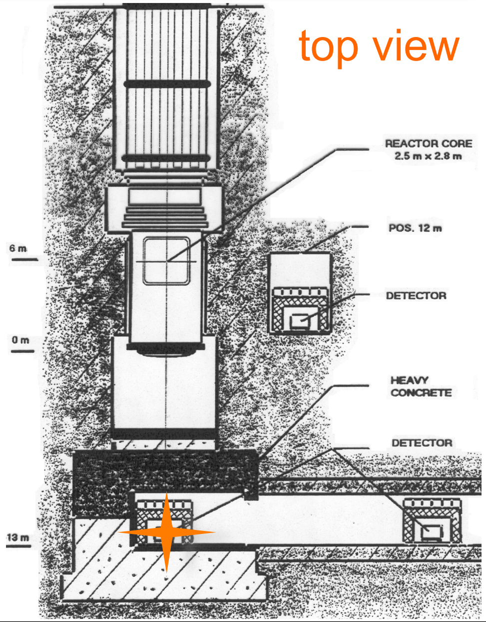


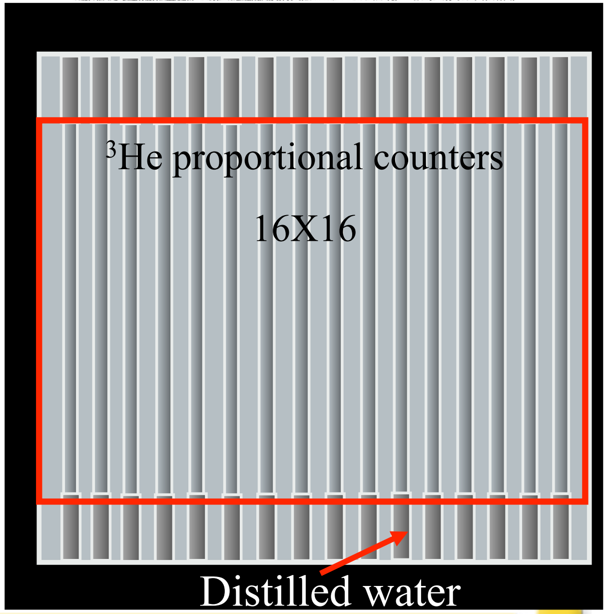
ROVNO-91 (JETP Lett., 54, 1991, 253)

- 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)

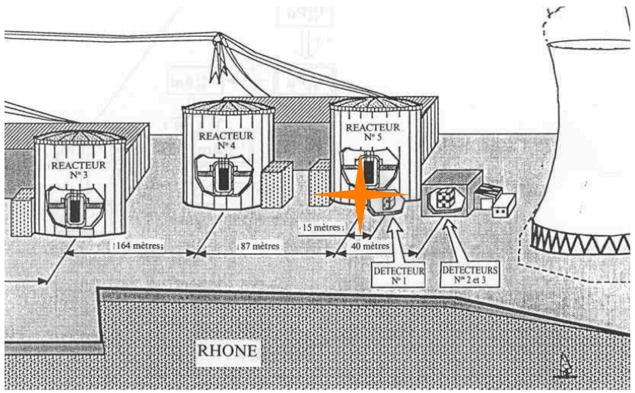


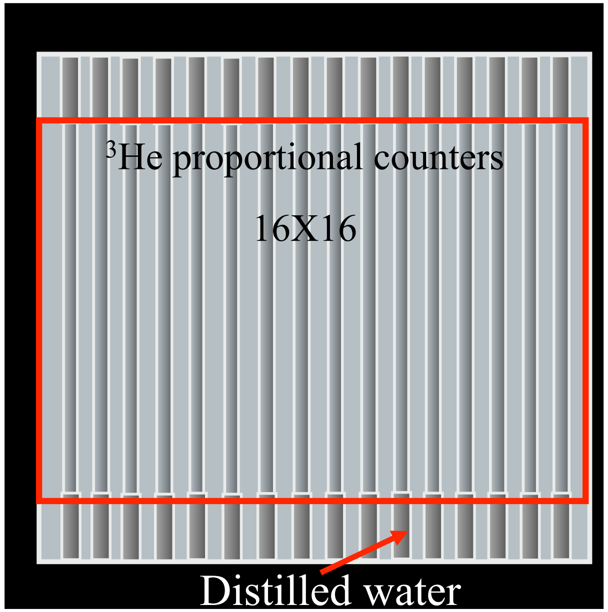


Bugey-4 (Phys. Lett. B338, 383, 1994)

- 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

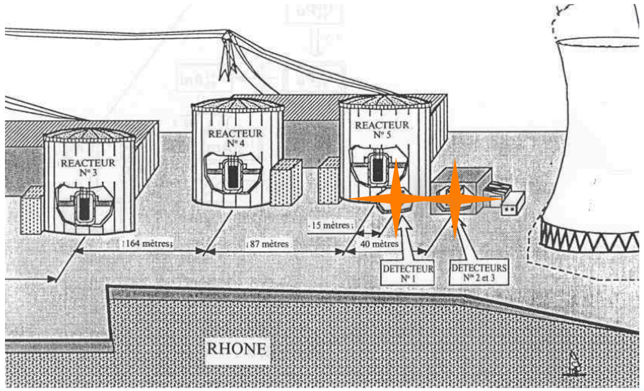


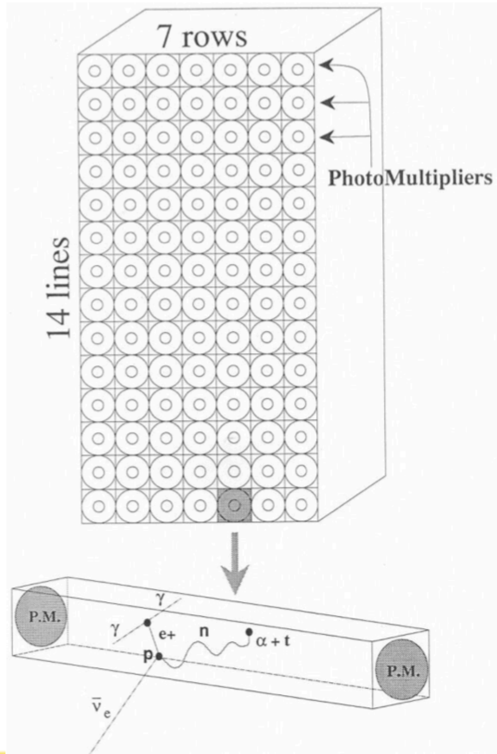


Bugey-3 (3 measurements, Nucl Phys B434, 504, 1995)

- Bugey, France, PWR, 80's
- **Technology**
  - Liquid scintillator segmented detectors doped with ^{6}Li
- **Fuel composition typical of PWR**

  53.8% ^{235}U, 32.8% ^{239}Pu, 7.8% ^{238}U 5.6% ^{241}Pu
- **Baselines**
  - 14m, 42m and 95m:
- **Uncertainties:**
  - statistics: 0.4%, 1.0%, 13.2%
  - systematics: 5.0%
- **Correlated with**
  - each other
- Stringent shape distortion analysis disfavoring sub-eV^2 oscillations

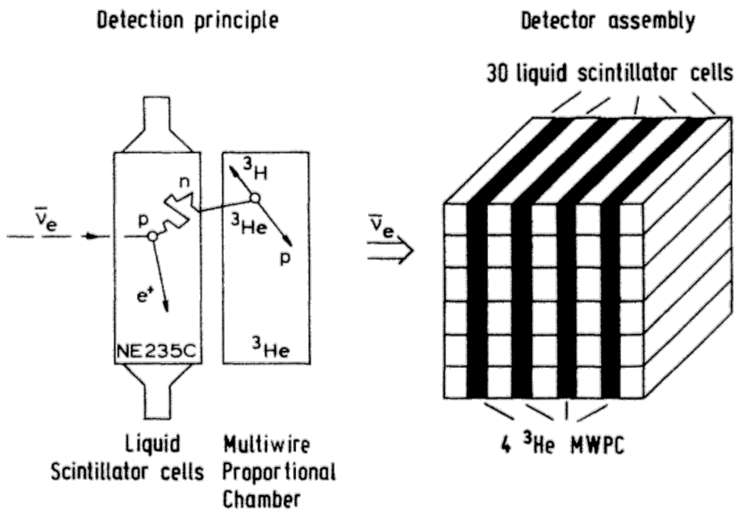




Goesgen (3 measurements, Phys Rev D34, 2621, 1986)

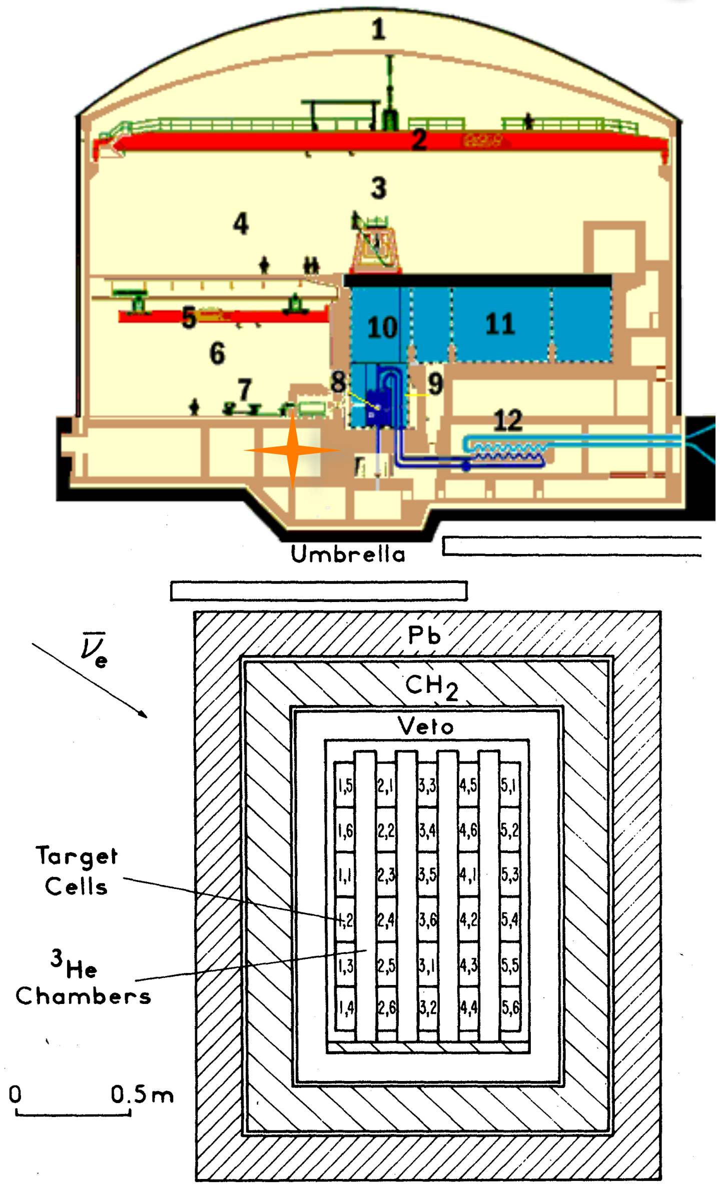
- Gösgen PWR, Switzerland, 1981-1984
- **Technology:**
  - liquid scintillator segmented detector + ^{3}He counters for neutron capture
- **Baselines:**
  - 37.9m, 45.9m, 64.7m
- **3 fuel compositions. Typical:**

  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



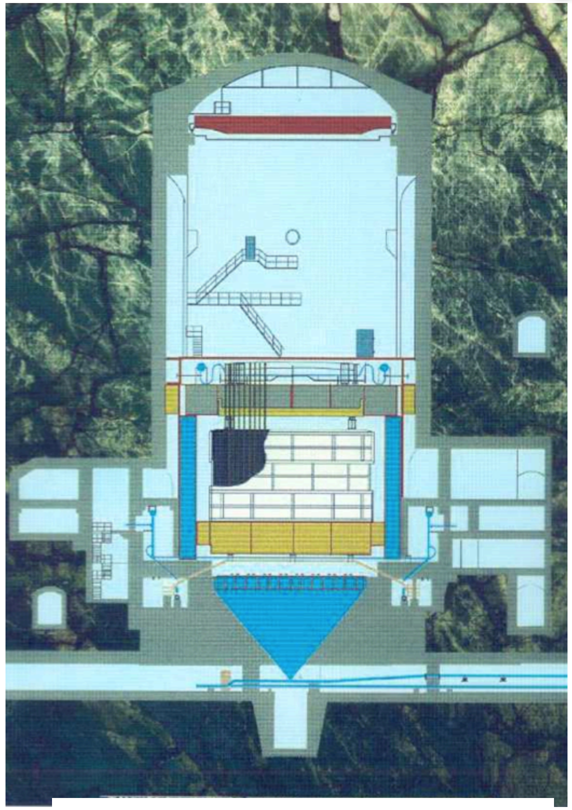
ILL-ν (Phys Rev D24, 1981, 1097)

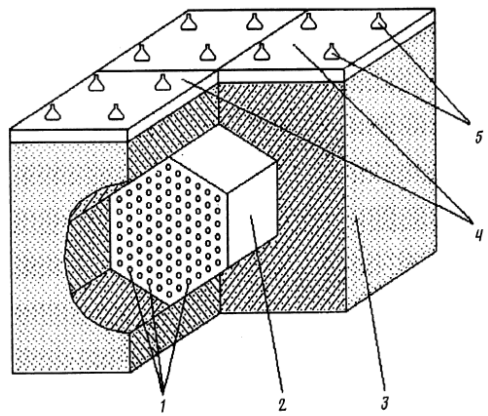
- ILL, Research Reactor, Grenoble, 80-81
- **Technology:**
  - Liquid scintillator segmented detector + ^{3}He counters for neutron capture
- **Baselines**
  - 8.76 (15) m
- **Fuel composition:**
  - almost pure ^{235}U
- **Uncertainties:**
  - statistics: 3.5%
  - systematics: 8.9%
- **Correlated with:**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



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:**
  - 33m, 92m from 2 reactors (1987)
  - 57.3m from 2 reactors (1994)
- **Fuel composition:**
  - mainly ^{235}U
- **Uncertainties (33m, 57m, 92m)**:
  - statistics: 3.6%, 1%, 19.9%
  - systematics: 4.8% to 5.5% (corr)
- **Correlated with:**
  - each other

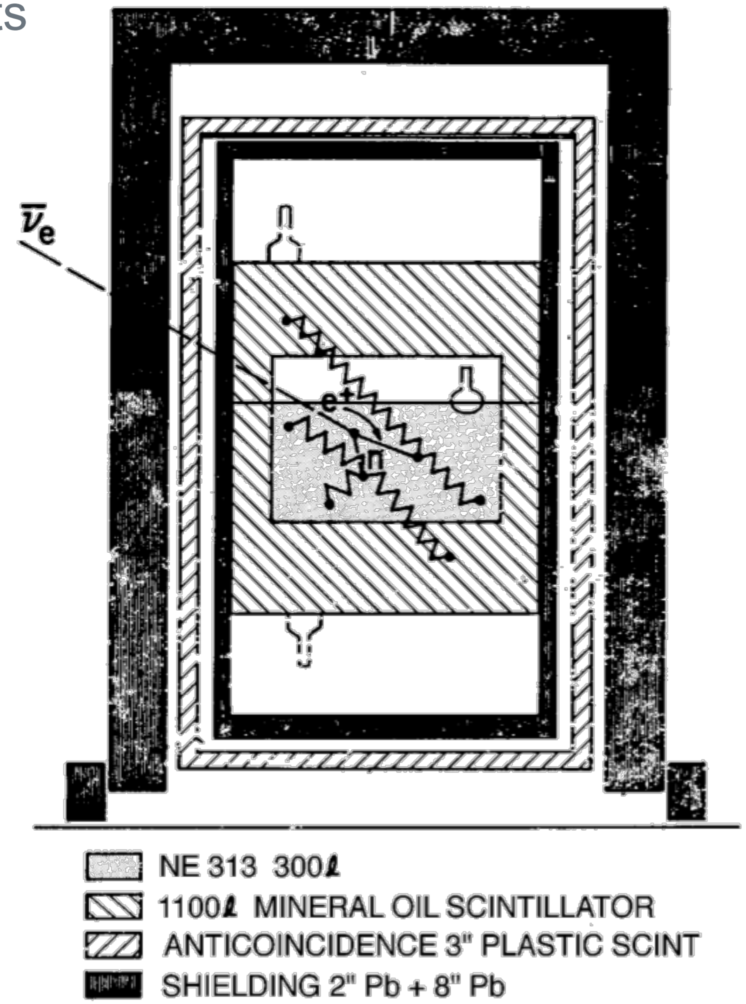




Savannah River Plant (2 measurements, PRD53, 6054, 1996)

- 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**
  - 18.2m 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

Neutrino Oscillation Detector



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
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.2	18
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

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	$^3He+H_2O$	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	$^3He+H_2O$	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	^6Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.946	4.8	4.8	15
4	Bugey-3-II	^6Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
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19 Experimental Results Revisited (L<100m)

Averaged Fuel Composition

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19 Experimental Results Revisited (L<100m)

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

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Error Budget & Correlations

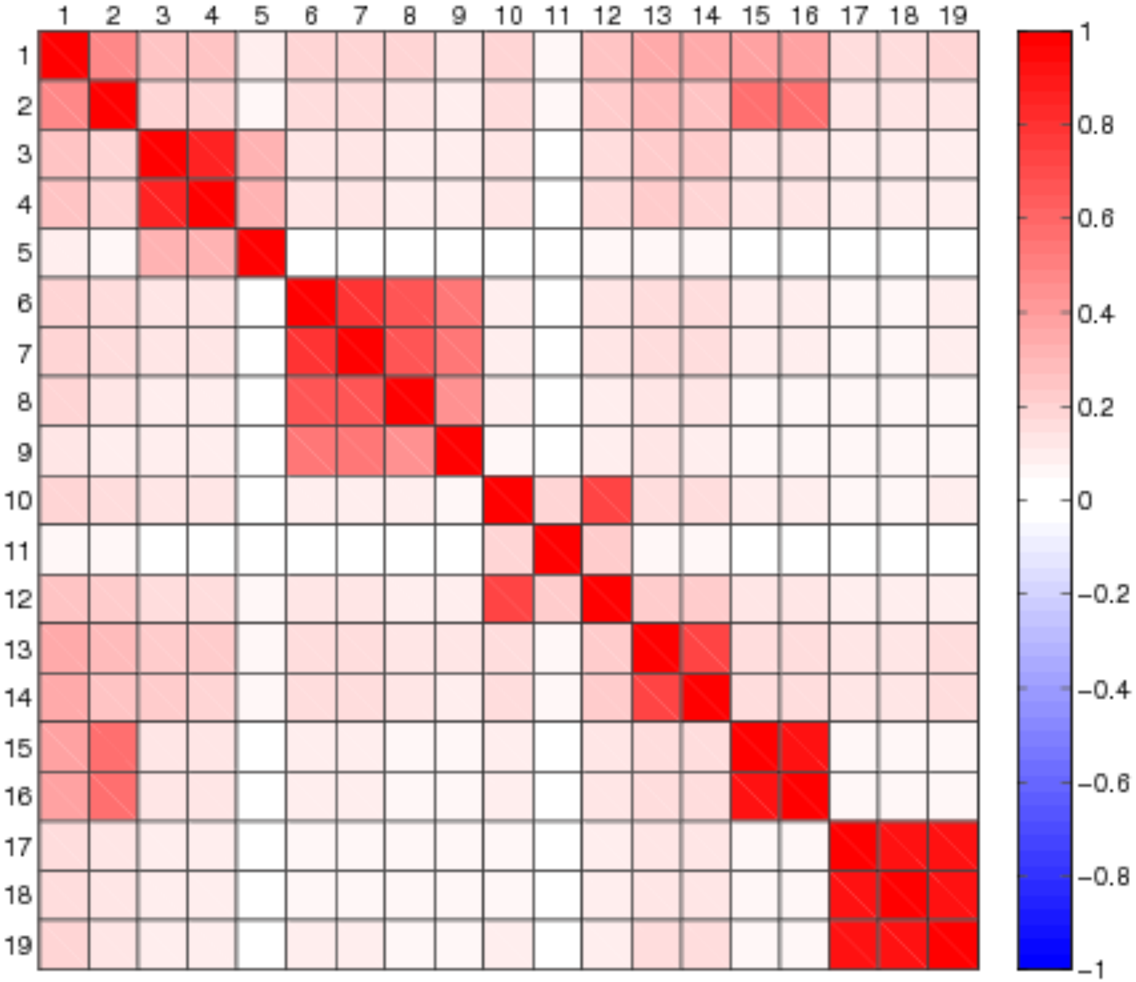
- Our guiding principles: Be conservative - Be stable numerically (SRP case)

- **Reactor Antineutrino Sources**
  - 2% systematic on ν-flux 100% correlated over ALL measurements
    - 1.8% corresponds to the normalization error on the ILL e- data
- **Detector: Non-flux systematic error correlations across measurements:**
  - Same experiment with same technology: 100% correlated
  - ILL shares 6% correlated error with Goesgen although detector slightly different. Rest of ILL error is uncorrelated.
  - Rovno88 integral measurements 100% corr. with Rovno 91 despite detector upgrade, but not with Rovno88 LS data
  - Rovno91 integral meas. 100% correlated with Bugey-4
  - Rovno88 integral meas. 50% correlated with Bugey-4

Experiments correlation matrix

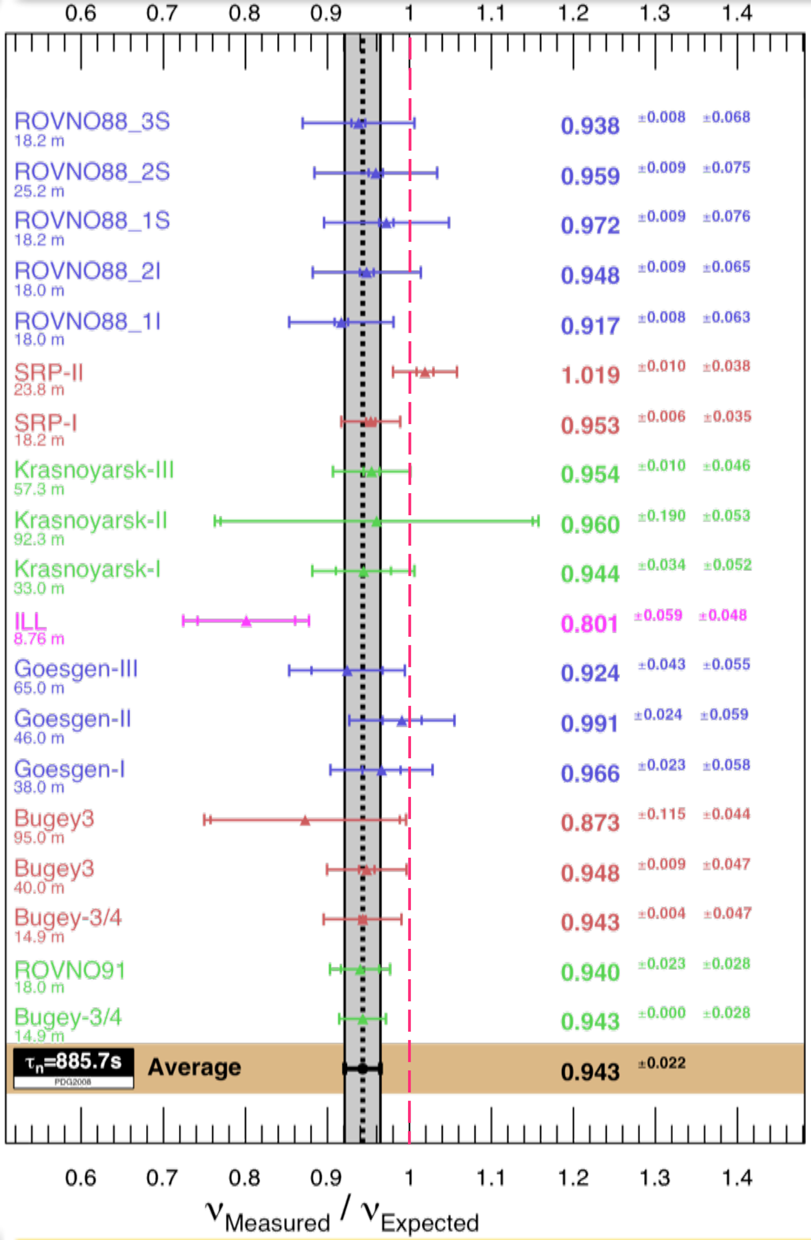
$\vec{R}$	$\Sigma_{tot.}$ (in %)	$\Sigma_{cor.}$ (in %)
Bugey-4 15m	3.0	3.0
Rovno91 18m	3.9	3.0
Bugey-3 15m	5.0	5.0
Bugey-3 40m	5.1	5.0
Bugey-3 92m	14.1	5.0
Goesgen 38m	6.5	6.0
Goesgen 45m	7.6	6.0
Goesgen 65m	9.5	6.0
ILL 9m	5.1	4.1
Krasno 33m	5.1	4.1
Krasno 92m	20.3	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7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



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

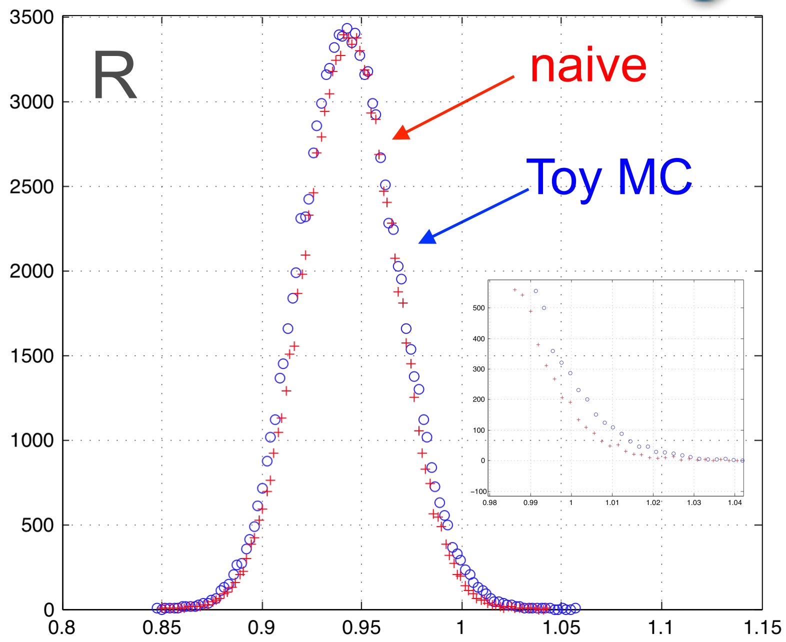
- **Best fit : μ = 0.943**
- **Uncertainty : 0.023**
- χ^2 = 19.6/19
- Deviation from unity
  - Naïve Gaussian : 99.3% C.L.
  - Toy MC: 98.6% C.L. (10^6 trials)
- No hidden covariance
  - 18% of Toy MC have χ^2_{min}<19.6

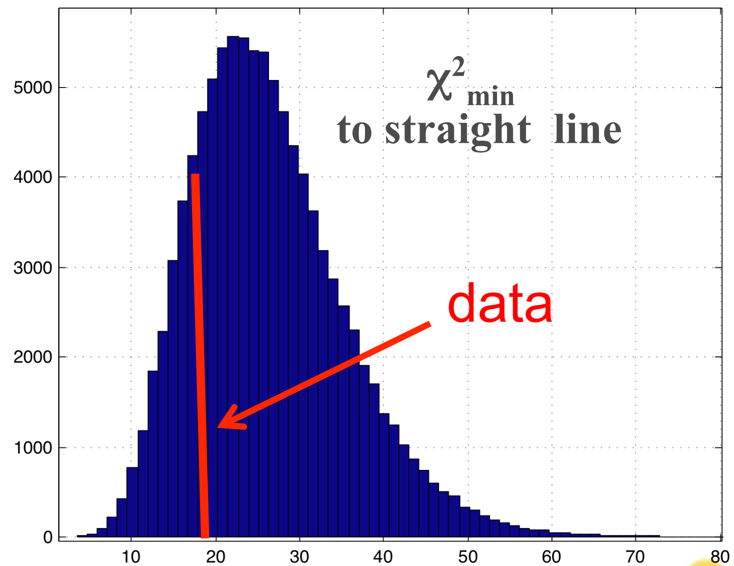
Are the ratios normally distributed?

- **Our data points are ratios of Gaussians:**
  - **Numerator**: measurement, Gaussian with stat & syst error, partially correlated
  - **Denominator**: common prediction, assumed to have Gaussian fluctuation of 2%

- **Toy MC with correlated denominator with 2% fluctuation → 10^6 events**
  - Estimate weighted average R of 19 random points with correlations around 0.943.
  - P-value for (R >= 1) : 1.4% (2.2σ) compared to naive Gaussian 2.4σ.
  - Our contours are reweighted by $(2.2/2.4)^2$ to take this slight non-normality into account

- **Hidden Covariance**
  - χ^2_{min} of data to straight line in the 18% quantile → Data not incompatible with fluctuations





The reactor rate anomaly

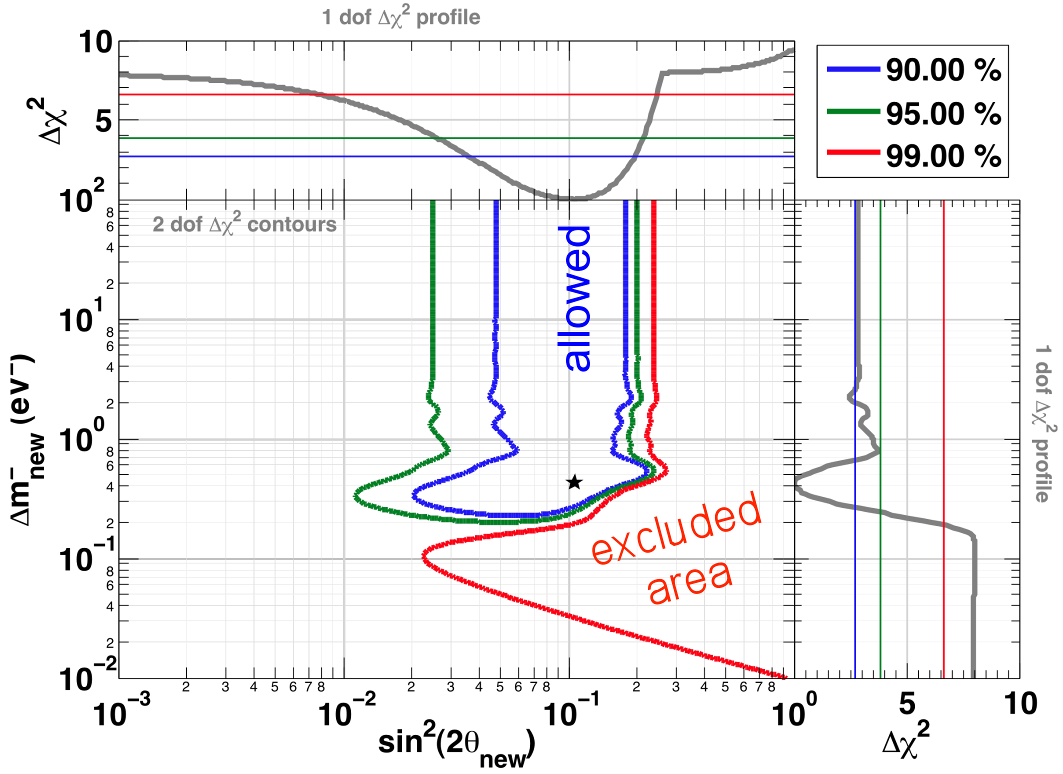
- 18/19 short baseline experiments <100m from a reactor observed a deficit of anti-ν_e compared to the new prediction
- The effect is statistically significant at more 98.6%
- Effect partly due to re-evaluation of cross-section parameters, especially updated neutron lifetime, accounting for off equ. effect
- **At least three alternatives:**
  - Our conversion calculations are wrong. Anchorage at the ILL electron data is unchanged w.r old prediction
  - Bias in all short-baseline experiments near reactors : unlikely…
  - New physics at short baselines, explaining a deficit of anti-ν_e :
    - **Oscillation towards a 4th, sterile ν ?**
    - **a 4th oscillation mode with 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

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

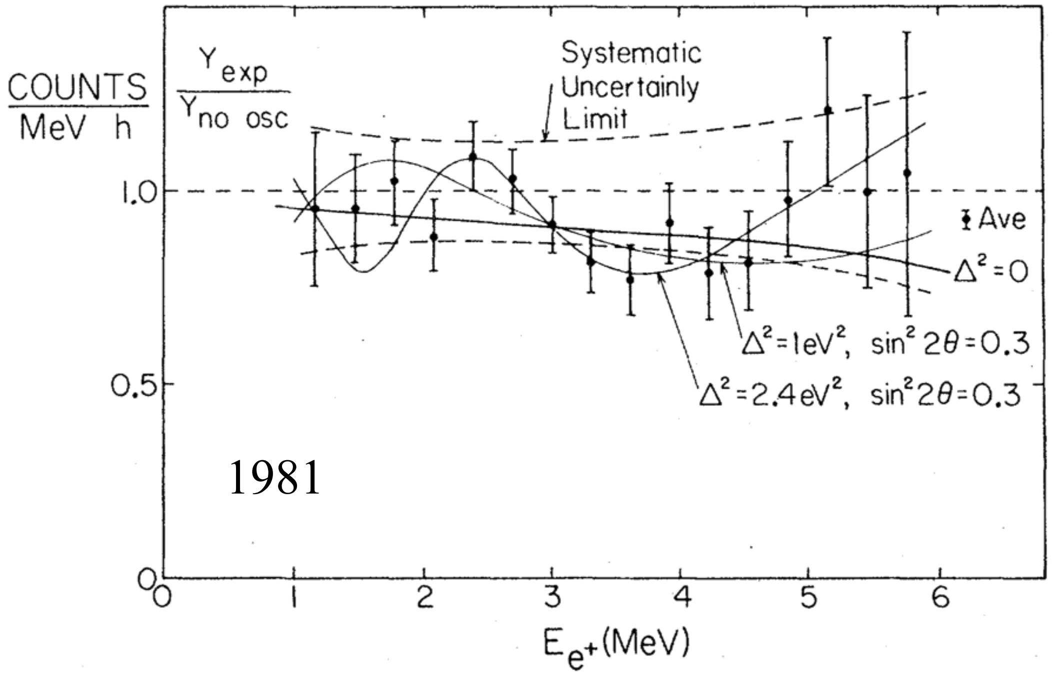
$$P_{\nu_e \to \nu_e}(L,E) = |\langle \nu_e(L)|\, \nu_e(L=0)\rangle|^2 = 1 - \sin^2(2\theta_{\rm new})\sin^2\left(\frac{\Delta m^2_{\rm new} L}{E}\right)$$

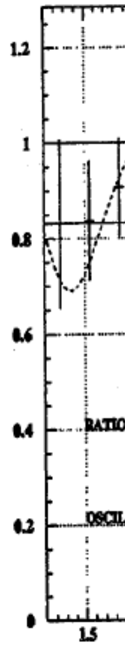


- Absence of oscillations disfavored at 98.6% C.L.

The 1981 ILL measurement

- Reactor at ILL with **almost pure ^{235}U**, with **compact core**
- Detector **8.76(?) m** from core. Any bias?
- Reanalysis in 1995 by part of the collaboration to account for overestimation of flux at ILL reactor by 10%... Affects the rate only





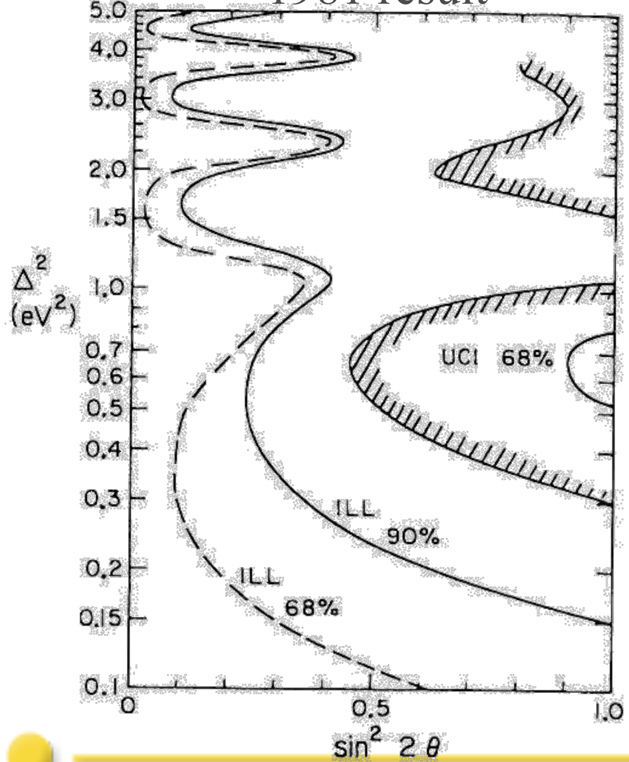
- Large errors, but a striking pattern is seen by eye ?

Our ILL re-analysis (reproduce no-oscillation claim)

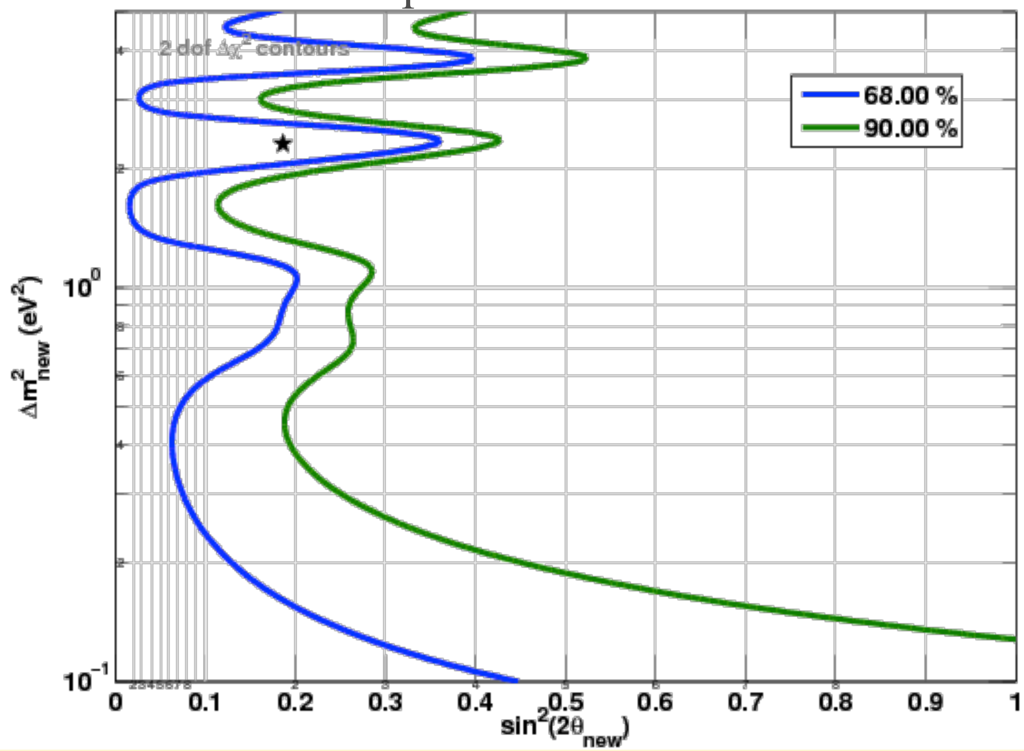
- 1981: Try to reproduce published contour
- 1995: Reproduce claim that global fit disfavors oscillation at 2σ

- **How ?** We add uncorrelated systematic in each bin until it's large enough
    - **Needed error : 11%, uncorrelated, in each bin.**

1981 result

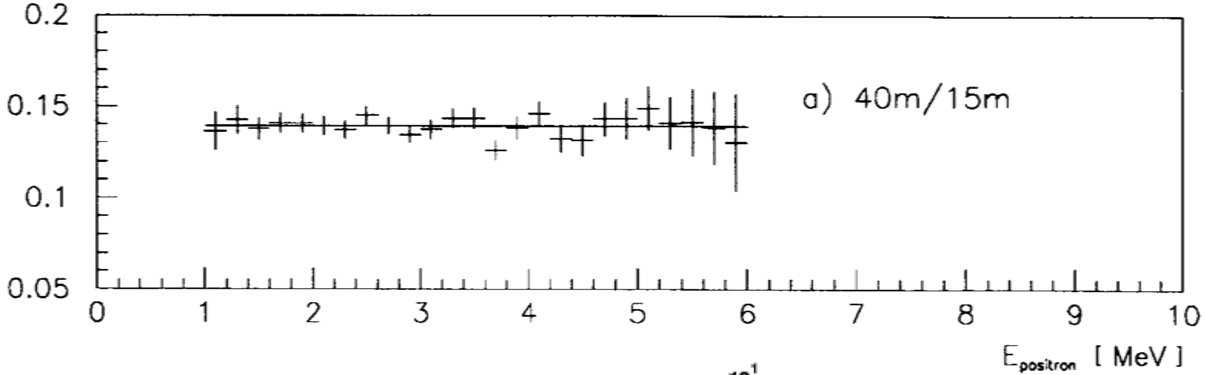


our reproduction of ILLresults



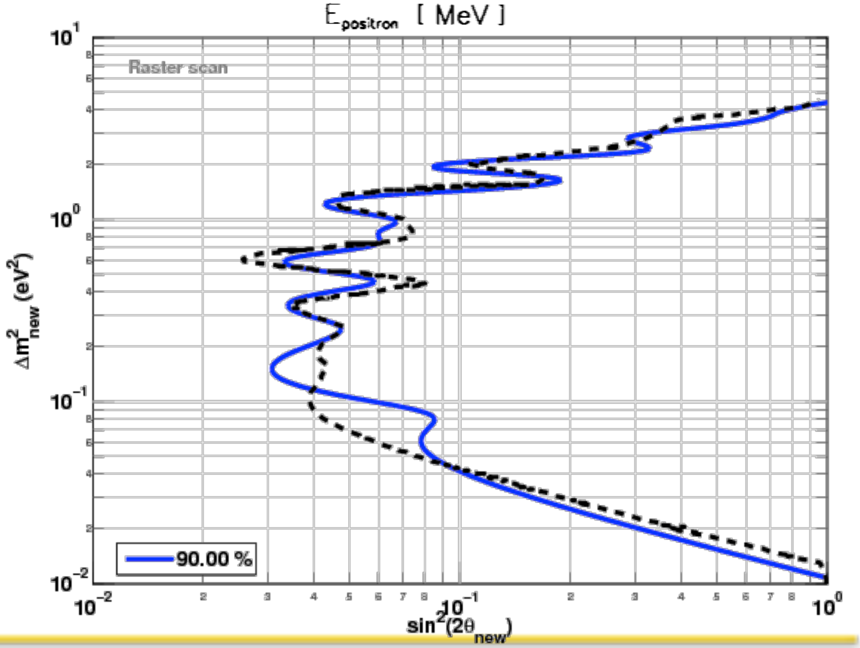
Spectral shape analysis of Bugey-3

- Bugey-3 spectral measurements at 15 m, 40 m, 90 m
  - Best constraint from high statistics R=15m/40m ratio
  - Very robust since it does not rely on reactor spectra

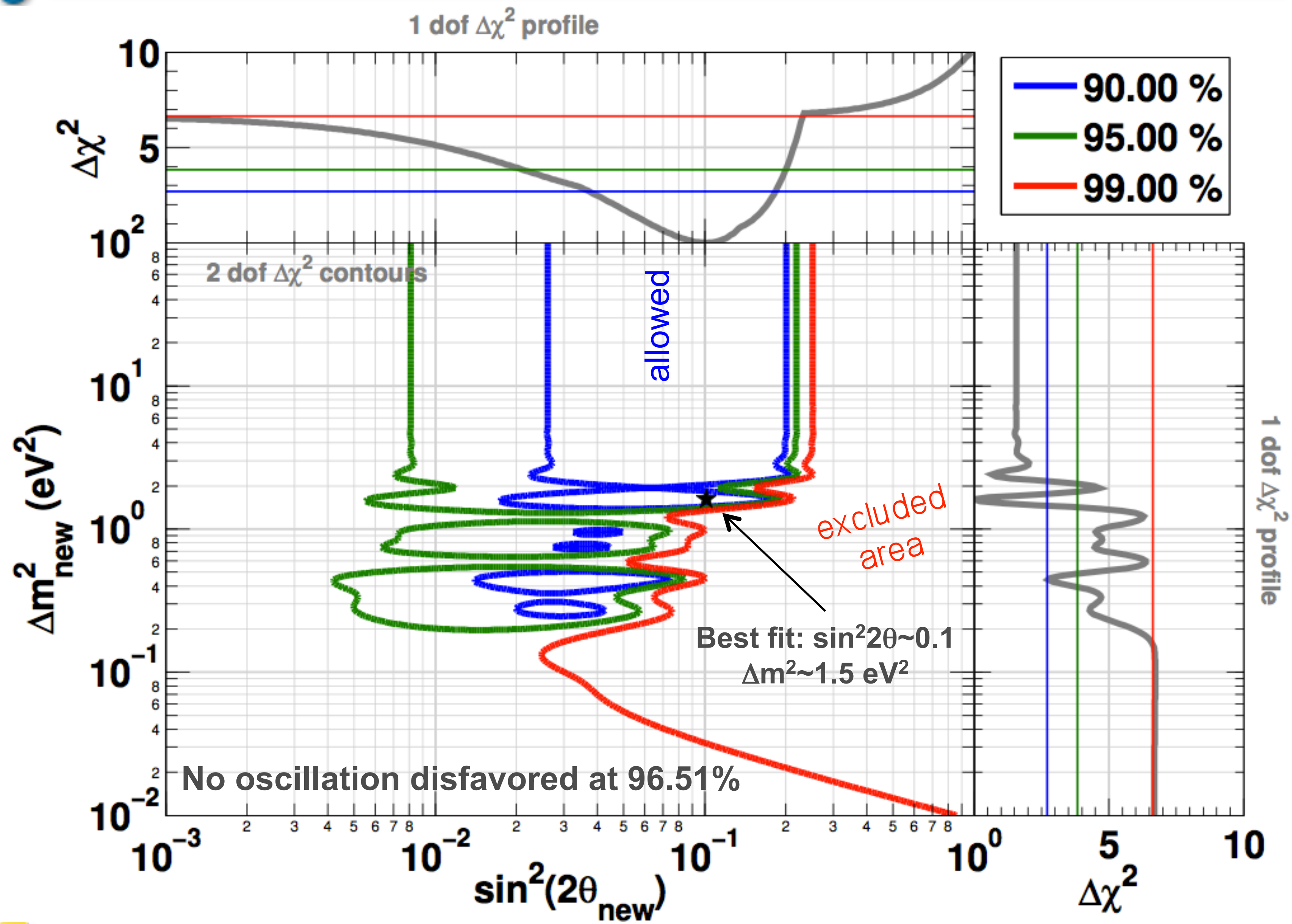


- $$\chi^2 = \sum_{i=1}^{N=25} \left(\frac{(1+a)R^i_{th} - R^i_{obs}}{\sigma_i} \right)^2 + \left(\frac{a}{\sigma_a} \right)^2$$

  - Reproduction of the collaboration's raster-scan analysis
  - Use of a global-scan in combined analysis



Combined Reactor Rate+Shape contours



The Gallium Neutrino Anomaly

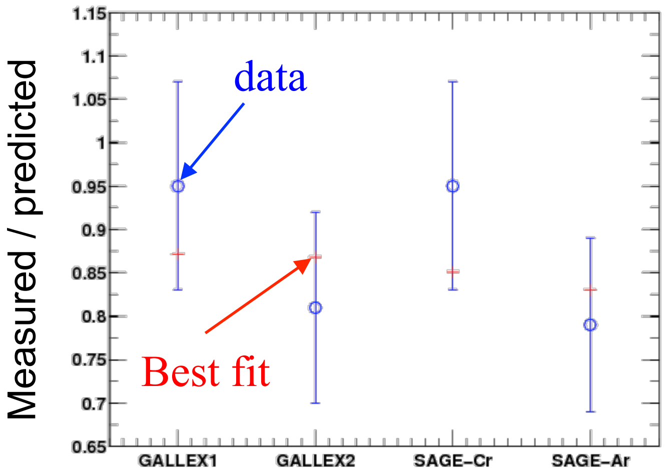
Based on PRD82 053005 (2010)

C. Giunti & M. Laveder

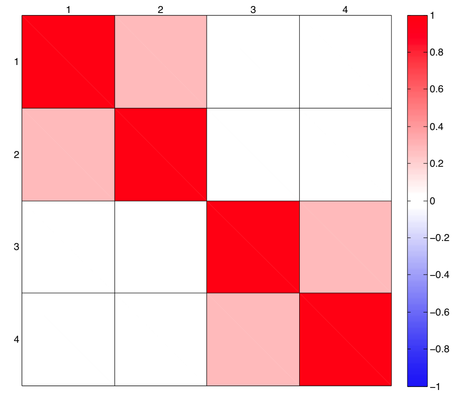
The Gallium anomaly

- **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 oscillation ?**

- **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

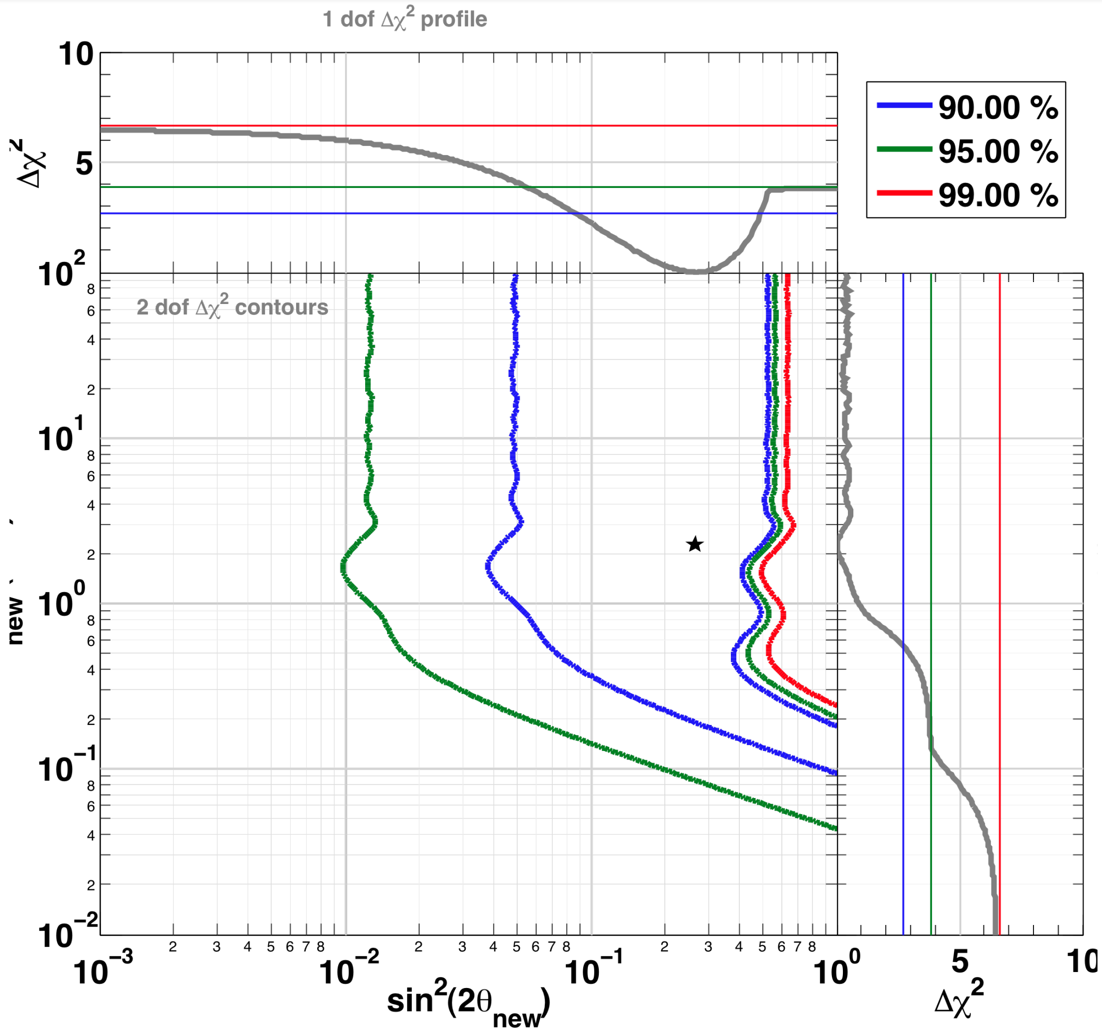


- Gallex-I
- Gallex-II
- Sage-Cr
- Sage-Ar



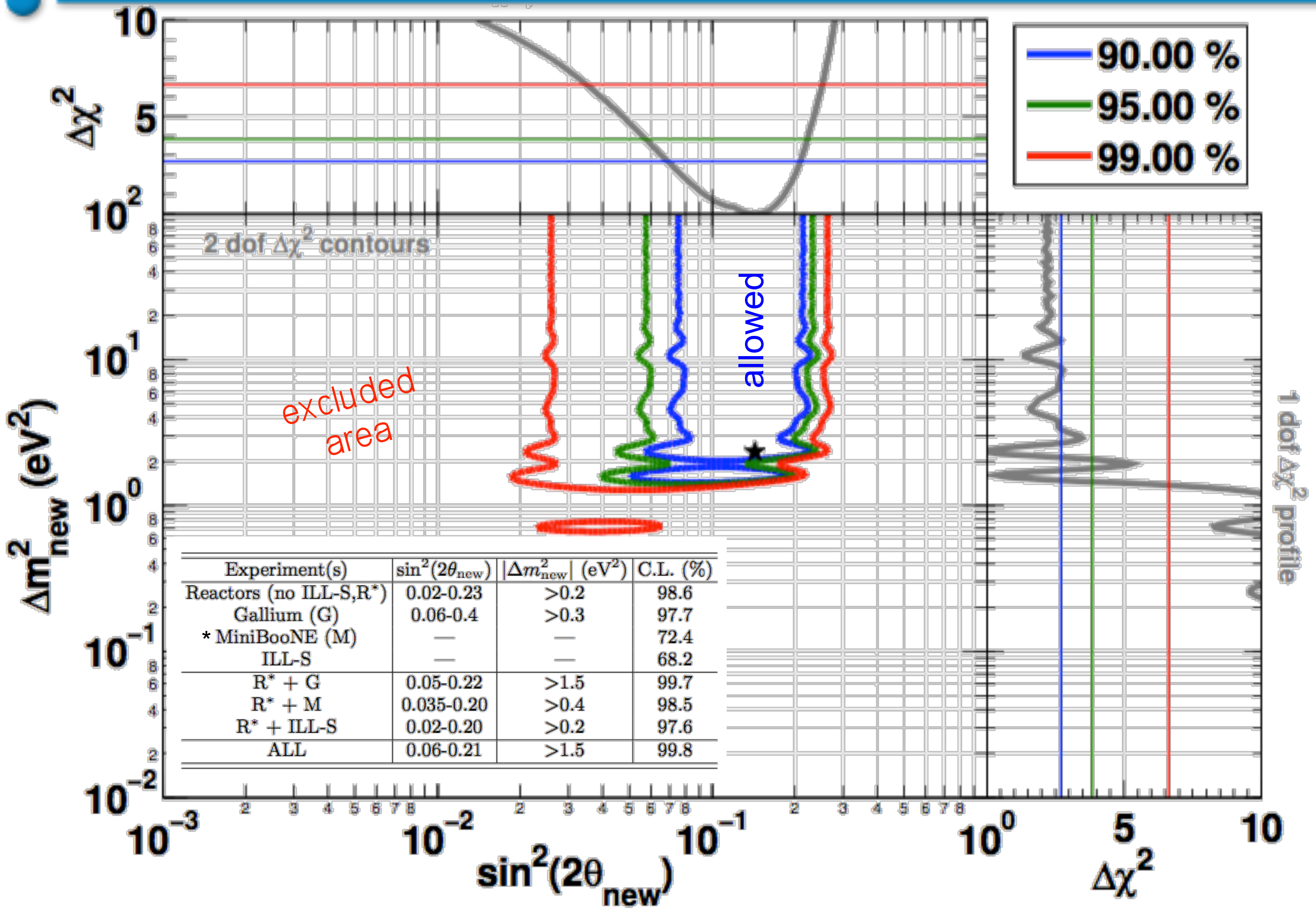
correlation matrix

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.

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



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

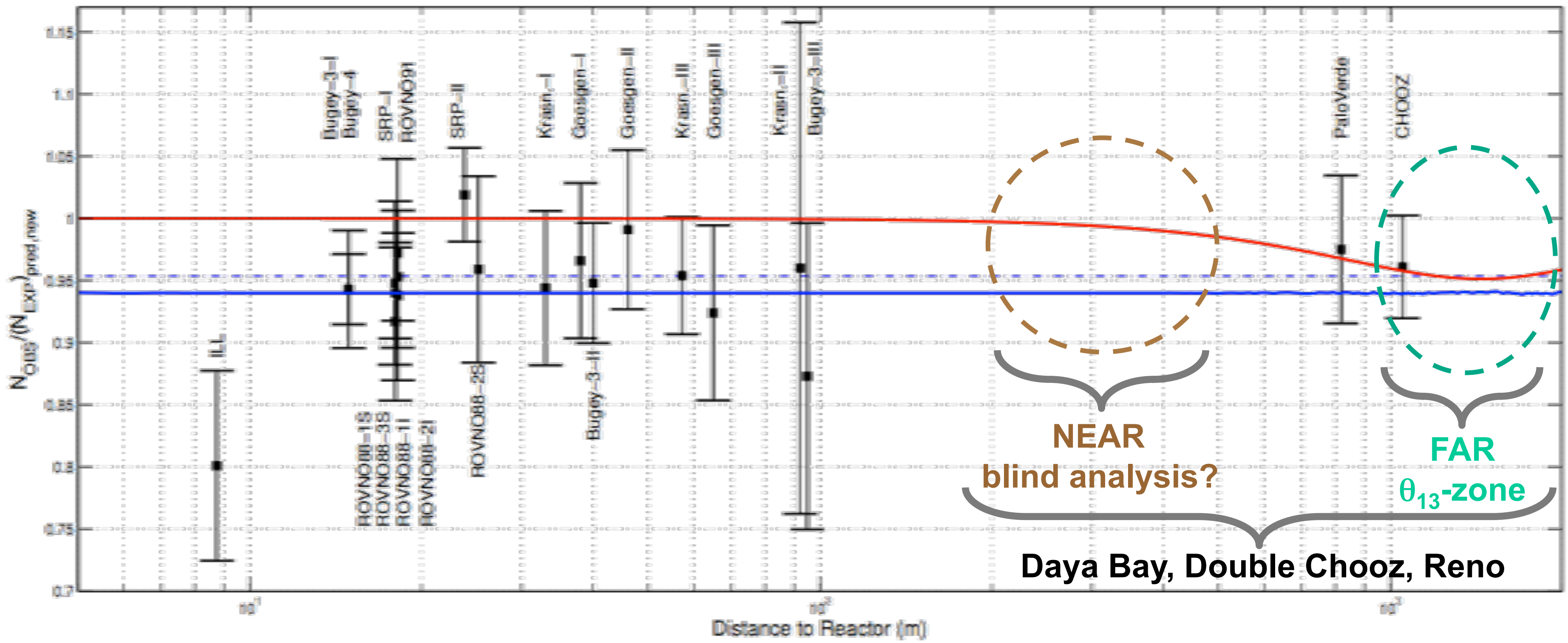
Implication for θ_{13}

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

- The choice of normalization is crucial for reactor experiments looking for θ_{13} without near detector

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

σ_f^{ano} : experimental cross section (best fitted mean averaged)



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

The Normalization Dilemma

- Experiments with baselines > 500 m
- How do you normalize the expected flux, knowing the fuel composition?
- **If near + far detector, not an issue anymore**

Choices

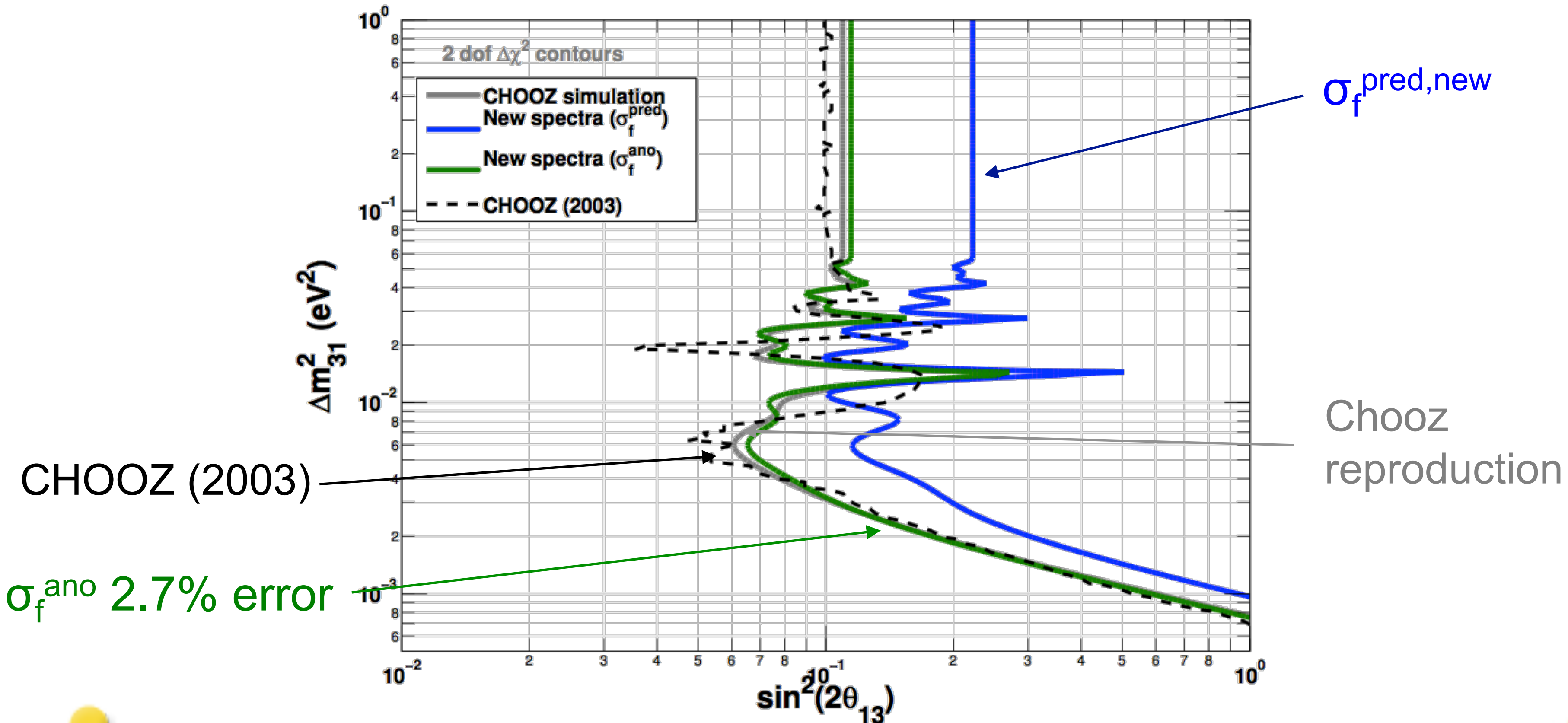
- σ_f^{pred}
  - Use $\sigma_f^{pred,new}$ =6.102 10^{-43} cm^2/fission ± 2.7%
  - Use $\sigma_f^{pred,old}$=5.850 10^{-43} cm^2/fission ± 2.7%
- σ_f^{exp}
  - Use σ_f^{exp} Bugey-4=5.750 10^{-43} cm^2/fission ± 1.4%
    Chooz's choice: use lower error (total 2.7% instead of 3.3%)
    Bugey-4 is a kind of "near detector" for Chooz
  - Use $<\sigma_f^{exp}>=\sigma_f^{ano}$=5.750 10^{-43} cm^2/fission ± 1% + ?% (syst.)
    Average over short-baseline expts.

in this slide assume Bugey-4 fuel comp.

CHOOZ reanalysis

- The choice of σ_f changes the limit on θ_{13}
- Chooz original choice was σ_f^{exp} from Bugey-4 with low error
- If $\sigma_f^{pred,new}$ is used, limit is worse by factor of 2
- If σ_f^{ano} is used with 2.7%, we obtain the original limit

→ But which error should we associate to σ_f^{ano} (burnup up error?)



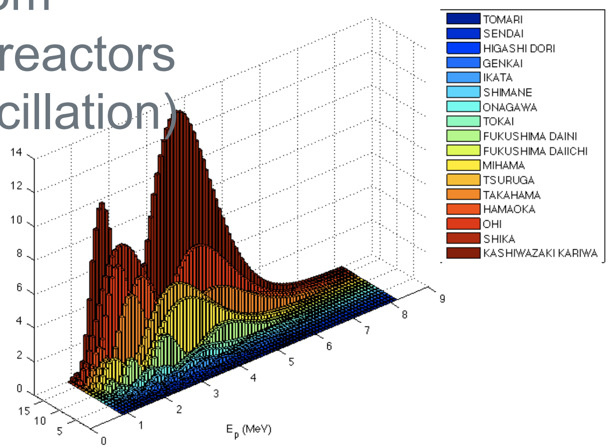
Reanalysis of KamLAND's 2010 results

arXiv:1009.4771v2 [hep-ex]

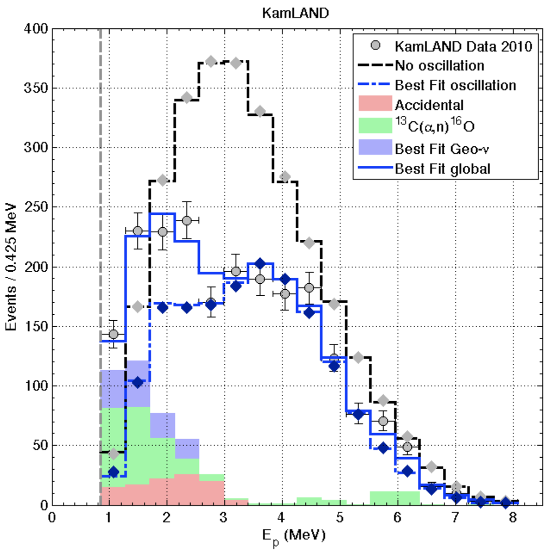
Systematics

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [31]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	2.4 / 2.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_p)$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section	0.2 / 0.2	Long-lived nuclei	0.3 / 0.4
	Total	2.3 / 3.0	Total	3.3 / 3.4

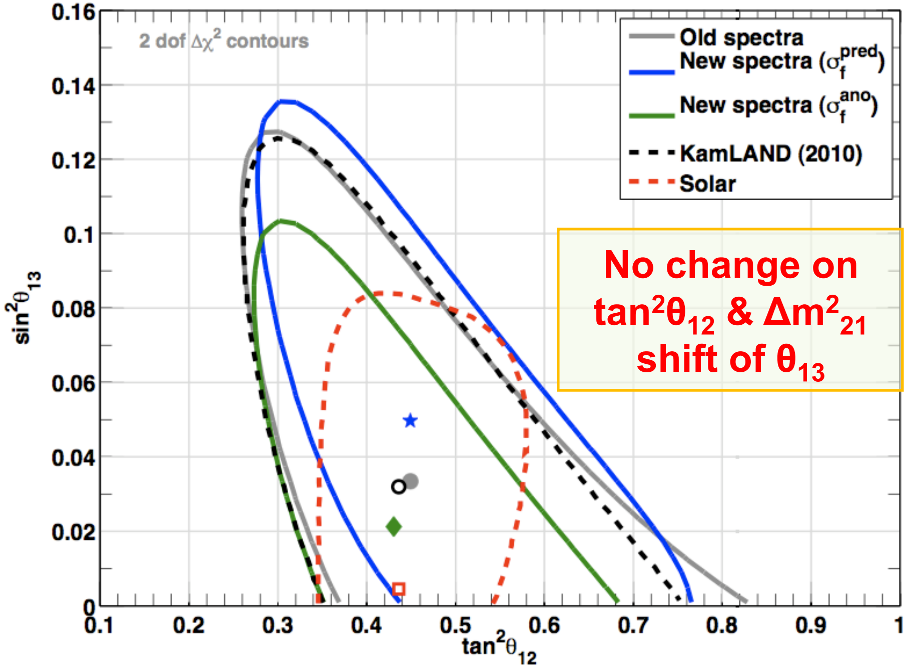
Spectra from Japanese reactors (with ν_e oscillation)



Reproduced KamLAND spectra within 1% in [1-6] MeV range



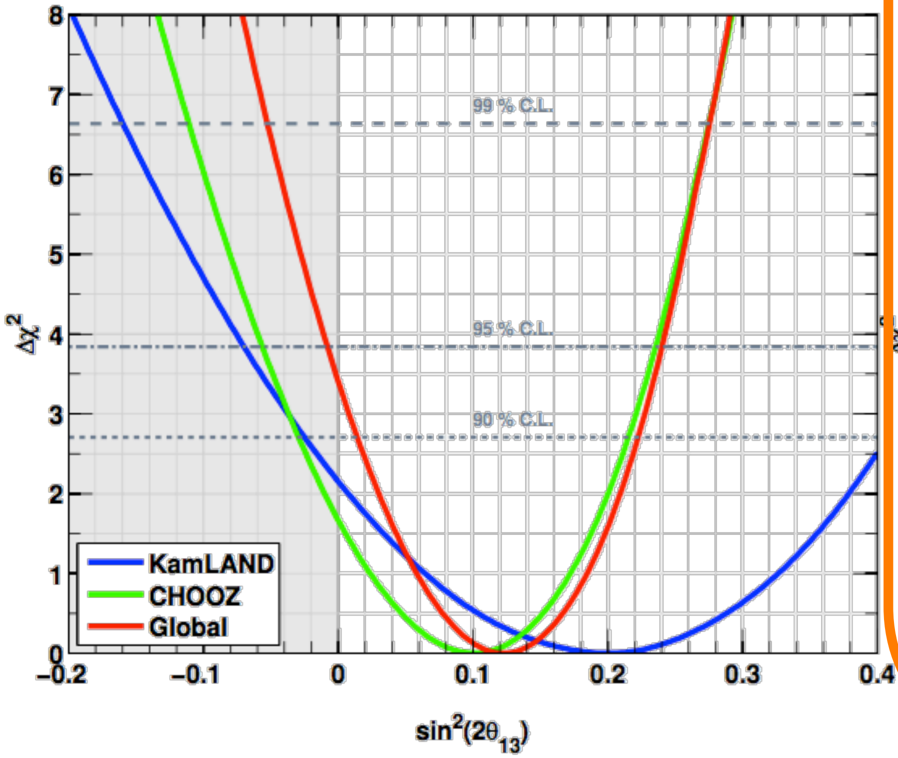
With new spectra predictions



CHOOZ and KamLAND combined limit on θ_{13}

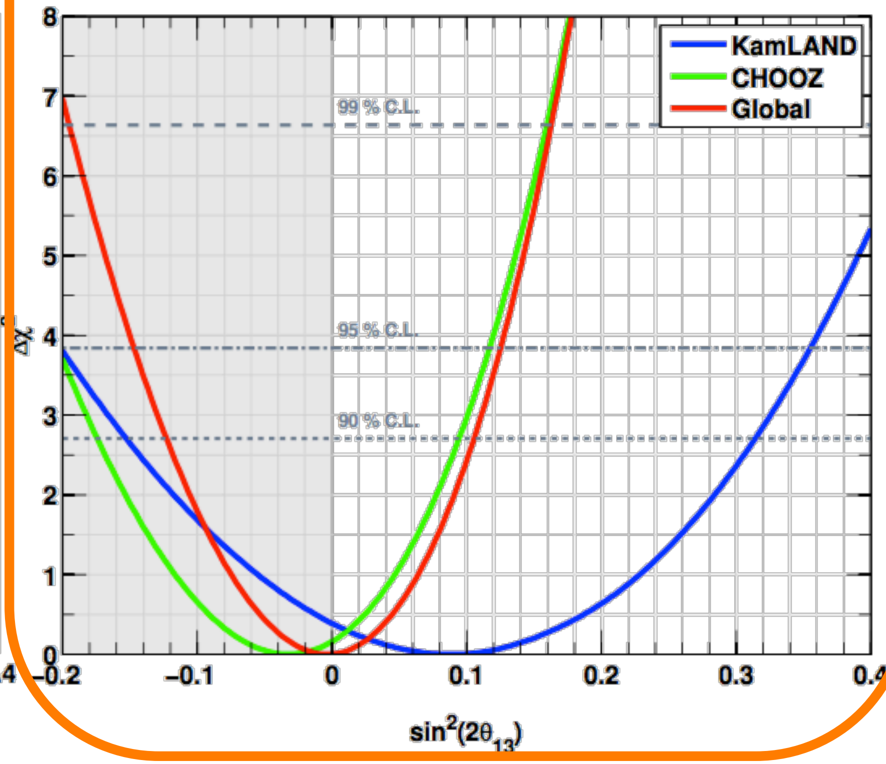
Normalization with $\sigma_f^{pred,new}$

3-ν framework & 2.7% uncertainty



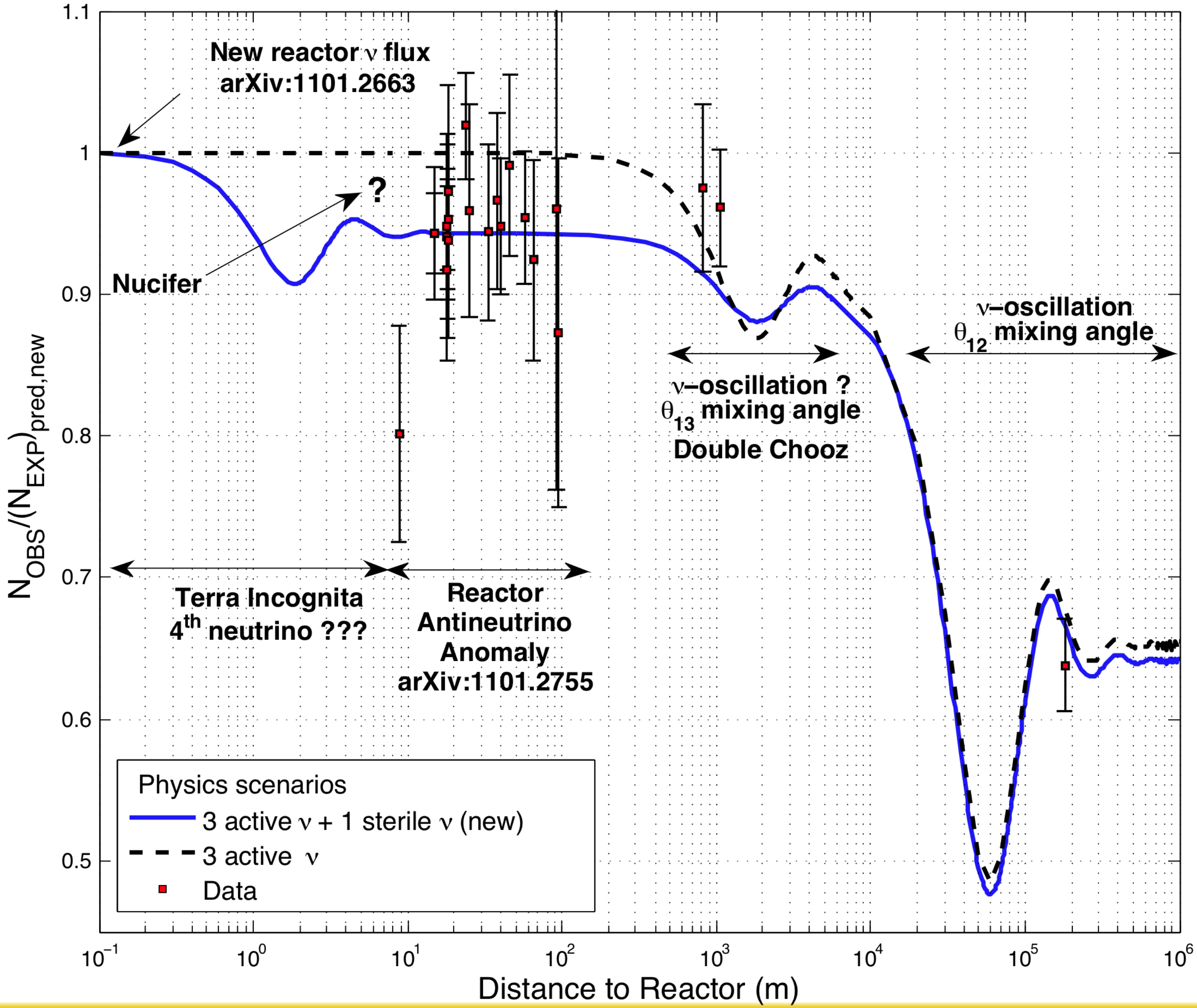
Normalization using σ_f^{ano}

3-ν framework & 2.7% uncertainty



- **Our interpretation** **(different from Arxiv:1103:0734 for KamLAND-$\sigma_f^{pred,new}$, T. Schewtz's talk)**
  - No hint on θ_{13}>0 from reactor experiments : $\sin^2(2\theta_{13})<0.11$ (90%C.L., 1dof)
  - CHOOZ 90 % CL limit stays identical to Eur. Phys. J. C27, 331-374 (2003)
  - Multi-detector experiments are not affected

Need for new experimental inputs !



Conclusion and perspectives

- **New Reactor Antineutrino Anomaly Discovered**
  - Experimental bias to be deeply investigated
  - New physics hypothesis tested: 4^{th} neutrino
    - no-oscillation hypothesis disfavored at 99.8%

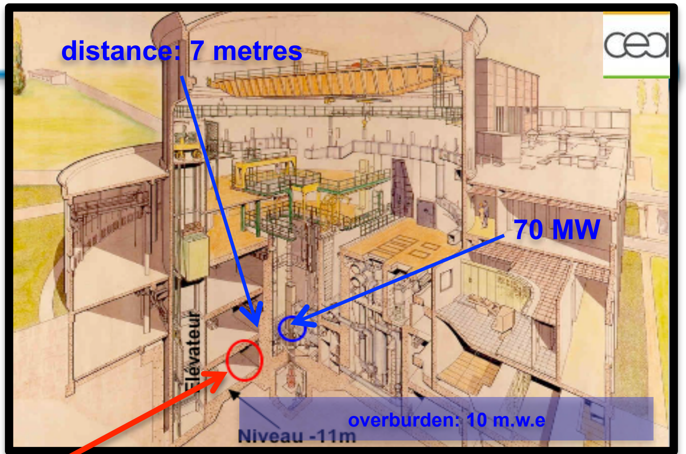
- **Clear experimental confirmation / infirmation is needed:**
  - L/E ≈ few m/MeV or km/GeV

- **New Experiment at Reactor**
  - Short Baseline – Shape + Rate Analysis
- **Mci neutrino generator in/close to a large liquid scintillator**
  - likeSNO+, Borexino, KamLAND
- **New neutrino beam experiment probing for electron GeV neutrino disappearance at 100 m & 1 km**
  - C. Rubbias's proposal at CERN-PS
  - Fermilab workshop in May

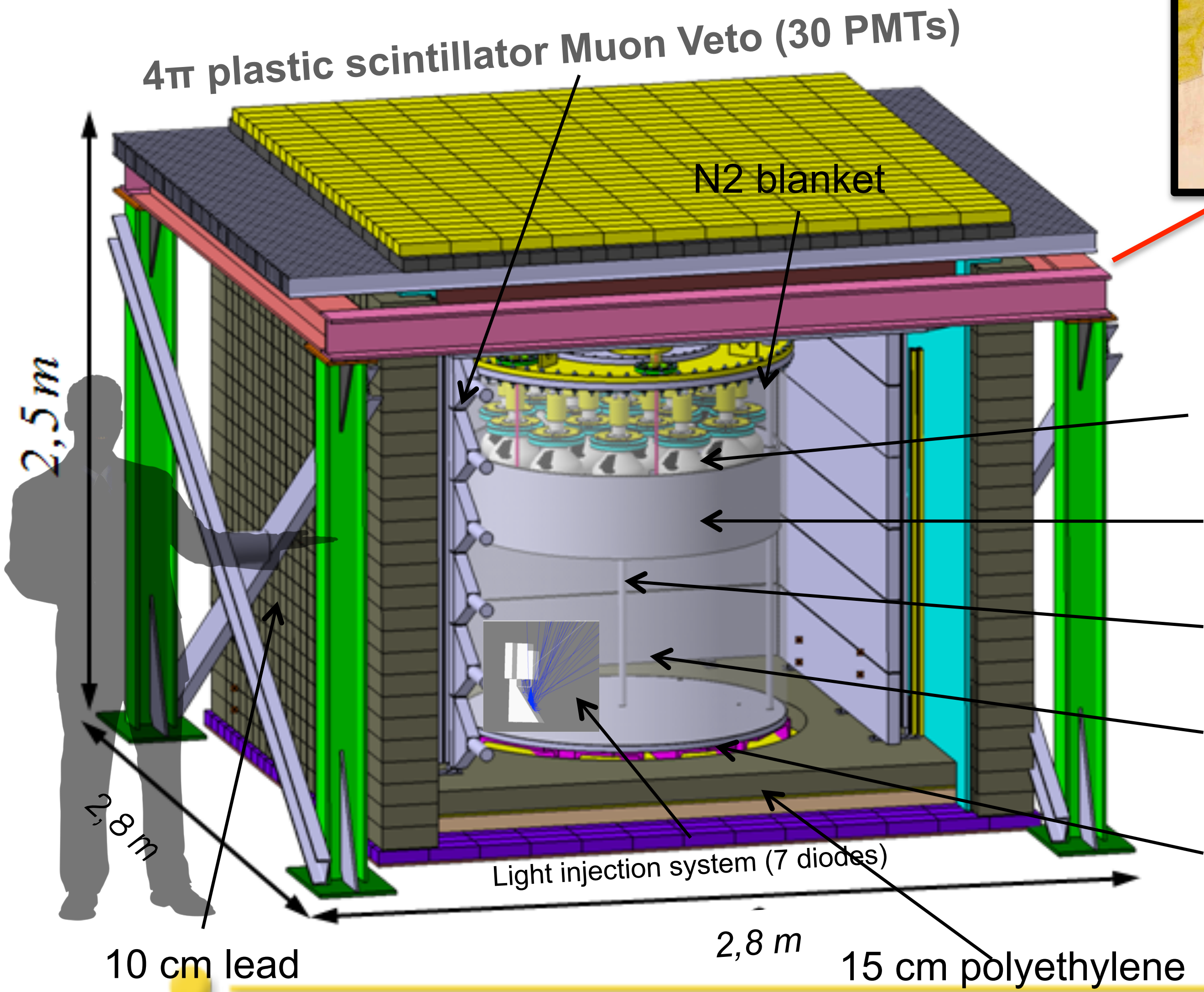
Nucifer

First goal: Non Proliferation

Thermal Power Measurement
Fuel Composition Measurement U/Pu



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



16 x 8' PMTs low background

25 cm acrylics buffer

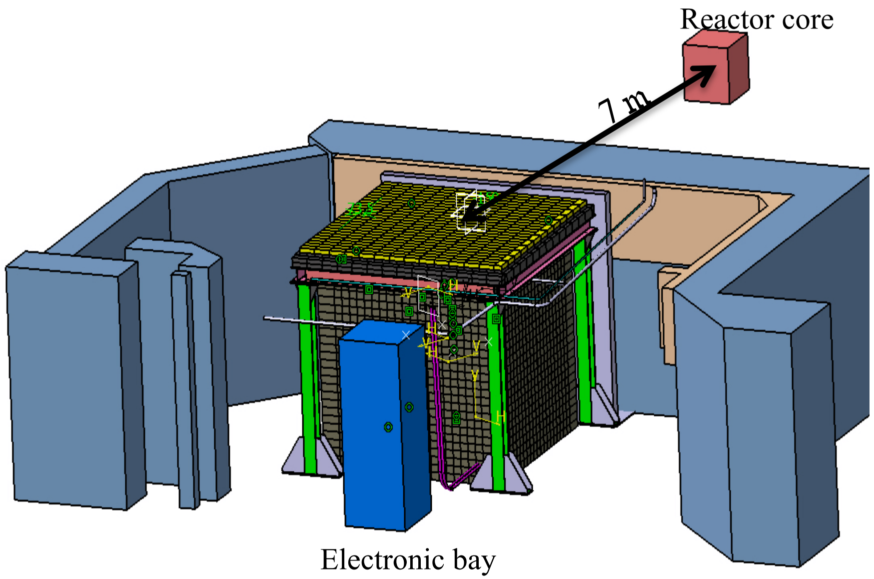
Calibration pipe

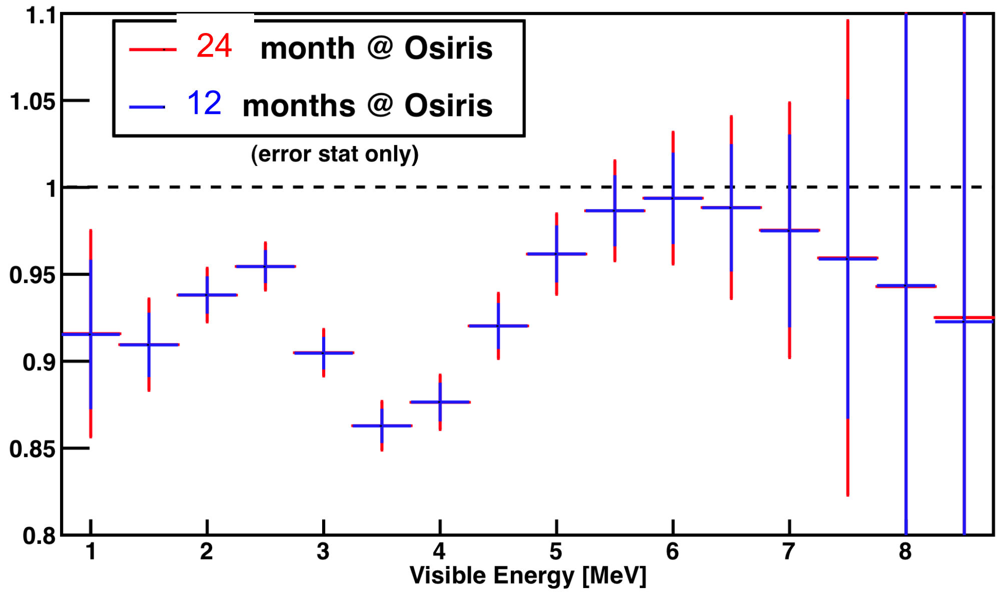
Target: 0.85 m^3 Gd-LS (0.5%)

Stainless steel double containment vessel coated with white Teflon coating inside

NUCIFER in Saclay

- Osiris-Saclay: Core Size: 57x57x60 cm
- Nucifer Detector Size : 1.2x0.7m (850l)
- Baseline distribution
  - <L>=7.0 m, σ=0.3 m → eV^2 oscillations are not washed out
- Folding Nucifer Geant4 Monte Carlo detector response
- $\Delta m^2 = 2.4\ eV^2$ & $\sin^2(2\theta)=0.15$
- No backgrounds. Thus to be taken with a grain of salt …

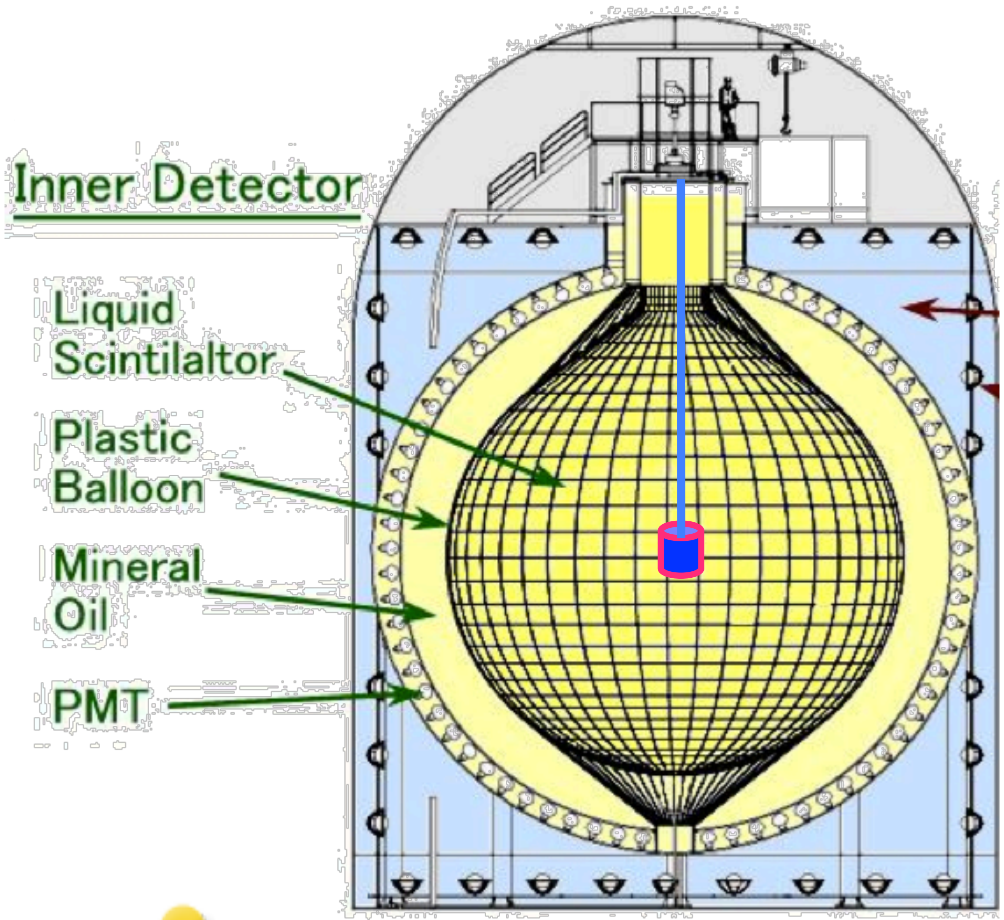




- Such pattern could not be seen at Bugey-3 (extended core & 14 m baselin

^{37}Ar Neutrino Generator Experiment

- A strong 1 Mci ν source in the middle of a large LS detector
- Elastic scattering on electrons (few 10000 evts, 150 days, >250 keV)
- A good resolution in position (15cm) – Low Backgrounds



Oscillation pattern VS radius (preliminary)