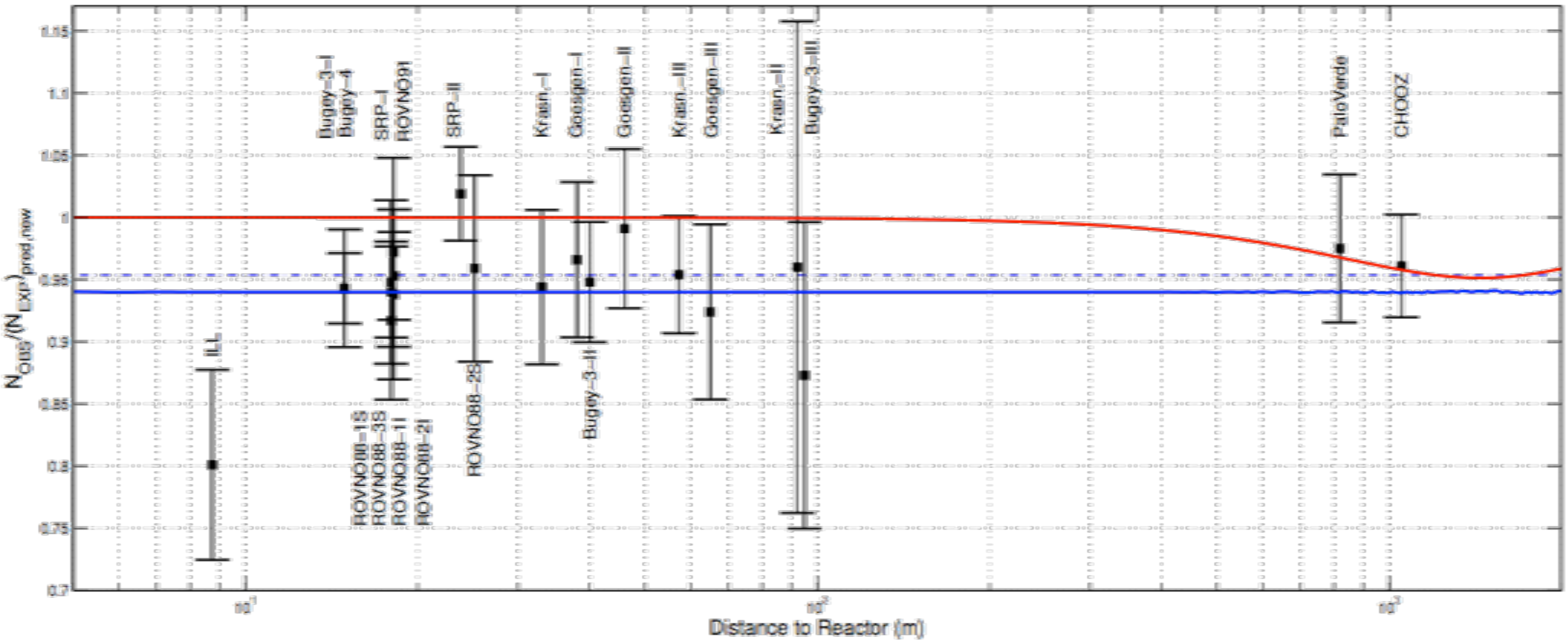
The Reactor Antineutrino Anomaly and implications



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

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], submitted to 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}

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

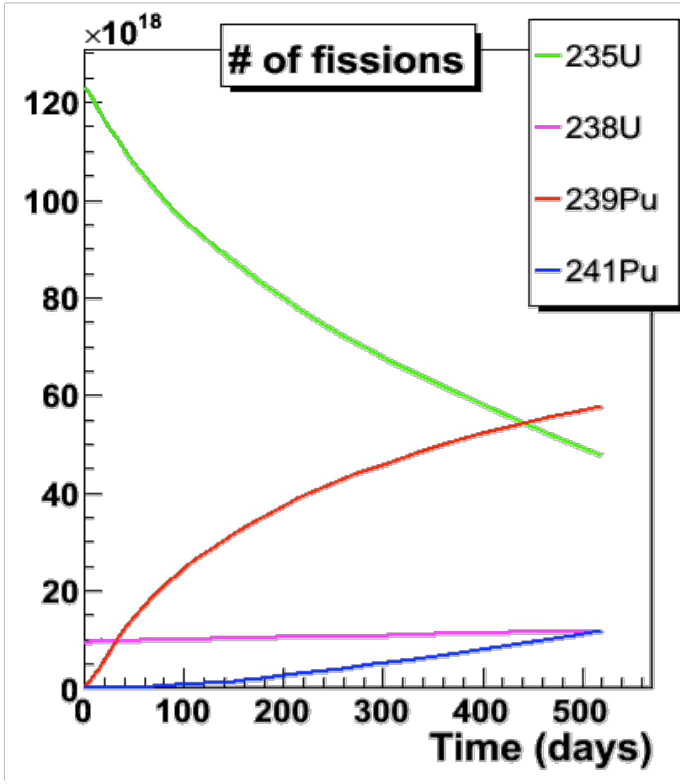
Nuclear databases

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

ν spectrum per fission

This work !

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



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 …

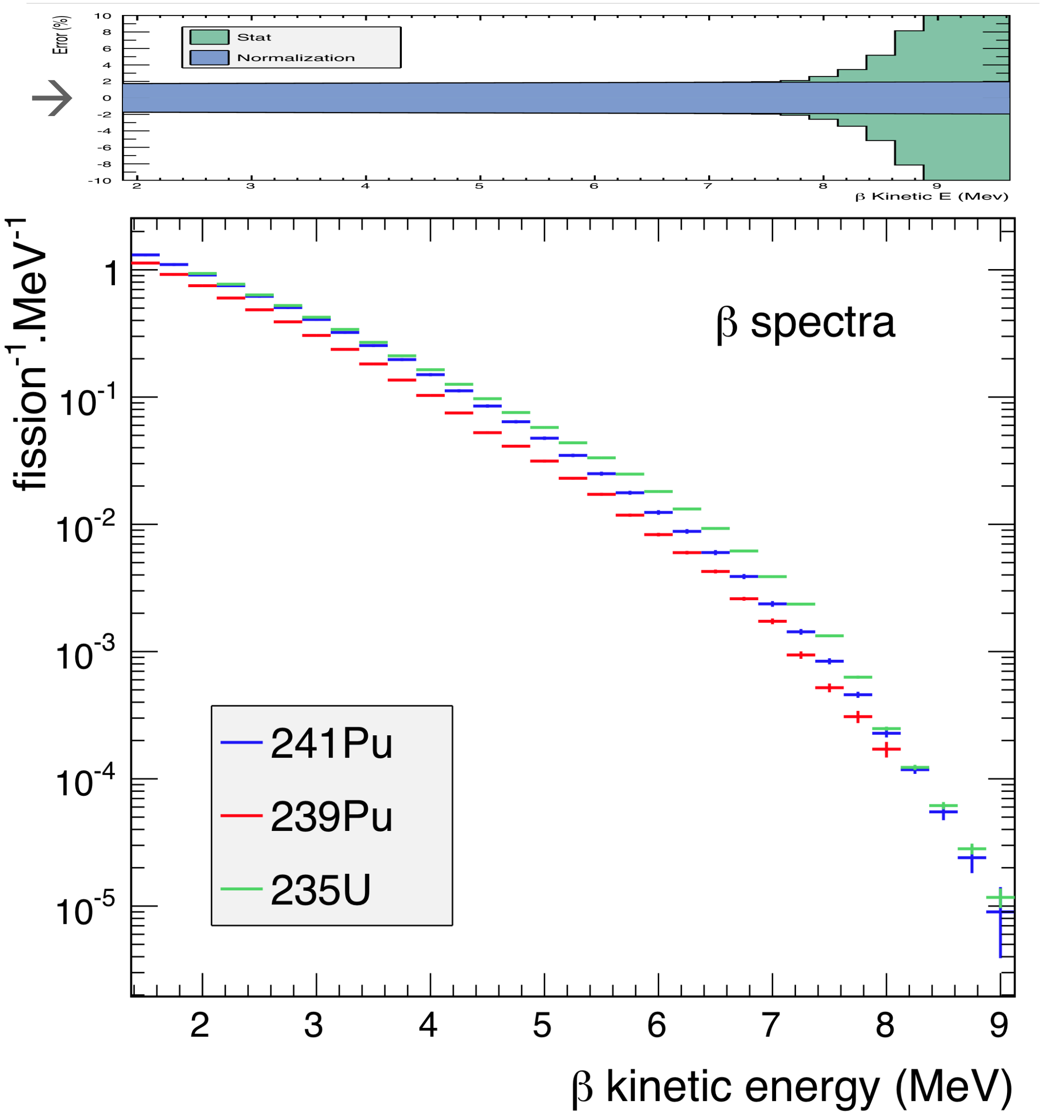
• ILL electron data

Full ab-inito | **Our mixed approach** | **Effective**

The ILL electron Data Anchorage

Unique reference to be met by any other measurement or calculation

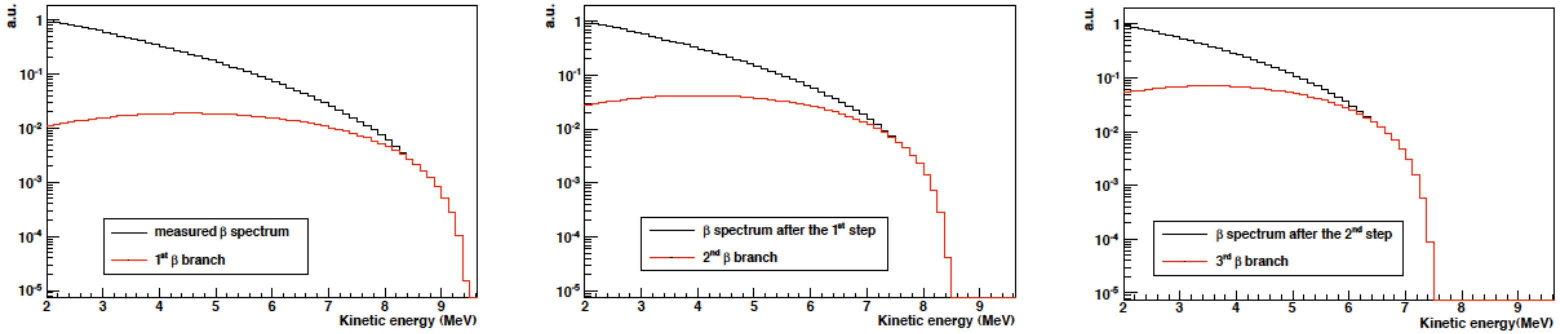
uncertainty →



- 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



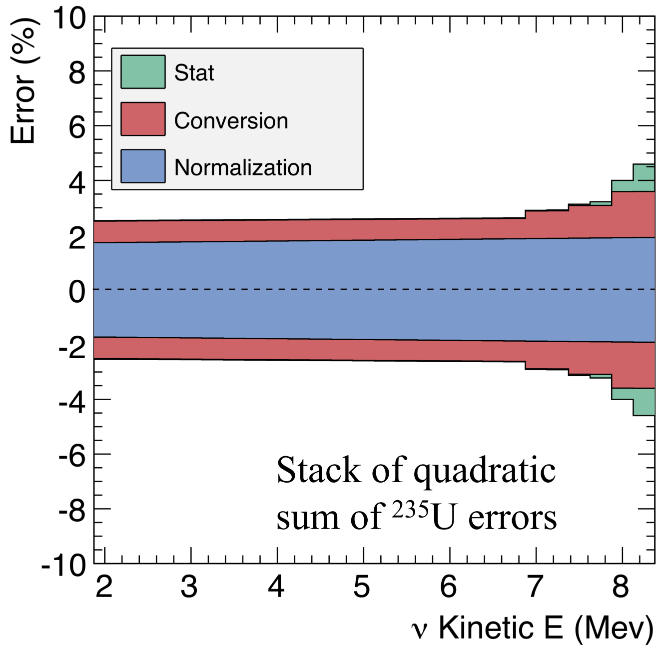
- **All theory included in these effective branches but:**
  - What Z? : Mean fit on nuclear data *Z=f(E0)*

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

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

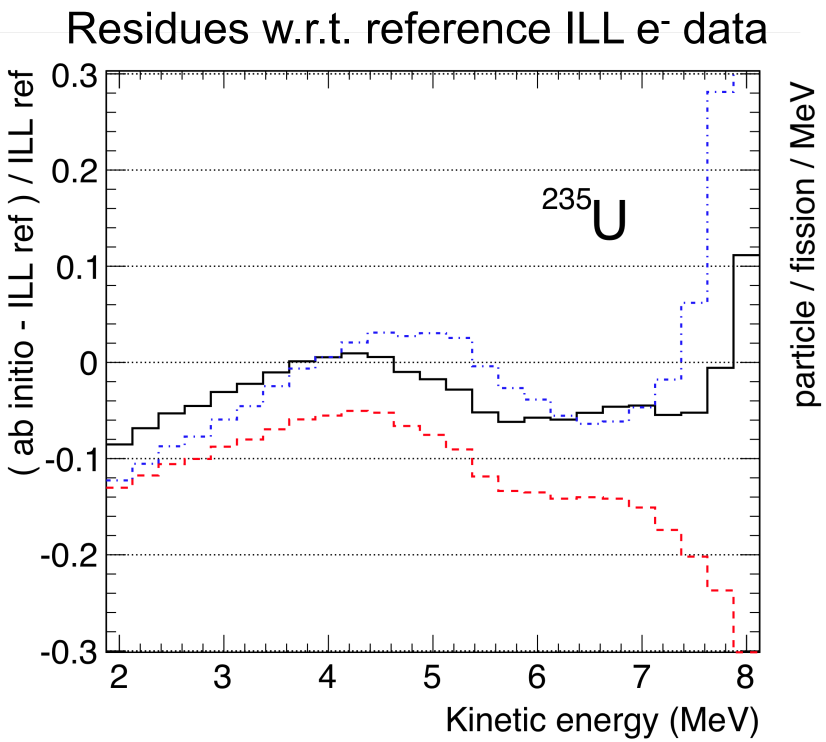
$$DN_n^{C,W}(E_n) \approx 0.65 \times (E_n - 4\text{MeV}) \quad \%$$

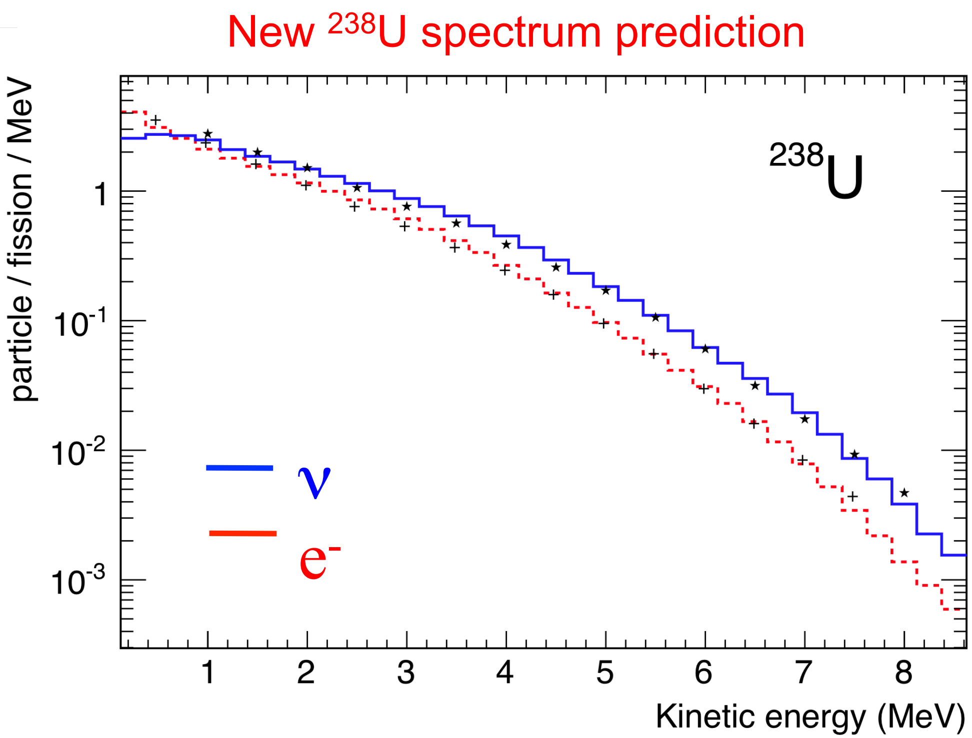
- **Conversion error from envelop of numerical studies**



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

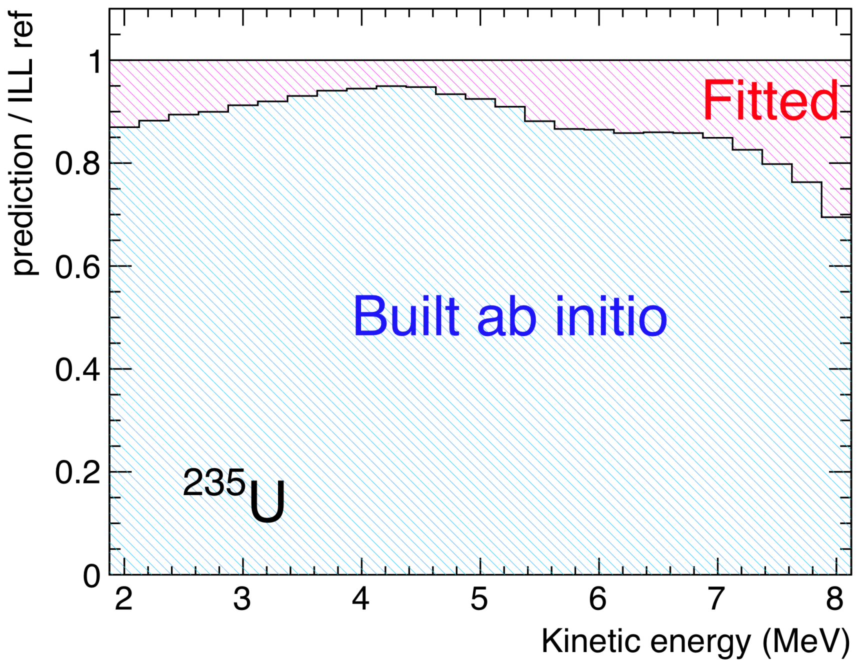


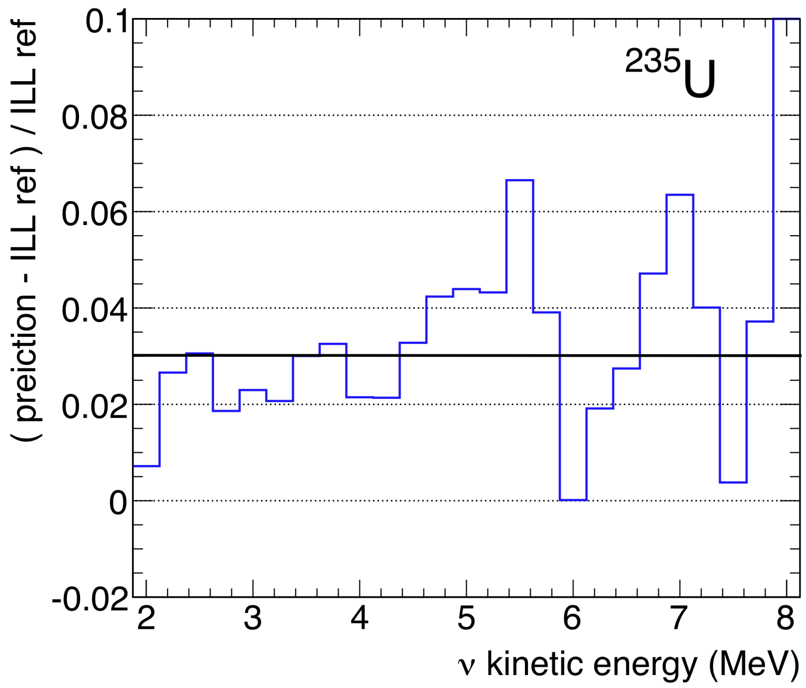


→ 95+/-5% of the spectrum reproduced but still not meeting required precision
→ Useful estimate of ^{238}U spectrum which couldn't be measured @ ILL
→ Measurement at FRMII ongoing (N. Haag & K Schreckenbach)

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**

Off-Equilibrium Effects

MURE evolution code (IN2P3/Subatech)

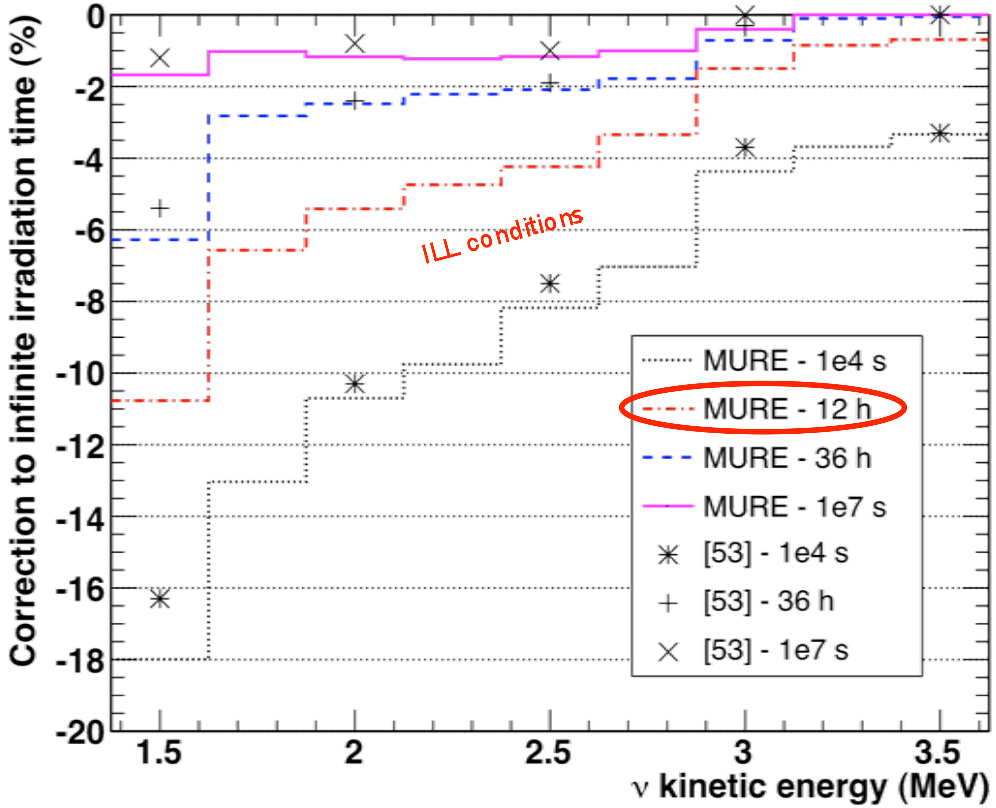
- ILL electron reference spectra : 12 hours to 1.8 days irradiation time
- Neutrino reactor experiments irradiation time >> months
- **BUT 10% of fission products have a β-decay life-time long enough to keep accumulating after several days**

→ 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



The Reactor Antineutrino Anomaly

→ Updated with 7 additional results

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M. Cribier, Th. Mueller D. Lhuillier, A. Letourneau,

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arXiv:1101.2755 [hep-ex], submitted to PRD
* corresponding author

V-A IBD Cross Section

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

- **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

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

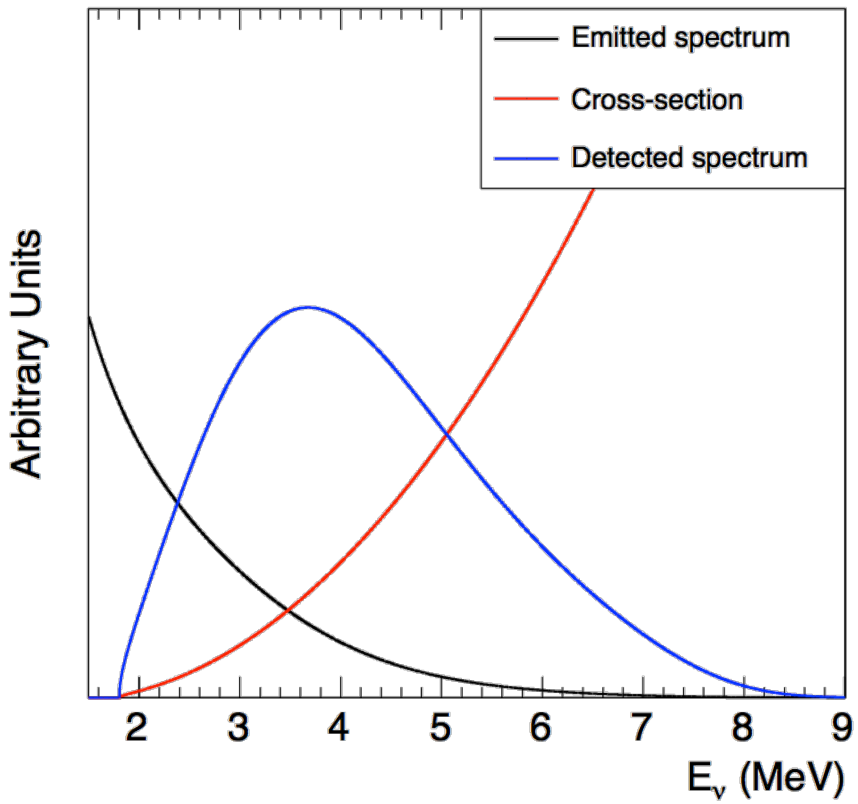
- **The pre-factor κ** (two pseudo-independent approaches)

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

- **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%)**

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%

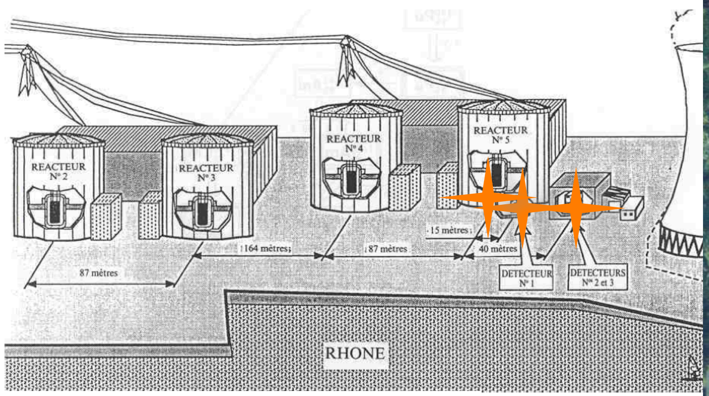
- **Final agreement to better than 0.1% on best known ^{235}U**

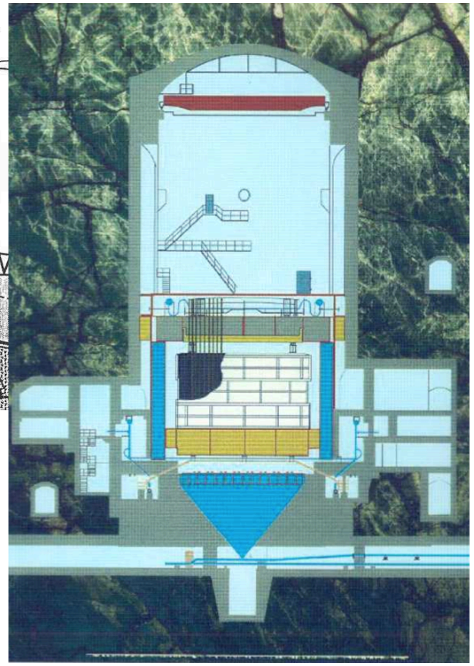
The New Cross Section Per Fission

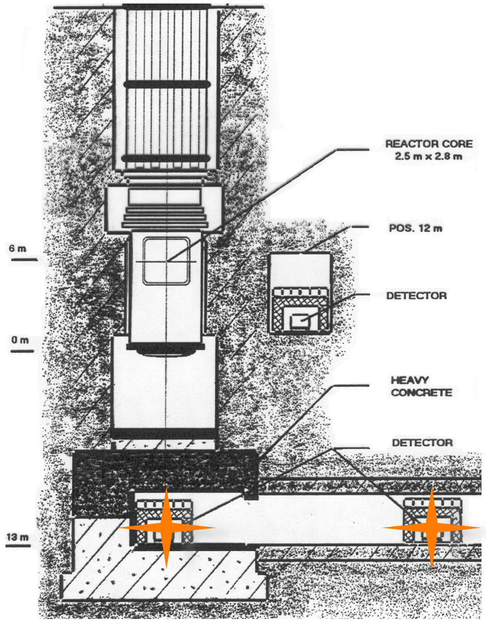
- ν-flux: ^{235}U +2.5%, ^{239}Pu +3.1%, ^{241}Pu +3.7%, ^{238}U +9.8% (σ_f^{pred} ➚)
- Off-equilibrium corrections now included (σ_f^{pred} ➚)
- Neutron lifetime decrease by a few % (σ_f^{pred} ➚)
- Slight evolution of the phase space factor (σ_f^{pred} ➔)
- Slight evolution of the energy per fission 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
$\sigma_{f,^{235}U}^{pred}$	6.39±1.9%	6.61±2.11%
$\sigma_{f,^{239}Pu}^{pred}$	4.19±2.4%	4.34±2.45%
$\sigma_{f,^{238}U}^{pred}$	9.21±10%	10.10±8.15%
$\sigma_{f,^{241}Pu}^{pred}$	5.73±2.1%	5.97±2.15%

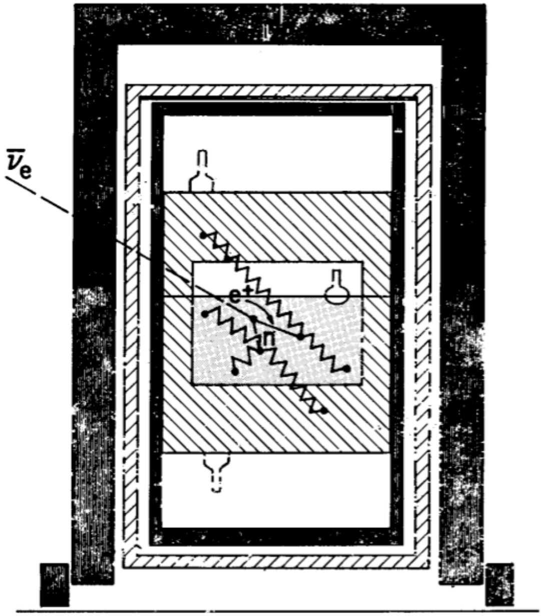
19 Experimental Results at L<100m

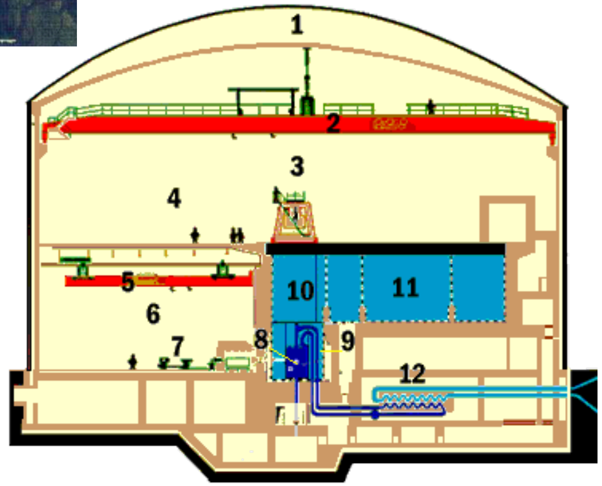






Neutrino Oscillation Detector





Measured cross sections are taken at their face values

19 Experimental Results Revisited (L<100m)

Technology | Baseline

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

19 Experimental Results Revisited (L<100m)

Neutron lifetime

#	result	techno	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He+H$_2$0	888.7	0.538	0.328	0.078	0.056	0.987	0.943	3.0	3.0	15
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4	Bugey-3-II	Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.948	5.1	5.0	40
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Averaged Fuel Composition

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18

19 Experimental Results Revisited (L<100m)

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

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7	Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.991	6.5	6.0	45
8	Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.924	7.6	6.0	65
9	ILL	^{3}He+LS	889	$\simeq 1$	<0.01	<0.01	<0.01	0.832	0.801	9.5	6.0	9
10	Krasn. I	^{3}He+PE	899	$\simeq 1$	<0.01	<0.01	<0.01	1.013	0.944	5.1	4.1	33
11	Krasn. II	^{3}He+PE	899	$\simeq 1$	<0.01	<0.01	<0.01	1.031	0.960	20.3	4.1	92
12	Krasn. II	^{3}He+PE	899	$\simeq 1$	<0.01	<0.01	<0.01	0.989	0.954	4.1	4.1	57
13	SRP I	Gd-LS	887	$\simeq 1$	<0.01	<0.01	<0.01	0.987	0.953	3.7	3.7	18
14	SRP II	Gd-LS	887	$\simeq 1$	<0.01	<0.01	<0.01	1.055	1.019	3.8	3.7	24
15	ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.8	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.8	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18

19 Experimental Results Revisited (L<100m)

Total Errors Exp.+ν-Spectra (%) & Correlated errors (%)

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

Error Budget & Correlations

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

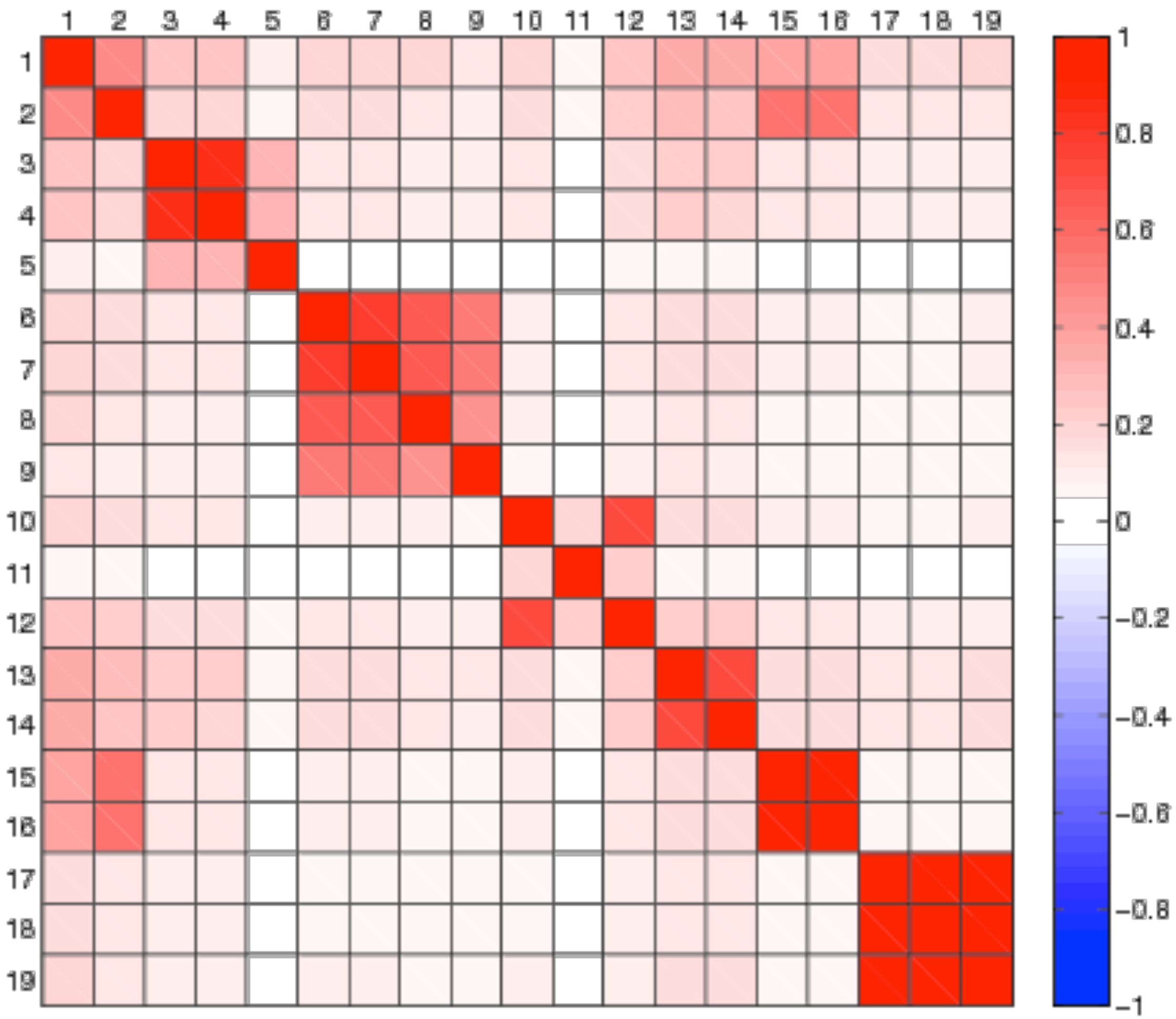
- **Reactor Antineutrino Sources**
  - 2% systematic on ν-flux 100% correlated over ALL measurements
    - Different from 2.7% published on Arxiv:1101.2755
    - 2% corresponds to the normalization error on the ILL e- data
- **Detector: Non-flux systematic error correlations across measurements:**
  - 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

Experimental correlation matrix

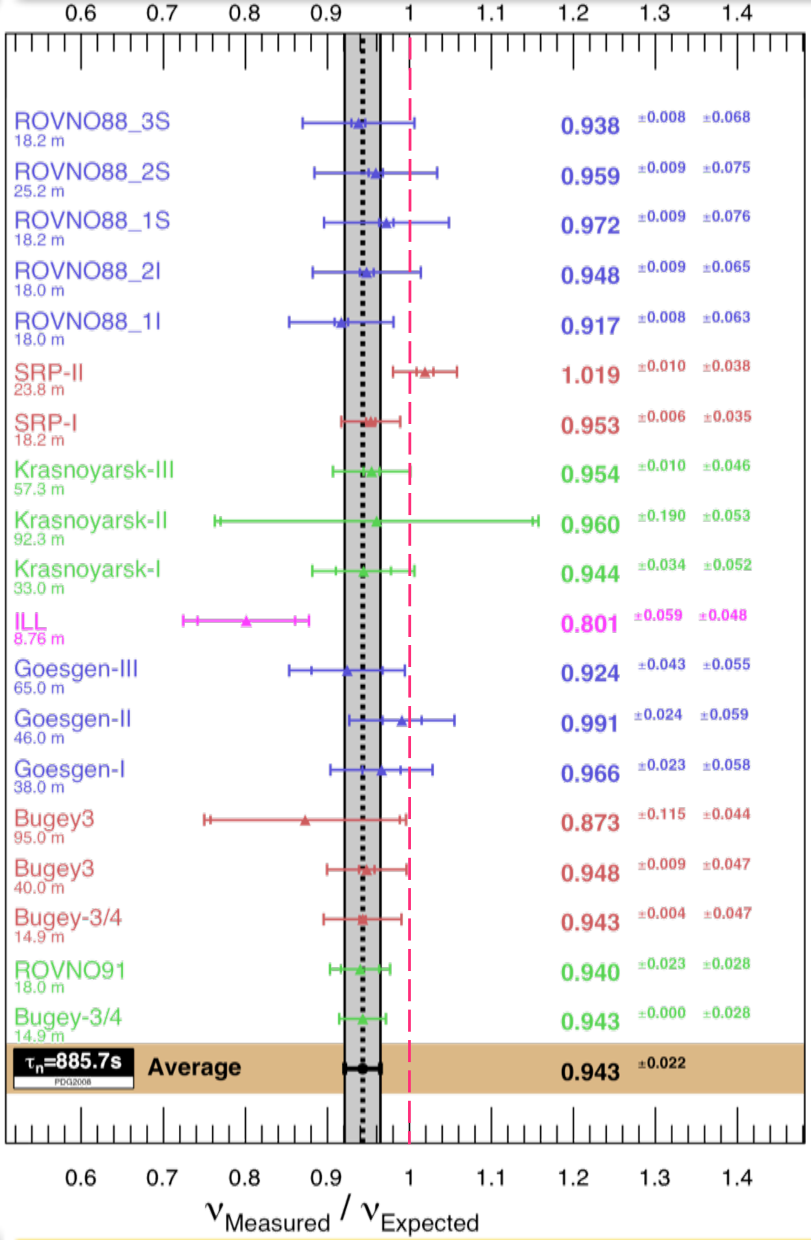
$\vec{R}$

- Bugey-4 15m
- Rovno91 18m
- Bugey-3 15m
- Bugey-3 40m
- Bugey-3 92m
- Goesgen 38m
- Goesgen 45m
- Goesgen 65m
- ILL 9m
- Krasno 33m
- Krasno 92m
- Krasno 57m
- SRP I 18m
- SRP II 25m
- Rovno88 1I 18m
- Rovno88 2I 18 m
- Rovno88 1S 18m
- Rovno88 2S 25m
- Rovno88 3S 18m

W



The reactor antineutrino anomaly



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

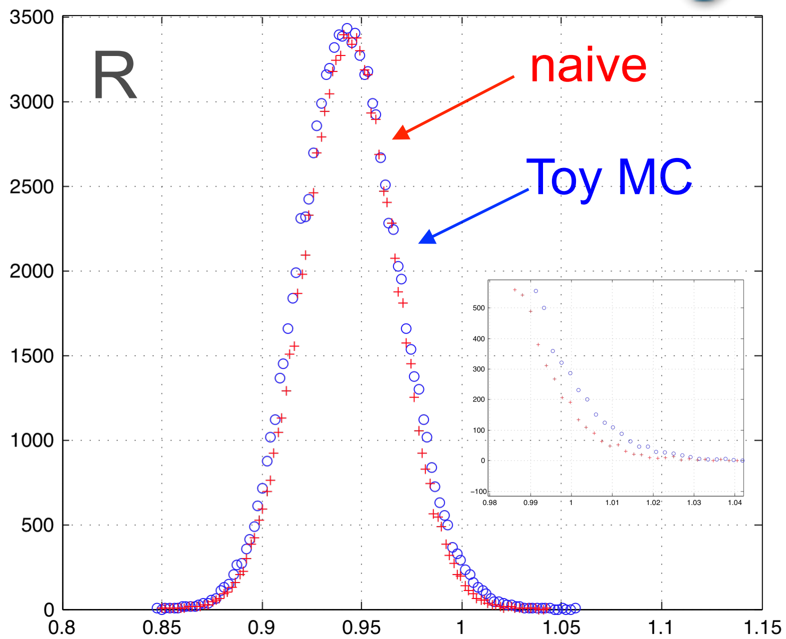
- **Best fit : μ = 0.943**
- **Uncertainty : 0.023**
- χ^2 = 19.6/19
- Deviation from unity
  - Naïve Gaussian : 99.3% C.L.
  - Toy MC: 98.6% C.L. (10^6 trials)
- No hidden covariance
  - 18% of Toy MC have χ^2_{min}<19.6

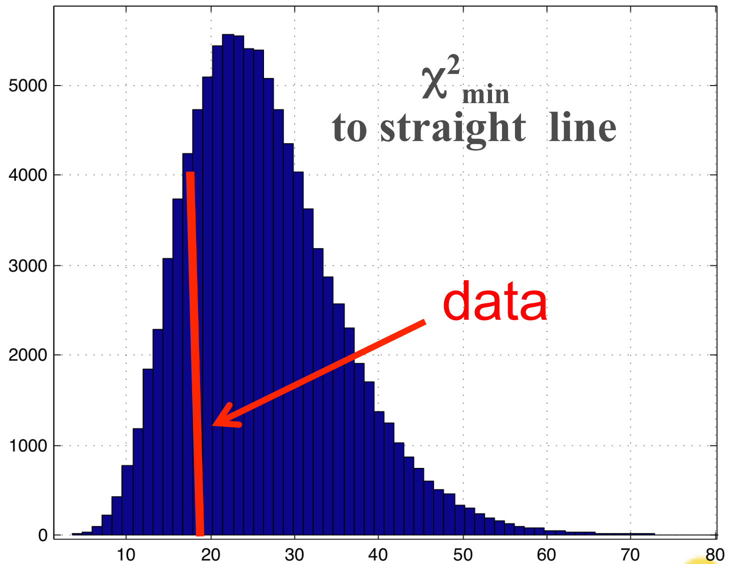
Are the ratios normally distributed?

- **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



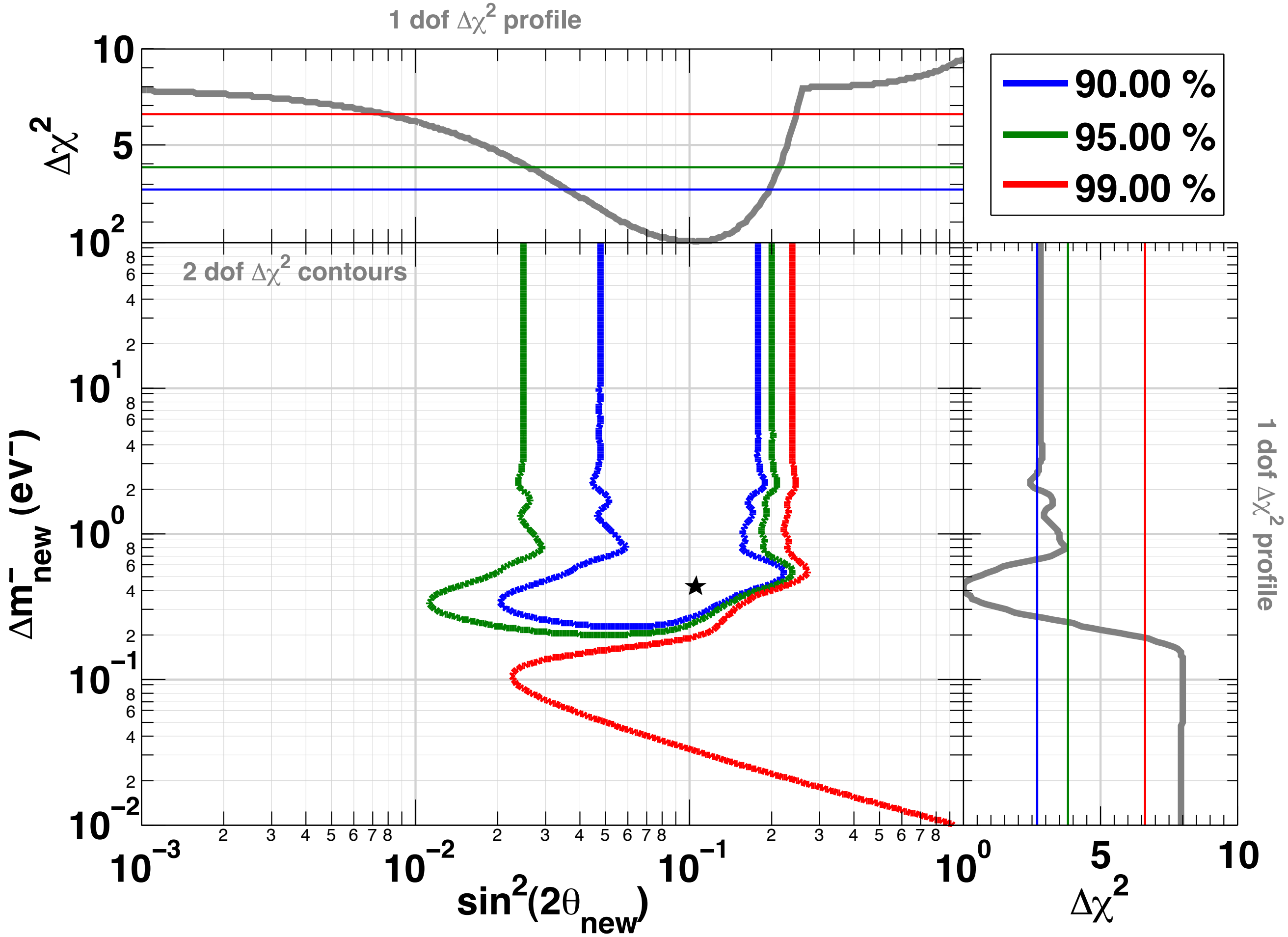


The reactor rate anomaly

- 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

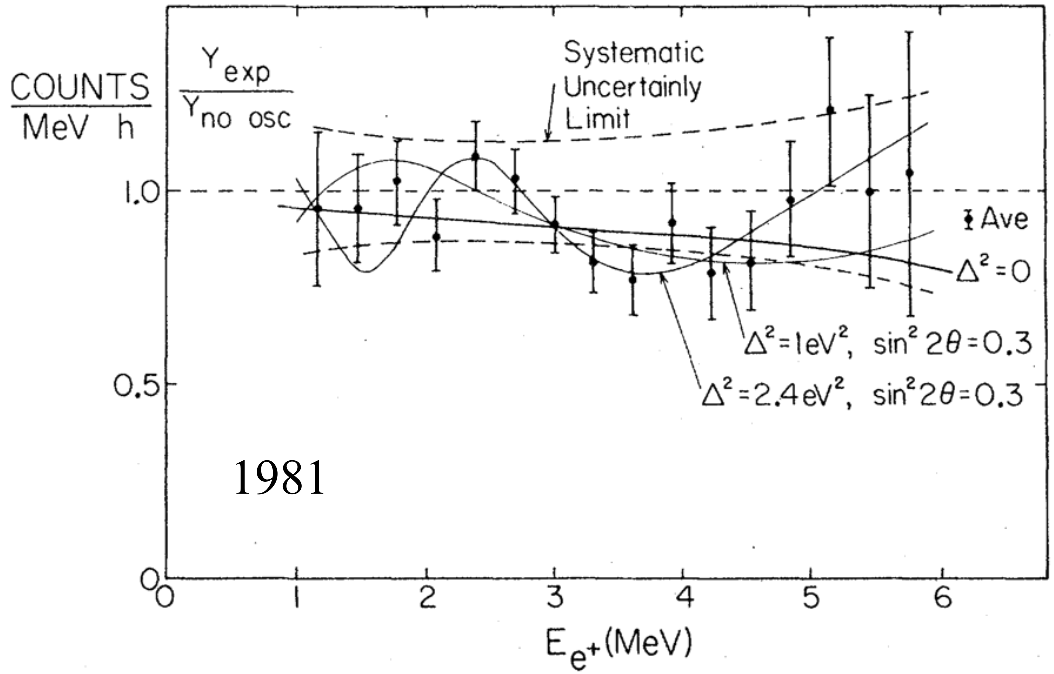
- Combine all rate measurements, no spectral-shape information
- Fit to anti-ν_e disappearance hypothesis

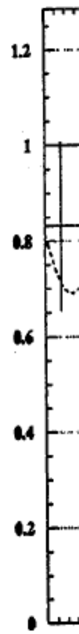


- Absence of oscillations disfavored at 98.6% C.L.

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





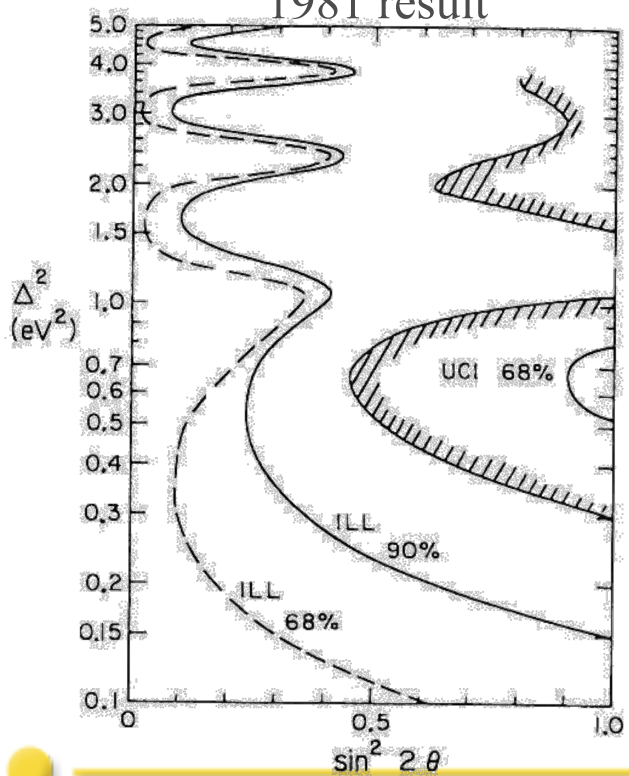
- Large errors, but a striking pattern is seen by eye ?

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

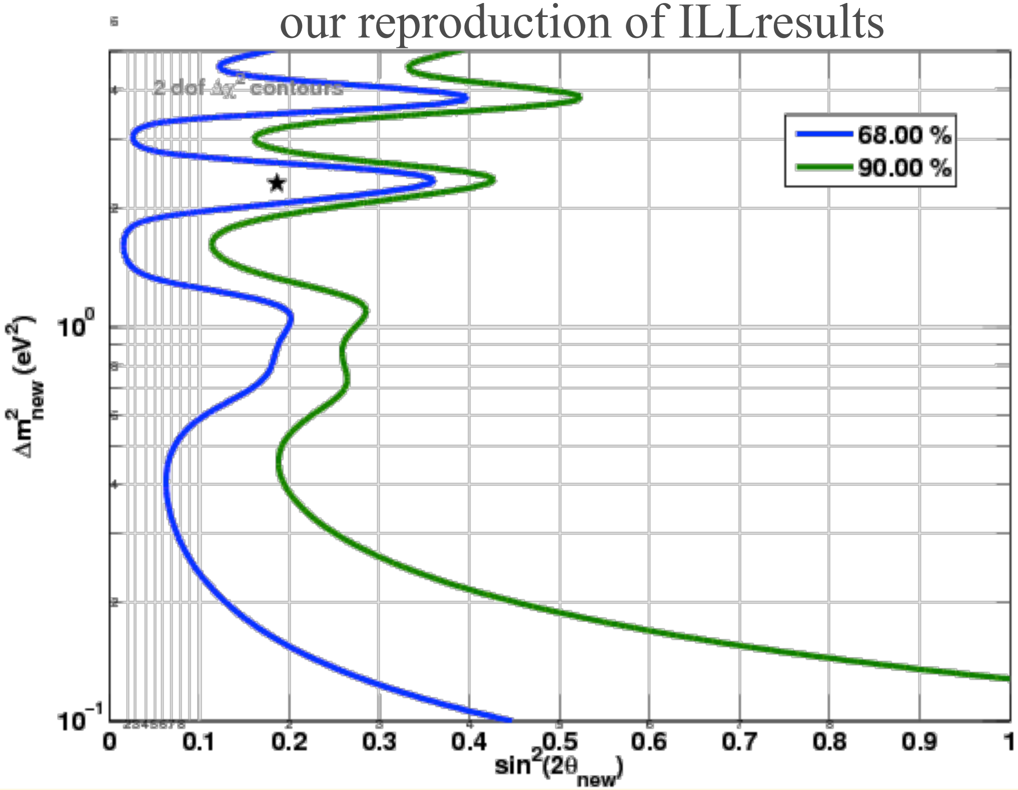
- 1981: Try to reproduce published contour
- 1995: Reproduce claim that global fit disfavors oscillation at 2σ

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

1981 result

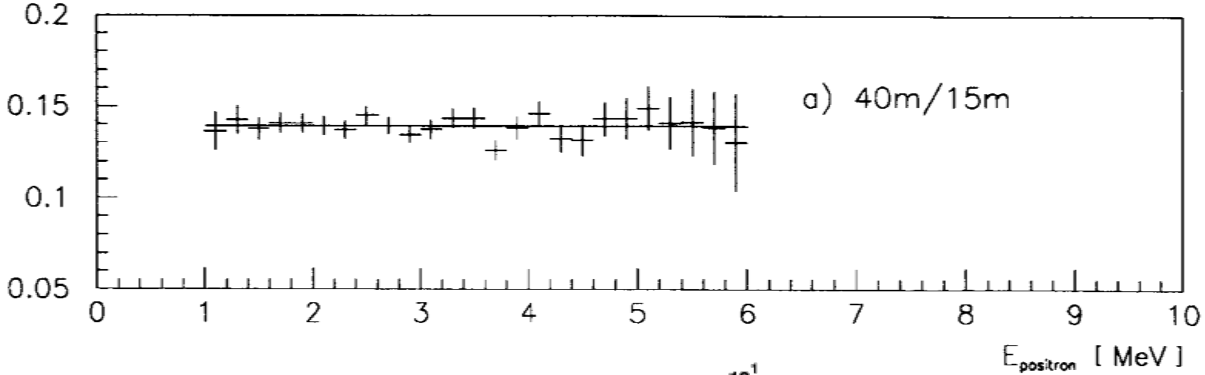


our reproduction of ILLresults

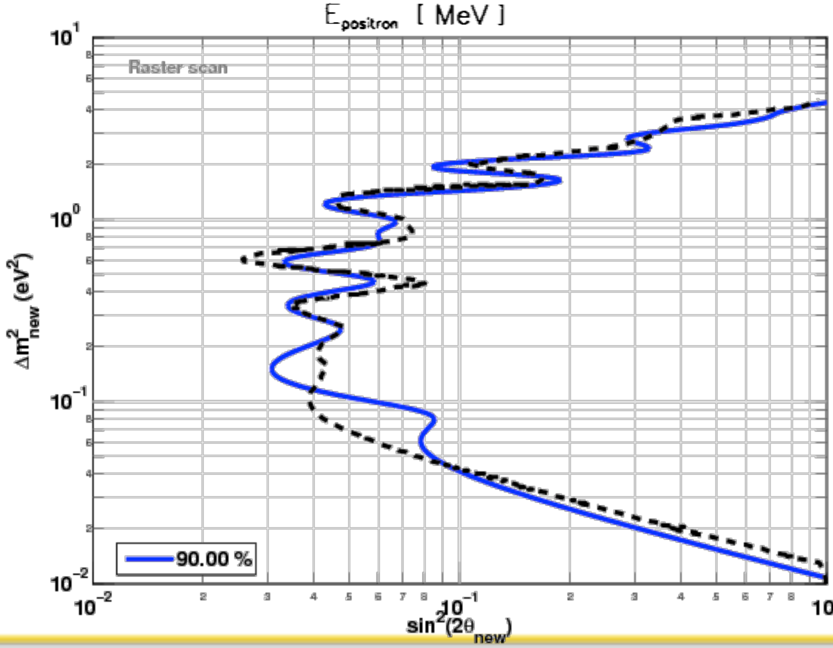


Spectral shape analysis of Bugey-3

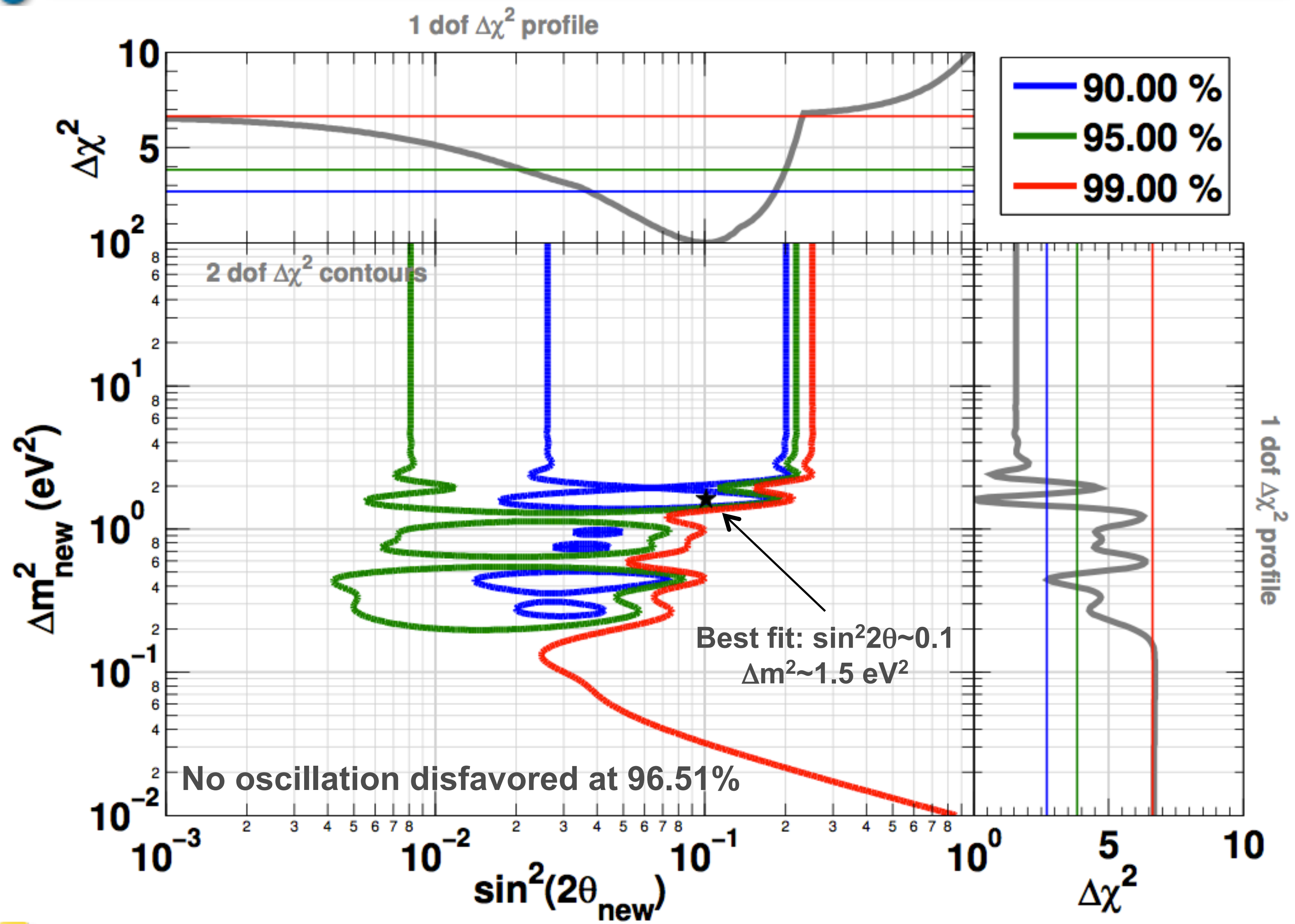
- Bugey-3 spectral measurements at 15 m, 40 m, 90 m
  - Best constraint from high statistics R=15m/40m ratio
  - Very robust since it does not rely on reactor spectra



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

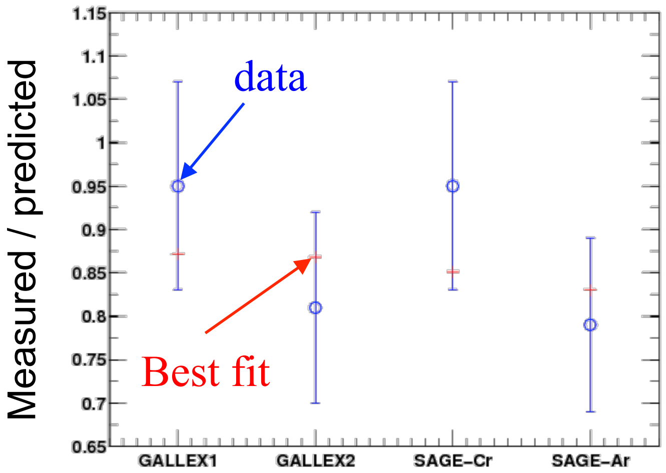
Based on PRD82 053005 (2010)

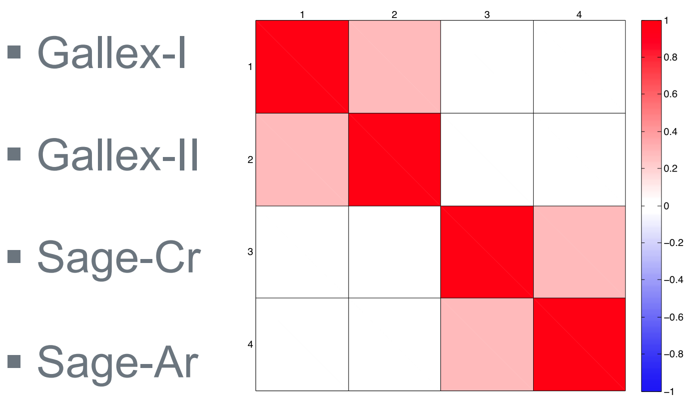
See C. Giunti's talk

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 ?**

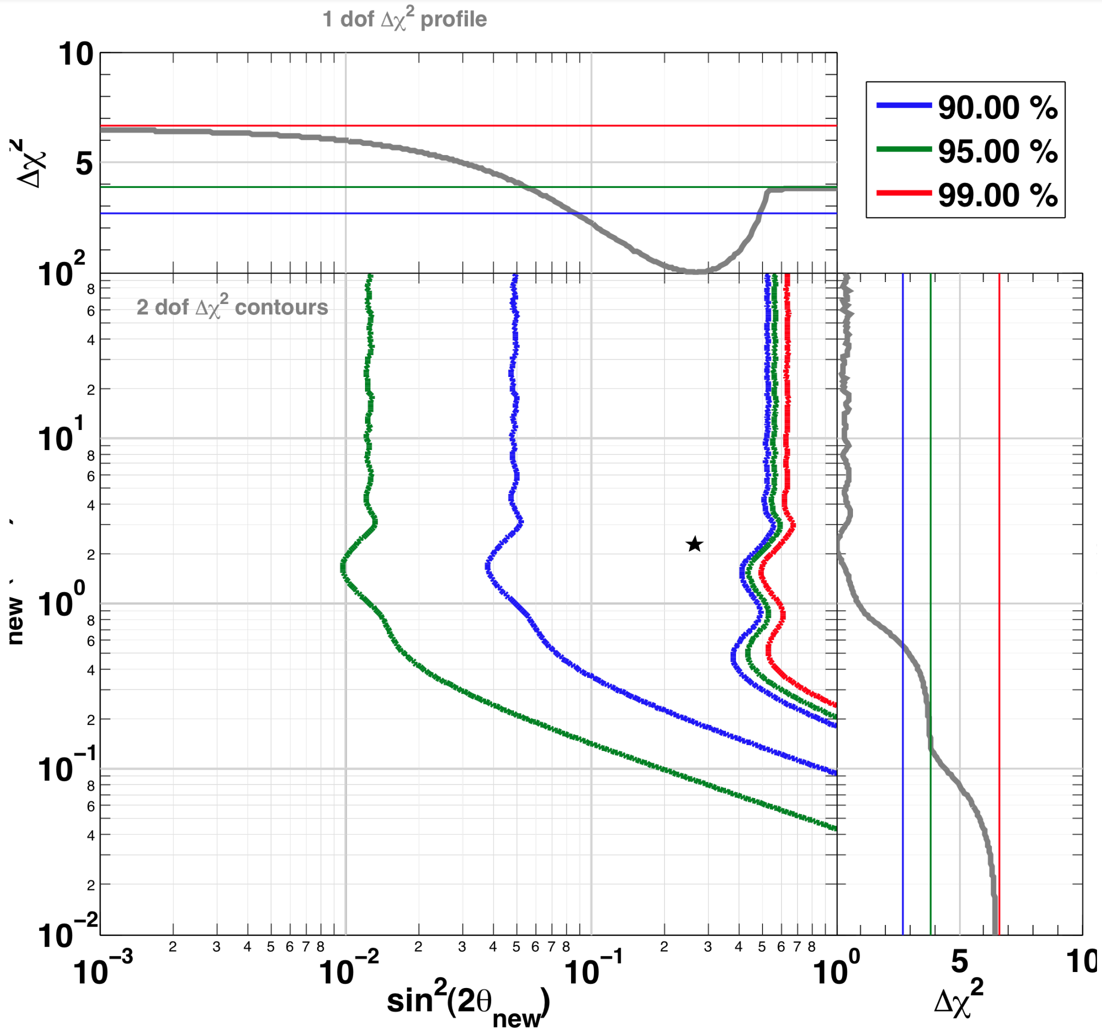
- **Our analysis for Gallex & Sage:**
  - Monte Carlo computing mean path lengths of neutrinos in Gallium tanks
  - **NEW** : Correlate the 2 Gallex runs together & the 2 SAGE runs together





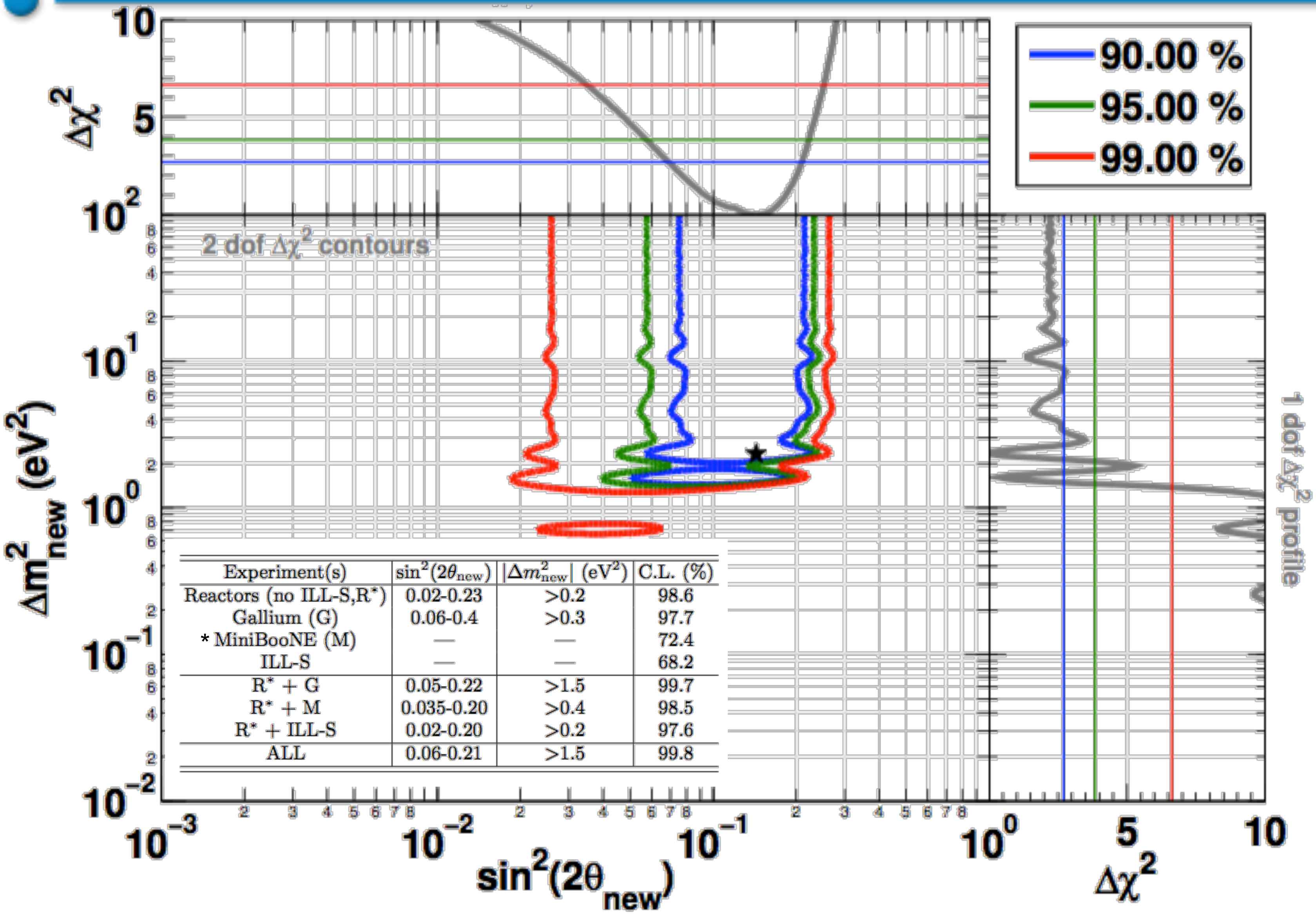
correlation matrix

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

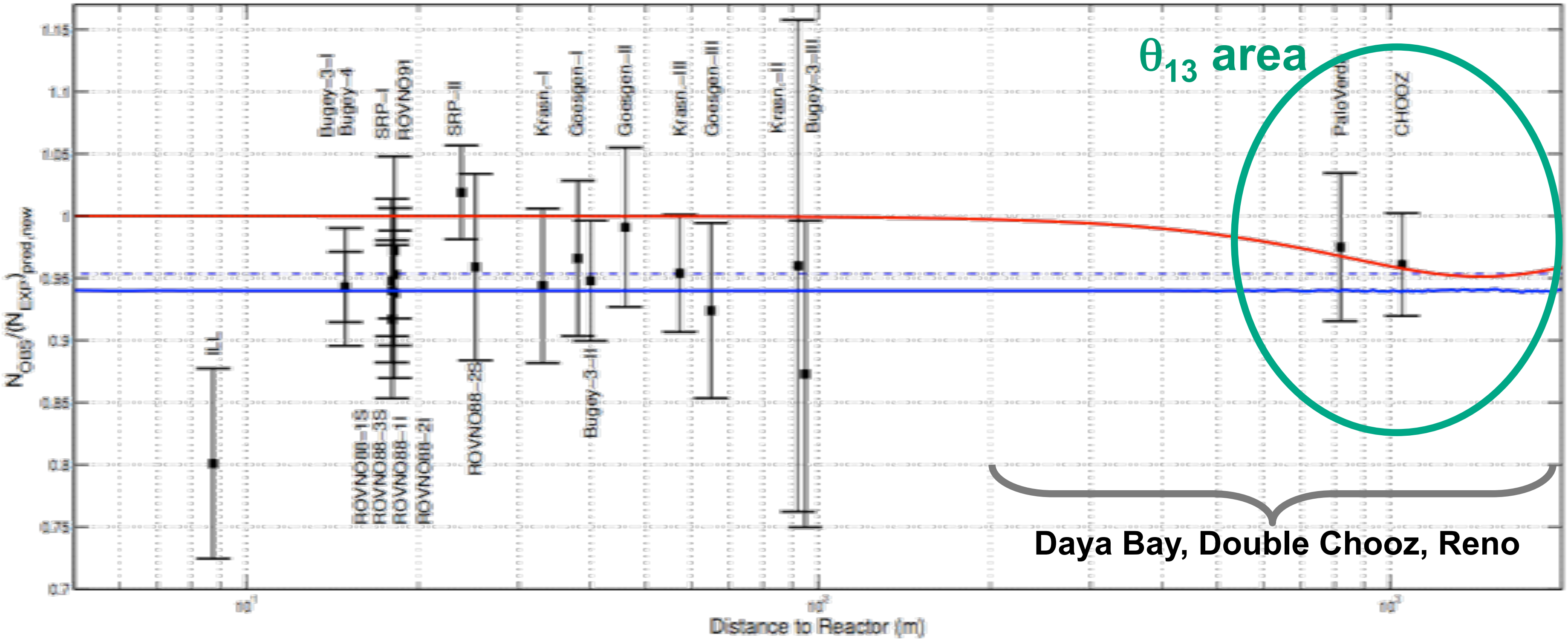
Implication for θ_{13}

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, new 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

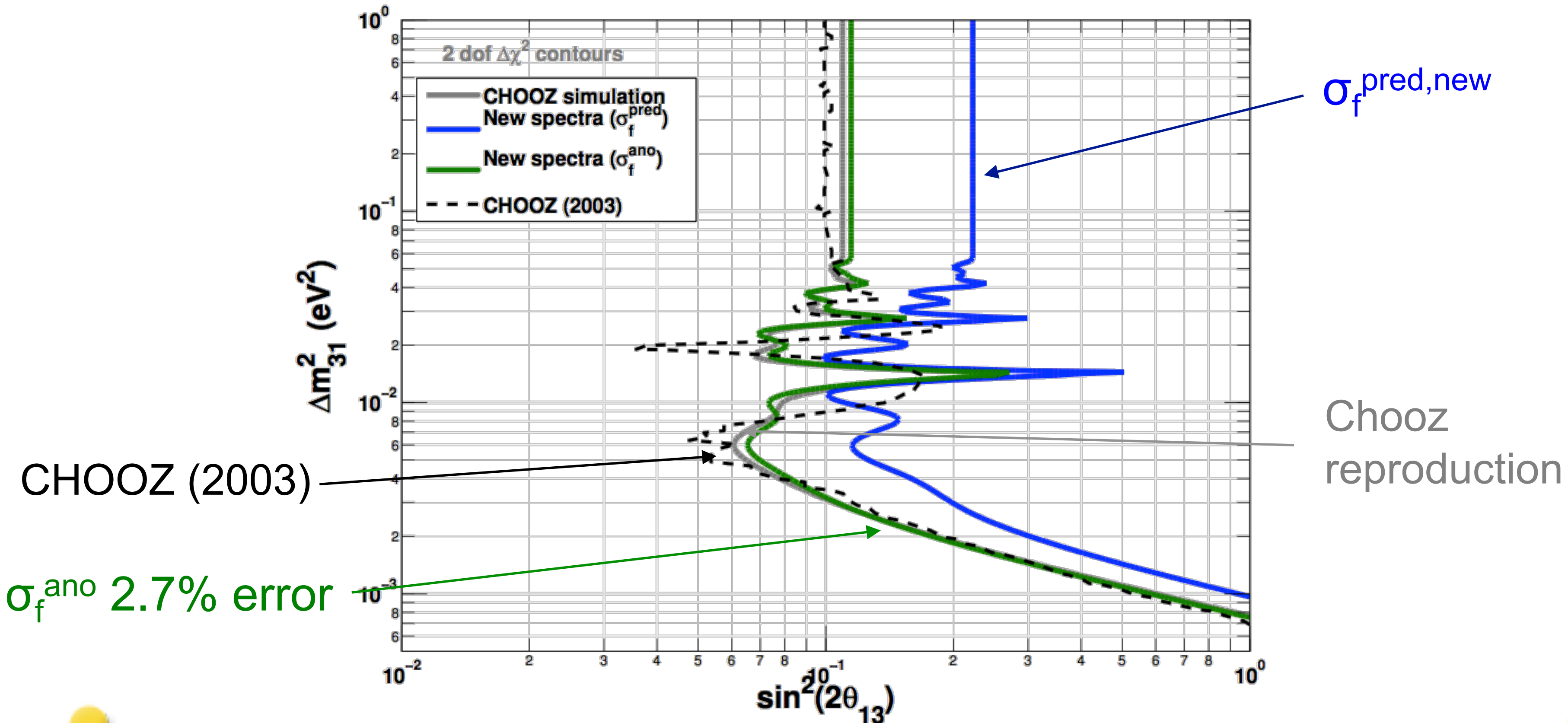
- **σ_f^{pred}**
  - Use $\sigma_f^{pred,new}$ =6.102 10^{-43} cm^2/fission ± 2.7%
  - Use $\sigma_f^{pred,old}$=5.850 10^{-43} cm^2/fission ± 2.7%
- **σ_f^{exp}**
  - Use σ_f^{exp} Bugey-4=5.750 10^{-43} cm^2/fission ± 1.4%
    Chooz's choice: use lower error (total 2.7% instead of 3.3%)
    Bugey-4 is a kind of "near detector" for Chooz
  - Use $<\sigma_f^{exp}>=\boldsymbol{\sigma_f^{ano}}$=5.39 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?)



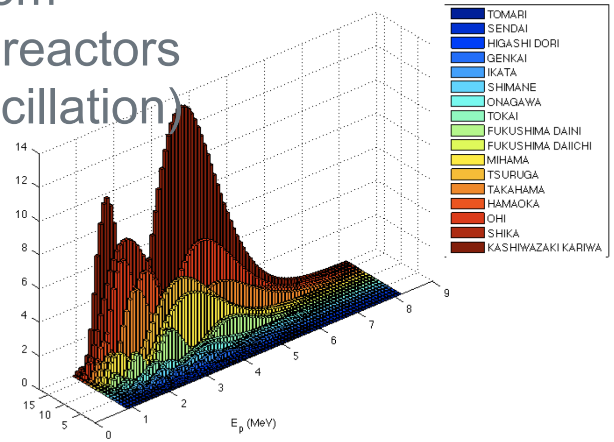
Reanalysis of KamLAND's 2010 results

arXiv:1009.4771v2 [hep-ex]

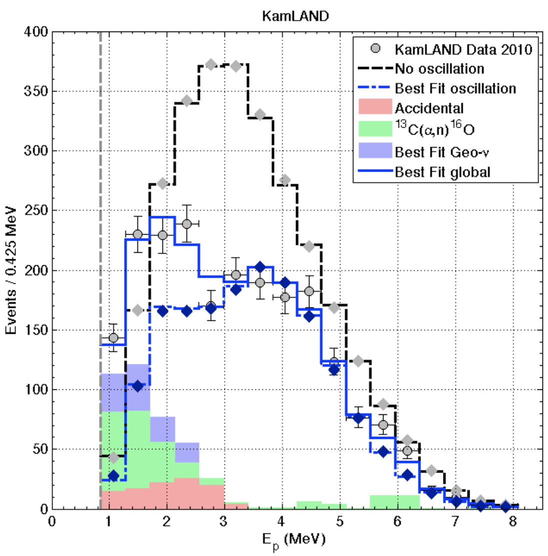
Systematics

	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

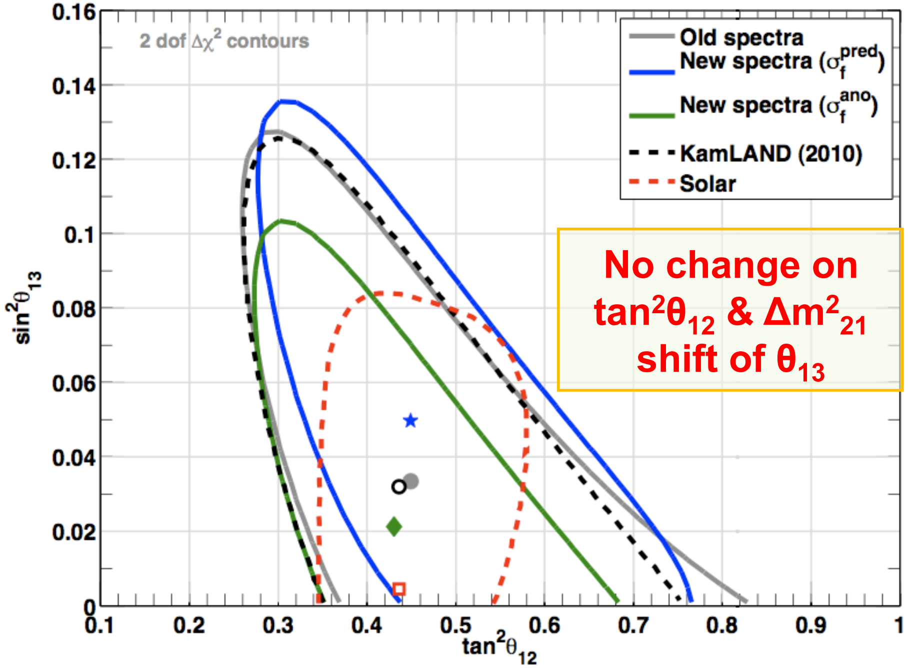
Spectra from Japanese reactors (with ν_e oscillation)



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



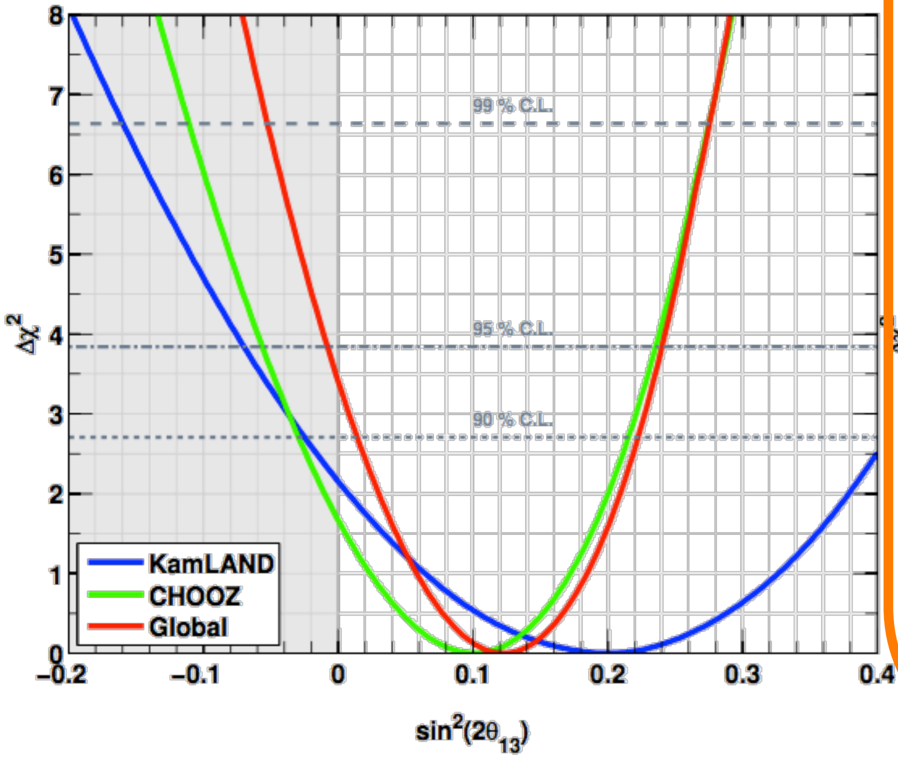
With new spectra predictions



CHOOZ and KamLAND combined limit on θ_{13}

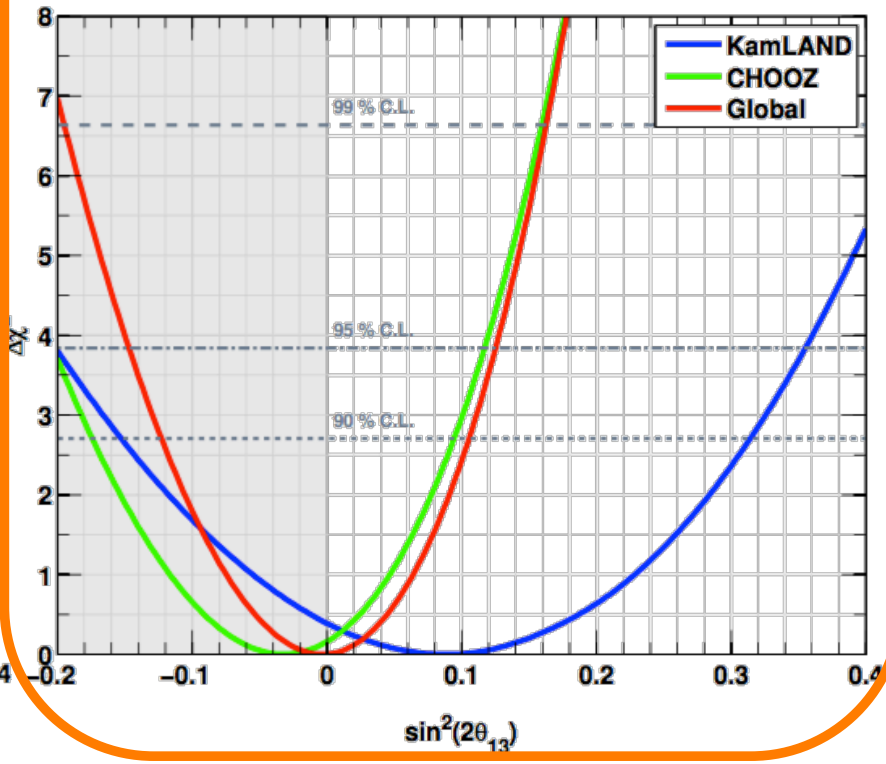
Normalization with $\sigma_f^{pred,new}$

3-ν framework & 2.7% uncertainty



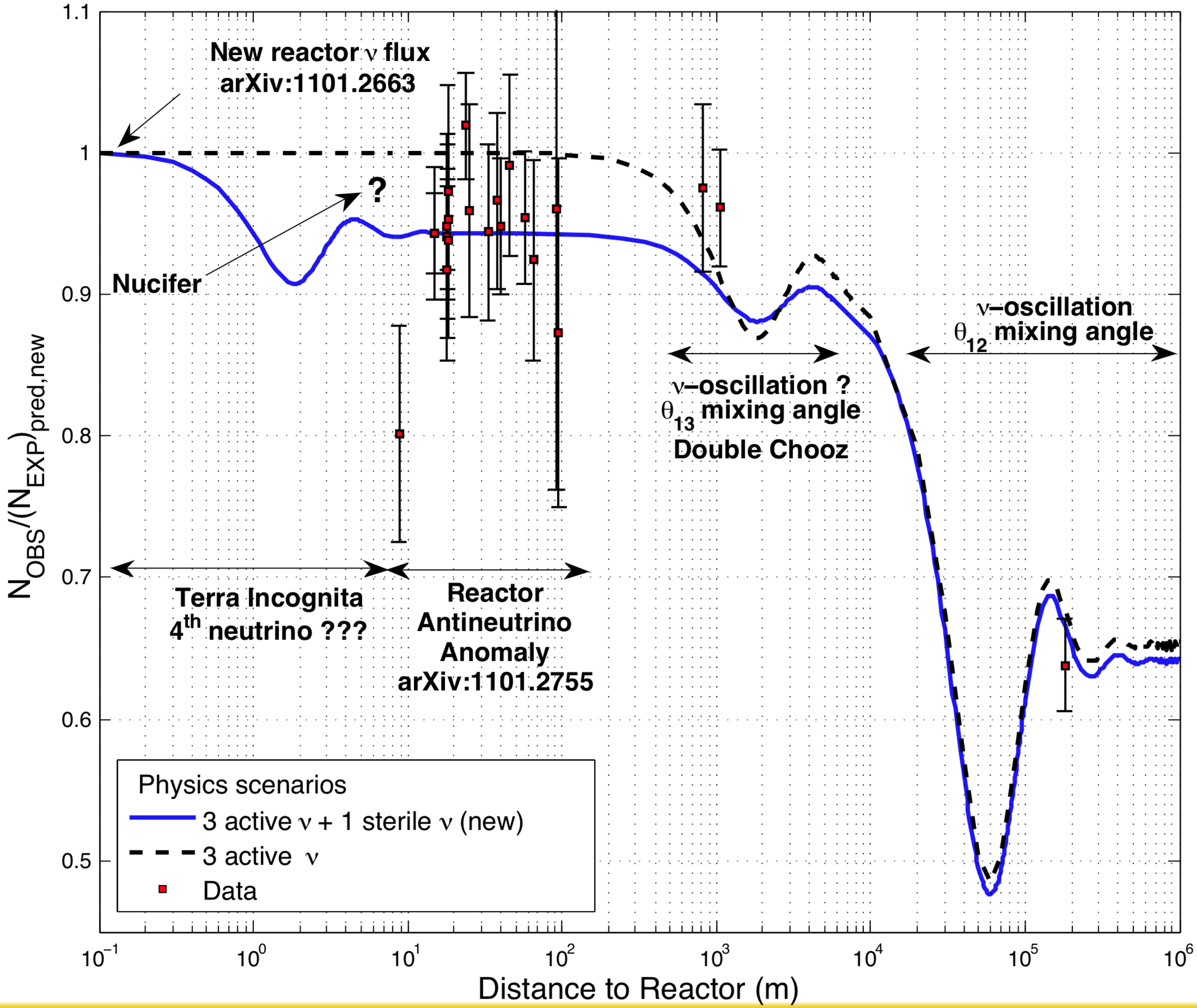
Normalization using σ_f^{ano}

3-ν framework & 2.7% uncertainty

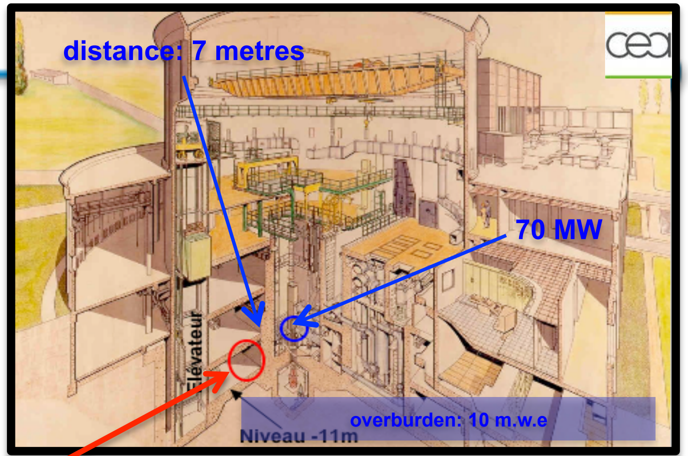


- **Our interpretation** (different from Arxiv:1103:0734 for KamLAND-$\sigma_f^{pred,new}$, T. Schewtz's talk)
  - No hint on θ_{13}>0 from reactor experiments : $\sin^2(2\theta_{13})<0.11$ (90%C.L., 1dof)
  - CHOOZ 90 % CL limit stays identical to Eur. Phys. J. C27, 331-374 (2003)
  - Multi-detector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

Need for new experimental inputs !

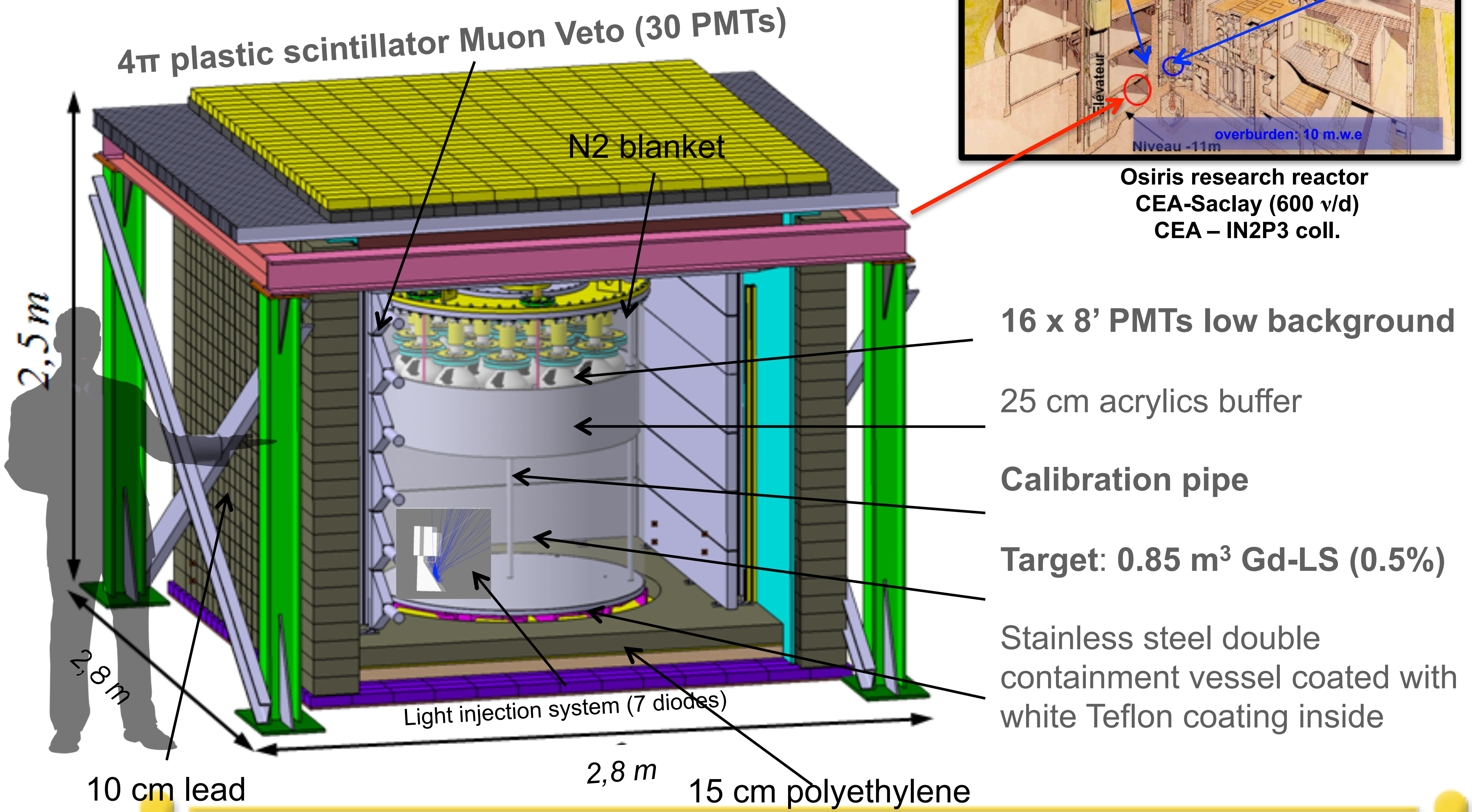


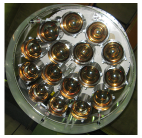
Nucifer



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

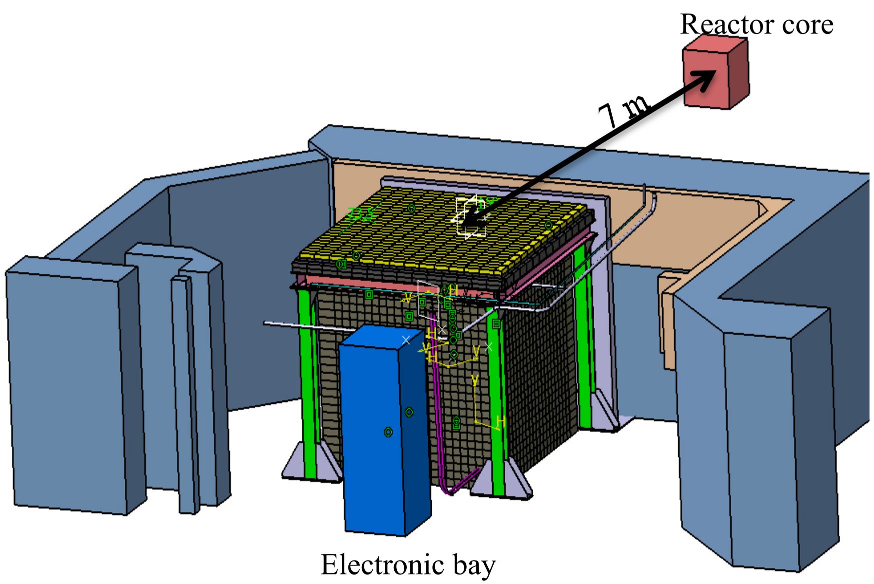
First goal: Non Proliferation
Thermal Power Measurement
Fuel Composition Measurement U/Pu

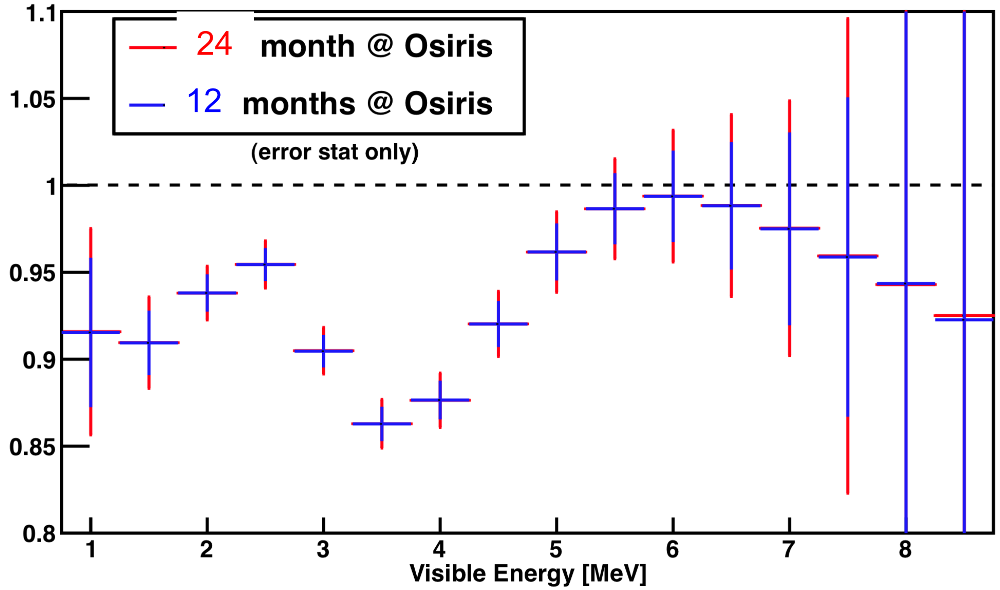




NUCIFER in Saclay

- 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
- Δm^2 = 2.4 eV^2 & $\sin^2(2\theta)$=0.15
- No backgrounds. Thus to be taken with a grain of salt …

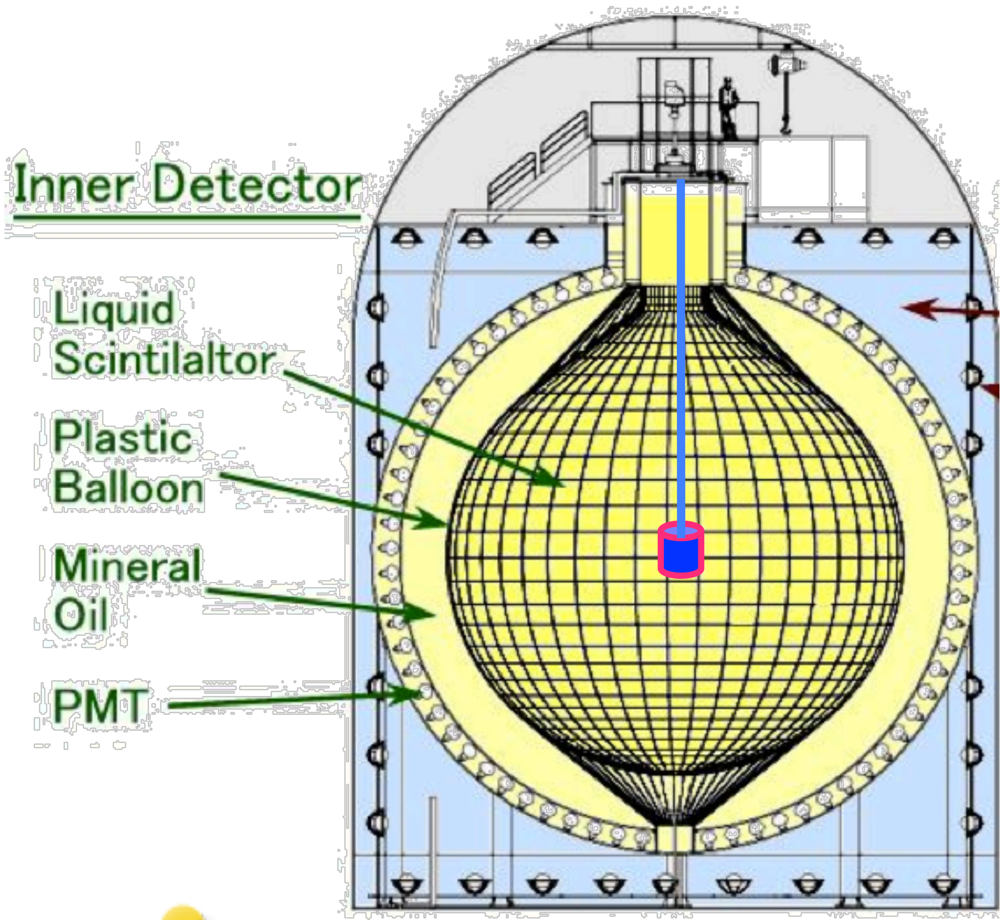




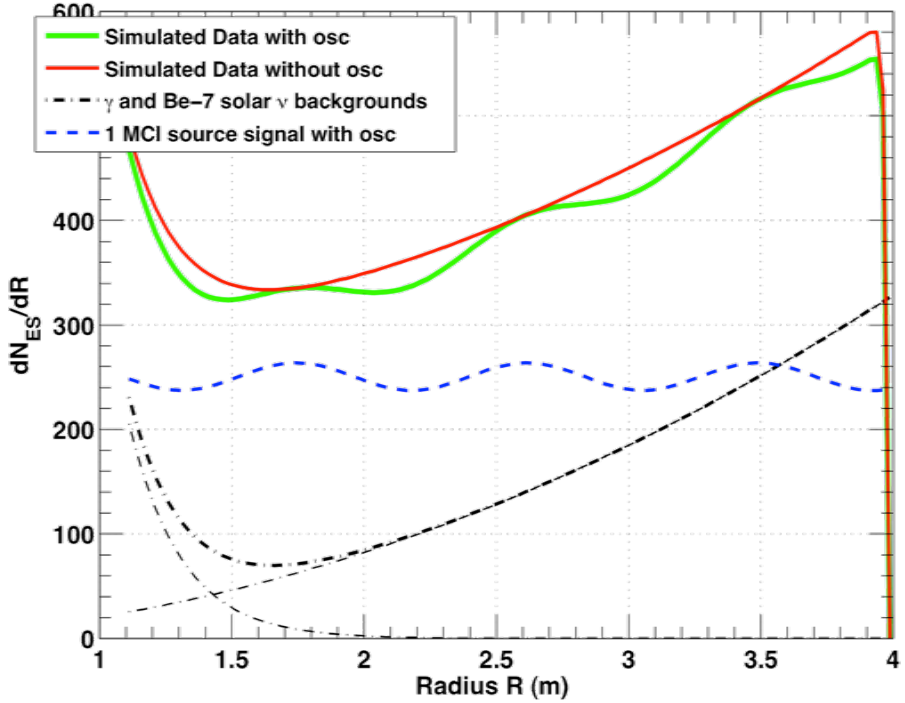
- Such pattern could not be seen at Bugey-3 (extended core & 14 m baselin

Mci $^{51}Cr/^{37}Ar$ Experiment Concept

- A strong 1 Mci ν source in the middle of a large LS detector
- Elastic scattering on electrons (few 1000 evts, 150 days, >250 keV)
- A good resolution in position (20 cm)

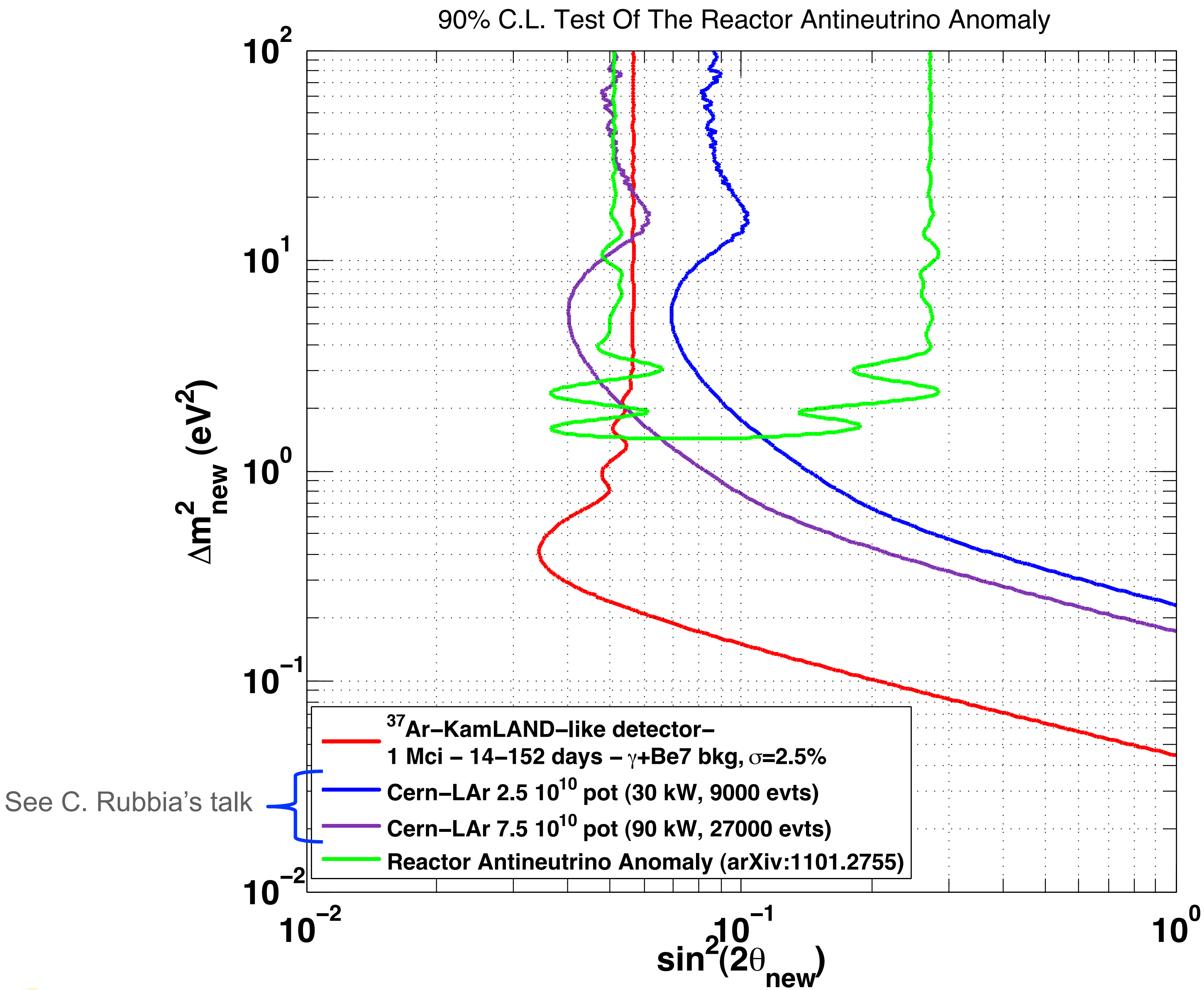


Real oscillation pattern VS radius (preliminary)



Similar efforts : V. Gavrin et al. arXiv:1006.2103
R. Raghavan et al. PRD 75, 093006; M.Wurm/S.Schoenert

Promising experimental prospect testing the RAA!

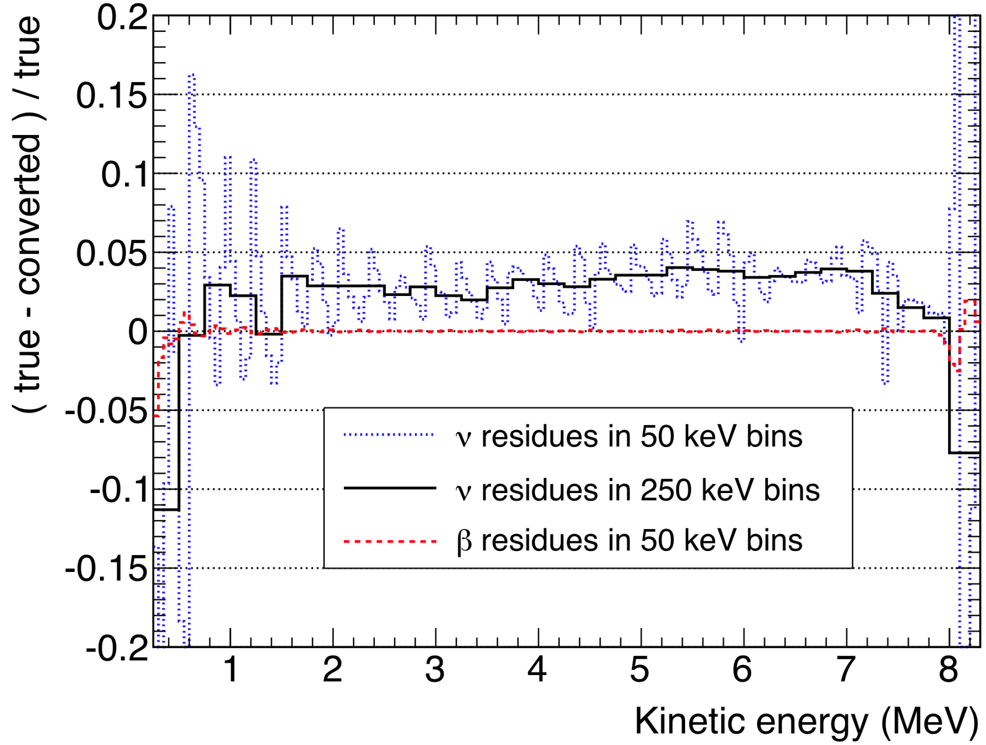


Backup

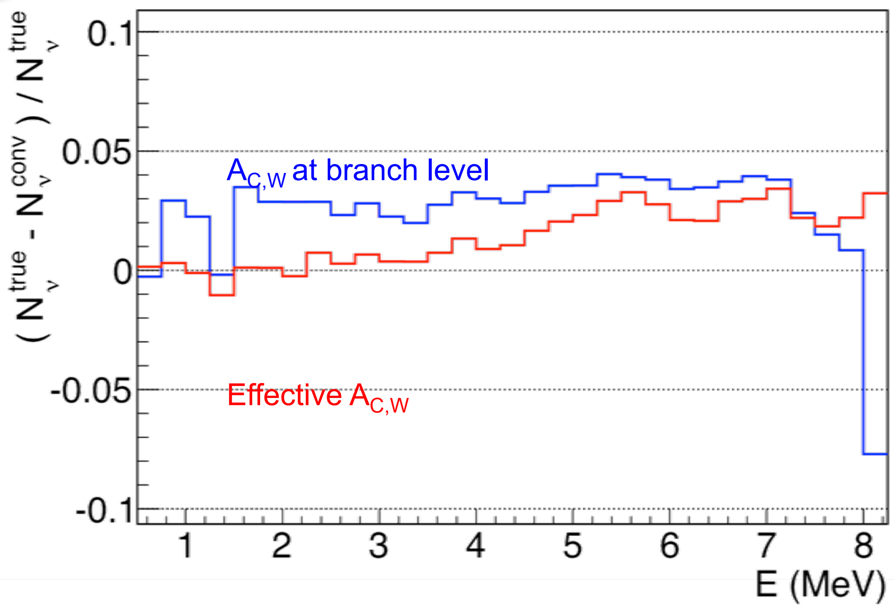
Consistency Check

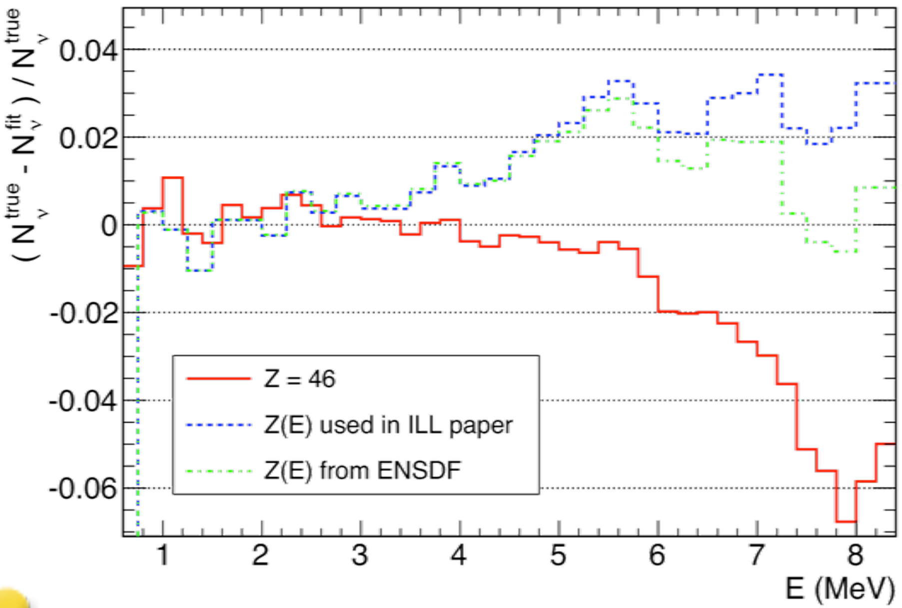
Stringent test

1. Define "true" e^- and ν spectra from reduced set of well-known ENSDF branches.
2. Apply exact same ILL conversion procedure to true e^- spectrum.
3. Compare converted ν spectrum to the true one.
4. 'old' effective method bias is confirmed



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

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