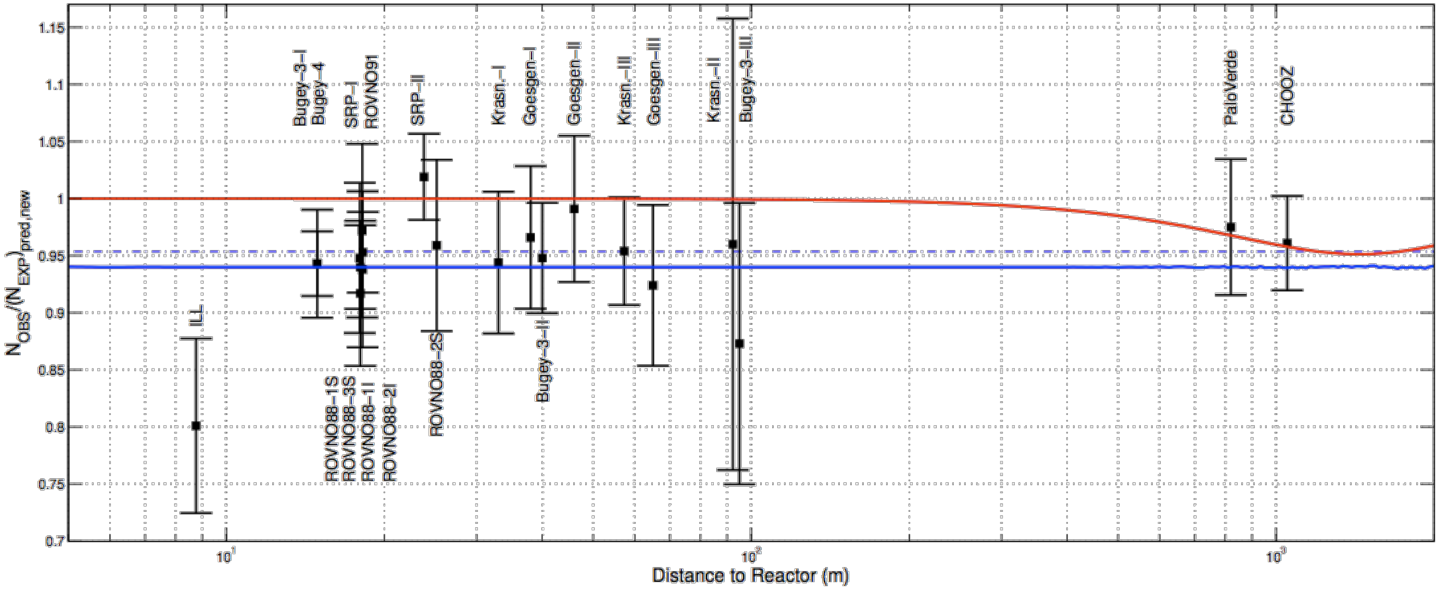
The Reactor Antineutrino Anomaly



G. Mention, M. Fechner, T. Lasserre,
M. Cribier, Th. Mueller, D. Lhuillier, A. Letourneau,
CEA / Irfu

arXiv:1101.2755 [hep-ex], PRD83, 073006 (2011)

linked to our new "improved prediction of reactor antineutrino spectra", done with Subatech group:

M. Fallot, S. Cormon, L. Giot,
J. Martino, A. Porta, F. Yerma

arXiv:1101.2663 [hep-ex], PRC83, 054615 (2011)

Overview

- **Reactor anti-neutrino spectra**
- **Reactor anti-neutrino anomaly**
- **Consequences**
- **Outlook**

ν spectrum emitted by a reactor

T. A. Mueller *et al.*, PRC83, 054615 (2011)

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

Electron antineutrinos emitted through decays of **Fission Products** of **^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu** $^A_ZX \longrightarrow {}^{\;\;A}_{Z+1}Y + e^- + \bar{\nu}_e$

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}

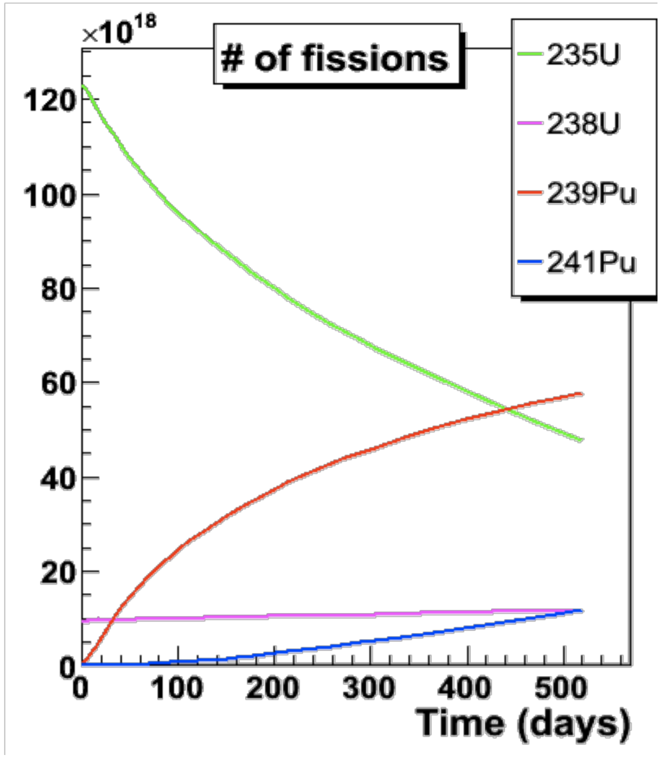
$$\Phi_\nu(E,t) = \frac{P_{th}(t)}{\sum_k \alpha_k(t)\, E_k} \times \sum_k \alpha_k(t)\, S_k(E)$$

Nuclear databases

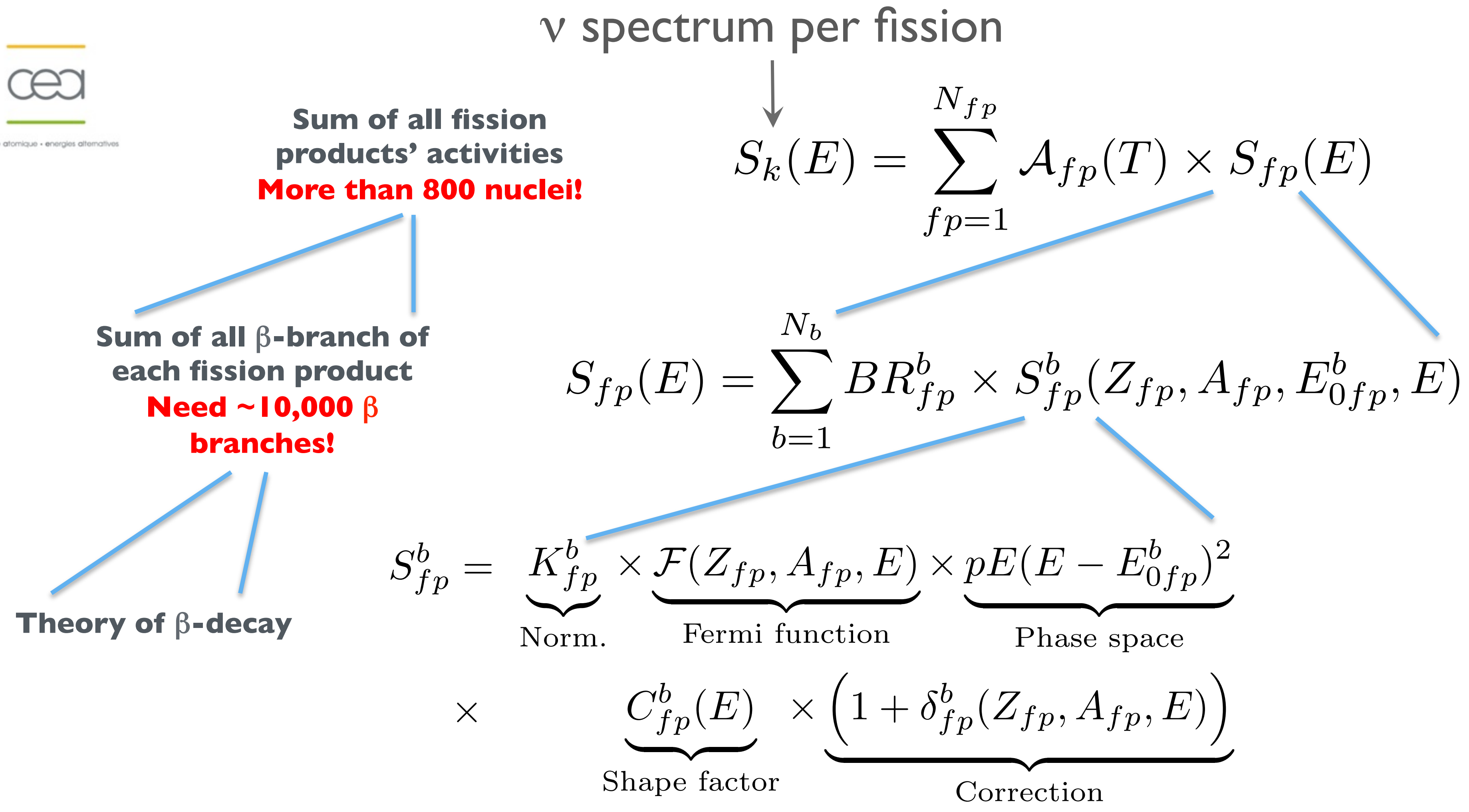
E released per fissions of isotope *k*, δE_k≈0.3%

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

ν spectrum per fission
This work !



The guts of $S_k(E)$



ν spectrum per fission

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

Sum of all fission products' activities
More than 800 nuclei!

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

Sum of all β-branch of each fission product
Need ~10,000 β branches!

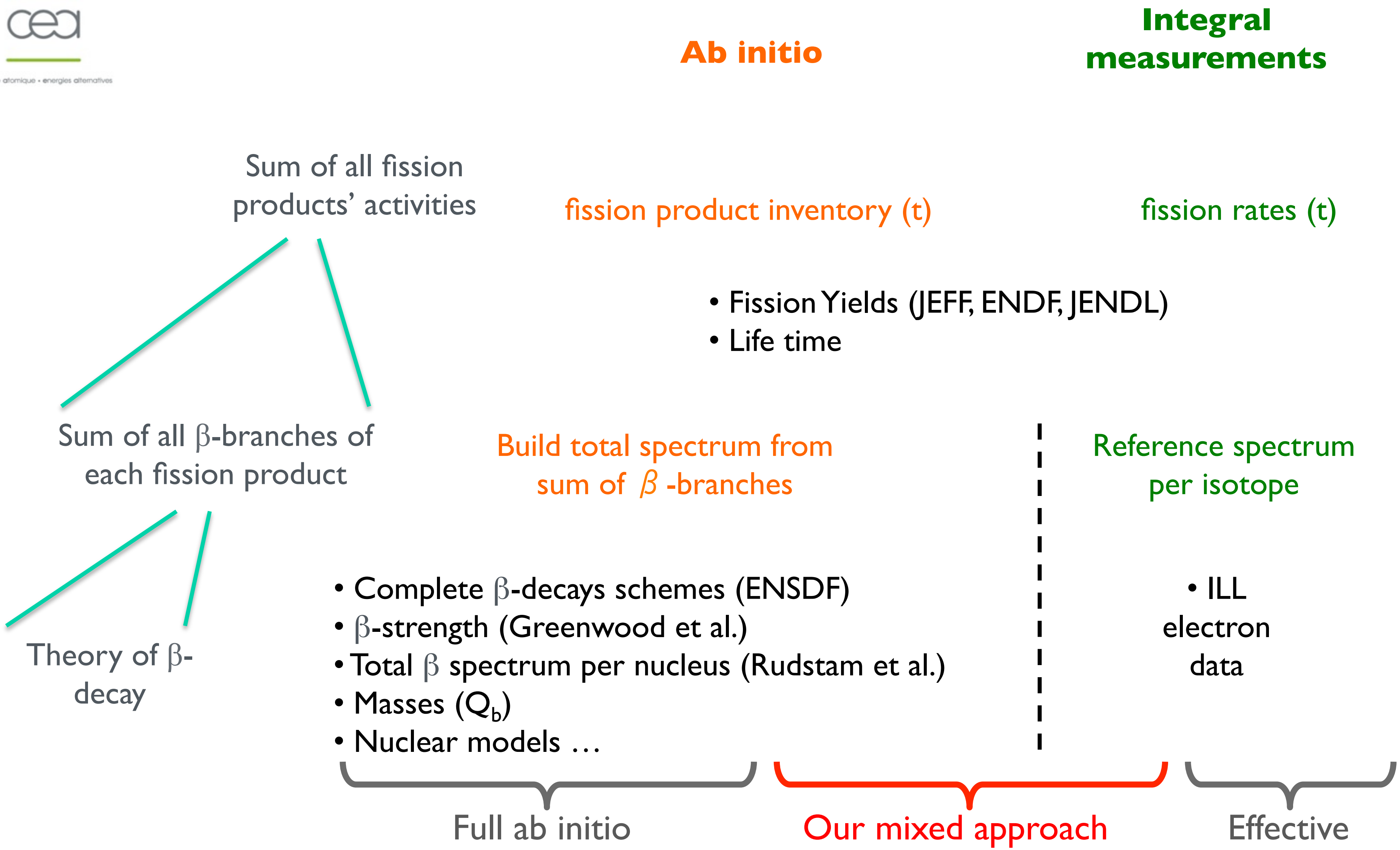
$$S_{fp}^b = \underbrace{K_{fp}^b}_{\text{Norm.}} \times \underbrace{\mathcal{F}(Z_{fp}, A_{fp}, E)}_{\text{Fermi function}} \times \underbrace{pE(E - E_{0fp}^b)^2}_{\text{Phase space}}$$

$$\times \underbrace{C_{fp}^b(E)}_{\text{Shape factor}} \times \underbrace{\left(1 + \delta_{fp}^b(Z_{fp}, A_{fp}, E)\right)}_{\text{Correction}}$$

Theory of β-decay

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

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

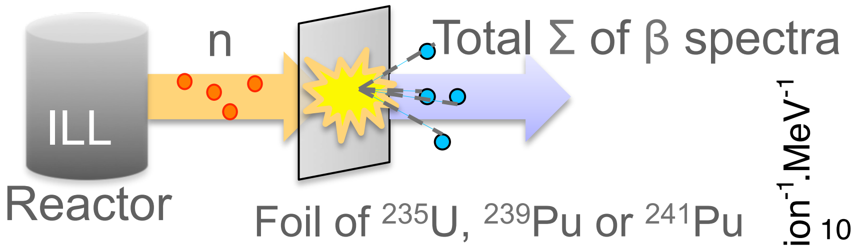
Full ab initio

Our mixed approach

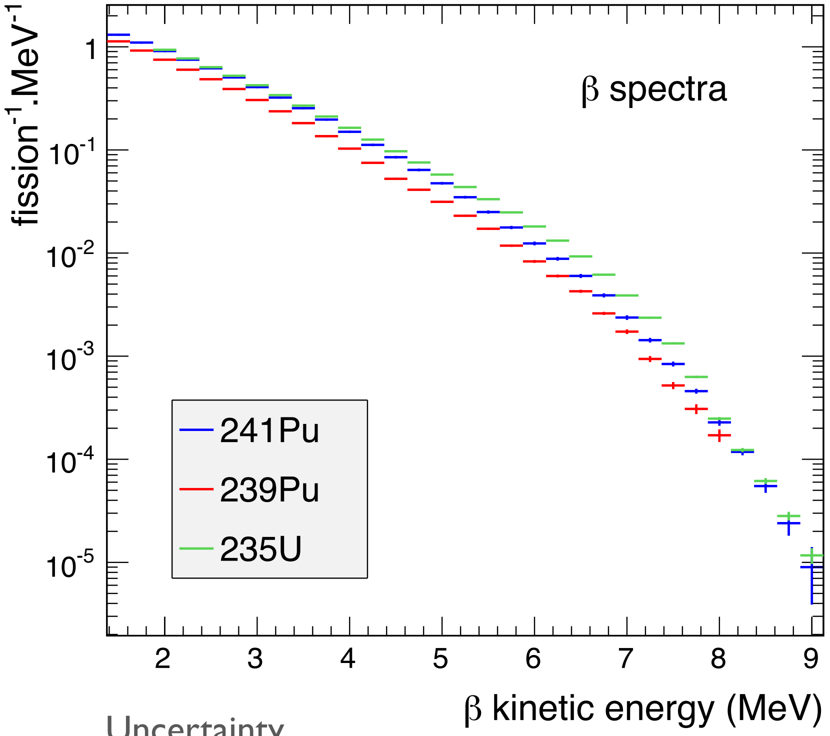
Effective

ν flux prediction: Anchor point of ILL electron data

Unique reference to be met by any other measurement or calculation



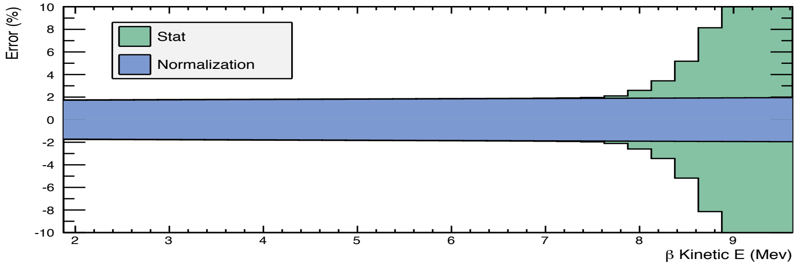
$$\sum_{A,Z}\{{}^{A}_{Z}X \longrightarrow {}_{Z+1}^{\;\;A}Y + e^{-} + \bar{\nu}_e\}$$



- Accurate measurements @ ILL in Grenoble (1980-89):
- High resolution magn. Spectrometer
- Intense and pure thermal n spectrum from the core (not suitable for ^{238}U which needs fast n)

→ Measure total e$^-$ spectrum from decays of fission product.

Uncertainty

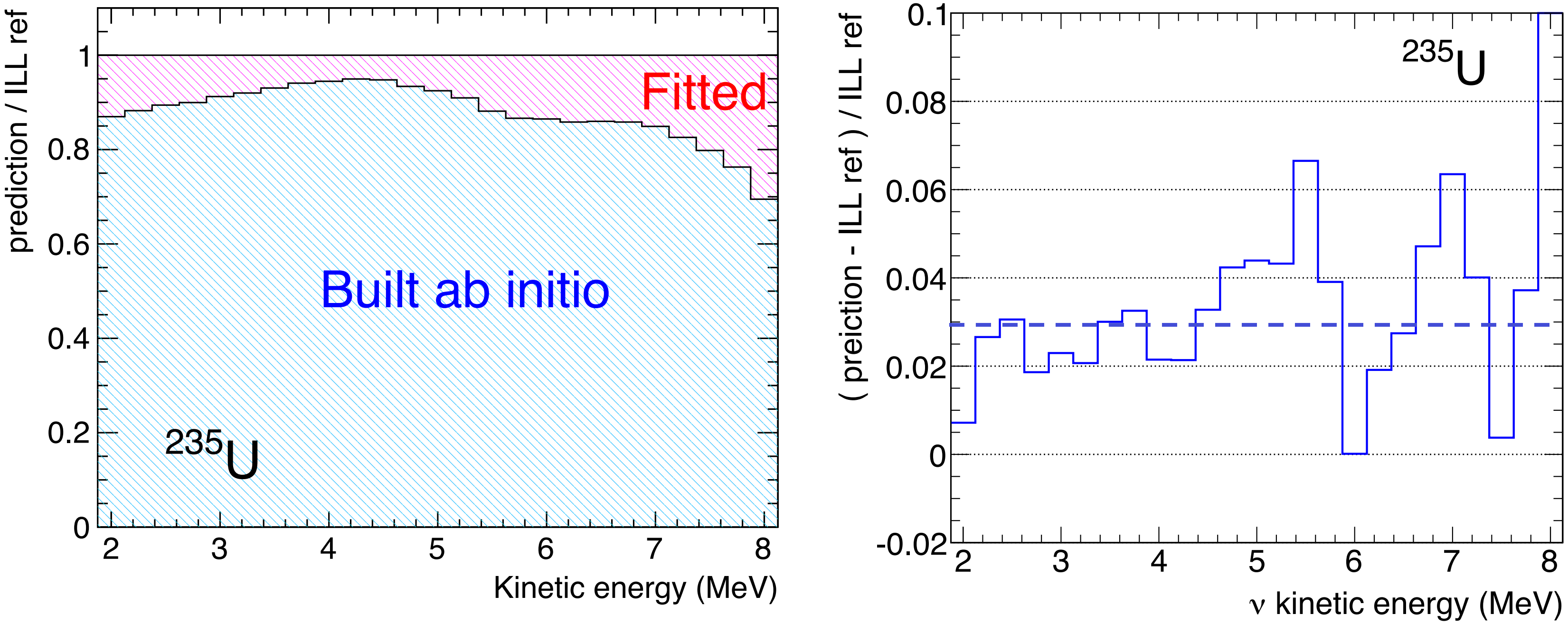


- Calibration through extensive use of reference internal conversion electron lines

  → Normalization syst. @ **1.8%**

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: reduce use of effective anchorage-branches to the remaining 10%.

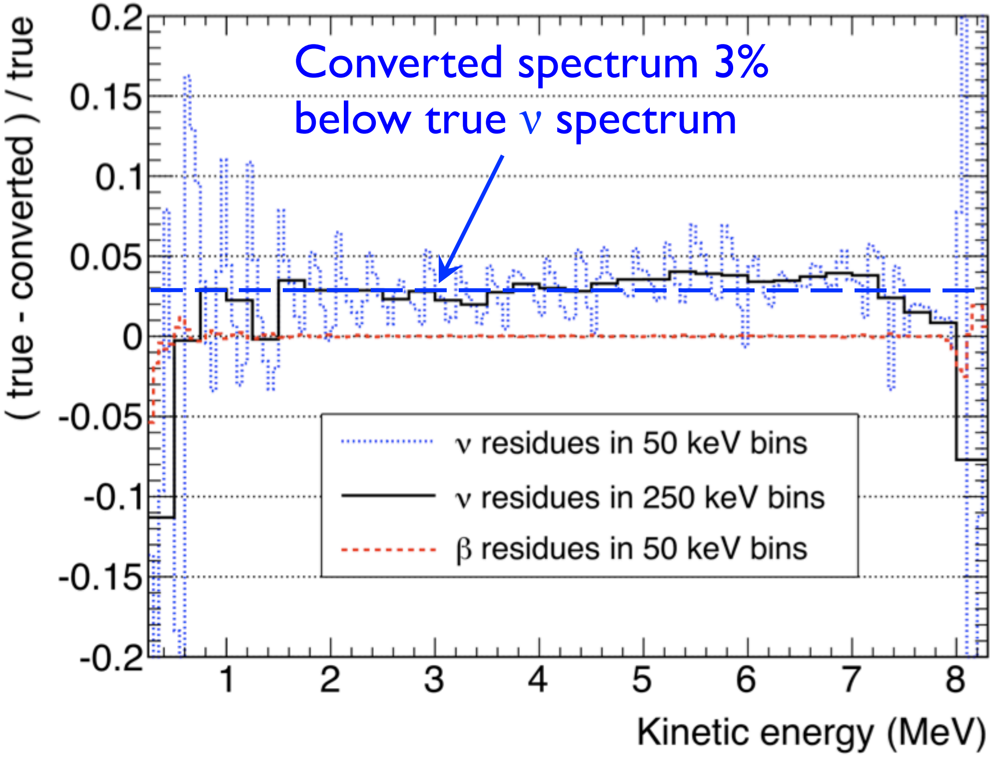


- **About +3% normalization shift with respect to old ν spectrum**
- **Similar result for all isotopes (^{235}U, ^{239}Pu, ^{241}Pu)**
- **Stringent Test Performed – Origin of the bias identified**

Average ~ +3% shift now independently confirmed by P. Huber: arXiv:1106.0687 although some difference in shape.

Consistency Check

1. Define "true" e$^-$ and ν spectra **from reduced set** of **well-known branches** from ENSDF nuclei data base. "Perfect knowledge" of both e and ν spectra.
2. Apply exact same **OLD** conversion procedure to true e$^-$ spectrum.
3. Compare the converted ν spectrum to the true one.
4. OLD 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

Off-equilibrium corrections to ILL β-spectra measurements

MURE evolution code: core composition and off equilibrium effects

(Subatech Nantes)

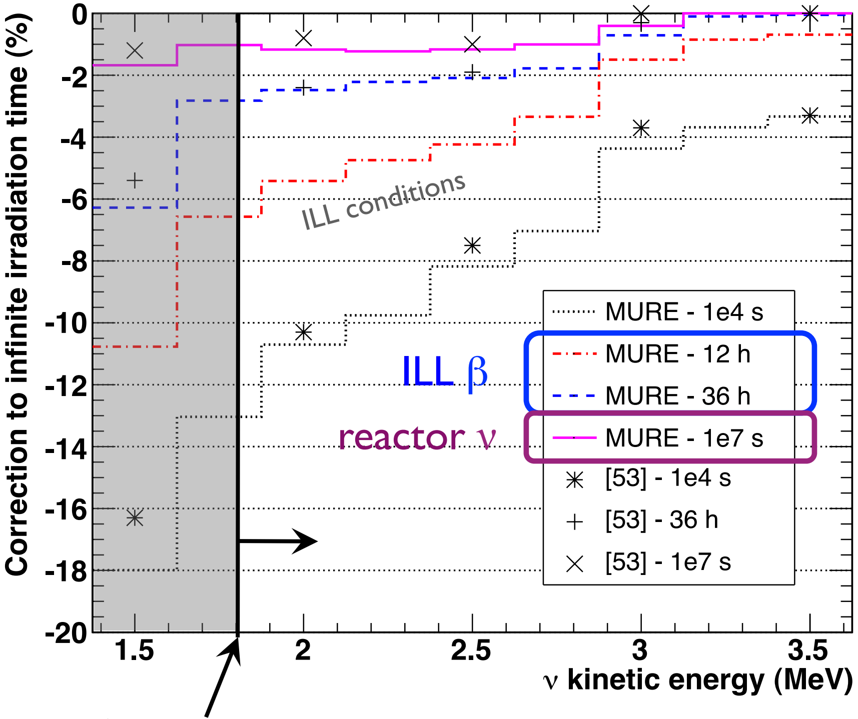
$$S_k(E) = \sum_{fp=1}^{N_{fp}} \mathcal{A}_{fp}(T) \times S_{fp}(E)$$

- Full simulation of reactor core
  → absolute prediction of isotopes inventory.

- Relative off-equilibrium effect: close to beta-inverse threshold**, a significant fraction of the ν spectrum takes weeks to reach equilibrium**

→ Sizeable correction in the ν oscillation range that depends on the exact chronology of ILL data taking.

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



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

Anti-ν_e Detection: V-A 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)

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

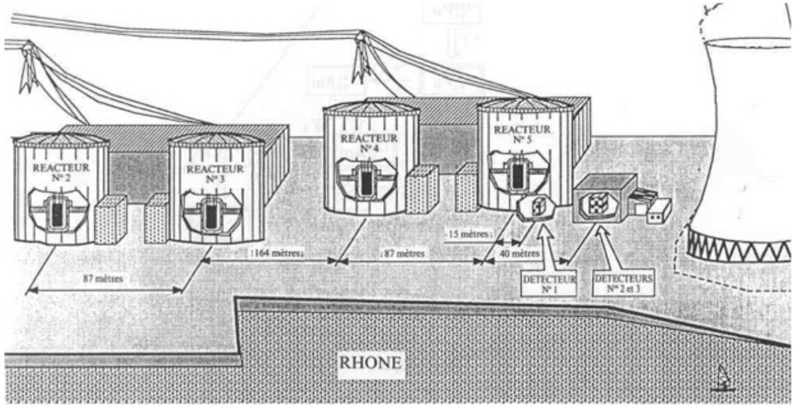
- **The pre-factor** κ (two pseudo-independent approaches)

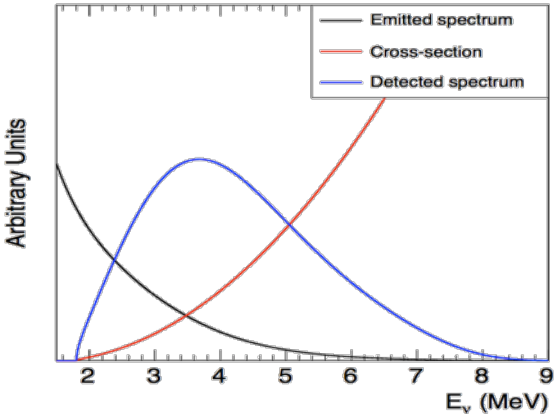
$$\kappa = \frac{G_F^2 cos^2(\theta_C)}{\pi}(1 + \Delta^R_{inner})(1 + 3\lambda^2) = \frac{2\pi^2}{m_e^5 f^R \tau_n} \qquad \lambda = |\frac{g_A}{g_V}|$$

- κ's **value raised over the history,** from 0.914 10^{-42} cm^2 MeV^{-2} in 1981
  - Vogel/Beacom 1999 : κ = 0.952 10^{-42} cm^2 MeV^{-2}
  - Our work is based on 2010 PDG τ_n : κ = 0.956 10^{-42} cm^2 MeV^{-2}
  - But we anticipate 2011 κ = 0.961 10^{-42} cm^2 MeV^{-2} ($<\tau_n>$ revision)

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 w.r.t. their computations
- This validates our calculation code.

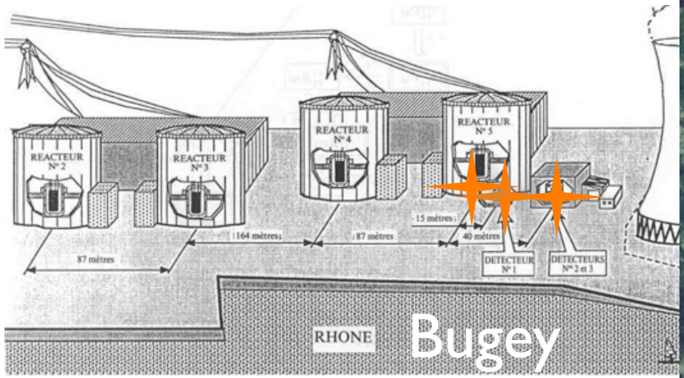
The New Cross Section Per Fission

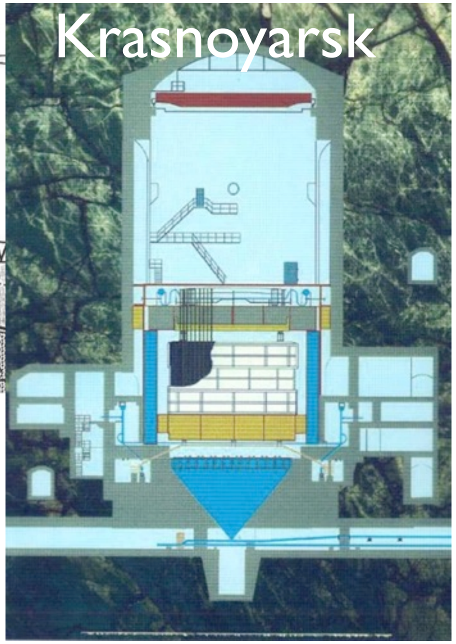
- **ν-flux**: ^{235}U : +2.5%, ^{239}Pu +3.1%, ^{241}Pu +3.7%, ^{238}U +9.8% (σ_f^{pred} ↗)
- **Off-equilibrium corrections** now included (σ_f^{pred} ↗)
- **Neutron lifetime** decrease by a few % (σ_f^{pred} ↗) $(\sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n)$
- Slight evolution of the phase space factor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

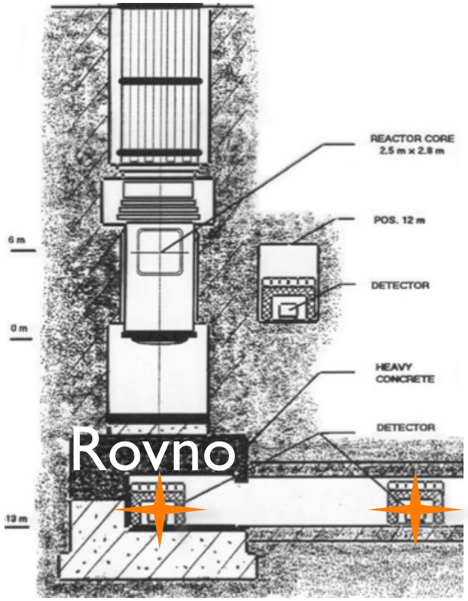
10^{-43} cm^2/fission	old [3]	new	relative effect ↓
$\sigma_{f,^{235}U}^{pred}$	6.39±1.9%	6.61±2.11%	**+3.4%**
$\sigma_{f,^{239}Pu}^{pred}$	4.19±2.4%	4.34±2.45%	**+3.6%**
$\sigma_{f,^{238}U}^{pred}$	9.21±10%	10.10±8.15%	**+9.6%**
$\sigma_{f,^{241}Pu}^{pred}$	5.73±2.1%	5.97±2.15%	**+4.2%**

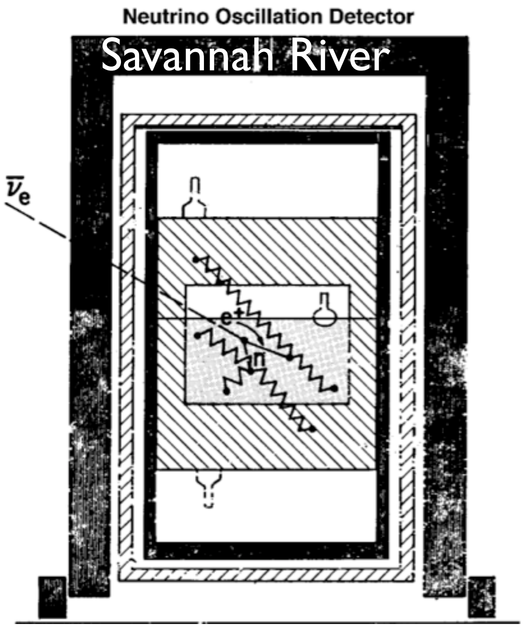
19 Experimental results at distances below 100 m

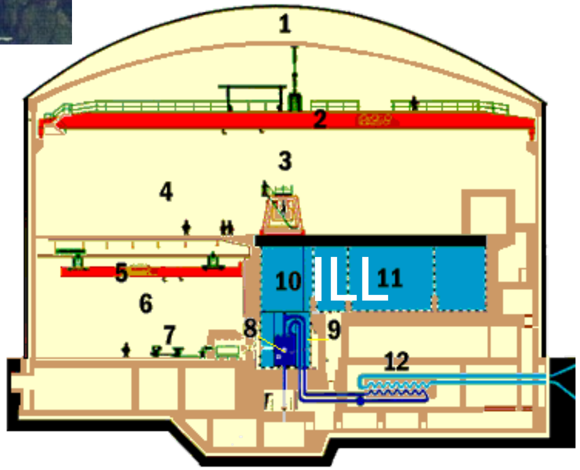
G. Mention *et al.* PRD83, 073006 (2011)









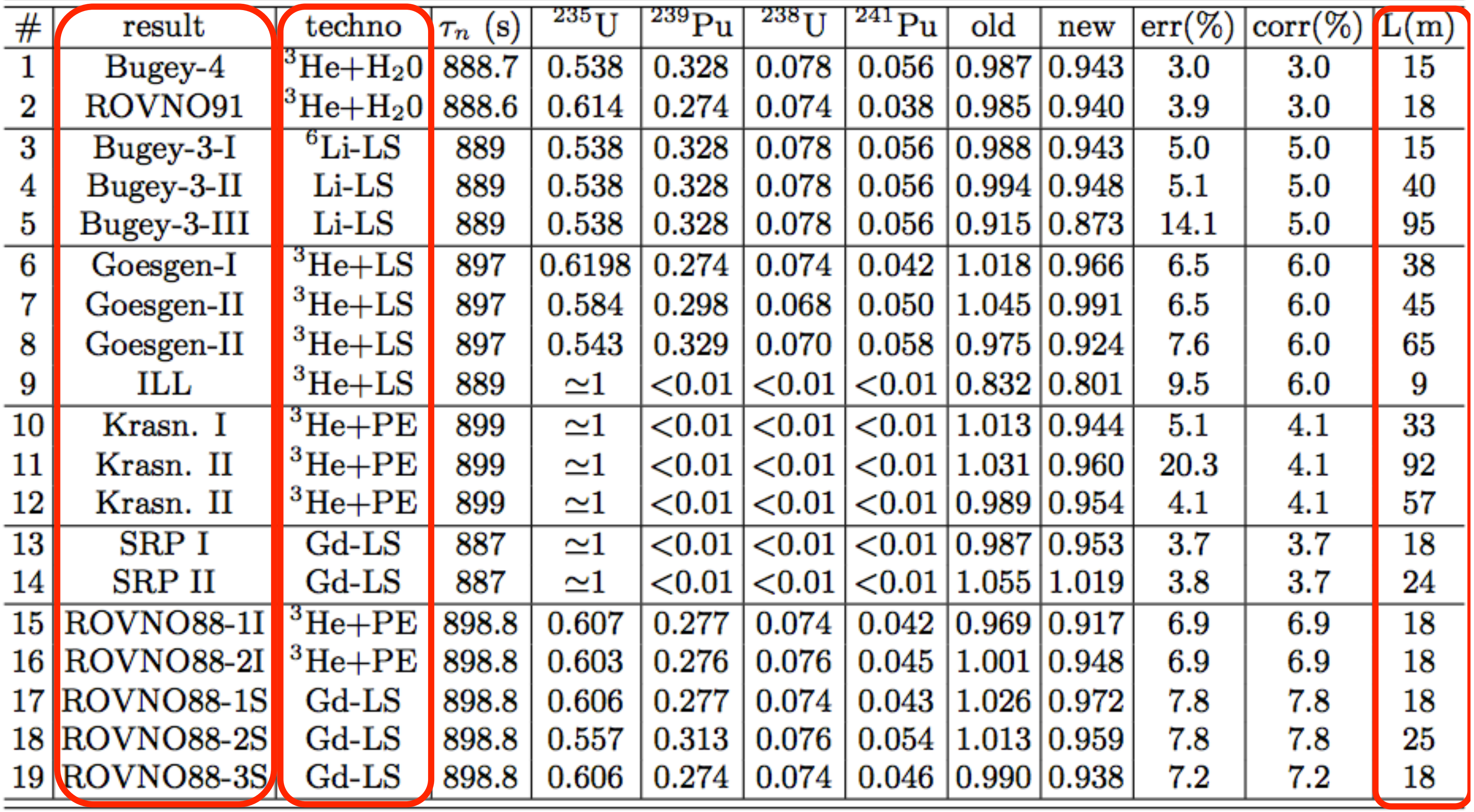


Measured neutrino rates and cross sections per fission σ_f

19 Experimental Results Revisited (L<100m)

Technology

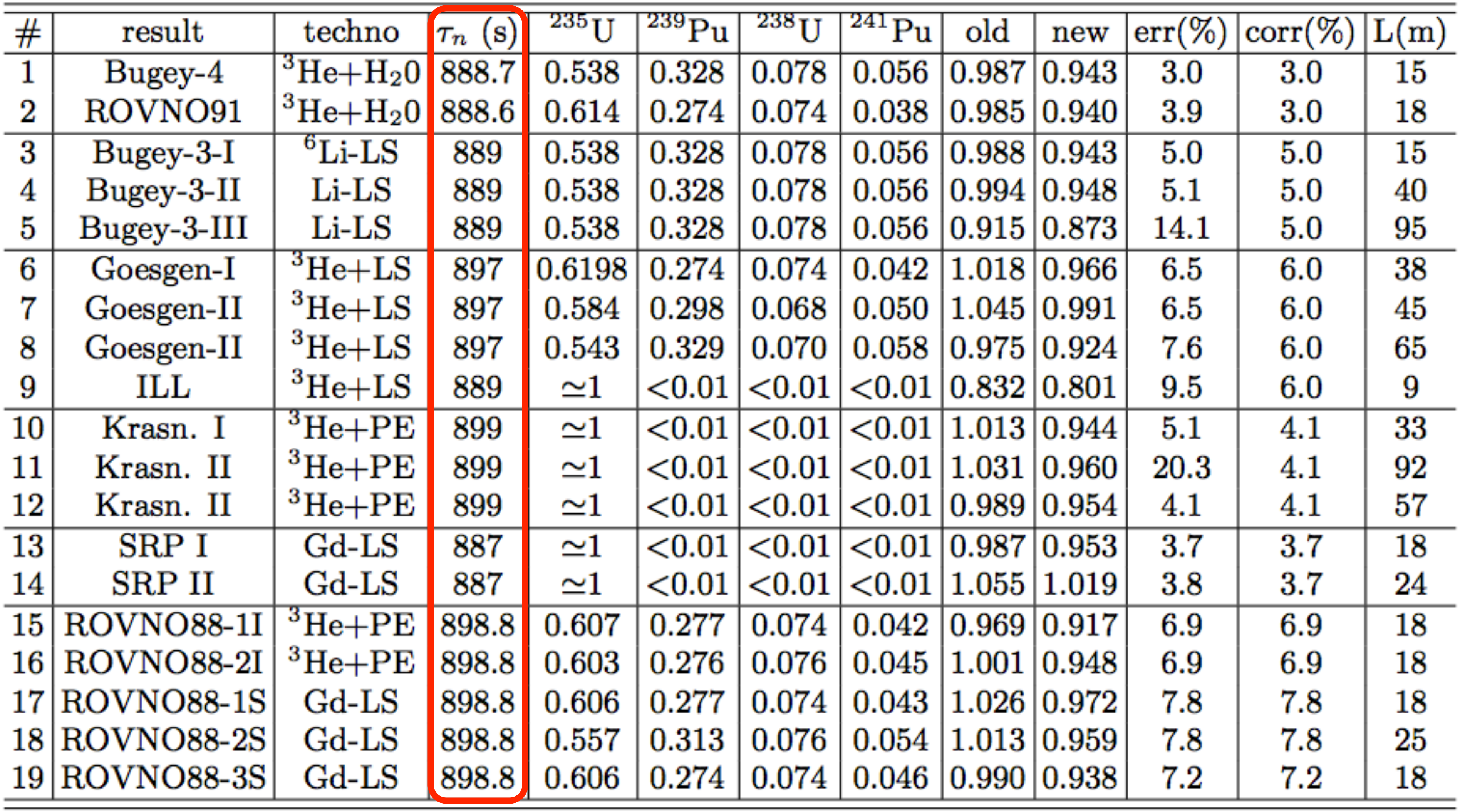
Baseline



#	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)

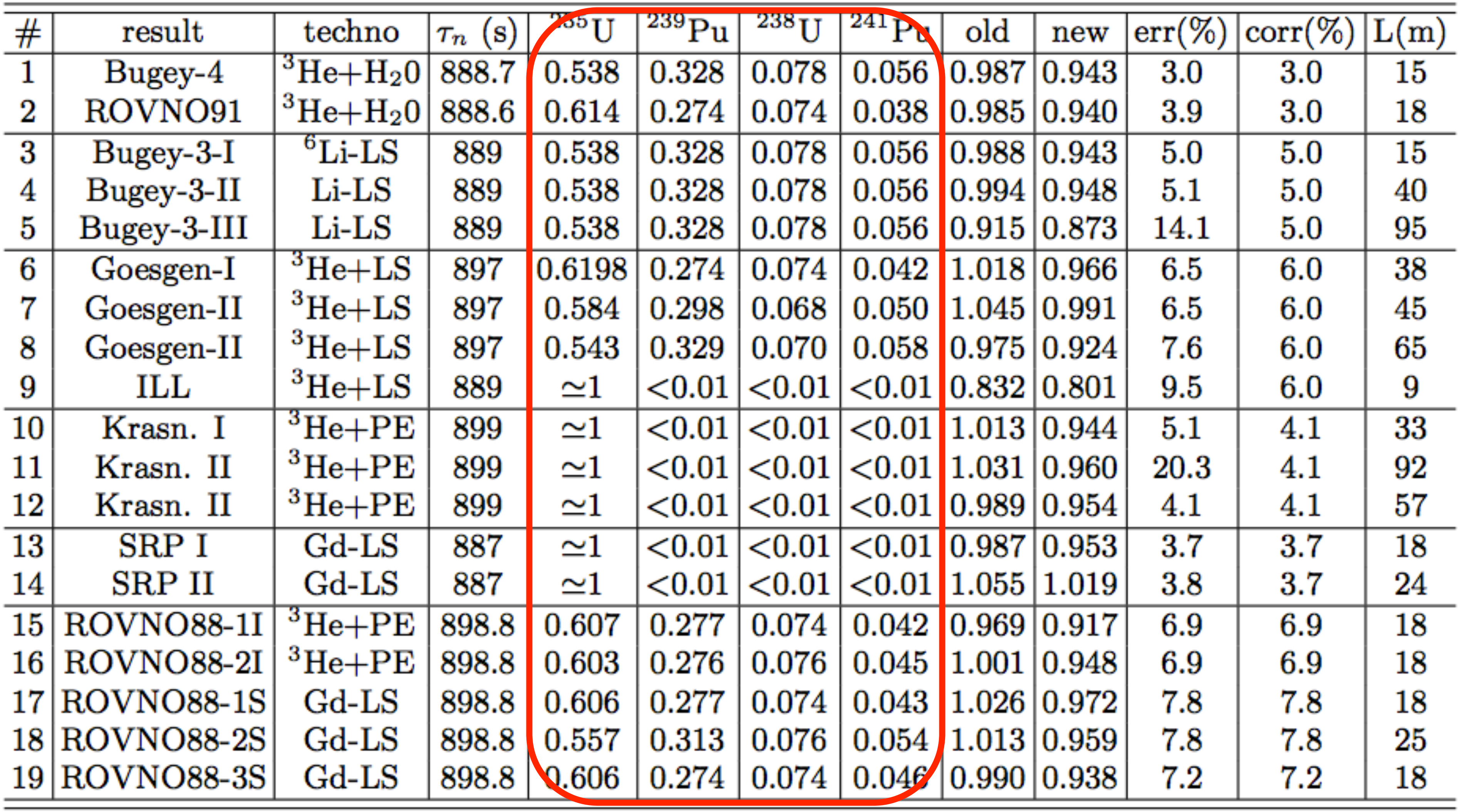
Neutron lifetime



#	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$0	888.7	0.538	0.328	0.078	0.056	0.987	0.943	3.0	3.0	15
2	ROVNO91	^{3}He+H$_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)

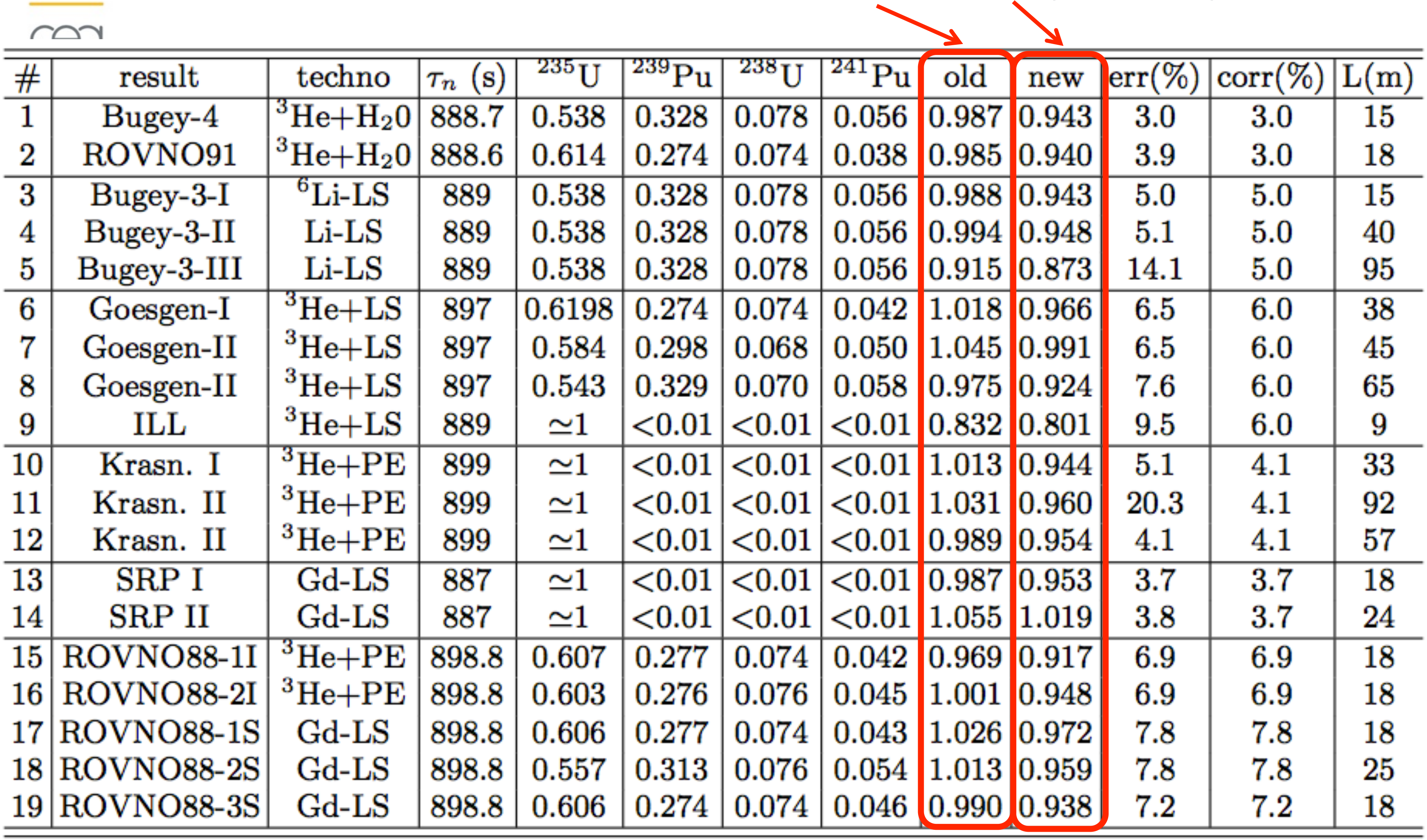
Averaged Fuel Composition



#	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)

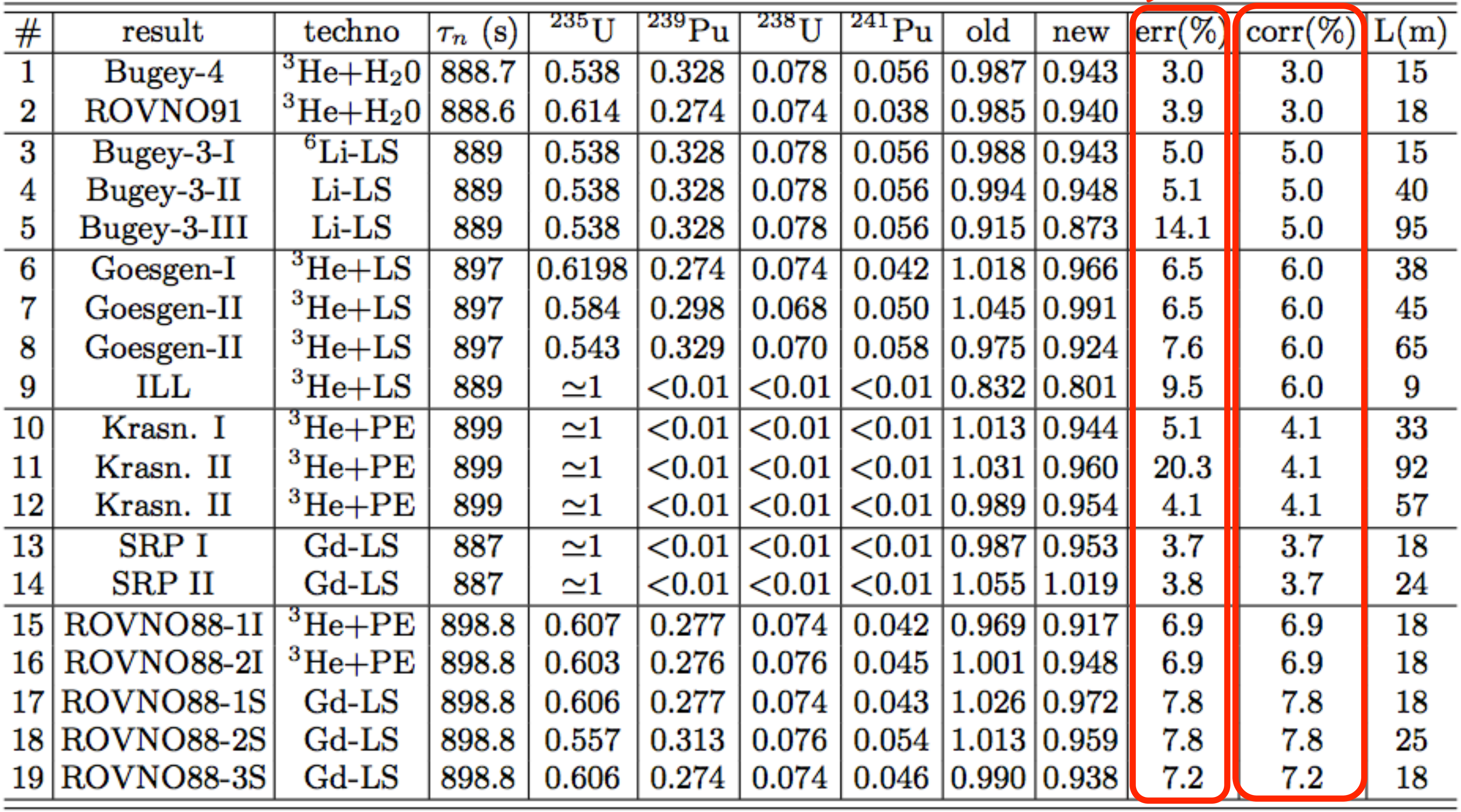
OBSERVED/PREDICTED ratios: OLD & NEW (this work)



#	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)

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
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

Error budget & Correlations

- Our guiding principles: Be conservative & stable numerically

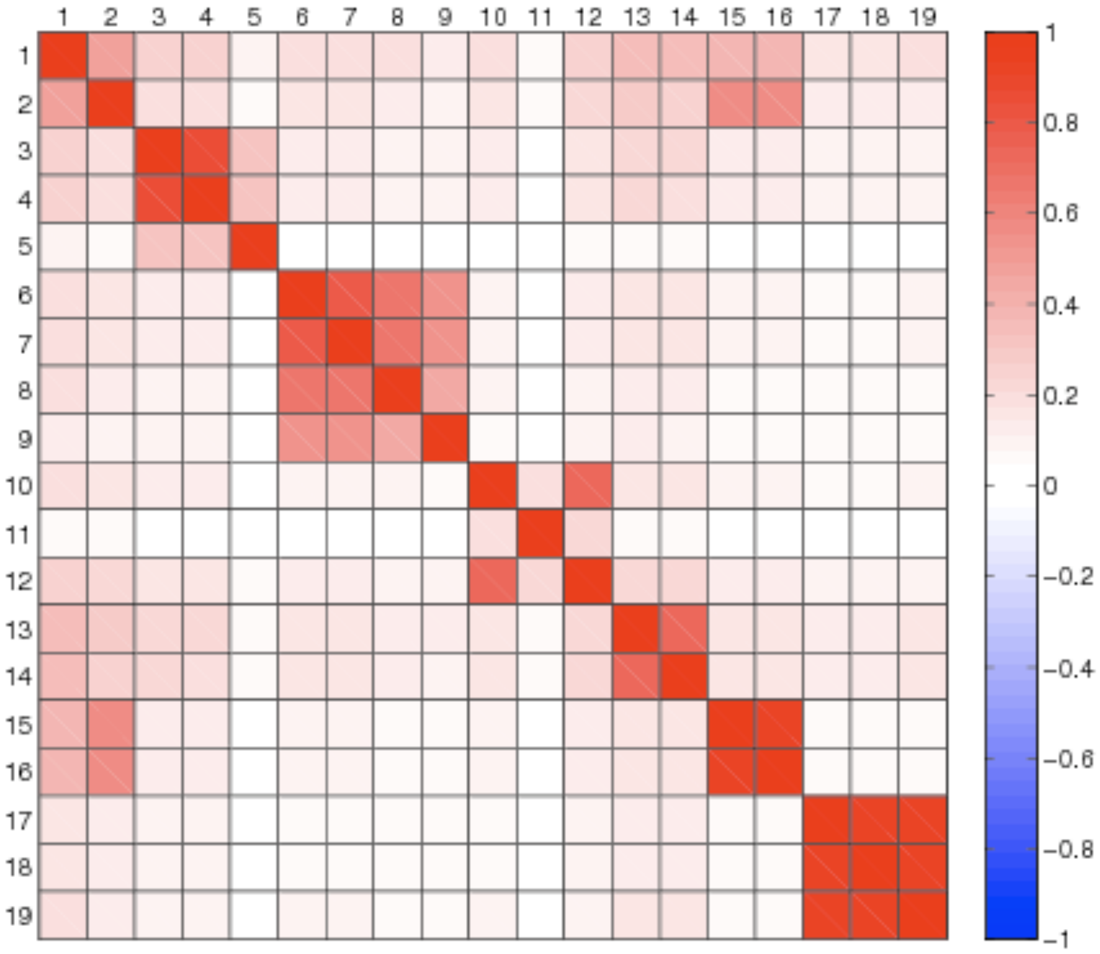
- We correlated experiments in the following way:
  - 2% systematic on flux fully correlated over all measurements of β-spectra of ILL

- Non-flux systematic error correlations across measurements:
  - Same experiment with same technology: 100% correlated
  - ILL shares 6% correlated error with Gösgen although detector slightly different. Rest of ILL error is uncorrelated.
  - Rovno 88 integral measurements 100% corr. with Rovno 91 despite detector upgrade, but not with Rovno 88 LS data
  - Rovno 88 integral meas. 50% correlated with Bugey-4

Experiments correlation matrix on ratios = meas./pred.

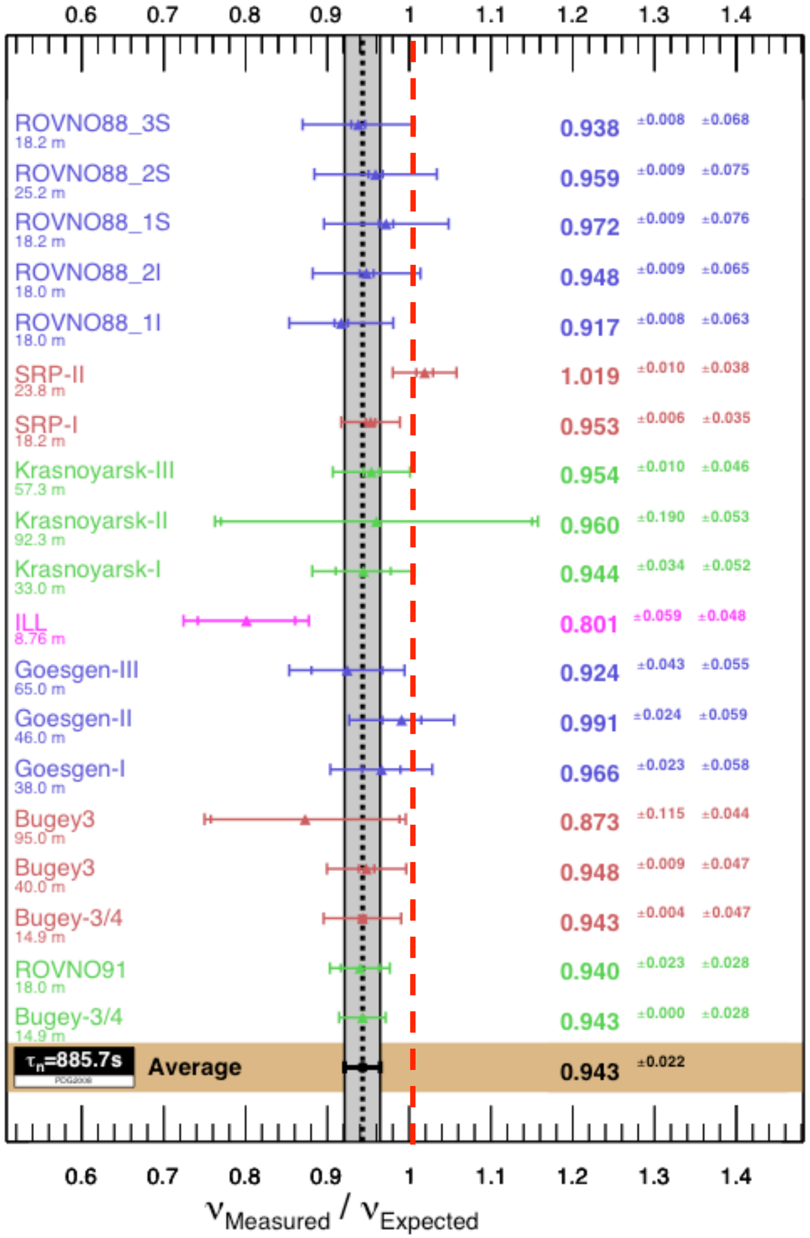
$\vec{R}$	$\Sigma_{tot.}$ (in %)	$\Sigma_{cor.}$ (in %)
Bugey-4 15m	3.0	3.0
Rovno91 18m	3.9	3.0
Bugey-3 15m	5.0	5.0
Bugey-3 40m	5.1	5.0
Bugey-3 92m	14.1	5.0
Goesgen 38m	6.5	6.0
Goesgen 45m	7.6	6.0
Goesgen 65m	9.5	6.0
ILL 9m	5.1	4.1
Krasno 33m	5.1	4.1
Krasno 92m	20.3	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7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



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

Weights: $W = \Sigma^2_{\mathrm{unc.}} + \Sigma_{cor.} C\, \Sigma_{cor.}$

with $\Sigma^2_{\mathrm{unc.}} = \Sigma^2_{\mathrm{tot.}} - \Sigma^2_{\mathrm{cor.}}$

The synthesis of published experiments at reactor-detector distances ≤ 100 m leads to a ratio R of observed event rate to predicted rate of

$\mu = 0.976 \pm 0.024$ (**OLD flux**)

With our **NEW flux** evaluation, this ratio shifts to

μ = **0.943 ± 0.023**,

leading to a deviation from unity at 98.6% C.L.

$\chi^2_{\mathrm{min}} = 19.6/18$

The reactor rate anomaly

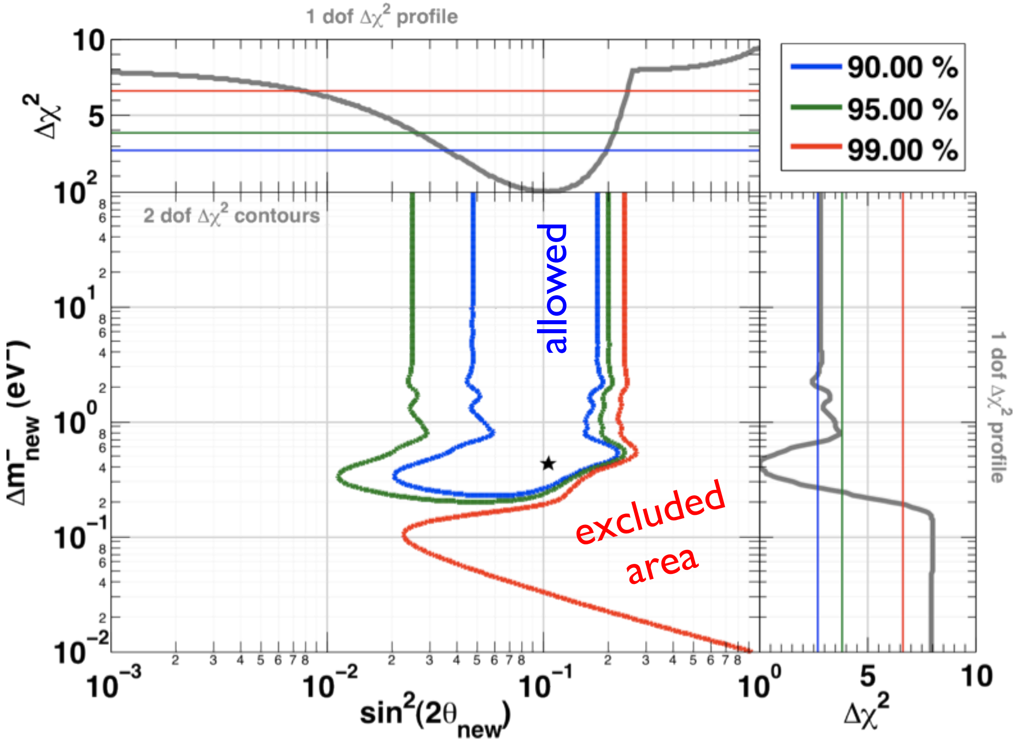
- 18/19 short baseline experiments <100m from a reactor observed a deficit of anti-ν_e compared to the new prediction
- The effect is statistically significant at more 98.6%
- Effect partly due to re-evaluation of cross-section parameters, especially updated neutron lifetime, accounting for off equ. effect
- **At least three alternatives:**
  - Our conversion calculations are wrong. Anchorage at the ILL electron data is unchanged w.r.t. 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**

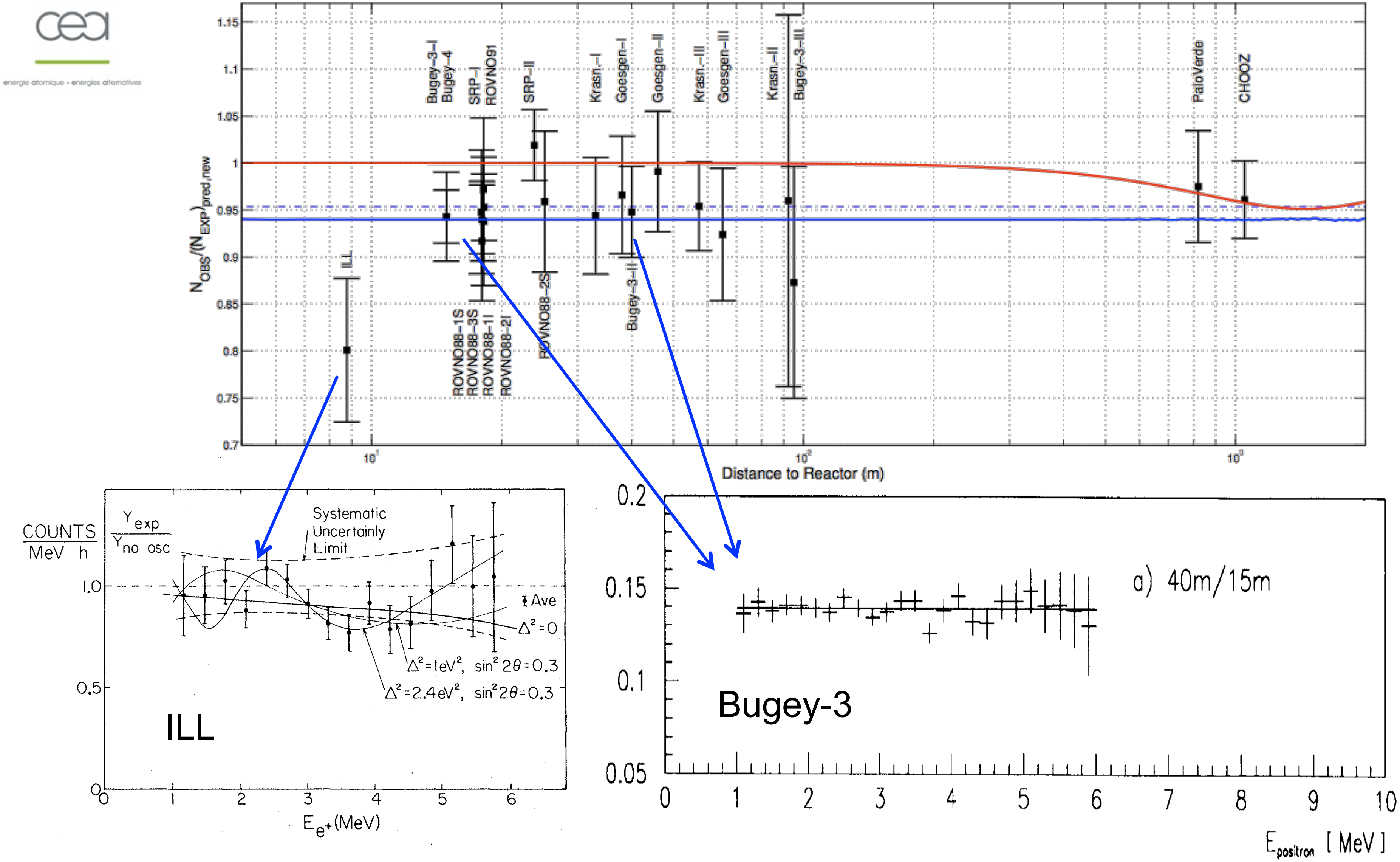
$$\begin{pmatrix}\nu_e\\ \nu_s\end{pmatrix} = \begin{pmatrix}\cos\theta_{\rm new} & \sin\theta_{\rm new}\\ -\sin\theta_{\rm new} & \cos\theta_{\rm new}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_{\rm new}\end{pmatrix}$$

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

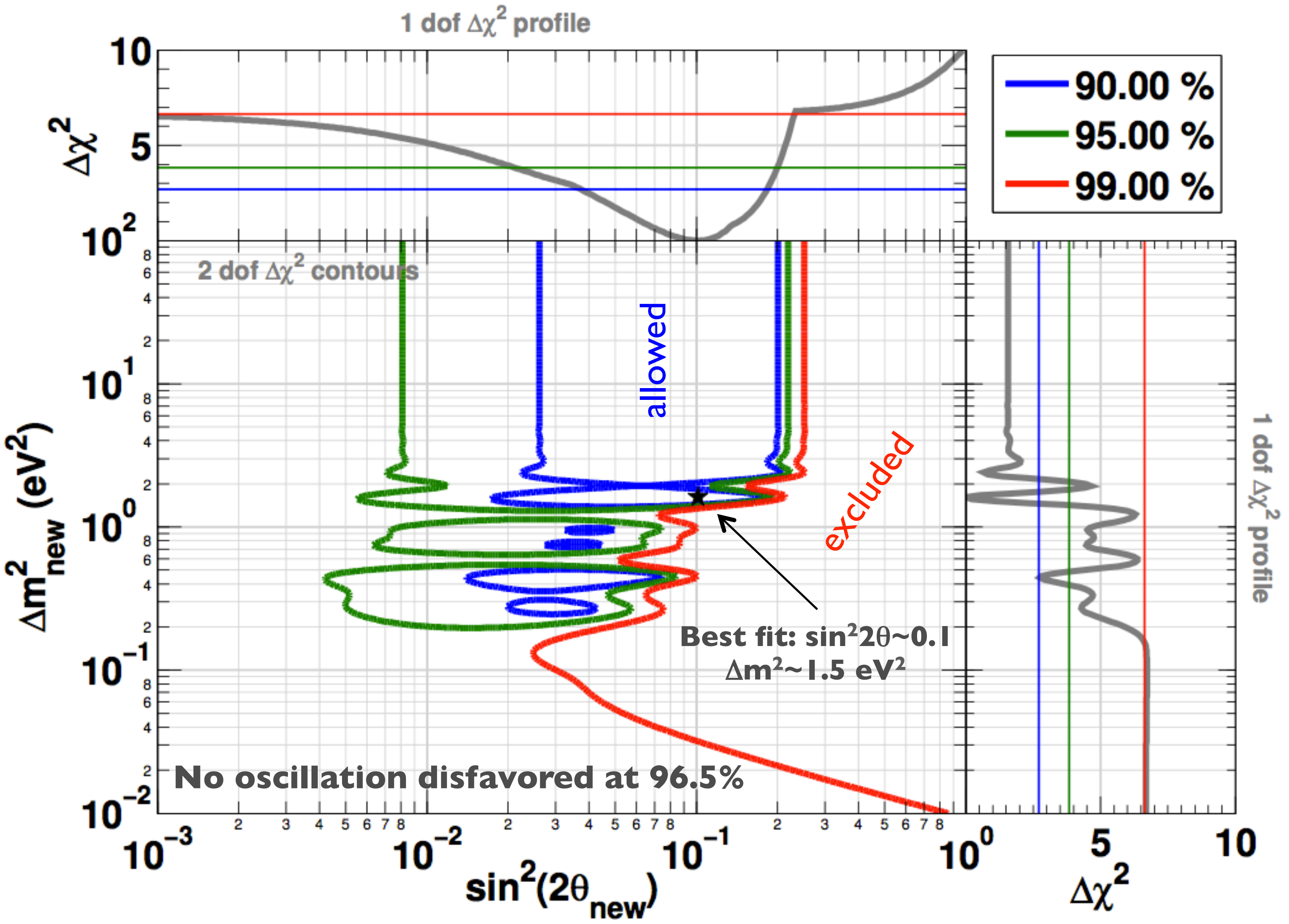


- **Absence of oscillations disfavored at 98.6% C.L.**

Energy dependent information: shape distortion



Combined Reactor Rate+Shape contours



allowed

excluded

Best fit: $\sin^2 2\theta \sim 0.1$
$\Delta m^2 \sim 1.5$ eV^2

No oscillation disfavored at 96.5%

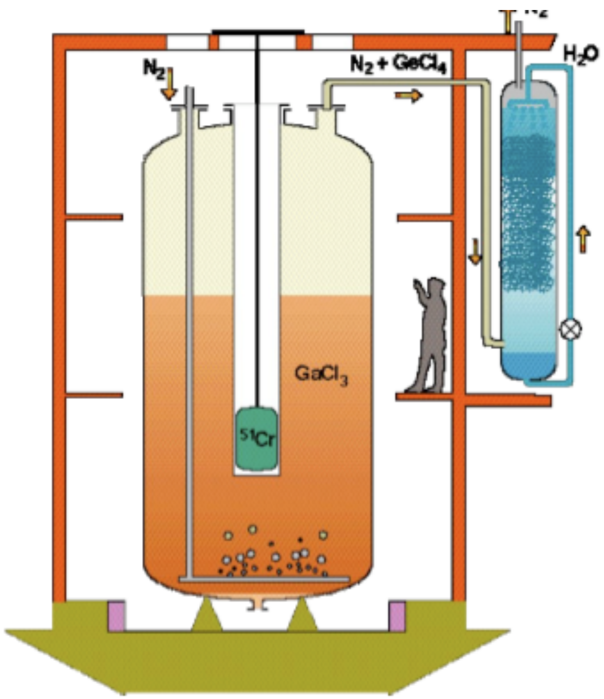
THE GALLIUM ANOMALY

Based on Giunti & Laveder, PRD82, 053005 (2010)

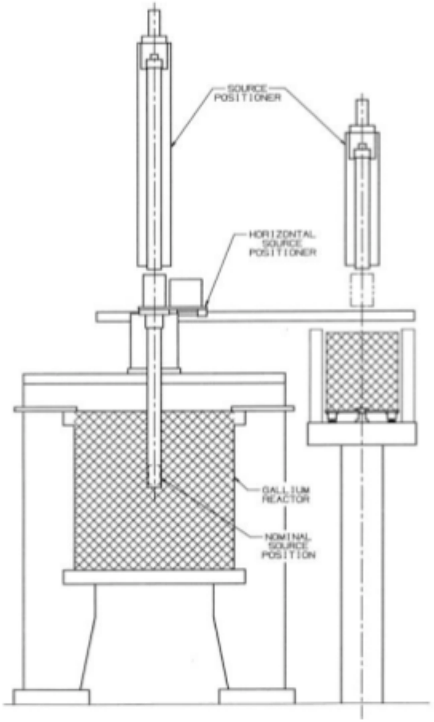
Radiochemical experiments Gallex (left) & Sage (right)

GALLEX ($GaCl_3$) and SAGE (liquid Ga) were radiochemical experiments, counting the conversion rate of ^{71}Ga to ^{71}Ge by (solar) neutrino capture [cannot detect anti-ν_e]

$$^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$$



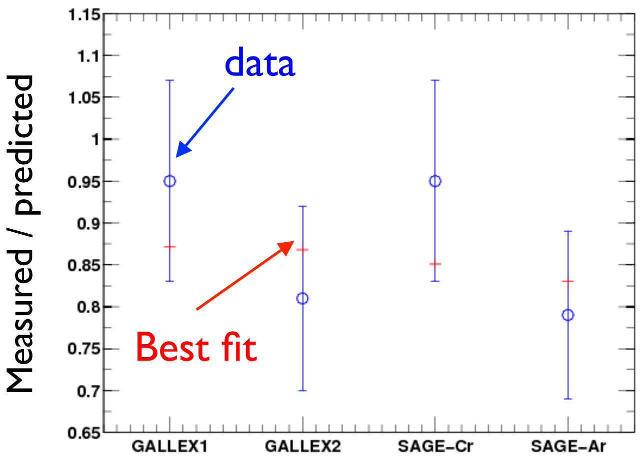
30.3 tons of Gallium
in an aqueous solution : $GaCl_3$ + HCl

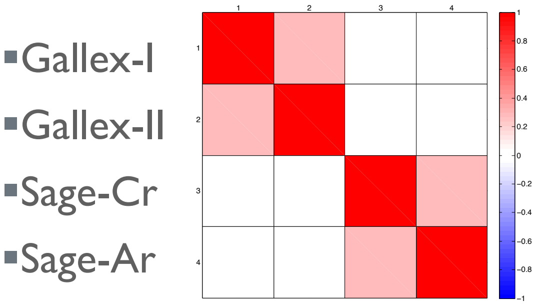


30 to 57 tons of Gallium (metal)
In 10 tanks

The Gallium anomaly

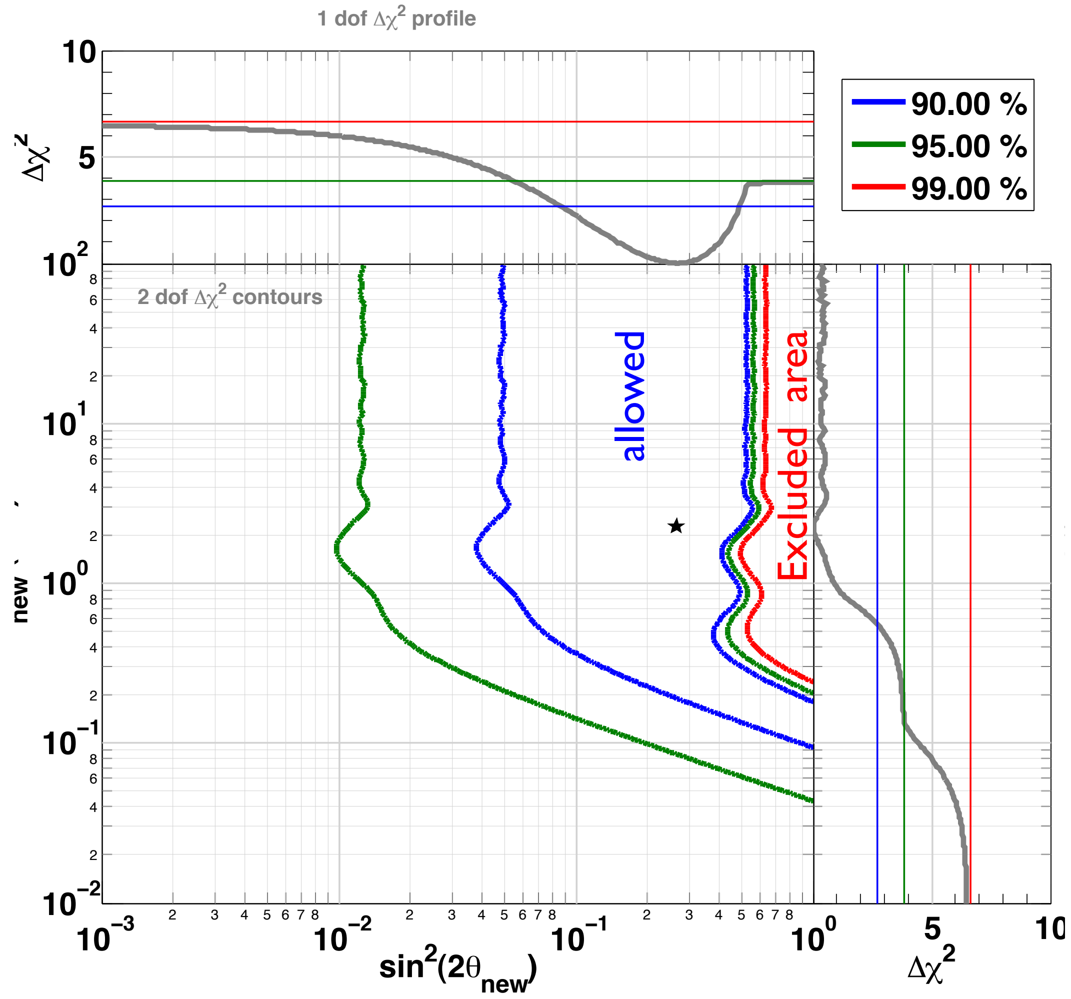
- 4 calibration runs with intense (~ MCi) ν_e (not anti-ν_e!) sources.
- Neutrinos detected through radiochemical counting of Ge nuclei: $^{71}\mathrm{Ga} + \nu_e \rightarrow {}^{71}\mathrm{Ge} + e^-$
  - 2 runs at GALLEX with a ^{51}Cr source (720 keV ν_e emitter)
  - 1 run at SAGE with a ^{51}Cr source
  - 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.**
- Our analysis:
  - Monte-Carlo simulation of GALLEX and SAGE + correlated the 2 GALLEX runs together and the 2 SAGE runs together (a bit more conservative than Giunti & Laveder PRD82 053005, 2010 to combine GALLEX & SAGE)





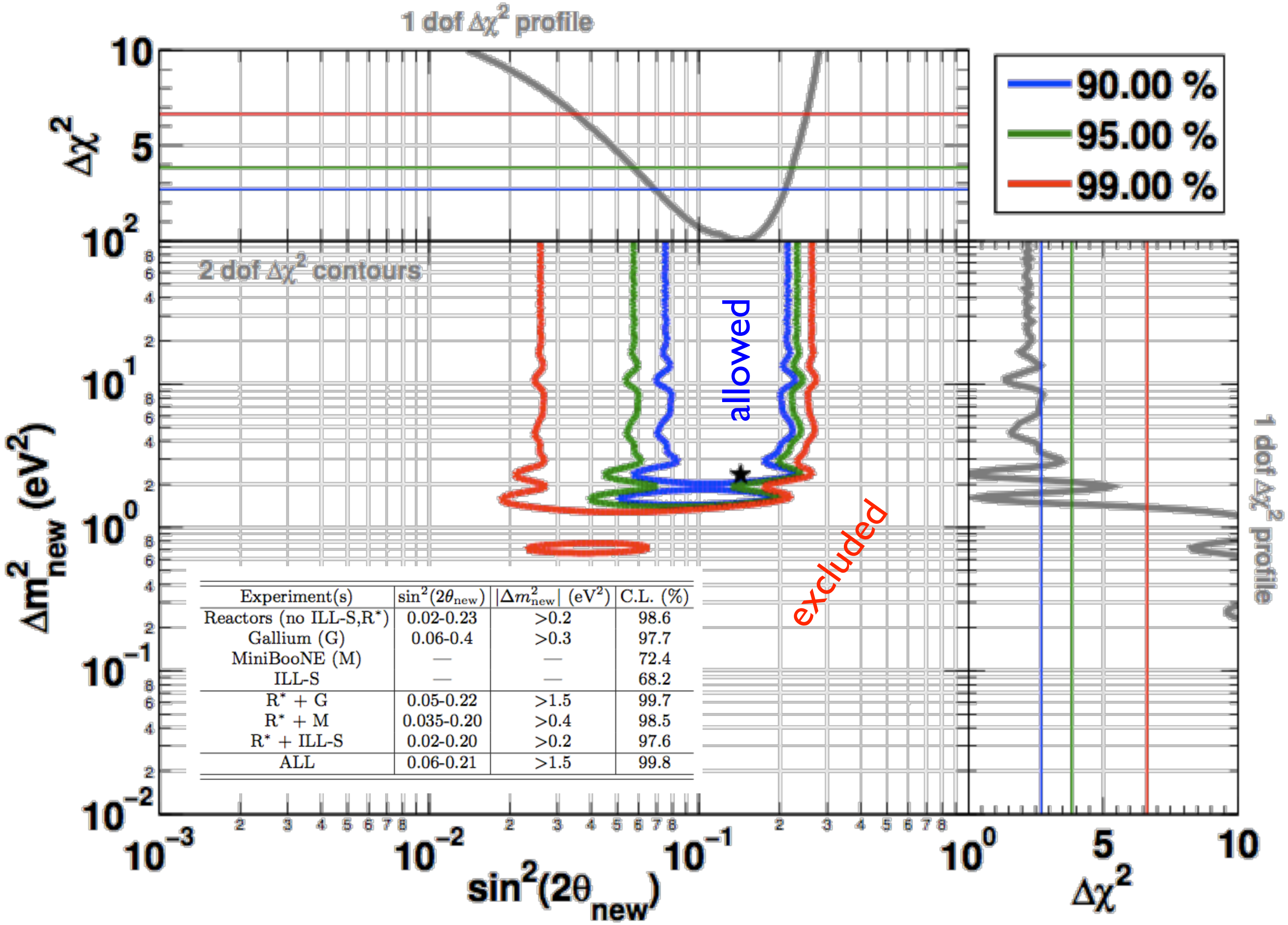
R = meas./pred. rates = 0.86 ± 0.06 (1 σ)

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



Experiment(s)	$\sin^2(2\theta_{\rm new})$	$\lvert\Delta m^2_{\rm new}\rvert$ (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

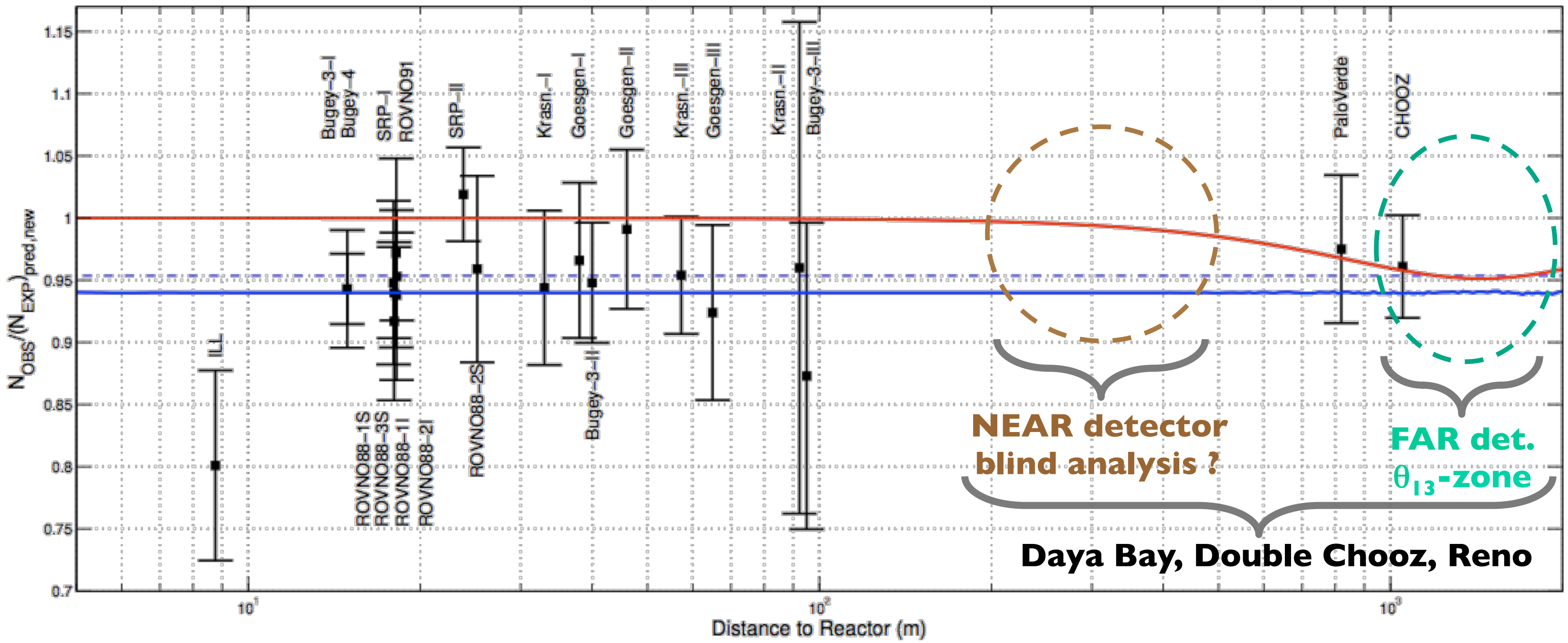
IMPLICATIONS FOR θ_{13}

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 flux, …)

Long baseline reactor experiments

- Experiments with baselines > 500 m
- How do you normalize the expected flux, knowing the fuel composition?

in this slide assume Bugey-4 fuel comp.

- If **near** + **far** detector, **not an issue** anymore

Choices
- $\sigma_f^{\mathbf{pred}}$
  - Use $\sigma_f^{\text{pred,new}}$ =6.102 10^{-43} cm^2/fission ± 2.7%
  - Use $\sigma_f^{\text{pred,old}}$=5.850 10^{-43} cm^2/fission ± 2.7%
- $\sigma_f^{\mathbf{exp}}$
  - 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 $<\sigma_f^{\text{exp}}>=\sigma_f^{\mathbf{ano}}$=5.39 10^{-43} cm^2/fission ± 1% (?)
    Average over short-baseline expts.

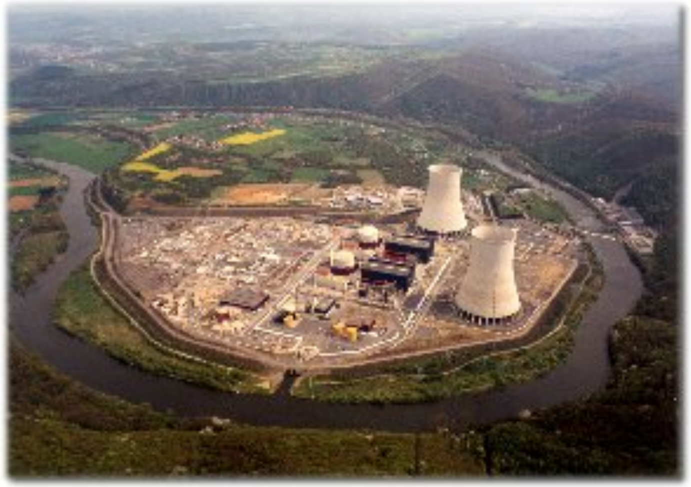
CHOOZ

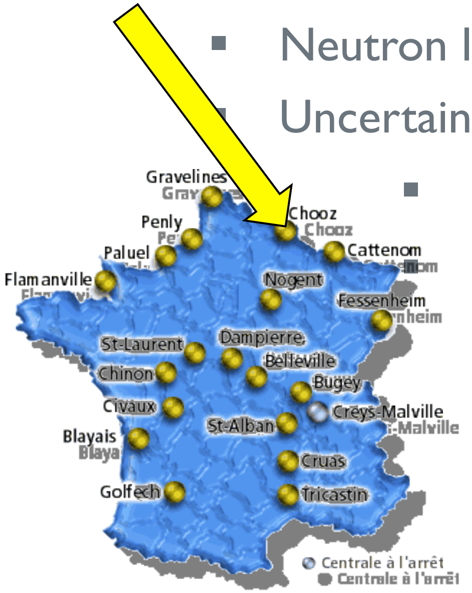
- Chooz (France) Power Station, late 90s , near French/Belgian border
- liquid scintillator doped with 1g/l Gd

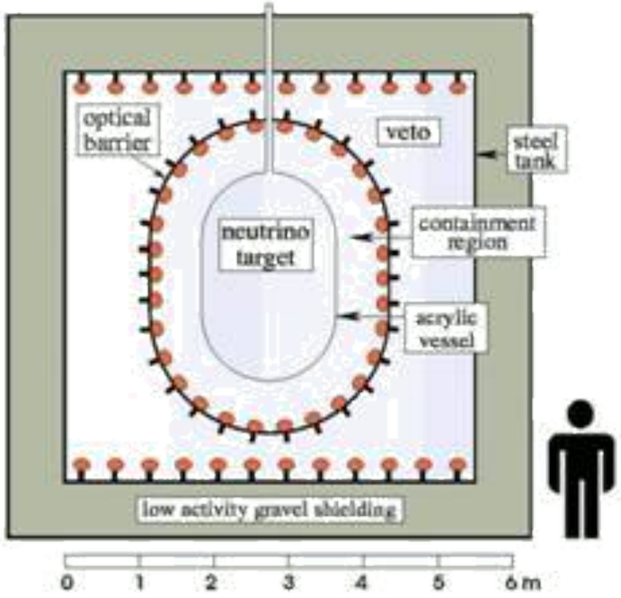
  5 tons, 8.4 GW, 300 mwe
- Detector placed at 1050m for the 2 cores
- Look for an oscillation at atm. frequency

  θ_{13} **mixing angle sensitivity, or more…**
- Fuel composition typical of starting PWR – 57.1% ^{235}U, 29.5% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- Neutron lifetime used in original paper: 886.7 s
- Uncertainties:
  - Stat: 2.8%

    Syst : 2.7% (3.3% in our work)

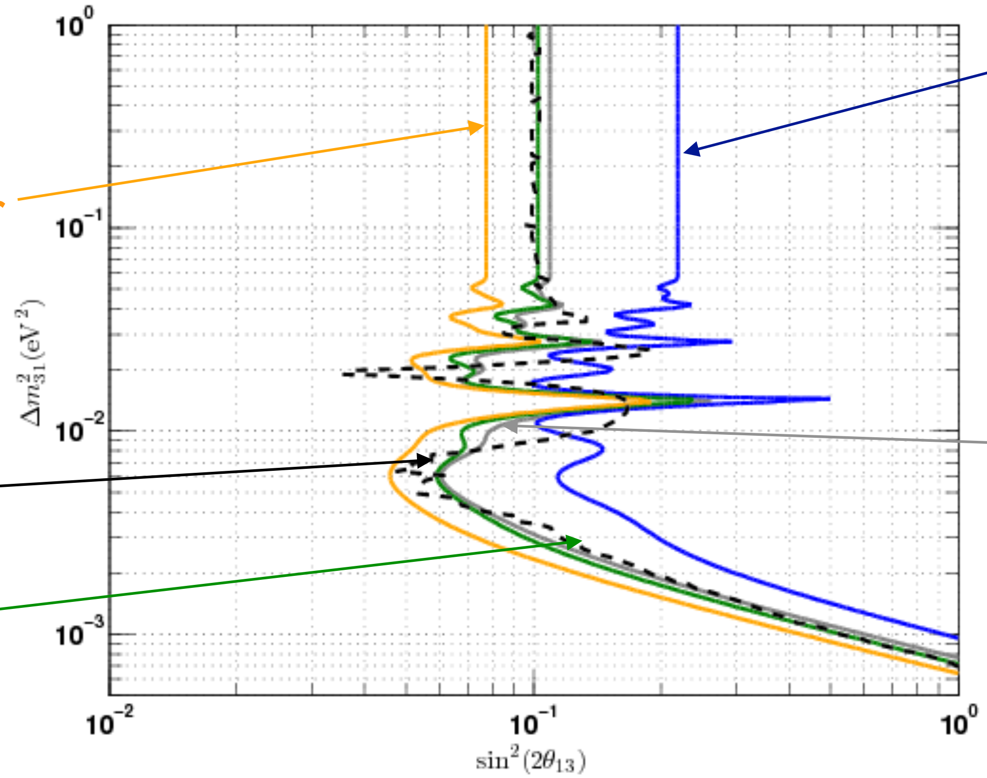






CHOOZ reanalysis

- 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}?



$\sigma_f^{pred,new}$

σ_f^{ano} 1% error

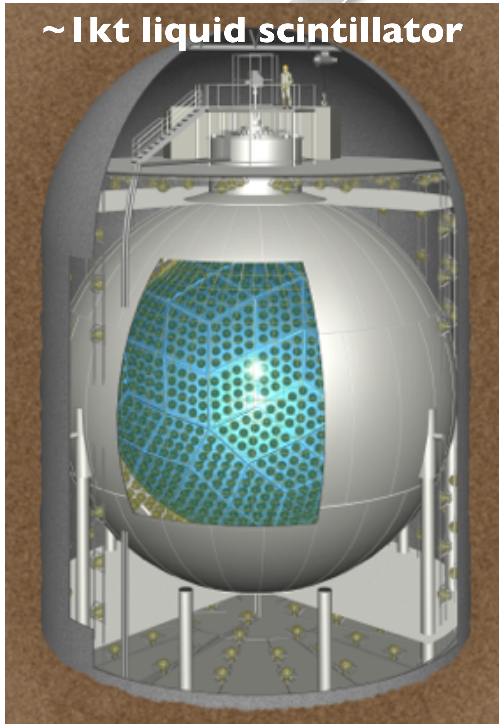
Chooz reproduction

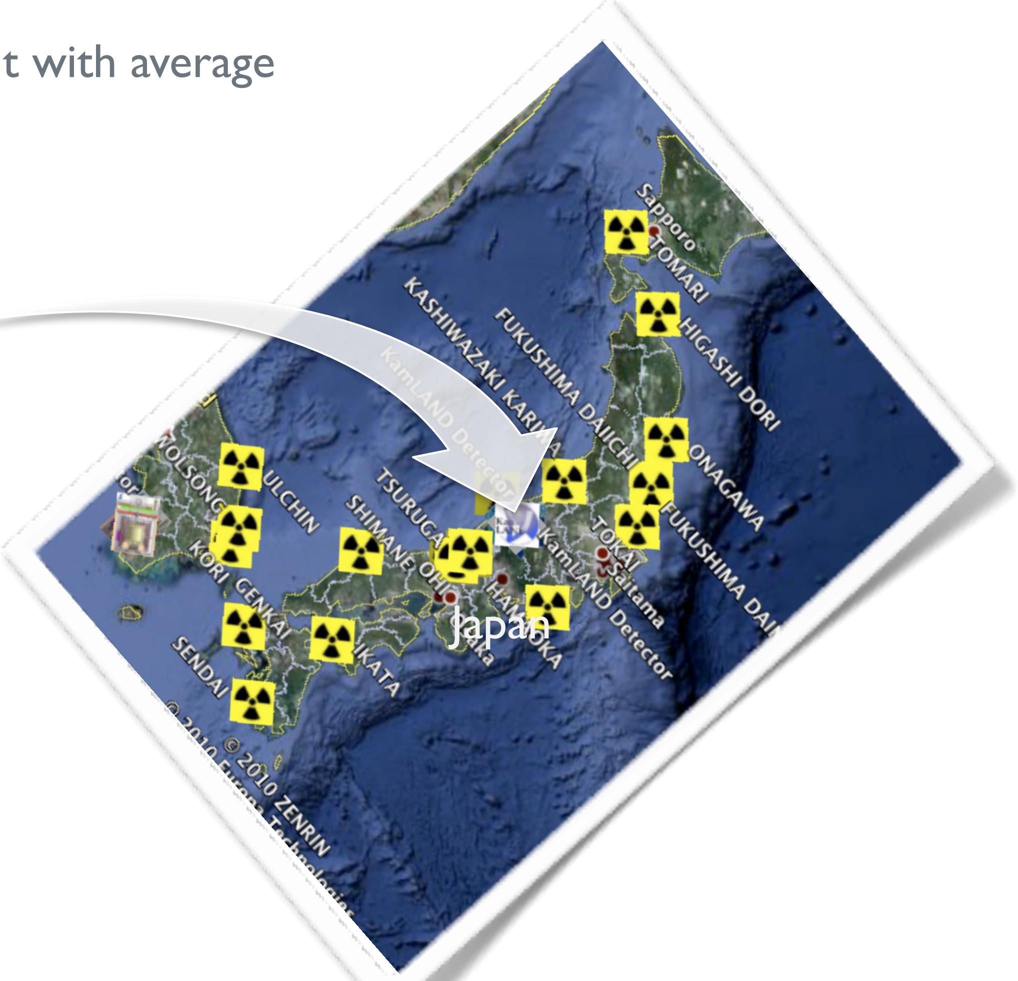
CHOOZ (2003)

σ_f^{ano} 2.7% error

KamLAND experiment

- Reactor anti-neutrino experiment with average baseline around 180 km.
- 80% of total flux comes from reactors 140 to 210 km away.
- Sensitive to « solar » oscillation (θ_{12}, Δm^2_{12})





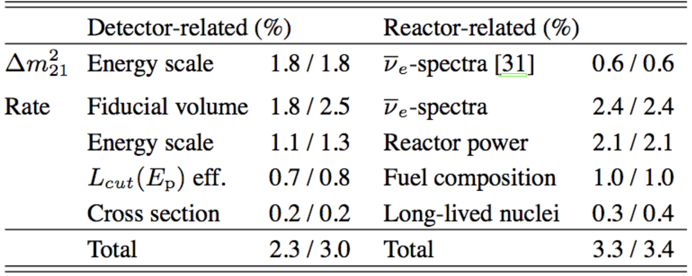
arXiv:1009.4771v2 [hep-ex]

KamLAND has some sensitivity to θ_{13} as well through the overall normalization of the spectrum

Reanalysis of KamLAND's 2010 results

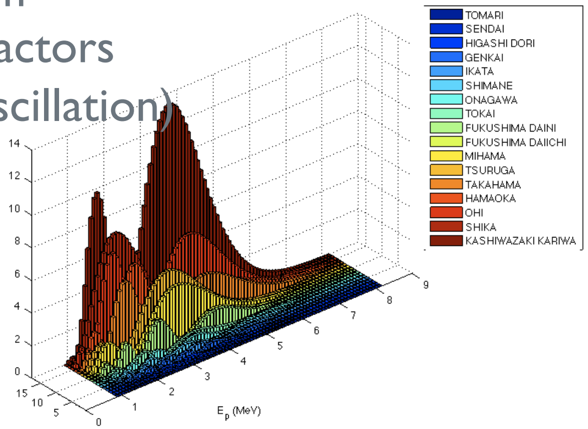
arXiv:1009.4771v2 [hep-ex]

Systematics

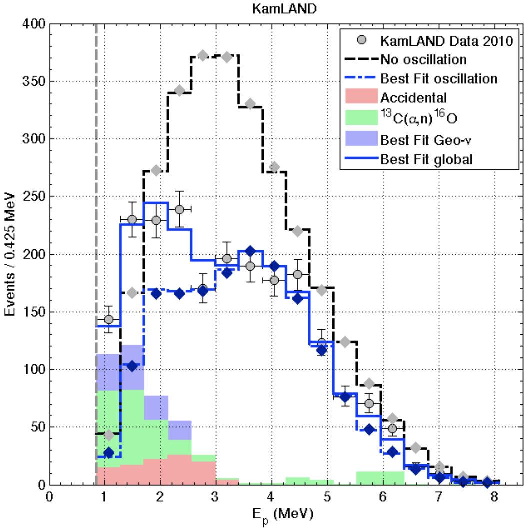


	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.8 / 1.8	$\overline{\nu}_e$-spectra [31]	0.6 / 0.6
Rate	Fiducial volume	1.8 / 2.5	$\overline{\nu}_e$-spectra	2.4 / 2.4
	Energy scale	1.1 / 1.3	Reactor power	2.1 / 2.1
	$L_{cut}(E_p)$ eff.	0.7 / 0.8	Fuel composition	1.0 / 1.0
	Cross section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

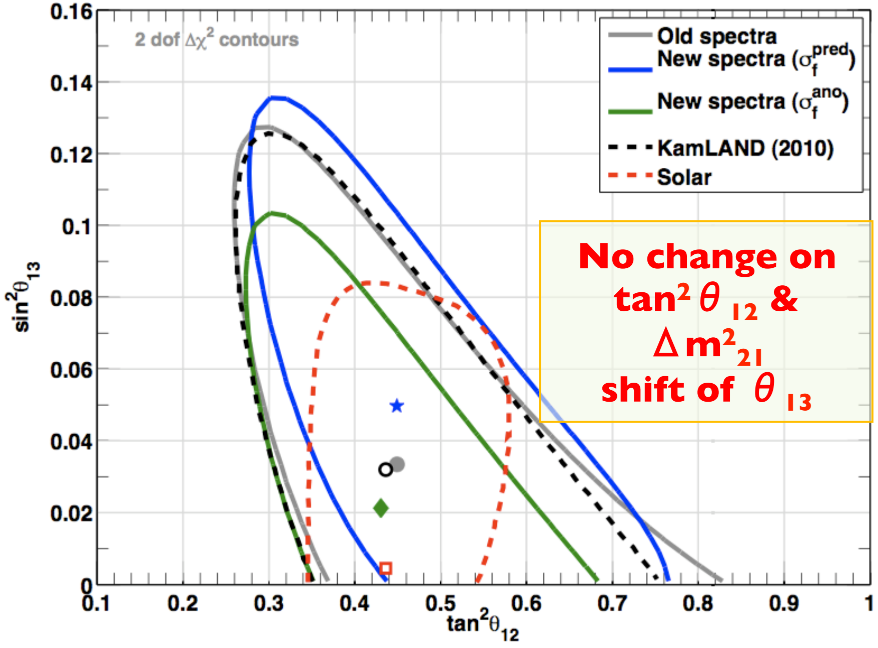
Spectra from Japanese reactors (with ν_e oscillation)



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

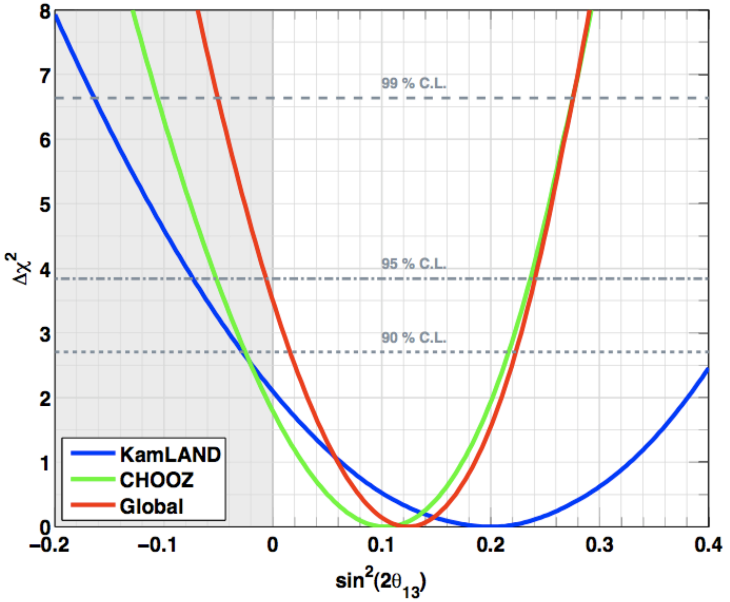


With new spectra predictions



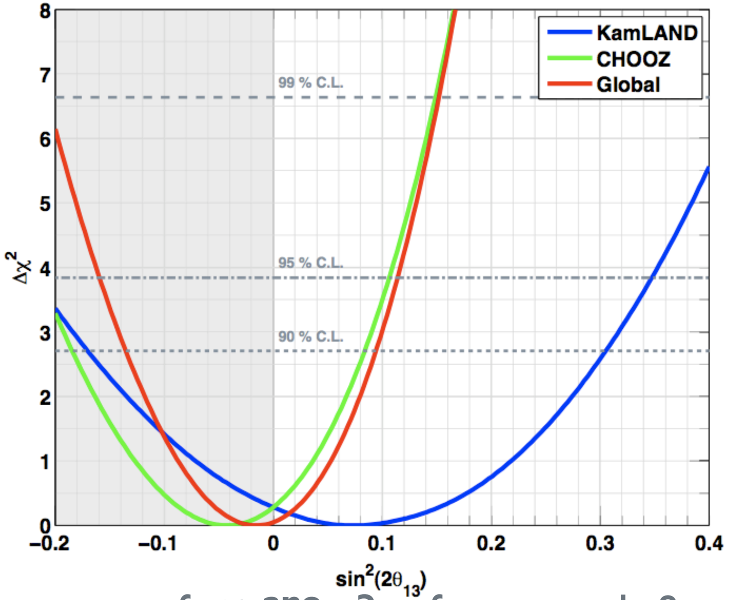
No change on $\tan^2\theta_{12}$ & Δm^2_{21}
shift of θ_{13}

CHOOZ and KamLAND combined limit on θ_{13}



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

use of $\sigma_f^{pred,new}$, 3-ν framework & 2.7% uncertainty

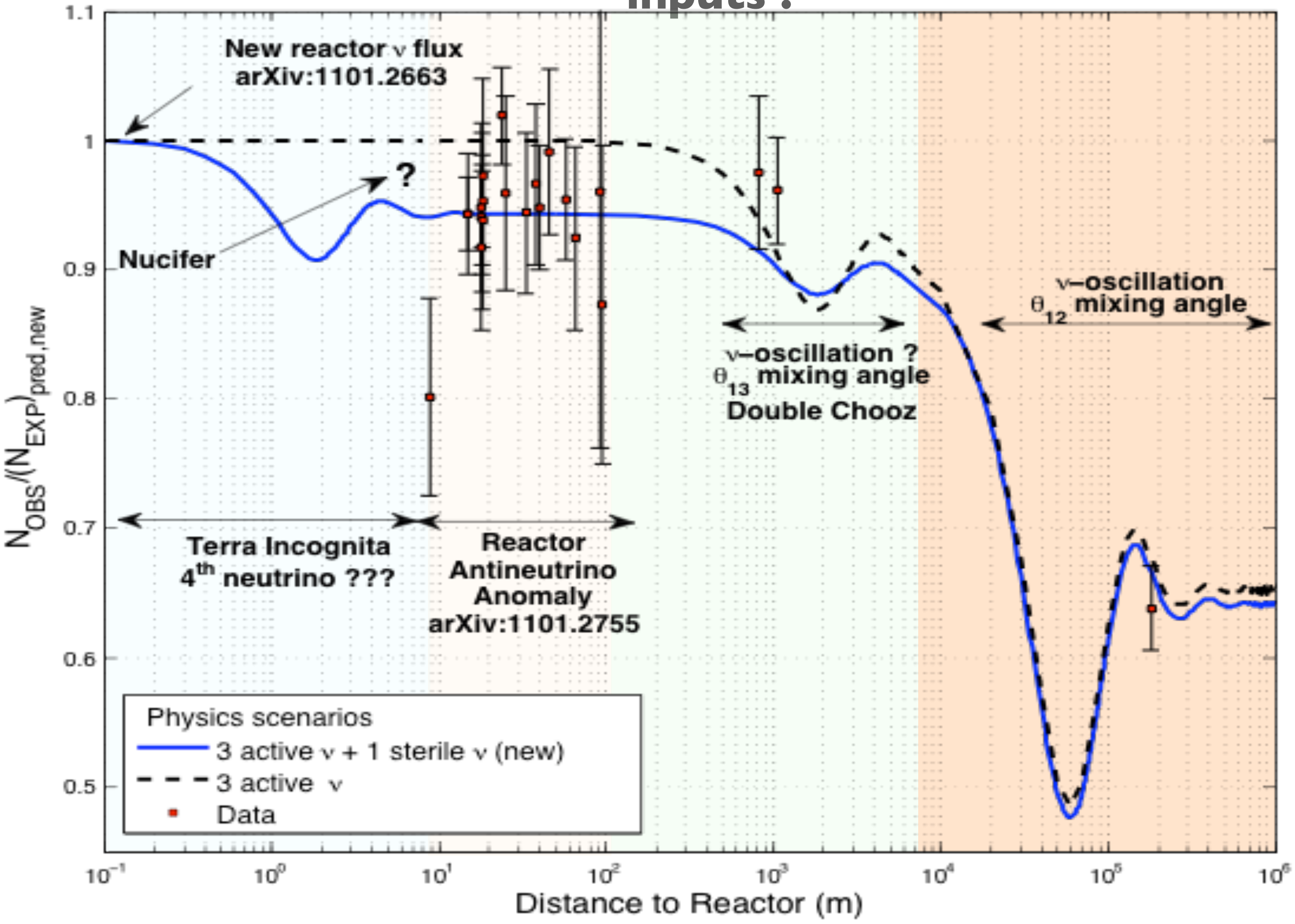


Normalization using σ_f^{ano}

use of σ_f^{ano}, 3-ν framework & 2.7% uncertainty (arbitrary…)

- **Our interpretation** (different from Arxiv:1103:0734 by Schwetz *et al.* or arXiv:1106.6028 by Fogli *et al.*)
  - No hint on $\theta_{13}>0$ from reactor experiments: $\sin^2(2\theta)<0.10$ (90%C.L., 1dof)
  - Global 90 % CL limit stays identical to previously published values
  - Multi-detector experiments are not affected

The 4th Neutrino Hypothesis: need new experimental inputs !



New Reactor Antineutrino Anomaly Discovered

- Experimental bias to be deeply investigated
- New physics hypothesis tested: 4th 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: SCRAAM, Nucifer,...

MCi or kCi neutrino generator in/close to a large liquid scintillator

Like SNO+, Borexino, KamLAND

New neutrino beam experiment probing for electron GeV neutrino disappearance at 100 m & 1 km

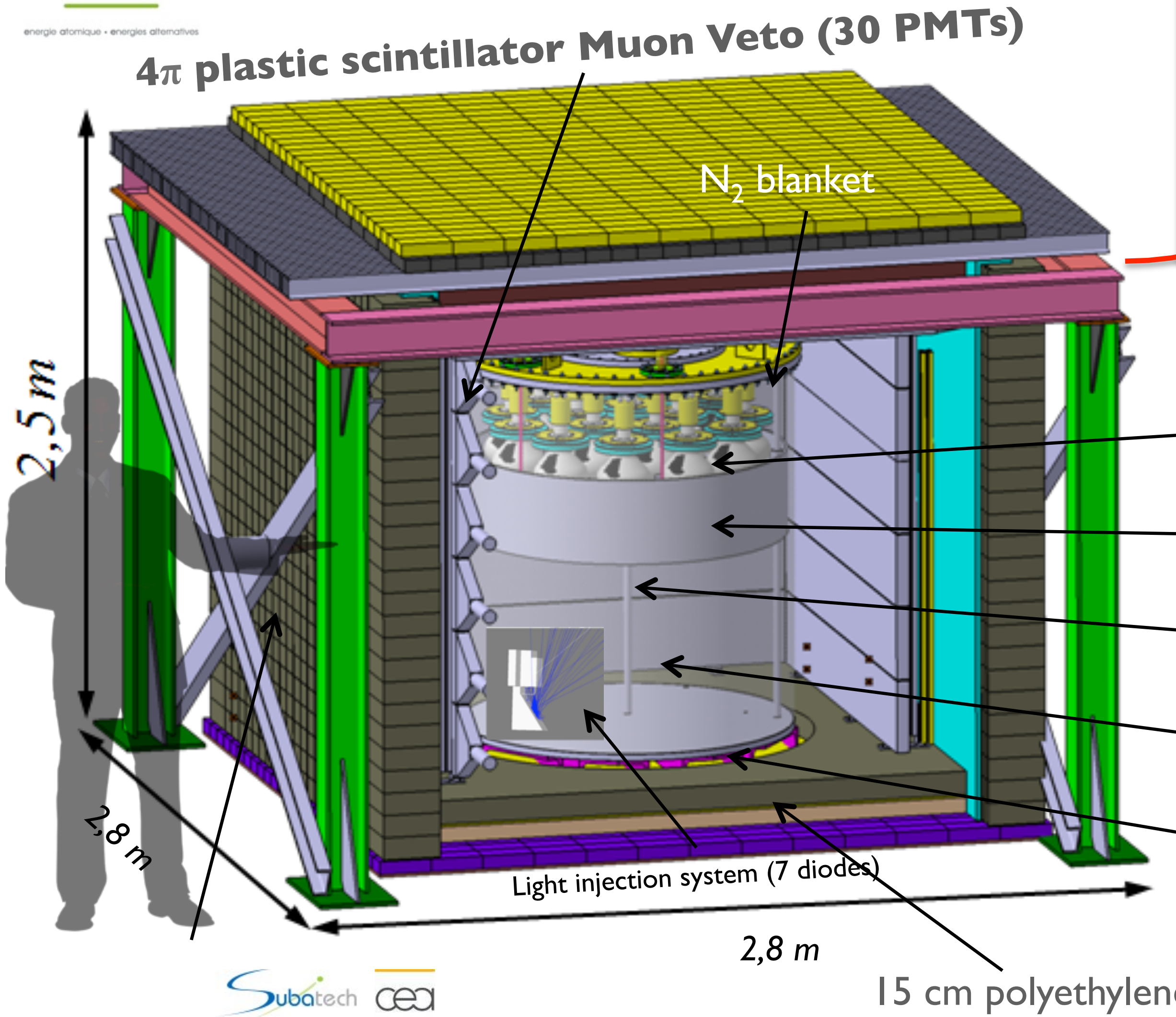
C. Rubbia's proposal at CERN-PS

… and many others …

Nucifer

First goal: Non Proliferation

Thermal Power Measurement
Fuel Composition Measurement U/Pu



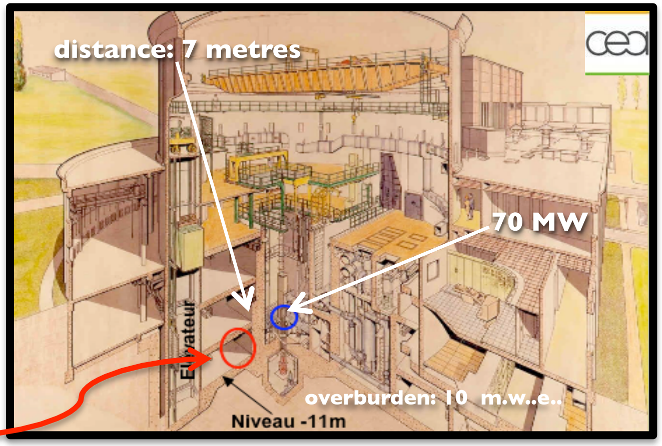
16 x 8' PMTs low background

25 cm acrylics buffer

Calibration pipe

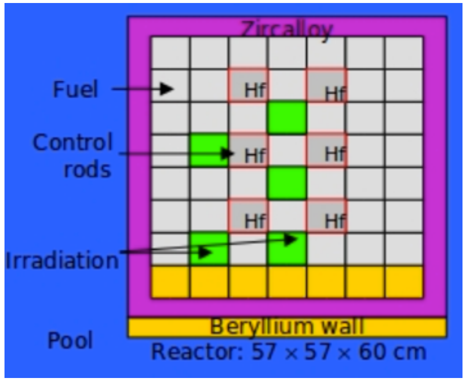
Target: **0.85 m^3 Gd-LS (0.5%)**

Stainless steel double containment vessel coated with white Teflon inside

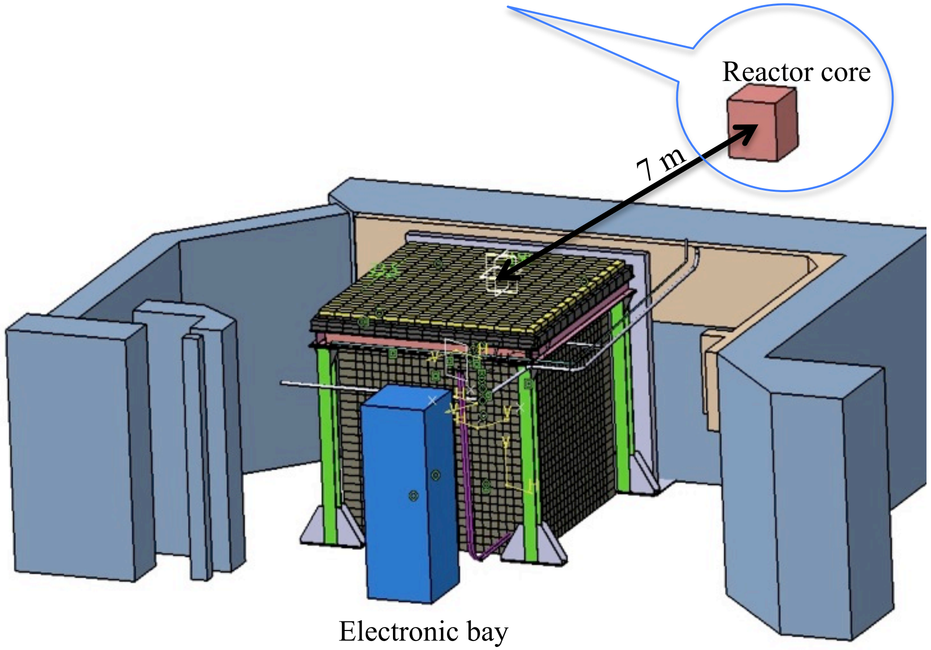


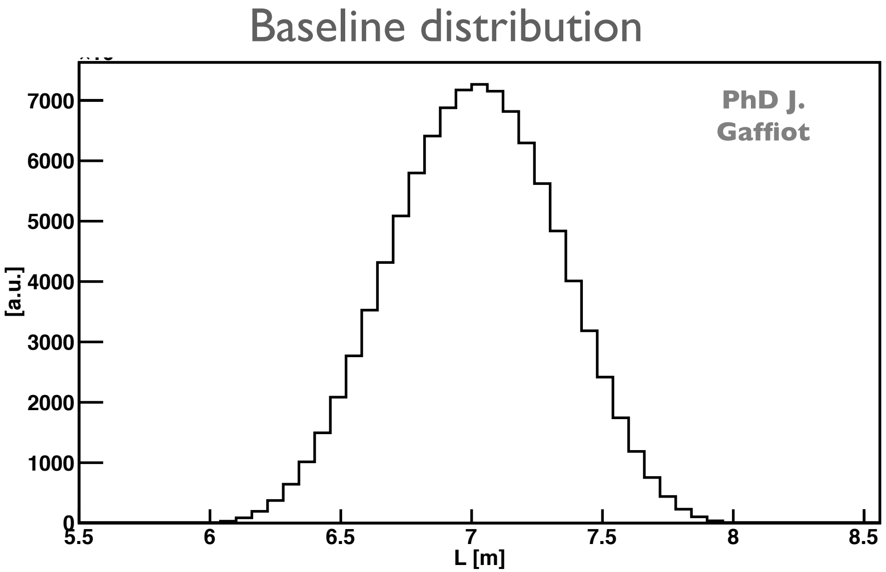
Osiris research reactor
CEA-Saclay (600 ν/d)
CEA – IN2P3 coll.

The nuclear core compactness



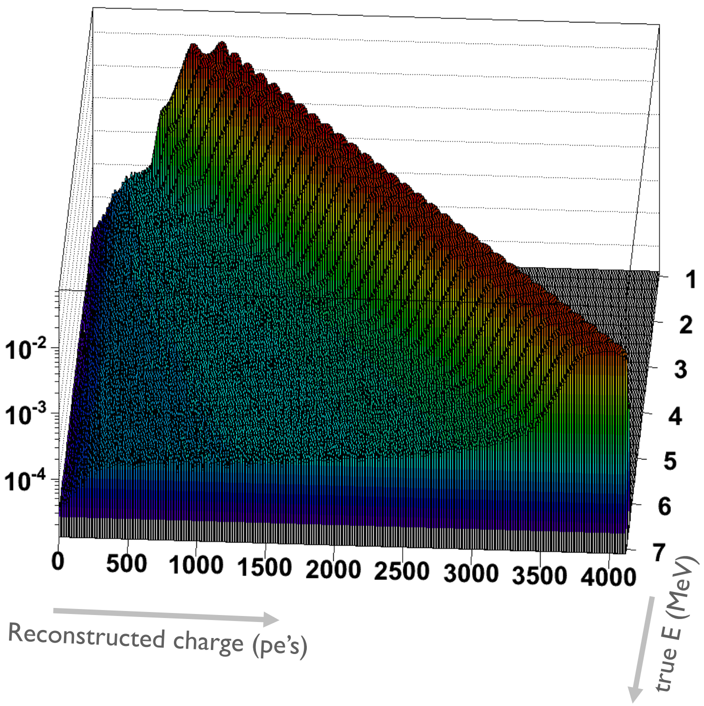
- **Core Size: 57x57x60 cm**
- **Detector Size : 1.2x0.7m (850l)**
- **baseline distribution**
  - <L>=7.0 m
  - variance : 0.3 m
  - eV^2 oscillations are not washed out

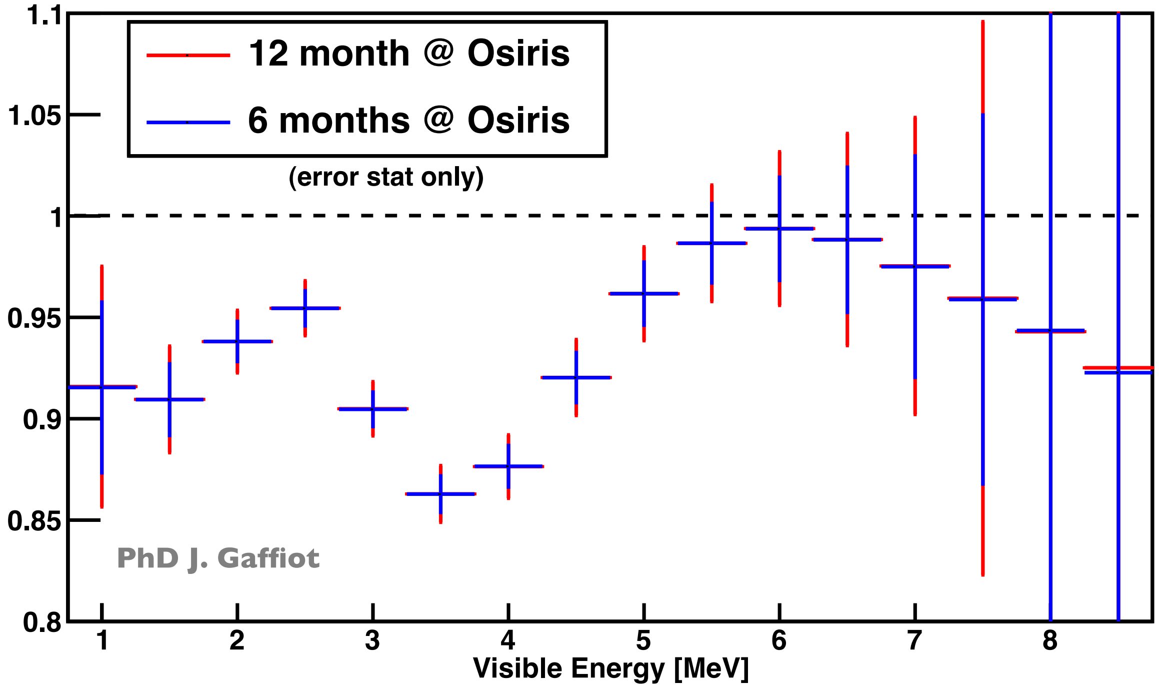




Nucifer attempt testing the anomaly

- Folding the Nucifer Geant4 Monte Carlo detector response
  - Energy resolution from Geant4 simulation (not fully tuned yet)
  - Statistical error bars for 12 & 24 months of data at Osiris
  - $\Delta m^2 = 2.4\ \mathrm{eV}^2$ & $\sin^2(2\theta)=0.15$
  - No backgrounds. Thus to be taken with a grain of salt …

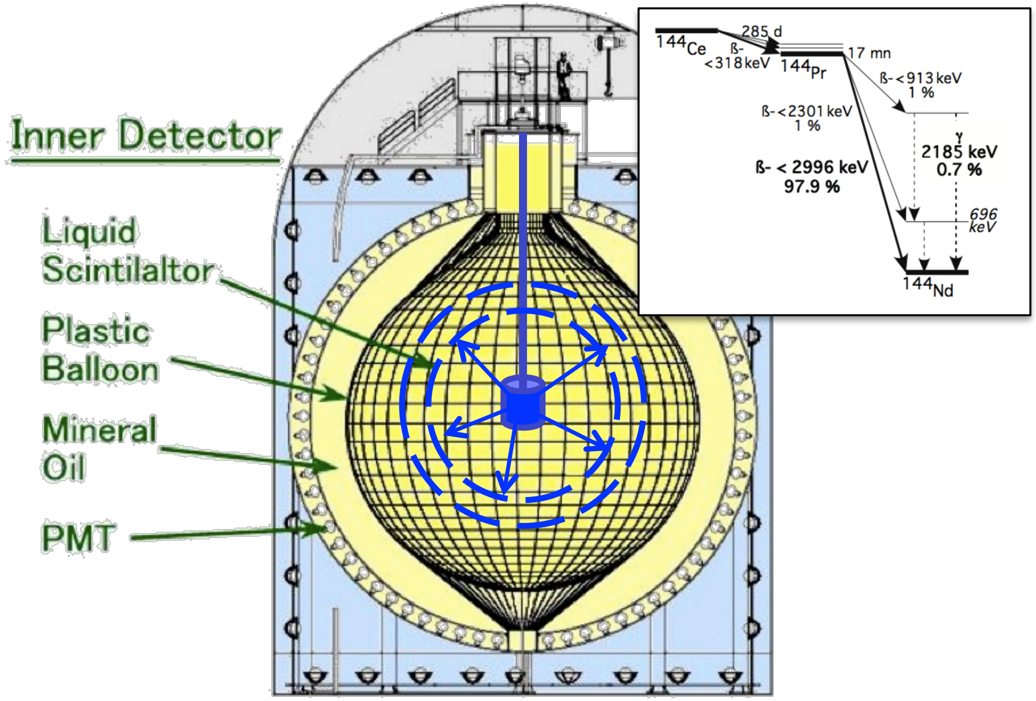




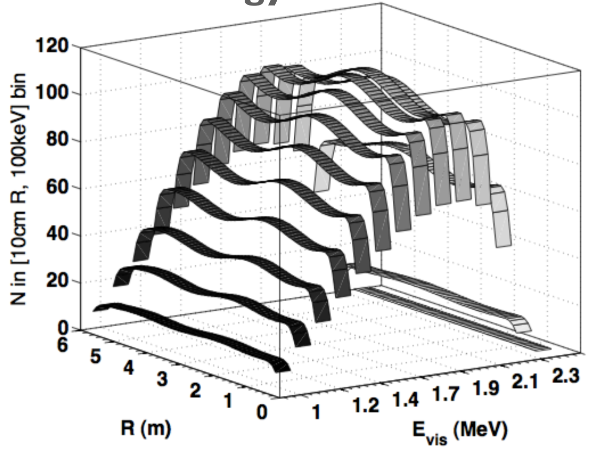
kCi Experiment Concept

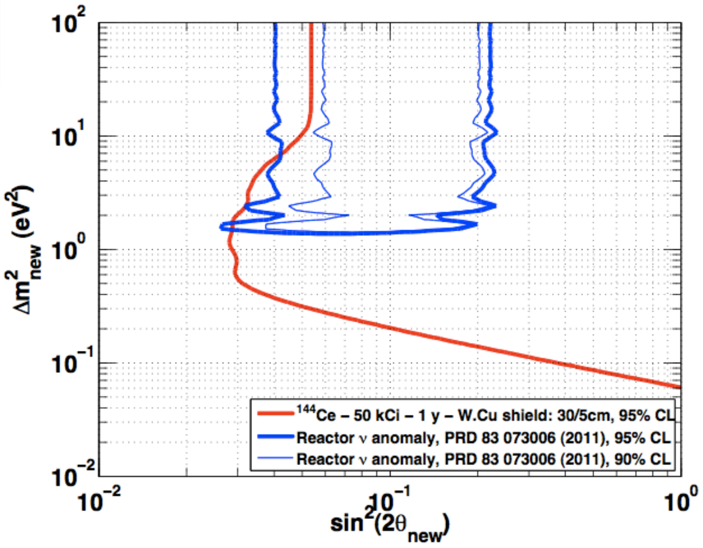
- A strong 50 kCi ^{144}Ce anti-ν_e source in the middle of a large LS detector
- Anti-ν_e detection (40,000 evts/yr)
- A good resolution in position (15 cm)
- Almost background free thanks to anti-ν_e coincidences
- Lifetime ~ 1 yr (285 d)
- Compactness of the source (<5cm)
- W and Cu shield

M. Cribier *et al.*, arXiv: [hep-ex] (2011)



Real oscillation pattern vs. both **radius** & **energy**



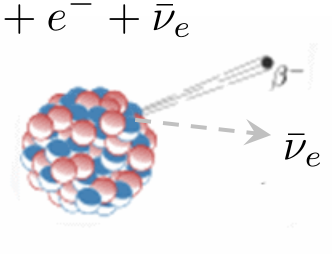


Thank you for your attention!

BACKUP

From e^- to anti-ν_e spectra

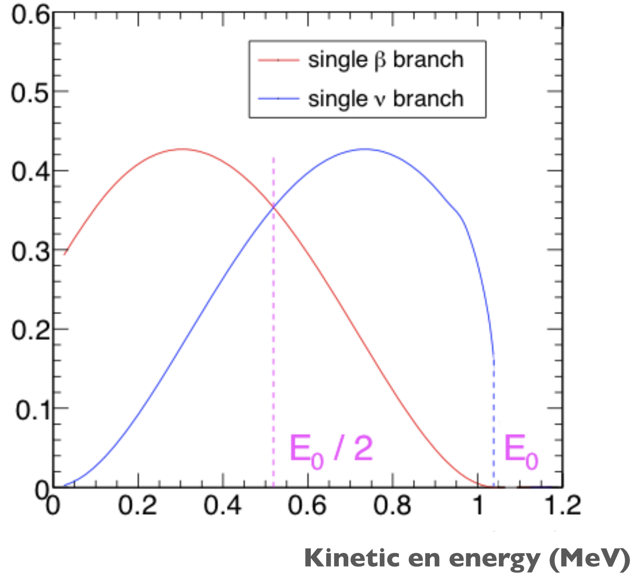
- **A single beta decay branch:** $^A_ZX \longrightarrow \, ^{\;\;A}_{Z+1}Y + e^- + \bar{\nu}_e$
  - depends on: nucleus (Z), branching ratio (BR), end point (Q), spin-parity
  - Energy conservation: $E_e + E_\nu = Q_e$



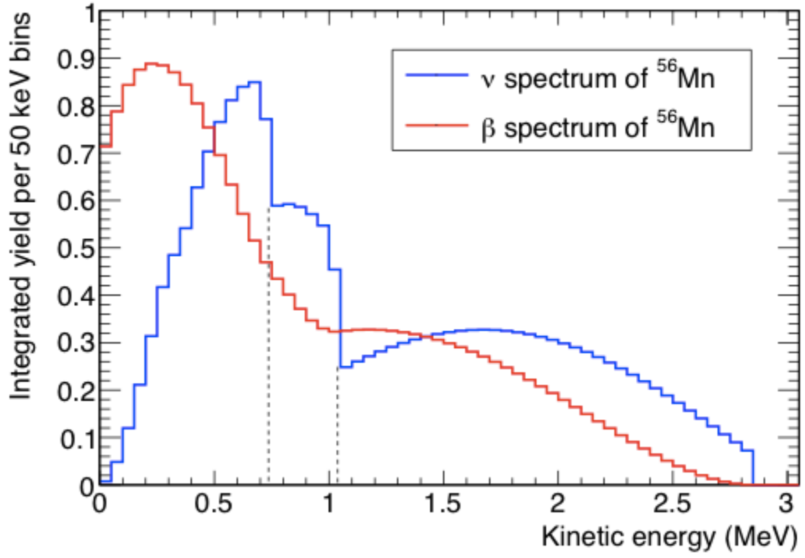
- Anti-ν spectra are computed from electron spectra by "inverting" each branch separately

- Cannot go from e^- to ν from a global e^- spectrum, need each individual branch from each contributing nucleus

β branch level

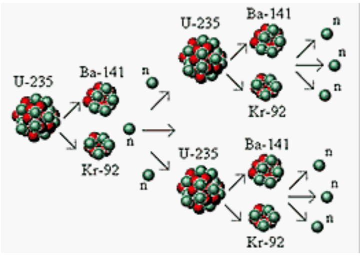


Fission product level (Σ of β branches)

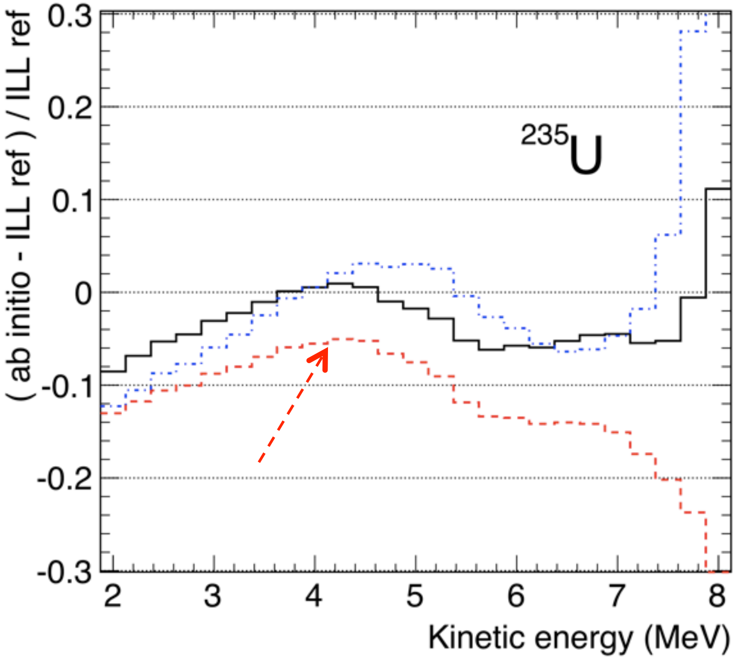


Full *Ab Initio* Attempt

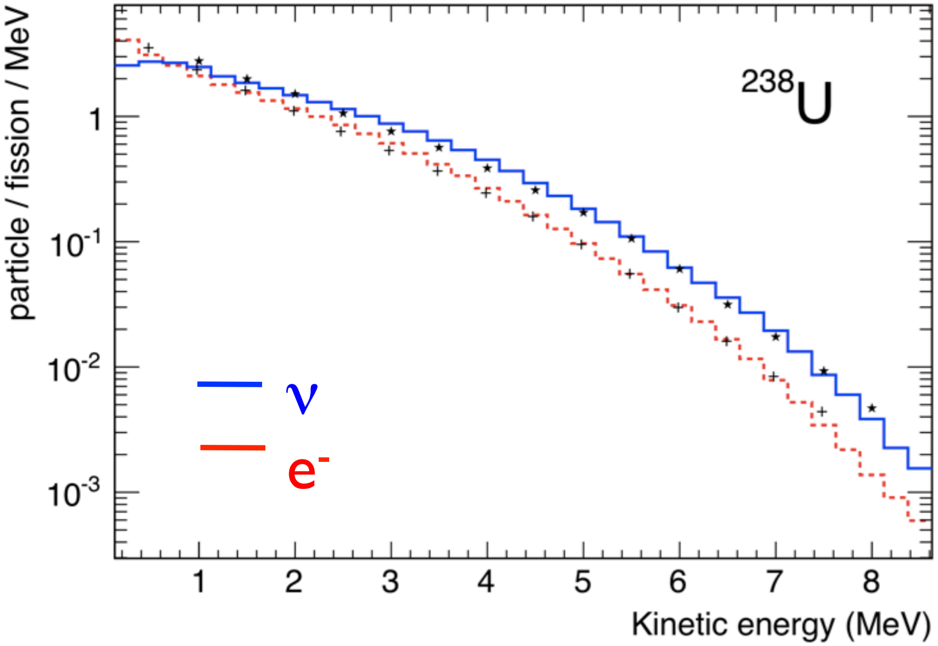
- MURE evolution code: nuclear reactor fuel composition and off equilibrium effects
- BESTIOLE code: build up database of ~800 nuclei and 10,000 β-branches



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



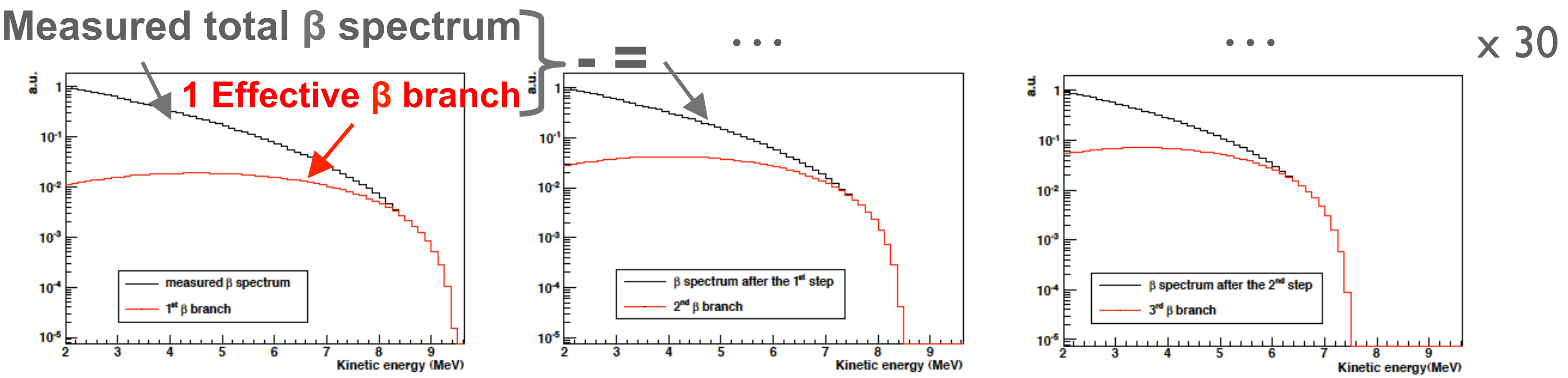
New ^{238}U spectrum prediction



→ 90 ± 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 for ^{238}U (N. Haag & K. Schreckenbach)

ILL data: OLD effective conversion to ν spectra

- Fit e⁻ spectrum with a sum of 30 effective β branches chosen by iterative method (instead of 10,000+ real branches)
- Conversion of the effective branches to ν spectra



Measured total β spectrum - = … … x 30

1 Effective β branch

- All theory included in these effective branches but:

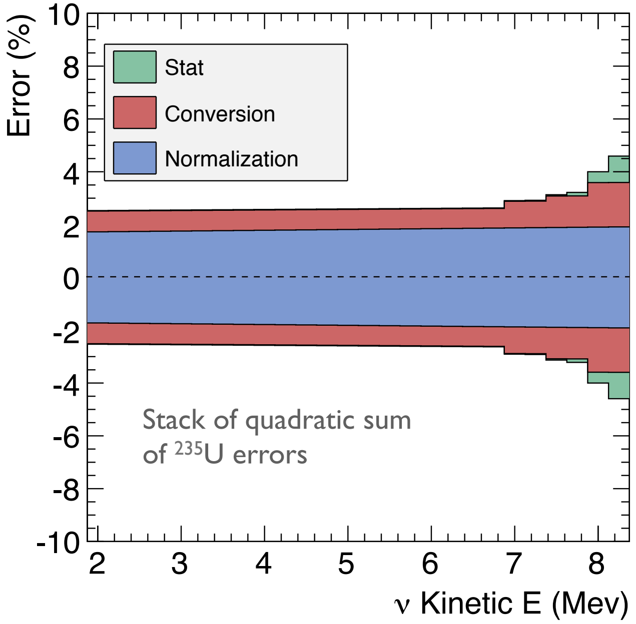
  - What Z? : Mean fit on nuclear data *Z=f(E0)*

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

  - What A_{CW}? : effective correction

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

- Conversion error from envelop of all numerical studies
- Can we do better?



Stack of quadratic sum of ^{235}U errors

Reactor Electron Antineutrino Detection

- **Inverse Beta Decay:** $\bar{\nu}_e + p \rightarrow e^+ + n$
    - Threshold: 1.806 MeV

Thermal power

Target free protons

- **Anti-ν_e interaction rate** $$n_\nu = \frac{1}{4\pi R^2}\frac{P_{\rm th}}{\langle E_f\rangle} N_p \varepsilon \sigma_f$$

E released / fission

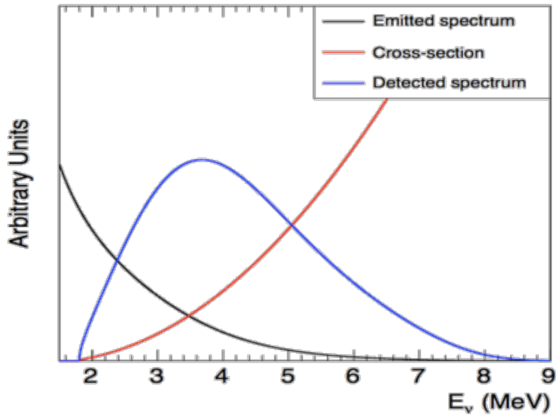
efficiency

- **Experimental cross section per fission:** σ_f

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

- **Predicted cross section per fission:** $\sigma_{\rm pred}$

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



What you should remember

- Obtaining the neutrino spectrum emitted by a nuclear reactor is hard!

- "Ab-initio" approaches do not work fully yet: sum of all β-decay modes of all possible nuclei is only reproduces ~90% of the measured spectra
  - Precision of 15% on ^{238}U (which represents <10% of the ν flux, so not a problem in what follows) → we updated the ν spectrum from ^{238}U fissions

- Solution: use precise electron data measured at ILL in the 1980's as an anchor point
  - "**OLD** method" used so far: fit these data to 30 "fake" electron β-spectra, which are then converted to ν spectra
  - **NEW** method: use all knowledge accumulated so far to rebuild ~90% of the ILL β-spectrum. Fit the 10% residual with 5 "fake" branches

- New method is superior because:
  - Corrections to β-spectra are applied branch by branch in a better fashion
  - Using all known β-branches matches distribution of Z and end-points Q better for 90% of the spectrum

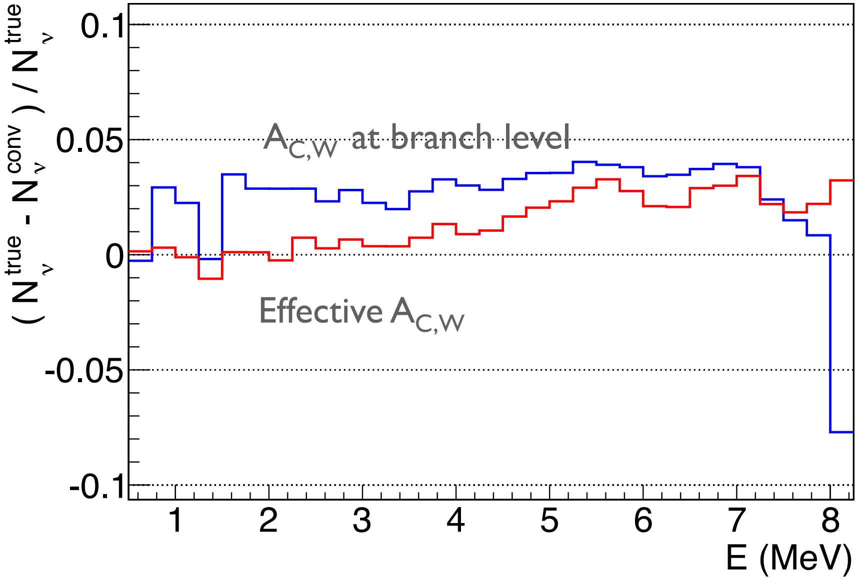
- **New method shows that ν spectra are 3% higher than previously thought**

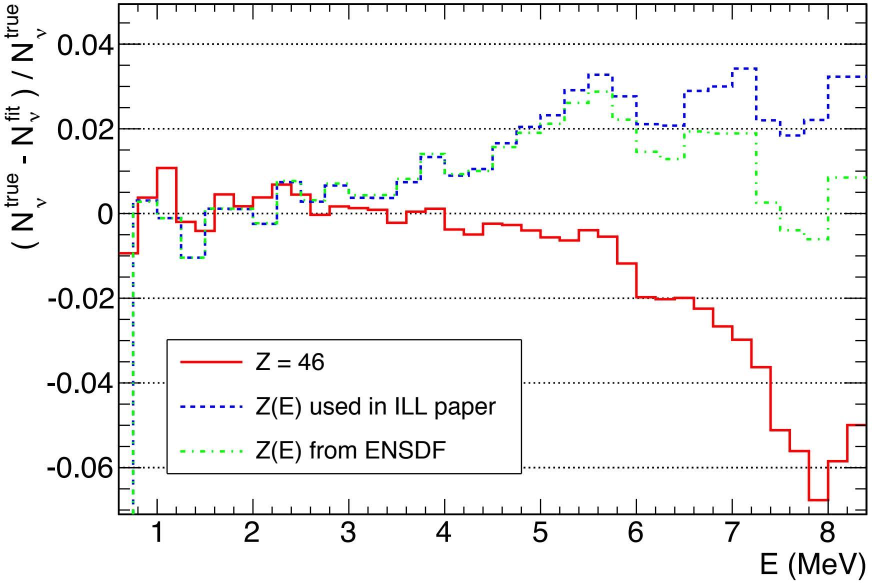
- **What is the impact on all ν experiments near nuclear power reactors?**

Origin of the 3% shift

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

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





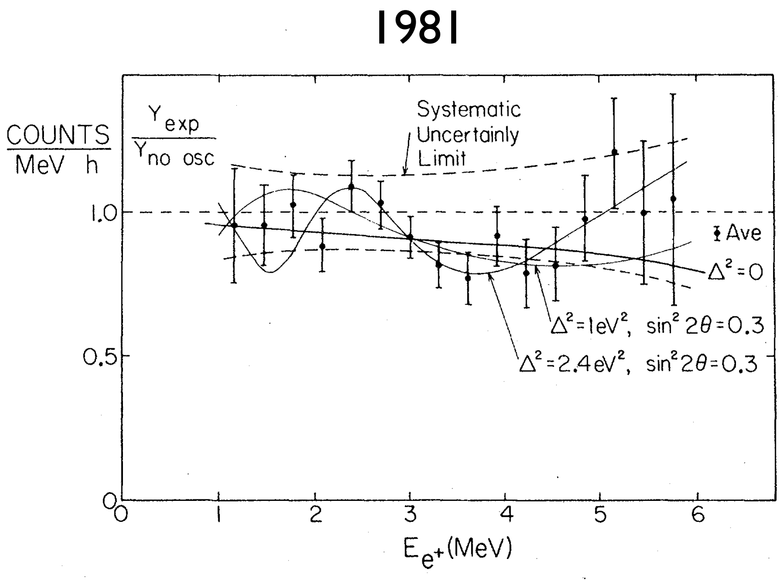
- **E >4 MeV**: mean fit of $Z(E_0)$ doesn't take into account the very large dispersion of Z around the mean curve

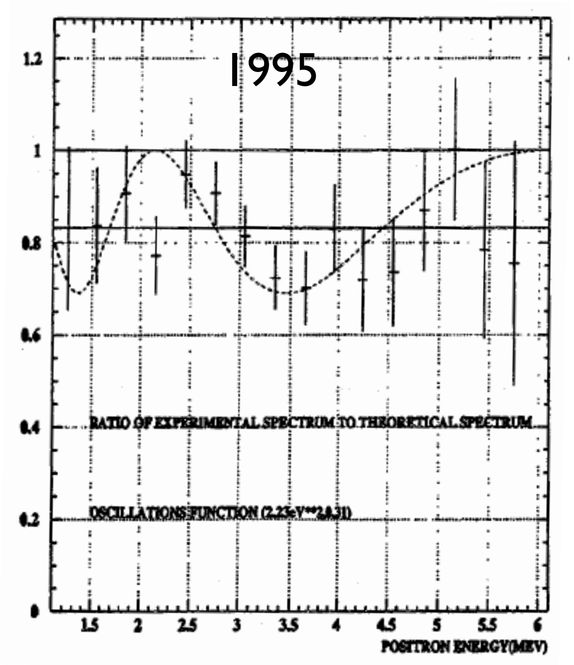
$$Z(E_0) \approx 49.5 - 0.7E_0 - 0.09E_0^2, \quad Z \geq 34$$

The 1981 ILL measurement

- Reactor at ILL with almost pure ^{235}U, with small core
- Detector 8.76 m from core
- Reanalysis in 1995 by part of the collaboration to account for overestimation of flux at ILL reactor

  Affects the rate but not the shape analysis

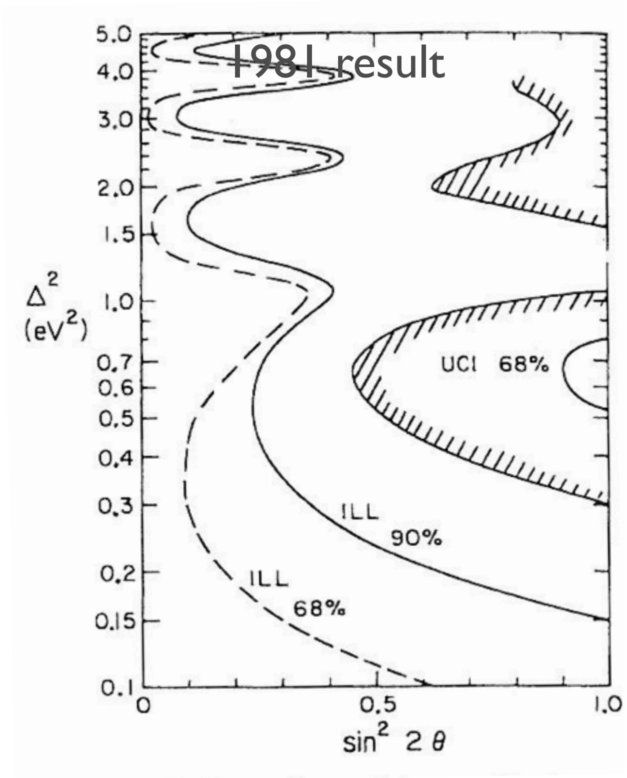


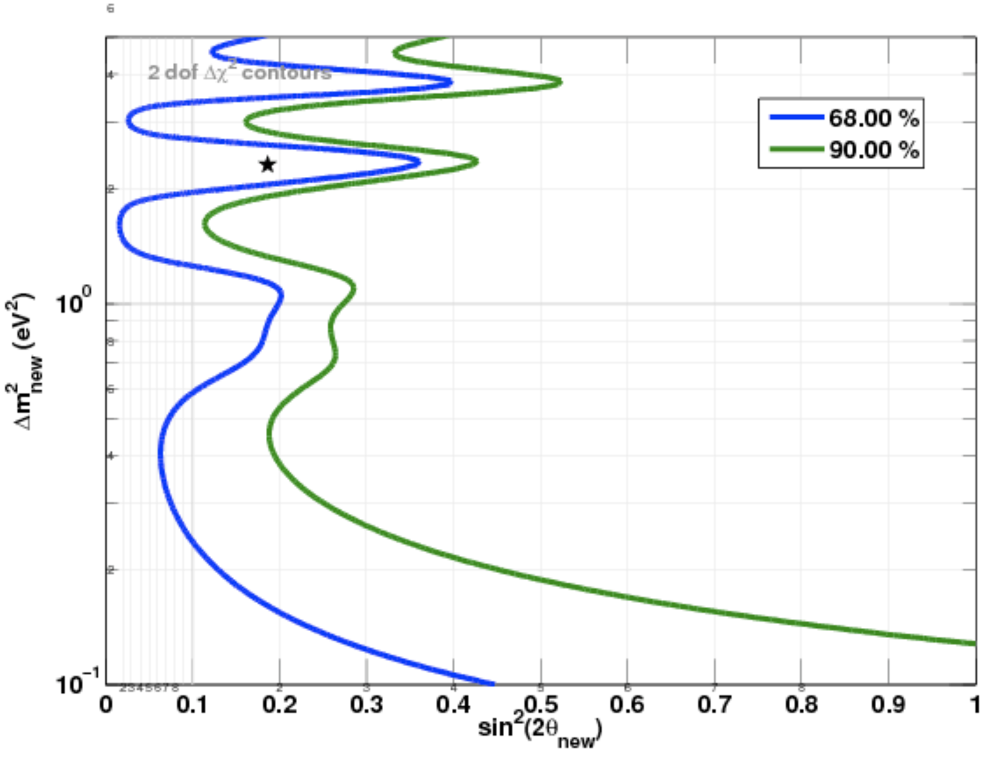


Large errors, but looks like an oscillation pattern by eye ?

Our ILL analysis

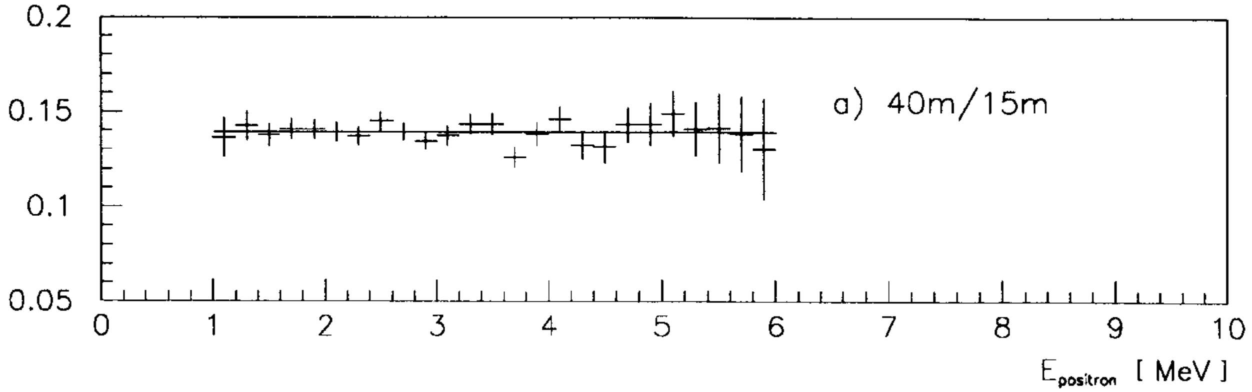
- 1981: Try to reproduce published contour
- 1995: Contour plot hard to follow, reproduce claim that global fit disfavors no-oscillation at 2σ
- How? Add uncorrelated systematic in each bin until it's large enough
- Quick simulation: Required error = 11%, uncorrelated, in each bin (mostly equivalent to the finite size of the reactor core in full simulation).
- We can reproduce the results quite well





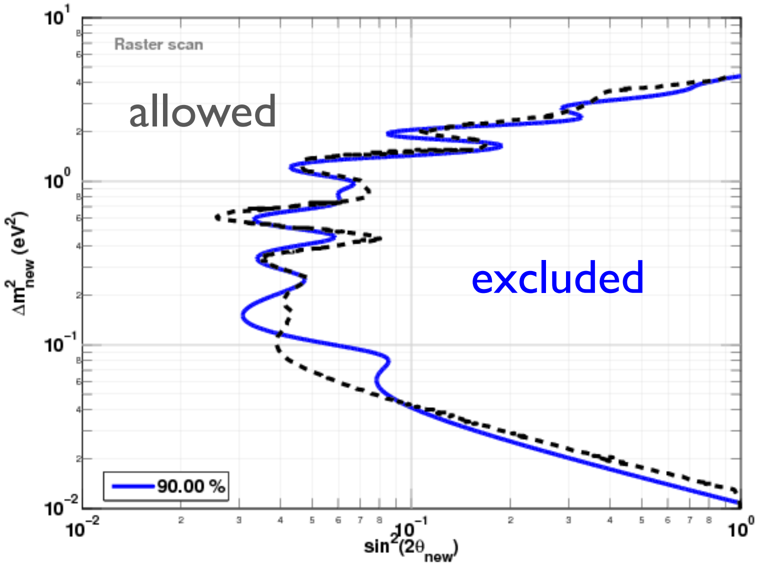
Spectral shape analysis of Bugey-3

- Bugey-3 spectral measurements at 15 m, 40 m, 90 m
  - Best constraint from high statistics R=40 m / 15 m ratio



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

- 2% relative systematic error
- Reproduction of the collaboration's raster-scan analysis
- Use of a global-scan in combined analysis



Promising experimental prospect testing the RAA!