The Reactor Antineutrino Anomaly

23rd Rencontres de Blois - Particle Physics and Cosmology

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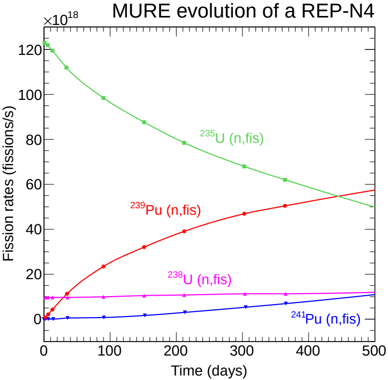
Antineutrino spectrum emitted by a reactor

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

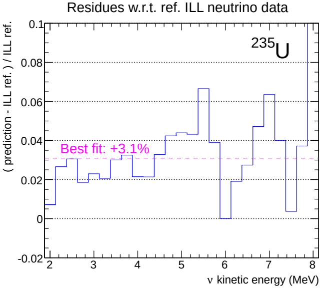
$$\Phi_\nu(E,t) = \frac{P_{\text{th}}}{\sum_k \alpha_k(t) E_k} \times \sum_k \alpha_k(t) S_k(E) \qquad k = {}^{235}\text{U},\ {}^{238}\text{U},\ {}^{239}\text{Pu},\ {}^{241}\text{Pu}$$

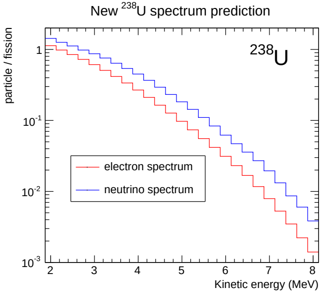
- What is needed?
  1. Reactor data: thermal power, $\delta P_{\text{th}} \leq 1\%$
  2. Nuclear databases: E released per fissions of isotope k, $\delta E_k \approx 0.3\%$
  3. Reactor evolution codes: fraction of fissions from isotope k, $\delta\alpha_k \approx$ few% but large anti-cor. @ fixed P_{th}
  4. ν spectrum per fission



Improved prediction of reactor $\bar{\nu}_e$ spectra, *Phys. Rev. C83 (2011) 054615*

1. ILL $\bar{\nu}_e$ spectra for ^{235}U, ^{239}Pu and ^{241}Pu
   $\Rightarrow$ reference for all reactor ν experiment so far
   - Accurate β measurement @ ILL (1980-89)
     - high resolution spectrometer
     - intense & pure thermal n spectrum
     - extensive use of reference internal conversion e^- lines $\Rightarrow$ norm. $\pm 1.8\%$
   - Conversion into corresponding $\bar{\nu}_e$ spectra using a fit with limited number of effective branches
2. New conversion method developped
   - $+3\%$ normalization shift w.r.t. old $\bar{\nu}_e$ spectrum
   - Stringent test performed = origin of the bias identified
3. ^{238}U spectrum not measured
   - Obtained through ab-initio calculations, $\pm 10\%$
   - Measurement at FRM-II on-going (N. Haag & K. Schreckenbach)





Off-equilibrium effects

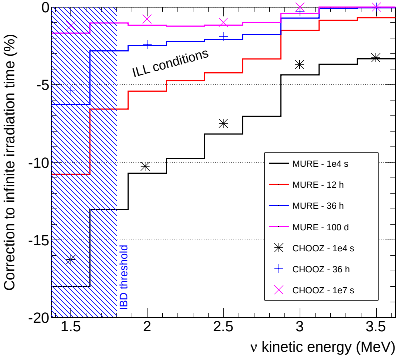
- ILL β reference spectra: 12 hours to 1.8 days irradiation time
- Neutrino reactor experiments irradiation time $\gg$ months
- 10% of fission products have a β-decay lifetime long enough to keep accumulating after several days

Off-equilibrium effects:

① need a correction through simulation

② not included prior to the CHOOZ experiment

Correction included by default in our new reference model



The V-A inverse β-decay cross section

- Inverse β-decay: $\bar{\nu}_e + p \to e^+ + n$
- Theoretical predictions:
  - *Fayans Sov. J. Nucl. Phys. 42 (1985)*
  - also agree with *Vogel-Beacom Phys. Rev. D60 (1999) 053003*
  - detailed review in *Strumia-Vissani Phys. Lett. B564 (2003)*

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

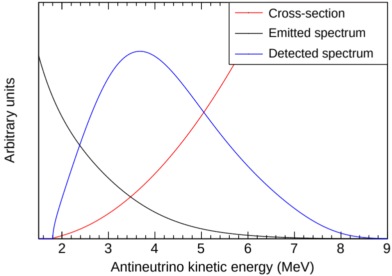
- The pre-factor κ (two pseudo-independent approaches)

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

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

Computing the expected rate and/or spectrum

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



- Bugey-4 benchmark
  - *Phys. Lett. B338 (1994) 383*
  - $\tau_n = 887.4$ s
  - "old" spectra
  - no off-equilibrium corrections

10^{-43} cm^2	Bugey-4	Our work
^{235}U	$6.39 \pm 1.9\%$	$6.39 \pm 1.8\%$
^{239}Pu	$4.18 \pm 2.4\%$	$4.19 \pm 2.3\%$
^{241}Pu	$5.76 \pm 2.1\%$	$5.73 \pm 1.9\%$

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

The new cross section per fission, *Phys. Rev. D83 (2011) 073006*

- ν-flux: ^{235}U $+2.5\%$, ^{239}Pu $+3.1\%$, ^{241}Pu $+3.7\%$, ^{238}U $+9.8\%$ $(\sigma_f^{\text{pred}} \nearrow)$
- Off-equilibrium corrections now included $(\sigma_f^{\text{pred}} \nearrow)$
- Neutron lifetime decrease by a few % $(\sigma_f^{\text{pred}} \nearrow)$ $\left[\ \sigma_{\text{V-A}}(E_\nu) \propto 1/\tau_n\ \right]$
- Slight evolution of the phase space factor $(\sigma_f^{\text{pred}} \rightarrow)$
- Slight evolution of the energy per fission per isotope $(\sigma_f^{\text{pred}} \rightarrow)$
- New results:

Isotopes	Old	New	New / Old
$\sigma_{f,^{235}\text{U}}^{\text{pred}}$	$6.39 \pm 1.9\%$	$6.61 \pm 2.11\%$	$+3.4\%$
$\sigma_{f,^{239}\text{Pu}}^{\text{pred}}$	$4.19 \pm 2.4\%$	$4.34 \pm 2.45\%$	$+3.6\%$
$\sigma_{f,^{238}\text{U}}^{\text{pred}}$	$9.21 \pm 10\%$	$10.10 \pm 8.15\%$	$+9.6\%$
$\sigma_{f,^{241}\text{Pu}}^{\text{pred}}$	$5.73 \pm 2.1\%$	$5.97 \pm 2.15\%$	$+4.2\%$

19 experimental results revisited ($L < 100$ m)

#	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

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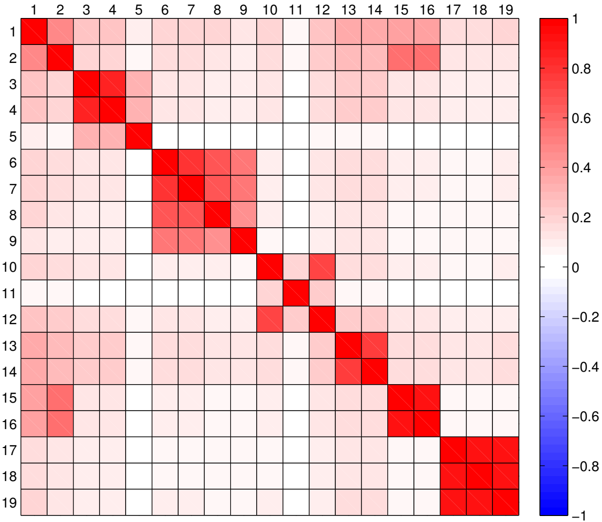
Error budget & correlations

- Our guiding principles: be conservative - be stable numerically (SRP case)
- Reactor antineutrino sources
  - 2% systematic on $\bar{\nu}_e$-flux 100% correlated over ALL measurements
  - 1.8% corresponds to the normalization error on the ILL β 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
  - Rovno88 integral measurement 100% correlated with Rovno91 despite detector upgrade, but not with Rovno88 LS data
  - Rovno91 integral measurement 100% correlated with Bugey-4
  - Rovno88 integral measurement 50% correlated with Bugey-4

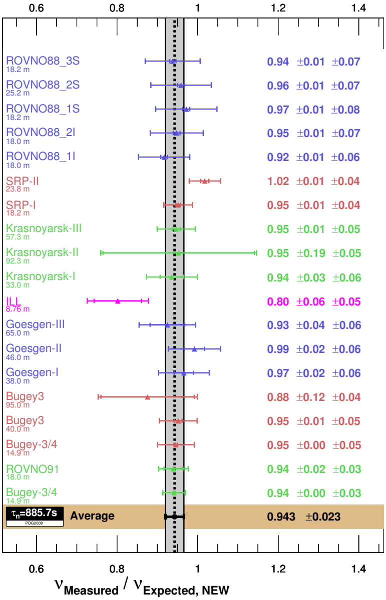
Experiments correlation matrix

$\vec{R}$	$\sum_{\text{tot.}}$	$\sum_{\text{cor.}}$
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.	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.	4.1
Krasno 57m	4.1	4.1
SRP I 18m	3.7	3.7
SRP II 25m	3.8	3.7
Rovno88 1I 18m	6.9	6.9
Rovno88 2I 18m	6.9	6.9
Rovno88 1S 18m	7.8	7.2
Rovno88 2S 25m	7.8	7.2
Rovno88 3S 18m	7.2	7.2



1) Main pink color comes from the 2% systematic on ILL β-spectra normalization uncertainty
2) The experiment block correlations come from identical detector, technology or $\bar{\nu}_e$ source

The Reactor Antineutrino Anomaly



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

- Best fit: $\mu = 0.943$
- Uncertainty: 0.023
- $\chi^2 = 19.6/19$
- 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 $\chi^2_{\text{min}} < 19.6$

The Reactor Antineutrino Anomaly (cont'd)

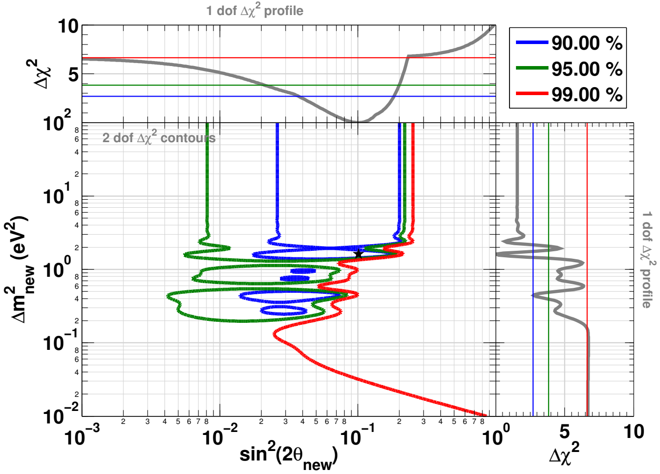
- 18(19) short baseline experiments < 100 m from a reactor observed a deficit of $\bar{\nu}_e$ compared to the new prediction
- The effect is statistically significant at more than 98.6%
- Effect partly due to re-evaluation of cross-section parameters, especially neutron lifetime, accounting for off-equilibrium effects
- At least three alternatives:
  1. Our calculations are wrong: ILL β data are unchanged w.r.t old prediction...
  2. Bias in all short-baseline experiments near reactors: unlikely...
  3. New physics at short baselines, explaining a deficit of $\bar{\nu}_e$. Oscillation towrads a 4th sterile ν?

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

$$P_{\nu_e\to\nu_e} = |\langle\nu_e(L)|\nu_e(0)\rangle|^2 = 1 - \sin^2(2\theta_{\text{new}})\sin^2\left(\frac{\Delta m^2_{\text{new}}L}{4E}\right)$$

The 4th neutrino hypothesis

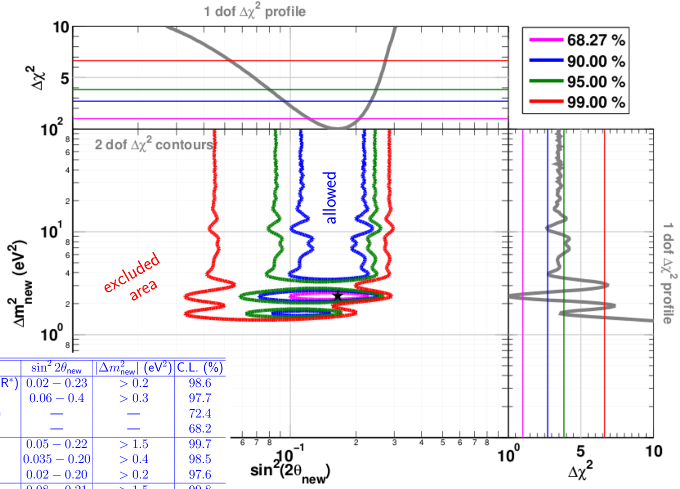
Fit to $\bar{\nu}_e$ disappearance hypothesis $\Rightarrow$ combined reactor rate + shape contours



Best fit: $\sin^2(2\theta_{\text{new}}) \sim 0.1$, $\Delta m^2_{\text{new}} \sim 1.5$ eV^2

The no-oscillation hypothesis is disfavored at 96.51%

Reactor rate + shape + Gallium + MiniBooNE

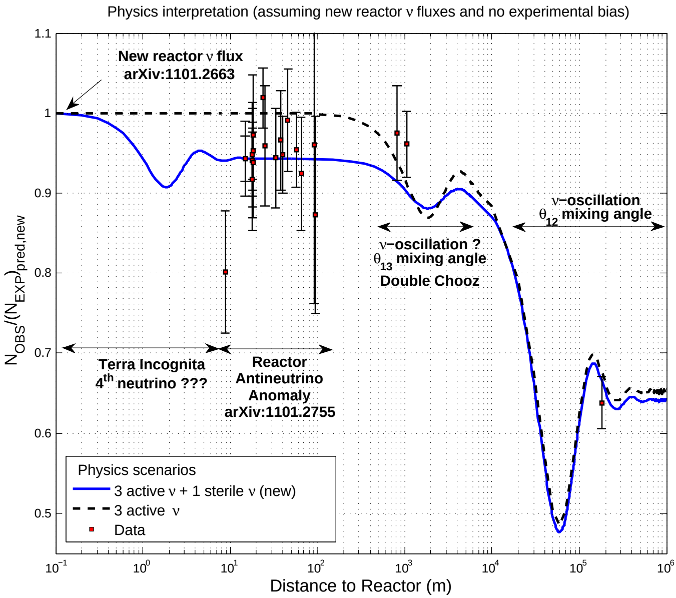


Experiment(s)	$\sin^2 2\theta_{\text{new}}$	$\lvert\Delta m^2_{\text{new}}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	$0.02 - 0.23$	> 0.2	98.6
Gallium (G)	$0.06 - 0.4$	> 0.3	97.7
MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R*+G	$0.05 - 0.22$	> 1.5	99.7
R*+M	$0.035 - 0.20$	> 0.4	98.5
R*+ILL-S	$0.02 - 0.20$	> 0.2	97.6
ALL	$0.08 - 0.21$	> 1.5	99.8

The no-oscillation hypothesis is disfavored at 99.8% C.L.

for Gallium neutrino anomaly, see *Giunti-Laveder Phys. Rev. D82 (2010) 053005*

Normalization dilemma: need for new experimental inputs!



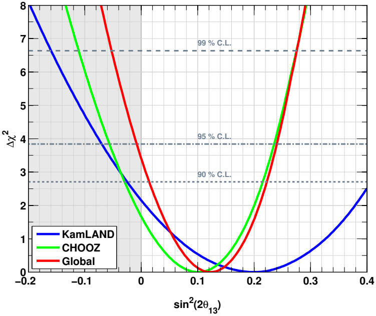
CHOOZ and KamLAND combined limit on θ_{13}

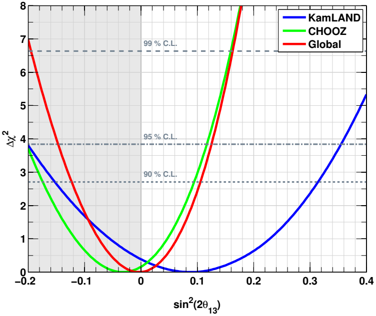
Normalization with $\sigma_f^{\text{pred,new}}$

3-ν framework & 2.7% uncertainty

Normalization using σ_f^{ano}

3-ν framework & 2.7% uncertainty





- Our interpretation:
  1. No hint on $\theta_{13} > 0$ from reactor experiments: $\sin^2(2\theta_{13}) < 0.11$ (90% C.L., 1 dof)
  2. CHOOZ 90% C.L. limit stays identical to *Eur. Phys. J. C27 (2003) 331-374*
  3. Multi-detector reactor experiments are not affected

Conclusion & perspectives

- Reactor antineutrino anomaly discovered
    1. Experimental bias to be deeply investigated
    2. New physics hypothesis tested: 4th neutrino
       $\Rightarrow$ no-oscillation hypothesis disfavored at 99.8%

- Multi-detector reactor experiments not affected → Daya Bay, RENO, Double Chooz

- Clear experimental confirmation / infirmation is needed:
    - $L/E \approx$ few m/MeV or km/GeV
    - New experiment at reactor: short baseline, shape + rate analysis
    - Mci ν_e / $\bar{\nu}_e$ source in / close to a large liquid scintillator: like SNO+, Borexino, KamLAND
    - New ν beam experiment probing for GeV ν_e disappearance at 100 m & 1 km

Back-up slides

BACK-UP SLIDES

The guts of $S_k(E)$

- Sum of all fission products' activities:

$$S_k(E) = \sum_{f=1}^{N_f} A_f(t) \times S_f(E)$$

- Sum of all β-branches of each fission product:

$$S_f(E) = \sum_{b=1}^{N_b} BR_f^b \times S_f^b(Z_f, A_f, E_{0,f}^b, E)$$

- Theory of β-decay:

$$S_f^b(Z_f, A_f, E_{0,f}^b, E) = \overbrace{K_f^b}^{\text{Normalization}} \times \overbrace{\mathcal{F}(Z_f, A_f, E)}^{\text{Fermi function}} \times \underbrace{pE(E - E_{0,f}^b)^2}_{\text{Phase space}} \times \underbrace{C_f^b(E)}_{\text{Shape factor}} \times \left(1 + \underbrace{\delta_f^b(Z_f, A_f, E)}_{\text{Corrections}}\right)$$

- Corrections to Fermi theory of β-decay :

$$\delta_f^b(Z_f, A_f, E) = \delta_{\mathsf{QED}}(E) + A_C(Z_f, A_f) \times E + A_W \times E$$

Complementary approaches to compute the ν flux

Ab-initio

Integral measurements
of electron spectra

Sum of all fission
products' activities

fission product inventory (t)

fission rates (t)

* Fission yields (JEFF, ENDF, JENDL...)
* Lifetime

Sum of all β-branches
of each fission product

Build total spectrum from
sum of β-branches

Reference spectrum
per isotopes

Theory of β
decay

* Complete β-decays schemes (ENSDF)
* β-strength (Greenwood et al.)
* Total β spect. per nucleus (Rudstam et al.)
* Masses (Q_β)
* Nuclear models...

* ILL electron data
* Effective conversion

Full ab-initio

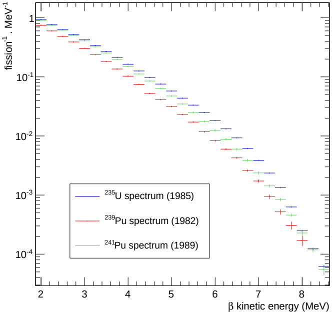
Our mixed approach

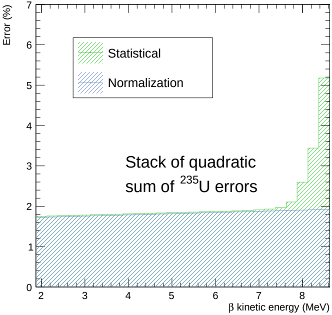
Effective

The ILL electron data anchorage

Unique reference to be met by any other measurement and/or calculation

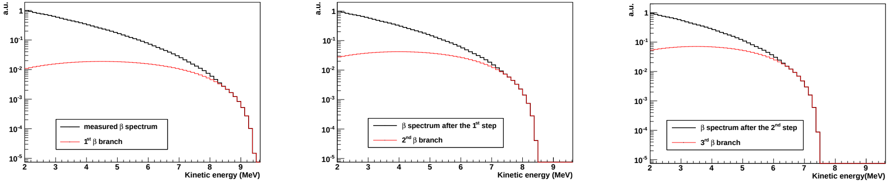
- Accurate electron spectra measurements @ ILL (1980-89)
- High resolution electromagnetic spectrometer
- Intense and pure thermal n spectrum from the core
- Extensive use of reference internal conversion electron lines ⇒ normalization $\pm 1.8\%$





ILL data: conversion to ν spectra

- Fit β spectrum with a sum of 30 effective branches
- Conversion of the effective branches to ν spectra $\equiv$ energy conservation



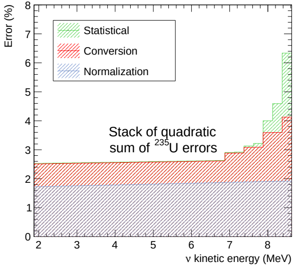
- All theory included in these effective branches but:
  - What Z? → mean fit on nuclear data $Z = f(E_0)$

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

  - What A_{WC}? → effective correction on the ν spectra

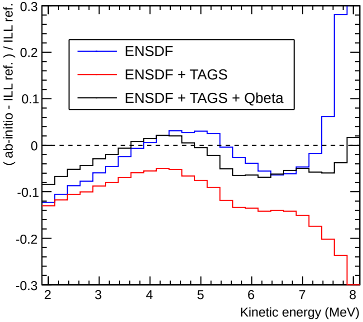
$$\Delta N_\nu^{\mathrm{WC}}(E_\nu) = 0.65 \times (E_\nu - 4\ \mathrm{MeV})\%$$

- Conversion error from envelop of numerical studies

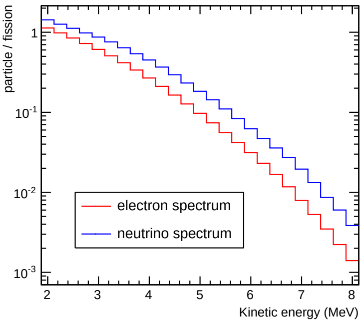


The full *ab-initio* attempt (electron data)

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



Residues w.r.t. reference ILL electron data

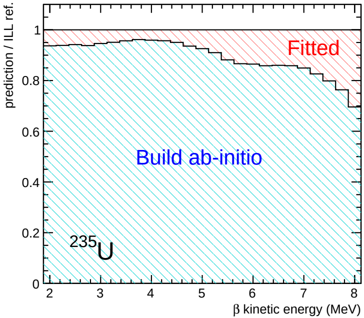


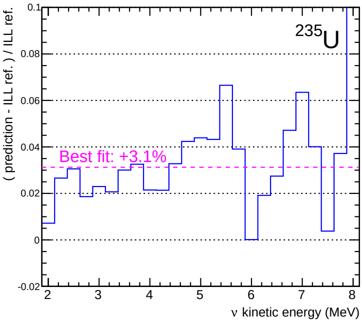
New ^{238}U spectrum prediction

1. $95 \pm 5\%$ of the spectrum reproduced but still not meeting required precision
2. Useful estimate of ^{238}U spectrum which couldn't be measured @ ILL
   ⇒ Measurement at FRM-II on-going (N. Haag & K. Schreckenbach)

The new mixed conversion approach

1. Same ILL β data anchorage
2. Ab-initio: “true” distribution of β-branches reproduces $> 90\%$ of ILL β data
3. Old procedure: 5 effective branches to the remaining 10%

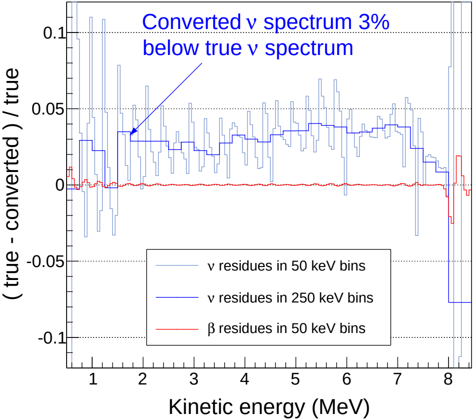




- $+3\%$ normalization shift with respect to old ν spectrum (^{235}U, ^{239}Pu & ^{241}Pu)
- Stringent test performed - origin of the biais identified

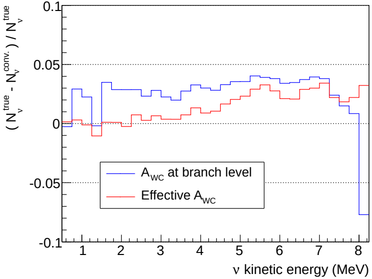
Consistency check

1. Define "true" β and $\bar{\nu}_e$ spectra from reduced set of well-known branches from ENSDF nuclei database
2. Apply exact same OLD conversion procedure to true β spectrum
3. Compare converted $\bar{\nu}_e$ spectrum to the true $\bar{\nu}_e$ spectrum
4. This technique gives a 3% biais to the true $\bar{\nu}_e$ spectrum



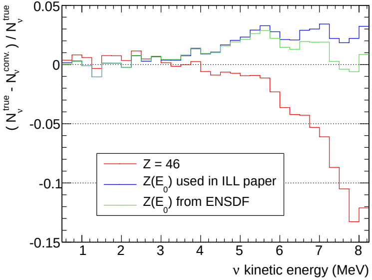
⇒ OLD effective conversion method biaises the predicted $\bar{\nu}_e$ spectrum at the level of $\sim 3\%$ in normalization

Origin of the 3% shift



- $E < 4$ MeV: deviation from effective linear A_{WC} correction of ILL data

$$\Delta N_\nu^{\text{WC}}(E_\nu) = 0.65 \times (E_\nu 4\ \text{MeV})\%$$



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

$$Z(E_0) = 49.5 - 0.7 \times E_0 - 0.09 \times E_0^2$$

Reactor Electron Antineutrino Detection

- Inverse β decay, threshold 1.806 MeV:

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

- $\bar{\nu}_e$ interaction rate:

$$n_\nu = \frac{1}{4\pi R^2} \frac{P_{\text{th}}}{\langle E_f \rangle} N_p \epsilon \sigma_f$$

- Experimental cross section per fission:

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

- Predicted cross section per fission:

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

ROVNO88, 5 measurements, *Sov. Phys. JETP 67 (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,
  - ROVNO-91 (integral measurement only),
  - with each other

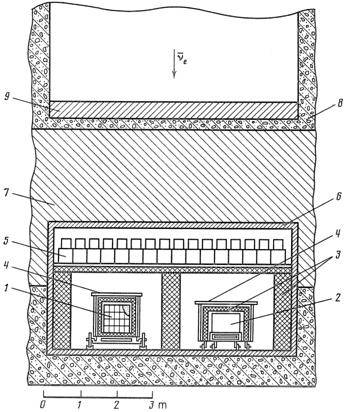


FIG. 1. Schematic diagram of the experimental setup: 1—integrating detector; 2—scintillation-counter spectrometer; 3—polyethylene; 4—scintillators of the anticoincidence shield; 5—tanks containing the liquid scintillator (anticoincidence "hood"); 6—steel; 7—heavy concrete; 8—concrete; 9—additional shielding.

ROVNO91, *JETP Lett. 54 (1991)*

- 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)

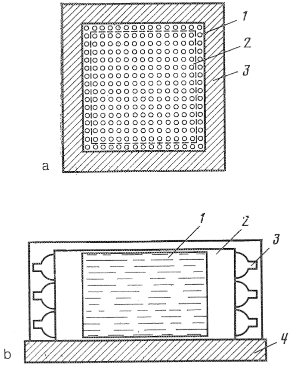


FIG. 4. Schematic diagram of the detectors: a—integrating detector; 1—proportional counter filled with ^{3}He; 2—polyethylene; 3—borated polyethylene; b—scintillation-counter spectrometer: 1—liquid scintillator; 2—lightguide; 3—FEU-49B; 4—borated polyethylene.

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

- Bugey, France, PWR, early 1990's
- Technology:
  - Integral detector: water target containing ^{3}He counters, only neutrons are detected
- Baselines:
  - 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.)

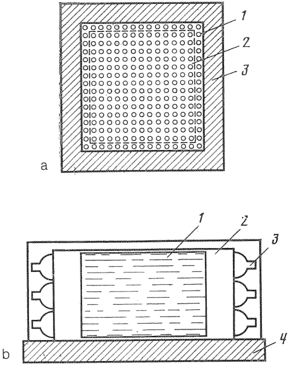


FIG. 4. Schematic diagram of the detectors: a—integrating detector; 1—proportional counter filled with ^{3}He; 2—polyethylene; 3—borated polyethylene; b—scintillation-counter spectrometer: 1—liquid scintillator; 2—lightguide; 3—FEU-49B; 4—borated polyethylene.

⇒ Experimental cross section used to normalize the CHOOZ experiment result

Bugey-3, 3 measurements, *Nucl. Phys. B434 (1995)*

- Bugey, France, PWR, early 80's
- Technology:
  - Liquid scintillator segmented detectors with ^{6}Li
- Baselines:
  - 14 m, 42 m & 95 m
- Fuel composition typical of PWR:
  - 53.8% ^{235}U, 32.8% ^{239}Pu, 7.8% ^{238}U, 5.6% ^{241}Pu
- Uncertainties:
  - statistics: 0.4%, 1.0% & 13.2%
  - systematics: 5.0%
- Correlated with:
  - each other

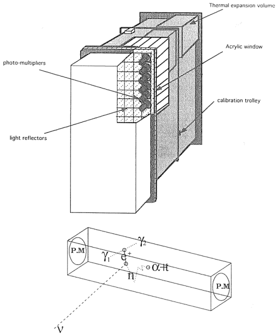


Fig. 1. A schematic view of one detection module and of the detection principle.

- Stringent shape distortion analysis disfavoring sub-eV^2 oscillations

Goesgen, 3 measurements, *Phys. Rev. D34 (1986)*

- Gösgen, Switzerland, PWR, 1981-1984
- Technology:
  - Liquid scintillator segmented detectors + ^{3}He counters for neutron capture
- Baselines:
  - 37.9 m, 45.9 m & 64.7 m
- 3 fuel composition. 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

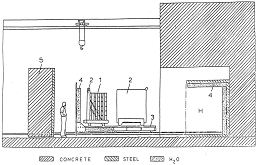


FIG. 8. Detector assembly of the neutrino experiments I—III at Gösgen. The central detector, normally located within the concrete house *H* is shown in its rolled out position. (1) is the central detector unit, (2) are the tanks of the active veto, (4) are water tanks, (5) is a movable concrete closing door. The various parts of the detector move on a system of rails (3).

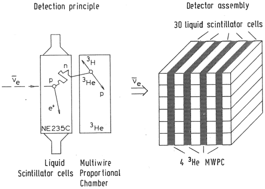


FIG. 3. Neutrino-detection principle and realization: The central neutrino-detector unit consists of 30 liquid-scintillator cells arranged in five planes for positron detection and four ^{3}He-filled wire chambers for neutron detection.

ILL-ν, *Phys. Rev. D24 (1981)*

- ILL, Reasearch reactor, Grenoble, 1980-81
- Technology:
  - Liquid scintillator segmented detectors + ^{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 collab. to correct 10% error on $P_{\rm th}$

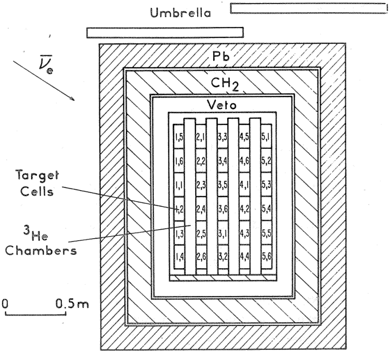


FIG. 1. Experimental arrangement of the detector system and shielding.

Krasnoyarsk, 3 measurements, *JETP 93 (1987)*

- Krasnoyarsk research reactor, Russia
- Technology:
  - Integral detector filled with PE + ^{3}He counters for neutron capture
- Baselines:
  - 33 m & 92 m from 2 reactors (1987)
  - 57.3 m from 2 reactors (1994)
- Fuel composition:
  - mainly ^{235}U
- Uncertainties (33 m, 57.3 m & 92 m):
  - statistics: 3.6%, 1.0% & 19.9%
  - systematics: 4.8% to 5.5% (corr.)
- Correlated with:
  - each other

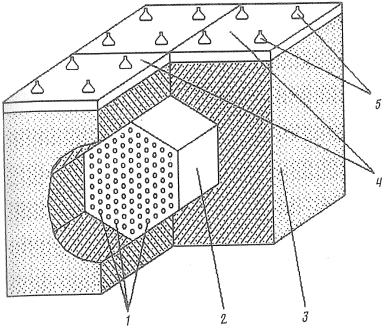


FIG. 1. Neutrino detector. *1*—^{3}He proportional neutrino counters; *2*—detector; *3*—shielding made of borated polyethylene; *4*—films for active shielding from cosmic-ray mesons; *5*—FEU-125 photomultiplier.

Savannah River Plant, 2 measurements, *Phys. Rev. D53 (1996)*

- Savannah River, USA, long standing program initiated by F. Reines. Only the last 2 results are included in our work
- Technology:
  - Liquid scintillator doped with 0.5% Gd
- Baselines:
  - 18.2 m & 23.8 m
- Fuel composition:
  - Difference with pure ^{235}U below 1.5%
- Uncertainties:
  - statistics: 0.6% & 1.0%
  - systematics: 3.7%
- Correlated with:
  - each other
  - but the two results are in slight tension

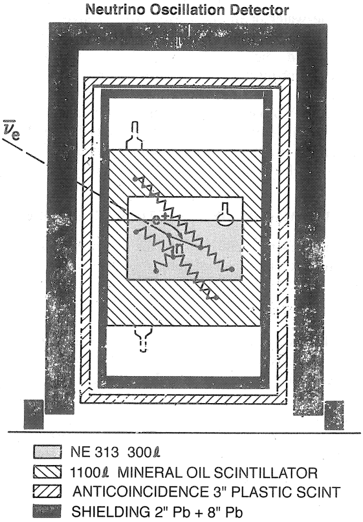
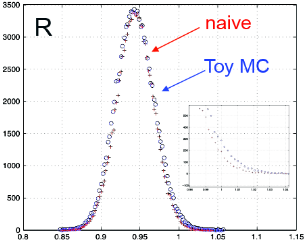
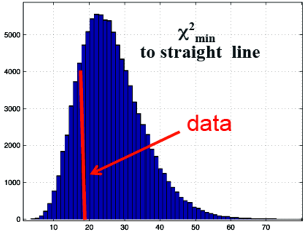


FIG. 1. The major components of the mobile detector.

Are the ratios normally distributed?

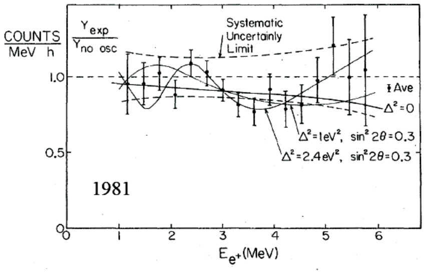
- Our data points are ratios of Gaussians :
  - Numerator: measurement, Gaussian with stat. and syst. error, partially correlated
  - Denominator: common prediction assumed to have Gaussian fluctuation of 2%
- Toy MC with correlated denominator with 2% fluctuation → 10^6 events
  - Estimate weighted average R of 19 random points with correlations around 0.943
  - P-value for $(R \geq 1)$: 1.4% (2.2σ) compared to nave 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

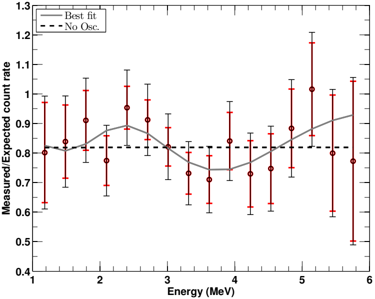




The 1981 ILL measurement

- 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

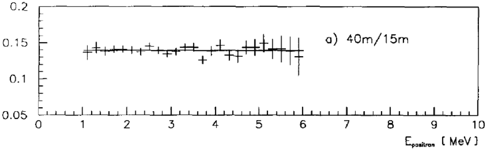




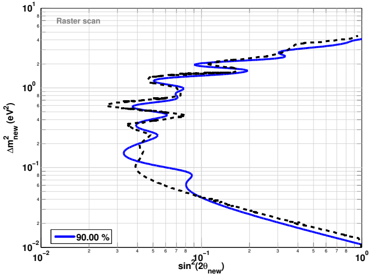
- Large errors, but a striking pattern is seen by eye?

Spectral shape analysis of Bugey-3

- Bugey-3 spectral measurement at 15 m, 45 m and 90 m
- Best constraint from high statistics R = 15 m / 40 m ratio
- Very robust since it does not rely on reactor spectra



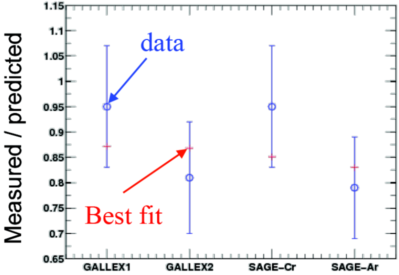
$$\chi^2 = \sum_{i=1}^{N=25} \left(\frac{(1+a)R^i_{\text{th}} - R^i_{\text{obs}}}{\sigma_i} \right) + \left(\frac{a}{\sigma_a} \right)^2$$



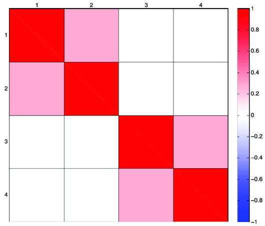
- Reproduction of the collaboration's raster-scan analysis
- Use of a global-scan in combined analysis

The Gallium anomaly, *Phys. Rev. D82 (2010)*

- 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 and 1 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 lenghts of neutrinos in gallium tanks
  - NEW: correlate the 2 Gallex runs together & the 2 SAGE runs together

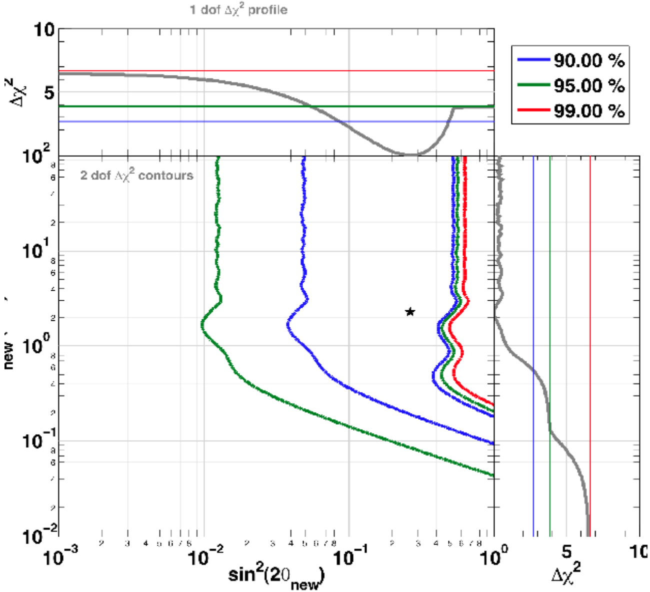


- Gallex-I
- Gallex-II
- Sage-Cr
- Sage-Ar



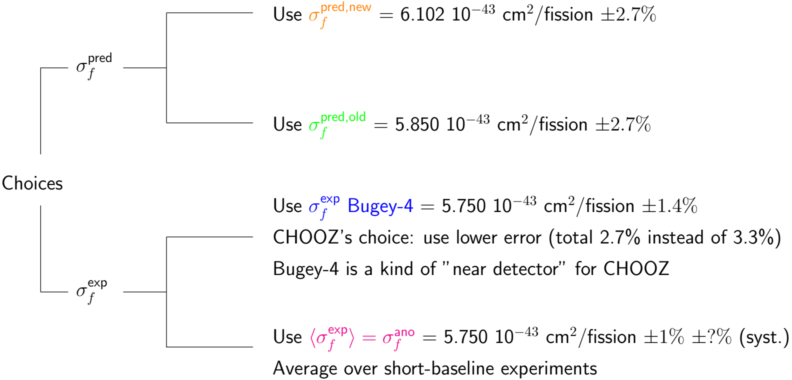
correlation matrix

The Gallium anomaly (cont'd)



The normalization dilemma

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



Choices

σ_f^{pred}

Use $\sigma_f^{\text{pred,new}} = 6.102\ 10^{-43}$ cm^2/fission $\pm 2.7\%$

Use $\sigma_f^{\text{pred,old}} = 5.850\ 10^{-43}$ cm^2/fission $\pm 2.7\%$

σ_f^{exp}

Use σ_f^{exp} Bugey-4 $= 5.750\ 10^{-43}$ cm^2/fission $\pm 1.4\%$

CHOOZ's choice: use lower error (total 2.7% instead of 3.3%)

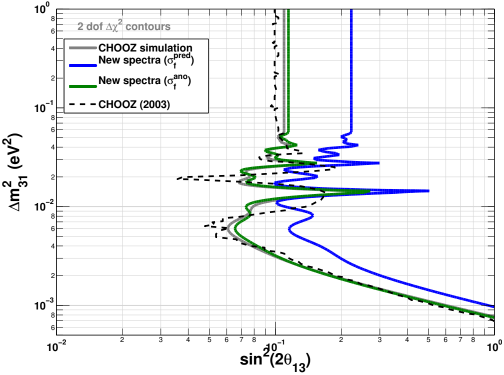
Bugey-4 is a kind of "near detector" for CHOOZ

Use $\langle \sigma_f^{\text{exp}} \rangle = \sigma_f^{\text{ano}} = 5.750\ 10^{-43}$ cm^2/fission $\pm 1\% \pm ?\%$ (syst.)

Average over short-baseline experiments

CHOOZ reanalysis

- The choice of σ_f changes the limit on θ_{13} /gallium
- CHOOZ original choice was σ_f^{exp} from Bugey-4 with low error



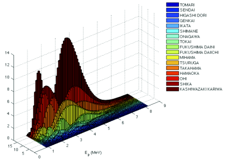
- If $\sigma_f^{\text{pred,new}}$ is used, limit is worse by factor of 2
- If σ_f^{ano} is used with 2.7%, we obtain the original limit → but which error should we associate to σ_f^{ano} (burnup)?

Reanalysis of KamLAND's 2010 results

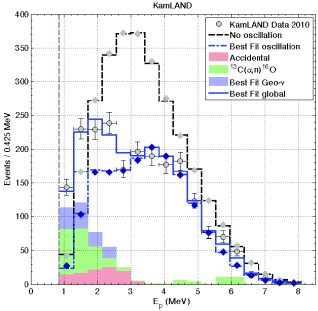
Systematics

	Detector-related (%)		Reactor-related (%)	
Δm^2_{21}	Energy scale	1.9	$\bar{\nu}_e$-spectra	0.6
Event rate	Fiducial volume	1.8	$\bar{\nu}_e$-spectra	2.4
	Energy threshold	1.5	Reactor power	2.1
	Efficiency	0.6	Fuel composition	1.0
	Cross section	0.2	Long-lived nuclei	0.3
	Total	2.3	Total	3.3

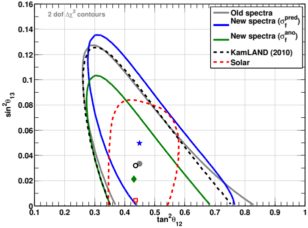
Spectra from Japanese reactors (with osc.)



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



With new spectra predictions



⇒ no changes $\tan^2\theta_{12}$ & Δm^2_{21}, shift θ_{13}