Evaluation of reactor neutrino flux: issues and uncertainties

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"*Never underestimate the joy people derive from hearing something they already know.*"

E. Fermi

Why do we care?

a) Nuclear reactors are powerful sources of low energy $\bar{\nu}_e$

b) There is a long tradition of using them in the study of neutrino properties:

   i) Proof that neutrinos are real particles

   ii) Accurate determination of Δm^2_{21} and the proof that neutrinos really oscillate

   iii) Determination of θ_{13}

   iv) Reactor anomaly, and its possible consequences

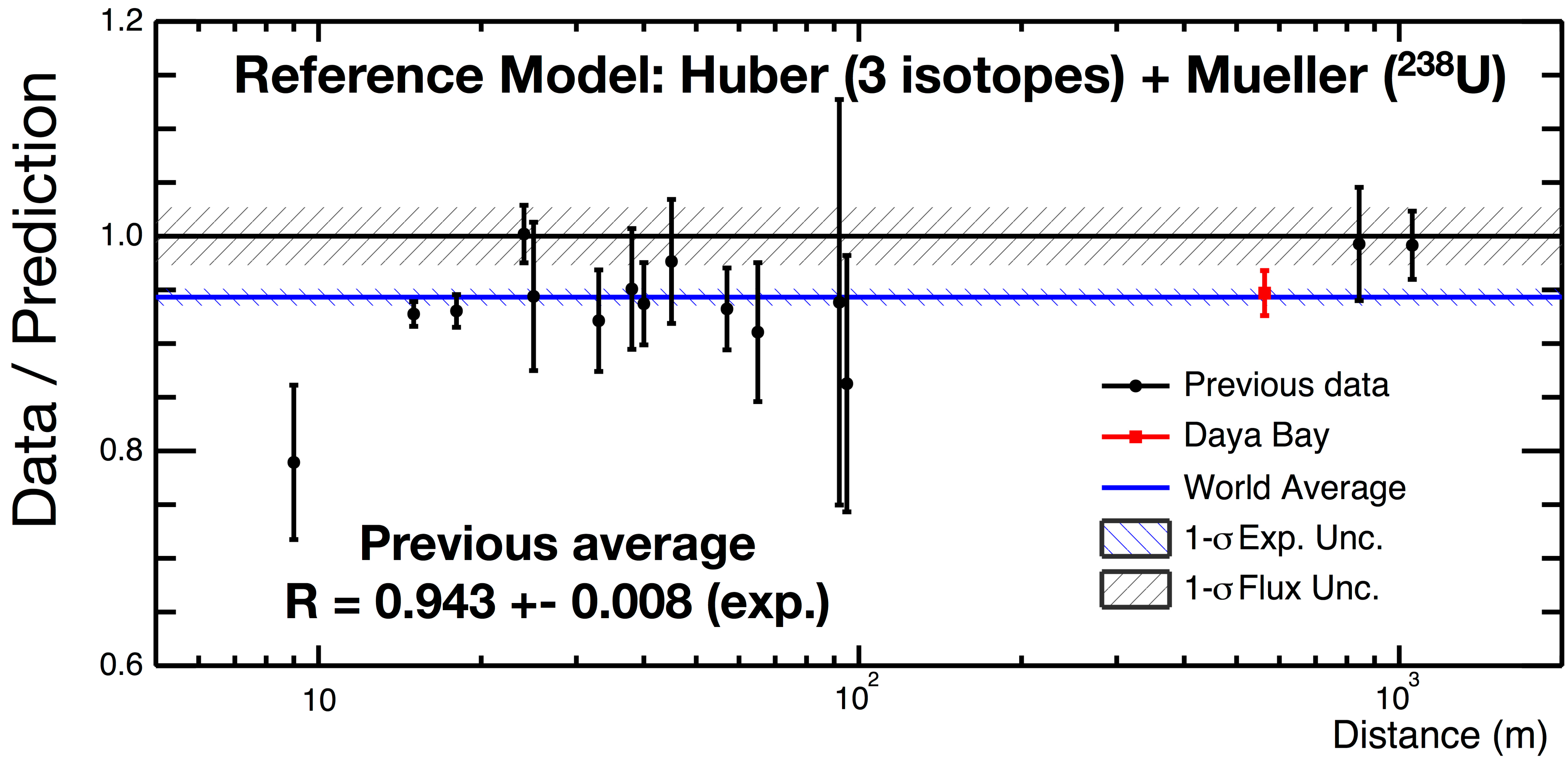
   v) The ``bump" in reactor spectrum

c) Ambitious planned experiments to determine the neutrino hierarchy

d) Attempts to see whether the light sterile neutrinos exist or not

1) Earlier neutrino experiments at nuclear reactors were one detector experiments, comparing the neutrino signal at some distance **L** with the expectation based on the calculated reactor neutrino flux. Recent ones (Daya-Bay, RENO, Double-Chooz) used a `monitor' close detector. Nevertheless, knowledge of that flux is a crucial input.
2) Reevaluation of the reactor flux in 2011 lead to the conclusion that the past experiments at **L** 9-100 meters **missed on average ~6% of the expected signal**.
3) This could be interpreted as either a signature of the **new physics**, e.g., existence of one or more sterile neutrinos with $\Delta m^2 \geq 1$ eV^2 , or as a problem with the reactor neutrino flux determination or its uncertainty.
4) Unlike other indications for sterile neutrinos (e.g. LSND, MiniBoone, Gallex and Sage calibration) in the reactor case there are many experiments at different reactors the total flux is well determined; the conclusions, however, crucially depend on the expected reactor flux.

From the talk of Ch. Zhang at Neutrino 2014.
Daya-Bay result agrees with the previous average.



The data are corrected for the known 3-flavor neutrino oscillations at each distance. The Daya-Bay entry is for L = 573 m, the flux averaged distance of the close detectors. The Daya-Bay ratio alone is 0.947 +- 0.022.

So, how is the reactor neutrino spectrum determined?

There are two ways, each with its strengths and weaknesses:

1) Add the beta decay spectra of **all** fission fragments. That obviously requires the knowledge of the fission yields (how often is a given isotope produced in fission), halflifes, branching ratios, and endpoints of all beta branches, and spectrum shape of each of them. And error bars of all of that.
2) Measure the **electron** spectrum associated with fission and convert it into the neutrino spectrum using the fact that the electron and neutrino share the available energy of each decay. Requires a realistic estimate of the error involved in the conversion. The electron spectra of ^{235}U,^{239}Pu, and ^{241}Pu fission were determined in 1980-1990 at ILL, Grenoble. They were republished with finer binning in arXiv 1405.3501. Less accurate ^{238}U spectrum for fast neutron fission is in Haag et al., PRL 112,122501 (2014).

Electron and antineutrino spectrum associated with fission is composed of ~6000 beta decay branches from the decay of the neutron rich fission fragments

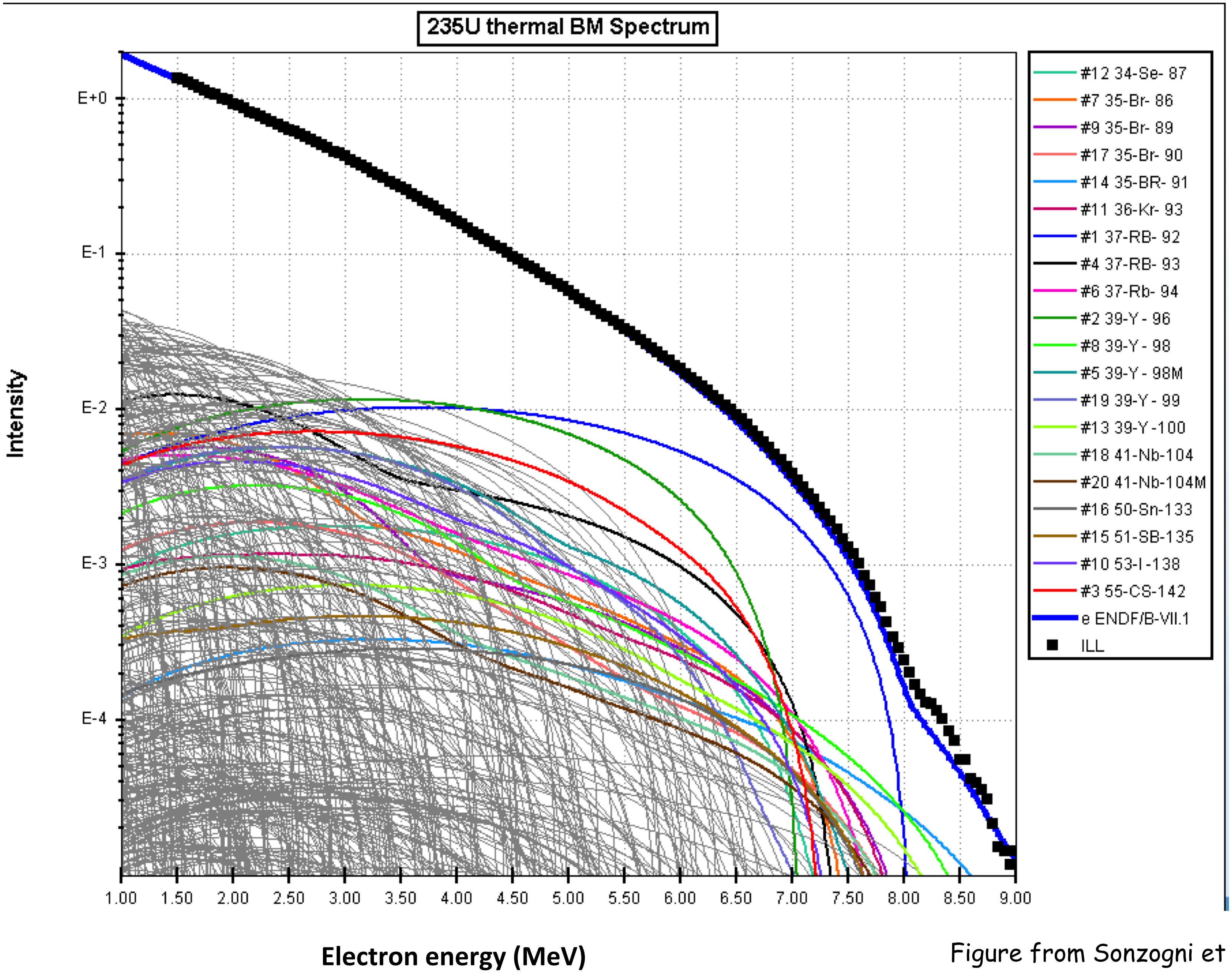
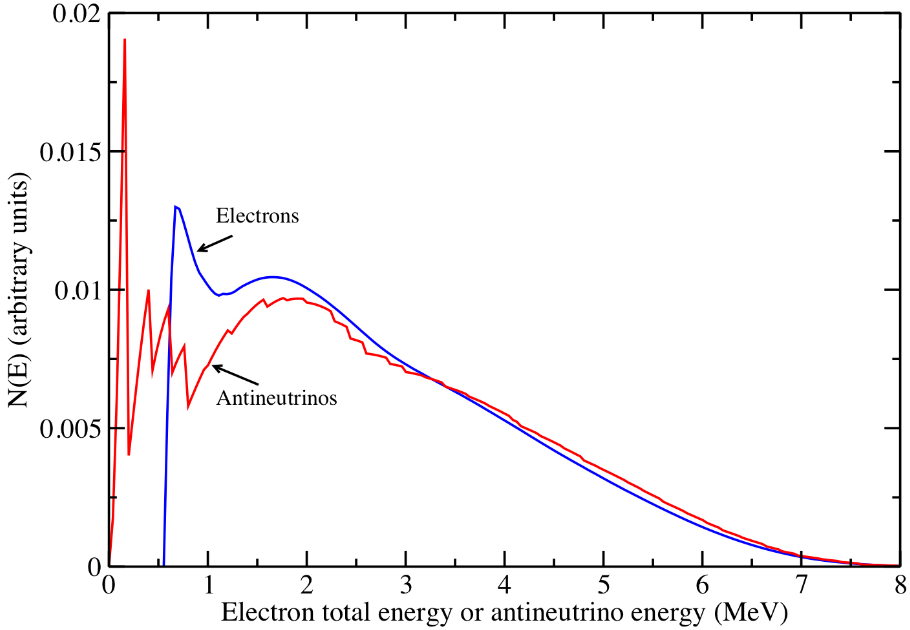
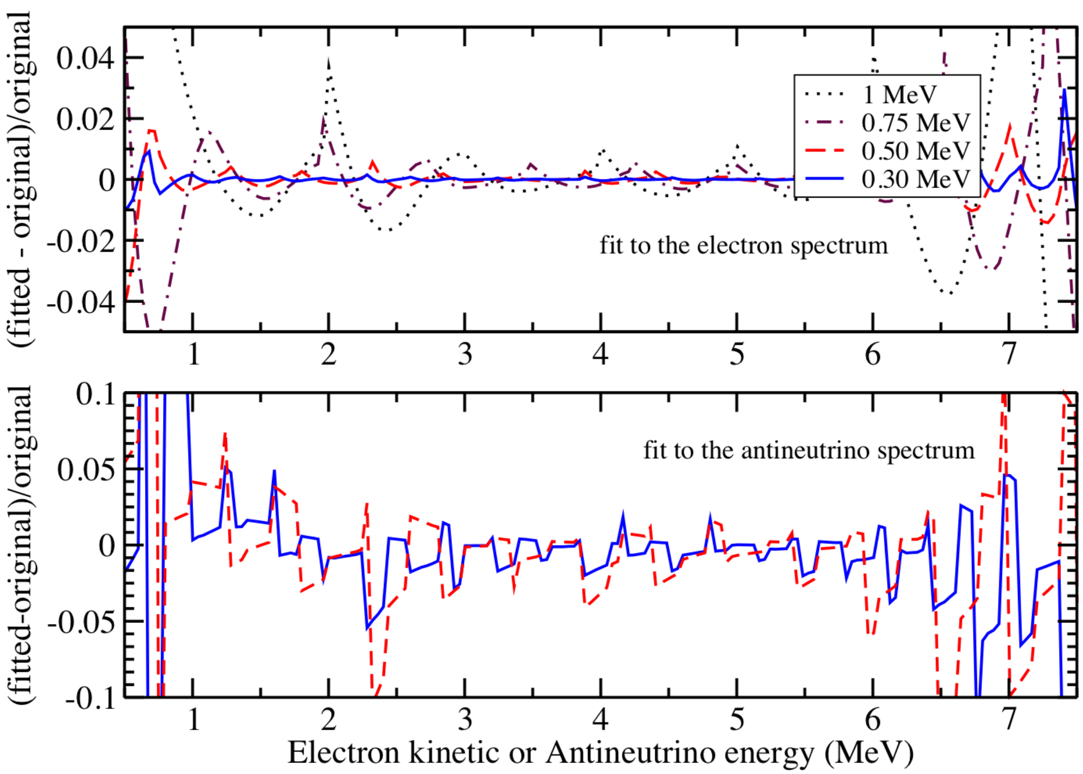


Figure from Sonzogni et al, PRC 91,011301

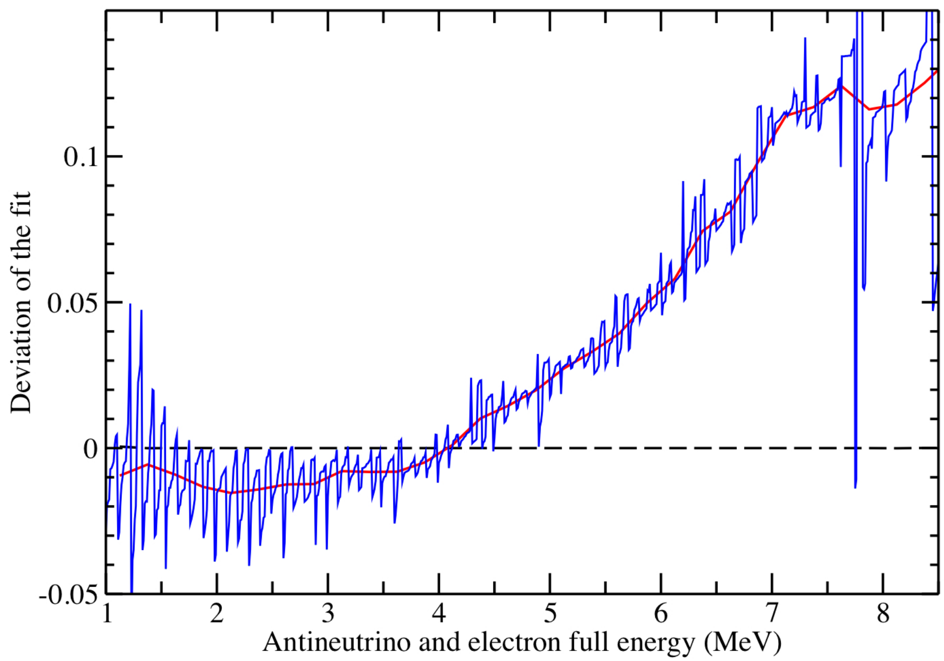


Example of a complex spectrum. Hypothetical β decay of Z=45 nucleus, with 40 branches with random endpoints and branching ratios. The largest Q-value is 8 MeV. Allowed spectrum shape is assumed.

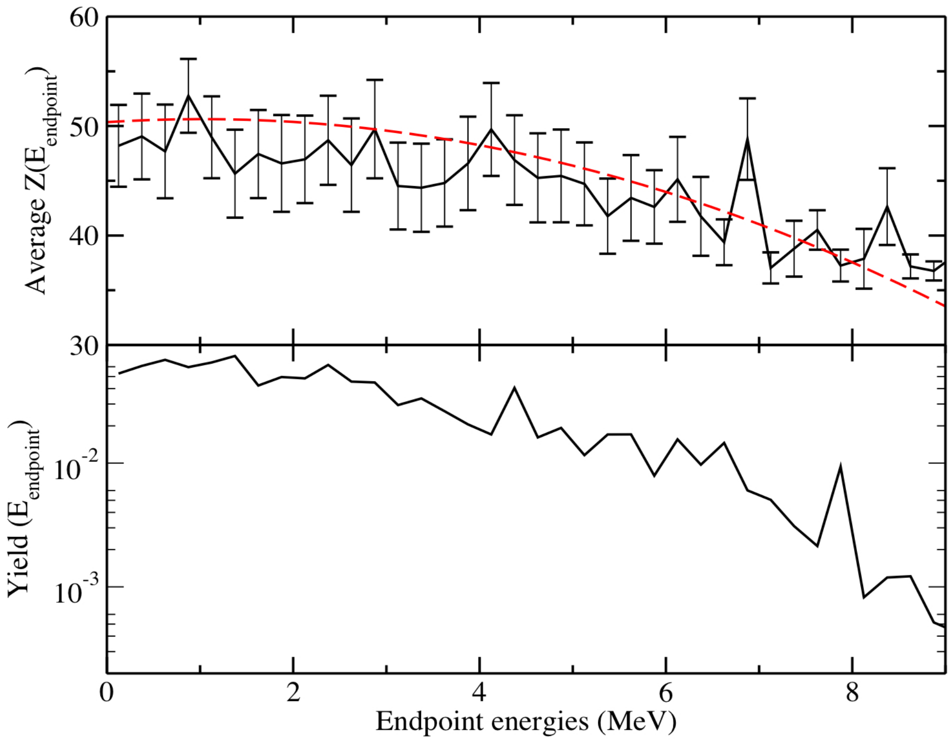


Fit to the above electron spectrum. The spacing of slices is indicated. Deviation of the fit is shown.

Same as above, but for the neutrino spectrum.



Fit to the ^{235}U spectrum assuming that all nuclei have a **single** Z = 47. The electron spectrum (dashed) is fitted perfectly, but the neutrino spectrum (jagged and smoothed in red) deviates from the input by as much as 10%.



The average Z as a function of the endpoint energy and a quadratic polynomial fit (dashed red).
With this function the ^{235}U spectrum is fitted to better than 1%.

The conversion procedure allows one to obtain the ν_e spectrum with < 1% error provided that the corresponding β decay shapes are all well known and described.

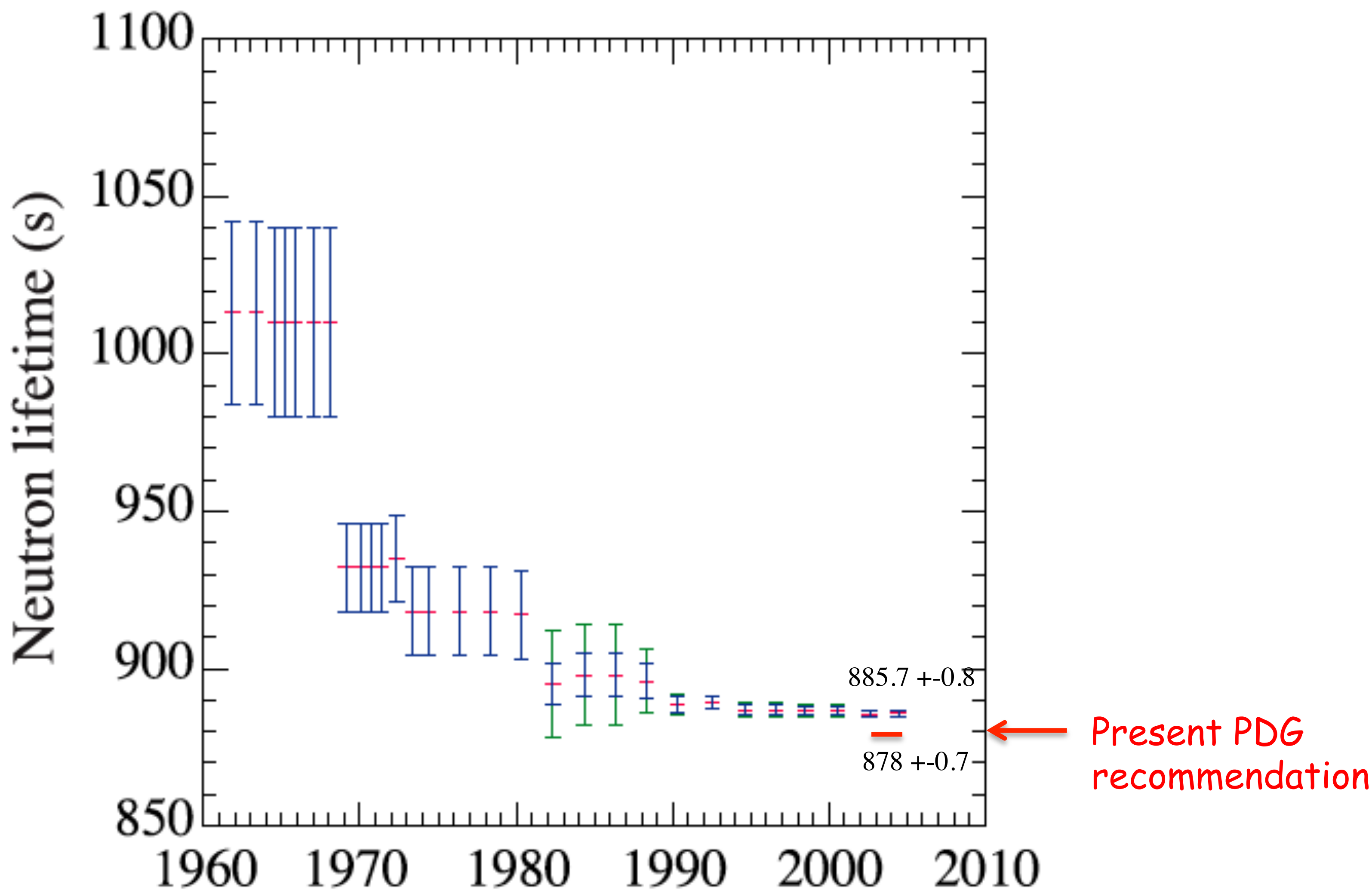
Why do the results of Mueller et al. differ from the old results of Schreckebach et al.?

There are several reasons, each relatively small, but by a strange conspiracy, they all act with **the same sign** increasing the flux at all energies, without changing the spectrum shape significantly:

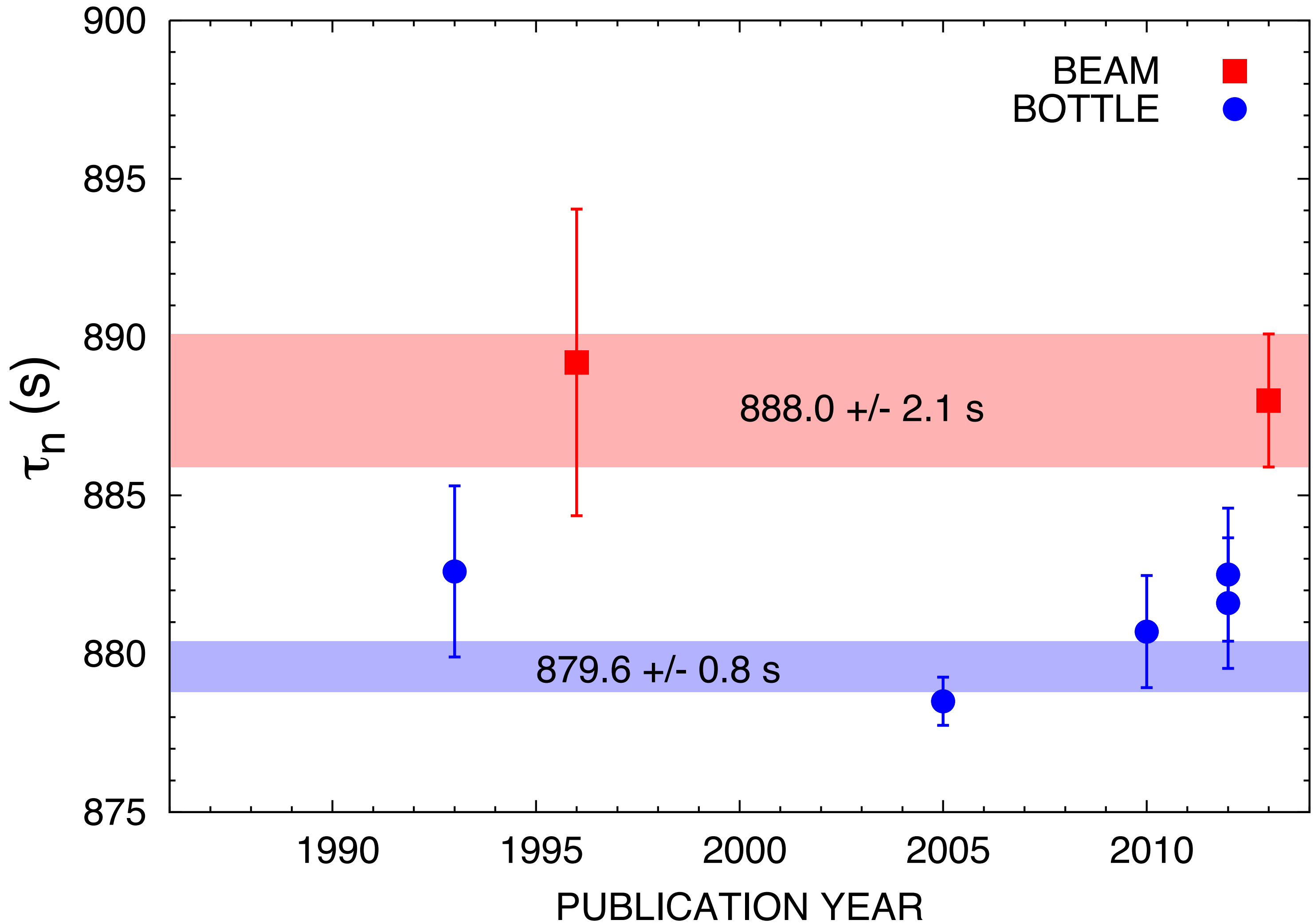
1)More consistent application of A_{WM} and A_{FS}	1-2%
2)Newer data used for $\langle Z \rangle(E_0)$	1-2%
3)Off equilibrium correction	~1%
4)Change in the measured neutron lifetime	~1%

This all looks quite reasonable, but is it all?
Lets look at the corrections to the allowed decays in more detail.

History of the neutron lifetime measurement. Serebrov 2005 result differs from the previous ones by ~6.5 σ. Present PDG recommendation is 880.2 +- 1.0.



There are two basic methods of the τ_n measurement. Either a beam of cold neutrons is used or ultracold neutrons are stored in magnetic bottles. These two methods give, so far, inconsistent results.



from Bowman et al. 1410.5311,

Spectrum shape of the individual β decays:

$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 C(E) F(E_e, Z, A)(\underline{1 + \delta(E_e, Z, A))}$$

Fractional corrections to the individual beta decay spectra:

$$\delta(E_e, Z, A) = \delta_{rad} + \delta_{FS} + \delta_{WM}$$

$$\left\{ \begin{array}{l} \delta_{\mathrm{rad}} = \text{Radiative correction (used formalism of Sirlin)} \\ \boxed{\begin{array}{l} \delta_{FS} = \text{Finite size correction to Fermi function} \\ \delta_{\mathrm{WM}} = \text{Weak magnetism} \end{array}} \end{array} \right.$$

F(E,Z,A) is the Fermi function to account for the Coulomb interaction of the emitted electron. To get the neutrino spectrum use $E_\nu = E_0 - E_e$.
C(E) is the shape factor. For allowed β decays C(E) = 1.
But for forbidden decays C(E) ≠ 1.

One of the main causes of the upward shift in the reactor spectrum evaluation of Mueller et al. and Huber, and hence to the \`reactor anomaly', was the more careful treatment of δ_{FS} and δ_{WM} for the allowed β decays.

Weak magnetism correction $1 + \delta_{WM} E_e$

$\delta_{WM} = 4/3[(\mu_v - 1/2)/Mg_A]$(Vogel 84) or $4/3[(\mu_v - 1/2)/Mg_A](1 - m_e^2/2E_e^2)$ (Hayes 13)
$\mu_v = \mu_p - \mu_n = 4.7$

Using CVC $\delta_{WM} = 4/3[6\Gamma_{M1}^3/\alpha E_\gamma^3]^{1/2}$ m_e for M1 transition of the analog state.
The table below shows available data, the average δ_{WM} = 0.67(0.26) % MeV^{-1} while the formula above gives ~0.5% MeV^{-1}. In calculations 100% error was assumed.

decay	$J_i \to J_f$	E_γ [keV]	Γ_{M1} [eV]	b_γ	ft [s]	c	b_γ/Ac	$\lvert dN/dE \rvert$ [% MeV^{-1}]	Ref.
^{6}He $\to$ ^{6}Li	$0^+ \to 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646	[28]
^{12}B $\to$ ^{12}C	$1^+ \to 0^+$	15110	43.6	37.9	11640.	0.726	4.35	0.62	[29]
^{12}N $\to$ ^{12}C	$1^+ \to 0^+$	15110	43.6	37.9	13120.	0.684	4.62	0.6	[30]
^{18}Ne $\to$ ^{18}F	$0^+ \to 1^+$	1042	0.258	242.	1233.	2.23	6.02	0.8	[31]
^{20}F $\to$ ^{20}Ne	$2^+ \to 2^+$	8640	4.26	45.7	93260.	0.257	8.9	1.23	[32]
^{22}Mg $\to$ ^{22}Na	$0^+ \to 1^+$	74	0.0000233	148.	4365.	1.19	5.67	0.757	[33]
^{24}Al $\to$ ^{24}Mg	$4^+ \to 4^+$	1077	0.046	129.	8511.	0.85	6.35	0.85	[34]
^{26}Si $\to$ ^{26}Al	$0^+ \to 1^+$	829	0.018	130.	3548.	1.32	3.79	0.503	[35]
^{28}Al $\to$ ^{28}Si	$3^+ \to 2^+$	7537	0.3	20.8	73280.	0.29	2.57	0.362	[36]
^{28}P $\to$ ^{28}Si	$3^+ \to 2^+$	7537	0.3	20.8	70790.	0.295	2.53	0.331	[36]
^{14}C $\to$ ^{14}N	$0^+ \to 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6	[29]
^{14}O $\to$ ^{14}N	$0^+ \to 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92	[26]
^{32}P $\to$ ^{32}S	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9	[37]

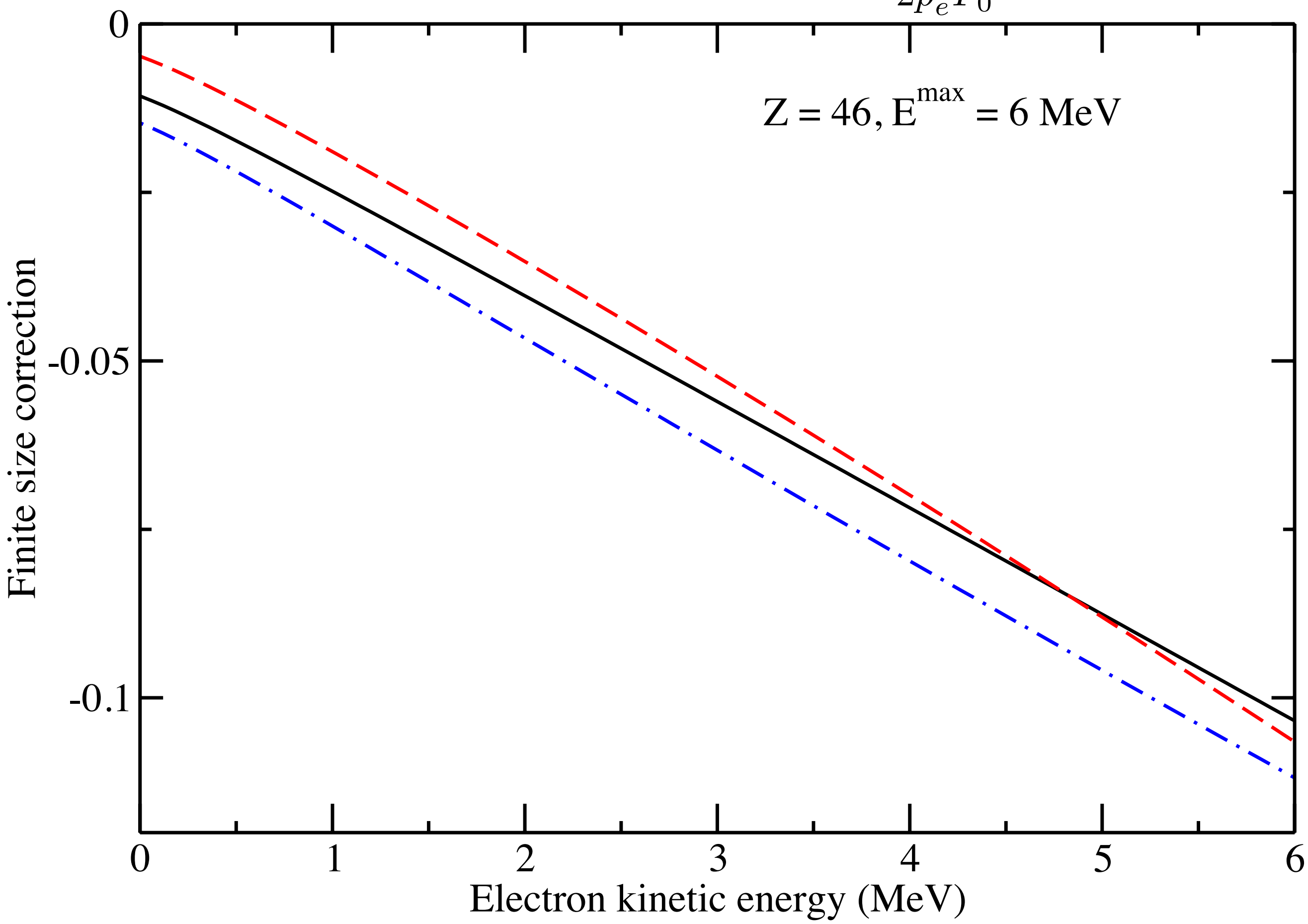
Table from P. Huber, Phys. Rev. C**84**, 024617(erratum C**85**, 02990(E) (2012)

Finite size correction δ_{FS}

$$\delta_{FS}^{(1)} = -\frac{8}{5}\frac{Z\alpha R E_e}{\hbar c}\left(1 + \frac{9}{28}\frac{m_e^2}{E_e^2}\right)$$ Hayes et al. (2014), full line

$$\delta_{FS}^{(2)} = -\frac{10}{9}\frac{Z\alpha R E_e}{\hbar c}\frac{\langle \sigma r^2\rangle}{\langle\sigma\rangle R^2} \cdot \quad \frac{\langle \sigma r^2\rangle}{\langle\sigma\rangle R^2} = 3/5$$

and replace F_0 by $F_0 L_0$, $L_0 = \frac{g_{-1}^2(r=0) + f_{+1}^2(r=0)}{2p_e^2 F_0}$, Vogel (1984), dot-dashed line

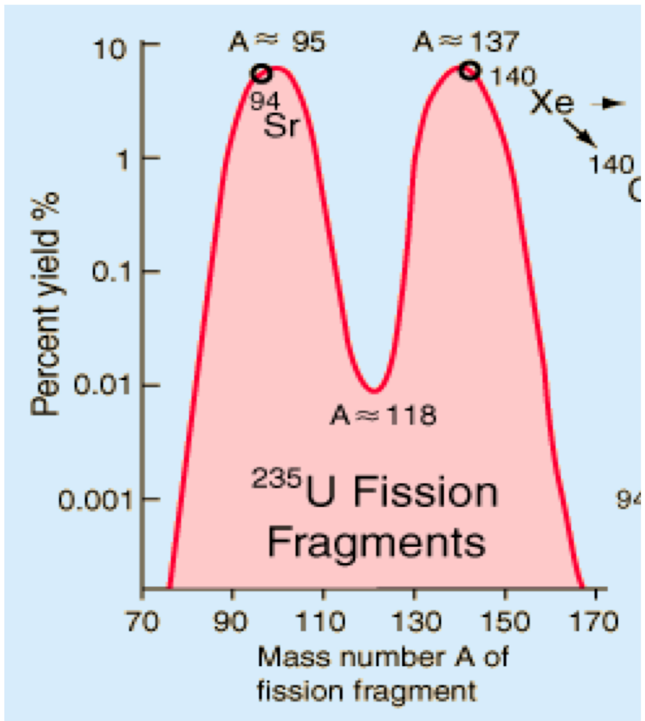


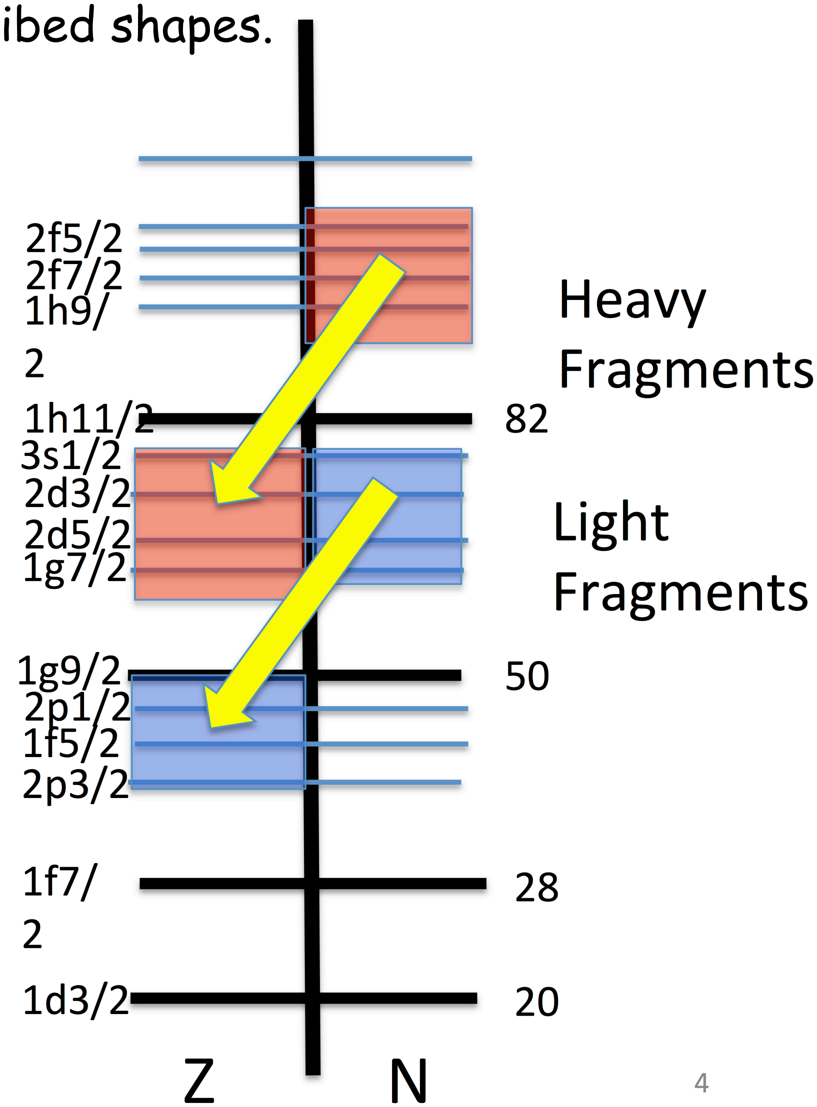
Different ways to take into account nuclear finite size exist in the literature.
In fact the resulting slopes are quite similar, and to some extent they compensate for the δ_{WM}

Dashed line is based on the fit by Wilkinson (1990) used by Huber (2011)

To emphasize the slope, the energy independent part was adjusted .

The fission fragments are neutron rich and in many of them the least bound neutrons and protons are in states of opposite parity. Thus, among the ~6000 beta decay branches, about 25% are first forbidden decays with somewhat different, and much less well described shapes.



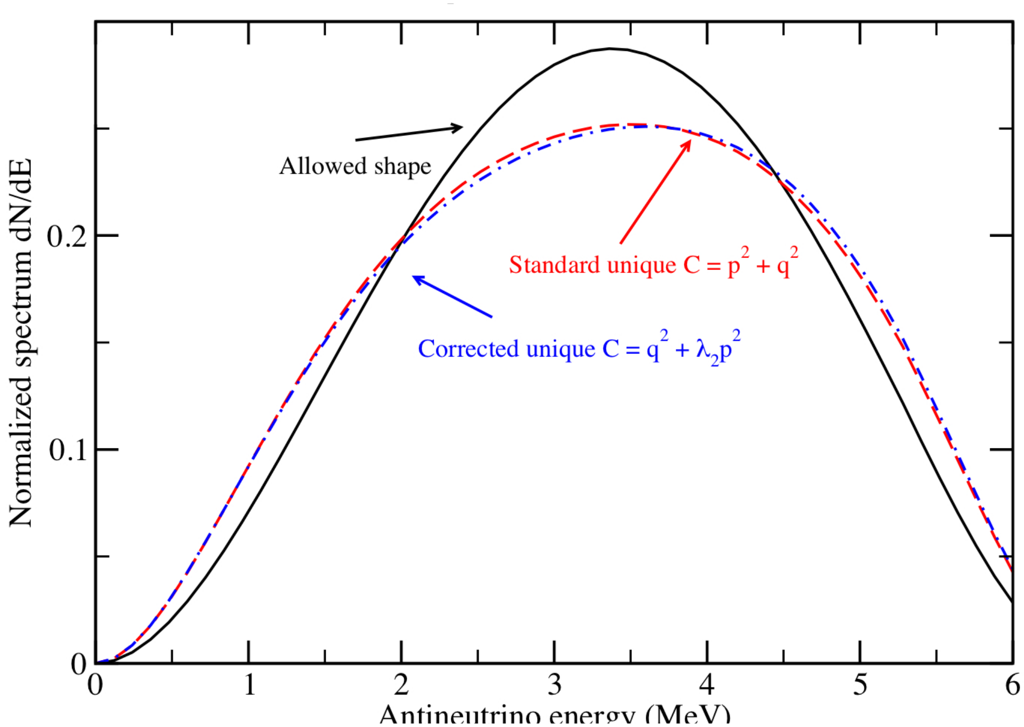


The error associated with the forbidden decays was not properly included in the previous analyses.

First forbidden decays are nominally suppressed by $(pR)^2 \ll 1$. But they do occur if the selection rules $\pi_i\pi_f = -1$, $\Delta J \leq 2$ require them.

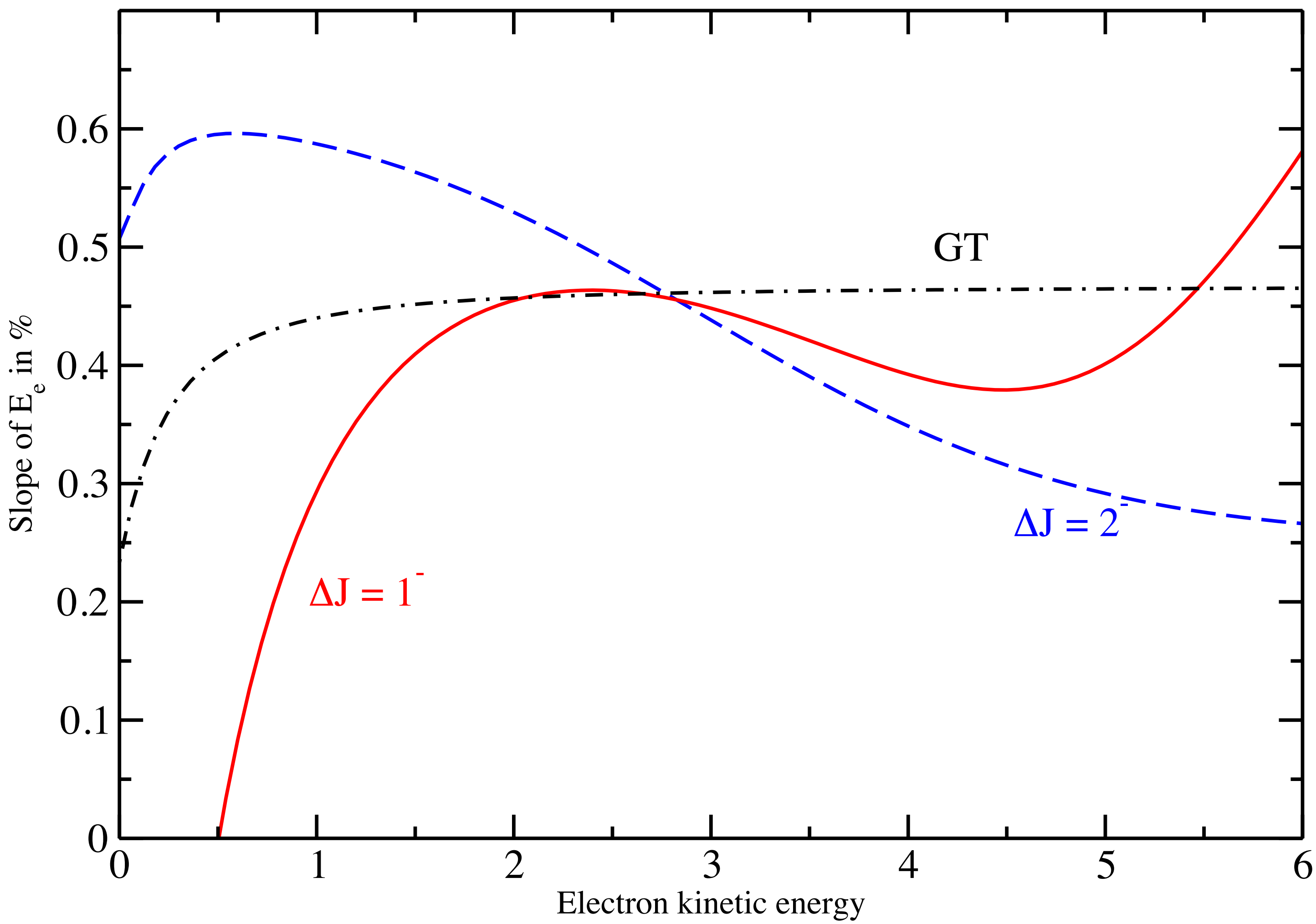
Unlike for the allowed GT decays with only one operator, there are up to six operators for the first forbidden decays that can interfere.

In a reasonable approximation, as long as $\xi = \alpha Z/R \gg E_0$, the spectrum shape is similar to the allowed one. But for fission fragments with large E_0, $\xi \sim E_0$. Also, even if $\xi \gg E_0$, there can be cancellation of matrix elements and hence deviations from the allowed shape.



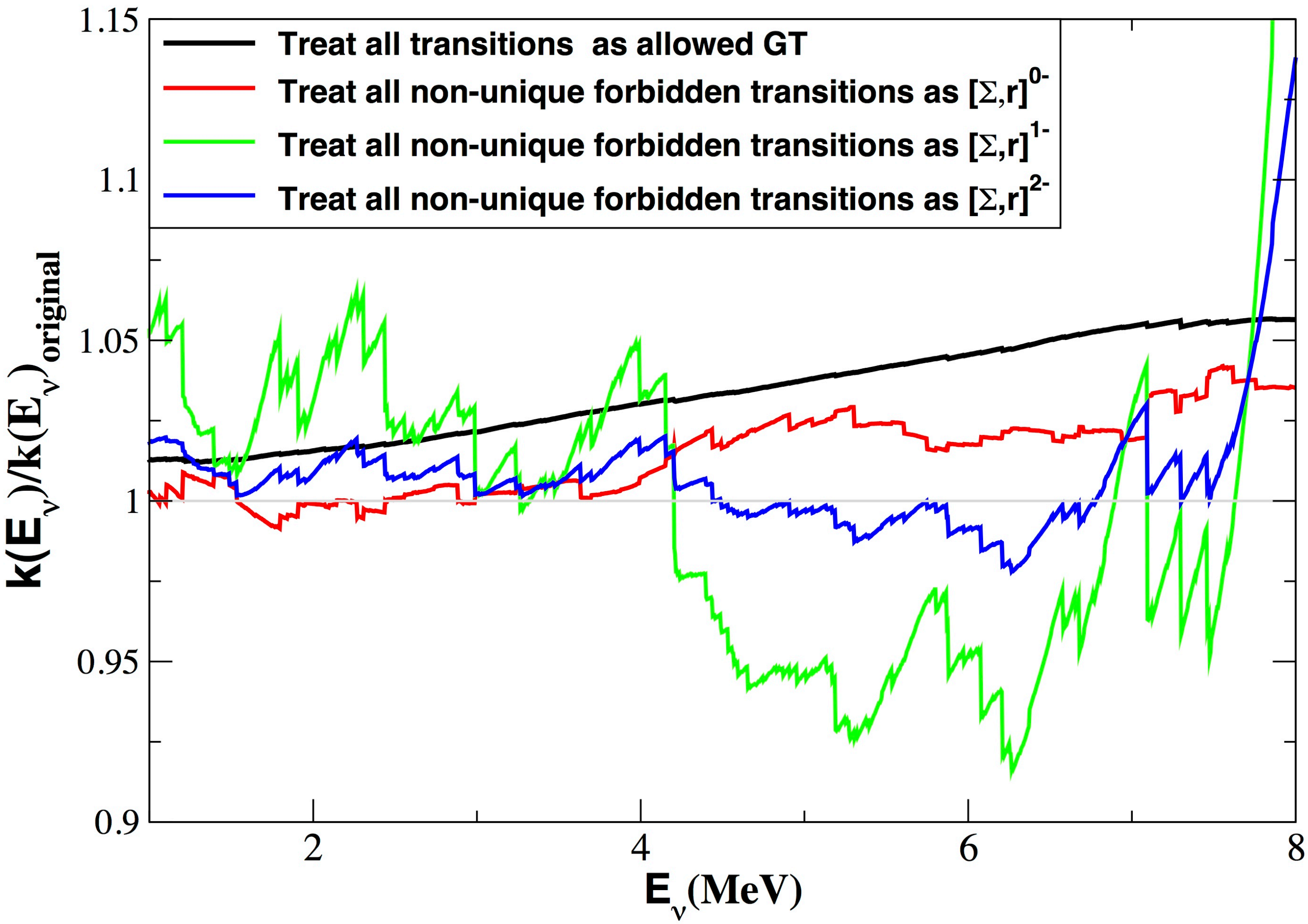
First forbidden decays with $|\Delta I| = 2$ are governed by only single matrix element and thus have again a simple shape.
Here is an example for Z=46, Q=6 MeV.

The weak magnetism corrections for the first forbidden decays are different from those in the allowed case. For $0^- \rightarrow 0^+$ $\delta_{WM} = 0.0$. For the other ones δ_{WM}/E_e is shown here.

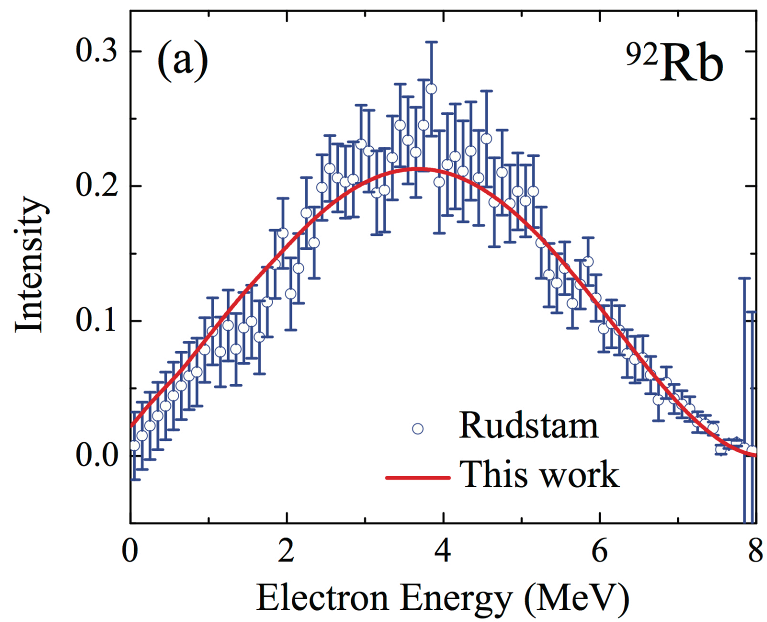


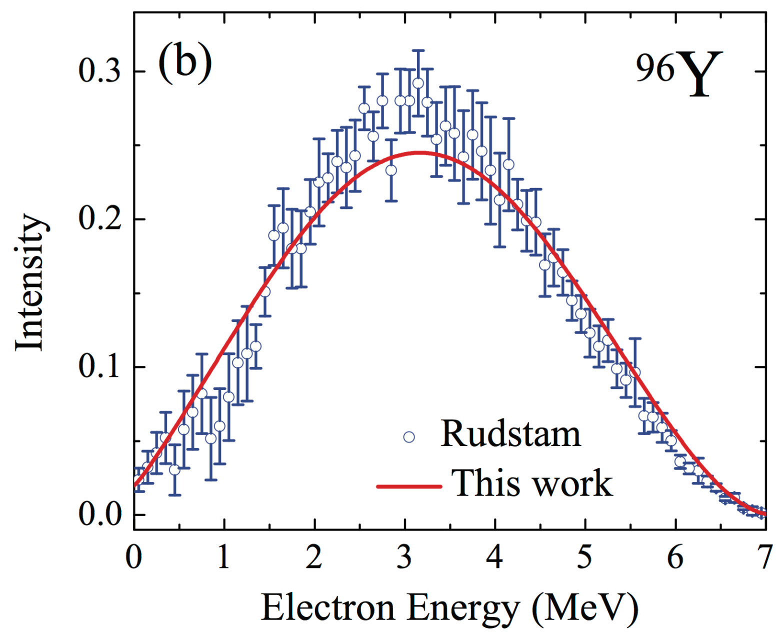
from A. Hayes et al, PRL **112**, 202501 (2014).

Ratio of the ν_e spectrum to the electron spectrum for ^{235}U normalized to the one obtained by assuming $E_\nu = E_e$ (kinetic).
Different shape factors assumed. No path leads to less than 5% error. Figure from A. Hayes et al, PRL **112**, 202501 (2014).



Note, however, that in reality a combination of shapes occurs. Thus these error limits must be considered as an illustration.





Examples of measured $0^- \rightarrow 0^+$ transitions of important fission fragments. Measurement of G. Rudstam et al. ADNT **45**, 239 (1990), calculations assuming the allowed shape of A. A. Sonzogni et al, PRC **91**, 011301 (2015). For these transitions δ_{WM} = 0.0

Table 3 The estimated uncertainties for the ingredients that make up the aggregate antineutrino spectra when the summation method is used. These estimates are subjective and are bases on the the educated guess of the authors. They do not represent statistical variances.

Quantity	type	ΔJ^{π}	uncertainty
Unknown branching and J^{π}	allowed and forbidden	all	50%
Finite size corr.	allowed	1^{+}	50%
Finite size corr.	forbidden	$0^{-}, 1^{-}, 2^{-}$	100%
Weak magnetism	allowed	1^{+}	20%
Weak magnetism	forbidden	0^{-}	0
Weak magnetism	forbidden	2^{-}	20%
Weak magnetism	forbidden	1^{-}	25%
Shape factor	allowed	1^{+}	0
Shape factor	forbidden	2^{-}	0
Shape factor	forbidden	$0^{-}, 1-$	30%
Fission yields	allowed and forbidden	all	10%
Missing spectra	allowed and forbidden	all	50%

From Hayes and Vogel, Ann. Rev. Nucl. Part. Sci. **66**,219 (2016)

1) The assumed uncertainty of ~2.7% (Mueller, Huber) was based on the assumption that the shapes of **all** β decays are known (either allowed or, if quantum numbers are known, than unique first forbidden).
2) Since ~25% of the decays are first forbidden, most of them non-unique, that assumption is not justified.
3) In view of this it is difficult to quantify the true uncertainty. Testing the conversion procedure suggests that ~5% uncertainty is a more realistic estimate.
4) To proceed further two possibilities exist:
   i) Accurately measure the spectrum shape of the ~20 most important first forbidden decays.
   ii) Perform accurate measurement using research reactors at small distance. This gives ^{235}U ν_e spectrum. Use the `ab initio' method to derive the spectra for the other fuels.
5) Until we have a reliable reactor spectrum, including realistic error bars, we cannot use the `reactor anomaly' as an argument for or against the existence of the light ~1 eV mass sterile neutrinos.

Besides the theoretical reasons, underestimate of the error by not properly treating the forbidden decays, there is an experimental reason as well. The theoretical calculation, until now, does not describe the recently observed spectrum feature, so-called `bump' .

The `bump' or shoulder observed in the positron spectra in RENO, Daya-Bay and Double-Chooz (about 4σ significance) and not predicted theoretically, was not observed in the ILL electron spectra, and neither it was observed in the 1996 Bugey-3 experiment.

We need to ask:

i) What is its origin ?
ii) Why it is not observed in the ILL spectrum ?
iii) Should we question the predicted spectrum in general ?

Note that the bump cannot be produced by the standard L/E oscillation dependence, nor by the structural material of the reactor. **Its origin must be the reactor fuel $\bar{\nu}_e$ emission.**

The bump at 4-6 MeV of the positron (5-7 MeV of the neutrino) energy as observed in the RENO experiment. It does not affect significantly the θ_{13} analysis. Very similar results obtained in Daya-Bay and Double-Chooz.

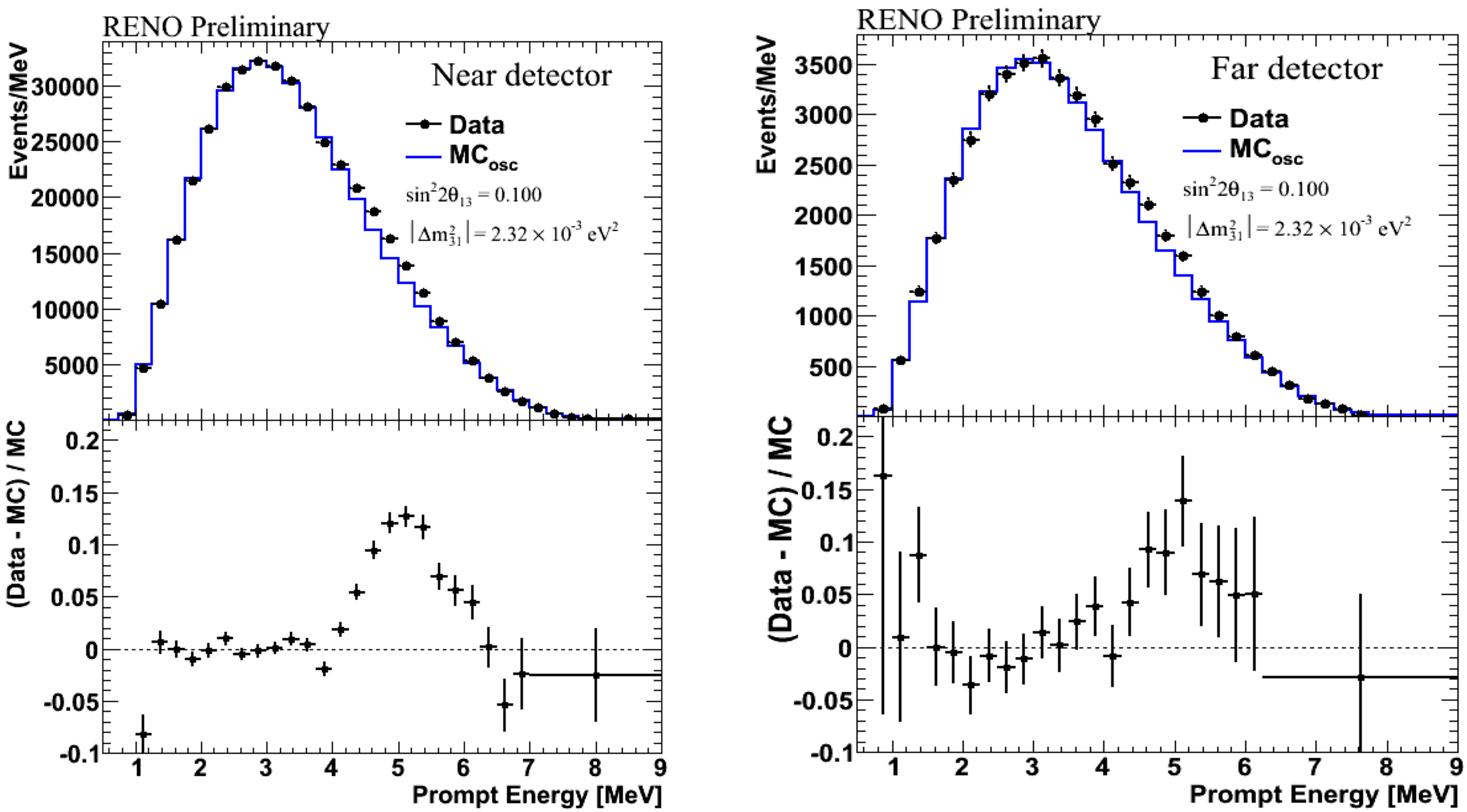
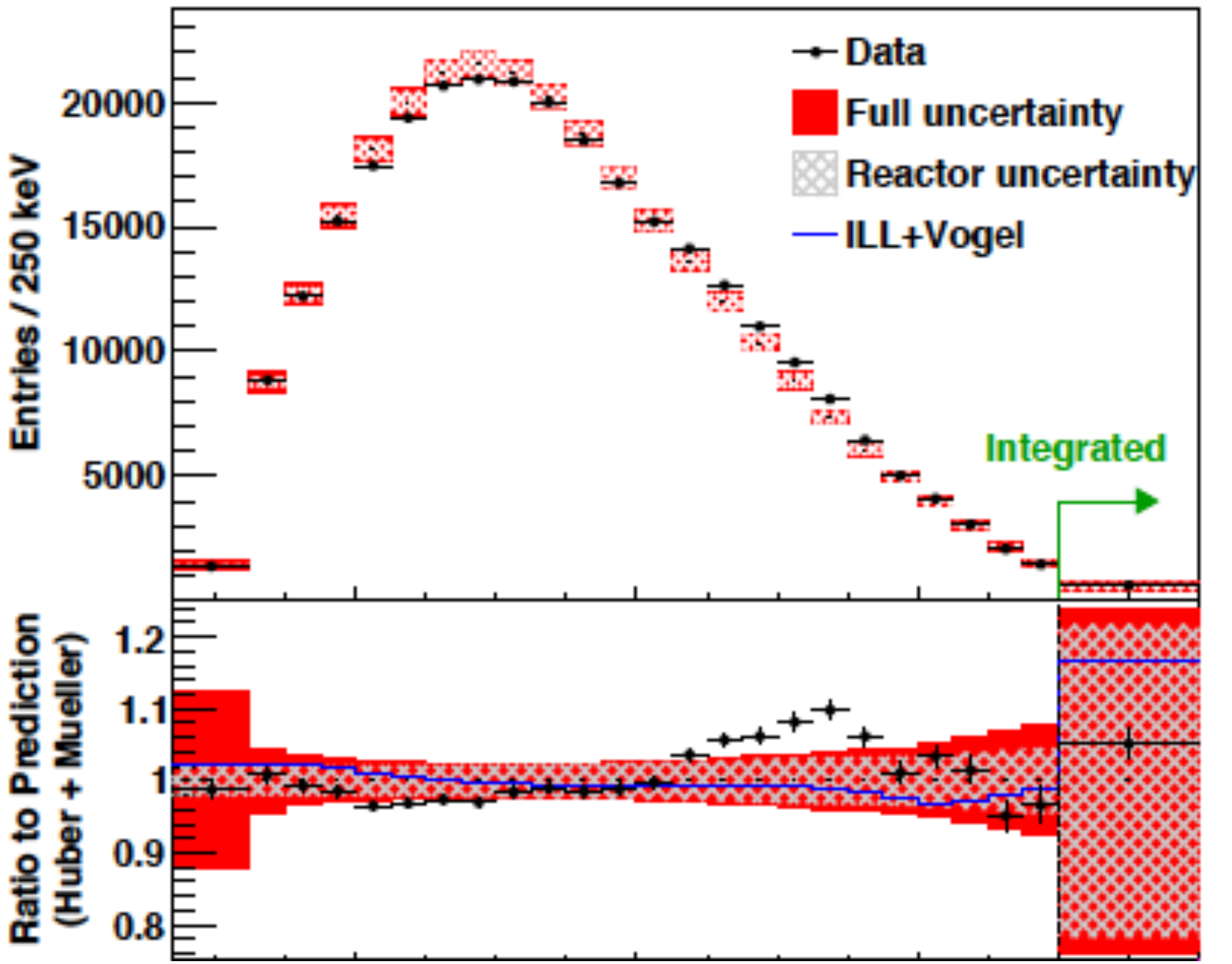
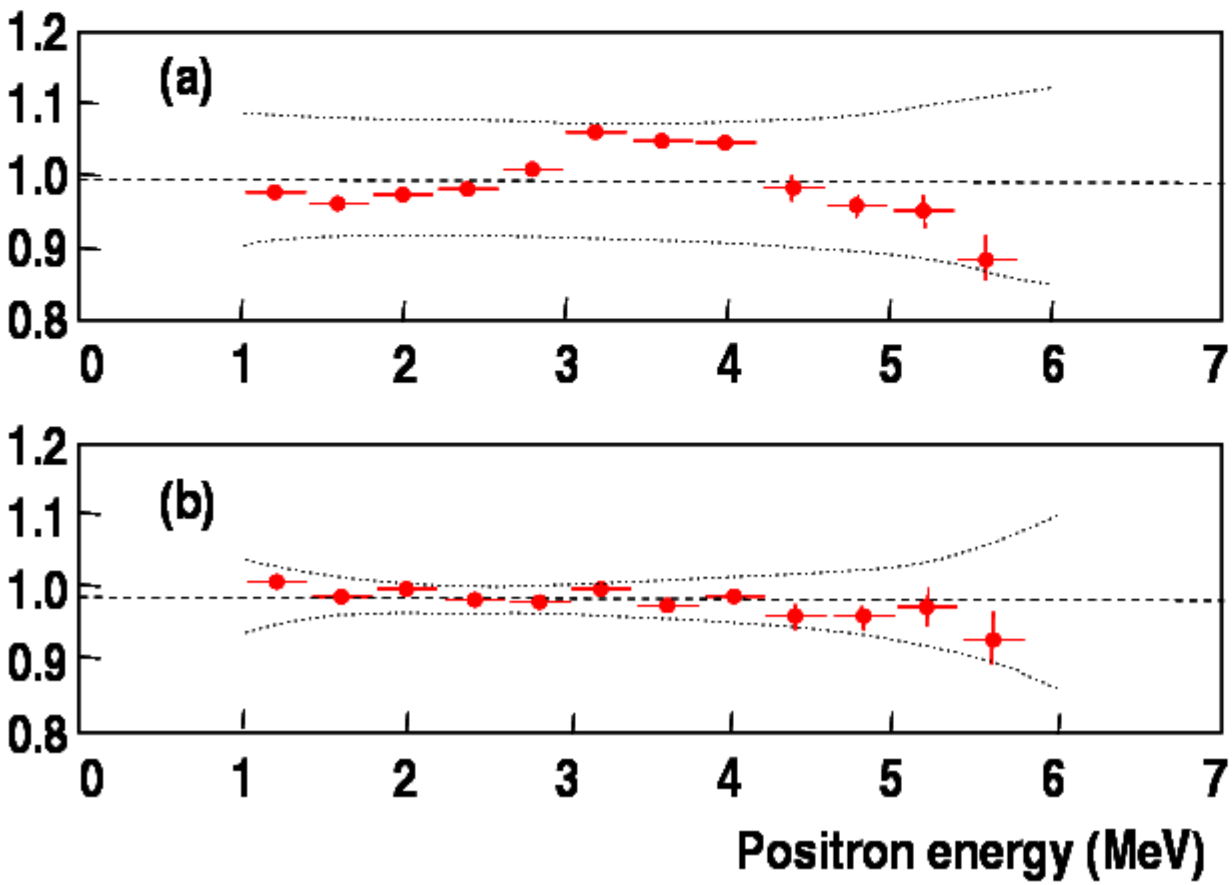


Figure from S-H Seo for RENO collaboration, talk at the Neutrino 2014 conference



The shoulder or ``bump" observed in the near detectors at Daya-Bay
(from An *et al.* Phys. Rev. Lett. 116, 061801 (2016))

Measured ν_e spectrum shape and normalization at Bugey (1996) agreed with the converted spectrum of Schreckenbach et al. to better than 5%. No sign of the ``bump”. This agreement, historically, increased the confidence that the converted ILL electron spectrum is accurate.



Calculation only
Klapdor and Metzinger, 1982

Beta calibrated
Schreckenbach, 1985
Hahn, 1989

Results of Bugey experiment (1996)

The bump or shoulder observed in Daya-Bay as a ratio to the Huber+Mueller prediction. The shoulder is visible when summing the individual branches using the ENDF data library, as shown by Dwyer and Langford in PRL **114**, 012502 (2015) but is absent when using the JEFF data library. However, it appears that the ENDF library contains some `trivial' errors (Sonzogni, private information). When corrected, the `bump' disappears and the two libraries agree with each other..

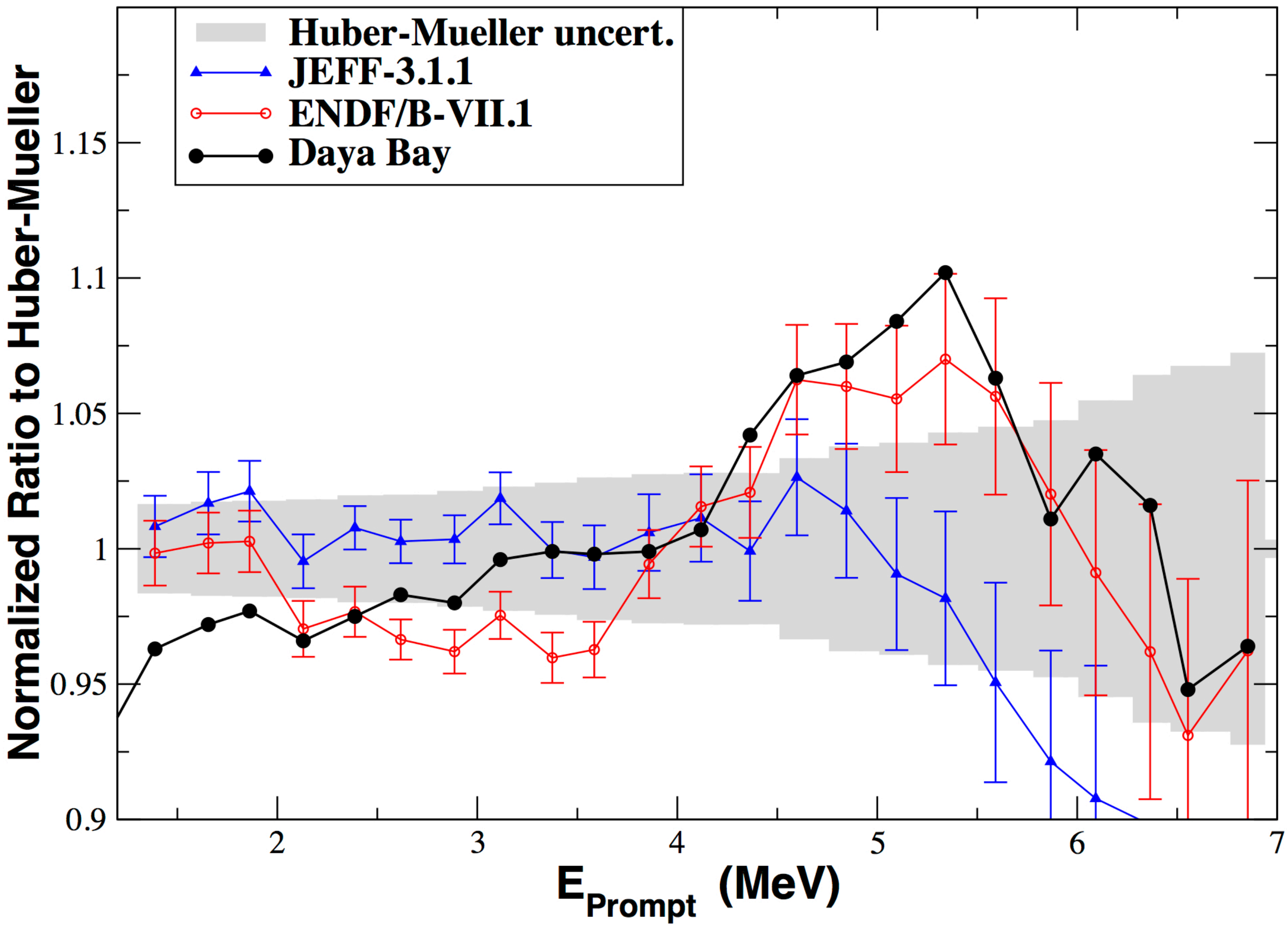
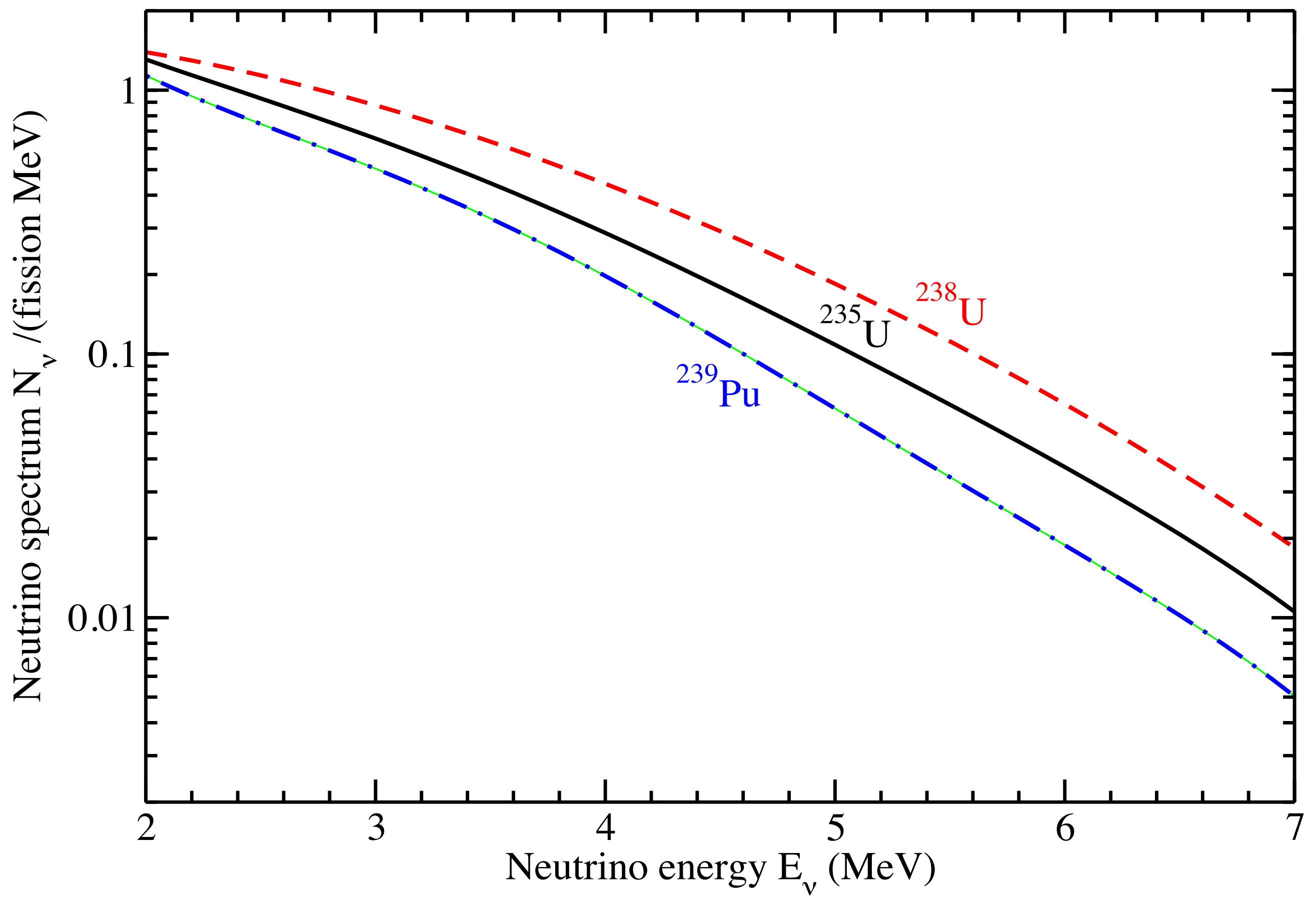
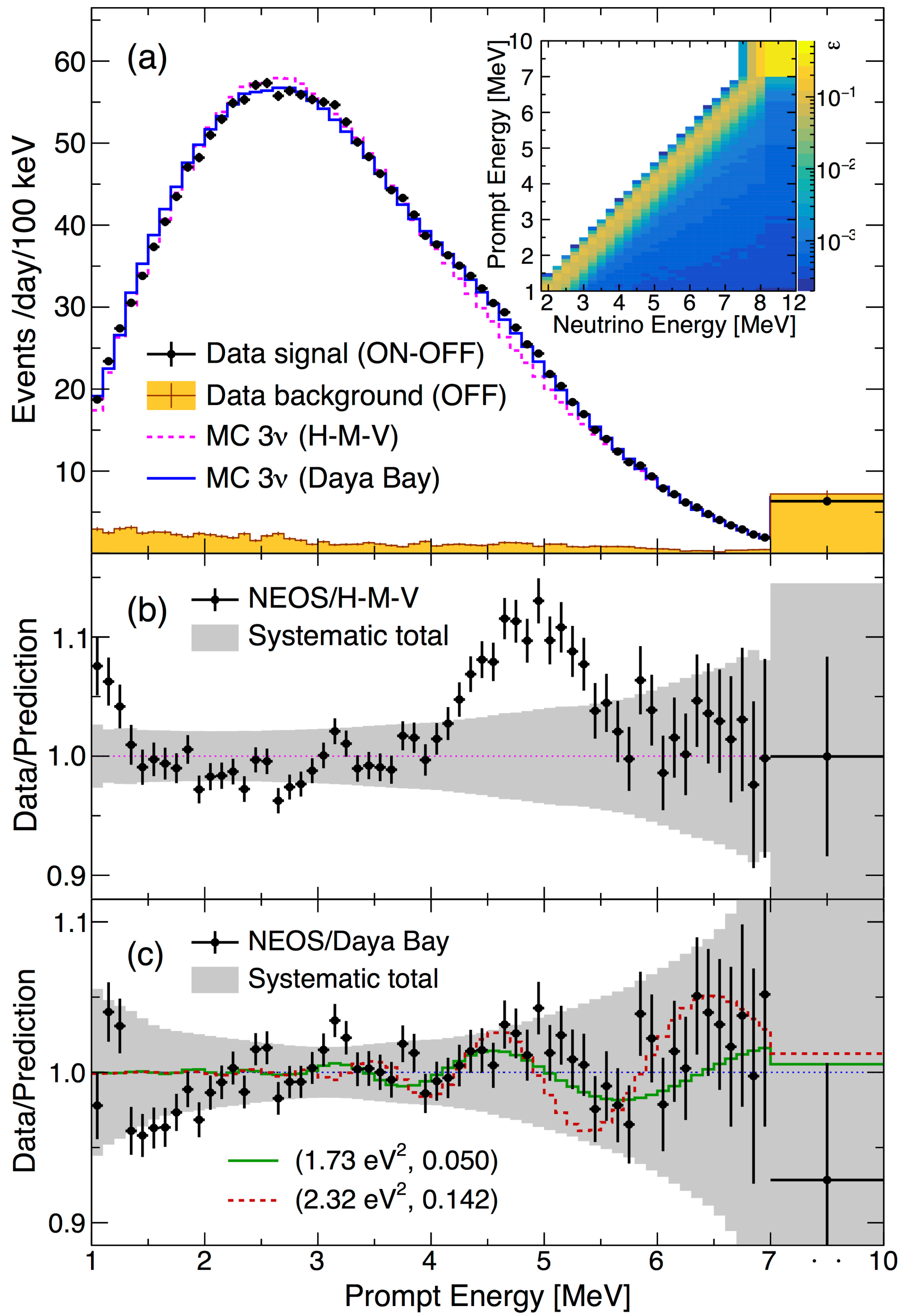


Figure 1 from A.C. Hayes et al., 1506.00583

If the agreement of the two libraries is confirmed this likely means for the issue of the ``bump" origin:

i) There is no problem with the ILL data
ii) We still do not know what is causing the `bump' but the ^{238}U fission is an unlikely possibility.
iii) Huber (1609.03910) argues that ^{239}Pu and ^{241}Pu are unlikely, and ^{235}U is preferred.

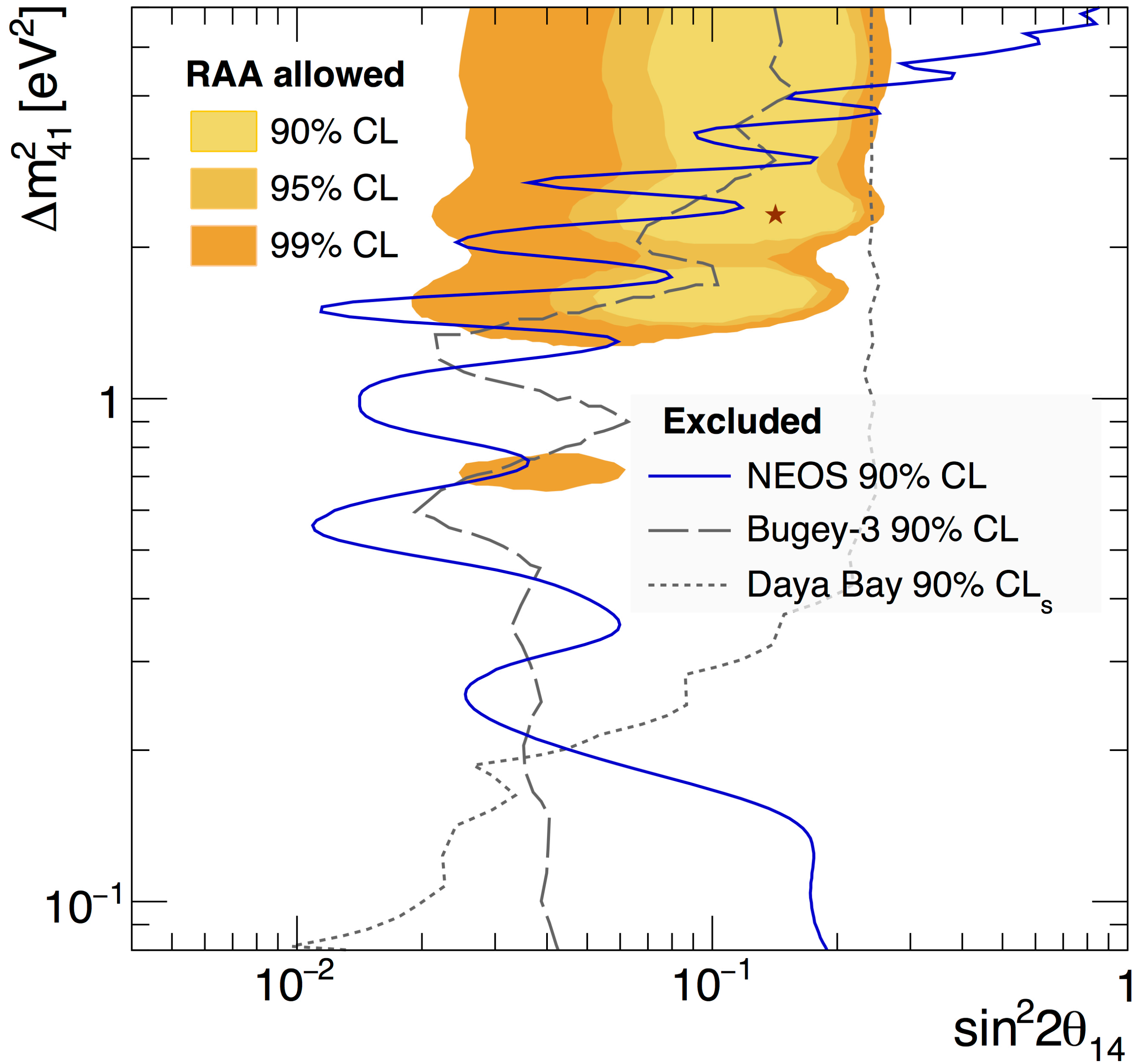




In the NEOS experiment (1610.05134) the detector is ~24 m away from a Korean power reactor (in the same complex as the RENO experiment).

The ``bump" is clearly observed, but no evidence for sterile neutrinos is found. Green and red lines indicate the best fit for the 3+1 oscillation scheme as indicated.

This is the first among the new short baseline experiments designed to test the ~1 eV sterile neutrino hypothesis.



Exclusion plot in The 3+1 sterile neutrino scheme by the NEOS experiment.
The best fit point of Mention et al. (star) is disfavored by $\Delta\chi^2 = 5.4$.

The best present fit point (1.73 eV^2, $\sin^2 2\theta_{14}$ = 0.05) has $\Delta\chi^2$ = 6.5 when compared to the $\sin^2 2\theta_{14}$ = 0, i.e. no sterile neutrino hypothesis.

If sterile neutrinos are the explanation of the `reactor anomaly' and the Mueller-Huber evaluation is correct, the rate should be the same for all four reactor fuels (^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U). However, recent Daya-Bay analysis suggests, at ~3σ, that ^{235}U is ~8% lower than the model, while ^{239}Pu agrees with the model. (The minor fuels ^{241}Pu, ^{238}U are treated approximately)

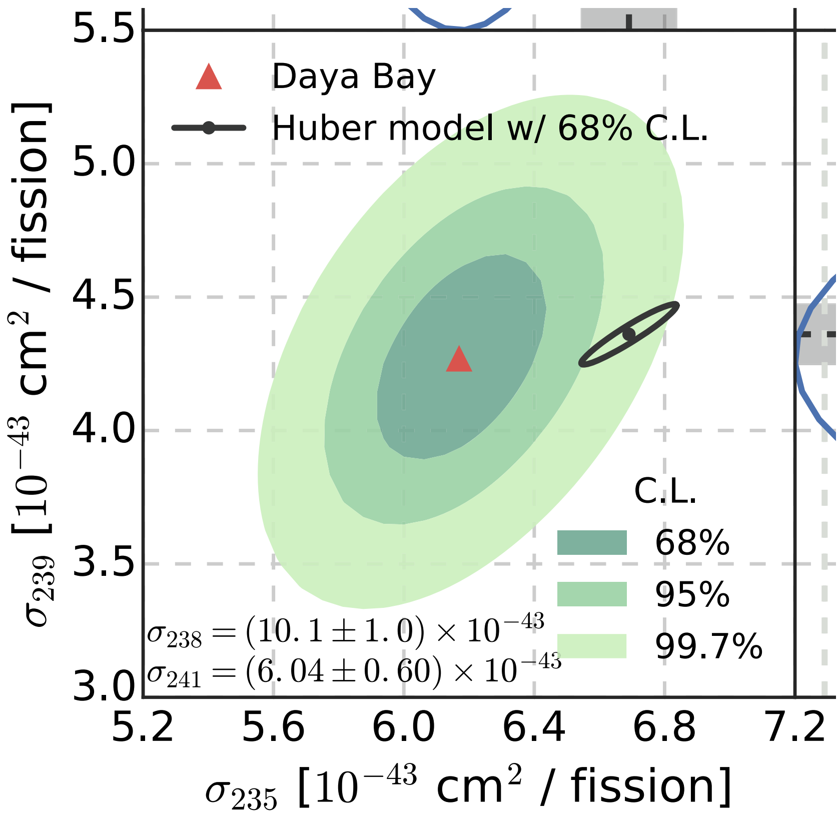


Figure from An *et al.*, PRL **118**, 251801

Summary and Conclusions

1) The average count rate of all reactor experiments is quite accurate (~1%) and consistent, including the very high statistics Daya Bay and RENO experiments.
2) However, the uncertainty in the prediction was very likely underestimated. Taking into account the ~25% of forbidden β decays increases the uncertainty to ~ 5%, making the anomaly much less significant.
3) Moreover, the observation of the bump or shoulder at 4-6 MeV visible energy, not predicted in the calculated spectrum, also indicates that the predictions is not as accurate as initially thought.
4) There are indications (to be confirmed) that the discrepancies between the model and reality are different for different fuels, in particular that ^{235}U is responsible for most of the effect.

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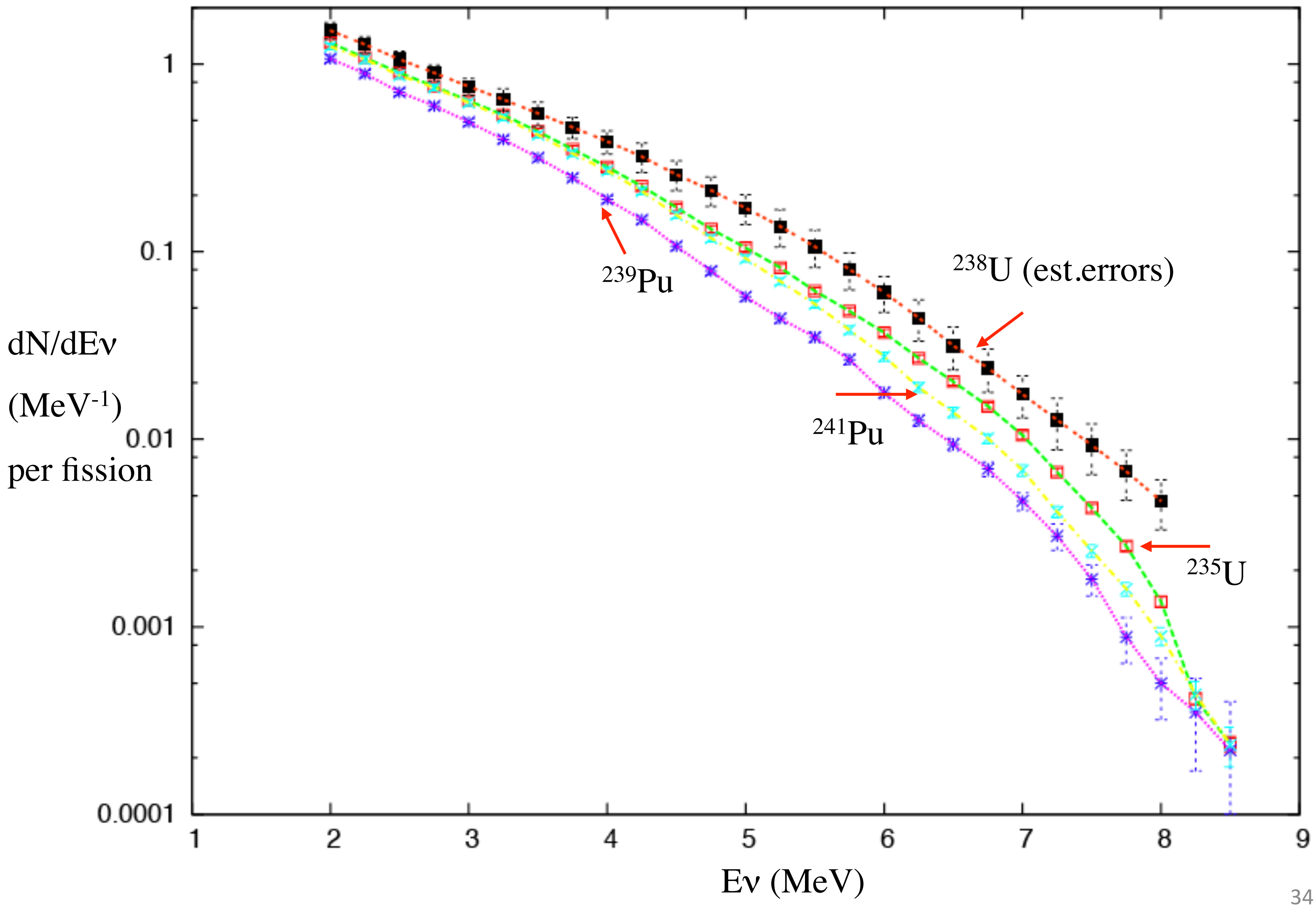
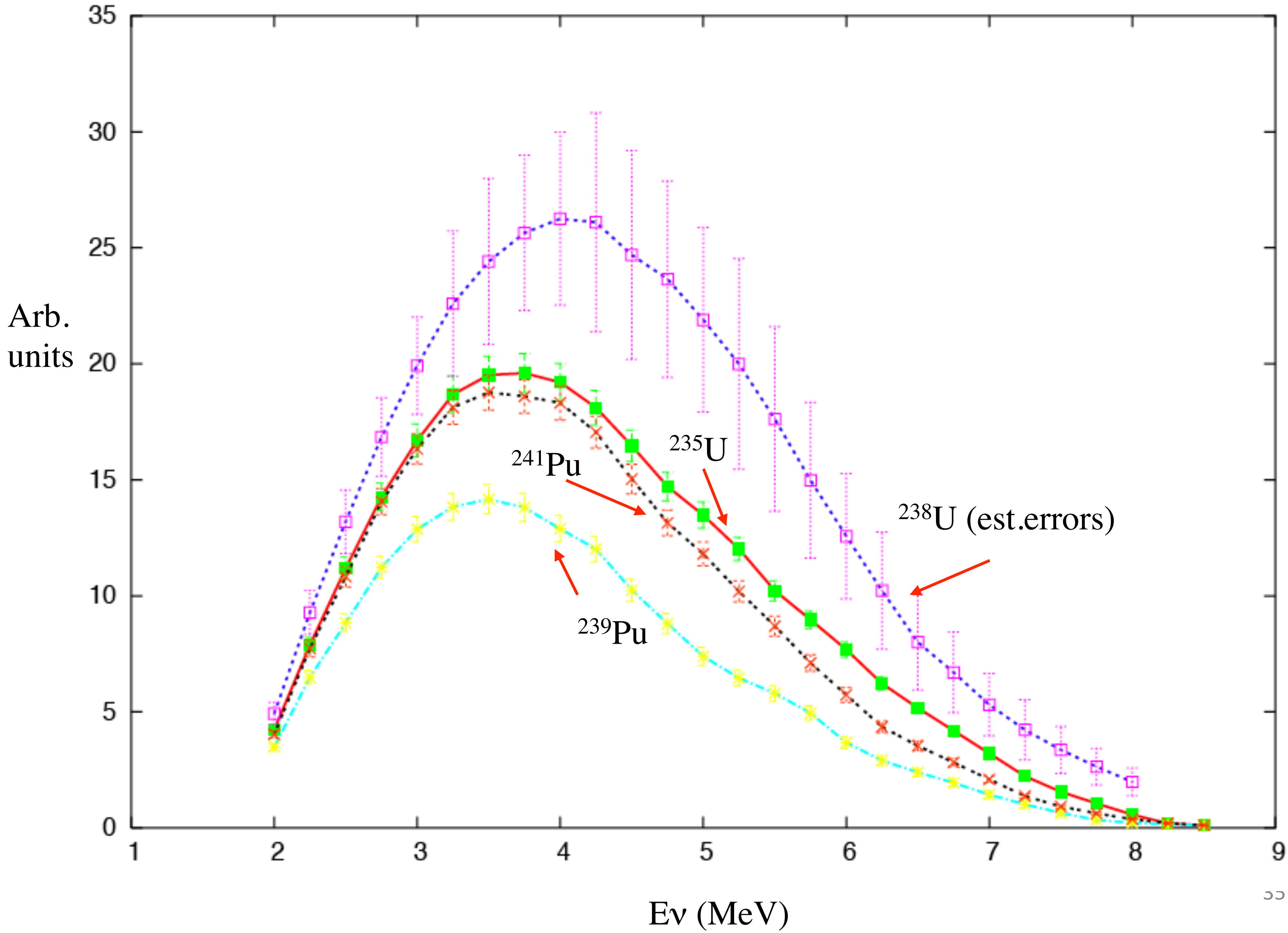
Spectra of ^{235}U, ^{239}Pu, ^{241}Pu derived from electron spectra, and ^{238}U calculated



Positron yields for different fuels



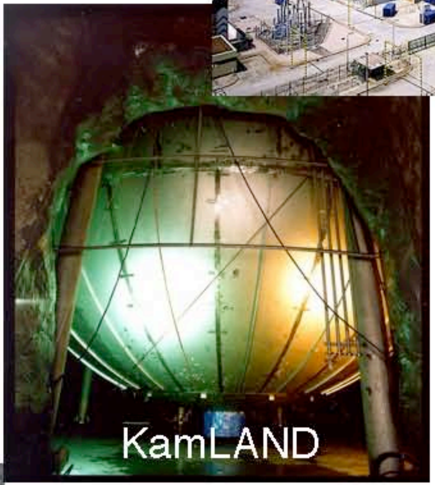
Neutrino Physics at Reactors

Next - Discovery and precision measurement of θ_{13} and precision tests of $\overline{\nu}_e$ disappearance

2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2004 - Evidence for spectral distortion

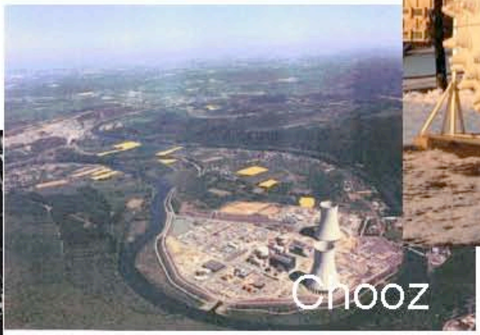
2003 - First observation of reactor antineutrino disappearance



1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

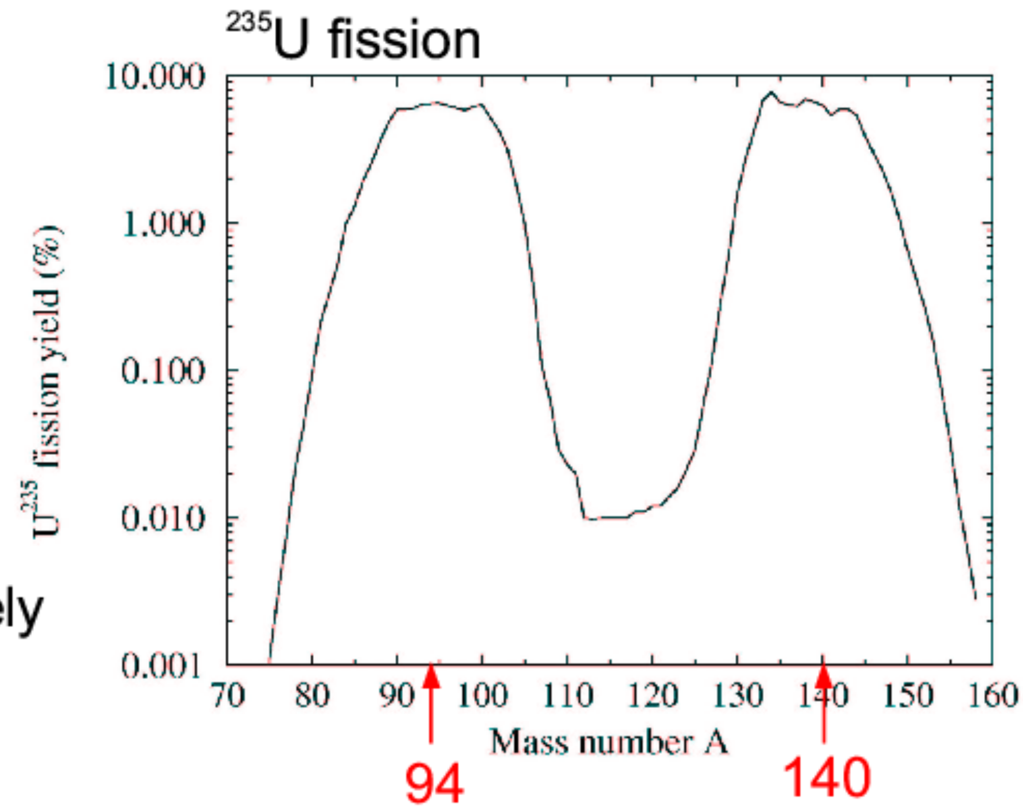


Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

slide of K. Heeger

Electron antineutrinos are produced by the β decay of fission fragments

$$^{235}_{92}U + n \rightarrow X_1 + X_2 + 2n$$



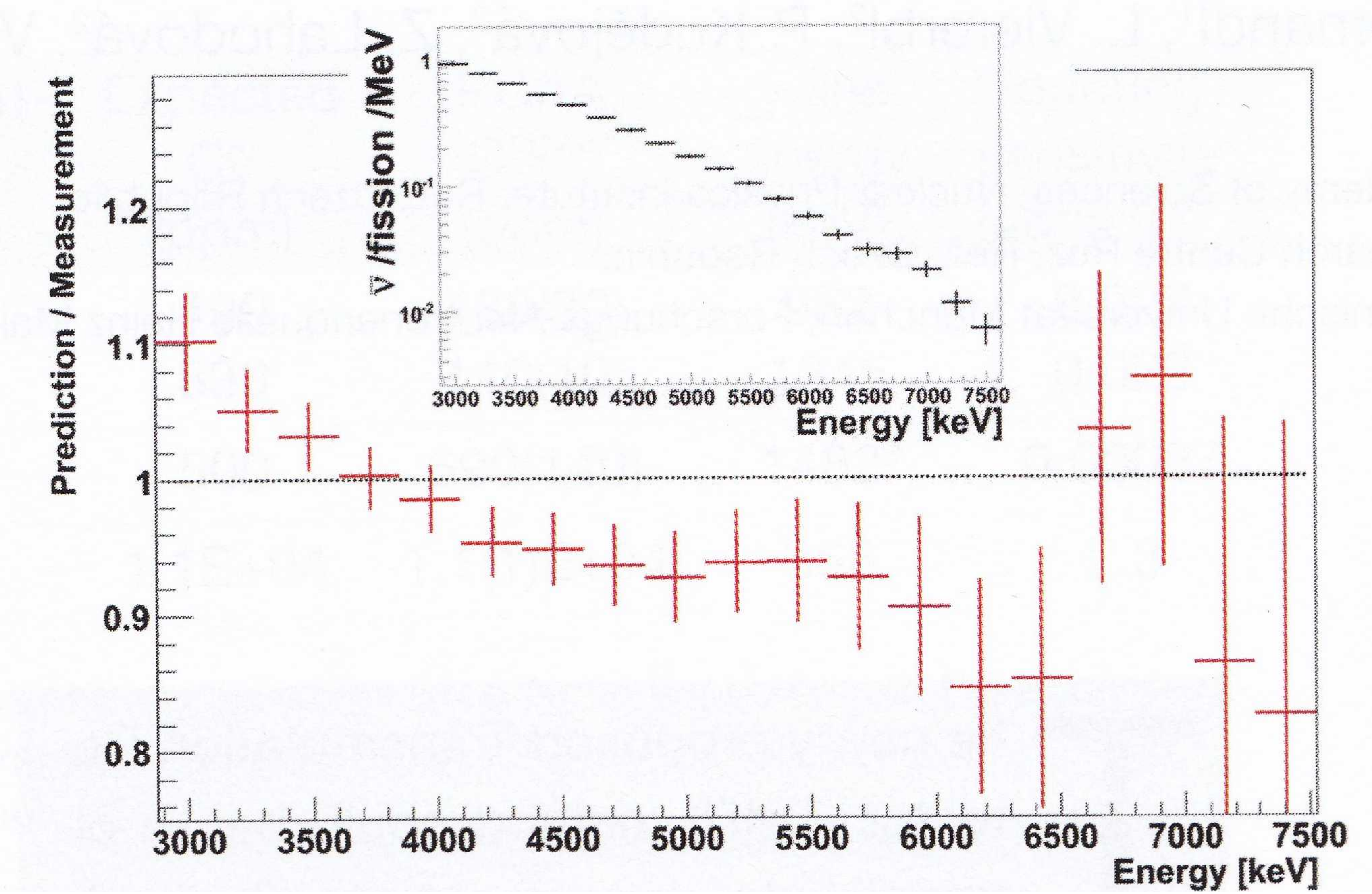
The stable products most likely from Uranium fission:

$$^{94}_{40}Zr \qquad ^{140}_{58}Ce$$

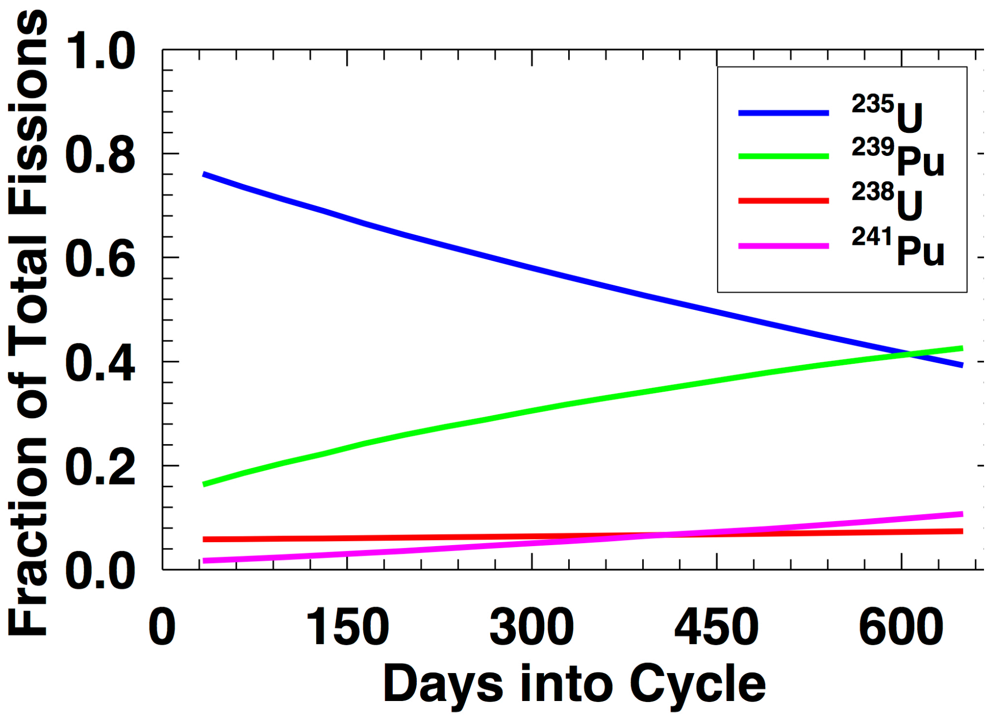
Together 98 protons and 136 neutrons

6 neutrons have to β-decay to reach stable matter: $6\overline{\nu}_e$ / fission

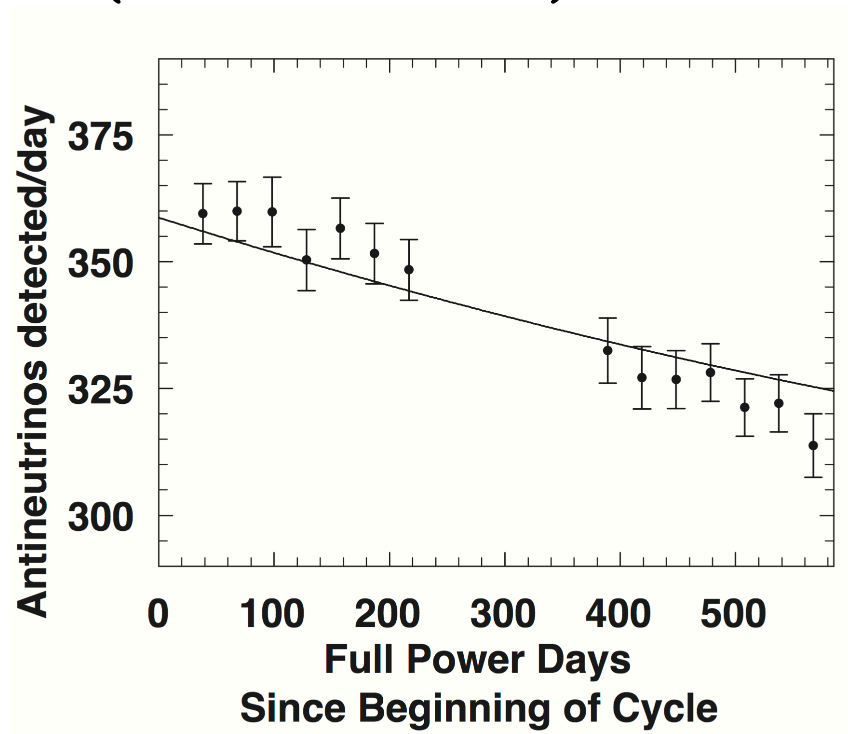
The ^{238}U spectrum has been missing. The calculations were used instead. The corresponding electron spectrum was determined at TU Munich recently, and converted into the antineutrino spectrum. The ratio to the Mueller et al. is plotted. (K. Schreckenbach and N. Haag, in TU annual report 2012)



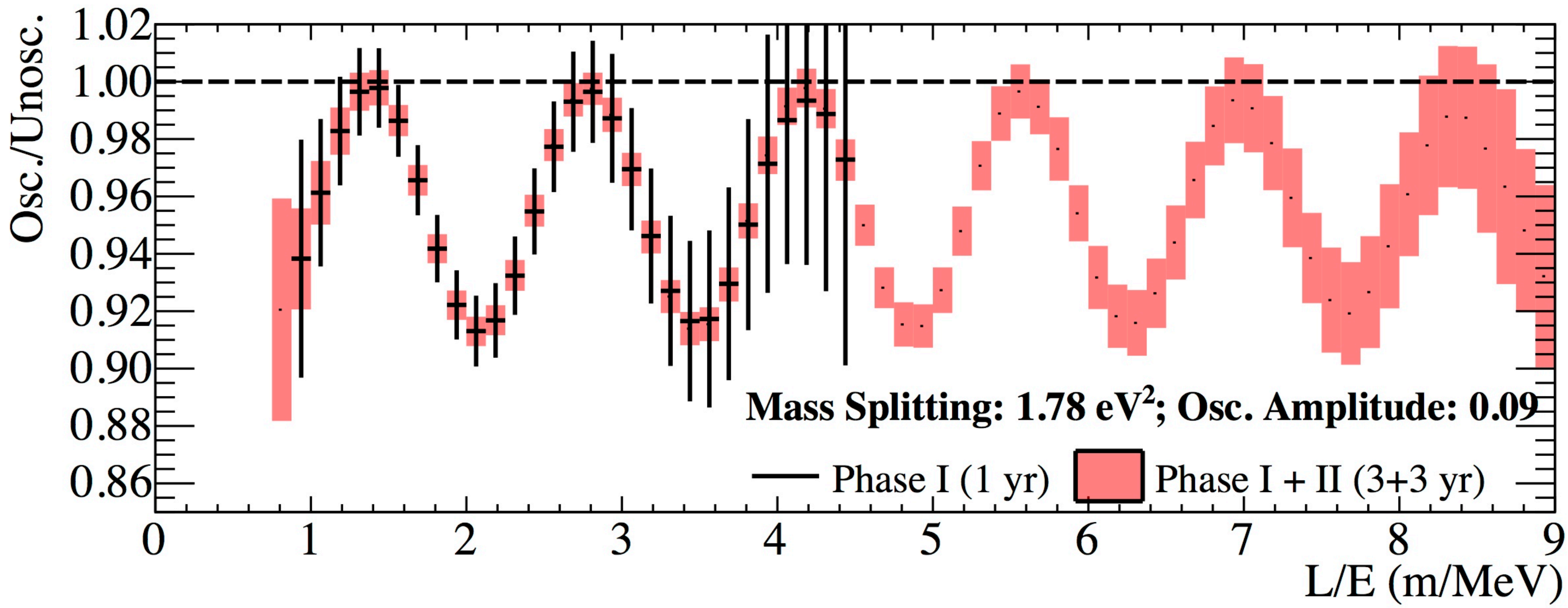
Changes in the fuel composition in a typical light water reactor



Changes in the daily antineutrino rate during the fuel cycle. (Bowden et al. 2009)

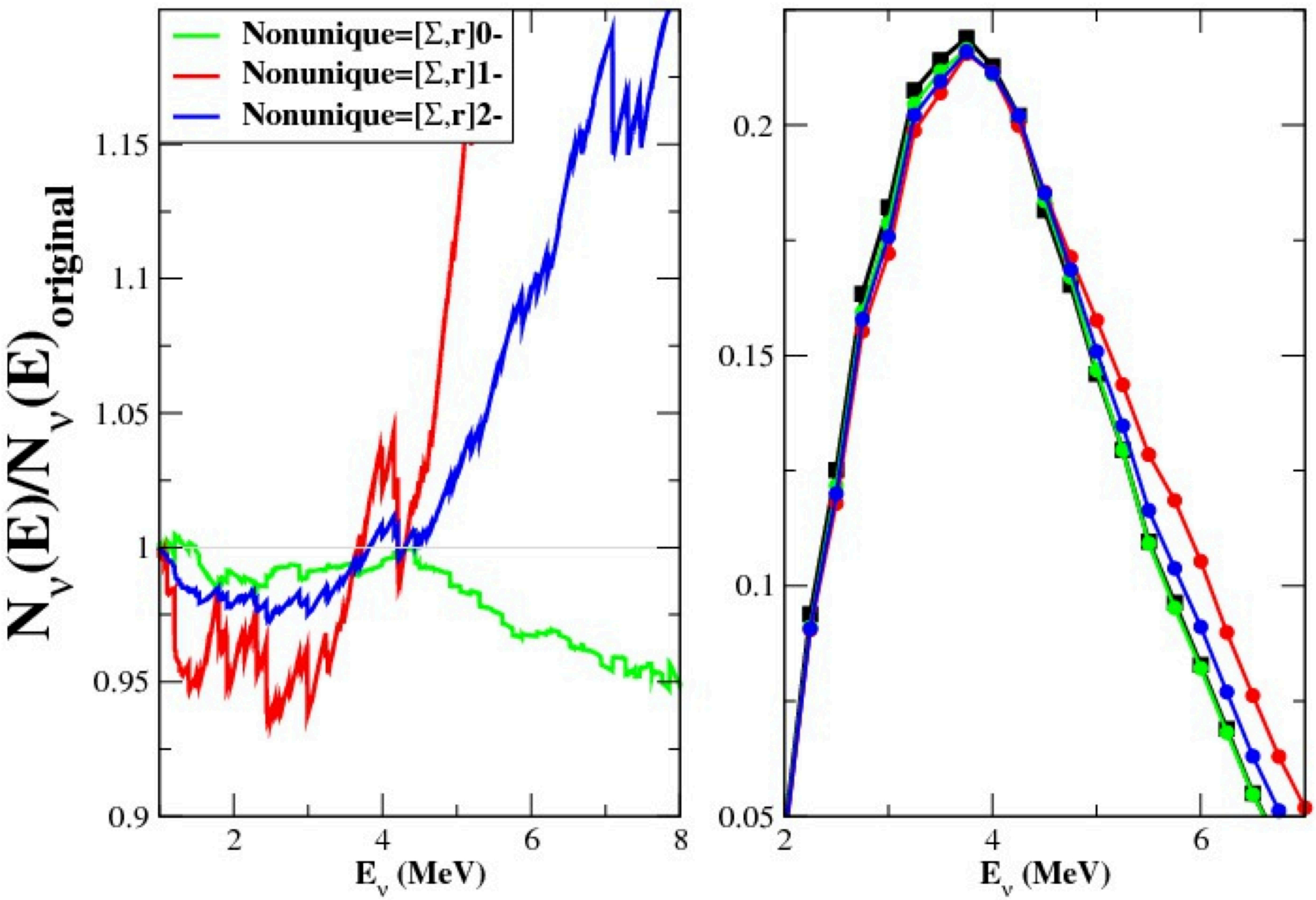


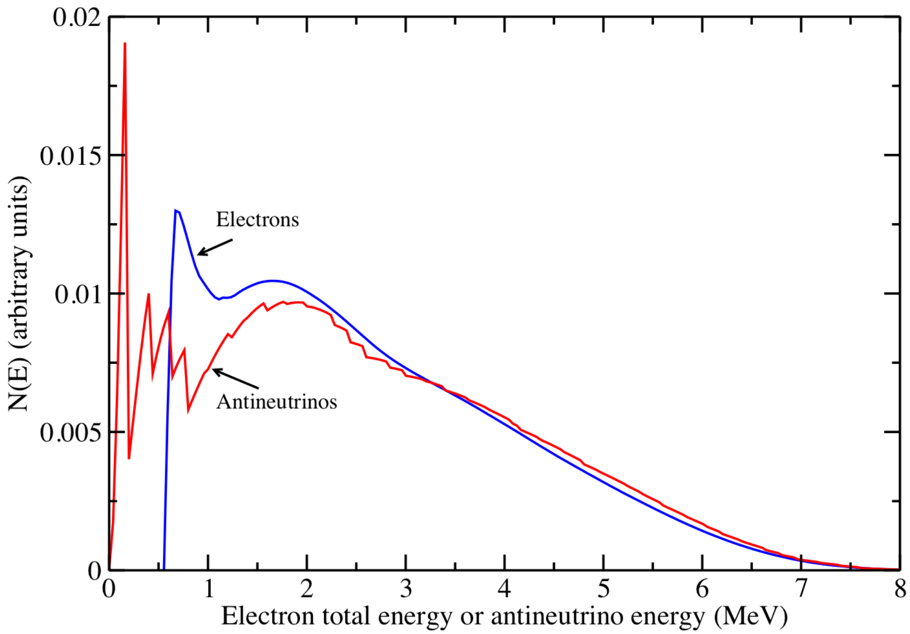
The only convincing way to check for the existence of the light sterile neutrinos using reactors is to observe the oscillatory behavior, as a function of L/E of the signal using a compact HEU reactor. Here is an example.



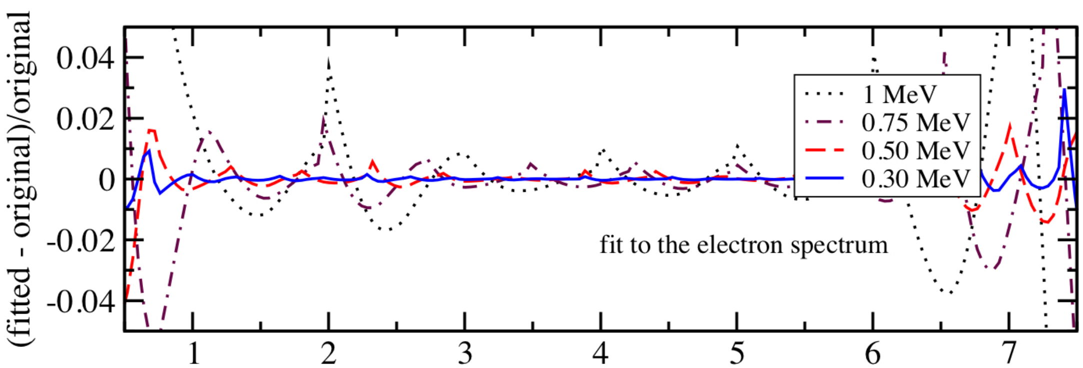
Expected sensitivity of the PROSPECT experiment using the best fit parameters of Kopp et al. JHEP 1305, 050 (2013) .
For global ν_e dissapearance fit they had $\Delta m^2{}_{41}$ = 1.78 eV^2 and
$\sin^2 2\theta_{14}$ = 0.09.
Figure from K. Gilje for PROSPECT collaboration arXiv:1511.00177

Modification of the reactor neutrino spectrum with respect to the original one(Schreckenbach et al.) when in the inversion procedure different assumptions about the shape factor C(E) are used. Figure from Hayes et al. (PRL **112**, 202501 (2014))

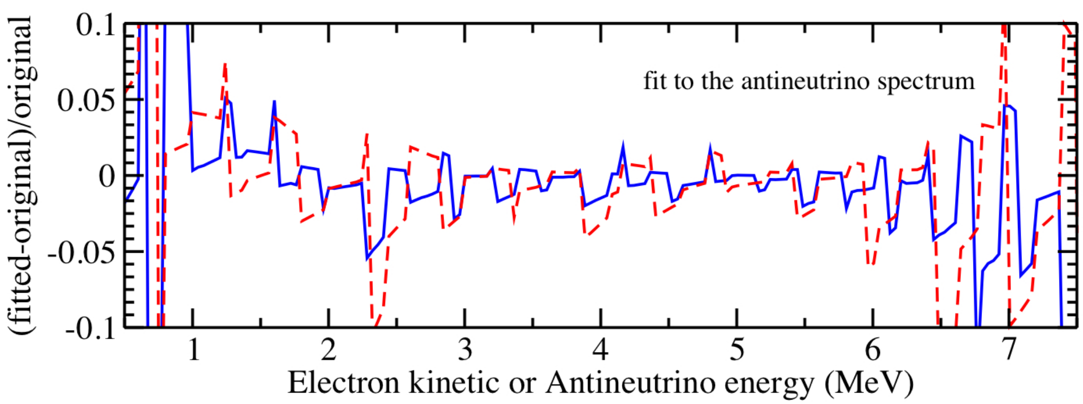




Example of a complex spectrum. Hypothetical β decay of Z=45 nucleus, with 40 branches with random endpoints and branching ratios. The largest Q-value is 8 MeV. Allowed spectrum shape is assumed.

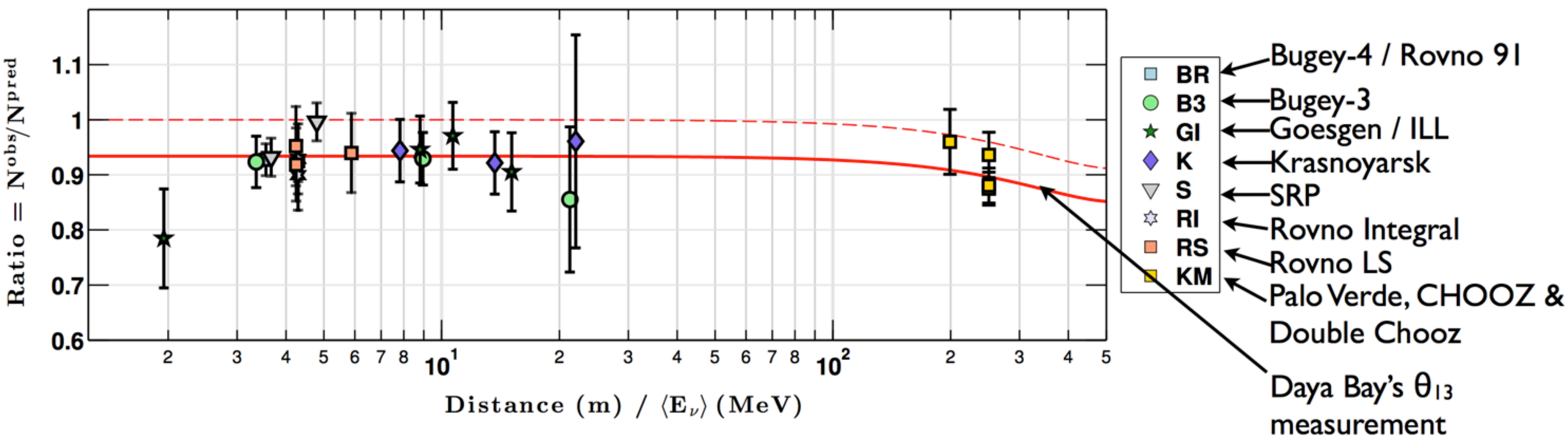


Fit to the above electron spectrum. The spacing of slices is indicated. Deviation of the fit is shown.



Same as above, but for the neutrino spectrum.

Reactor Anomaly

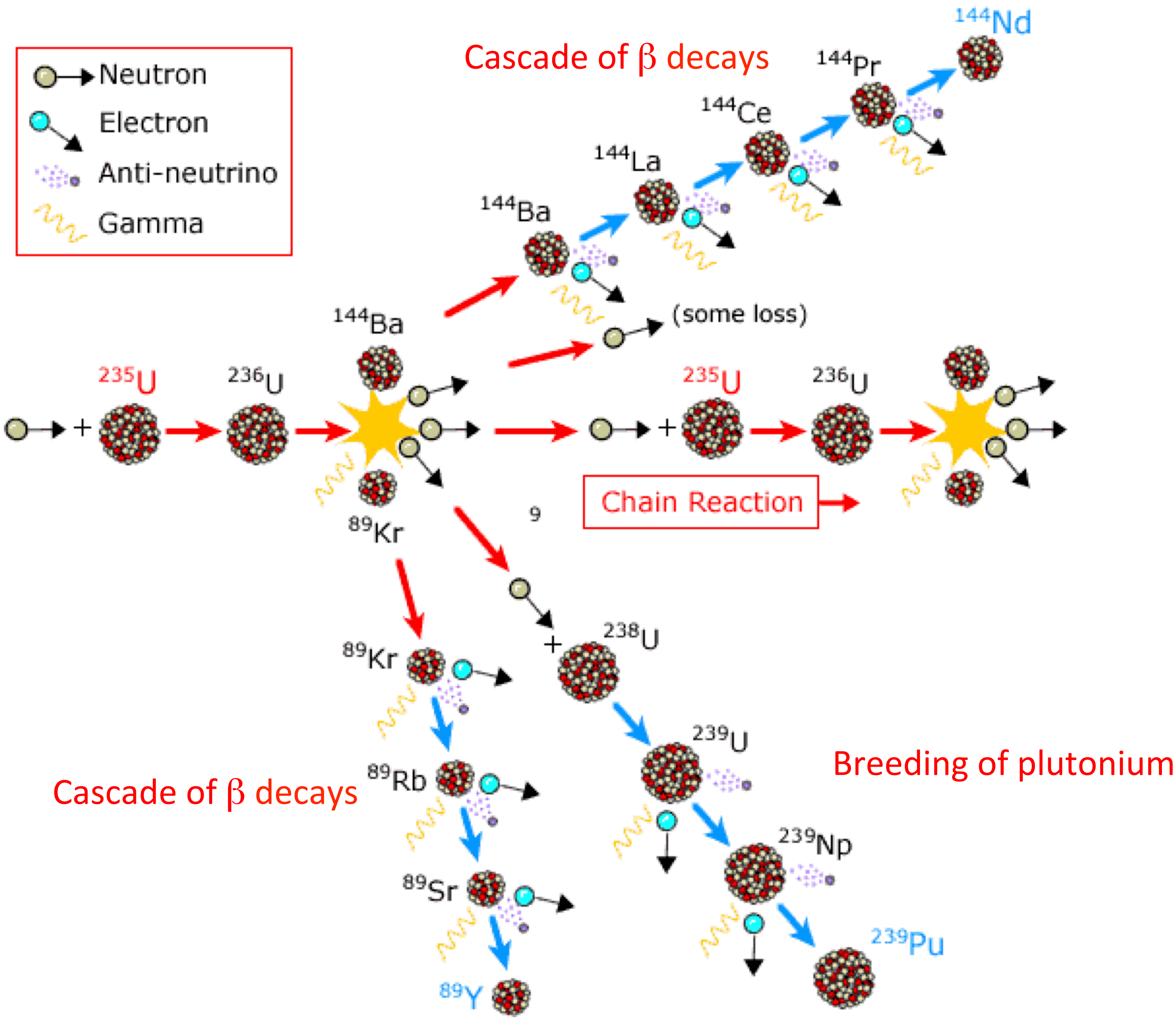


Updated result including :

- Km baseline results
- Corrected statistical bias (1% shift)
- Neutron mean life (τ_n = 881.5 s)
- Refined treatment of experimental uncertainties and parameters

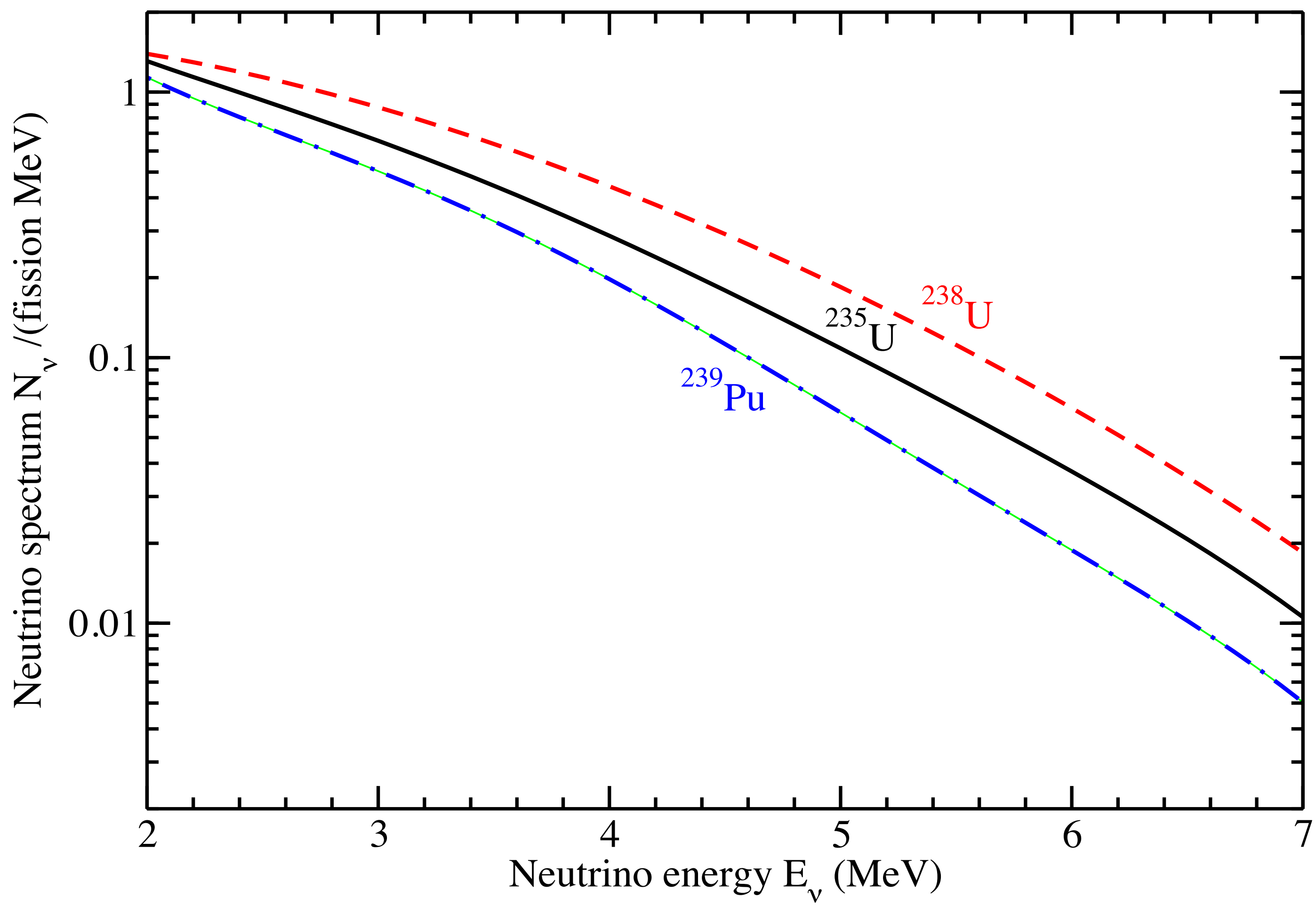
- 2013 result: $\mu = 0.936 \pm 0.024$, 2.7σ deviation from unity

From the talk by L. Lhuillier at Neutrino 2014


Neutron
Electron
Anti-neutrino
Gamma
Cascade of β decays
144Nd
144Pr
144Ce
144La
144Ba
(some loss)
144Ba
235U
236U
235U
236U
89Kr
9
Chain Reaction
89Kr
238U
239U
Breeding of plutonium
89Rb
Cascade of β decays
89Sr
239Np
239Pu
89Y

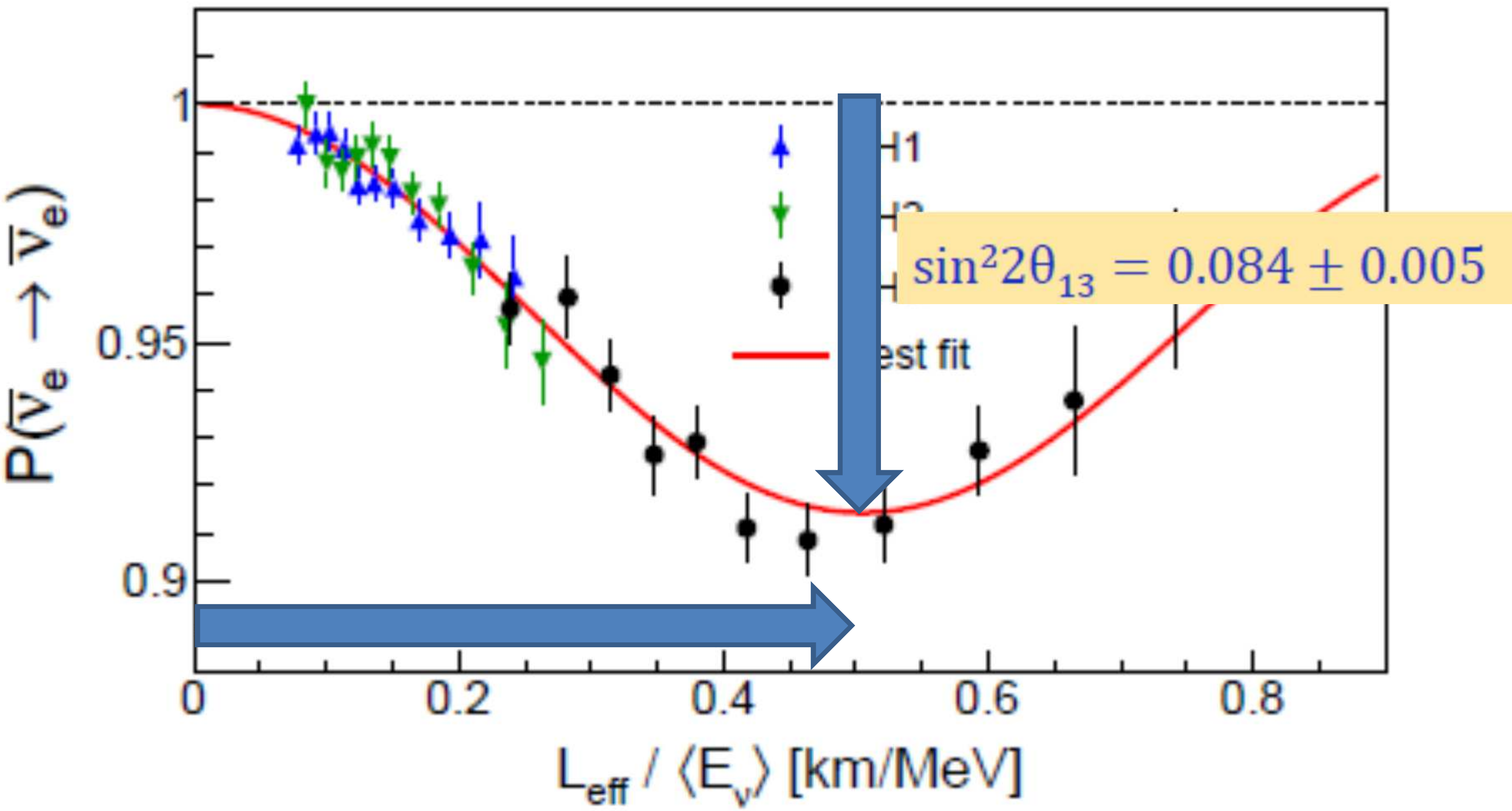
Brief history of the reactor neutrino spectrum determination:

1. First `modern' evaluations were done in late 1970 and early 1980 (Davis et al. 1979, Vogel et al. 1981, Klapdor & Metzinger 1982)
2. During the 1980-1990 a series of measurements of the **electron** spectra associated with the fission of ^{235}U, ^{239}Pu and ^{241}Pu were performed at ILL Grenoble by Schreckenbach et al. These were **converted** into the electron antineutrino spectra by the authors.
3. This is basically what was used until now, even though some effort was made to measure the β decay of various short lived fission fragments (Tengblad et al, 1989, Rudstam et al. 1990) and new calculations were performed (see e.g. Kopeikin et al, hep-ph/0308186).
4. New evaluation (Mueller et al. 2011, Huber 2011) uses a combination of the *ab initio* approach with updated experimental data and the input from the converted electron spectra (see 2) above). **This results in the upward shift by ~3% of the reactor flux (keeping the shape almost unchanged).** (Neutron lifetime is ~1% shorter now increasing the expected signal, and correction caused by not full equilibrium in the ILL experiment also caused an ~1% increase.)



Neutrino spectrum N_ν /(fission MeV)
1
0.1
0.01
2
3
4
5
6
7
Neutrino energy E_ν (MeV)
238U
235U
239Pu

ELECTRON ANTINEUTRINO OSCILLATION CURVE MEASURED BY DAYA BAY



$$\sin^2 2\theta_{13} = 0.084 \pm 0.005$$

$$|\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} \mathrm{eV}^2$$