# Spectra of neutrinos from reactors: Issues and Challenges

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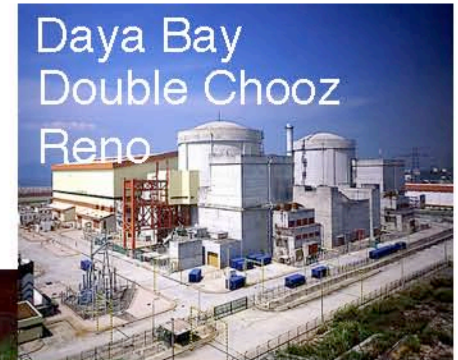
Pontecorvo School, Prague, Aug. 30., 2017

# There is a long tradition of Neutrino Physics at Reactors

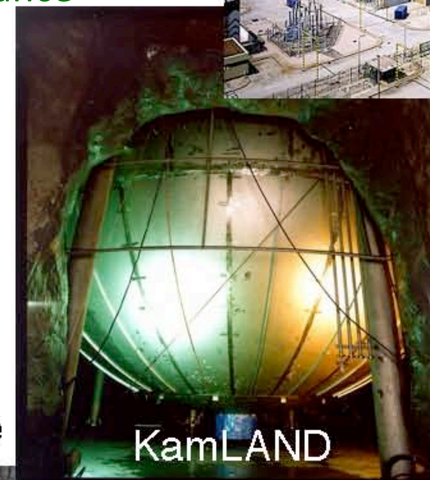
**Next -** Discovery and precision measurement of $\theta_{13}$ And tests of $\nu_e$ disappearance



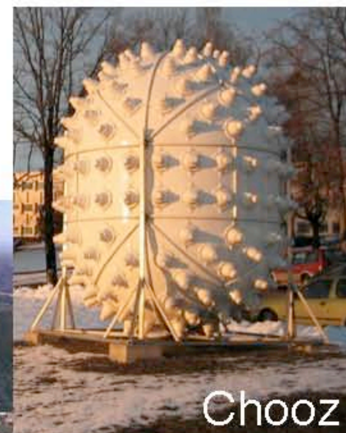

**2008** - Precision measurement of $\Delta m_{12}^2$ . Evidence for oscillation

**2004** - Evidence for spectral distortion

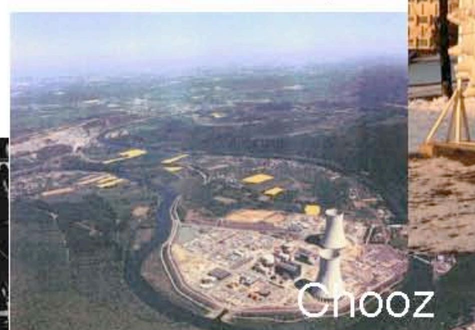
**2003** - First observation of reactor antineutrino disappearance




**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

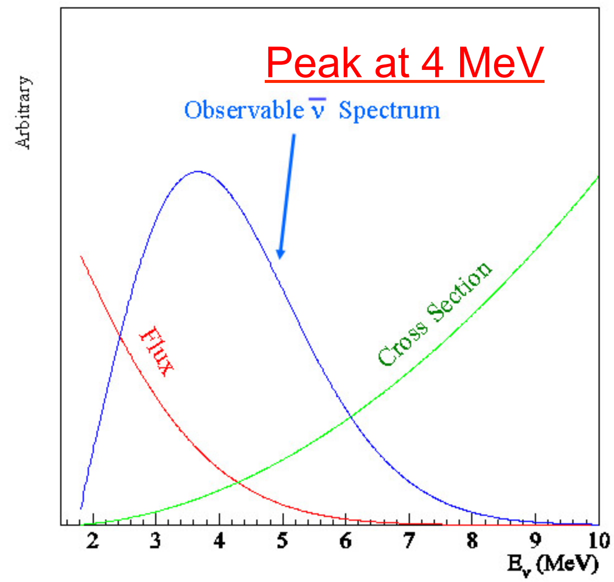
# Reactor electron antineutrinos are detected through the inverse neutron beta decay (IBD)

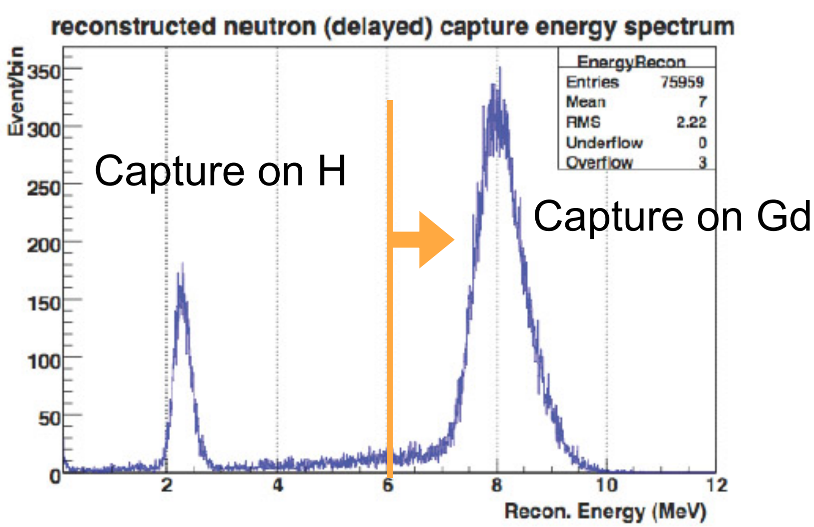
Prompt signal

$$e^+ + e^- \rightarrow 2\gamma$$

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

Capture on H or Gd,
Delayed signal, 2.2, 8 MeV



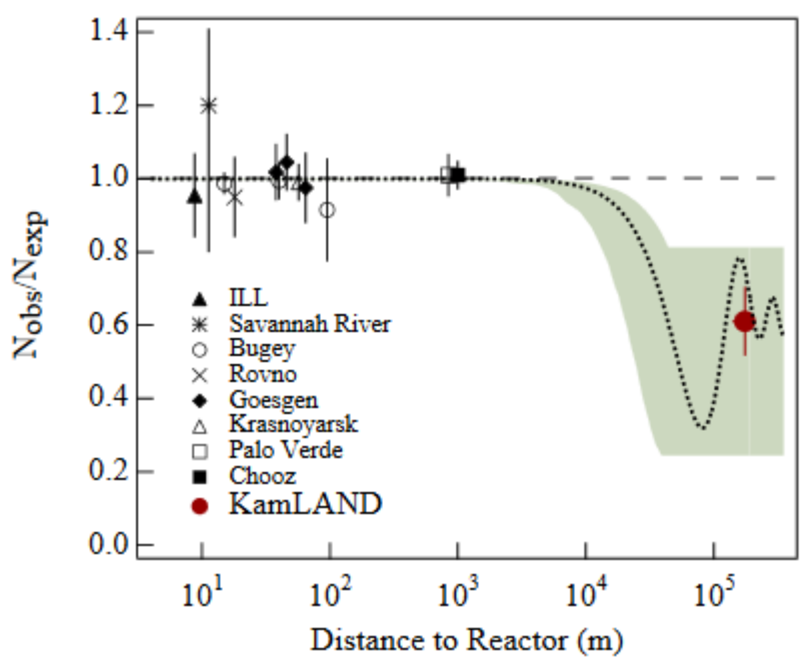

**Neutron capture after thermalization**

- **Inverse beta decay reaction,** proposed by Pontecorvo, called Cowan-Reines reaction
- **Coincidence of**
  - ⇨ Prompt: positron, energy correlated to neutrino energy
  - ⇨ Delayed: neutron capture
- **10,000 times bkg reduction**

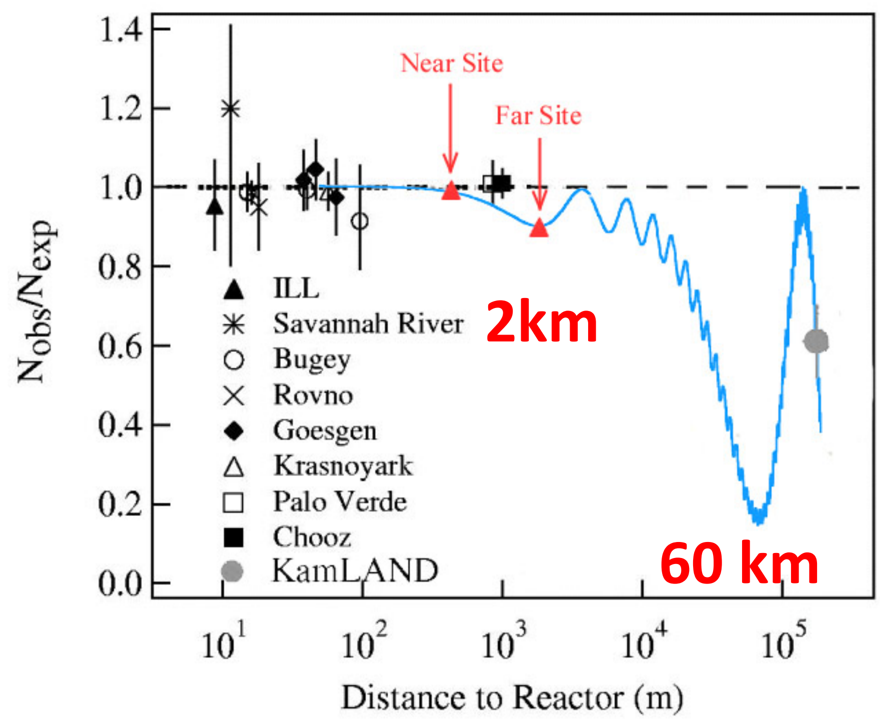
To test for oscillations one looks for the neutrino disappearance

In the two flavor approximation the survival probability is

$$P_{sur} = 1 - \sin^2 2\theta_{ij} \sin^2(1.27\, \Delta m_{ji}^2\, L/E)$$




**KamLAND (2003)**




**Daya-Bay 2012**

# Why do we care about the reactor $\bar{\nu}_e$ spectrum ?

There are, at present two unexplained phenomena

a) ``Reactor anomaly", and its possible consequences
(see lectures by Profs. Link and Giunti)
b) The ``bump" in reactor spectrum

And, in near future, there are

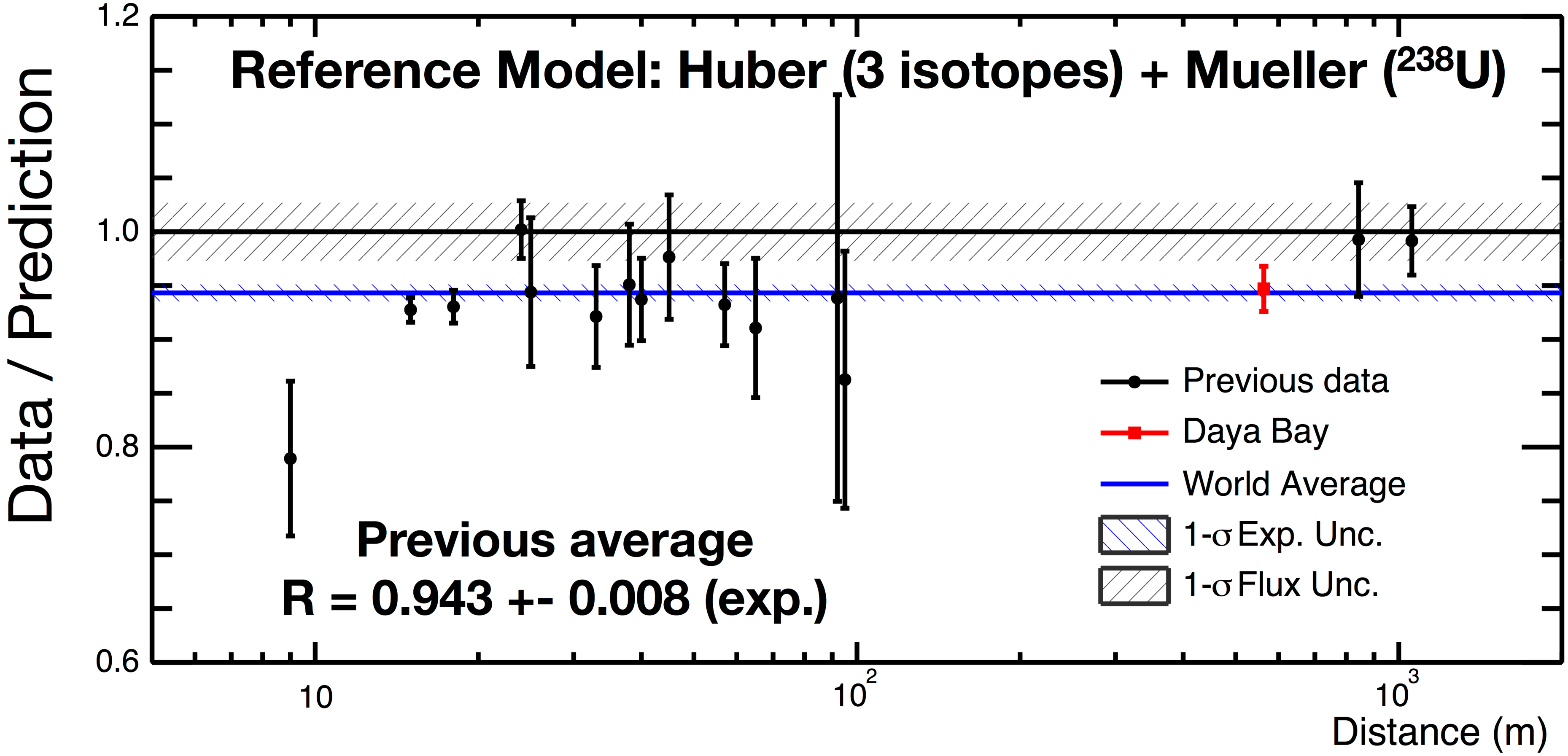
c) Ambitious planned experiments to determine the neutrino mass hierarchy
(see lectures by Prof. Wang)

d) Attempts to see whether the light sterile neutrinos exist or not
(see also lectures by Profs. Link and Giunti)

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 the 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.

## Reactor `anomaly':

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.

Here is a list of hints for the existence of sterile neutrinos with ~ eV mass scale. These results (~2-3 $\sigma$) are not confirmed but also not ruled out by other experiments.

- LSND
- MiniBooNE $\nu$
- MiniBooNE $\overline{\nu}$
- Reactor Anomaly
- Radioactive Neutrino Source Anomaly

LSND and MiniBoone involve indications for the **appearance** of $\nu_e$ or $\overline{\nu}_e$ in the beams that were initially $\nu_\mu$ or $\overline{\nu}_\mu$ at $L/E_\nu$ ~ 1 m/MeV that is incompatible with standard oscillation paradigm.

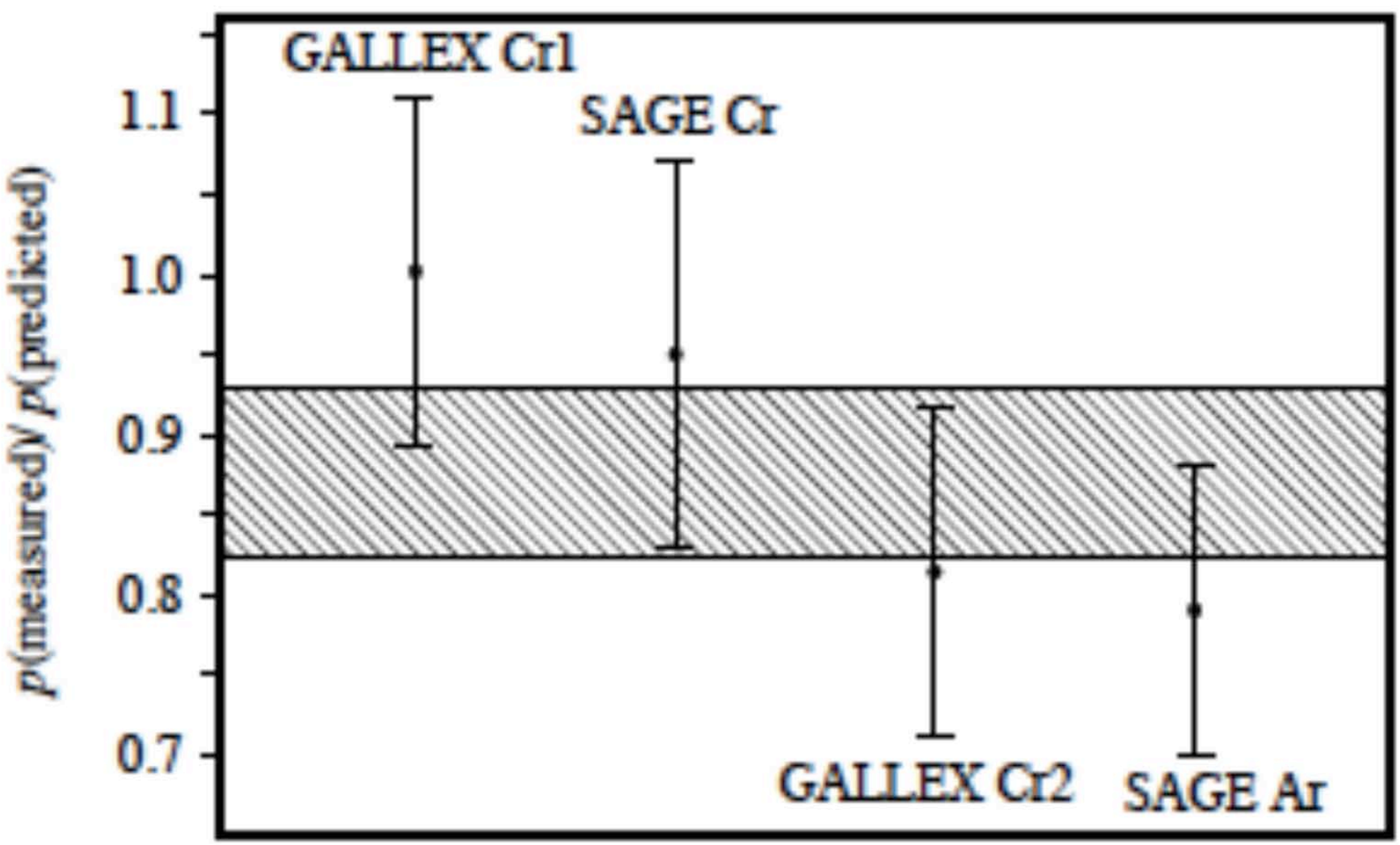
Reactor experiments involve indications of the **disappearance** of $\overline{\nu}_e$ again at $L/E_\nu$ ~ 1 m/MeV .

Calibration of the gallium solar neutrino detectors with radioactive sources involve indications of the **disappearance** of $\nu_e$ again at $L/E_\nu$ ~ 1 m/MeV .

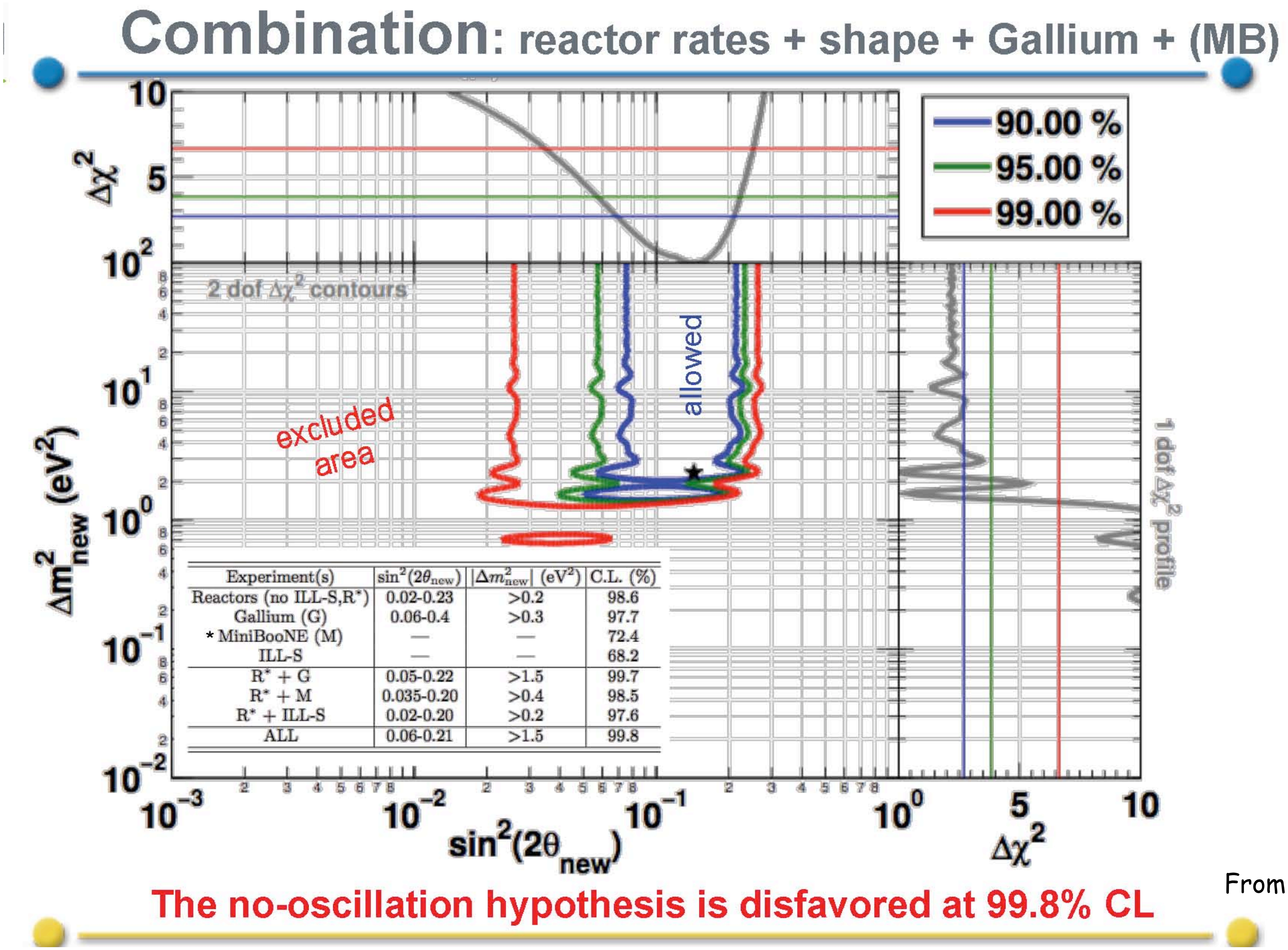
The solar neutrino detectors GALLEX and SAGE based on the $\nu_e$ capture on $^{71}Ga$ leading to $^{71}Ge$ were tested with strong man-made radioactive sources of $^{51}Cr$ and $^{37}Ar$ which were placed inside the detectors. $^{51}Cr$ and $^{37}Ar$ produce monoenergetic $\nu_e$ by electron capture (Q = 751 and 814 keV).

There were four calibration runs. The corresponding measured/expected ratios are shown below. When averaged they give **$\langle R \rangle$ = 0.86±0.05**

When one tries to explain these ratios as resulting from oscillations, the best fit values are $\Delta m^2$ = 2.24 eV$^2$ and $\sin^2 2\theta$ = 0.50 (Giunti & Lavender, Phys. Rev C**83**,065504(2011)).



Analysis based on $P(\nu_e \rightarrow \nu_e) = 1 - \sin^2(2\theta_{new})\sin^2(\Delta m^2_{new} L/E_\nu)$
Best fit $\Delta m^2_{new} = 2.35 \pm 0.1$ eV$^2$, $\sin^2(2\theta_{new}) = 0.165 \pm 0.04$

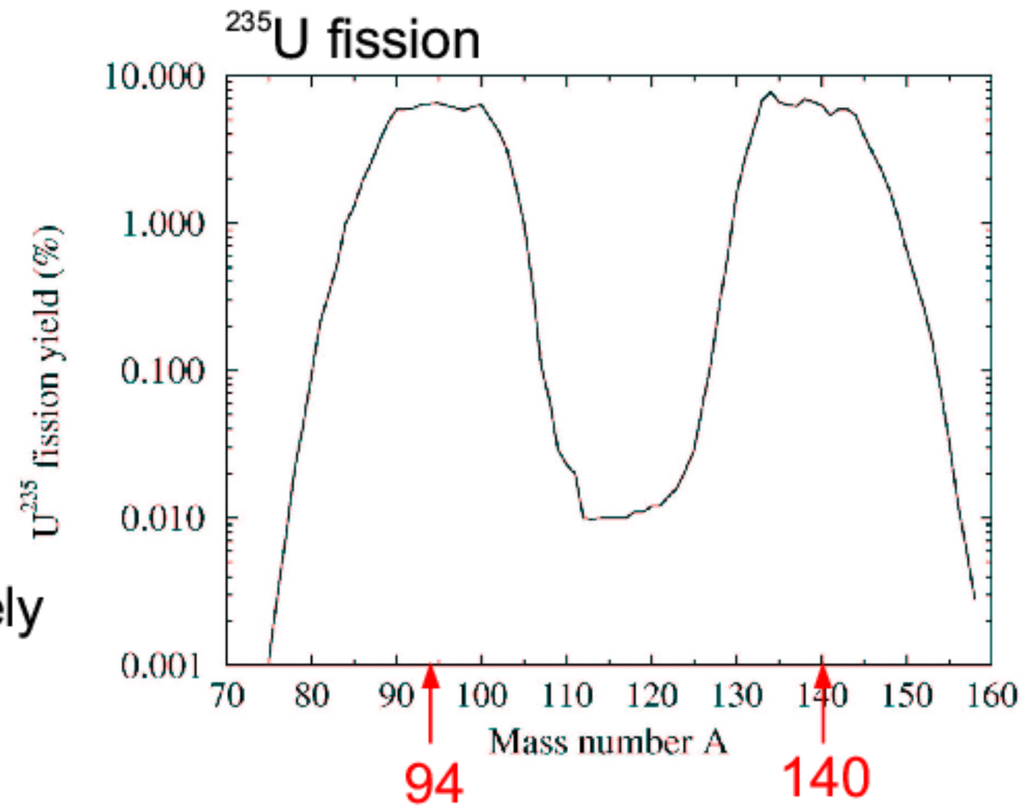



| Experiment(s) | $\sin^2(2\theta_{new})$ | $\lvert\Delta m^2_{new}\rvert$ (eV$^2$) | C.L. (%) |
|---|---|---|---|
| Reactors (no ILL-S,R*) | 0.02-0.23 | >0.2 | 98.6 |
| Gallium (G) | 0.06-0.4 | >0.3 | 97.7 |
| * MiniBooNE (M) | — | — | 72.4 |
| ILL-S | — | — | 68.2 |
| R* + G | 0.05-0.22 | >1.5 | 99.7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

From Mention *et al. (2011)*

# Electron antineutrinos in reactors are produced by the $\beta$ 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 $\beta$-decay to reach stable matter: $6\overline{\nu}_e$ / fission

# 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

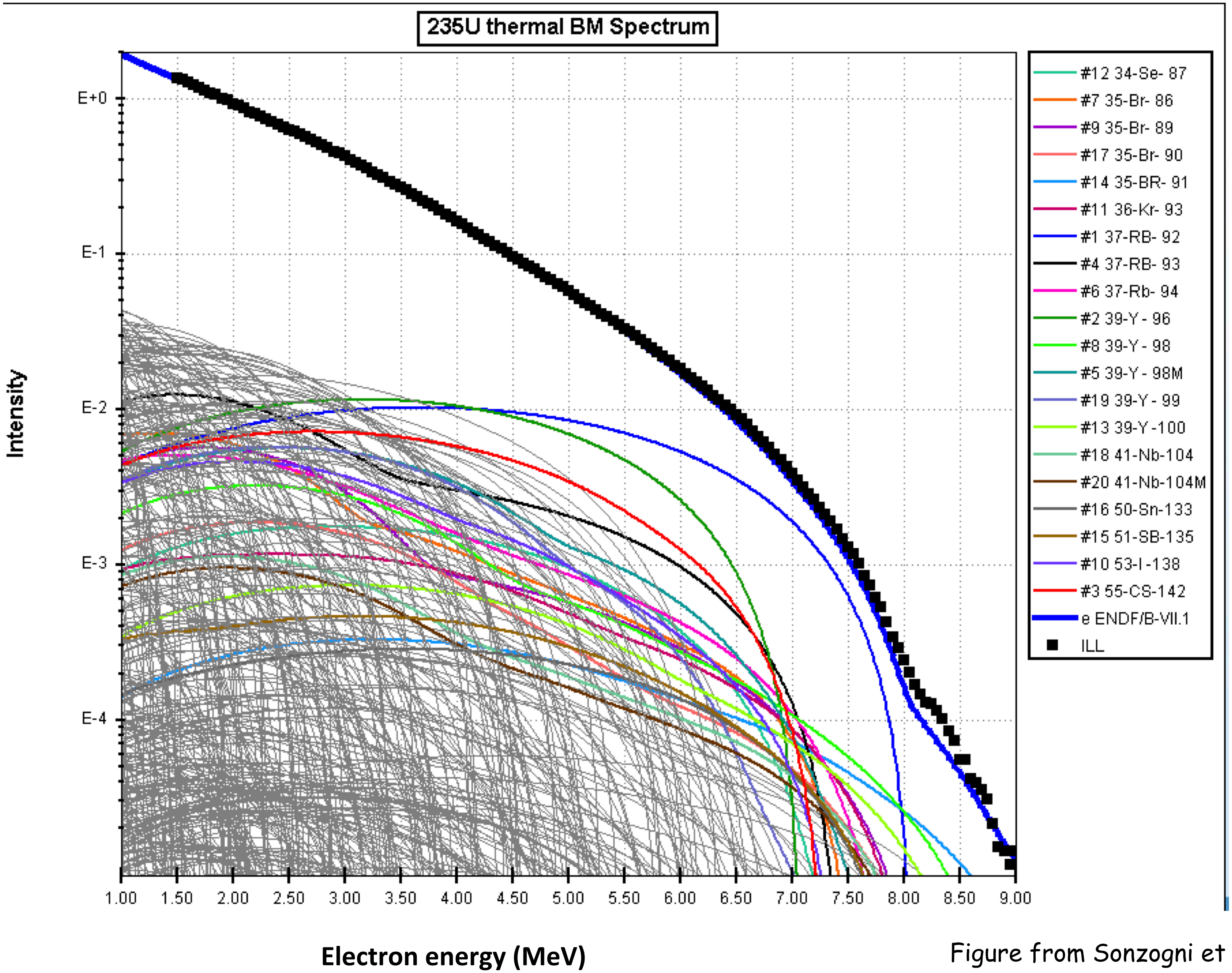
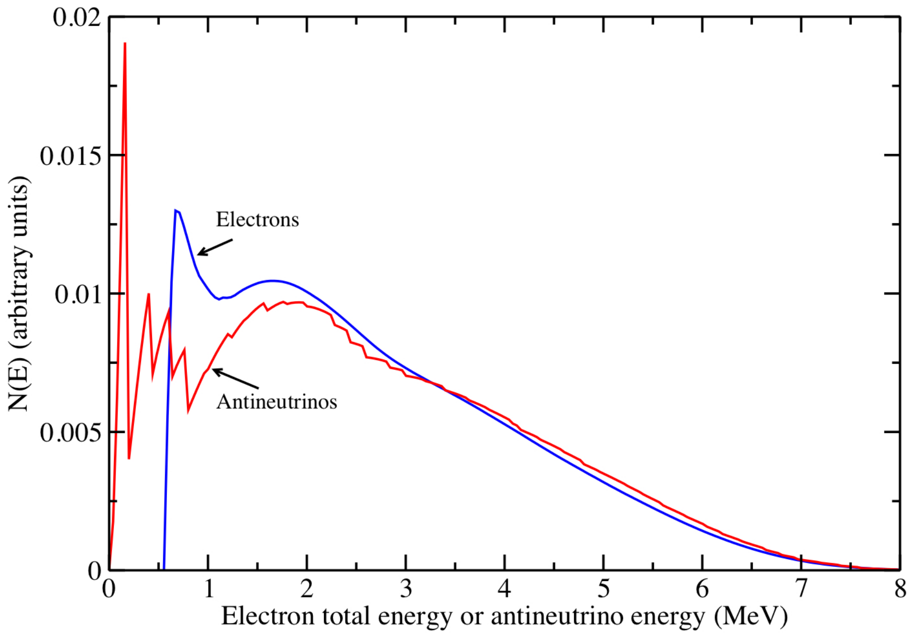
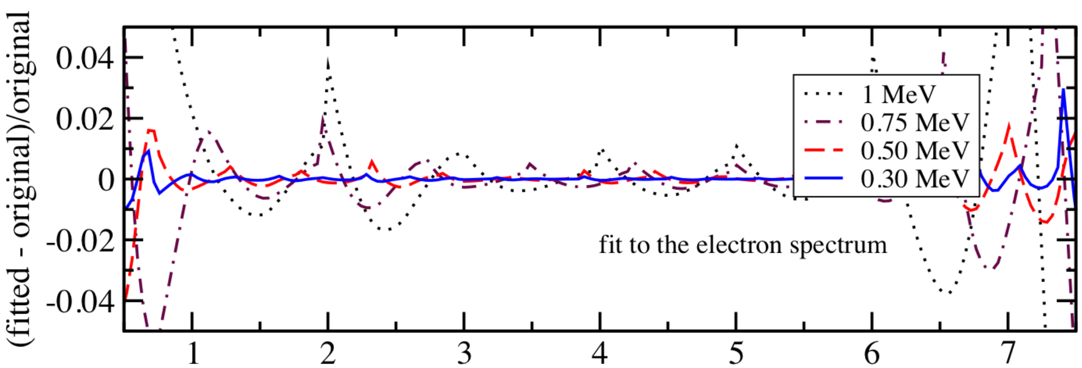


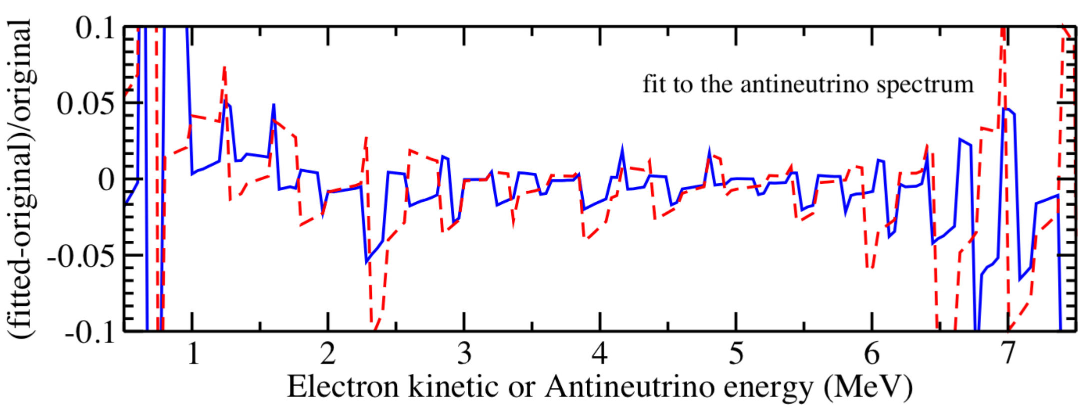

Figure from Sonzogni et al, PRC 91,011301



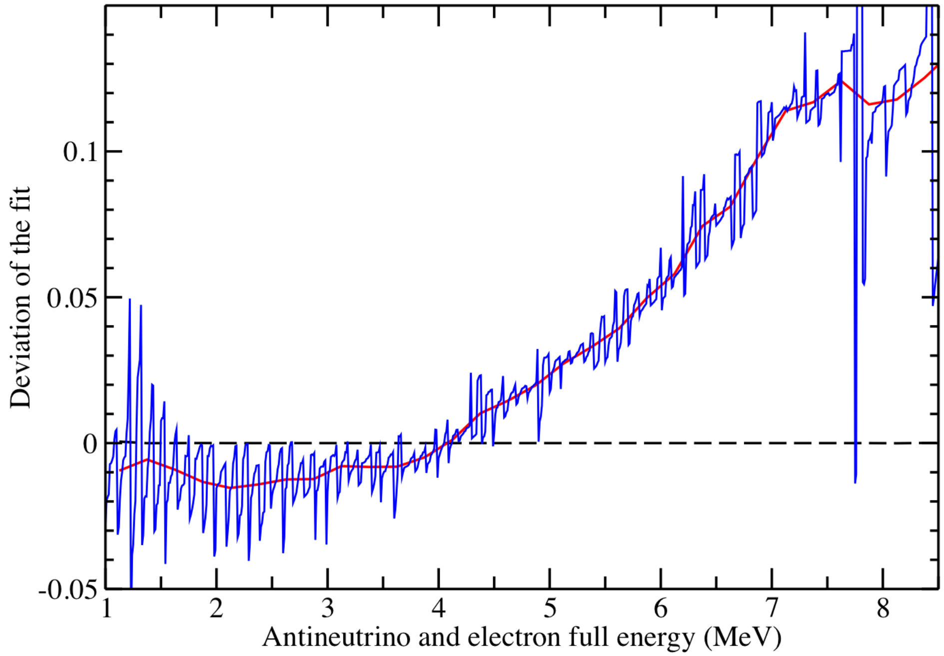

Example of a complex spectrum. Hypothetical β decay of Z=45 nucleus, with 40 branches with random endpoints and branching ratios. The largest Q-value is 8 MeV. Allowed spectrum shape is assumed.



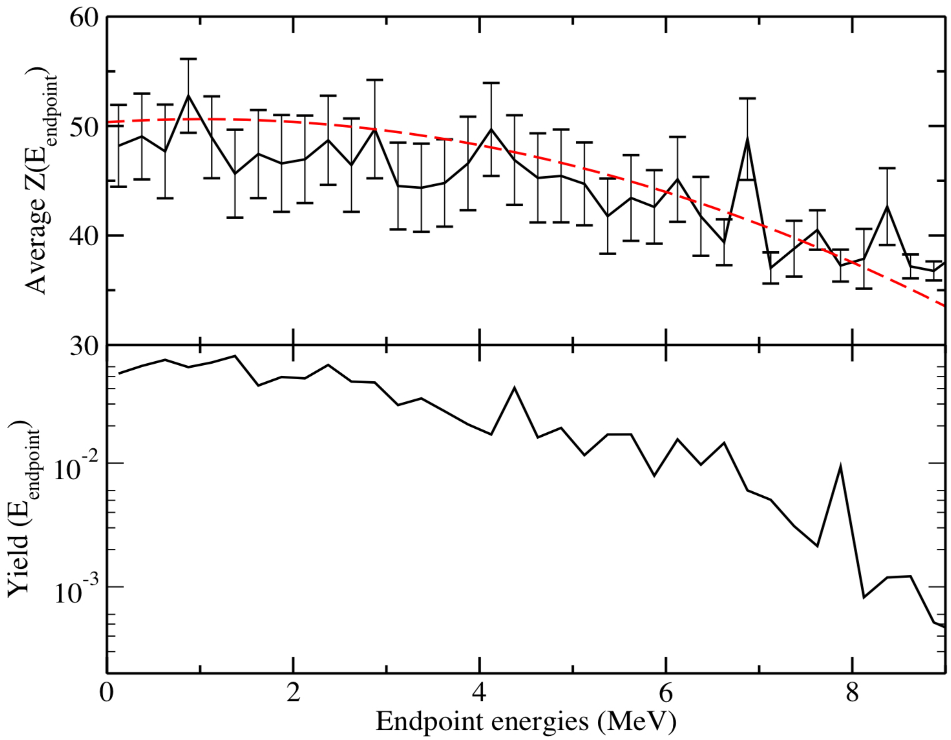

Fit to the above electron spectrum. The spacing of slices is indicated. Deviation of the fit is shown.




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 $\nu_e$ spectrum with < 1% error provided that the corresponding $\beta$ decay shapes are all well known and described.**

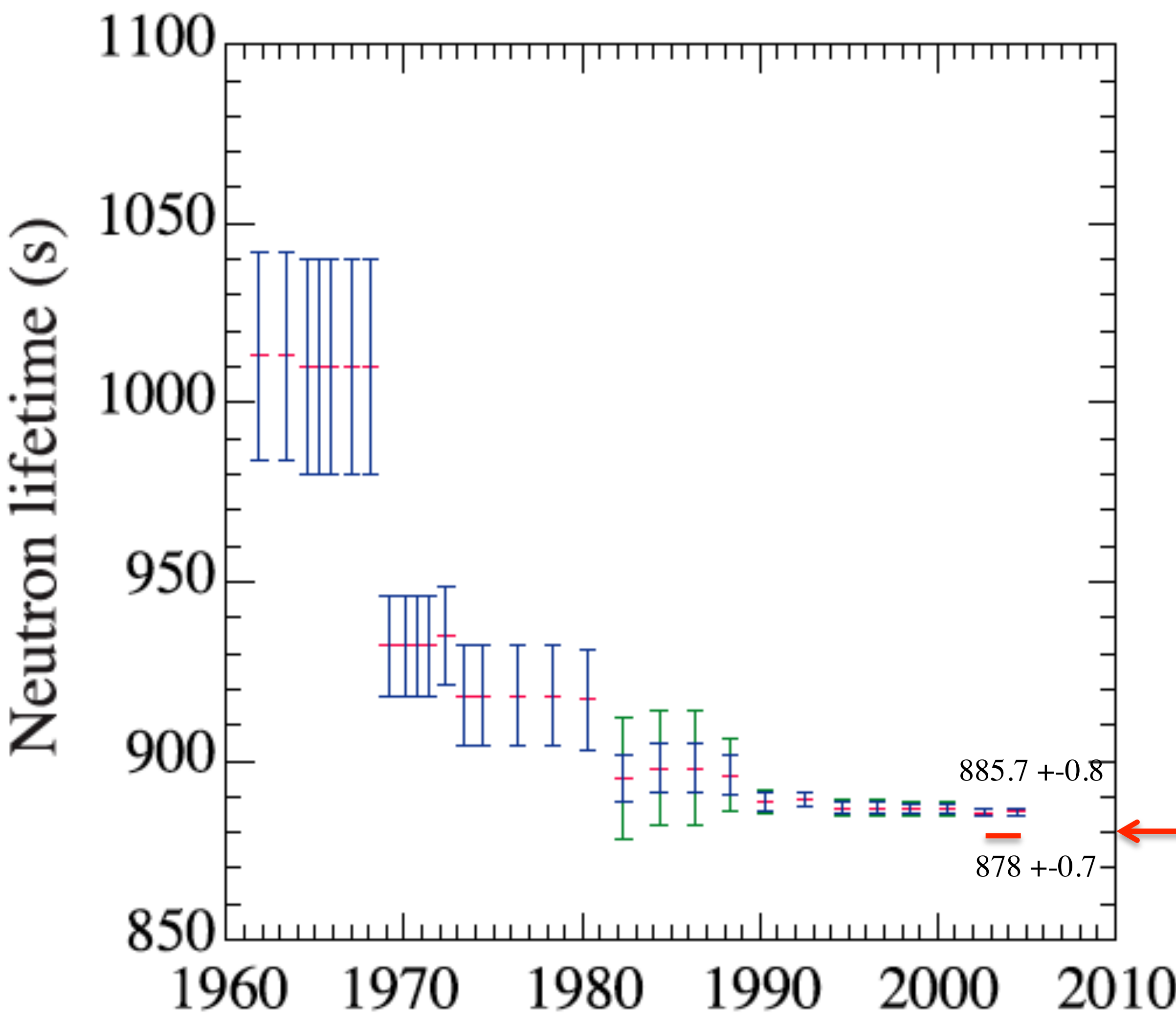
# Why do the results of Mueller et al. differ from the old results of Schreckebach et al.?

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% |

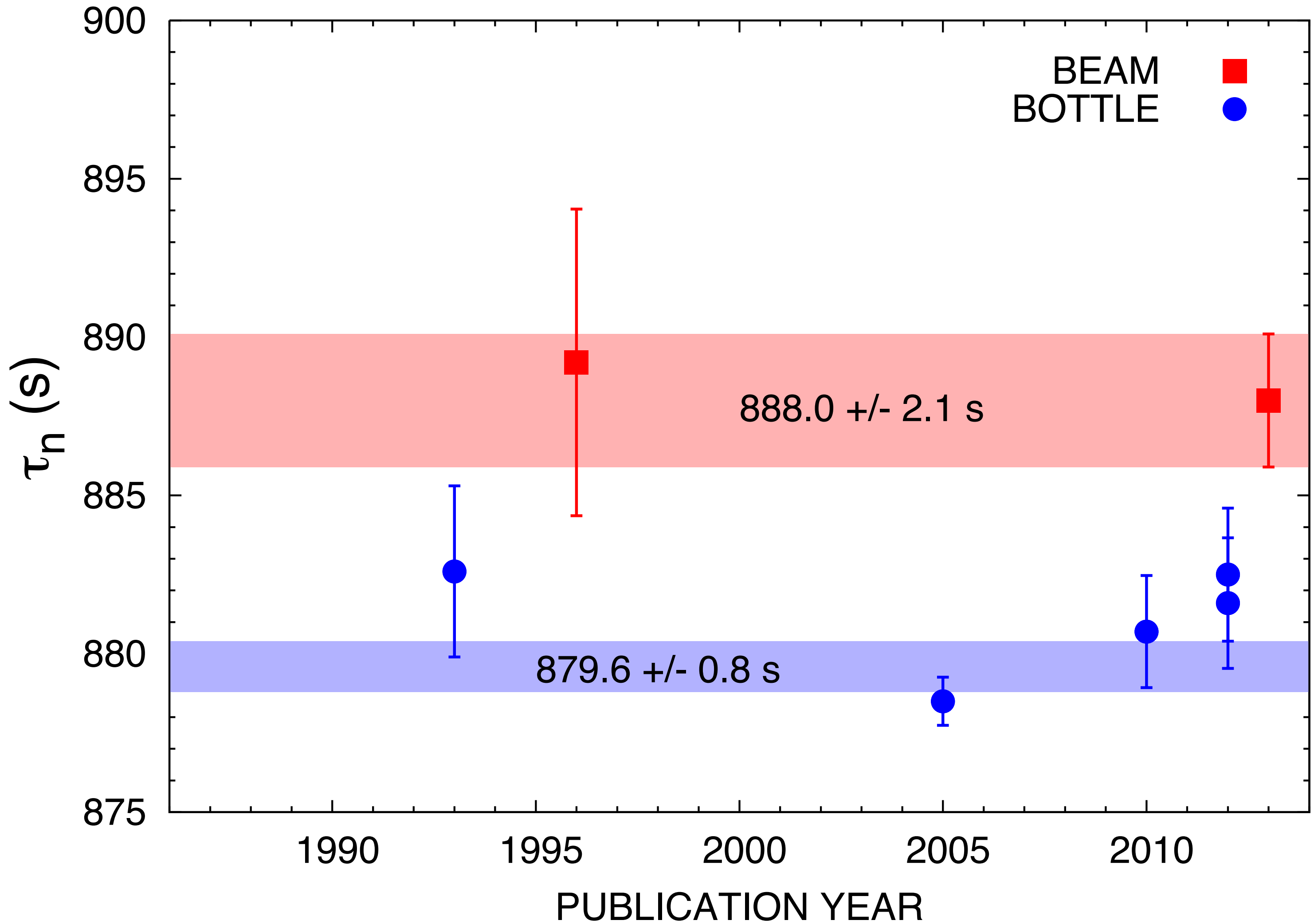
This all looks quite reasonable, but is it all?

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.




Present PDG recommendation

There are two basic methods of the $\tau_n$ 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:

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

**Fractional corrections to the individual beta decay spectra:**

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

$\delta_{\mathrm{rad}}$ = Radiative correction (used formalism of Sirlin)

$\delta_{FS}$ = Finite size correction to Fermi function

$\delta_{\mathrm{WM}}$ = Weak magnetism

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 $\delta_{FS}$ and $\delta_{WM}$ 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 $\delta_{WM} = 0.67(0.26)$ % MeV$^{-1}$ while the formula above gives ~0.5% MeV$^{-1}$. In calculations 100% error was assumed.

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

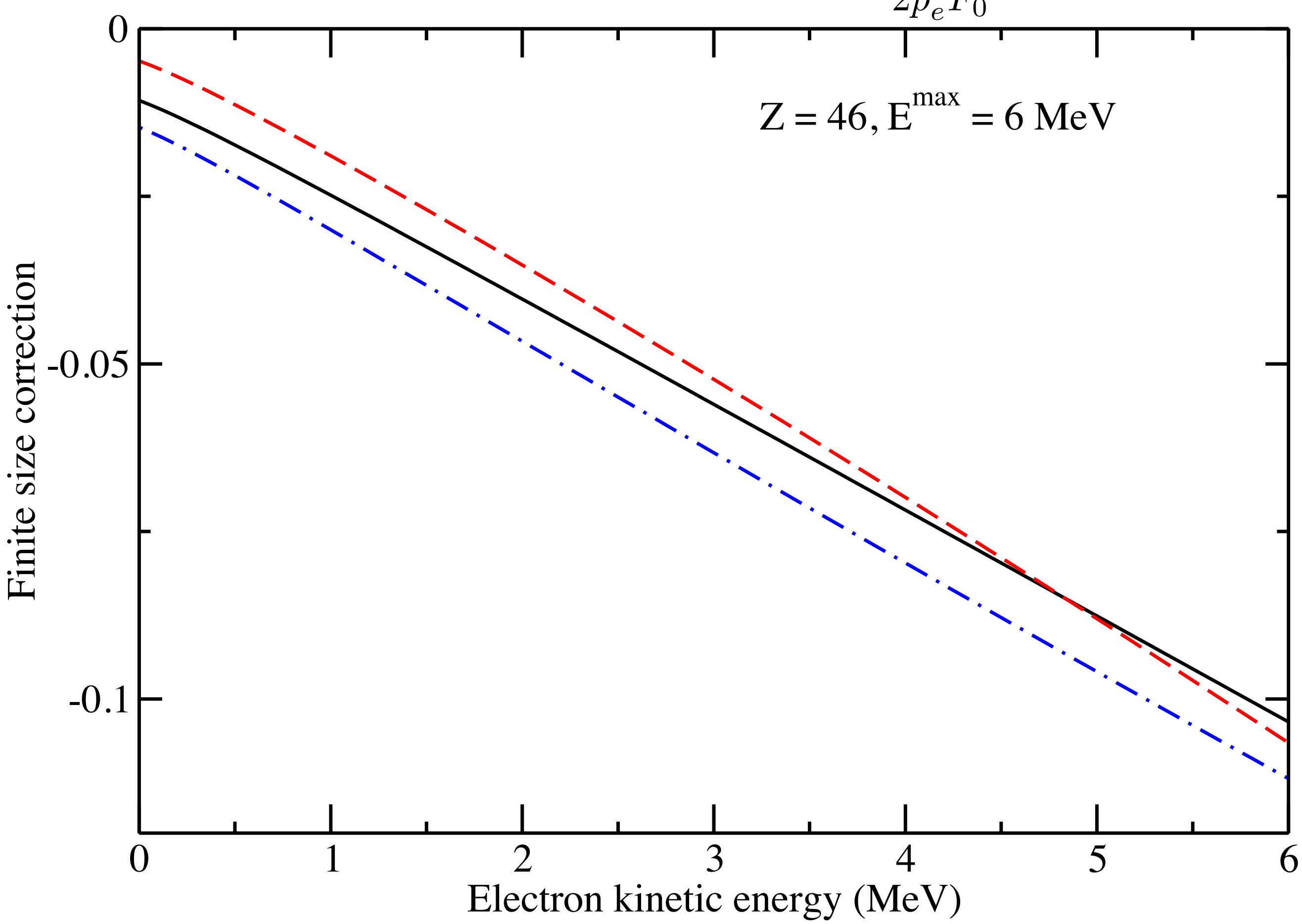
Table from P. Huber, Phys. Rev. **C84**, 024617(erratum **C85**, 02990(E) (2012)

# Finite size correction $\delta_{FS}$

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

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

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

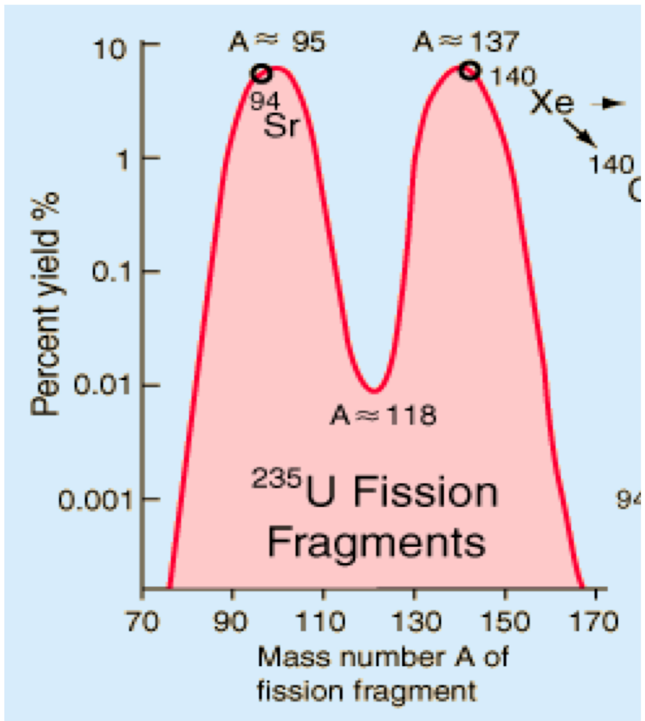


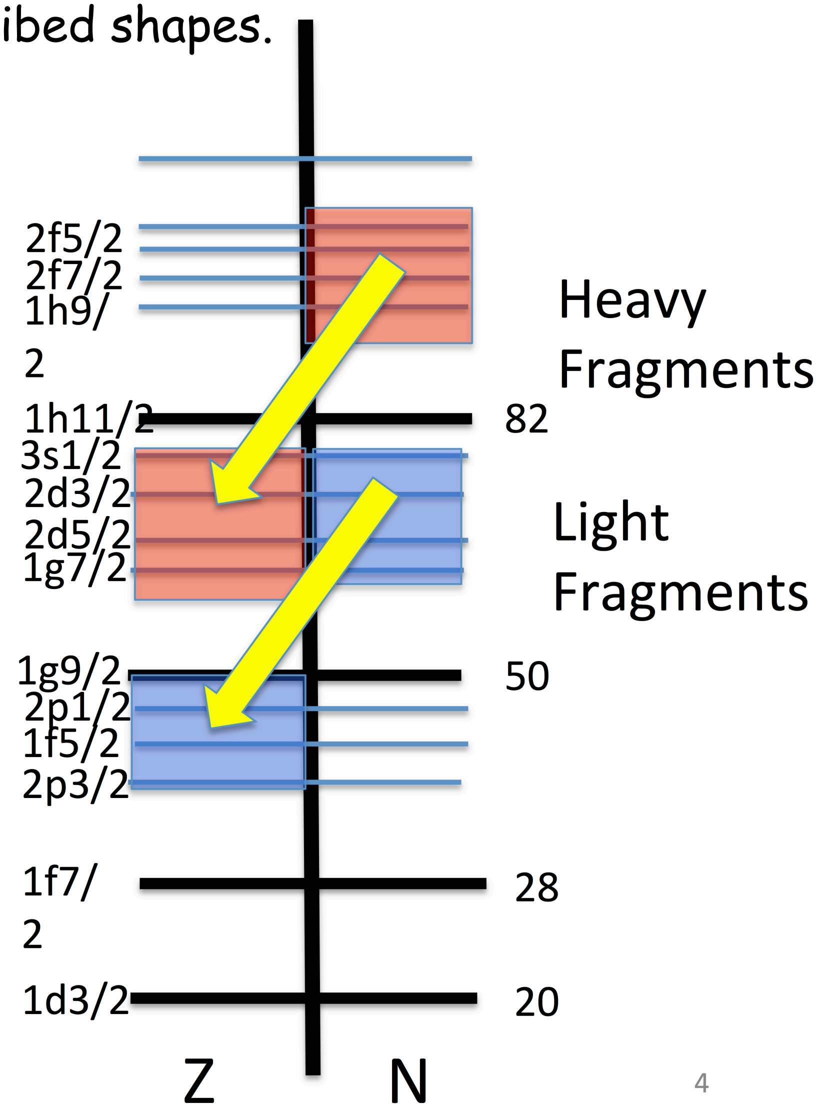

Different ways to take into account nuclear finite size exist in the literature.
In fact the resulting slopes are quite similar, and to some extent they compensate for the $\delta_{WM}$

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.



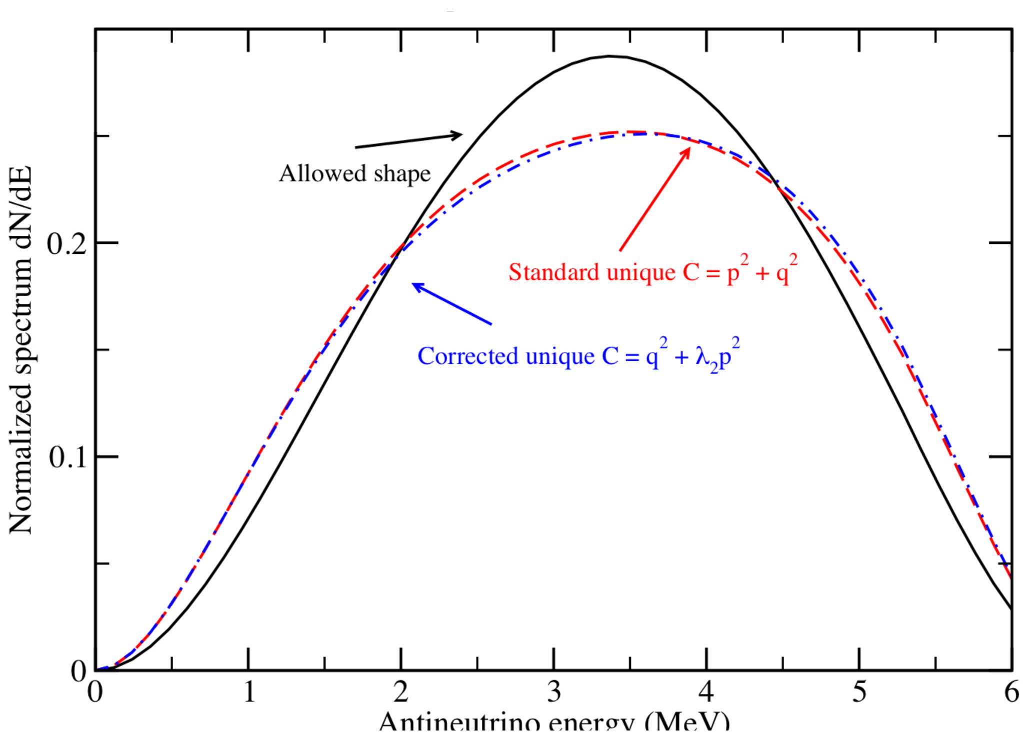




The error associated with the forbidden decays was not properly included in the previous analyses.

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.

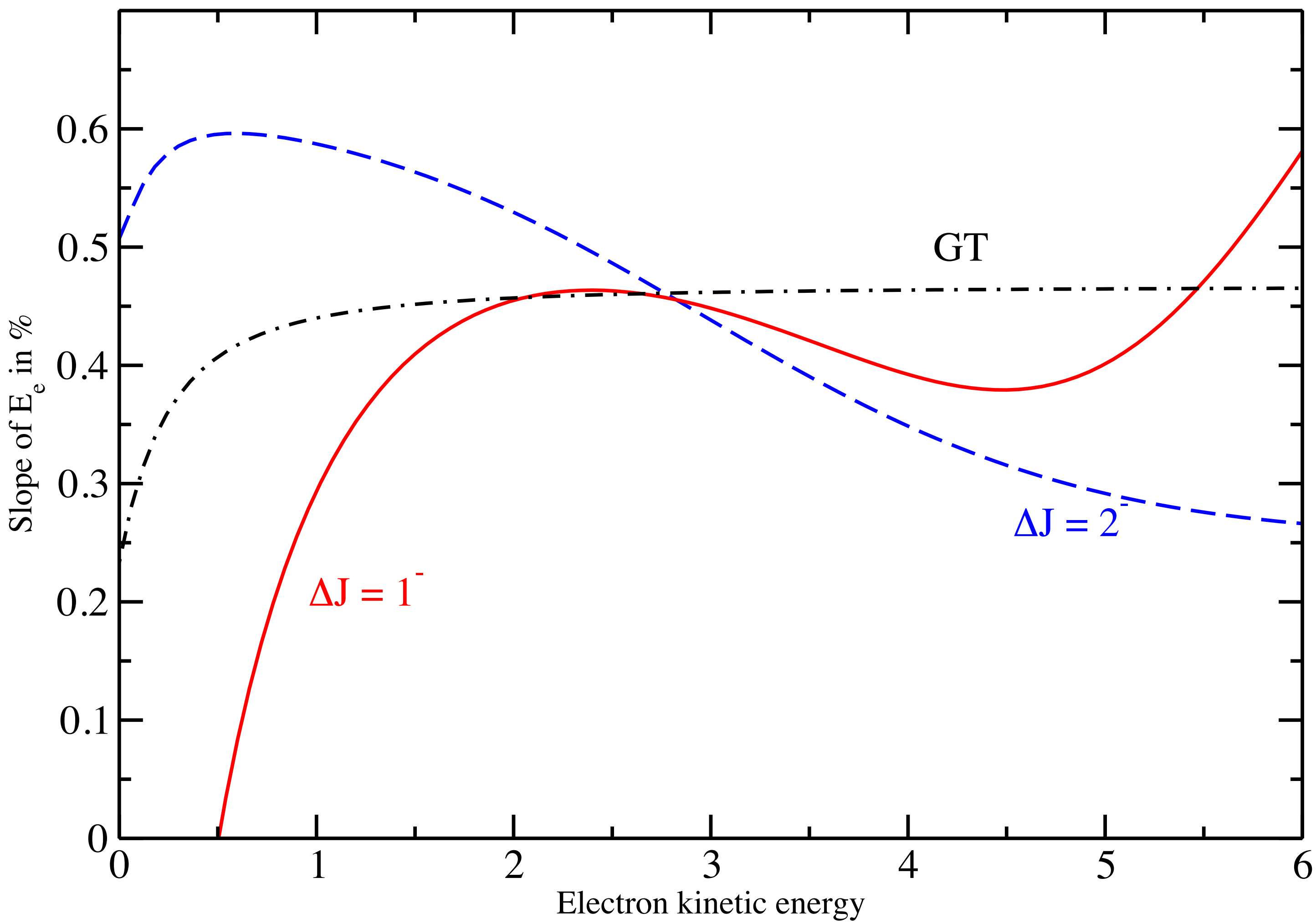
Unlike for the allowed GT decays with only one operator, there are up to six operators for the first forbidden decays that can interfere.

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.



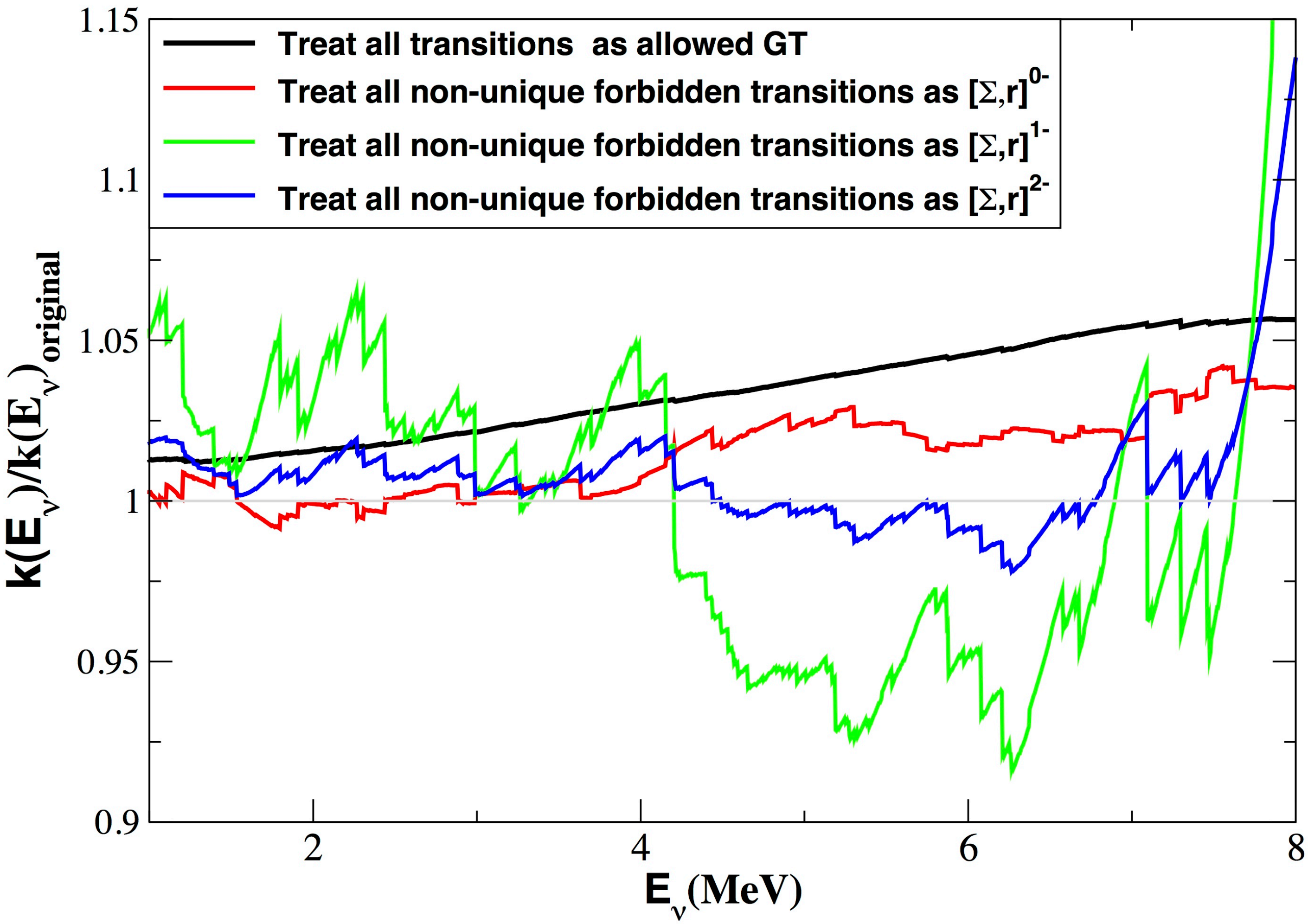

First forbidden decays with $|\Delta I| = 2$ are governed by only single matrix element and thus have again a simple shape.
Here is an example for Z=46, Q=6 MeV.

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 $\delta_{WM}/E_e$ is shown here.

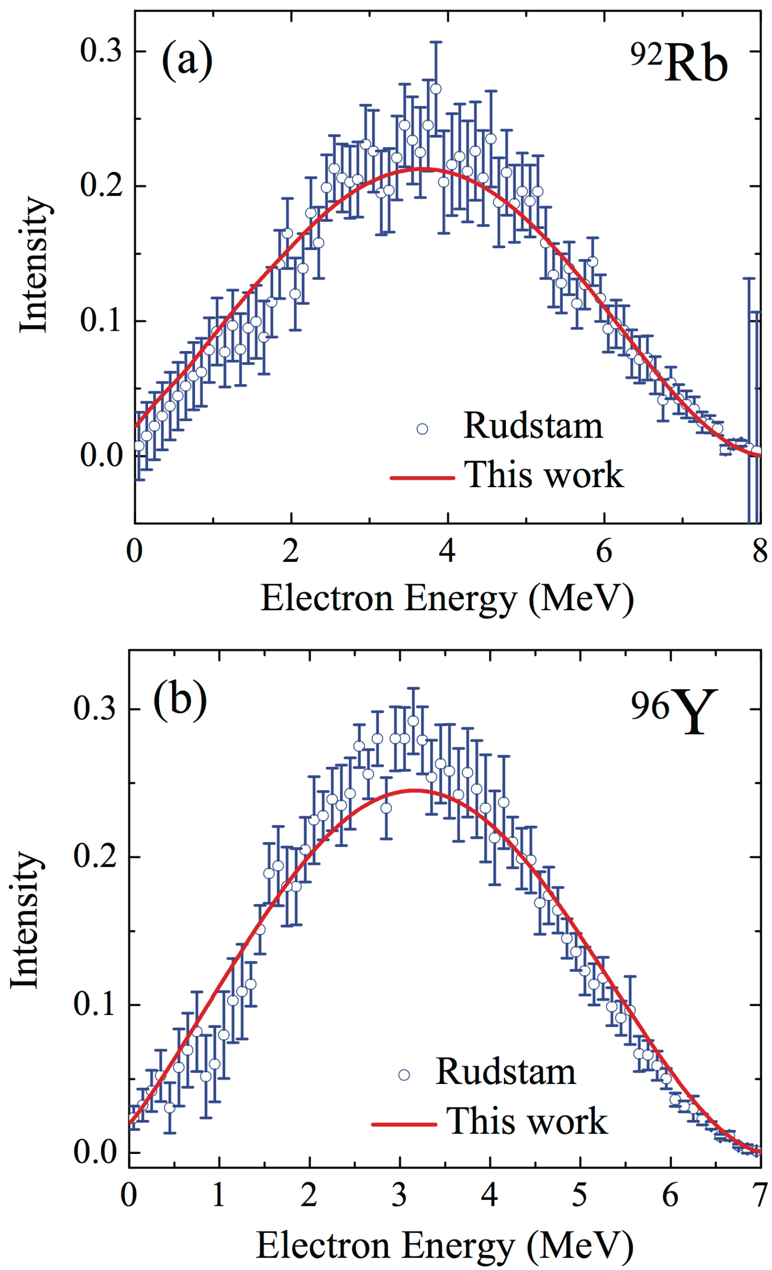



from A. Hayes et al, PRL **112**, 202501 (2014).

Ratio of the $\nu_e$ 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).



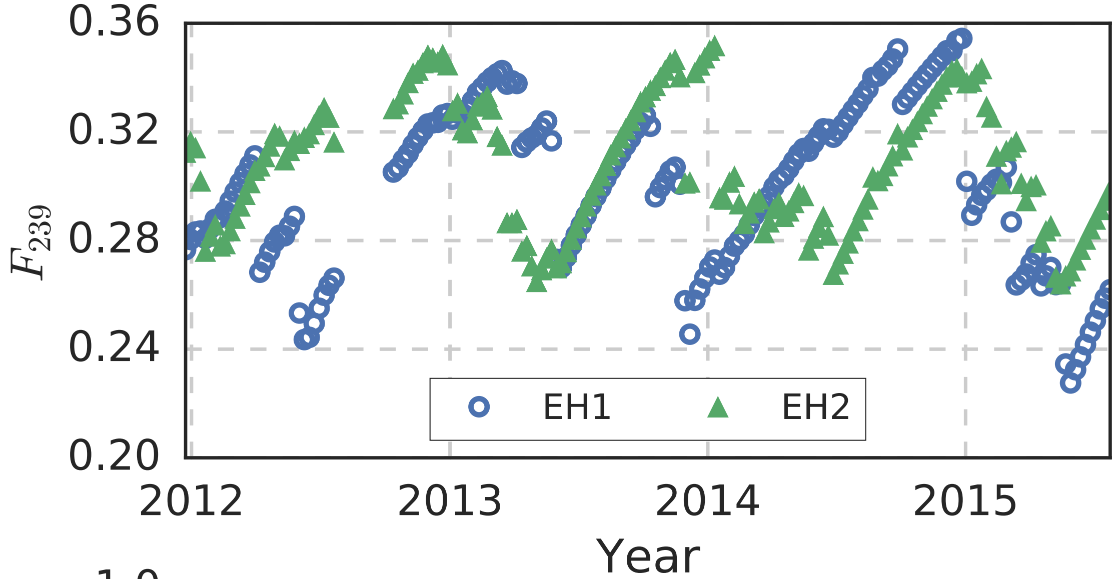

Note, however, that in reality a combination of shapes occurs. Thus these error limits must be considered as an illustration.



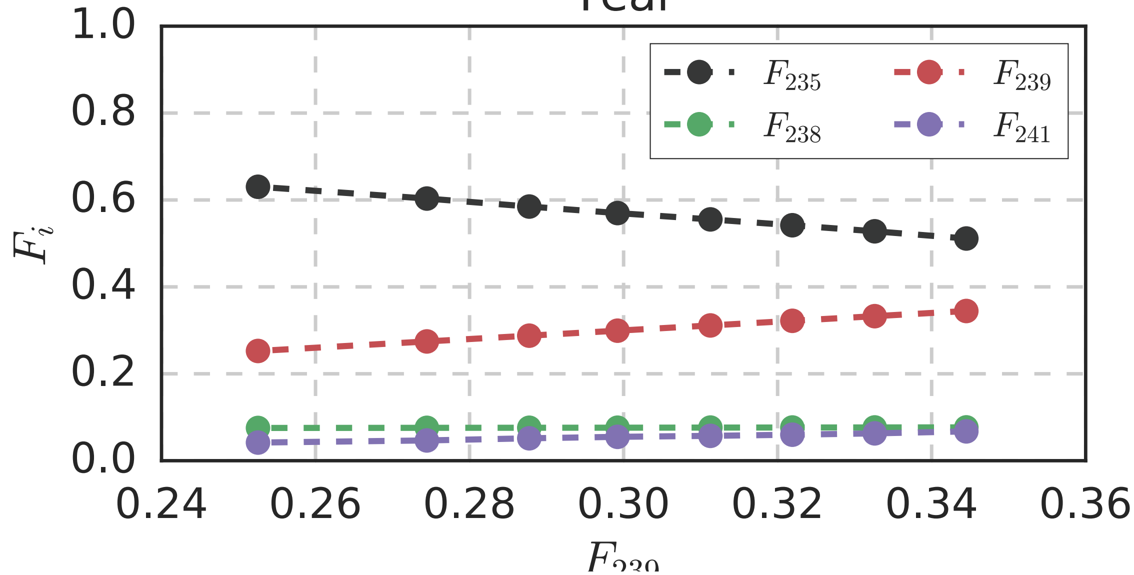

Examples of measured $0^- \rightarrow 0^+$ transitions of important fission fragments. Measurement of G. Rudstam et al. ADNT **45**, 239 (1990), calculations assuming the allowed shape of A. A. Sonzogni et al, PRC **91**, 011301 (2015). For these transitions $\delta_{WM}$ = 0.0

1) The assumed uncertainty of ~2.7% (Mueller, Huber) was based on the assumption that the shapes of **all** $\beta$ 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 $^{235}U$ $\nu_e$ 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.

Fission fraction stemming from $^{235}U$ decreases over the reactor refueling cycle and of $^{239}Pu$ increases. In Daya-Bay close detectors more than $10^6$ events were recorded. It was, therefore, possible to determine separately the two fluxes.




Weakly changes of $^{239}Pu$ fission fraction in the two close detectors.




Effective fission fractions of the four fuels as a function of $^{239}Pu$ fraction.

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 ~3$\sigma$, 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)

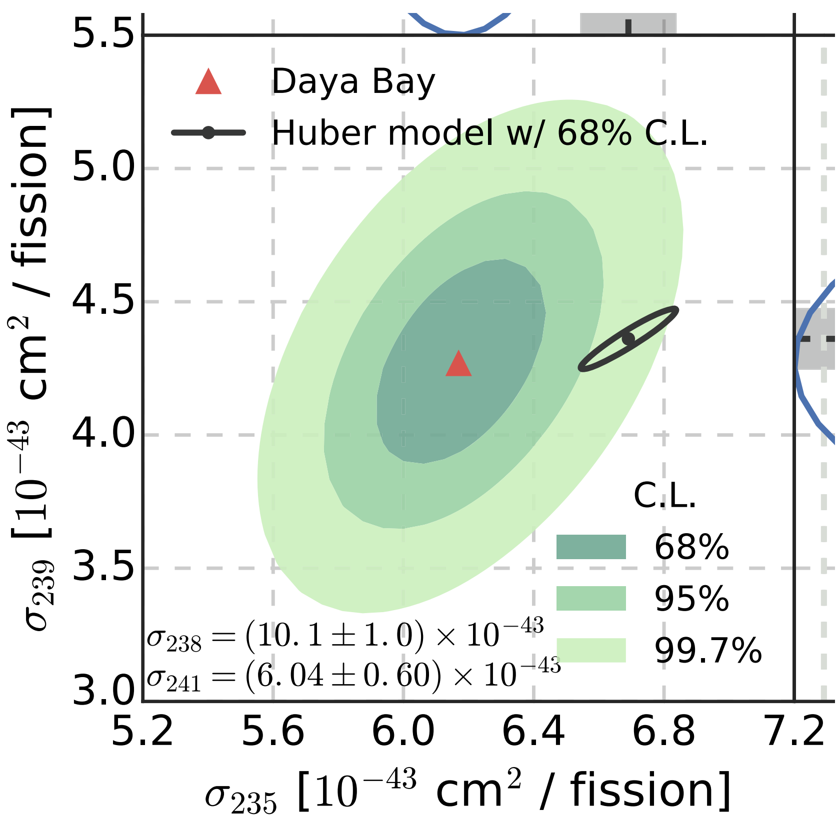



Figure from An *et al.*, PRL **118**, 251801

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 4$\sigma$ 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 $\theta_{13}$ analysis. Very similar results obtained in Daya-Bay and Double-Chooz.

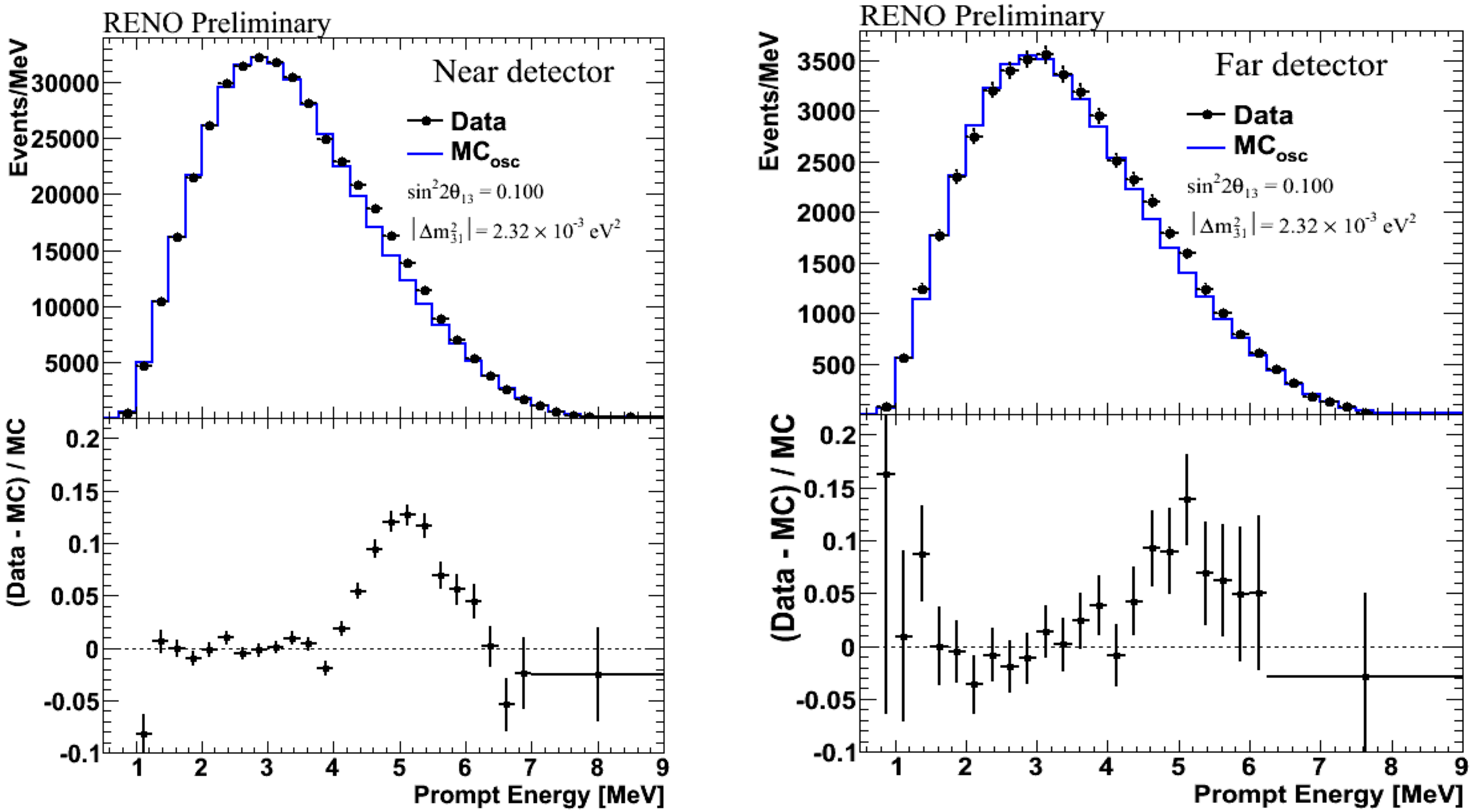
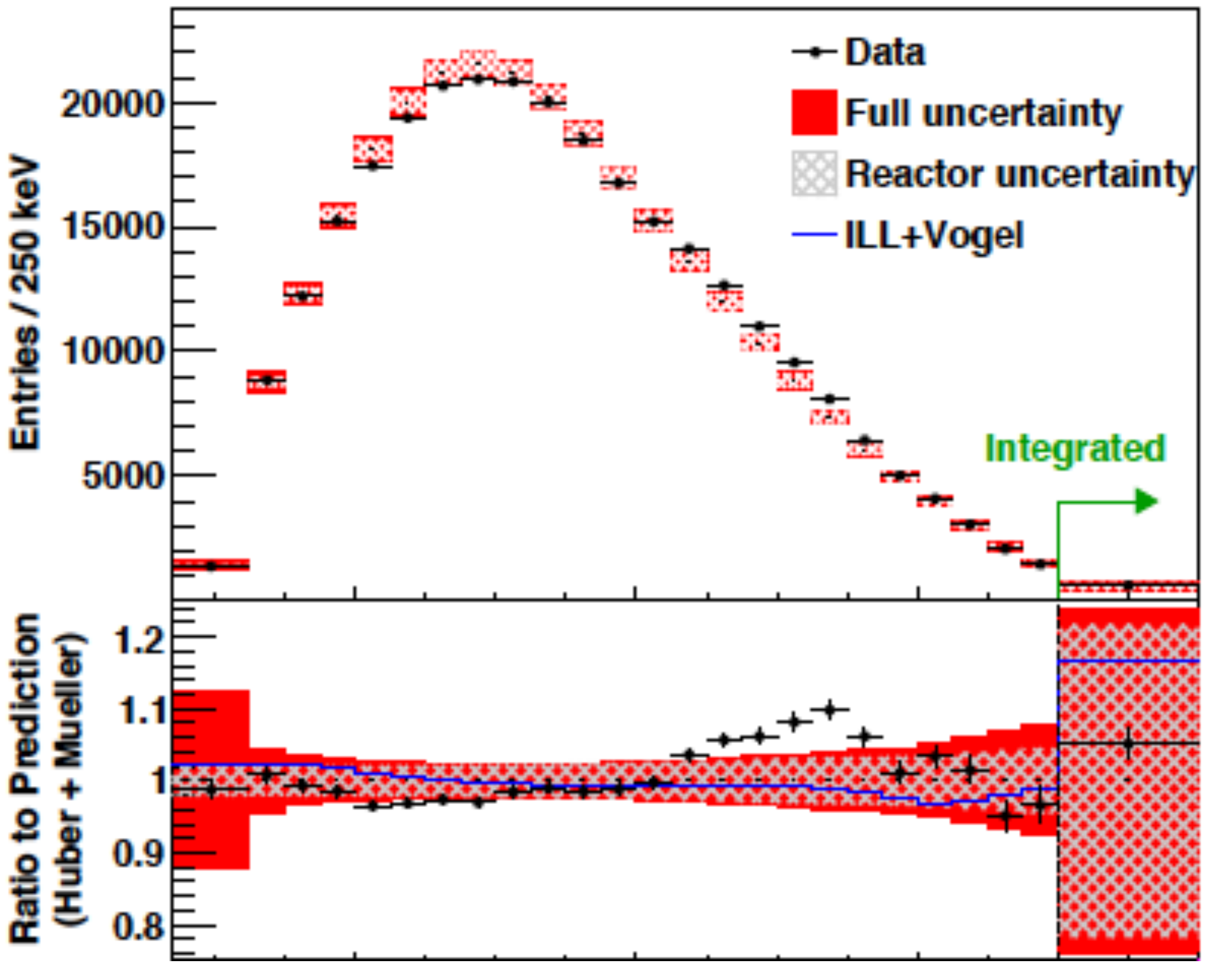
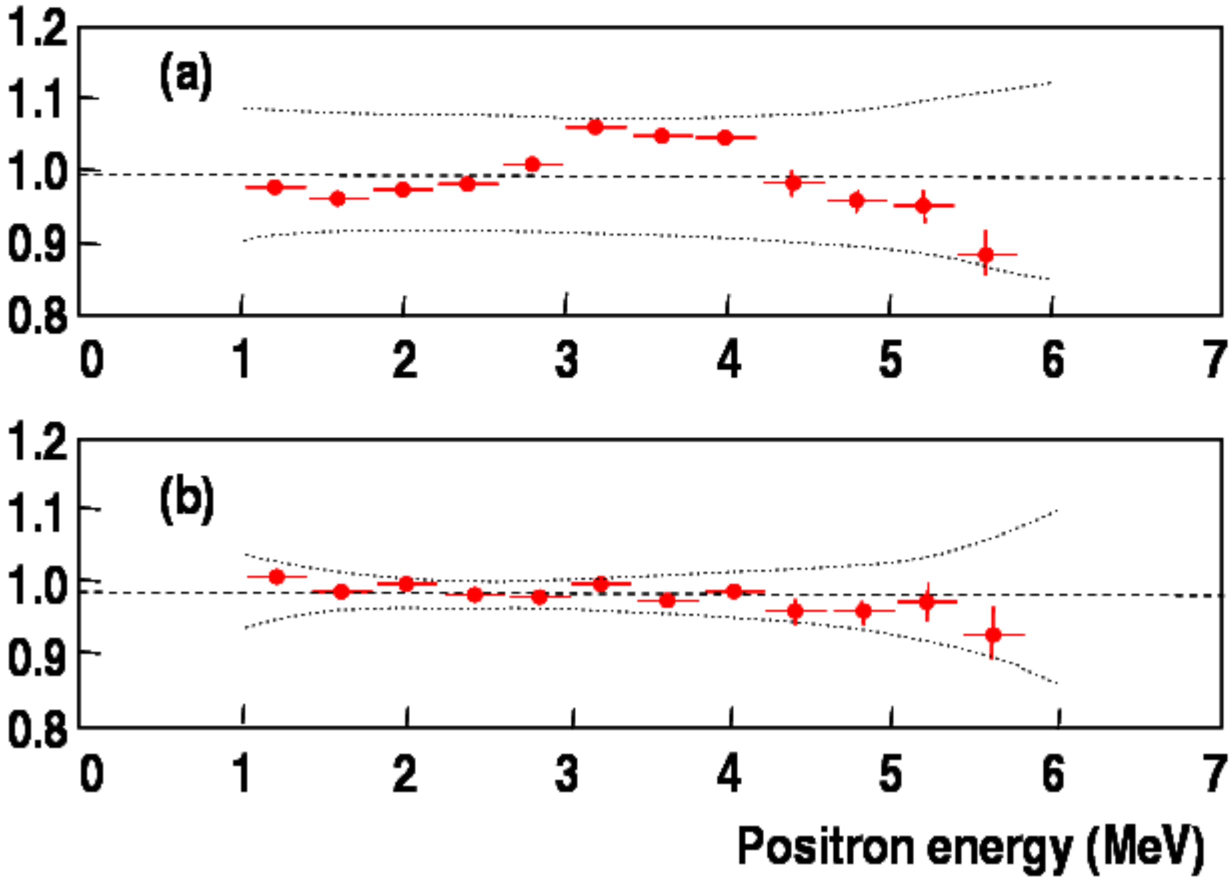



Figure from S-H Seo for RENO collaboration, talk at the Neutrino 2014 conference




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

Measured $\nu_e$ 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.

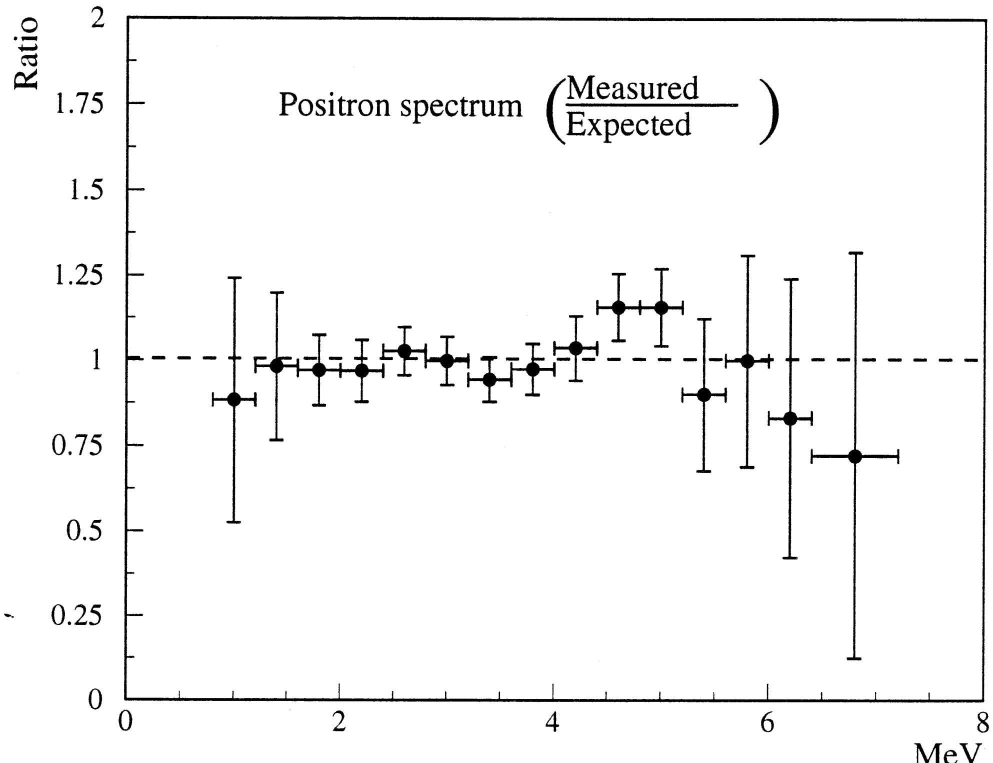



Calculation only
Klapdor and Metzinger, 1982

Beta calibrated
Schreckenbach, 1985
Hahn, 1989

*Results of Bugey experiment (1996)*

Consequently, the recent observation of the ``bump" was presented as a surprise. However, in hindsight it was presumably observed earlier, e.g. in the Chooz experiment: M. Apollonio *et al.*, Phys Lett. B**466**, 415 (1999)




Positron spectrum compared to the expectations based on the converted ILL electron observation. Note, that one presumably see the ``bump" there. The total rate agreed with the expectations of that time: $R = 1.01 \pm 2.8\%(\text{stat}) \pm 2.7\%(\text{syst})$.

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..

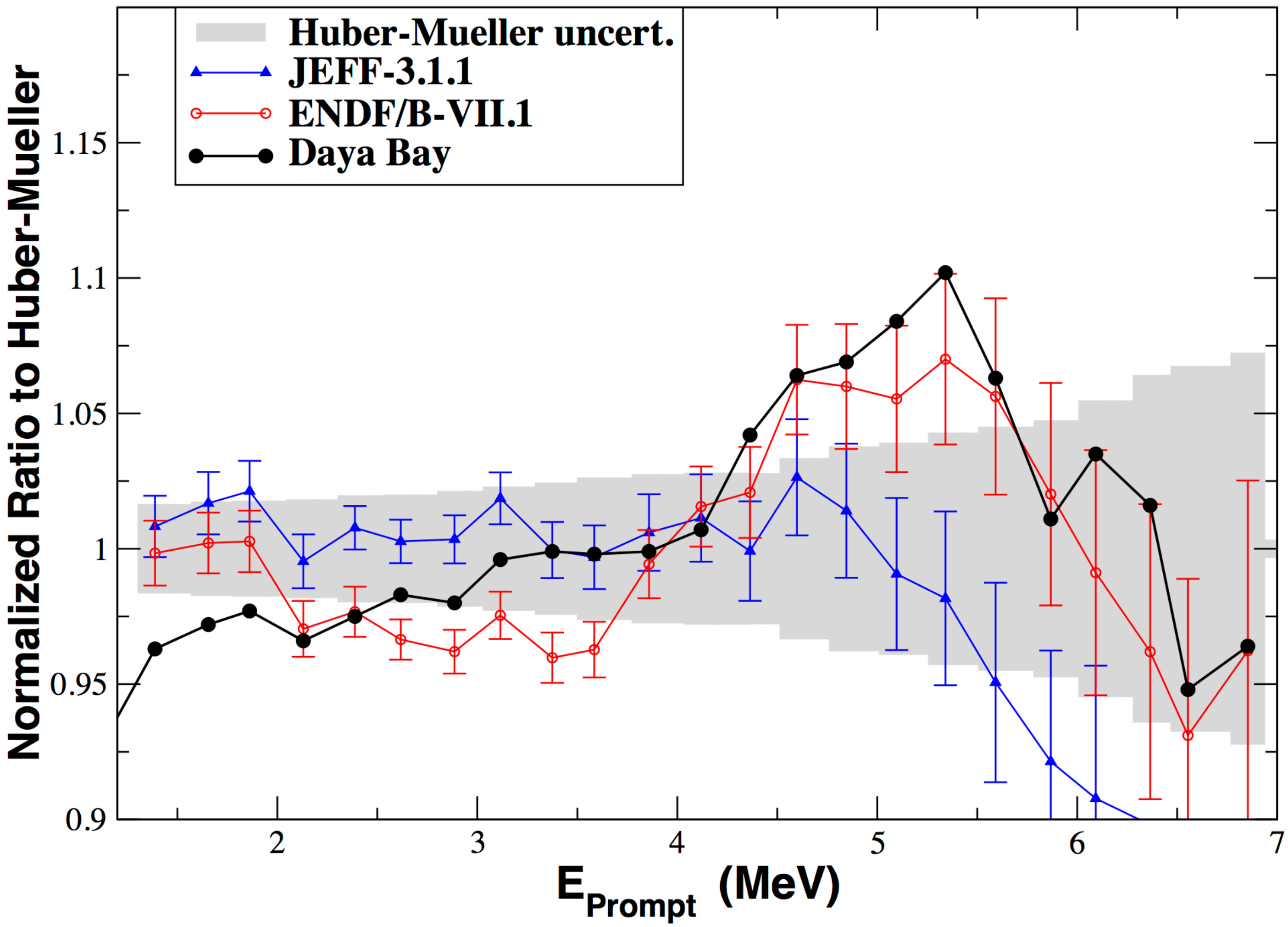
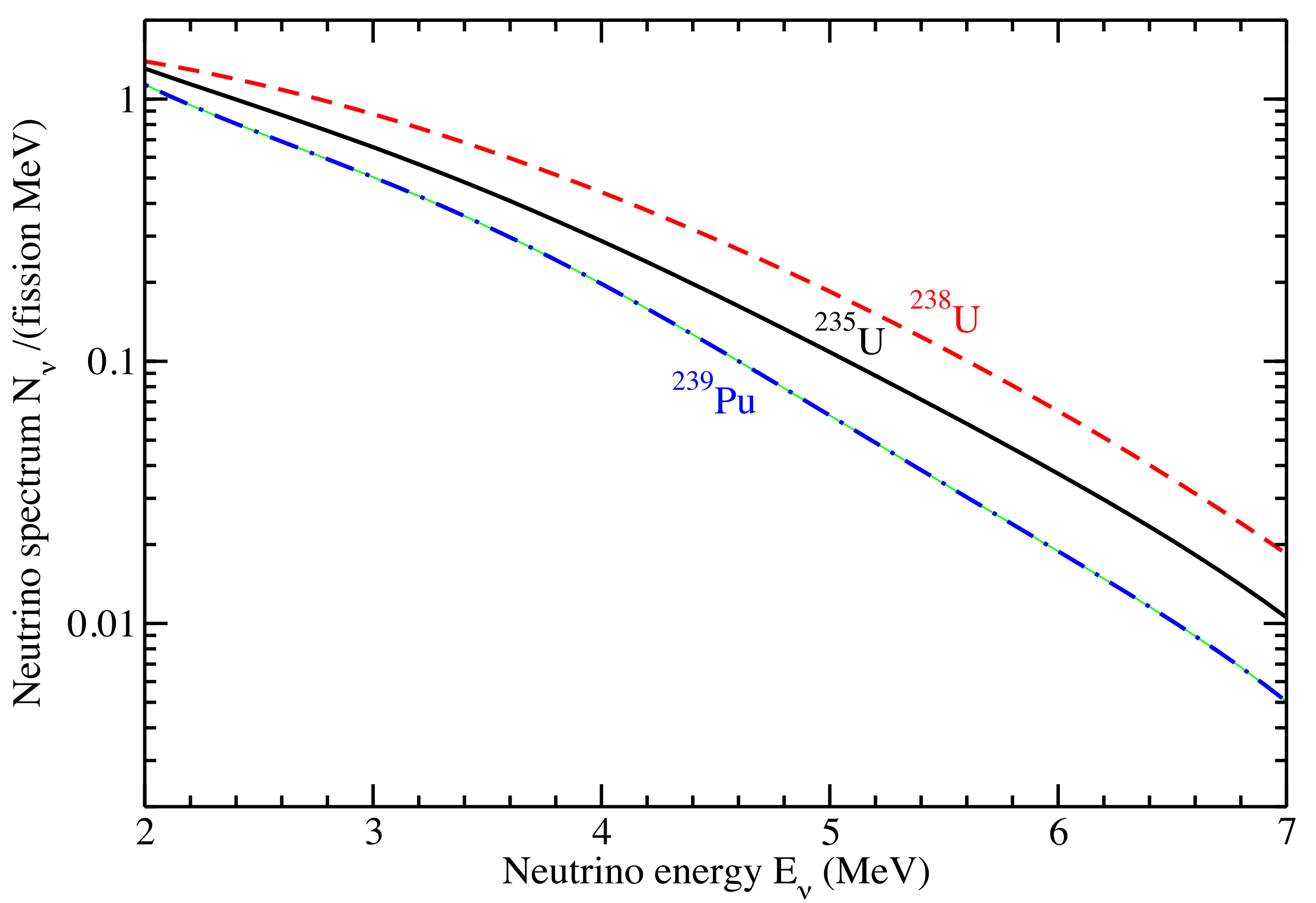
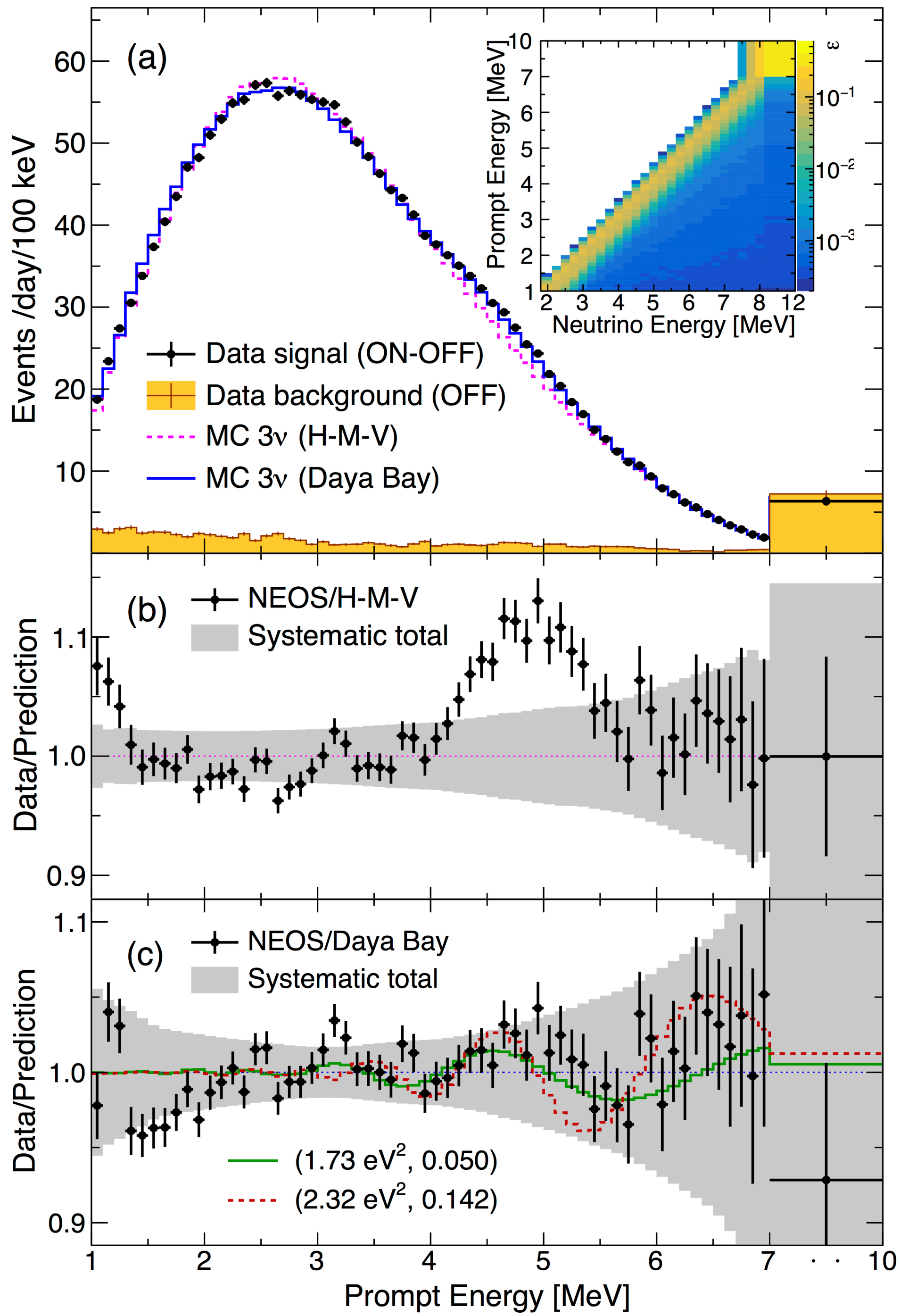



Figure 1 from A.C. Hayes et al., 1506.00583

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.

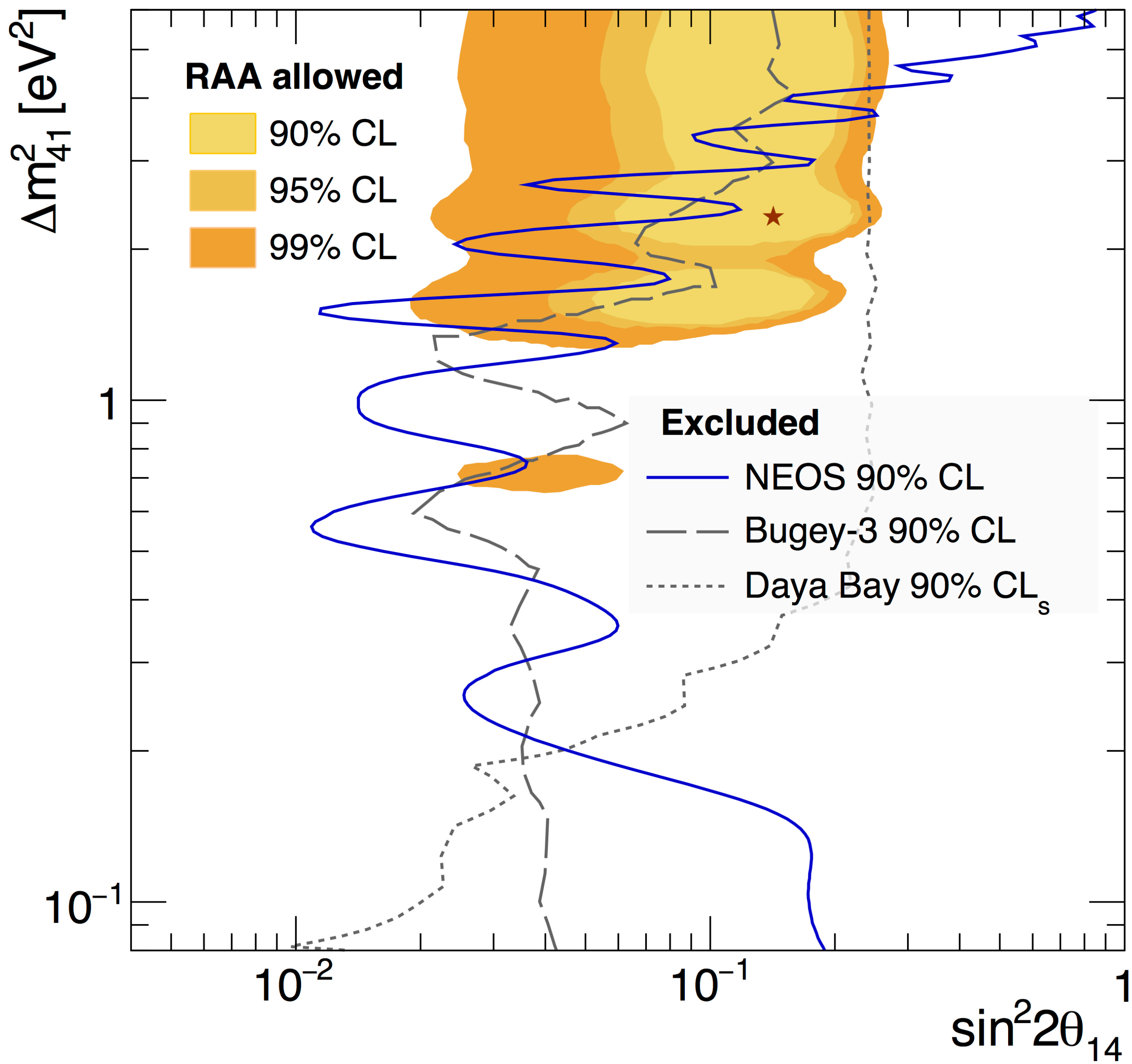





In the NEOS experiment (1610.05134) the detector is ~24 m away from a Korean power reactor (in the same complex as the RENO experiment).

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 $\Delta\chi^2 = 5.4$.

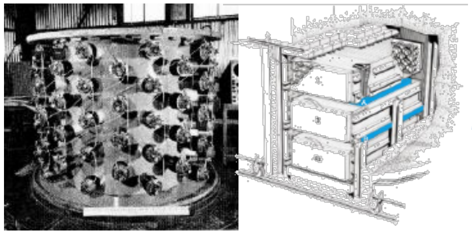
## Summary and Conclusions

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 $\beta$ decays might increase 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.

spares

# Brief history of reactor neutrinos

Discovery of ν



1953, Hanford, 0.3 ton
1956, Savannah River, 4.2 ton

**Early searches for oscillation**

1980 Savannah,

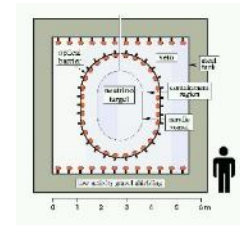
1980 ILL,

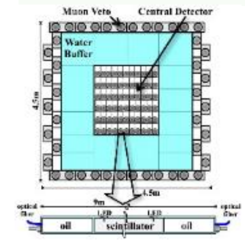
1984 Bugey,

1986 Gosgen,

1995 Bugey-3,

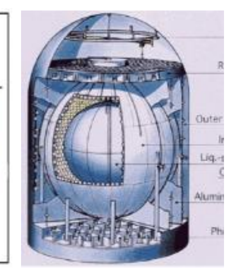
Reactor ν spectra ~2%

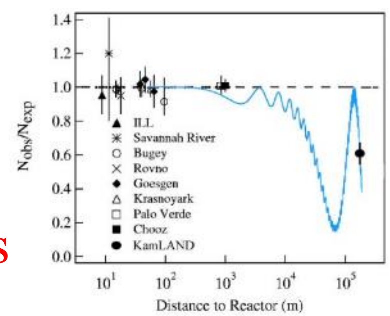





1997, CHOOZ, 8 ton
2000, Palo Verde, 12 ton

$\sin^2 2\theta_{13} < 0.15$

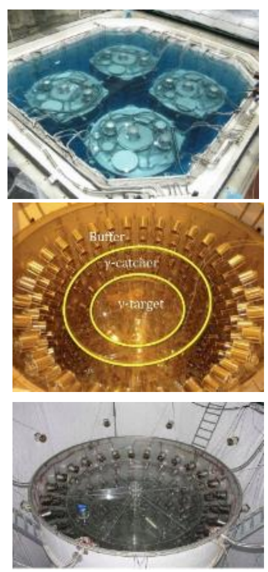



2002, KamLAND, **1000 ton**

Reactor ν oscillations ($\Delta m_{21}^2$)

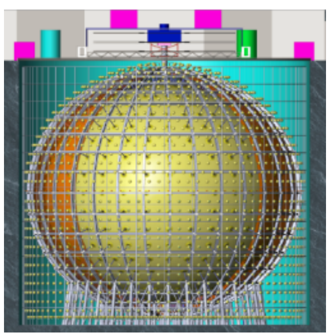
2012,
Daya Bay, 160 ton
Double Chooz, 16 ton
RENO, 32 ton




Non-zero $\theta_{13}$

Mass Hierarchy,
Precision meas.

2020, JUNO, **20 000 ton**

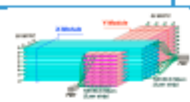
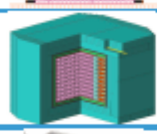
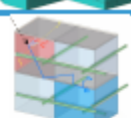


**Very short baseline exp. for sterile ν**

Slide by J. Cao

# Experiments to test the sterile neutrino hypothesis

- Different technologies: (Gd, Li, B) (seg.)(movable)(2 det.)
- Most have sensitivity 0.02~0.03 @$\Delta$m~1eV$^2$ @90%CL

| Experiment | Reactor Power/Fuel | Overburden (mwe) | Detection Material | Segmentation | Optical Readout | Particle ID Capability |
|---|---|---|---|---|---|---|
| DANSS (Russia)  | 3000 MW LEU fuel | ~50 | Inhomogeneous PS & Gd sheets | 2D, ~5mm | WLS fibers. | Topology only |
| NEOS (South Korea)  | 2800 MW LEU fuel | ~20 | Homogeneous Gd-doped LS | none | Direct double ended PMT | recoil PSD only |
| nuLat (USA)  | 40 MW $^{235}$U fuel | few | Homogeneous $^{6}$Li doped PS | Quasi-3D, 5cm, 3-axis Opt. Latt | Direct PMT | Topology, recoil & capture PSD |
| Neutrino4 (Russia)  | 100 MW $^{235}$U fuel | ~10 | Homogeneous Gd-doped LS | 2D, ~10cm | Direct single ended PMT | Topology only |
| PROSPECT (USA)  | 85 MW $^{235}$U fuel | few | Homogeneous $^{6}$Li-doped LS | 2D, 15cm | Direct double ended PMT | Topology, recoil & capture PSD |
| SoLid (UK Fr Bel US)  | 72 MW $^{235}$U fuel | ~10 | Inhomogeneous $^{6}$LiZnS & PS | Quasi-3D, 5cm multiplex | WLS fibers | topology, capture PSD |
| Chandler (USA)  | 72 MW $^{235}$U fuel | ~10 | Inhomogeneous $^{6}$LiZnS & PS | Quasi-3D, 5cm, 2-axis Opt. Latt | Direct PMT/ WLS Scint. | topology, capture PSD |
| Stereo (France)  | 57 MW $^{235}$U fuel | ~15 | Homogeneous Gd-doped LS | 1D, 25cm | Direct single ended PMT | recoil PSD |

Talk by Nathaniel Bowden @NEUTRINO2016