Reactor Antineutrino Spectra


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The predicted number of detectable reactor antineutrinos has evolved upward over time

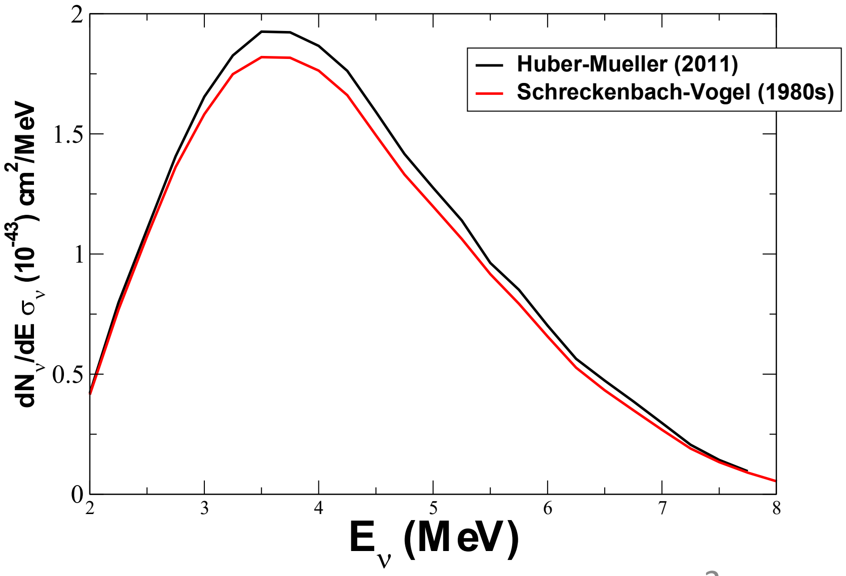
In the 1980s two predictions became the standards for the field:

- Schreckenbach *et al*. converted their measured fission β-spectra for ^{235}U, ^{239}Pu and ^{241}Pu into antineutrino spectra
- Vogel *et al*. used the nuclear databases to predict the spectrum for ^{238}U

In 2011 both Mueller *et al.* and Huber predicted that improvements in the description of the spectra increase the expected number of antineutrinos by 5-6%.

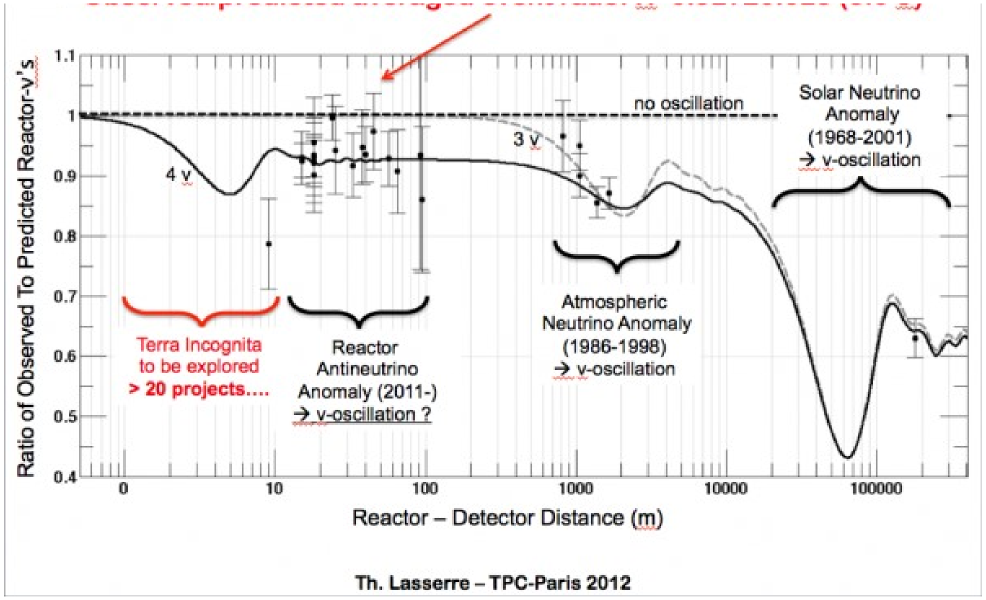
The change was largely as a consequence of:

- A predicted increase in the energy of the Schreckenbach antineutrino flux for ^{235}U, ^{239}Pu , and ^{241}Pu.
- An overall increase in the ^{238}U antineutrino flux due to enhanced nuclear databases over 25 years.



This led to a 5-6% shortfall in the antineutrino flux in all short baseline reactor experiments - Reactor Neutrino Anomaly

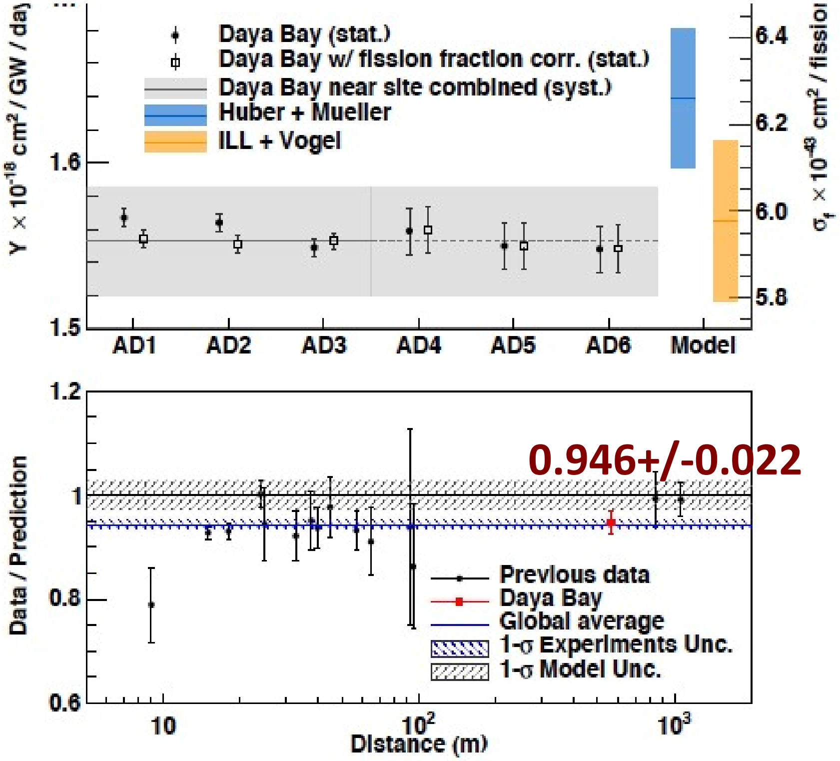
From Th. Lasserre, 2012



If this is an oscillation phenomenon, it requires a 1 eV sterile neutrino.

Results from Daya Bay, 2016

PRL,116 (2016) 061801



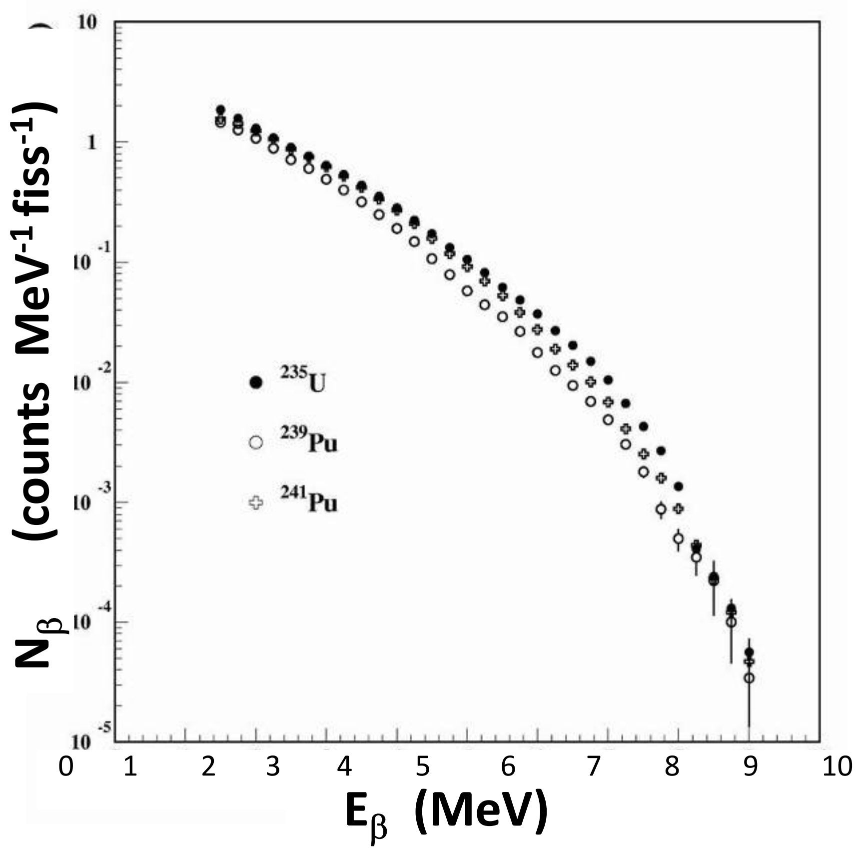
0.946+/-0.022

The very accurate measurements of the total flux at Daya Bay, RENO and Double Chooz confirms the shortfall.

The issue then becomes ones of:

- **Confirming/re-examining the expectations and their uncertainties**
- **Confirming/denying the existence of 1 eV sterile neutrinos**

The Original Expected Fluxes were Determined from Measurements of Aggregate Fission β-Spectra (electrons) at the ILL Reactor in the 1980s



- The thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu were measured at ILL.
- These β-spectra were converted to antineutrino spectra by fitting to 30 end-point energies
- ^{238}U requires fast neutrons to fission – difficult to measure at a reactor

⇒ Vogel *et al*. used the ENDF-5 nuclear database to estimate for ^{238}U.

Vogel, et al., Phys. Rev. C24, 1543 (1981).

K. Schreckenbach et al. PLB118, 162 (1985)

A.A. Hahn et al. PLB160, 325 (1989)

FIT

$$S_\beta(E) = \sum_{i=1,30} \boxed{a_i}\, S^i(E, E_o^i)$$

Parameterized

$$S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, \boxed{Z_{eff}})(1 + \boxed{\delta_{corrections}})$$

Two inputs are needed to convert an aggregate β-spectrum to an antineutrino spectrum: (1) the Z of the fission fragments for the Fermi function, and (2) the sub-dominant corrections

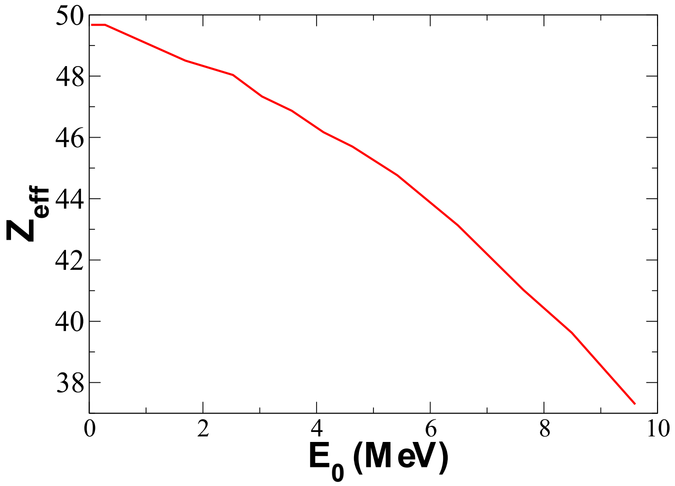
$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E,\ Z)(1+\ \delta_{corrections})$$

The Zeff that determines the Fermi function:

On average, higher end-point energy means lower Z.

- Comes from nuclear binding energy differences

$$Z_{eff} \sim a + b\,E_0 + c\,E_0^2$$



The corrections

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

δ_{FS} = Finite size correction to Fermi function

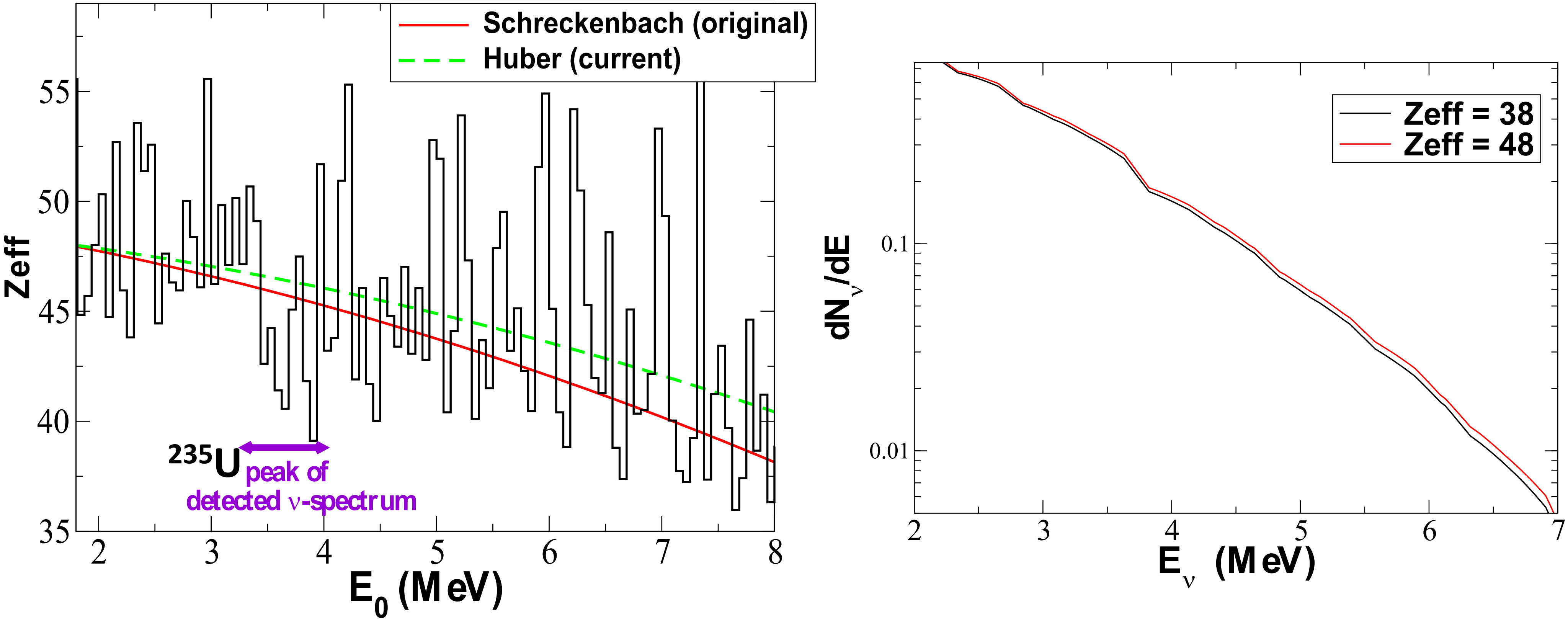
δ_{WM} = Weak magnetism

δ_R = Recoil correction

δ_{rad} = Radiative correction

A change to the approximations used for these effects led to the anomaly

The higher the average nuclear charge Zeff in the Fermi function used to convert the β-spectrum, the higher ν–spectrum



$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, \boxed{Z_{eff}(E_0)})(1+\delta)$$

- **Huber's new parameterization of Zeff with end-point energy E_0 changes the Fermi function and accounts for 50% of the current anomaly.**
- **Both fits (original & new) used a quadratic fit** $Z_{eff} = a + b\,E_0 + c\,E_0^2$

The finite size and weak magnetism corrections account for the remainder of the anomaly

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

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

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

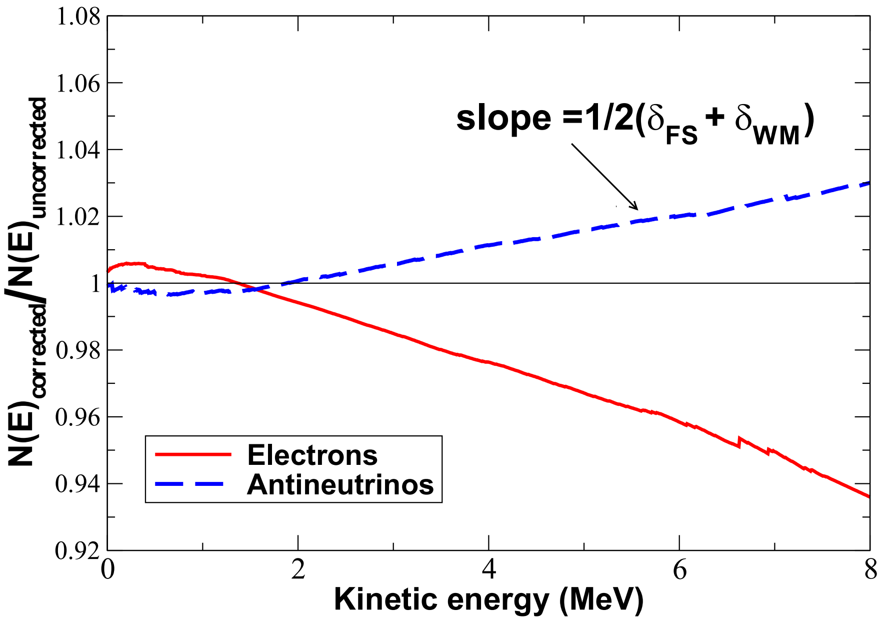
Originally approximated by a parameterization: $\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4MeV))$

In the updated spectra, both corrections were applied on a state-by-state basis

An approximation was used for each:

$$\delta_{FS} = -\frac{10 Z\alpha R}{9\hbar c} E_\beta; \quad R = 1.2 A^{1/3}$$

$$\delta_{WM} = +\frac{4(\mu_V - 1/2)}{3M_n} 2E_\beta$$



Led to a systematic increase of in the antineutrino flux above 2 MeV

Uncertainties in the detailed contributions to the total spectra

30% of the beta-decay transitions involved are so-called forbidden
Allowed transitions ΔL=0; Forbidden transitions ΔL=0

Forbidden transitions introduce a shape factor C(E):

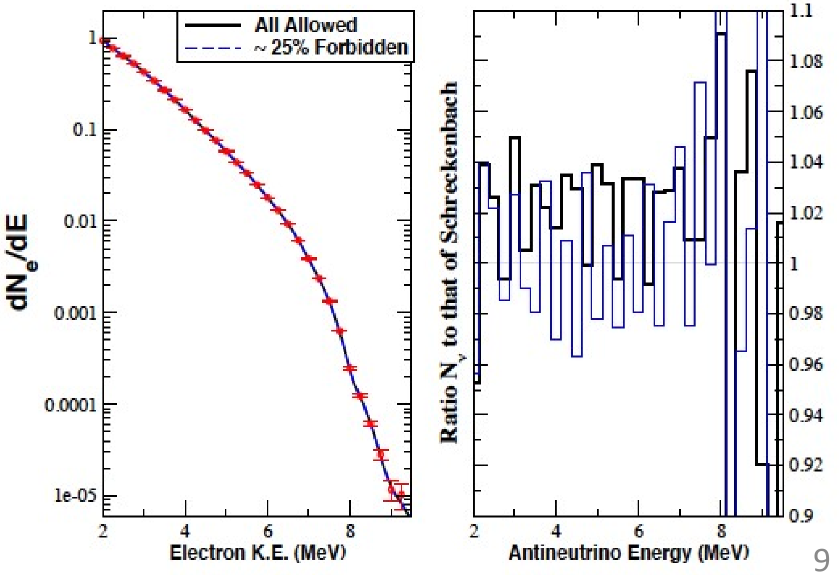
$$S(E_e, Z, A) = \frac{G_F^2}{2\pi^3} p_e E_e (E_0 - E_e)^2 \underline{C(E)} F(E_e, Z, A)(1 + \delta_{corr}(E_e, Z, A))$$

The corrections δ for forbidden transitions are also different and sometimes unknown :

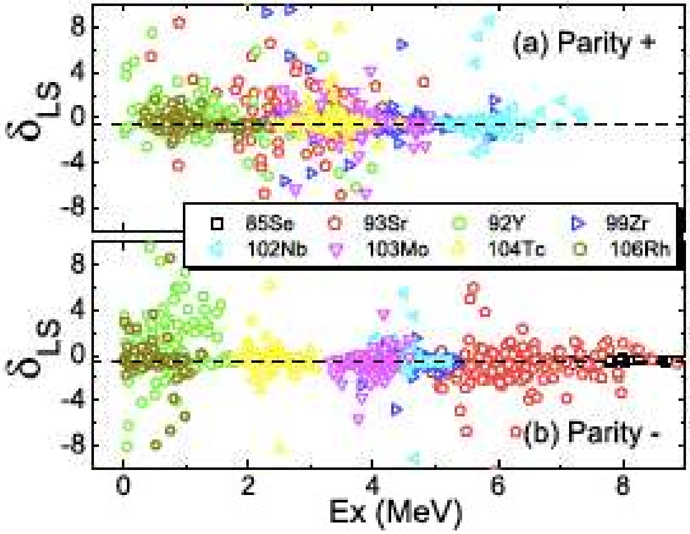
Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v - 1/2}{M_N g_A}\right](E_e\beta^2 - E_\nu)$
Non-unique 1st Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1st Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1st Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2 - 4\beta^2 E_\nu E_e/3)}\right]$
Unique 1st Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2 + E_\nu^2)}\right]$
Allowed F	0^+	τ	1	
Non-unique 1st Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	
Non-unique 1st Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	

The forbidden transitions increase the uncertainty in the expected spectrum.

Two equally good fits to the Schreckenbach β-spectra, lead to ν-spectra that differ by 4%.

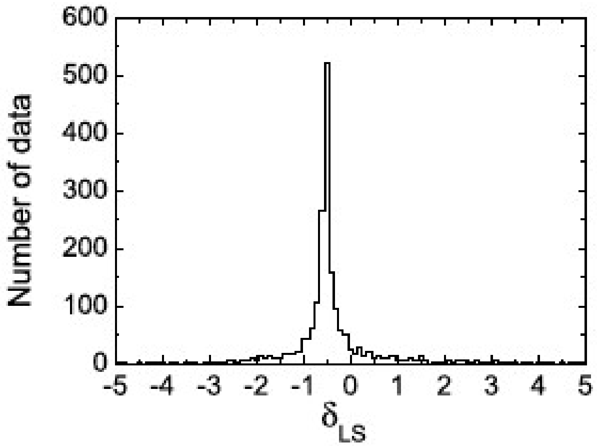


Weak Magnetism has an uncertainty arising from the approximation used for the orbital contribution and from omitted 2-body currents. But, dominant 0+→0- transitions have zero δ_{WM}, with no uncertainty



$$\delta_{WM}^{GT} = \frac{4(\mu_V - \frac{1}{2})}{6 M_N g_A}(E_e \beta^2 - E_\nu)$$

$$\delta_{LS}^{j_f j_i} \equiv \frac{\langle J_f \| \vec{\Lambda} \| J_i \rangle}{\langle J_f \| \vec{\Sigma} \| J_i \rangle} \simeq -\frac{1}{2}$$



- **Checked for a subset of fission fragments.**
- **A check for all fission fragments, including 2-body terms, requires a large super-computing effort.**

Estimated uncertainty ~ 30% for this 4% correction to the spectra

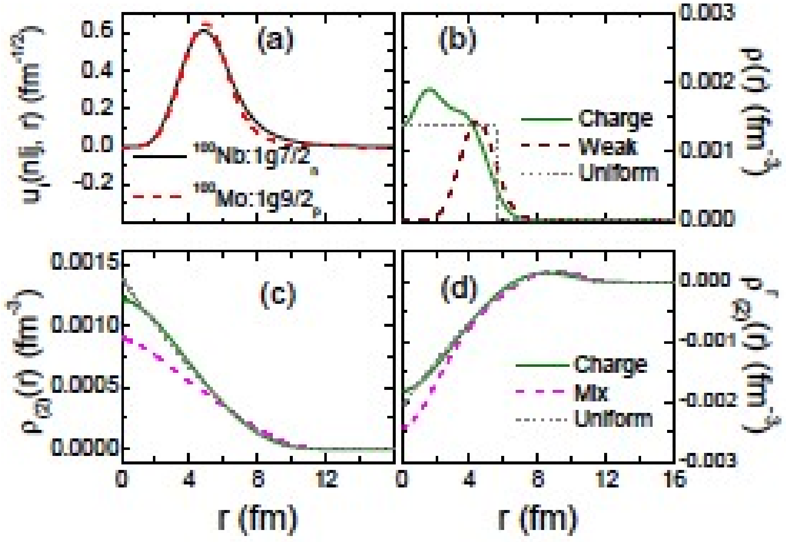
Wang and Hayes, Phys. Rev. C 95, 064313 (2017) .

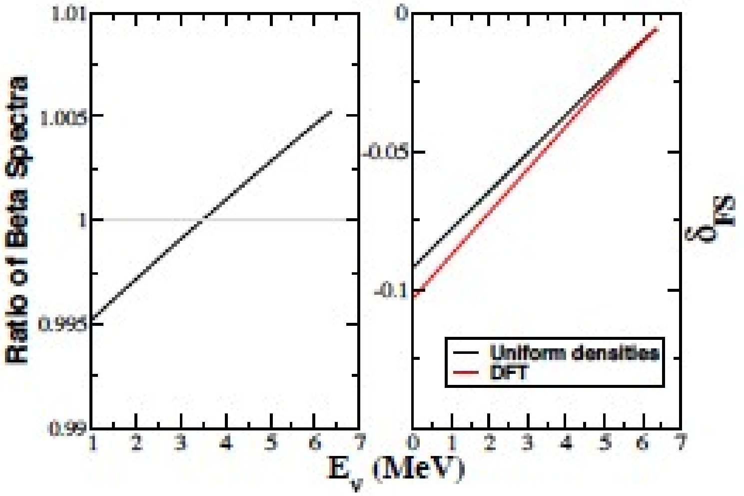
The Finite Size Correction can be expressed in terms of Zemach moments

$$\delta_{FS} = \Delta F_{\rm REL}/F_{\rm REL} = -\frac{Z\alpha}{3\hbar c}\left(4E\langle r\rangle_{(2)} + E\langle r\rangle^{r}_{(2)} - \frac{E_\nu \langle r\rangle^{r}_{(2)}}{3} + \frac{m^2c^4}{E}\left(2\langle r\rangle_{(2)} - \langle r\rangle^{r}_{(2)}\right)\right)$$

Approximated as :

$$\delta_{FS} = -\frac{3Z\alpha}{2\hbar c} < r >_{(2)} \left(E_e - \frac{E_\nu}{27} + \frac{m^2c^4}{3E_e}\right)$$



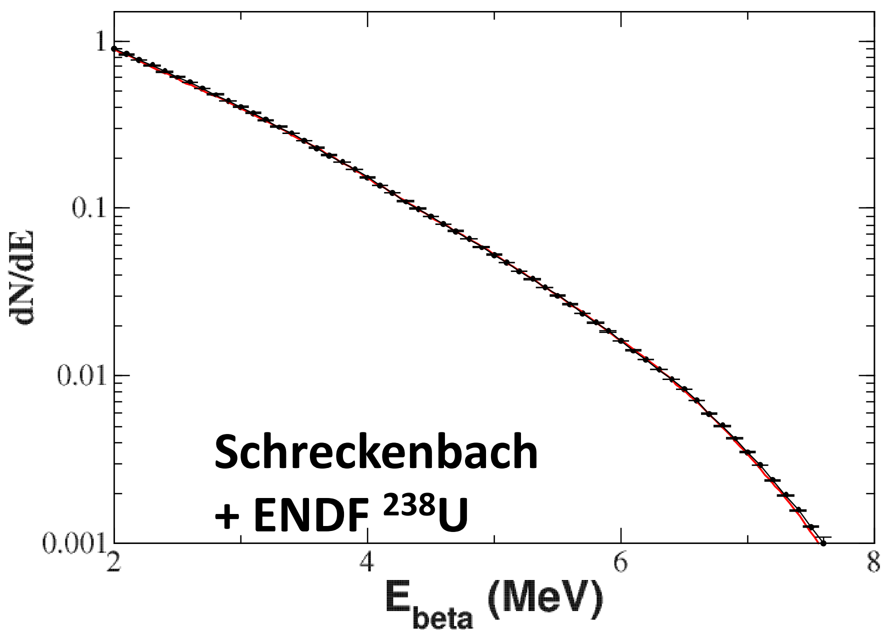


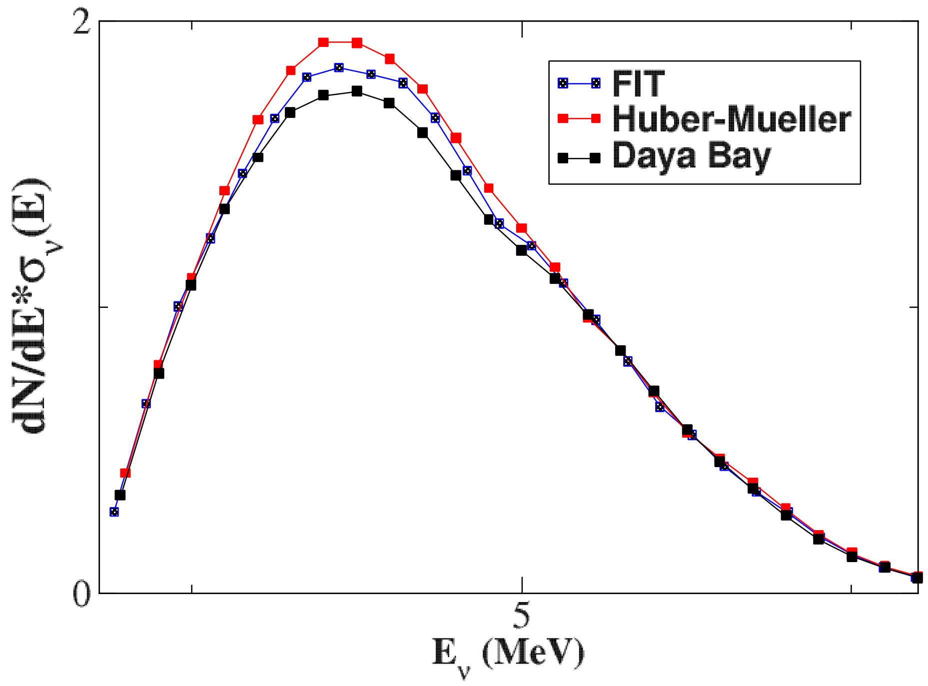
- **Found to be a good approximation for allowed transitions.**
- **Not checked for forbidden transitions.**

Estimated uncertainty ~ 20% for this 5% correction to the spectra

Wang, *et al.* PRC, 94, 034314 (2016)

Simultaneous fit of the Daya Bay antineutrino spectrum and the equivalent aggregate β–spectrum with (1) point-wise Z_{eff} and (2)improved descriptions of forbidden transitions reduces the anomaly from 5% to 2.5%

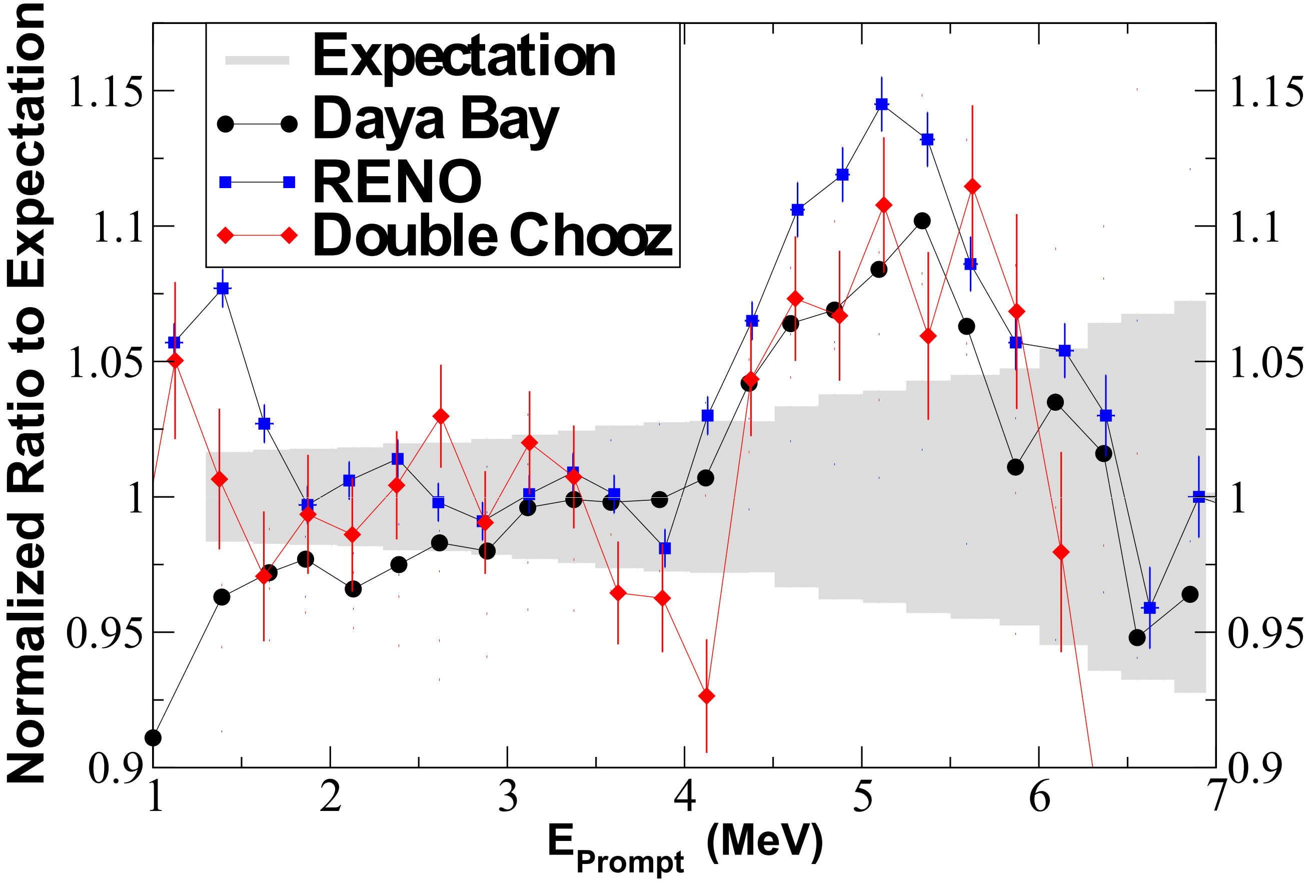




The magnitude of the IBD cross sections change, depending on assumptions, but not the ratio of one isotope to another

	all allowed $Z_{\text{eff}}^{\text{Huber}}$	all allowed Z_{eff}	allow.+forbid. Z_{eff}	allow.+forbid. $(Z_{\text{eff}}^2)^{1/2}$
^{235}U	6.69	6.58	6.47	6.48
^{239}Pu	4.36	4.3	4.22	4.23
ratio	1.534	1.530	1.533	1.532

The Reactor Neutrino ‘BUMP’



All recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations.

- **The current expectations are Huber (^{235}U,^{239,241}Pu) and Mueller (^{238}U)**
- **RENO observed the largest bump**
- **Double-Chooz used Huber and Haag (^{238}U) for expected flux**

P. Huber, Phys. Rev. C 84, 024617 (2011); Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011); N. Haag, Phys. Rev. Lett. 112, 122501 (2014).

Possible Origins of the 'Bump'

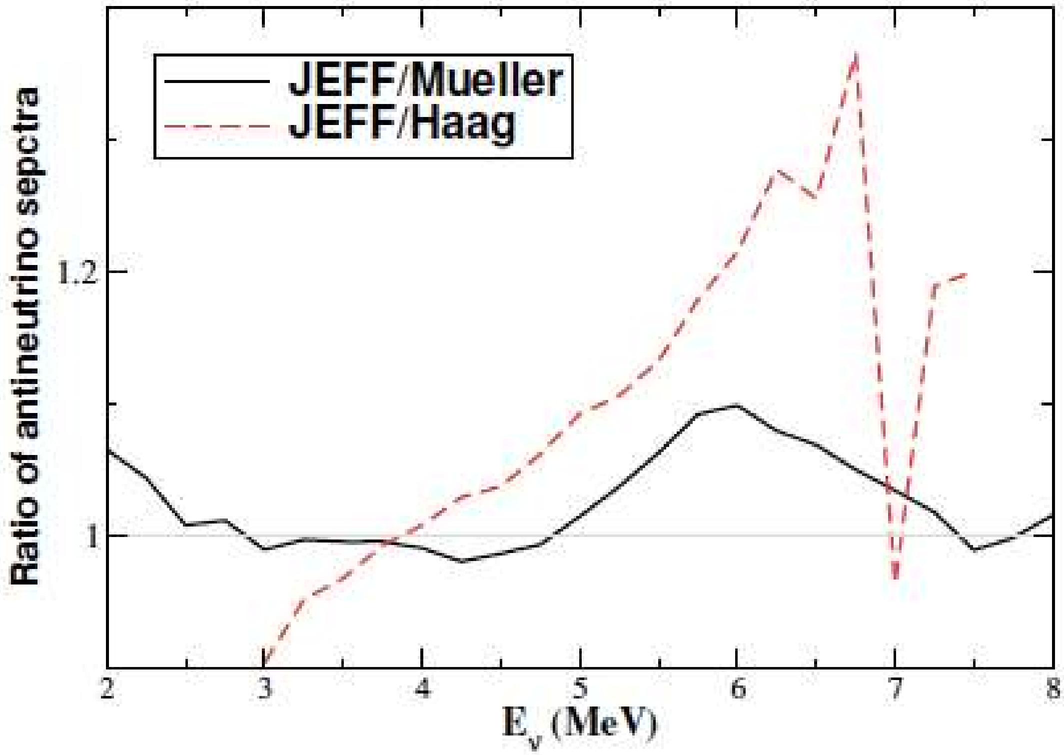
- ^{238}U as a source of the shoulder
  – Possible because ^{238}U has a hard spectrum and contributes significantly in the Bump energy region. It is also the most uncertain actinide.

- A possible error in the ILL β-decay measurements
  - Possible but not predicted by current updated nuclear databases.

- The harder PWR Neutron Spectrum
  - Possible but not predicted by standard fission theory.
  - no convincing experimental data either way.

All of these are nuclear physics explanations pointing to the problem lying with the 'expected spectra'.

For example, if the BUMP does not change with the fuel evolution, ^{238}U is a likely source



Relative to the JEFF database, both Mueller and Haag show a BUMP.

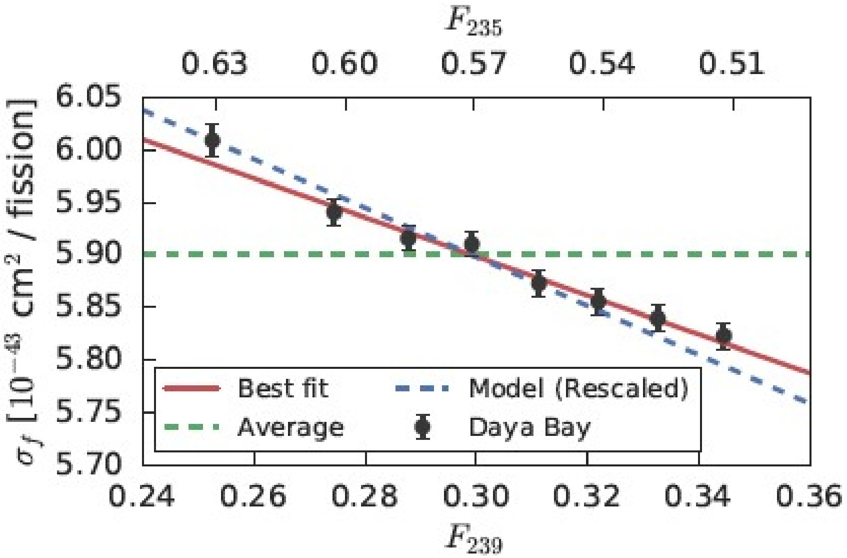
The harder spectrum of ^{238}U increases it's relative importance.

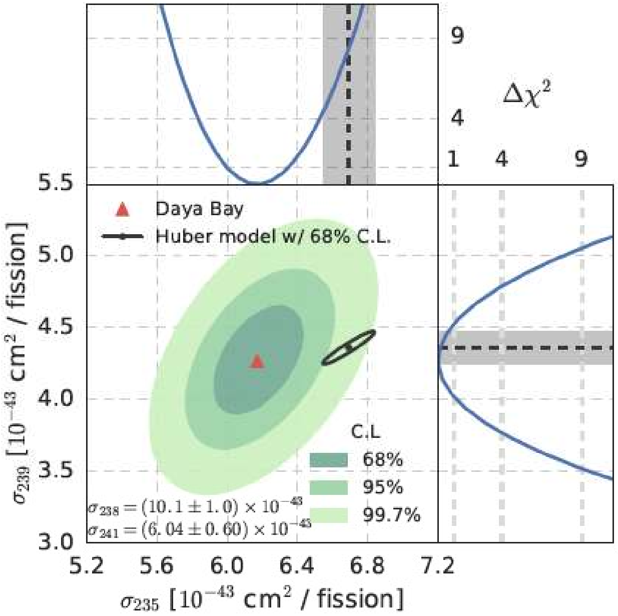
- If this is the correct explanation, the current VSBL experiments with highly enriched ^{235}U reactor will not see a BUMP.
- If, on the other hand, the ILL data are responsible <u>all</u> VSBL expts will see the Bump.

Hayes + Vogel, Ann. Rev. of Nucl & Part. Sci, 66 219 (2016)
Mohanty, arXiv: 1711.1.02801

Changes in the Antineutrino Spectra with the Reactor Fuel Burnup

The Total Number of Antineutrinos Decreases with Burnup, but the Huber-Mueller Model does not agree with the measured slope





$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

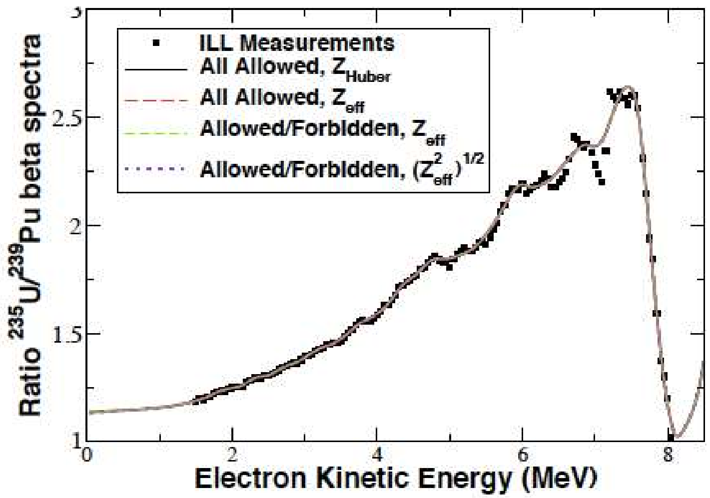
$$d\sigma_f/dF_{239} \quad = \quad (-1.86 \ \pm \ 0.18) \times 10^{-43} \ \ \mathrm{cm}^2/\mathrm{fission}$$

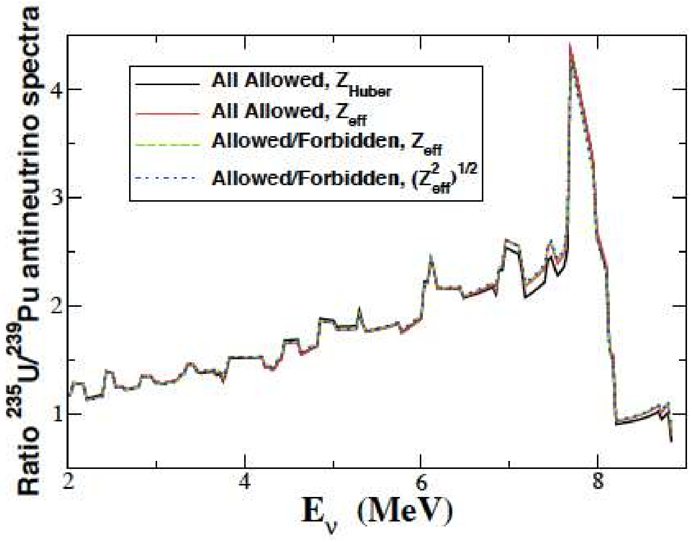
Experiment

$$(-2.46 \pm 0.06) \times 10^{-43} \mathrm{cm}^2/\mathrm{fission}$$

Expected

The discrepancy between current Huber-Mueller model predictions and the Daya Bay results can be traced to the original Schreckenbach measured $^{235}U/^{239}Pu$ ratio





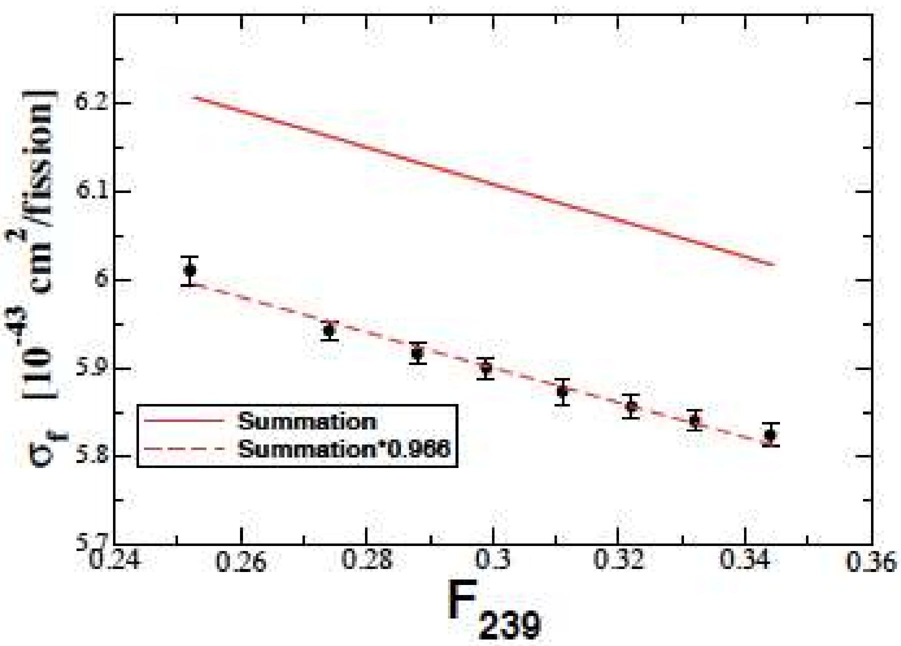
Using different assumptions in fitting the Schreckenbach data will change the IBD cross sections for ^{235}U and ^{239}Pu.

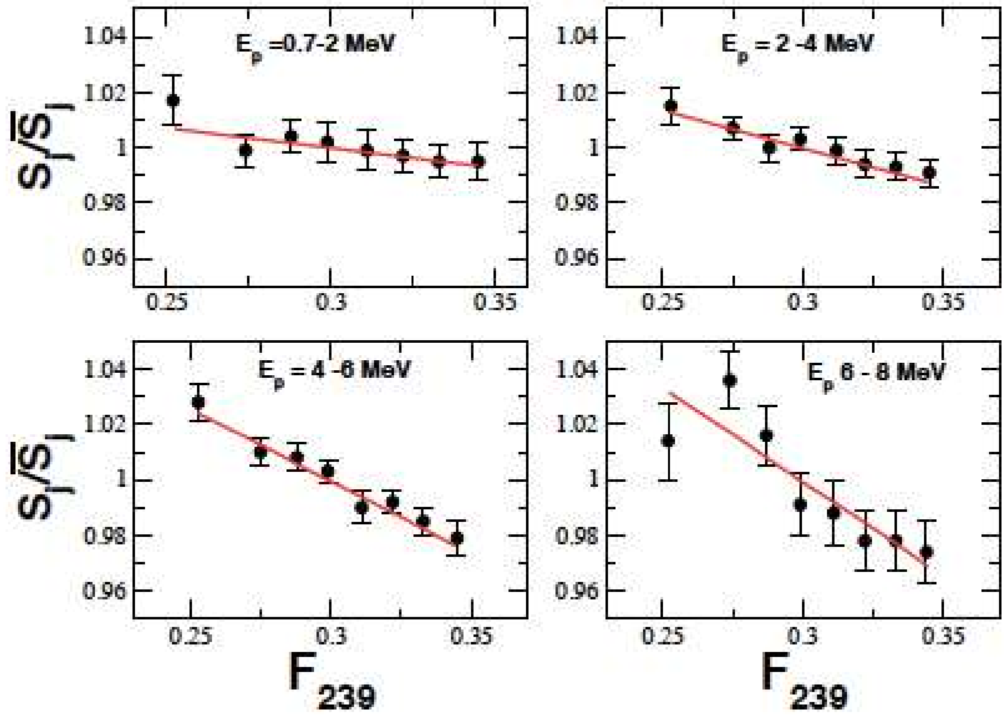
But the ratio of $^{235}U/^{239}Pu$ is fixed.

$\sigma 5/\sigma 9$ = 1.53 +/- 0.05 (Schreckenbach)

$\sigma 5/\sigma 9$ = 1.445 +/- 0.097 (Daya Bay)

The Nuclear database explains all of the Daya Bay fuel evolution data, but still allows for a (smaller) anomaly





- The IBD yield is predicted to change with the correct slope.
- But the absolute predicted value is high by 3.5%.
- This anomaly is not statistically significant but it means that Daya Bay evolution data do not rule out sterile neutrinos.

Summary

- **Changes in the treatment (1) Zeff of fission fragments used in the Fermi function (2) the sub-dominant corrections to beta-decay led to the reactor neutrino anomaly.**

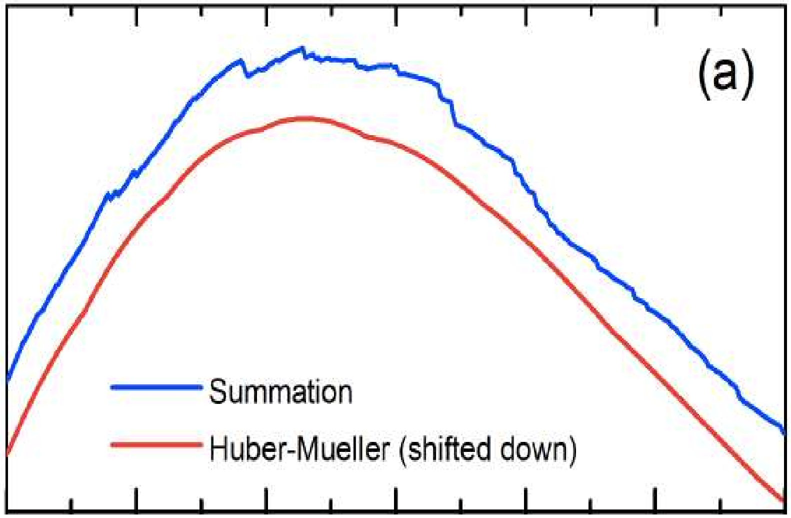
- **Improved treatments reduce the size of the anomaly.**

- **The BUMP is due to standard nuclear physics issues and may be from ^{238}U, especially if the BUMP does not change with fuel evolution.**

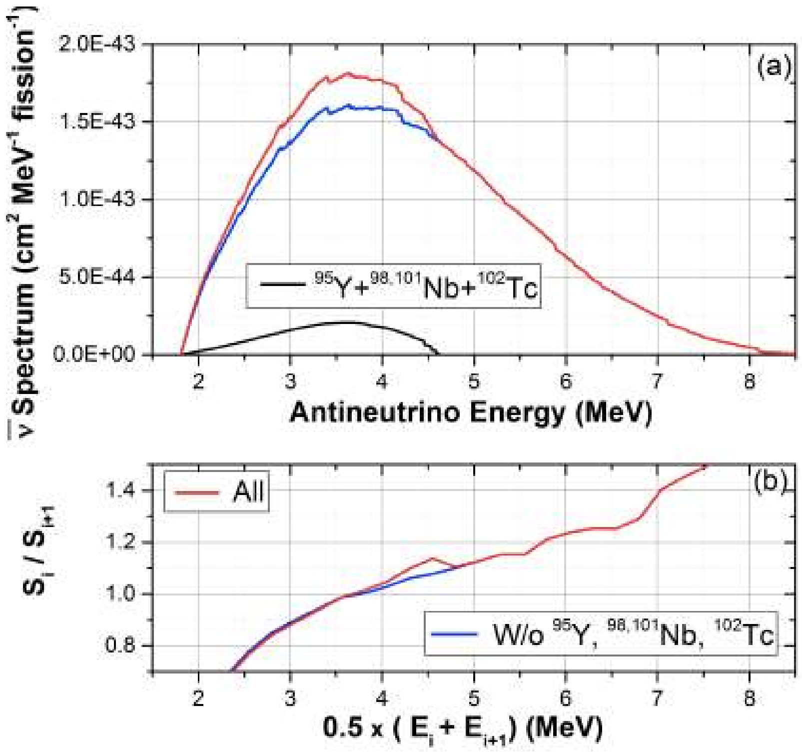
- **The Daya Bay fuel evolution data suggest that the Schreckenbach ^{235}U/^{239}Pu ratio is incorrect, but these data do not rule out sterile neutrinos.**

- **The new short baseline experiments will likely address all of the remaining puzzles.**

Sawtooth-like Structures exist in the antineutrino spectra



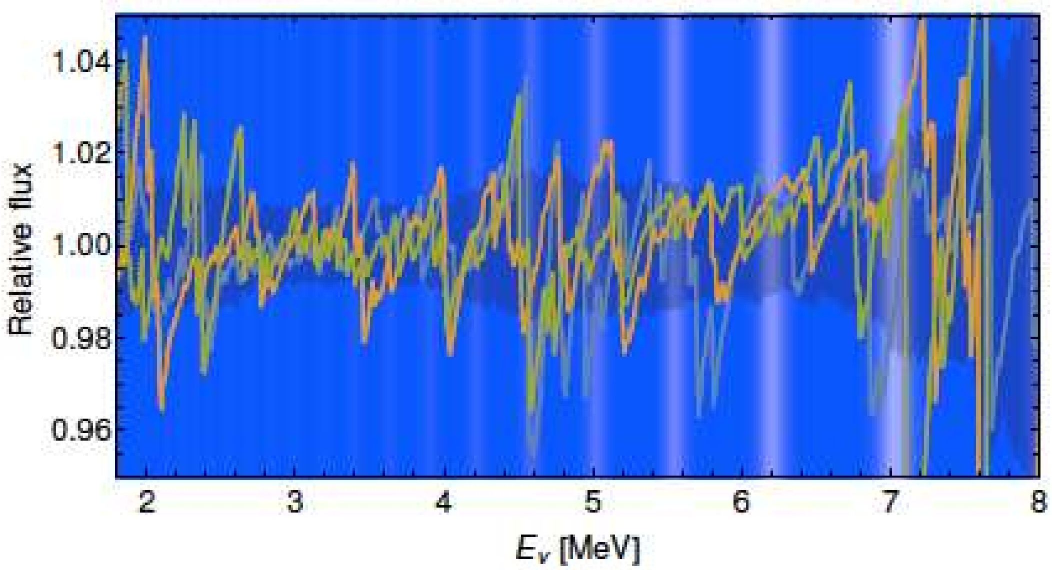
Sonzogni, Nina, & McCutchan have analyzed these structures in the Daya Bay spectrum.



They have shown that these structures correspond to individual contribution of strong fission fragments.

Sonzogni et al. arXiv: 1710.000092v2

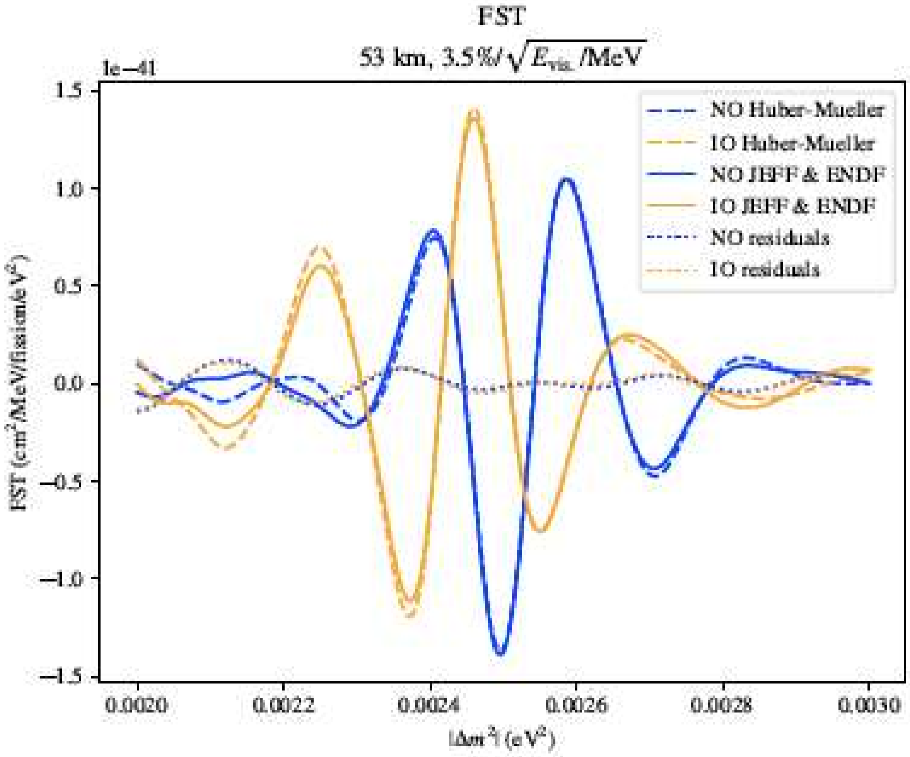
It has been suggested that these structures represent a serious problem for JUNO



Some of these structures have a frequency similar to Δm_{31}^2 oscillations

But they are only a few % in magnitude

Forero, Hawkins, Huber, arXiv: 1701.07378

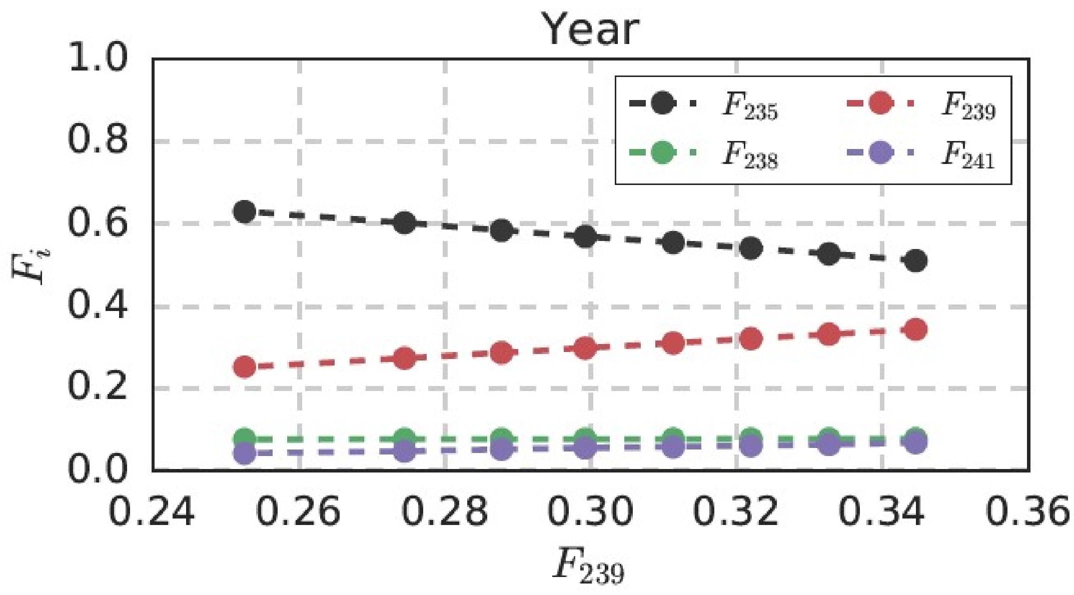


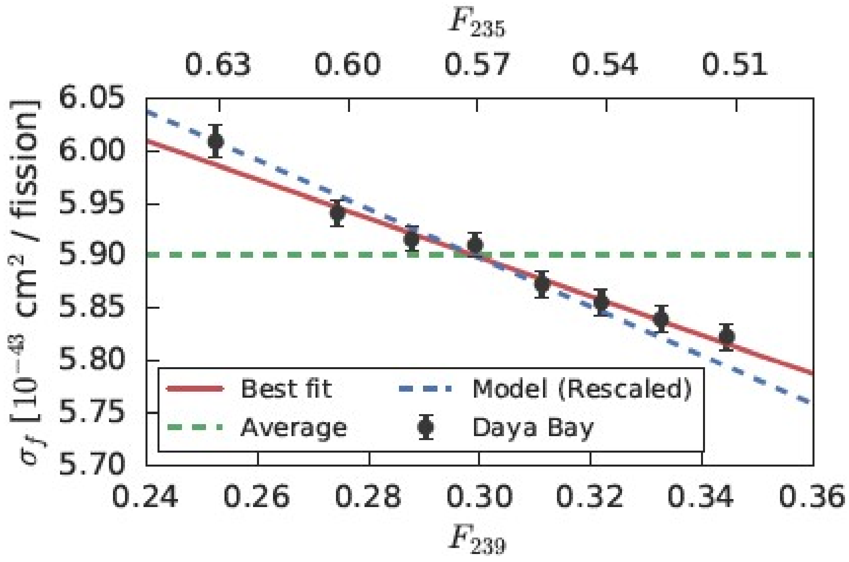
However, if construction of a Fourier transform of the spectrum is possible, these structure are not a problem

- **They don’t have the correct frequency.**

But, if a JUNO analysis is restricted to E-space, the sawtooth structures will affect our ability to distinguish ‘degenerate’ hierarchy solutions.

As the Fuel burns, the fraction of fissions from ^{235}U decreases and ^{239}Pu increase

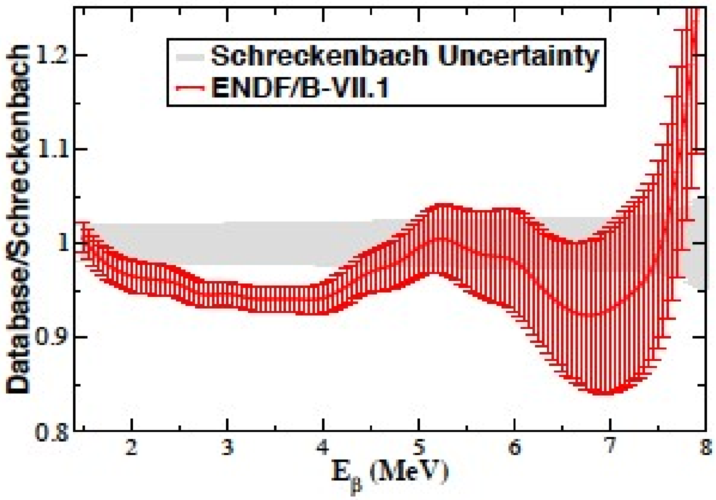




$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

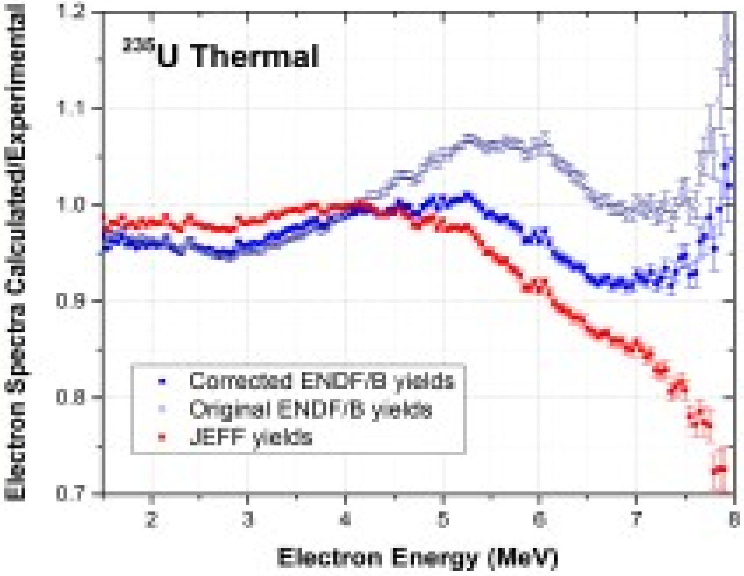
$$d\sigma_f/dF_{239} \quad = \quad (-1.86 \ \pm \ 0.18) \times 10^{-43} \ \text{cm}^2/\text{fission}$$

ILL Measurements as the source of the BUMP: First ‘Yes’ then ‘No’



- Dwyer and Langford pointed out that the ENDF database predicts an analogous bump in the beta-spectrum relative to Schreckenbach.

Dwyer & Langford, PRL 114, 012502 (2014)



- Songzoni updated in the database for fission yields and ENDF no longer predicts a bump.

Sonzogni, et al. PRL, . 116, 132502, 2016

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