Studies of the Reactor Neutrino Anomaly

In collaboration with:

G. Jungman, J.L. Friar, and G. Garvey, Los Alamos
E. McCutchan and A. Sonzogni, Brookhaven National Lab
Xiaobao Wang, Huzhou University, China

Four Experimental Anomalies Do Not Fit Within the 3ν Mixing Picture

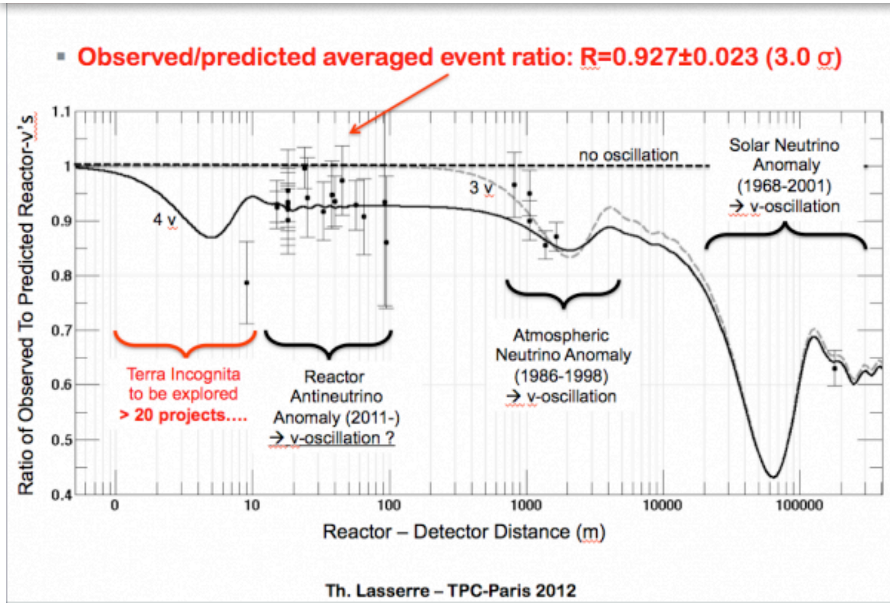
- **LSND**
- **MiniBooNE**
- **The Gallium Anomaly**
- **The Short Base-Line Reactor Neutrino Anomaly**

These anomalies possibly suggest a fourth sterile neutrino, requiring a mass on the 1 eV scale.

However, there are also complex nuclear physics issues associated with each anomaly.

The Reactor Neutrino Anomaly is a 5-6% shortfall in the antineutrino flux in all short baseline reactor experiments, relative to expectations

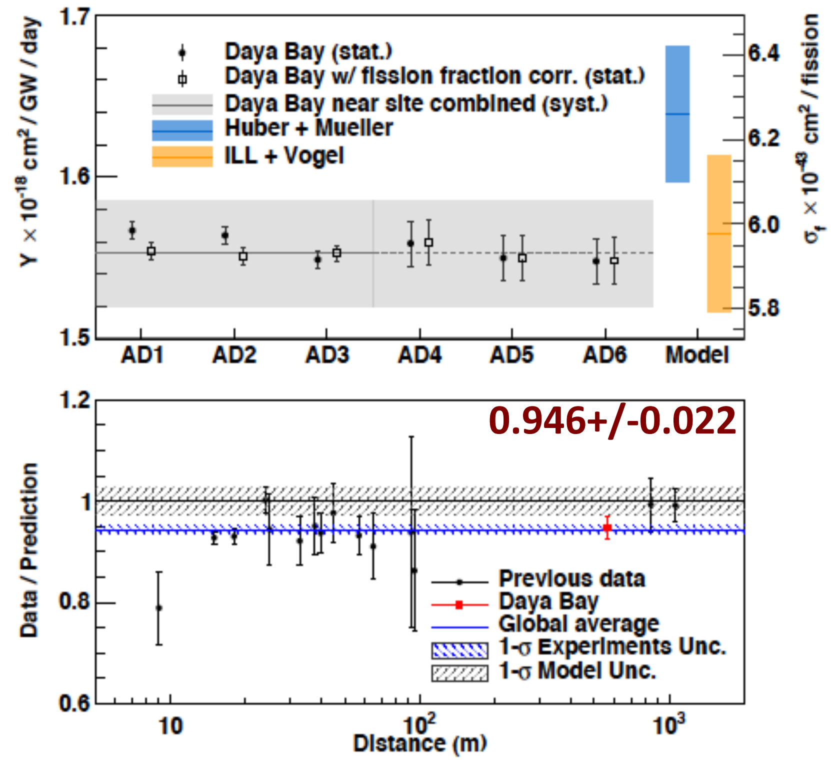
From Th. Lasserre, 2012



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

Recent results from Daya Bay, 2016

PRL,116 (2016) 061801

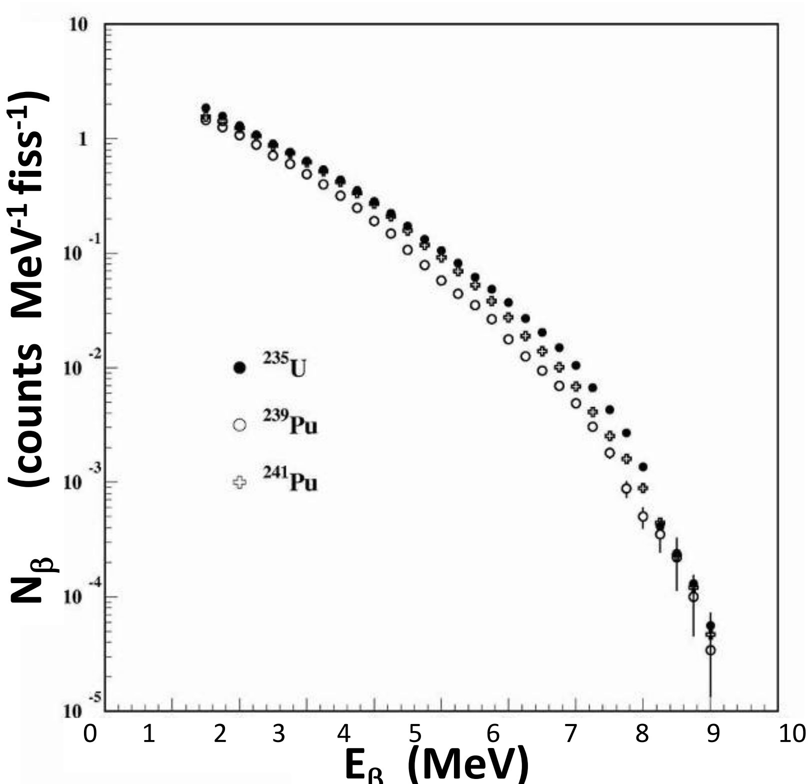


The measurements of the total flux at Daya Bay and RENO confirm the shortfall

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



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

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

- Measurements at ILL of thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- 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

⇒ Used Vogel *et al*. ENDF nuclear database estimate for ^{238}U.

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

FIT

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

Parameterized

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

Two inputs are needed to convert from an aggregate electron spectrum to an antineutrino spectrum – the Z of the fission fragments for the Fermi function and the sub-dominant corrections

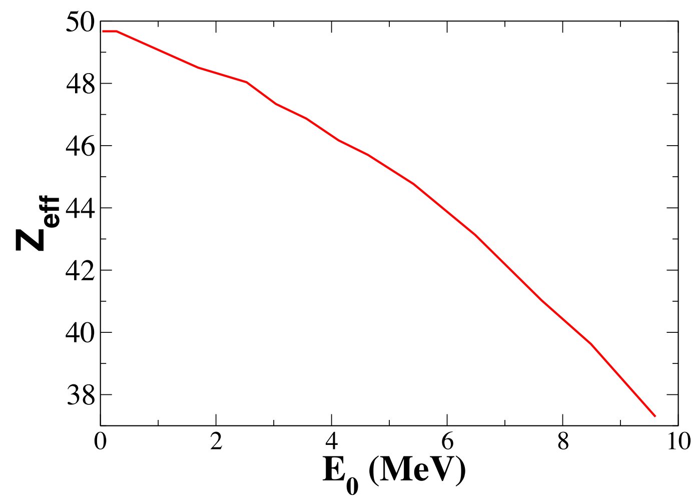
$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1+ \delta_{corrections})$$

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

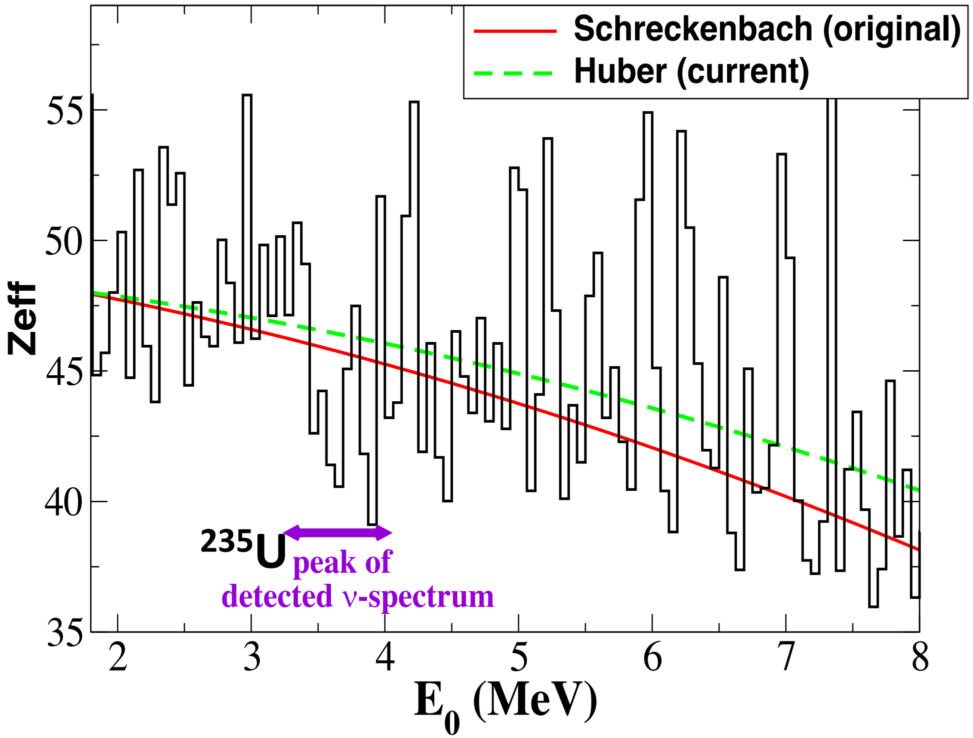
δ_{WM} = Weak magnetism

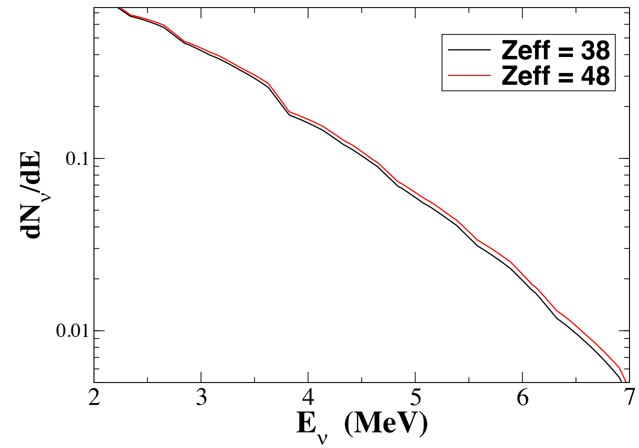
δ_R = Recoil correction

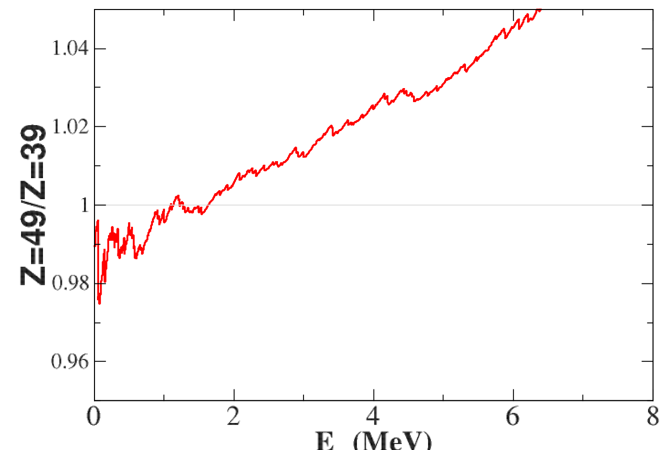
δ_{rad} = Radiative correction

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







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

- **Huber's new parameterization of Zeff with end-point energy E_0 changes the Fermi function and accounts for 50% of the current anomaly.**
- **At the peak of the detected neutrino spectrum both fits (original & new) may be high.** $Z_{eff} = a + b\ E_0 + c\ E_0^2$ **form for the fits causes this.**

There are different ways of estimating Z-average(E_0)

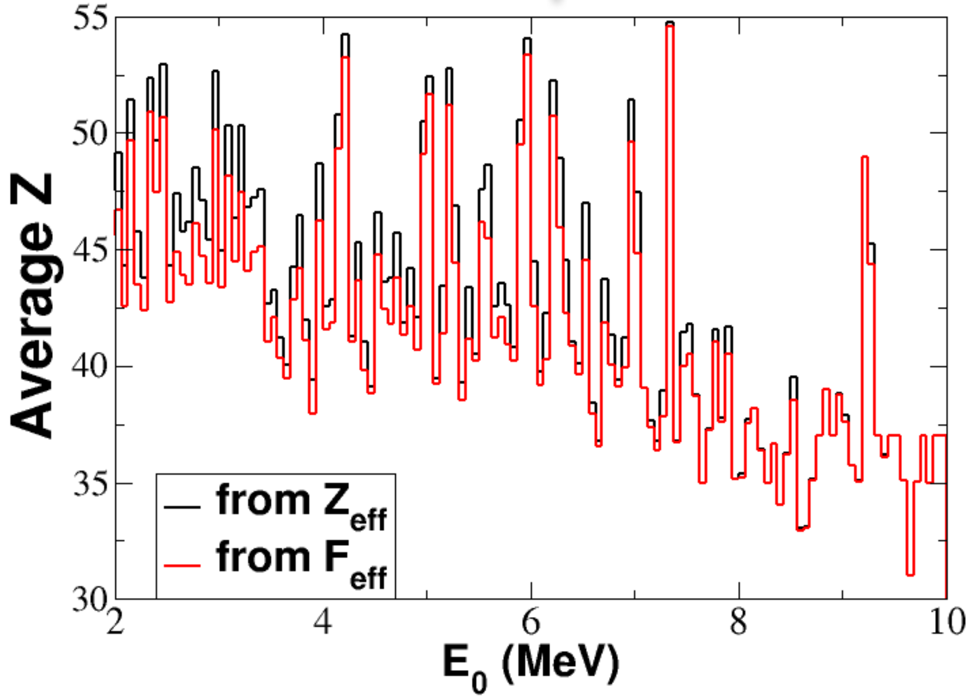
Examples:

$$\frac{Z_{eff}(E_0) = \sum_{E_0-\Delta E}^{E_0+\Delta E} (Y^i_{fiss} Z_i)}{\sum_{E_0-\Delta E}^{E_0+\Delta E} (Y^i_{fiss})}$$

$$\frac{F(E, Z_{eff}) = \sum_{E_0-\Delta E}^{E_0+\Delta E} (Y^i_{fiss} F(E, Z_i))}{\sum_{E_0-\Delta E}^{E_0+\Delta E} (Y^i_{fiss})}$$

1. Same as Huber, but instead of fitting this function to a quadratic , Zeff is determined in each energy window E-ΔE → E+ΔE .

2. Find the Z-average that gives the best fit to the average Fermi function up to E_0, for the average fission yield weighted Fermi function.



Z-average for the linear combination of
235U : 0.561
238U : 0.076
239Pu : 0.307
214Pu : 0.050
reported by Daya Bay

Fermi-function averaging gives a lower Z

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

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

δ_{FS} = Finite size correction to Fermi function

δ_{WM} = Weak magnetism

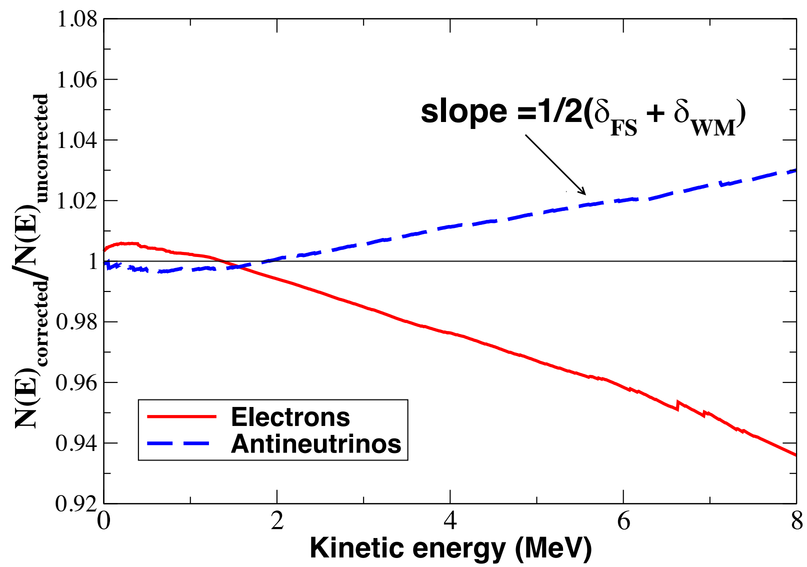
Originally approximated by a parameterization: $\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4MeV)$

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

An approximation was used for each:

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

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



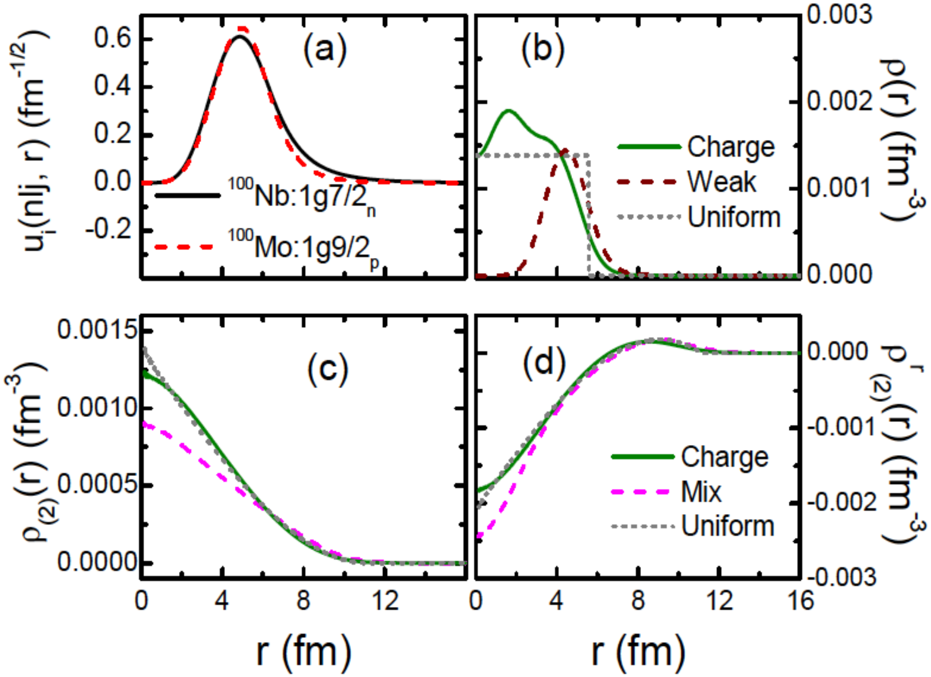
Led to a systematic increase of in the antineutrino flux above 2 MeV

Uncertainties in the Corrections

Nuclear Finite Size correction was (a) only derived for allowed transitions and (b) approximated by expressing Zemach moments in terms of charge radii

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

$$\delta_{FS} = -\frac{3}{2}\frac{Z\alpha}{\hbar c}\langle r\rangle_{(2)}\left(E - \frac{E_\nu}{27} + \frac{m^2c^4}{3E}\right)$$



X.B. Wang, J.L. Friar, A.C. Hayes, Phys. Rev. C94, 034314 (2016)].

- Examined a set of nuclei accessible to Hartree-Fock calculations, using a Skyrme-like energy density functional, **found small uncertainty for allowed transitions**.
- Should probably expand study to look at a broader set of nuclei.

- **Unknown uncertainty for forbidden transitions.**

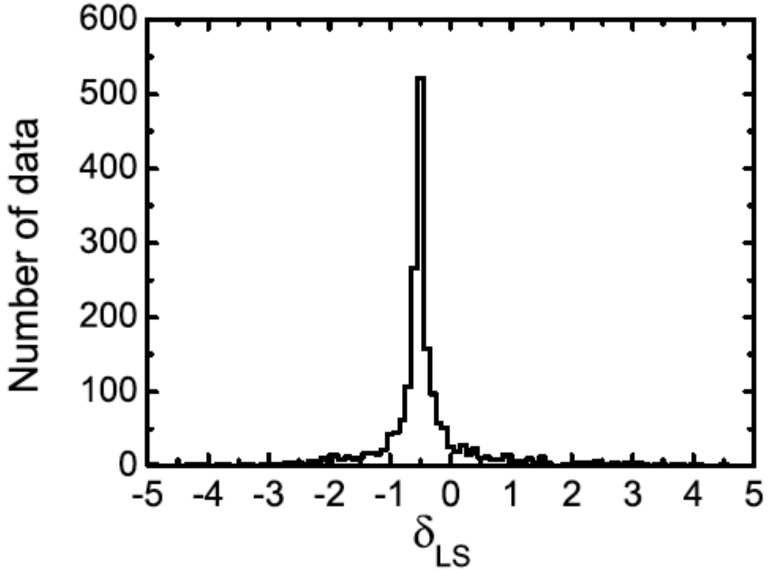
Weak Magnetism has a uncertainty arising from (a) an approximation to the one-body current and (b) the omission of two-body currents

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

From the approximation

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

$$\vec{\Lambda} = \sum_i \tau_i^{\pm} l_i \qquad \vec{\Sigma} = \sum_i \tau_i^{\pm} \vec{\sigma}_i$$



For fission fragment nuclei found only small uncertainty for 1-body current.

2-body meson-exchange corrections in light nuclei are typically ~ 25%.

=> Suggests an uncertainty in δ_{WM} ~ 25%

X.B.Wang, A.C. Hayes, Phys. Rev. C95, 064313 (2017)

Uncertainty arising from the fact that one-third of the transitions making up the fission antineutrino spectra are forbidden

30% of the beta-decay transitions involved are so-called forbidden

Allowed transitions ΔL=0; Forbidden transitions ΔL≠0

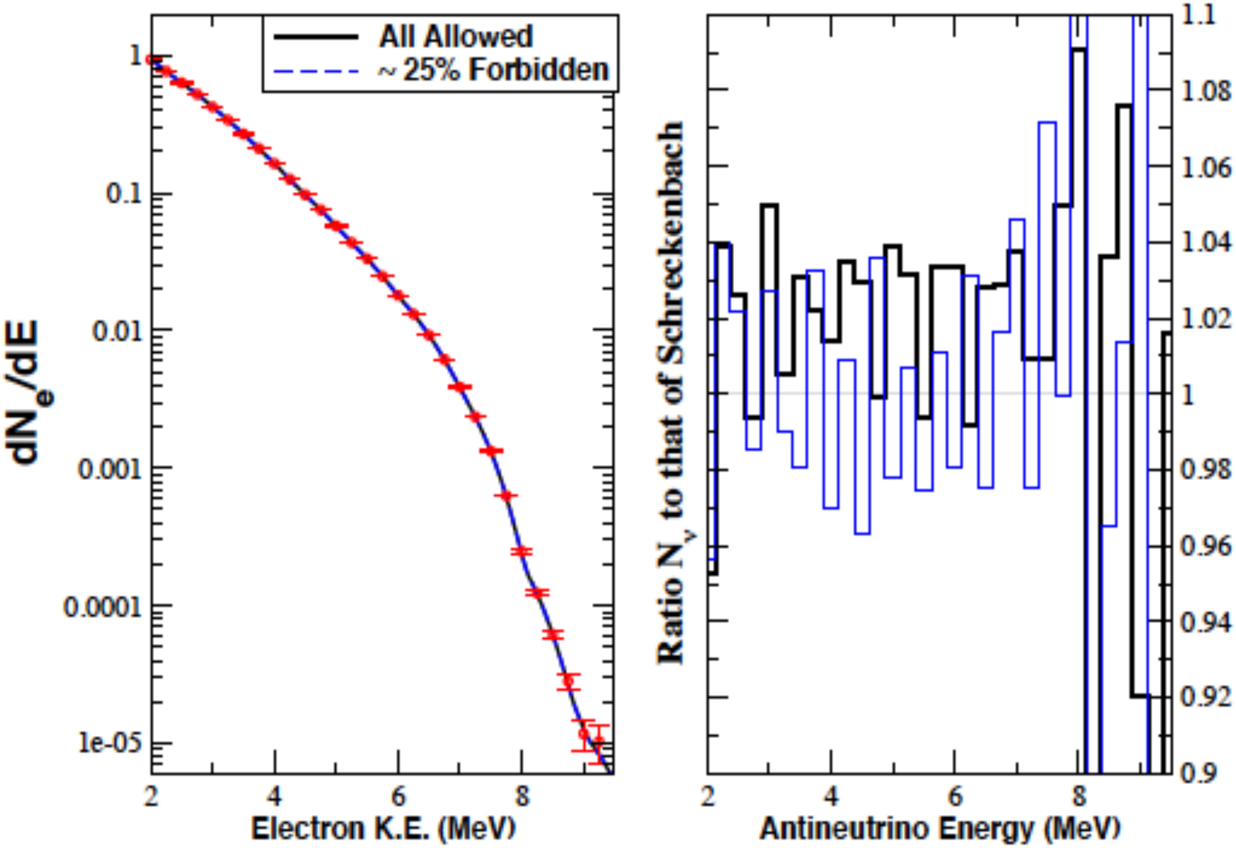
Forbidden transitions introduce a shape factor C(E):

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

The corrections for forbidden transitions are different and sometimes unknown.

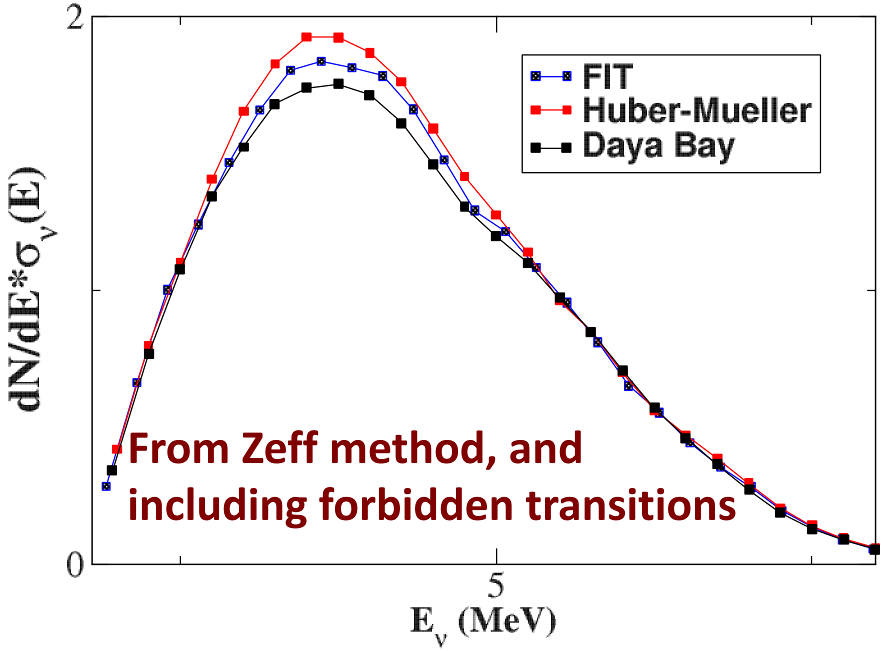
Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma \equiv \sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v-1/2}{M_N g_A}\right](E_e\beta^2-E_\nu)$
Non-unique 1^{st} Forbidden GT	0^-	$[\Sigma,r]^{0-}$	$p_e^2+E_\nu^2+2\beta^2E_\nu E_e$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

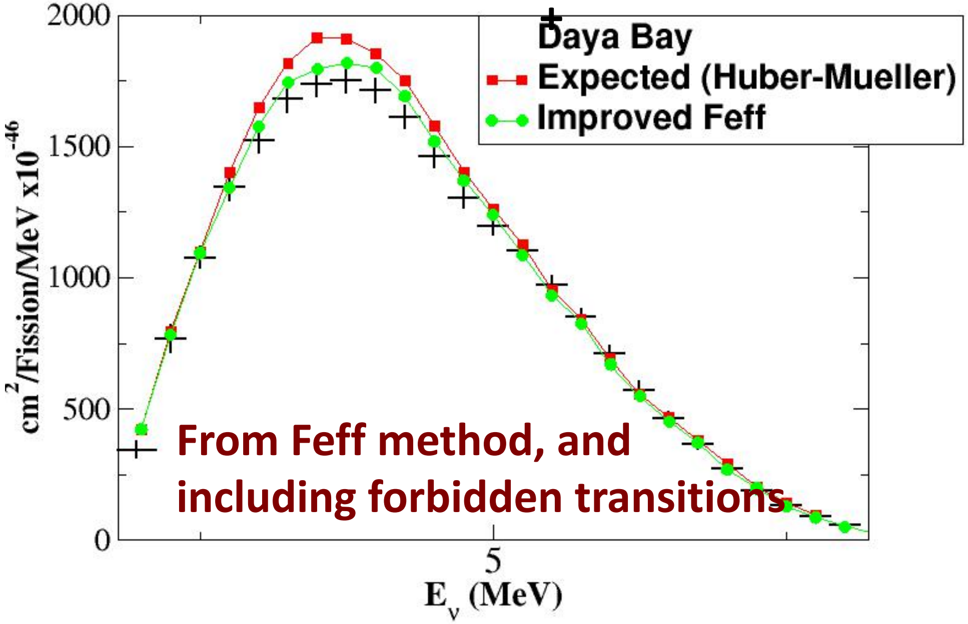
The forbidden transitions increase the uncertainty in the expected spectrum to ~4%



Two equally good fits to Schreckenbach's β-spectrum, with and without forbidden transitions, lead to ν-spectra that differ by 4%

An improved description of the Zeff, forbidden transitions and sub-dominant corrections lowers the anomaly





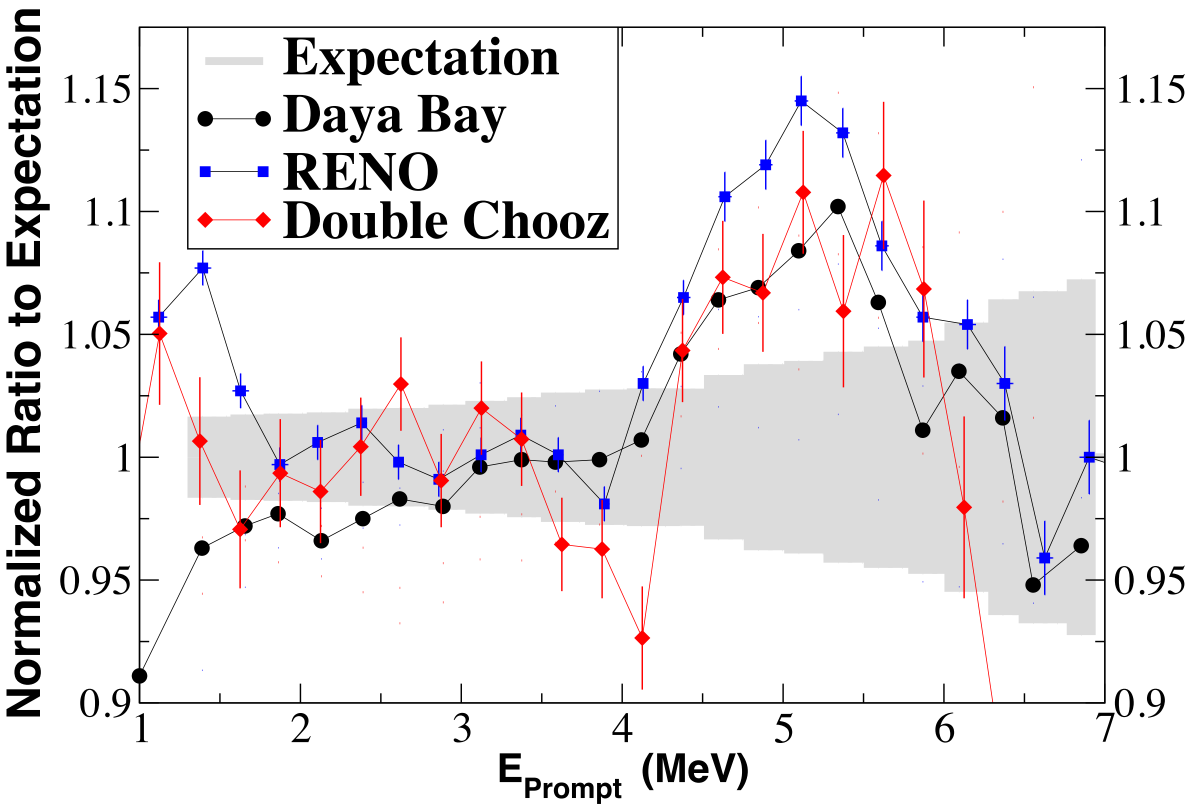
Both the magnitude and the shape of the predicted spectrum depends on the method used to fit the spectrum. Improved methods generally lower the expected spectrum.

=> Conservatively, increases the uncertainty in the expected neutrino spectrum

However, serious problems remain

- **There is an unexplained ‘BUMP’ in the spectrum.**
- **The Daya Bay reactor fuel evolution data question the Schreckenbach measurements.**
- **The anomaly is reduced but has not necessarily gone away.**

The Reactor Neutrino 'BUMP'



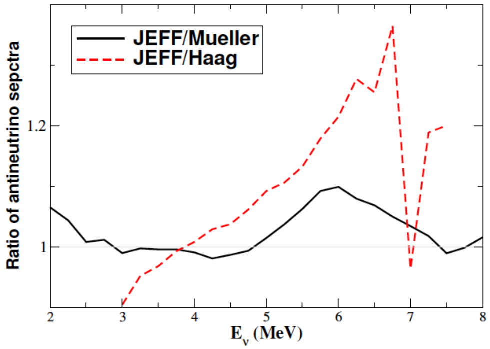
All three recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations.

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

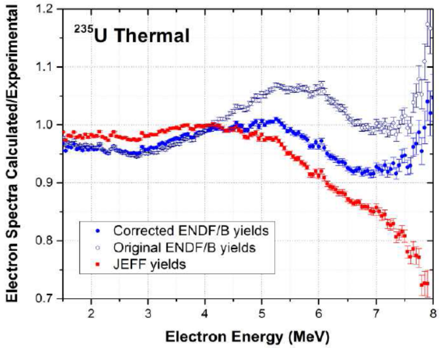
P. Huber, Phys. Rev. C 84, 024617 (2011); Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011); N. Haag, Phys. Rev. Lett. 112, 122501 (2014).

Possible Origins of the 'Bump'

- Non-fission sources of antineutrinos in the reactor
  - NO. MCNP & reactor simulations show Eν from structural material too low in energy.
- From the conversion method, e.g., forbidden transitions
  - Unlikely, < 1% effect.
- The harder PWR Neutron Spectrum
  - Possible but not predicted by standard fission theory.



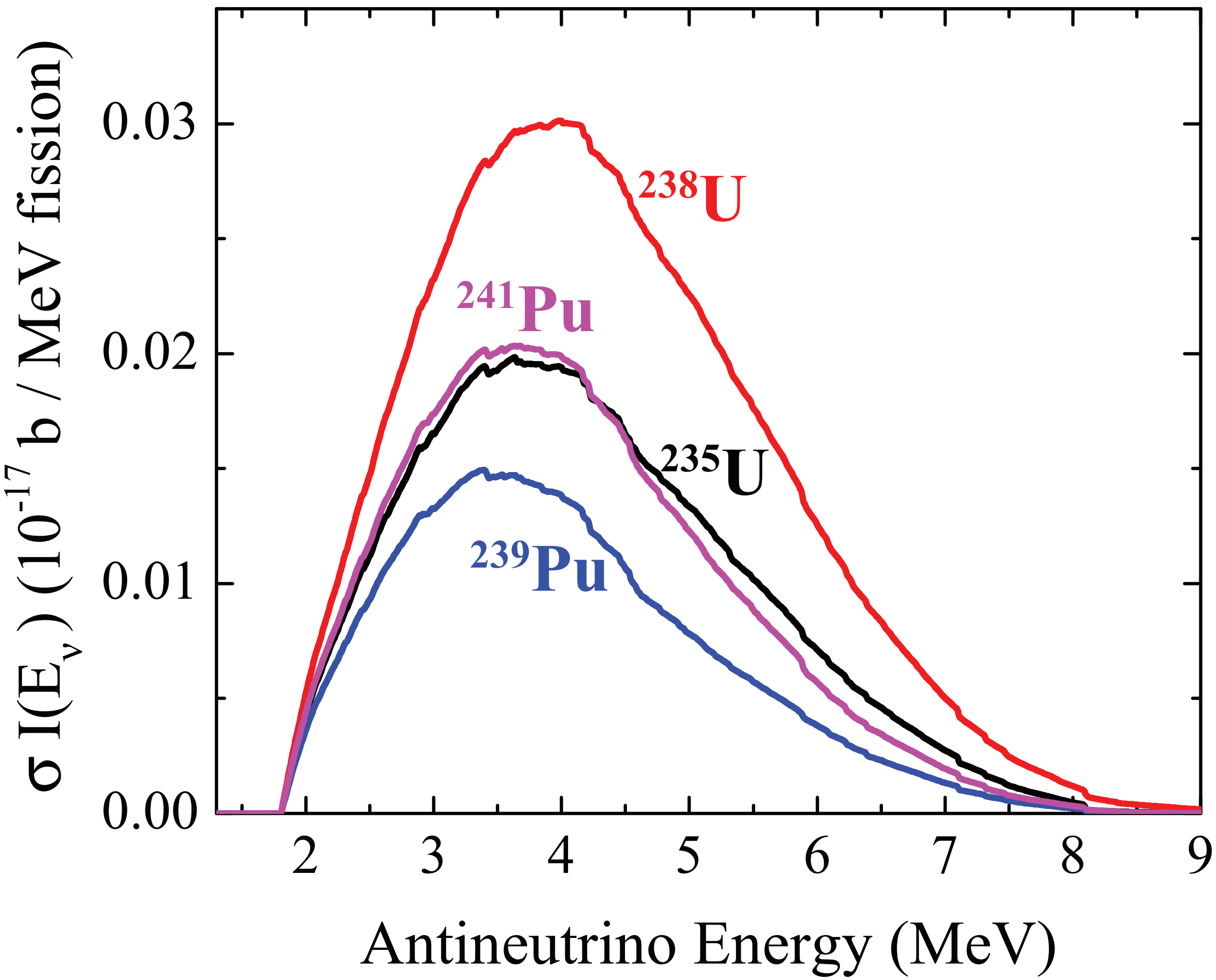
- ^{238}U as a source of the shoulder
  - –Likely. ^{238}U has largest uncertainty and exhibits structure.



- A possible error in the ILL β-decay measurements
  - At first 'Yes', but BNL analysis suggests 'less likely'.

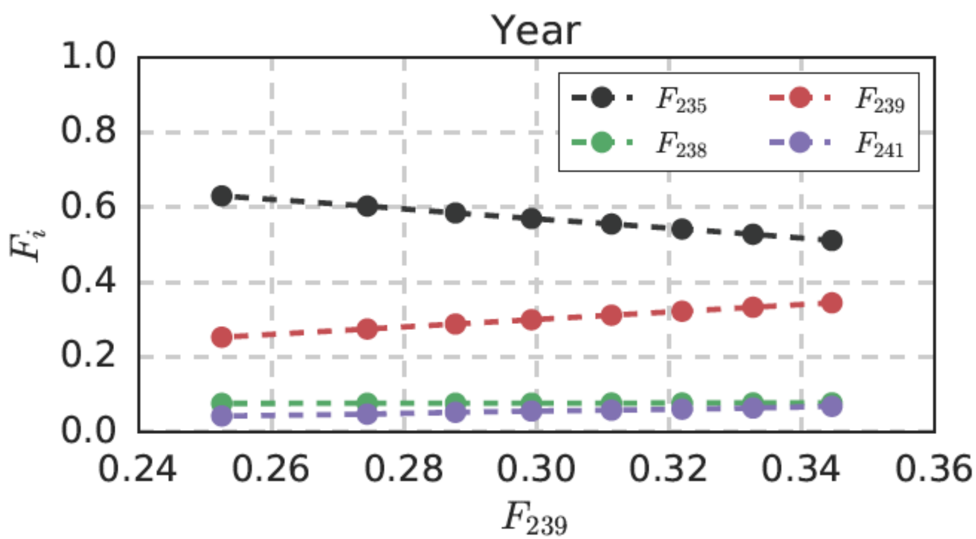
Changes in the Antineutrino Spectra with the Reactor Fuel Burnup

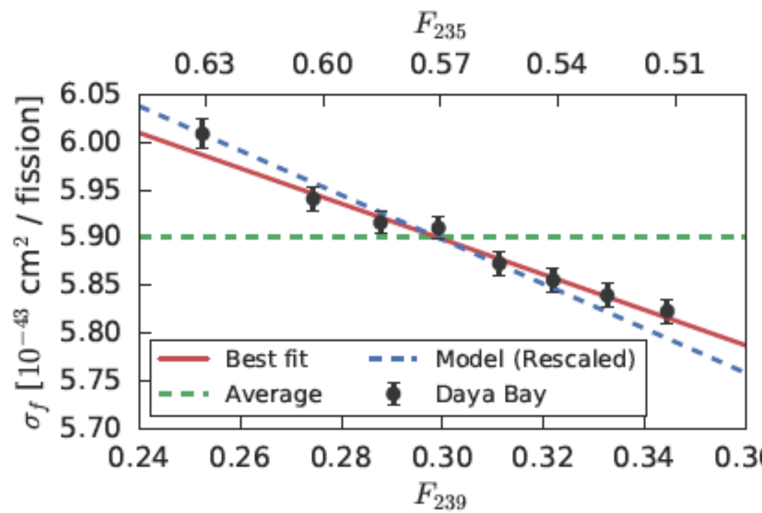
Antineutrino Spectrum for ^{239}Pu is only 70% that of ^{235}U, so as ^{239}Pu grows in the reactor, the total number of antineutrinos drops



A. A. SONZOGNI, T. D. JOHNSON, AND E. A. MCCUTCHAN PHYSICAL REVIEW C **91**, 011301(R) (2015)

As the fraction of fissions from ^{235}U decreases and ^{239}Pu increases, and Daya Bay observed an clear antineutrinos decrease

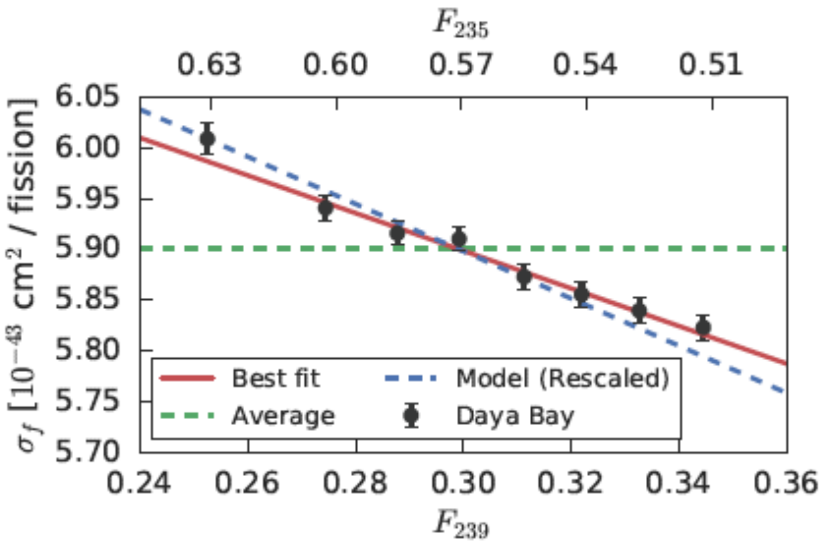


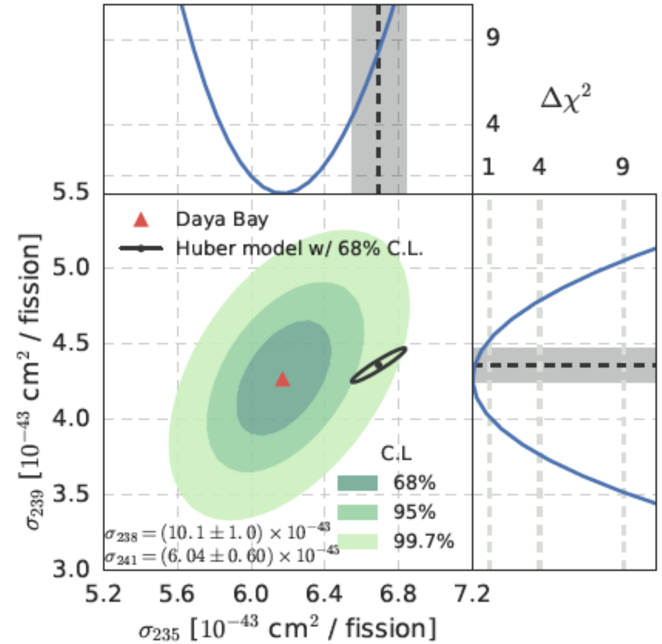


$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

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

But the Huber-Mueller Model (EXPECTED) does not agree with the measured slope, as seen with the increase in ^{239}Pu





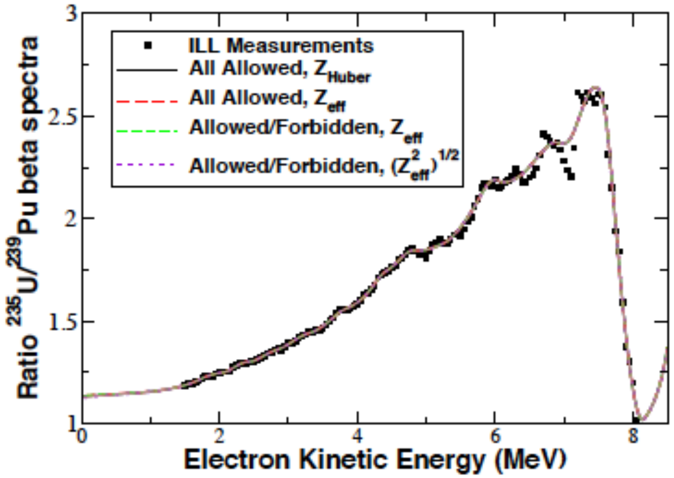
$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

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

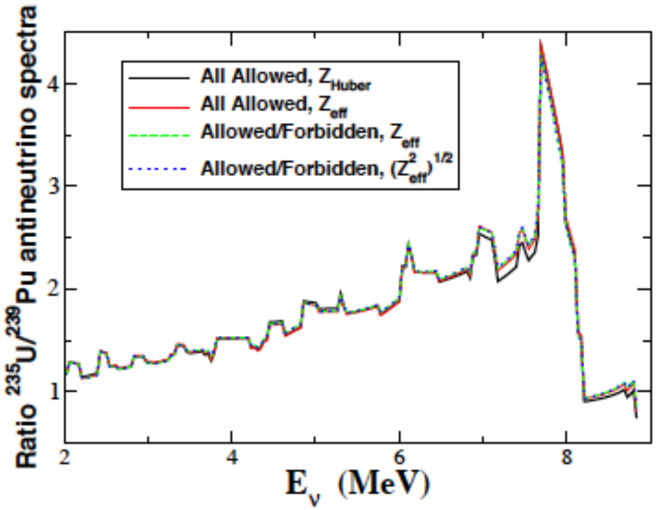
$$(-2.46 \pm 0.06) \times 10^{-43} \text{cm}^2/\text{fission}$$ **Theory/'expected'**

A number of science news magazines declared that this ruled sterile neutrinos out!

The Issue is the $^{235}U/^{239}Pu$ ratio for the aggregate beta spectra



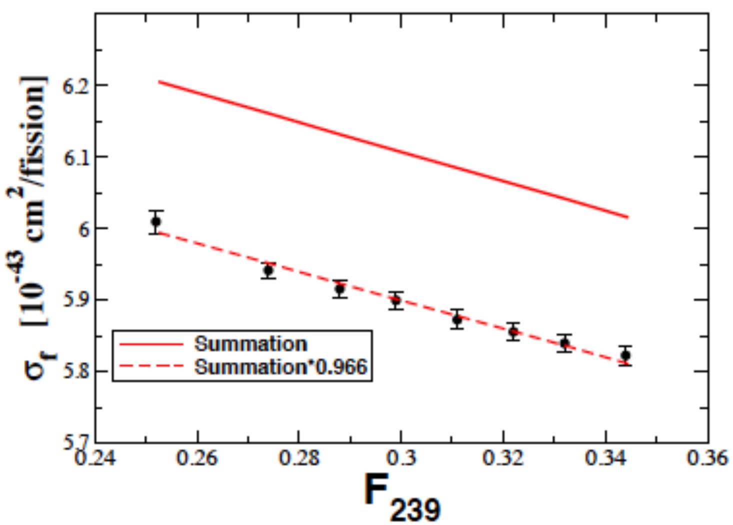
	all allowed Z_{eff}^{Huber}	all allowed Z_{eff}	allow.+forbid. Z_{eff}	allow.+forbid. $(Z_{eff}^2)^{1/2}$
^{235}U	6.69	6.58	6.47	6.48
^{239}Pu	4.36	4.3	4.22	4.23
ratio	1.534	1.530	1.533	1.532

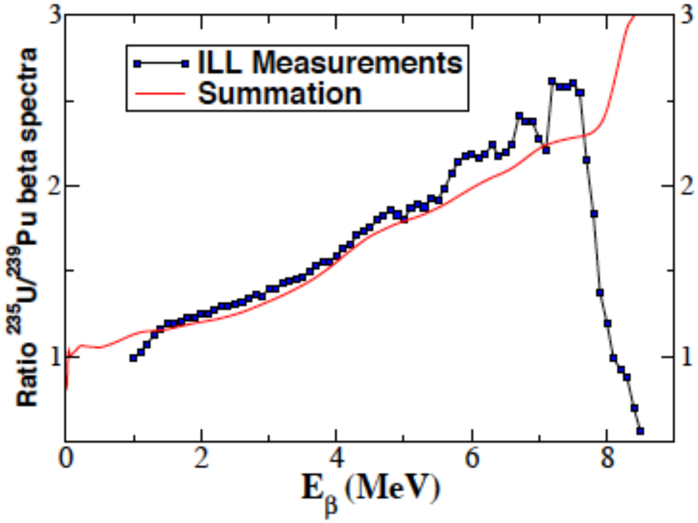


If we start with the Schreckenbach spectra

- The size of the anomaly depends on how the spectra were fitted- forbidden transition and Z_{eff} – anomaly varies from 3-6%.
- Better methods tend to lower the anomaly.
- But the ratio of $^{235}U/^{239}Pu$ and $d\sigma_f/dF_9$ do not change with the method.
- The derived slope of the antineutrino signal, from the Schreckbenbach β-spectra, with fuel burnup is always too high.

Schreckenbach data show a larger $^{235}U/^{239}Pu$ ratio than is predicted by a nuclear database summation method or than Daya Bay

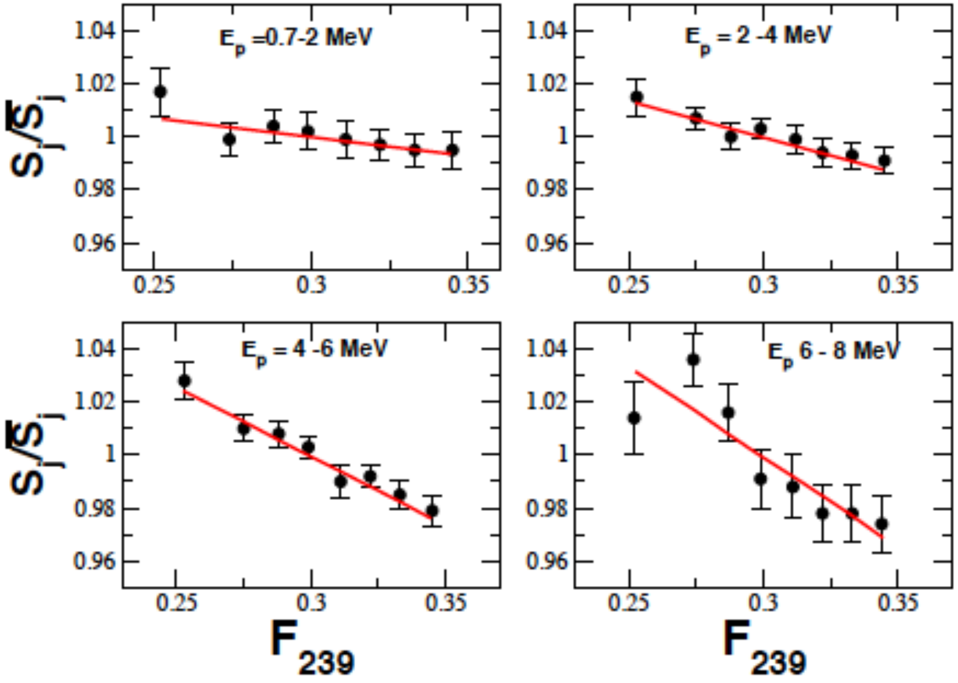


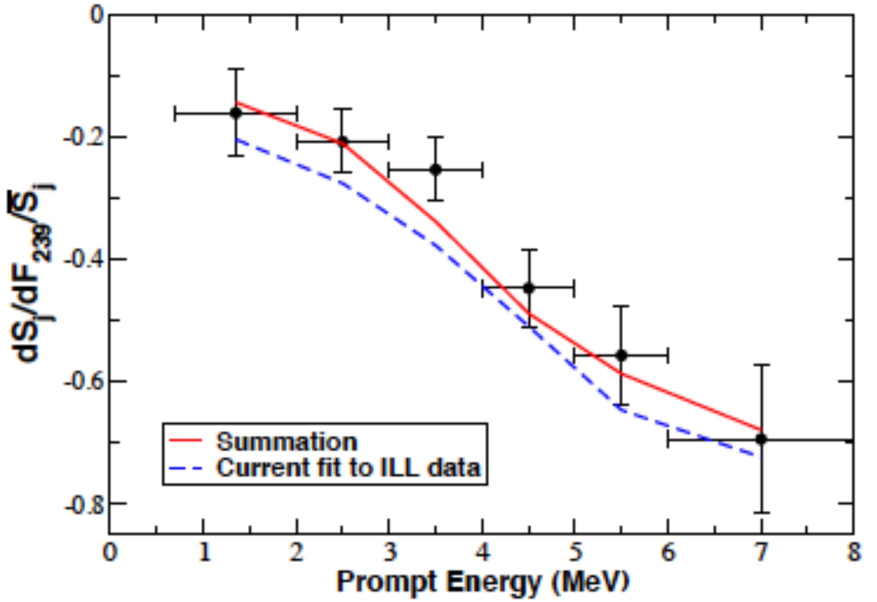


	DB[a]	Summation	H-M[b]
$\overline{\sigma}_f (10^{-43}\text{cm}^2)$	5.9± 0.13	6.11	6.22±0.14
$\frac{d\sigma_f}{dF_{239}} (10^{-43}\text{cm}^2)$	-1.86± 0.18	-2.05	-2.46±0.06
σ_5/σ_9	1.445±0.06	1.445	1.53± 0.025

- **Databases reproduce the evolution of antineutrino spectra, but still allows for a 3.5% anomaly.**
- **It is difficult to assign uncertainties to the nuclear databases. Simply adding uncertainties in quadrature suggests 2%, but we estimate that the uncertainties are closer to ~5%.**

The Shape of the Antineutrino Spectrum also changes with fuel burnup





Both the database and the Schreckenbach data predict a similar change in shape with fuel burnup.

A.C. Hayes, G. Jungman, G. Garvey, E. McChutchan, A. Sonzogni, X.B. Wang, arxiv.org/abs/1707.07728

Summary of Current Status

- The original Schreckenbach fission beta data predict a 3-6% anomaly, depending on how the β-spectra are converted to antineutrino spectra.
- But Schreckenbach data but do not reproduce the reactor fuel burnup data from Daya Bay.
- The summation method (using nuclear databases) explains all of the fuel evolution data and still allows for a 3.5% anomaly – but not a statistically significant one.
- The database spectra provide a counter example, showing that the Daya Bay data alone do not rule out sterile neutrinos
- New experiments are needed to resolve the both the neutrino and nuclear physics problems.