Reactor Antineutrino Spectra

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PINS 2019

Four Experimental Anomalies do not fit within the 3ν Mixing Picture

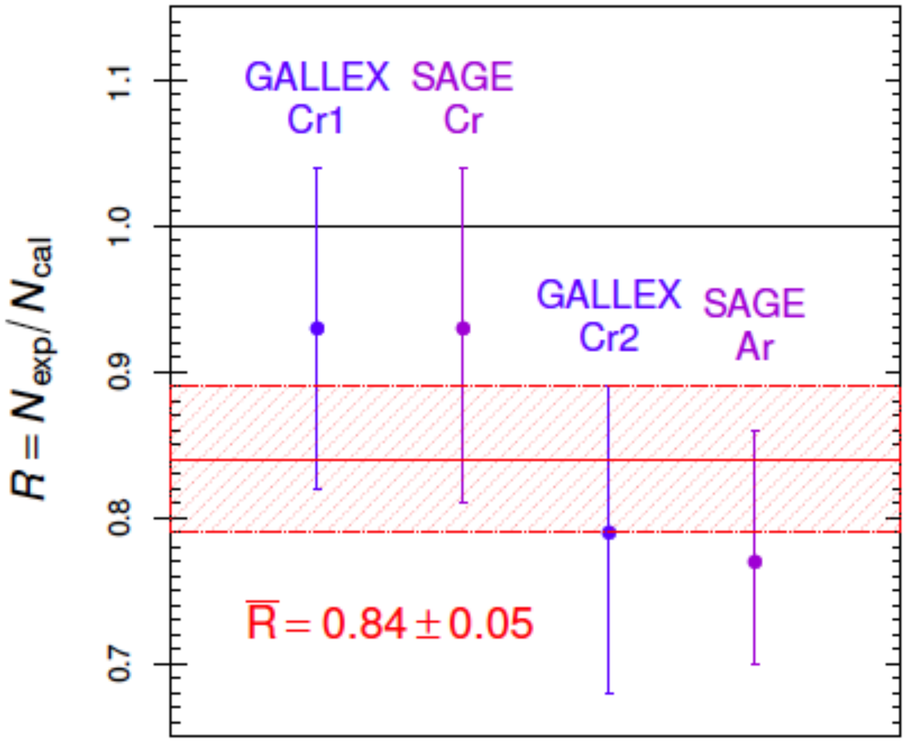
- LSND
- MiniBooNE
- The Gallium Anomaly
- The Short BaseLine Reactor Neutrino Anomaly

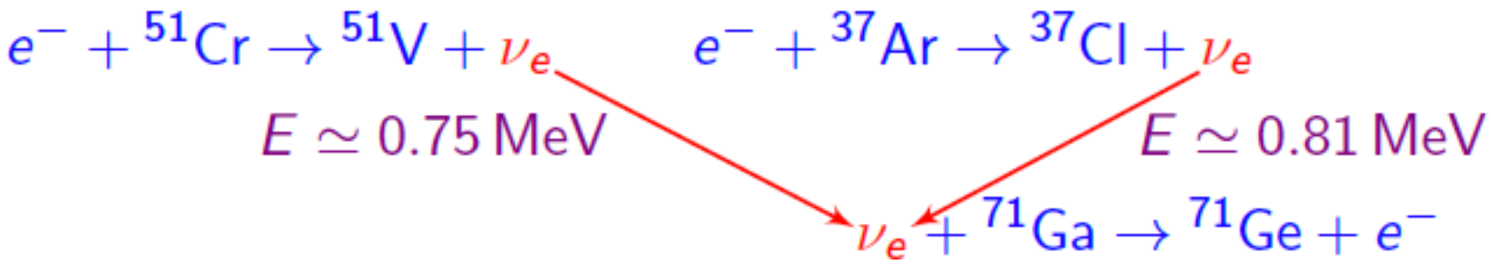
These anomalies possibly suggest a fourth sterile neutrino, requiring a mass on the 1 eV scale.

But there are also complex nuclear physics issues associated with these anomalies.

The Gallium Anomaly

Monoenergetic neutrino sources used to test the SAGE and GALLEX detectors suggest too few neutrinos being detected.





Expected comes from cross section based on $t_{1/2}$ of ^{71}Ge

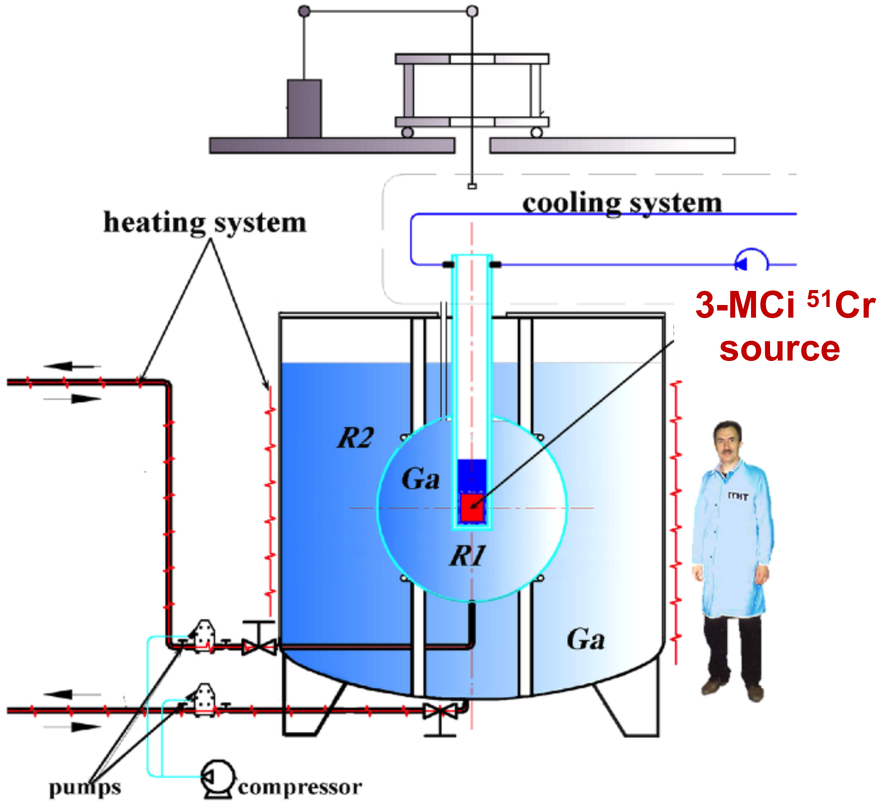
Bahcall + Haxton

<L>$_{\mathrm{GALLEX}}$ = 1.9 m; <L>$_{\mathrm{SAGE}}$ = 0.6 m

=> $\Delta m^2_{\mathrm{SBL}} \gtrsim 0.5\,\mathrm{eV}^2$

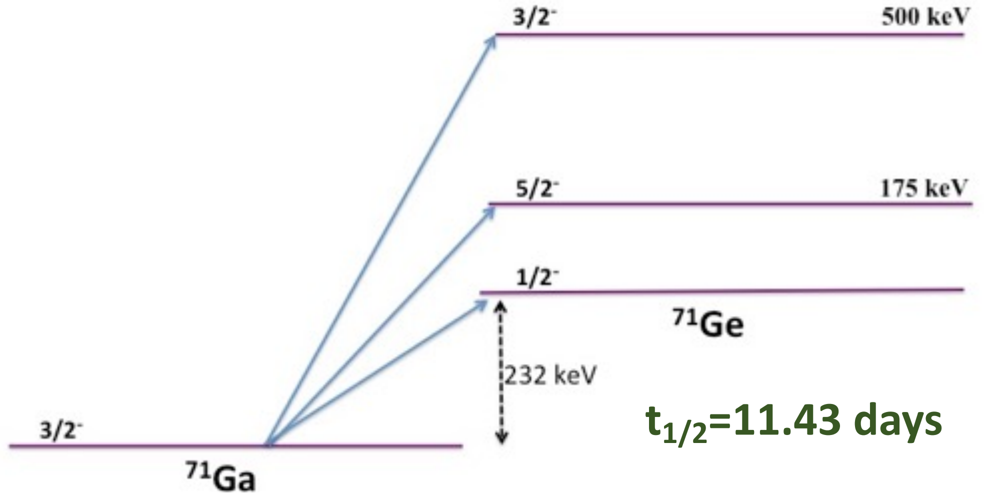
Abdurashitov et al. (SAGE) 2006 PRC73 045805.; Anselmann et al. (GALLEX) 1995 PLB342; Hampel et al. (GALLEX) 1998 PLB420 114; Giunti, Phys. Rev. C **83**, 065504, and more recent update.

Gallium Anomaly – New experiments and Theory



Baksan Experiment for Sterile Transitions
- Two concentric zones filled with Gallium.

^{71}Ge in each Ga zone analyzed separately



$$\sigma = \sigma_{gs}\left(1 + \xi_{175}\frac{\mathrm{BGT}_{175}}{\mathrm{BGT}_{gs}} + \xi_{500}\frac{\mathrm{BGT}_{500}}{\mathrm{BGT}_{gs}}\right)$$

Bachall PRC55 3391 (1997); Haxton,PLB B353, 422 (1995) and PLB 431, 110 (1998).

Subdominant corrections to the cross section need to be recalculated.

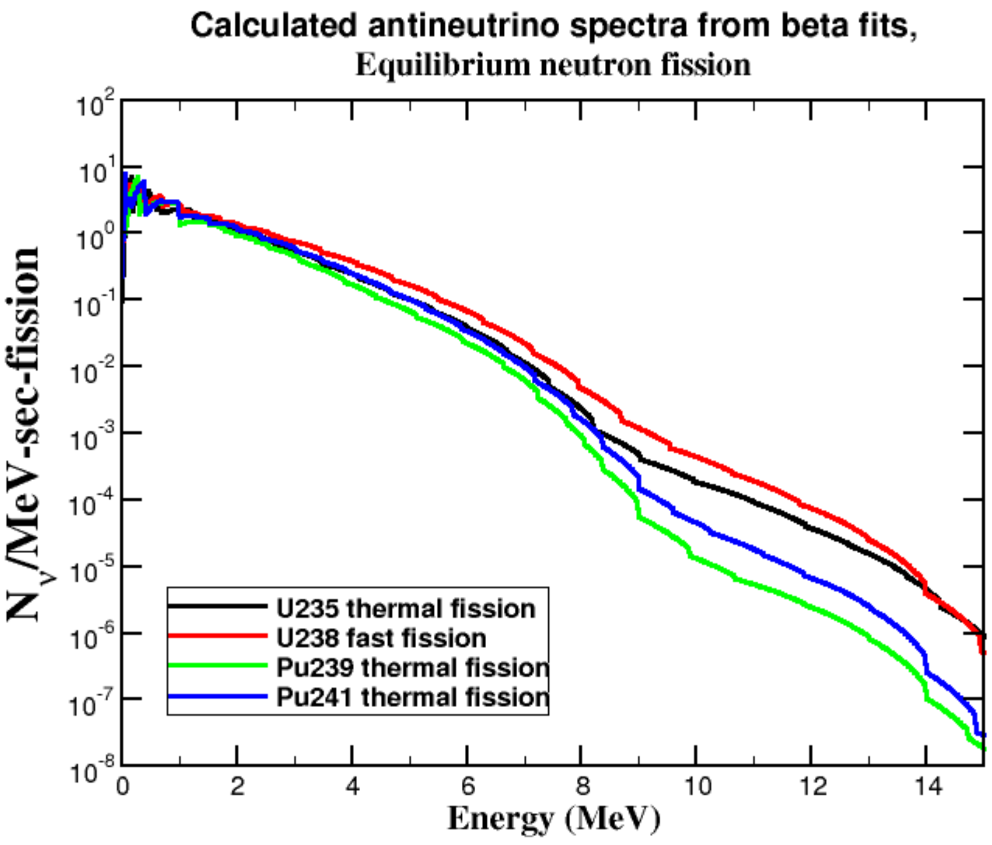
Excited state cross sections also being checked.

The Reactor Neutrino Anomaly

1 GW Reactor emits 10^{21} antineutrinos/sec
Allowing for precision oscillations experiments

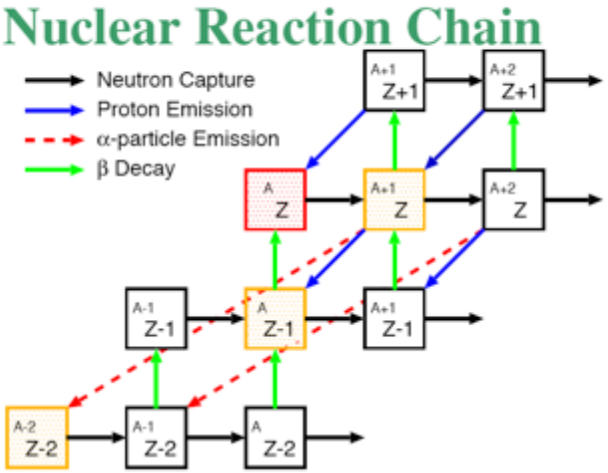
Intense Source of Neutrinos Emitted from Reactors

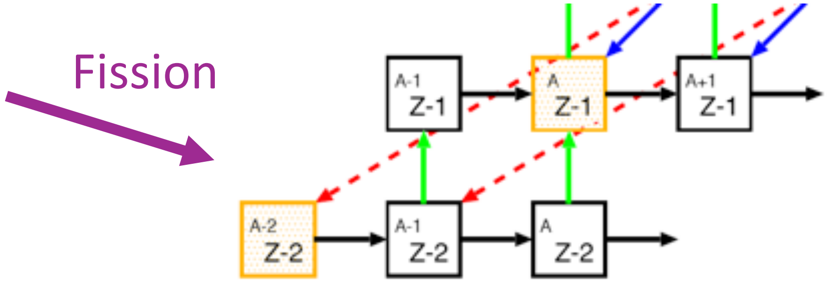
3 GW reactor emits 10^{21} antineutrinos per second



4 actinides contribute to reactor spectra:
^{238}U, ^{235}U, *^{239}Pu, and* ^{241}Pu

Beta Decay of Fission Fragments is the Source of Anti-neutrinos

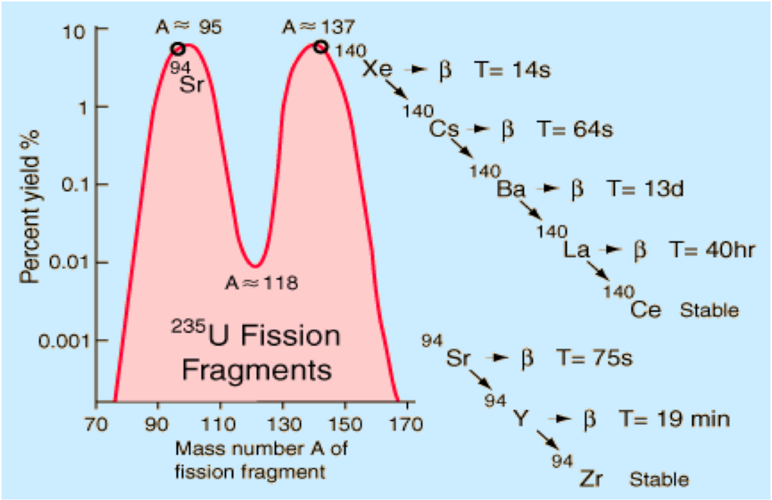




- About 1000 fission fragments – **neutron rich**

- Most fragments β-decays with several branches

$\Rightarrow$ About 5-6 ν_e per fission
$\Rightarrow$ Aggregate spectrum made up of thousands of end-points



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

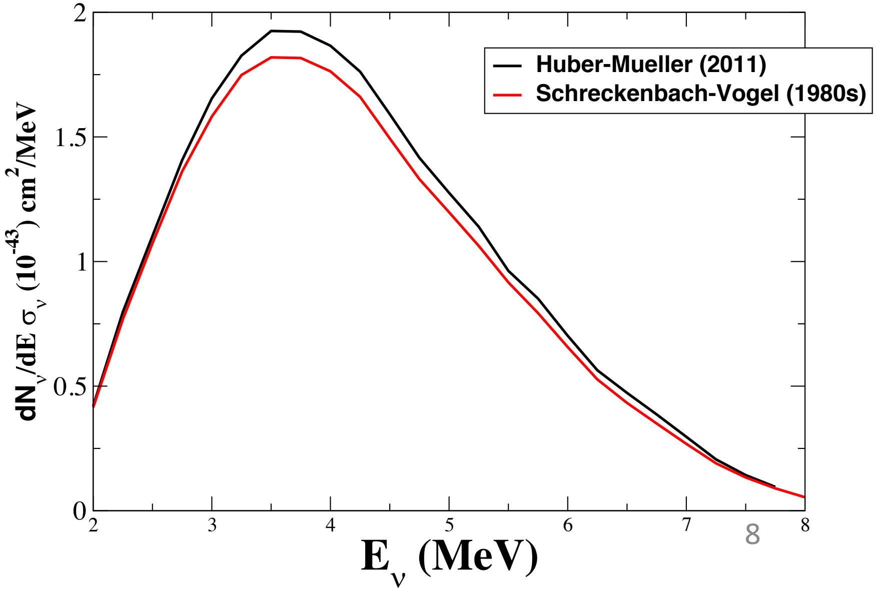
In the 1980s two predictions became the standards for the field:

- Schreckenbach *et al*. converted their measured fission b-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 about 5%.

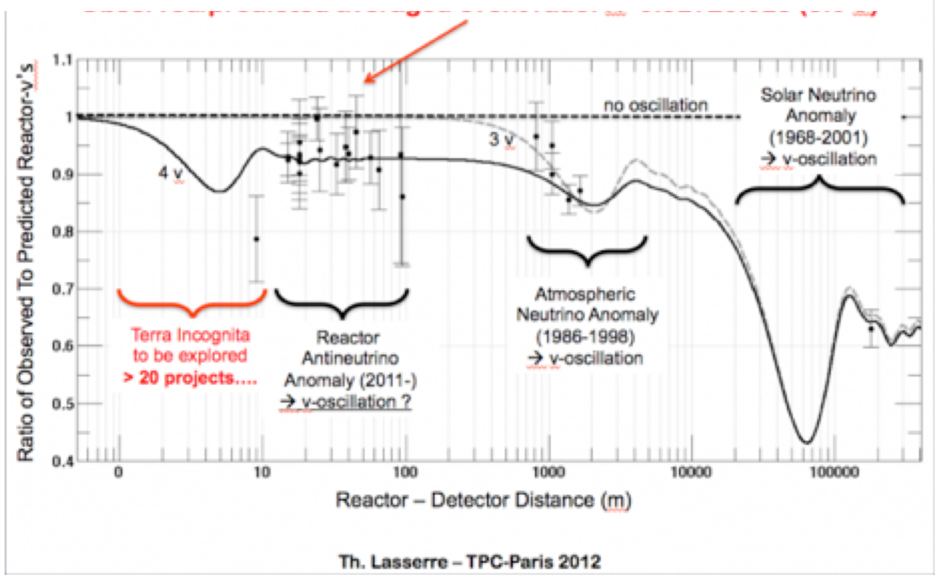
The change was largely as a consequence of:

- 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

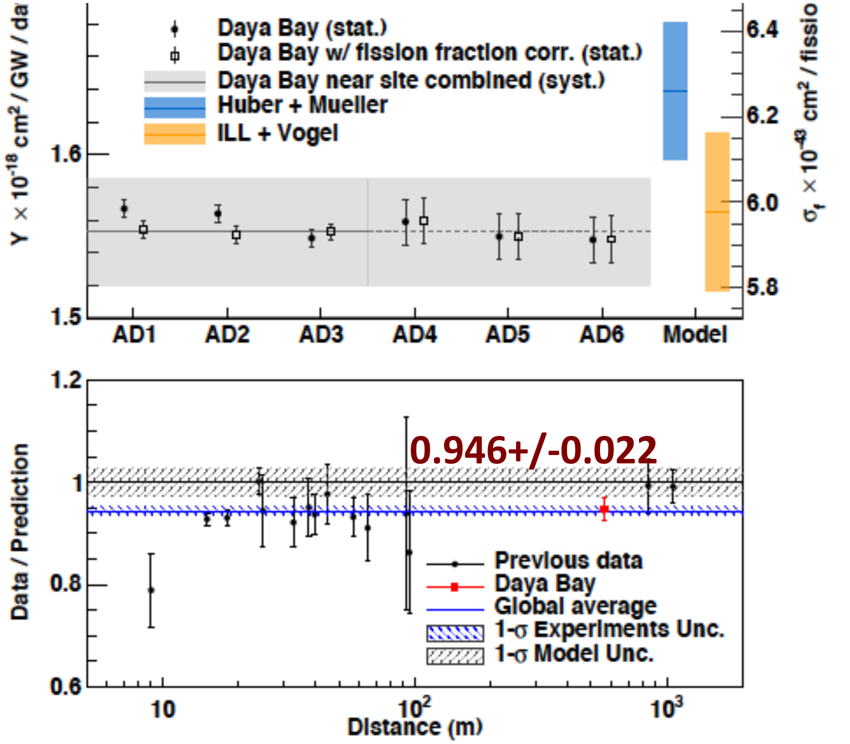
From Th. Lasserre, 2012



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

Results from Daya Bay, 2016

PRL,116 (2016) 061801

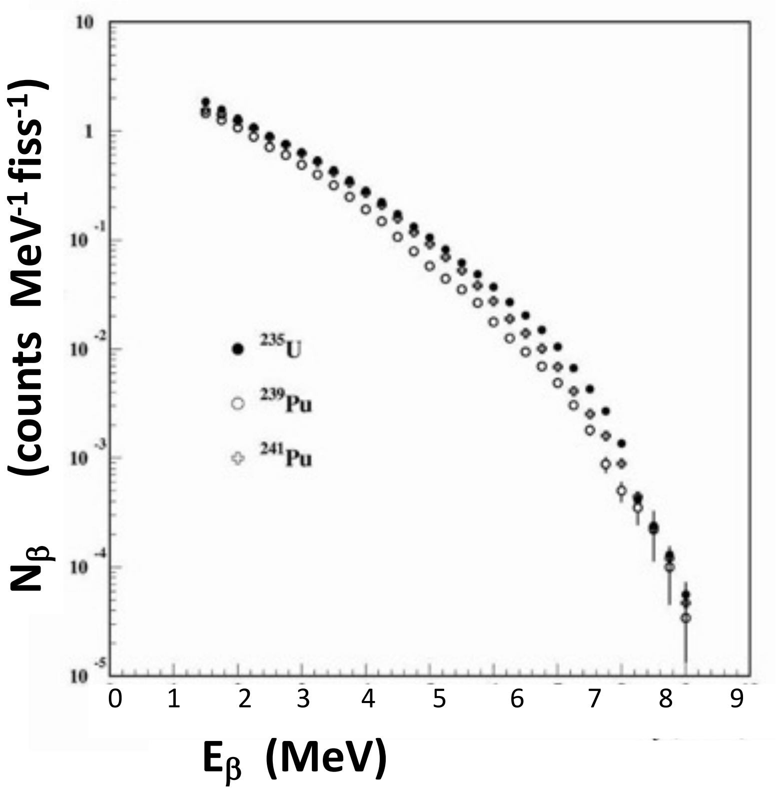


Accurate measurements of the total flux at Daya Bay, RENO and Double Chooz confirms the shortfall.

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



K. Schreckenbach et al. PLB118, 162 (1985)
A.A. Hahn et al. PLB160, 325 (1989)

- 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
- Vogel *et al*. used the ENDF-5 (nuclear database to estimate ^{238}U, which requires fast neutron fission

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

FIT

Parameterized

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

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

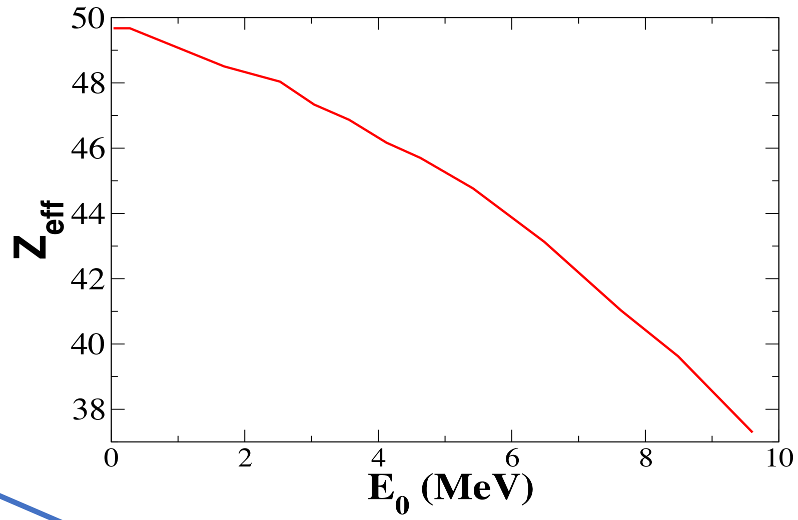
Two inputs are needed to convert β-spectra to antineutrino spectra: (1) Z of the fission fragments for the Fermi function, (2) sub-dominant corrections

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

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

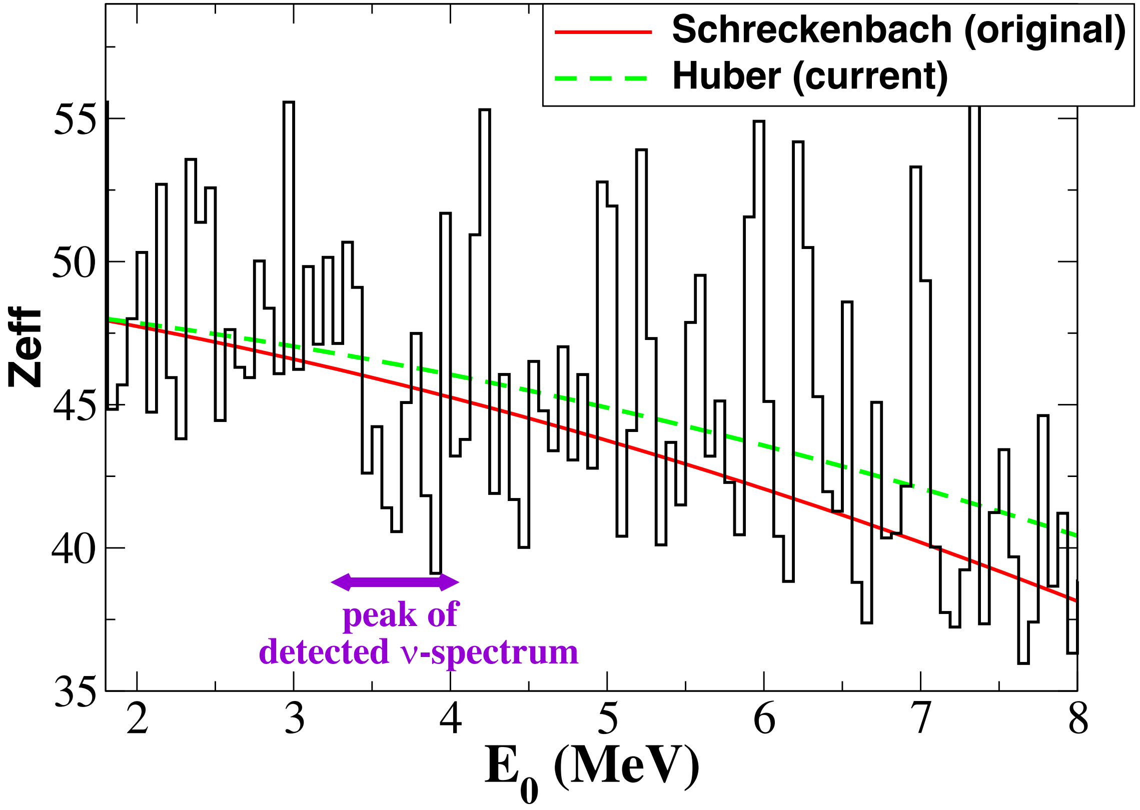
δ_{WM} = Weak magnetism

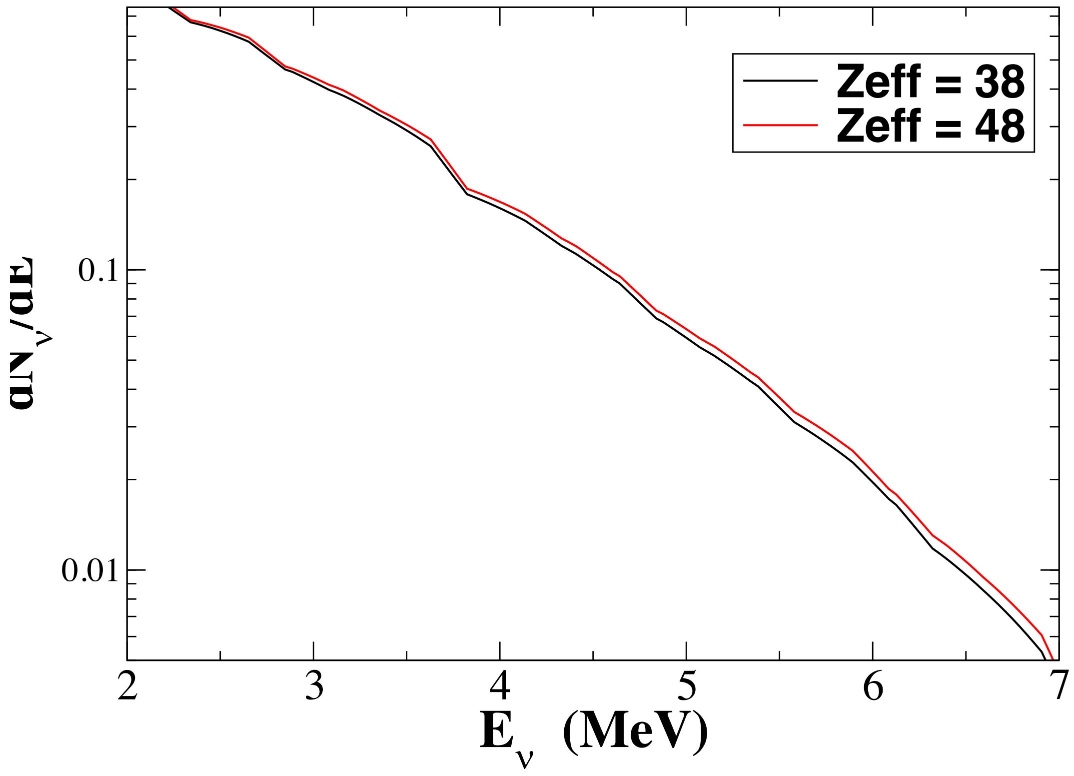
δ_{R} = Recoil correction

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 beta-spectrum, the higher ν–spectrum





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

- New parameterization of Zeff with end-point energy E_0 accounts for 50% of the current anomaly.
- At the peak of the detected neutrino spectrum both fit may be high.

  $Z_{eff} = a + b\,E_0 + c\,E_0^2$ form for the fits causes this.

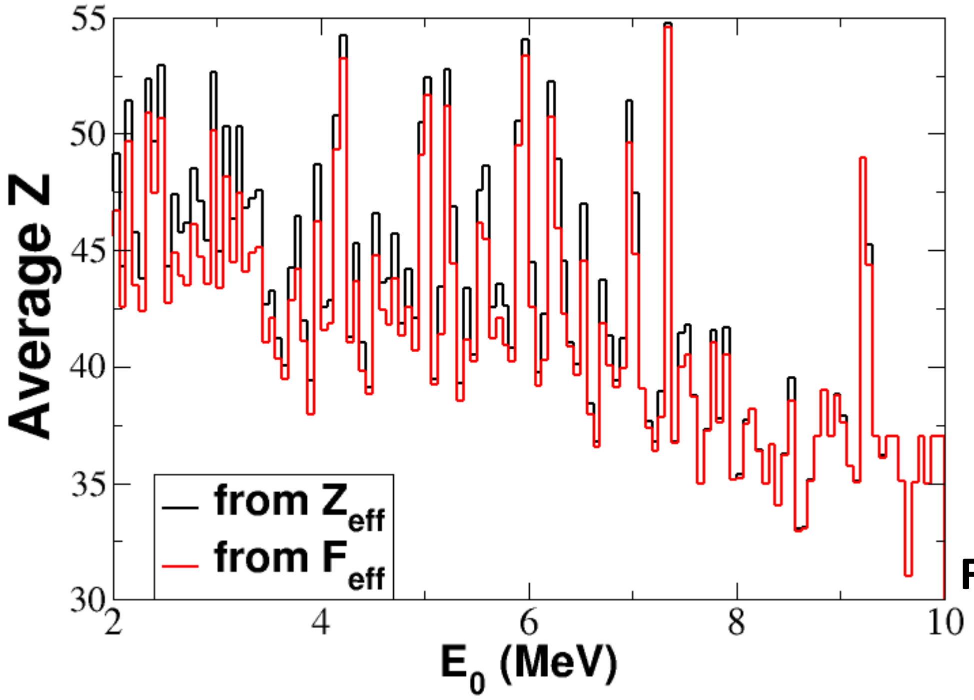
Examined different ways of estimating Z-average(E_0)

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

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

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

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
241Pu : 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

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

δ_{FS} = Finite size correction to Fermi function

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

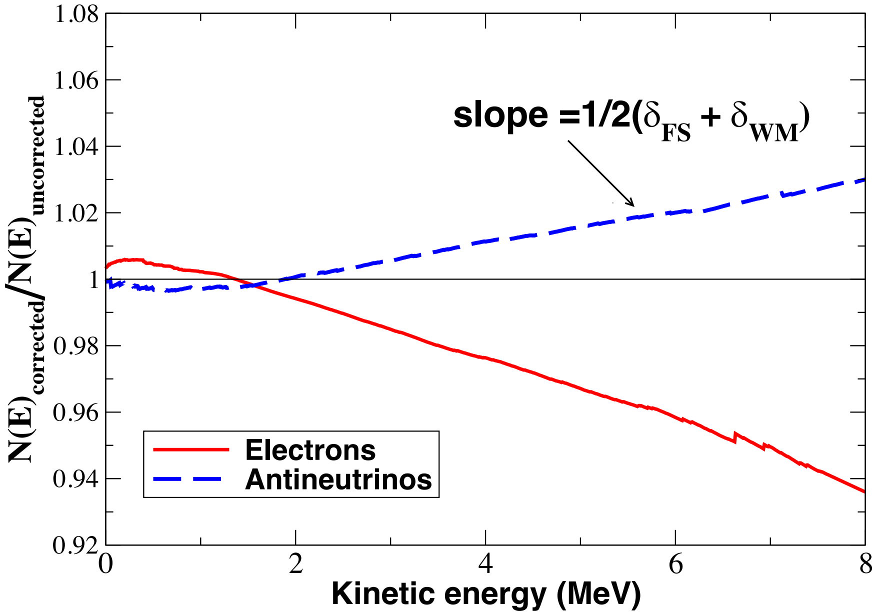
Originally approximated by a parameterization: $\delta_{FS}+\delta_{WM}=0.0065(E_\nu-4MeV))$

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

An approximation was used for each:

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

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



Th. A. Mueller, et al., PRC 83, 054615 (2011)

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

Uncertainties in the detailed contributions to the total spectra

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

Allowed transitions ΔL=0; Forbidden transitions ΔL≠0.

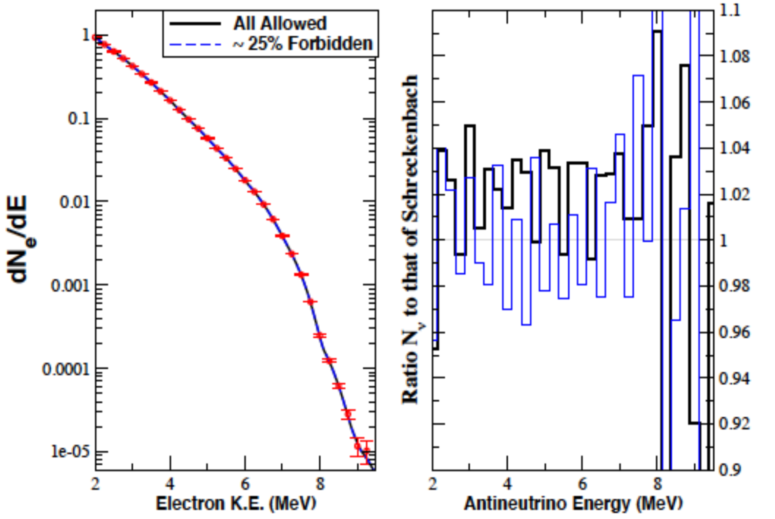
Forbidden transitions introduce a shape factor C(E) and corrections are different and sometimes unknown:

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

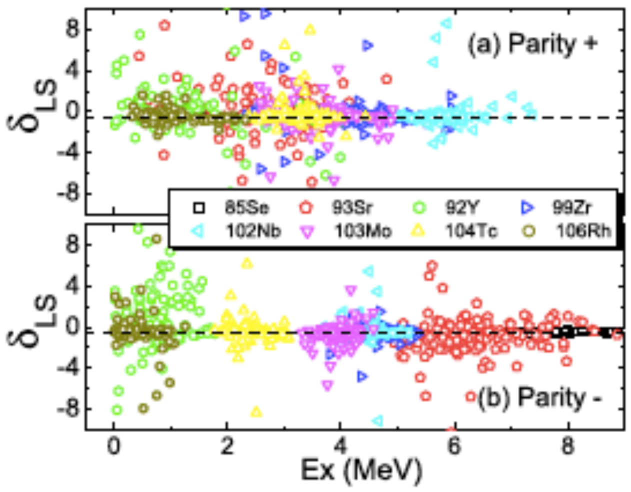
Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma\equiv\sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v-1/2}{M_N g_A}\right](E_e\beta^2-E_\nu)$
Non-unique 1^{st} Forbidden GT	0^-	$[\Sigma,r]^{0-}$	$p_e^2+E_\nu^2+2\beta^2E_\nu E_e$	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	
Non-unique 1^{st} Forbidden F	1^-	$r\tau$	$p_e^2+E_\nu^2+\frac{2}{3}\beta^2E_\nu E_e$	
Non-unique 1^{st} 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 Schreckenbach's β-spectrum, lead to ν-spectra that differ by 4%

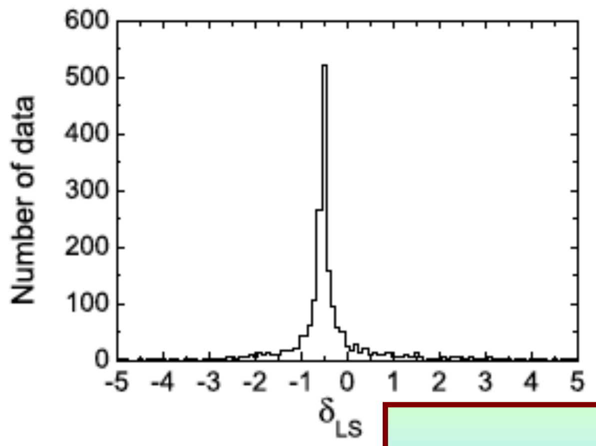


Weak Magnetism has an uncertainty arising from the approximation used for the orbital contribution and from omitted 2-body currents.
But, dominant 0+→0- transitions have zero δ_{WM}, with no uncertainty



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

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



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

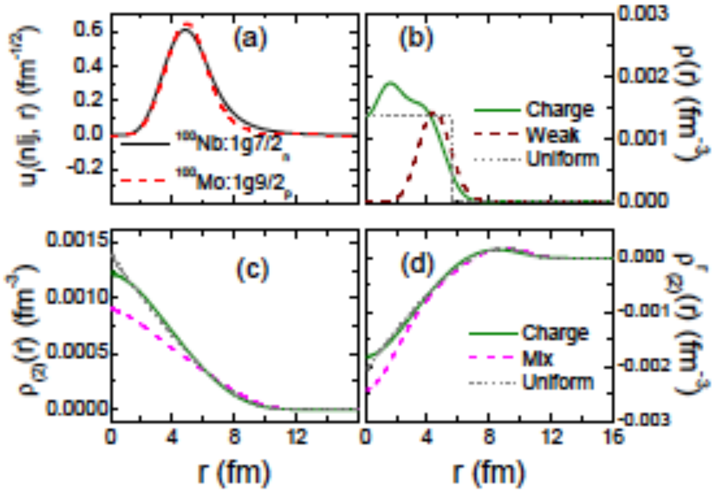
Estimated uncertainty ~ 30-50% for this 4% correction to the spectra

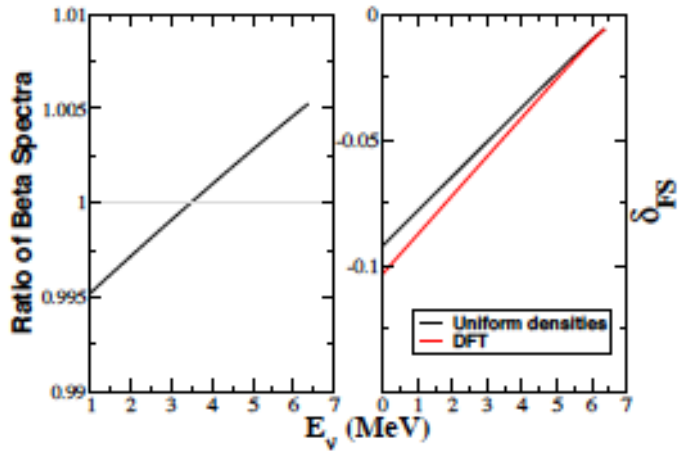
Wang and Hayes, Phys. Rev. C 95, 064313 (2017) .

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

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

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



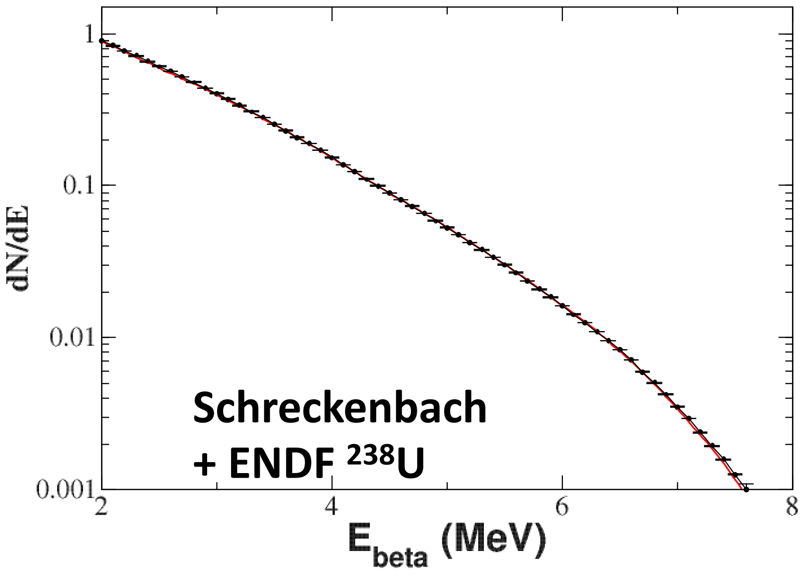


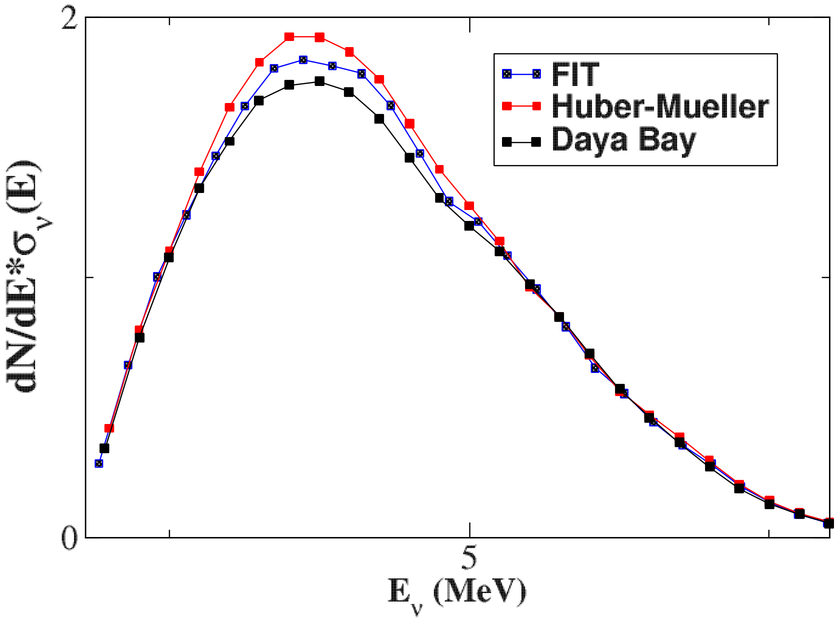
- **Found to be a good approximation for allowed transitions.**
- **Not checked for forbidden transitions.**

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%



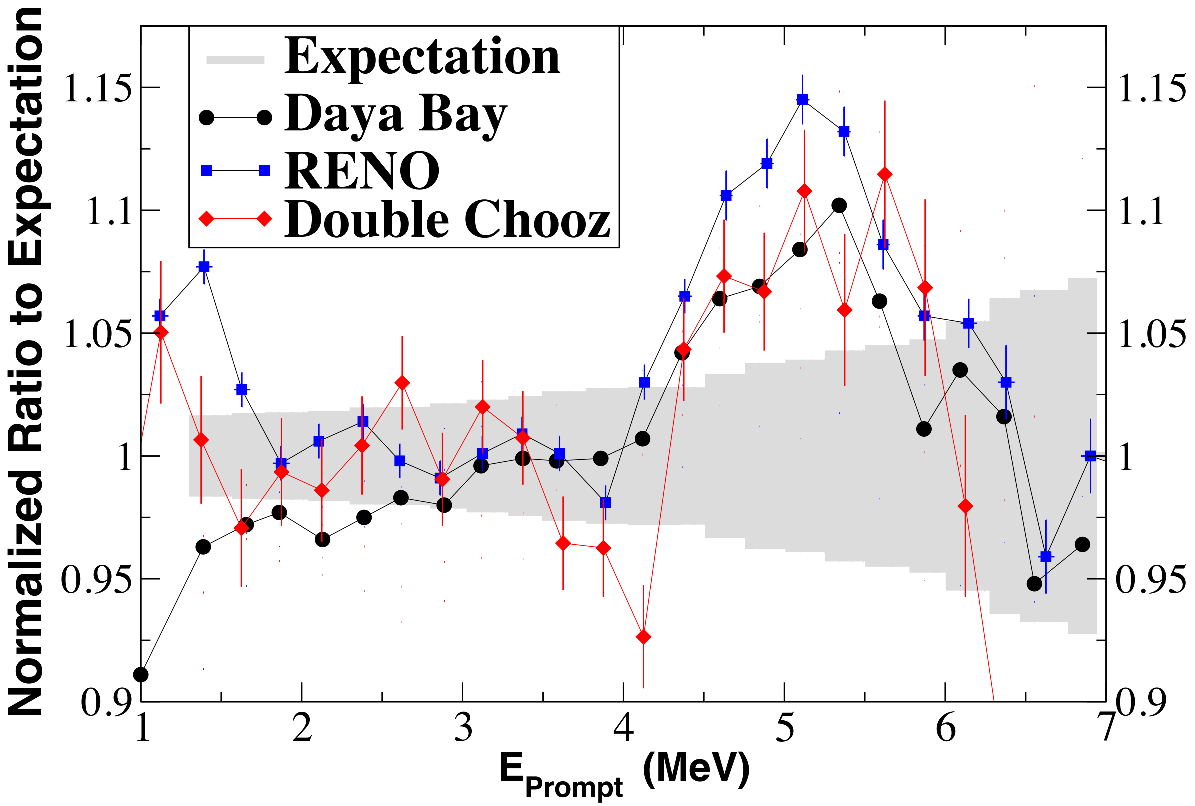


The magnitude of the IBD cross sections change, depending on assumptions, but not the ratio of one isotope to another

	all allowed $Z_{\rm eff}^{\rm Huber}$	all allowed $Z_{\rm eff}$	allow.+forbid. $Z_{\rm eff}$	allow.+forbid. $(Z_{\rm eff}^2)^{1/2}$
^{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 BUMP

The Reactor Neutrino 'BUMP'



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

- **Suggests a problem with the shape of the expected spectra.**
- **^{238}U may also be contributing.**

Possible Origins of the 'Bump'

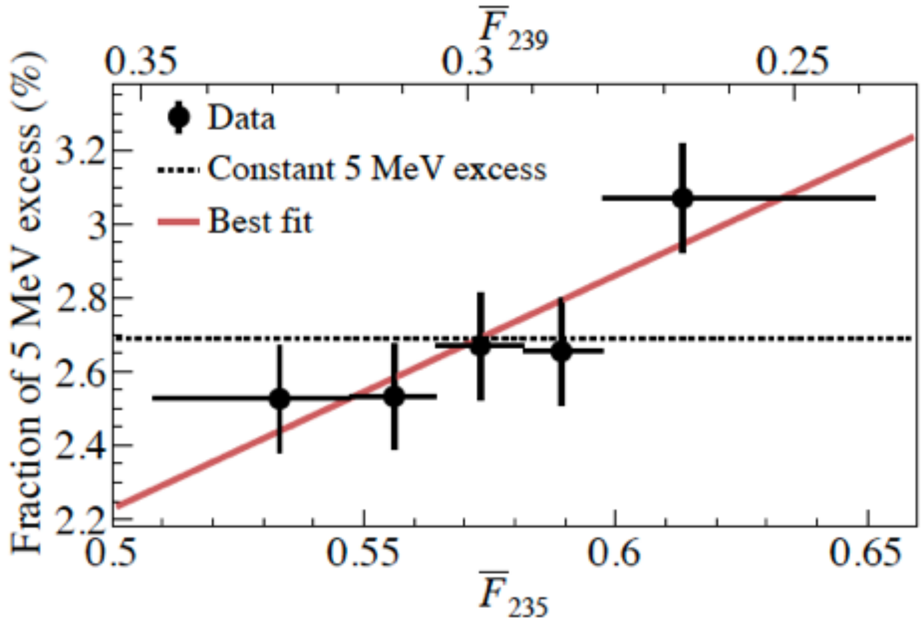
- ^{238}U as a source of the shoulder
  – Possible because ^{238}U has a hard spectrum and contributes significantly in the Bump energy region. It is also the most uncertain actinide.

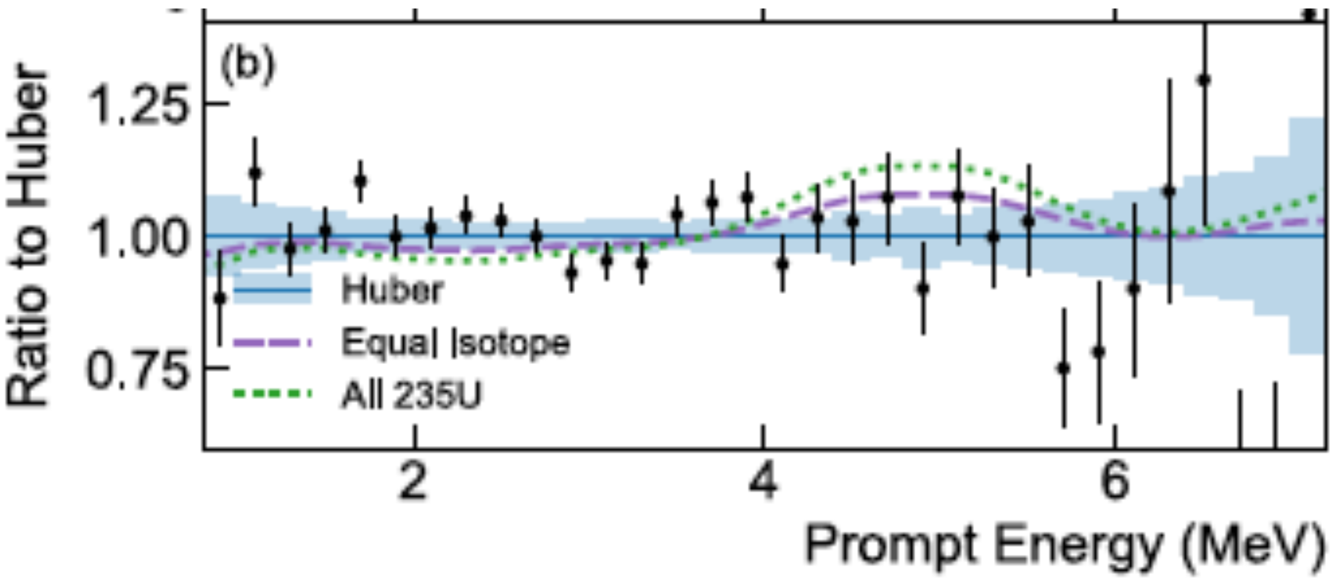
- A possible error in the ILL b-decay measurements
  - Possible but not predicted by current updated nuclear databases.

- 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'.

Antineutrino experiments are not yet definitive on the origin of the BUMP.





RENO report a correlation between 5 MeV excess and ^{235}U fission fraction.

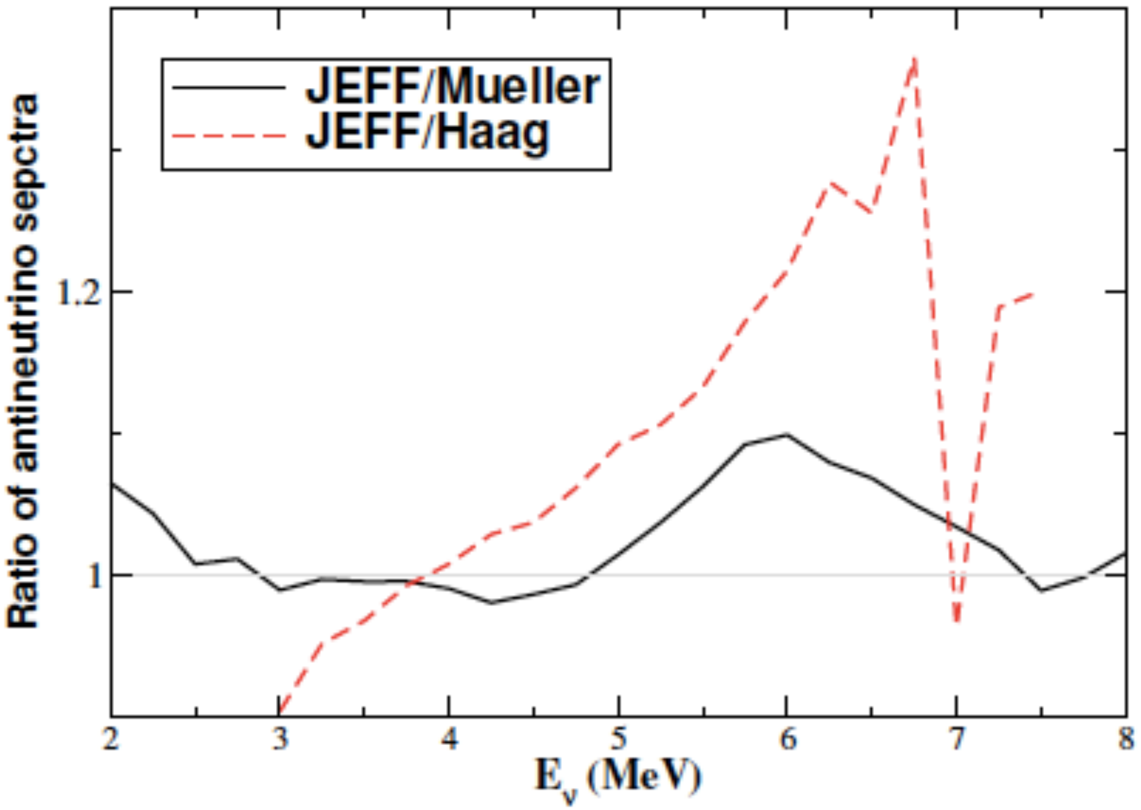
- Not clear whether this is consistent with spectrum simply getting softer?

RENO, arXiv:1806.00574v3

PROSPECT disfavors a solely ^{235}U cause at the ~3σ level

PROSPECT, Phys. Rev. Lett. 121, 251802 (2018)

A change in the BUMP with the fuel evolution is important in determining whether ^{238}U is a likely source



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

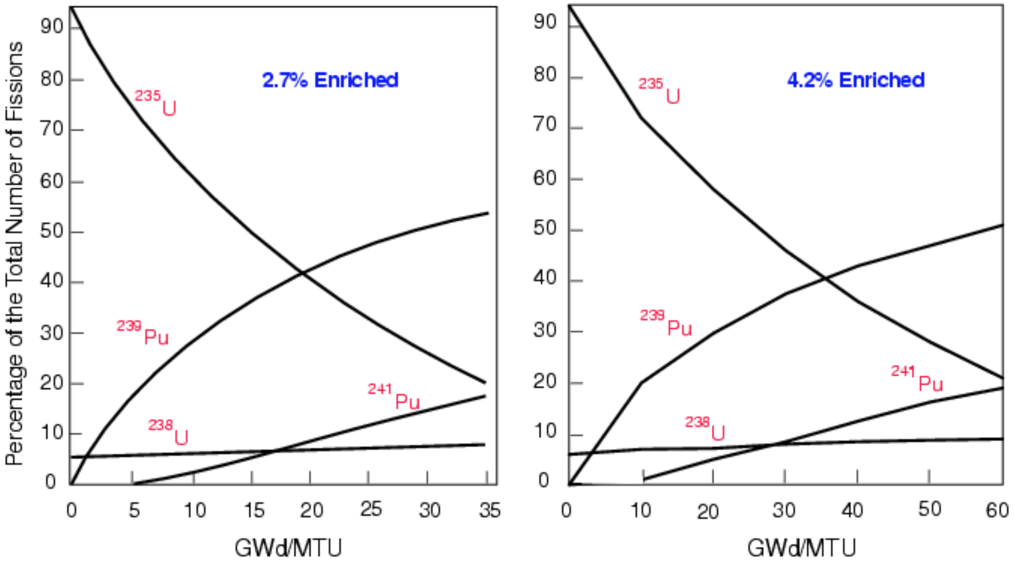
The harder spectrum of ^{238}U increases it's relative importance.

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

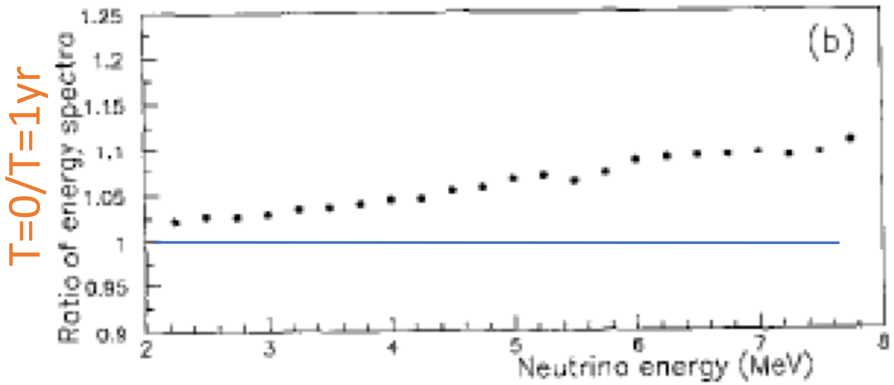
Reactor Fuel Burnup Data shed light on the anomaly

As Burn Proceeds, Different Combination of Isotopes Fissioning

^{239}Pu steadily grows in via:
$^{238}U+n \rightarrow ^{239}U \rightarrow ^{239}Np \rightarrow ^{239}Pu$
Followed by higher mass Pu



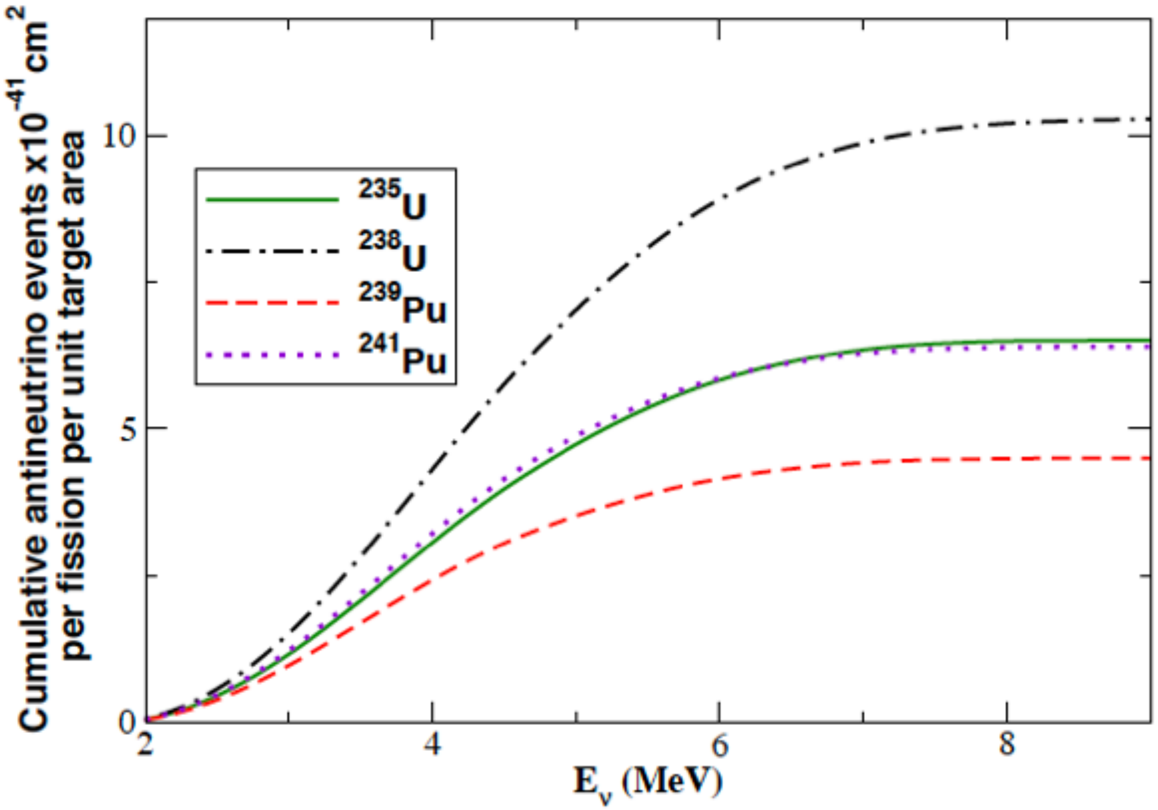
This change translates into a change in the antineutrino spectrum emitted from the beginning to the end of a burn cycle

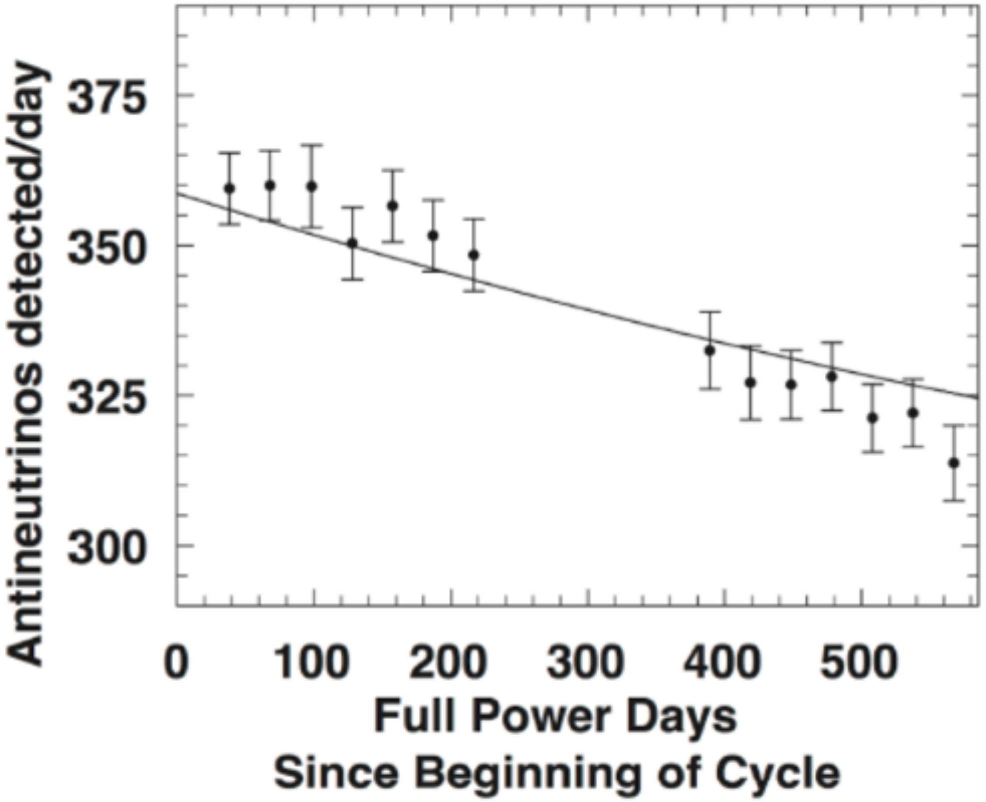


Bugey-3 energy-dependent decrease after 1 year

$\Rightarrow$ 5% fewer detected antineutrinos after 1 yr
$\Rightarrow$ Must be taken into account in osc. expts.
$\Rightarrow$ Basis of some non-proliferation schemes

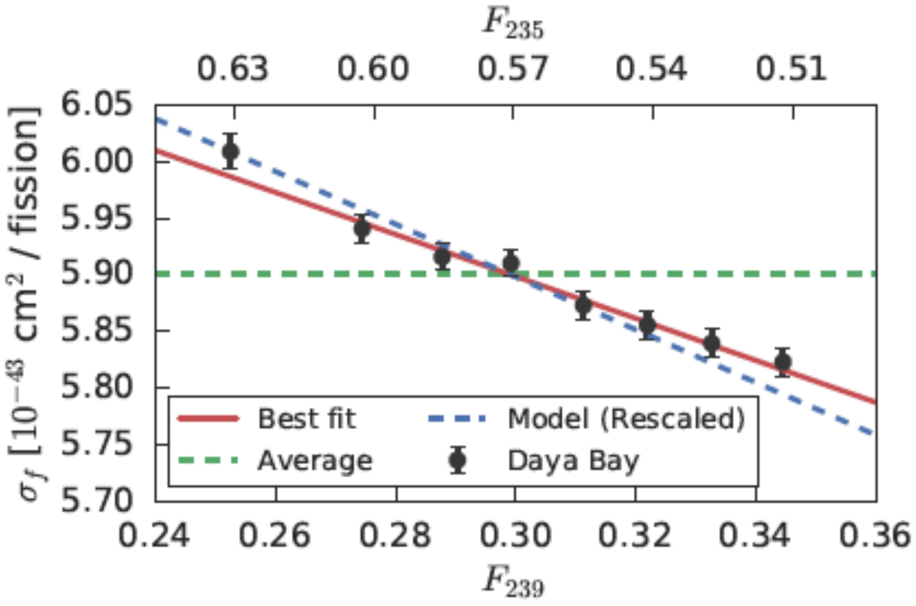
Fewer antineutrinos from ^{239}Pu than from ^{235}U
Observable as the fuel burnups.

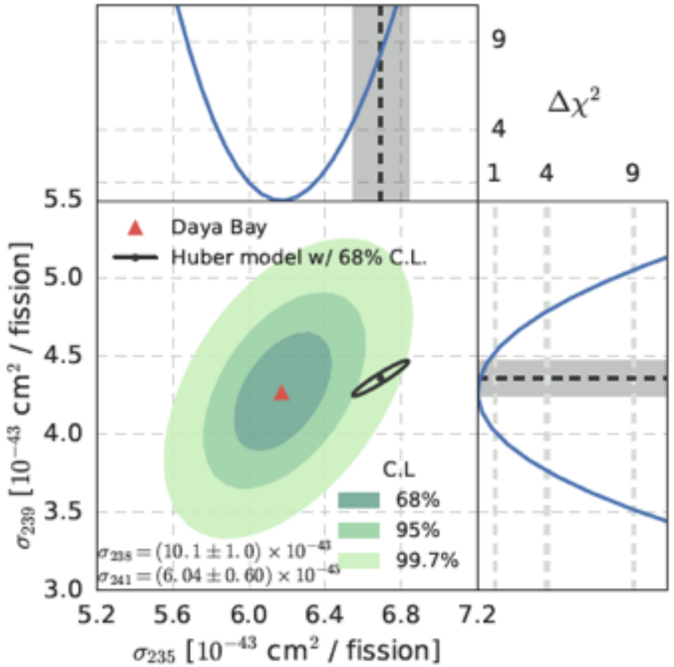




From Bowden et al. 2009 from a pressurized reactor

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



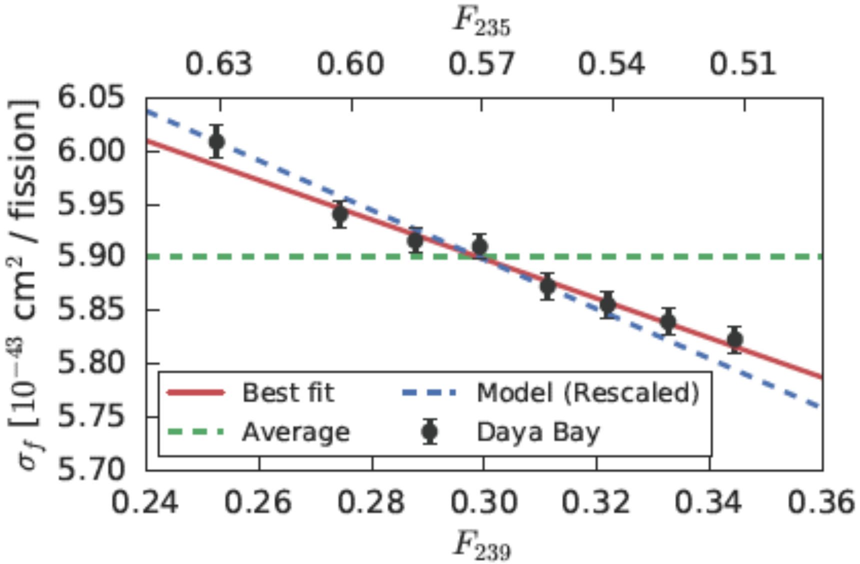


$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

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

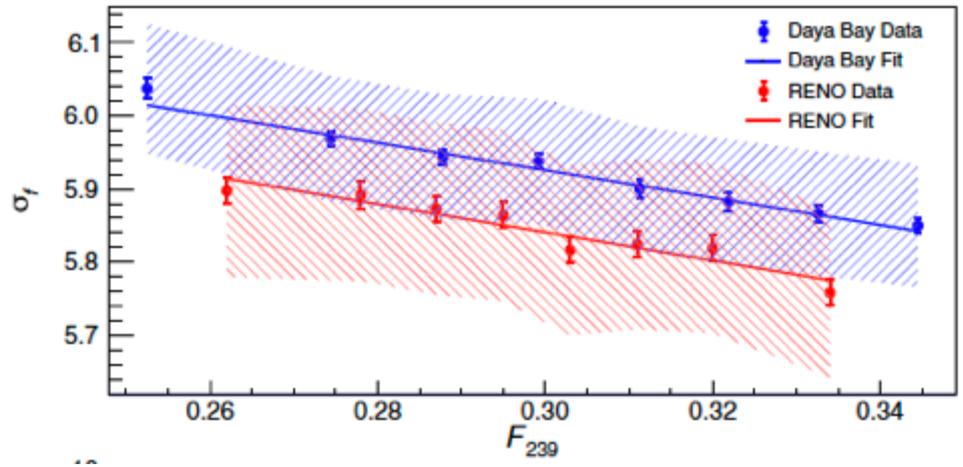
$$(-2.46 \pm 0.06) \times 10^{-43} \mathrm{cm}^2/\mathrm{fission}$$ **Expected**

As expected, the total number of antineutrinos decreases with burnup, but the slope from theory based on the Conversion Method seems too high



Daya Bay

Daya Bay, Phys. Rev. Lett. **118**, 251801



Daya Bay versus RENO

RENO, arXiv:1806.00574v3
Giunti et al., PRD 99 073005 (2019)

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

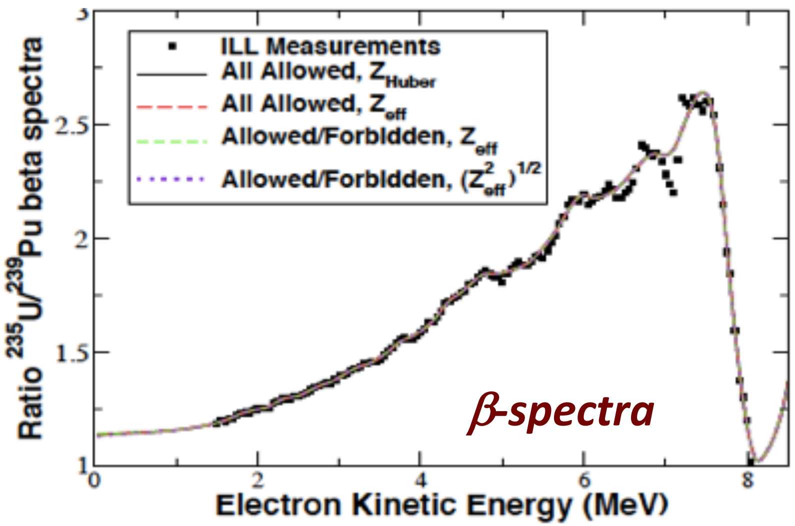
$$d\sigma_f/dF_{239} = (-1.86 \pm 0.18) \times 10^{-43} \text{ cm}^2/\text{fission}$$ Daya Bay Experiment

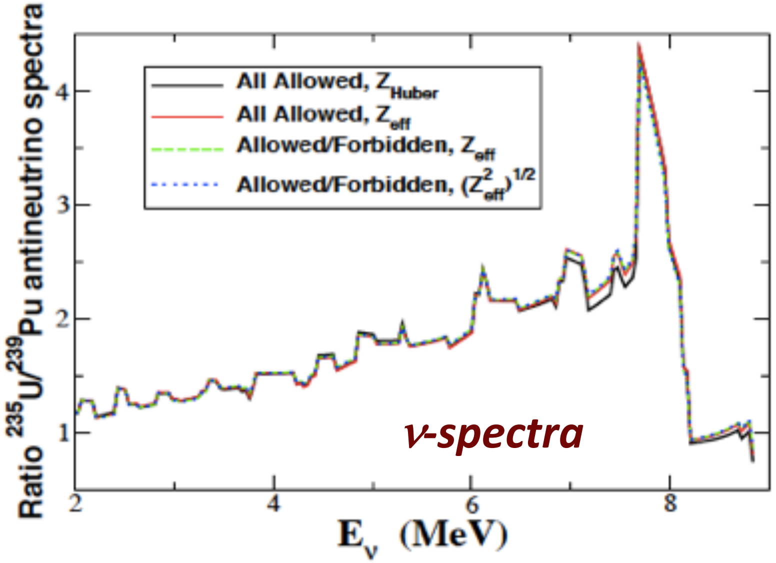
$(-1.93 \pm 0.29) \times 10^{-43}$ cm^2/fission — RENO Experiment

$(-2.46 \pm 0.06) \times 10^{-43}$ cm^2/fission — Theory based on conversion method

Raises the question of how well the ILL reactor normalization was monitored from experiment to experiment.

The fuel evolution data point to a problem with the original measured beta-spectral $^{235}U/^{239}Pu$ ratio





Different Zeff forbidden transitions assumptions in fits the Schreckenbach data results in up to 4% changes the ^{235}U and ^{239}Pu IBD cross sections

But the <u>$^{235}U/^{239}Pu$ ratio is fixed</u>:

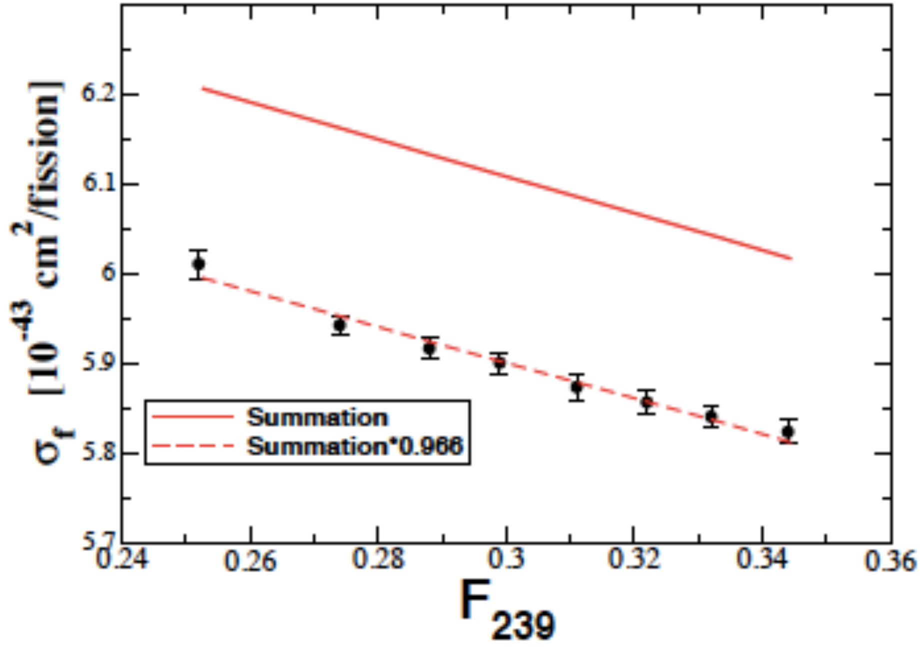
$\sigma5/\sigma9$ = 1.53 +/- 0.05 (Schreckenbach)

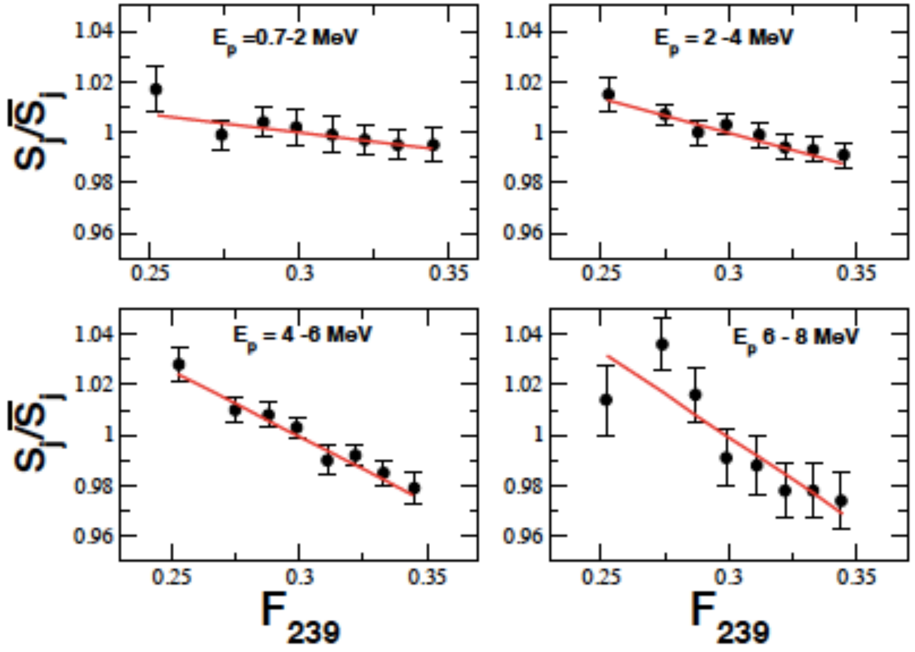
$\sigma5/\sigma9$ = 1.445 +/- 0.097 (Daya Bay)

$\sigma5/\sigma9$ = 1.471 +/- 0.1 (RENO)

Daya Bay, PRL 118, 251801 (2017); RENO, **arXiv:1806.00574v3**
Hayes, et al , Phys. Rev. Lett. **120**, 022503 (2018)

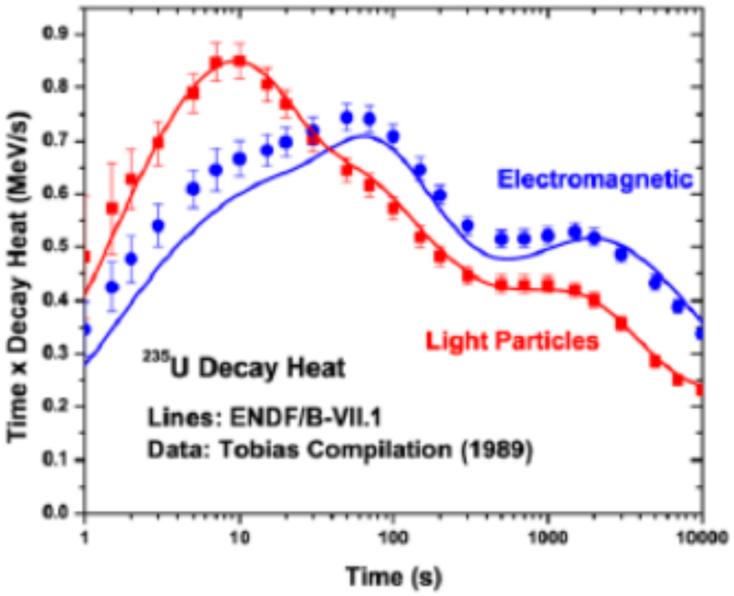
The Nuclear database explains all of the Daya Bay fuel evolution data, but still allows for a (smaller) anomaly

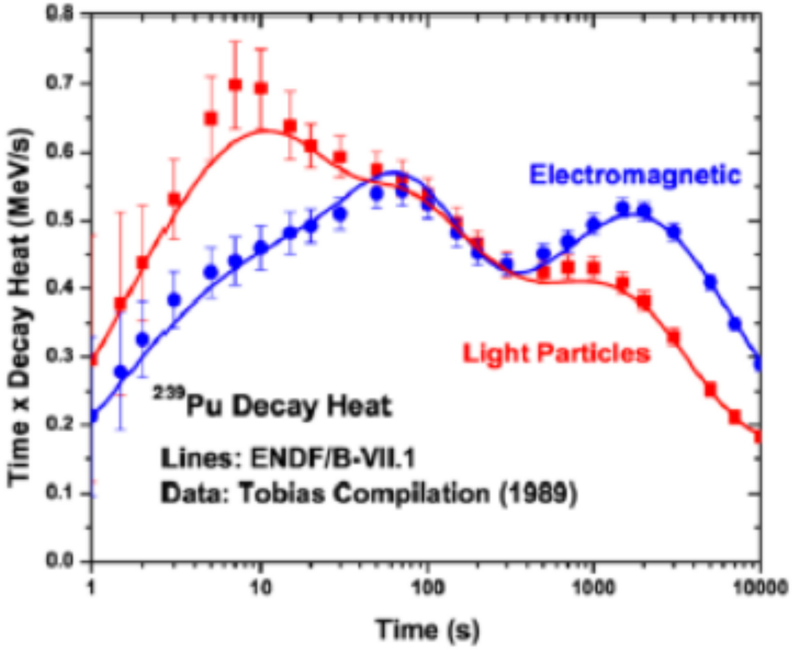


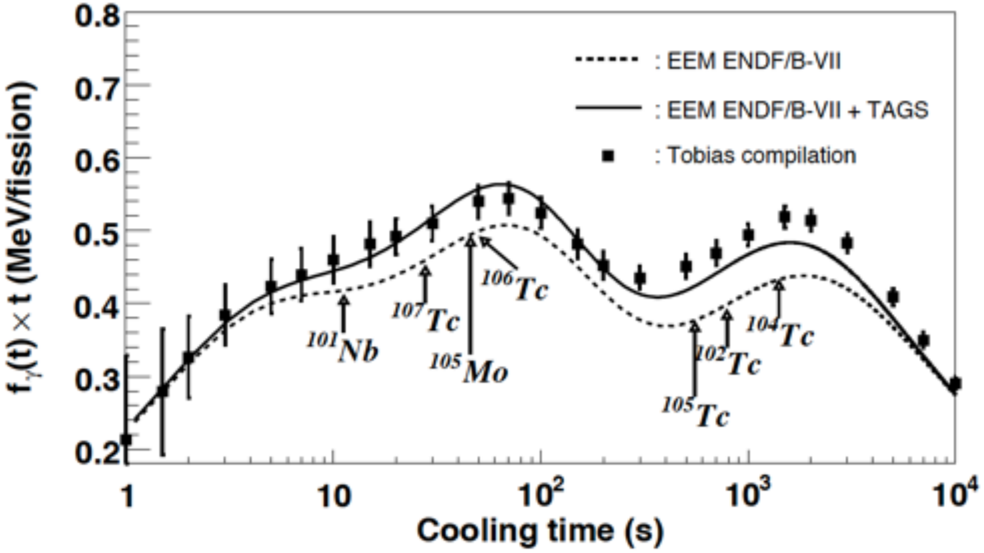


- The IBD yield is predicted to change with the correct slope.
- But the absolute predicted value is high by 3.5%.
- This anomaly is not statistically significant but it means that Daya Bay evolution data do not rule out sterile neutrinos.

Many of the same fission isotopes contribute to reactor decay heat

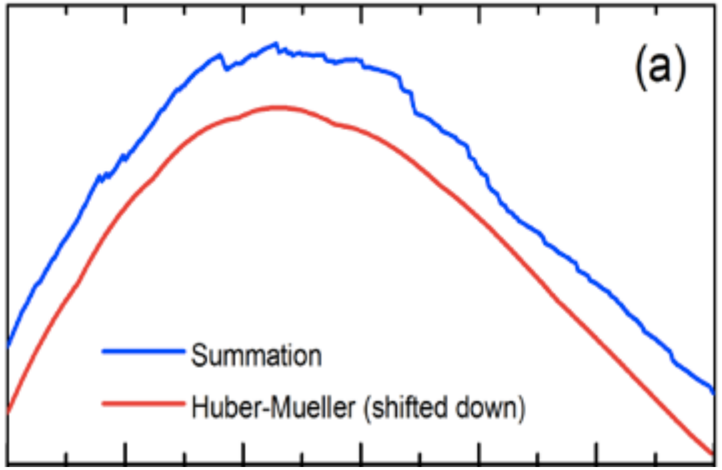


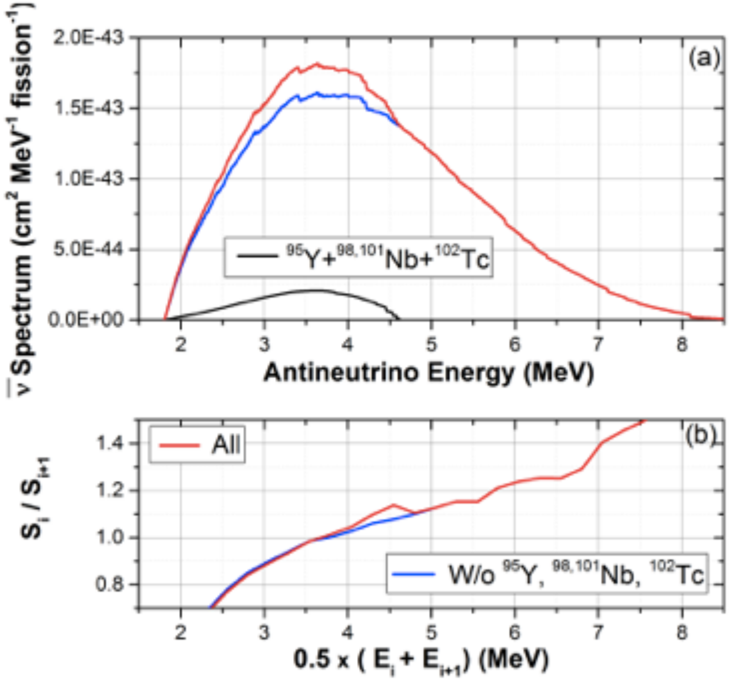




$$f(t) = \sum_i (\overline{E}_{\beta,i} + \overline{E}_{\gamma,i} + \overline{E}_{\alpha,i})\lambda_i N_i(t)$$

Sawtooth-like Structures exist in the antineutrino spectra - have been associated with individual fission isotopes



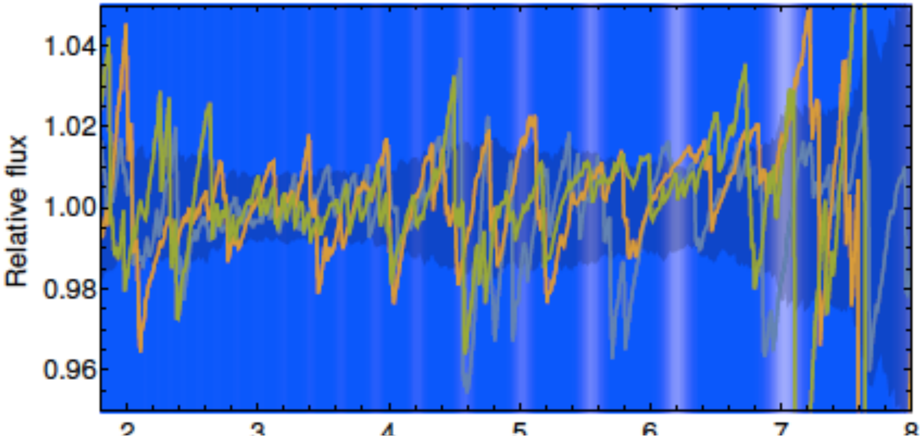


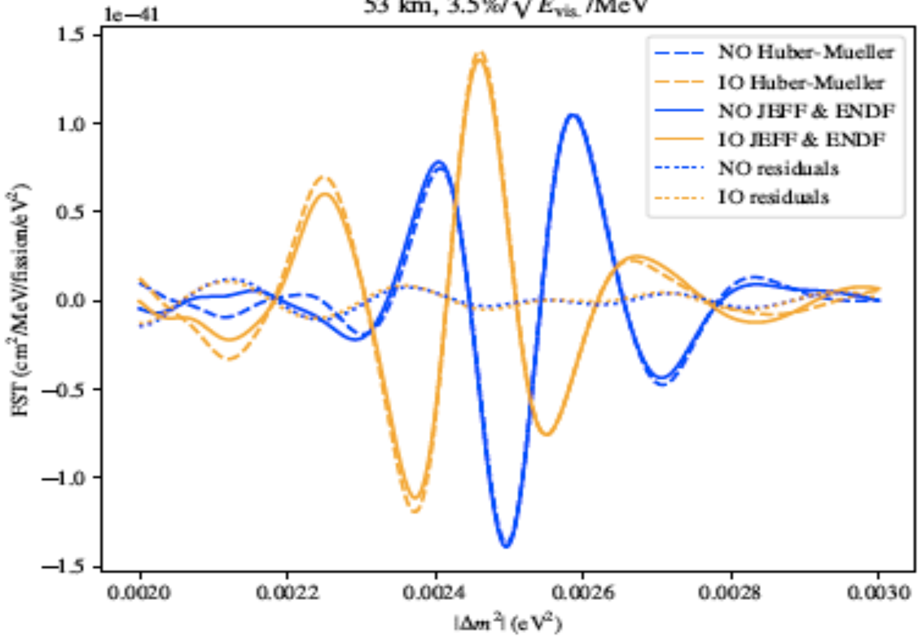
Sonzogni, Nina, & McCutchan have analyzed these structures in the Daya Bay spectrum.

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

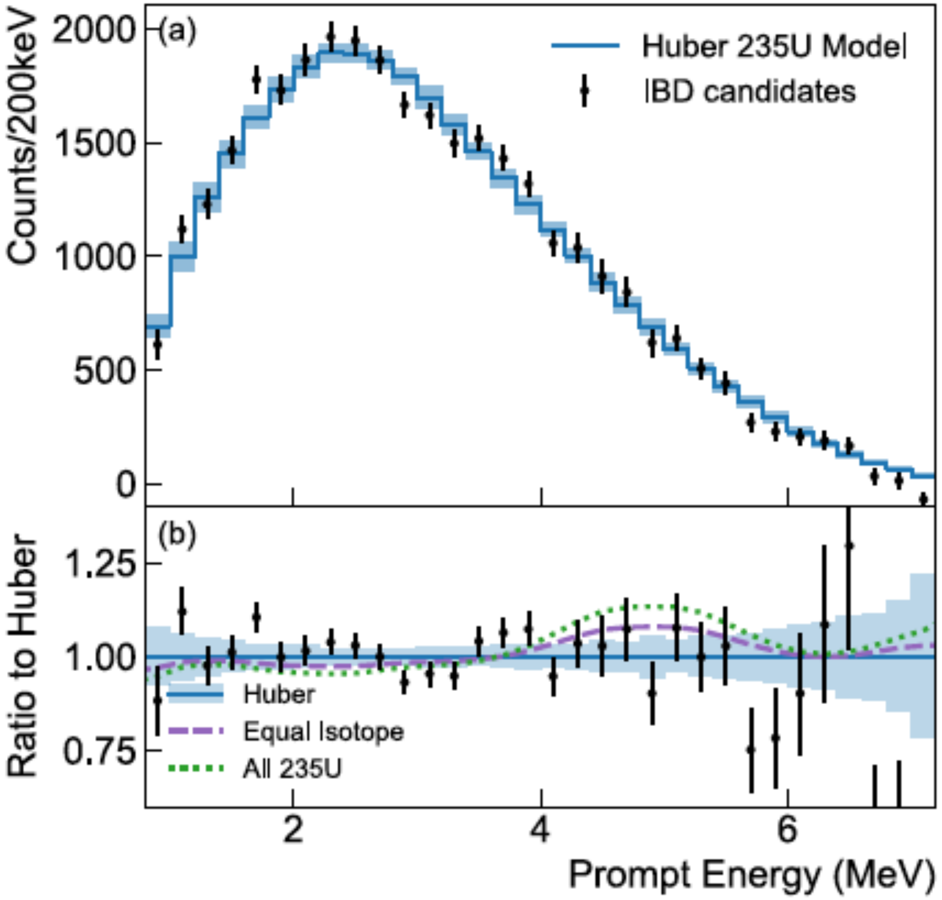
Forero, Hawkins, Huber, arXiv: 1701.07378

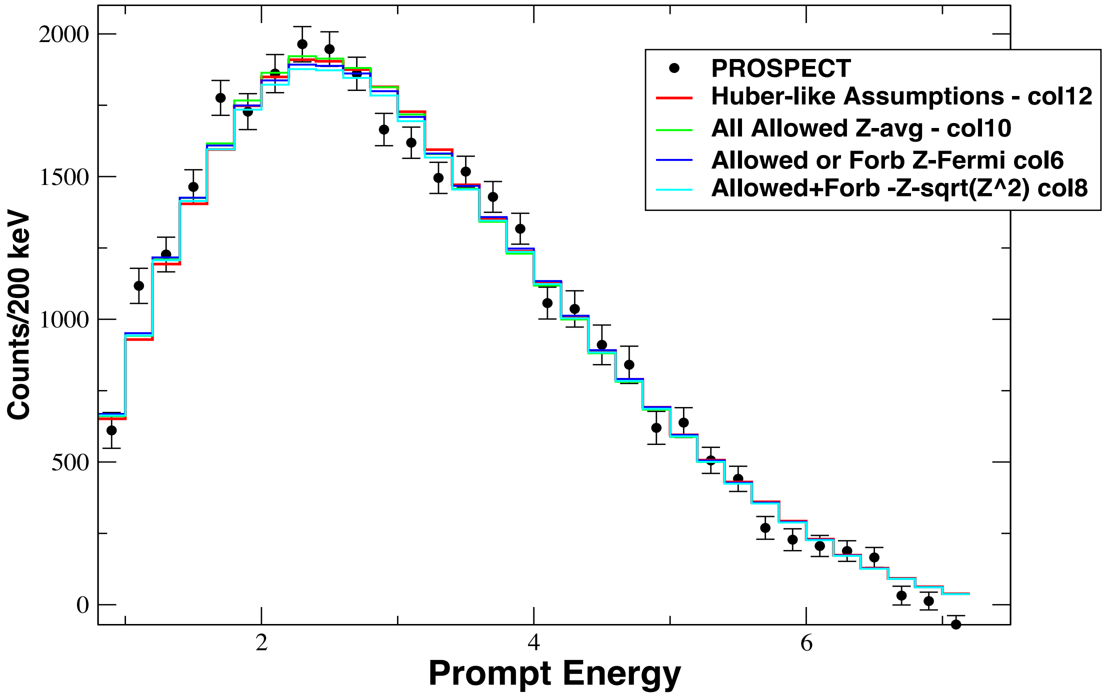
However, if construction of a Fourier transform of the spectrum is possible, these structure are not a problem

- **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.

PROSPECT provides a preliminary ^{235}U ν-spectrum shape





"Okay" fits obtained using Schreckenbach
- Includes detector response

Adding forbidden spectra doesn't really improve the fits.

Summary

1. There are currently 4 anomalies in neutrino oscillation physics

2. The Reactor anomaly does not appear to be related to sterile neutrinos
   - There are issues with the predicted spectra, both Conversion and Summation.
   - Uncertainties need to be increased.

3. The 'BUMP' suggests a problem in at least one of the expected spectra ~5 MeV.

4. The fuel evolution data suggest that the Schreckenbach $^{235}U/^{239}Pu$ ratio is high.
   - JEFF/ENDF databases get this right, but still predict (non-significant) 3.5% anomaly.

5. The SBL reactor experiments will provide spectra for ^{235}U.