Reactor Antineutrino Spectra

Anna Hayes, Los Alamos

Isola d'Elba, June 24th - 28th 2019

The majority of neutrino oscillation experiments converge on a consistent 3ν oscillation framework

The three lepton flavor eigenstates $\nu_\alpha=(\nu_e, \nu_\mu, \nu_\tau)$ are related to three mass eigenstates $\nu_\iota=(\nu_1, \nu_2, \nu_3)$ through a unitary transformation.

Requires that the collective set of experiments is consistent with:

- **Three mixing angles: $(\theta_{12}, \theta_{13}, \theta_{23})$;**
- **CP-violating phase δ**
- **Two mass differences: $\delta m^2=m_2^2 - m_1^2 > 0$**

  $\Delta m^2 = m_{23} -(m_1^2 +m_2^2)/2$

Kajita and McDonald shared the Nobel Prize in 2015

The mixing parameters are deduced from solar, atmospheric, accelerator, and reactor neutrino experiments.

$\delta m^2/10^{-5}$ eV^2	7.54	7.32 - 7.80
Δm^2 /10^{-3} eV^2	2.43 (2.38)	2.32 - 2.49
$\sin^2\theta_{12}/10^{-1}$	3.08	2.91 - 3.25
$\sin^2\theta_{13}/10^{-2}$	2.34 (2.40)	2.15 - 2.59
$\sin^2\theta_{23}/10^{-1}$	4.37 (4.55)	4.14 - 5.94
δ/π	1.39 (1.31)	0.98 - 1.77

F. Capozzi, et al. Phys. Rev. D **89**, 093018 2014

However, 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.

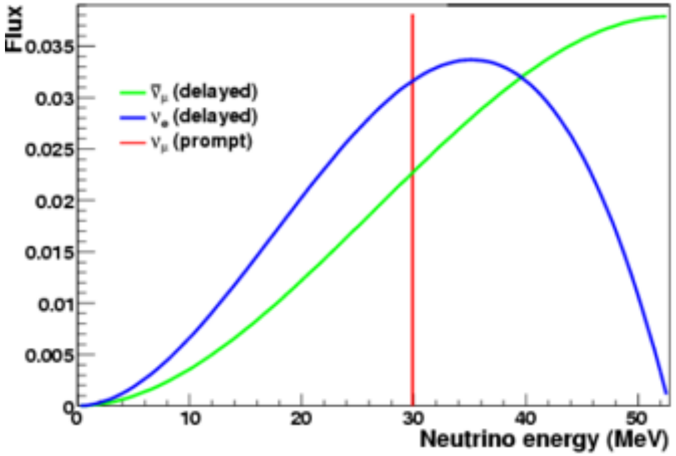
But there are also complex nuclear physics issues associated with these anomalies.

LSND

LSND used neutrinos from stopped pions to search for neutrino oscillations.

For two-state mixing:

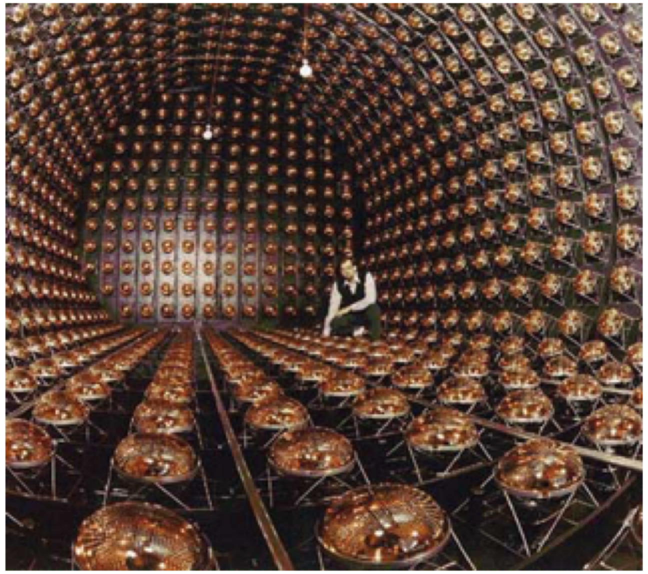
$$P = \sin^2 2\theta \ \sin^2(1.27\Delta m^2(L/E))$$



=> The detector was 30 m from the source and $\langle E_\nu \rangle \sim$ 30 MeV.

800 MeV proton beam at LANSCE produces π^- (mostly get stopped) and π^+ that produce neutrinos

$$\pi^+ \rightarrow \nu_\mu \mu^+$$
$$\mu^+ \rightarrow \bar{\nu}_\mu \nu_e e^+$$

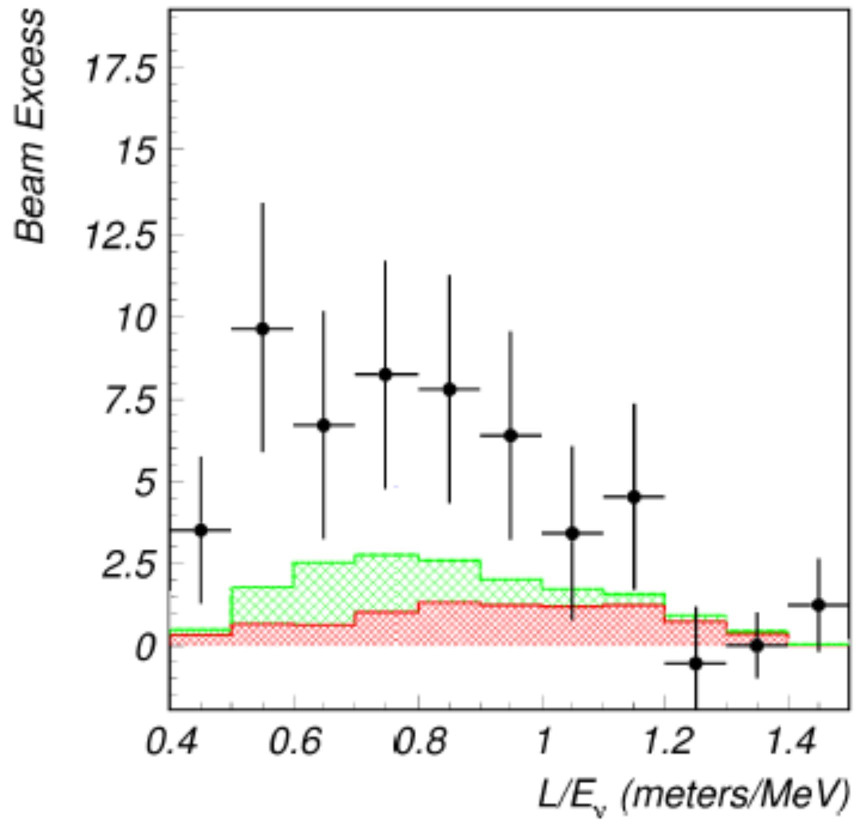


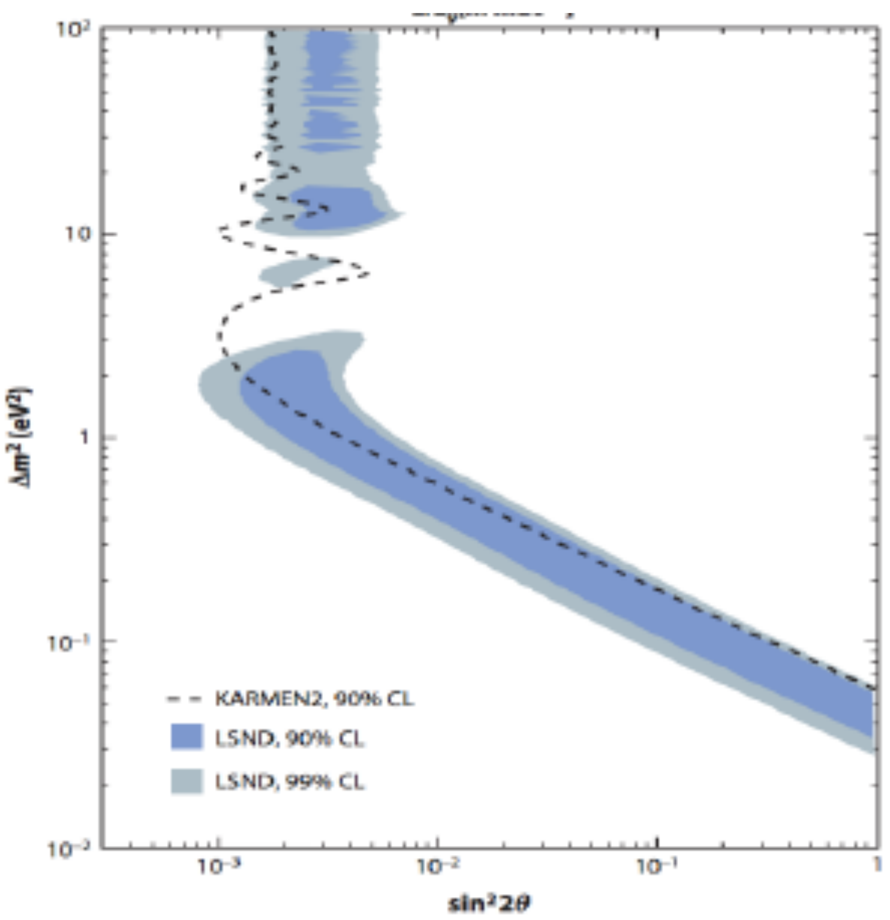
Searched for: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

via Inverse Beta Decay
$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$n + p \rightarrow D + \gamma(2.2\ MeV)$$

Athanassopoulos et al., PRL. 75, 2650 (1995);PRL. 77, 3082 (1996) ; PRL 81, 1774 (1998)

LSND Observed a 3.8σ excess





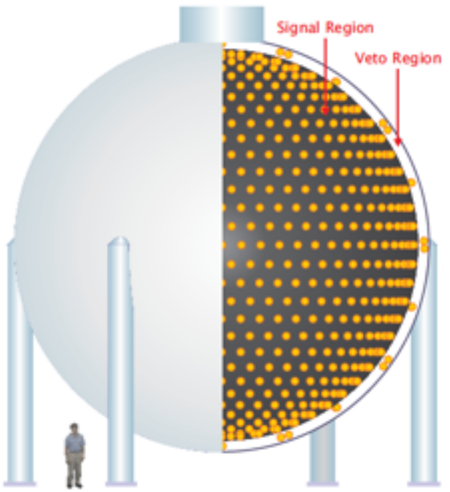
En-Chuan Huang, Neutrino 2018
Ann. Rev. Nucl. Part. Sci, 63, (1) 45

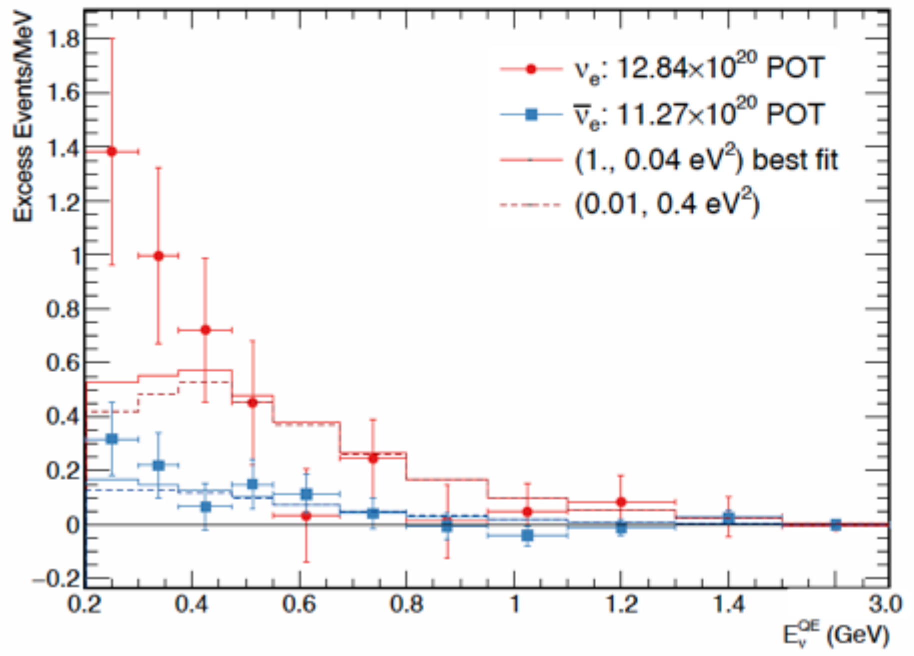
MiniBooNE

Uses the Booster Neutrino Beam at Fermilab
Designed to test LSND , same L/E, but with <E>~ GeV, L=541 m

$$P = \sin^2 2\theta \ \sin^2(1.27\Delta m^2(L/E))$$

Searched for: $\nu_\mu \to \nu_e \ (\mathrm{or}\ \bar{\nu}_\mu \to \bar{\nu}_e)$





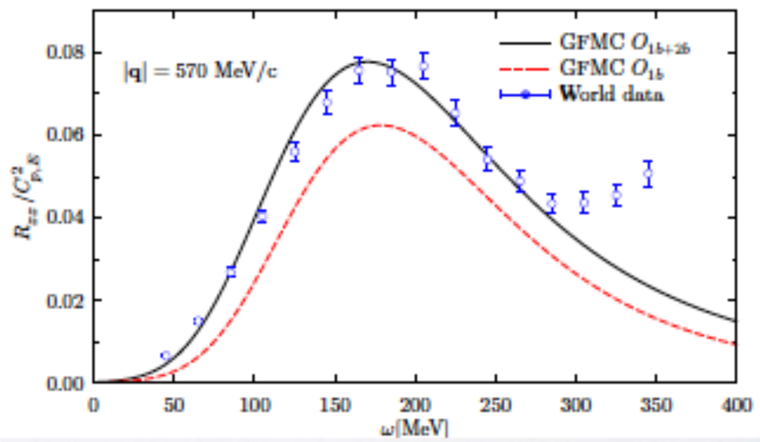
PRL, 98 (23): 231801

En-Chuan Huang, Neutrino 2018

Observed an excess in both ν and $\bar{\nu}$ channels

Conrad et al., Rev. Nucl. Part. Sci. 63, 45 (2013)

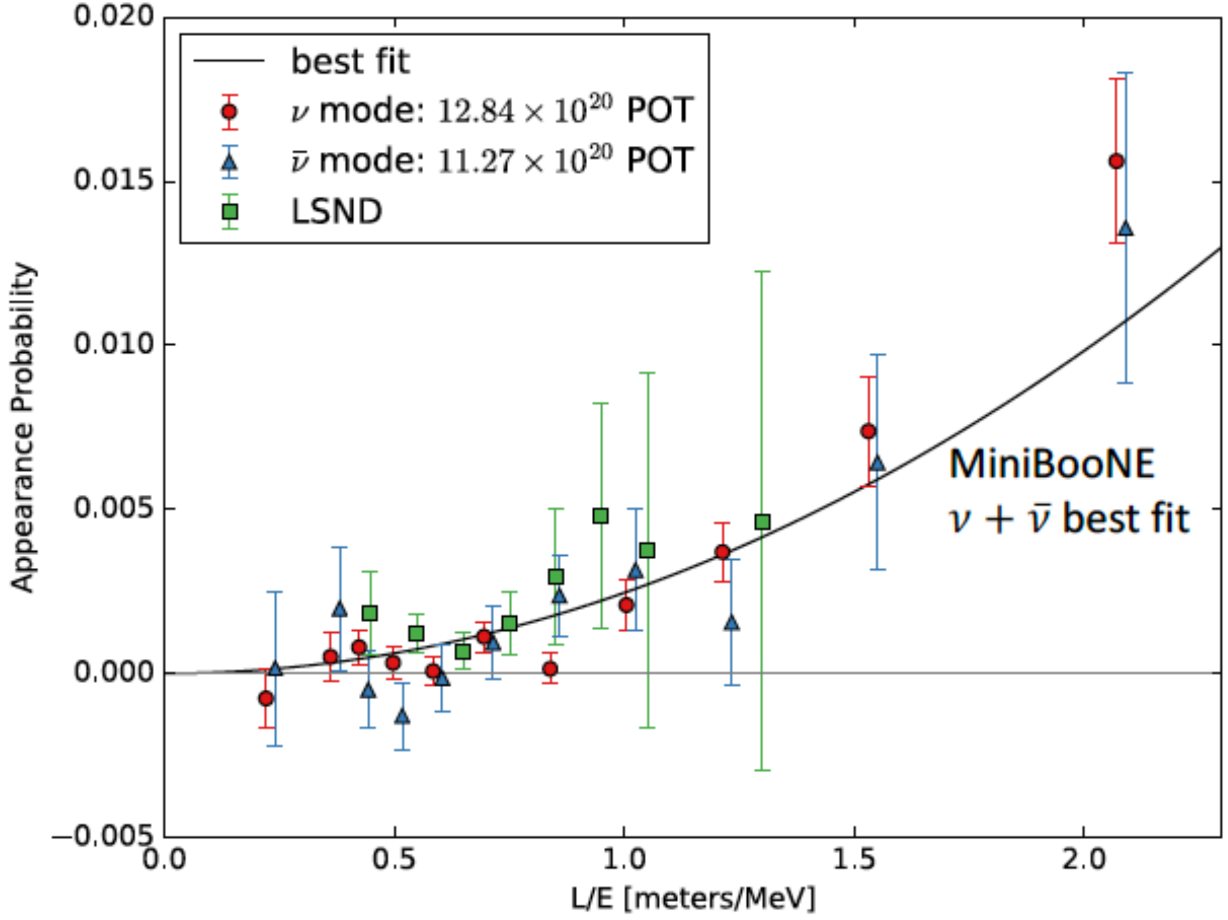
Kopp, JHEP05(2013)050; Gariazzo et al., JHEP, 06 (2017) 135



Lavato *et al.* find that 2-body currents enhance both the vector and axial contributions to the neutrino cross sections

arXiv:1509.00451
Phys. Rev. Lett. **112**, 182502

The two MiniBooNE signals ($\nu+\bar{\nu}$) and LSND are consistent with the same L/E appearance signature

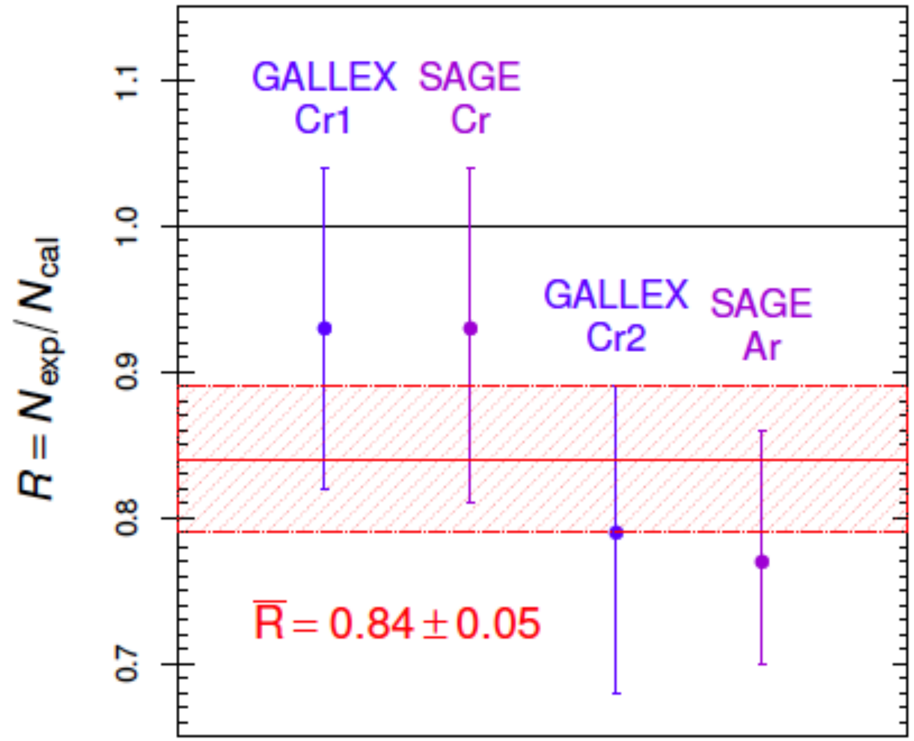


$$P = \sin^2 2\theta \ \sin^2(1.27\Delta m^2(L/E))$$

En-Chuan Huang, Neutrino 2018

The Gallium Anomaly

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



$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$ $\quad E \simeq 0.75\,\mathrm{MeV}$

$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$ $\quad E \simeq 0.81\,\mathrm{MeV}$

$\nu_e + {}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge} + e^-$

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

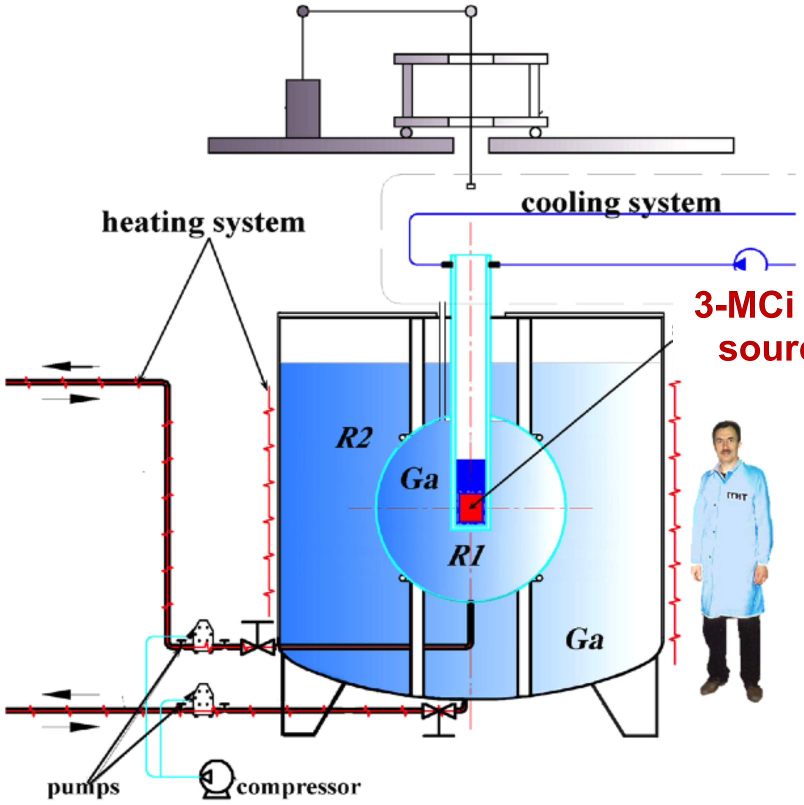
Bahcall + Haxton

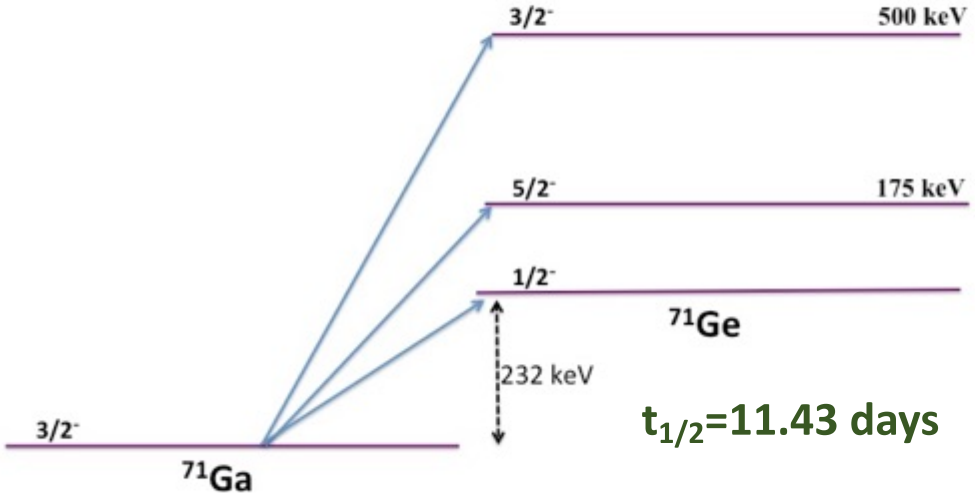
$\langle L \rangle_{GALLEX}$ = 1.9 m; $\langle L \rangle_{SAGE}$ = 0.6 m

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

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.

Gallium Anomaly – New experiments and Theory





$t_{1/2}$=11.43 days

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

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

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

^{71}Ge in each Ga zone analyzed separately

Subdominant corrections to the cross section need to be recalculated.

But find agreement with the previous estimates.

Excited state cross sections also being checked.

The Reactor Neutrino Anomaly

1 GW reactor emits 10^{21} antineutrinos/sec, allowing for precision oscillations experiments

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

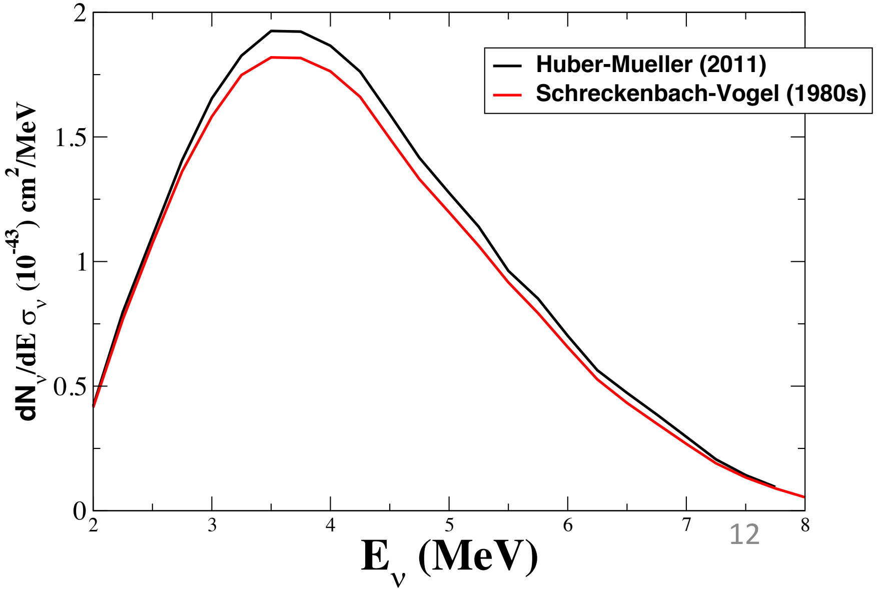
- Vogel *et al*. used the nuclear databases to predict the spectrum for ^{238}U

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%.

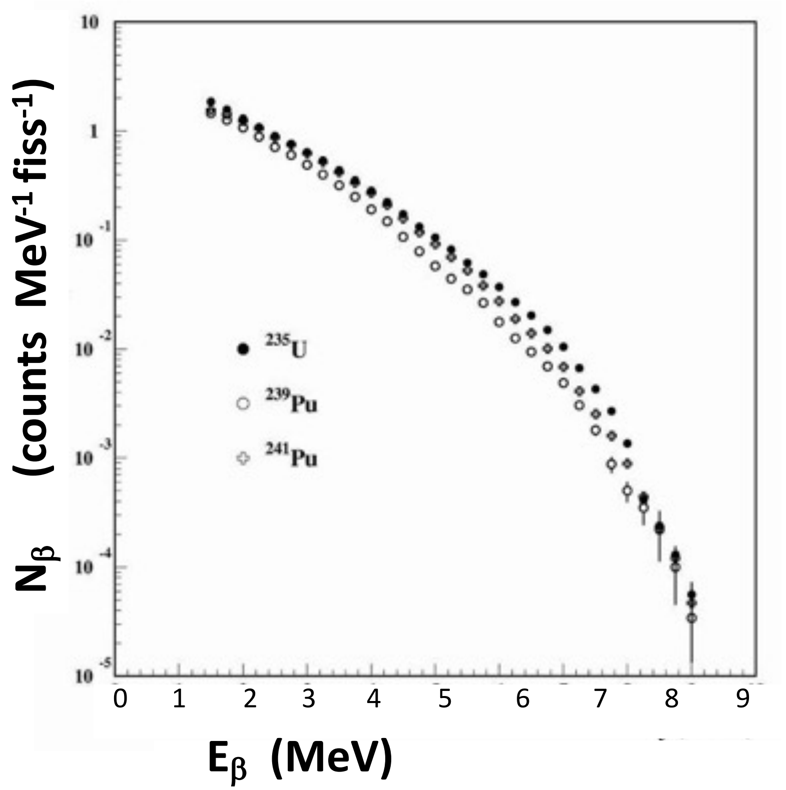
The change was largely as a consequence of:

- 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.



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

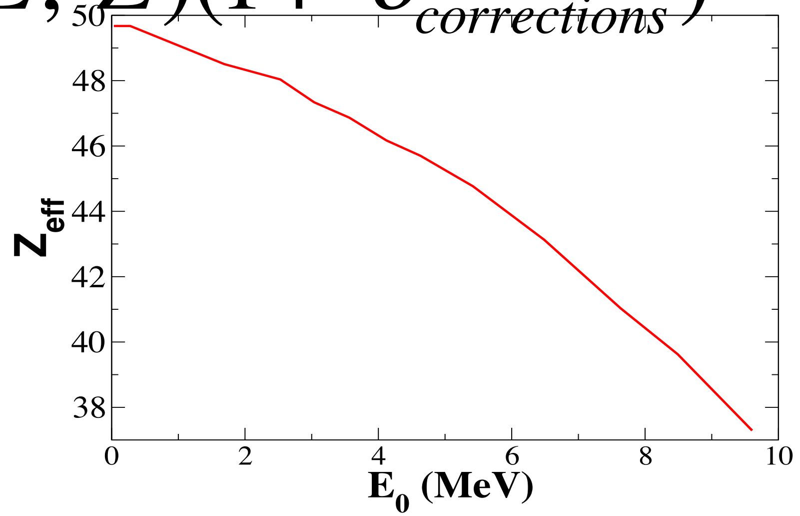
$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E,Z)(1+\ \delta_{corrections})$$

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

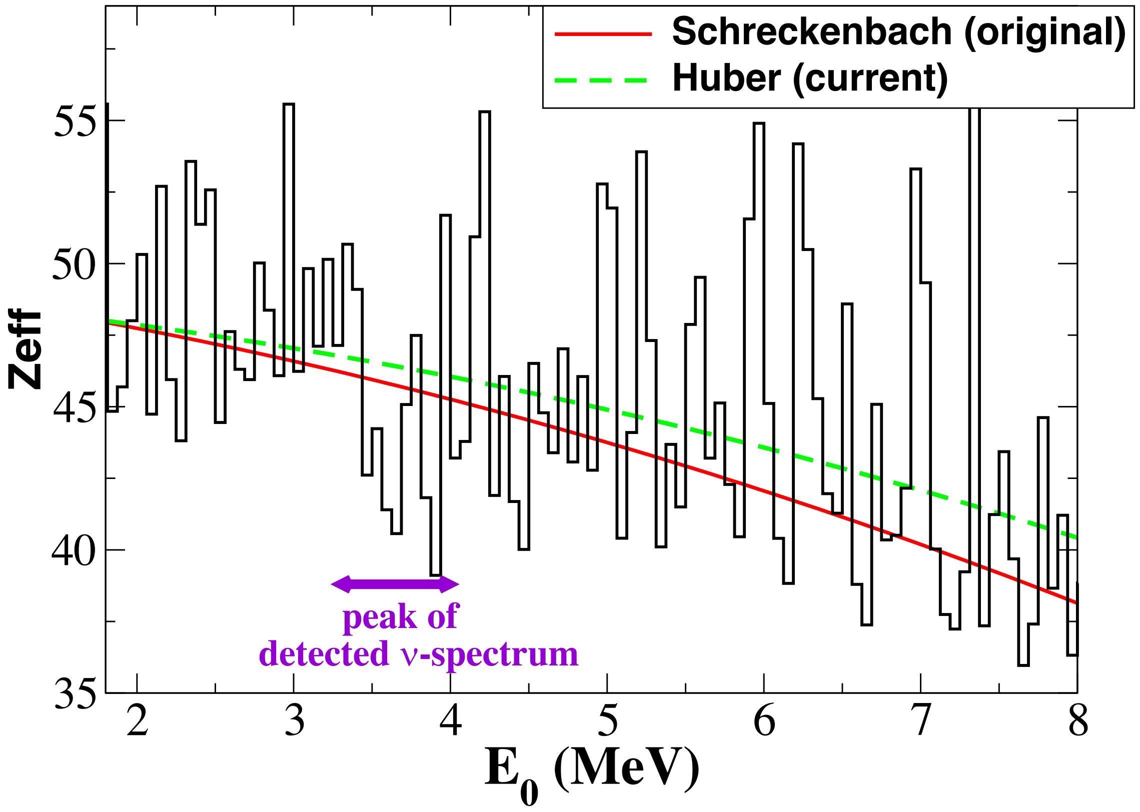
δ_{WM} = Weak magnetism

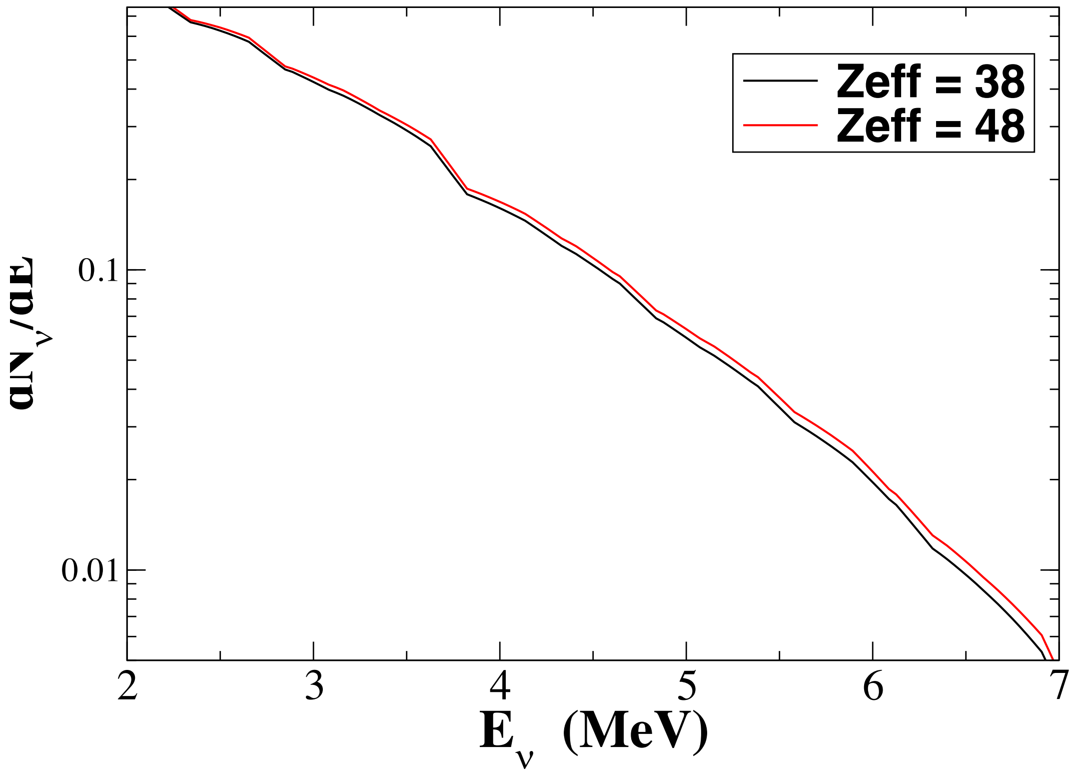
δ_{R} = Recoil correction

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.

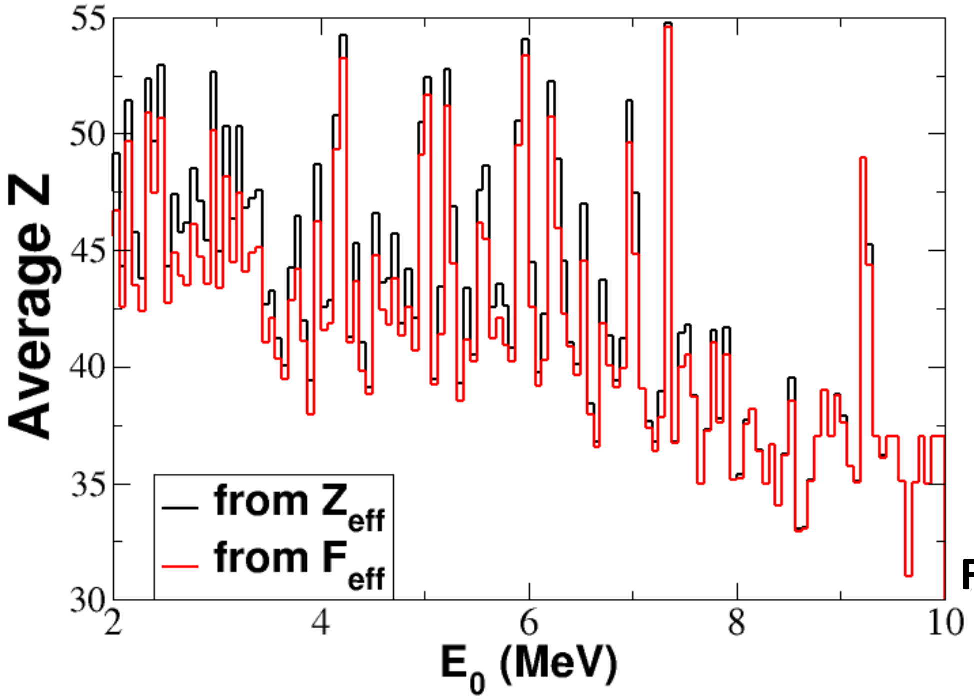
Examined different ways of estimating Z-average(E_0)

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

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

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

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.

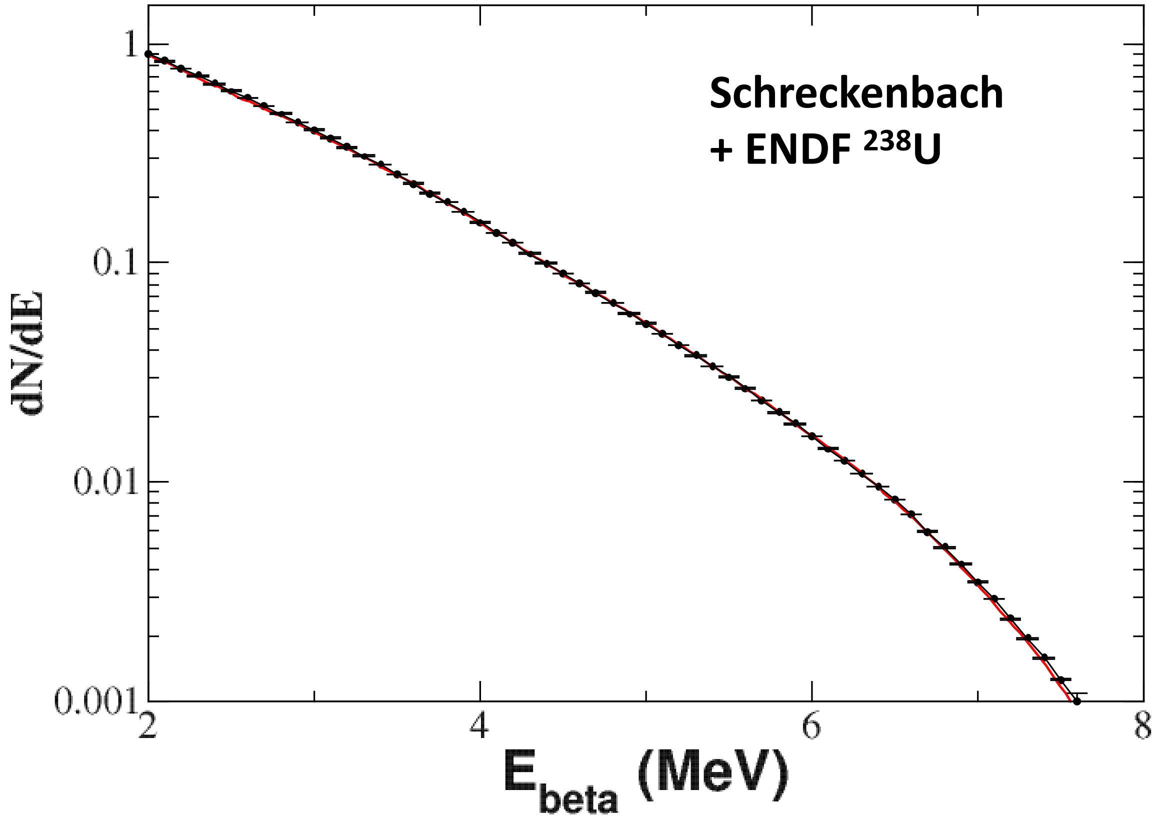


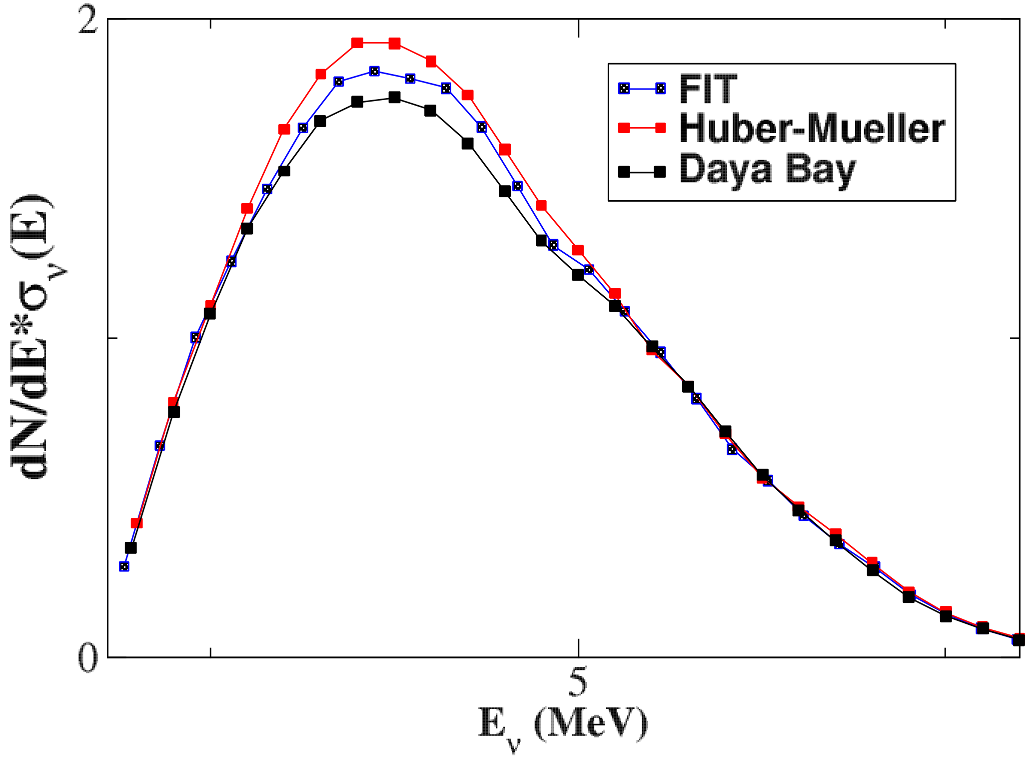
Z-average for the linear combination of
235U : 0.561
238U : 0.076
239Pu : 0.307
241Pu : 0.050
reported by Daya Bay

Fermi-function averaging gives a lower Z

Improved treatments of the conversion method, with simultaneous fit of β and ν data, reduce the anomaly to 2.5%

Simultaneous fit to Daya Bay's and same combination of β-spectra





- **More accurate description of Zeff and the inclusion of forbidden decays gives closer fit to Daya Bay.**
- **But generally, predictions too high around E_ν ~3-4, but within 1σ of experiment (2.5% anomaly).**

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

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

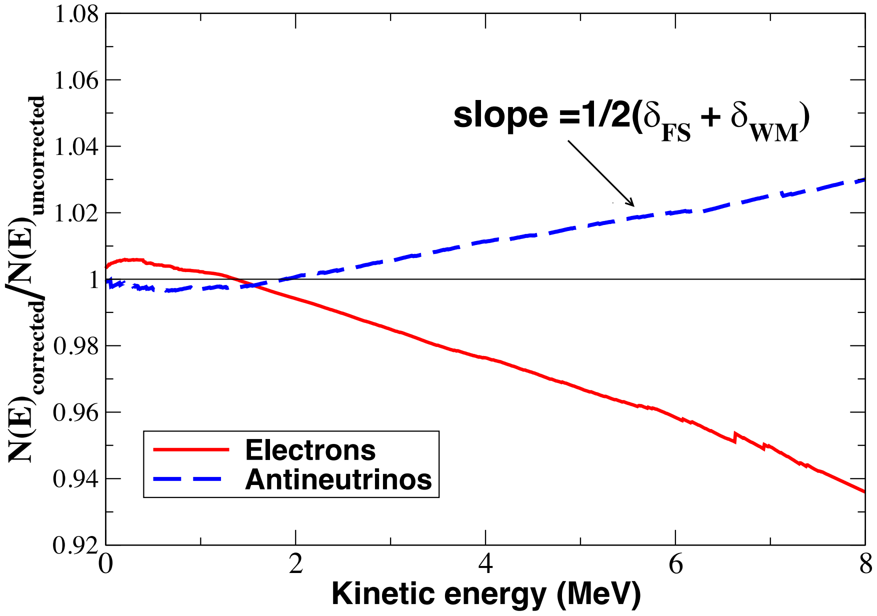
δ_{FS} = Finite size correction to Fermi function
δ_{WM} = Weak magnetism

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:

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

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



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

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

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

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

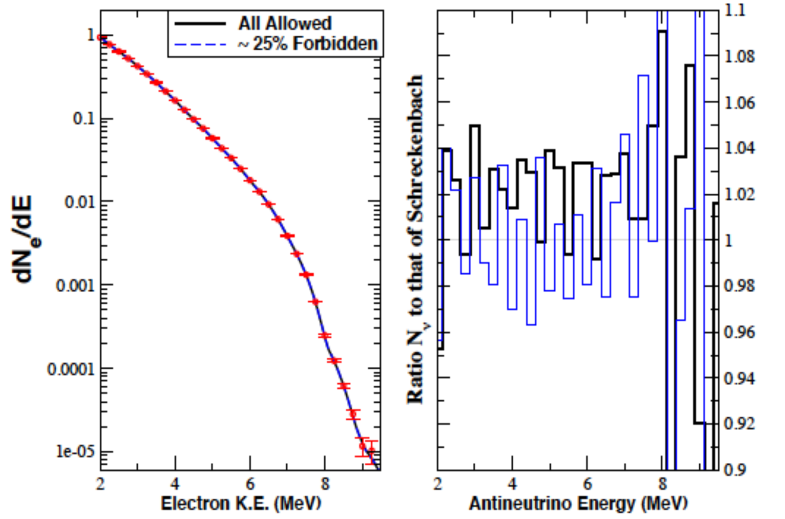
Forbidden transitions introduce a shape factor C(E) and corrections are different and sometimes unknown:

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

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	

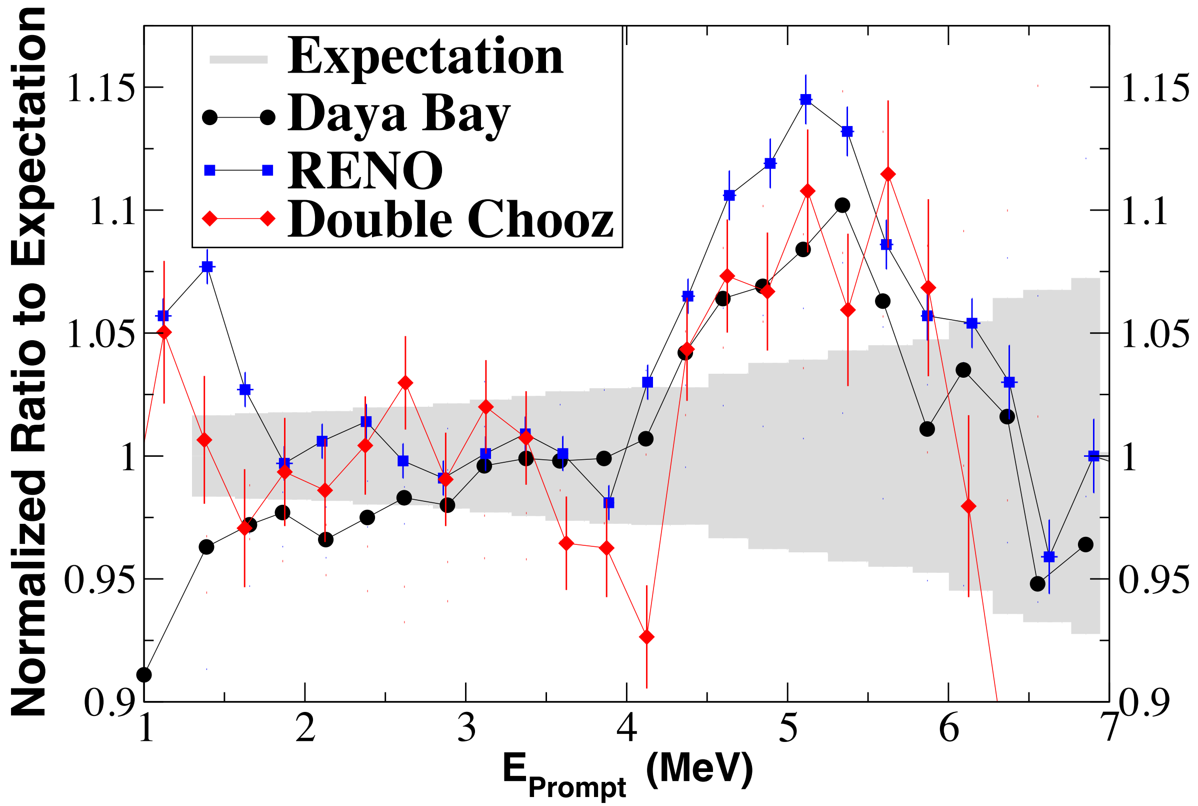
The forbidden transitions increase the uncertainty in the expected spectrum

Two equally good fits to Schreckenbach's β-spectrum, lead to ν-spectra that differ by 4%



The BUMP

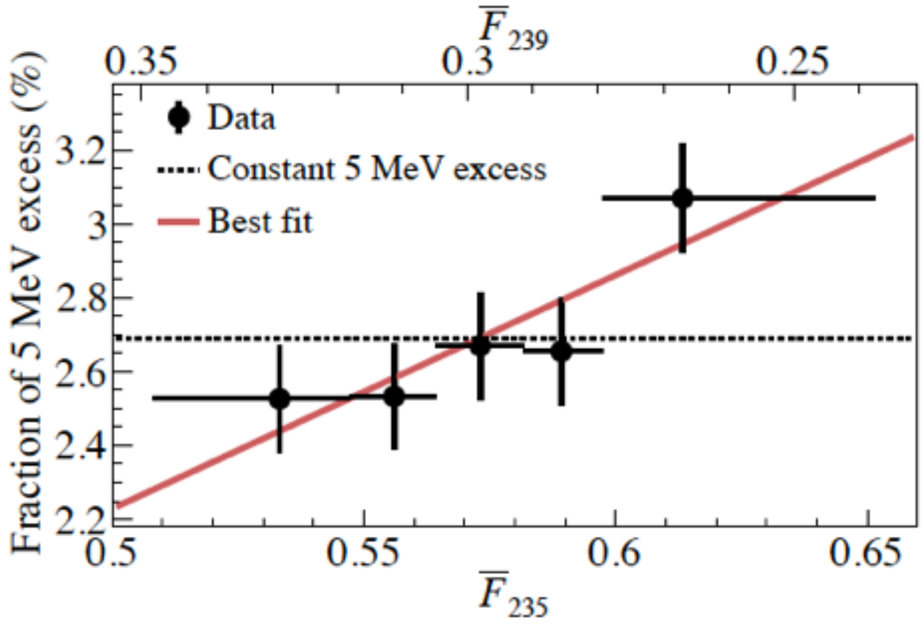
The Reactor Neutrino 'BUMP'

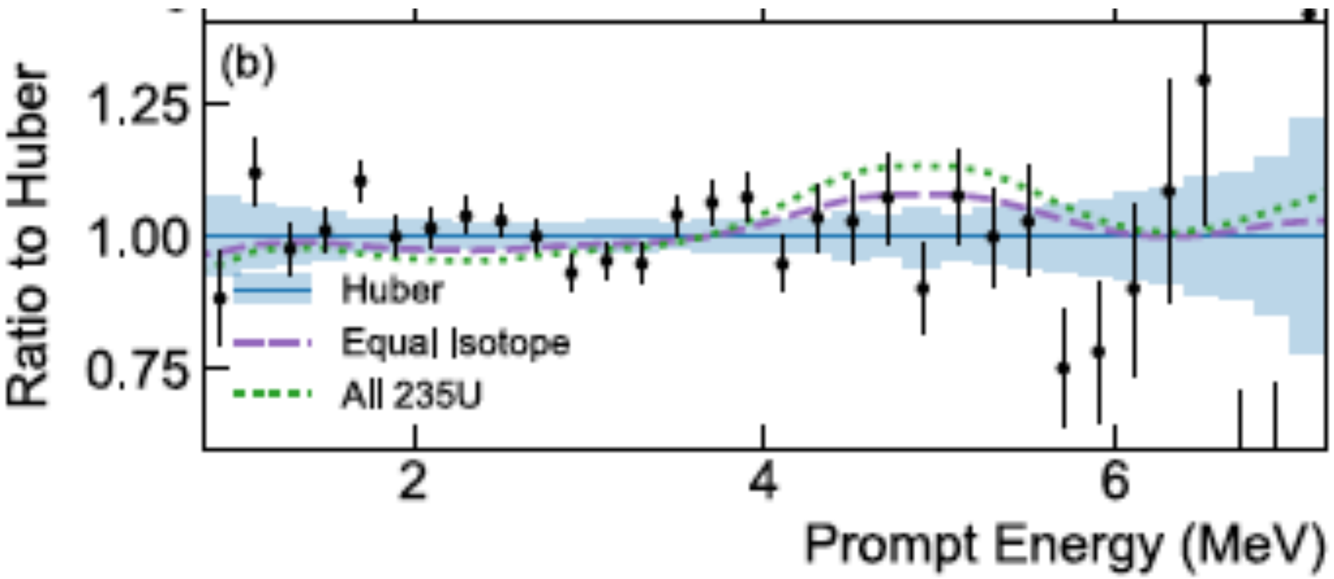


All recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations.

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

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.

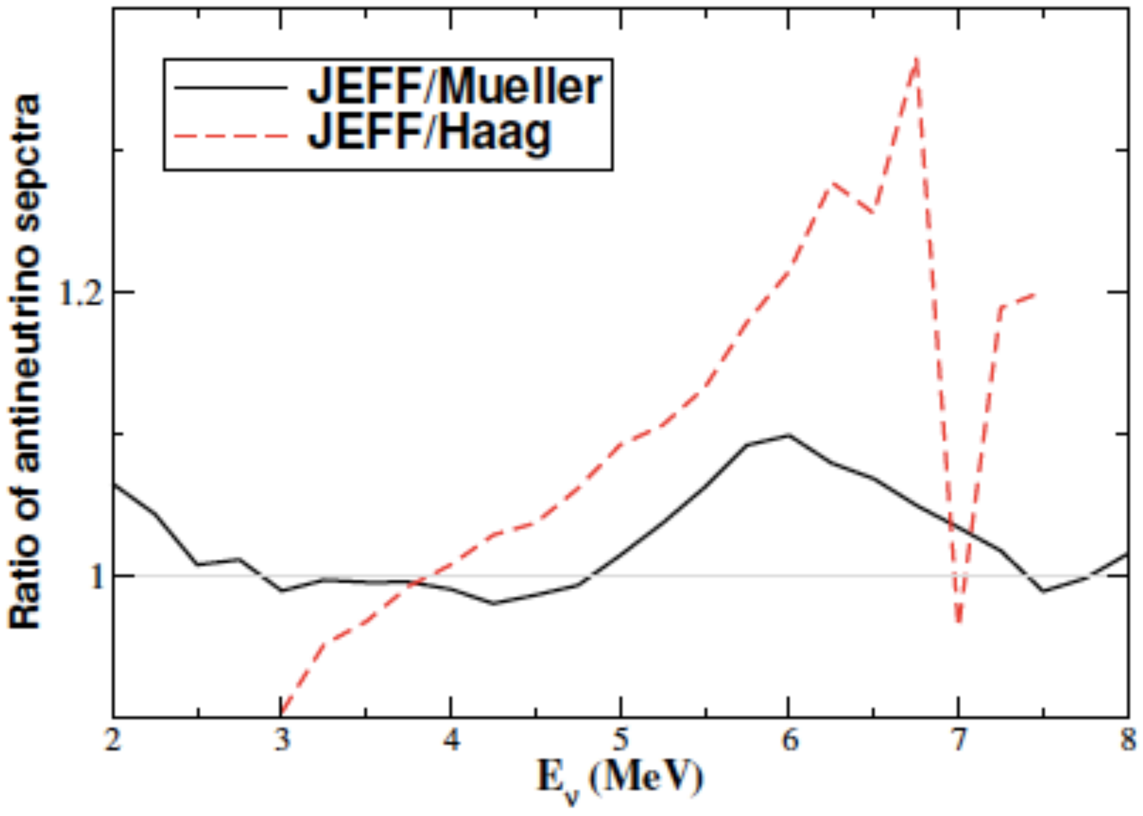
- Not clear whether this is consistent with spectrum simply getting softer?

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



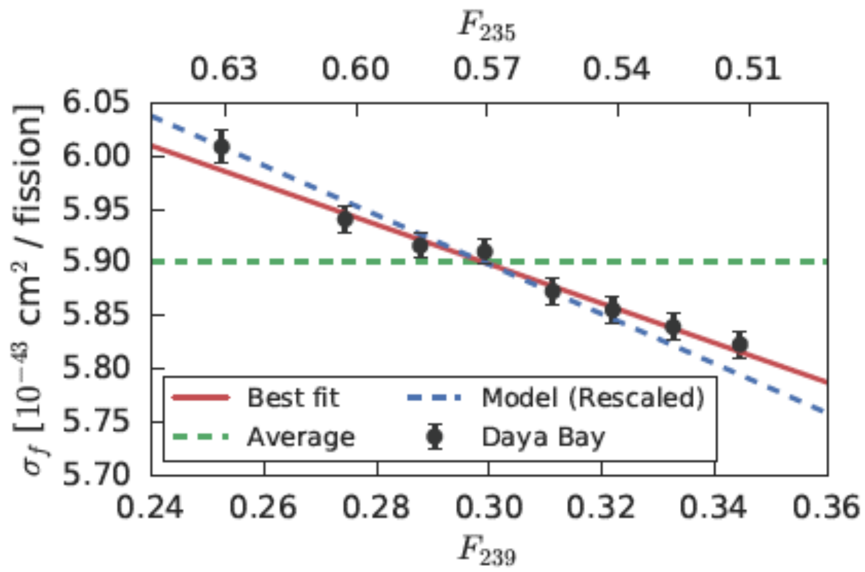
Relative to the JEFF database, both Mueller and Haag show a BUMP.

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

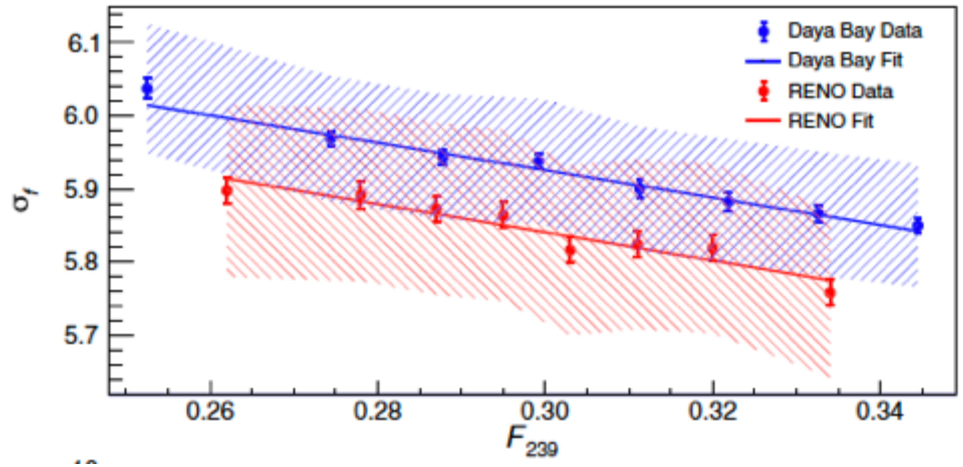
Reactor Fuel Burnup Data shed light on the anomaly

As 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)

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

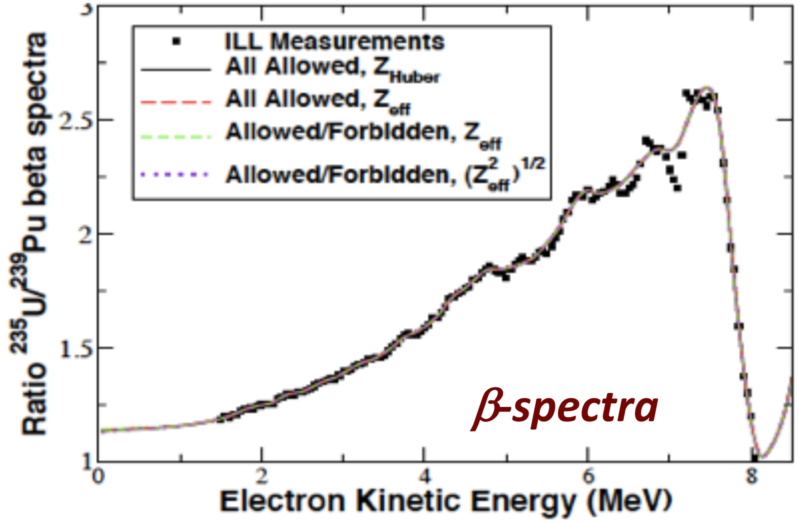
$d\sigma_f/dF_{239} = (-1.86 \pm 0.18) \times 10^{-43}$ cm^2/fission — Daya Bay Experiment

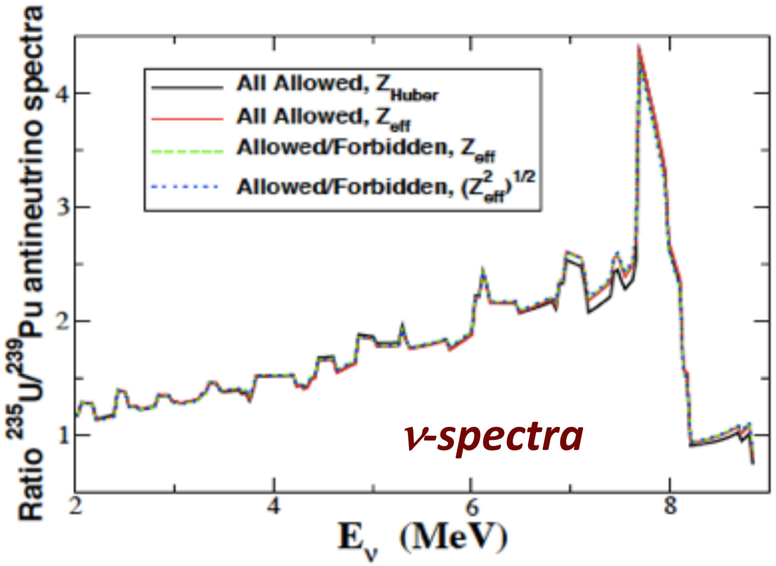
$(-1.93 \pm 0.29) \times 10^{-43}$ cm^2/fission — RENO Experiment

$(-2.46 \pm 0.06) \times 10^{-43}$ 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 $^{235}U/^{239}Pu$ ratio is fixed:

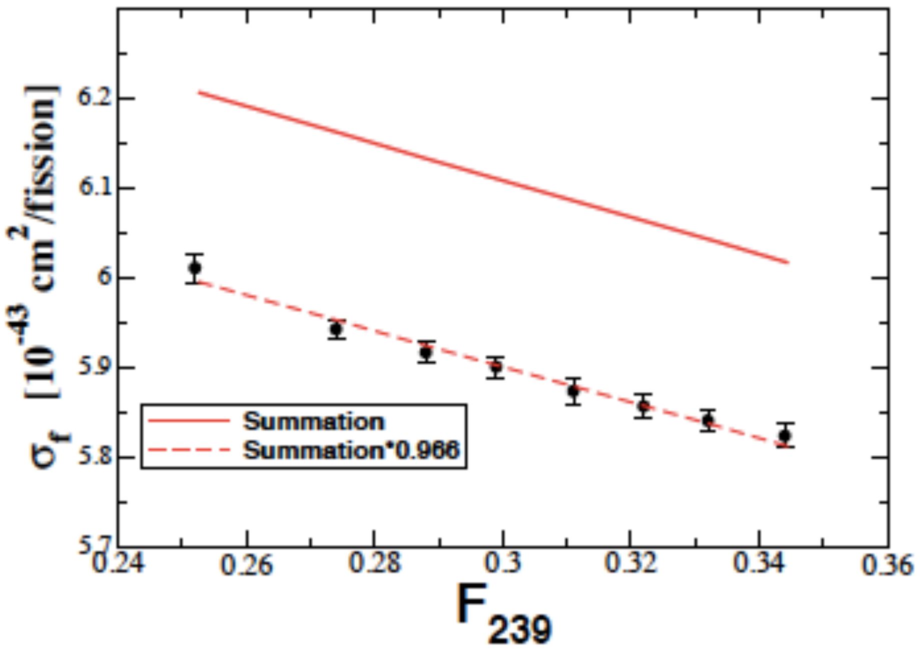
$\sigma5/\sigma9$ = 1.53 +/- 0.05 (Schreckenbach)

$\sigma5/\sigma9$ = 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 JEFF Nuclear database explains all of the Daya Bay fuel evolution data, but still results in a small 3.5% anomaly.



- The IBD yield is predicted to change with the correct slope.
- But the absolute predicted value is high by 3.5%.
- This is not statistically significant from a BSM physics point of view, but suggests a possible problem with the database.

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.