The Neutrino Anomalies

XII Rencontres du Vietnam

High Sensitivity Experiments Beyond the Standard Model

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Outline

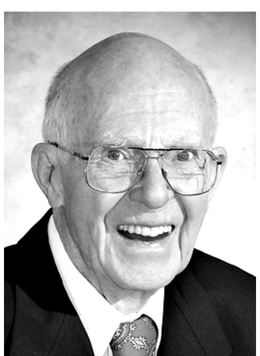
- The 3ν oscillation framework
- The current 4 anomalies that don't fit this framework
    - LSND
    - MiniBoone
    - The Gallium Anomaly
    - **The Reactor Neutrino Anomaly**
- Summary

The majority of experimental results on neutrino oscillations converge towards a consistent 3ν oscillation framework

The flavor states $\nu_\alpha=(\nu_e, \nu_\mu, \nu_\tau)$ mix with the massive states $\nu_\iota=(\nu_1, \nu_2, \nu_3)$ via

- three mixing angles (θ_{12}, θ_{13}, θ_{23})
- a CP-violating phase δ
- $\delta m^2=m_2^2 - m_1^2 > 0$
- $\Delta m^2 = m_3^2 -(m_1^2 + m_2^2)/2 \quad > 0$ (NH), < 0 (IH)

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



$\delta m^2/10^{-5}$ eV^2	7.54	7.32 - 7.80
$\Delta m^2/10^{-3}$ 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 Base-Line Reactor Neutrino Anomaly

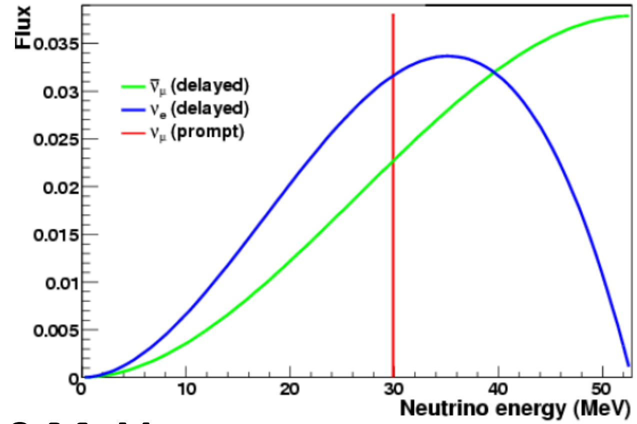
These anomalies possibly suggest a fourth sterile neutrino, requiring a mass on the 1 eV scale.

They refer to ν_e,ν_μ appearance/disappearance experiments

They also involve complex nuclear physics issues.

LSND

LSND used neutrinos from stopped pions to search for neutrino oscillations with $\Delta m^2 \sim 1 eV^2$.



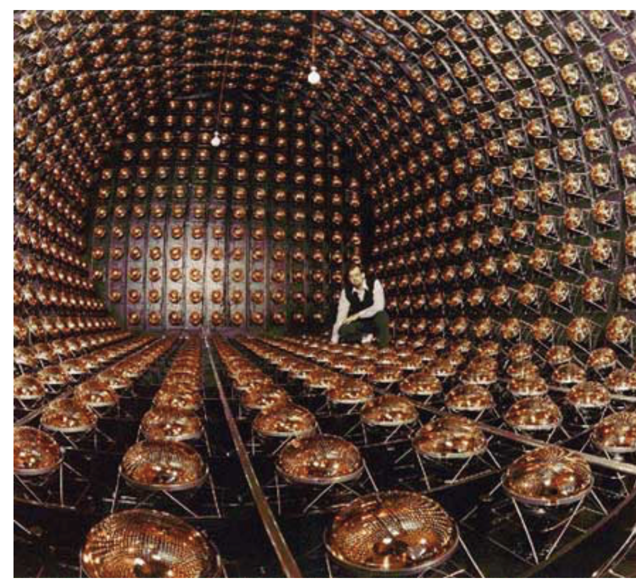
For two-state mixing:

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

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

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

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



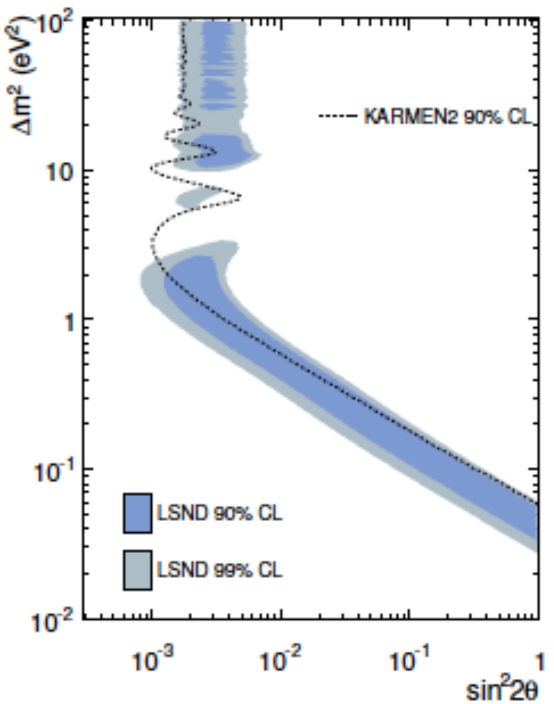
Searched for $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

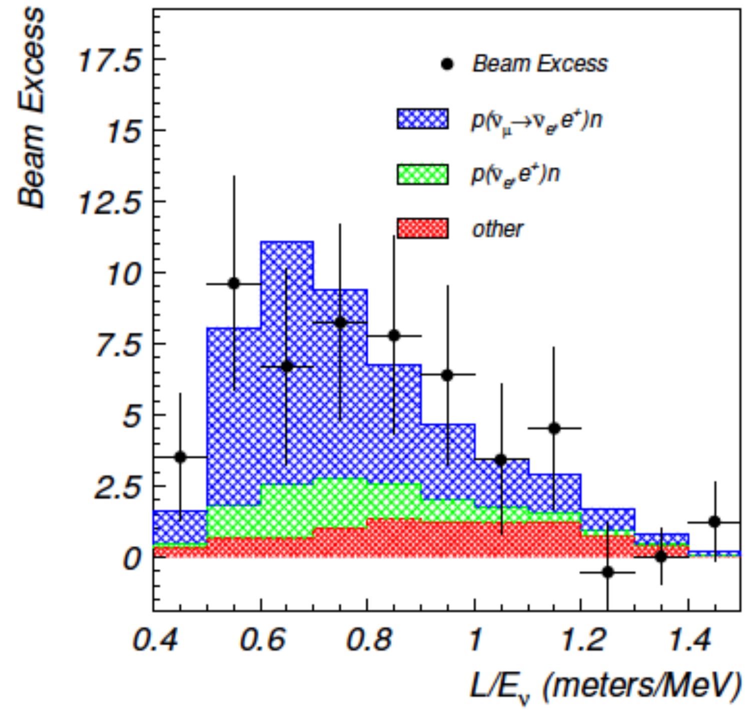
via IBD

$$\bar{\nu}_e + p \rightarrow n + e^+$$
$$n + p \rightarrow D + \gamma\,(2.2\ MeV)$$

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

LSND

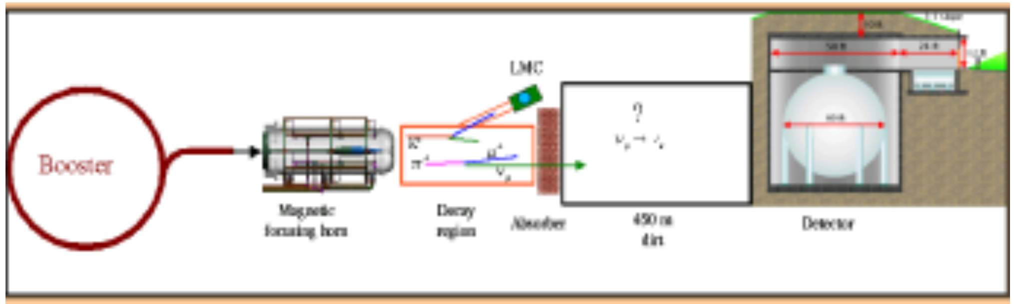




- **LSND (at 30 m) observed an excess of 87.9+/-22.4+/-6.0 events**
- **KARMEN at 17.7 m from the Rutherford ISIS DAR neutrino source observed no oscillations.**
- **KARMEN is sometimes analyzed as a near detector equivalent for LSND**

Review: J. Conrad, W. Louis, M. Shaevitz, Annu. Rev. Nucl. Part. Sci. 63, 45 (2013)

MiniBooNE

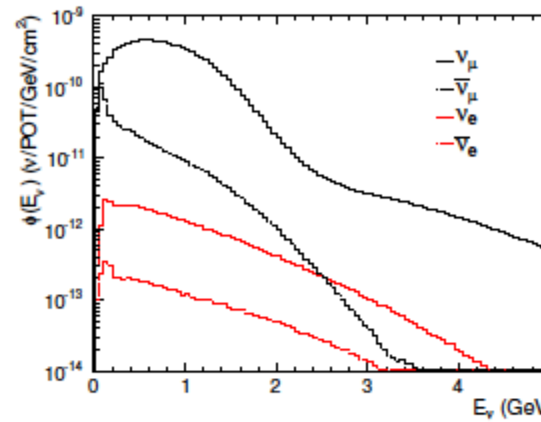


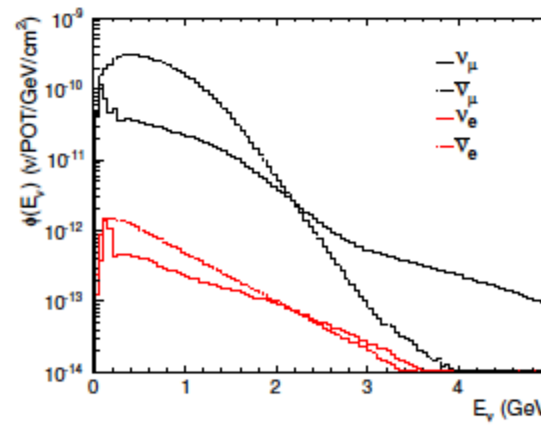
Used the Booster Neutrino Beam at Fermilab

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

Designed to test LSND , same L/E, but with
<E>~ GeV, L=541 m
8 GeV protons on Be target+> neutrinos from:

- **π^+ decay**
- **$K^{+/-}$ decay**
- **K^0 decay**



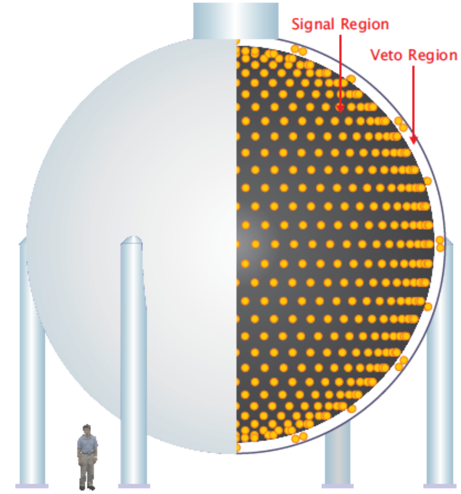


Searched for: $\nu_\mu \rightarrow \nu_e$ (or $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)

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

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

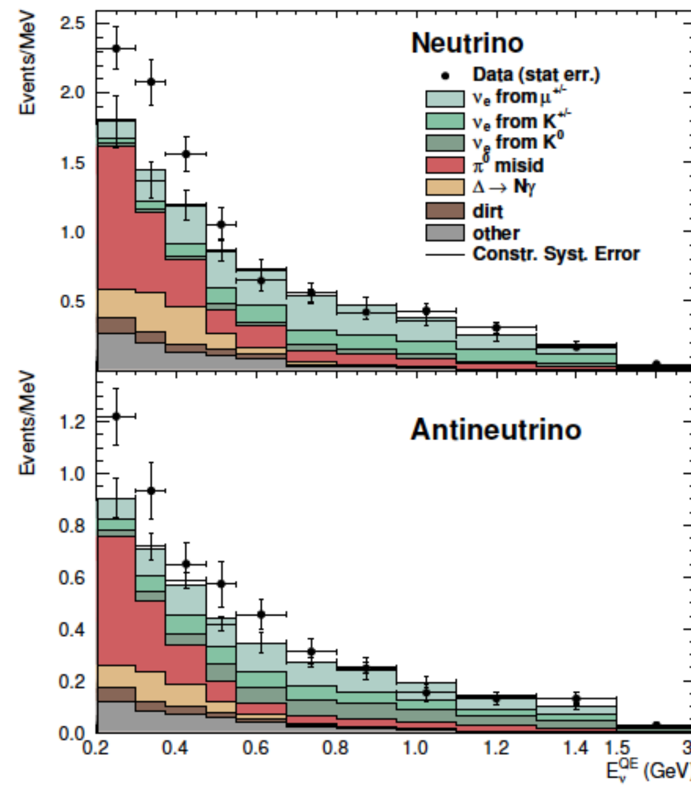
MiniBooNE



Observed an excess of 240+/-63 for 1430 events
Observed no excess above 500 MeV for neutrinos

The magnitude of the neutrino excess is similar to that expected from LSND, but the shape is quite different.

The antineutrino excess is consistent with LSND.



To explain <u>both</u> LSND and MiniBooNe by oscillation requires 3 active & 2-3 sterile neutrinos ~ 1eV

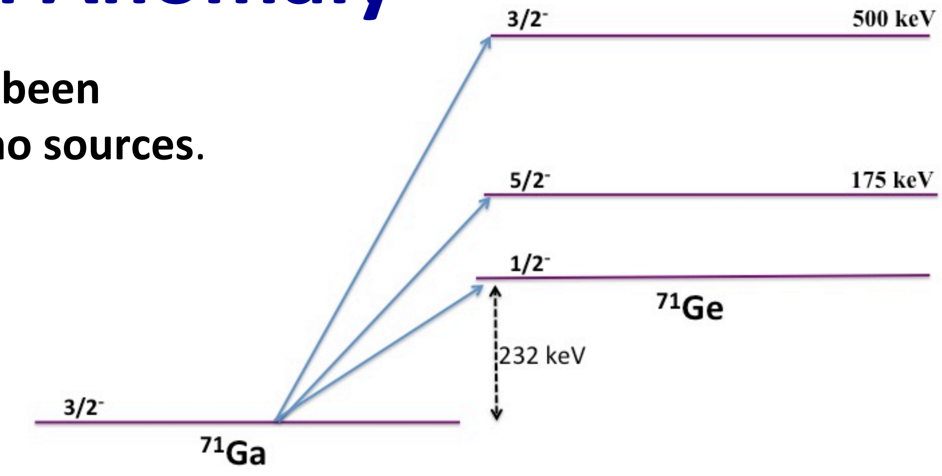
MiniBooNE, PRL, **98** (23): 231801

Kopp, JHEP05(2013)050; Gariazz0 et al., arXiv:1507.08204 (2015)

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

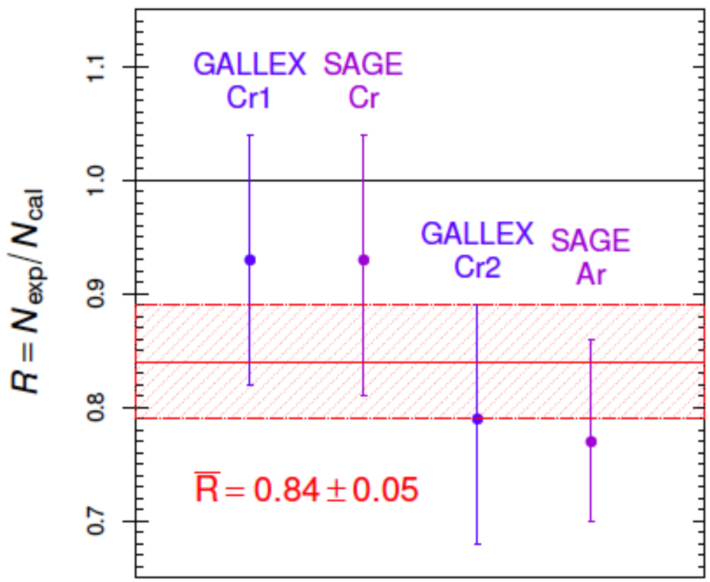
Gallium Anomaly

The Ga detectors for GALLEX and SAGE have been tested using ^{37}Ar and ^{51}Cr radioactive neutrino sources.



$$e^- + {}^{37}\mathrm{Ar} \to {}^{37}\mathrm{Cl} + \nu_e$$
$$e^- + {}^{51}\mathrm{Cr} \to {}^{51}\mathrm{V} + \nu_e$$

	^{51}Cr				^{37}Ar	
E [keV]	747	752	427	432	811	813
branching ratio	0.8163	0.0849	0.0895	0.0093	0.902	0.098



Abdurashitov et al. (SAGE) 2006 PRC73 045805
Anselmann et al. (GALLEX) 1995 PLB342 440
Hampel et al. (GALLEX) 1998 PLB420 114

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

The ground state cross is determined from the half-life of ^{71}Ge. **Bachall PRC55 3391 (1997).**

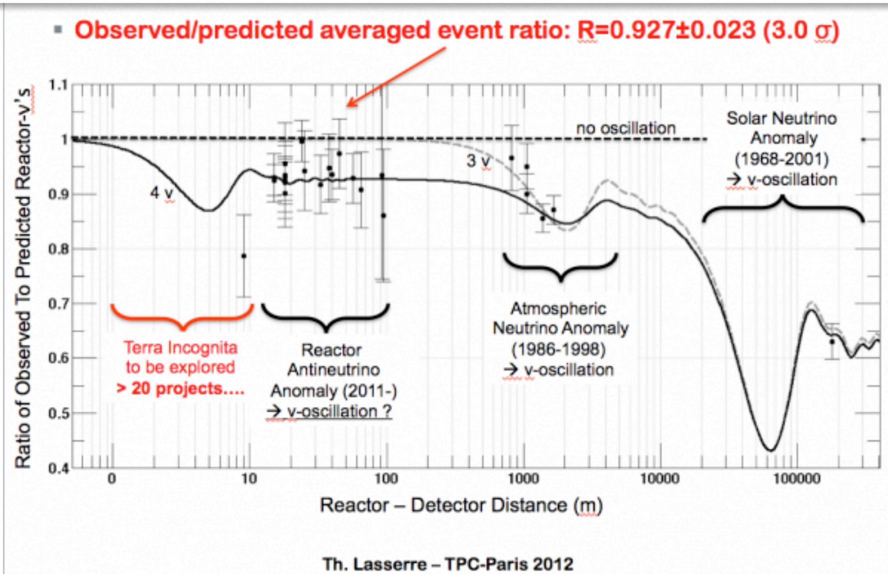
The excited state cross section have been estimated **by Haxton, *et al.* PLB B353, 422 (1995) and PLB 431, 110 (1998).**

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

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

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

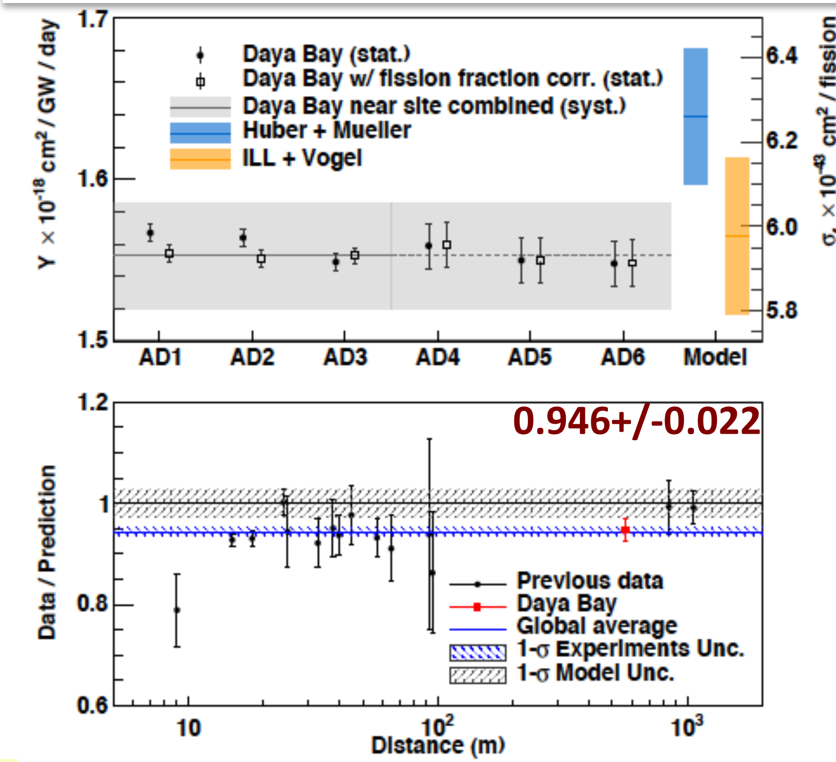
From Th. Lasserre, 2012



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

Most recent results from Daya Bay, 2016

PRL,116 (2016) 061801

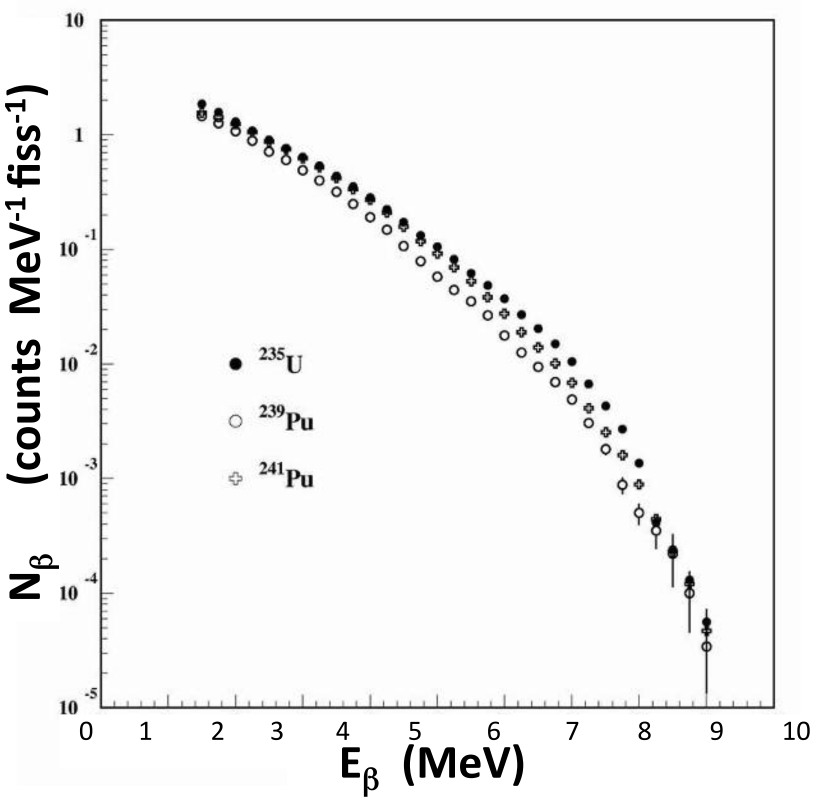


The very accurate measurement of the total flux at Daya Bay and RENO confirms the shortfall

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)

- **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

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

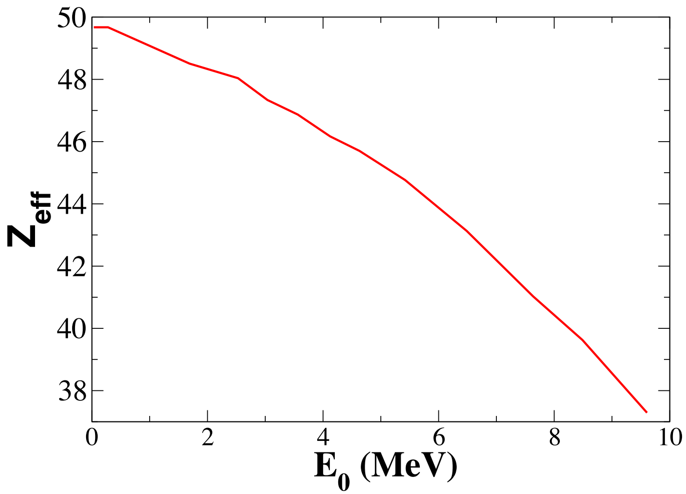
$$S^i(E,E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z)(1+ \delta_{corrections})$$

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

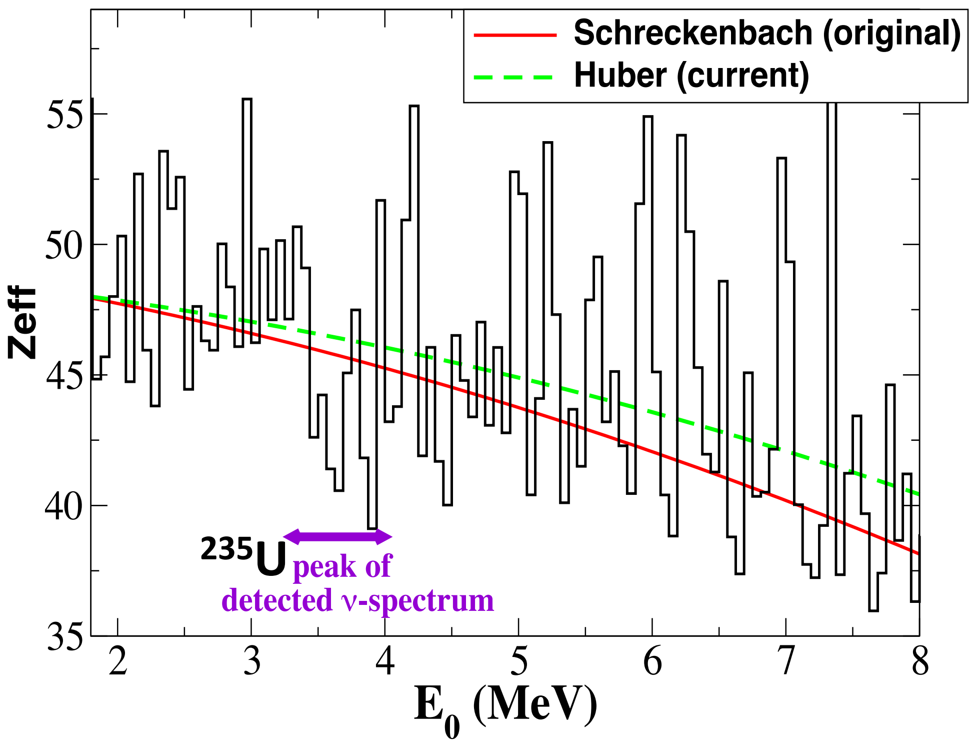
δ_{WM} = Weak magnetism

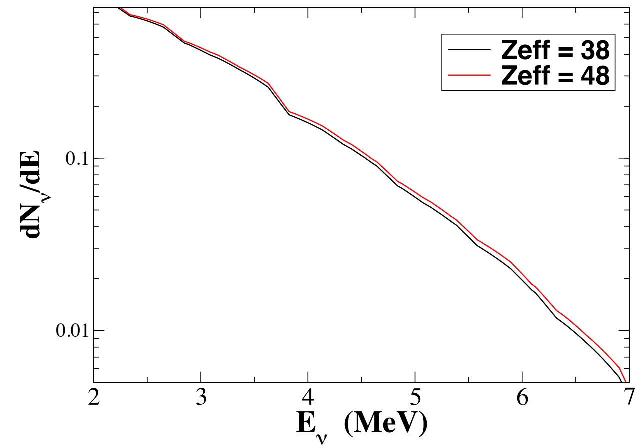
δ_R = Recoil correction

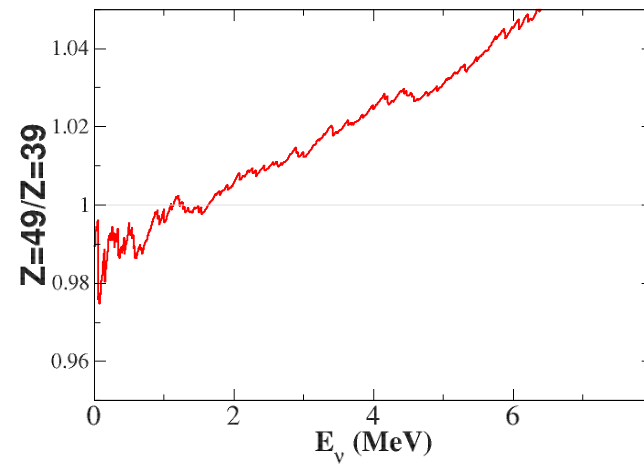
δ_{rad} = Radiative correction

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



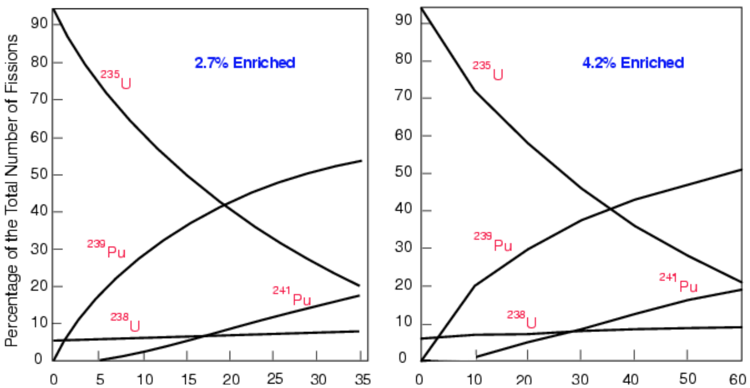




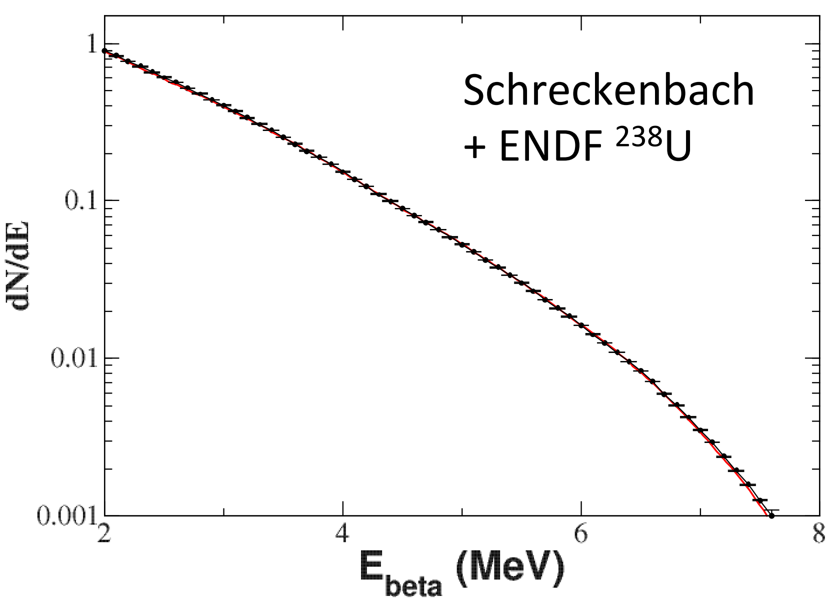
$$S^i(E, E_0^i) = E_\beta p_\beta (E_0^i - E_\beta)^2 F(E, Z_{eff}(E_0))(1 + \delta)$$

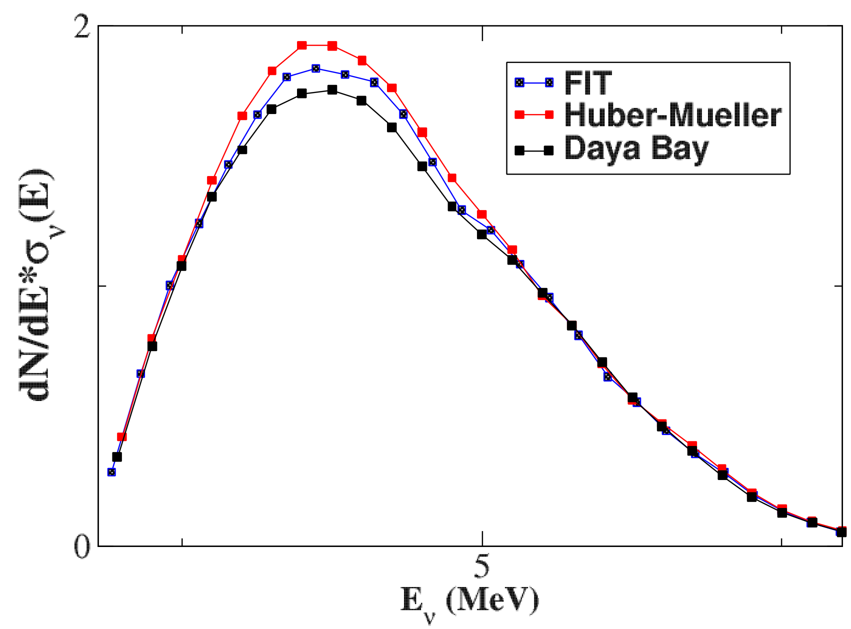
- **Huber's new parameterization of Zeff with end-point energy E_0 changes the Fermi function and accounts for 50% of the current anomaly.**
- **At the peak of the detected neutrino spectrum both fits (original & new) may be high.** $Z_{eff} = a + b\,E_0 + c\,E_0^2$ **form for the fits causes this.**

Simultaneous fit of the Daya Bay Neutrino Spectrum and the Equivalent Aggregate Beta spectrum with ENDF point-wise Z_{eff} Reduces the Anomaly from 5% to 2.5%



	235U	238U	239Pu	241Pu
Daya Bay	58.6	7.6	28.8	5
RENO	62.0	12.0	21	5
Double Chooz	49.6	8.7	35.1	6.6





Hayes, in preparation

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

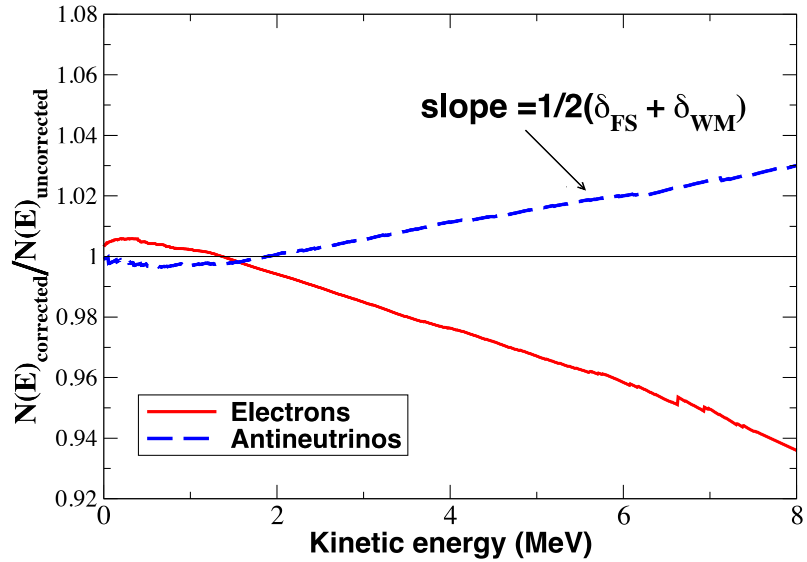
Originally approximated by a parameterization: $\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4MeV))$

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

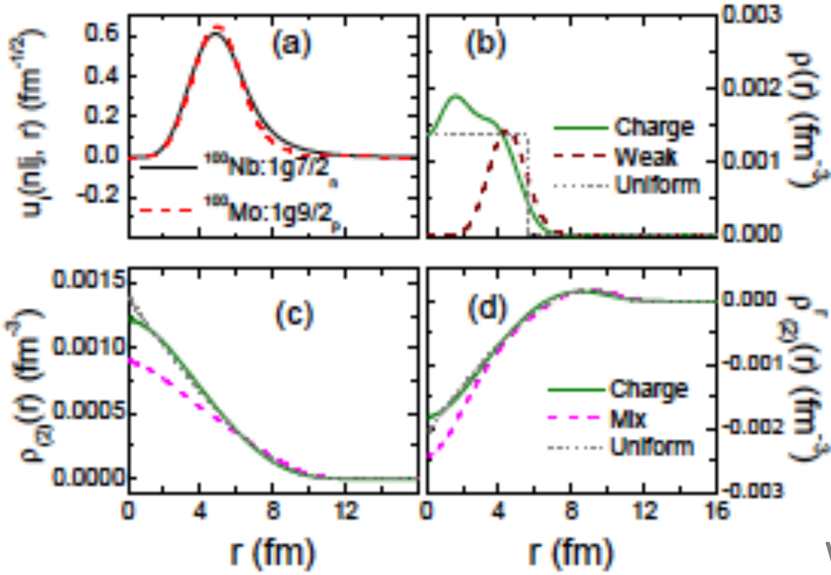
Uncertainties in the Corrections

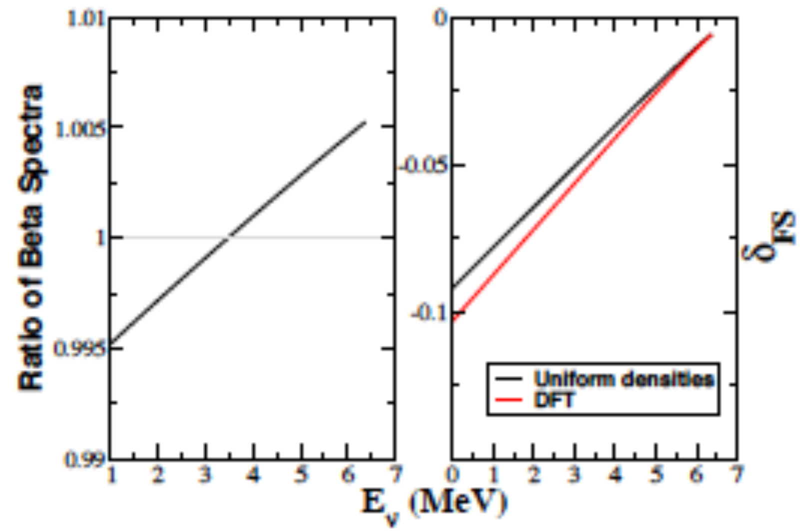
Nuclear FS only derived for allowed transitions:

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

Found to have small uncertainty for allowed transitions.

Unknown uncertainty for forbidden transitions.





Wang, Friar, Hayes, arXiv:1607.02149

Weak Magnetism has a uncertainty arising from 2-body currents

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

2-body meson-exchange corrections omitted.

=>Uncertainty ~ 25%

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

Allowed transitions $\Delta L=0$; Forbidden transitions $\Delta L\neq 0$

Forbidden transitions introduce a shape factor C(E):

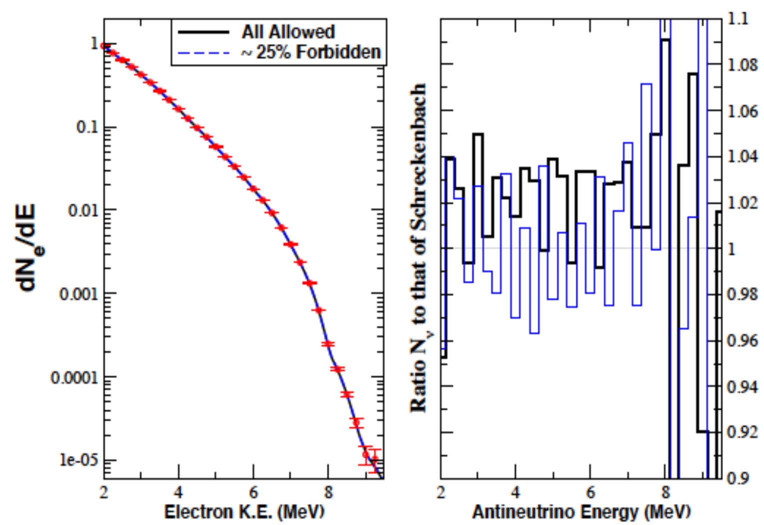
$$S(E_e,Z,A)=\frac{G_F^2}{2\pi^3}p_eE_e(E_0-E_e)^2\underline{C(E)}F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

The corrections for forbidden transitions are different and sometimes unknown :

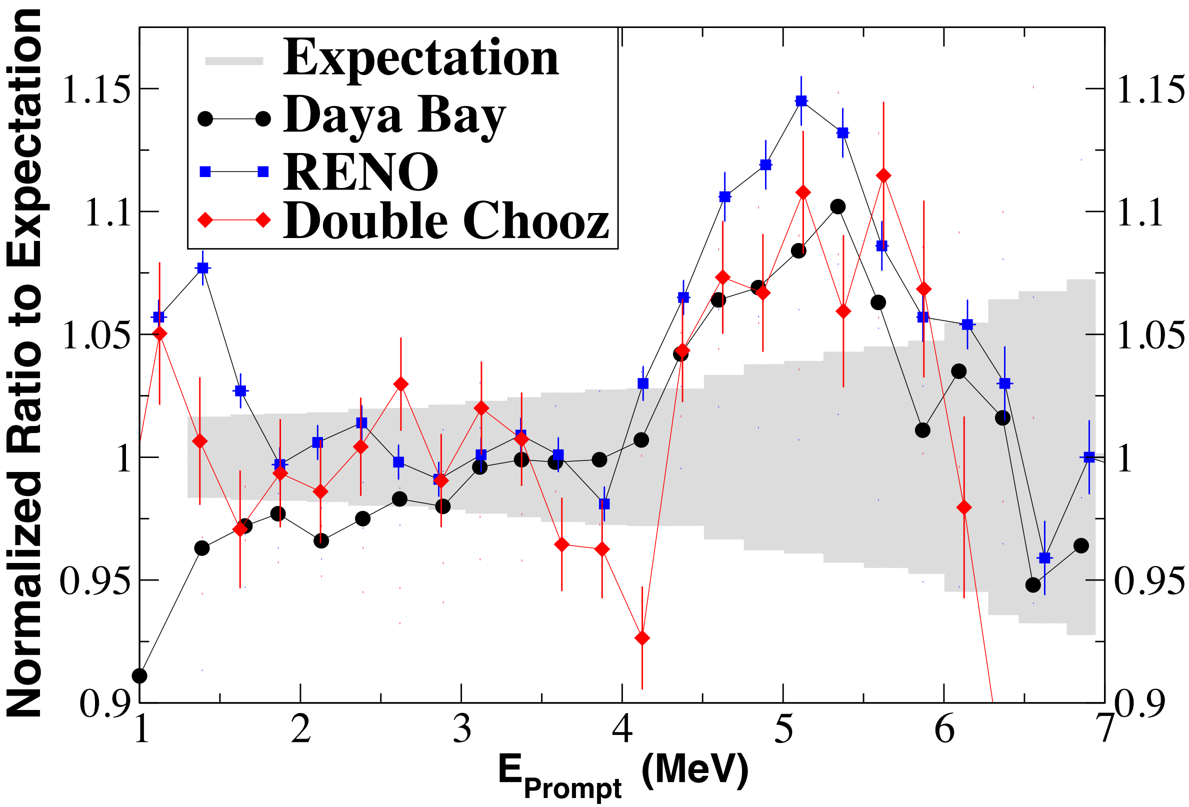
Classification	ΔJ^π	Operator	Shape Factor $C(E)$	Fractional Weak Magnetism Correction $\delta_{WM}(E)$
Allowed GT	1^+	$\Sigma\equiv\sigma\tau$	1	$\frac{2}{3}\left[\frac{\mu_v-1/2}{M_N g_A}\right](E_e\beta^2-E_\nu)$
Non-unique 1^{st} Forbidden GT	0^-	$[\Sigma,r]^{0-}$	$p_e^2+E_\nu^2+2\beta^2E_\nu E_e$	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	
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 further increase the uncertainty in the expected spectrum

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



The Reactor Neutrino 'BUMP'



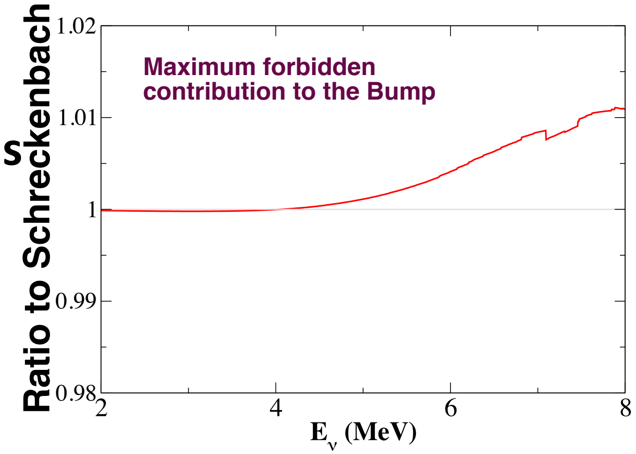
All three recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations.

- **The current expectations are Huber (^{235}U,$^{239,241}Pu$) and Mueller (^{238}U)**
- **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).

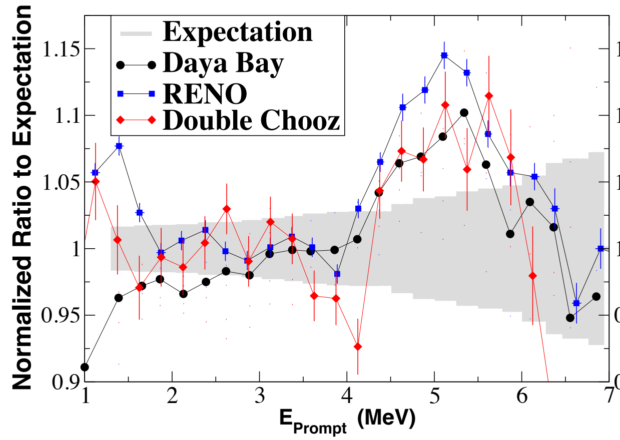
Possible Origins of the 'Bump'

- Non-fission sources of antineutrinos in the reactor
  - **NO**, eliminated by MCNP and reactor simulations.
  - Neutrinos from structural material too low in energy.



- From the conversion method, e.g., forbidden transitions
  - Unlikely, < 1% effect.

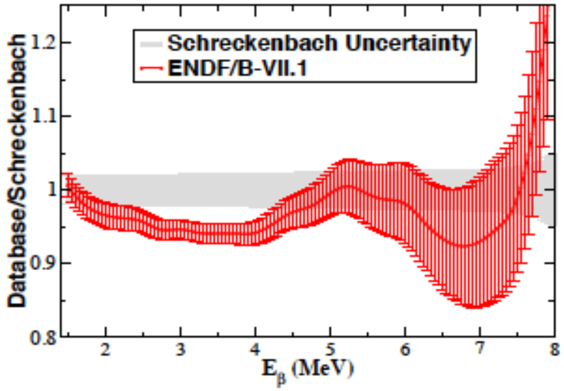
- The harder PWR Neutron Spectrum
  - Possible. Not predicted by standard fission theory, but no convincing experimental data either way.



- ^{238}U as a source of the shoulder
  – Possible. RENO suggests this – has largest bump and largest fraction of 238U. Needs more experiments.

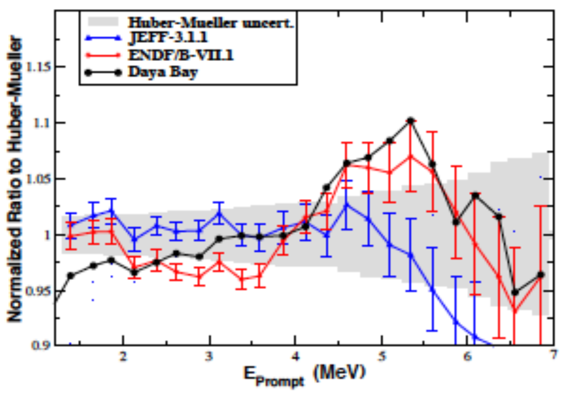
- A possible error in the ILL β-decay measurements
  - At first 'Yes', now 'Unlikely'.

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



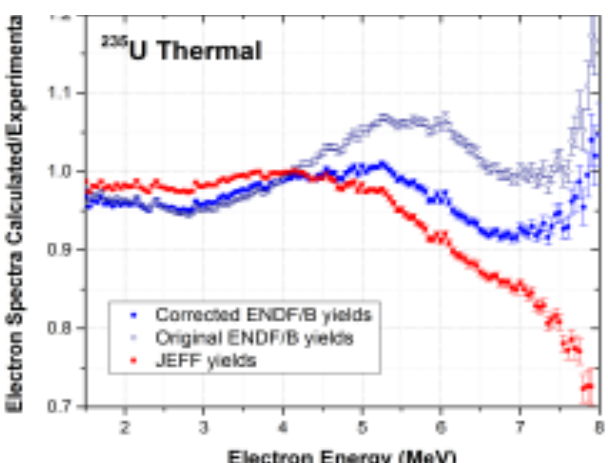
- Dwyer and Langford pointed out that the ENDF database predicts an analogous bump in the beta-spectrum relative to Schreckenbach.

  Dwyer & Langford, PRL 114, 012502 (2014)



- However, the European database JEFF does not predict the bump for Daya Bay or RENO.

  Hayes, *et al.* PRD, 92, 033015 (2015)



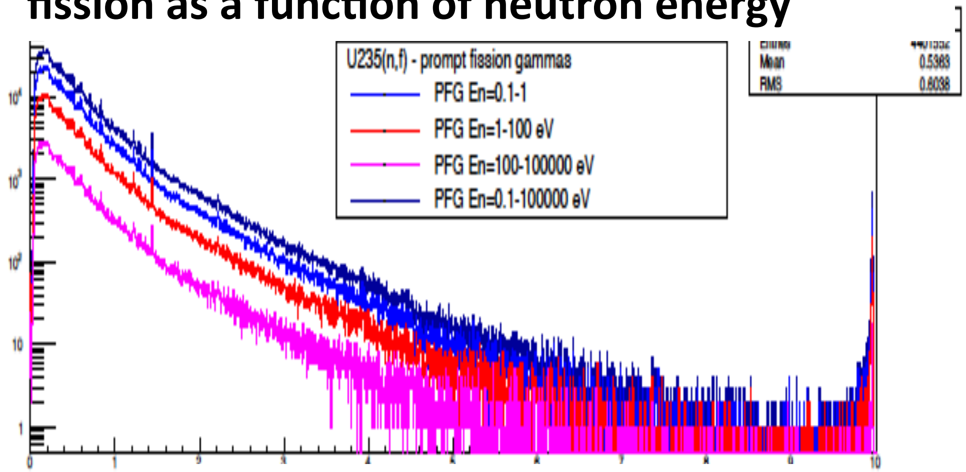
- Sonzongi pointed out that the bump in ENDF is largley a **mistake** in the database for fission yields at mass A=86. They also pointed to other shortcomings in ENDF. When the database is corrected, ENDF no longer predicts the bump.

  Sonzogni, et al. PRL, March 2016

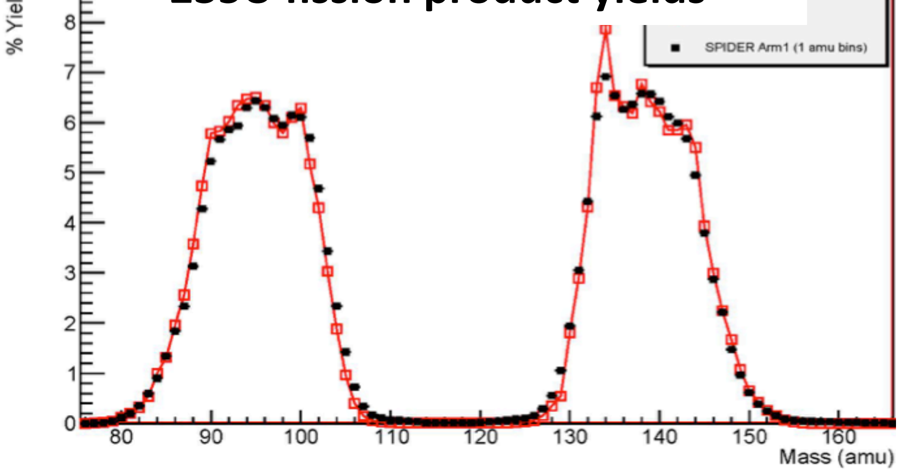
Need for New Experiments
both for
Standard Nuclear Physics Issues
and for
Sterile Neutrino Searches

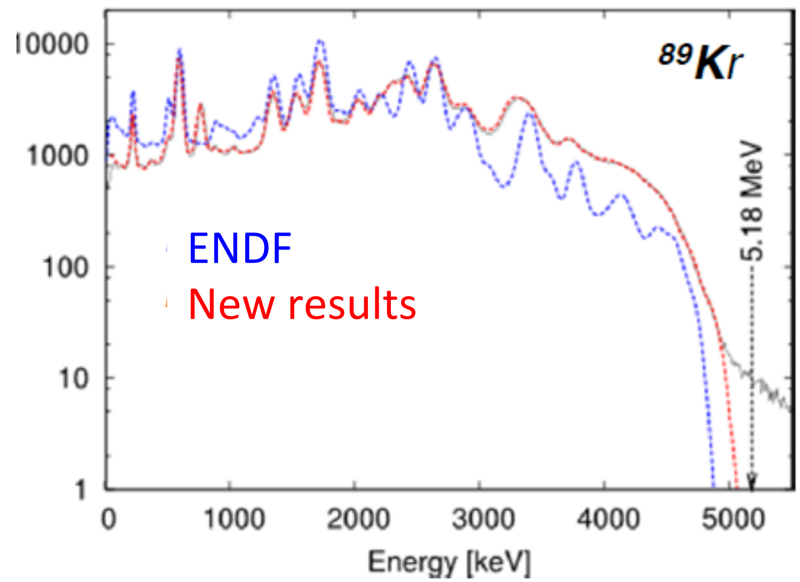
Several standard nuclear physics experiments examining the problem. Interest is partially motivated by the fact that the same fission fragments determine reactor decay heat – very important in an emergency shutdown.

Examining the prompt γ-ray spectrum from fission as a function of neutron energy



New measurements of 235U fission product yields





Improved β-decay spectra for dominant fission products

Several very short baseline experiments to search for possible anomaly related sterile neutrinos

Experiment	Power (MW_{th})	Baseline (m)	Mass (tons)	Dopant	Segmented
PROSPECT	85	6-20	3	6Li	Y
SoLid	100	5.5	2 (initially)	6Li	Y
NUCIFER	70	7	0.7	Gd	N
STEREO	58	10	1.8	Gd	N
NEUTRINO-4	100	6-12	1.5	Gd	N
POSEIDON	100	5-8	1.3	Gd	N
HANARO	30	6	0.5	Gd	Y
Nu-Lat	1500	3-8	1.0	10B, 6Li	Y
DANASS	3000	11	0.9	Gd	Y
SOX	Cr-51 & Ce-144 sources		BOREXINO		

Summary

- **There are currently several puzzles associated with short-baseline neutrino experiments**

  - LSND, MiniBooNE, The Gallium Anomaly, and the Reactor Anomaly

- **If neutrino oscillations are responsible, ~1 eV sterile neutrinos would be required**

- **Possible nuclear physics origins have been suggested but none proven definitively**

- **Solving these problems will require:**
  - **Experiments designed to confirm/deny the existence of 1 eV sterile neutrinos**

    A number of these will use HEU, and will determine the spectrum for ^{235}U
  - **Nuclear physics studies to re-examine the expectations and their uncertainties**

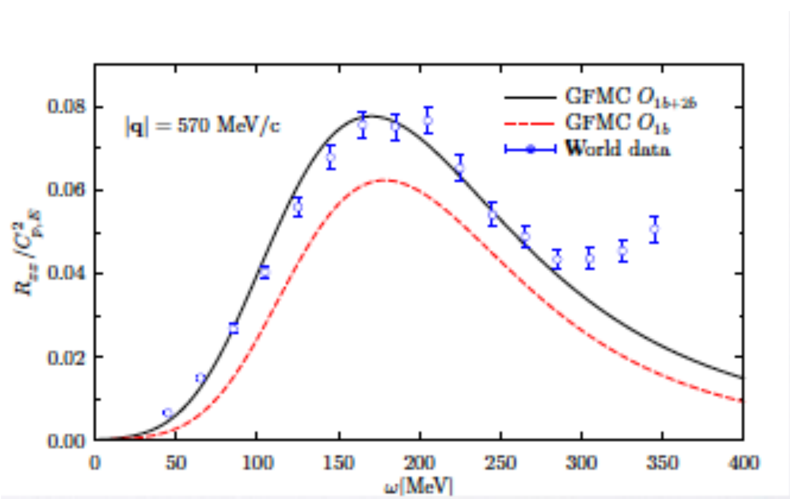
Nuclear Physics Issues for MiniBoone

- **Reconstructed neutrino energy:** Depends on the shape of the flux and the cross section

$$F(E_\nu,\overline{E_\nu}) = c\frac{\Phi(E_\nu)}{\int dE_\nu \Phi(E_\nu)} \int_{E_\mu^{\min}}^{E_\mu^{\max}} dE_\mu \left[\frac{d^2\sigma}{d\omega\ d\cos\theta}\right]_{\omega=E_\nu-E_\mu,\ \cos\theta=\cos\theta(E_\mu,\overline{E_\nu})}$$

There is a distribution of neutrino energies for each reconstructed average Eν, which is not necessarily symmetric.

M. Martini et al. Phys. Rev. C 80 065501 (2009); 81 045502 (2010) 84 055502 (2011) Phys. Rev. D 85 093012 (2012); 87 013009 (2013). U. Mosel et al., PRC86, 054606 (2012)



Lavato *et al.* find that 2-body currents enhance both the vector and axial contributions to the neutrino cross sections.
arXiv:1509.00451