Reactor Antineutrino Fluxes
Current Status

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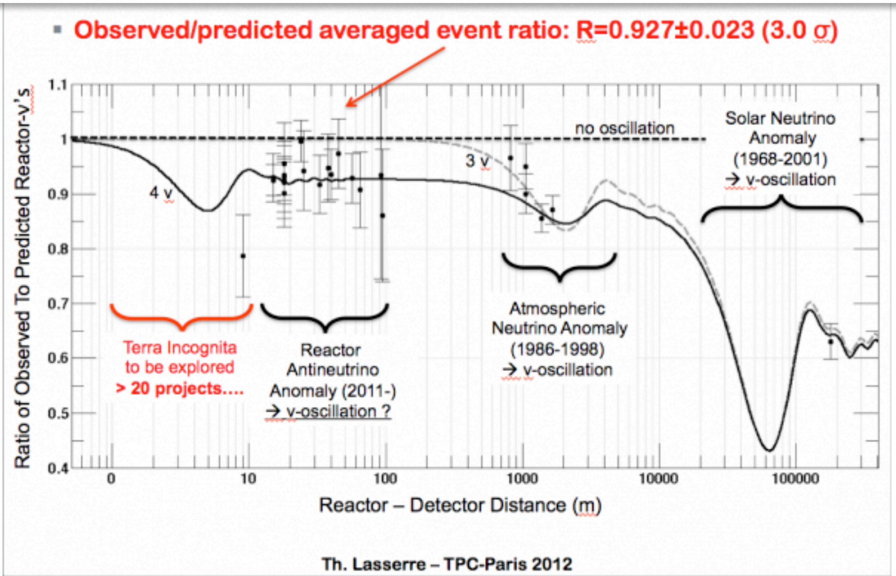
Outline

- Current discrepancies between measured and expected ν-fluxes
  - The Anomaly
  - The 'Bump'
- The expectations and their evolution with time
- Analyses of the possible 'nuclear physics' issues involved
- Needed experiments to resolve the issues

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

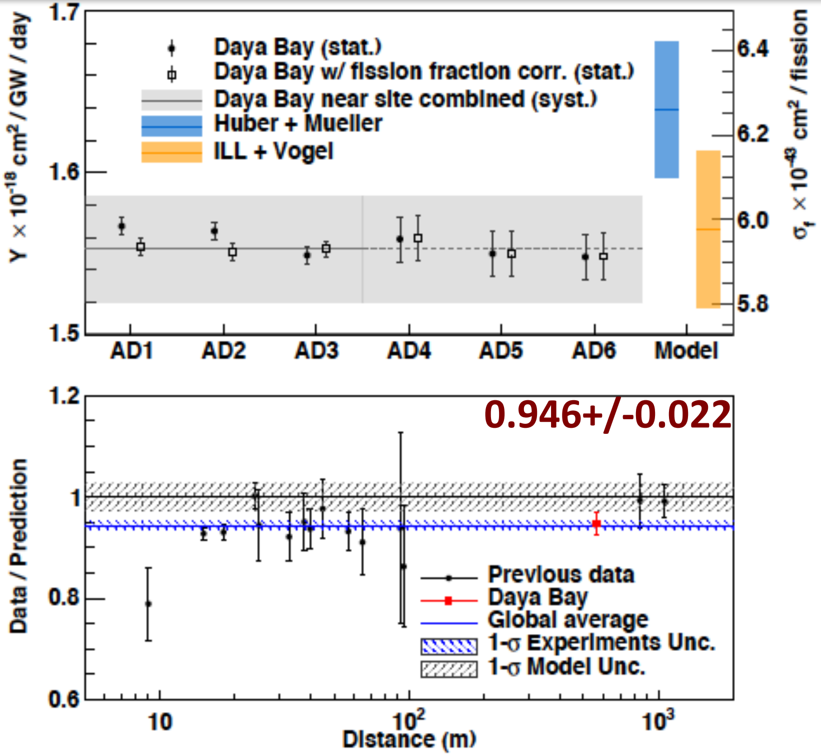
From Th. Lasserre, 2012



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

Most recent results from Daya Bay, 2016

PRL,116 (2016) 061801

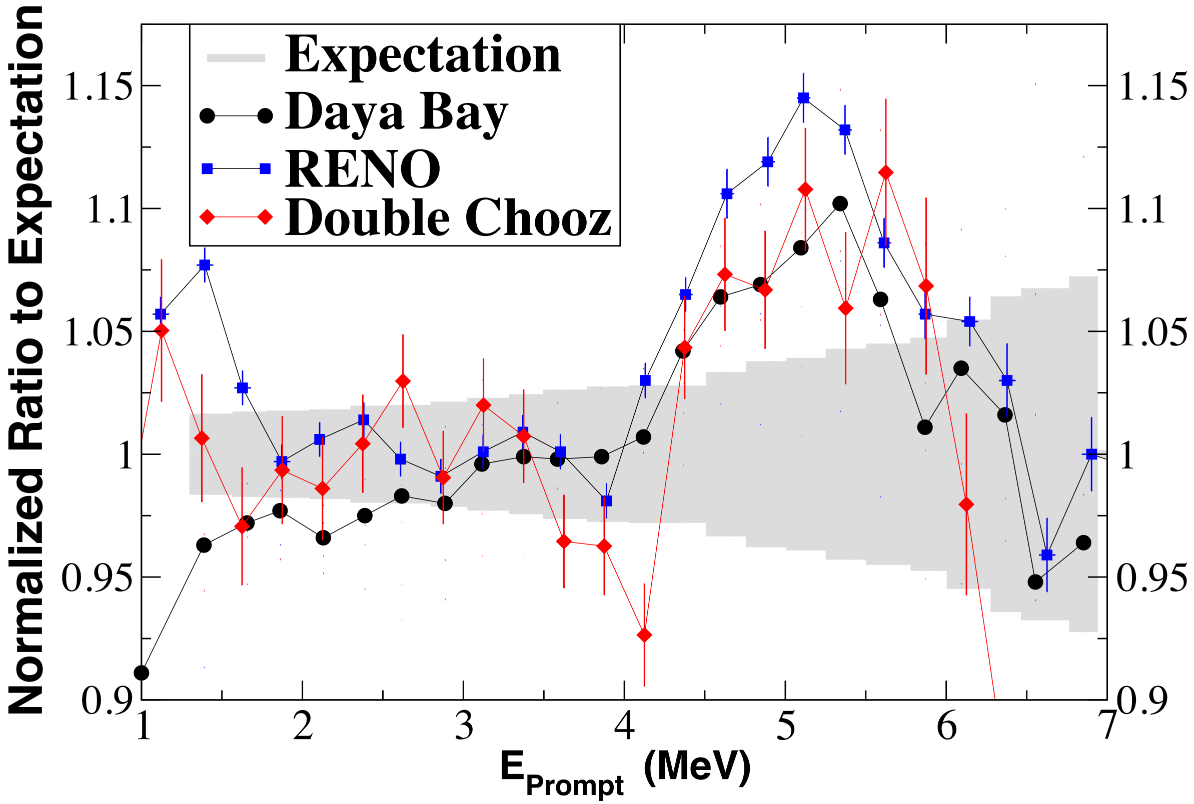


The very accurate measurement of the total flux at Daya Bay confirms the shortfall

The issue then becomes ones of:

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

All three recent reactor neutrino experiments observed a shoulder at 4-6 MeV, relative to expectations –the 'Bump'



- 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

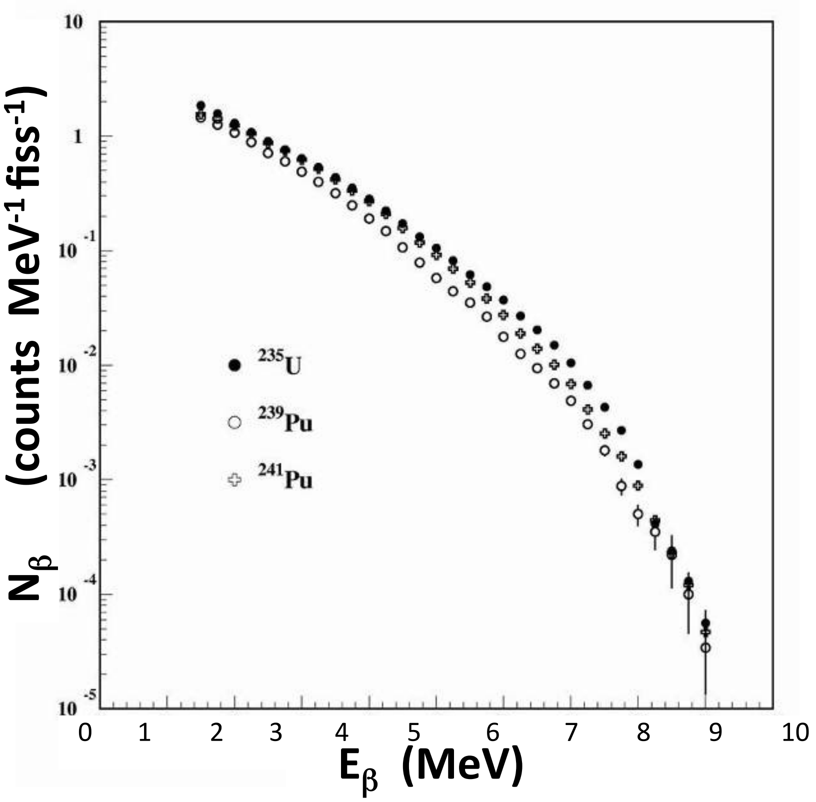
P. Huber, Phys. Rev. C 84, 024617 (2011); Th. A. Mueller et al., Phys. Rev. C 83, 054615 (2011); N. Haag, Phys. Rev. Lett. 112, 122501 (2014).

The EXPECTED flux

and

its systematic shift upward in 2011

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



- 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).

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

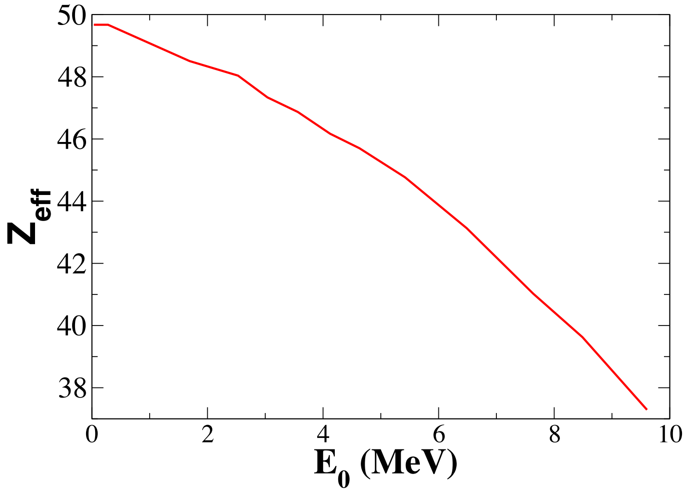
$$S^{i}(E,E_{0}^{i}) = E_{\beta}p_{\beta}(E_{0}^{i}-E_{\beta})^{2}F(E,\ Z)(1+\ \delta_{corrections})$$

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

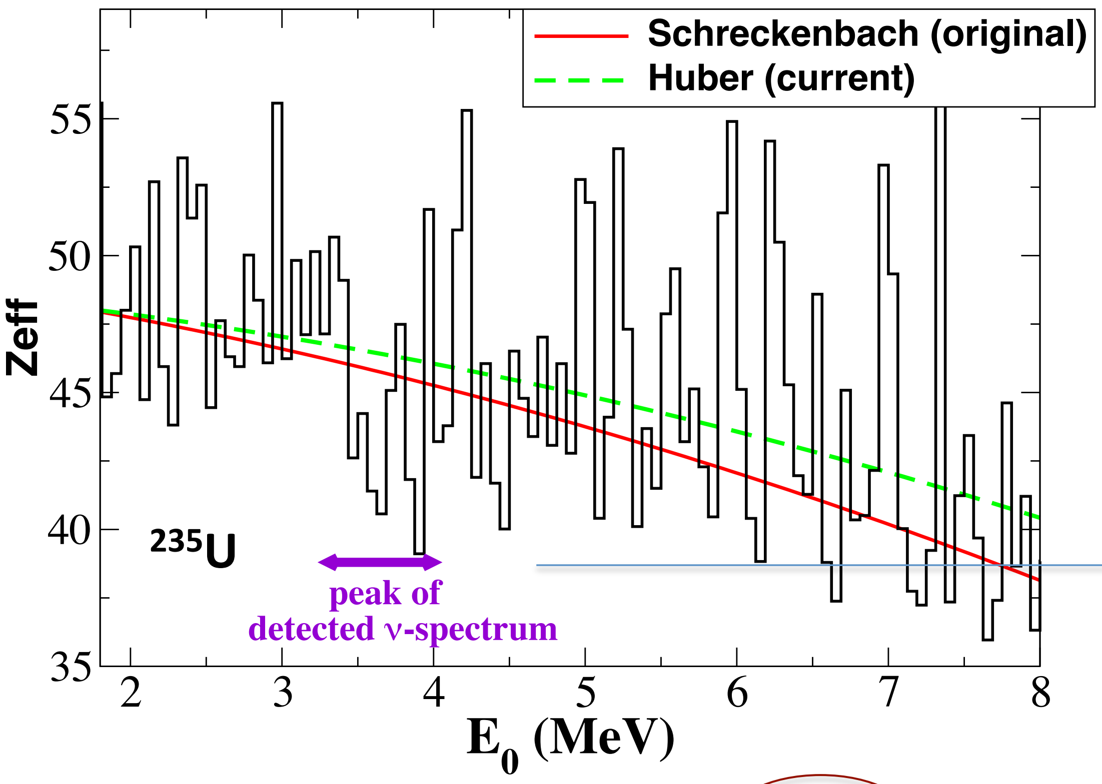
δ_{WM} = Weak magnetism

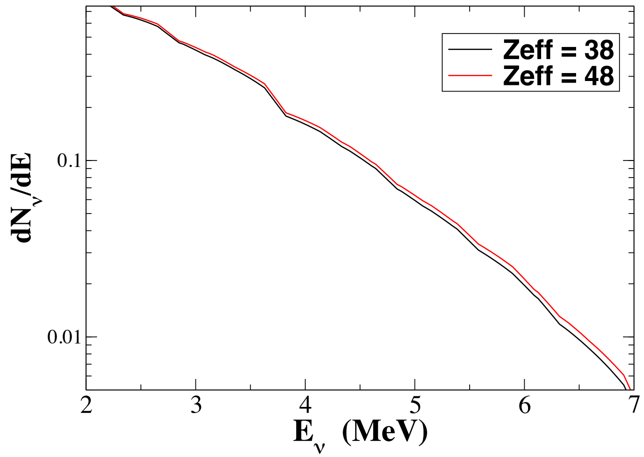
δ_{R} = Recoil correction

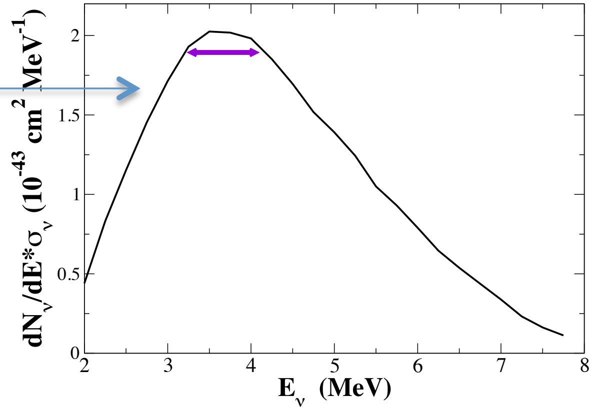
δ_{rad} = Radiative correction

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







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

- **Huber's new parameterization of Zeff with end-point energy E_0 changes the Fermi function and accounts for 50% of the current anomaly.**
- **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.**

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

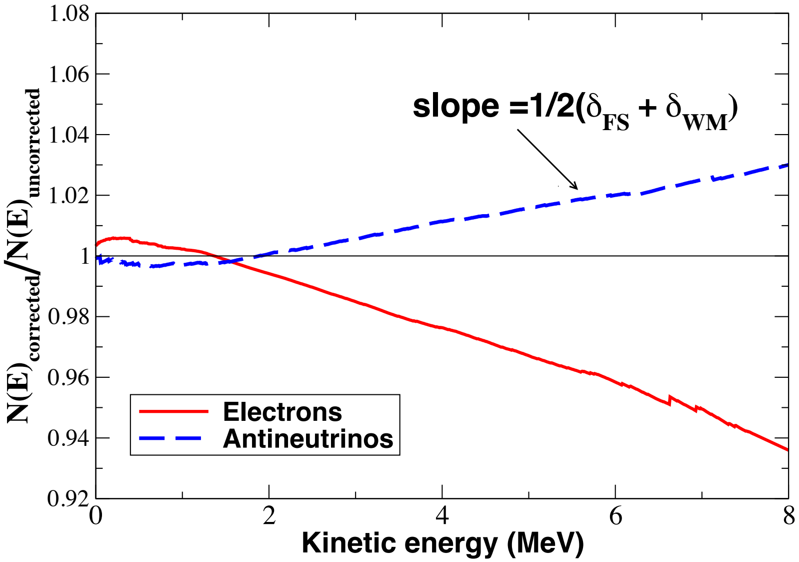
Originally approximated by a parameterization: $\delta_{FS}+\delta_{WM}=0.0065(E_\nu-4MeV))$

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

An approximation was used for each:

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

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



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

Uncertainties in the Corrections are larger than first estimated

Nuclear FS:

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

$$< r >_{(2)} = \int r\, d^3r \int d^3s\, \rho_W(|\vec{r} - \vec{s}\,|)\ \rho_{ch}(s)$$

1st Zemach moment $<r>_{(2)}$ very nuclear structure dependent.

Uncertainty ~ 50%

Weak Magnetism:

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

WM involves omitted 2-body meson-exchange corrections.

Uncertainty ~ 25%

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):

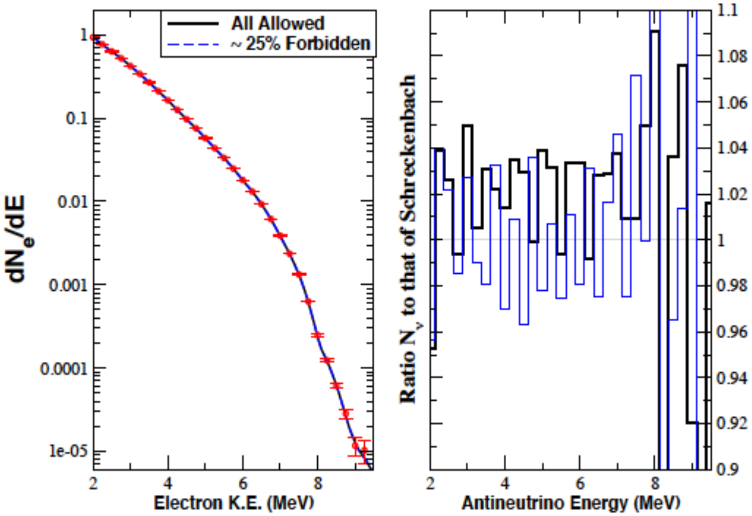
$$S(E_e,Z,A)=\frac{G_F^2}{2\pi^3}p_eE_e(E_0-E_e)^2\underline{C(E)}F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

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 1st Forbidden GT	0^-	$[\Sigma, r]^{0-}$	$p_e^2+E_\nu^2+2\beta^2E_\nu E_e$	0
Non-unique 1st Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1st Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2+E_\nu^2-\frac{4}{3}\beta^2E_\nu E_e$	$\left[\frac{\mu_v-1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2E_e-E\nu)+2\beta^2E_eE_\nu(E_\nu-E_e)/3}{(p_e^2+E_\nu^2-4\beta^2E_\nu E_e/3)}\right]$
Unique 1st Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2+E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v-1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2E_e-E\nu)+2\beta^2E_eE_\nu(E_\nu-E_e)/3}{(p_e^2+E_\nu^2)}\right]$
Allowed F	0^+	τ	1	
Non-unique 1st Forbidden F	1^-	$r\tau$	$p_e^2+E_\nu^2+\frac{2}{3}\beta^2E_\nu E_e$	
Non-unique 1st 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%

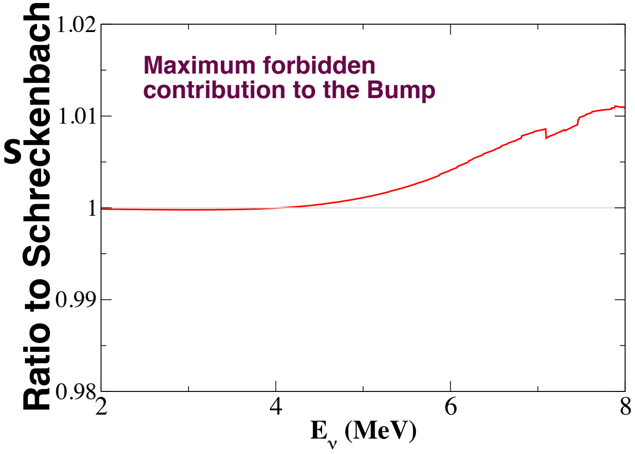


The BUMP

Possible Origins of the 'Bump'

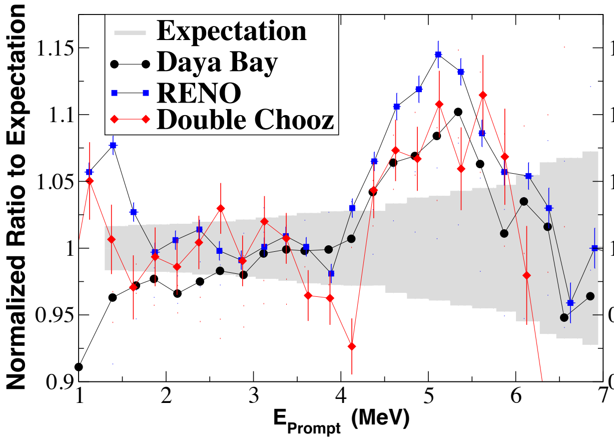
- Non-fission sources of antineutrinos in the reactor
  - NO, eliminated by MCNP and reactor simulations.
  - Neutrinos from structural material too low in energy.

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



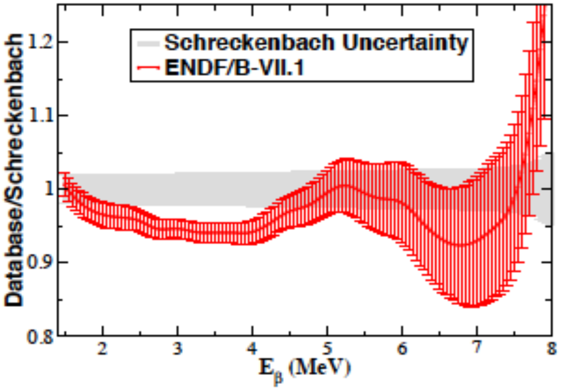
- The harder PWR Neutron Spectrum
  - Possible. Not predicted by standard fission theory, but no convincing experimental data either way.

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



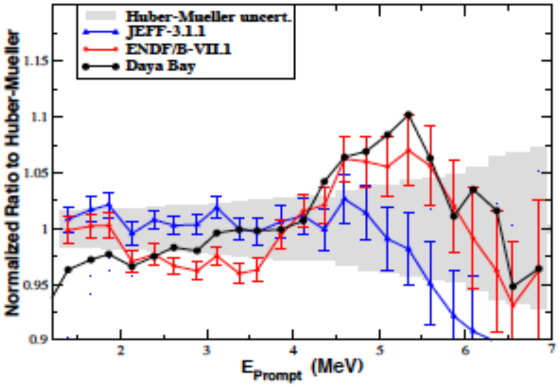
- A possible error in the ILL β-decay measurements
  - At first 'Yes', now 'Unlikely'.

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



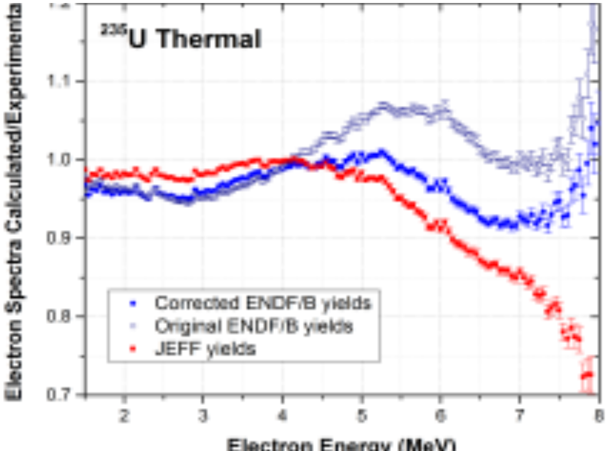
- Dwyer and Langford pointed out that the ENDF database predicts an analogous bump in the beta-spectrum relative to Schreckenbach.

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)



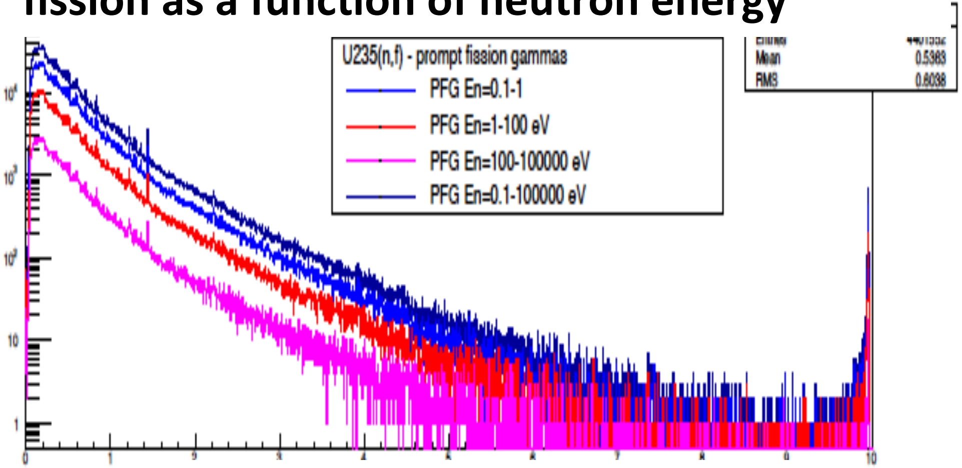
- Songzoni pointed out that the bump in ENDF is a **mistake** in the database for fission yields at mass A=86. When the database is corrected, ENDF no longer predicts the bump.

Sonzogni, et al. PRL, March 2016

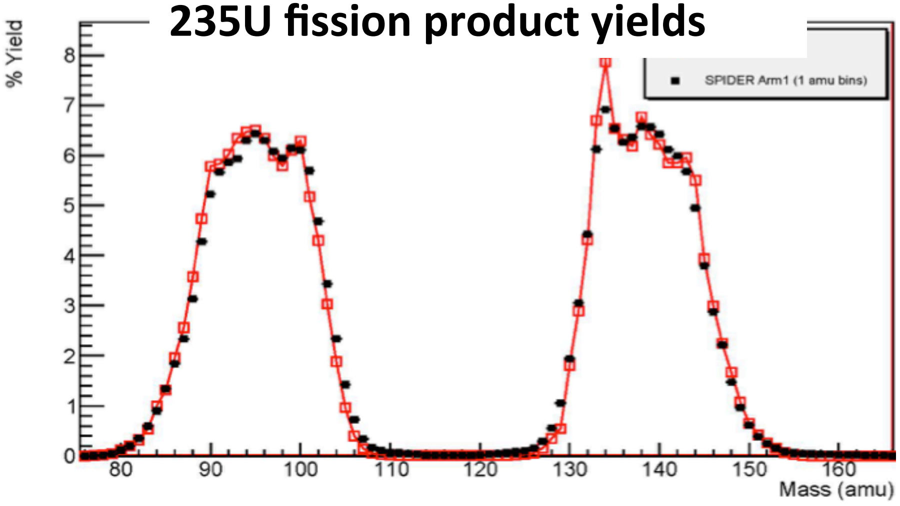
Need for New Experiments
both for
Standard Nuclear Physics Issues
and for
Sterile Neutrino Searches

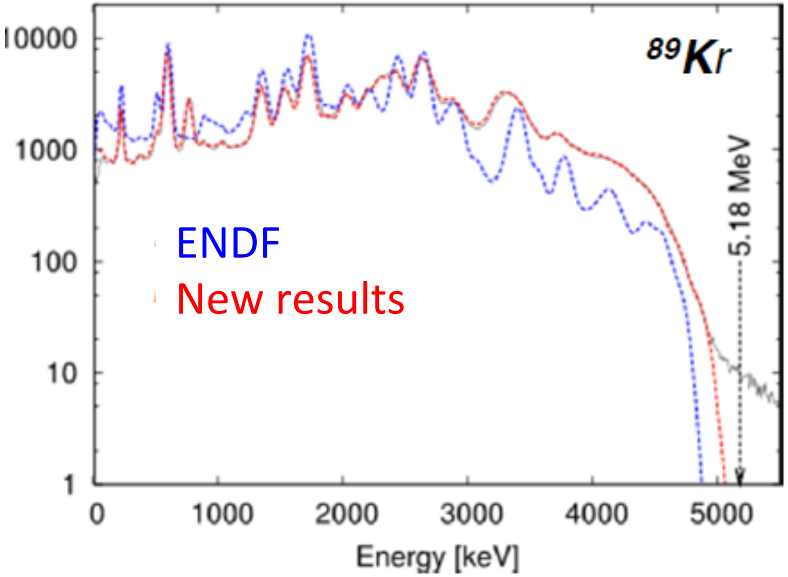
Several standard nuclear physics experiments examining the problem. Interest is partially motivated by the fact that the same fission fragments determine reactor decay heat – very important in an emergency shutdown.

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 two puzzles associated with reactor neutrino fluxes
  - The magnitude or the anomaly
  - The shape or the BUMP

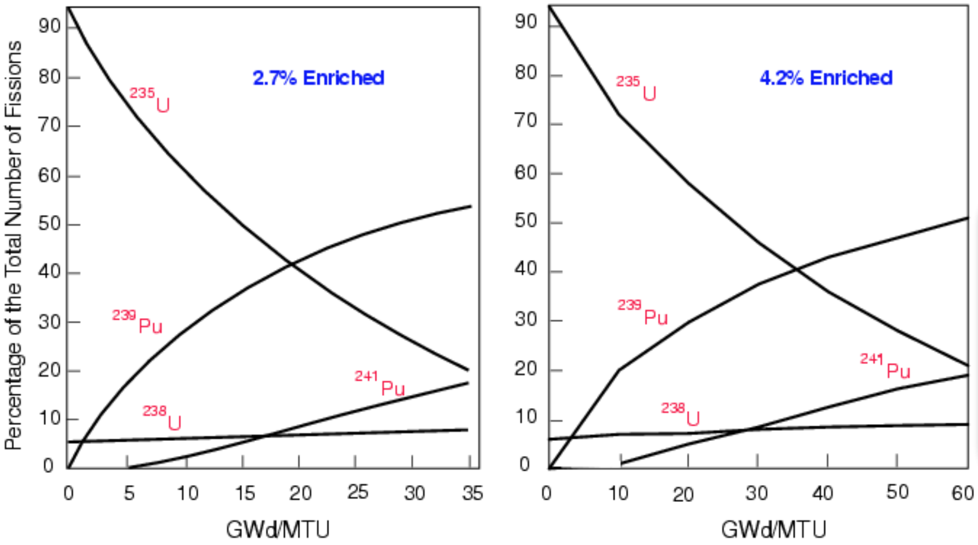
- Possible nuclear physics origins have been suggested but none proven definitively
  - The original Schreckenbach measurements do not appear to be the main issue

- Solving the problem 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

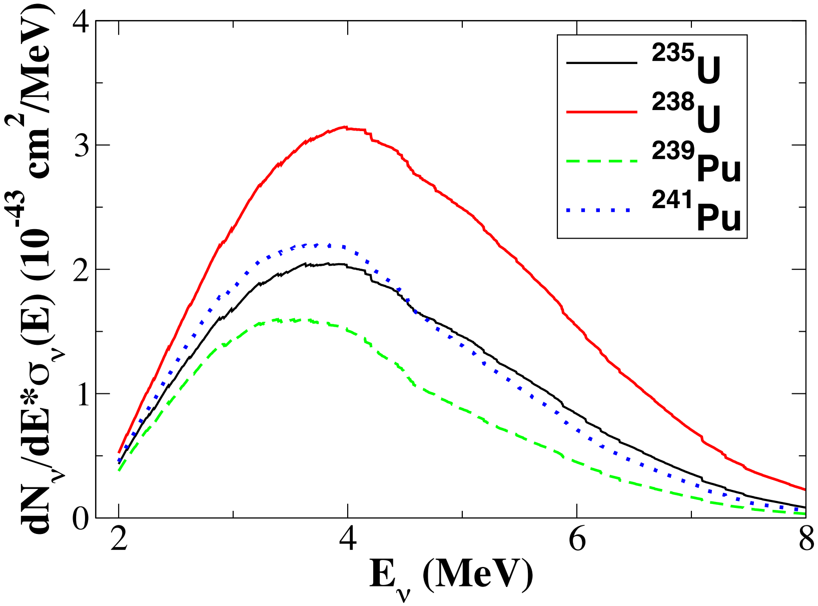
^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu dominate the reactor burn and the antineutrino flux emitted from any commercial reactor.

Need the antineutrino spectrum per fission for each of these actinides



The combination of the 4 actinides burning is reactor dependent, and is part of 'expected'.

	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



The spectrum from each of these 4 nuclei differ in both shape and magnitude because the distribution of fission fragments emitting neutrinos in β-decay is actinide dependent.