Spectra of Antineutrinos from Nuclear Reactors

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Los Alamos

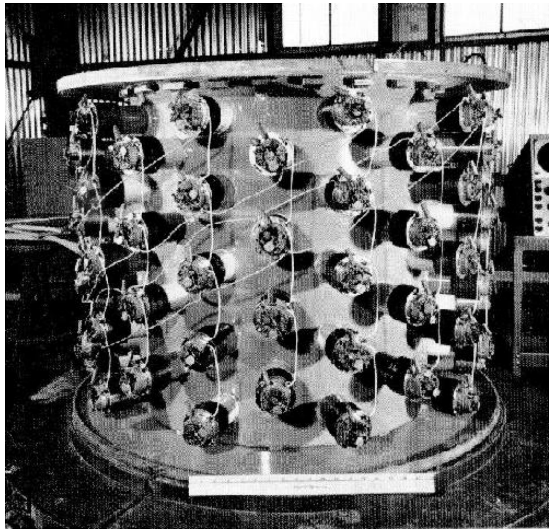
VIII *International Pontecorvo School*
Sinaia, Romania
Sept. 1-10, 2019

The neutrino was discover at a reactor (1956), and Pontecorvo speculated (1957) that neutrinos might have mass, mix, and oscillate

- Reines and Cowan detected the anti-neutrino at the Savannah River Reactor in 1956 via:

$$\bar{\nu}_e + p \rightarrow n + e^+$$

$$n + {}^{108}\mathrm{Cd} \rightarrow {}^{109}\mathrm{Cd} + \gamma$$



- Pontecorvo began on theories to allow for neutrino mass and oscillations in 1957, including the possibility of sterile neutrinos.

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:

Takaaki Kajita
Super-K

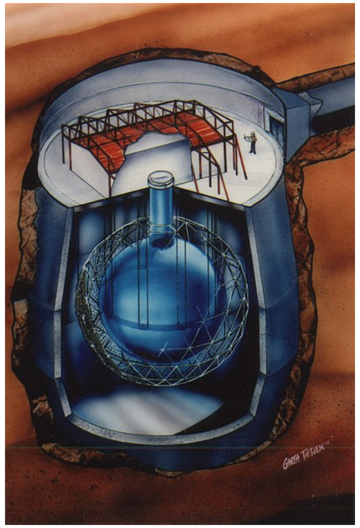
- Three mixing angles: $(\theta_{12}, \theta_{13}, \theta_{23})$;
- CP-violating phase δ
- Two mass differences: $\delta m^2=m_2^2 - m_1^2 > 0$

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

Art McDonald
SNO

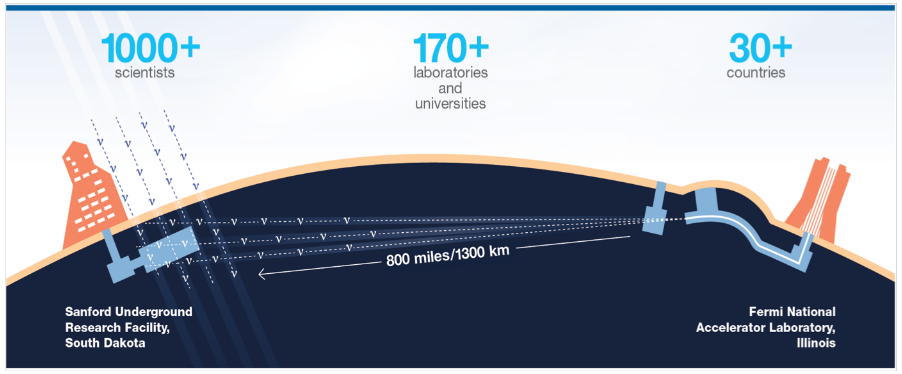
Kajita and McDonald shared the Nobel Prize in 2015

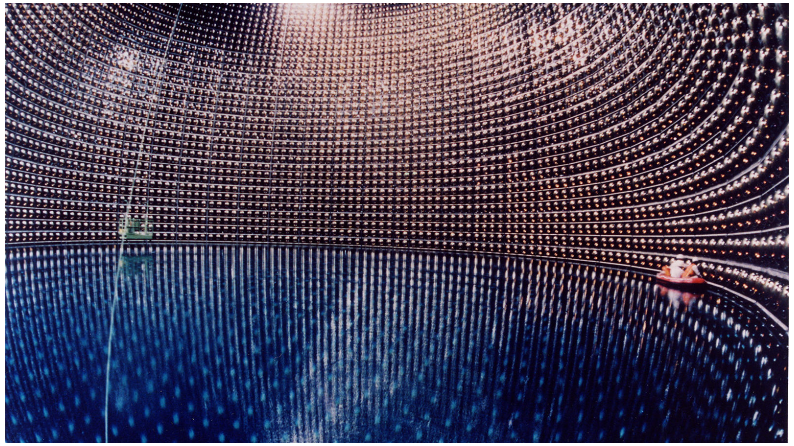
The mixing parameters are deduced from solar, atmospheric, accelerator, and reactor neutrino experiments.



$\delta m^2/10^{-5}\ eV^2$	7.54	7.32 - 7.80
$\Delta m^2\ /10^{-3}\ eV^2$	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

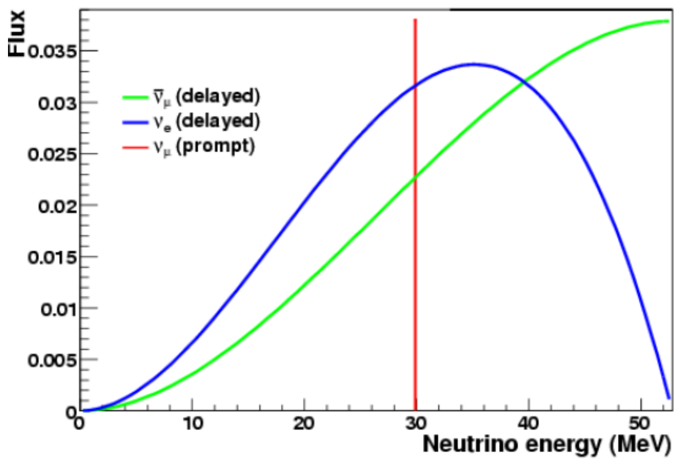
- **LSND**
- **MiniBooNE**
- **The Gallium Anomaly**
- **The Short Base-Line Reactor Neutrino Anomaly**

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

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

LSND

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

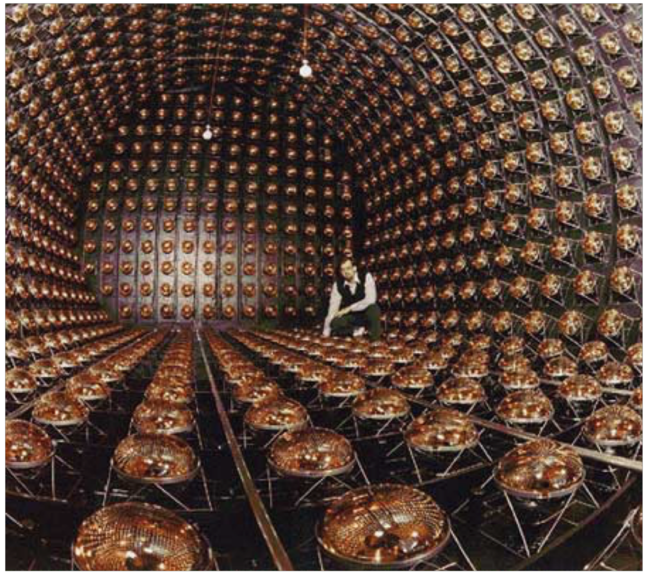


For two-state mixing: $$P = \sin^2 2\theta\ \sin^2(1.27\Delta m^2(L/E))$$

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

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

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



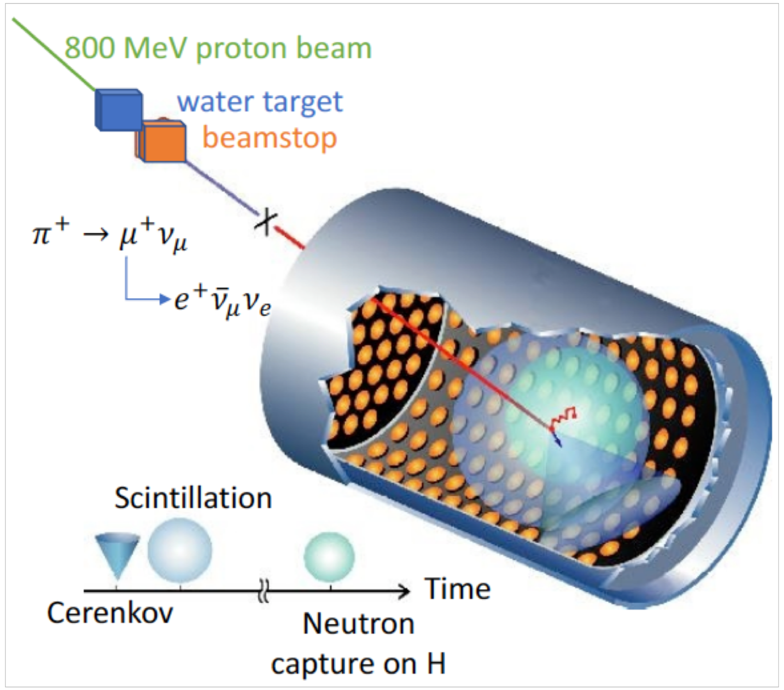
Searched for: $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

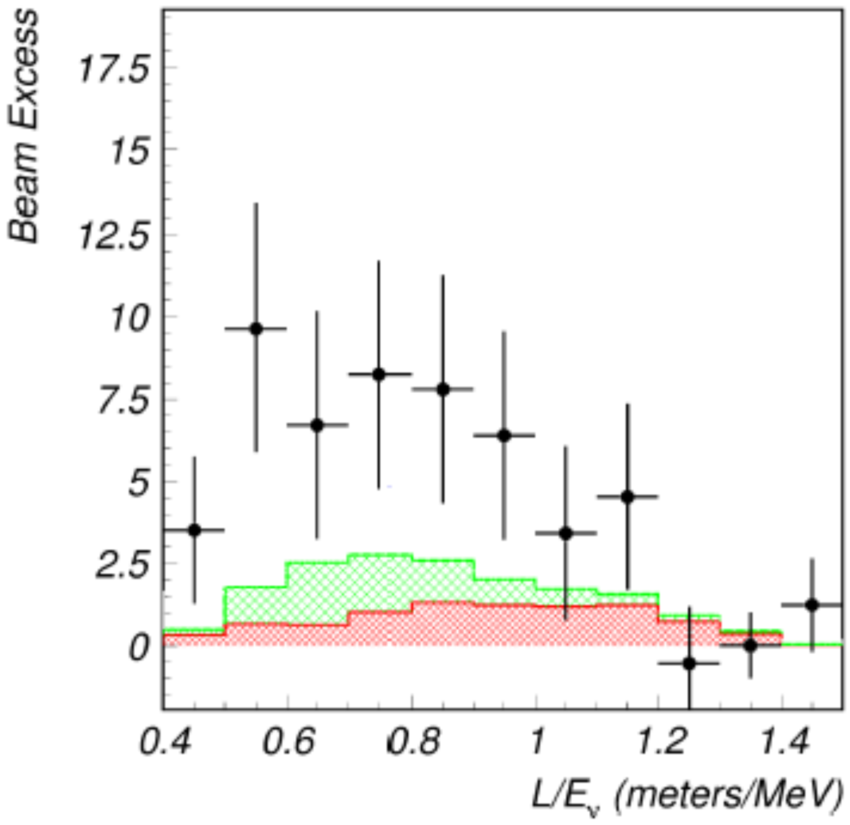
Detected via Inverse Beta Decay

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

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

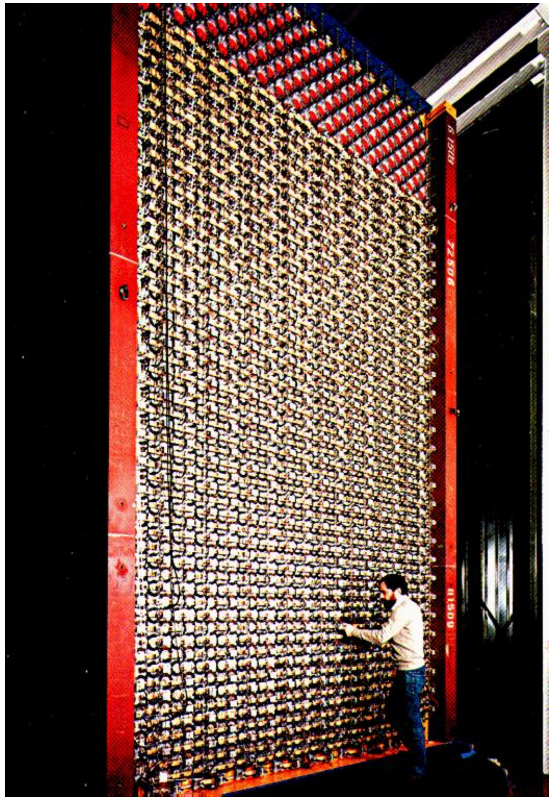
LSND Observed a 3.8σ excess

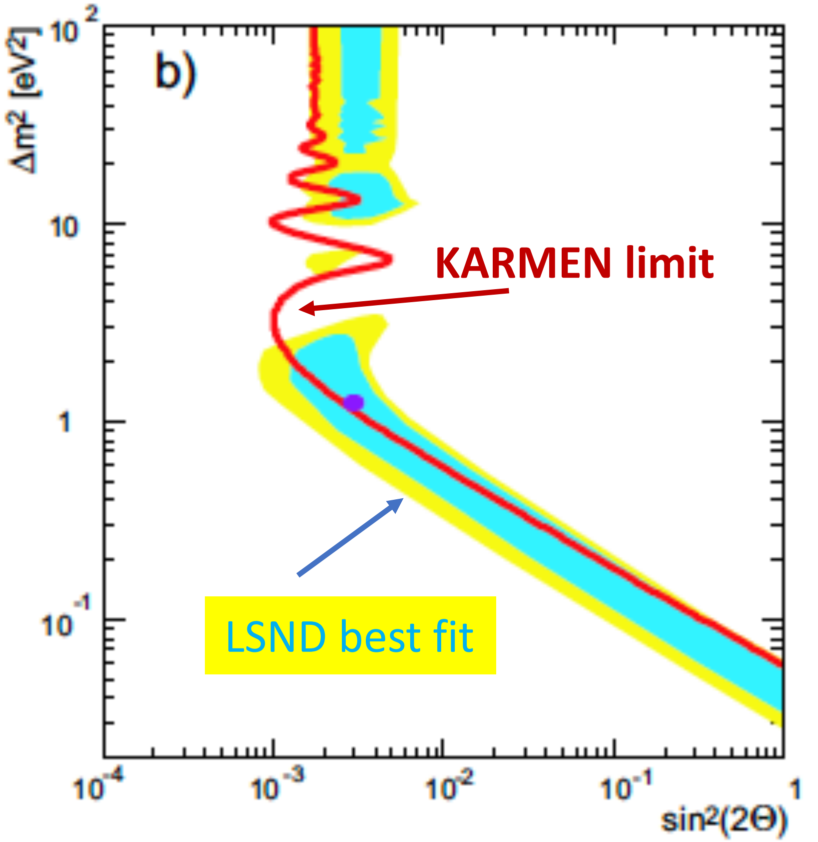




En-Chuan Huang, Neutrino 2018
Ann. Rev. Nucl. Part. Sci, 63, (1) 45

However, Karmen, at 17 m, did not see evidence for $\bar{\nu}_\mu \to \bar{\nu}_e$





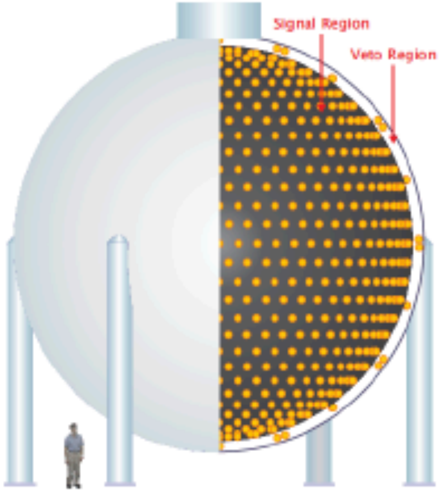
A combined analyses, with KARMEN as the near detector (17 m) and LSND as far detector (30 m), finds two possible solutions at the 64% confidence level: $\Delta m^2 \approx 7 eV^2/c^4$ or $\Delta m^2 < 1\ eV^2/c^4$

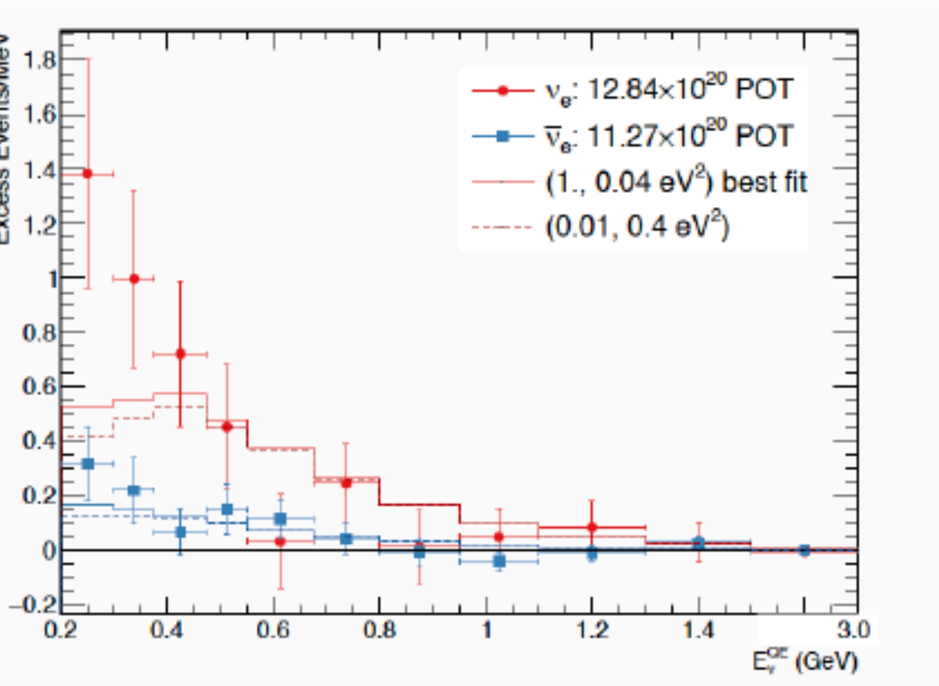
MiniBooNE

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





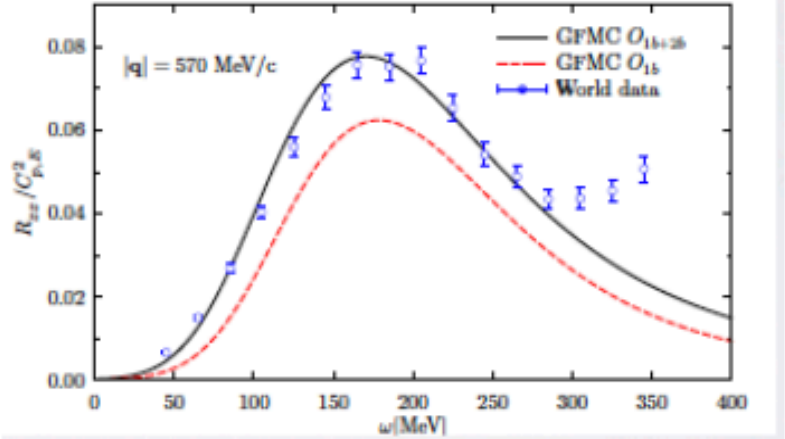
PRL, 98 (23): 231801

En-Chuan Huang, Neutrino 2018

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

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

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

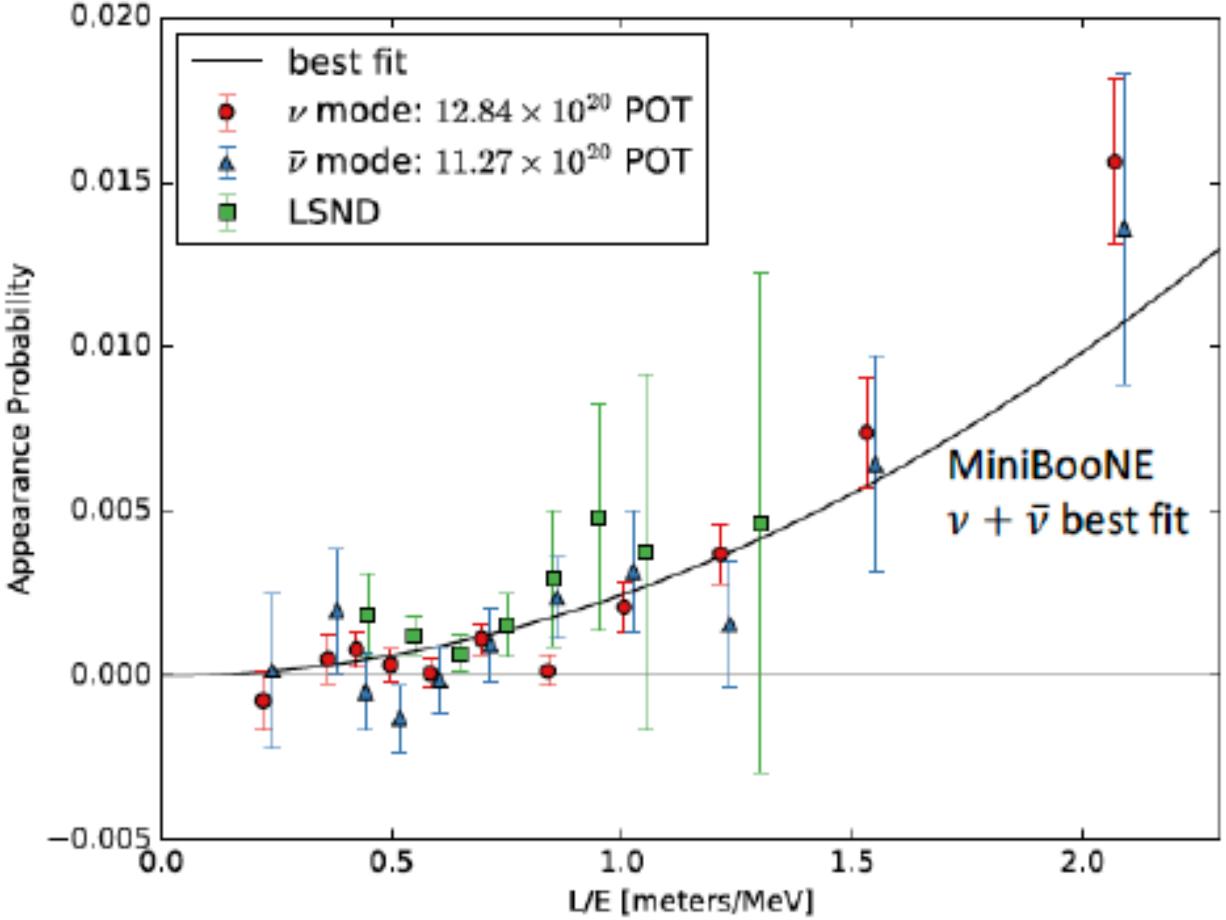


Lavato *et al.* *(T-Div)* find that 2-body currents enhance both the vector and axial contributions to the neutrino cross sections

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

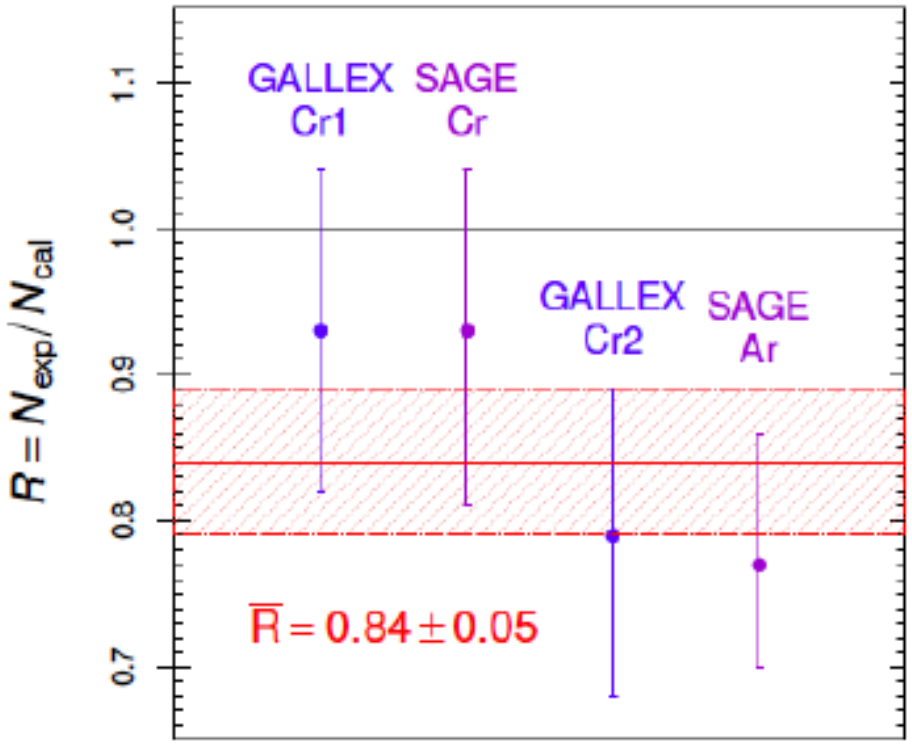


$$P = \sin^2 2\theta \ \sin^2(1.27\Delta m^2 (L/E))$$

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.



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

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

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

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

Bahcall + Haxton

$$\boxed{\begin{array}{l} \langle L\rangle_{GALLEX} = 1.9\text{ m};\ \langle L\rangle_{SAGE} = 0.6\text{ m} \\ \Rightarrow \qquad \Delta m^2_{SBL} \gtrsim 0.5\,\text{eV}^2 \end{array}}$$

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.

Use half-life of ^{71}Ge to determine ^{71}Ge+ν_e Zeroth-order cross section – which needs corrections at the few percent level.

$$\sigma_\nu = \frac{G_F^2 g_A^2\, p' E'\, F}{\pi(2J_i+1)} \left\{ S - \frac{2}{3} A \left[E - E' + \frac{m_e^2}{E'} \right] + \frac{2D}{3M g_A} \left[(E+E') - \frac{m_e^2}{E'} \right] \right\}$$

Electron capture rate: $$r_{\rm ec} = \frac{2\, G_F^2\, g_A^2\, E_\nu^2\, |\phi_K(0)|^2}{2\pi(2J_i'+1)} \left[S + \frac{2}{3} A\, E_\nu + \frac{2D}{3M g_A} E_\nu \right]$$

Nuclear matric elements S, A, & D

$$S = \overline{\sum_{f,i}} |\langle f|\Sigma|i\rangle|^2 = |\langle J_f||\Sigma_1||J_i\rangle|^2$$

$$A = \mathrm{Re} \overline{\sum_{f,i}} \langle f|\Sigma|i\rangle \cdot \langle f|\mathrm{i\,a}|i\rangle^* = \mathrm{Re}\langle J_f||\Sigma_1||J_i\rangle\langle J_f||\mathrm{i}\,a_1||J_i\rangle^*$$

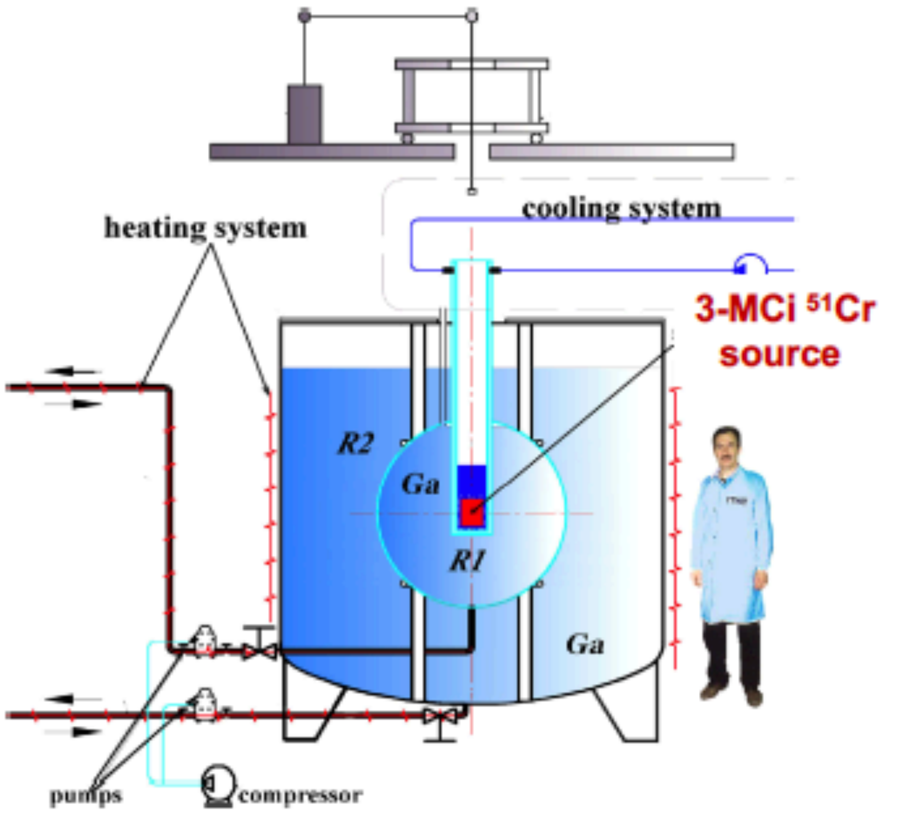
$$D = \mathrm{Re} \overline{\sum_{f,i}} \langle f|\Sigma|i\rangle \cdot \langle f|\boldsymbol{\mu}_W|i\rangle^* = \mathrm{Re}\langle J_f||\Sigma_1||J_i\rangle\langle J_f||\mu_W||J_i\rangle^*$$

$$\Sigma = \sum_{i=1}^{A} \boldsymbol{\sigma}_i \frac{\tau_z(i)}{2}$$

$$\mathrm{a} = \sum_{i=1}^{A} \left\{ \frac{\boldsymbol{\sigma}_i \cdot \mathrm{p}_i}{2M}, \mathrm{x}_i \right\} \frac{\tau_z(i)}{2} + \mathrm{a}_{\rm MEC}$$

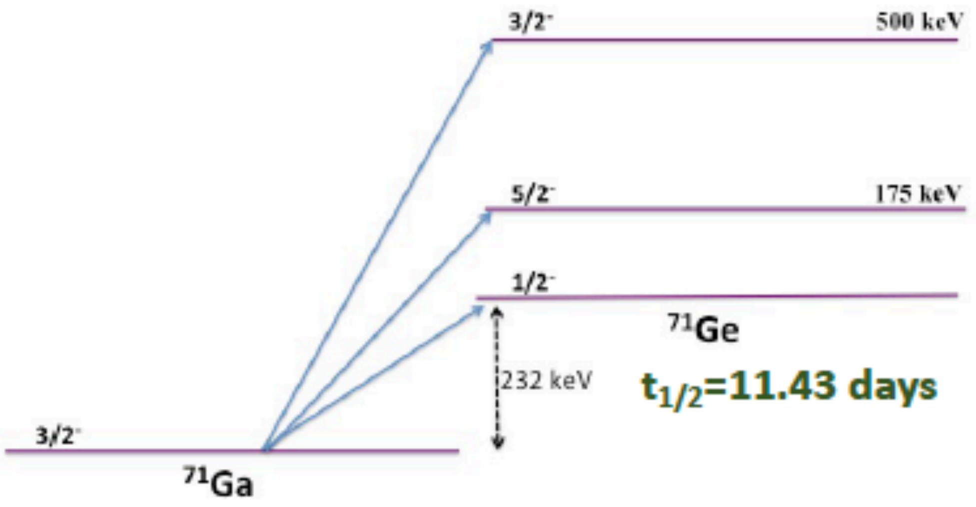
$$\boldsymbol{\mu}_W = \sum_{i=1}^{A} (\boldsymbol{\sigma}_i\, \hat{\mu}_i^{\rm nc} + \mathrm{l}_i\, \hat{e}_i^{\rm nc}) + \boldsymbol{\mu}_{\rm MEC}$$

Understanding the Gallium Anomaly will require new experiments and a reinvestigation of the 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:

- **Weak magnetism, Finite size**
- **1st forbidden currents**

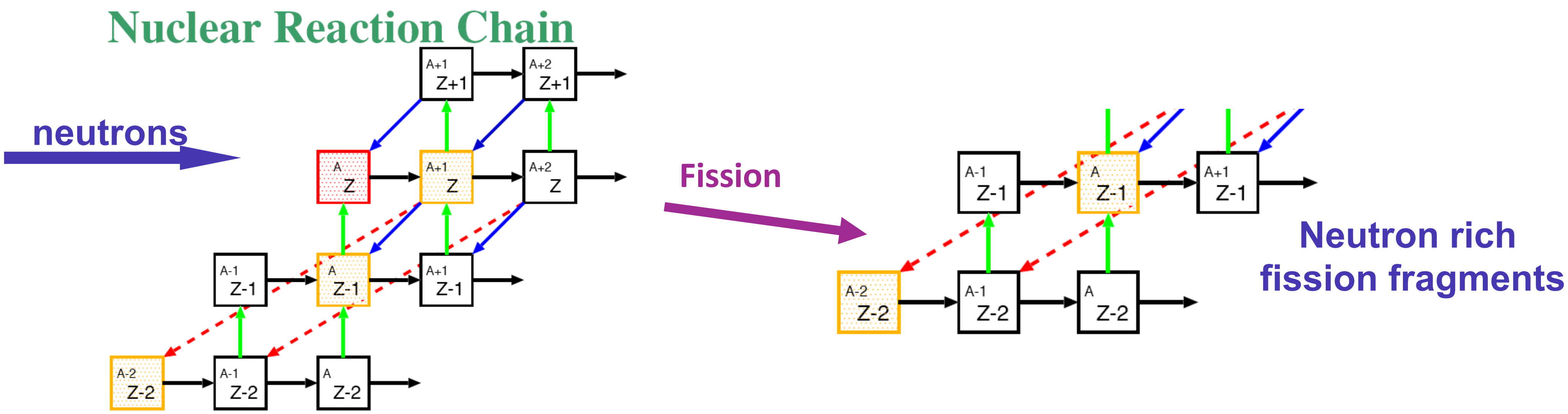
Reactor Neutrino Anomaly

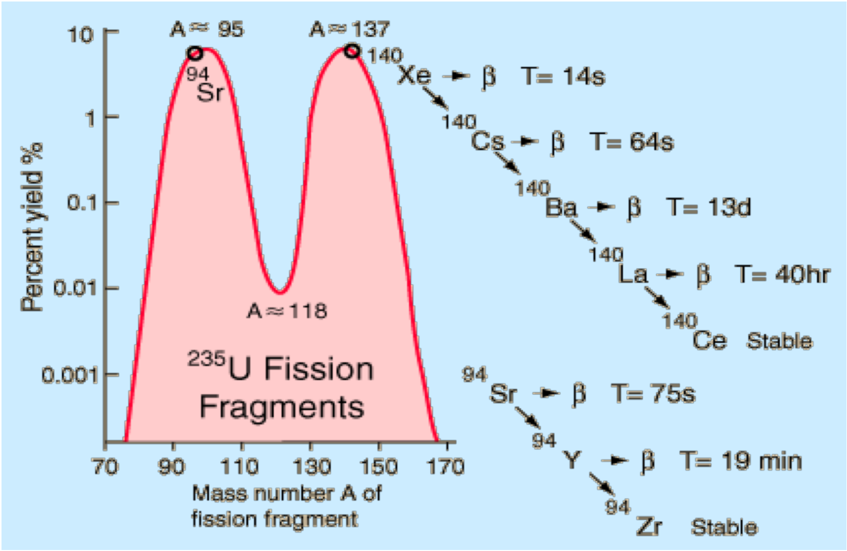
Requires an understanding of reactor anti-neutrino spectra.

This is also important for precision neutrino oscillations experiments.

A 1 GW reactor emits 10^{21} antineutrinos/sec.

Beta Decay of fission fragments are the source of reactor anti-neutrinos, with ~ 6 ν_e emitted per fission.



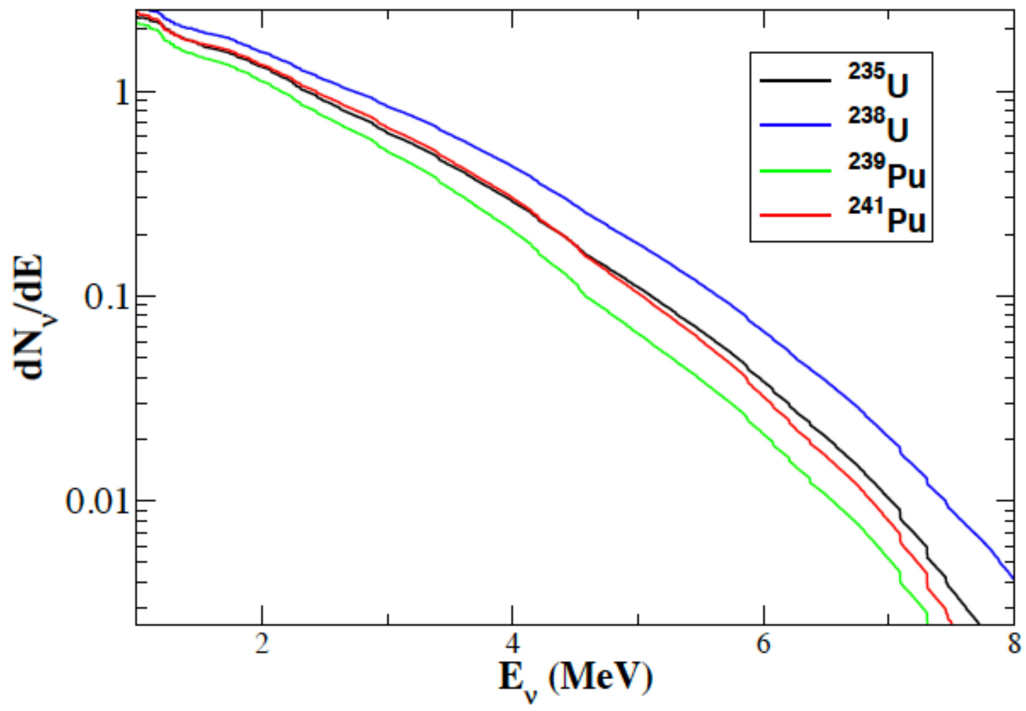


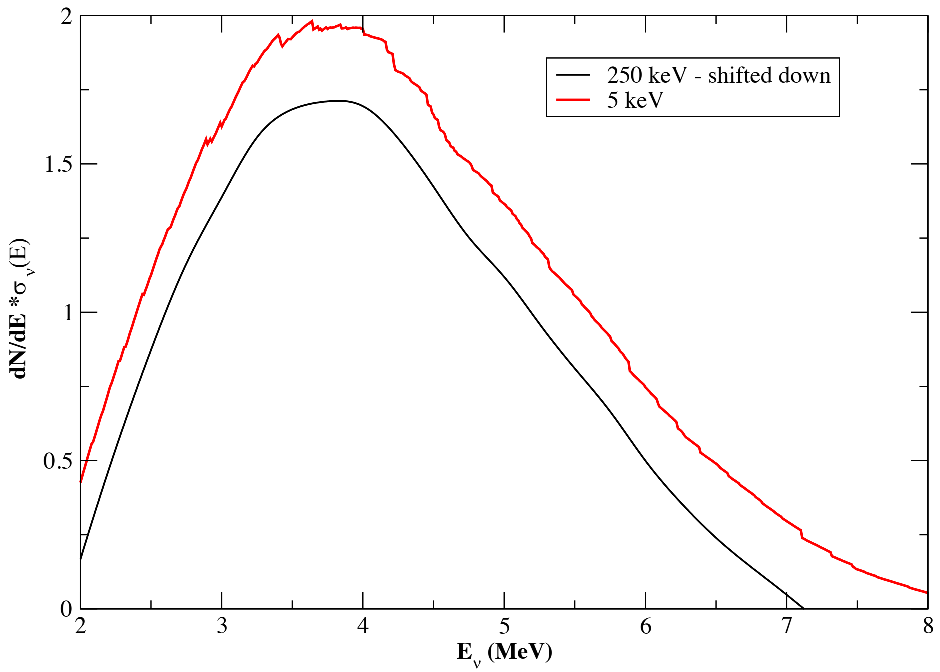
- Hundreds of fission fragments – **most all are neutron rich**
- Most fragments β-decays with several branches

$\Rightarrow$ About 6 ν_e per fission

$\Rightarrow$ Aggregate spectrum made up of thousands of end-point energies

Basic emitted and detected spectra





After folding with IBD detection cross section

Nucleus	Energy from mass excess	Without ν	E_{TOT} including n-captures
^{235}U	202.7±0.1	192.9±0.5	201.7±0.6
^{238}U	205.9±0.3	193.9±0.8	205.0±0.9
^{239}Pu	207.2±0.3	198.5±0.8	210.0±0.9
^{241}Pu	210.6±0.3	200.3±0.8	212.4±1.0

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$S(E_\nu) = \frac{W_{th}}{\Sigma_i (f_i/F) e_i} \Sigma_i \frac{f_i}{F} \left(\frac{dN_i}{dE_\nu} \right)$$

$$W_{th} = \Sigma_i f_i e_i$$

Two ways to determine the antineutrino spectra

- The summation method – Sum up all the beta decays, weighted by their fission yields.

$$\frac{dN_\nu}{dE_\nu} = \sum Y(Z,A) \sum B(E_0) P(E, E_0, Z, A)$$

Cumulative Fission yields

Beta branching ratios

Individual spectra

- The conversion method - Measure the beta electron spectrum and convert into an anti-neutrino spectrum

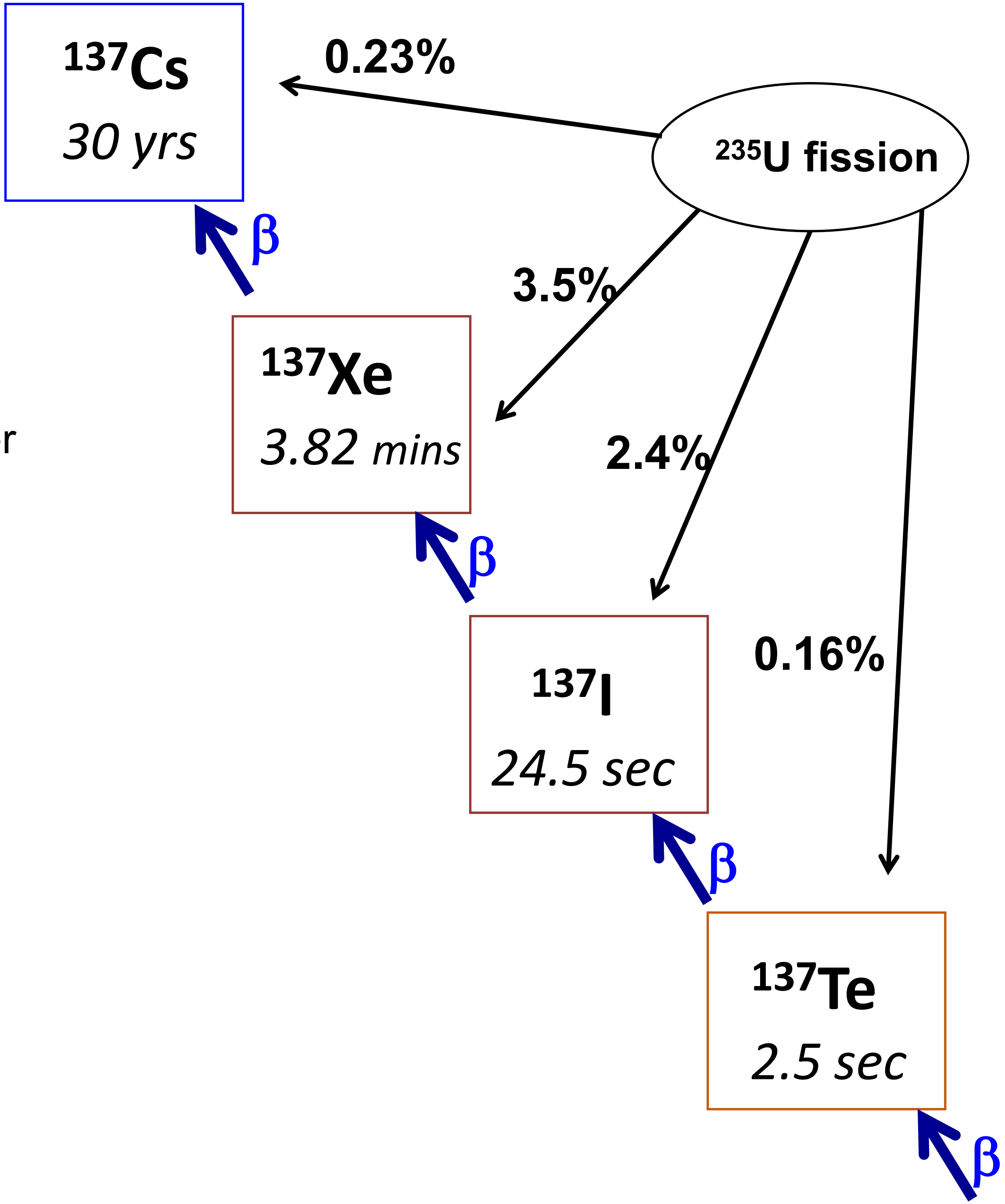
$$\frac{dN_e}{dE_e} \dashrightarrow \frac{dN_\nu}{dE_\nu}$$

Both methods introduce uncertainties

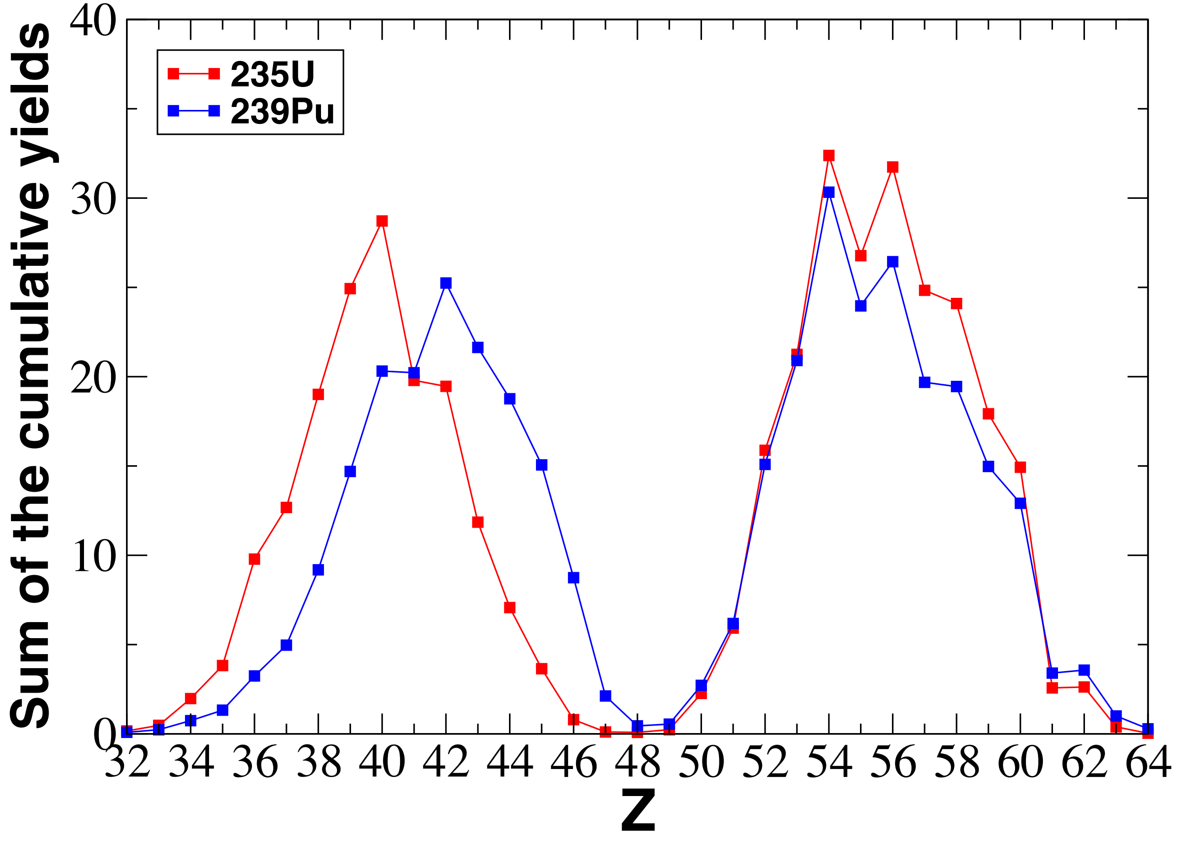
Cumulative fission yields determine the importance of a given fission fragment

- The cumulative yield is the number of atoms of a specific nuclide produced directly <u>plus</u> via decay of precursors per fission reaction.

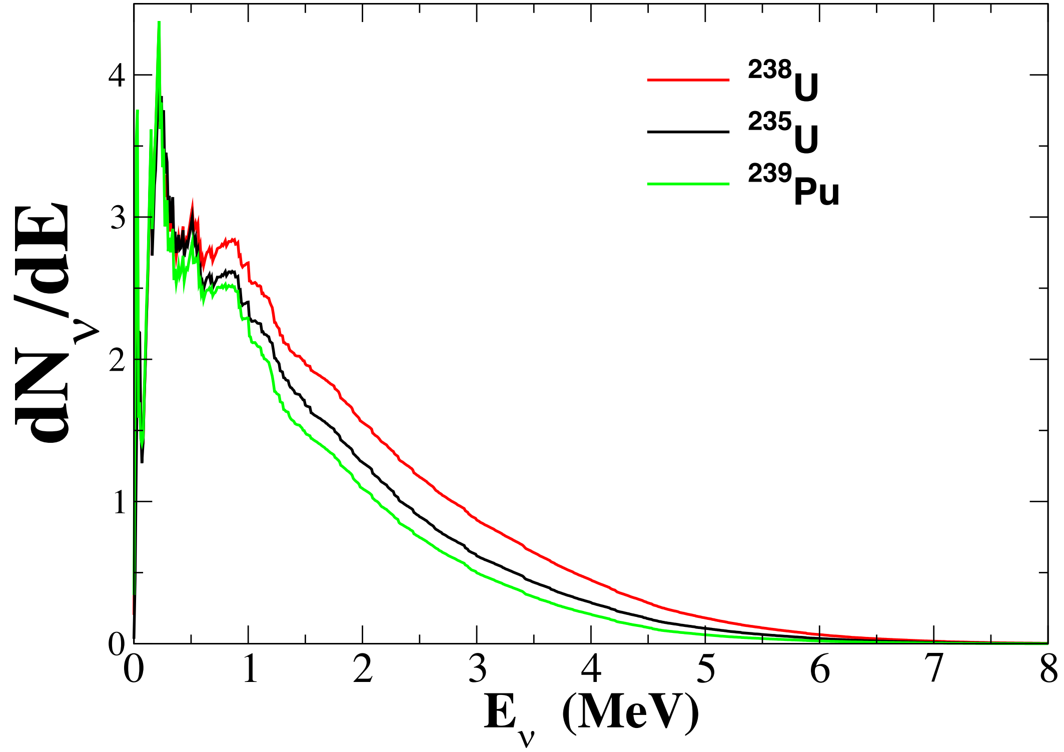
- If half-life is long the isotope never contributes in equilibrium and must be treated separately.

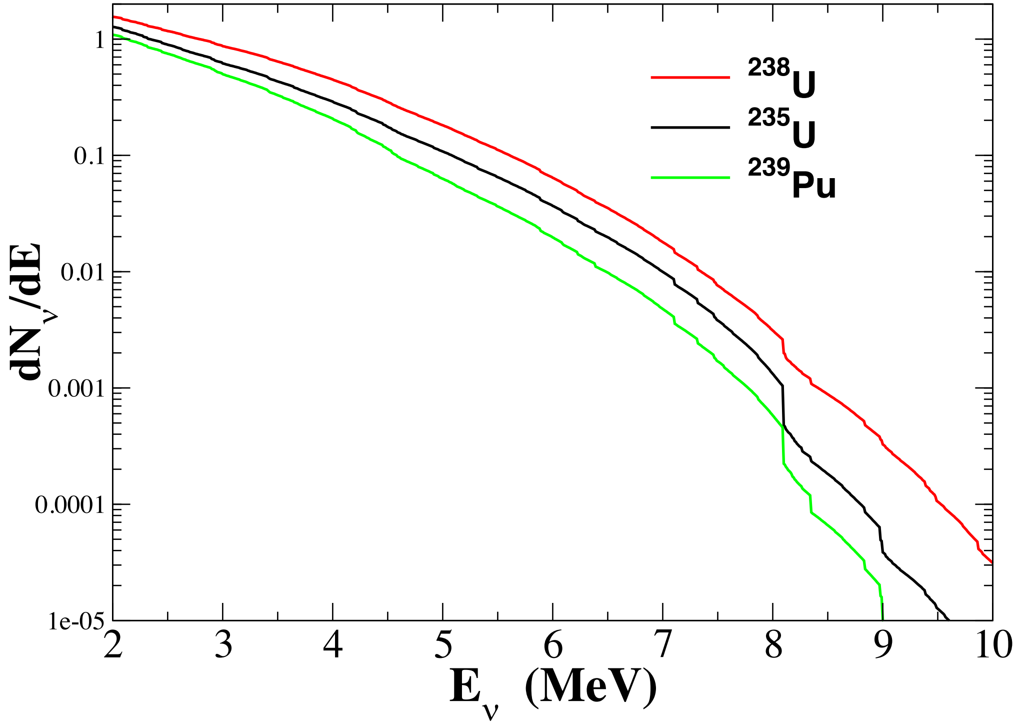


The anti-neutrino spectra for different actinides differ because of their fission fragment cumulative yields



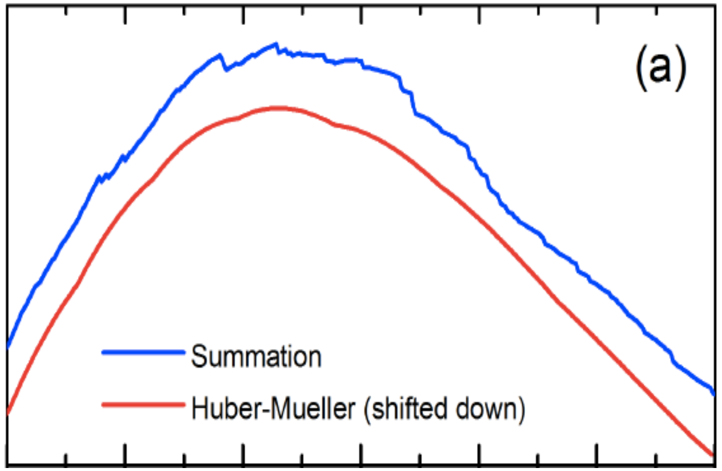
The resulting aggregate fission anti-neutrino spectra from the summation method range from 0-10 MeV, and falls off rapidly with increasing energy.

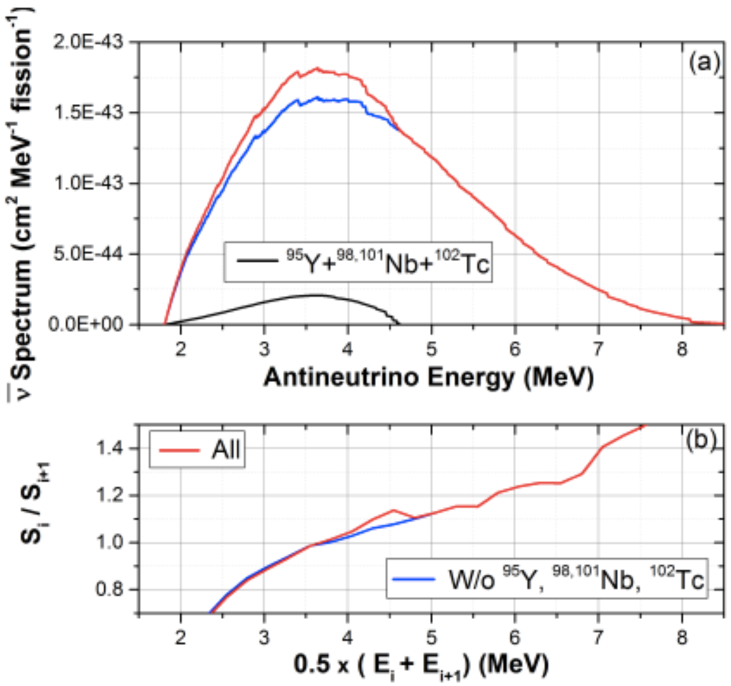




^{238}U, ^{235}U, ^{239}Pu, ^{241}Pu spectra similar in shape, but differ in magnitude by ~50%.

The Summation Method shows that Sawtooth-like Structures exist in the antineutrino spectra



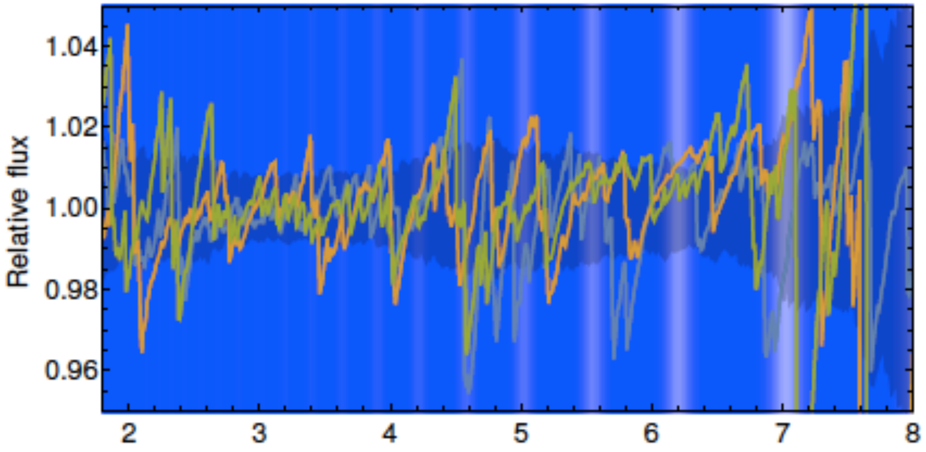


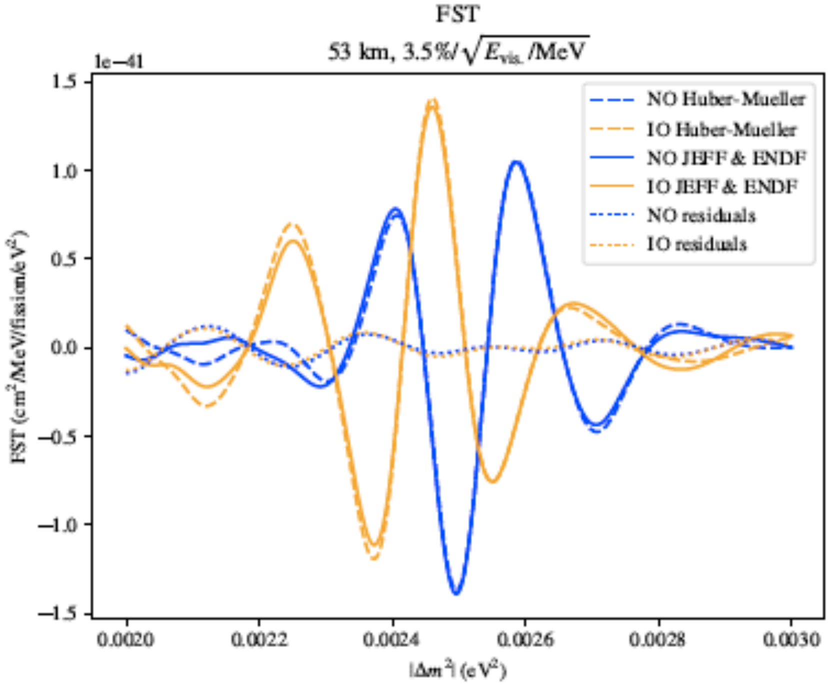
Sonzogni, Nina, & McCutchan have analyzed these structures in the Daya Bay spectrum.

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 need more analysis

D. L. Danielson, A. C. Hayes, and G. T. Garvey
Phys. Rev. D **99**, 03600

The Reactor Anomaly

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

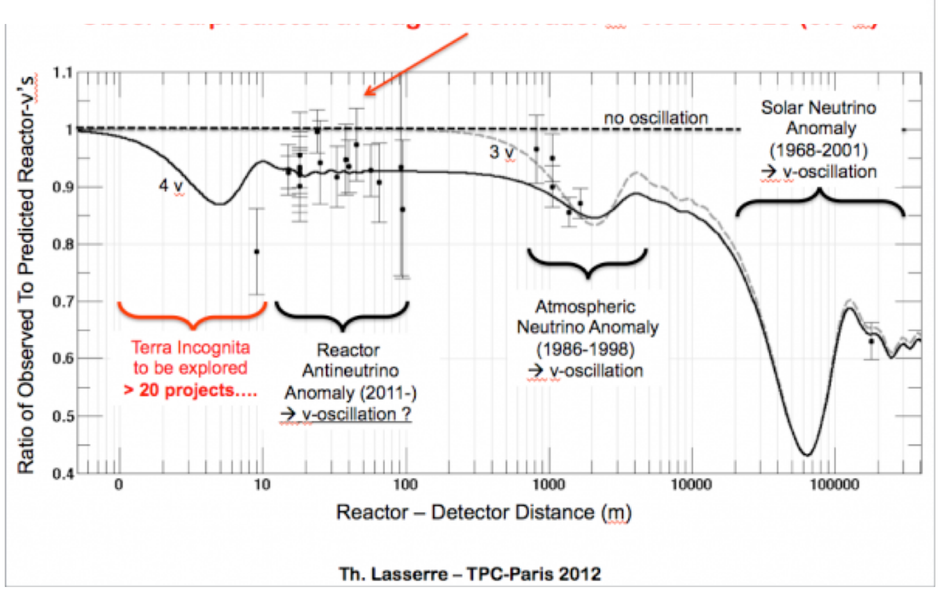
In the 1980s two predictions became the standards for the field:

- 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 5-6%.

This led to a 5-6% shortfall in the antineutrino flux in all short baseline reactor experiments - Reactor Neutrino Anomaly

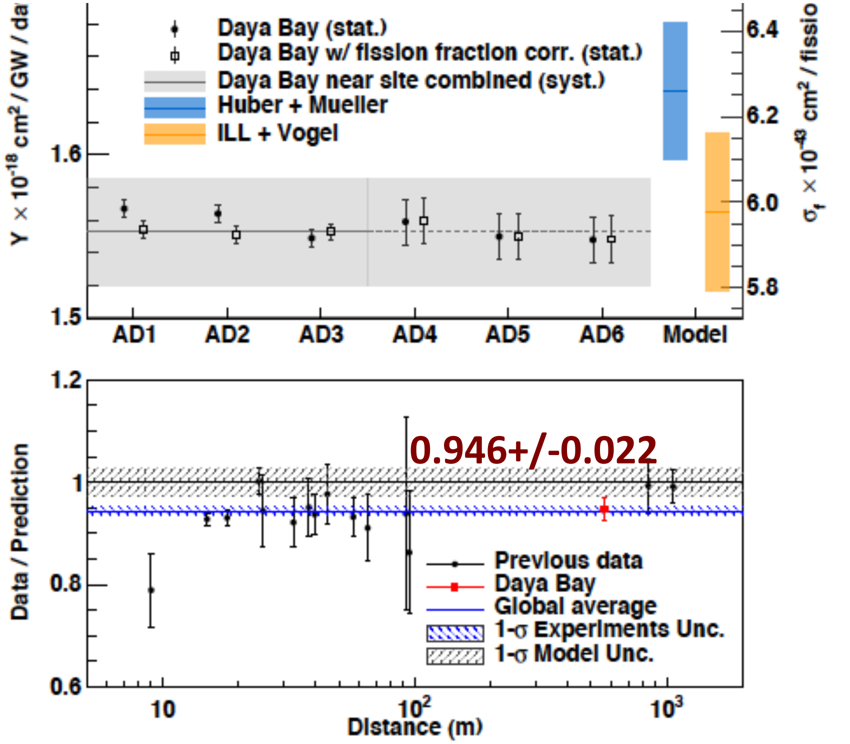
From Th. Lasserre, 2012



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.

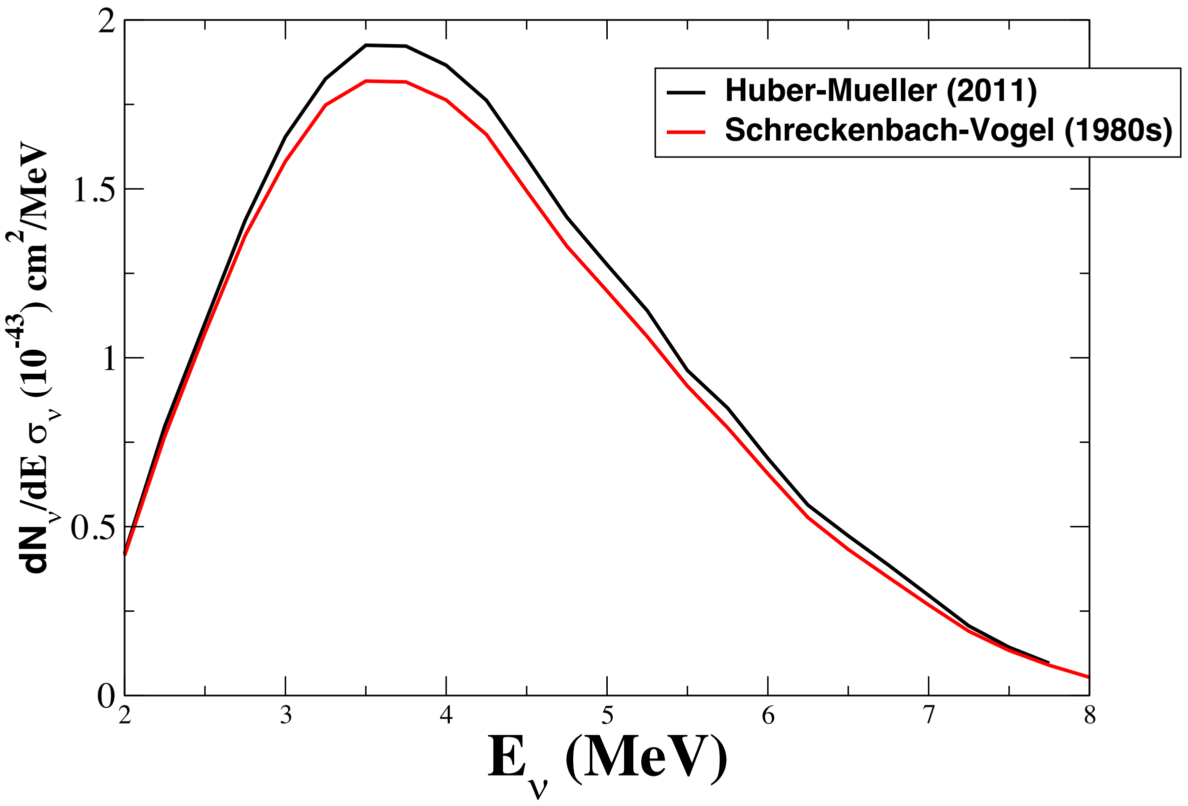
The issue then becomes ones of:

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

The change was largely as a consequence of:

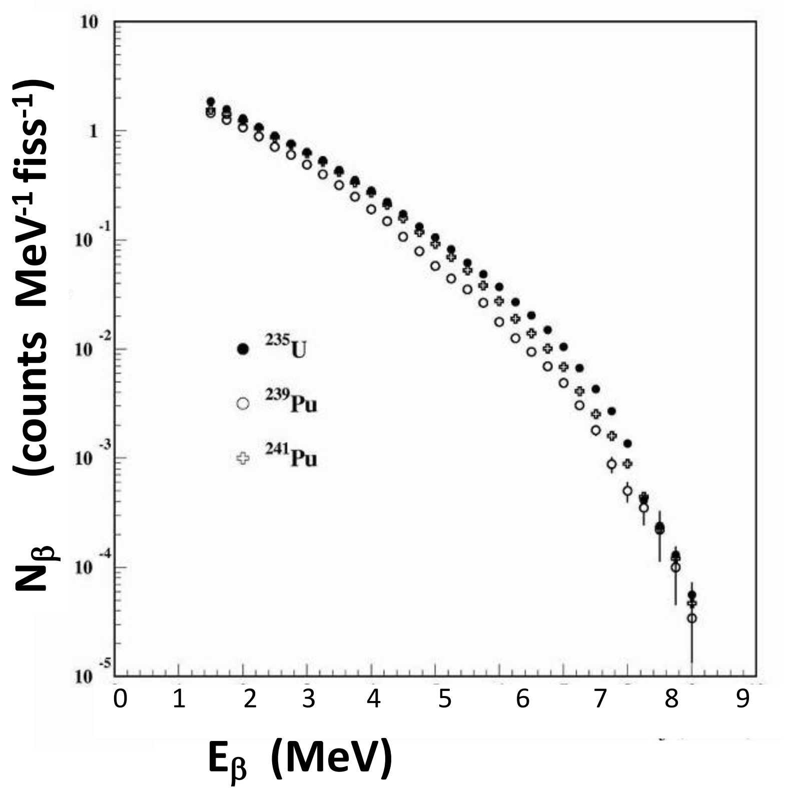
- A predicted increase in the energy of the Schreckenbach antineutrino flux for ^{235}U, ^{239}Pu , and ^{241}Pu.

- An overall increase in the ^{238}U antineutrino flux due to enhanced nuclear databases over 25 years.



For Daya Bay combination of fuel

The Original Expected Fluxes were determined via the Conversion Method using β-Spectra (electrons) made 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

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

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 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 Fermi function:

Z_{eff} used for Fermi function

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

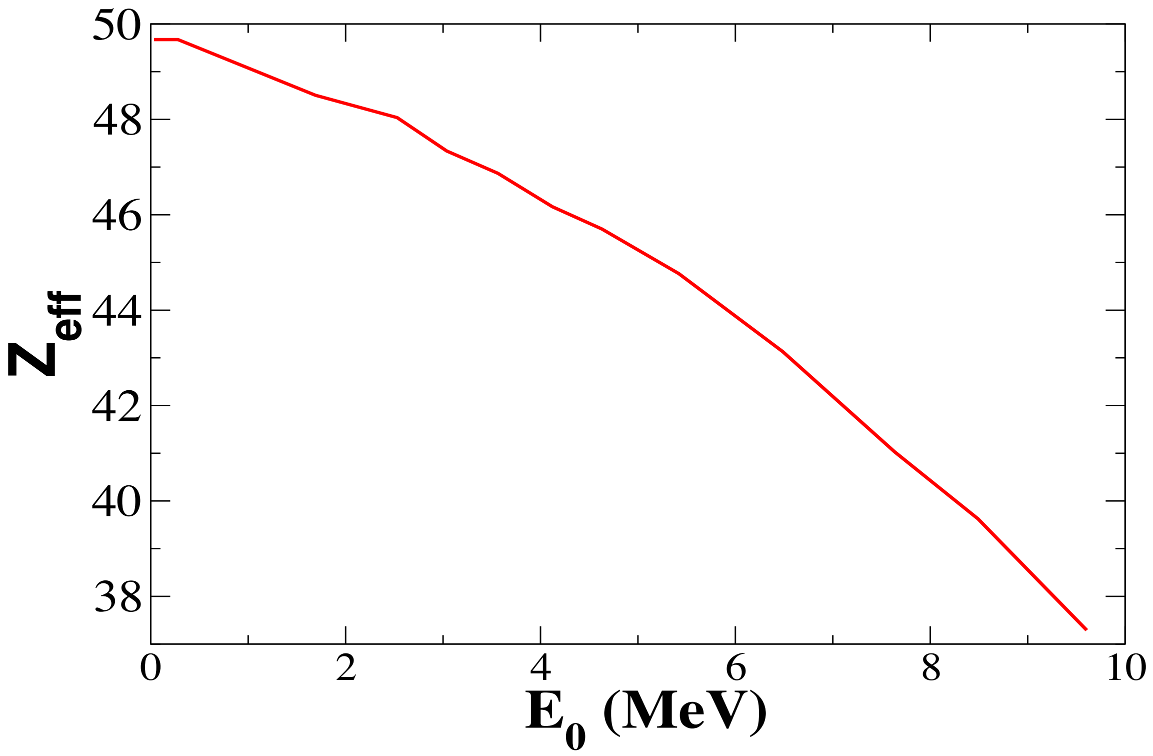
An energy-dependent Zeff representing the fission fragments is needed to determine the Fermi function

- On average, higher end-point energy means lower Z.
- Comes from nuclear binding energy differences

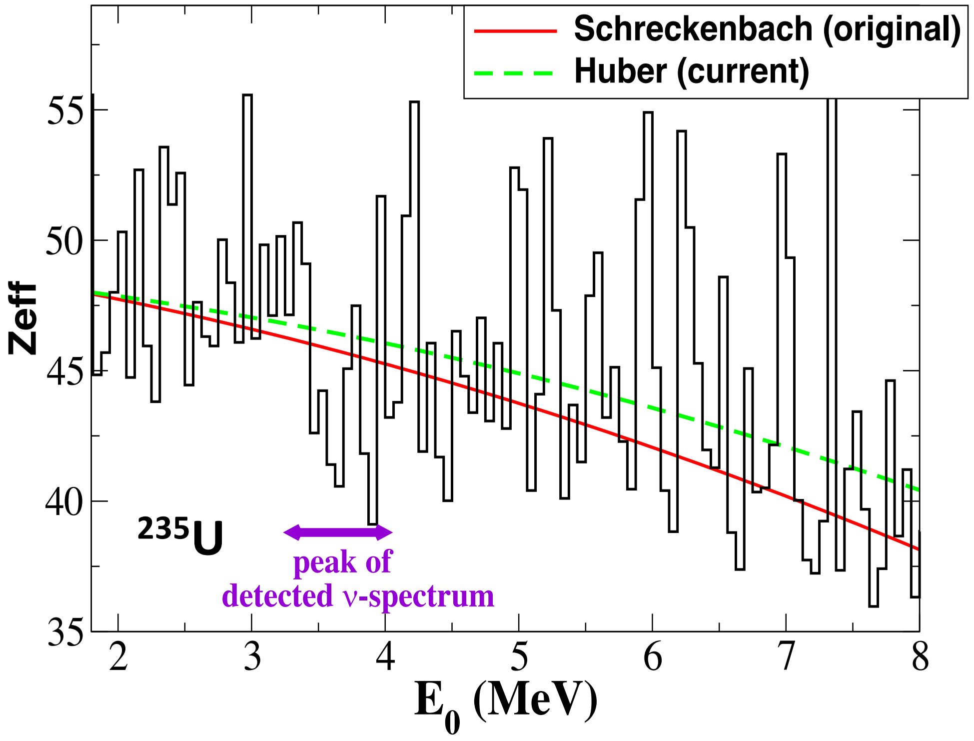
Parameterized used by both Schreckenbach and Huber involved a quadratic function:

$$Z_{eff} \sim a + b\ E_0 + c\ E_0^2$$

But the difference in their parameterizations is a large part of the problem anomaly.



The newer fit to Zeff used in the Fermi function for the conversion of the aggregate β-spectrum, led to a higher ν-spectrum



- **Huber's new parameterization of Zeff with end-point energy E_0 changes the Fermi function, accounting for 50% of the current anomaly.**
- **But the data do not follow a simple quadratic form.**

The corrections

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

$$\delta_{correction}(E_e, Z, A) = \delta_{FS} + \delta_{WM} + \delta_R + \delta_{rad}$$

δ_{FS} = Finite size correction to Fermi function

δ_{WM} = Weak magnetism

δ_{R} = Recoil correction

δ_{rad} = Radiative correction

- Recoil and radiative corrections are well-known and nucleus independent.

- The finite size and weak magnetism corrections are nucleus dependent and should be applied to each β-decay transition, which is a problem for the conversion method.

Corrections for GT Transitions

1. Finite size of the nucleus

Vogel, (Mueller)

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

Friar, Holstein

$$\delta_{FS} = A_c = -\frac{3 Z\alpha R}{2\hbar c}\left(E_\beta - \frac{E_\nu}{27} + \frac{m_e^2}{E_\beta}\right); \; R = \frac{36}{35}(1.2 A^{1/3})$$

2. Weak magnetism

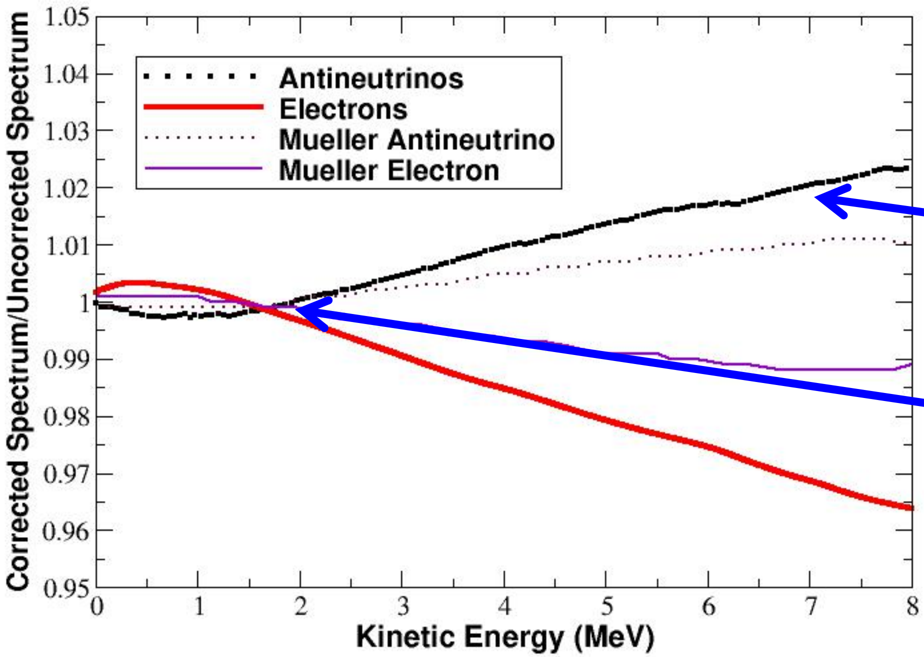
Vogel, (Mueller)

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

Friar, Holstein

$$\delta_{WM} = A_w = \frac{4(\mu_V - 1/2)}{6M_n}(E_\beta \beta^2 - E_\nu)$$

Effect of FS and MW Corrections to Spectrum using ENDF/B-VII, and assuming that all Transitions are allowed



$$\cong \frac{1}{2}\left[\frac{4(\mu_v - \frac{1}{2})}{3} - \frac{3Z\alpha R}{2\hbar c}\right]$$

$$\overline{E}_0 / 2$$

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

Uncertainties in the detailed contributions to the total spectra

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):

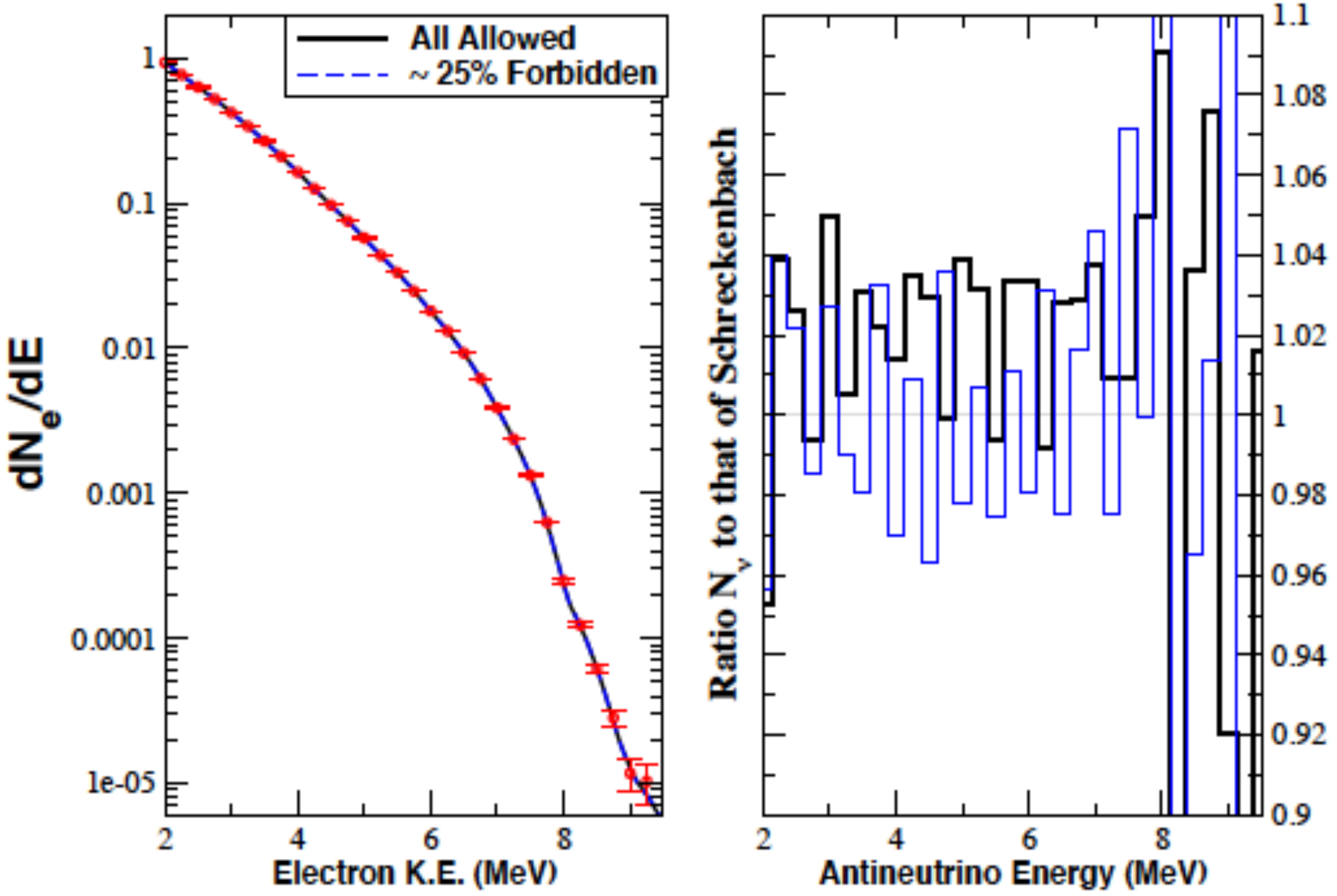
$$S(E_e,Z,A)=\frac{G_F^2}{2\pi^3}p_eE_e(E_0-E_e)^2\underline{C(E)}F(E_e,Z,A)(1+\delta_{corr}(E_e,Z,A))$$

The corrections for forbidden transitions are also 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	0
Non-unique 1st Forbidden F	1^-	$r\tau$	$p_e^2+E_\nu^2+\frac{2}{3}\beta^2E_\nu E_e$	0
Non-unique 1st Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	-

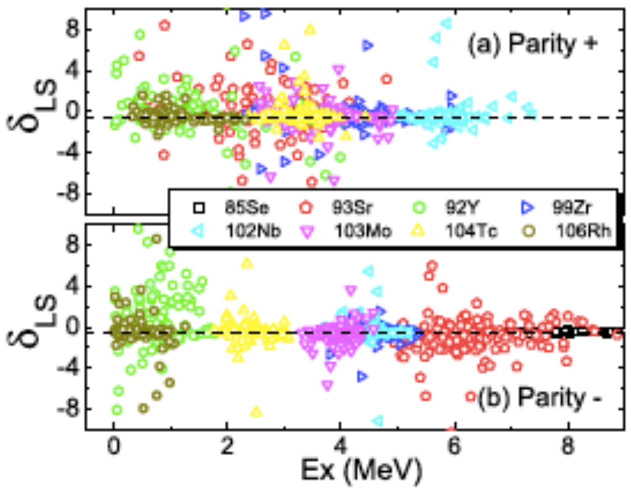
The forbidden transitions increase the uncertainty in the expected spectrum.

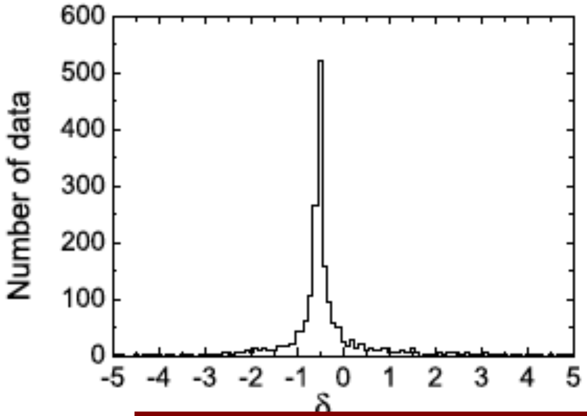
The forbidden transitions increase the uncertainty in the expected spectra.



Two equally good fits to the Schreckenbach β-spectra, 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





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

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

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

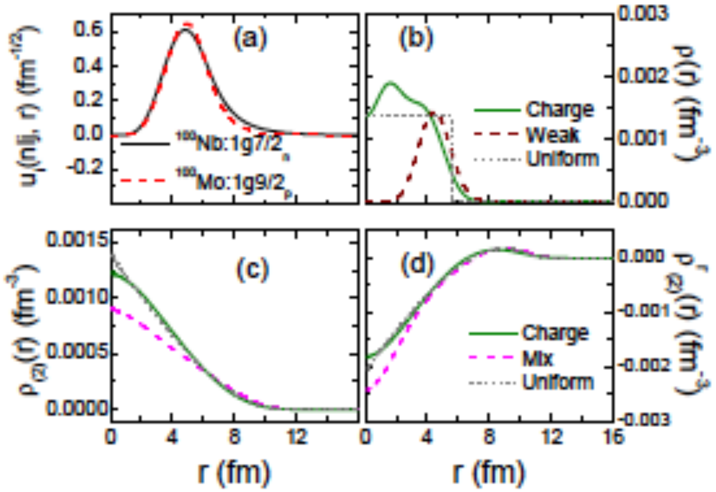
Estimated uncertainty ~ 30% for this 4% correction to the spectra

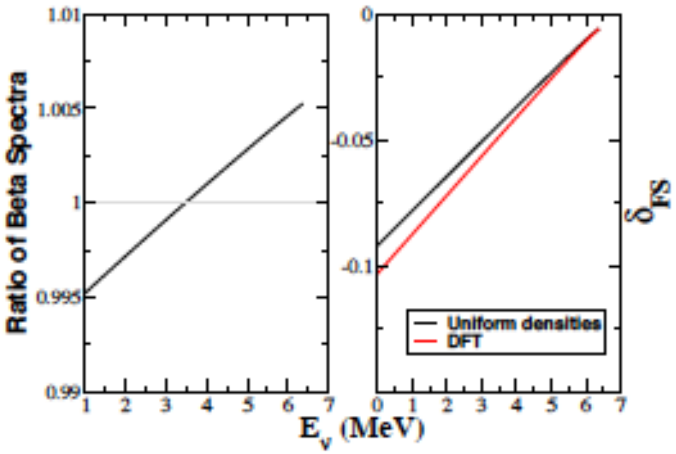
Wang and Hayes, Phys. Rev. C 95, 064313 (2017) .

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

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

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



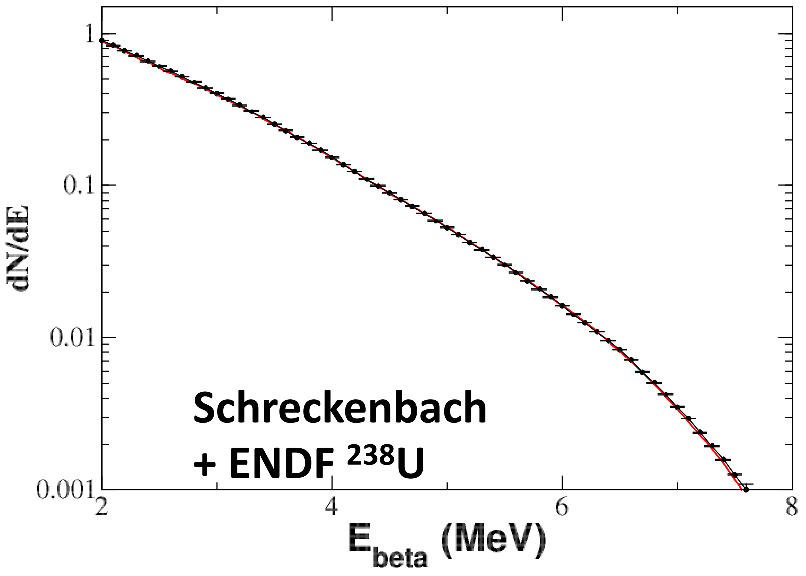


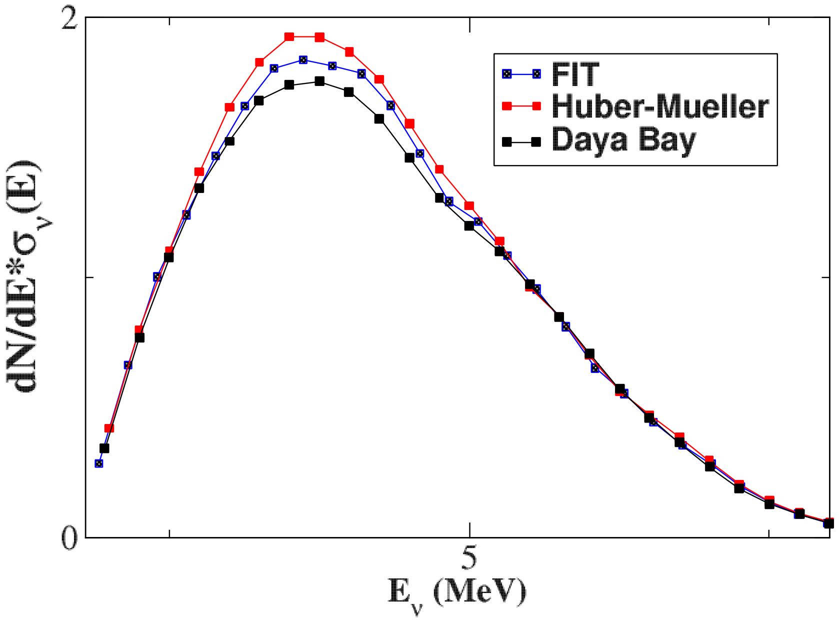
- **Found to be a good approximation for allowed transitions.**
- **Not checked for forbidden transitions.**

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%



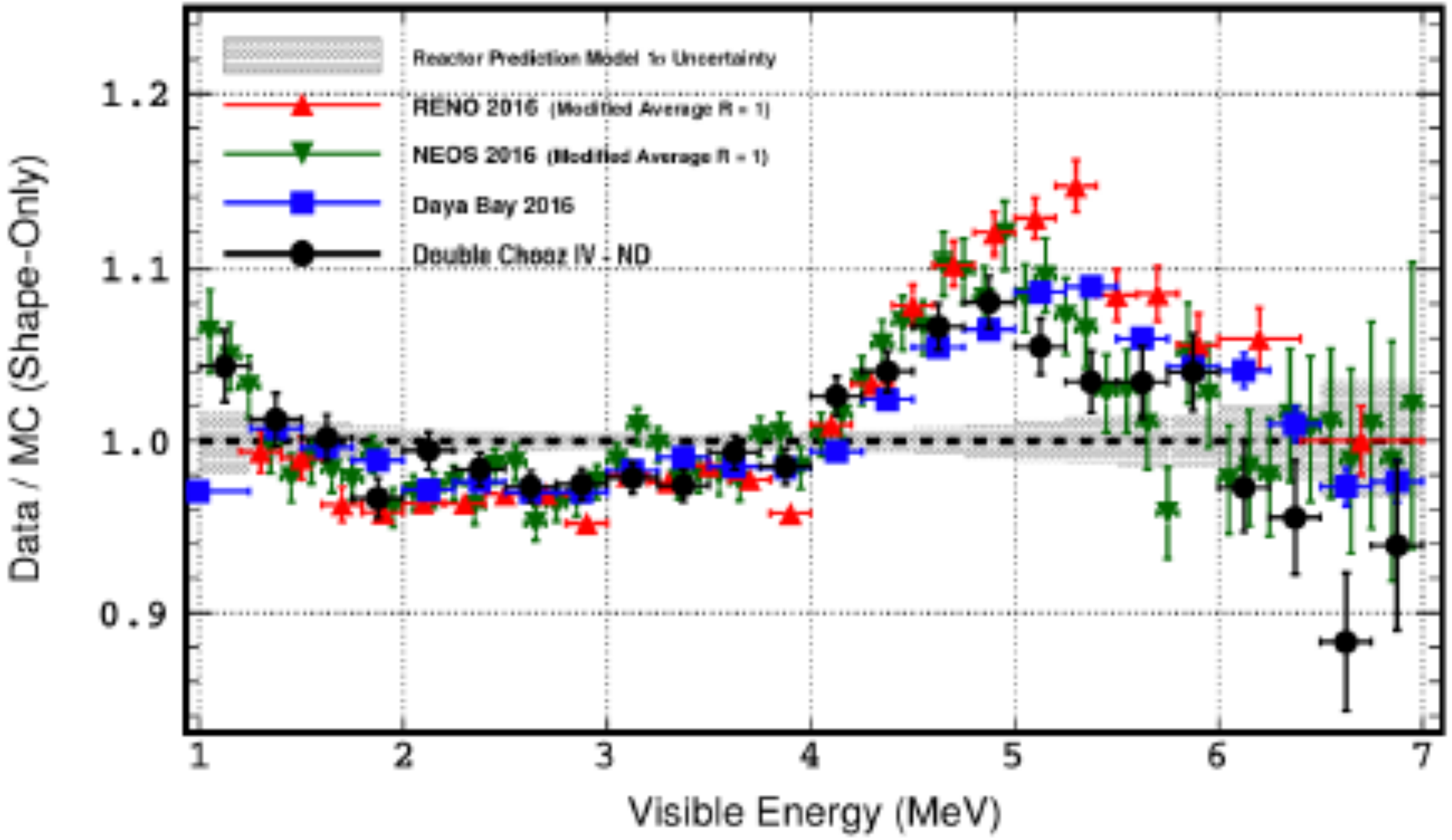


The magnitude of the IBD cross sections change, depending on assumptions, but not the ratio of one isotope to another

	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

A ‘BUMP’ is seen in the Measured Spectra compared to predictions

The Reactor Neutrino ‘BUMP’



Expectations:
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).

Laura Bernard, STEREO (from Moriond 2019)

Possible Origins of the 'Bump'

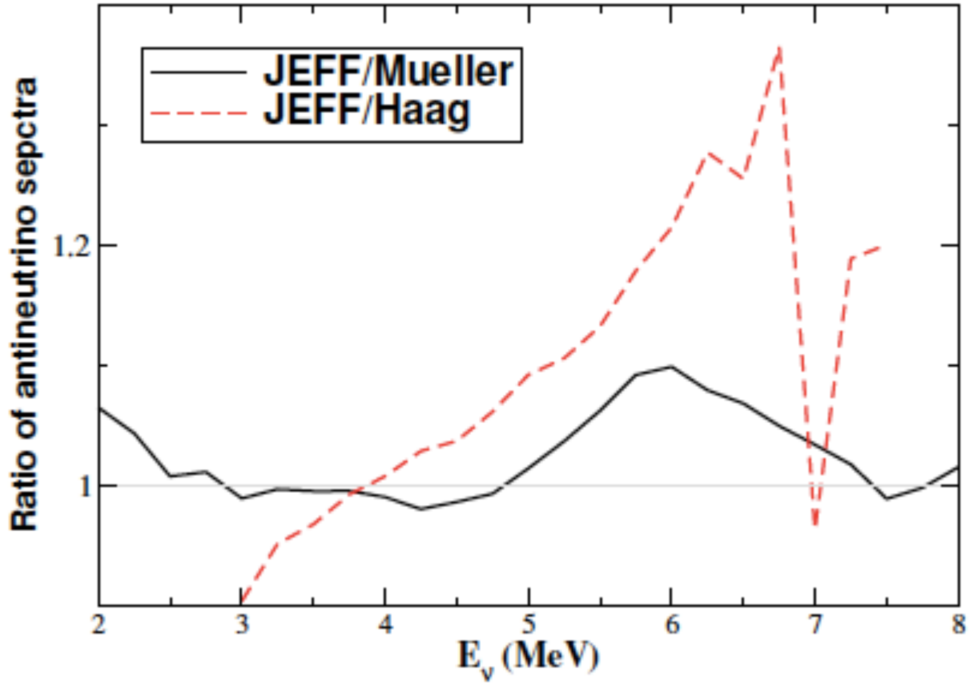
- ^{238}U as a source of the shoulder
  – Possible because ^{238}U has a hard spectrum and contributes significantly in the Bump energy region. It is also the most uncertain actinide.

- 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'.

For example, if the BUMP does not change with the fuel evolution, ^{238}U is a likely source



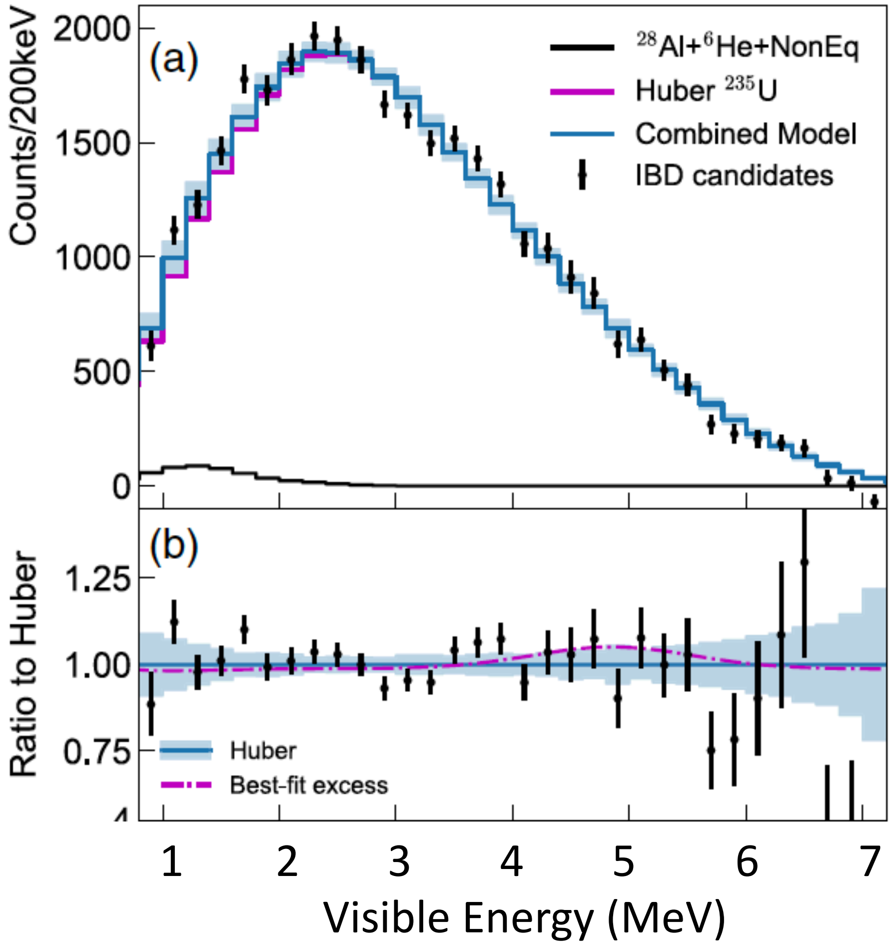
Relative to the JEFF database, both Mueller and Haag show a BUMP.

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

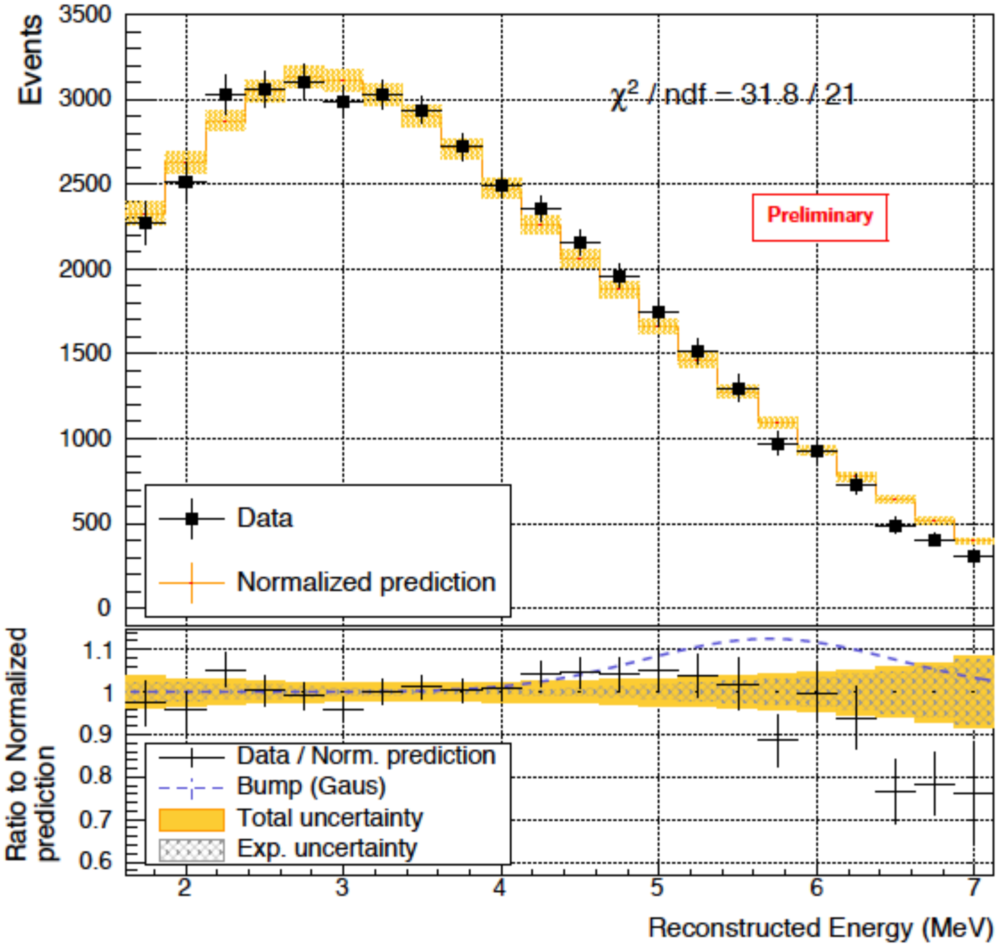
- If this is the correct explanation, the current VSBL experiments with highly enriched ^{235}U reactor will not see a BUMP.
- If, on the other hand, the ILL data are responsible <u>all</u> VSBL expts will see the Bump.

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

VSBL Measurements by STEREO (ILL) and PROSPECT (HIFR), both 100% ^{235}U



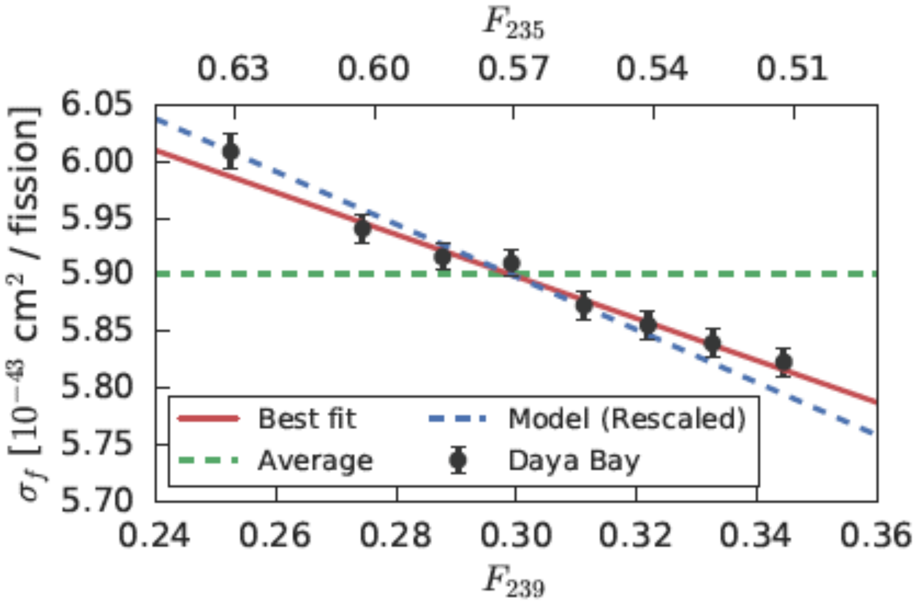
PROSPECT

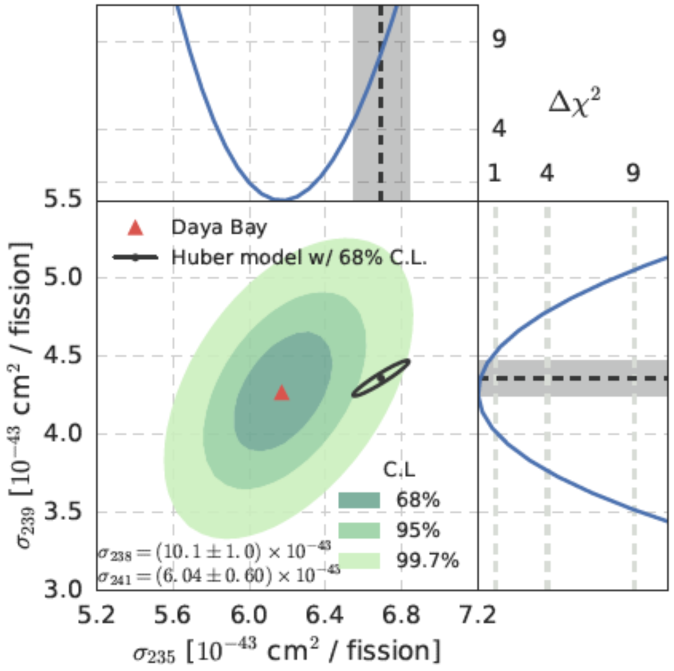


STEREO

Changes in the Antineutrino Spectra with the Reactor Fuel Burnup

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



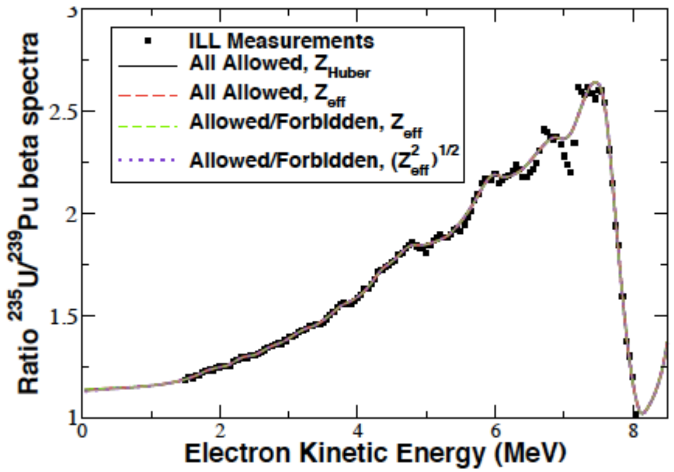


$$\sigma_f(F_{239}) = \bar{\sigma}_f + \frac{d\sigma_f}{dF_{239}}(F_{239} - \overline{F}_{239})$$

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

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

The discrepancy between current Huber-Mueller model predictions and the Daya Bay results can be traced to the original Schreckenbach measured $^{235}U/^{239}Pu$ ratio



Using different will change the IBD cross sections for ^{235}U and ^{239}Pu.

	all allowed $Z_{\rm eff}^{\rm Huber}$	all allowed $Z_{\rm eff}$	allow.+forbid. $Z_{\rm eff}$	allow.+forbid. $(Z^2_{\rm eff})^{1/2}$
^{235}U	6.69	6.58	6.47	6.48
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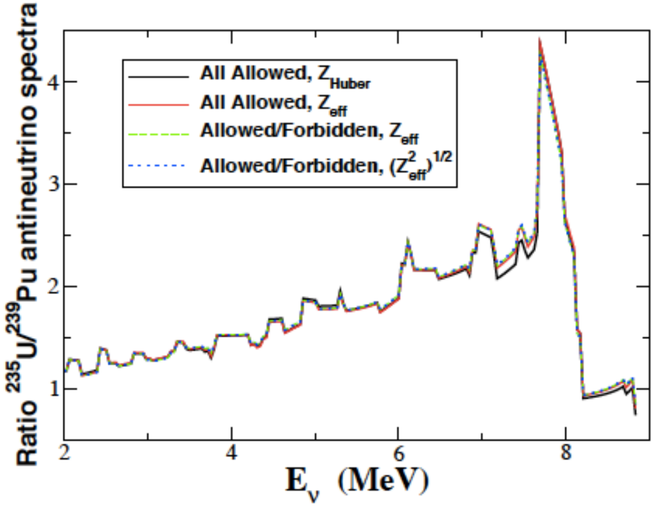
ratio	1.534	1.530	1.533	1.532

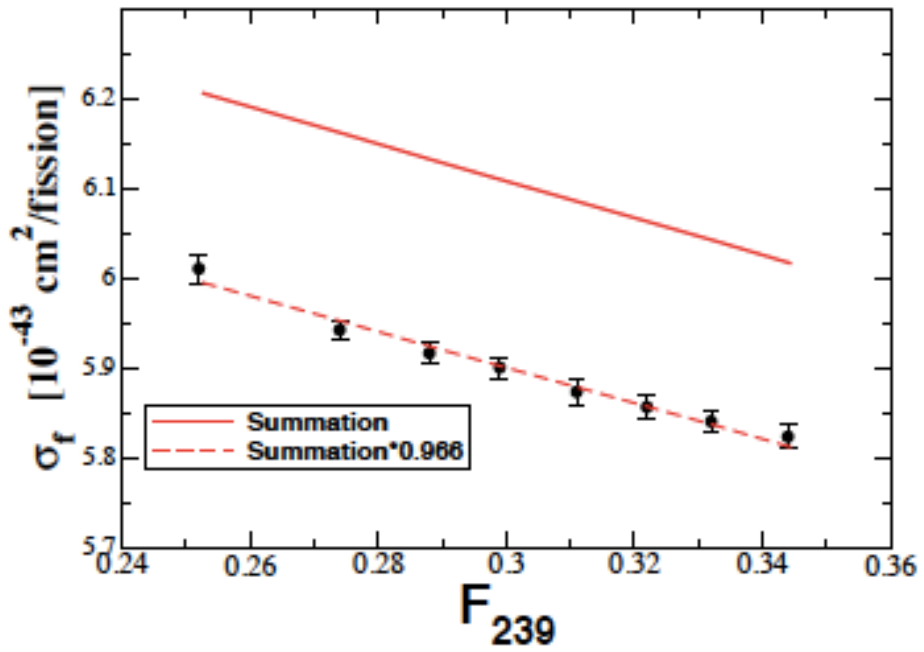


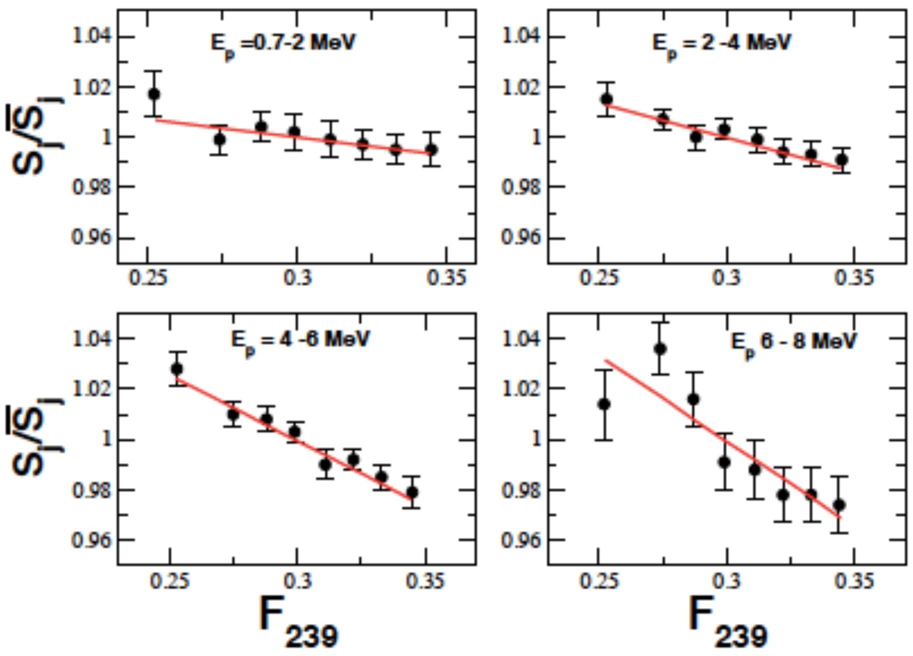
But the ratio of $^{235}U/^{239}Pu$ is fixed.

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

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

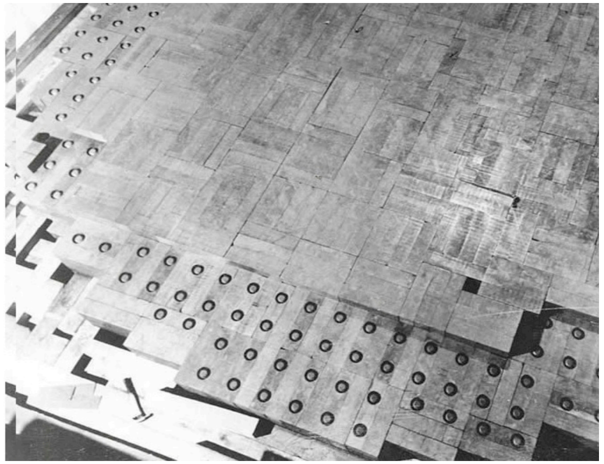
The Nuclear database explains all of the Daya Bay fuel evolution data, but still allows for a (smaller) anomaly





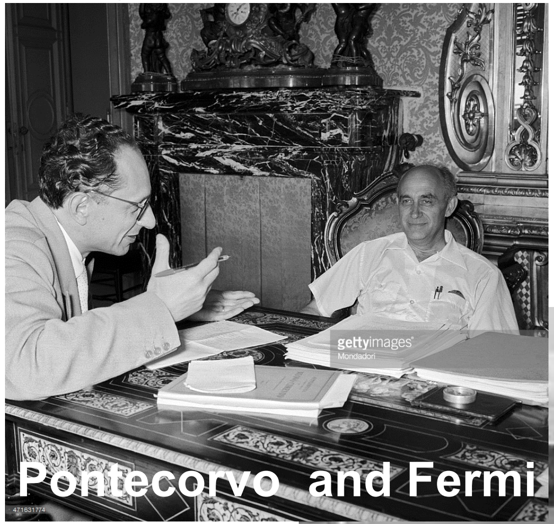
- **The IBD yield is predicted to change with the correct slope.**
- **But the absolute predicted value is high by 3.5%.**
- **This anomaly is not statistically significant but it means that Daya Bay evolution data do not rule out sterile neutrinos.**

Neutrino Physics and Applied Reactor Physics share many scientists and research interests



1st Reactor

- **Fermi** designed and built the first reactor.
- His four-fermion weak theory of weak interactions works remarkably well.



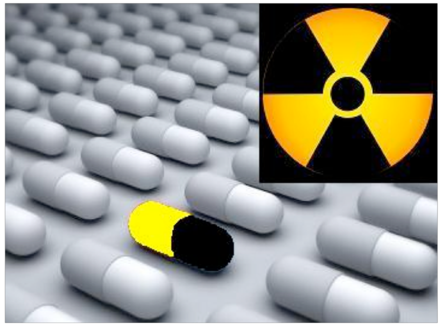
Pontecorvo and Fermi

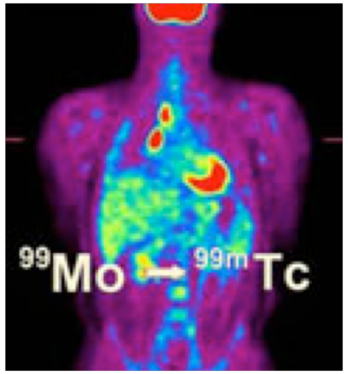
- **Pontecorvo** worked on the world's first heavy water nuclear reactor at Chalk River, Ontario.
- Many papers on reactor physics, including the theory of breeder reactors.

NRX, Chalk River

Unique Properties of Fission Fragments are used Address Many "Societal Needs"

- **Energy**
- **Reactor safety - Decay Heat**





- **Medical radio-pharmaceuticals**
- **Medical Imaging**

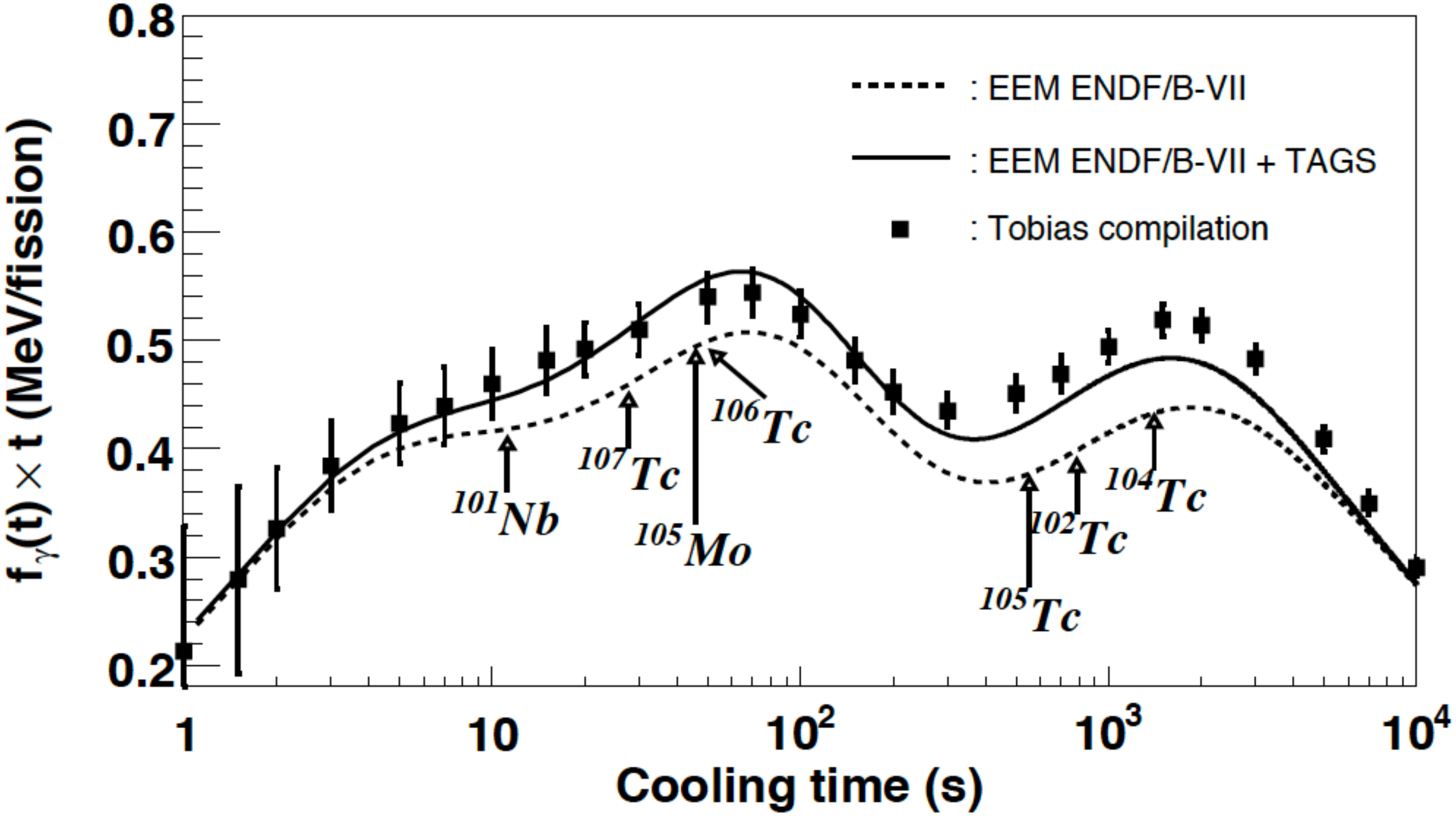
- **Non-proliferation**
- Reactor Safeguards nuclear Weapons production monitoring

Reactor Neutrino Studies directly contributing to these applied fields.

A. Hayes, Applications of NP, Rep. Prog. Phys. 80 (2017) 026301

NP Decadal Study: Exploring the Heart of Matter (2013)

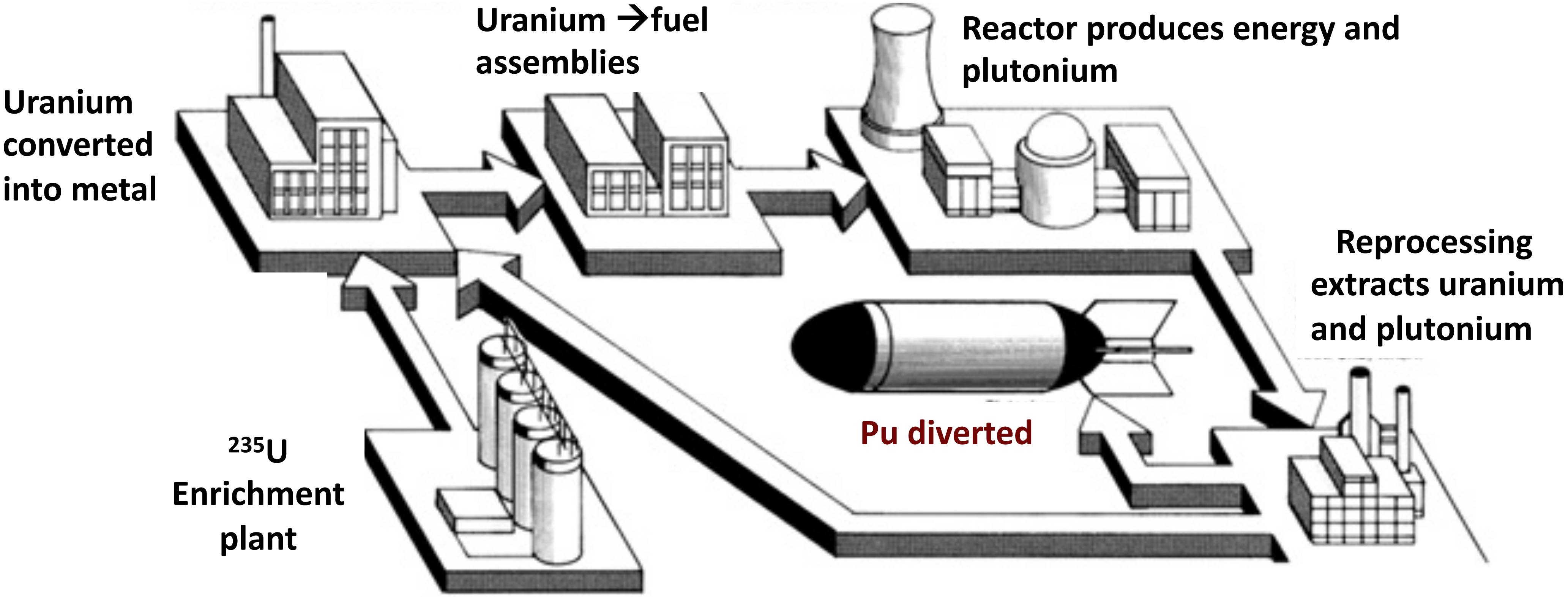
The same fission fragments dominate both decay heat and anti-neutrino spectra



Knowledge of decay heat crucial for safe reactor shutdown

Applied physics community now play a lot of attention to their ability to reproduce measured anti-neutrino spectra

Monitoring for Weapons Production in the Nuclear Fuel Cycle also uses knowledge of cumulative fission fragment yields

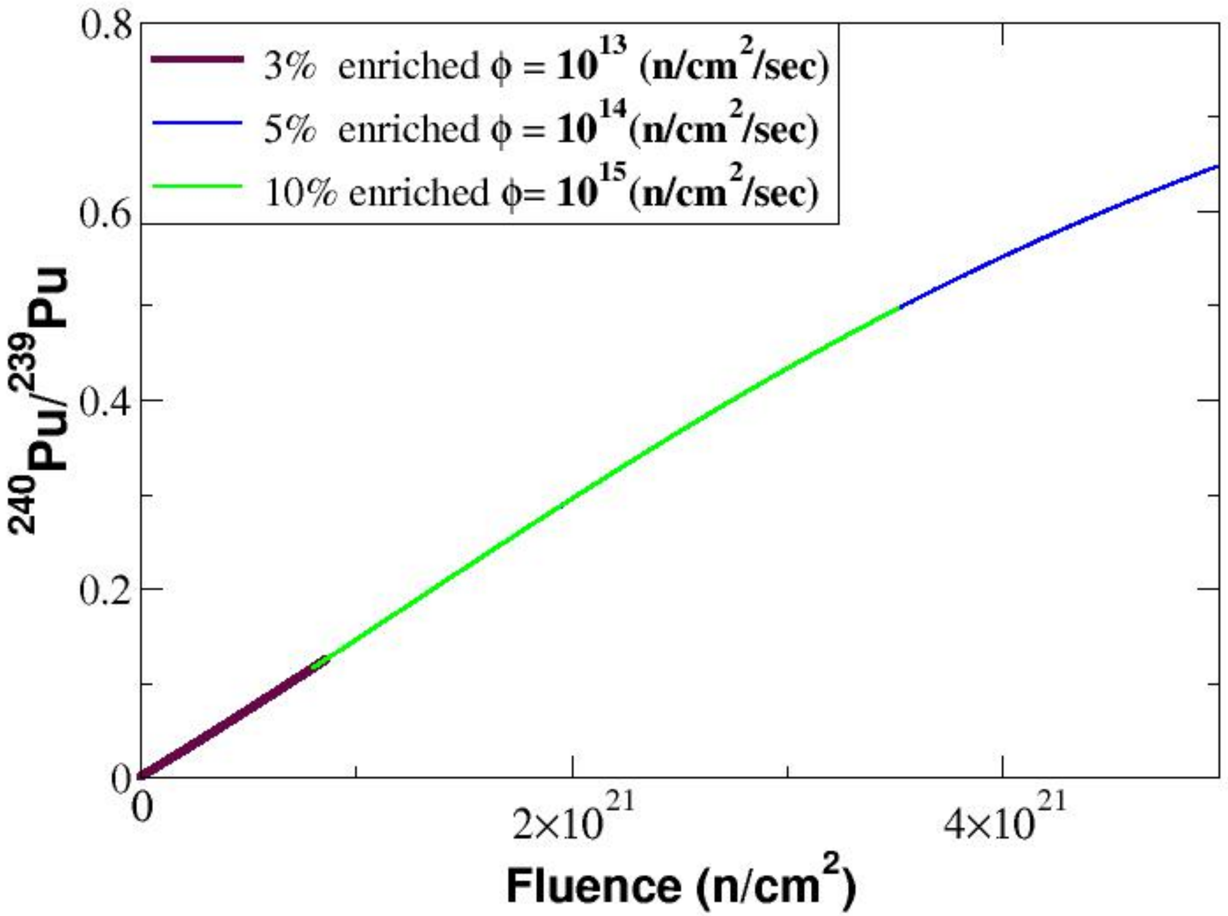


Looking for undeclared weapons-grade Pu production in fuel cycle

Pu Grade and neutron fluence

Pu Grade determined solely by Neutron Fluence

- Not separately dependent on the neutron flux or U enrichment
- Fluence can be determined from fission fragments in the fuel



$$\frac{^{240}Pu}{^{239}Pu} = \tfrac{1}{2}\sigma\,\Phi_n + O(\Phi^2)$$

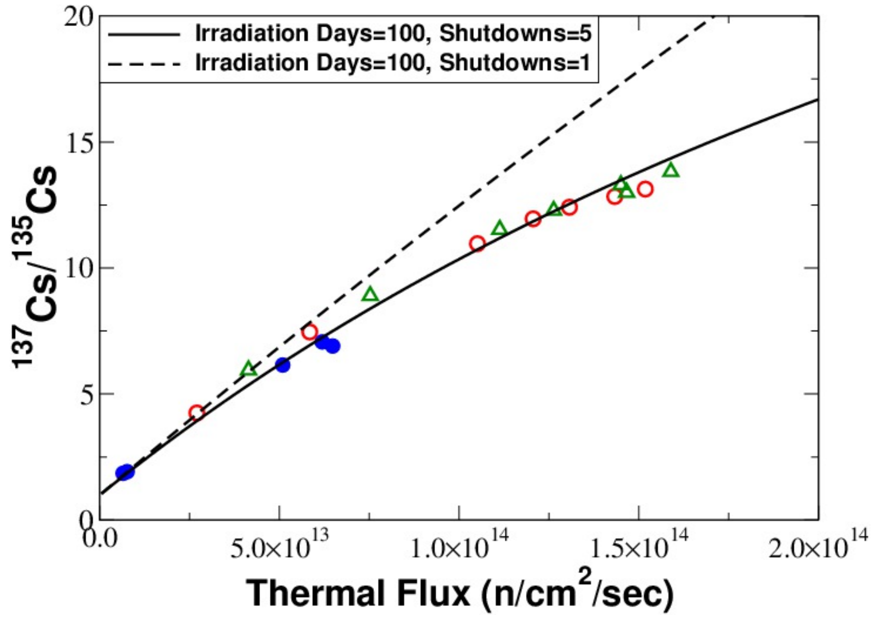
Weapons: 93% ^{239}Pu, 6% ^{240}Pu + 1%higher
Reactor: 60% ^{239}Pu, 25% ^{240}Pu + 15%higher

Neutron fluence determinations also reply on cumulative fission yields

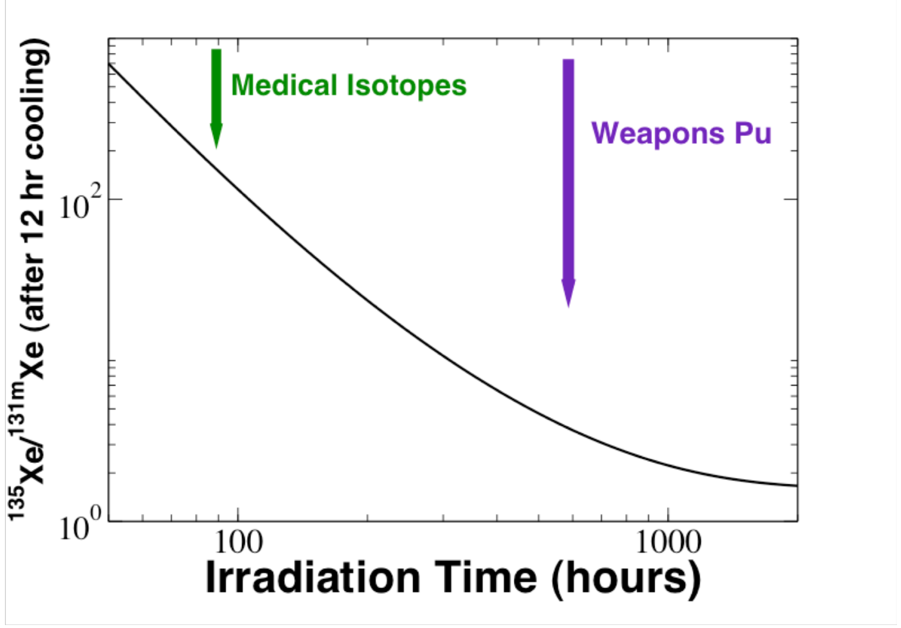
Divide the Problem into Two Quantities

Neutron Fluence = Flux * Irradiation Time

Deduce from ^{136}Xe or ^{135}Cs



Deduce from the competition between beta decay rates and fission rates



A.C.H., G. Jungman, Nucl.Inst. Meth,.690 2012, Pages 68-74

Summary

- Four classes of experiments do no fall into the standard 3-ν oscillation picture:
  LSNL, MiniBooNE, the Reactor Anomaly and the Gallium Anomaly.

- Several of the Anomalies involve detailed nuclear physics issues.

- Much of the physics feeds into Applied Nuclear Physics.

- Improved treatments of the nuclear physics tends to reduce the size of the reactor neutrino anomaly.

- The new short baseline experiments will address all of the remaining puzzles.