Uncertainties in the Reactor Neutrino Anomaly

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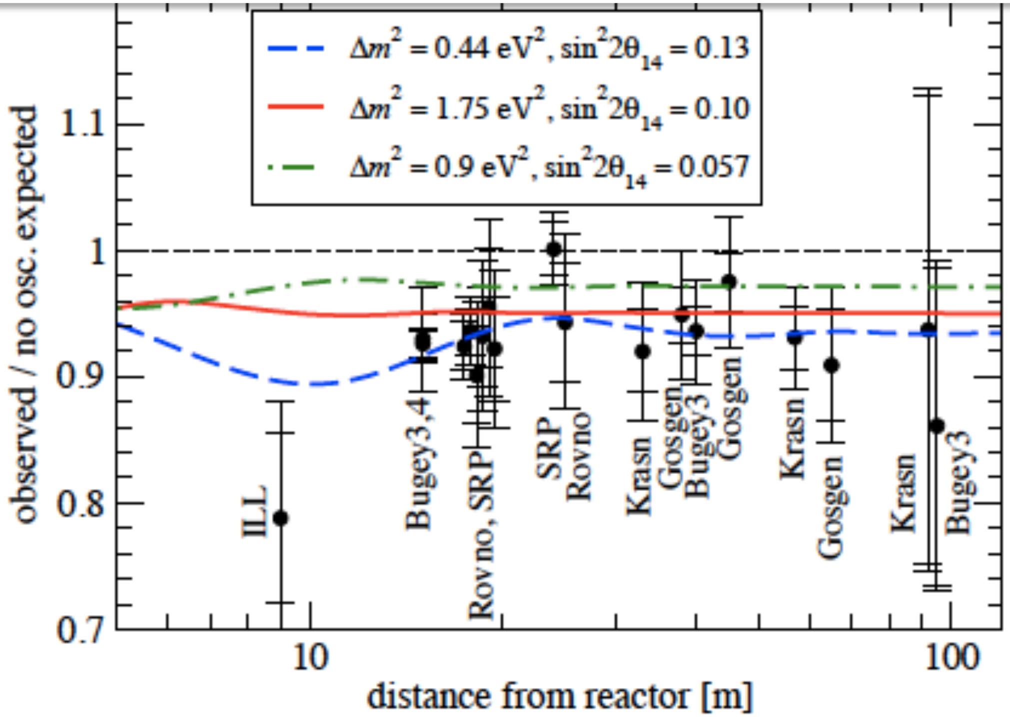
The Reactor Antineutrino Anomaly

obs/expected=0.94 (~3σ) deficit in the detected antineutrinos from short baseline reactor experiments



From J. Kopp, et al.
JHEP 05 (2013)050

The effect mostly comes from the detailed physics involved in the nuclear beta-decay of fission fragments in the reactor

Additional contributions from (1) Off-equilibrium nuclei and (2)Increase in the detection cross section

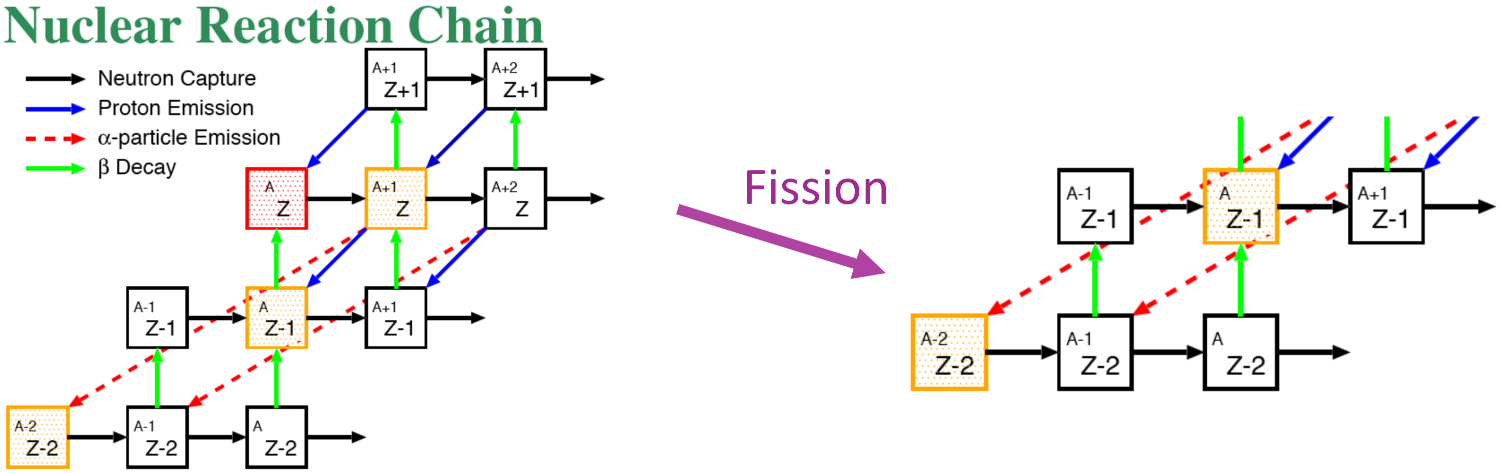
Outline

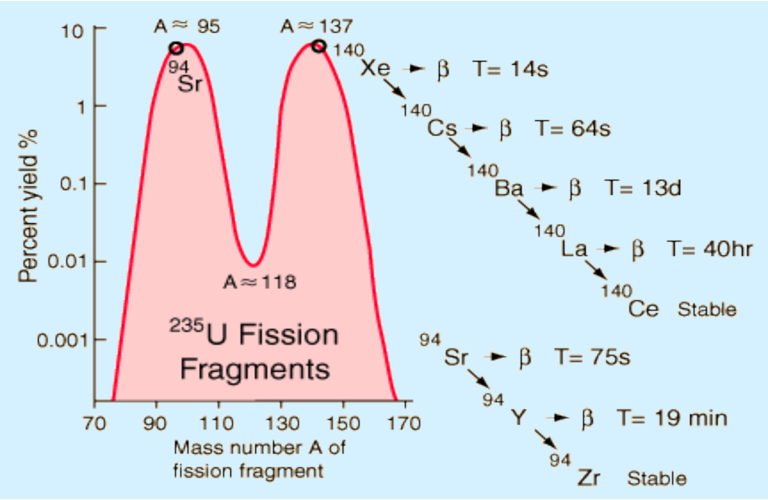
- **The origin if the anomaly**
  - Correction to beta-decay (finite size and weak magnetism)
  - The form of the corrections and the effect on the antineutrino spectrum

- **The large role of forbidden transitions**
  - Uncertainty in the correction
  - Uncertainty in the fit of the beta spectrum to obtain the antineutrino spectrum

- **The 'BUMP' in the measured antineutrino spectra**
  - The apparent origin of the bump
  - Significant implications of the bump for the uncertainty in the 'expected' antineutrino spectrum

Beta-decay of fission fragments produce antineutrinos at a rate of ~10^{20} ν/sec for a 1 GW reactor





- •Hundreds of fission fragments – all neutron rich

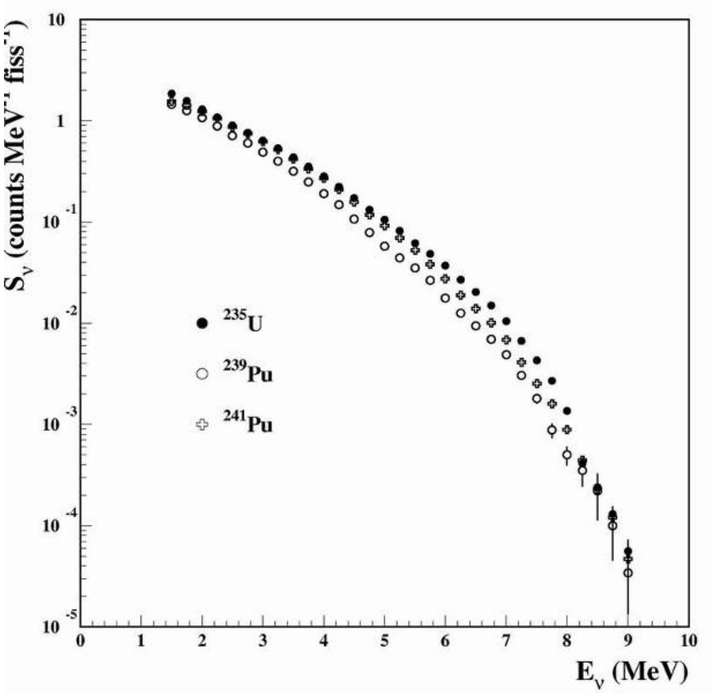
- Most fragments β-decays with several branches

⇒ Approximately 6 ν_e per fission

⇒ Aggregate spectrum made up of about six thousands of end-points

About 1500 of these transitions are so-called forbidden transitions

The antineutrino flux used in oscillations experiments is from a conversion of the aggregate beta spectra from ILL



K. Schreckenbach et al. PLB118, 162 (1985)

A.A. Hahn et al. PLB160, 325 (1989)

P. Vogel et al., PRC 24 1543 (1981)

- Measurements at ILL of thermal fission beta spectra for ^{235}U, ^{239}Pu, ^{241}Pu
- Converted to antineutrino spectra by fitting to 30 end-point energies
- Use Vogel *et al*. ENDF estimate for ^{238}U ^{238}U ~ 7-8% of fissions =>small error
- All transitions were treated as allowed GT

FIT

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

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

Known corrections to β-decay are the main source of the anomaly

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

Fractional corrections to the individual beta decay spectra:

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

δ_{rad} = Radiative correction (used formalism of Sirlin)

δ_{FS} = Finite size correction to Fermi function

δ_{WM} = Weak magnetism

Originally approximated as:

$$\delta_{FS} + \delta_{WM} = 0.0065(E_\nu - 4MeV))$$

The difference between this original treatment and an improved treatment of these corrections is the main source of the anomaly

The finite nuclear size correction

Normal (point-like) Fermi function:
Attractive Coulomb Interaction *increases* electron density at the nucleus
=> beta-decay rate *increases*

Finite size of Nucleus:
Decreases electron density at nucleus (relative to point nucleus Fermi function)
=> Beta decay rate *decreases*

Two contributions: nuclear charge density $\rho_{ch}(r)$ and nuclear weak density $\rho_W(r)$

For GT transitions:

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

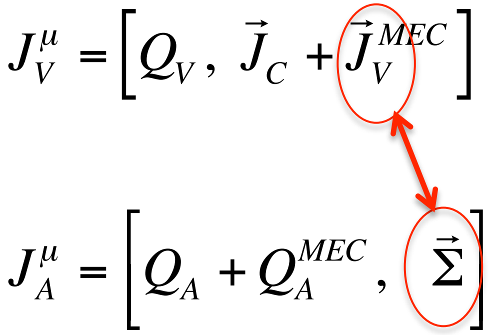
$$< r >_{(2)} = \int r\, d^3r \int d^3s\, \rho_W(|\vec{r} - \vec{s}\,|)\ \rho_{ch}(s)$$

-First moment of convoluted weak and charge densities
= 1st Zemach moment

The weak magnetism correction

Interference between the magnetic moment distribution of the vector current and the spin distribution of the axial current.

This *<u>increases</u>* the electron density at the nucleus => beta decay rate *<u>increases</u>*



$$J_V^{\mu} = \left[Q_V \,,\ \vec{J}_C + \vec{J}_V^{MEC} \right]$$

$$J_A^{\mu} = \left[Q_A + Q_A^{MEC} \,,\ \vec{\Sigma} \right]$$

Affects GT transitions

+

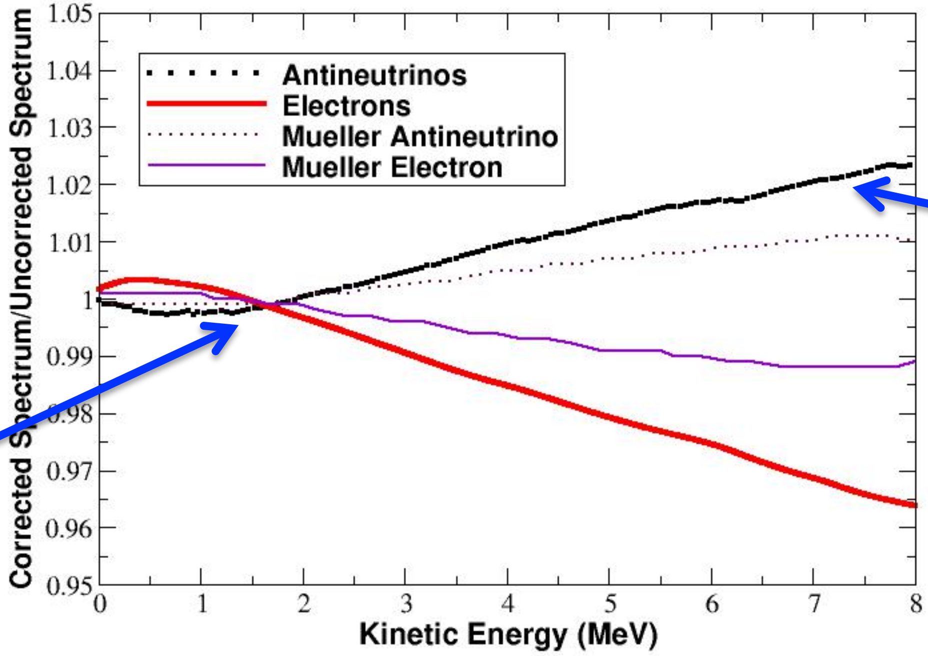
Equivalent correction for spin-flip component of forbidden transitions

The correction is operator dependent:

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

$$\delta_{WM}^{unique1^{st}} = \frac{3(\mu_V - \tfrac{1}{2})}{5 M_N g_A}\left[\frac{(p_e^2 + p_\nu^2)(p_e^2 / E_e - E_\nu) + \frac{2}{3}\frac{p_e^2 E_\nu (E_\nu - E_e)}{E_e}}{(p_e^2 + p_\nu^2)}\right]$$

If all forbidden transitions are treated as allowed GT, the corrections lead to an anomaly - the ν_e spectrum is shifted to higher energy



$$\cong \frac{1}{2}\left[\frac{4(\mu_\nu - \frac{1}{2})}{6M_n g_A} - \frac{3Z\alpha R}{2\hbar c}\right]$$

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

- **Obtain larger effect & stronger energy dependence than Mueller because the form of our corrections are different**

- **Linear increase in the number of antineutrinos with E_ν>2 MeV**

Two Major sources of uncertainty

- 30% of the transitions making up the spectrum are forbidden

- The newly measured antineutrino spectra show a bump relative to expectations

Unique forbidden versus non-unique forbidden transitions

Allowed: Fermi τ and Gamow-Teller $\Sigma=\sigma\tau$

Forbidden: $\Delta L \neq 0$; $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J=\Delta L}$, $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J=\Delta L-1}$, $\Delta\pi = (-)^{\Delta \mathrm{L}}$

$\vec{r}^{\,L}\vec{\tau}, \ \dfrac{\vec{\nabla}\vec{\tau}}{\mathrm{M}}, \ \ldots$

Unique if $(\vec{\mathrm{L}} \otimes \vec{\Sigma})^{\Delta J=\Delta L+1}$, e.g., 2^-

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

Unique transitions only involve one operator & there is a unique shape change

e.g., 2- the phase space is multiplied by C(E) = p^2+q^2

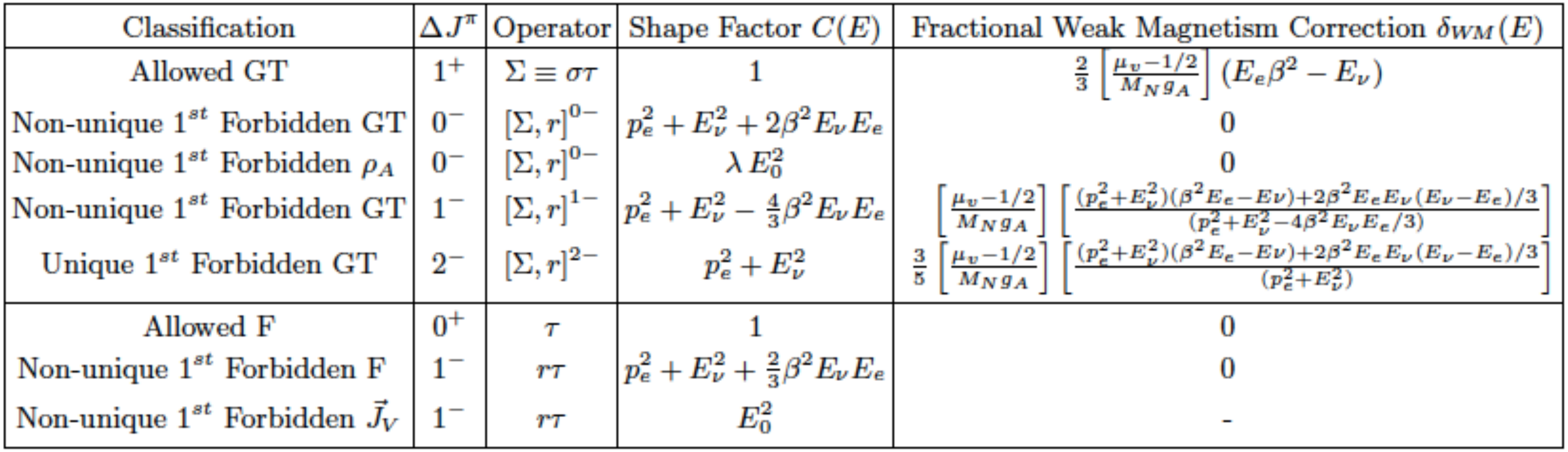
Also, a well defined weak magnetism correction

Non-unique transitions involve several operators

The C(E) shape factor is operator dependent

WM and FS are also operator dependent

Without detailed nuclear structure information there is no method of determining which operators determine the forbidden transitions



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^-	$[\Sigma, r]^{0-}$	$p_e^2 + E_\nu^2 + 2\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden ρ_A	0^-	$[\Sigma, r]^{0-}$	λE_0^2	0
Non-unique 1^{st} Forbidden GT	1^-	$[\Sigma, r]^{1-}$	$p_e^2 + E_\nu^2 - \frac{4}{3}\beta^2 E_\nu E_e$	$\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2-4\beta^2 E_\nu E_e/3)}\right]$
Unique 1^{st} Forbidden GT	2^-	$[\Sigma, r]^{2-}$	$p_e^2 + E_\nu^2$	$\frac{3}{5}\left[\frac{\mu_v - 1/2}{M_N g_A}\right]\left[\frac{(p_e^2+E_\nu^2)(\beta^2 E_e - E\nu) + 2\beta^2 E_e E_\nu (E_\nu - E_e)/3}{(p_e^2+E_\nu^2)}\right]$
Allowed F	0^+	τ	1	0
Non-unique 1^{st} Forbidden F	1^-	$r\tau$	$p_e^2 + E_\nu^2 + \frac{2}{3}\beta^2 E_\nu E_e$	0
Non-unique 1^{st} Forbidden $\vec{J}_V$	1^-	$r\tau$	E_0^2	-

Table lists the situation for 6 operators that enter 1st forbidden transitions

Many transitions are 2nd forbidden, etc.

Have not derived a similar table for the Finite Size corrections

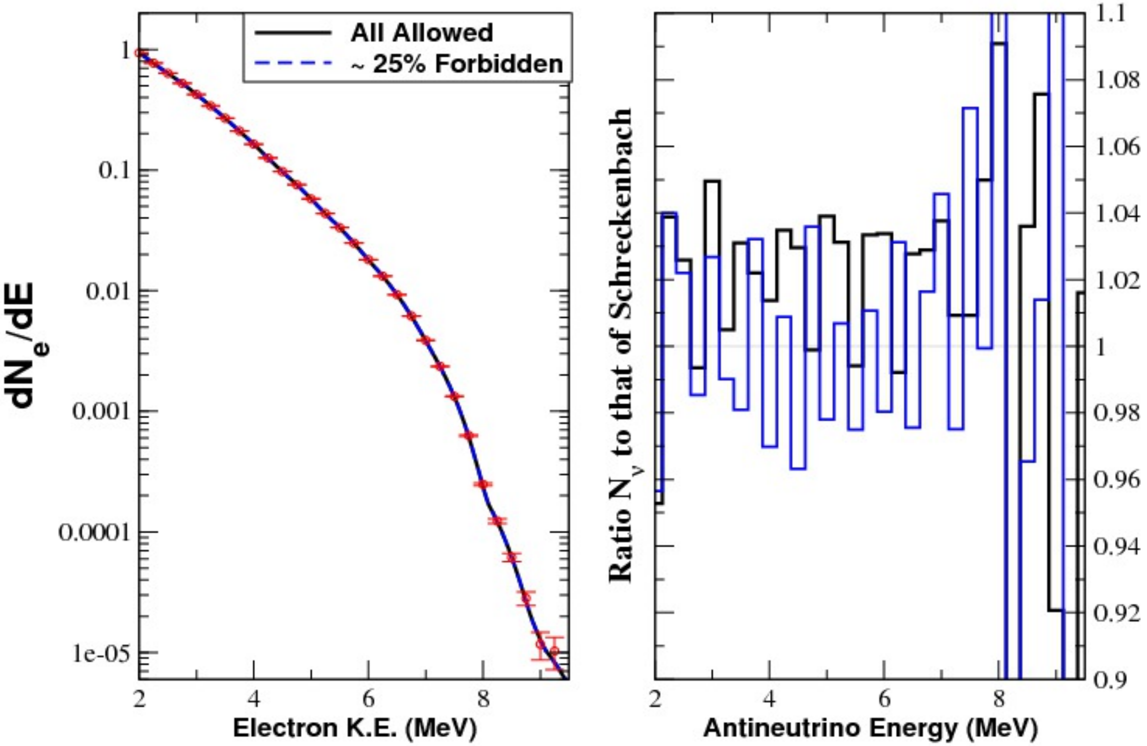
Uncertainty in how to treat the forbidden transitions introduces an uncertainty in the antineutrino flux

- No way to determine what combination of operators and hence corrections to use for this (25%) component of the spectra
- No clear way to estimate the uncertainty due the non-unique forbidden transitions
- Therefore, we examined the uncertainties using several prescriptions.

For different choices of the forbidden operators we examined:

- » 1. Compare antineutrino spectra from a fit to the beta spectra, with and without a treatment for forbidden transitions
- » 2. Changes in $k(E_e, E_\nu) = N_\nu(E_\nu)/N_\beta(E_e)$
- » 3. Changes in $R \equiv \sum_i \left[\frac{\partial N_\nu(E_\nu)}{\partial a_i}\right] / \left[\frac{\partial N_\beta(E_e)}{\partial a_i}\right]$
- » 4. Change in the predicted antineutrino spectra

1. Fit to Schreckenbach's beta spectrum



If all allowed:
⇒ +2.2% antineutrinos

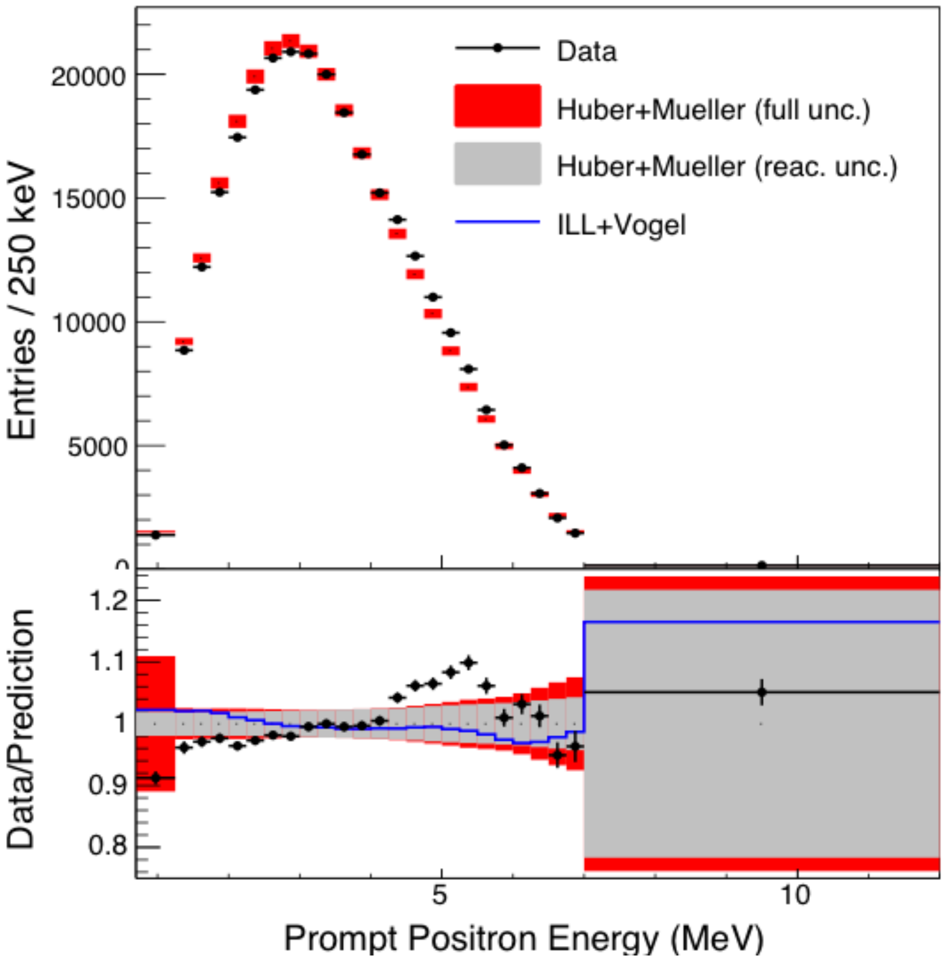
If 25% forbidden transitions
=> +0.06% antineutrinos

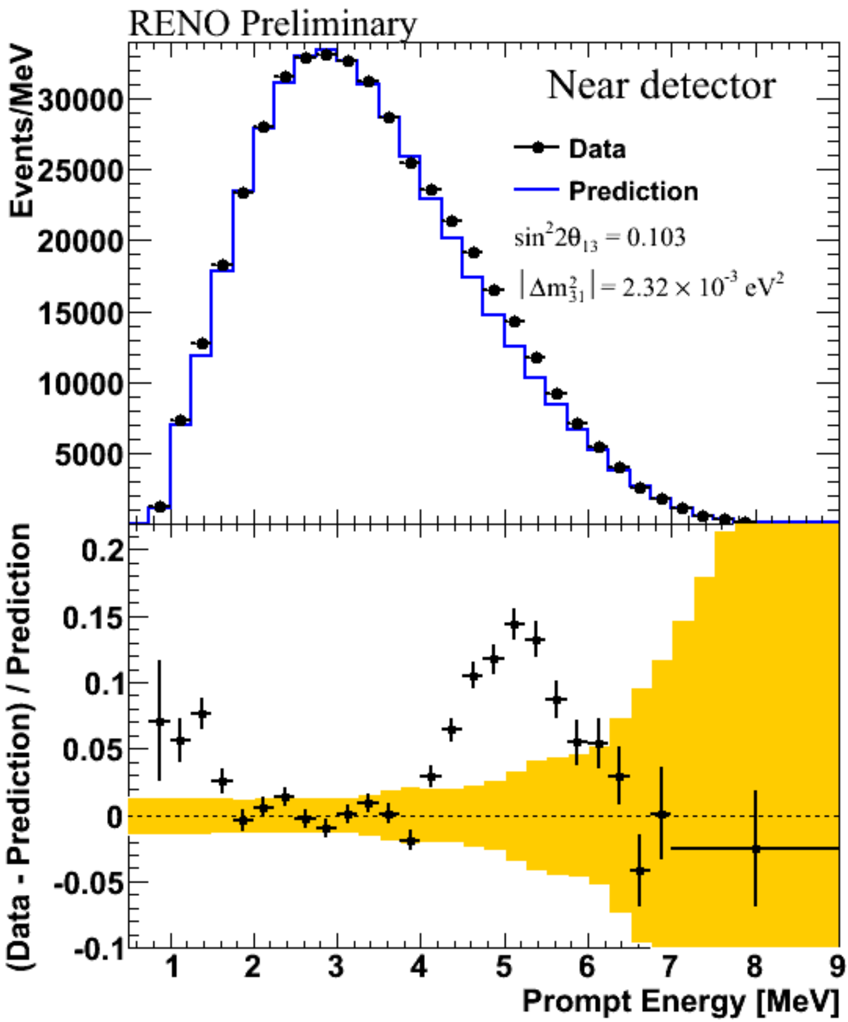
Different fitting procedures: (1) all allowed; (2)all branches either allowed or forbidden; (3) 30% forbidden equally spaced ;(4) 30% forbidden with a bias to higher energies + several different combinations of forbidden operators

Changes in the antineutrino spectrum range from 0-4%
Problem arises because of lack of knowledge on how to treat forbidden transitions

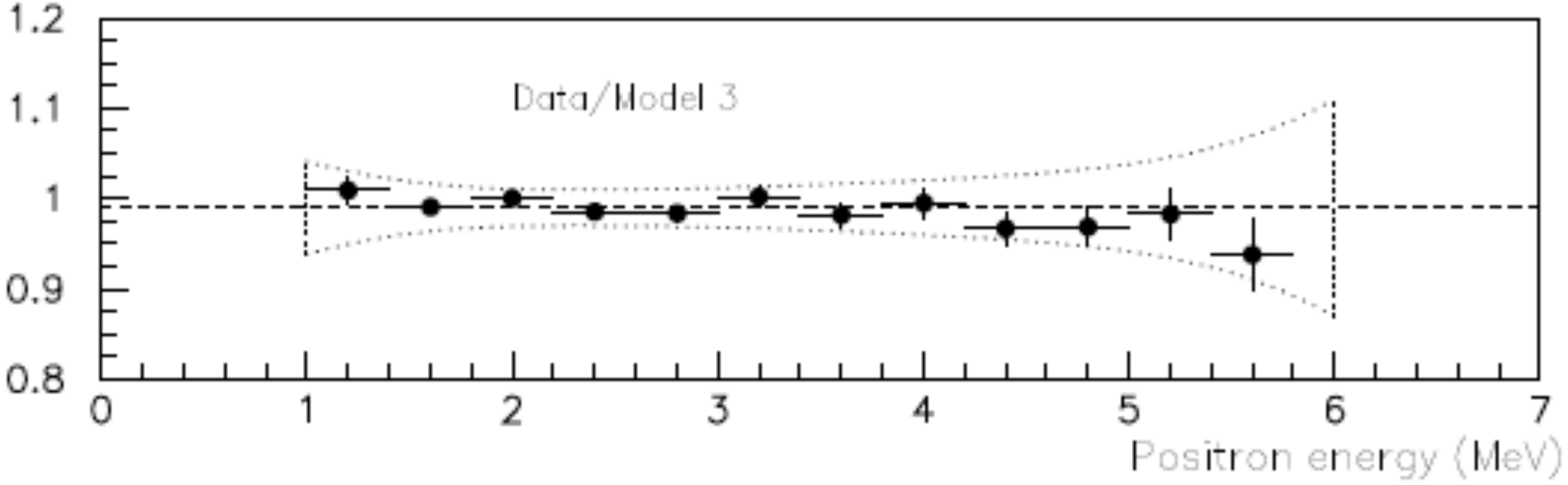
The BUMP

Significant Shoulder seen in the Near Detector at E_{promt}~4-6.5 MeV at both Dayabay and RENO. Also seen in the far detectors





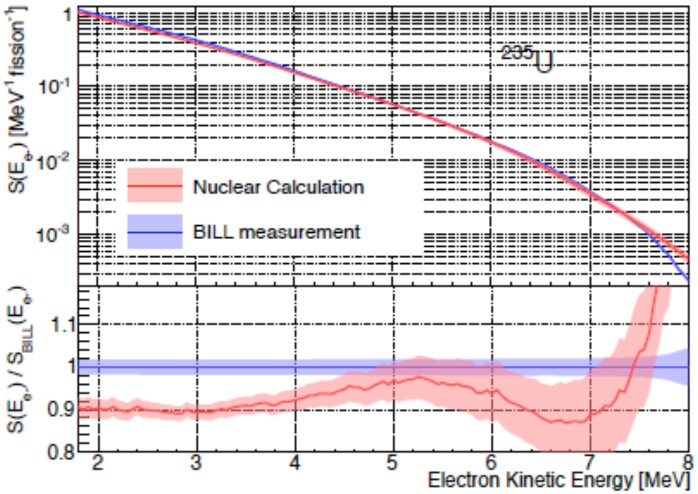
Bugey 3 did not report any significant distortions?

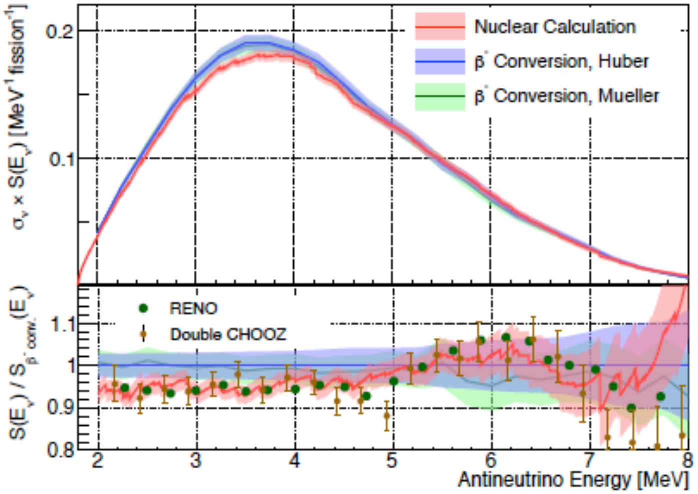


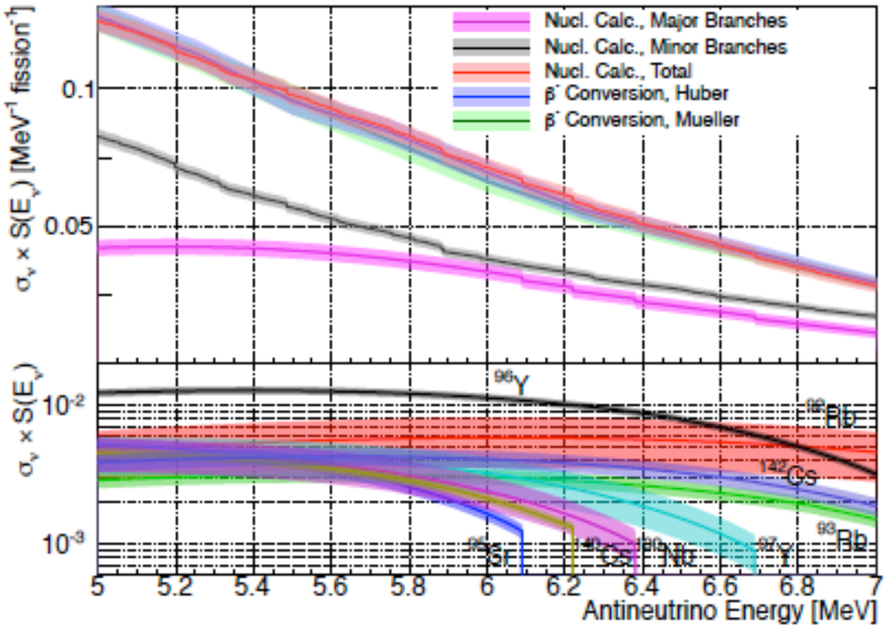
The good comparison between Bugey and Schreckenbach was key to small uncertainties being put on the 'Expected' antineutrino spectrum

Analysis of Dwyer and Langford of Database for a subset of the transitions shows that the bump is predicted to be due to many nuclei

arXiv: 1407:1281



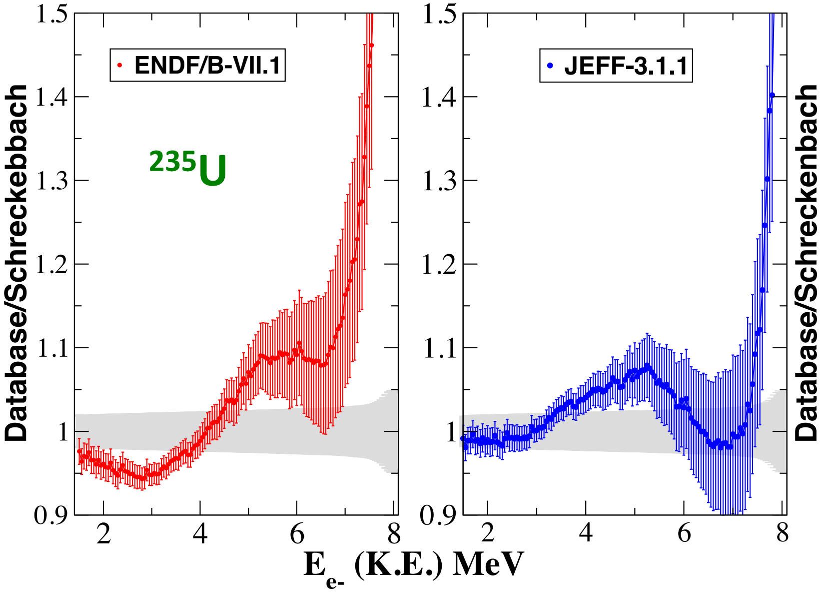


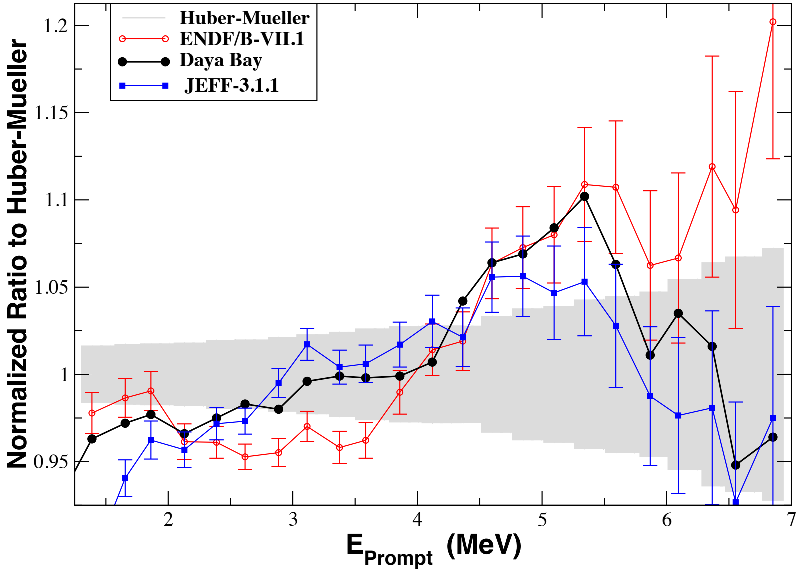


Difficult to see how the database could be grossly wrong for all of these nuclei

However, there are large uncertainties in the databases

Current analysis with full database and comparison between the US and European databases also suggests the 'BUMP' should be there





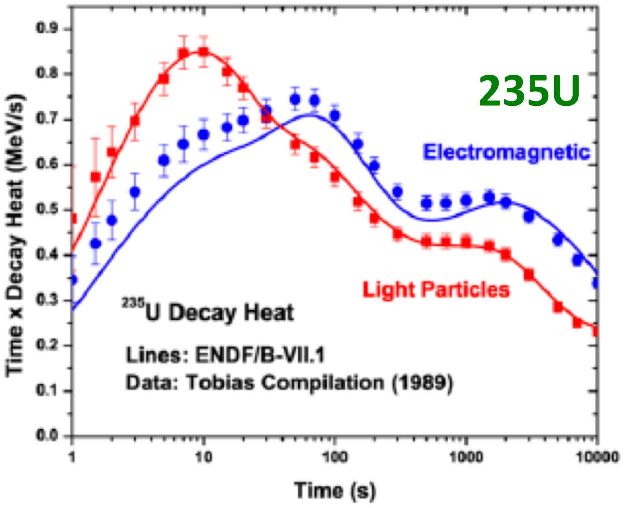
Both the beta and the antineutrino spectra show a shoulder relative to Schreckenbach and Huber-Mueller.

There are large uncertainties in the databases and the two evaluations do not agree with one another on the fission fragment yields

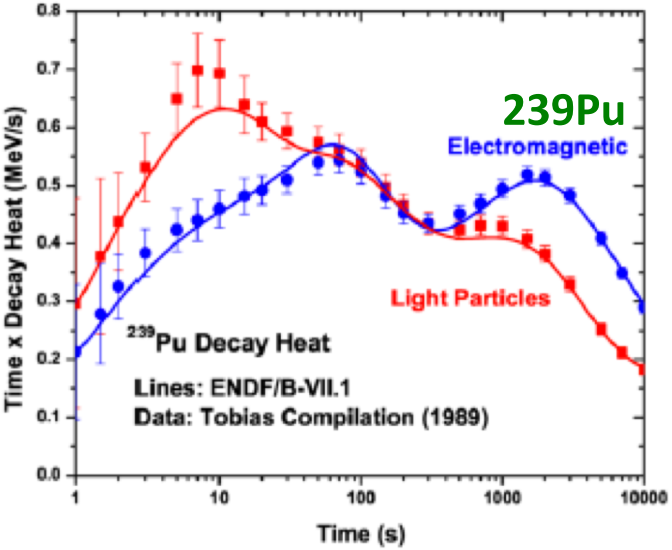
Nonetheless, both databases predict that several nuclei contribute to the shoulder.

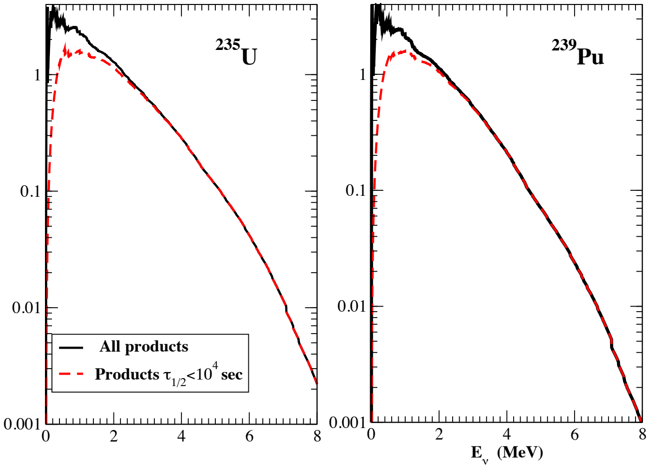
Database shoulder is about the same magnitude and in the same energy window as the near detector data

Many of nuclei contributing to the 'BUMP' are important contributors to Decay Heat



Decay Heat





Antineutrino spectrum with and without Half-life cut-off

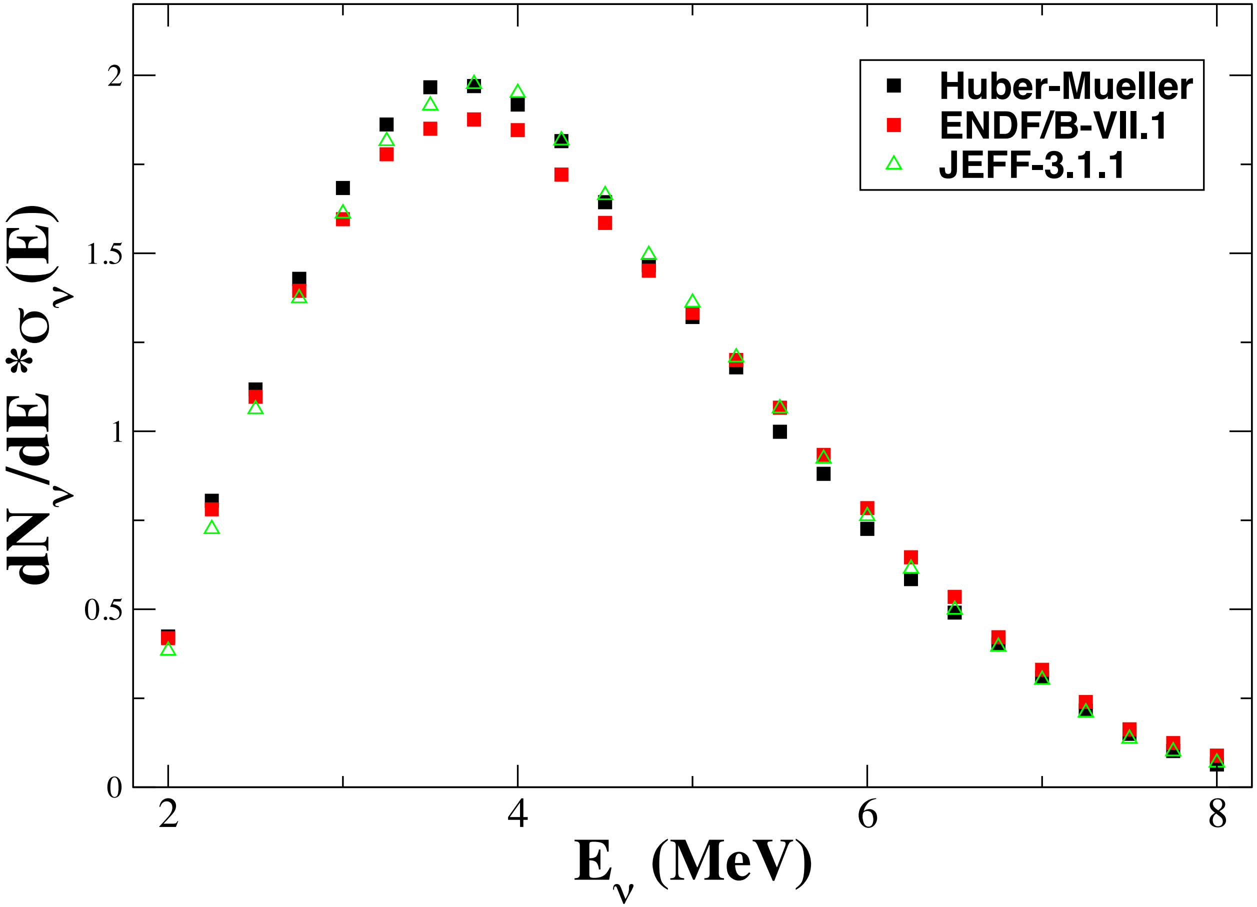
Decay heat :

$$D(t) \sim \sum \lambda_i \left\langle E_i^\beta \right\rangle$$

$$t_{1/2} < 10^4\ \mathrm{sec}$$

No reasonable adjustment of the databases can remove the prediction of a shoulder wrt Huber-Muller or Schreckenback

Both databases see a deficit relative to Huber-Mueller at low energies, and then the shoulder



The measured spectra can be accommodated with database expectations

But there are large uncertainties in both databases, so no definitive conclusion can be drawn

There are Two Major Sources of Uncertainties in the Reactor Neutrino Anomaly

1. No unique way to fit the β^- spectra because 30% of the transitions
are forbidden, and the corrections + shape factors unknown
=> up to 4% uncertainty in the deduced antineutrino spectra

2. The near detectors at Daya Bay and RENO see a **‘bump’** in the energy region E_{prompt} = 4-6 MeV (also seen in Double CHOOZ)
So do the database predictions

2b. Observed deficits seen in near detectors E_ν<~4-5 MeV are consistent with database predictions

Suggestive that the measured β^- spectra and
the ‘expected’ antineutrino spectra may be wrong!
But databases involve large uncertainties