Reactor Antineutrino Fluxes

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Beta decay theory

In Fermi theory, the spectrum of massless neutrinos is obtained from

$$E_\nu = E_0 - E_e$$

In reality there are many corrections: finite nuclear size, radiative corrections, screening effects, induced currents, … which in principle can be computed for allowed decays but not for forbidden ones.

There is a sizable fraction of around 40% of all neutrinos coming from forbidden decays, essentially for reasons of combinatorics.

Neutrinos from fission

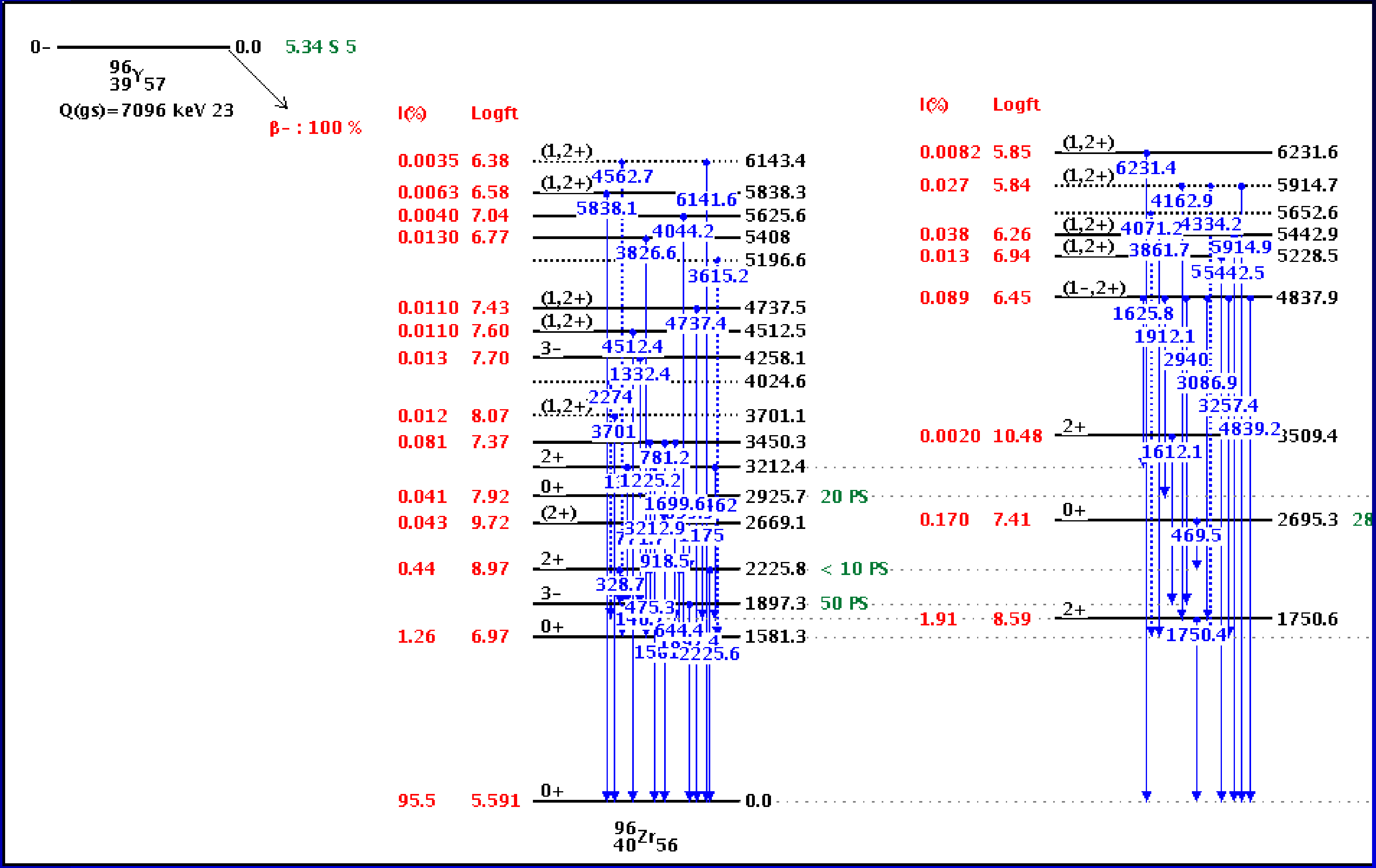
For a single branch energy conservation implies a one-to-one correspondence between β and $\bar{\nu}$ spectrum.

However, here there are about 500 nuclei and 10 000 individual β-branches involved; many are far away from stability.

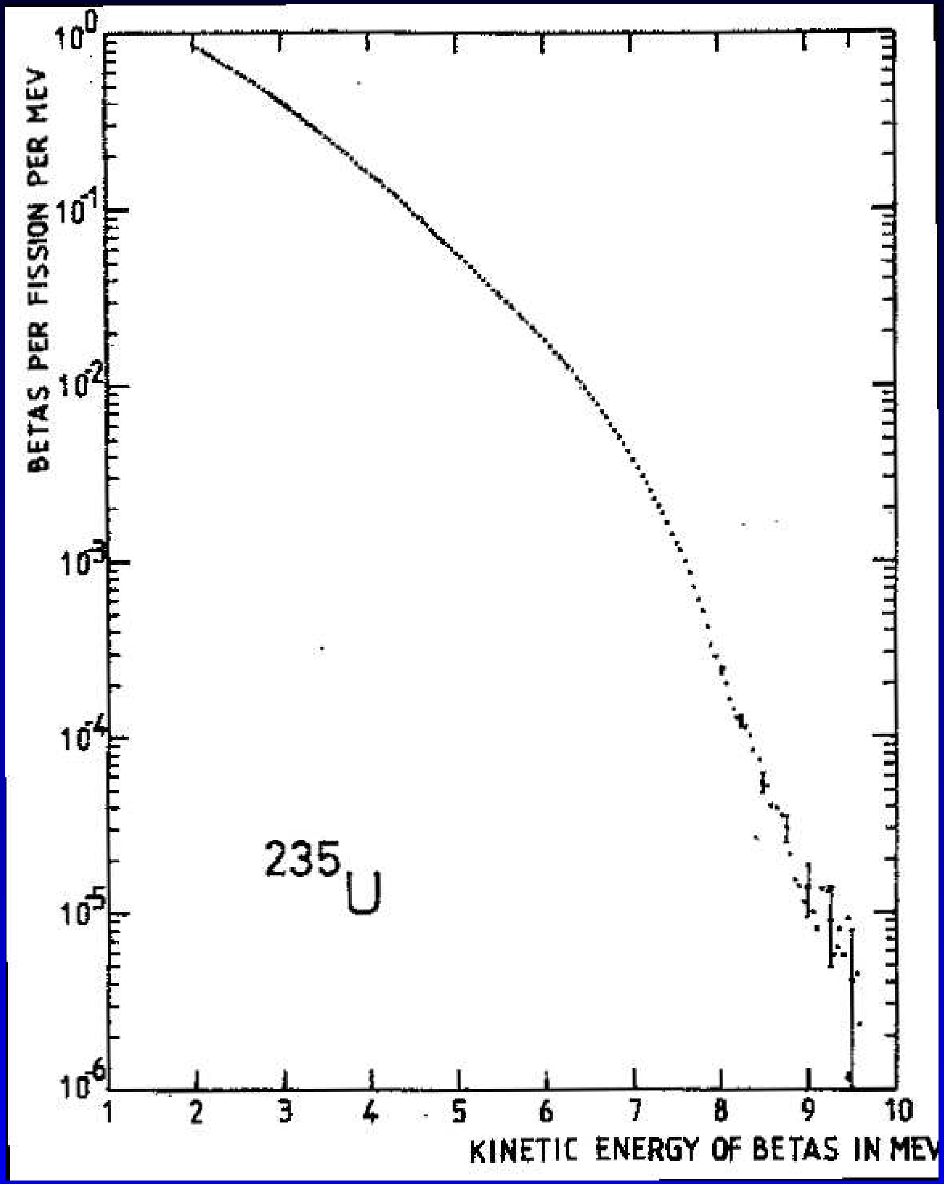
Direct β spectroscopy of single nuclei never will be complete, and even then one has to untangle the various branches

γ spectroscopy yields energy levels and branching fractions, but with limitations, *cf.* pandemonium effect

β branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

For ^{238}U reliance on the theory – small contribution to overall neutrino spectrum

Extraction of ν-spectrum

The total β-spectrum is a sum of all decay branches

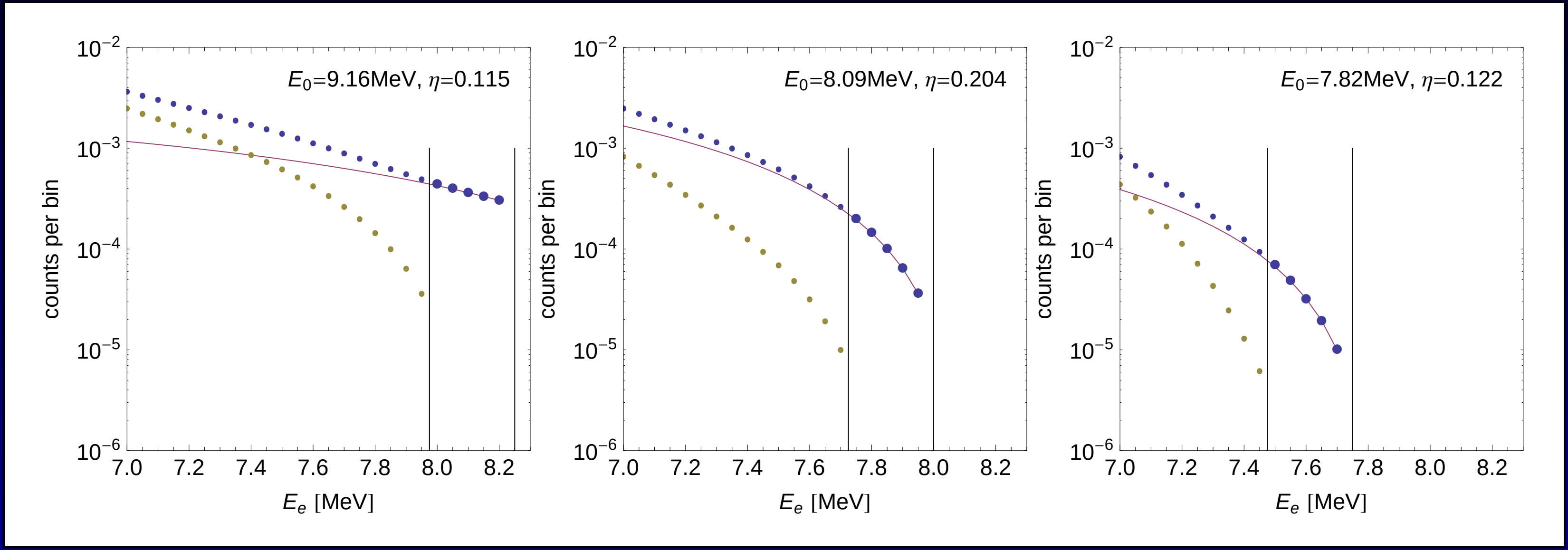
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z})\,\eta(E_0)\,.$$

with $\bar{Z}$ effective nuclear charge and $\eta(E_0)$, the underlying distribution of endpoints

This is a so called Fredholm integral equation of the first kind – mathematically ill-posed, *i.e.* solutions tend to oscillate, needs regulator.

This approach is the basis for “virtual branches” Schreckenbach *et al.*, 1982, 1985, 1989 and is used in the modern calculations as well Mueller *et al.* 2011, Huber 2011

Virtual branches



1 – fit an allowed β-spectrum with free normalization η and endpoint energy E_0 the last s data points

2 – delete the last s data points

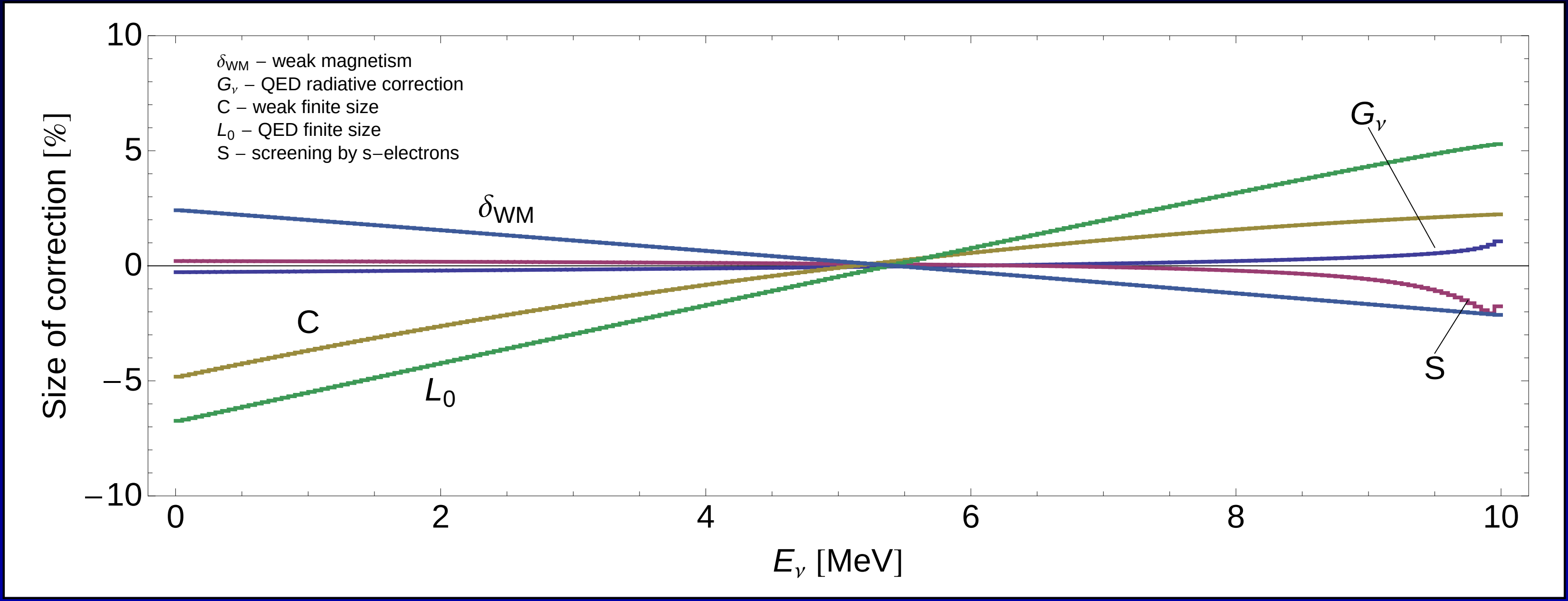
3 – subtract the fitted spectrum from the data

4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all. *e.g.* Vogel, 2007

Corrections to β-shape

There are numerous correction to the β-spectrum



Many of these correction depend on the nuclear charge Z, but Z is not determined by the β-spectrum measurement ⇒ nuclear databases.

For forbidden decays many of these corrections are not known – potentially large uncertainty.

Weak magnetism & β-spectra

Nuclear structure effects can be summarized by the use of appropriate form factors F_X^N.

The weak magnetic nuclear, F_M^N form factor by virtue of CVC is given in terms of the analog EM form factor as

$$F_M^N(0) = \sqrt{2}\mu(0)$$

The effect on the β-decay spectrum (in allowed decays) is given by

$$1 + \delta_{\mathrm{WM}} W \simeq 1 + \frac{4}{3M} \frac{F_M^N(0)}{F_A^N(0)} W$$

What is the value of δ_{WM}?

Three ways to determine δ_{WM}

- impulse approximation – universal value $0.5\%\,\mathrm{MeV}^{-1}$
- using CVC – F_M from analog M1 γ-decay width, F_A from ft value
- direct measurement in β-spectrum – only very few, light nuclei have been studied. In those cases the CVC predictions are confirmed within (sizable) errors.

In the following, we will compare the results from CVC with the ones from the impulse approximation.

CVC at work

Collect all nuclei for which we

- can identify the isospin analog energy level
- and know Γ_{M1}

then, compute the resulting δ_{WM}. This exercise has been done in Calaprice, Holstein, Nucl. Phys. **A273** (1976) 301. and they find for nuclei with $ft < 10^6$

$$\delta_{WM} = 0.82 \pm 0.4\%\,\mathrm{MeV}^{-1}$$

which is in reasonable agreement with the impulse approximated value of $\delta_{WM} = 0.5\%\mathrm{MeV}^{-1}$. Our result for $ft < 10^6$ is $\delta_{WM} = (0.67 \pm 0.26)\,\%\,\mathrm{MeV}^{-1}$.

CVC at work

Decay	$J_i \to J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ/Ac	$\lvert dN/dE \rvert$ (% MeV^{-1})
$^{6}\mathrm{He} \to {}^{6}\mathrm{Li}$	$0^+ \to 1^+$	3563	8.2	71.8	805.2	2.76	4.33	0.646
$^{12}\mathrm{B} \to {}^{12}\mathrm{C}$	$1^+ \to 0^+$	15110	43.6	37.9	11640.	0.726	4.35	0.62
$^{12}\mathrm{N} \to {}^{12}\mathrm{C}$	$1^+ \to 0^+$	15110	43.6	37.9	13120.	0.684	4.62	0.6
$^{18}\mathrm{Ne} \to {}^{18}\mathrm{F}$	$0^+ \to 1^+$	1042	0.258	242.	1233.	2.23	6.02	0.8
$^{20}\mathrm{F} \to {}^{20}\mathrm{Ne}$	$2^+ \to 2^+$	8640	4.26	45.7	93260.	0.257	8.9	1.23
$^{22}\mathrm{Mg} \to {}^{22}\mathrm{Na}$	$0^+ \to 1^+$	74	0.0000233	148.	4365.	1.19	5.67	0.757
$^{24}\mathrm{Al} \to {}^{24}\mathrm{Mg}$	$4^+ \to 4^+$	1077	0.046	129.	8511.	0.85	6.35	0.85
$^{26}\mathrm{Si} \to {}^{26}\mathrm{Al}$	$0^+ \to 1^+$	829	0.018	130.	3548.	1.32	3.79	0.503
$^{28}\mathrm{Al} \to {}^{28}\mathrm{Si}$	$3^+ \to 2^+$	7537	0.3	20.8	73280.	0.29	2.57	0.362
$^{28}\mathrm{P} \to {}^{28}\mathrm{Si}$	$3^+ \to 2^+$	7537	0.3	20.8	70790.	0.295	2.53	0.331
$^{14}\mathrm{C} \to {}^{14}\mathrm{N}$	$0^+ \to 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6
$^{14}\mathrm{O} \to {}^{14}\mathrm{N}$	$0^+ \to 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92
$^{32}\mathrm{P} \to {}^{32}\mathrm{S}$	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9

What happens for large ft?

Decay	$J_i \to J_f$	E_γ (keV)	Γ_{M1} (eV)	b_γ	ft (s)	c	b_γ/Ac	$\lvert dN/dE\rvert$ (% MeV^{-1})
^{14}C $\to^{14}$ N	$0^+ \to 1^+$	2313	0.0067	9.16	1.096×10^9	0.00237	276.	37.6
^{14}O $\to^{14}$ N	$0^+ \to 1^+$	2313	0.0067	9.16	1.901×10^7	0.018	36.4	4.92
^{32}P $\to^{32}$ S	$1^+ \to 0^+$	7002	0.3	26.6	7.943×10^7	0.00879	94.4	12.9

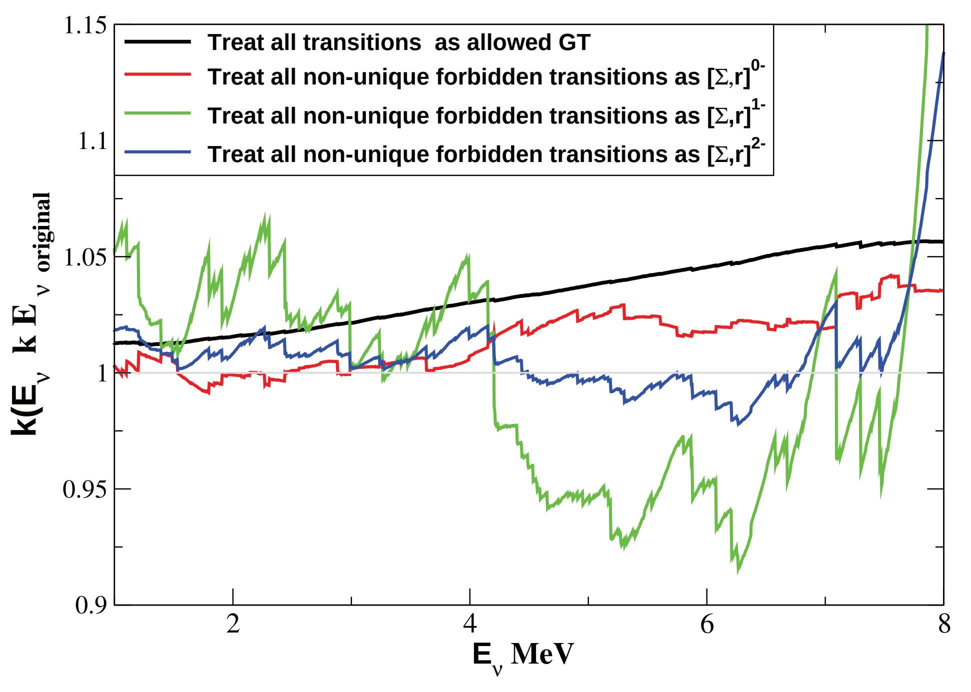
Including these large ft nuclei, we have

$$\delta_{WM} = (4.78 \pm 10.5)\,\%\,\mathrm{MeV}^{-1}$$

which is about 10 times the impulse approximated value and this are about 3 nuclei out of 10-20...

NB, a shift of δ_{WM} by $1\%\mathrm{MeV}^{-1}$ shifts the total neutrino flux above inverse β-decay threshold by $\sim 2\%$.

WM in forbidden decays



Approximate upper bound for the flux error due to forbidden decays.

Hayes *et. al*, arXiv:1309.4146 point out that in forbidden decays a mixture of different operators are involved, and that while for many of the individual operators the corrections can be computed, the relative contribution of each operator is generally unknown.

My interpretation: it is again the WM which is the leading cause for the large combined uncertainty they find.

Impact on fluxes

Following the nomenclature of Hayes *et al.*, the forbidden correction, κ, reads

$$\kappa(E_e) = C(E_e)\,[1 + \delta_{\mathrm{WM}}(E_e)]$$

and the neutrino correction $\Lambda(E_\nu)$ is obtained by

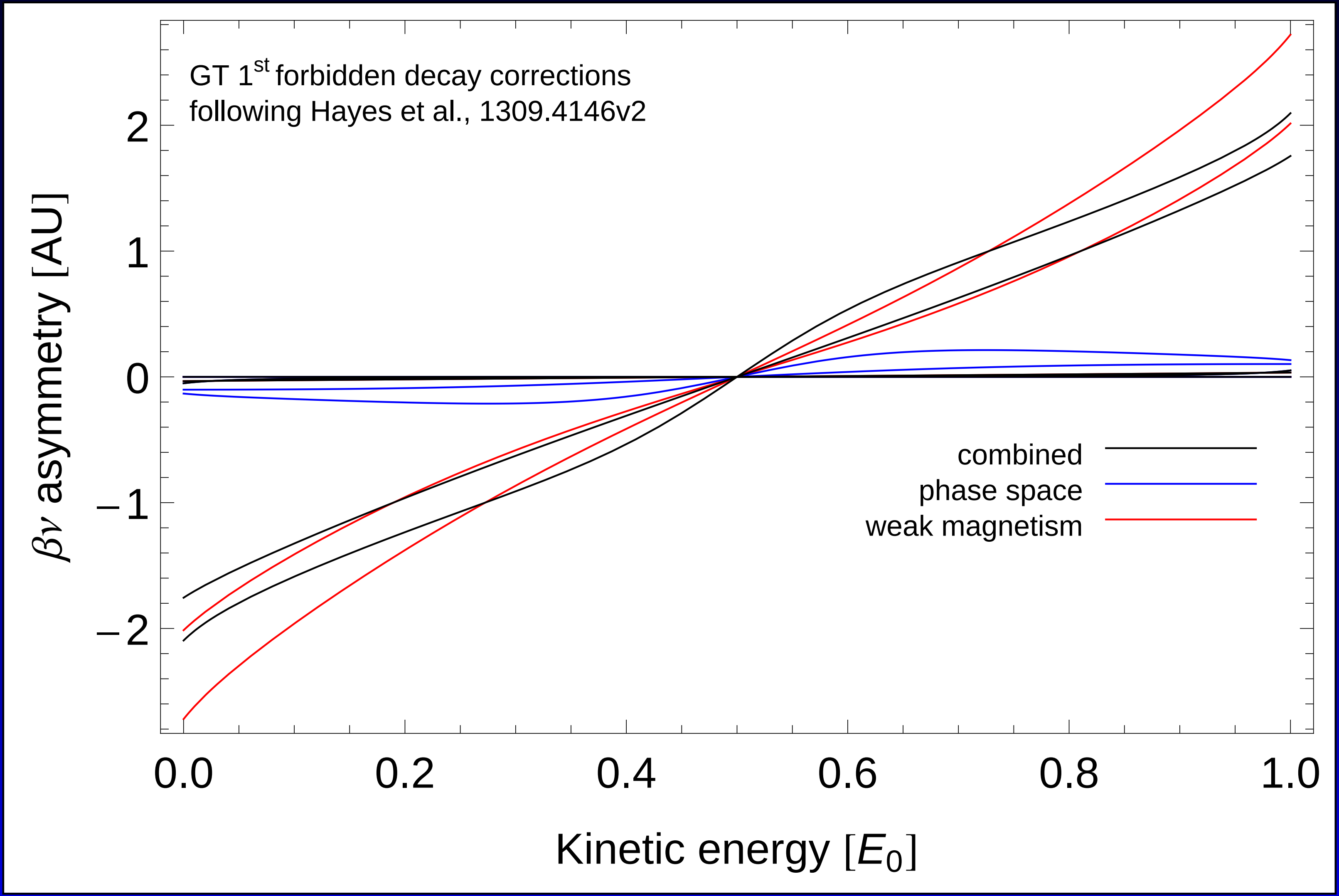
$$\Lambda(E_\nu) = \kappa(E_0 - E_\nu)$$

Given that the total β-spectrum is fixed by the ILL measurements, what matters are effects which change the neutrino and β-spectrum in different ways, and we define

$$\beta\nu(T) := \frac{\kappa(T) - \Lambda(T)}{\kappa(T) + \Lambda(T)}\,,$$

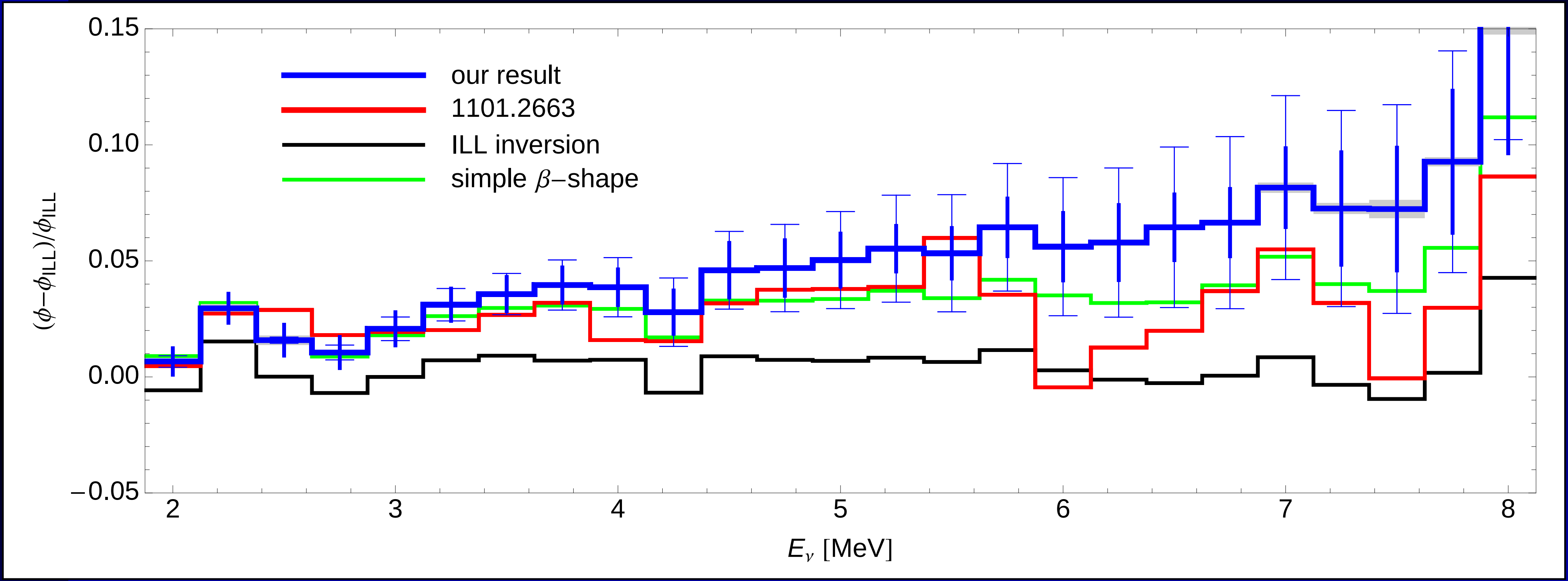
with T being the lepton kinetic energy.

Impact on fluxes



The vast majority of the effect is due to weak magnetism

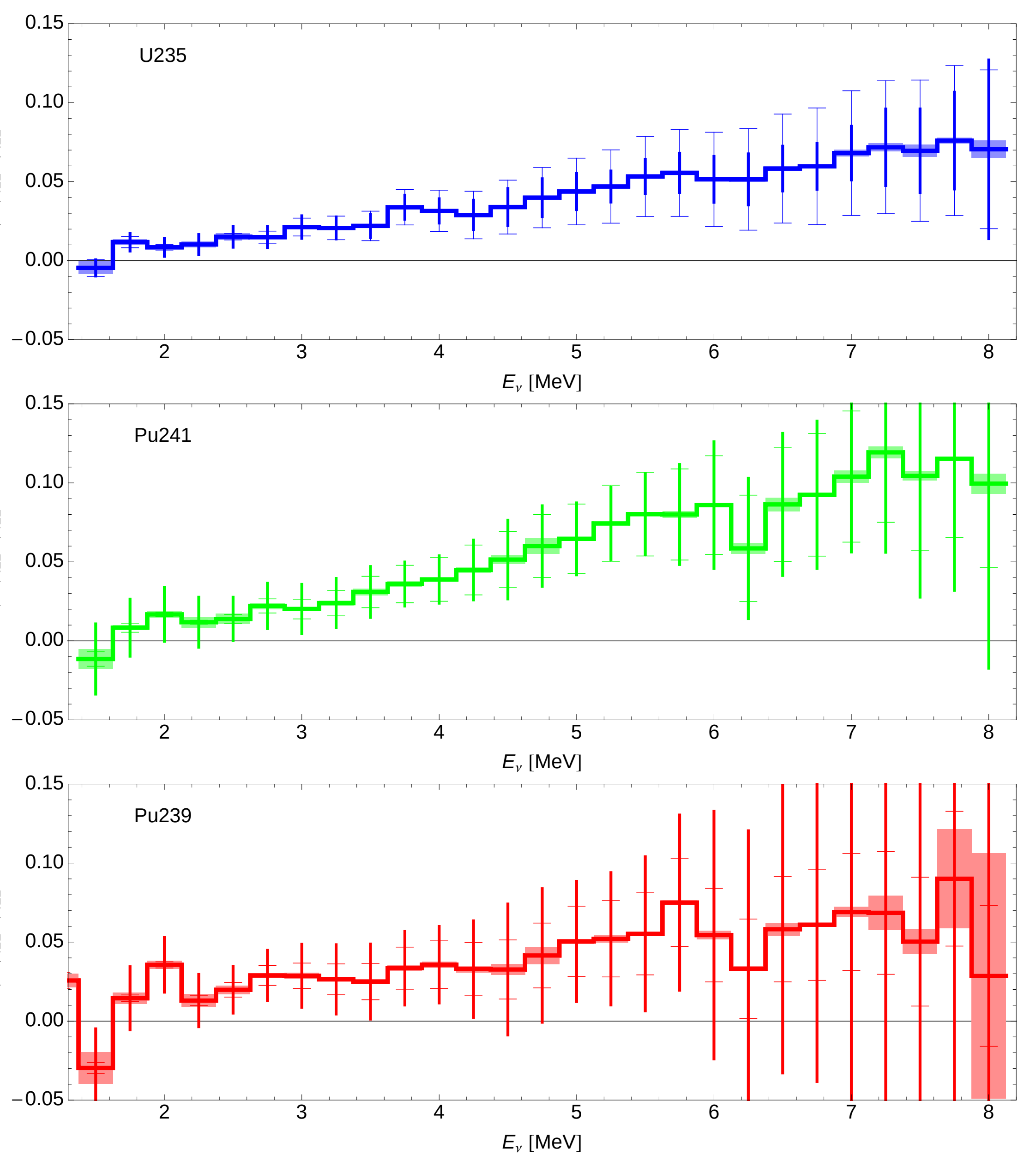
Reactor antineutrino fluxes



Shift with respect to ILL results, due to

a) different effective nuclear charge distribution
b) branch-by-branch application of shape corrections

Comparison of isotopes

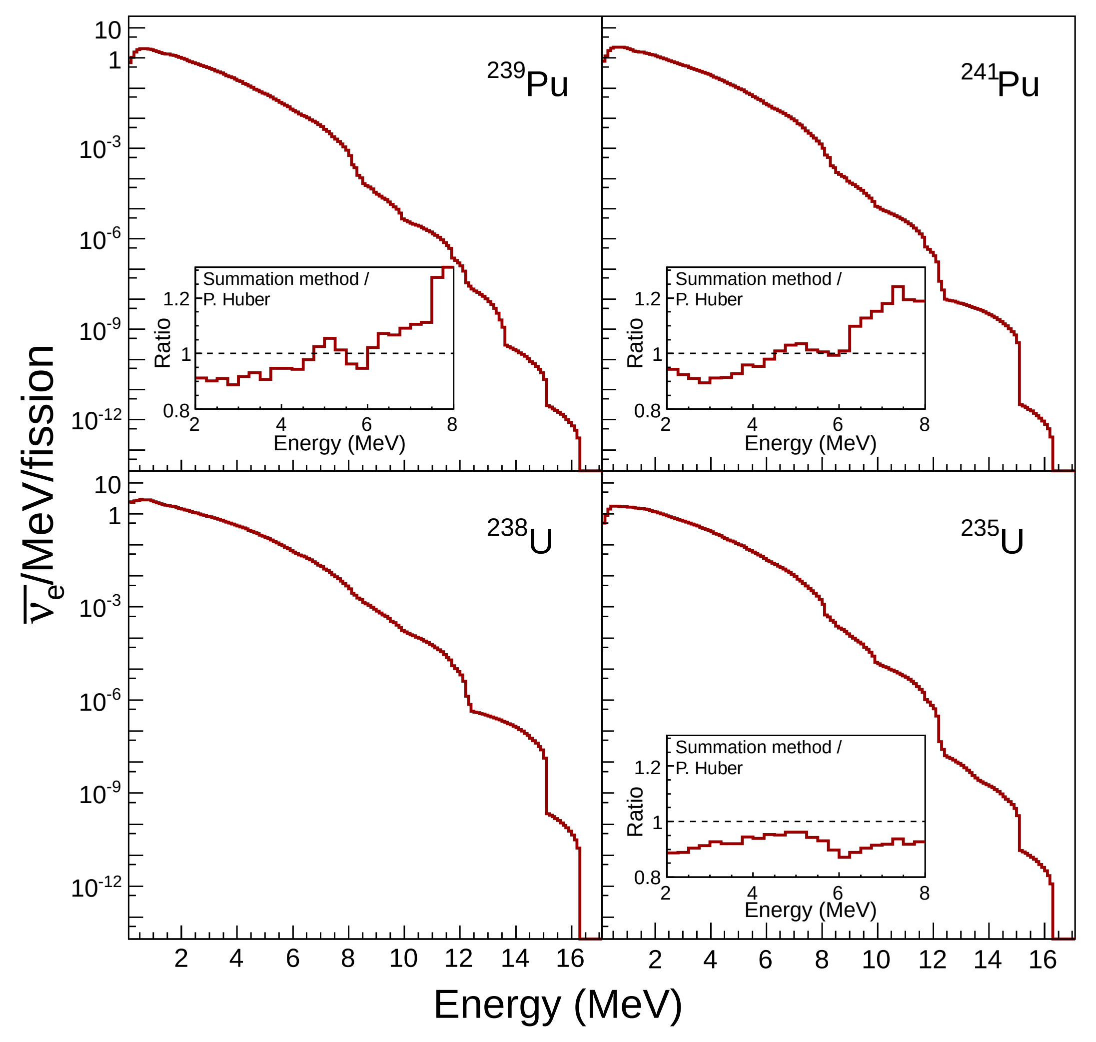


Same shift in all isotopes

Statistical errors of different size, direct consequence of different ILL data quality

^{239}Pu most problematic due to large fission fraction

Improving *a priori* calculations



Fallot *et al.*, 2012

Updated β-feeding functions from total absorption γ spectroscopy (safe from pandemonium) for the isotopes: ^{102,104,105,106,107}Tc, ^{105}Mo and ^{102}Nb

Still a 10-20% discrepancy with the measured total β-spectra.

Next steps?

Future neutrino measurements

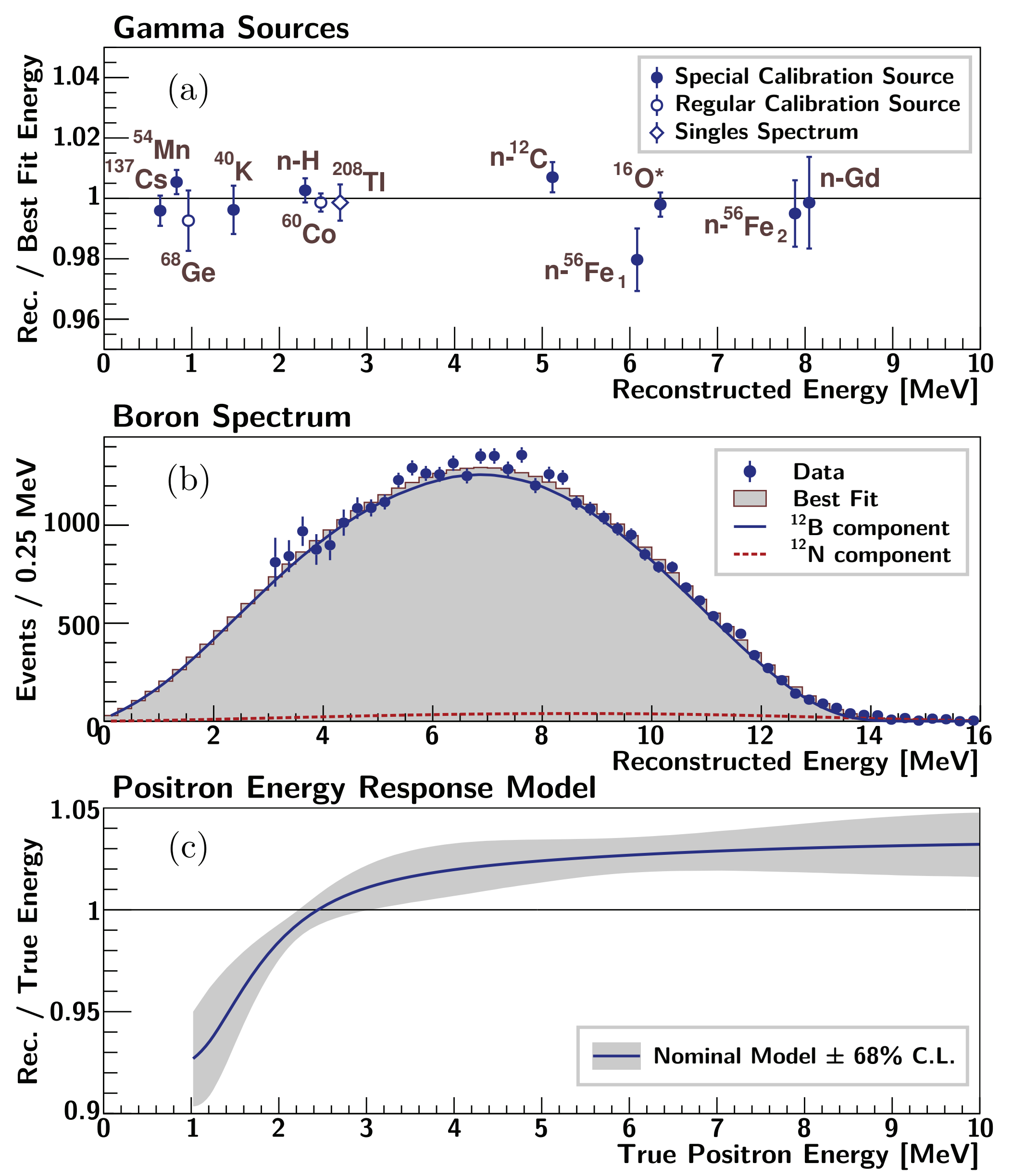
The Daya Bay near detectors collect about 1M events per year

They do this at a distance where all sterile oscillations are averaged away – no confusion between nuclear physics and new physics

Daya Bay detectors are nearly completely active volume – nonetheless the events the acrylic vessel have an impact on the energy response

Daya Bay surface to volume ratio much smaller than for any of the new experiments (and Daya Bay has a γ-catcher)

Daya Bay example



Overall energy scale uncertainty 1-2%

Basically all effects from nuclear physics will end up producing a linear slope of maybe 1-5% plus higher order corrections

Entirely unclear how that will be improved…

Daya Bay, 1310.6732

Future β-measurements

To my knowledge we can expect a ^{238}U spectrum soon from a group working at the FRM II in Germany – important to reduce reliance on a priori spectra

There is a proposal to trap Cf spontaneous fission products (CARIBU) in an ion trap and perform detailed β-spectroscopy for a group of isotopes (LLNL).

There is a proposal to use spallation neutrons to essentially redo the ILL measurements at FNAL Asner *et al.*, 1304.4205.

All these will provide useful information – quantitative impact depends very strongly on experimental accuracies and systematics!

Open issues

Reactors are complex neutrino sources – our current understanding is at the 2-5% level

Pushing into the 1-2% region (or below) will require better theory – not clear how → dedicated workshop next week at the INT in Seattle

New data will have to have systematics around 1% or better to make a real difference – again not obvious how to achieve that

The Daya Bay data set will remain a benchmark which we need to exploit to its fullest

Low energy, total rate measurements may offer a robust tool PH, AAP2012