Physics case for short-baseline oscillation measurements

Patrick Huber

Center for Neutrino Physics
Virginia Tech

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Outline

- Reactor anomaly
- Gallium anomaly
- LSND *et al.*
- Future efforts & summary

Neutrinos from fission

$$^{235}U + n \rightarrow X_1 + X_2 + 2n$$

with average masses of X_1 of about A=94 and X_2 of about A=140. X_1 and X_2 have together 142 neutrons.

The stable nuclei with A=94 and A=140 are $^{94}_{40}$Zr and $^{140}_{58}$Ce, which together have only 136 neutrons.

Thus 6 β-decays will occur, yielding 6 $\bar{\nu}_e$. About 2 will be above inverse β-decay threshold.

The problem is to determine how many exactly are above inverse β-decay threshold.

Beta decay theory

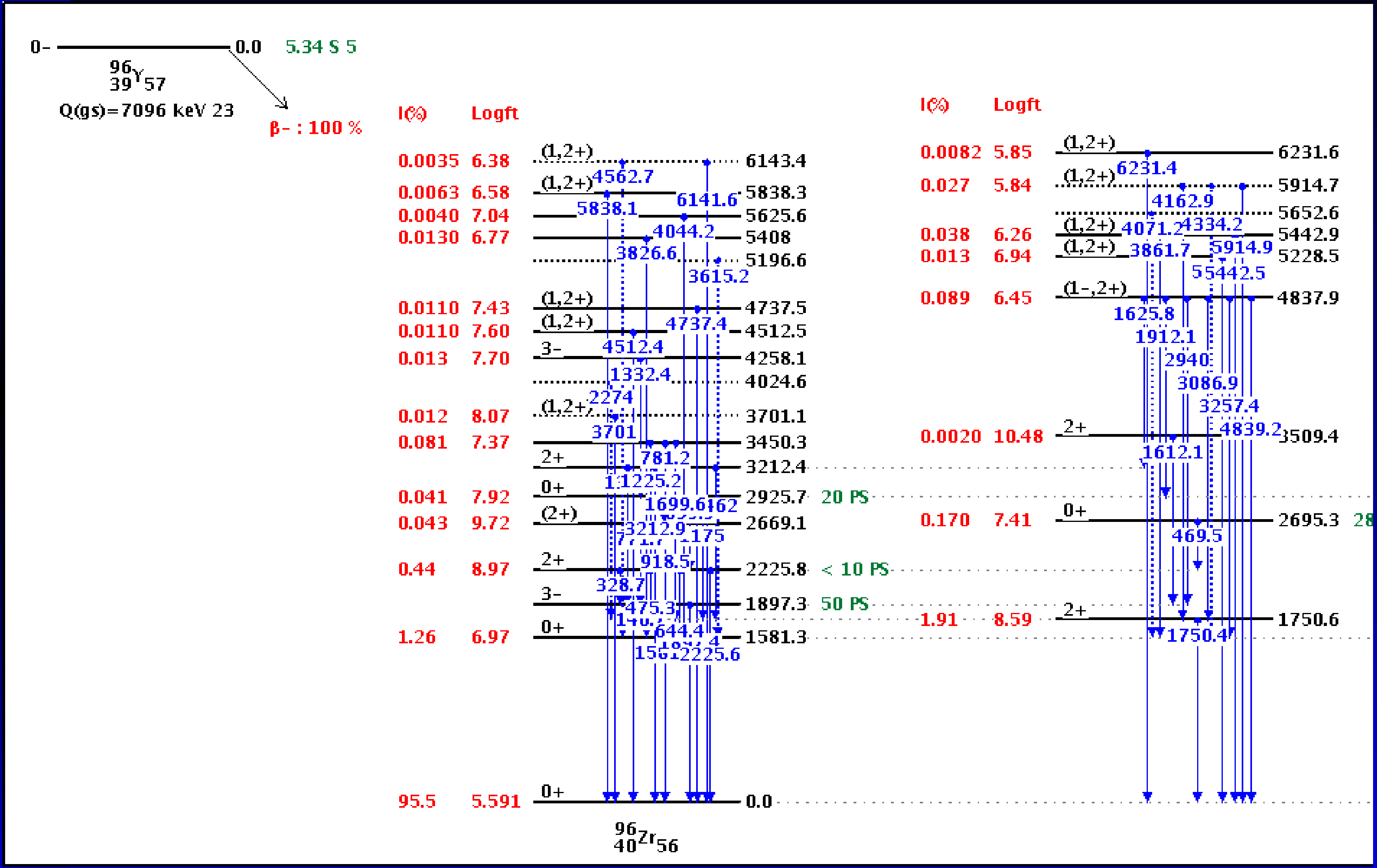
In Fermi theory, the spectrum of massless neutrinos is obtained from

$$E_\nu = E_0 - E_e$$

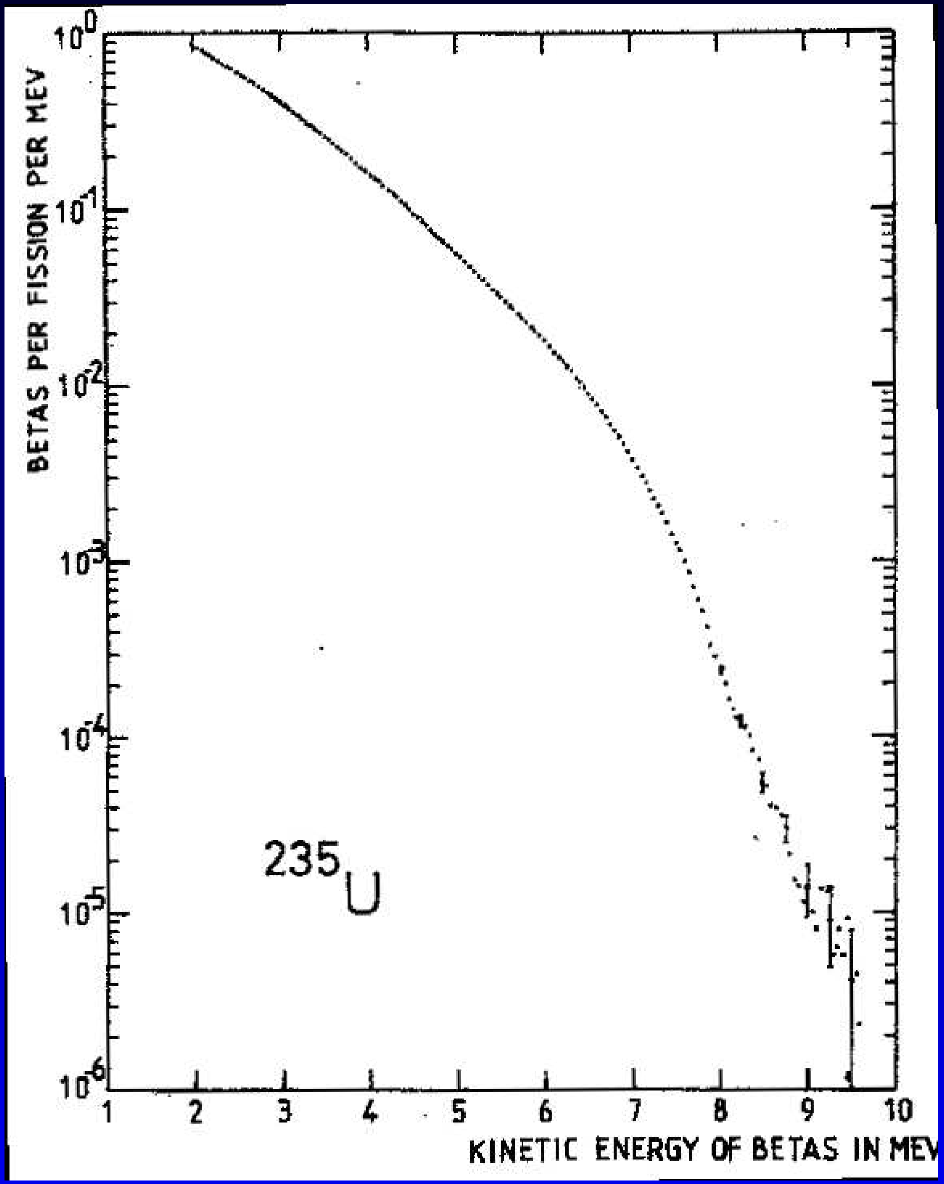
In reality there are many corrections: finite nuclear size, radiative corrections, screening effects, induced currents, ... which in principle can be computed for allowed decays but not for forbidden ones.

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

β branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

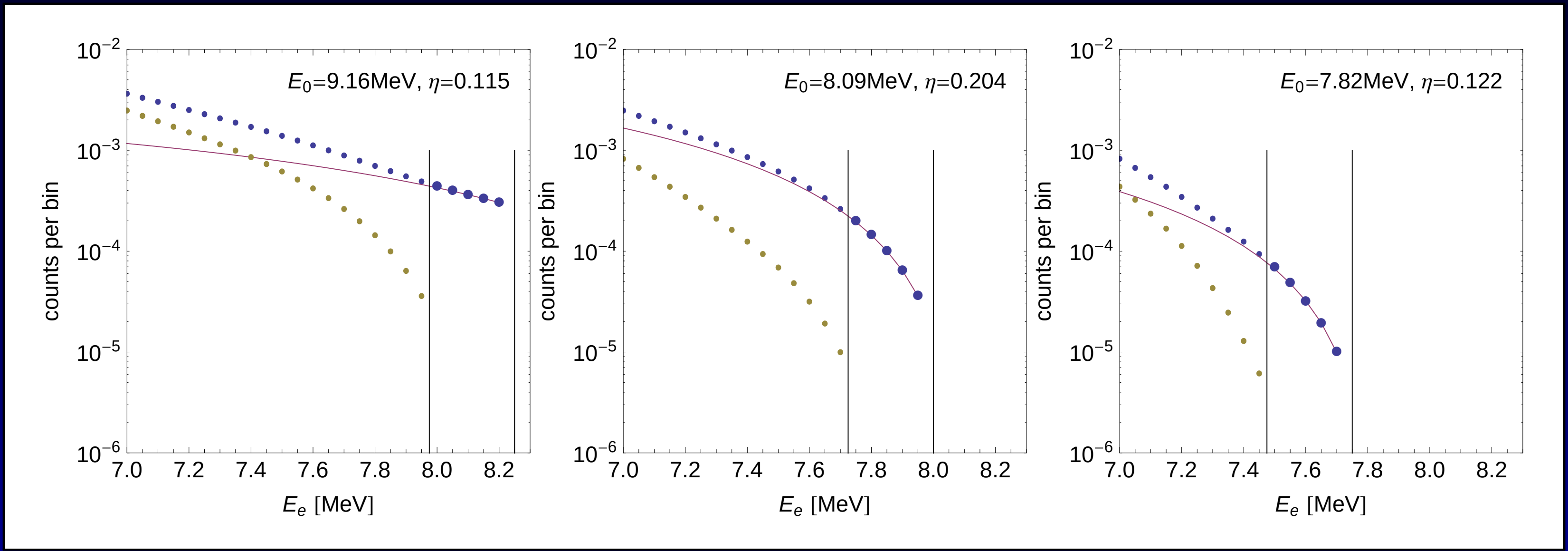
^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

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

^{238}U recently measured by Haag *et al.*, 2013.

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

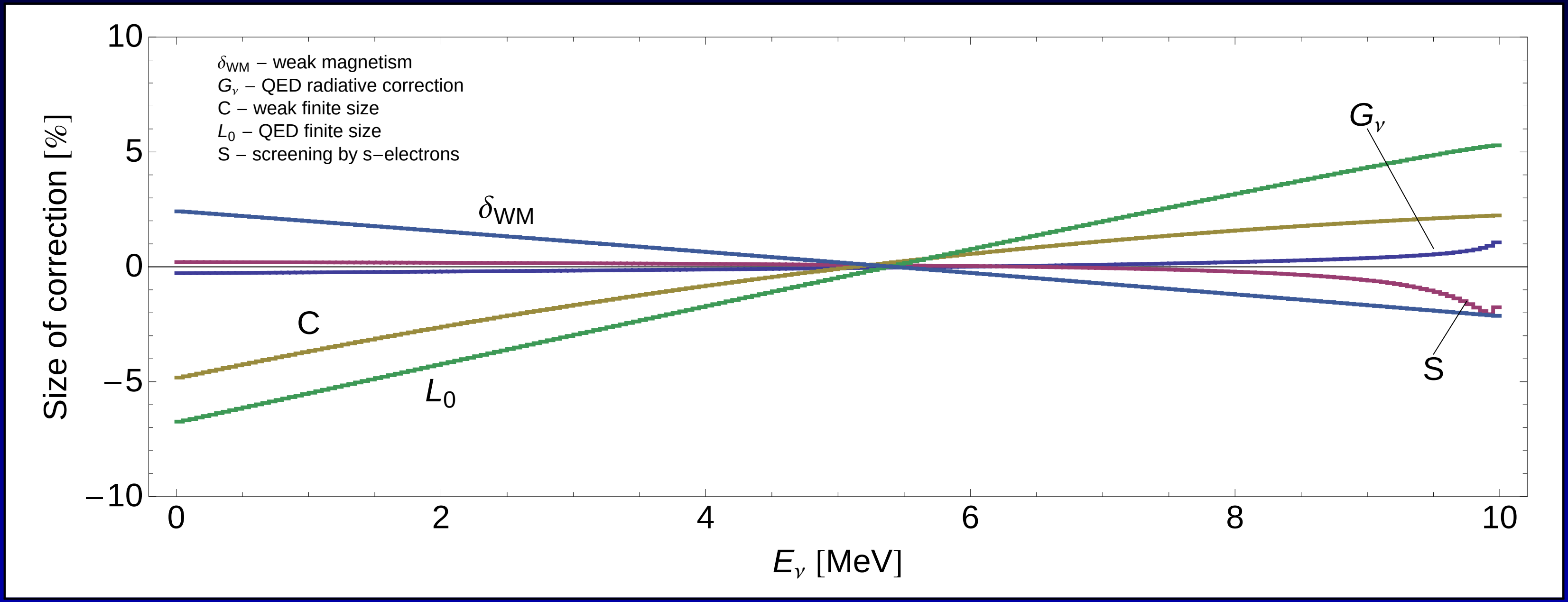
3 – subtract the fitted spectrum from the data

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

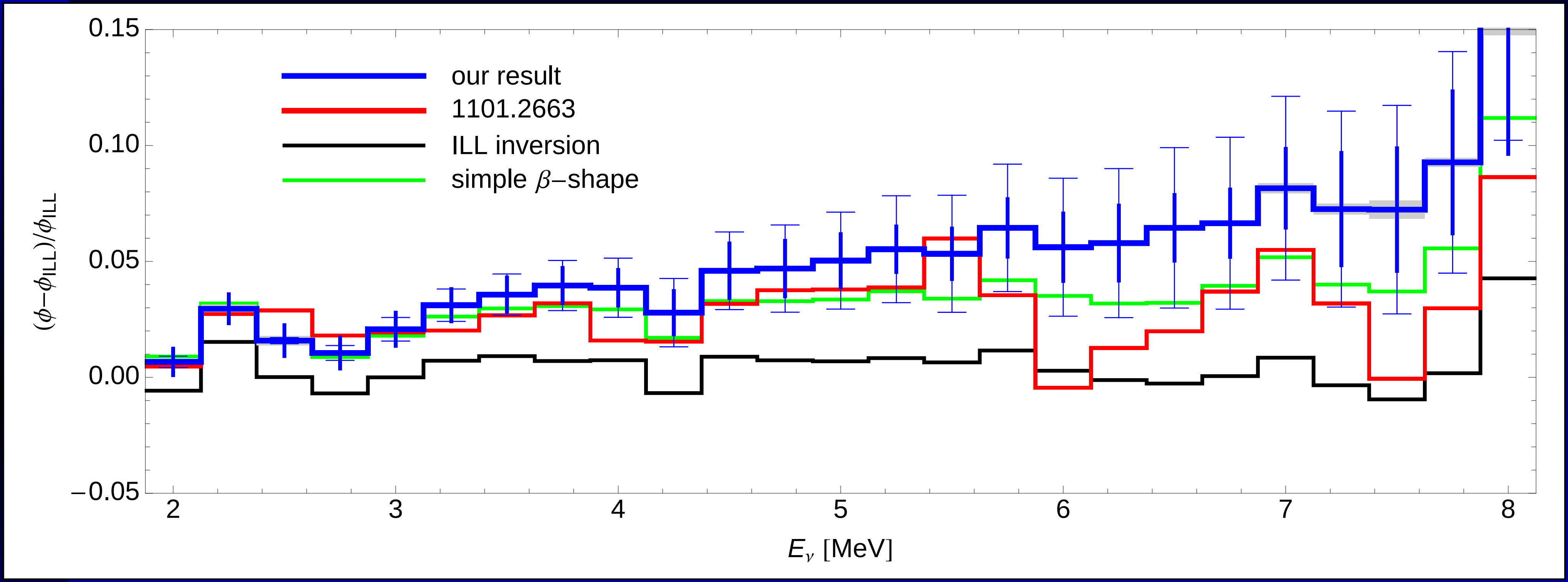
There are numerous correction to the β-spectrum



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

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

Reactor antineutrino fluxes

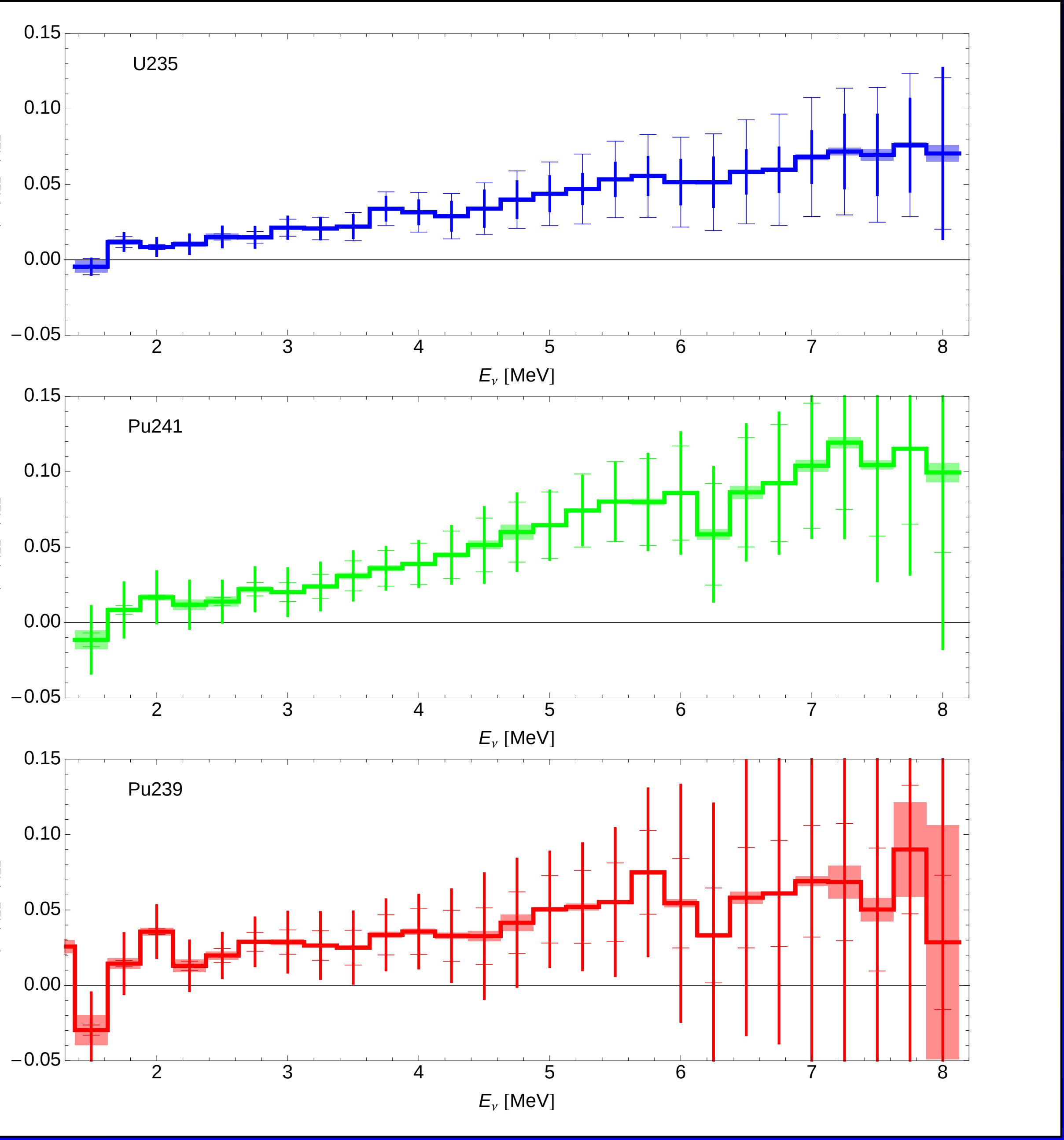


Shift with respect to ILL results, due to

a) different effective nuclear charge distribution

b) branch-by-branch application of shape corrections

Comparison of isotopes

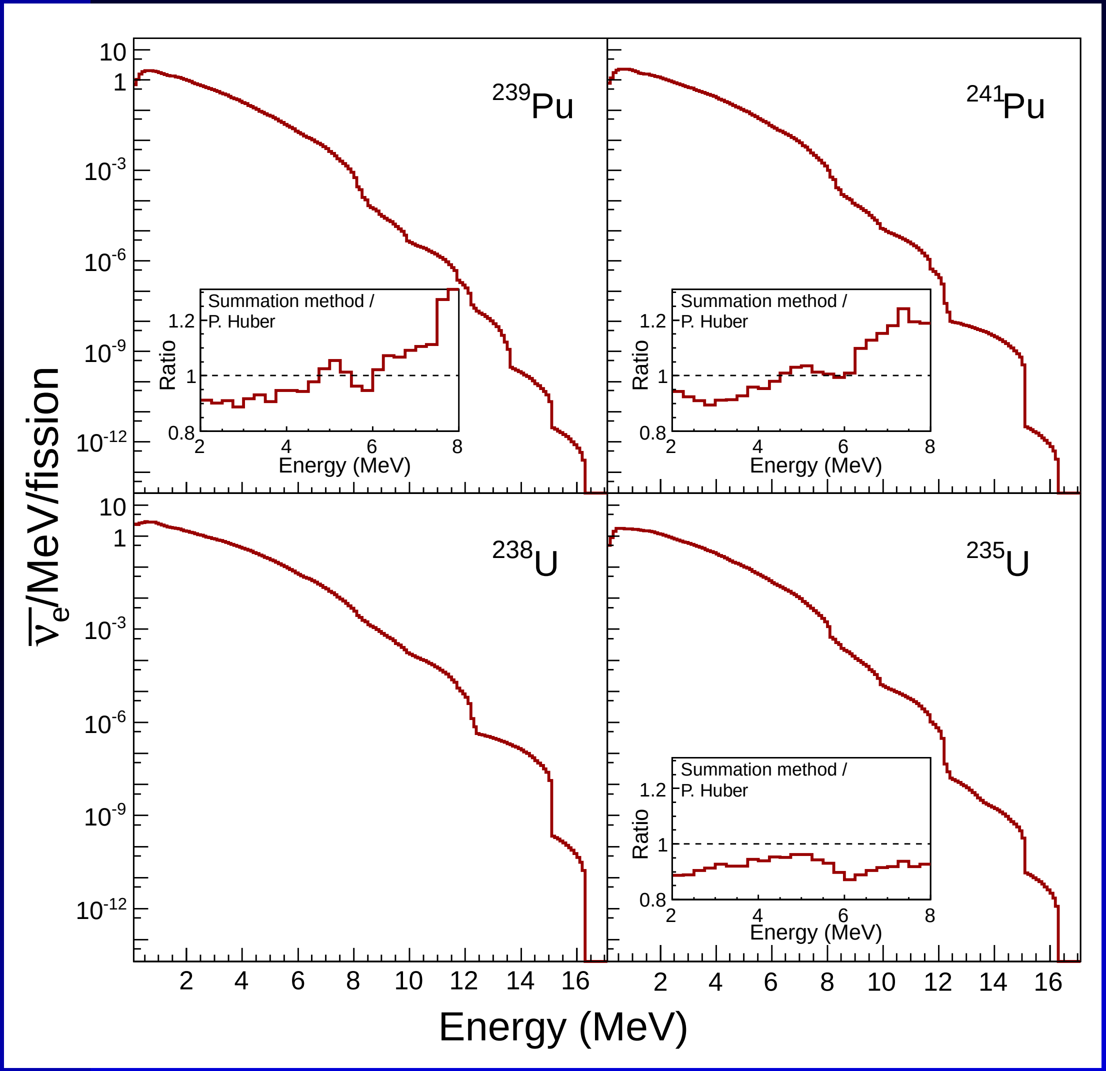


Same shift in all isotopes

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

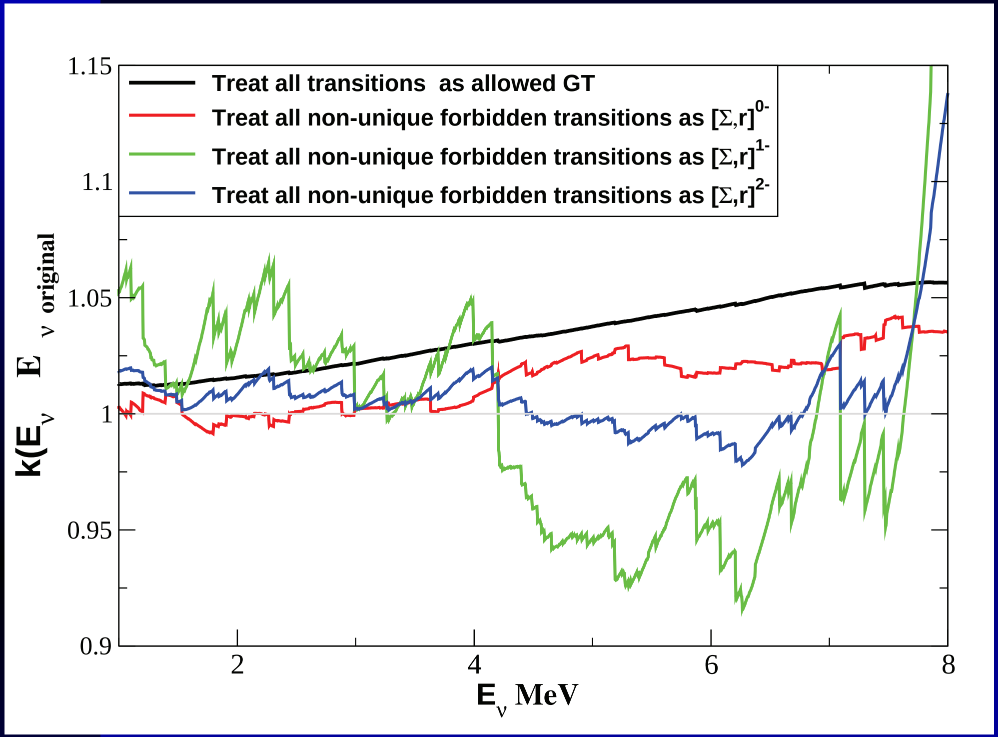


Updated β-feeding functions from total absorption γ spectroscopy (safe from pandemonium) for the isotopes: ^{102,104,105,106,107}Tc, ^{105}Mo and ^{102}Nb

Still a 10-20% discrepancy with the measured total β-spectra, also for ^{238}U.

Fallot *et al.*, 2012

Forbidden decays

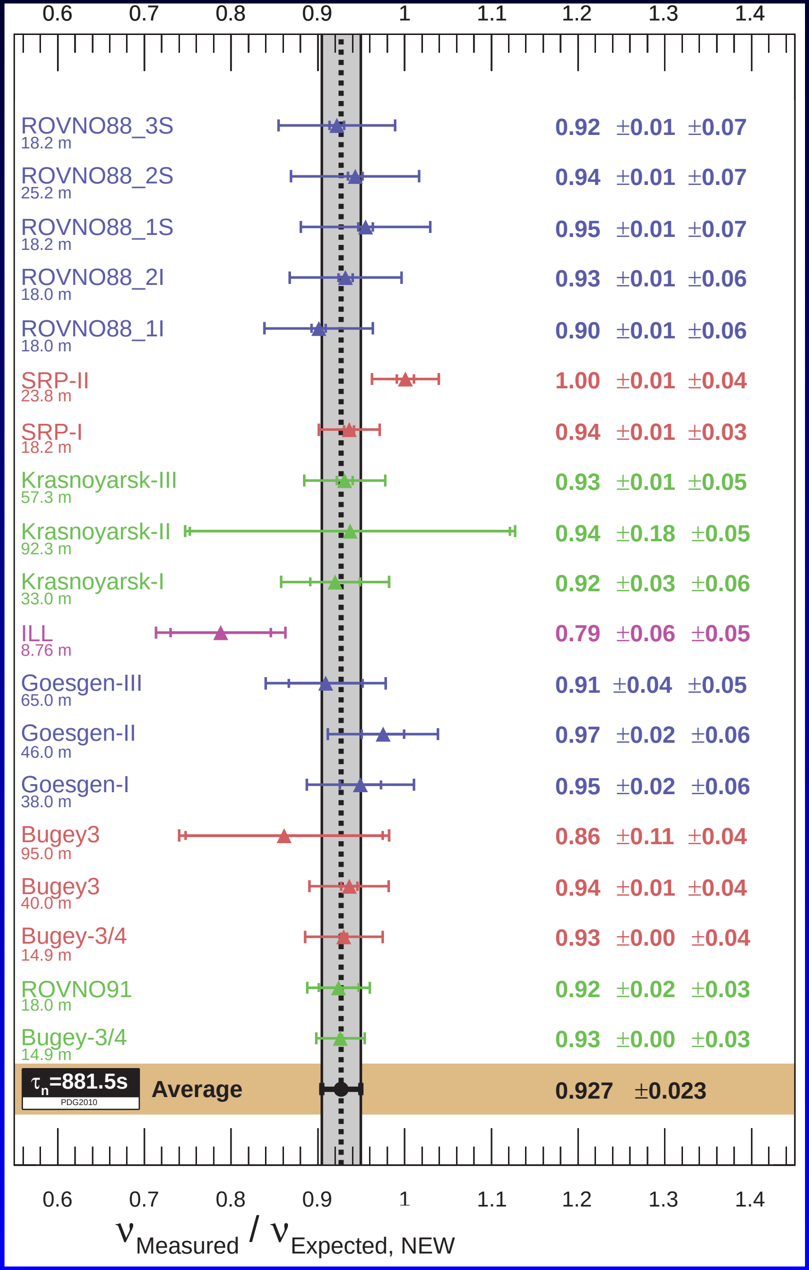


Approximate upper bound for the flux error due to forbidden decays.

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.

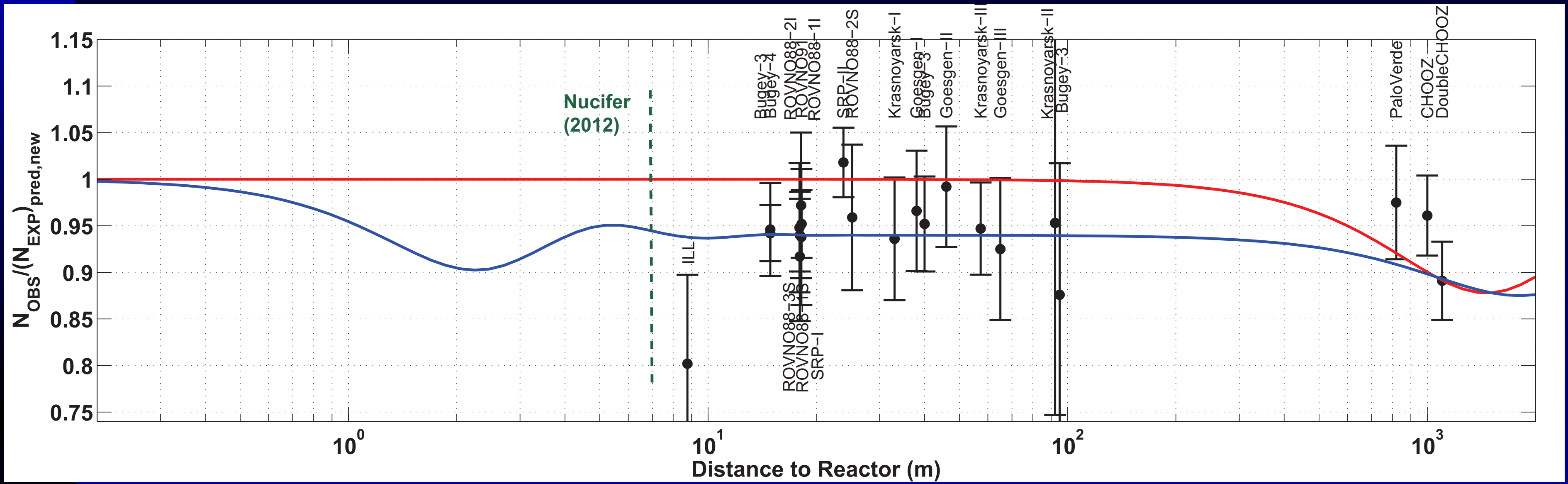
The reactor anomaly



The increase in predicted neutrino fluxes, triggered a re-analysis of existing reactor data

And this was found by Mueller *et al.*, 2011, 2012 – where are all the neutrinos gone?

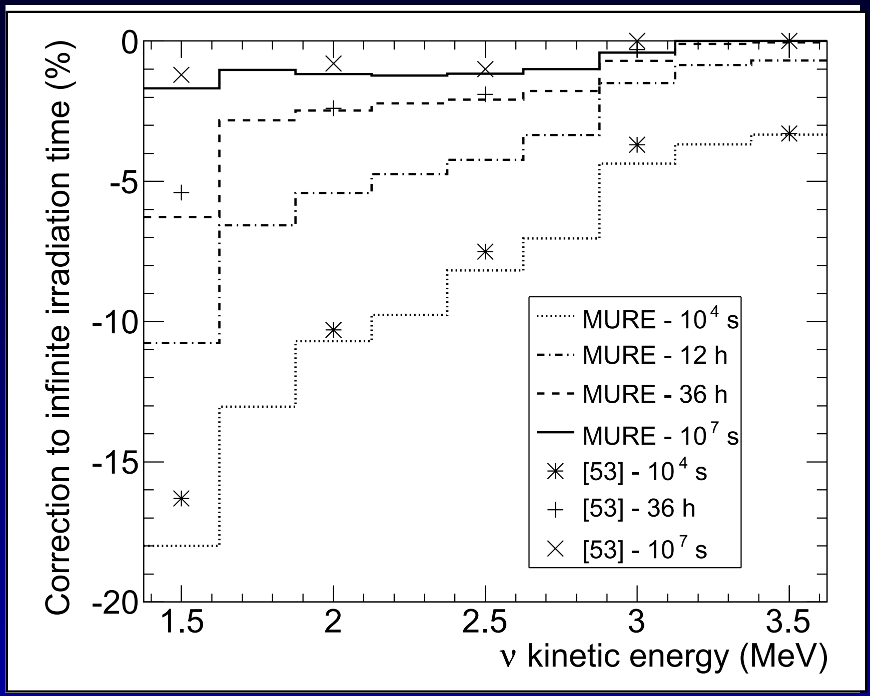
Reactor anomaly



6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime
- inclusion of long-lived isotopes (non-equilibrium correction)

Non-equilibrium corrections



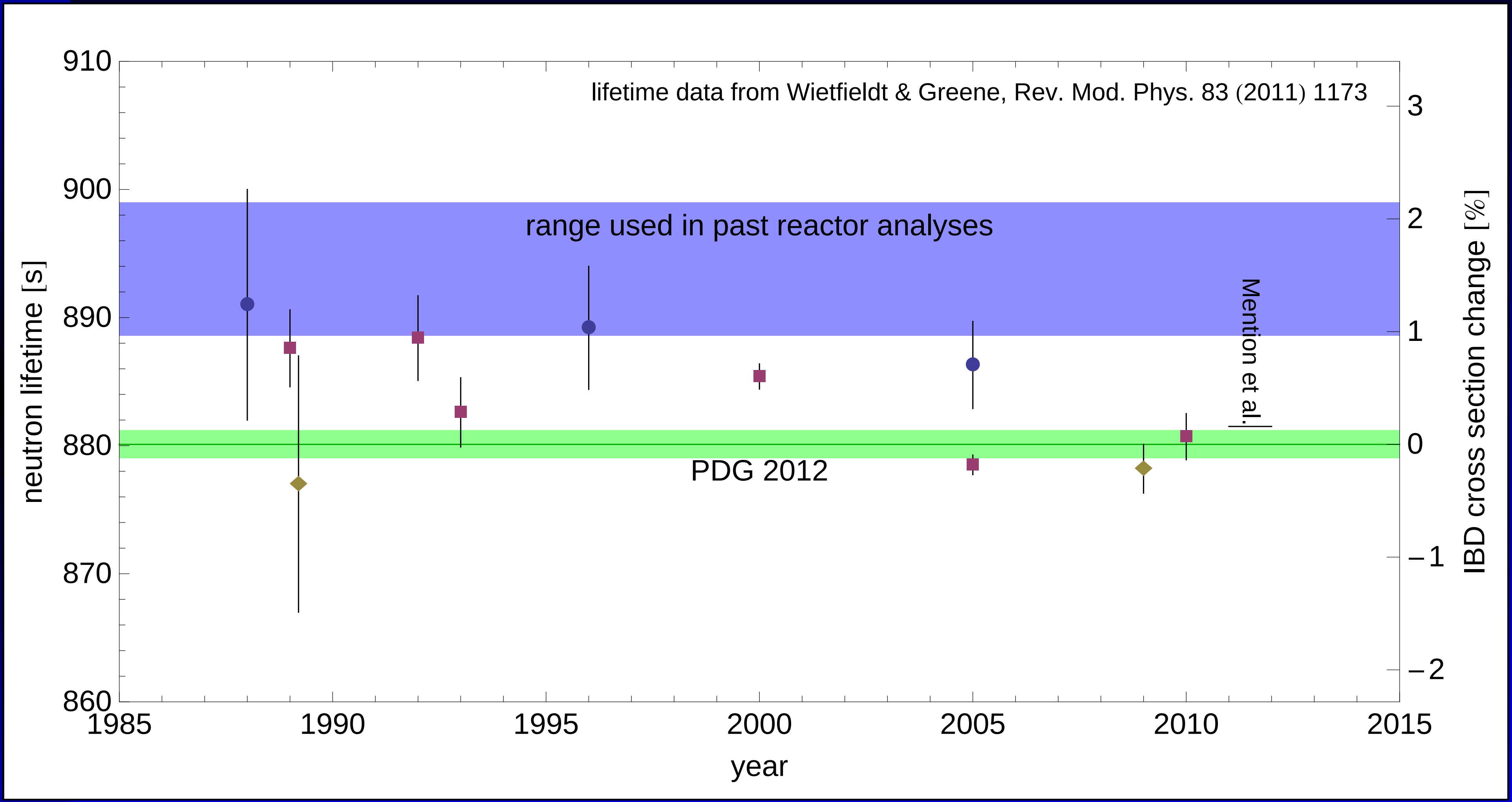
Mueller, *et al.*, RRC 83 (2011) 054615

only 2 dozen isotopes with $t_{1/2} > 12\,\mathrm{h}$ above inverse β-decay threshold

Extra shift due to long-lived isotopes

a) small nuclear physics uncertainty in β-decay
b) depends on detailed fuel history

Neutron lifetime



Gallium anomaly

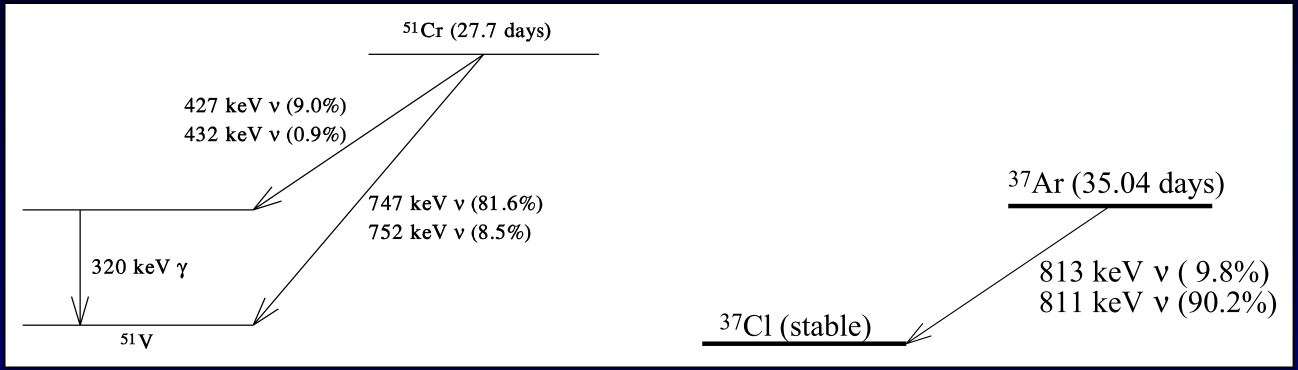
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_{B}	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
R^k_{H}	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

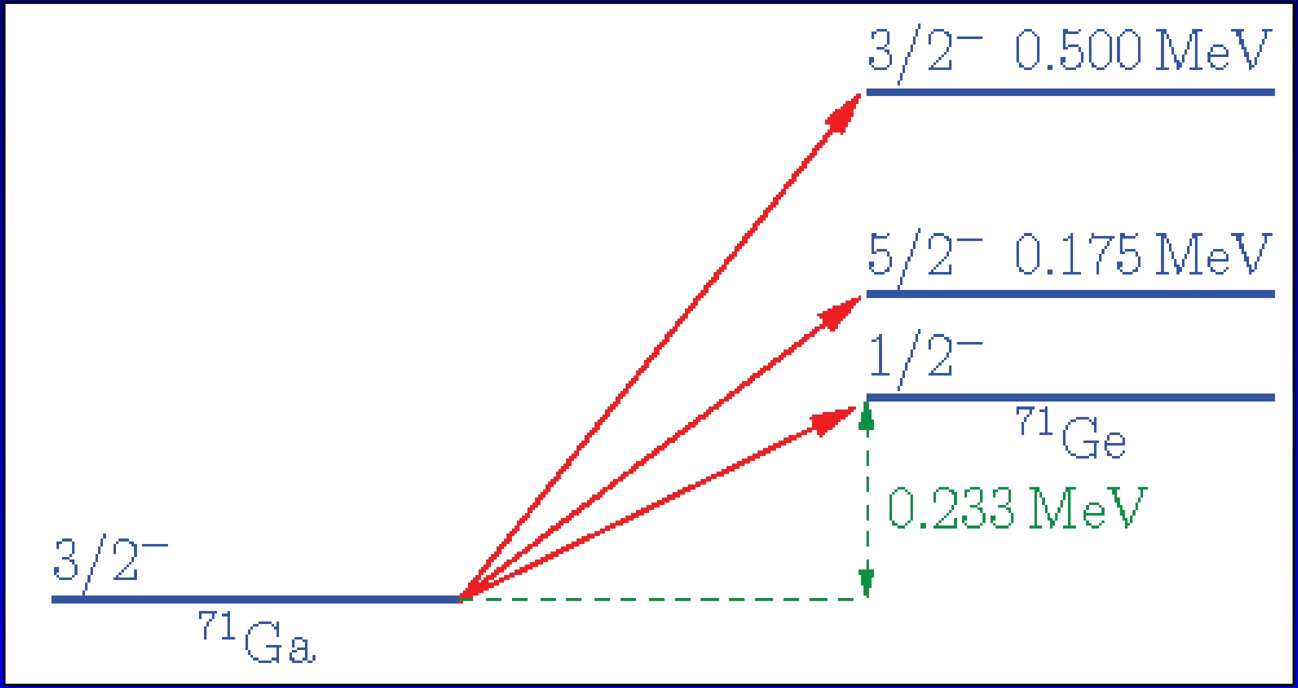
25% deficit of ν_e from radioactive sources at short distances

Effect depends on nuclear matrix elements

This measurement was intended as a calibration – is R a physics measurement or a calibration constant?

Nuclear matrix elements





Where are all the neutrinos?

A simple explanation for all these results is given by neutrino oscillation

$$P(\nu_e \to \nu_e) = 1 - \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E} \simeq 0.8 - 0.9$$

explains both the reactor and gallium results.

$$L/E_{\mathrm{reactor}} = 2.5 - 25\,\mathrm{m/MeV}$$
$$L/E_{\mathrm{gallium}} \simeq 5\,\mathrm{m/MeV}$$

$L/E = 5\,\mathrm{m/MeV}$ corresponds to $\Delta m^2 \simeq 0.25\,\mathrm{eV}^2$

Why sterile?

We need a Δm^2 of order eV^2, but we already have measured two other Δm^2 to be around $7 \times 10^{-4}\,\mathrm{eV}^2$ and $2.4 \times 10^{-3}\,\mathrm{eV}^2$.

Given $\Delta m_{ij} = m_i^2 - m_j^2$, 3 different values of Δm^2 require at least 4 different values for m $\rightarrow$ we need 4 or more neutrinos

The number of neutrinos coupling to the Z is

$$N_\nu = 2.9840 \pm 0.0082 \ll 4$$

Any extra light neutrinos do not participate in weak interactions – they have NO Standard Model interactions at all – likely portal to hidden sector.

Sterile oscillation

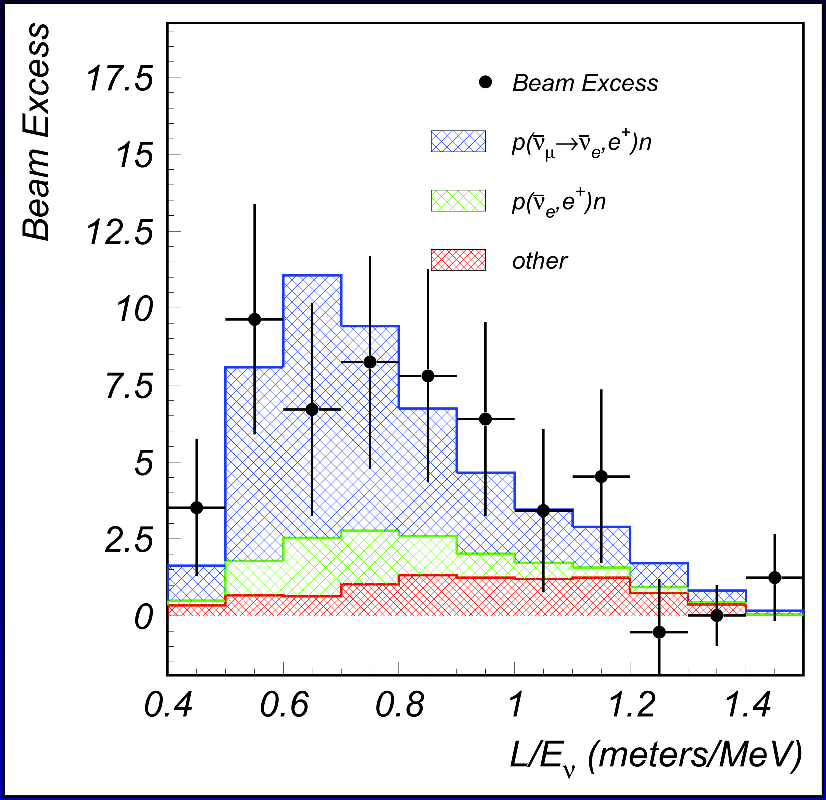
In general, in a 3+N sterile neutrino oscillation model one finds that the energy averaged probabilities obey the following inequality

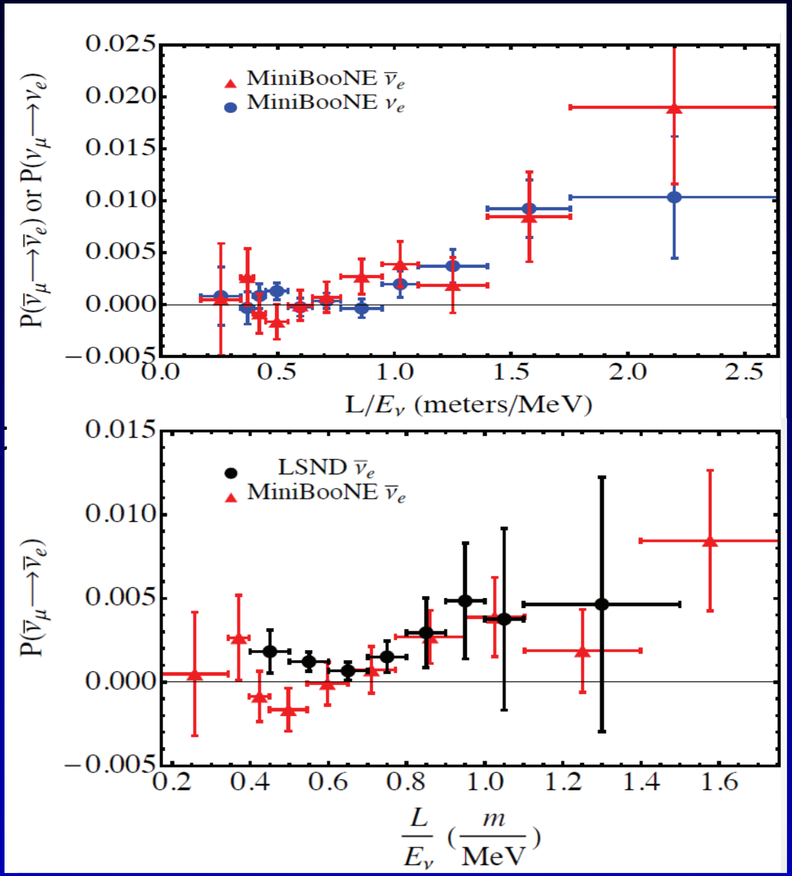
$$P(\nu_\mu \to \nu_e) \leq 4[1 - P(\nu_e \to \nu_e)][1 - P(\nu_\mu \to \nu_\mu)]$$

independent of CP transformations. Therefore, a stringent test of the model is to measure

- $P(\nu_\mu \to \nu_e)$ – appearance
- $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ – appearance
- $P(\nu_\mu \to \nu_\mu)$ or $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$ – disappearance
- $P(\nu_e \to \nu_e)$ or $P(\bar{\nu}_e \to \bar{\nu}_e)$ – disappearance

LSND and MiniBooNE

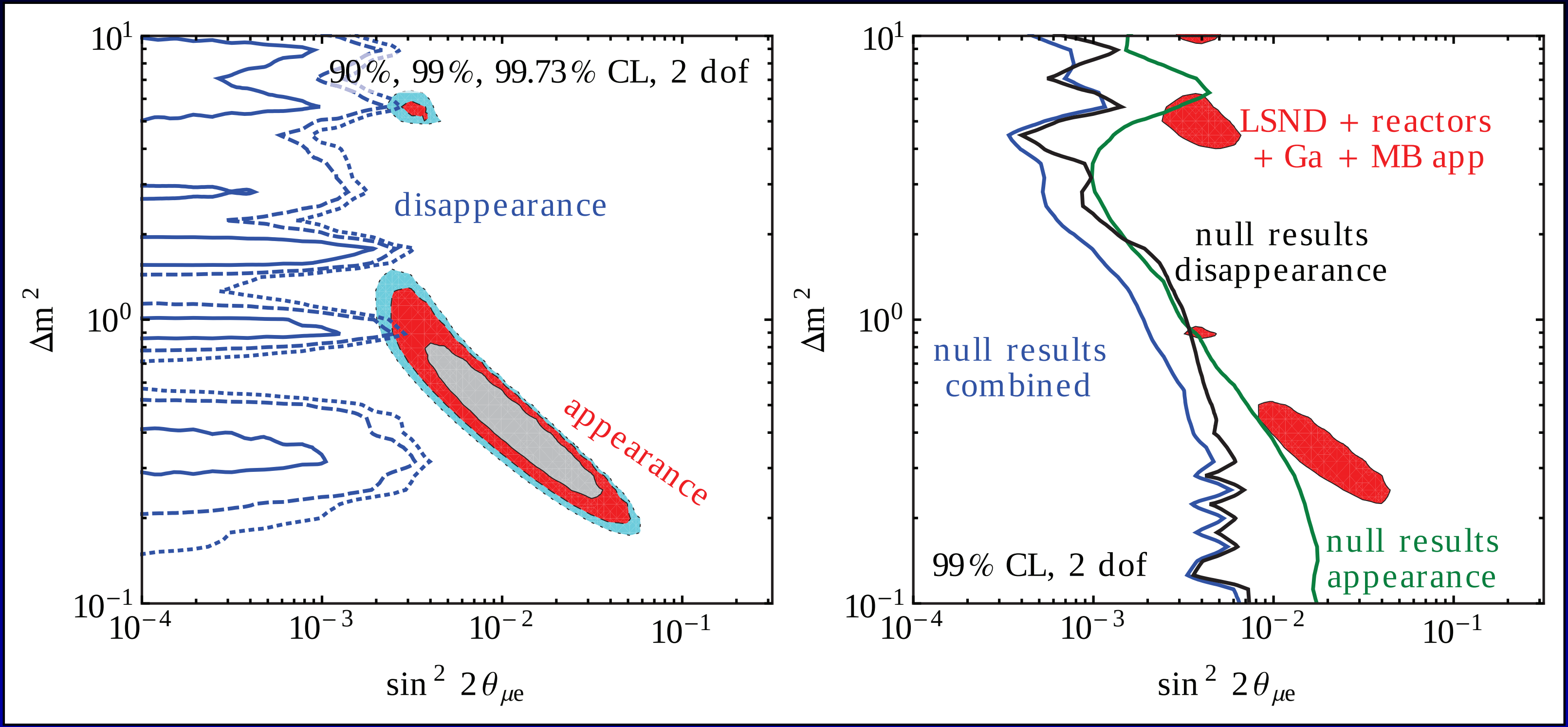




$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

The L/E values correspond to a $\Delta m^2 \sim 0.1 - 10\,\mathrm{eV}^2$

Disappearance constraints



No effects in

- atmospheric
- Bugey
- CDHS
- MINOS
- ...

Resolution will require new experiments, both for appearance and disappearance

Figure from arXiv 1303.3011

Astrophysics

Effective neutrino species from Planck Abe, *et al.*, 2013

$$N_{eff} = 3.36 \pm 0.34$$

but, Planck also finds the Hubble parameter at $H_0 = 67.4 \pm 1.4\,\mathrm{km\,s^{-1}Mpc^{-1}}$ which is about $2.6\,\sigma$ below the value found by the Hubble Space Telescope. Combining HST and Planck yields

$$N_{eff} = 3.62 \pm 0.25$$

quoting from the Planck paper

> It is up to the reader to decide how to interpret such results, but it is simplistic to assume that all astrophysical data sets have accurately quantified estimates of systematic errors. We have there-

Future experimental efforts

There is number of planned reactor experiments

Nucifer	France	research	liquid (Gd)	data taking
DANSS	Russia	PWR	plastic (Gd)	under construction
Stereo	France	research	liquid (Gd)	approved
SoLid	Belgium	research	plastic (^{6}Li)	prototype
PROSPECT	USA	research	liquid	R&D

SOX – radioactive sources in Borexino

kCi ^{144}Ce $\bar{\nu}_e$ source – inverse beta-decay

MCi ^{51}Cr ν_e source – elastic electron scattering

And whatever Fermilab will do in the Booster neutrino beam, ICARUS?

Summary

- Reactors are complex sources – the reactor anomaly may be a true deficit in neutrinos or just a result of the complexity of the source
- Pion decay based beams have about 1% ν_e and the appearance signal is $\sim 0.1\%$ – precision measurements with S/N=0.1?
- For both appearance and disappearance measurements, NuSTORM offers unrivaled sensitivity