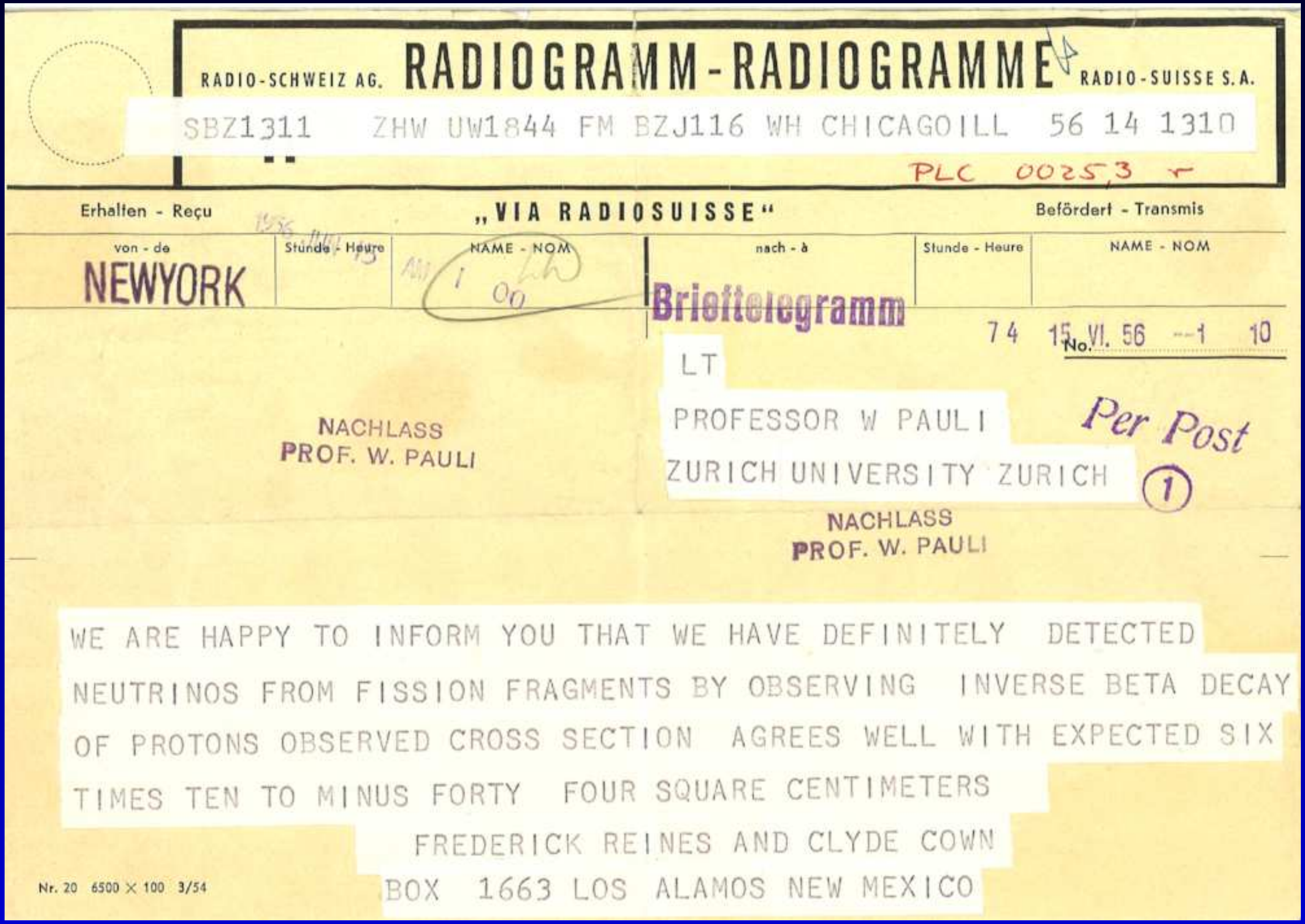
Neutrino Flux Predictions at Reactors

Patrick Huber

Center for Neutrino Physics – Virginia Tech

Neutrino Oscillation Workshop 2018 – NOW 2018
Ostuni, Italy, September 9–16, 2018

1956



RADIO-SCHWEIZ AG. RADIOGRAMM-RADIOGRAMME RADIO-SUISSE S.A.

SBZ1311 ZHW UW1844 FM BZJ116 WH CHICAGOILL 56 14 1310

PLC 00253

Erhalten - Reçu „VIA RADIOSUISSE" Befördert - Transmis

von - de	Stunde - Heure	NAME - NOM	nach - à	Stunde - Heure	NAME - NOM
NEWYORK			Brieftelegramm		

74 15.VI.56 --1 10

LT

PROFESSOR W PAULI

ZURICH UNIVERSITY ZURICH

Per Post

NACHLASS PROF. W. PAULI

WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS

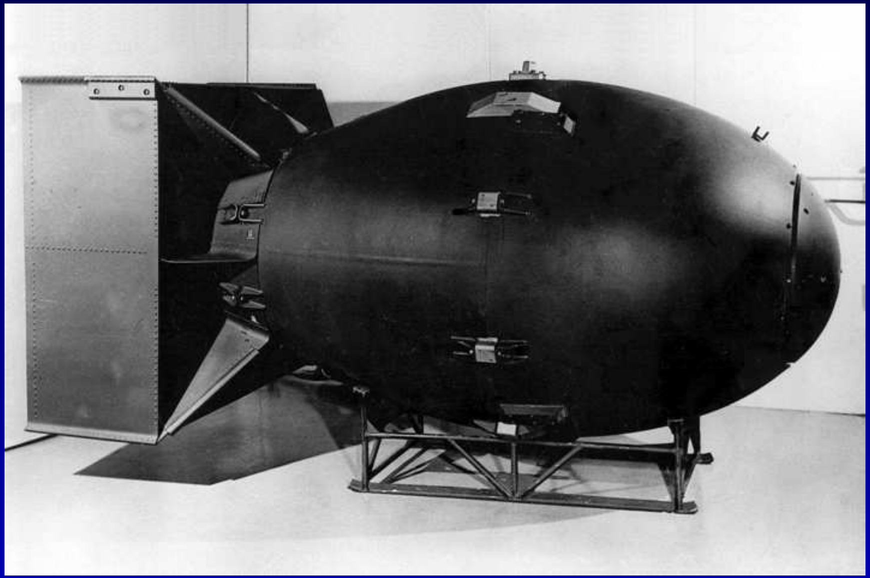
FREDERICK REINES AND CLYDE COWN

BOX 1663 LOS ALAMOS NEW MEXICO

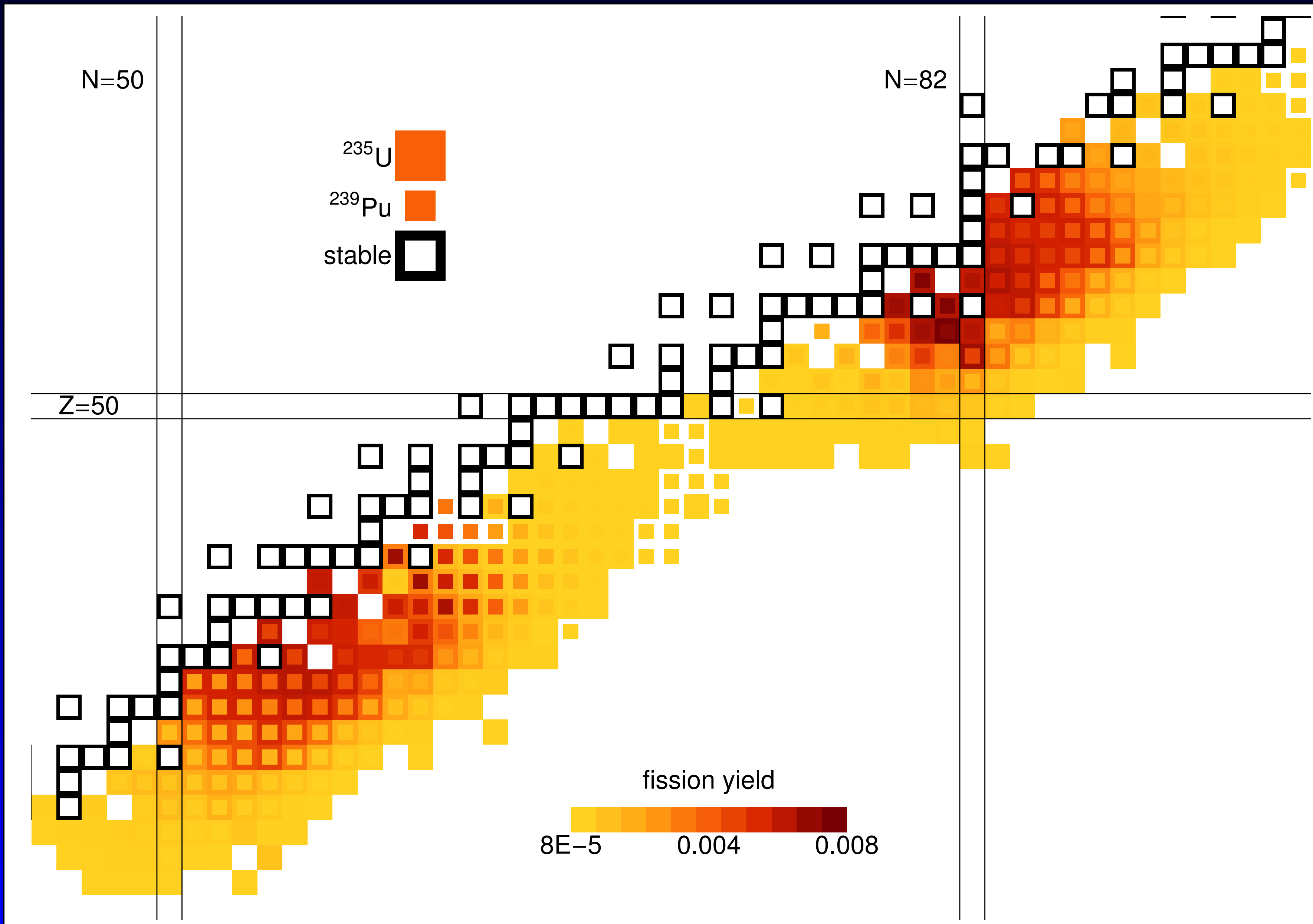
Nr. 20 6500 × 100 3/54

They report a cross section (!) of $6 \times 10^{-44}\,\mathrm{cm}^{-2} \rightarrow$ to measure a cross section one needs to know the flux.

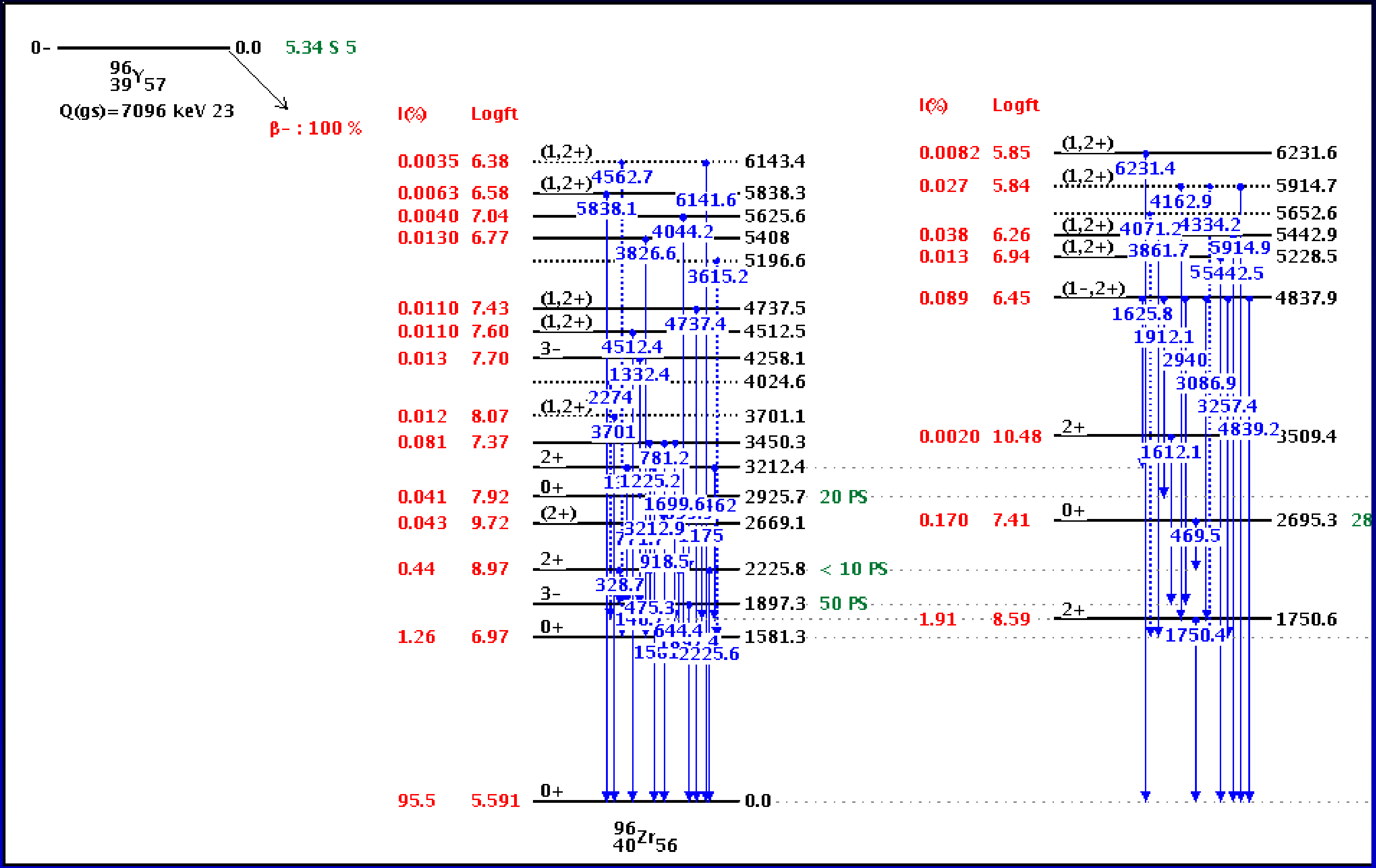
Why care today?



Neutrinos from fission

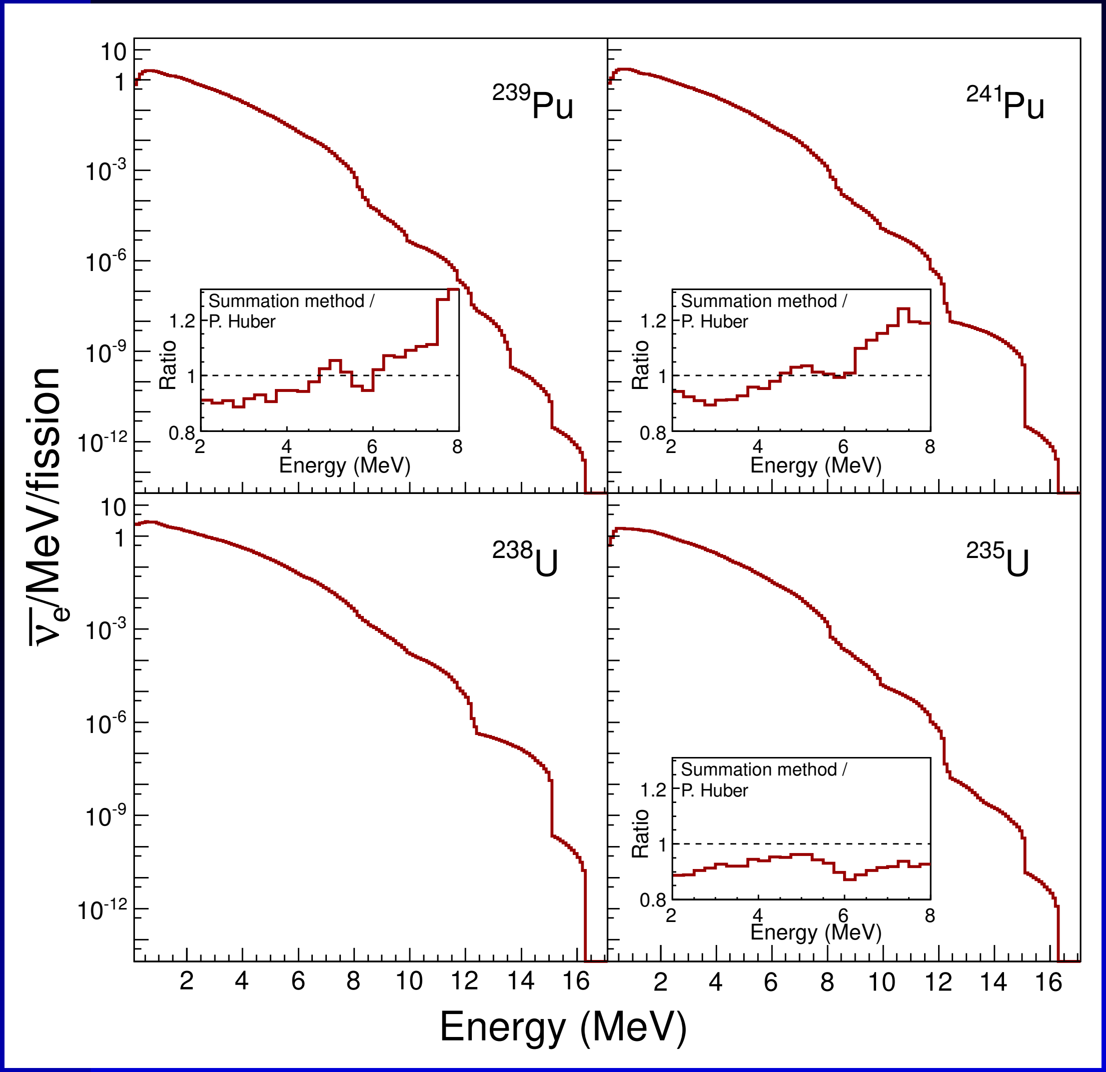


β-branches



NB: Sizable fraction of fission product beta-decay information in ENSDF is based on so called gross beta decay theory.

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

The calculation for ^{238}U agrees within 10% with measurement of Haag *et al.*

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

β-decay – Fermi theory

$$N_\beta(W) = K \underbrace{p^2(W - W_0)^2}_{\text{phase space}} F(Z,W)\,,$$

where $W = E/(m_e c^2) + 1$ and W_0 is the value of W at the endpoint. K is a normalization constant. $F(Z,W)$ is the so called Fermi function and given by

$$F(Z,W) = 2(\gamma+1)(2pR)^{2(\gamma-1)} e^{\pi\alpha Z W/p} \frac{|\Gamma(\gamma + i\alpha Z W/p)|^2}{\Gamma(2\gamma+1)^2}$$

$\gamma = \sqrt{1-(\alpha Z)^2}$

The Fermi function is the modulus square of the electron wave function at the origin.

Corrections to Fermi theory

$$N_\beta(W) = K\, p^2 (W - W_0)^2\, F(Z,W)\, L_0(Z,W)\, C(Z,W)\, S(Z,W) \times G_\beta(Z,W)\, (1 + \delta_{\rm WM} W)\,.$$

The neutrino spectrum is obtained by the replacements $W \to W_0 - W$ and $G_\beta \to G_\nu$.

L_0 and S have been recently re-evaluated for fission fragments Wang, Friar, Hayes, 2016.

The whole set of corrections has been critically examined McCutchan, Sonzogni, Hayes, 2017.

$\Rightarrow$ all well under control for allowed decays!

Induced weak currents

Describe protons and neutrons as spinors which are solutions to the free Dirac equation, but which are not point-like, we obtain for the hadronic current

$$V_\mu^h = i\bar{\psi}_p \left[g_V(q^2)\gamma_\mu + \frac{g_M(q^2)}{8M}\sigma_{\mu\nu}q_\nu + i g_S(q^2) q_\mu \right] \psi_n$$

$$A_\mu^h = i\bar{\psi}_p \left[g_A(q^2)\gamma_\mu\gamma_5 + \frac{g_T(q^2)}{8M}\sigma_{\mu\nu}q_\nu\gamma_5 + i g_P(q^2) q_\mu\gamma_5 \right] \psi_n$$

Weak magnetism & β-spectra

g_M is called weak magnetism and the question is how it manifests itself in nuclear β-decay. 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 is given by

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

Size of WM correction

In impulse approximation

$$F_M^N(0) = \mu_p - \mu_n \simeq 4.7 \quad \text{and} \quad F_A^N(0) = C_A \simeq 1.27\,,$$

and thus

$$\delta_{WM} \simeq 0.5\%\,\mathrm{MeV}^{-1}$$

This value, in impulse approximation, is universal for all β-decays since it relies only on free nucleon parameters.

There are good reasons to doubt this value, but recent work Wang, Hayes, 2017 indicates that this value is OK for allowed decays.

Extraction of ν-spectrum

We can measure the total β-spectrum

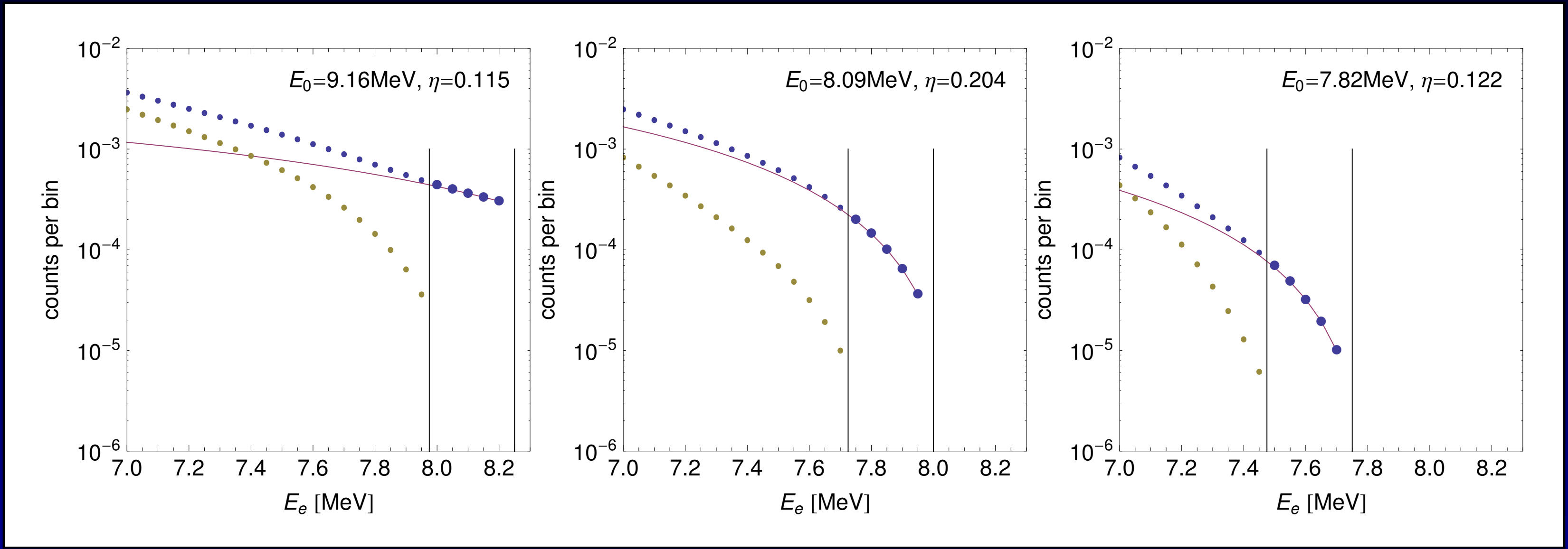
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z})\, \eta(E_0)\,. \qquad (1)$$

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

This is a so called Fredholm integral equation of the first kind – mathematically ill-posed, *i.e.* solutions tend to oscillate, needs regulator (typically energy average), however that will introduce a bias.

This approach is know as "virtual branches"

Virtual branches



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

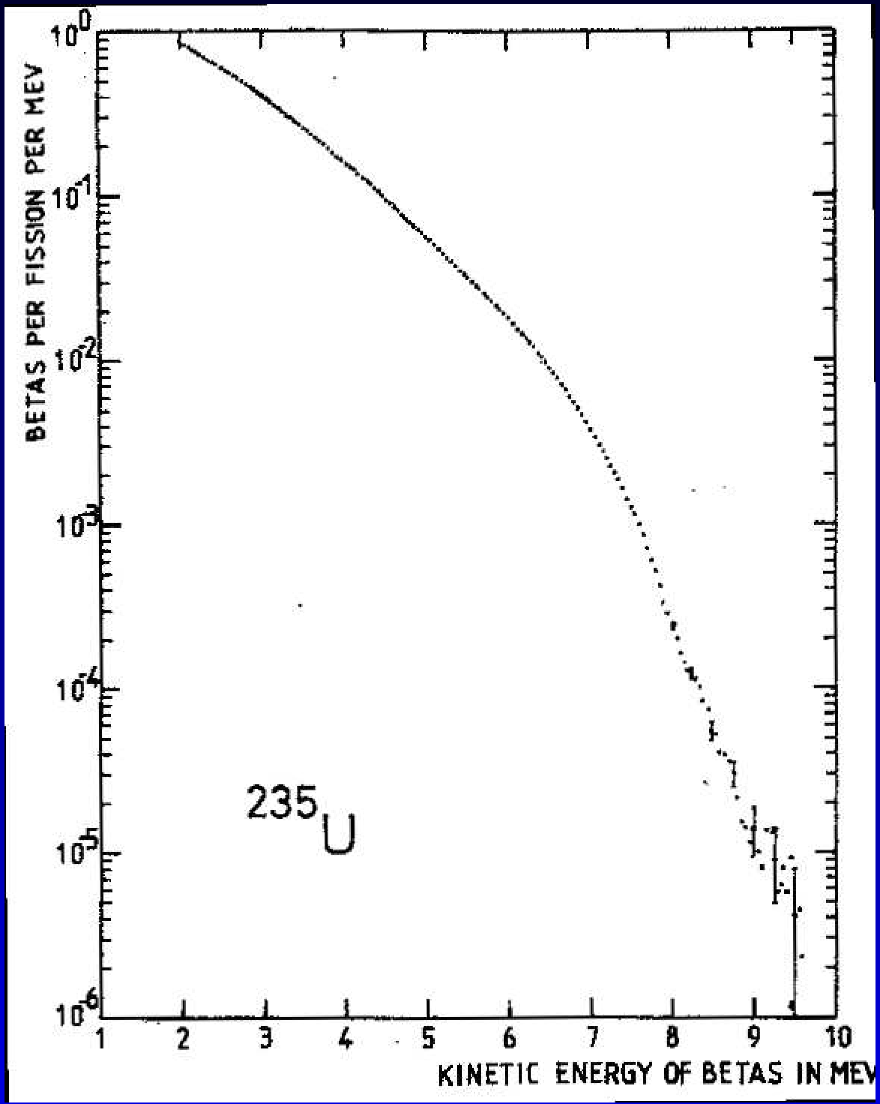
2 – delete the last s data points

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.

β spectrum from fission

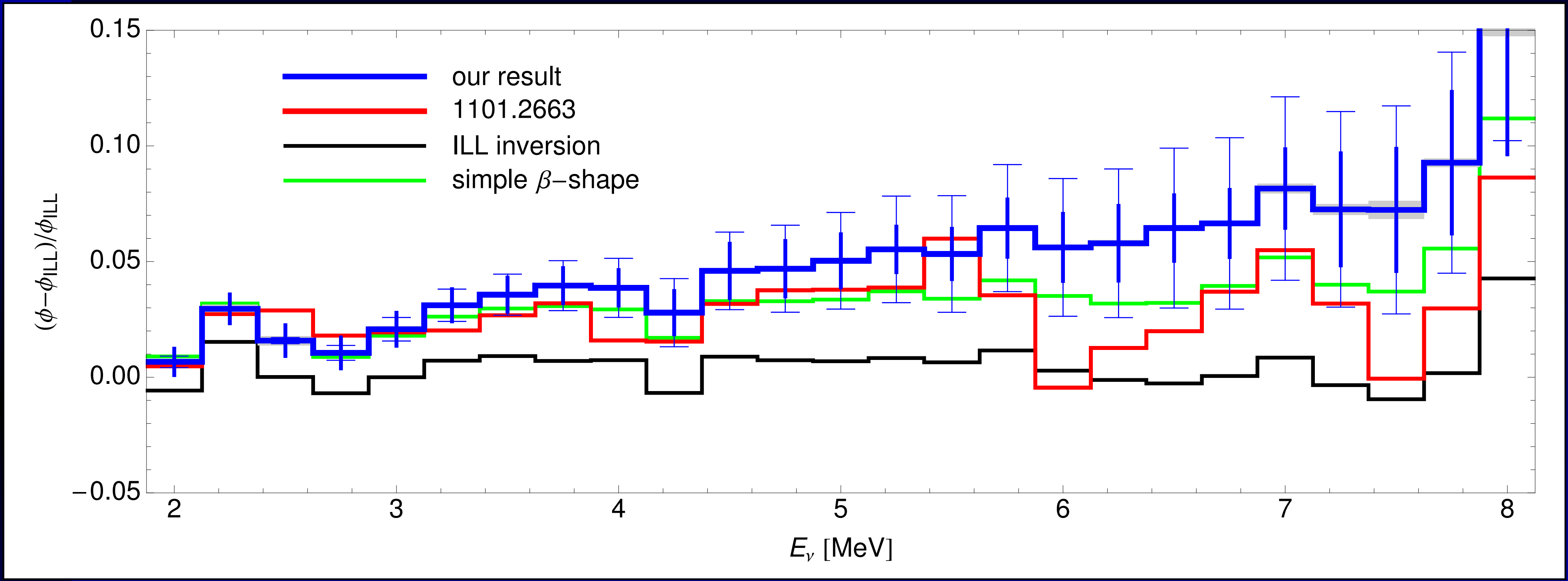


Schreckenbach, *et al.* PLB **160**, 325 (1985).

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

Electron spectroscopy with a magnetic spectrometer

Result for ^{235}U



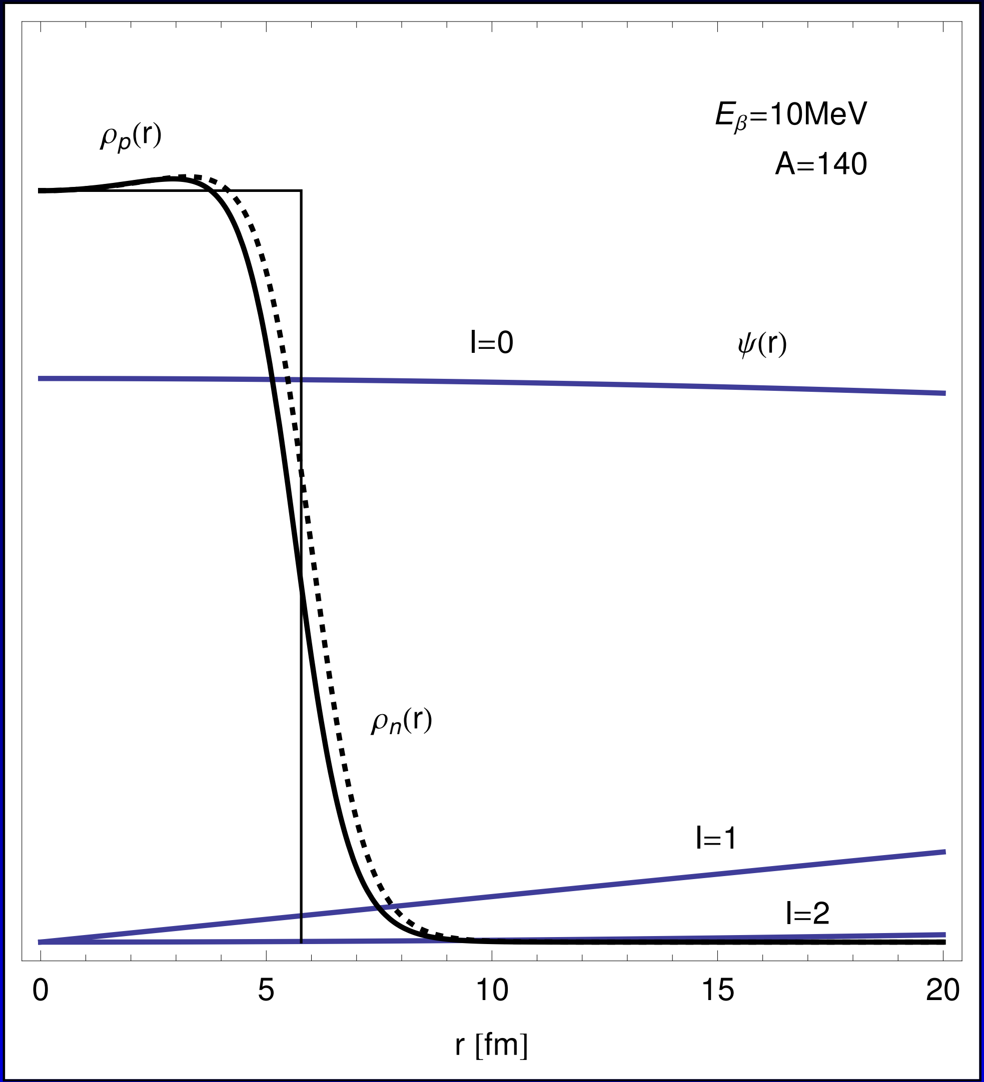
Shift with respect to ILL results, due to

a) different effective nuclear charge distribution

b) branch-by-branch application of shape corrections

If there were only allowed decays involved, the error bars would be firm.

Forbidden decays



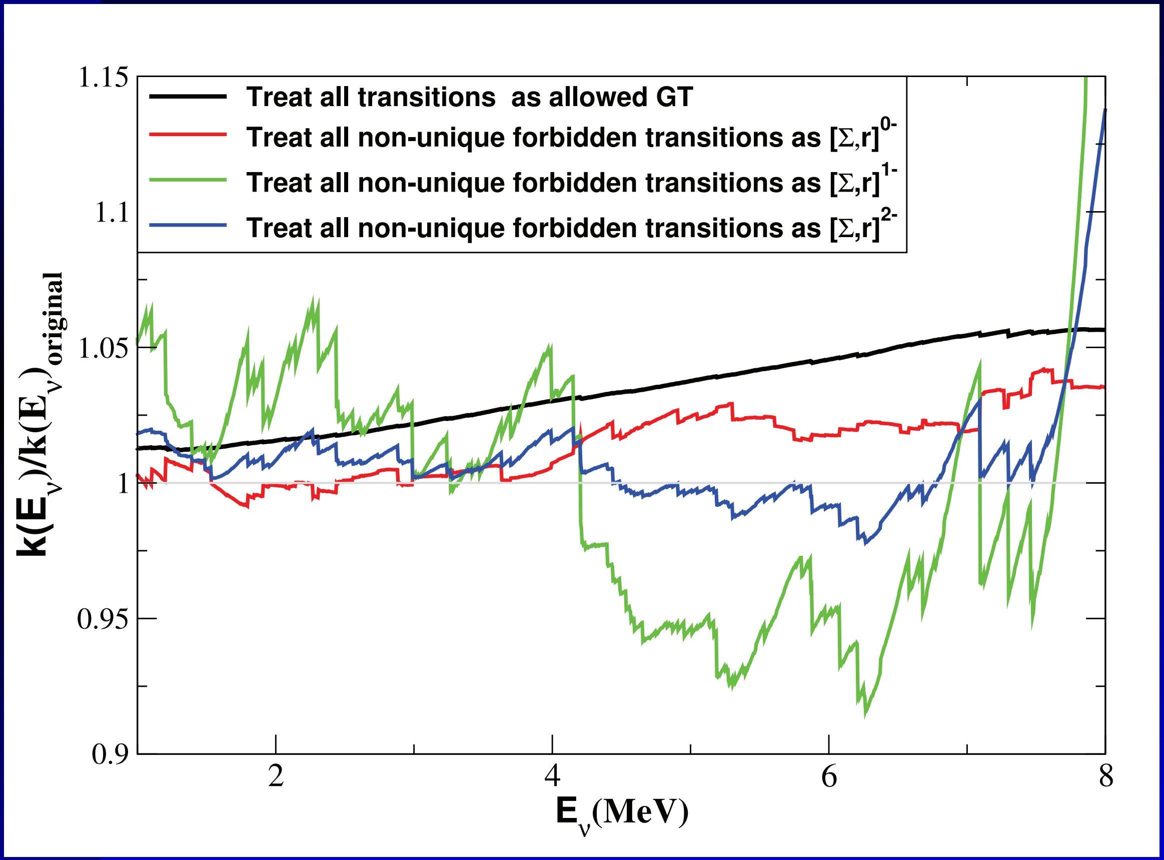
$e,\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

Allowed:
s-wave emission ($l = 0$)

Forbidden:
p-wave emission ($l = 1$) or $l > 1$

Significant dependence on nuclear structure in forbidden decays$\rightarrow$ large uncertainties!

Forbidden decays

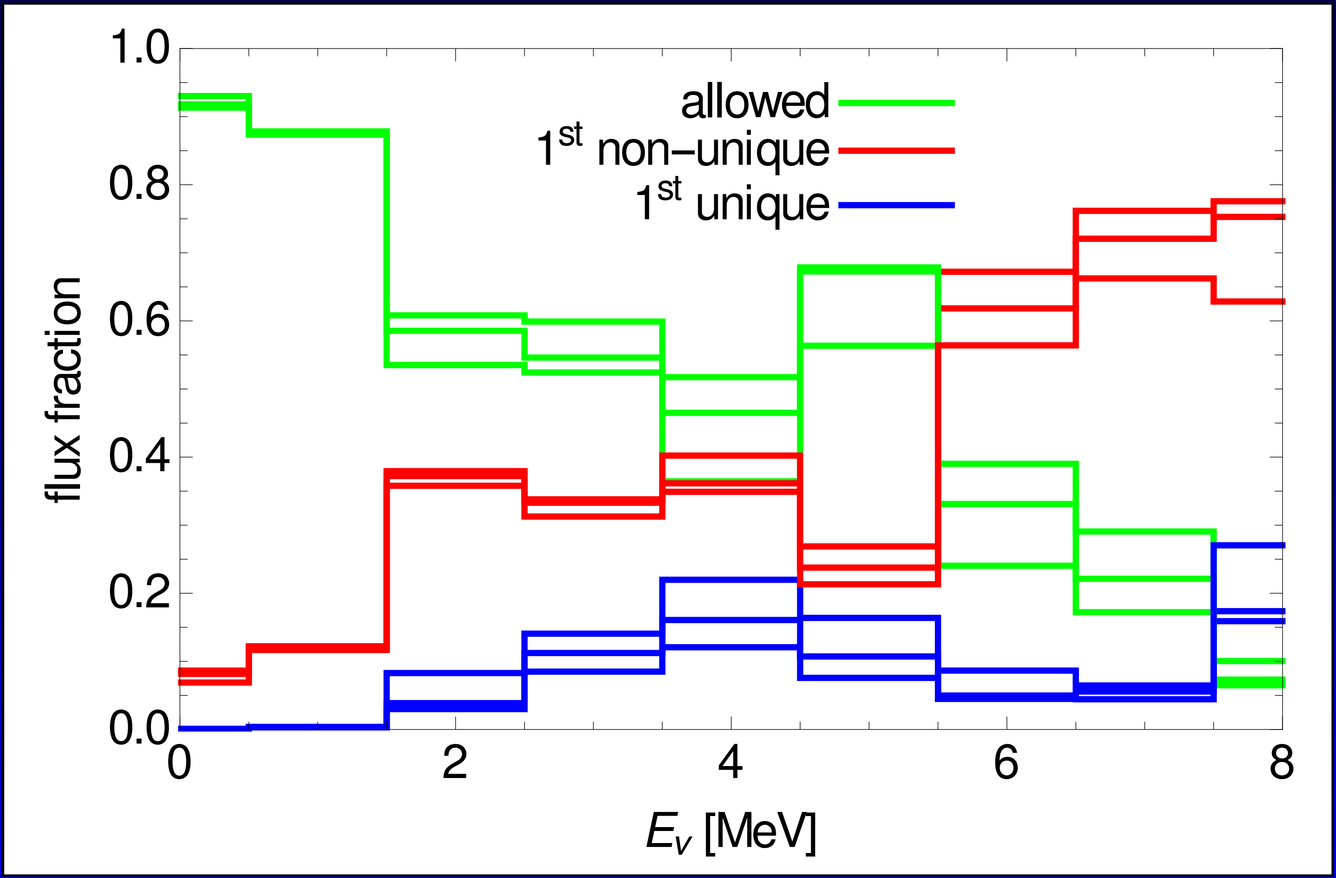


Hayes *et. al*, 2013 point out that in forbidden decays a mixture of different operators are involved.

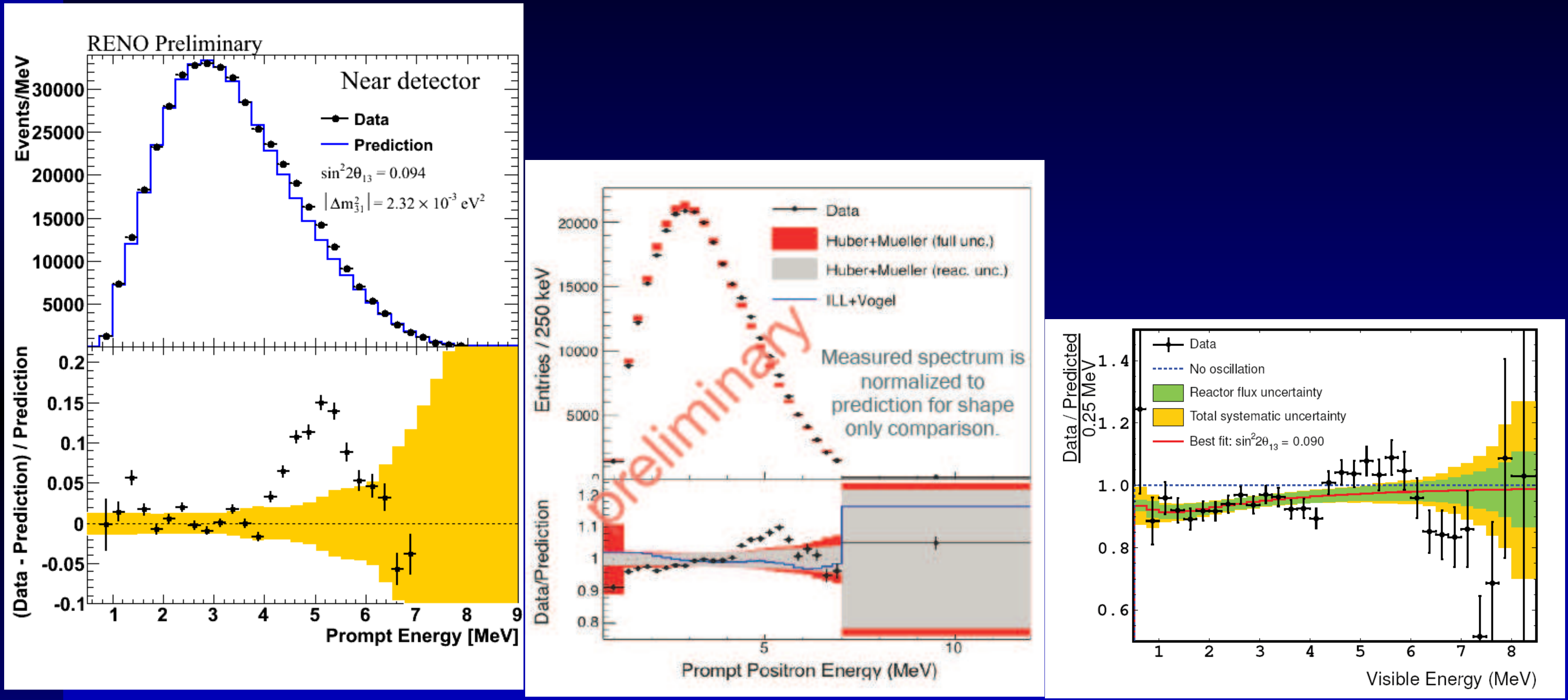
Large source of uncertainty.

A coincidence?

Based on JEFF fission yields and using ENSDF spin-parity assignments



The 5 MeV bump



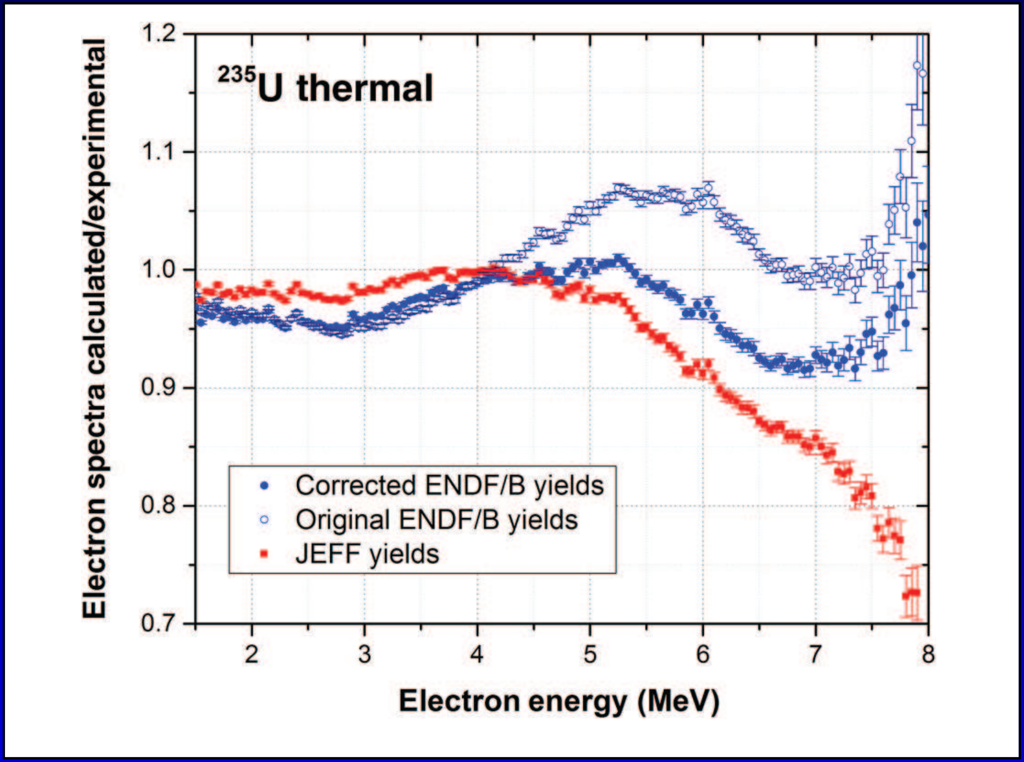
Seen by all three reactor experiments

Tracks reactor power

Seems independent of burn-up

Explanations?

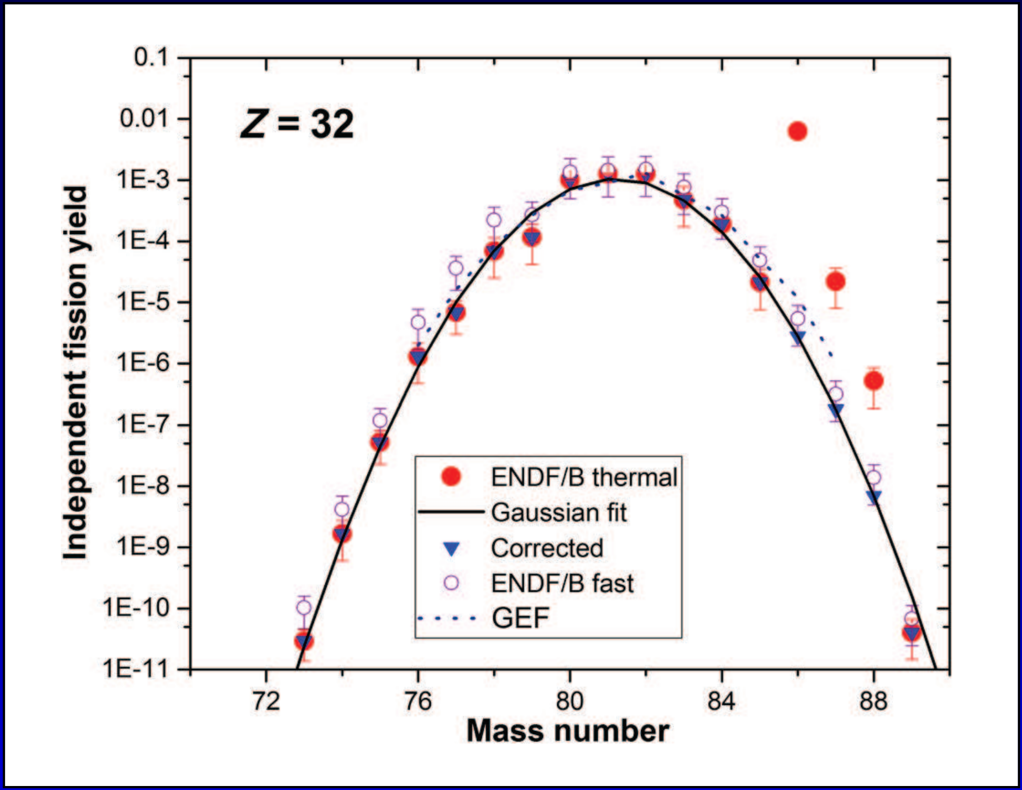
Dwyer and Lanford, 2014 propose a direct summation. Latest ENSDF database with allowed beta-spectrum shape Sonzogni *et al.*, 2016



This direct summation, as all other direct summations, does not agree with the Schreckenbach measurement.

What happened?

Fission yield data has been suspected previously Hayes *et al.* 2015 and this what Sonzogni *et al.*, 2016 found:

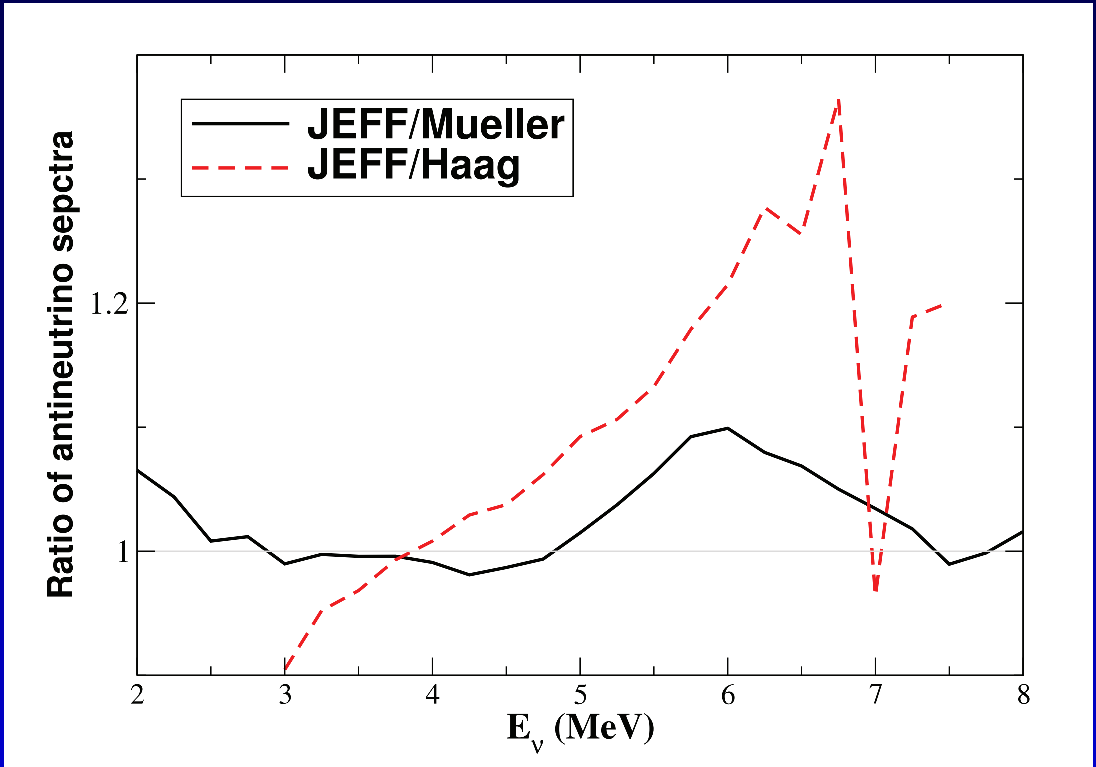


Who is the odd-one-out?

Fission yields for germanium-86 wrong in ENDF/B but not in JEFF.

Uranium-238?

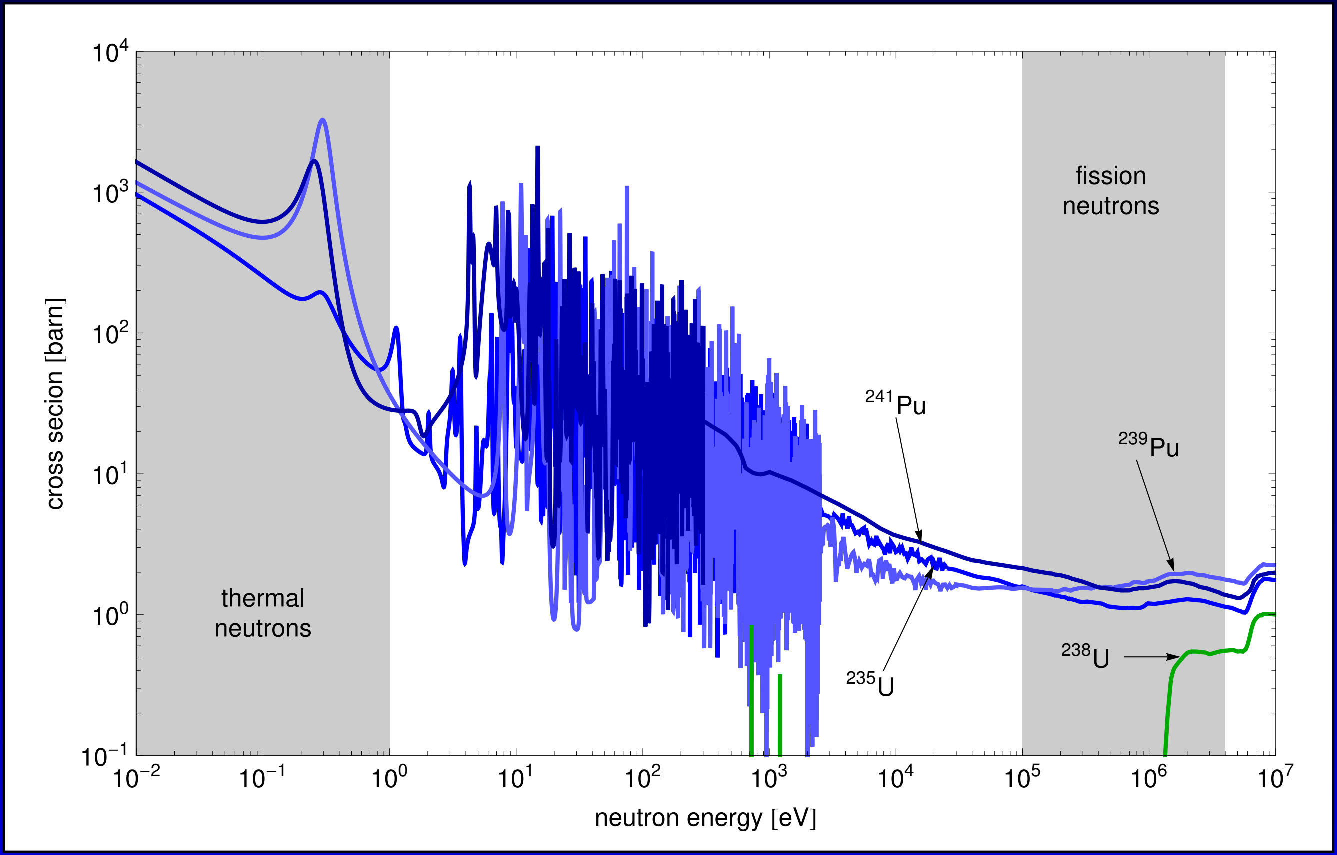
Hayes and Vogel, 2016 point out that fast neutron fission of ^{238}U could be responsible for the bump



If true, NO bump should be seen a reactors running on HEU (nearly pure ^{235}U).

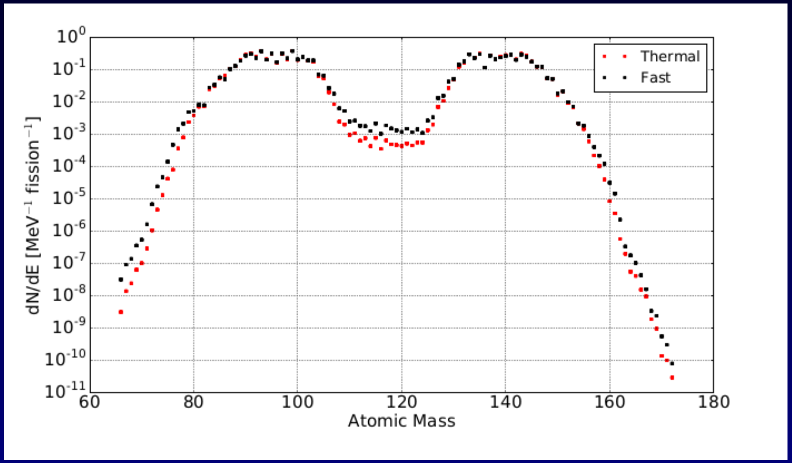
Neutron spectrum?

Hayes and Vogel, 2016 point also out that the neutron spectrum is important

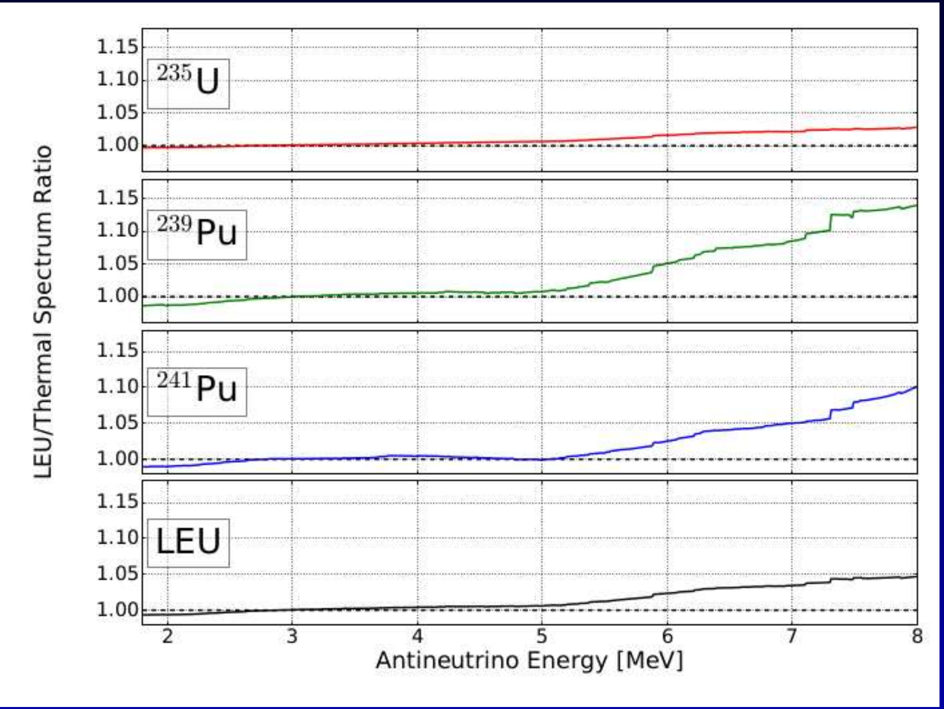


If true, NO bump should be seen a reactors running on HEU (nearly pure ^{235}U).

Not the neutron spectrum



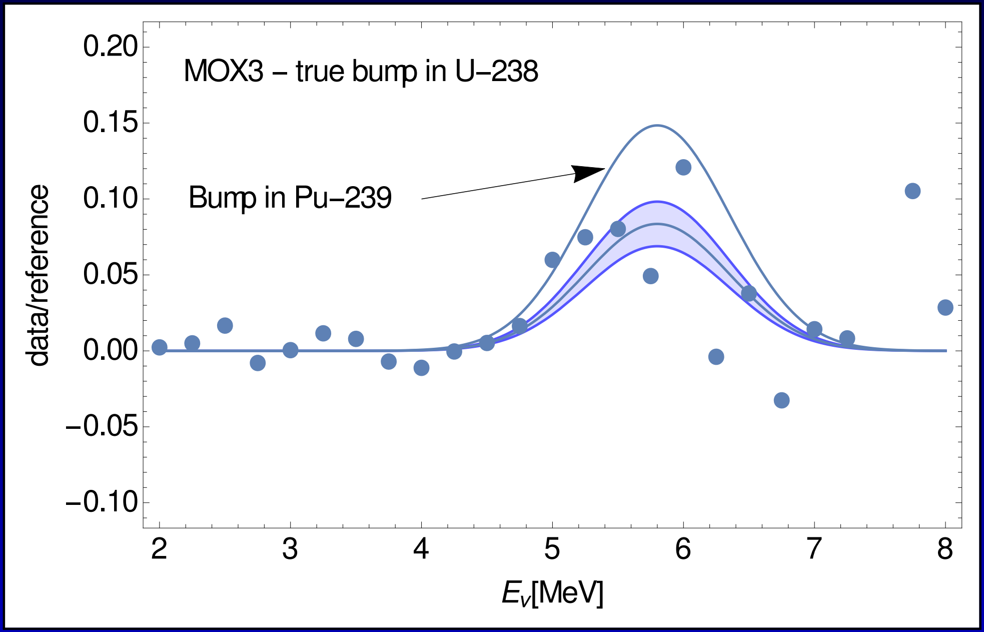
Fission fragment distributions do depend on incoming neutron energy.
Littlejohn, *et al.*, 2018



Enhancement of the high-end of the neutrino spectrum for a realistic neutron spectrum, no bump-like structure and too small.

Different reactors

Optimistic flux errors (per isotope) from Huber, 2011 and bump put by hand to match Daya Bay result

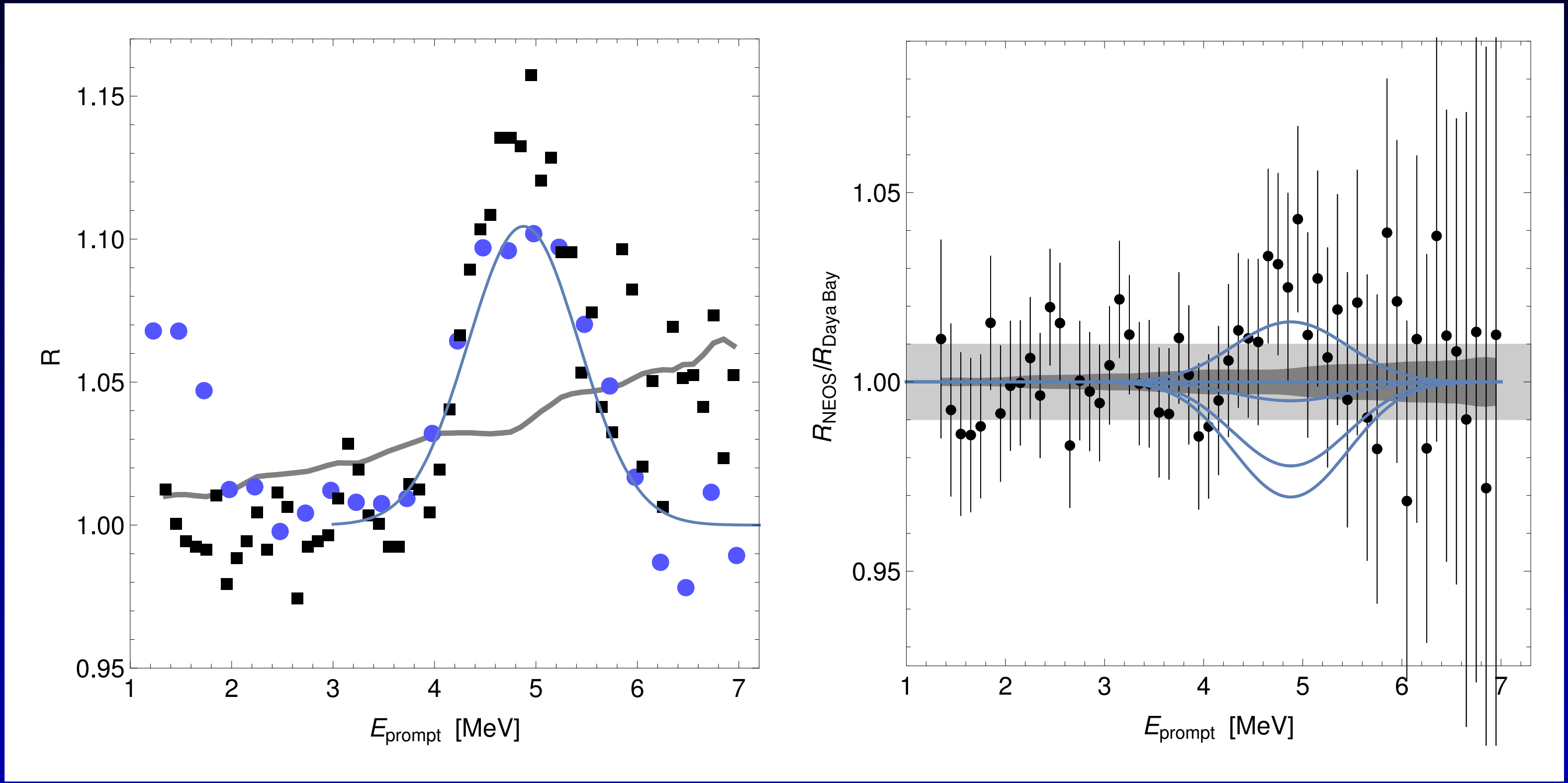


MOX3				
Fit/True	^{235}U	^{238}U	^{239}Pu	^{241}Pu
^{235}U	-	> 4	> 4	> 4
^{238}U	> 4	-	3.8	0.6
^{239}Pu	> 4	3.7	-	> 4
^{241}Pu	> 4	0.7	> 4	-

Requires good statistics: 5 ton, 40% efficient, 1 year data taking.

Huber, 2016, see also Buck *et al.*, 2015

NEOS vs Daya Bay

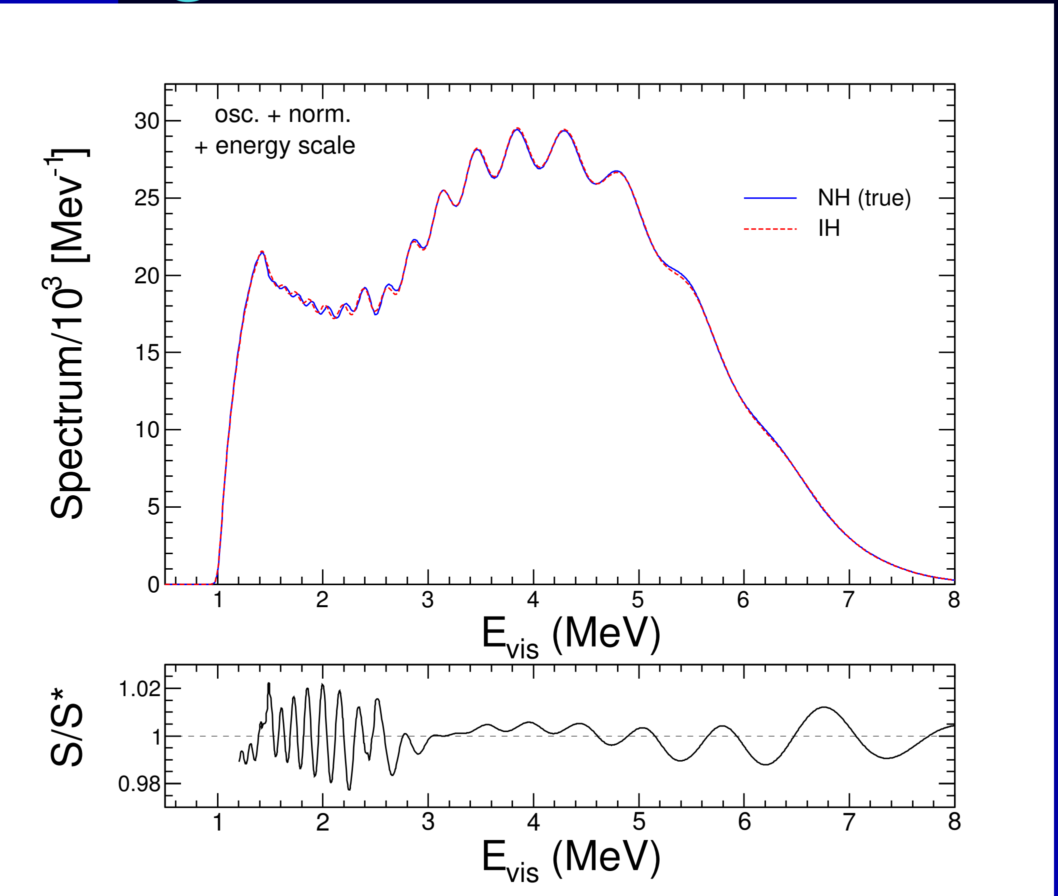


Huber, 2017

There is more U235 in NEOS, since core is fresh $\Rightarrow$ $3-4\,\sigma$ evidence against Pu as sole source of bump, but equal bump size is still allowed at better than $2\,\sigma$.

NB: This paper was conceived during NOW 2016!

JUNO



JUNO is sensitive to mass hierarchy by observing the beat frequency between solar and atmospheric Δm^2 driven oscillation

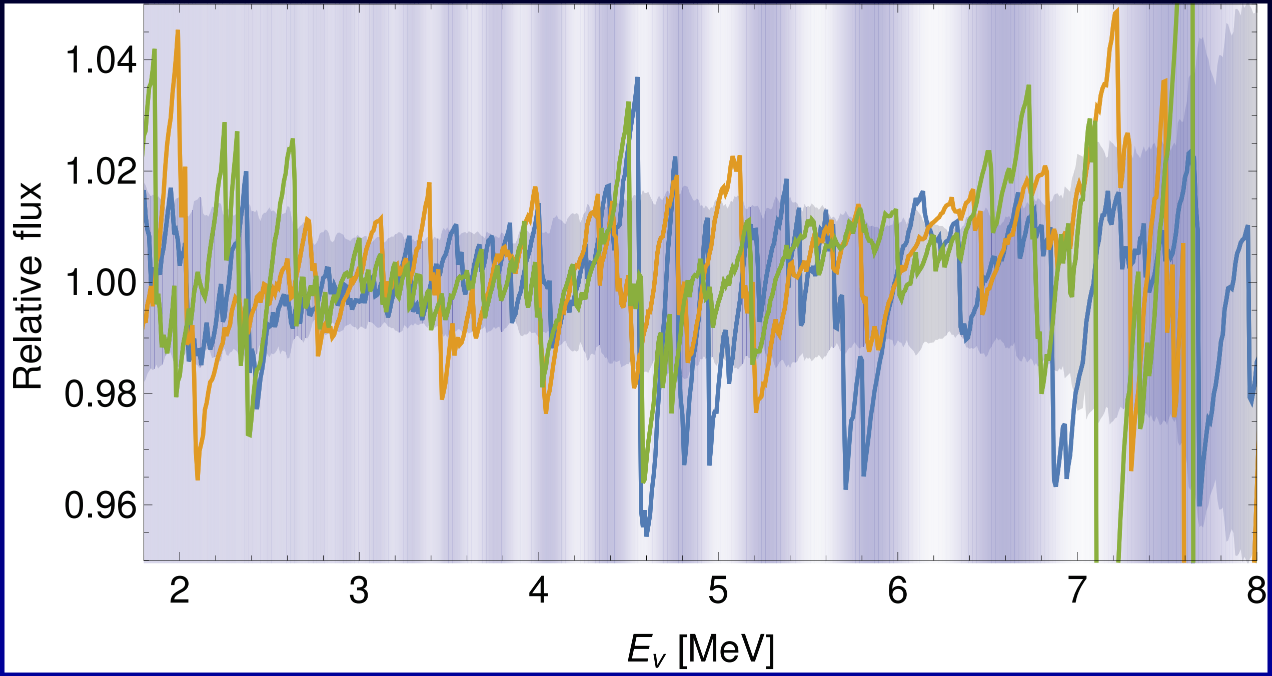
Small effect, detector non-linearities very important

Capozzi, Lisi, Marrone, 2015

The interplay of high frequency shape uncertainties and detector non-linearities is difficult to study using Fourier transforms.

for details see talk by G. Ranucci on Tuesday

Fine structure



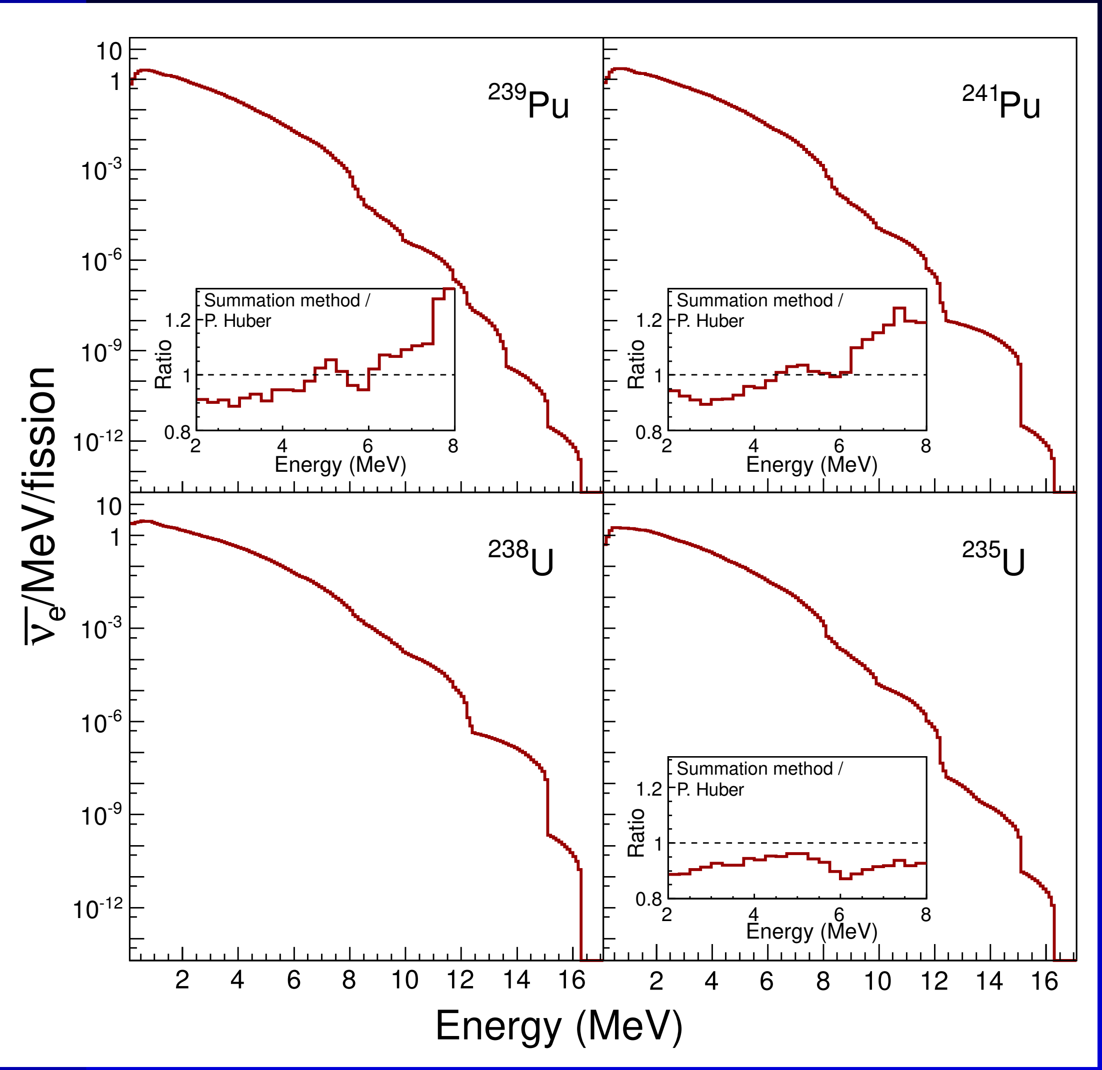
Forero, Hawkins, PH, 2017

Some authors find negligible impact:

Qian et al $\Rightarrow$ no variation of database numbers.

Danielson, Hayes, Garvey, 2018 $\Rightarrow$ small variation of database numbers.

Pandemonium

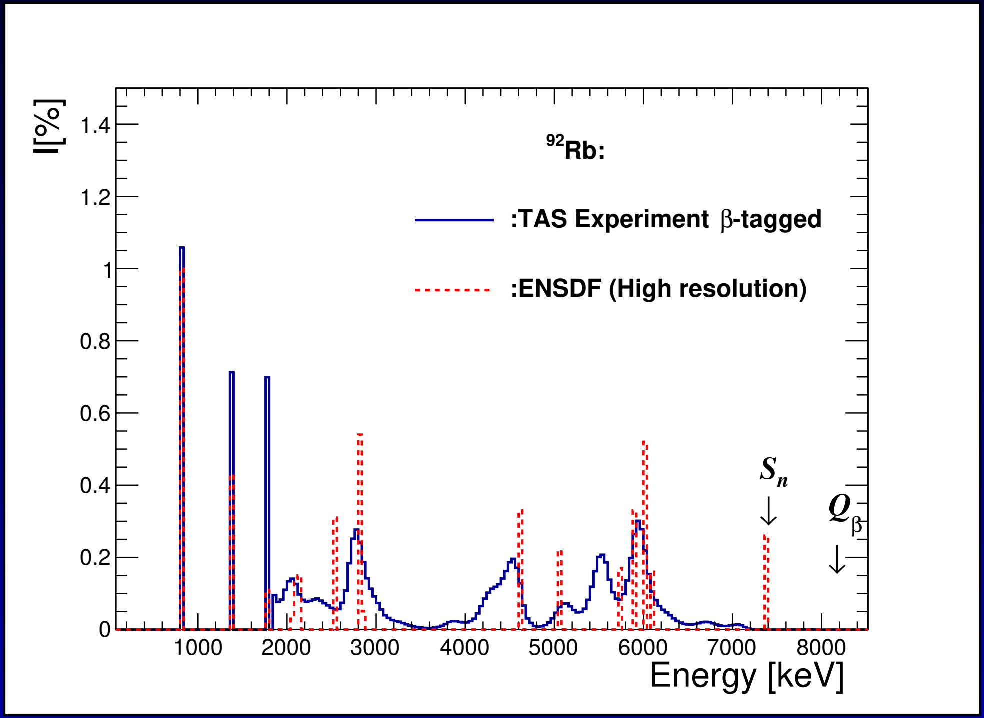


Fallot *et al.*, 2012

Pandemonium effect:
Ge-detectors have a low gamma ray absorption efficiency, hence faint lines are overwhelmed by Compton scattering backgrounds from strong lines.

Note, uranium-235 has been "pandemonium corrected" in this calculation.

TAGS feeding functions

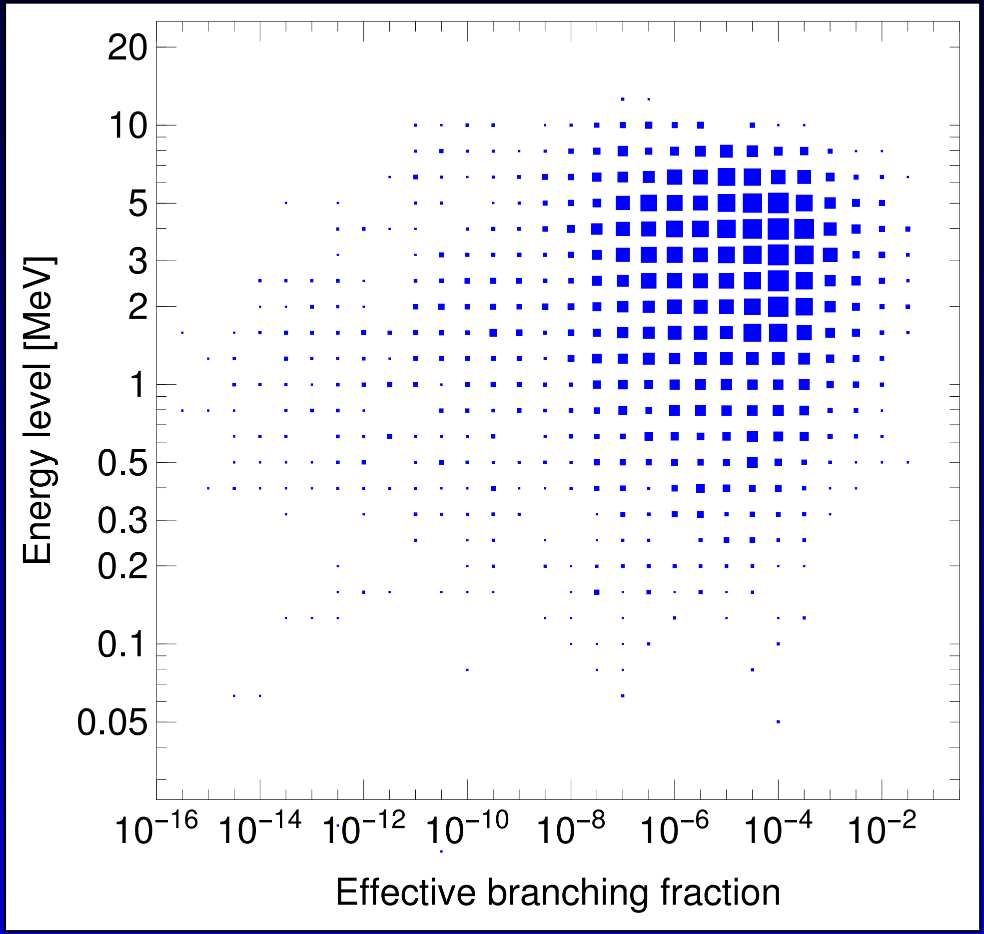


IGISOL collab. 2015

Many more Q-values allowed by more accurate TAGS data

Creates extra fine structure not contained in ENSDF database

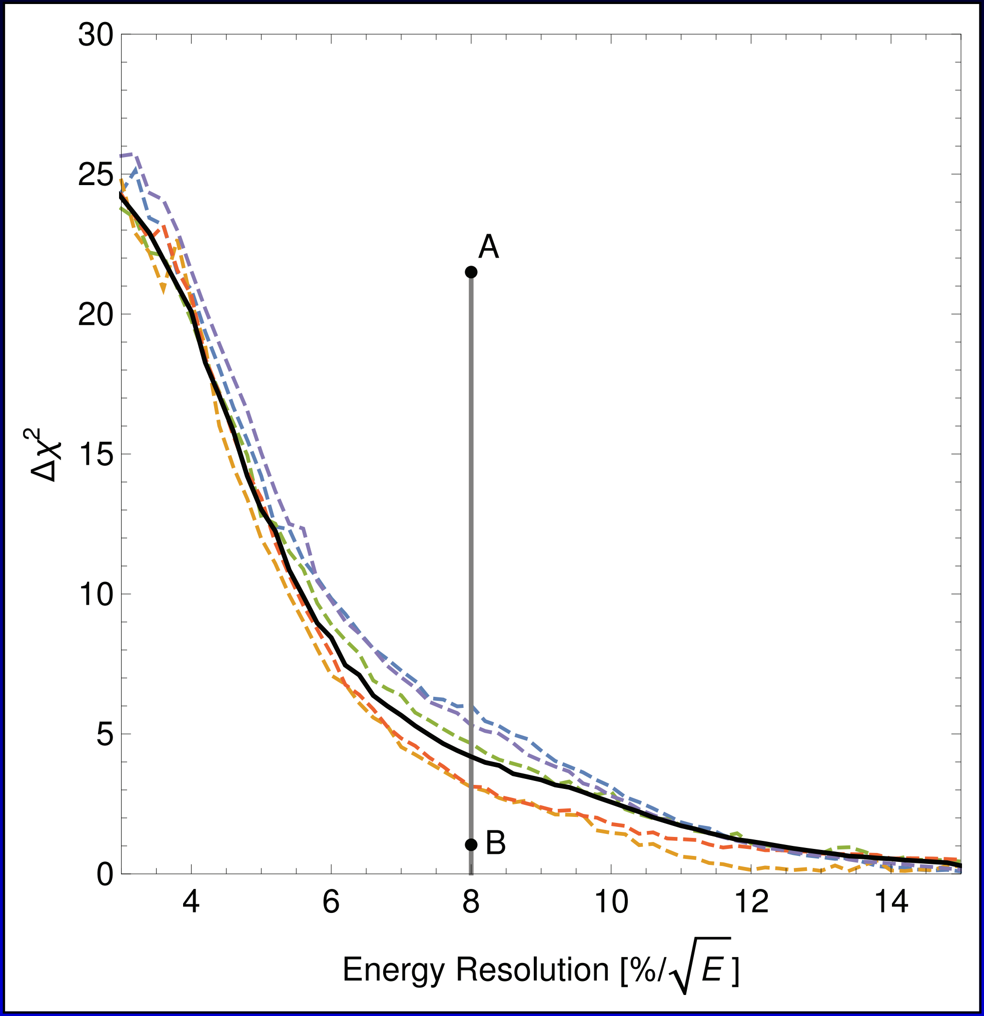
Random spectra



Distribution of fission yield-weighted end-points and branching fractions for thermal fission in uranium-235.

We draw beta-branches from this distribution till we have the right total number of neutrinos $\Rightarrow$ one random spectrum, repeat many times to obtain ensemble.

Near detector to the rescue



Forero, Hawkins, PH, 2017

Shown is χ^2-difference between NO and IH as a function of energy resolution of the near detector.

Points at 8% show result with neglecting fine structure (point A) and no near detector but theory prior from our random spectra (point B).

Summary

Reactor anti-neutrino fluxes are complex and reliable a priori calculations are elusive.

Measured integrated beta-spectra form the starting point for the most accurate flux predictions.

Forbidden decays introduce very significant (percent-level) nuclear structure related uncertainties.

The 5 MeV bump likely is due to nuclear physics, but no quantitative viable models have been demonstrated.

Better understanding will come from neutrino measurements at many different reactors.

This has become precision science!