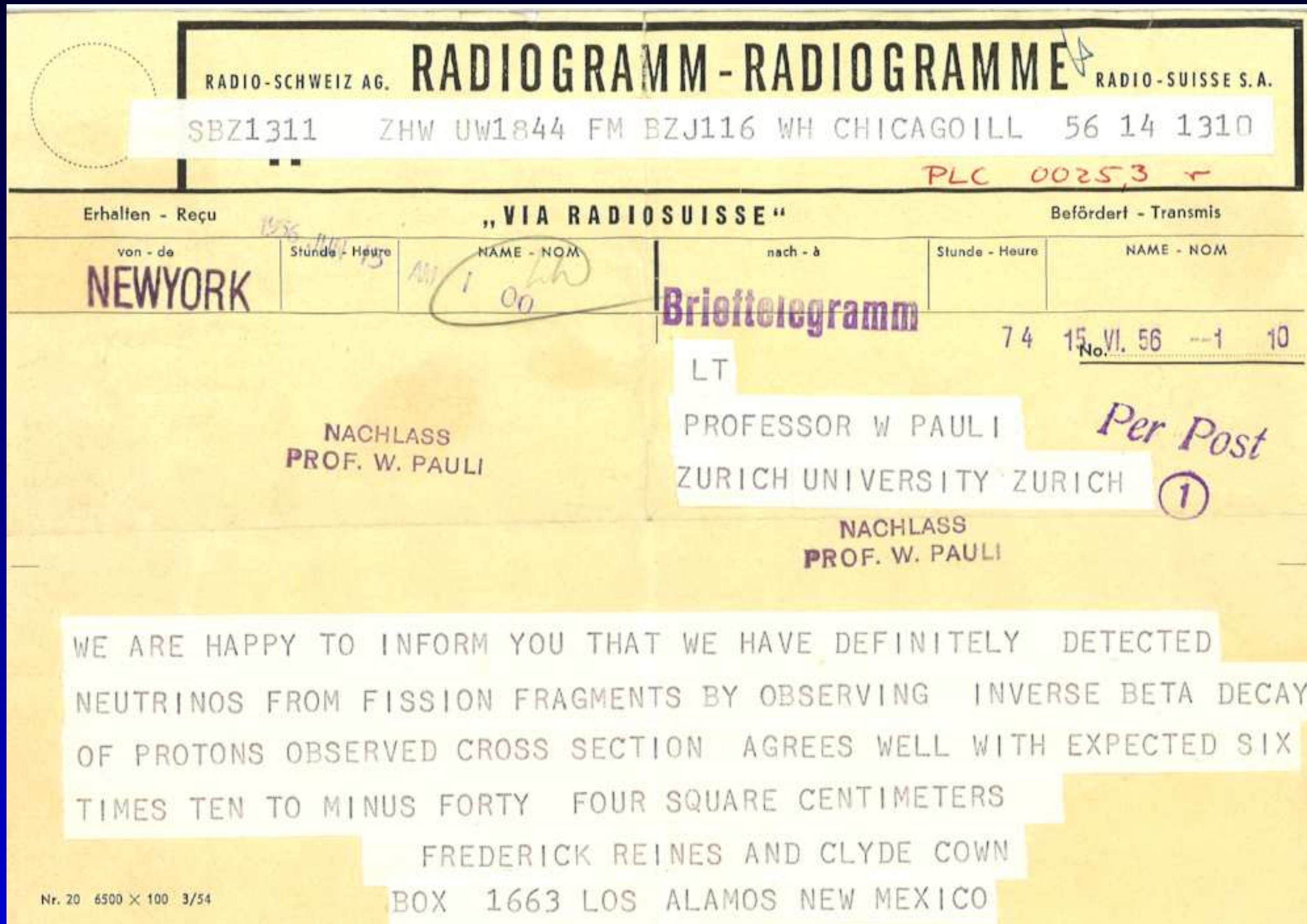
Reactor fluxes for CEvNS

Patrick Huber

Center for Neutrino Physics – Virginia Tech

The Magnificent CEvNS
University of Chicago, November 2–3, 2018

1956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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.

1956–2017

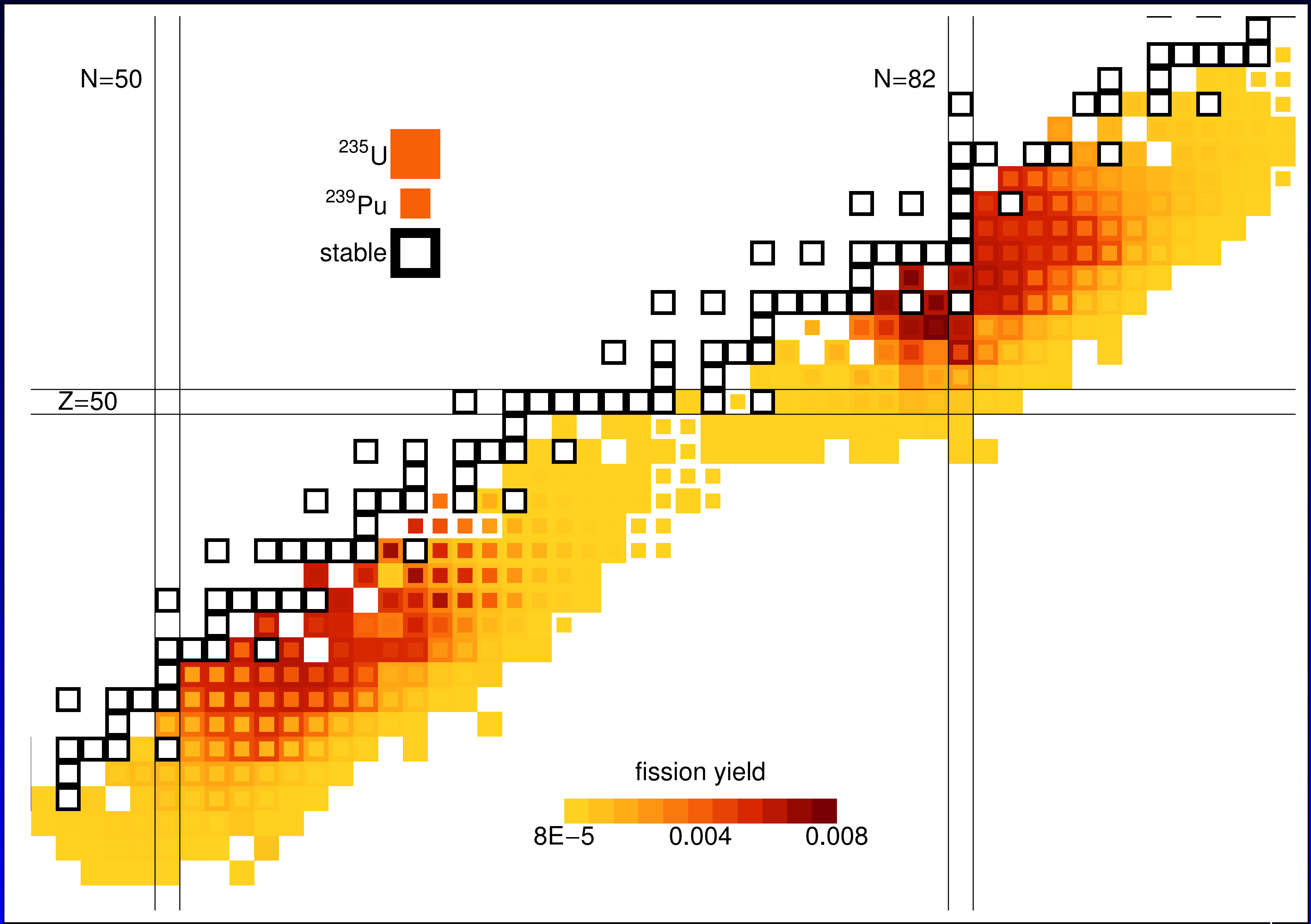
We have seen about 5 million inverse beta decay (IBD) events from nuclear reactors. . . , but this reaction has a threshold of 1.8 MeV.

With CEvNS we can go below IBD threshold, but recoil energies are small even at 1.8 MeV:

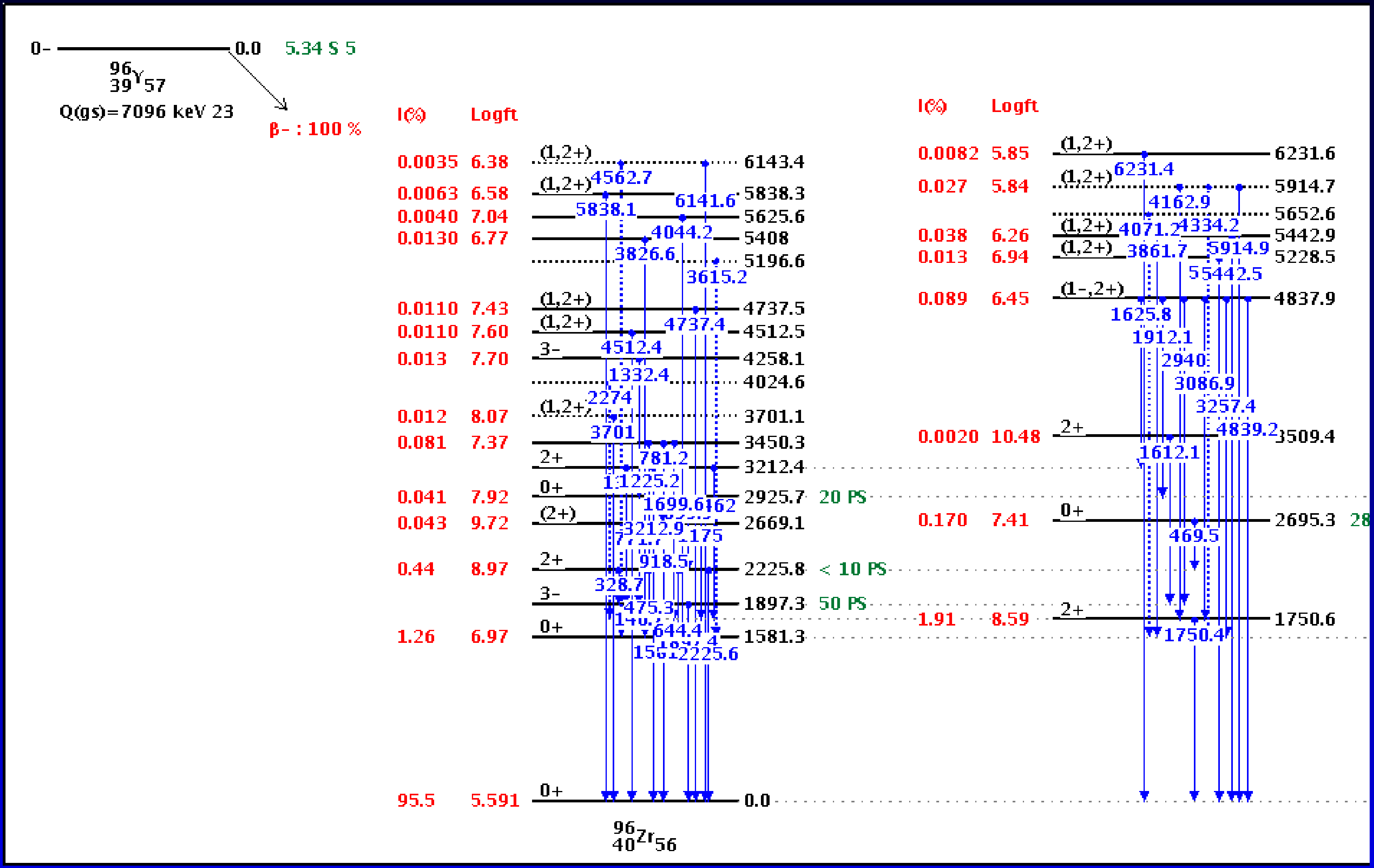
	Si	Ar	Ge	Xe
$T_{\max}^{\mathrm{IBD}}[\mathrm{eV}]$	250	175	100	50

Very little work for below IBD energy reactor fluxes has been done.

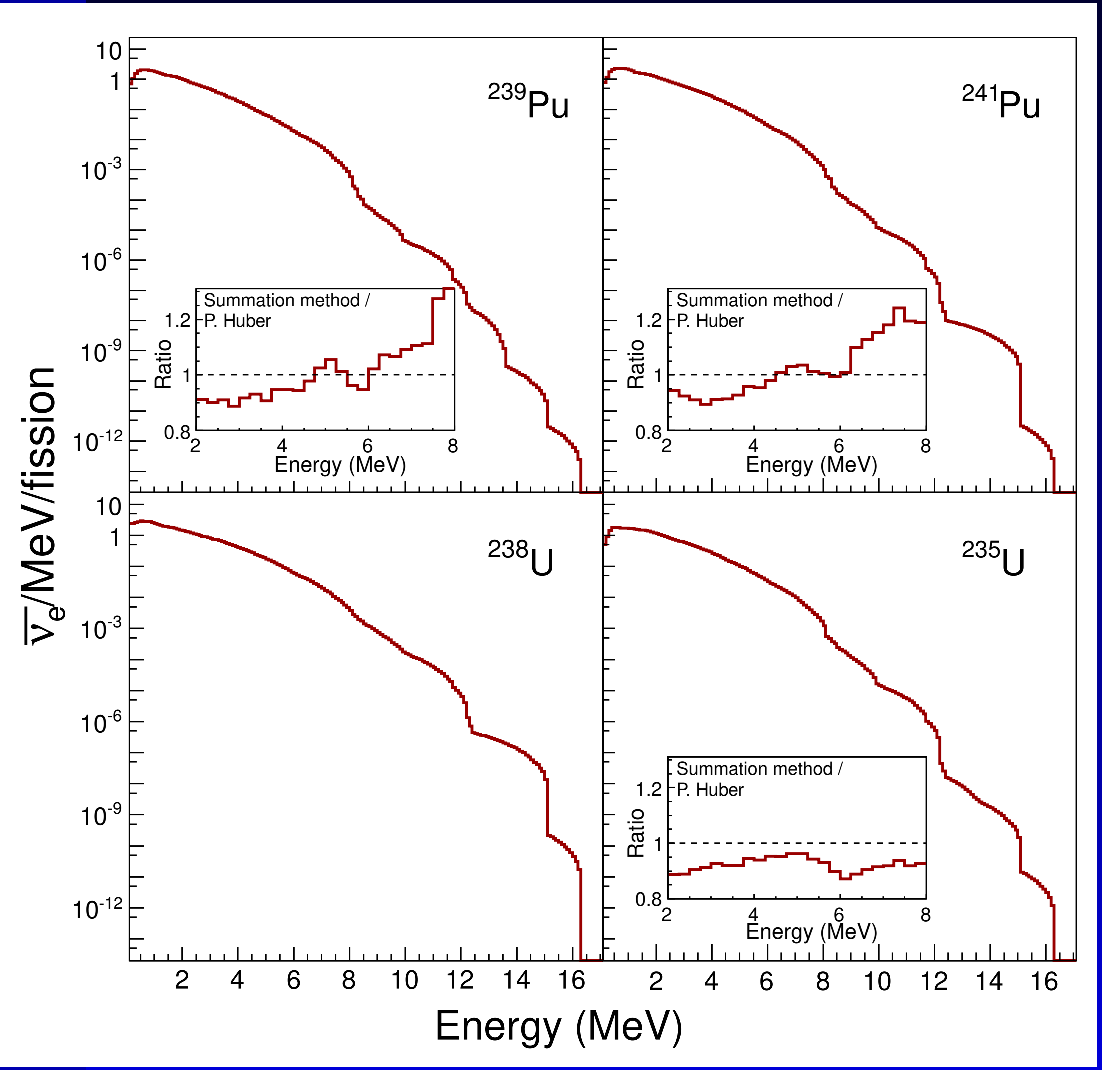
Neutrinos from fission



β-branches



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.

Extraction of ν-spectrum

We can measure the total β-spectrum

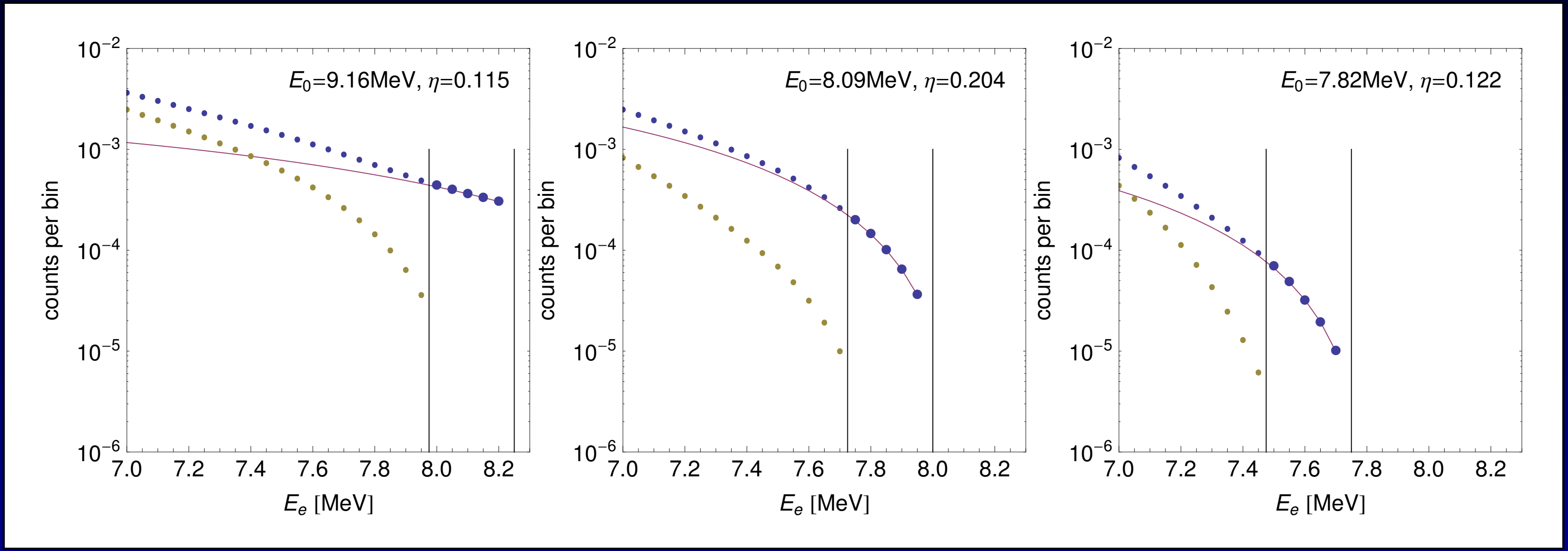
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z})\, \eta(E_0)\,. \qquad (1)$$

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

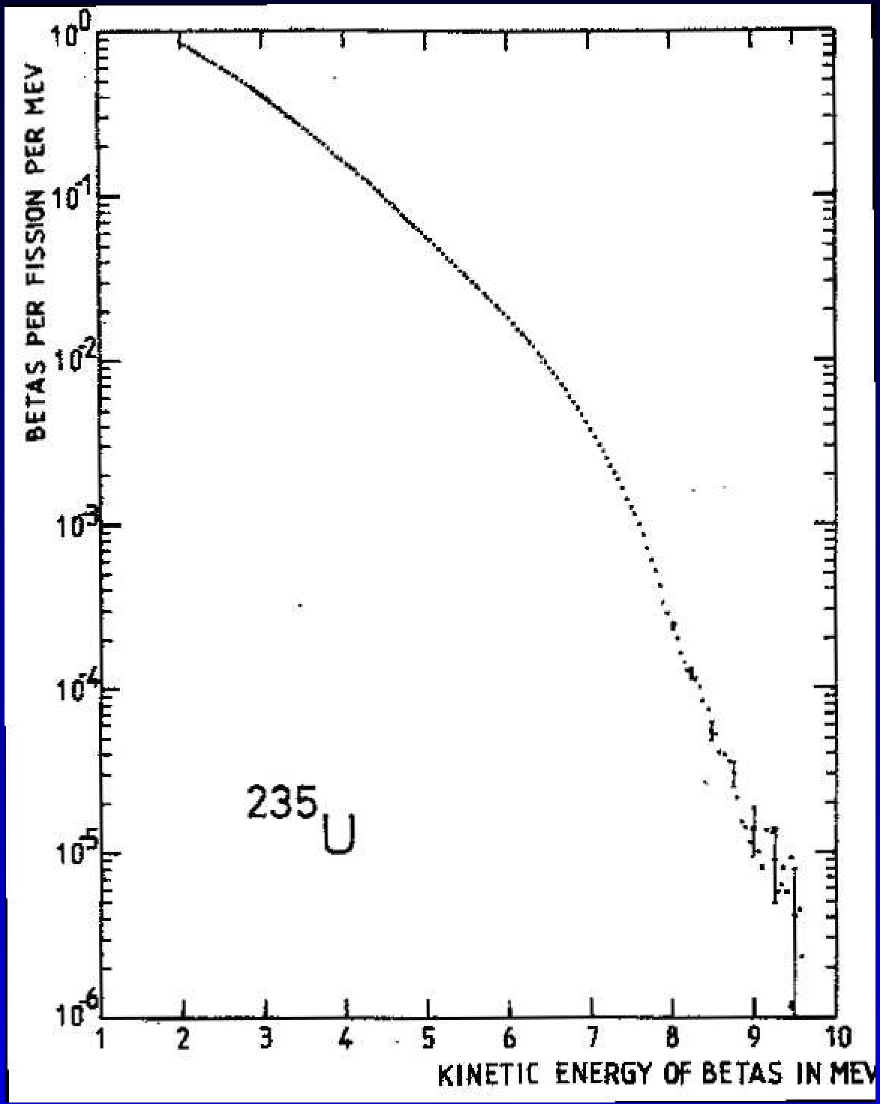
2 – delete the last s data points

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

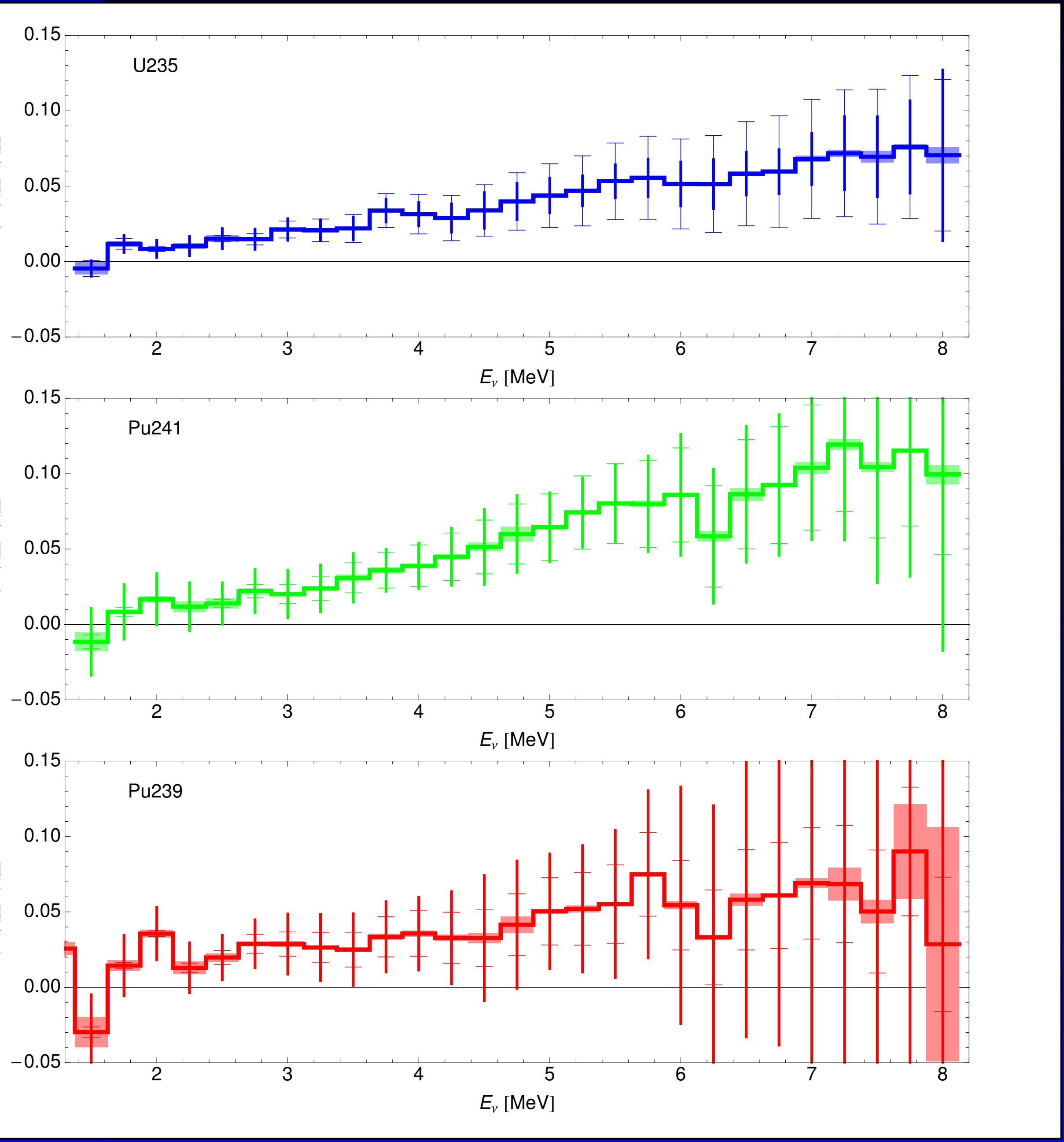


Schreckenbach, *et al.* PLB **160**, 325 (1985).

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

Electron spectroscopy with a magnetic spectrometer

Comparison of isotopes

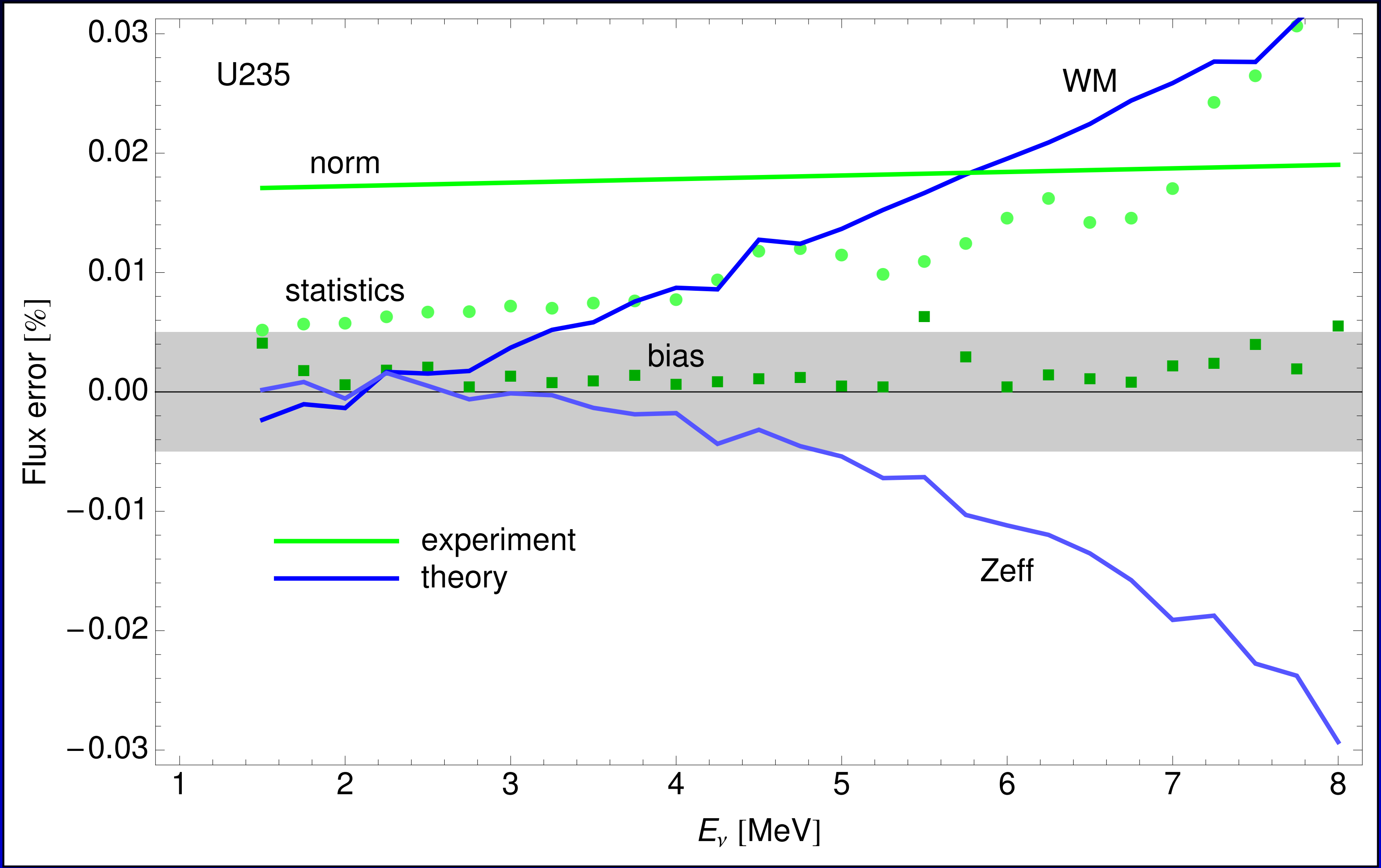


Same shift in all isotopes

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

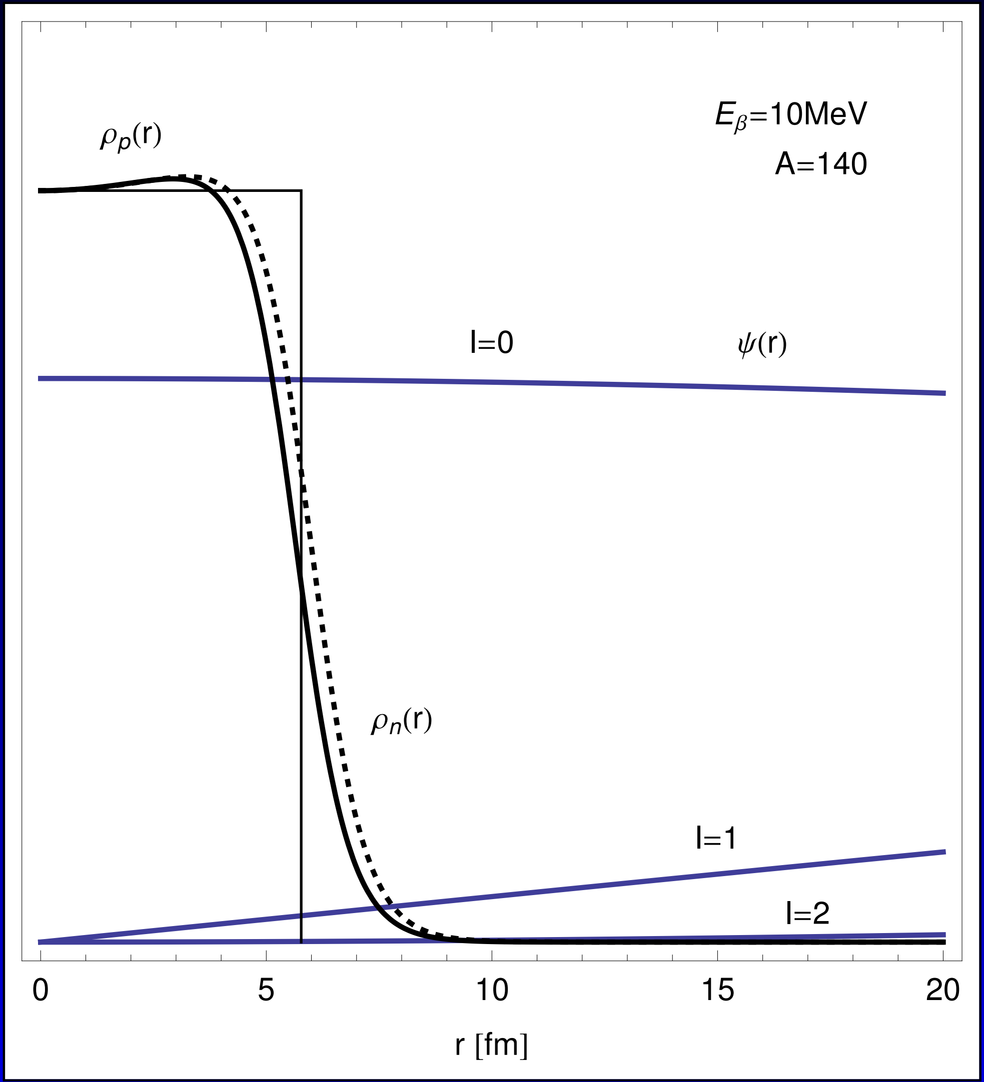
^{239}Pu most problematic due to large fission fraction

The fluxes & their errors



Below 3.5 MeV theory errors are much smaller

Forbidden decays



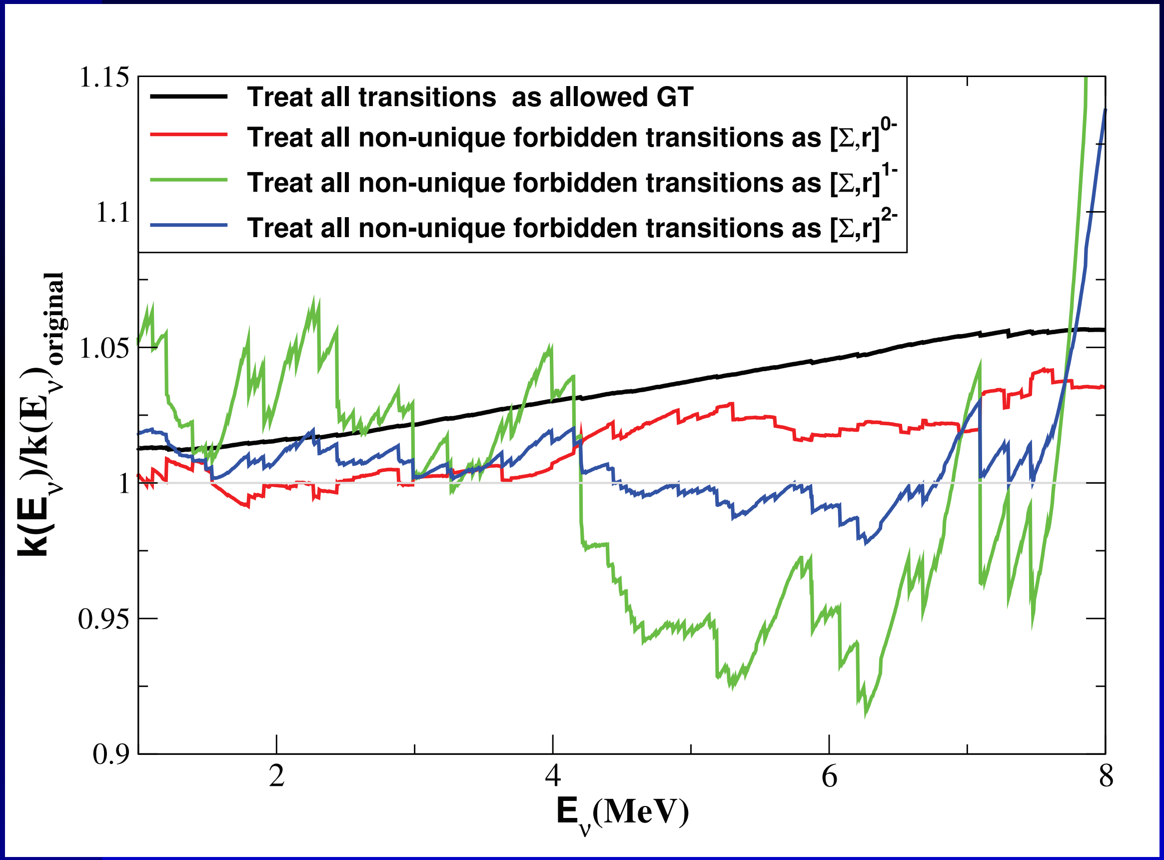
$e,\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

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



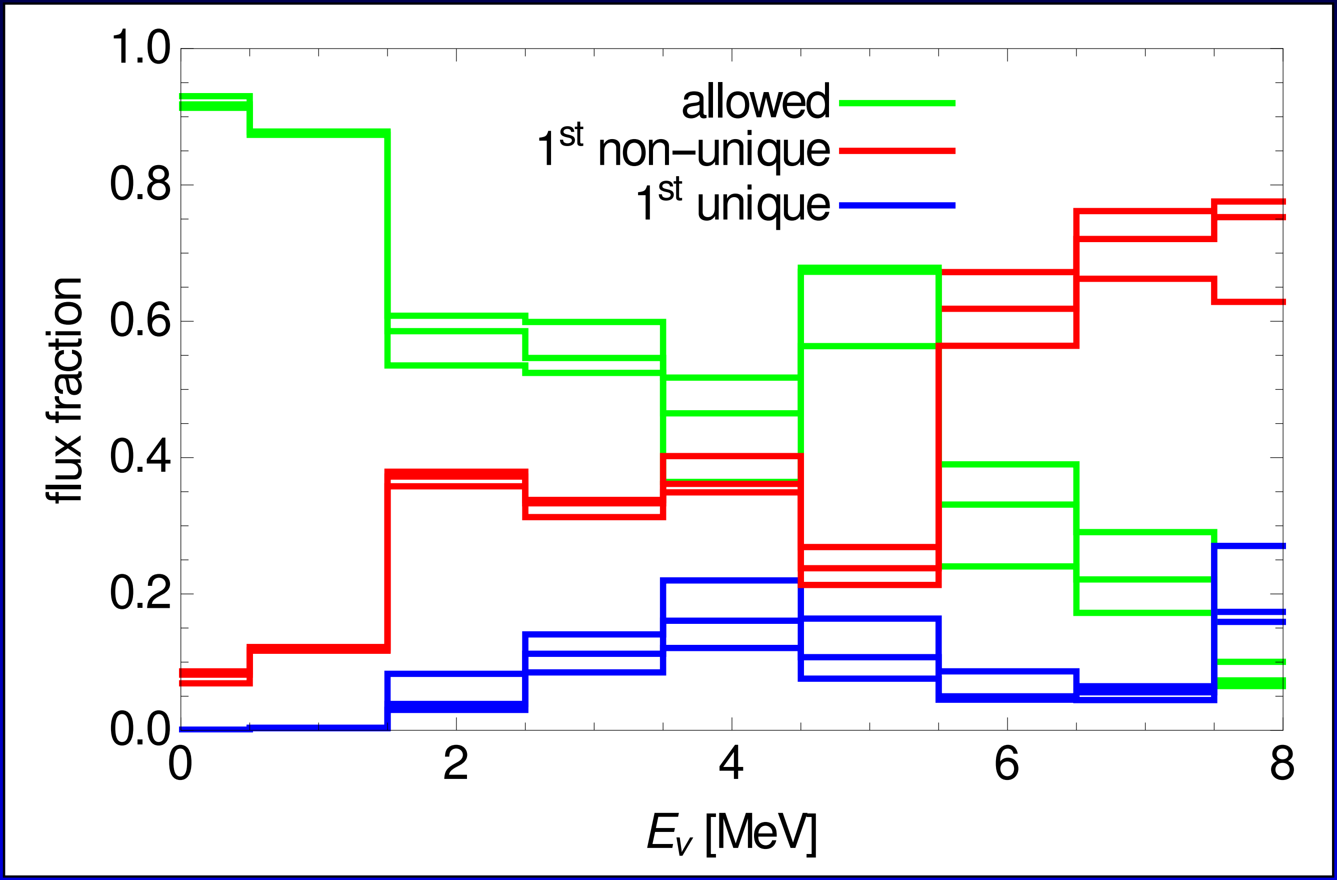
Hayes *et. al*, 2013 point out that in forbidden decays a mixture of different operators are involved.

Note, this all related to the weak magnetism correction.

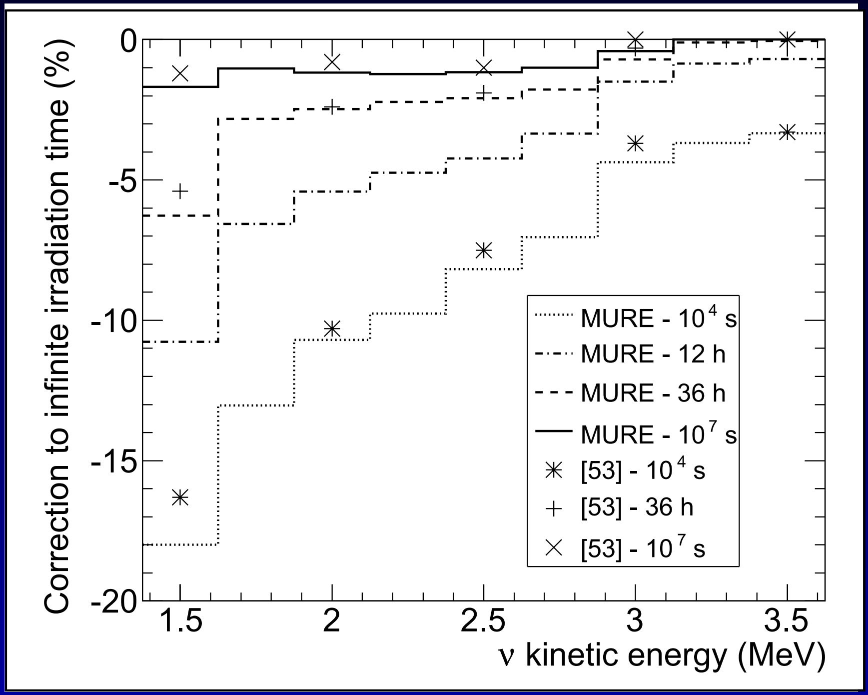
Large source of uncertainty.

Forbidden decays vs energy

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



Non-equilibrium corrections



Mueller, *et al.*, PRC 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
c) much more important at low energy

Neutron capture

Breeding reactions dominate antineutrino flux around 1–1.5 MeV see Cogswell talk

$$^{238}\mathrm{U+n} \rightarrow {}^{239}\mathrm{U} \xrightarrow{\beta} {}^{239}\mathrm{Np} \xrightarrow{\beta} {}^{239}\mathrm{Pu}$$

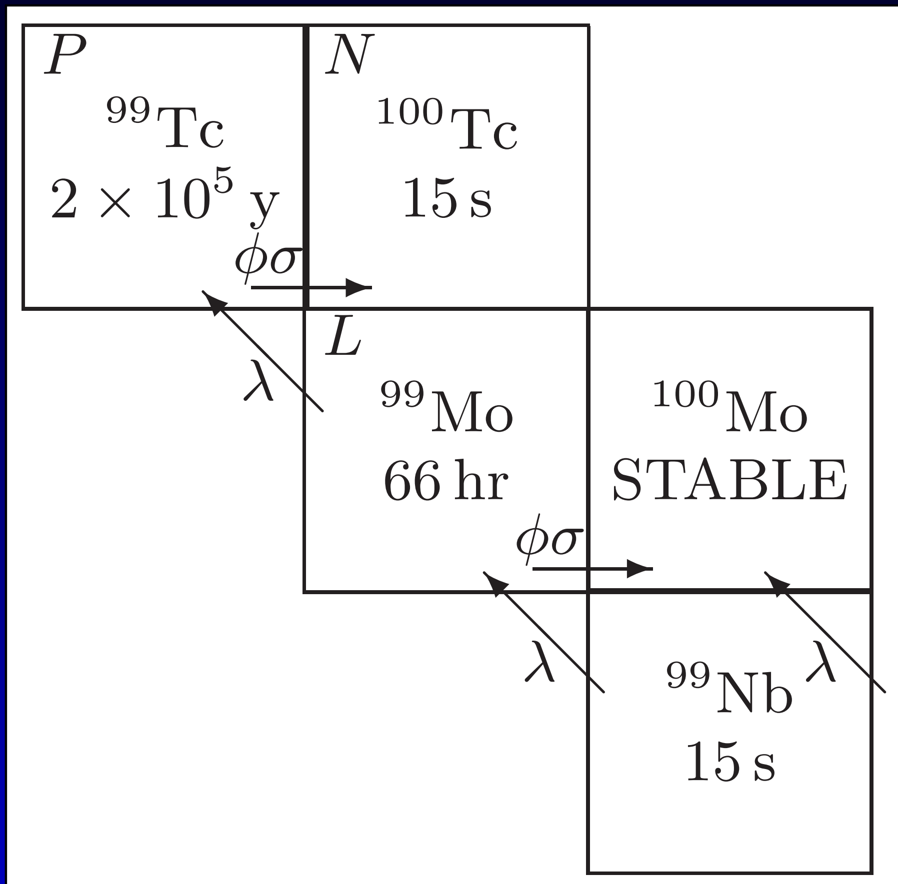
If present in core (research reactors)

$$^{27}\mathrm{Al+n} \rightarrow {}^{28}\mathrm{Al} \xrightarrow{\beta} {}^{28}\mathrm{Si}$$

2.8 MeV antineutrino, comparable to regular flux
Conant, Mumm, Erickson, 2018

Generally, a lot of structural materials may play a role at low energies and there may even be some neutrino emitters.

Non-linear isotopes



Jaffke, Huber, 2015

Out of 20 $\beta\beta$-isotopes made in fission, only 4 contribute to IBD rates in reactors:

^{100}Tc, ^{104}Rh, ^{110}Ag, ^{142}Pr

Order 1% below 3 MeV, what happens at lower energies?

$$\Gamma_{nonlinear} \propto \underbrace{\Sigma_{\text{fiss}} \phi Z_P T_{\text{irr}}}_{\text{atoms of P}} \sigma^c_P \phi \propto T_{\text{irr}} \phi^2 \propto T_{\text{irr}}$$

Summary

Above 1.8 MeV

- Reactor fluxes are know at roughly the 5% level
- Theory progress not likely soon

Below 1.8 MeV

- New, large components from breeding and neutron capture
- Error budget at low energies very different, maybe overall lower
- No detailed calculations exist
- Reactor details will matter
- Schreckenbach data only down to 1.5 MeV