Reactor Data Overview

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Public Service Announcement

Save the date!

The 3rd IAEA Technical Meeting on Nuclear Data Needs for Antineutrino Spectra Applications will be held at **Seoul National University**, Seoul, April 7 to 11, 2025.

For more information, contact Vivian Dimitriou, P.Dimitriou@iaea.org

Also, **ND2025** in Madrid, June 22-27, 2025, www.nd2025madrid.com
Deadline to submit abstracts is November 4, 2024, a week from now!

How are antineutrinos produced in a nuclear reactor?

Electron antineutrinos are produced by neutron rich fission products during beta-minus decay.

The fission products population follows a set of linearly coupled differential equations:

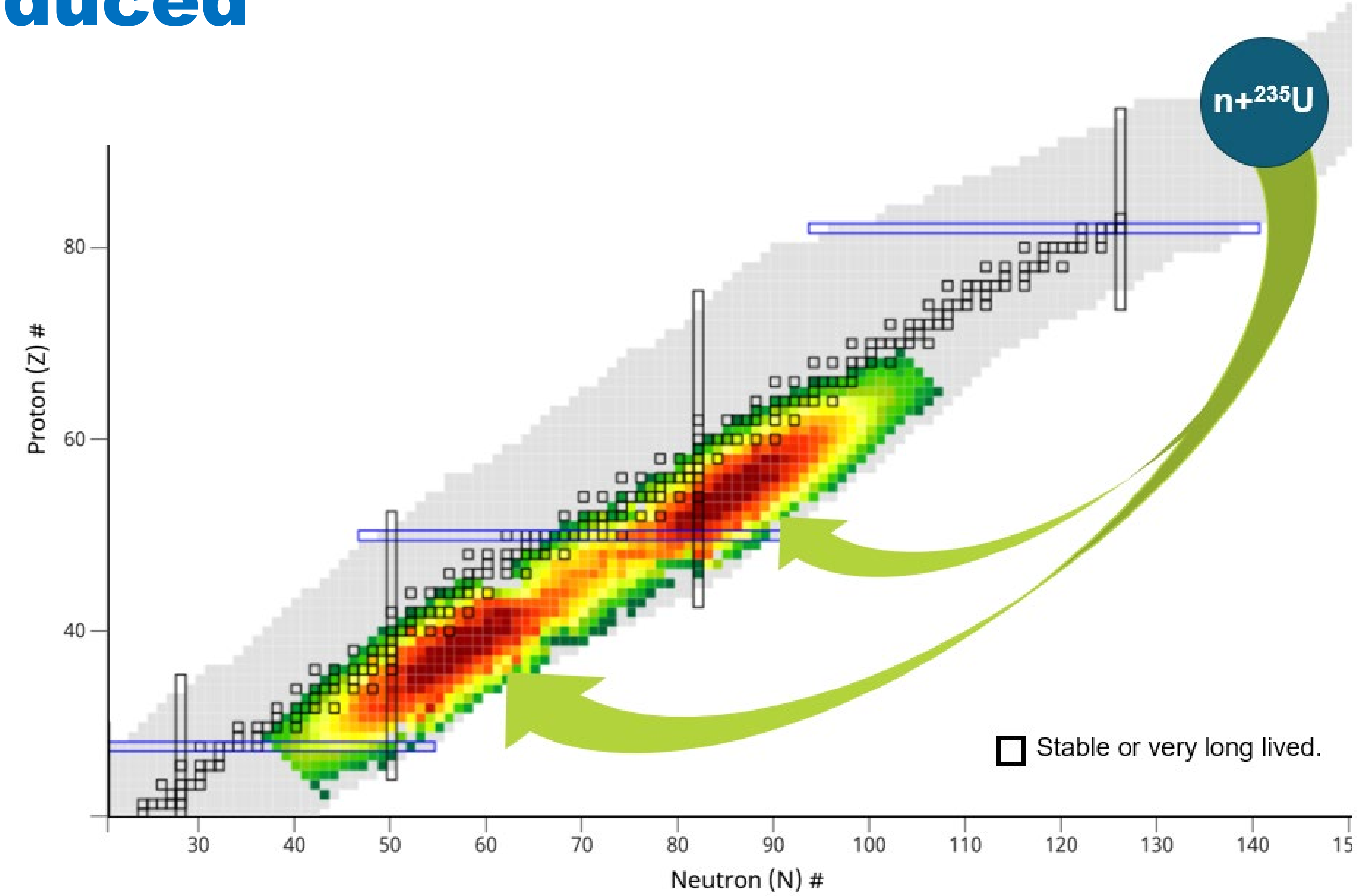
$dN_k/dt = F \times I_k - \lambda_k N_k + \Sigma \lambda_j P_{jk} N_j$

F: fission rate,
I: probability of produced directly by fission,
λ: decay constant,
P: decay probability j to k

If steady state, $dN_k/dt = 0$, then $N_k / F = C_k / \lambda_k$
C: cumulative yield,

Then:

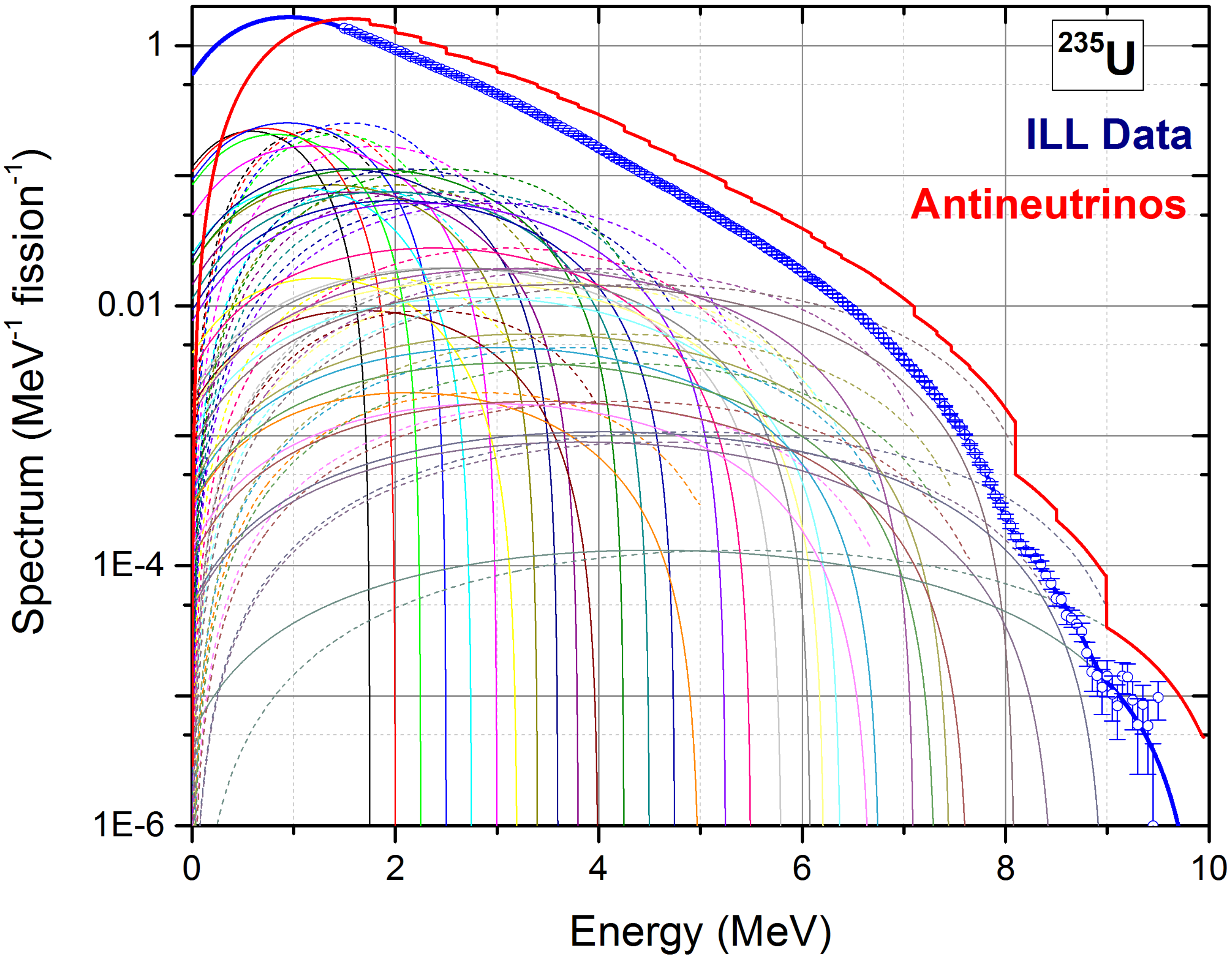
$S(E) = \Sigma C_k S_k(E)$



Summation method:
Calculate $S_k(E)$ using decay databases and use C_k from fission databases.

Conversion method:
Measure electron spectrum and fit as many ‘average’ branches as you can.

Conversion Method



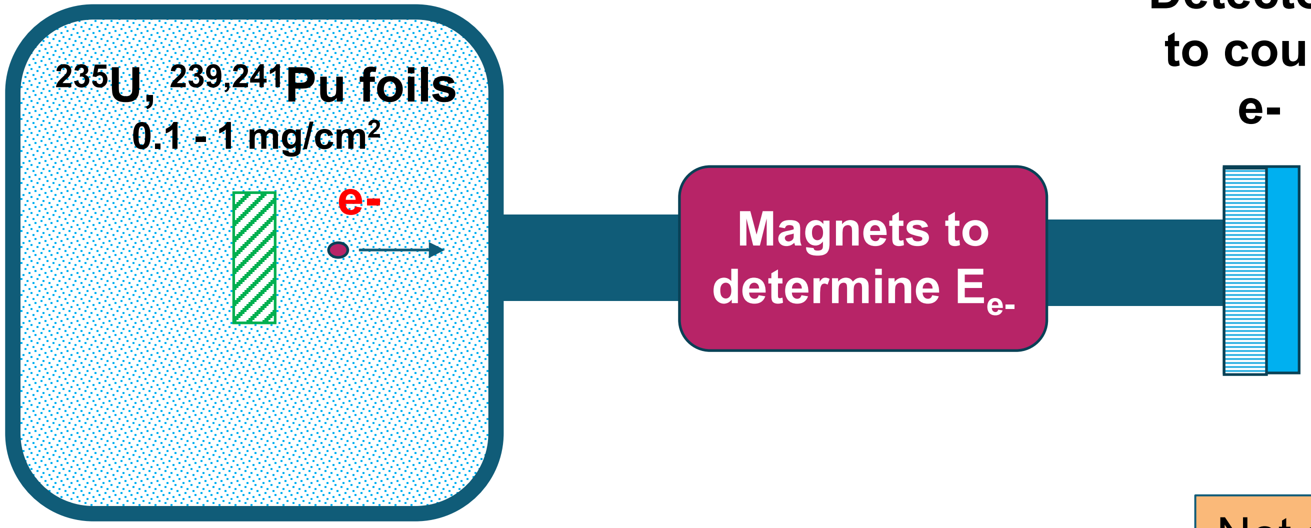
Electron Spectrum measured at ILL, K. Schreckenbach *et al.*, Phys. Lett. **160B**, 325 (1985).

Assume **allowed shape** and must know **$Z_{eff}(E)$**, from ENSDF & ENDF/B or JEFF.

Best current estimates, P. Huber ^{235}U and ^{239,241}Pu antineutrino spectra, PRC **84**, 024617 (2011).

For ^{238}U, we use the summation values from Mueller *et al.*, PRC **83**, 054615 (2011).

Electron spectra measurements at ILL



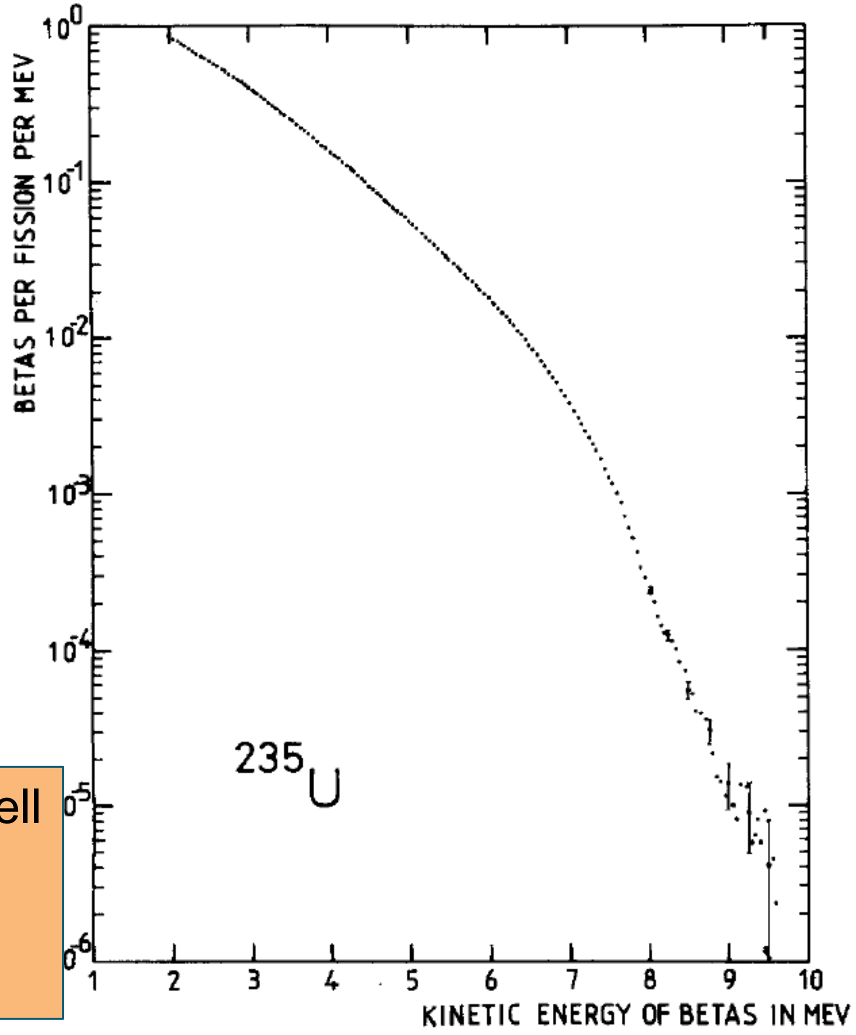
ILL Reactor
$\Phi \sim 10^{14}$ neutrons/cm^2 s

^{235}U, ^{239,241}Pu foils
0.1 - 1 mg/cm^2

e-

Magnets to determine E_{e-}

Detectors to count e-



To normalize spectrum, we must know:

- Foil thickness
- Fission cross section
- Neutron flux
- Detection efficiency

Well known cross sections

Not so well known cross section

Use ^{113}Cd, ^{115}In, ^{197}Au, and ^{207}Pb K conversion electrons following neutron capture, with well known cross sections, electron energies, and electron K conversion coefficients.

Neutron flux at the ILL reactor

Absolute spectra were obtained from:

$$N_\beta(per\ fission, \Delta E) = \frac{N_e^f}{N_e^{st}} \frac{\alpha\, \sigma_{st}(n_{th},\gamma)}{\sigma(n_{th},f)} \frac{n_{st}}{n_f}$$

N_e: number of detected electrons, **f** from fission, **st** from the calibration foil,

α: K internal conversion coefficient,

$\sigma_{st}(n,\gamma)$: neutron capture cross section, **$\sigma(n,f)$**: neutron fission cross section,

n: Number of nuclides in the foils.

^{235}U: conversion electrons from **^{115}In** and **^{207}Pb**
^{239}Pu: **^{115}In** and **^{197}Au**
^{241}Pu: **^{113}Cd**, **^{115}In**, and **^{207}Pb**.

We reviewed all the data documented in the ILL articles and found **one problem case**.

ILL references:
W. Mampe *et al.*, NIM 154, 127 (1978).
F. von Feilitzsch, A. A. Hahn, and K. Schreckenbach, Phys. Lett. B **118**, 162 (1982).
K. Schreckenbach *et al.*, Phys. Lett. B 160, 325 (1985).
A. A. Hahn *et al.*, Phys. Lett. B **218**, 365 (1989).

^{207}Pb neutron capture cross section

Value used by ILL to normalize ^{235}U spectrum: **712 ± 10 mb**, best value available in 1981, 1985.
source: 1981 S.F. Mughabghab evaluation, based on an indirect measurement published in a 1963 conference proceeding.

Value from 2018 S.F. Mughabghab evaluation: **647 ± 9 mb**
Sources:
610 ± 30 mb, Blackmon *et al*., PRC 65, 045801 (2002).
649 ± 14 mb, Schillebeeckx *et al*., EPJA 49, 143 (2013).

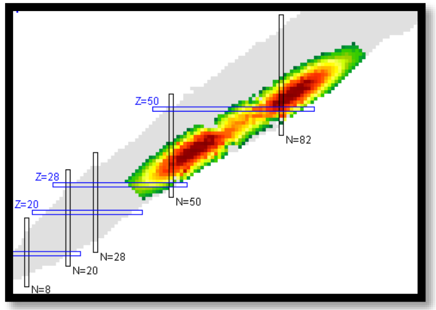
Ratio of cross sections: **647 / 712 = 0.908**.

Larger cross section --> Lower neutron flux --> Larger electron spectrum.

For more details, see Phys. Rev. C **108**, 024617 (2023).

I heard at Neutrino 2024 that the ‘raw’ ILL data was lost when moving from ILL to Munich, so a re-analysis of it including current cross sections is not possible…

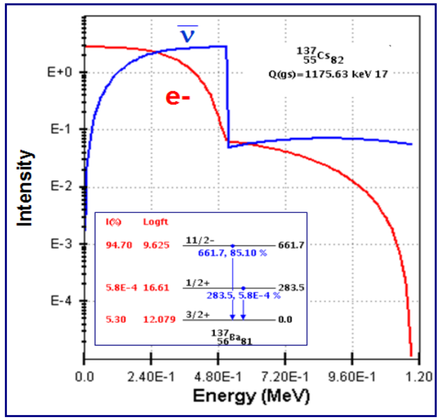
Using Nuclear Databases

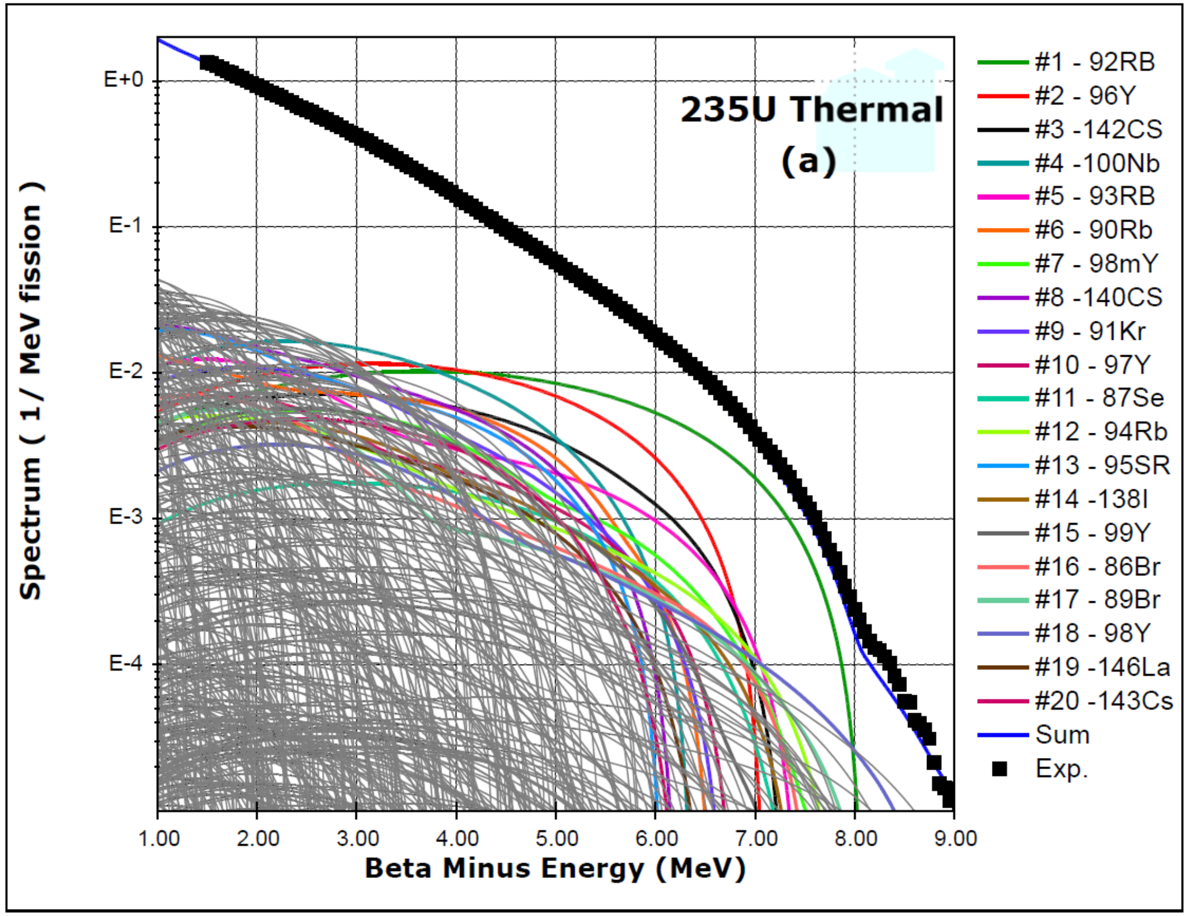


$$S(E) = \sum CFY_i S_i(E)$$

Cumulative Fission Yields

Individual spectra





First calculation of this type performed by P. Vogel et al in 1981 using ENDF/B-V.

JEFF-3.3 is the only reliable source of fission yield data for this purpose, even though some isomers in JEFF-3.3 don't exist, for instance, ^{114}Rh.

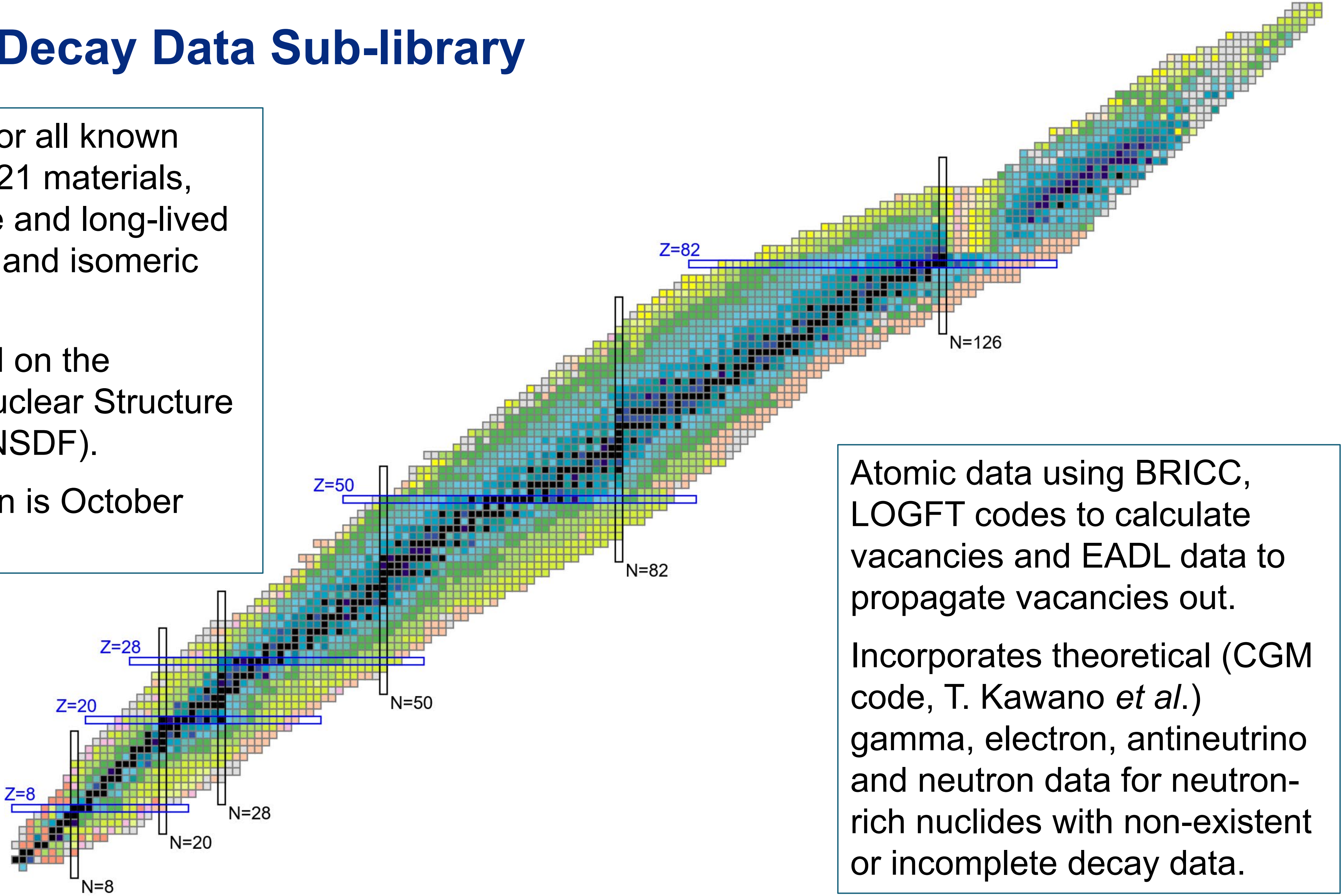
Do not use **ENDF/B yields.**

ENDF/B Decay Data Sub-library

Decay data for all known nuclides, 3,821 materials, that is, stable and long-lived ground state and isomeric levels.

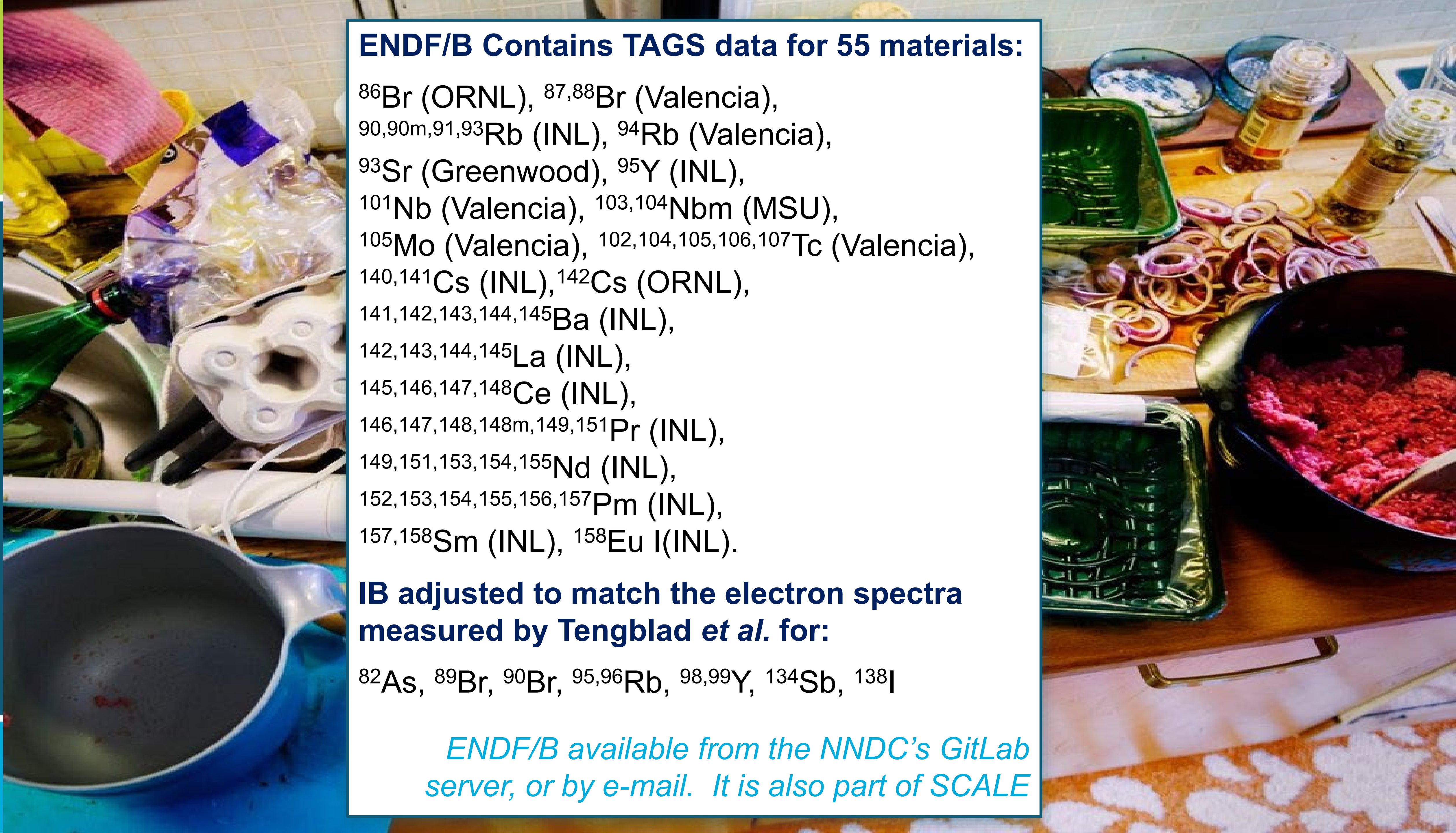
Mostly based on the Evaluated Nuclear Structure Data File (ENSDF).

Latest version is October 2023



Atomic data using BRICC, LOGFT codes to calculate vacancies and EADL data to propagate vacancies out.

Incorporates theoretical (CGM code, T. Kawano *et al.*) gamma, electron, antineutrino and neutron data for neutron-rich nuclides with non-existent or incomplete decay data.



ENDF/B Contains TAGS data for 55 materials:

^{86}Br (ORNL), ^{87,88}Br (Valencia),
^{90,90m,91,93}Rb (INL), ^{94}Rb (Valencia),
^{93}Sr (Greenwood), ^{95}Y (INL),
^{101}Nb (Valencia), ^{103,104}Nbm (MSU),
^{105}Mo (Valencia), ^{102,104,105,106,107}Tc (Valencia),
^{140,141}Cs (INL),^{142}Cs (ORNL),
^{141,142,143,144,145}Ba (INL),
^{142,143,144,145}La (INL),
^{145,146,147,148}Ce (INL),
^{146,147,148,148m,149,151}Pr (INL),
^{149,151,153,154,155}Nd (INL),
^{152,153,154,155,156,157}Pm (INL),
^{157,158}Sm (INL), ^{158}Eu I(INL).

IB adjusted to match the electron spectra measured by Tengblad *et al.* for:

^{82}As, ^{89}Br, ^{90}Br, ^{95,96}Rb, ^{98,99}Y, ^{134}Sb, ^{138}I

ENDF/B available from the NNDC’s GitLab server, or by e-mail. It is also part of SCALE

Consistency Issues

In ENSDF, absolute gamma + CE and beta intensities are related by the intensity balance at each level.

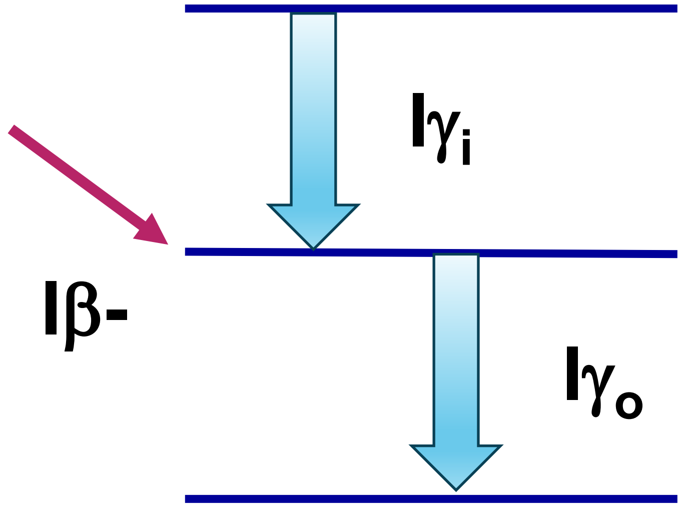
In ENDF/B we use TAGS data for beta intensities and ELP, <Ee->, and EEM, <Eγ>.

The use of TAGS data in ENSDF and ENDF/B breaks the intensity balance, creating inconsistencies, that must be documented to alert the user.

If the ENSDF data agrees *within 10%* with the TAGS data, then we use ENSDF to avoid inconsistencies.

There are also inconsistencies if we use ELP, EEM and Iβs from TAGS and theoretical gamma, & neutron if present, spectra from CGM.

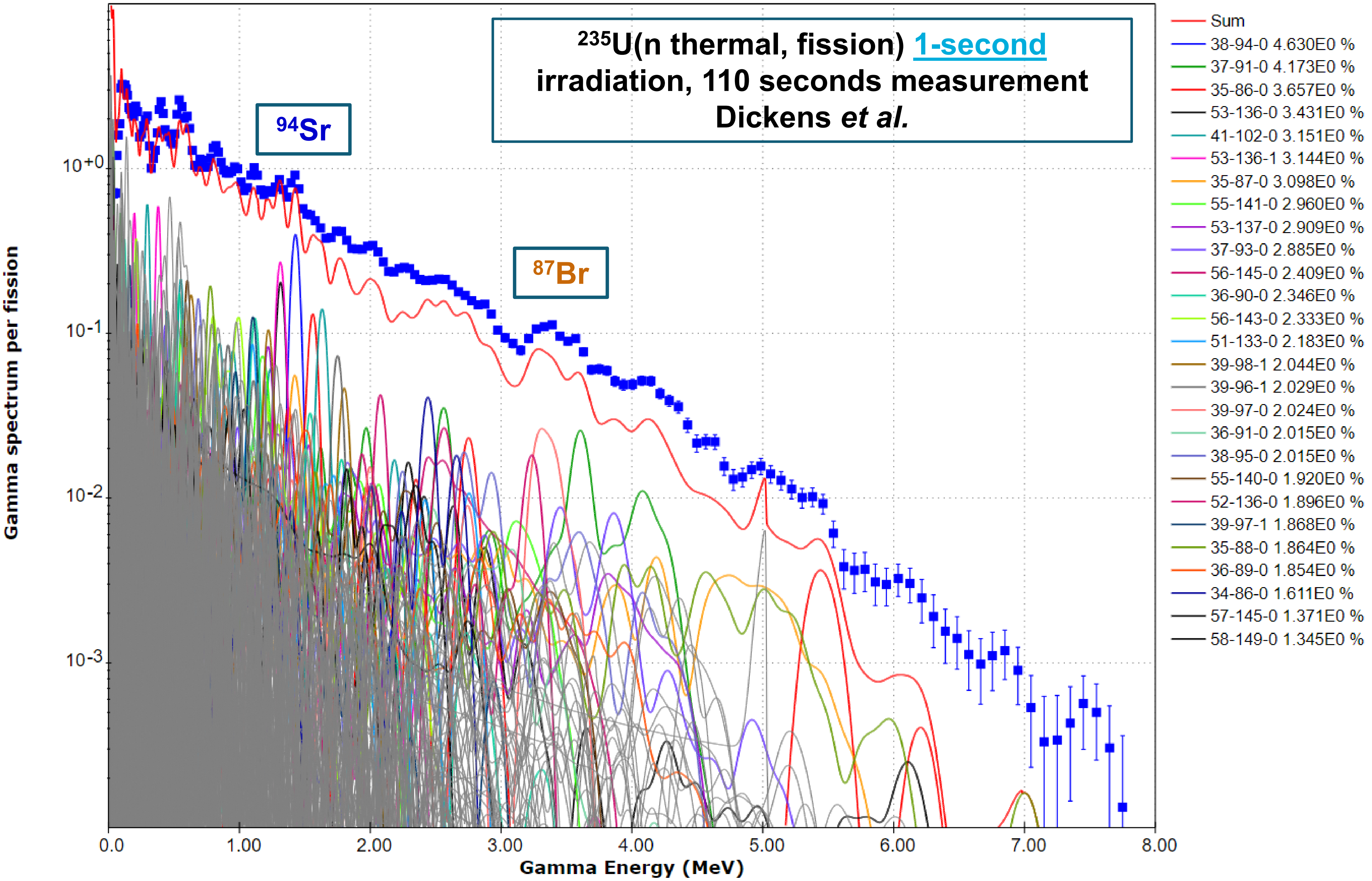
Also, gamma spectra from TAGS data are not available, with noticeable consequences.



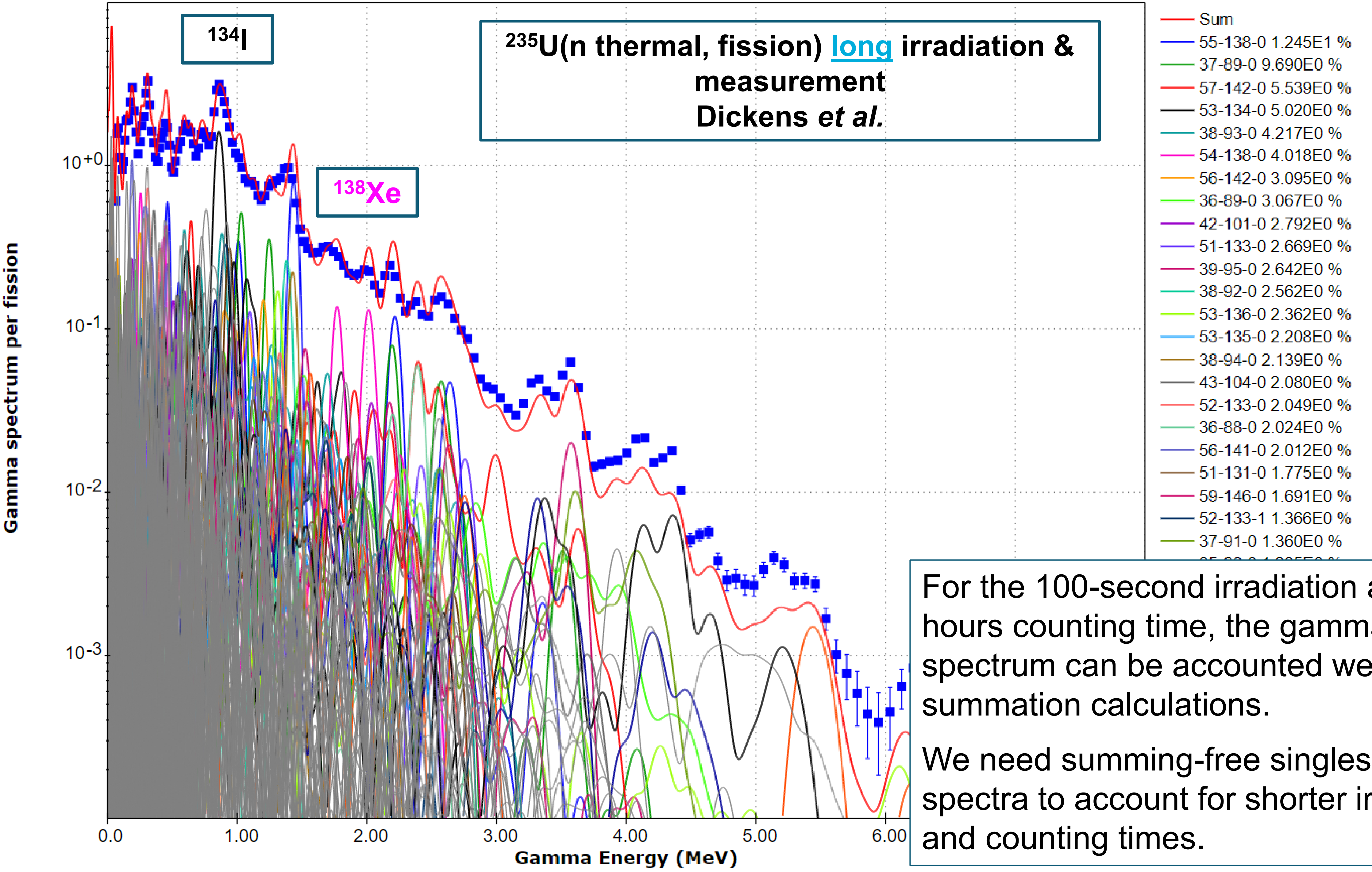
Intensity balance

$I\beta- = I\gamma_o - I\gamma_i$

^{235}U(n thermal, fission) 1-second irradiation, 110 seconds measurement Dickens *et al.*



^{235}U(n thermal, fission) long irradiation & measurement
Dickens *et al.*



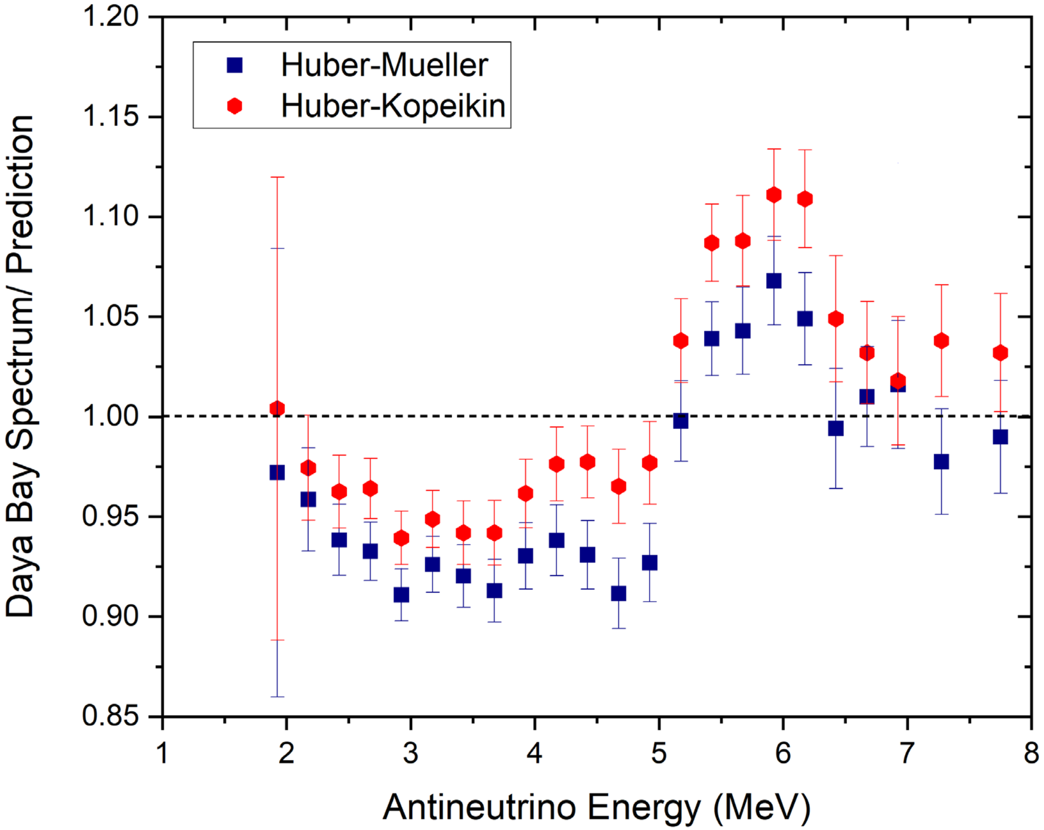
For the 100-second irradiation and 3 hours counting time, the gamma spectrum can be accounted well by summation calculations.

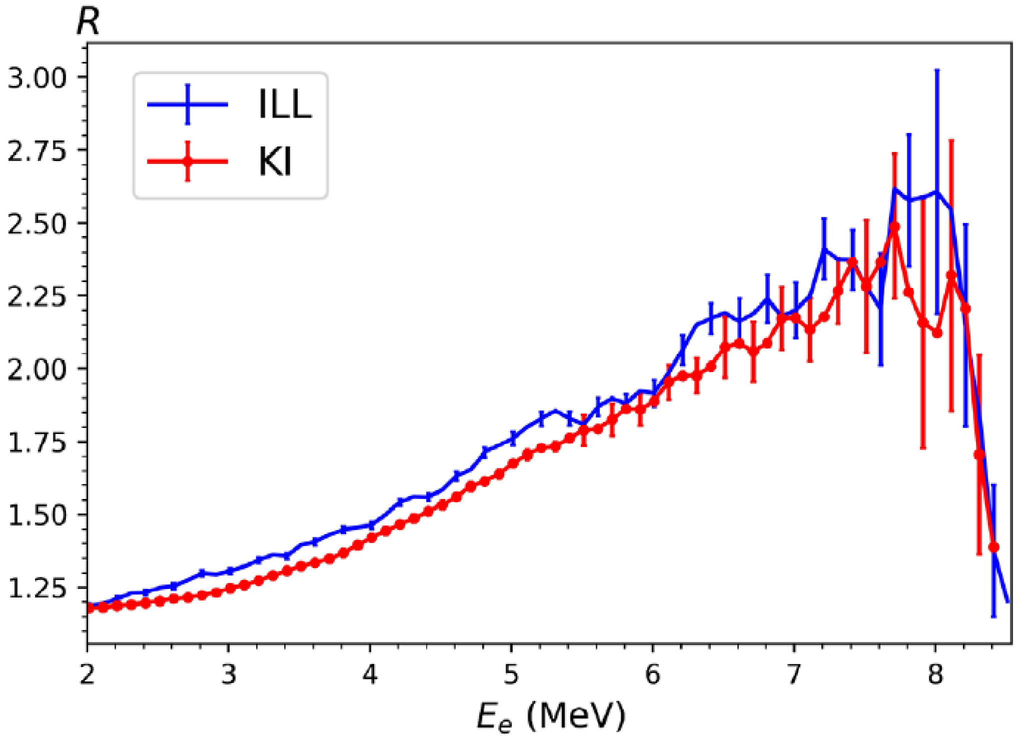
We need summing-free singles gamma spectra to account for shorter irradiations and counting times.

Kopeikin *et al.*, 2021

Phys. Rev. D **104**, L071301 (2021).

- Measurement of ^{235}U / ^{239}Pu electron spectra ratio R_{59} using scintillators outside reactor core.
- ϕ=7 x 10^6 n s^{-1} cm^{-2}
- Ratio of ^{235}U to ^{239}Pu electron spectra is about 5% lower than ILL values.

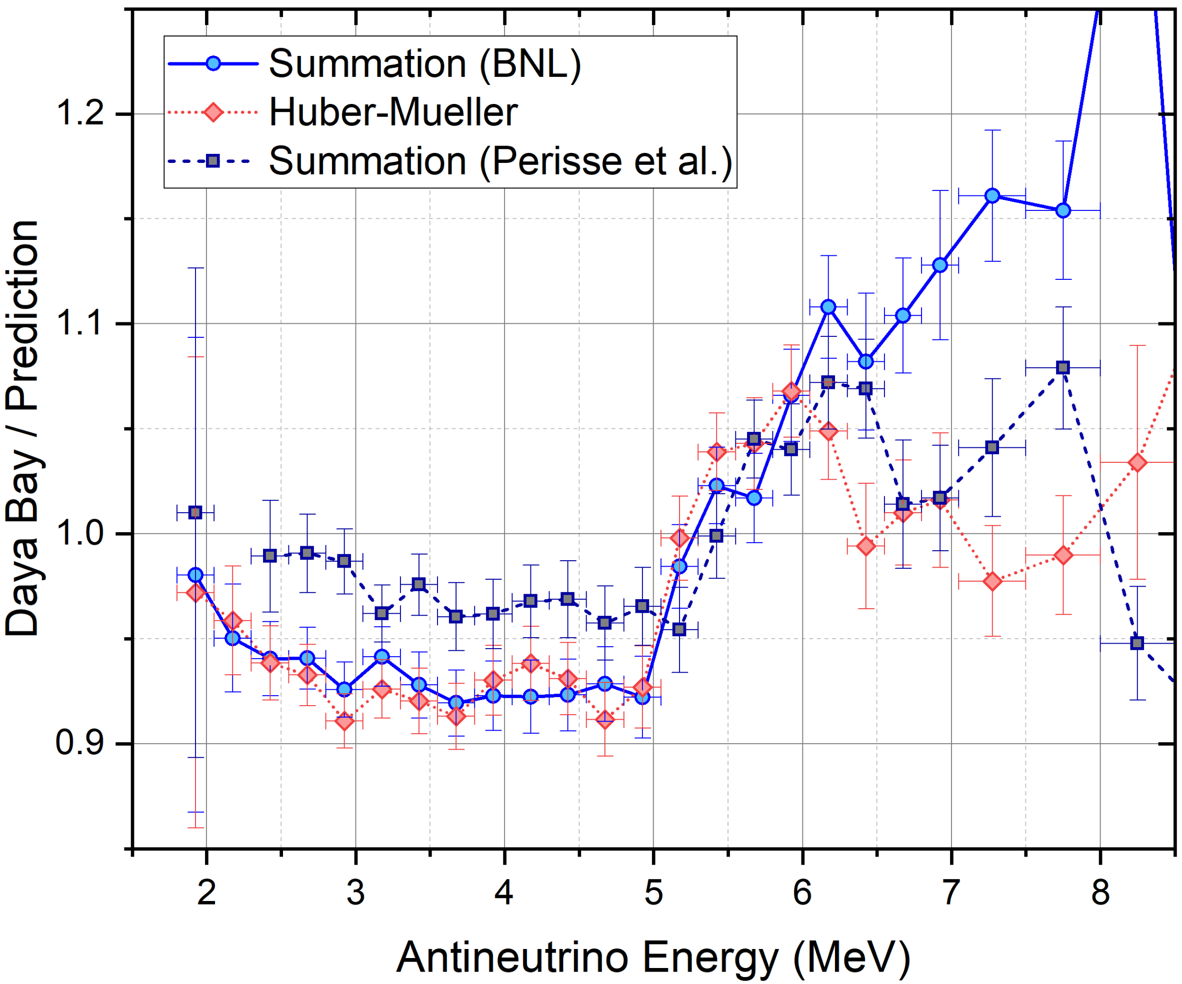


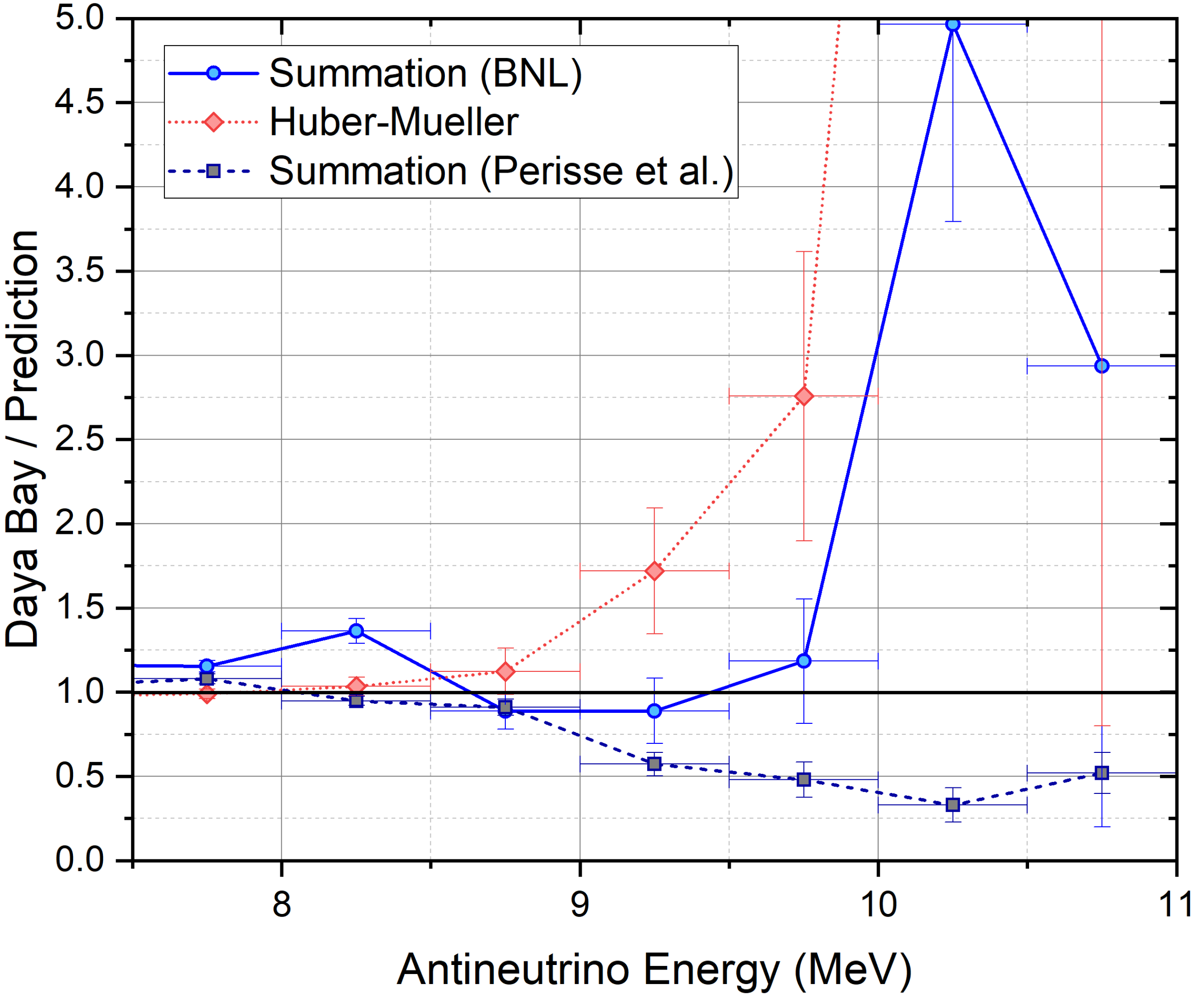


- Data must be read off the plot, numerical values are not available – **please request supplemental material if refereeing**.
- Assuming that ILL ^{239}Pu and ^{241}Pu spectra are correct, renormalize ^{235}U Huber and ^{238}U Haag spectra using this ratio.
- Deficit improves, but still present. Bump gets more visible. A constant correction doesn't solve the problem.

A very recent summation calculation

L. Perisse *et al.*, PRC **108**, 055501 (2023)

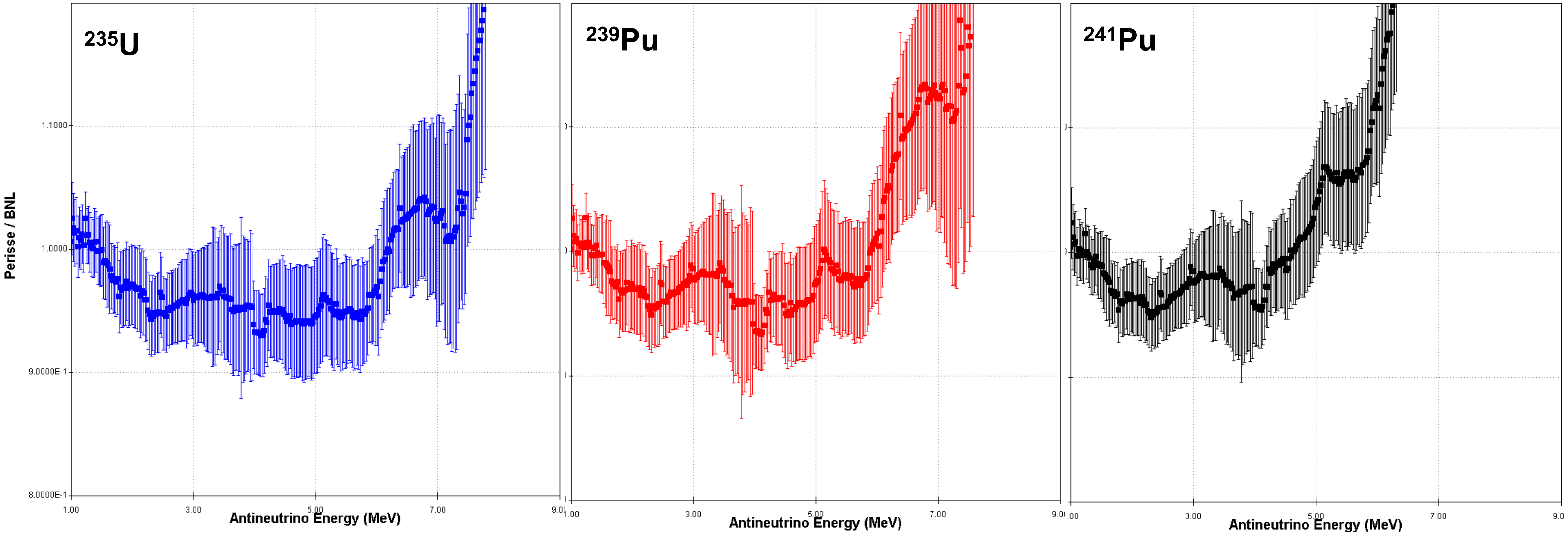




Perisse *et al.* see a **smaller anomaly** and **'broader' bump**, also a consistently **over prediction** at high energies.
<u>Note</u>: only DB uncertainties are plotted.

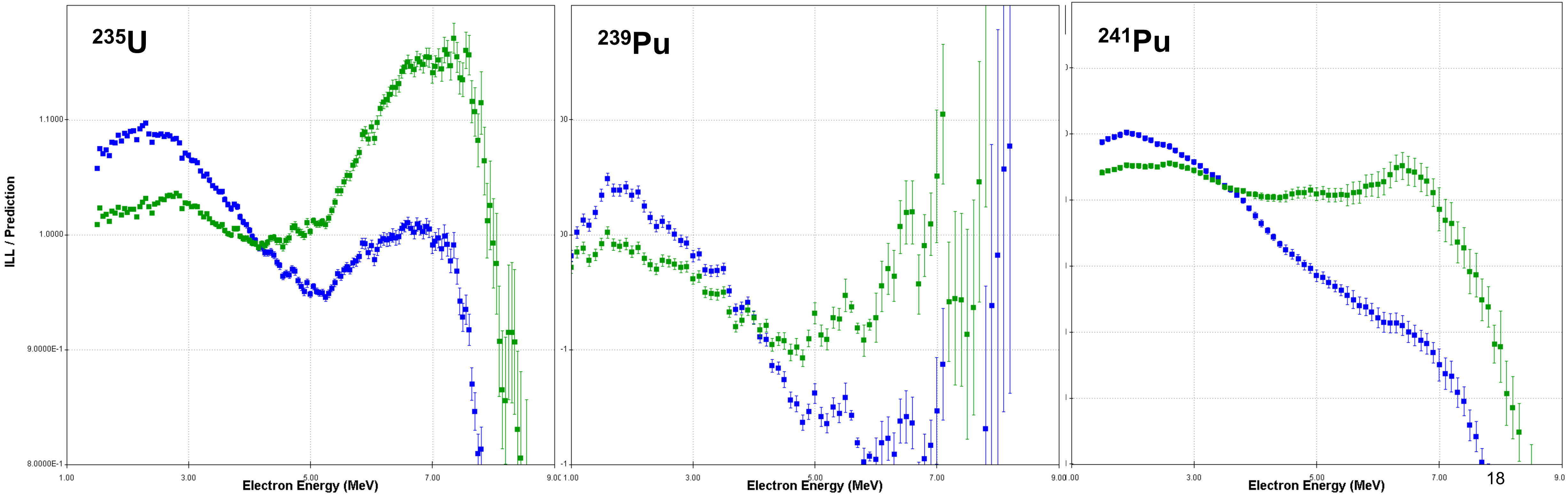
Perisse *et al*. vs BNL summation – antineutrino spectra

Uncertainties are Perisse’s only



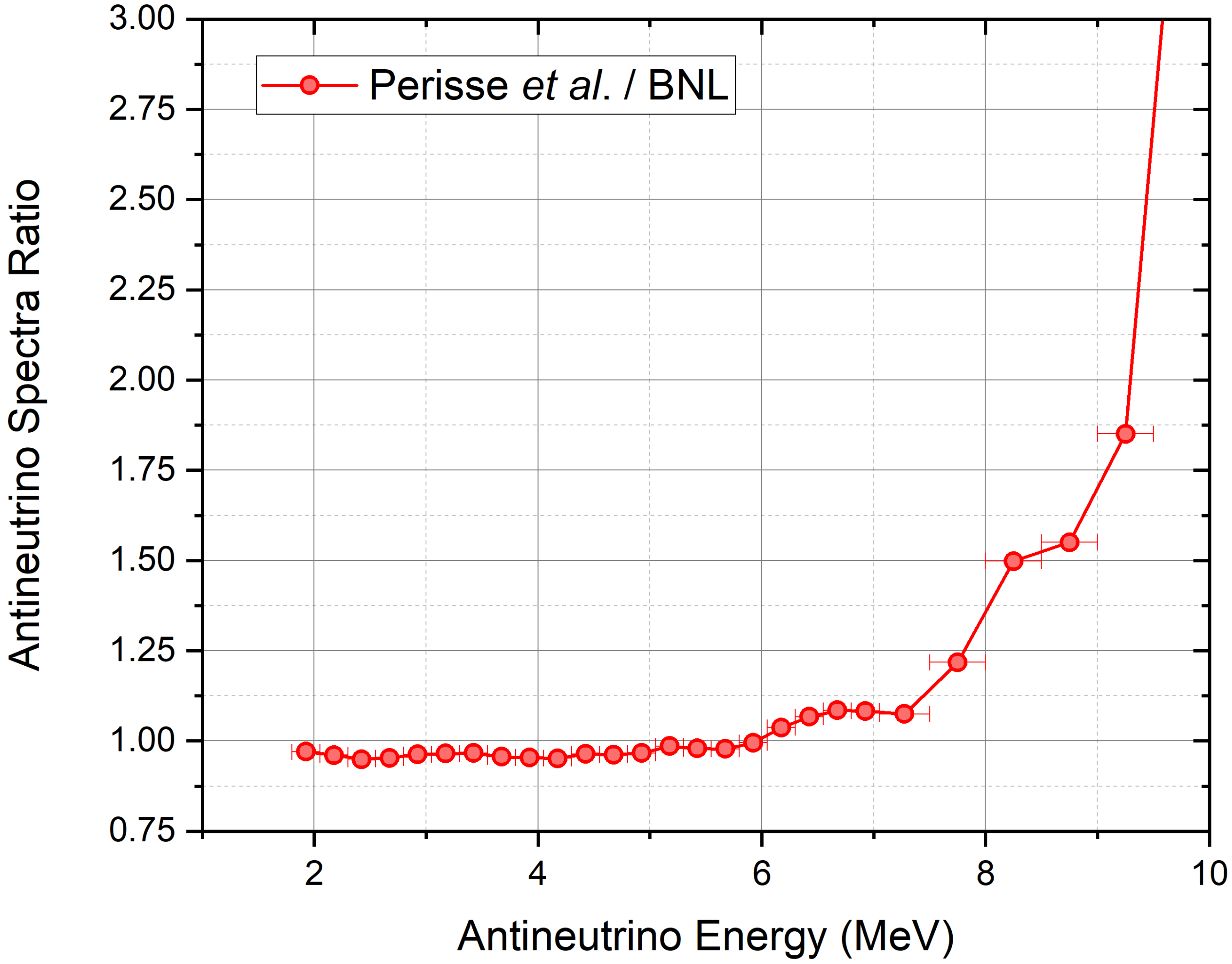
ILL electron vs Summation Calculations

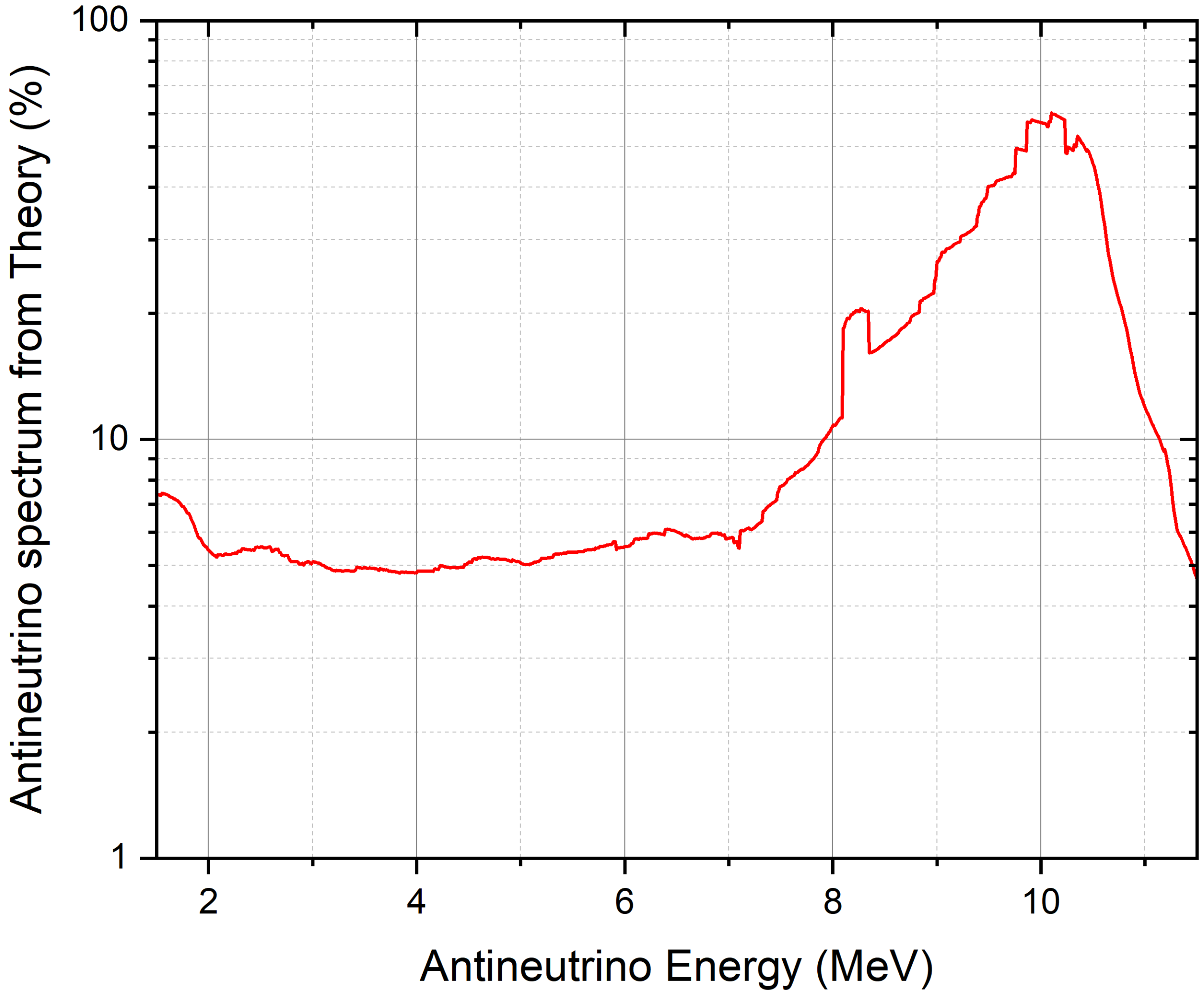
Perisse *et al*., **BNL**, uncertainties are ILL only



Main reason for the difference between Perisse *et al*. and BNL??

After all, we are most likely using the same experimental beta intensities & fission yields data

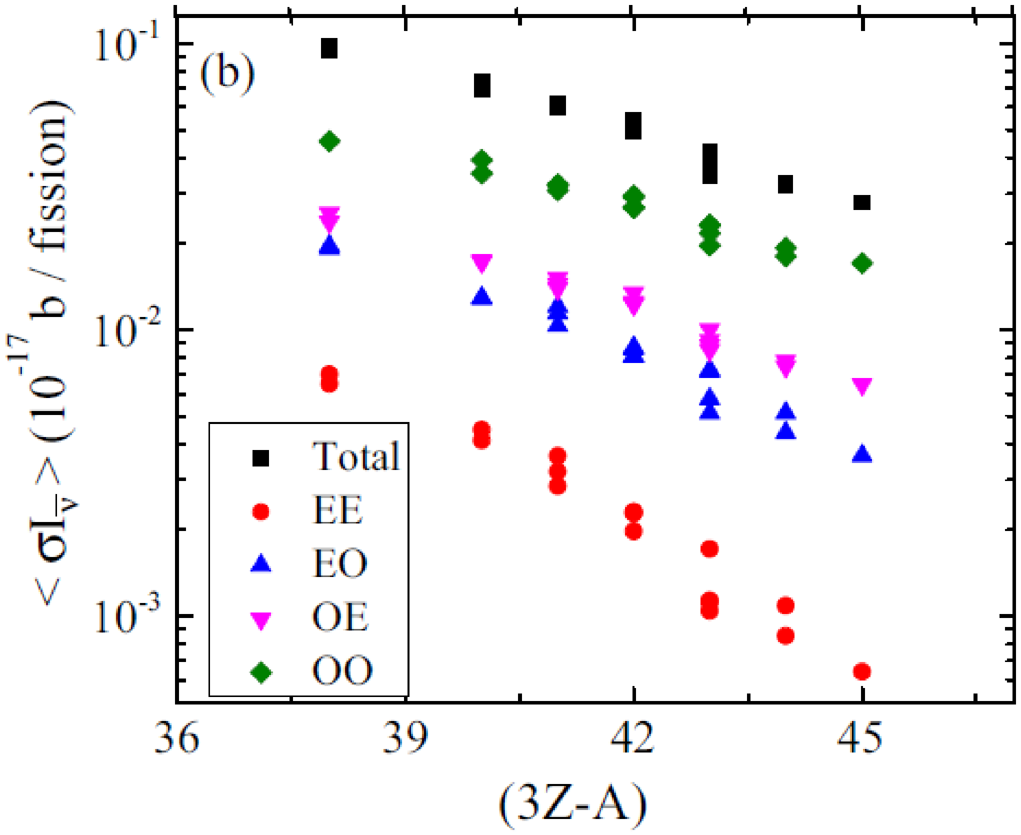




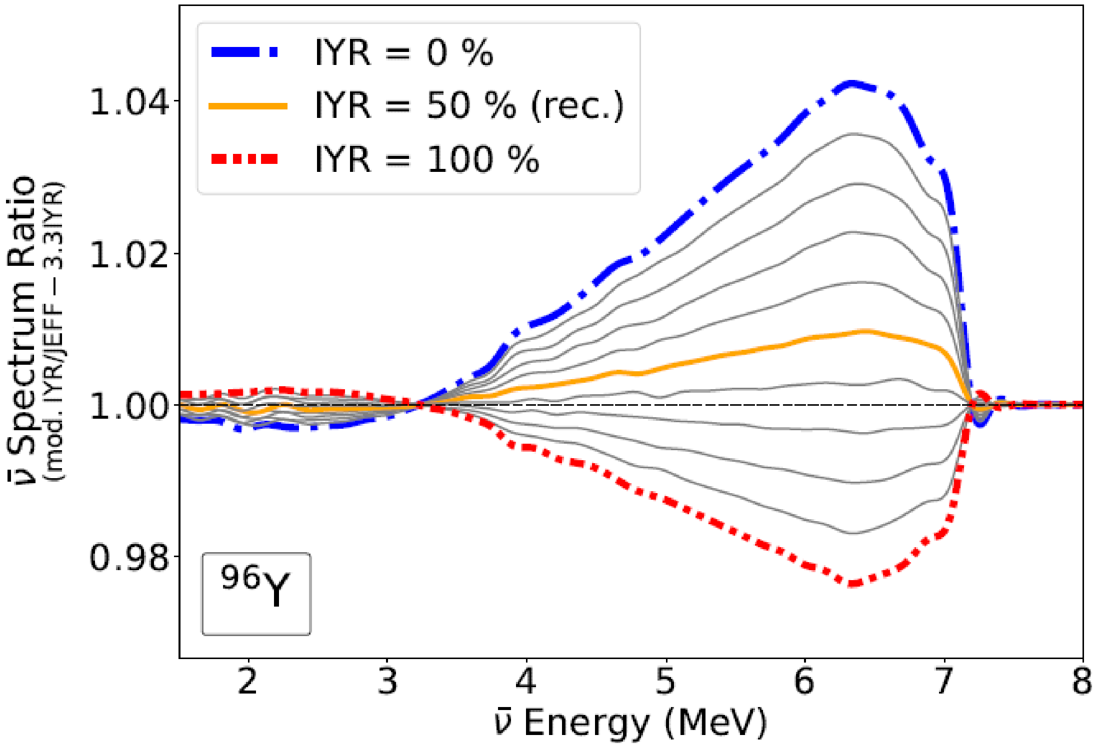
5%-70% of the antineutrino spectrum for the Daya Bay fission fractions comes theoretical calculations due to unknown or incomplete decay schemes. That may explain the difference between the two summation sets.

In addition to poorly known or incomplete decay schemes…

Most of the IBD antineutrinos are produced by odd-Z, odd-N nuclides, due to their larger Qβ-.
These nuclides typically have two long-lived levels, a low-spin and a high-spin one. The low spin will produce many more IBD antineutrinos.

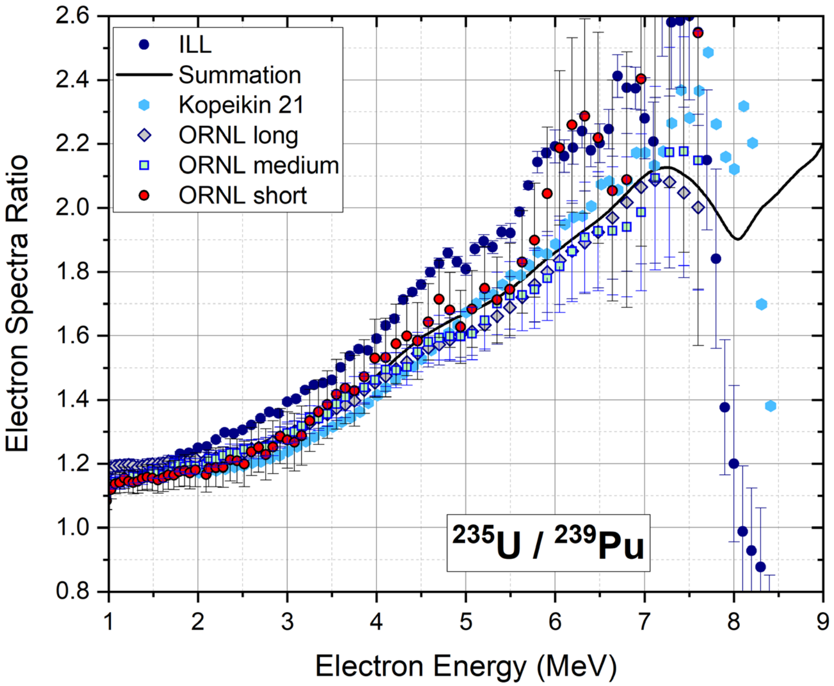


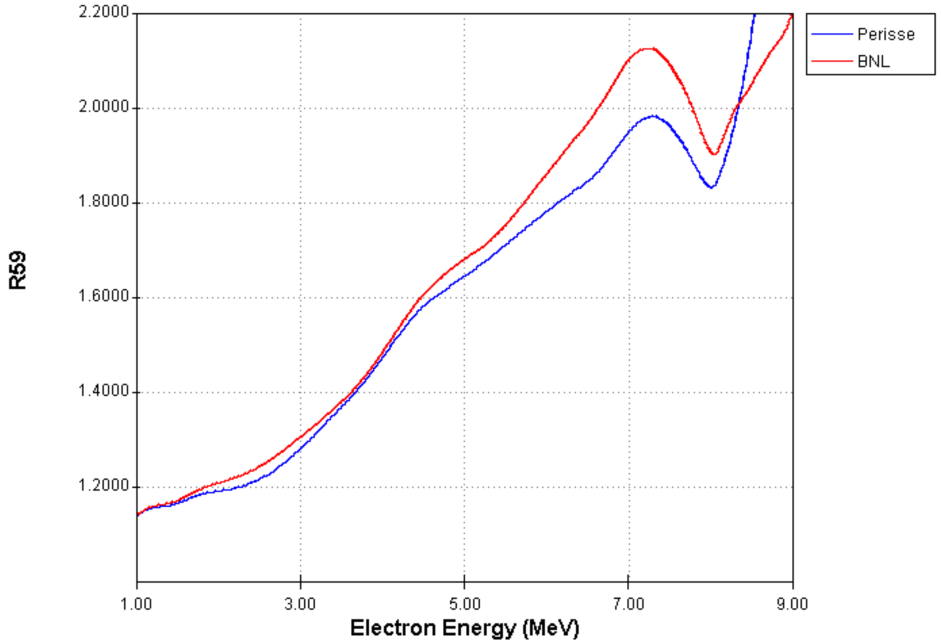
^{96}Y is the most representative case, with an isomeric ratio of 50% from ^{232}Th(p,fission). The thermal neutron one is likely smaller and impacts our understanding of the ‘bump’ origin (A. Mattera to be published).

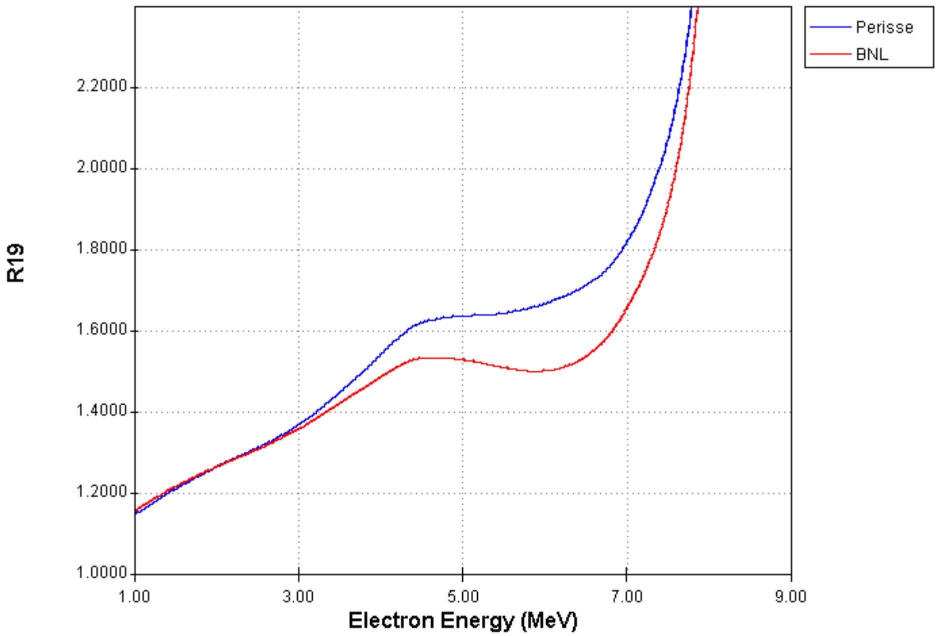


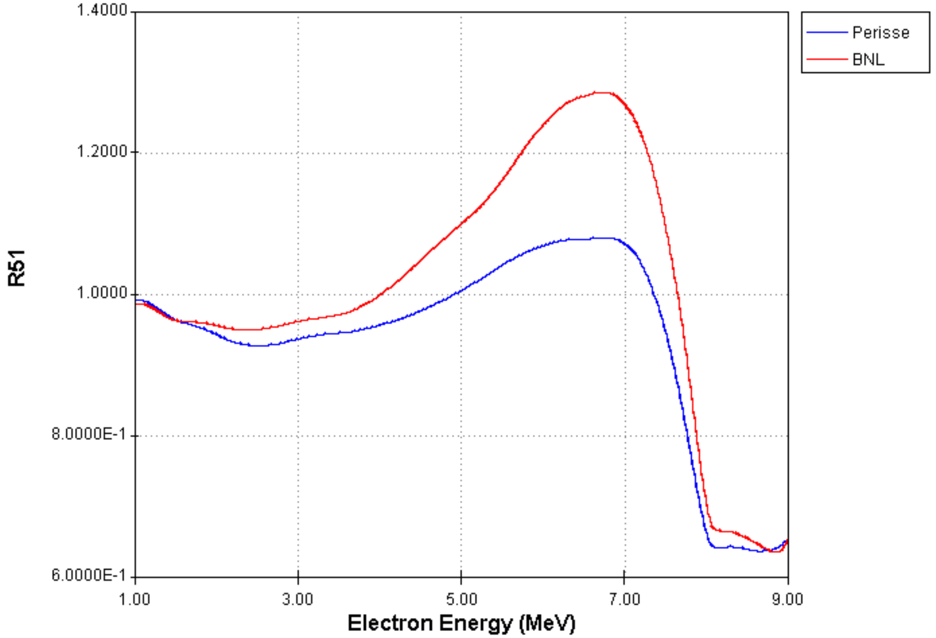
Two summation calculations,

R_{59}, R_{19}, and R_{51}



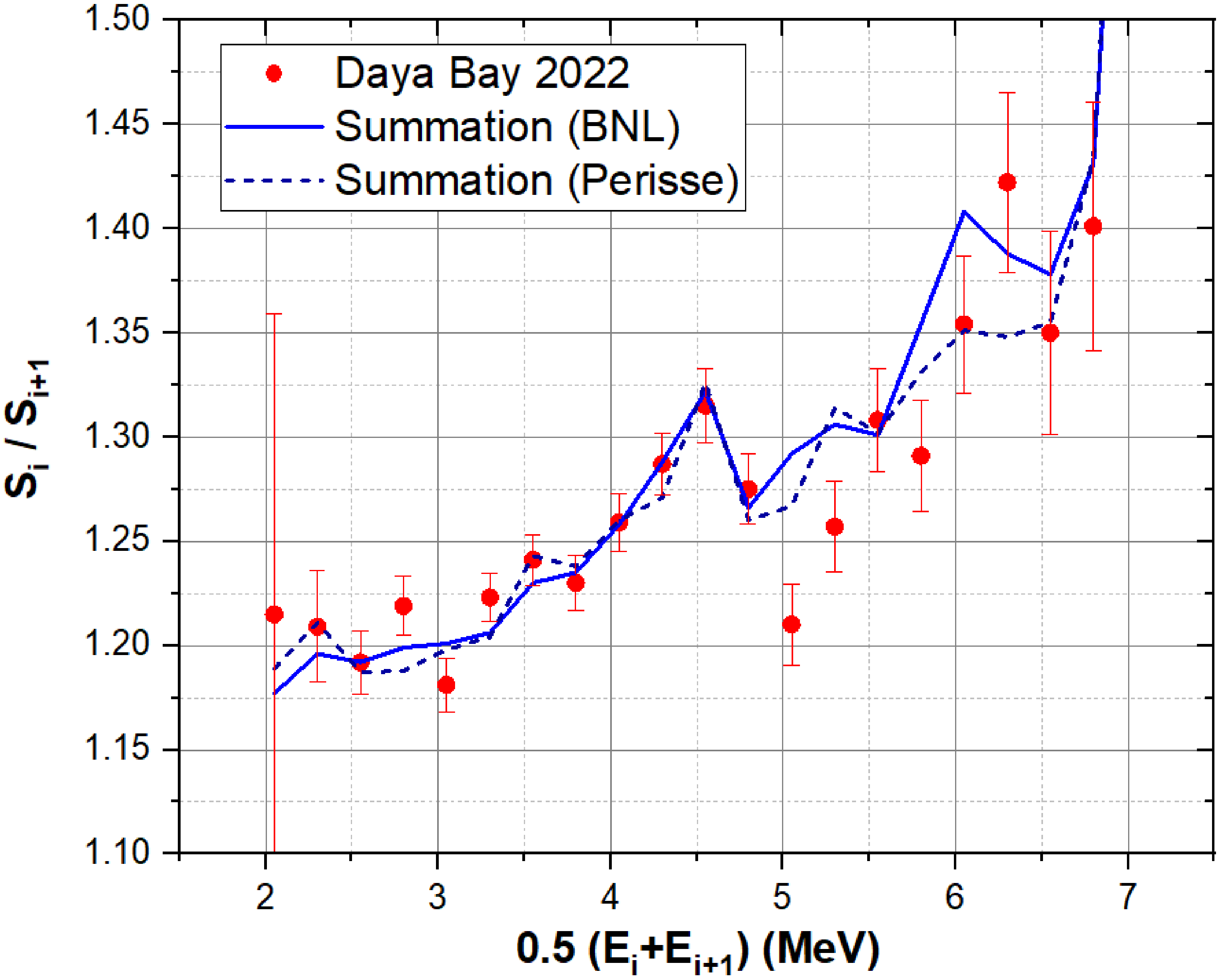






Brookhaven National Laboratory

Fine structure, two summation calculations



Daya Bay 'High Energy'
F.P. An *et al*., PRL **129**, 041801 (2022)

<u>Note</u>: ratio of antineutrino spectrum, with the IBD cross section factored out.

Remarkably good agreement between the Perisse *et al*. and BNL summation calculations!

Some recent and preliminary summer work

New paradigm for antineutrino spectrum

Currently, we parametrize the antineutrino spectrum using a polynomial fit:

$S(E) = \exp(a_0 + a_1E + a_2E^2 + a_3E^3 + a_4E^4 + a_5E^5)$

It creates a very smooth spectrum, which we think hinders the identification of individual fission products.

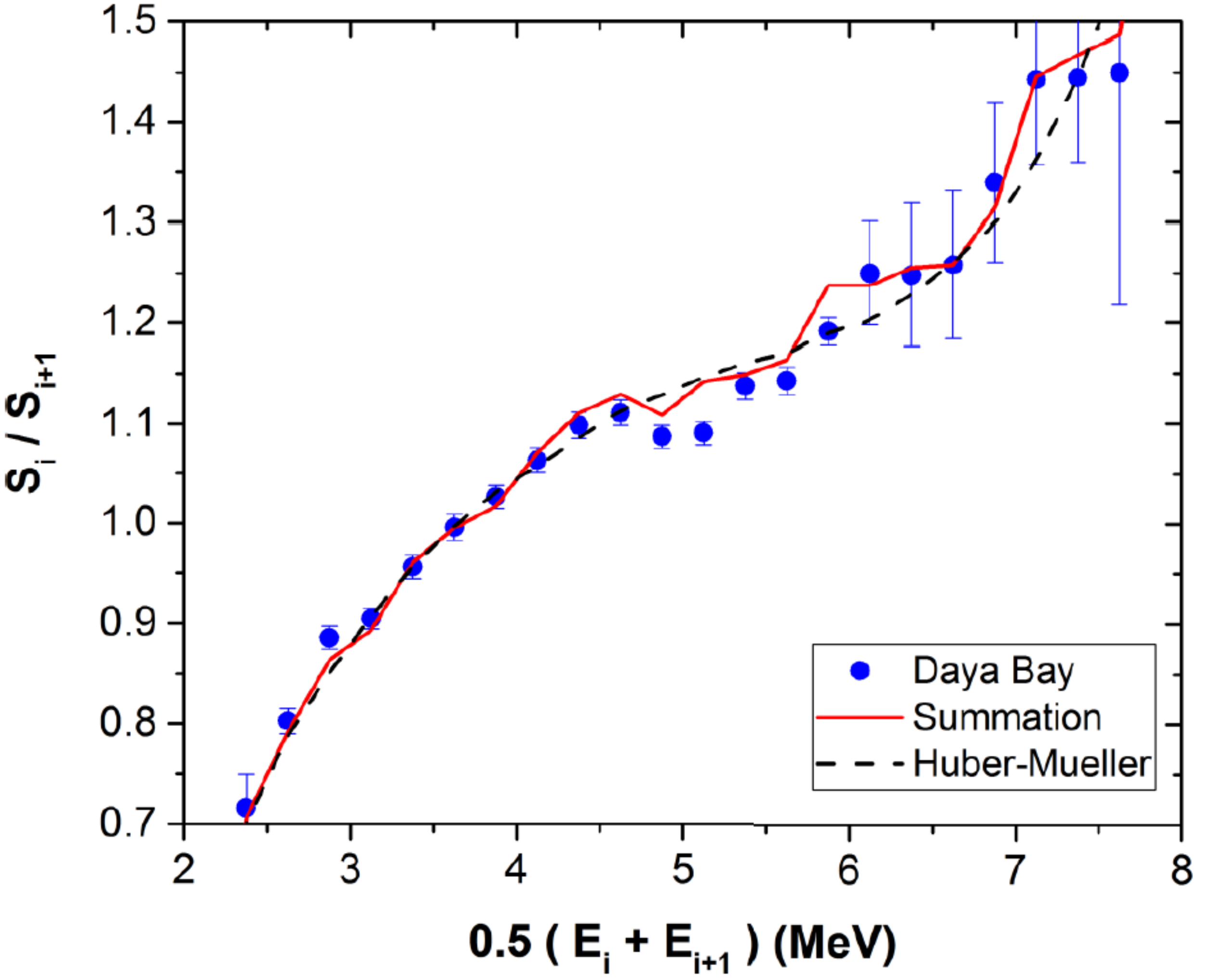
It will create additional problems when comparing with the current resolution and statistics standards.

We start with the Daya Bay 50 keV IBD data

First, we divide by the IBD cross section.

Second, we perform a polynomial fit to the logarithm of the antineutrino spectrum.

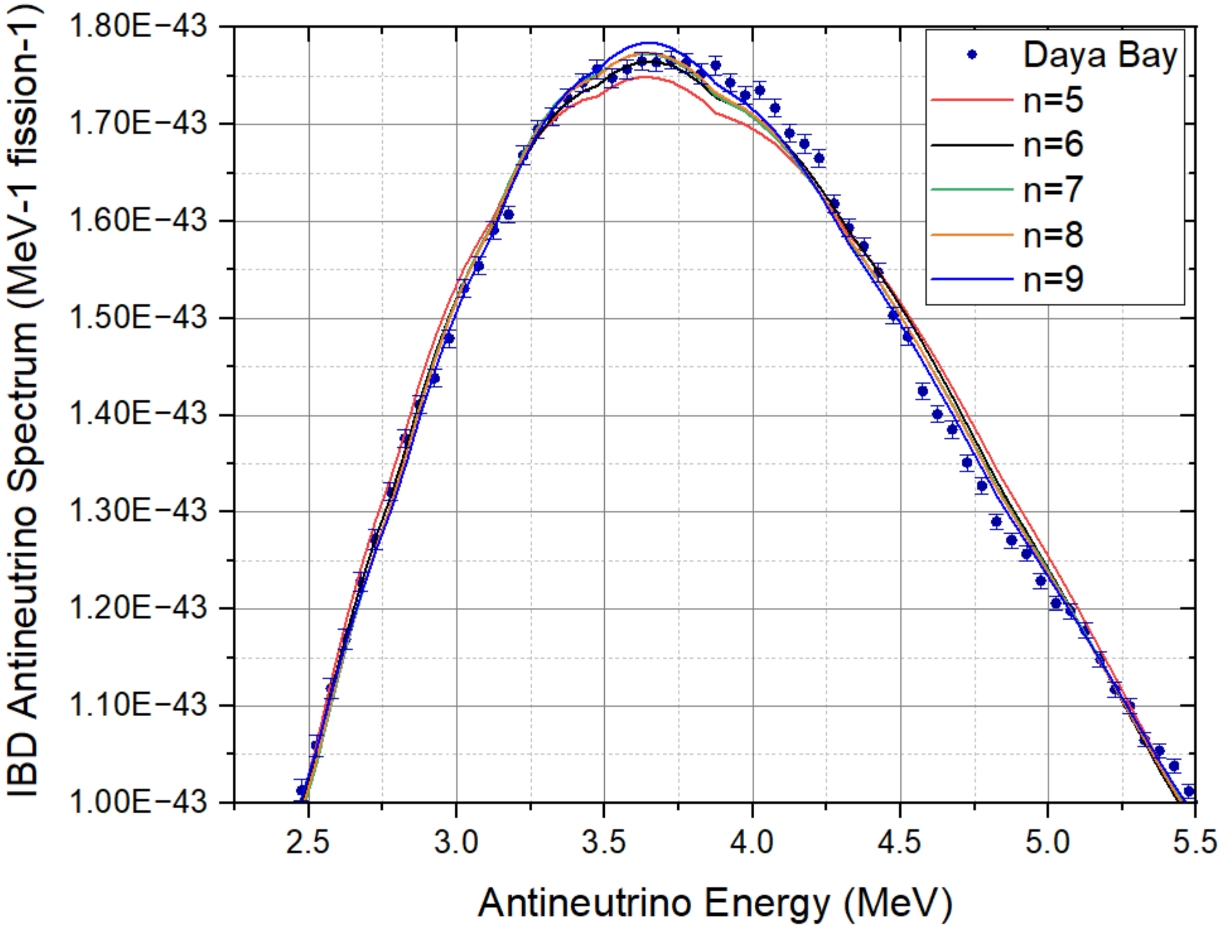
We then multiply the parametrized spectrum by the IBD cross section and compared to the original data.

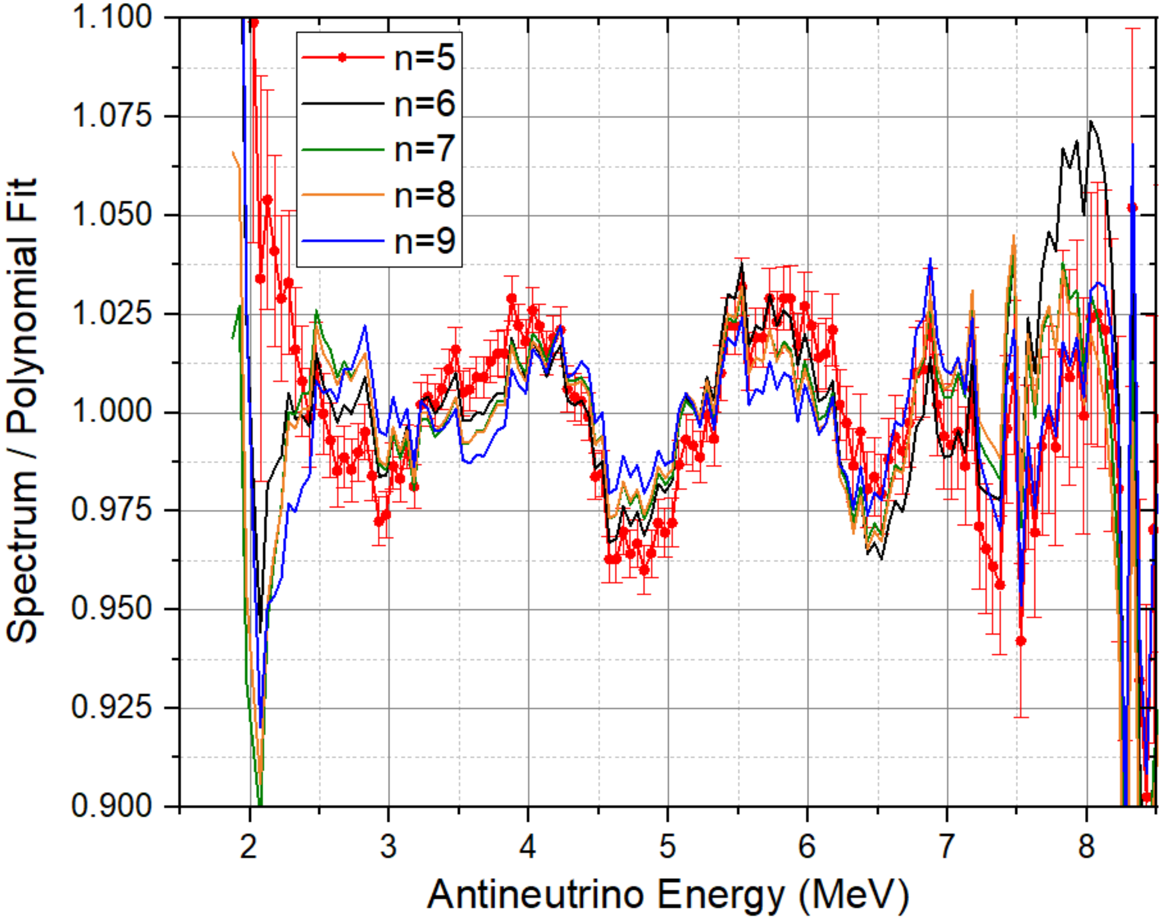


New paradigm for antineutrino spectrum

Daya Bay 50 keV IBD data

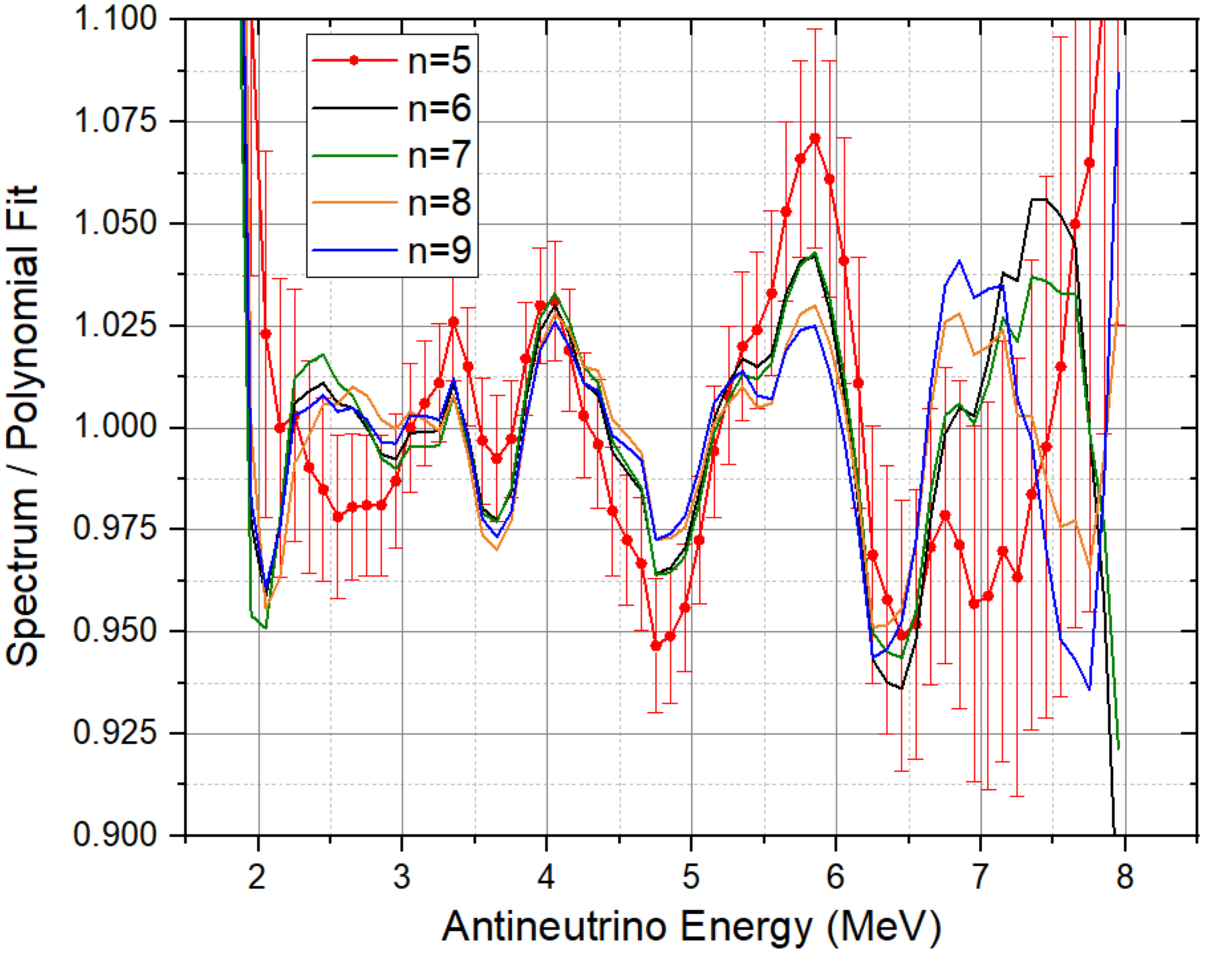
Fit performed using **Origin** software with **W = 1/(ΔS)^2**

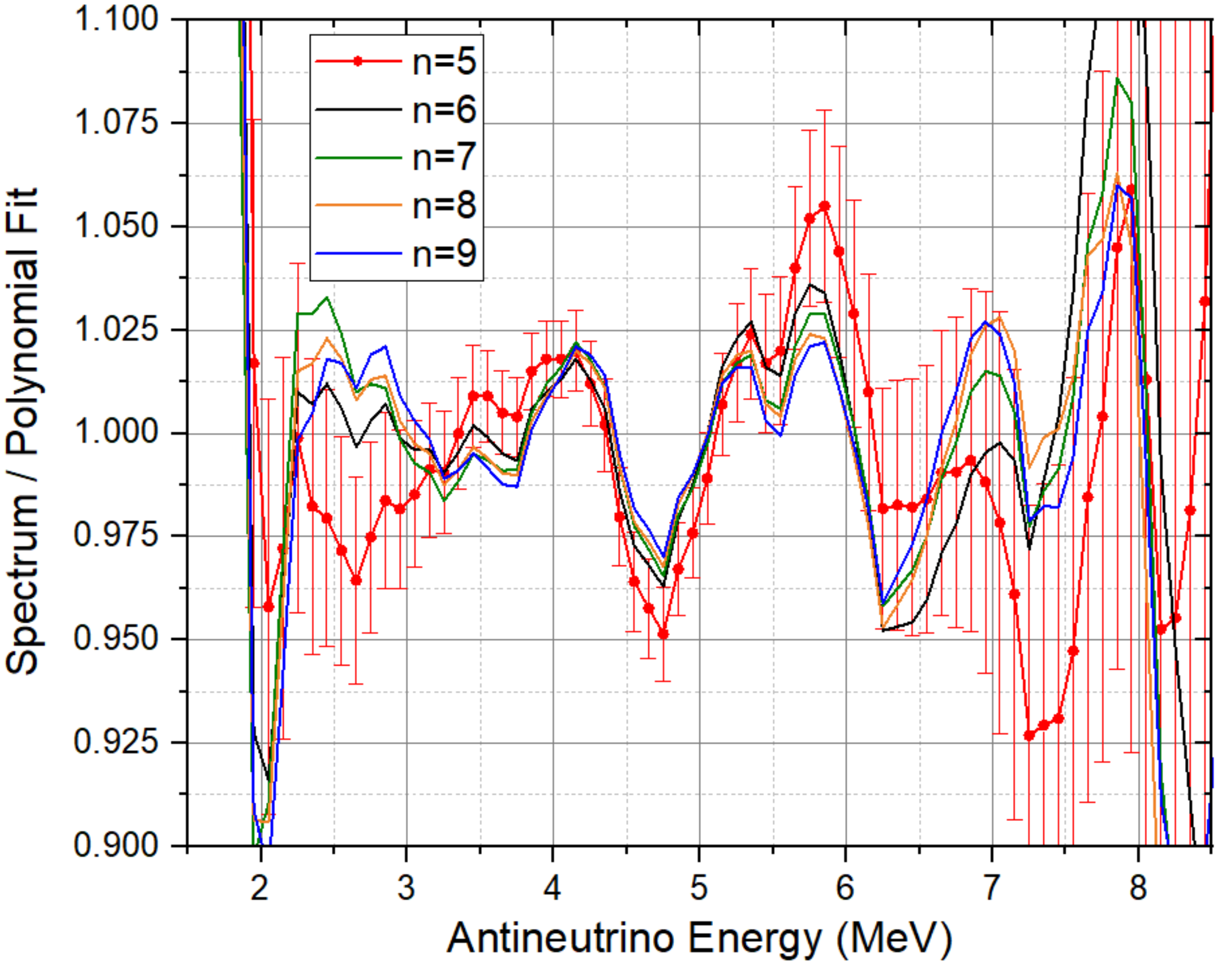




New paradigm for antineutrino spectrum

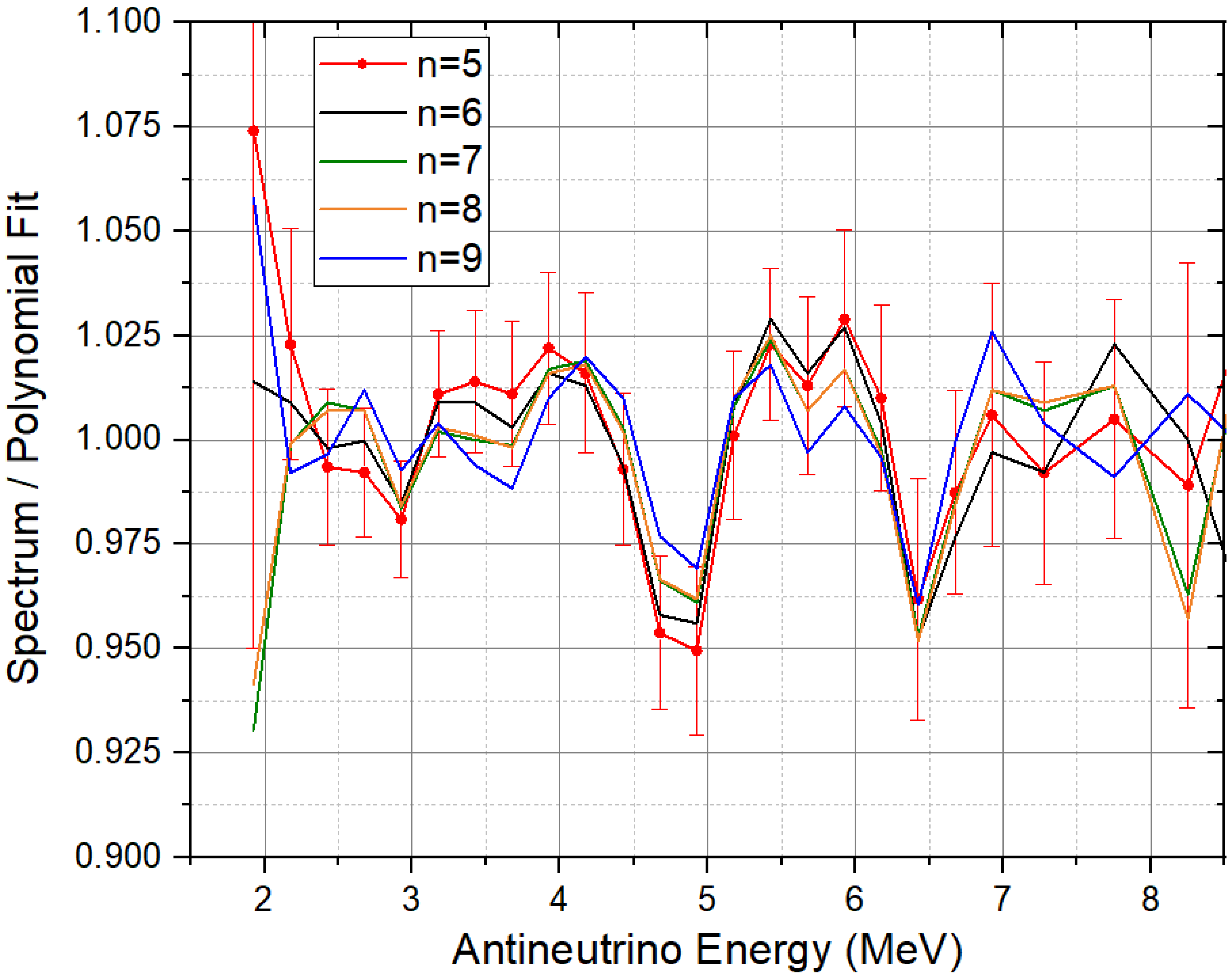
Similar features observed for NEOS and RENO data





New paradigm for antineutrino spectrum

And for Daya Bay High Energy data



<u>Solution</u>:

Point-wise function, spectrum given every 10 keV

Straightforward for Summation

We need to think how to do it for Conversion

Conclusions

- ☐ We think that the source of the **RAA** is the use of a higher **^{207}Pb(n,γ)** cross section to normalize the ILL ^{235}U electron spectrum.
- ☐ We really need to re-measure the ^{235,238}U and ^{239,241}Pu electron spectra with (i) high resolution, (ii) high signal to noise ratio, and (iii) very robust normalization procedure.
- ☐ We think that with the current level of energy resolution and event statistics, we need to improve on the polynomial fit for antineutrino spectra derived from a conversion analysis.

Collaborators

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Anthony Caraballo, Jackson Hacias, Zharia Harris, Becket Hill, Ross MacFayden,
Michael Nino, Adam Oppenheimer, Ophelia Palaguachi, Matthew Seeley,
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