Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Updates on Reactor Neutrino Flux modeling

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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:

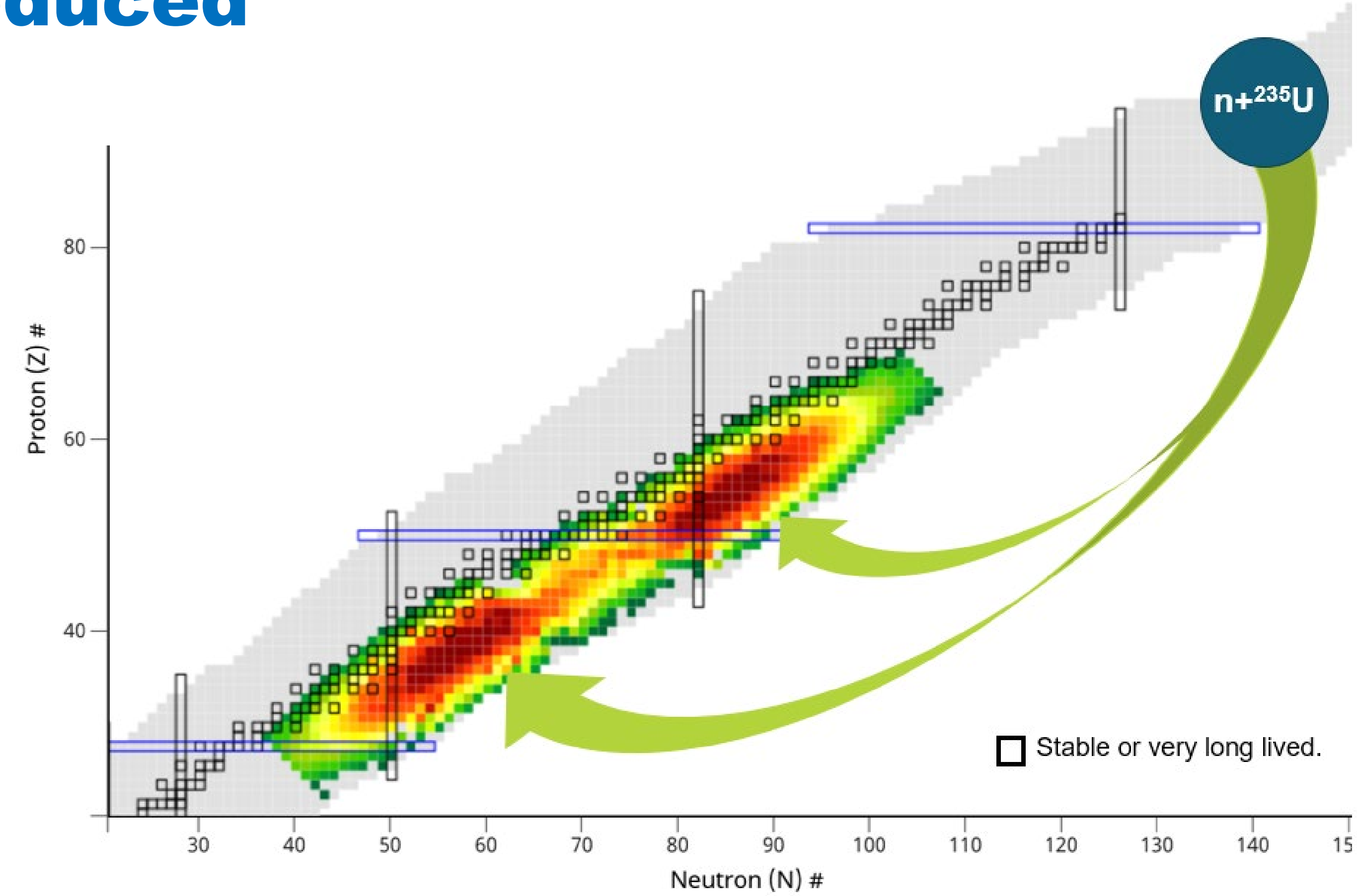
$$dN_k/dt = F \times I_k - \lambda_k N_k + \Sigma \lambda_j P_{jk} N_j$$

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:

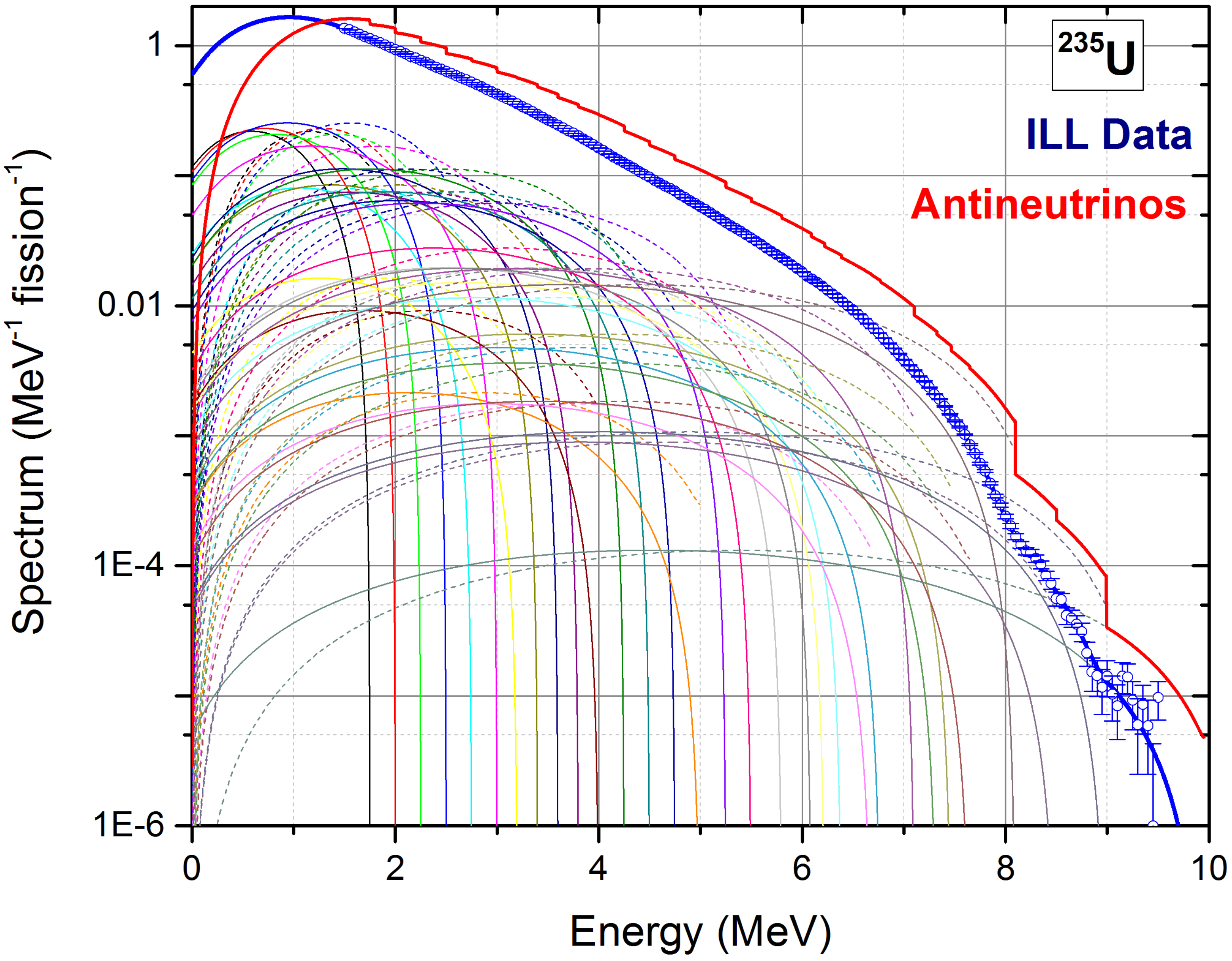
$$S(E) = \Sigma C_k S_k(E)$$



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



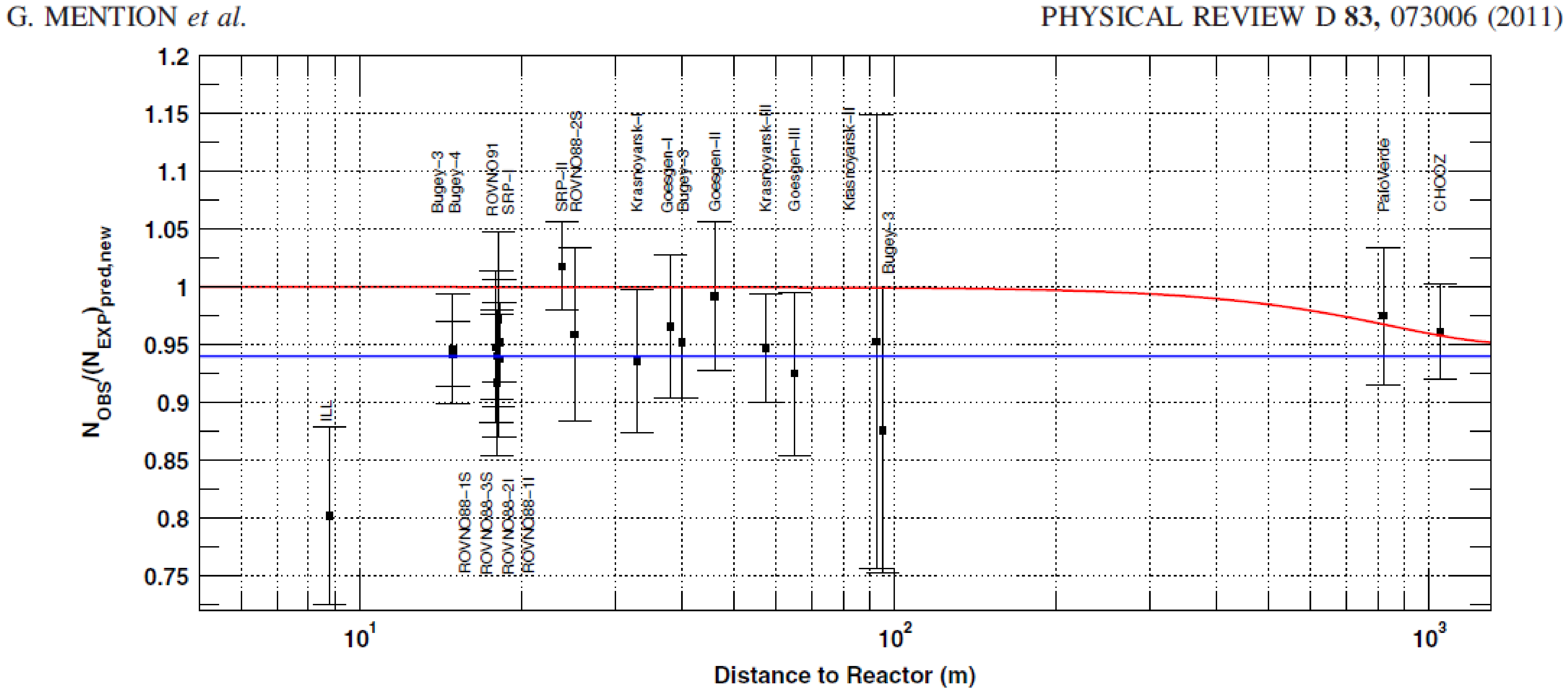
Electron Spectrum measured at ILL, K. Schreckenbach *et al.*, Phys. Lett. **160B**, 325 (1985).

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).

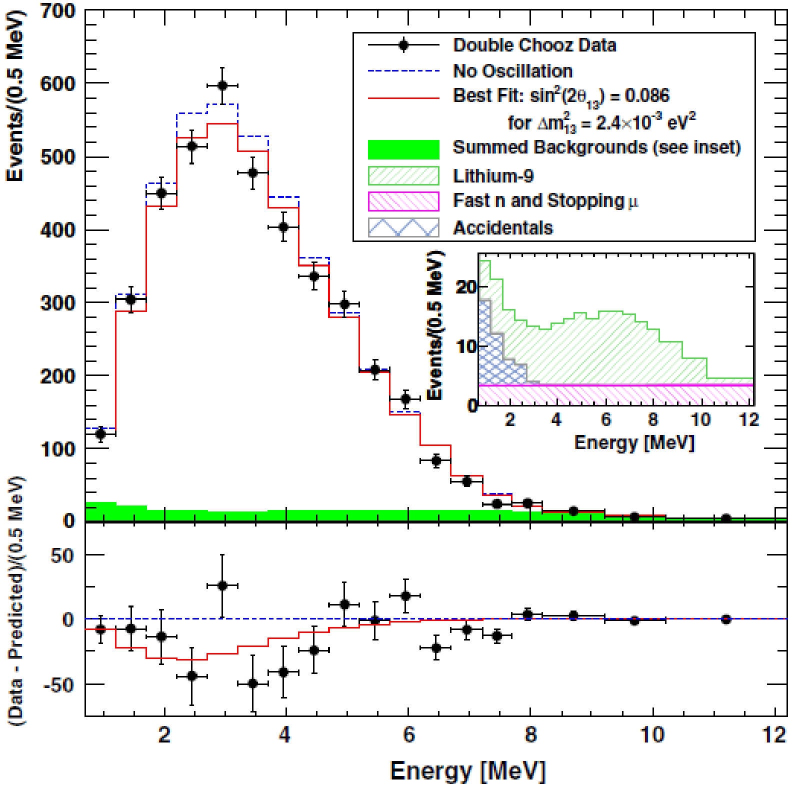
Consequences…


G. MENTION *et al.* PHYSICAL REVIEW D 83, 073006 (2011)

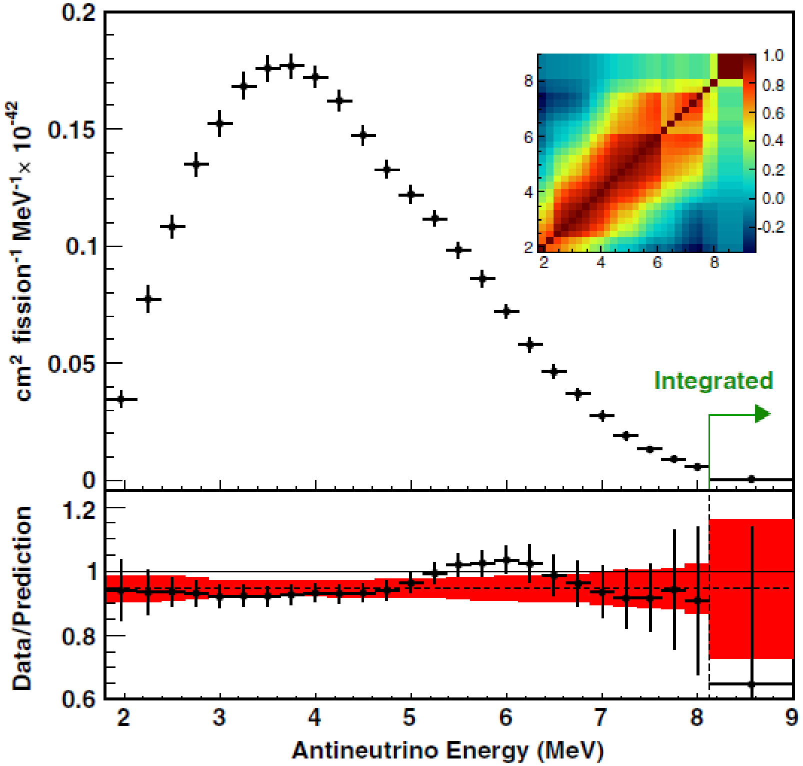
An analysis of earlier experiments with the updated antineutrino spectra reveal a ~6% deficit at short distances.
The term **Reactor Antineutrino Anomaly (RAA)** has been coined to refer to this deficit.

Comparison with some of the recent experiments

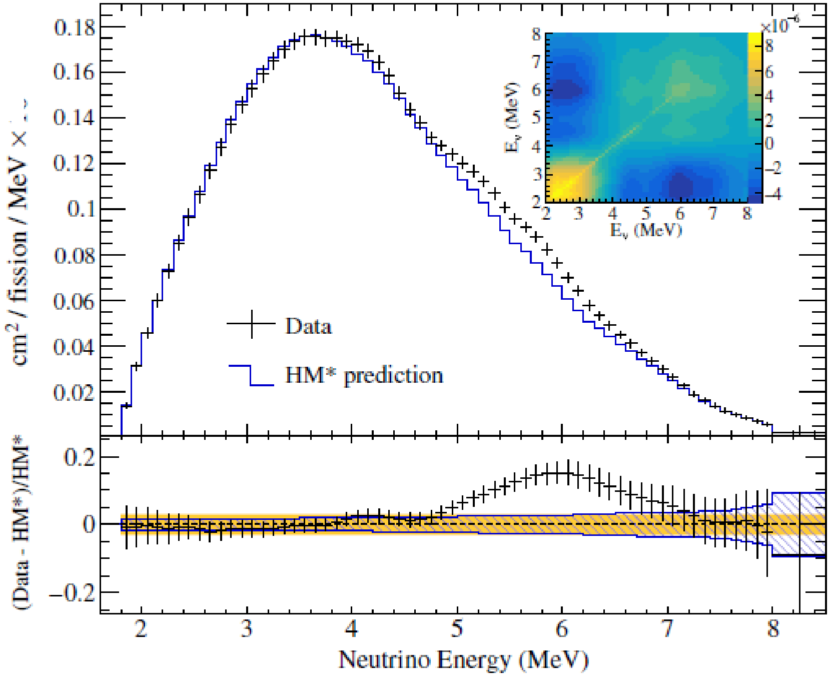
Double Chooz,
PRL **108**, 131801 (2012)



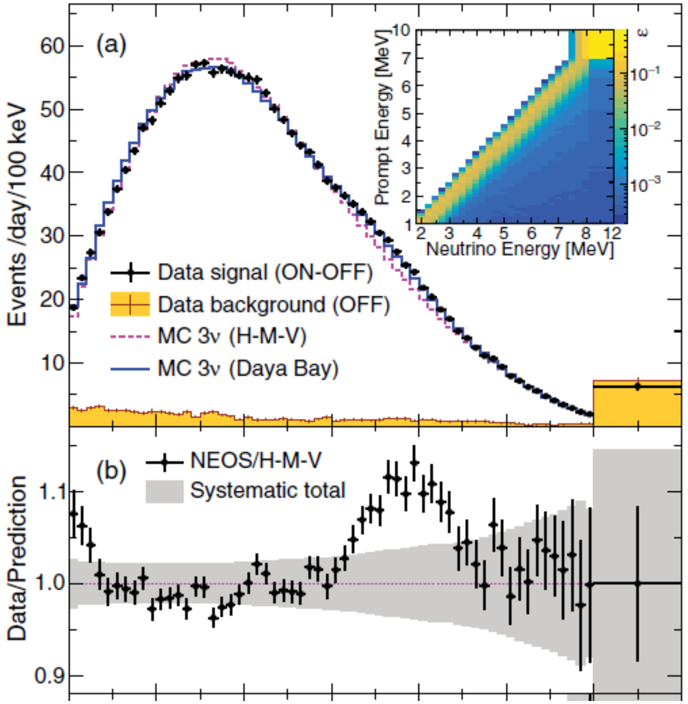
Daya Bay,
PRL **108**, 171803 (2012)



RENO,
PRD **104**, L111301 (2021)



NEOS,
PRL **118**, 121802 (2017)

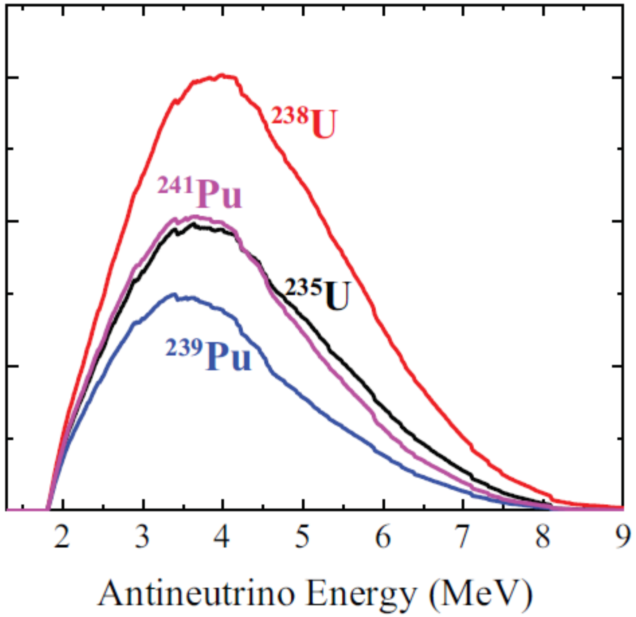


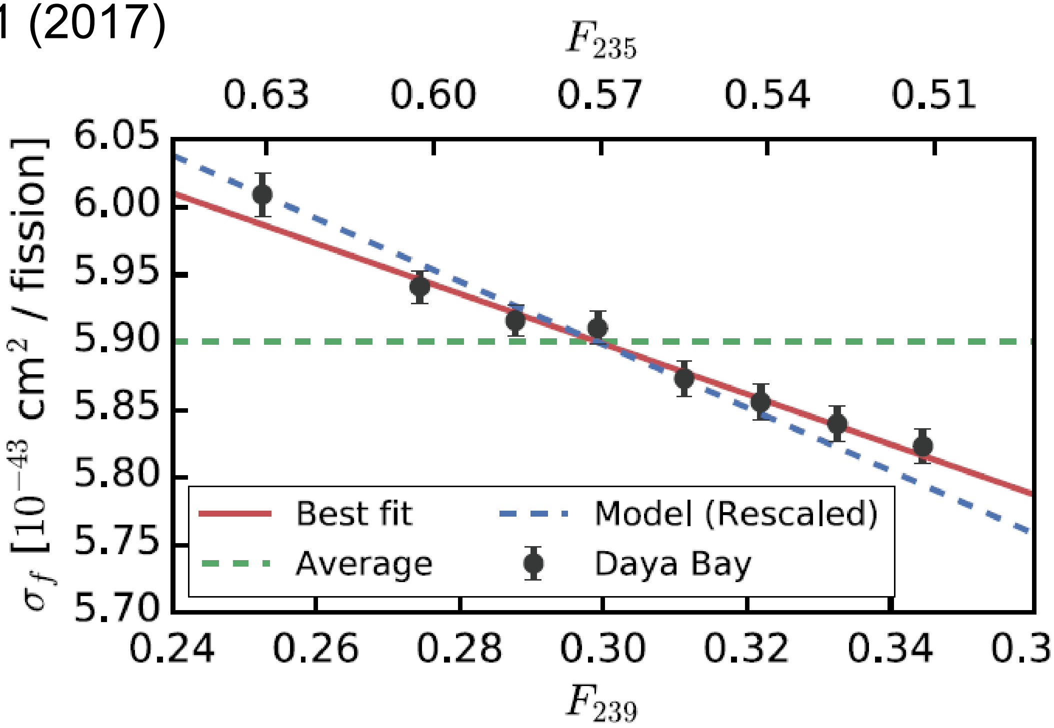
- RAA manifest better as an overprediction at the top of the spectrum.
- An excess of antineutrinos at ~6 MeV is observed, the ‘bump’.

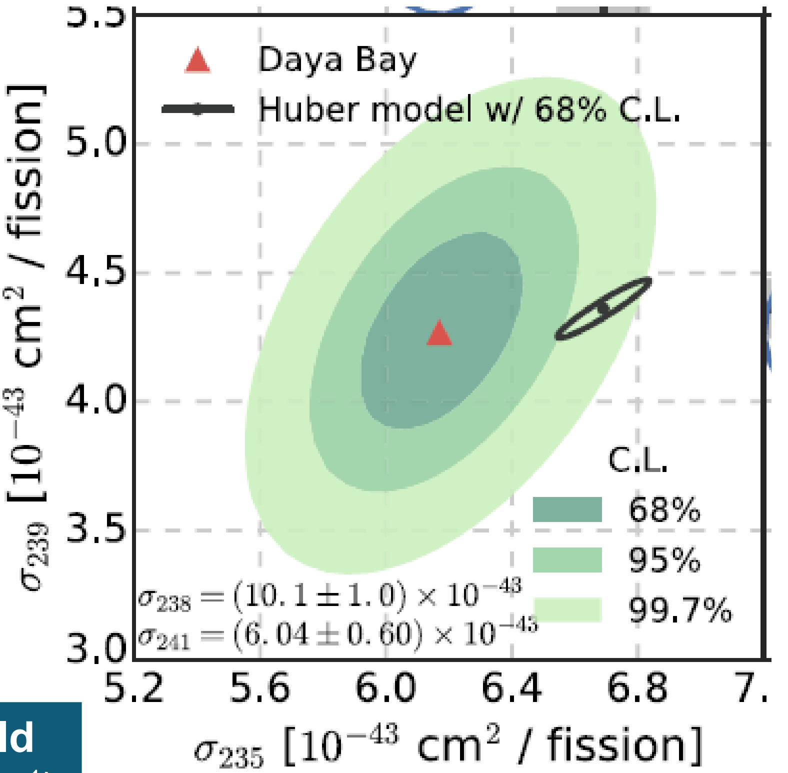
Understanding the origin of the anomaly

Evolution of the Reactor Antineutrino Flux and Spectrum at Daya Bay

F.P. An et al., PRL **118**, 251801 (2017)

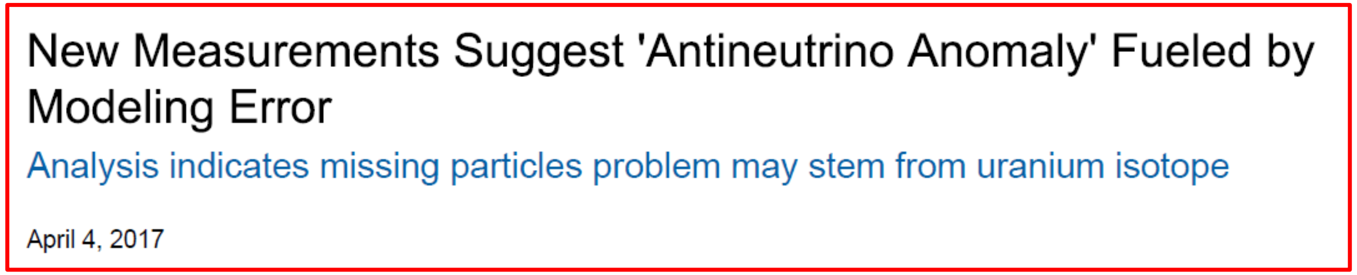






$$\sigma = F_{235} \times \sigma_{235} + F_{239} \times \sigma_{239} + F_{238} \times \sigma_{238} + F_{241} \times \sigma_{241}$$

Nucleus	Daya Bay IBD Yield (10^{-43} cm^2 fission^{-1})	Huber IBD Yield (10^{-43} cm^2 fission^{-1})
^{235}U	6.17 +- 0.17	6.69 +- 0.15
^{239}Pu	4.27 +- 0.26	4.36 +- 0.11



New Measurements Suggest 'Antineutrino Anomaly' Fueled by Modeling Error

Analysis indicates missing particles problem may stem from uranium isotope

April 4, 2017

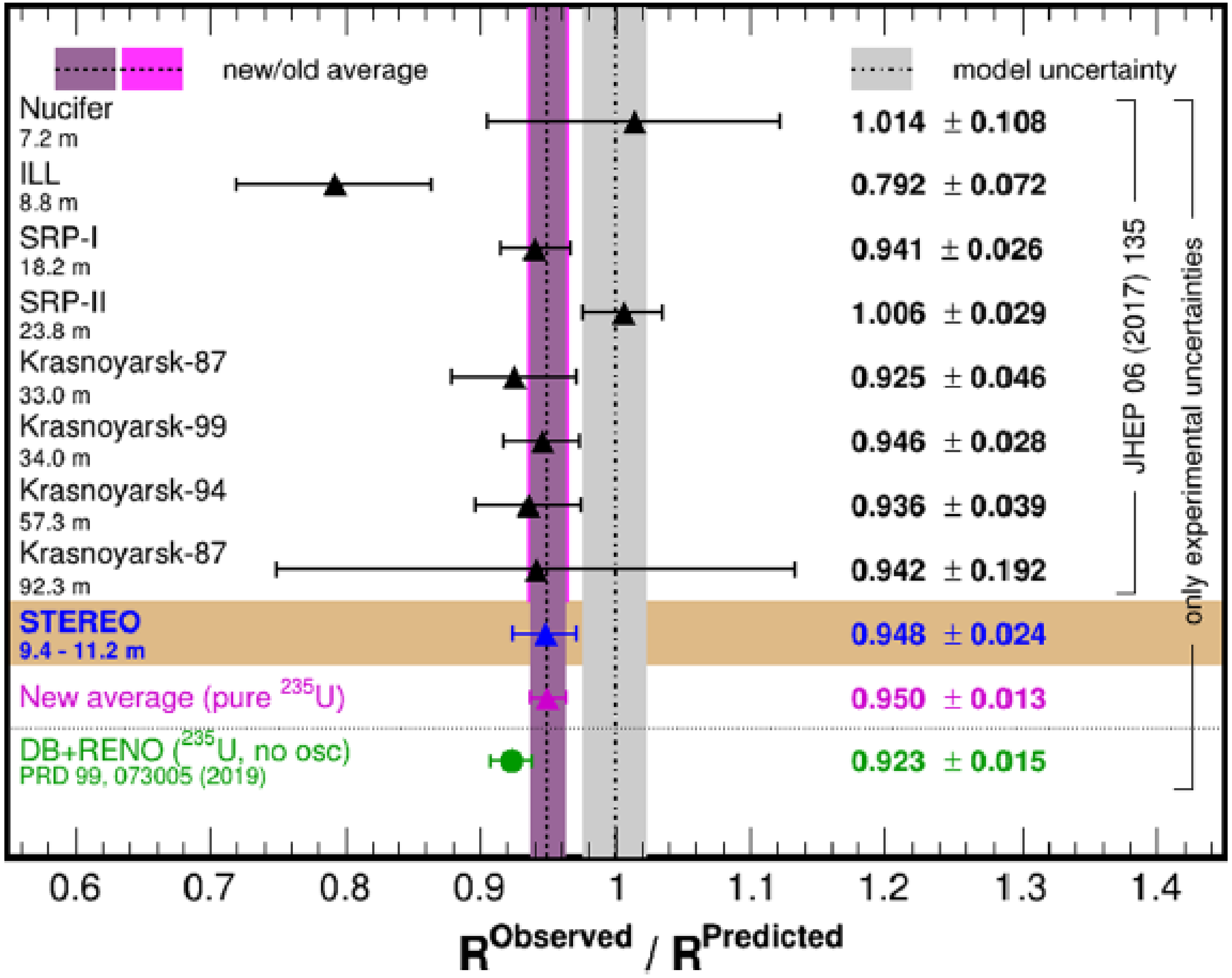
Brookhaven National Laboratory

Confirmation from STEREO

Accurate Measurement of the Electron Antineutrino Yield of ^{235}U Fissions from the STEREO Experiment with 119 Days of Reactor-On Data

H. Almazán *et al.*, PRL **125**, 201801 (2020)

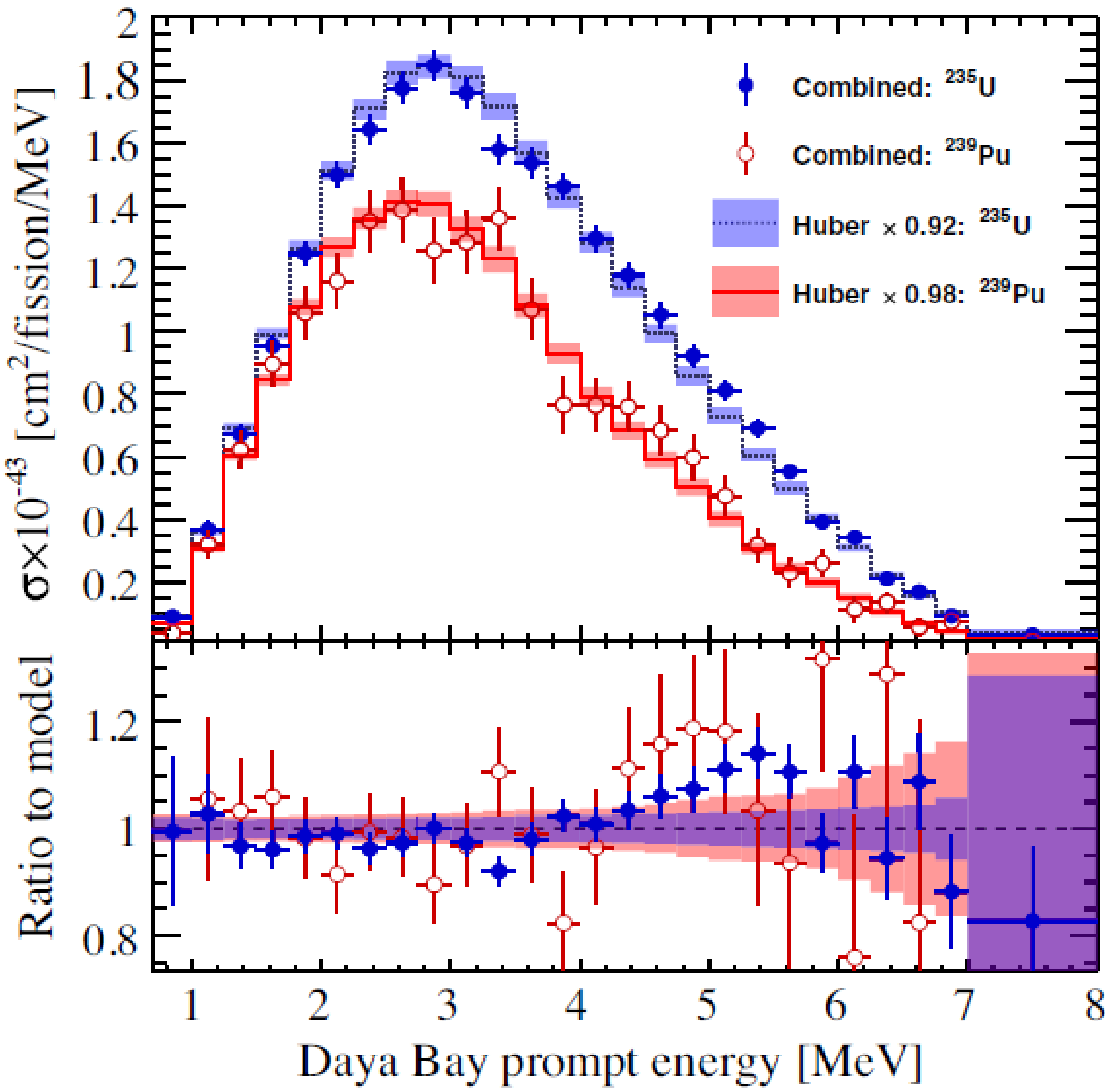
- ☐ ILL reactor, 93.5% ^{235}U enrichment.
- ☐ F_{235}=99.3%
- ☐ Detector at 9.4 m from the core
- ☐ Confirms Daya Bay and RENO results



Joint Determination of Reactor Antineutrino Spectra from ^{235}U and ^{239}Pu Fission by Daya Bay and PROSPECT

F.P. An et al., PRL **128**, 081801 (2022)

- PROSPECT, short baseline experiment at ORNL with a Highly-Enriched Uranium reactor (HFIR)
- Using fuel evolution, spectrum as function of F_{239}, as well as the PROSPECT ^{235}U spectrum, the individual ^{235}U and ^{239}Pu IBD spectra were deduced.
- The ^{239}Pu IBD spectrum agrees fairly well with Huber's (-2%).
- The ^{235}U IBD spectrum multiplied by a factor of **0.92** shows good agreement with Huber's.

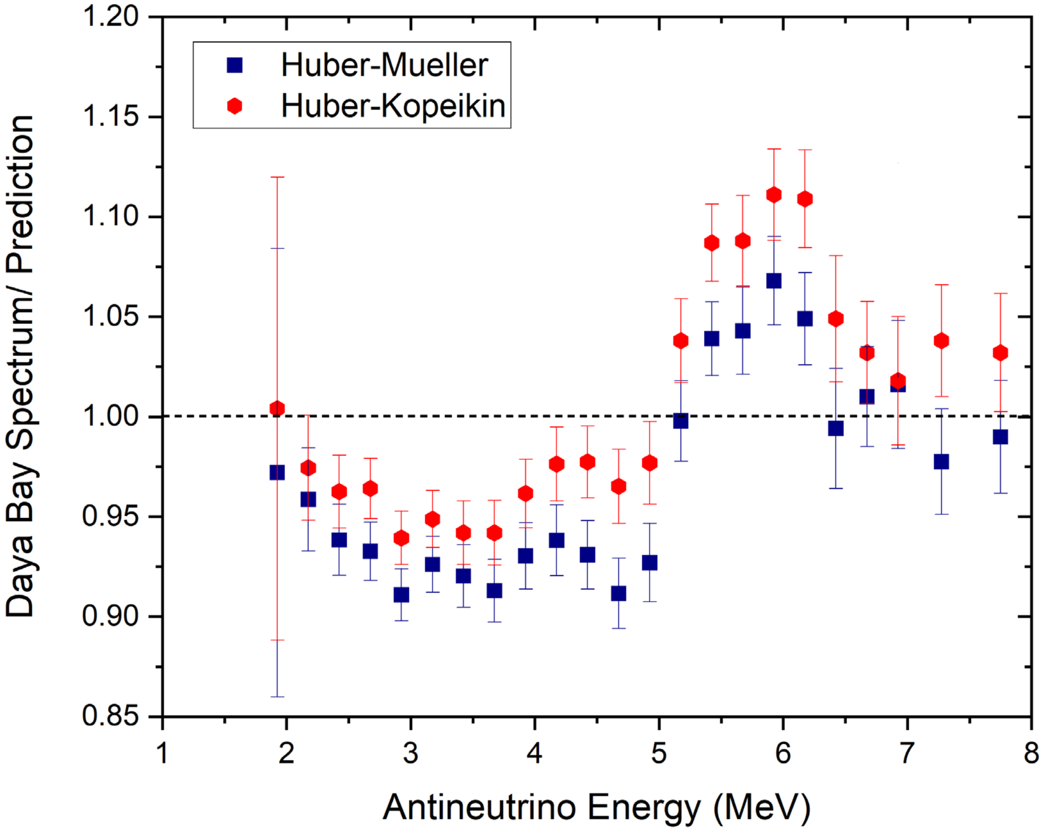


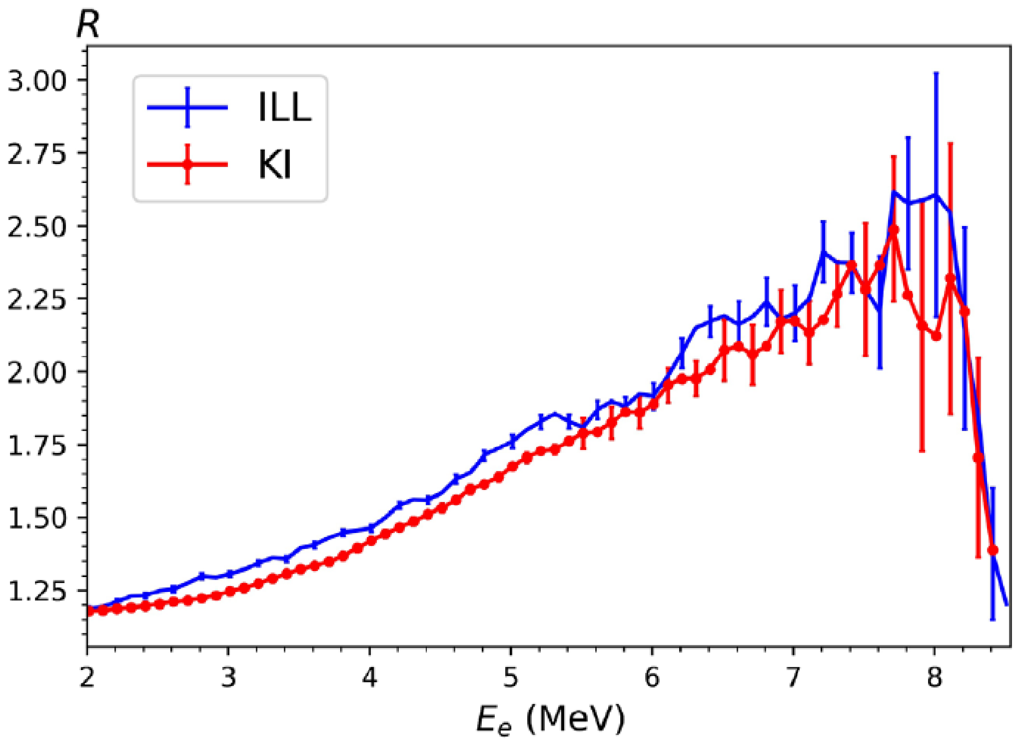
$$S = F_{235} \times S_{235} + F_{239} \times S_{239} + F_{238} \times S_{238} + F_{241} \times S_{241}$$

Kopeikin *et al.*, 2021

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

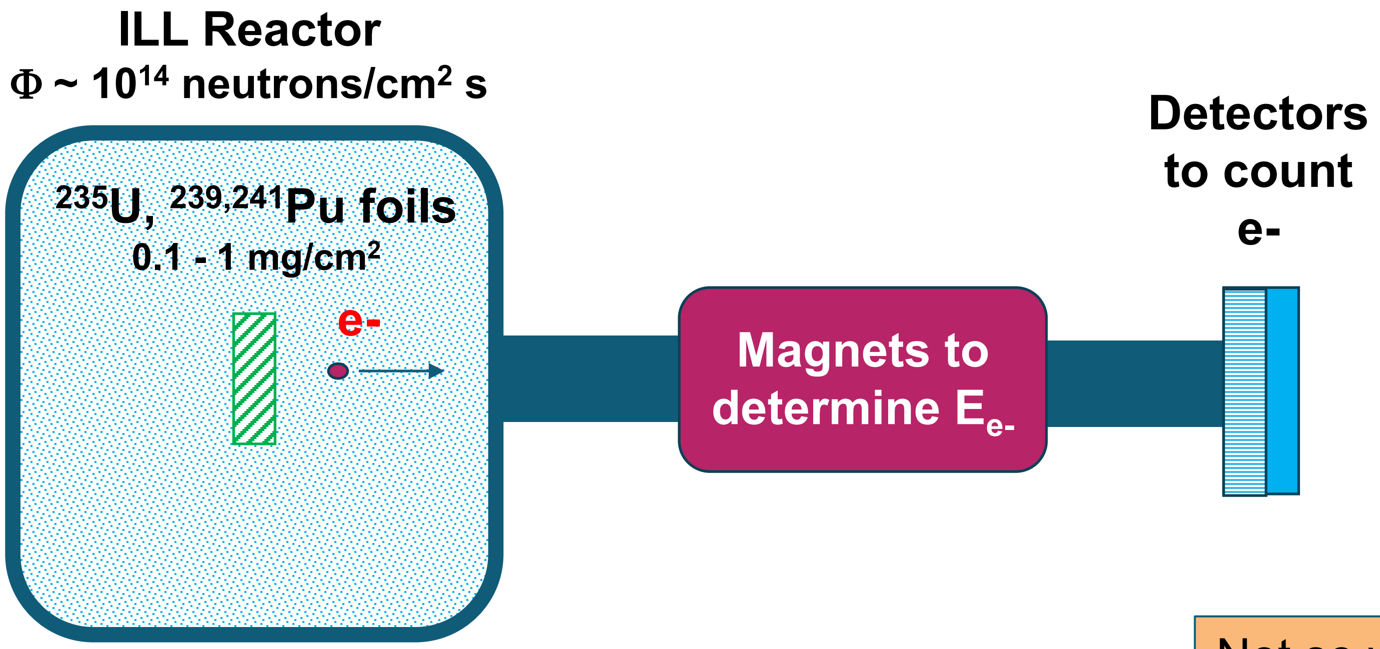
- Measurement of ^{235}U / ^{239}Pu electron spectra ratio R_{59} using scintillators outside reactor core.
- $\phi = 7 \times 10^6$ n s^{-1} cm^{-2}
- Ratio of ^{235}U to ^{239}Pu electron spectra is about 5% lower than ILL values.





- 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.
- Why is the ^{235}U ILL spectrum normalization not correct? After all it seems to be the best of the 3 ILL datasets.

Electron spectra measurements at ILL

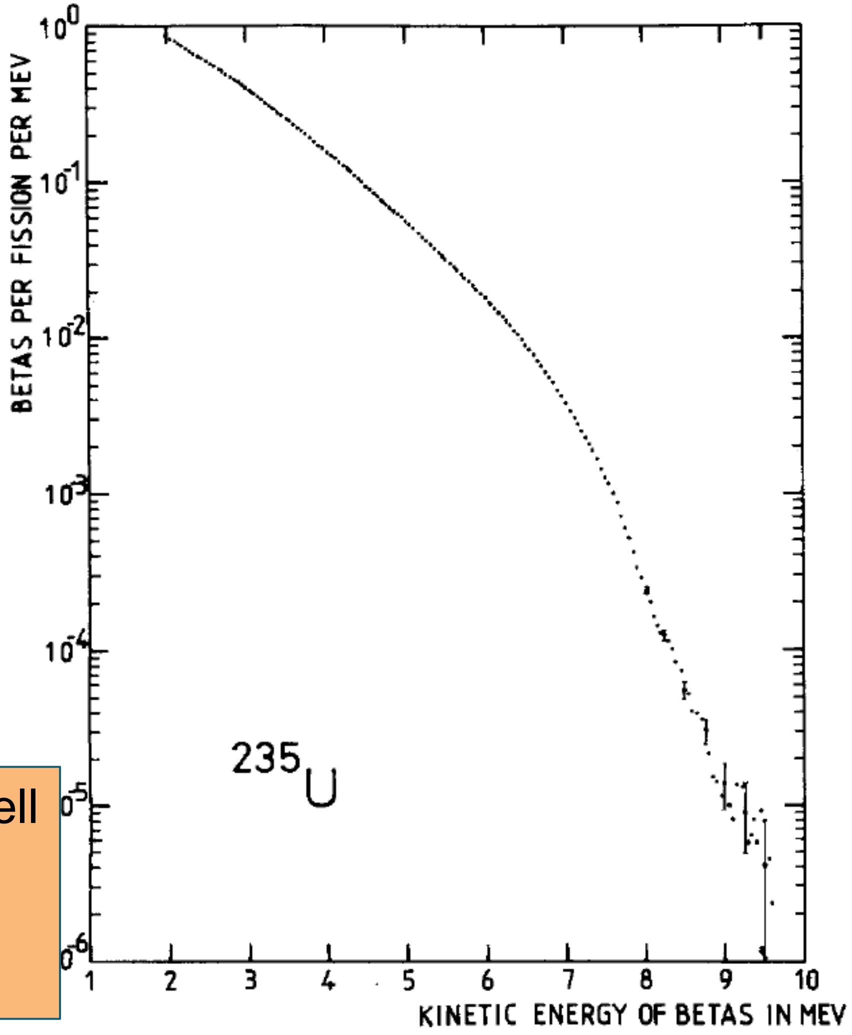


ILL Reactor
$\Phi \sim 10^{14}$ neutrons/cm^2 s

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

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.

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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).

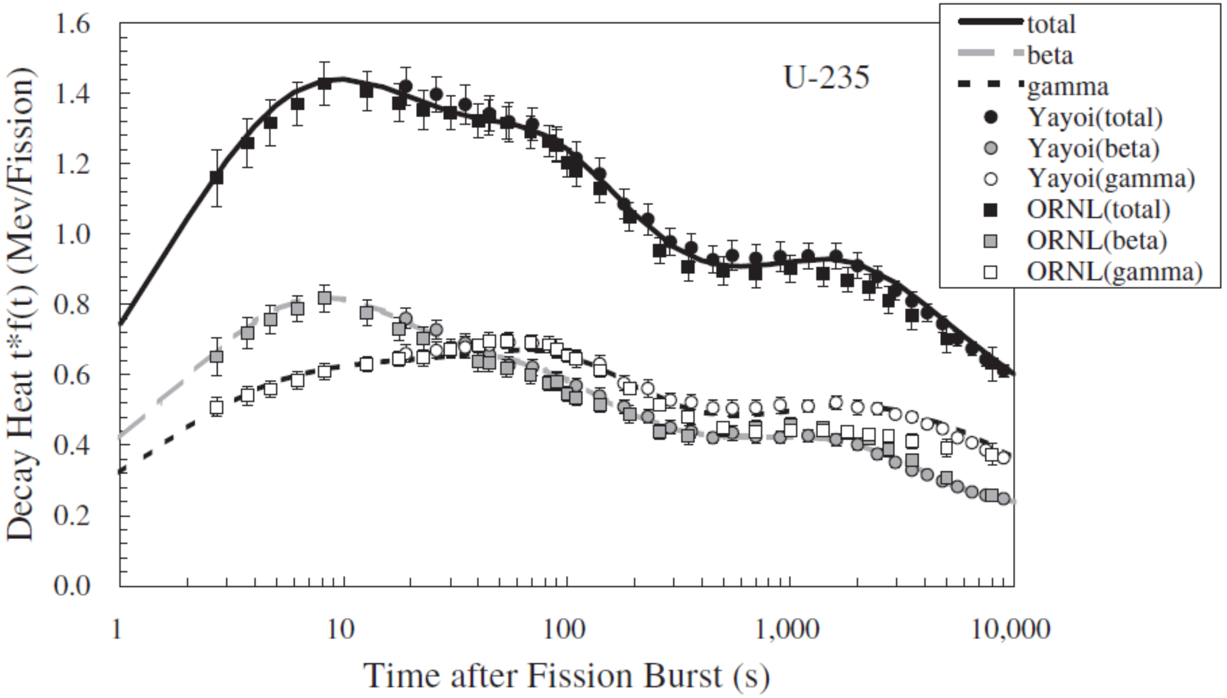
Ratio of cross sections: **647 / 712 = 0.908**.

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

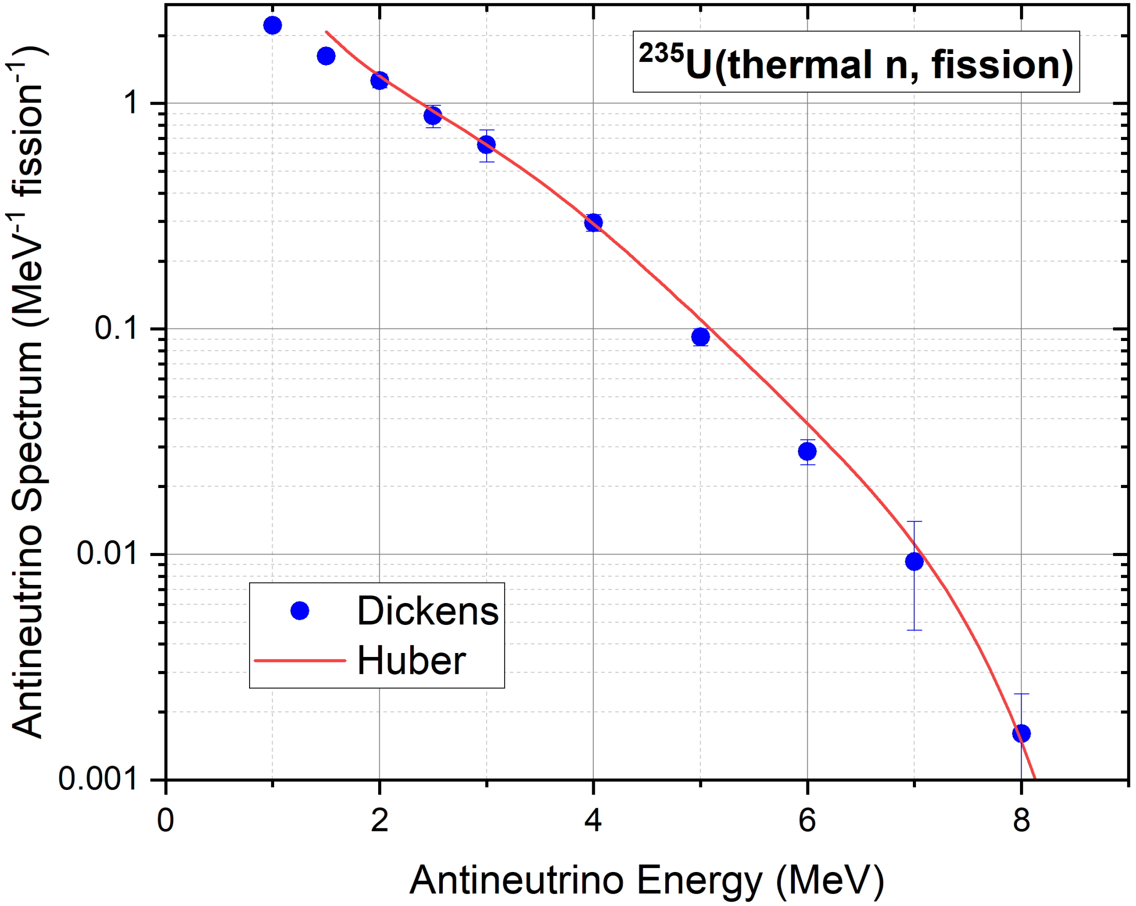
For more details, see Phys. Rev. C **108**, 024617 (2023).

Decay Heat

- Ionizing radiation energy released by the fission products, per unit time as function of time.
- Divided in two components, gammas and betas.



N. Hagura, T. Yoshida, T. Tachibana, Journal of Nuclear Science and Technology, 43:5, 497 (2012)

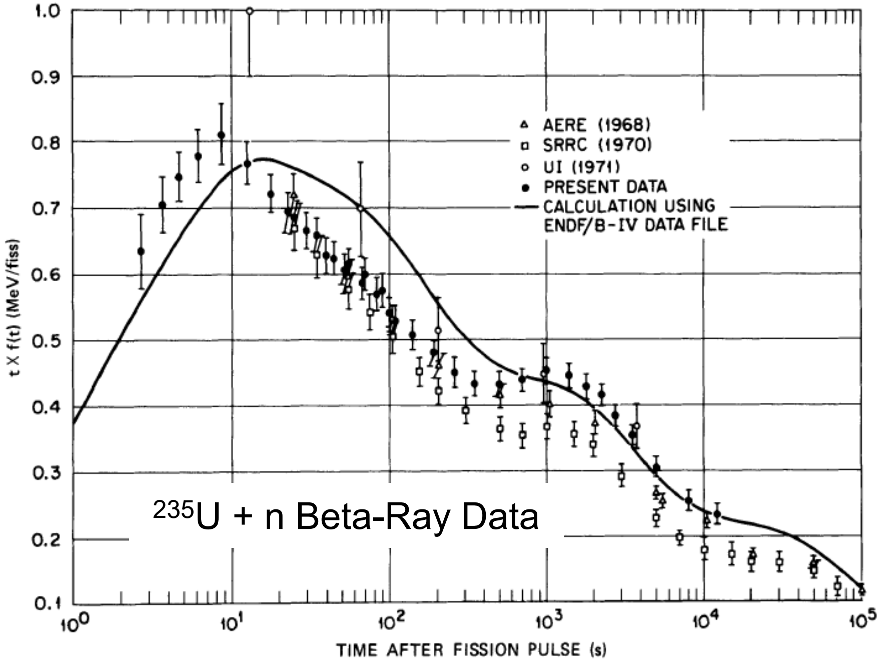


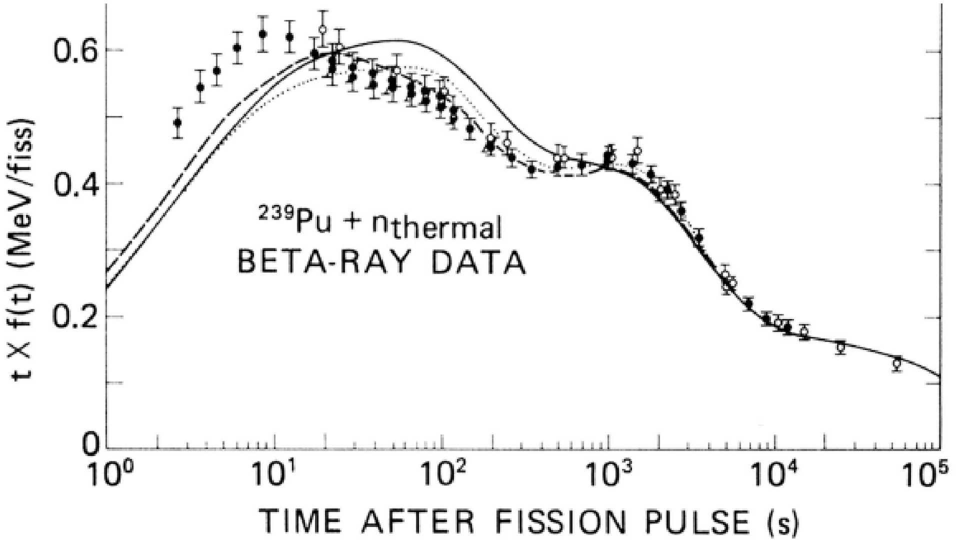
The ORNL ^{235}U electron data was used to obtain the corresponding antineutrino spectrum by J. K. Dickens, Phys. Rev. Lett. **46**, 1061 (1981).

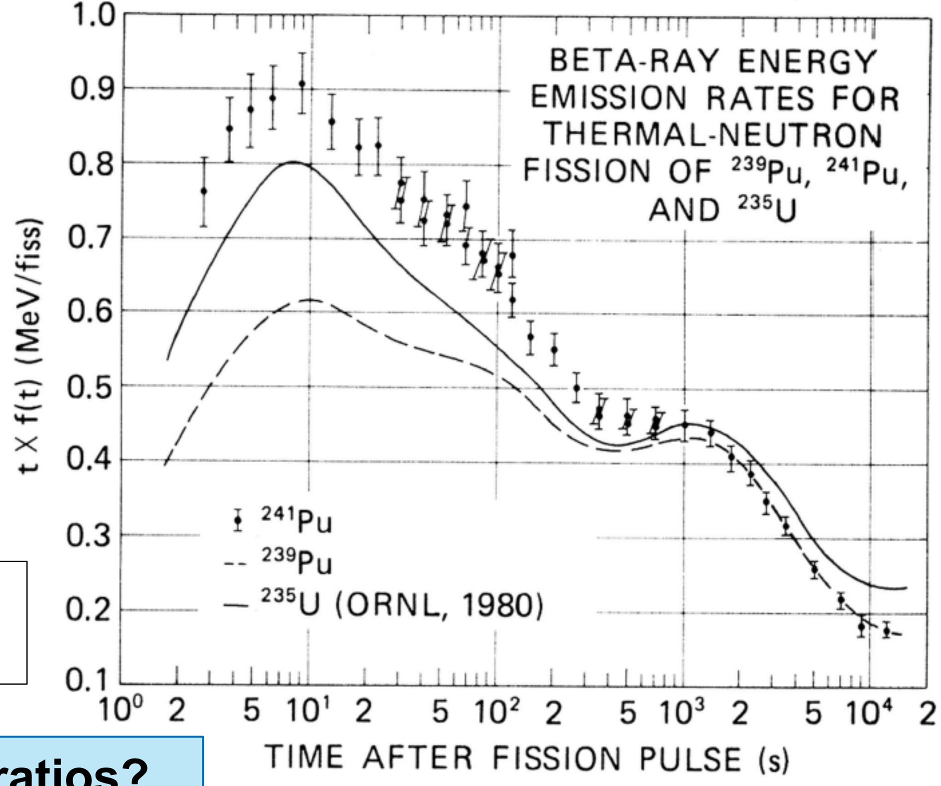
Quite a good agreement with the corresponding Huber spectrum.

Decay Heat

- In 2020 we found in our library the ORNL reports with the gamma and beta spectra data used to obtain the decay heat values.
- Data quality and completeness don't allow to perform a conversion analysis.







J.K. Dickens, T.A. Love, J.W. McConnell, R.W. Peelle, NSE, **78**, 126 (1981)
J.K. Dickens, T.A. Love, J.W. McConnell, R.W. Peelle, NSE, **74**, 106 (1980)

Could we obtain electron spectra ratios?

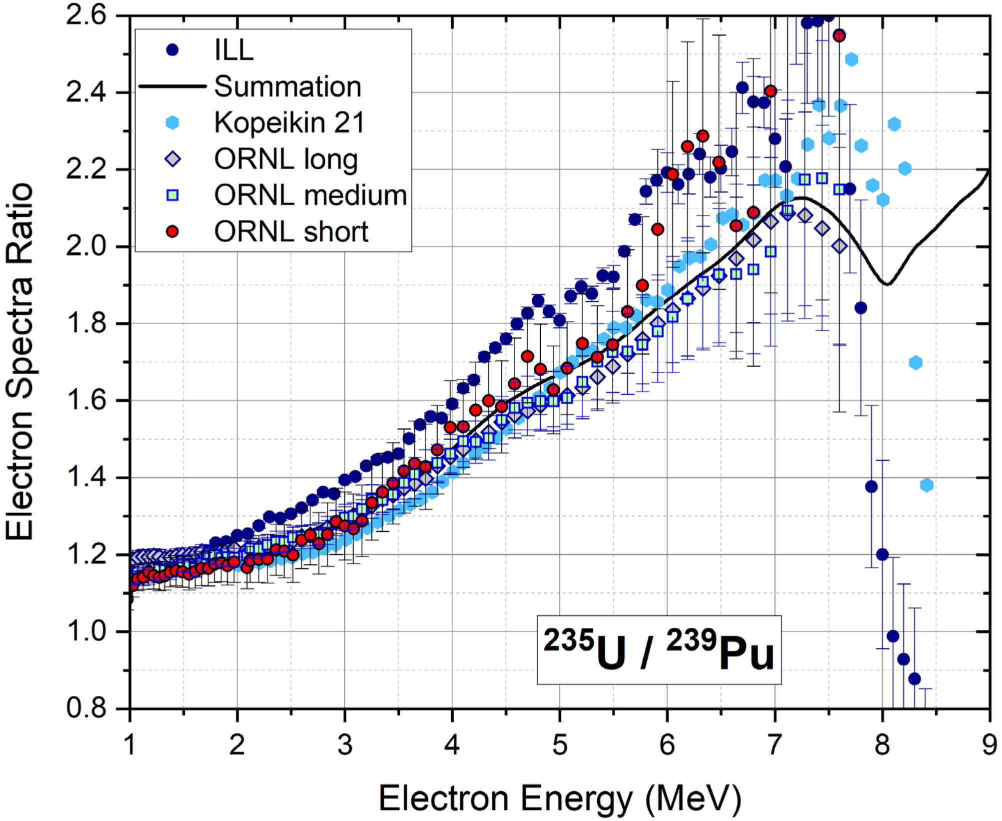
Electron Spectra Ratios

With the assistance of ENDF/B-VIII.1β decay data and JEFF-3.3 fission yields, we are able to obtain ratios of electron spectra in equilibrium.

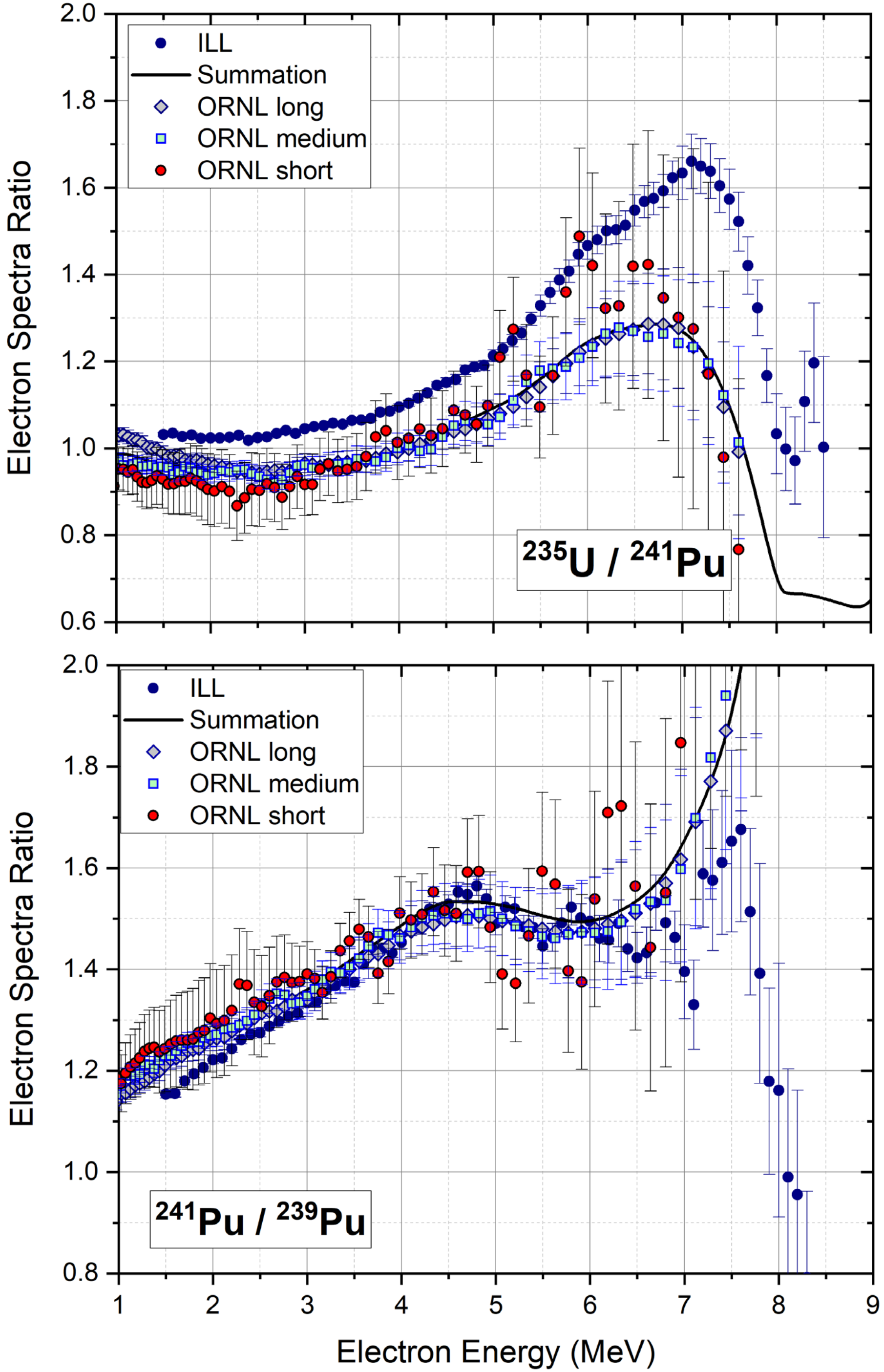
R_{59} agrees better with Kopeikin *et al.*

R_{51} also illustrates issues with ^{235}U normalization.

Behavior of ILL ***R_{59}*** and ***R_{19}*** at high energies disagree with summation, possibly indicating issues in the ^{239}Pu target.



PRC **108**, 024617 (2023).



Can we obtain antineutrino spectra?

We have derived electron spectra in equilibrium using:

$$S^{a}_{eq,i} = S^{a}_{m,i} + \sum (CFY^{a}_{j} - Y^{a}_{j,i}) S_{j},$$

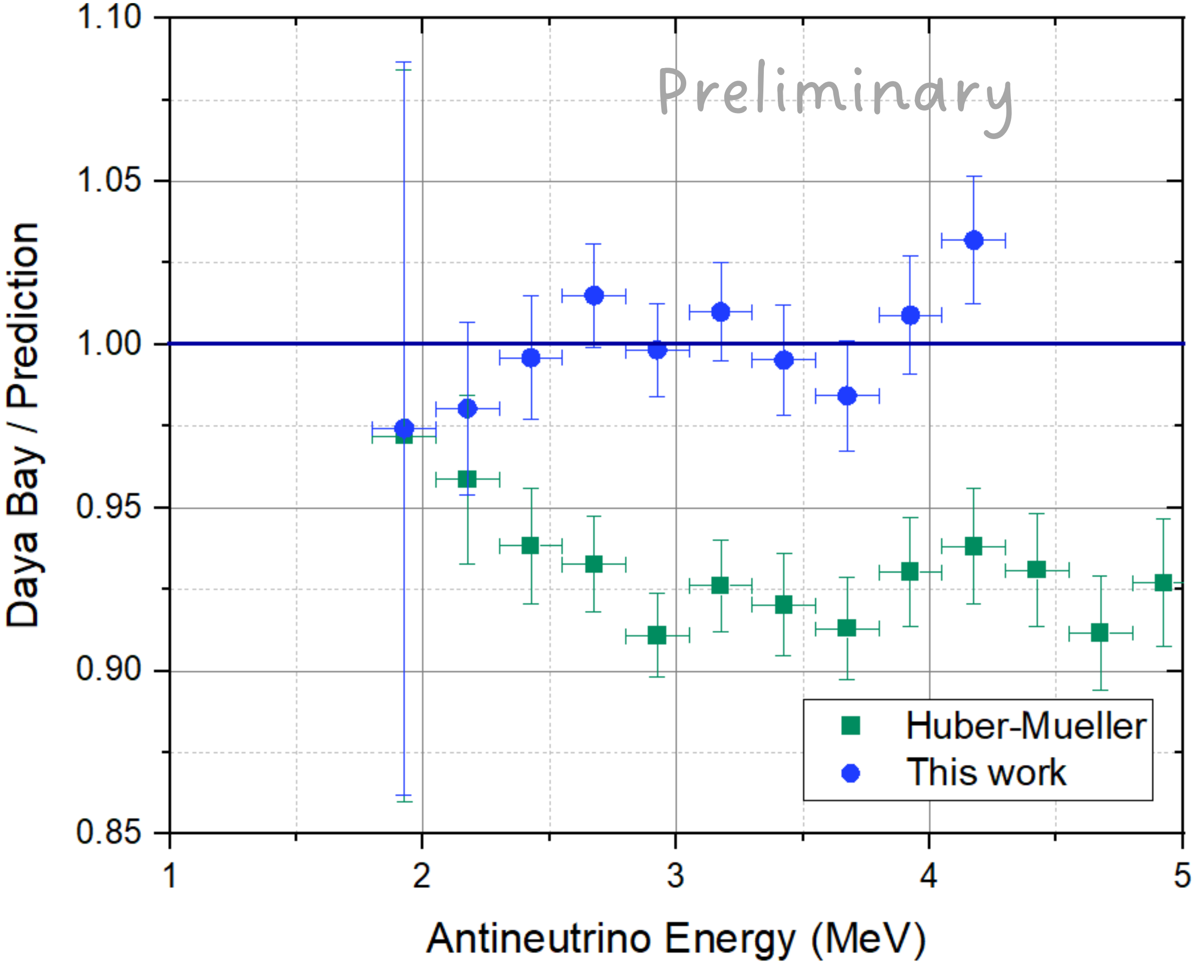
We derived corresponding antineutrinos by:

- renormalize ILL data,
- perform a conversion fit.

Note that:

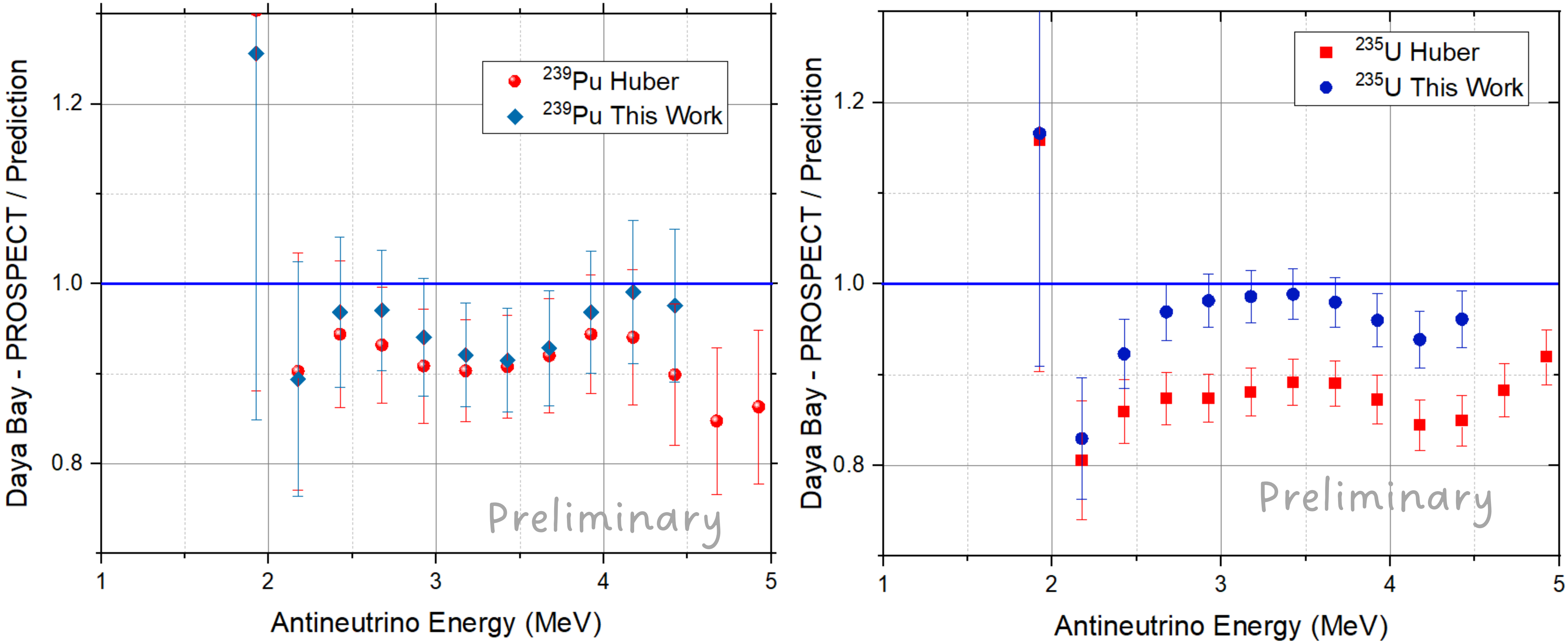
- Plot only contains **DB uncertainties**.
- $\Delta S^{a}_{m,i}$ are not known, so we can only obtain approximate antineutrino spectrum uncertainties.
- ORNL electron spectra data is only reliable up to 4.5 MeV.

DB ref.: F.P. An *et al*., PRL **129**, 041801 (2022).



- The underprediction at the top of the IBD spectrum – the source of the anomaly, goes away.
- Unfortunately, we can't access the energy area relative to the bump.
- Only way forward is a new measurement with high resolution, high signal to noise ratio, and a robust normalization procedure.

Can we obtain antineutrino spectra?



Daya Bay – PROSPECT ref.: F.P. An *et al.*, PRL **128**, 081801 (2022)

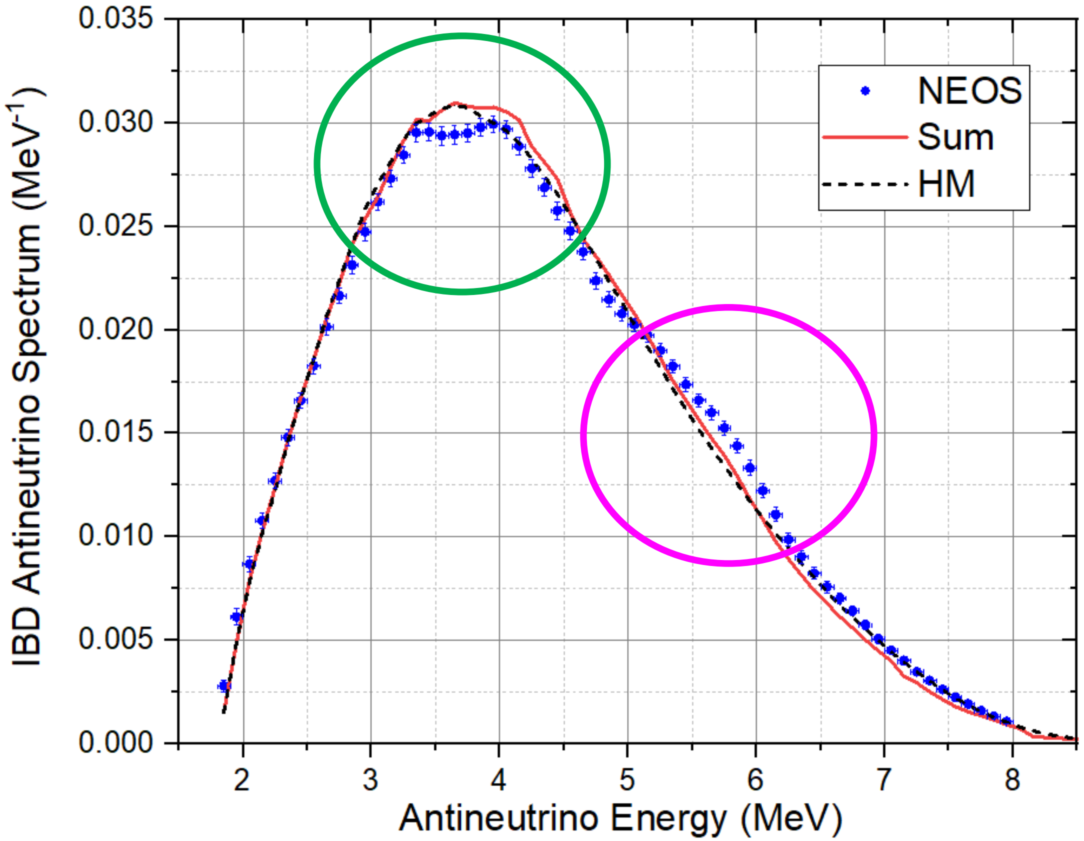
We really need high-quality electron spectra data to accurately account for nuclear reactors antineutrino spectra!!

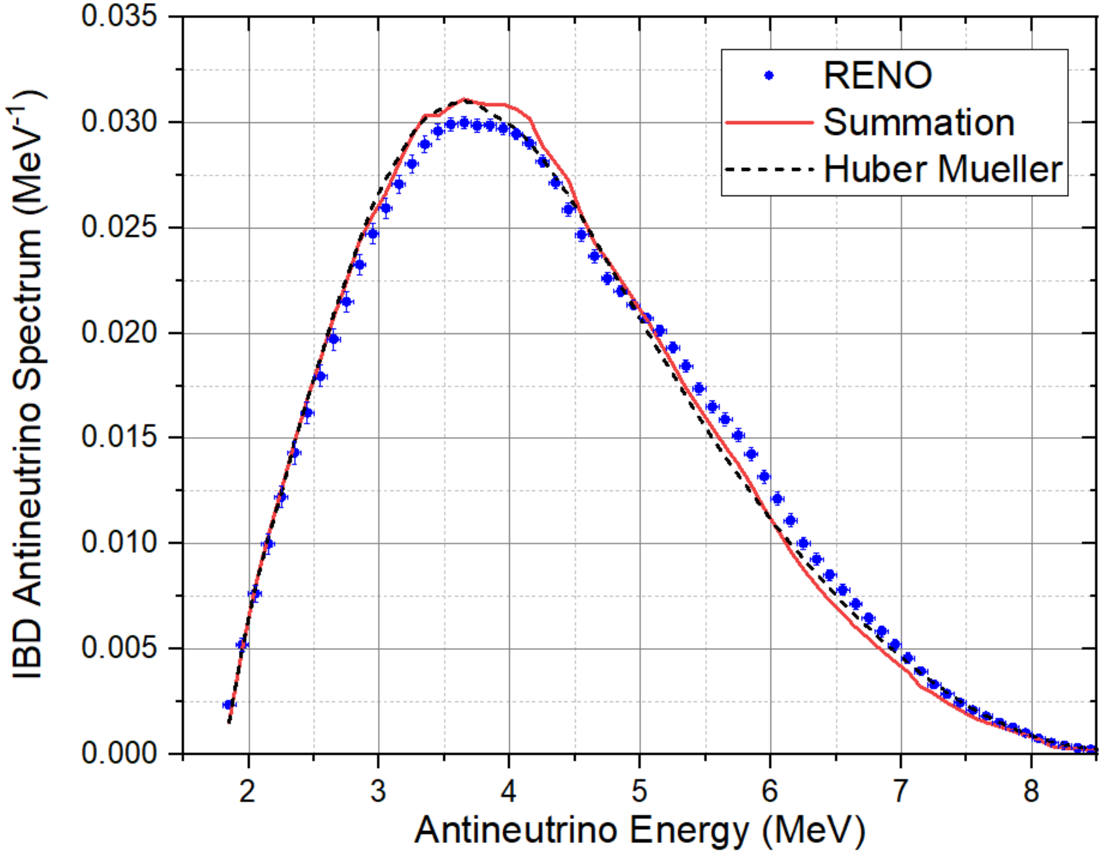
Some Intriguing Observations

2022 NEOS & RENO Spectra

Z. Atif *et al.*, PRD **105**, L111101 (2022).

Hanbit Nuclear Power Plant,
6 reactors with 2.8 GW_{th} maximum power each.





180 days of data, 24 m from one reactor,

f_{235}=0.655, f_{238}=0.072, f_{239}=0.235, f_{241}=0.038.

Possibly the highest resolution and statistics of all short baseline experiments to date.

Also, the highest f_{235} of all power reactor experiments.

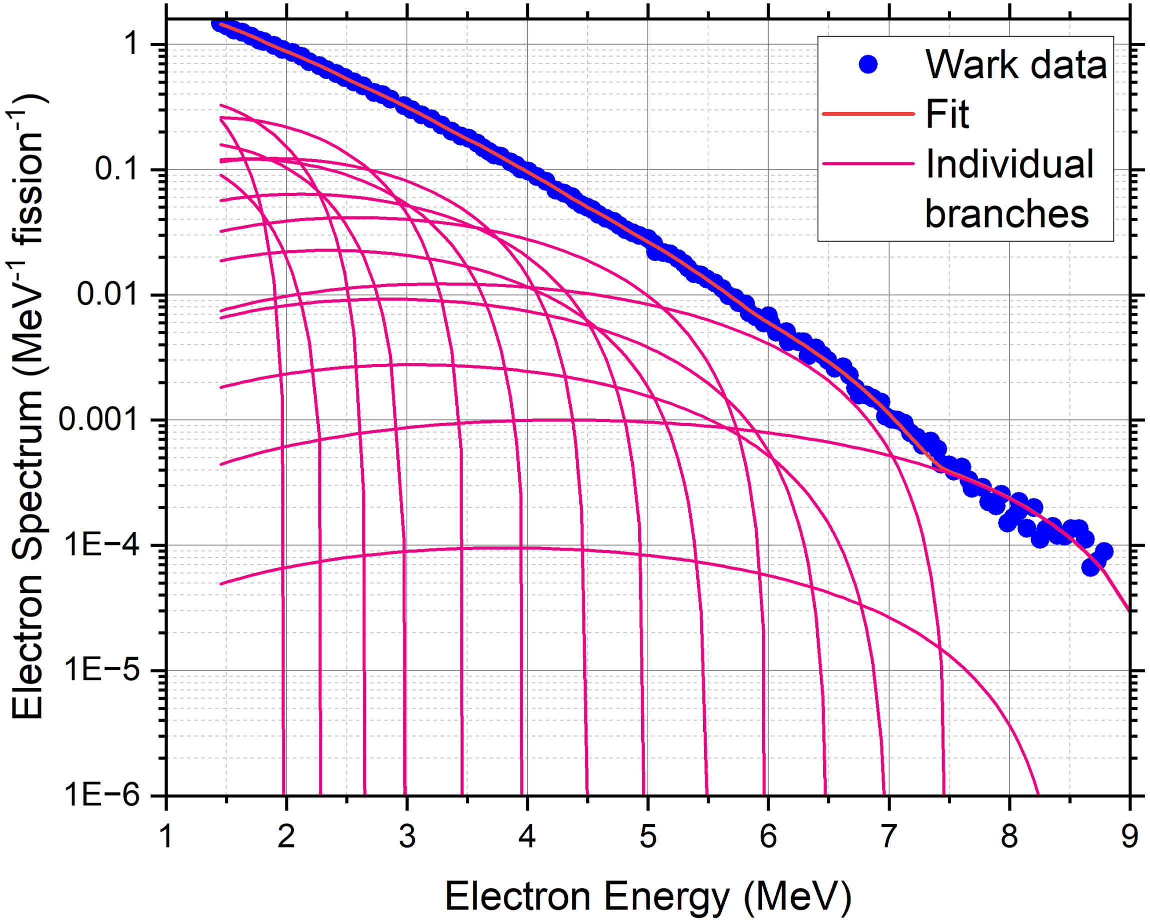
2509 days of data, 419 m flux-weighted baseline.
f_{235}=0.571, f_{238}=0.073, f_{239}=0.300, f_{241}=0.056.

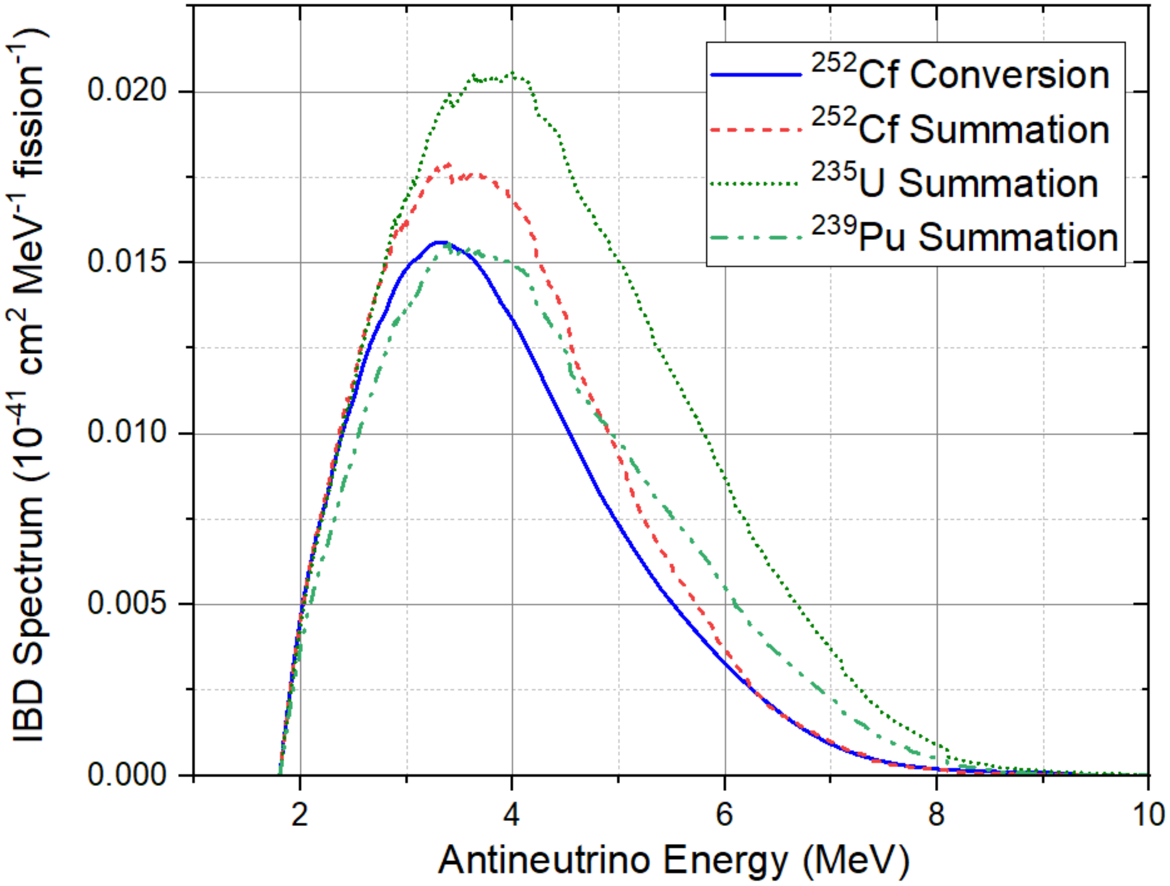
Very pronounced bump!

Double peak at the top of NEOS?

^{252}Cf IBD antineutrino spectrum

The β spectrum following fission of ^{252}Cf, David L. Wark, PhD Thesis, Caltech (1987).



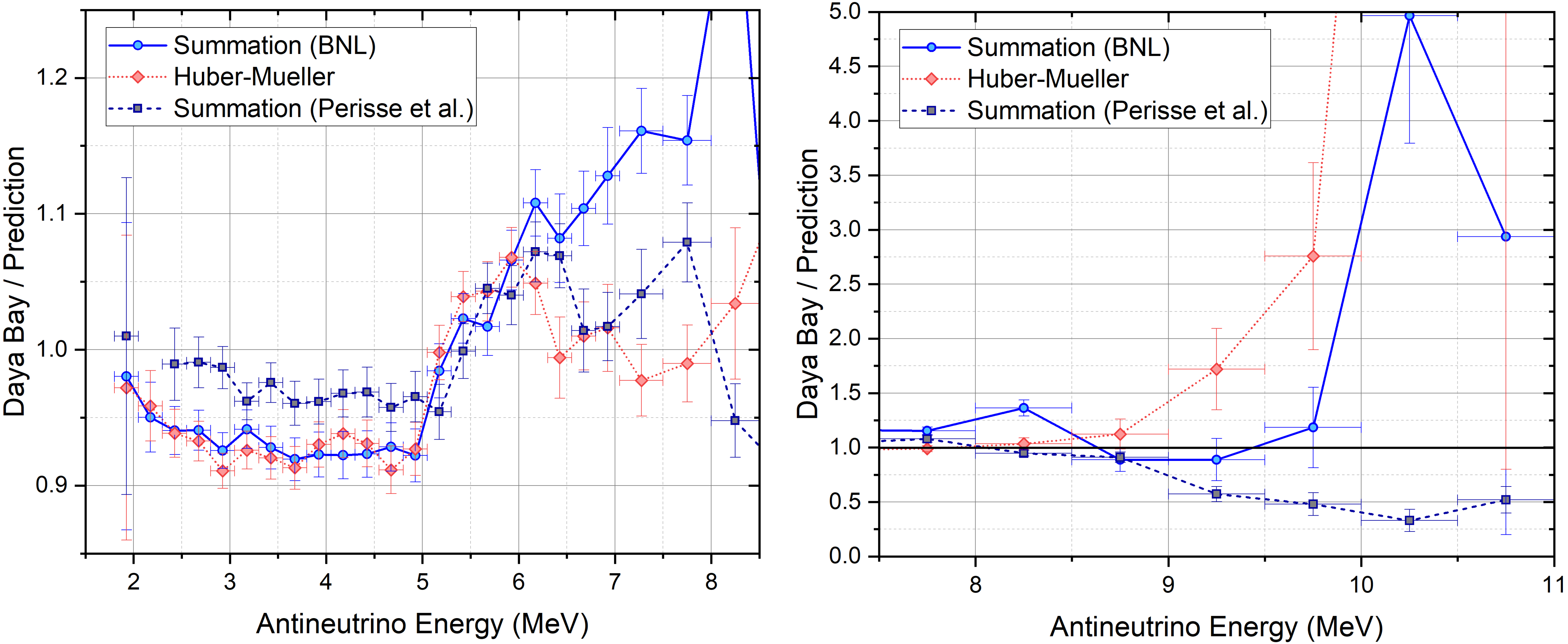


- ☐ A conversion fit to Wark's data shows **no bump**.
- ☐ Our summation calculations **don't produce a bump** either.

Fun with Summation!

A very recent summation calculation

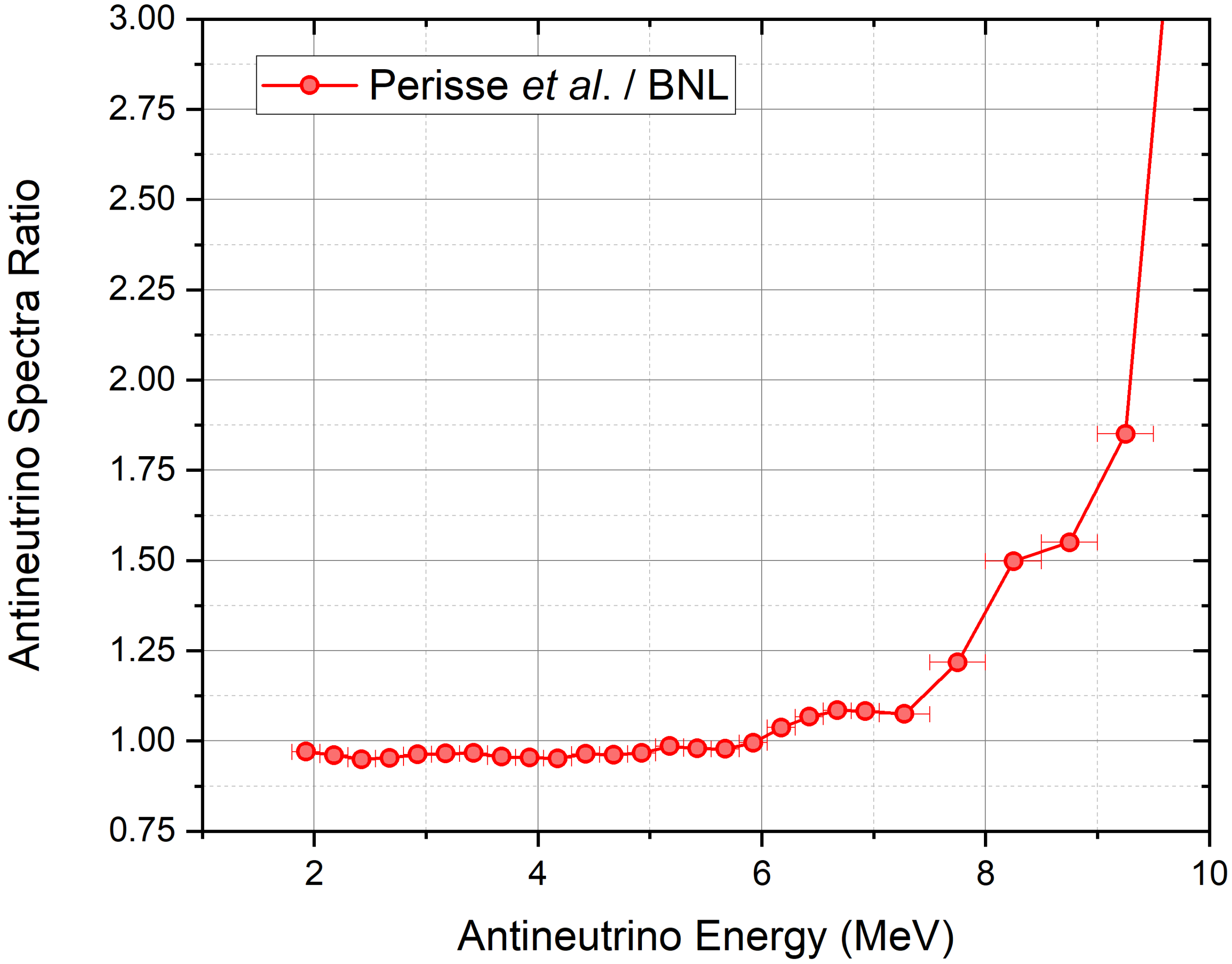
L. Perisse *et al.*, PRC **108**, 055501 (2023)

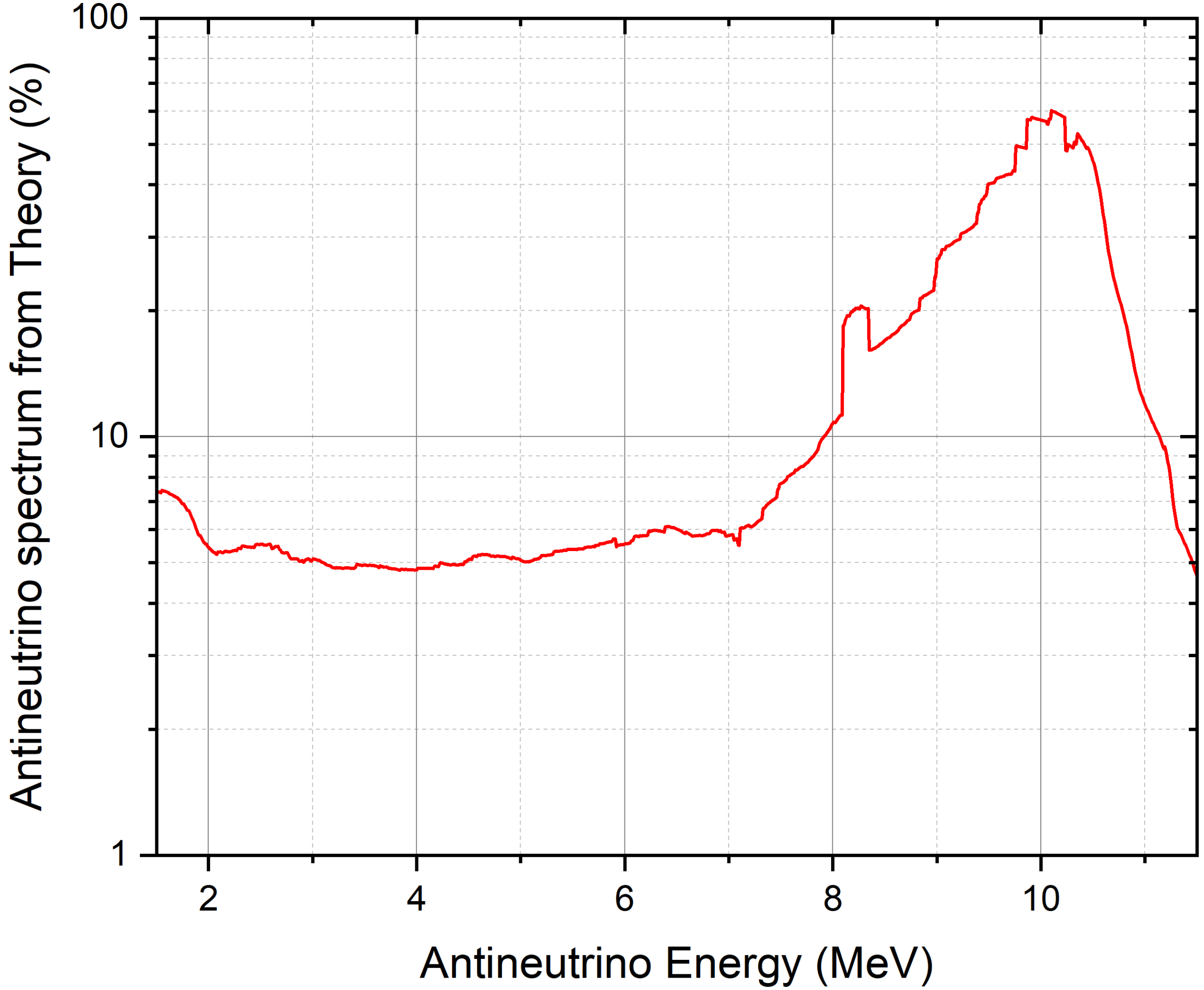


Perisse *et al.* see a **smaller anomaly** and **'broader' bump**, also a consistently **over prediction** at high energies.
Note: only DB uncertainties are plotted.

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



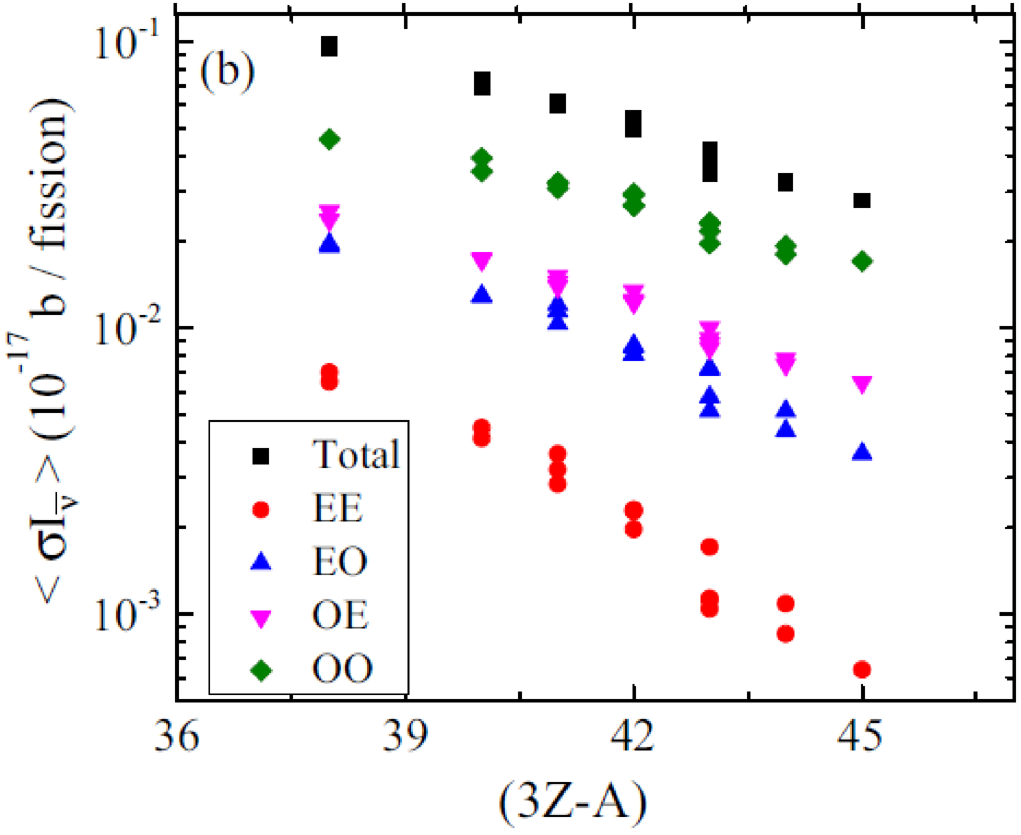


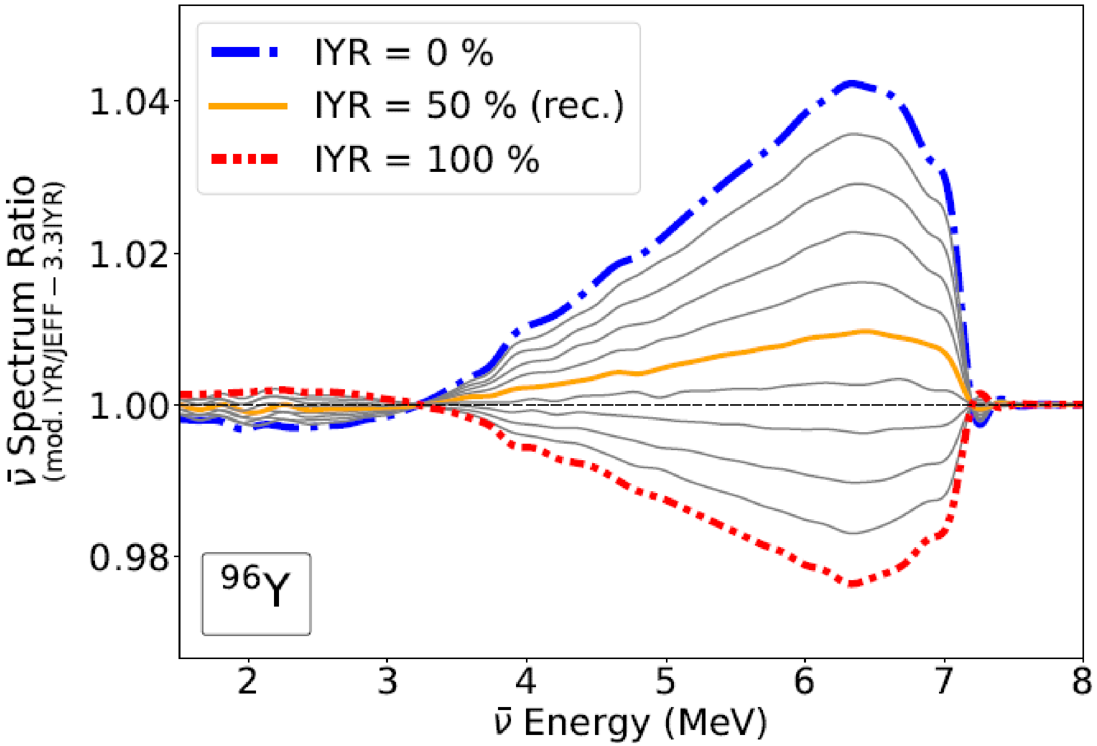
5%-70% of the antineutrino spectrum for the Daya Bay fission fractions comes theoretical calculations due to unknown or incomplete decay schemes. That may explain the difference between the two summation sets.

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.

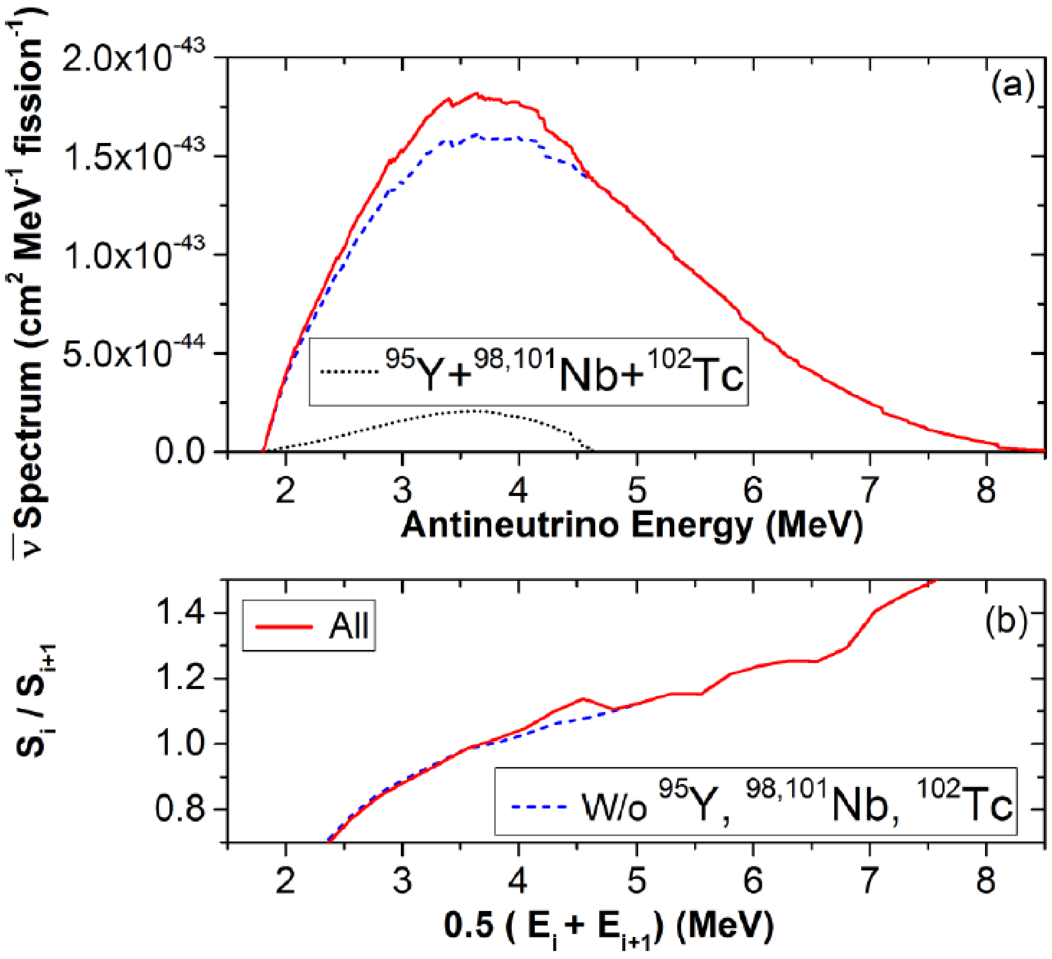
^{96}Y is the most representative case, with an isomeric ratio of 50% from ^{232}Th(p,fission). The thermal neutron one is likely smaller, and impacts our understanding of the 'bump' origin (A. Mattera to be published).

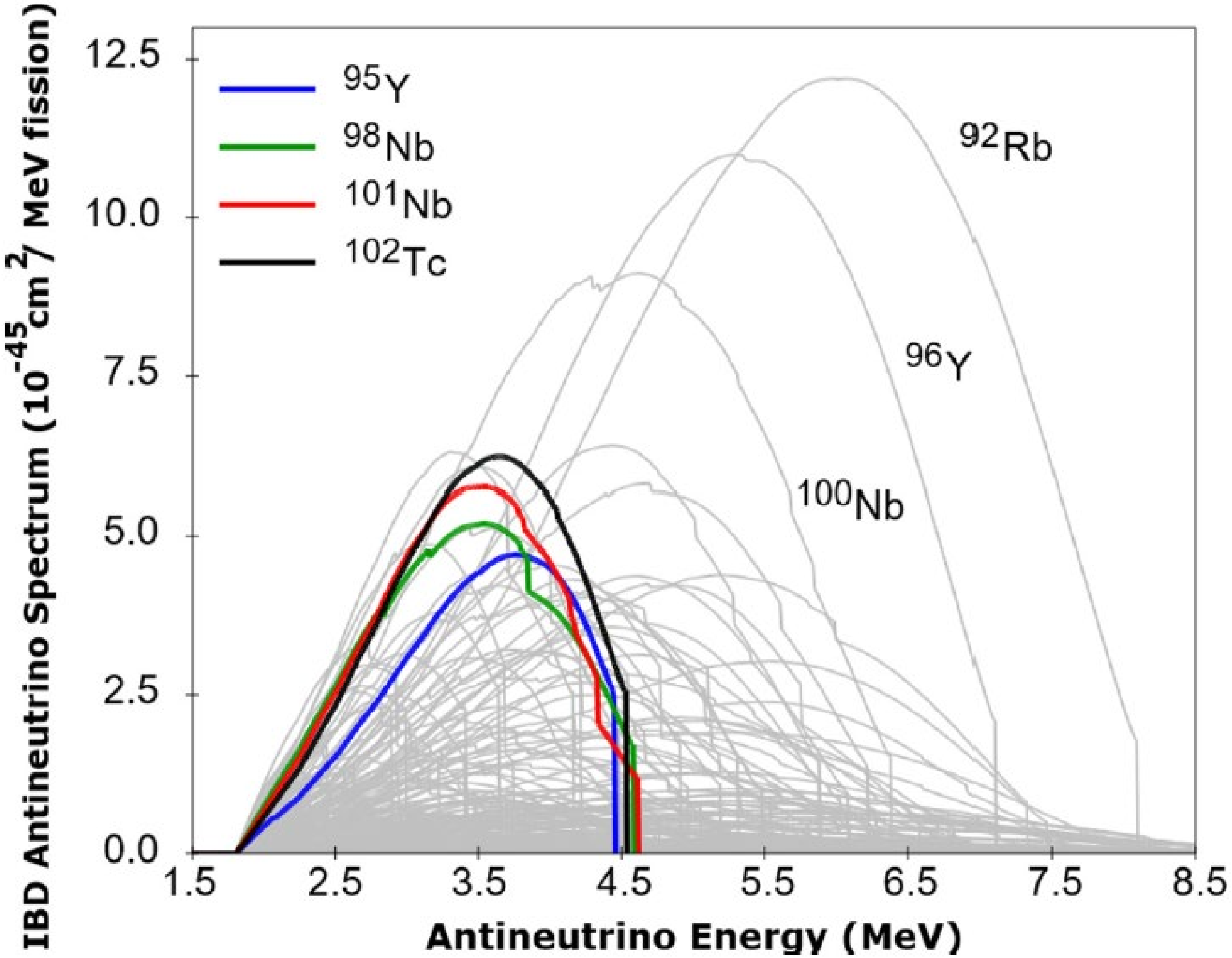




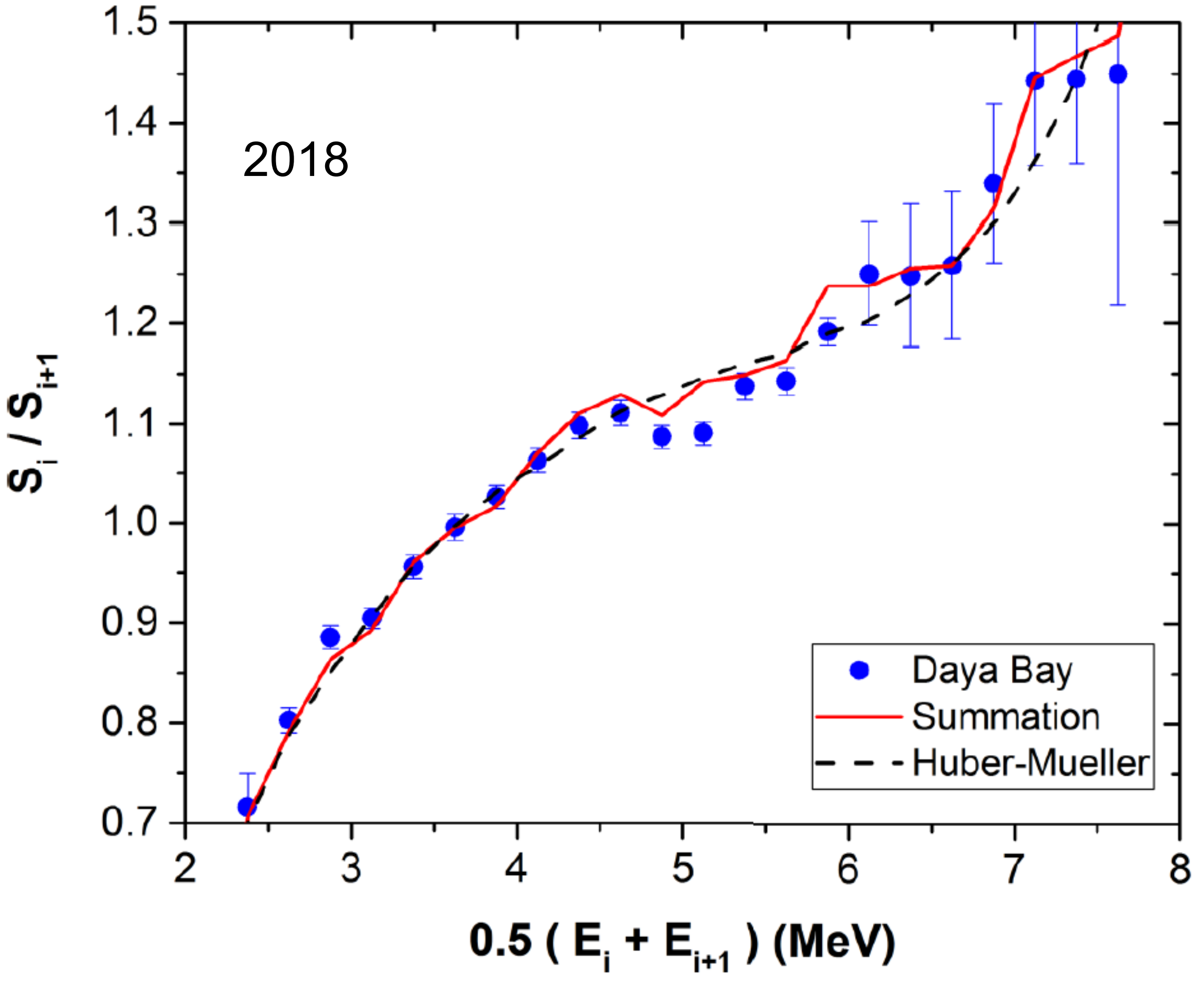
Individual fission products signature – aka fine structure

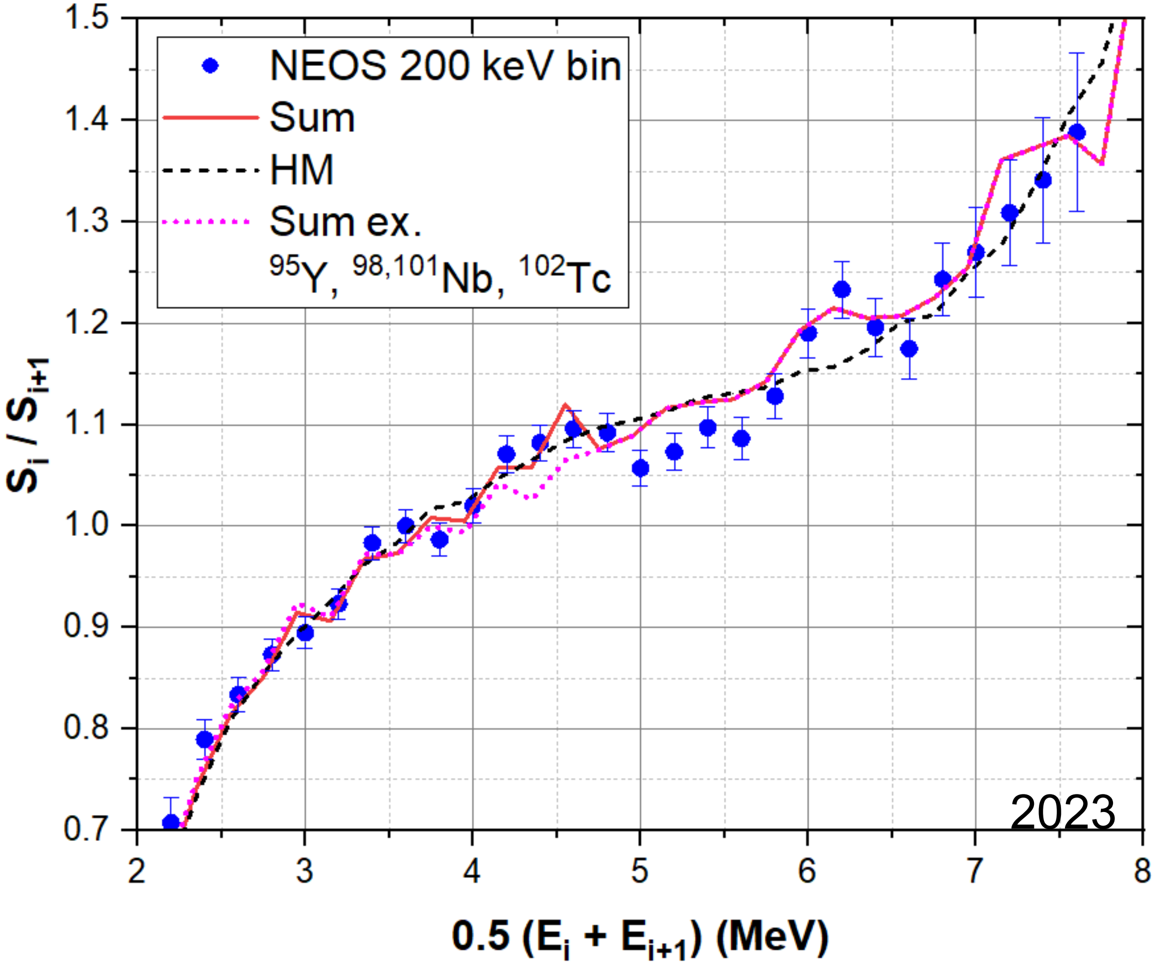
Phys. Rev. C **98**, 014323 (2018)





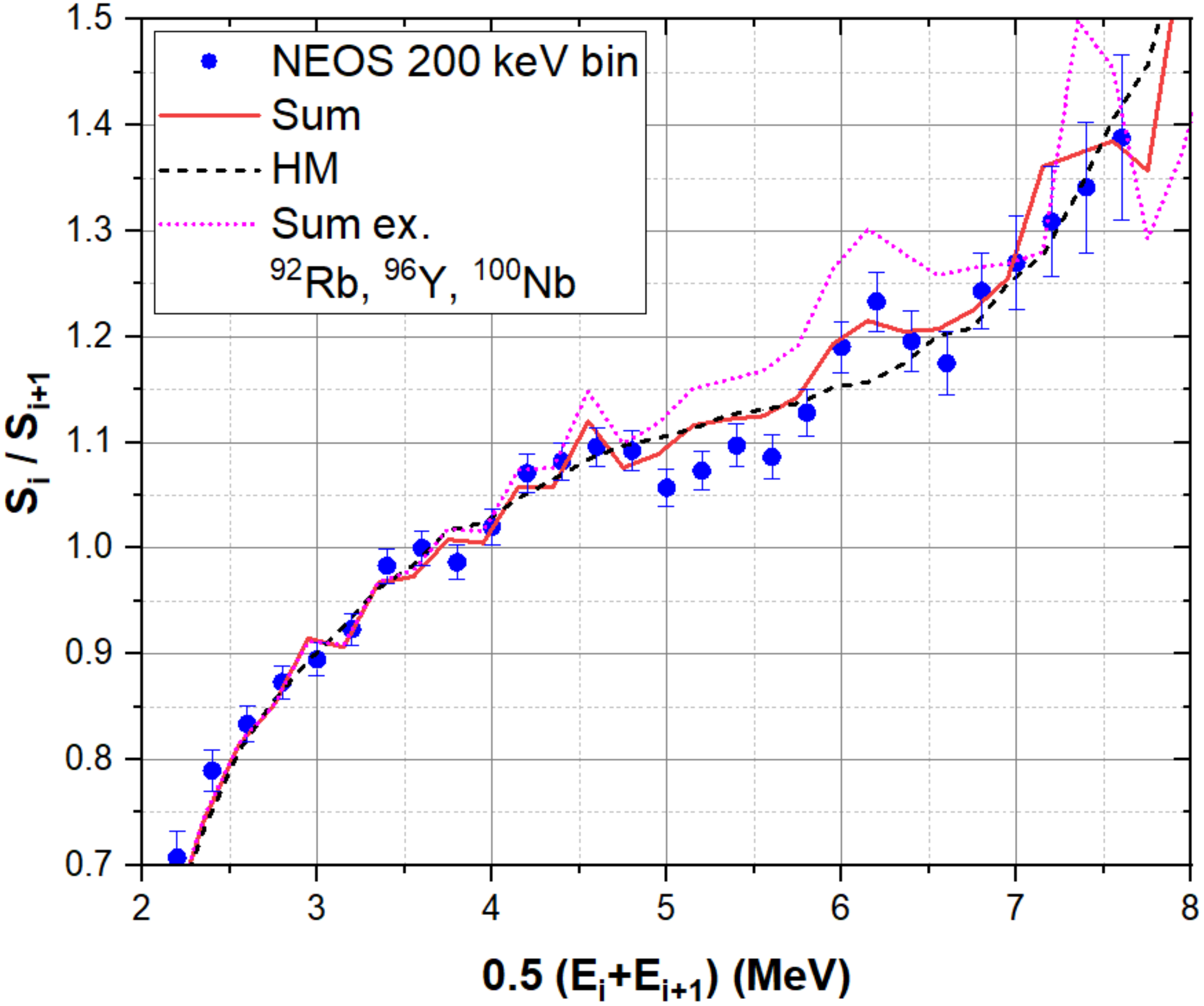
Fine structure, Daya Bay 2016 & NEOS 2022

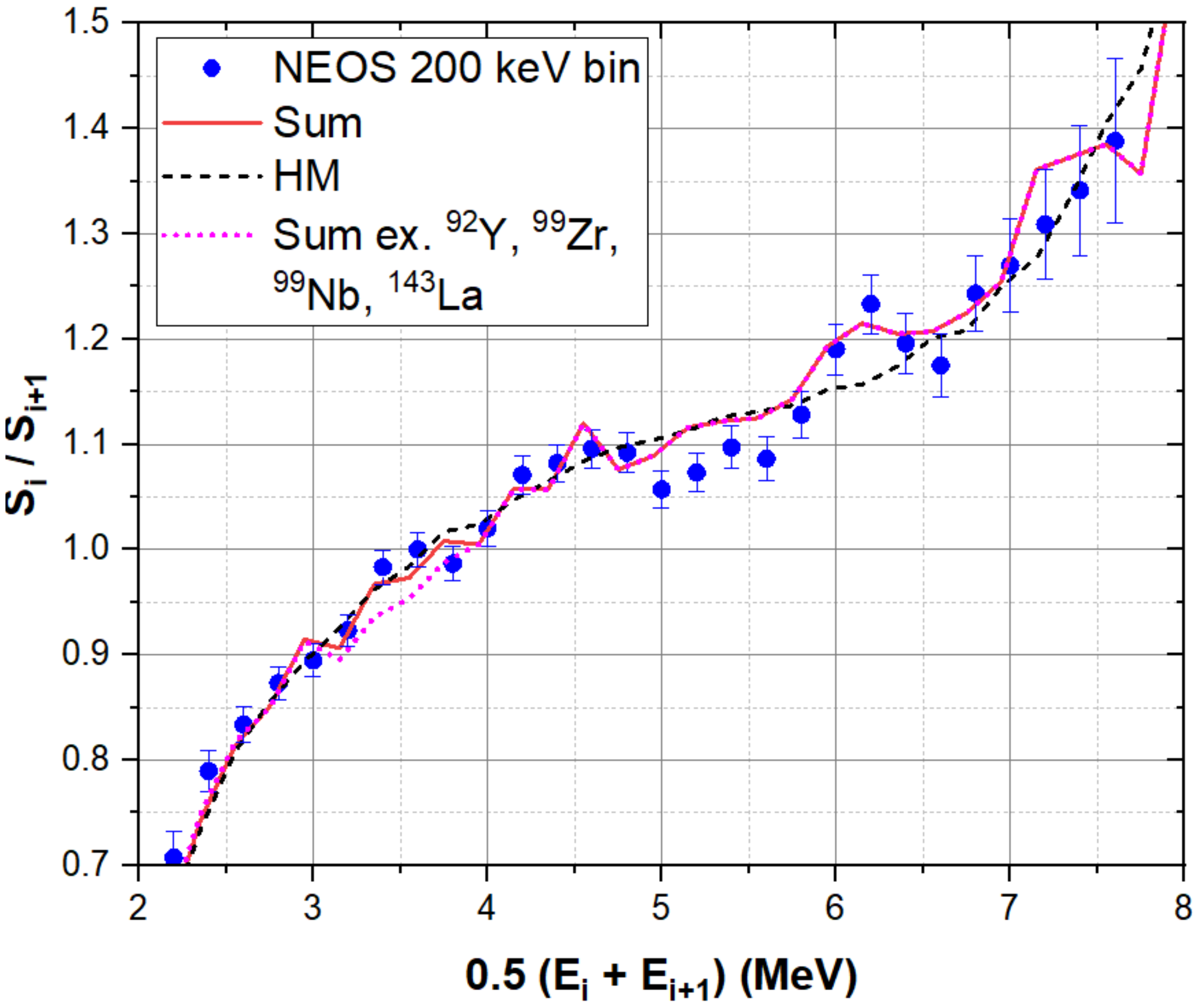




Daya Bay antineutrino spectrum data from F.P. An *et al.*, PRL **116**, 061801 (2016)

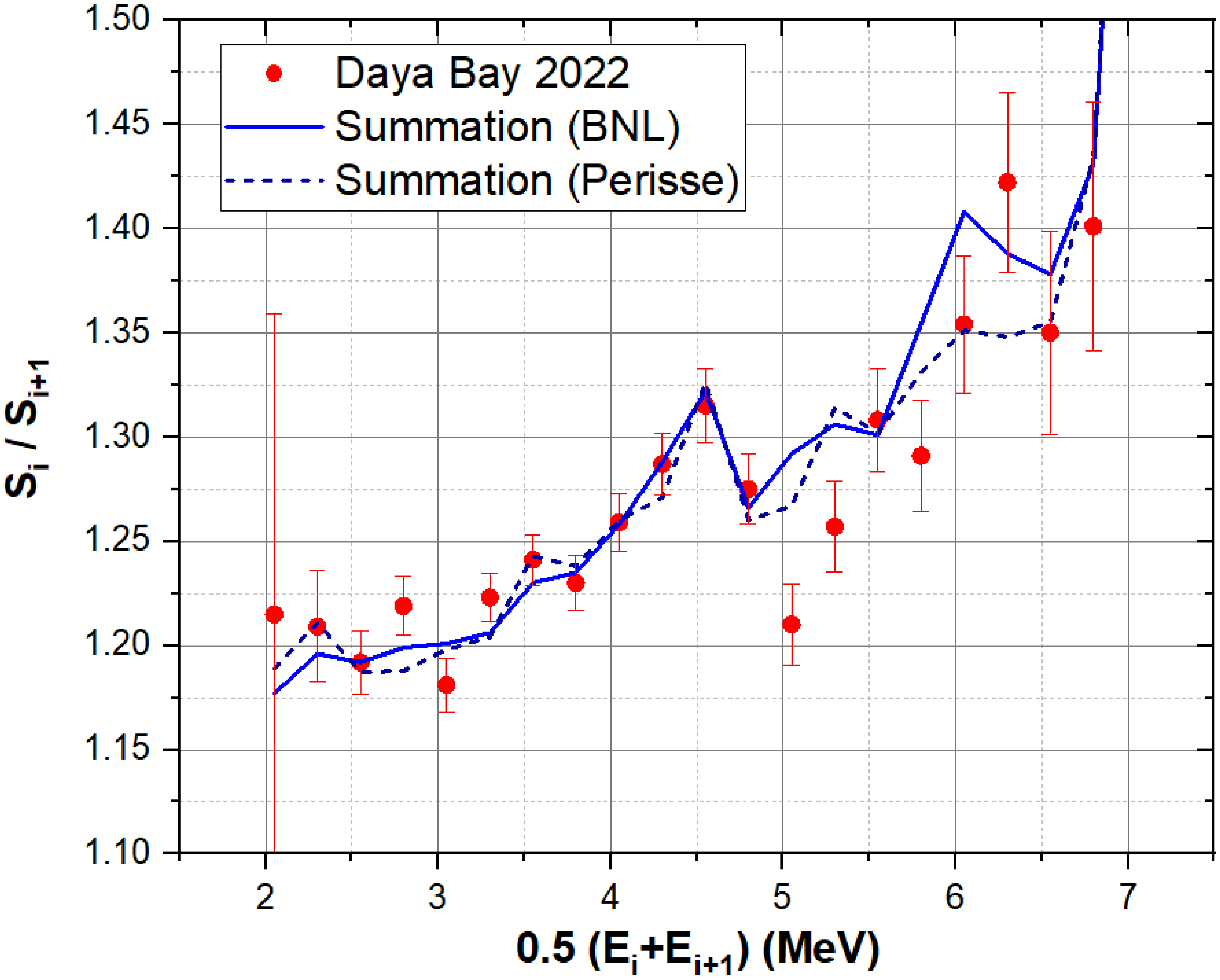
Fine structure, some more nuclides





Antineutrino spectrum data from F.P. An *et al.*, PRL **116**, 061801 (2016)

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!

Summary and Outlook

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.

- ❑ The ILL's $\boldsymbol{R_{59}}$ and $\boldsymbol{R_{19}}$ values at electron energies higher than 7.5 MeV is disquieting. Possibly indicating a non-negligible ^{235}U or ^{241}Pu amount in the ^{239}Pu target?

- ❑ Renormalization of the ILL spectra data with the ORNL ones lead to a considerable better agreement with Daya Bay IBD spectrum, **eliminating the RAA**.

- ❑ 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.

- ❑ No bump observed in the ^{252}Cf IBD conversion spectrum, need to remeasure this spectrum.

- ❑ We need to improve the data behind summation calculations, nearly all of this data have been taken with other applications in mind.

- ❑ Eagerly looking forward to measurements with much higher resolution antineutrino detectors near HEU and LEU reactors, JUNO-TAO, PROSPECT II, SuperChooz, CLOUD.

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GRAZIE!!