Reactor Antineutrino Flux Predictions - Nuclear Data

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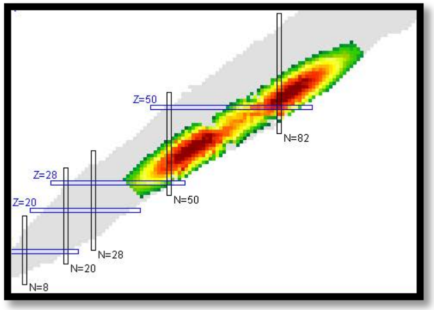
BROOKHAVEN NATIONAL LABORATORY

a passion for discovery

U.S. DEPARTMENT OF ENERGY | Office of Science

Summation Method

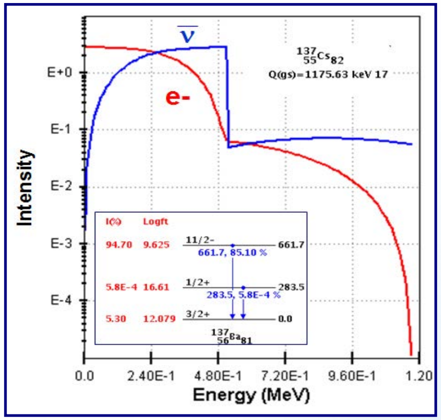
First calculation of this type performed by P. Vogel *et al.* in 1981 using ENDF/B-V.



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

Cumulative Fission Yields

Individual Spectra



We have used:

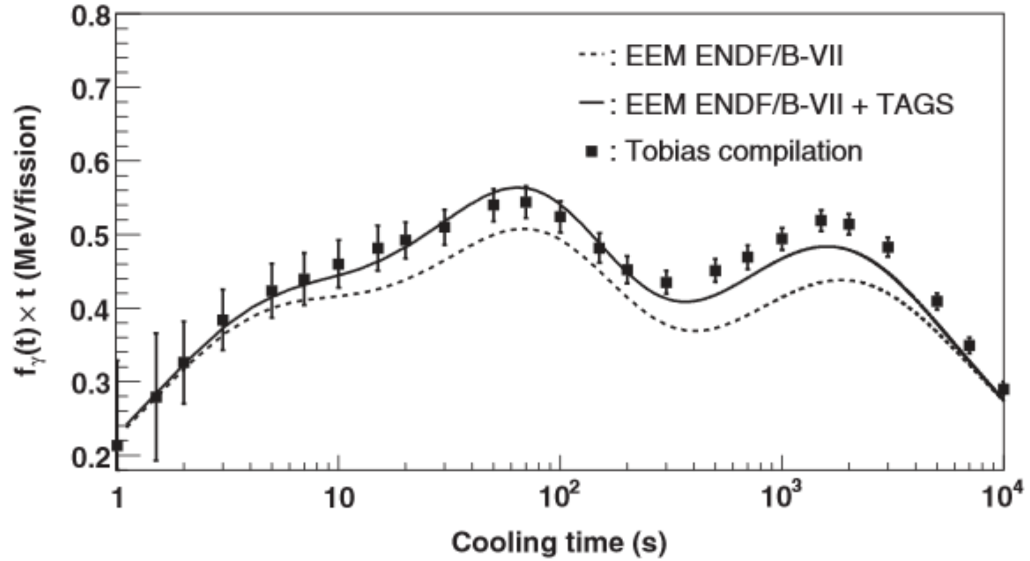
ENDF/B-VIII.0 Decay Data together with the JEFF-3.1.1 Fission Yields

JEFF-3.1.1 FY implicit nuclear structure data fairly compatible with ENDF/B-VIII.0

ENDF/B-VIII.0 includes the latest TAGS data relevant to antineutrino applications. Simplified versions of the library available on request.

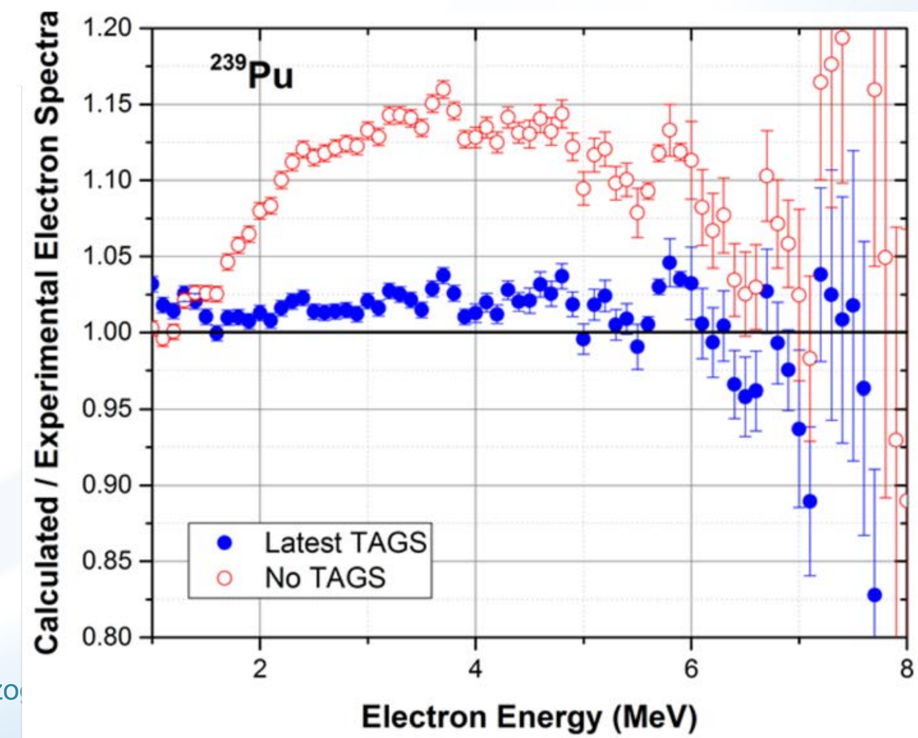
TAGS data

The use of mean gamma and beta energies obtained from TAGS data has improved the agreement with decay heat data following the fission of actinide nuclides.

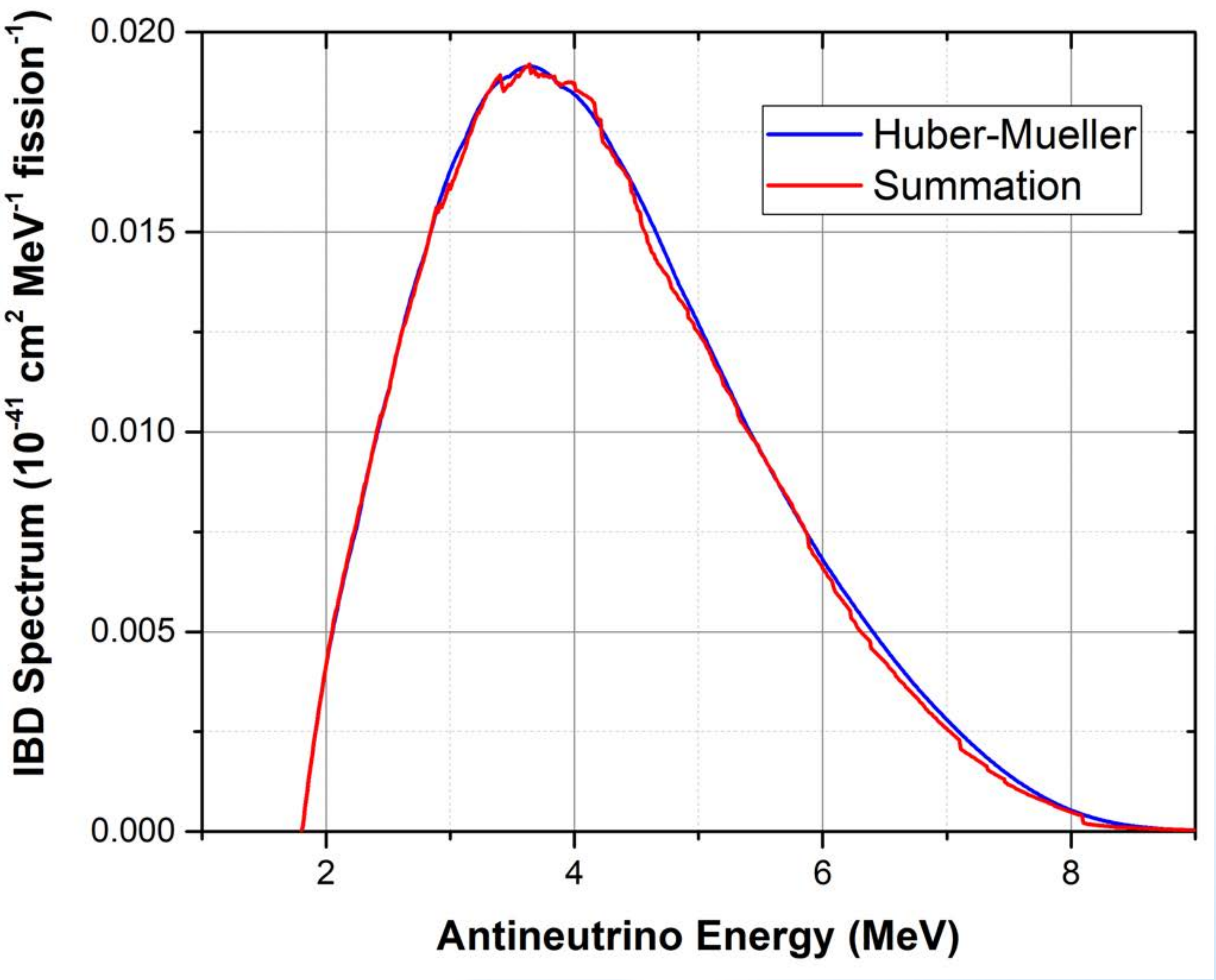


A. Algora et al, PRL 105, 202501 (2010).

Using beta-minus intensities obtained from TAGS data also improves the calculation of electron spectra

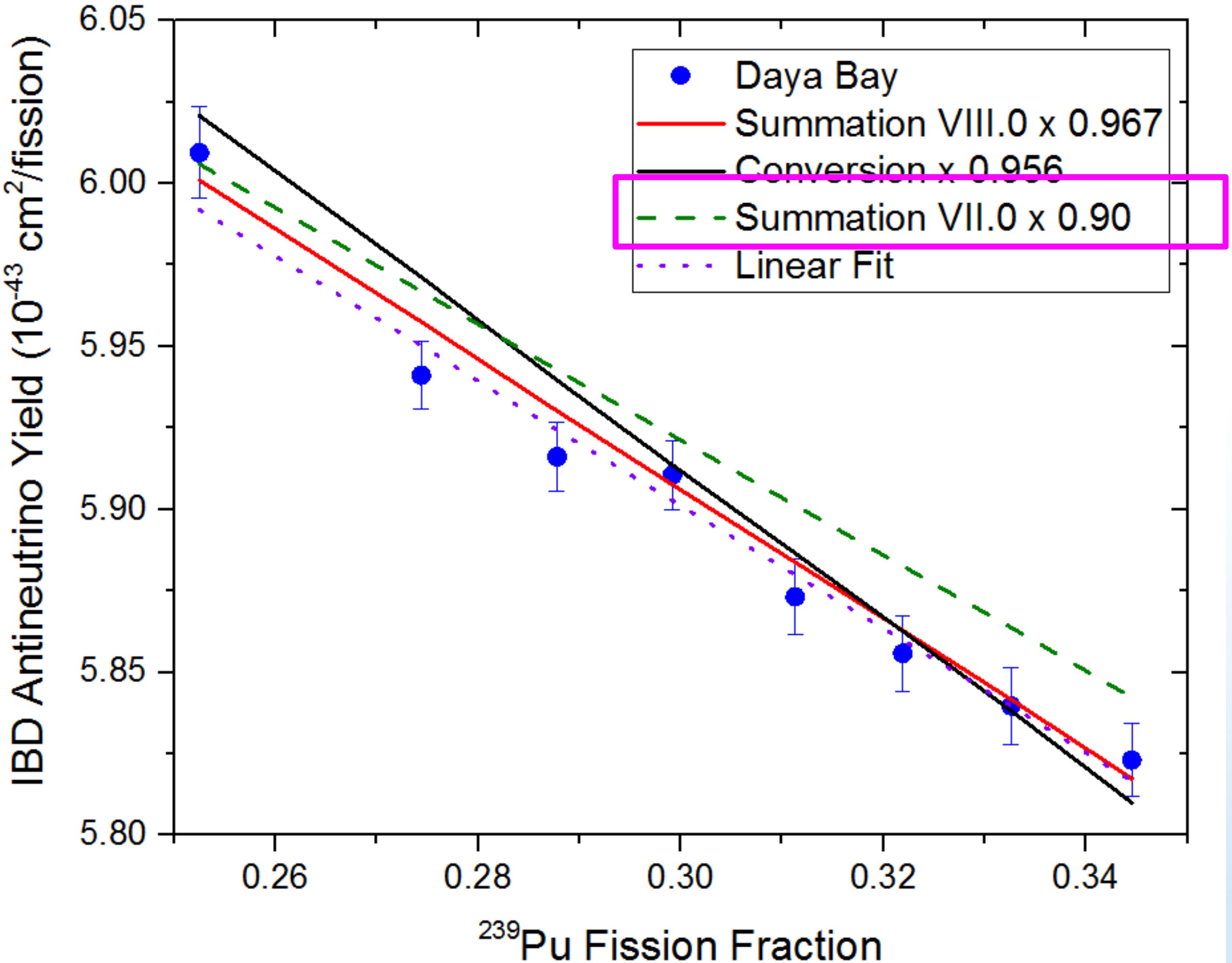


Comparison with Huber-Mueller



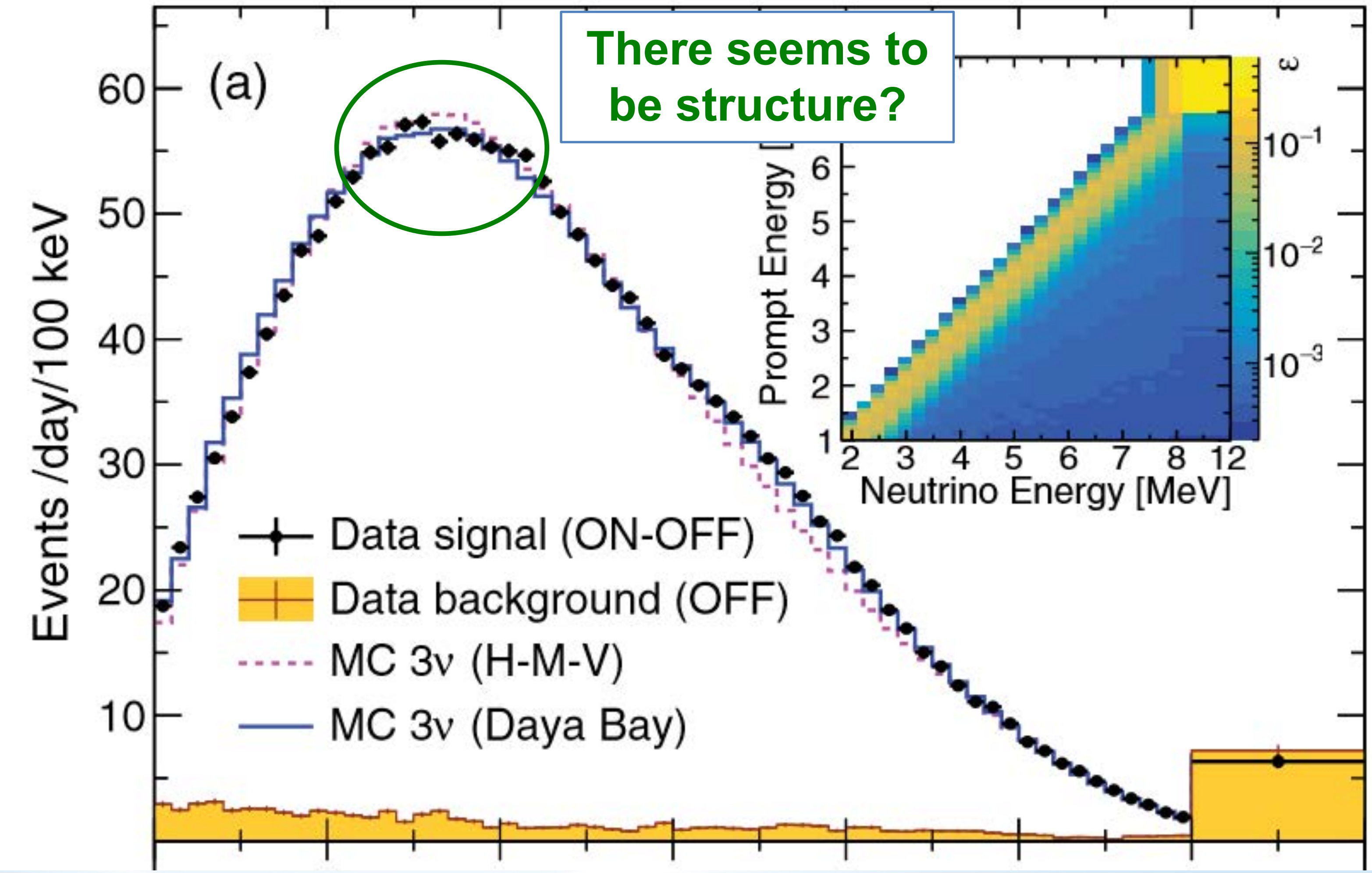
The very small differences with HM represent most of this talk!

A closer look at the evolution data



Fine Structure: individual nuclides effect

NEOS data, 30 m from a power reactor

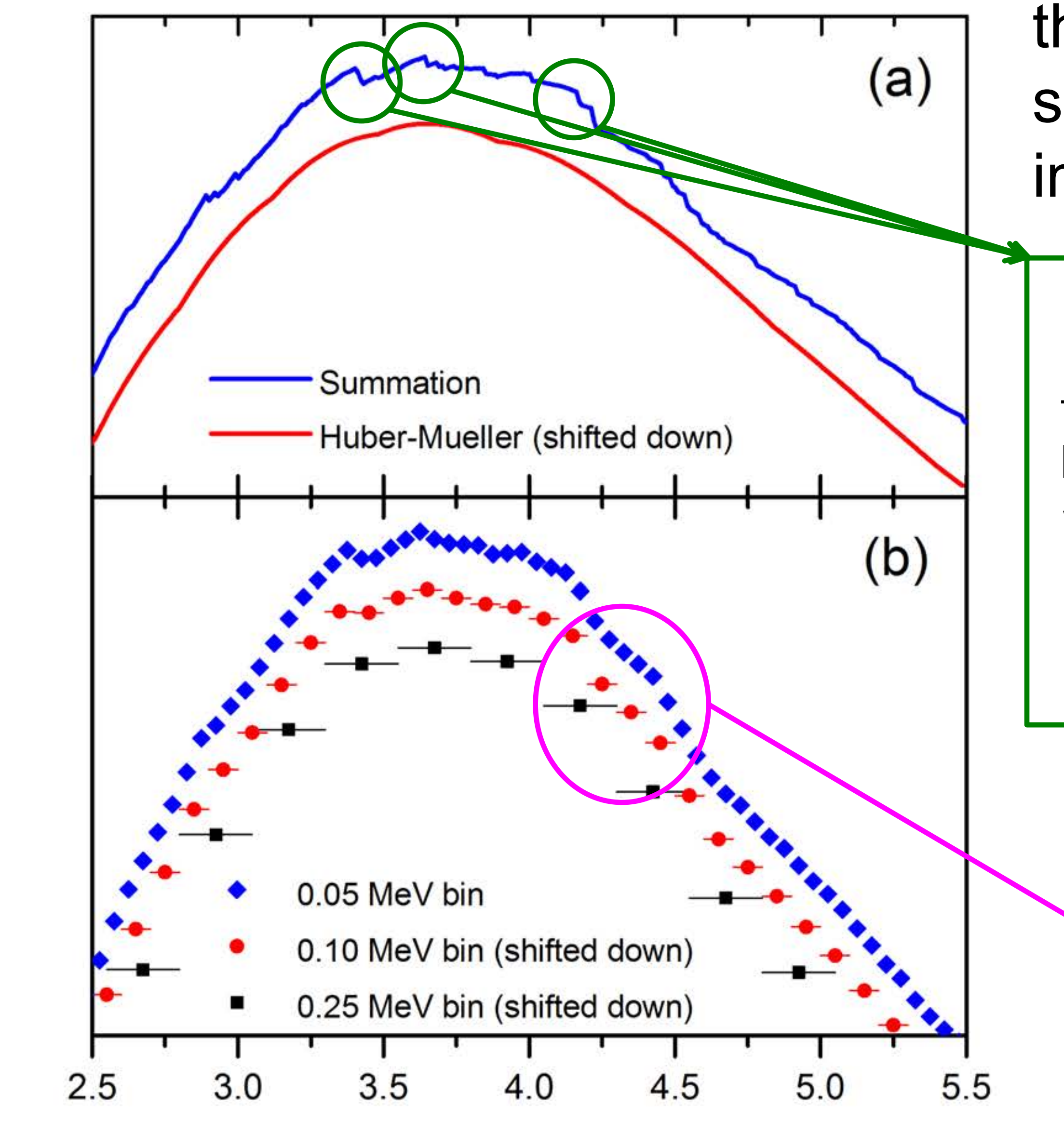


There seems to be structure?

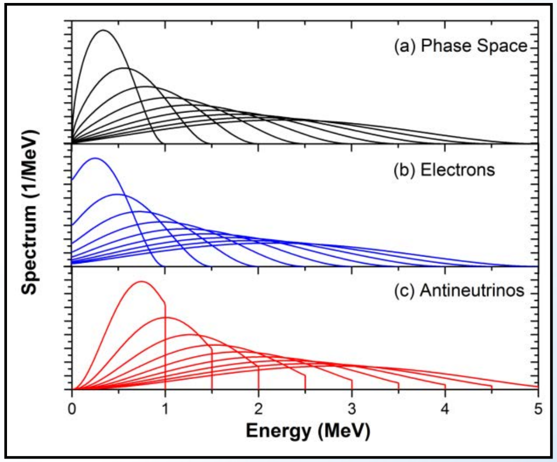
Ko et al, PRL **118**, 121802 (2017)

Fine Structure

As the reactor spectrum is the sum of ~800 individual spectra, can we seen individual effects?



Sharp cutoffs that can be seen with 0.1 MeV binning or less



Shoulder spanning several 100s keV

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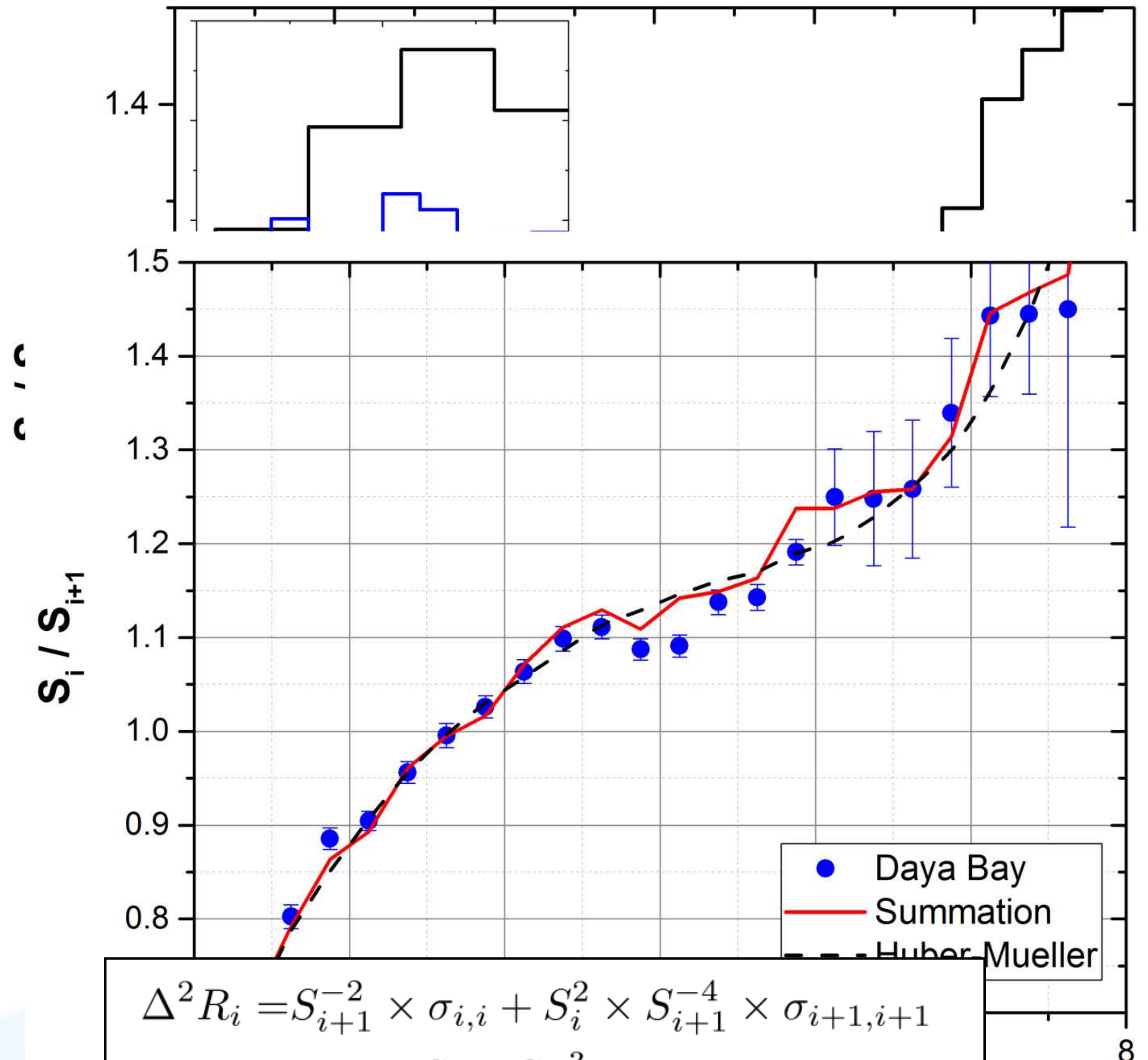
How to reveal Fine Structure?

Ratio of adjacent points:

$$R_i = S_i / S_{i+1}$$

Surprisingly, even with a 0.25 MeV binning a structure can be seen.

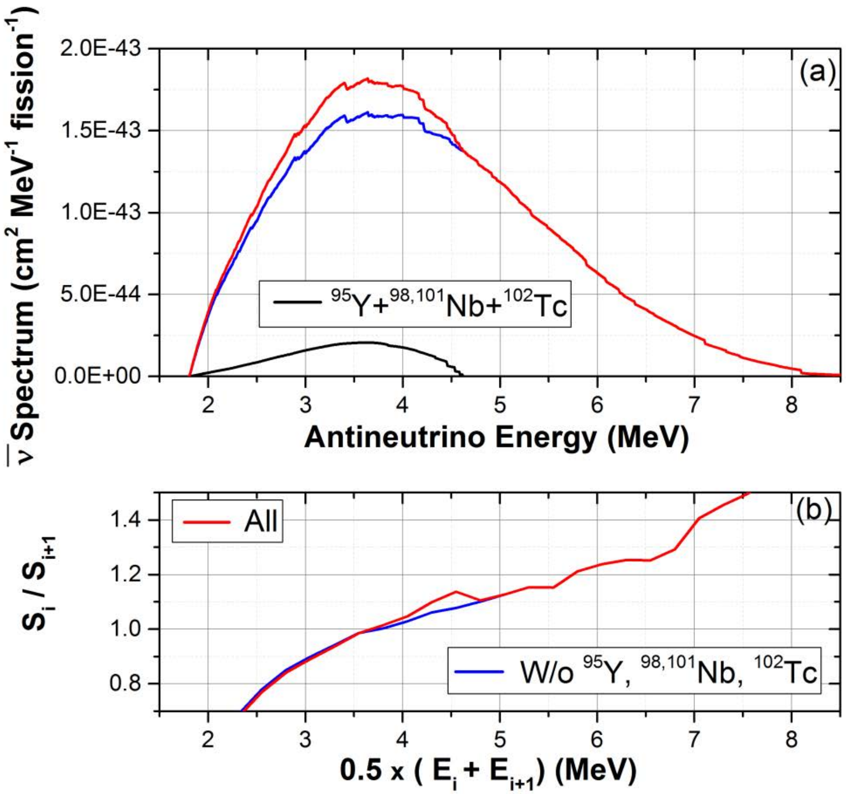
Structure observed in Daya Bay data, covariance matrix crucial for analysis.



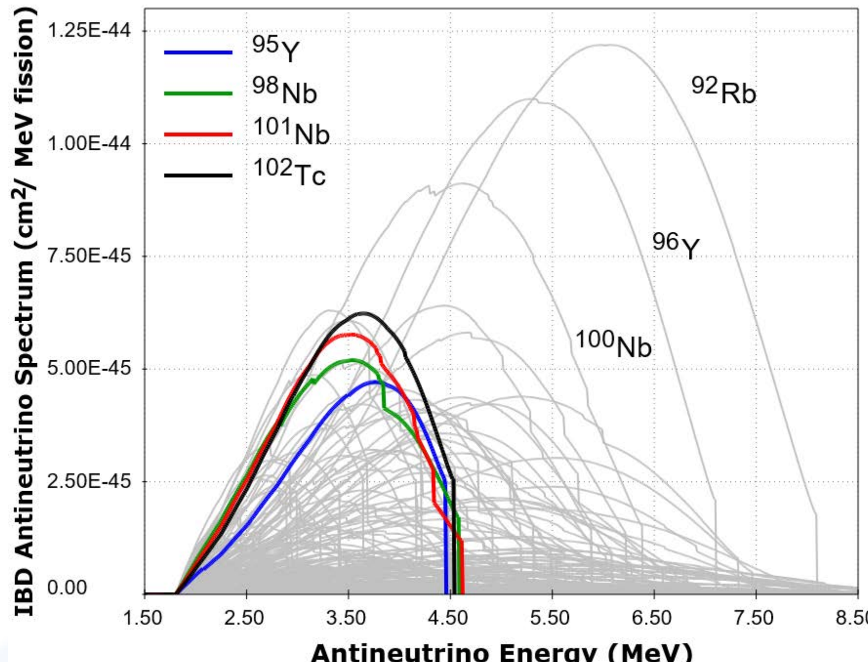
$$\Delta^2 R_i = S_{i+1}^{-2} \times \sigma_{i,i} + S_i^2 \times S_{i+1}^{-4} \times \sigma_{i+1,i+1} - 2 \times S_i \times S_{i+1}^{-3} \times \sigma_{i,i+1},$$

Nuclides behind fine structure

Looking for trees in the forest



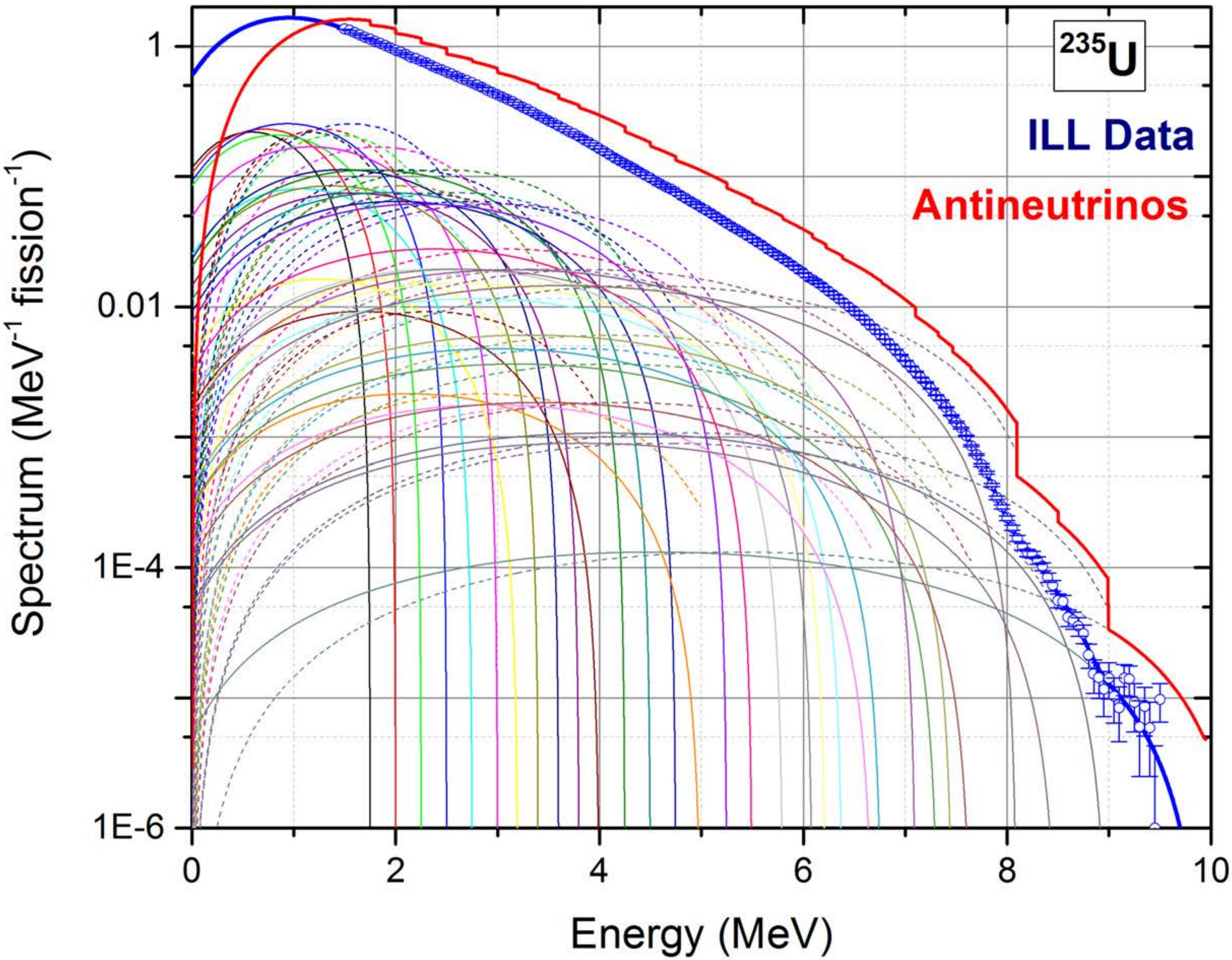
This "Fine structure" can be attributed to just 4 nuclides



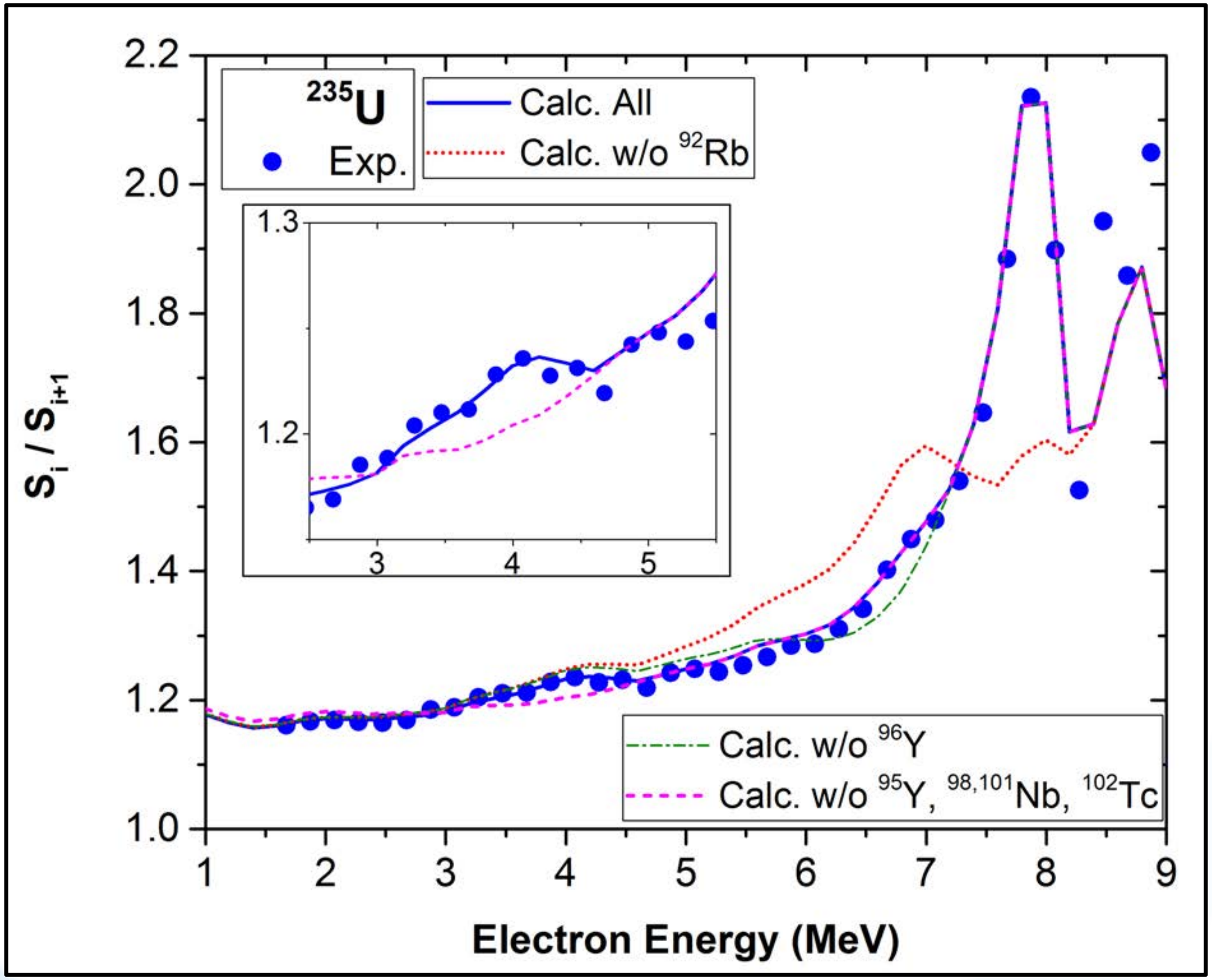
For more details, see:
A.A. Sonzogni, M. Nino, E.A. McCutchan PRC98, 014323 (2018)

We need to confirm this finding by other means.
Also, could this be a low value Δm^2_{41} (< 0.1 eV^2) effect?

In the Conversion Method



Fine Structure



The structure at around 7.8 MeV is basically due to ^{92}Rb

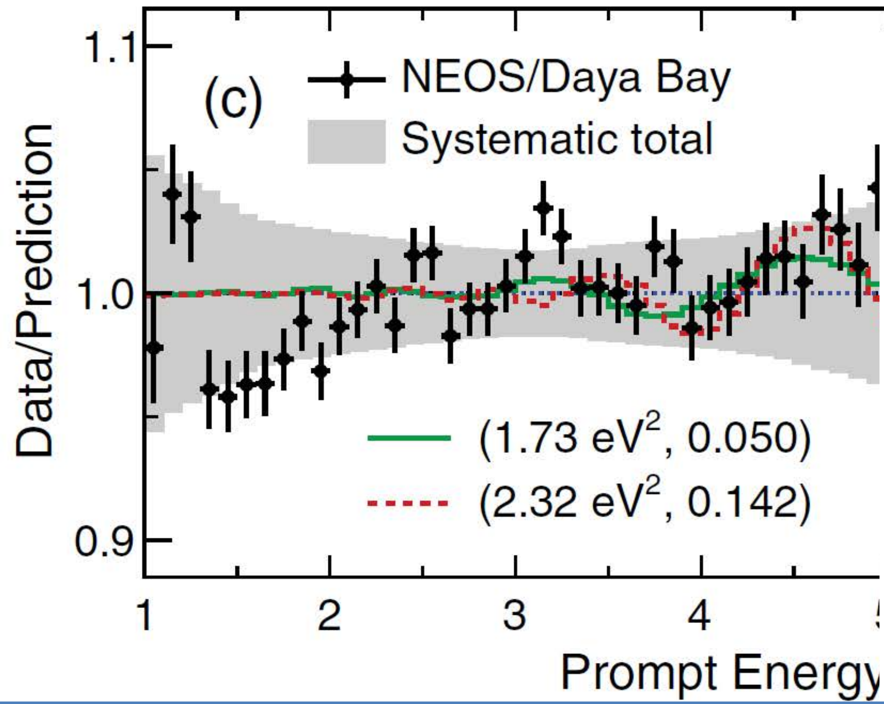
The shoulder at around 7 MeV due to ^{96}Y

And the structure at around 4 MeV due to ^{95}Y, ^{98,101}Nb, ^{102}Tc.

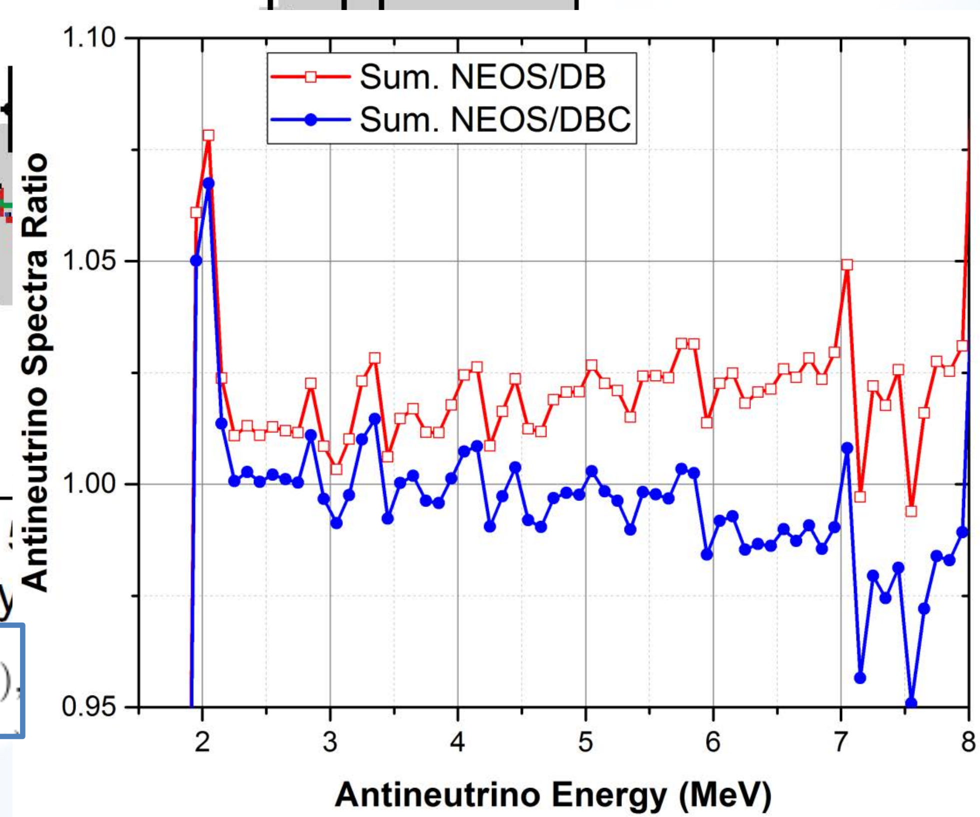
Therefore, the structure at 4.5 MeV antineutrino energy is due to the decay of individual fission products

Fine Structure

NEOS obtained oscillation parameters for a fourth neutrino using the NEOS/Daya Bay ratio:



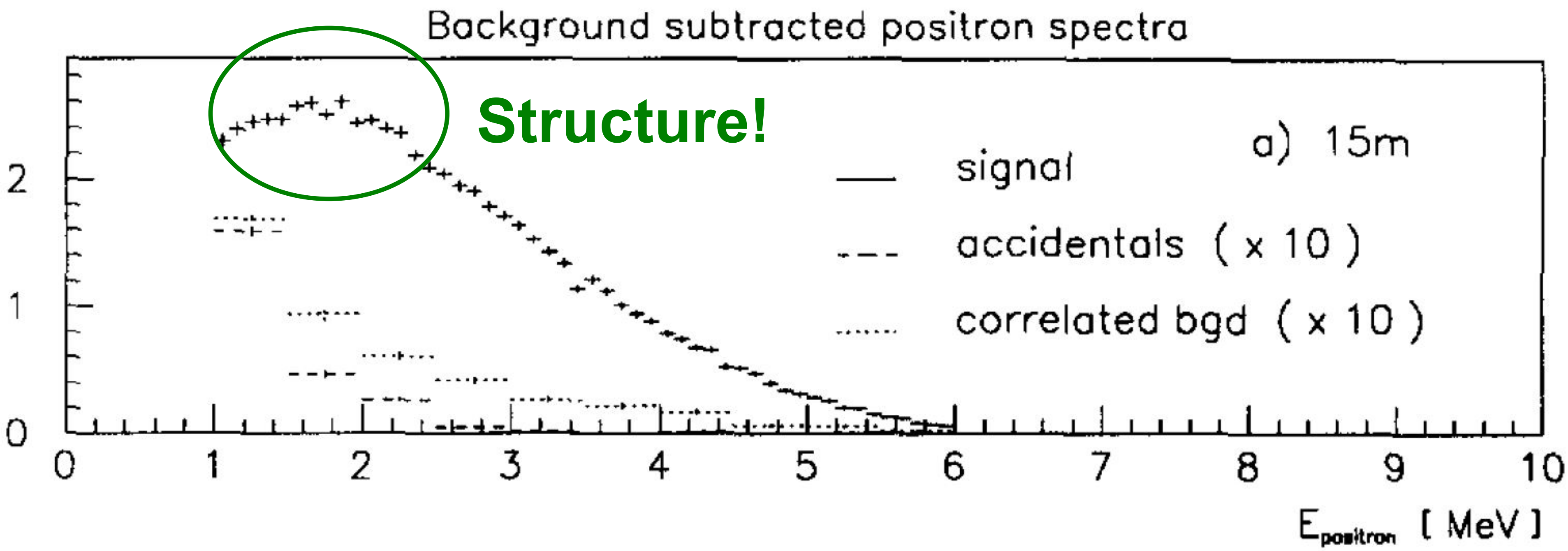
$$S_{DBC} = S_{DB} + \sigma_{IBD} \sum S_i^{HM} \times (f_i^{NEOS} - f_i^{DB}),$$



Some of the structure may simply be due to individual nuclides effects appearing due to a finer binning and better resolution

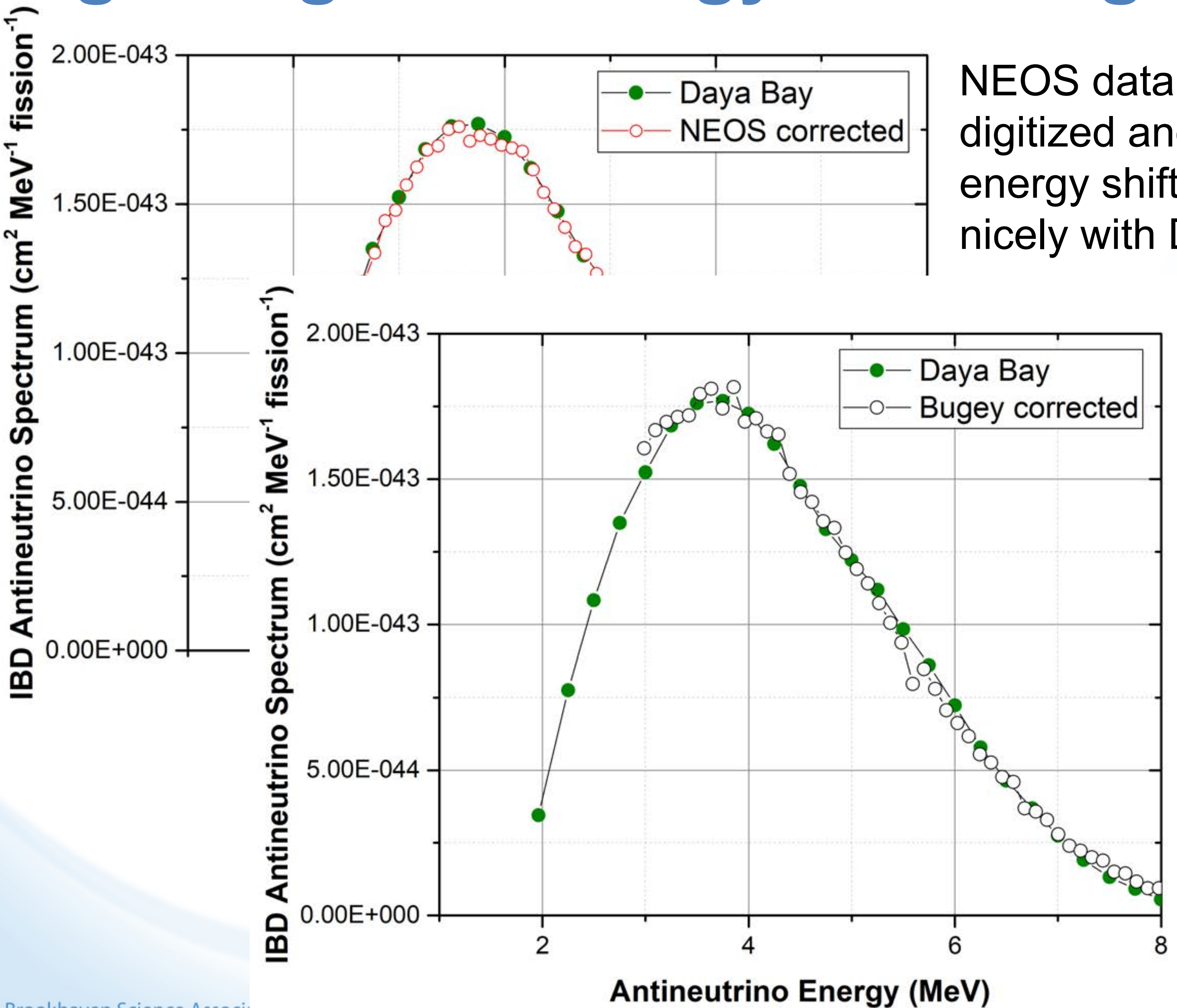
Fine Structure at the top of the spectum

We found only one other measurement with 100 keV bins,Bugey-3,
B. Achkar *et al.*, NPB **434**, 503 (1995).



Unfortunately, data are not available and given as function of positron energy → Must digitize and shift!

Digitizing and Energy matching

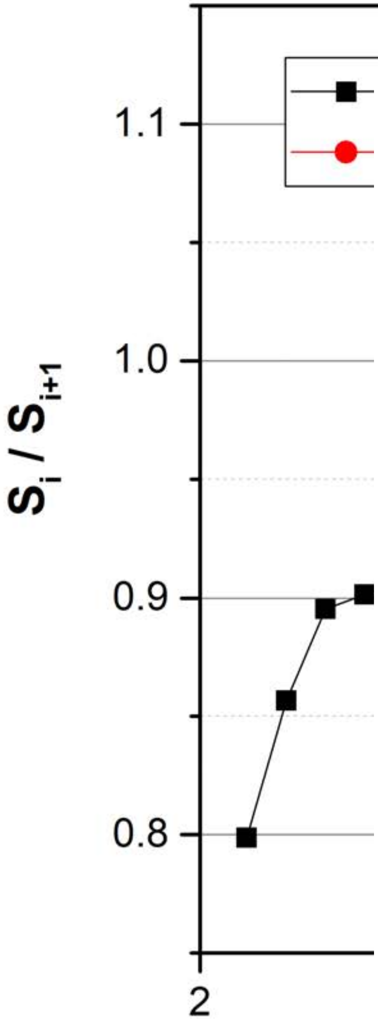


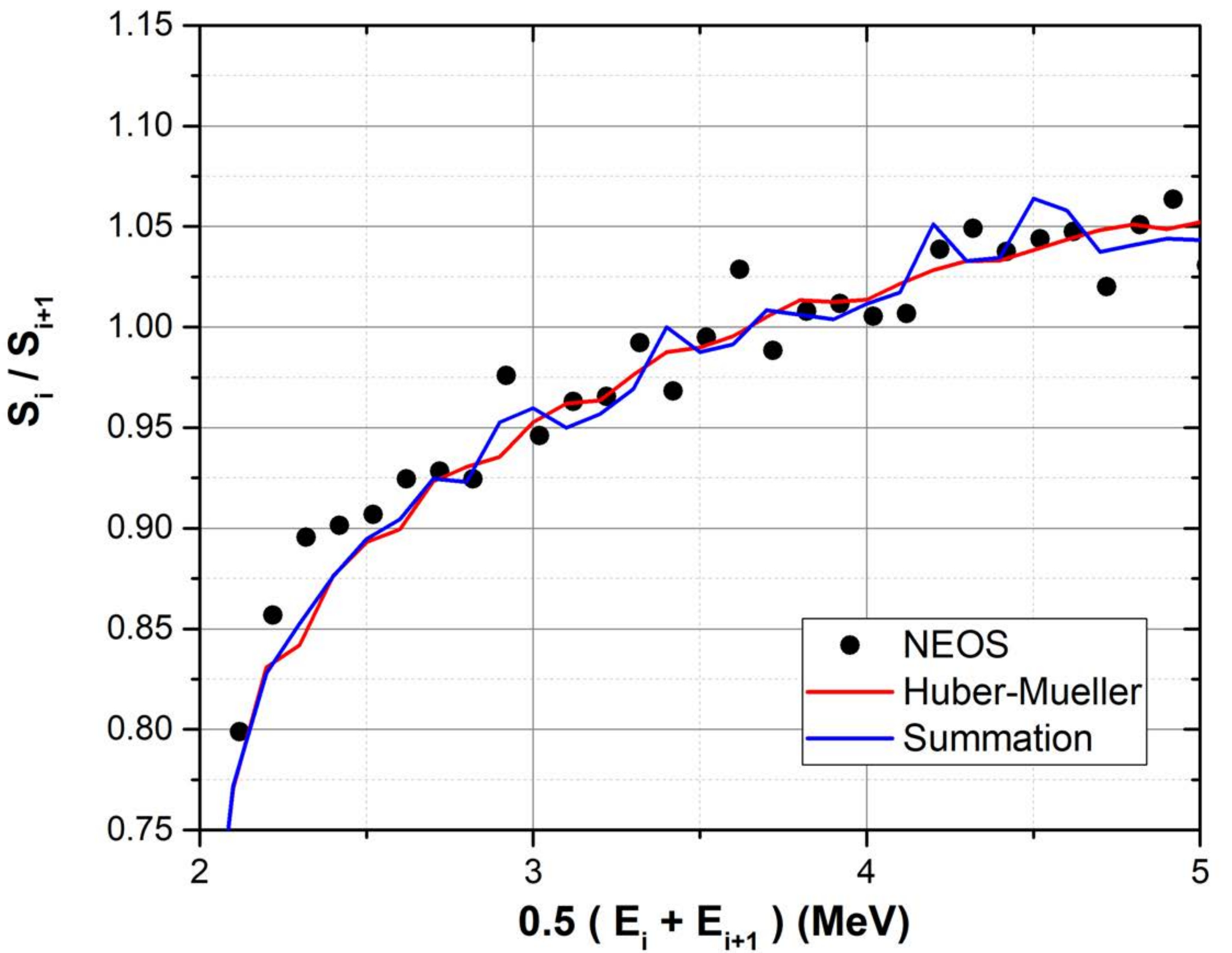
NEOS data was digitized and an energy shift aligned it nicely with Daya Bay

Bugey data was digitized, alignment with Daya Bay also required a linear term.

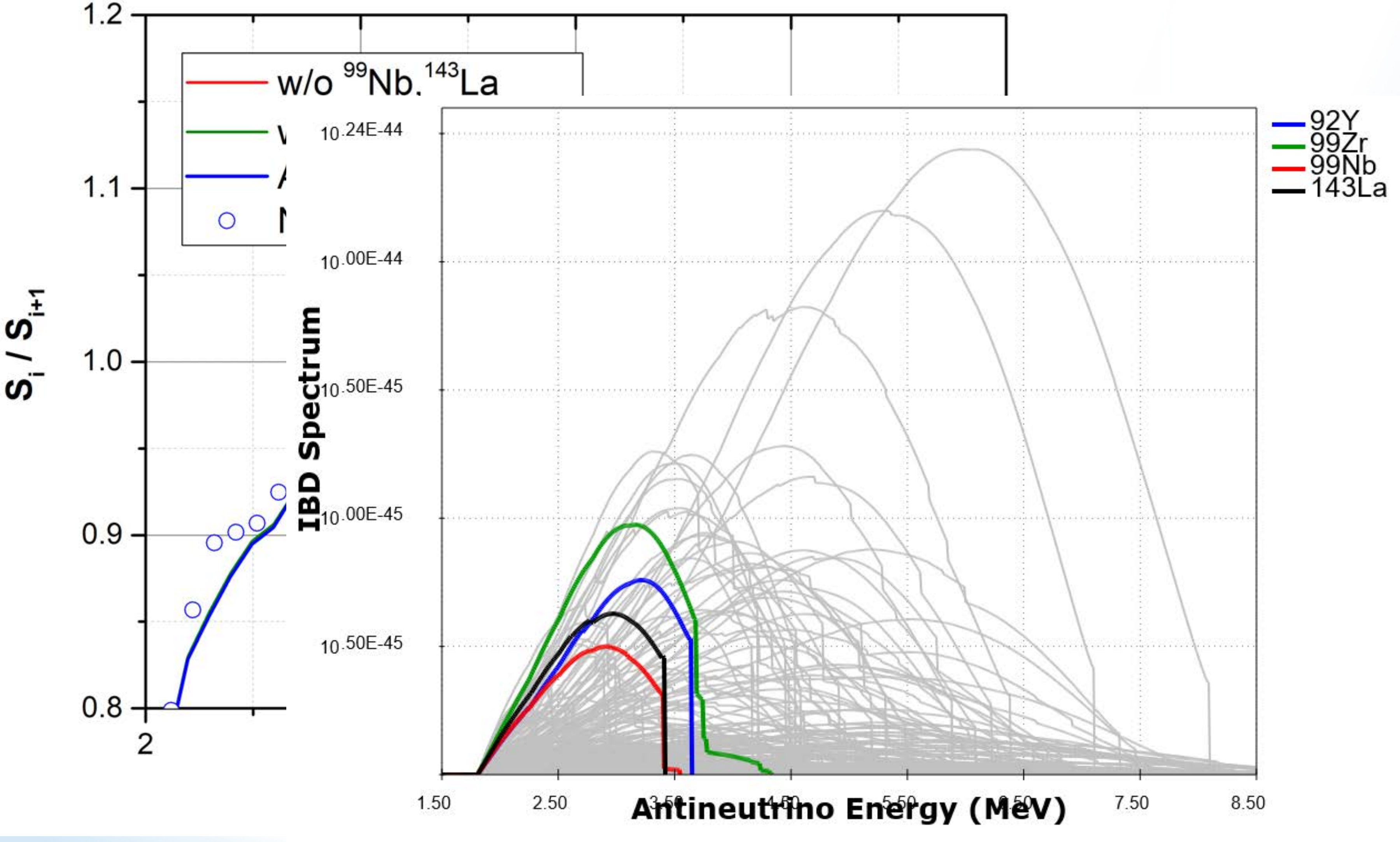
The agreement between NEOS and Bugey-3 ratios is quite good, a

As well as the agreement between NEOS and the summation calculation



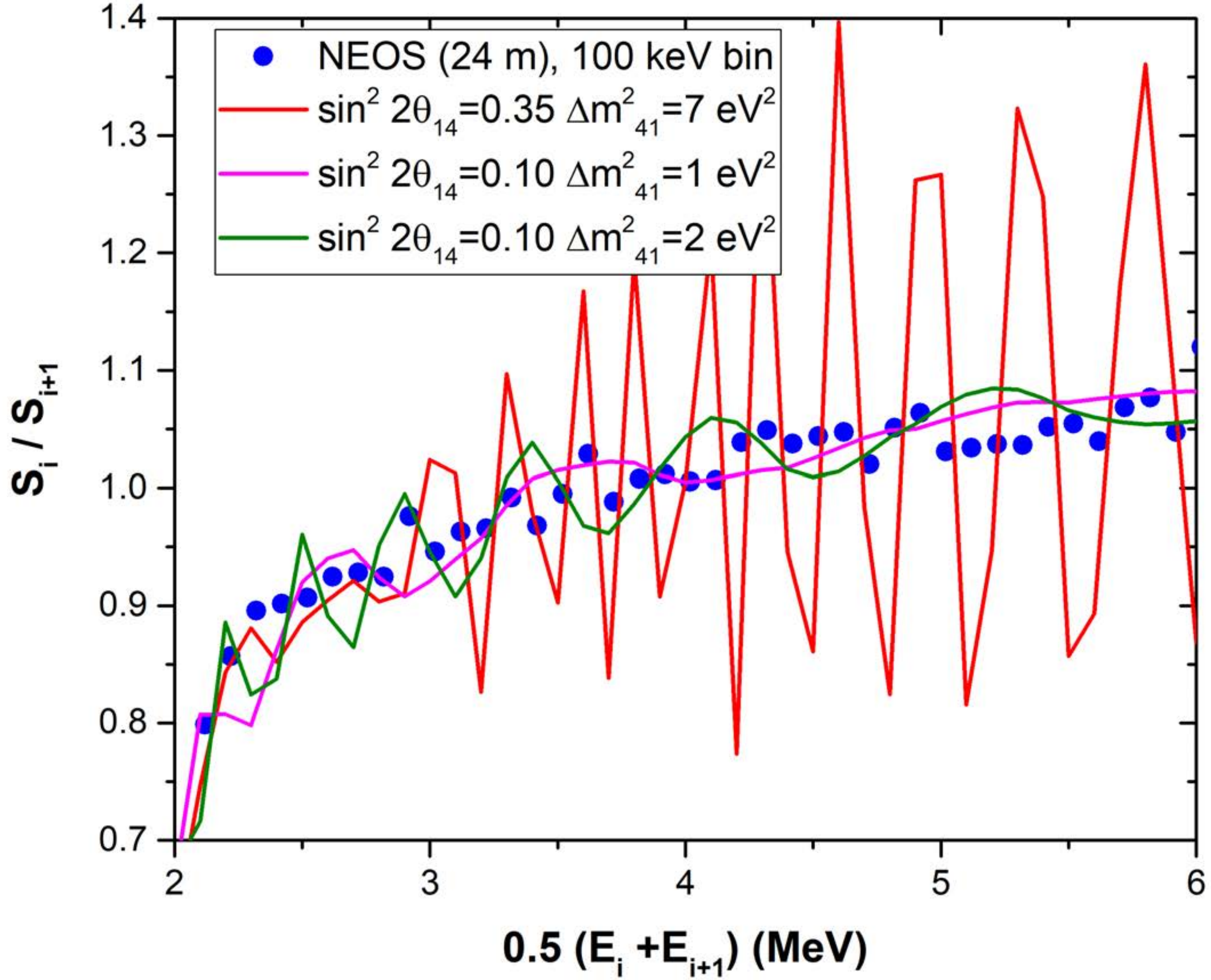


Nuclides behind fine structure at the top

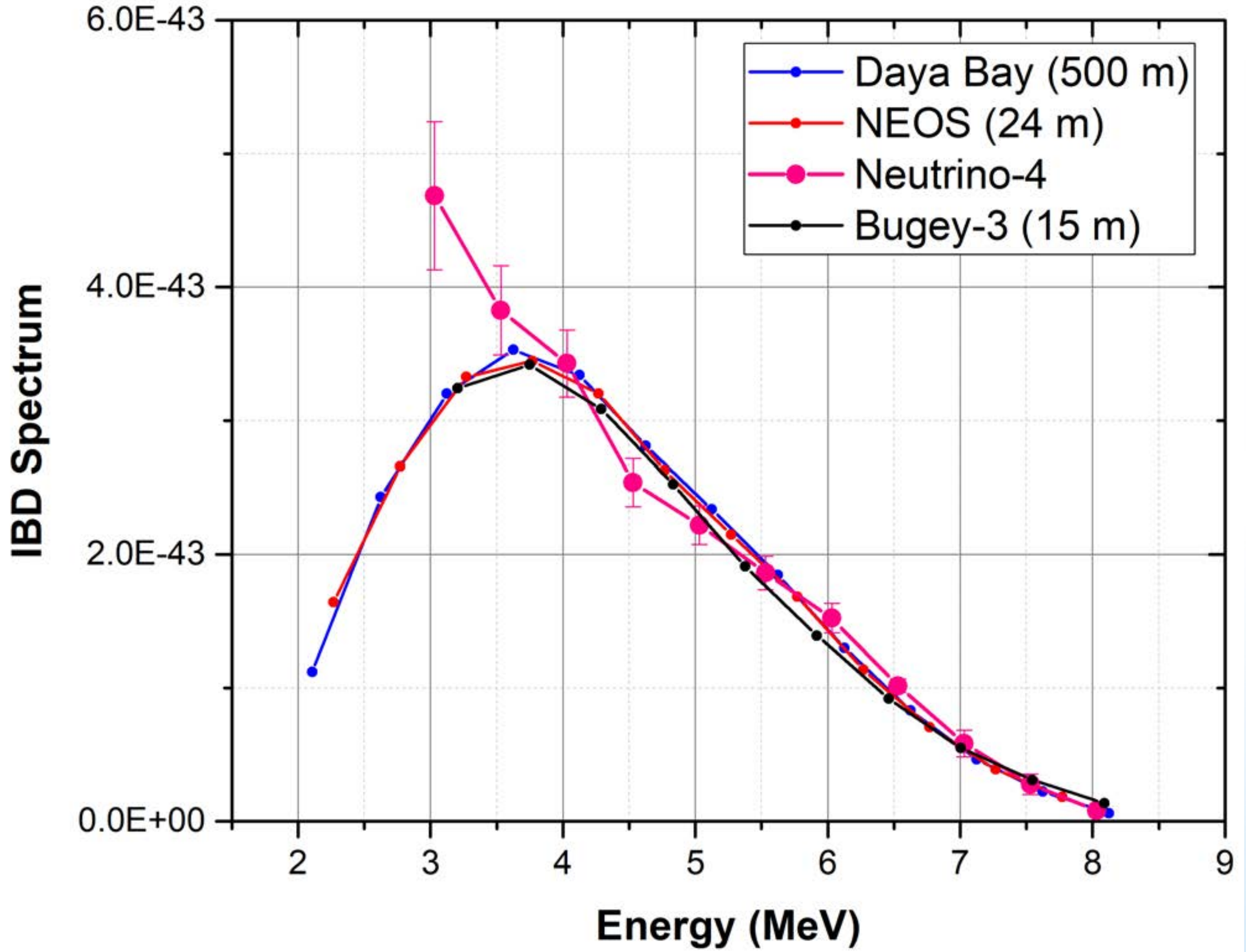


NEOS adjacent points ratio plot more consistent with databases than with 3+1 model

$$P \simeq 1 - \sin^2 2\theta_{14} \sin^2 \left[1.27 \frac{\Delta m_{41}^2 L}{E_\nu} \left(\frac{\mathrm{eV}^2 \cdot \mathrm{m}}{\mathrm{MeV}} \right) \right]$$



Something strange could be happening at distances shorter than 15 m



Analysis relies on digitizing and converting unpublished NEOS and Bugey-3 data

Conclusions I

- Preserving the data of very **C O $ T L Y Experiments is a must!**

- Referees and editors can help on this regard.

- Only two experiments have published their results: **Daya Bay** and **Gösgen**, and only Daya Bay has published IBD spectrum as function of antineutrino energy in absolute units, together with its covariance matrix.

- The **NNDC** and the **IAEA** have been working for the last ~50 years to preserve nuclear data. If anyone knows how to obtain the Bugey-3 data, please let us know.

- The **NNDC** publishes the **Nuclear Data Sheets** journal, **2017 IF=1.96**, where long articles (~100 pages) can be published.

Conclusions II

- With better resolution and small bin intervals, the contributions from individual nuclides, not captured in the conversion, begin to appear. **Must rely on nuclear databases to understand them.**

- Nuclear databases **have not been tweaked / fine tuned** to match ILL electron nor Daya Bay antineutrino spectra.

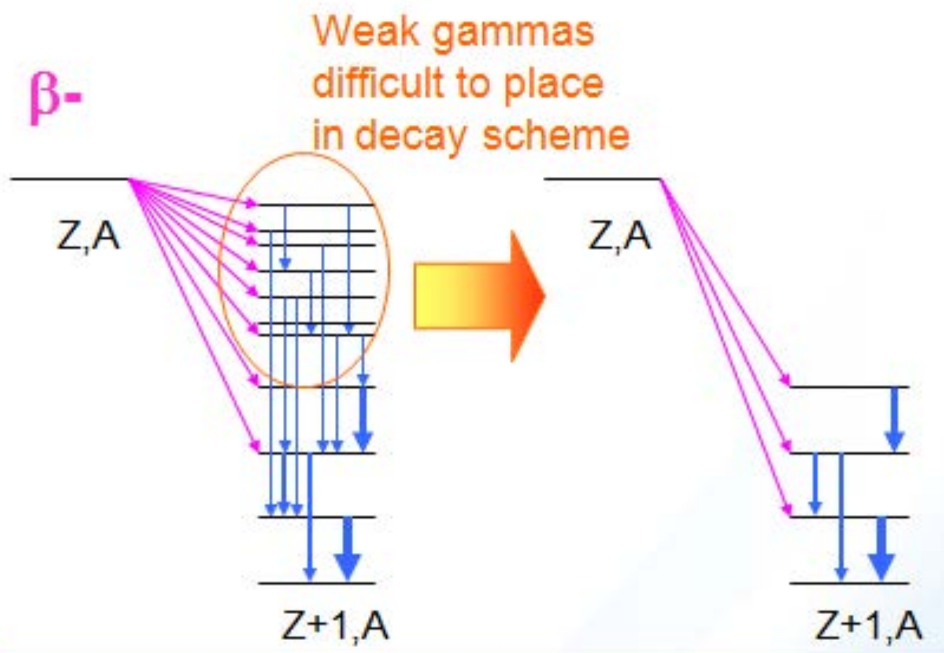
- Nuclear databases **should be revised** to include data incorporated in the last 15 years.   Methods to calculate uncertainties should be finalized.

- Individual fission product effects (fine structure, sharp cutoffs) were most likely **first observed by Bugey-3**, but not recognized as such until now.

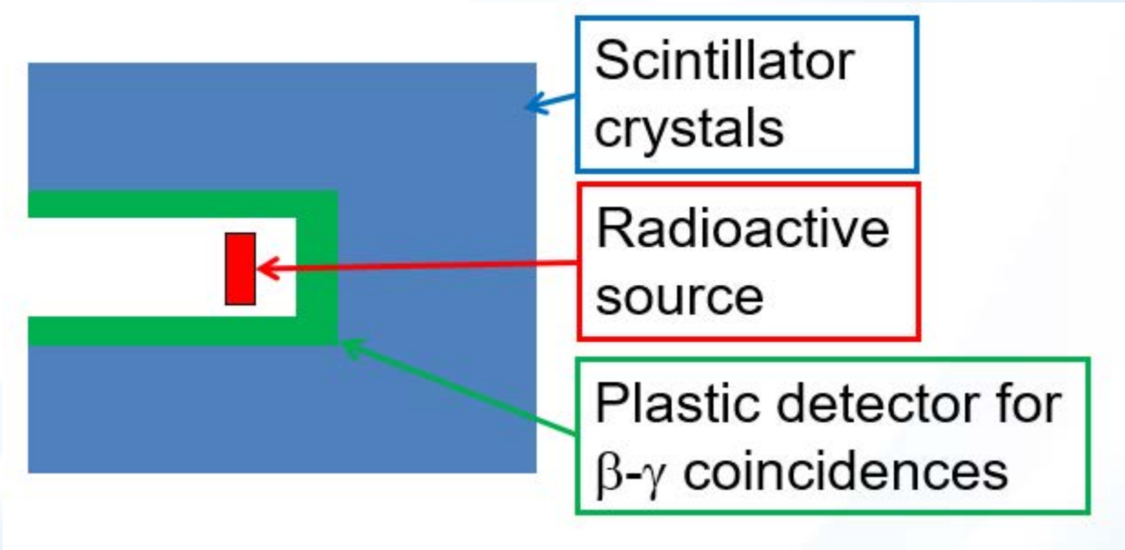
- While summation calculations are less precise than conversion ones, they are nevertheless more reliable as they contain contributions from more than 500 experiments.

TAGS Data

For nuclides with a large Q-values, decay schemes obtained using a few Germanium detectors lead to large beta intensities for low-lying levels.



A possible solution would be to use data from Total Absorption Gamma Spectroscopy (TAGS) experiments.



TAGS experiments measure the gamma spectrum after beta decay with low resolution but high efficiency.