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Developments in reactor neutrino modeling

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I shall discuss two aspects of the reactor spectrum:

1) General comments on the theoretical limitations of the achievable accuracy of the spectrum evaluation
2) Analysis of the ``reactor anomaly" and arguments for the reevaluation of its significance.

The reactor neutrino spectrum $S(E_\nu)$ can be expressed as

$$S(E_\nu) = W_{th}/\Sigma_{i\,(}(f_i/F)\ e_i)\ \Sigma_i\ (f_i/F)\ (dN_i/dE_\nu),$$

where W_{th} is the reactor thermal power, (f_i/F) is the fraction of fissions of the actinide *I* and e_i is the energy of fission of the isotope i. In power reactors, with low ^{235}U enrichment, the fraction (f_i/F) changes during the reactor cycle, ^{235}U contribution is decreasing and ^{239}Pu contribution is increasing. In research reactors the ^{235}U enrichment is high, $f_{235U} = 1$ there.

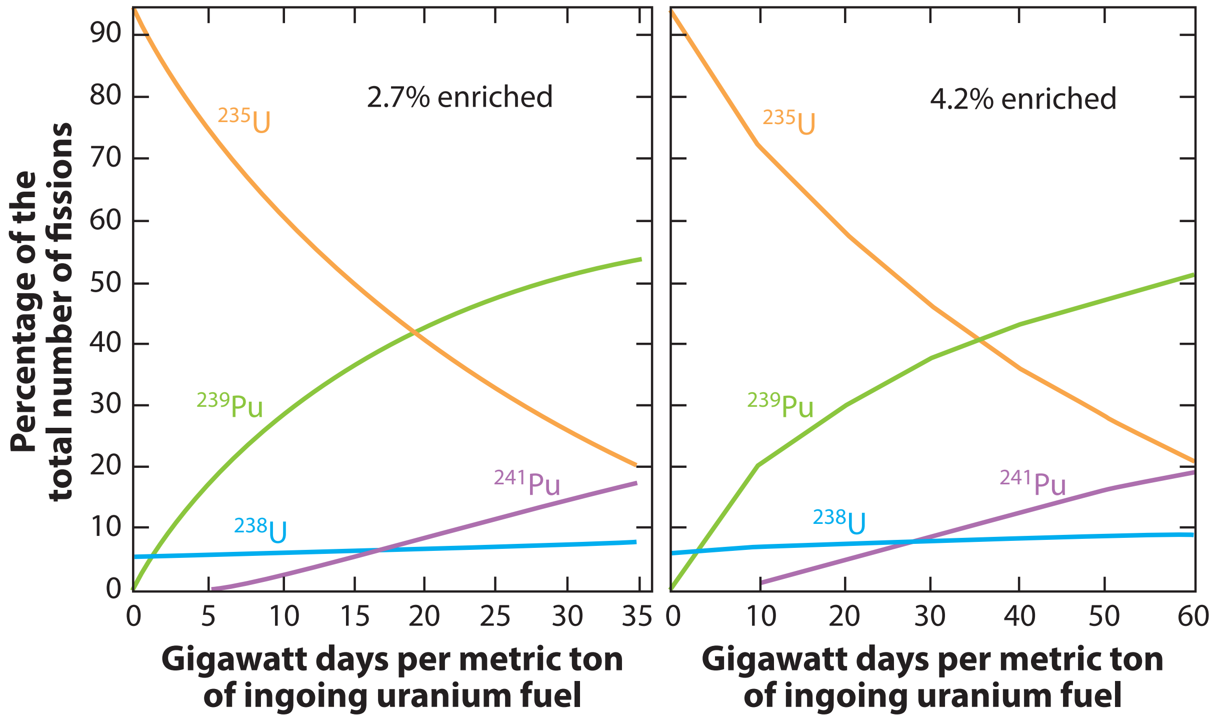


Figure from Nieto MM, et al. *Nucl. Sci. Eng.* 149:270 (2004)

The neutrino spectrum of the actinide isotope *i* (^{235}U,^{239}Pu,^{241}Pu,^{238}U) is

$$dN_i/dE_n = \Sigma_n Y_n(Z,A,t)\ \Sigma_\varphi\ b_{n,j}(E_0{}^j)\ P(E_n,E_0{}^j,Z) \qquad (1)$$

where $Y_n(Z,A,t)$ is the fission yield of the fragment *n*, $b_{n,j}(E_0{}^j)$ is the branching ratio of the β-decay branch with the endpoint $E_0{}^j$, and most importantly, the function) $P(E_n,E_0{}^j,Z)$ is the spectrum of that β-decay branch.

In every β-decay an electron and an antineutrino are emitted together and share the endpoint energy E_0, i.e. $E_e = E_0 - E_n$. The electron spectrum of the Isotope *I*, dN/dE_e is then given by the same formula above with the substitution $E_e = E_0 - E_n$. There is one to one correlation between the two spectra.

$$dN_i/dE_e = \Sigma_n Y_n(Z,A,t)\ \Sigma_\varphi\ b_{n,j}(E_0{}^j)\ P(E_e = E_0{}^j - E_n,E_0{}^j,Z) \qquad (2)$$

Given that, the neutrino spectrum can be determined by the **summation**, using eq. (1) and experimental data on Y_n, $b_{n,j}$ and $E_0{}^j$.
Alternatively, if the electron spectrum dN_i/dE_e in eq.(2) is known experimentally, one can **convert** it into the neutrino spectrum dN_i/dE_n, essentially without the use of other empirical input.

In the **conversion** method it is assumed that the electron spectrum dN_i/dE_e can be represented by a sum of *m* virtual β decay branches

$$dN_i/dE_e = \Sigma_k^m N_k P(E_e, E_0^k, Z), \qquad (3)$$

where E_0^k is a set of chosen (usually equidistant) endpoints and the set of *m* normalization coefficients obtained by fitting to the experimental electron spectrum on the lefthand side of (3). Once this is done, the neutrino spectrum is trivially obtained

$$dN_i/dE_n = \Sigma_k^m N_k P(E_n = E_0^k - E_e, E_0^k, Z) \qquad (4)$$

Note that, for either of these two methods to describe the neutrino spectrum correctly, it is necessary that the shape of the individual β branches, $P(E_e, E_0^k, Z)$, and consequently also of $P(E_n, E_0^k, Z)$, is accurately known.

In the nuclear β decay there is a small parameter $p_eR \sim p_nR << 1$. Keeping only the terms of the lowest order, i.e. assuming that all decay all `allowed', means that the shapes **$P(E_e, E_0^k, Z)$** are all universal. There is only one nuclear matrix element for each transition, fixed when the lifetime is known.

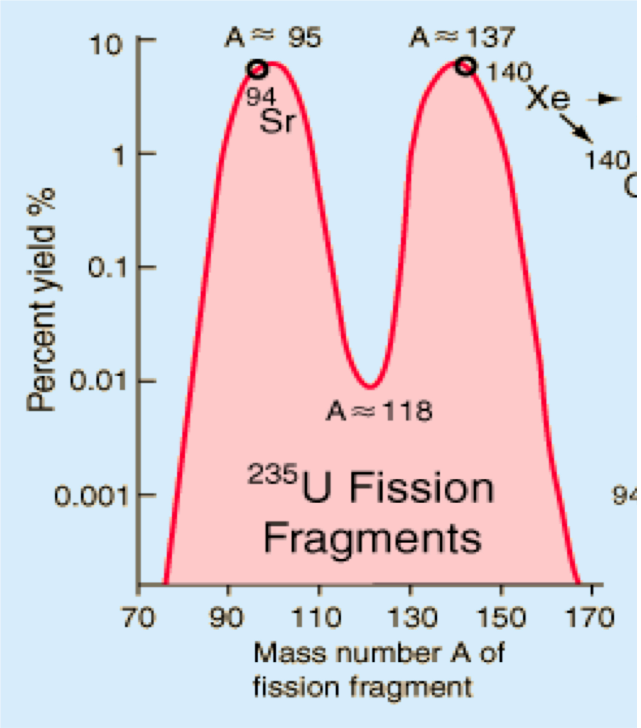
However, when accuracy of O(1%) is required, lower order corrections must be included, i.e. the right formula is then

$$\mathbf{P(E_e, E_0^k,Z) = P(E_e, E_0^k,Z)_{allowed} \times (1 + \delta_{QED} + \delta_{finite\ size} + \delta_{weak\ magnetism}).}$$

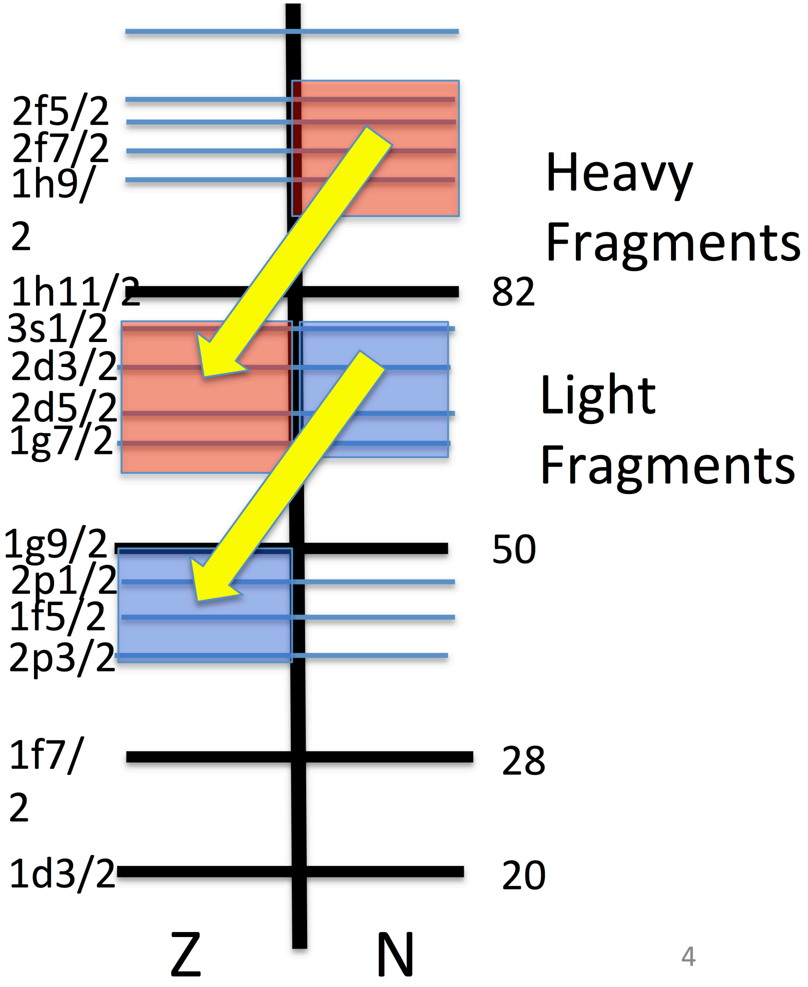
These corrections, in principle, involve additional nuclear matrix elements so that the universality of the spectrum shape is lost. However, since all these corrections are only at a few % level, it is legitimate to use some properly determined `average' nuclear matrix elements and thus still have a universal individual spectrum shapes. In fact, in the changes of the predicted reactor spectrum in 2011 in the papers by Mueller et al. and by Huber, the more careful treatment of these corrections played an important role.

While the treatment of the allowed β decays appears to be accurate to O(1%), the first forbidden β decays, connecting states with opposite parity, need to be considered.

The fission fragments are neutron rich and in many of them the least bound neutrons and protons are in states of opposite parity. Thus, among the ~6000 beta decay branches, about 25% are first forbidden decays with somewhat different, and much less well described shapes.

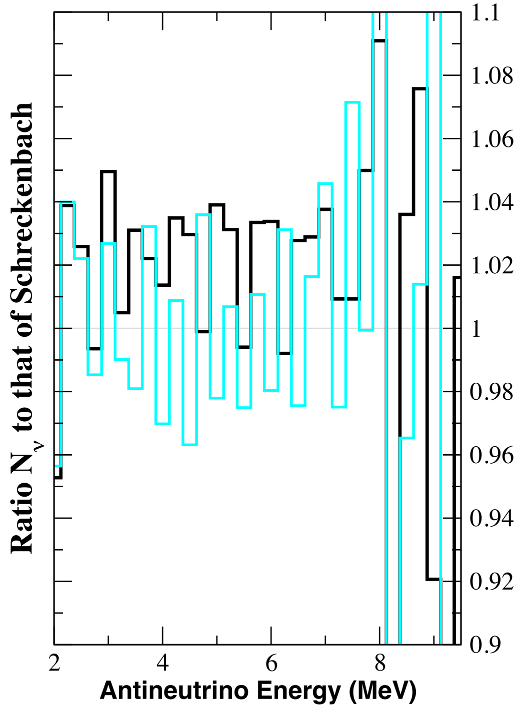


The error associated with the forbidden decays was not properly included in the previous analyses.



Many first forbidden decays have nearly allowed shapes, particularly when ξ = aZ/R >> E_0/m_e. For many high Q value decays (about E_0 > 5 MeV) this inequality is not fulfilled. Accurate treatment of all individual first forbidden decays (ffb) in the summation method is impractical. Thus, it is worthwhile to consider `worst case scenario' to estimate the uncertainty involved.

Consider the ratio $k(E_e,E_\nu) = N_\nu(E_\nu\}/N_e(E_e)$. When $N_\nu(E_n)$ is evaluated using the existing nuclear data with 25% of ffb transitions governed by only one of the possible operators, the deviation from the case of only the allowed transitions are up to 5%. However, in reality, cancellations are possible, and some other ffb operators result in the allowed shapes. It is likely that the overall effect of ffb decays on the total iBD rate is not larger than about 2%. This is an irreducible uncertainty at present time. (However, see later discussion of the Hayen et al. approach)



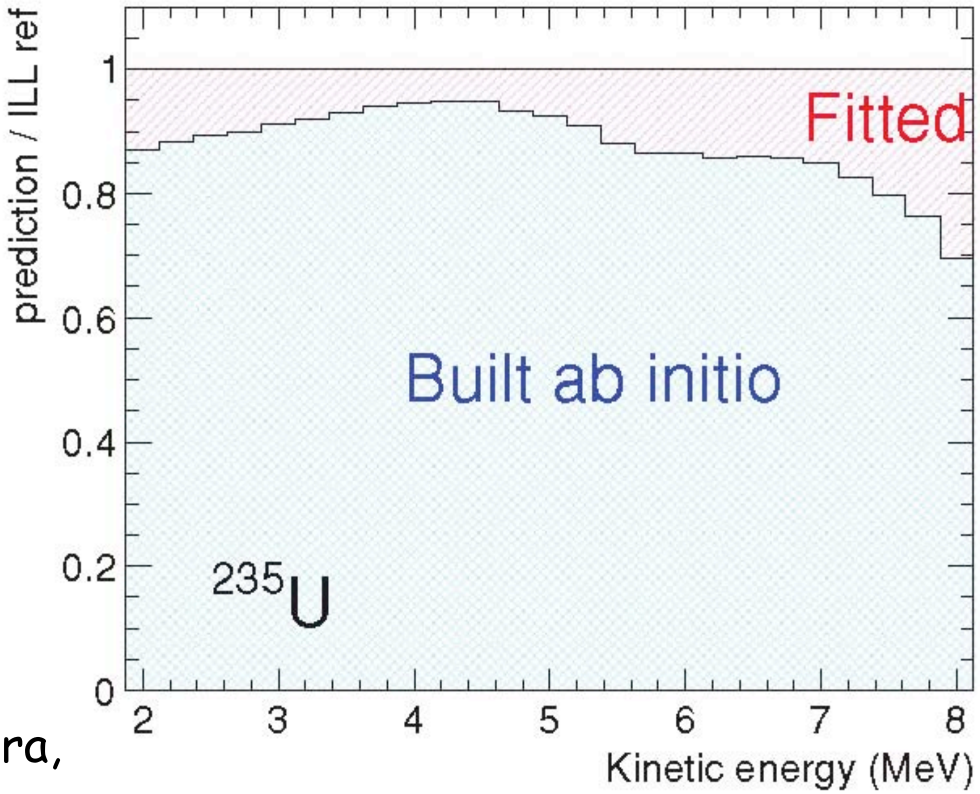
In the figure the $N_\nu(E_\nu)$ ratio to the original ILL prediction Is shown with allowed decays only (black) and with 25% of ffb decays (blue),

figure from Hayes et al, PRL **112**, 202501 (2014)

Electron spectra $N_e(E_e)$ associated with fission of ^{235}U, ^{239}Pu, and ^{241}Pu were determined in a series of measurements at ILL, Grenoble, France in 1981-89 by a group led by K. Schreckenbach. Those unique results are a foundation of **all** present reactor neutrino theoretical evaluations.

The present standard theoretical reactor neutrino spectrum is based on works of Mueller et al. (PRC **83**,054615 (2011)) by the summation method, and by Huber (PRC **84**,024617 (2011)) by the conversion method. In both ways the corresponding electron spectra agree with the ILL result by construction.

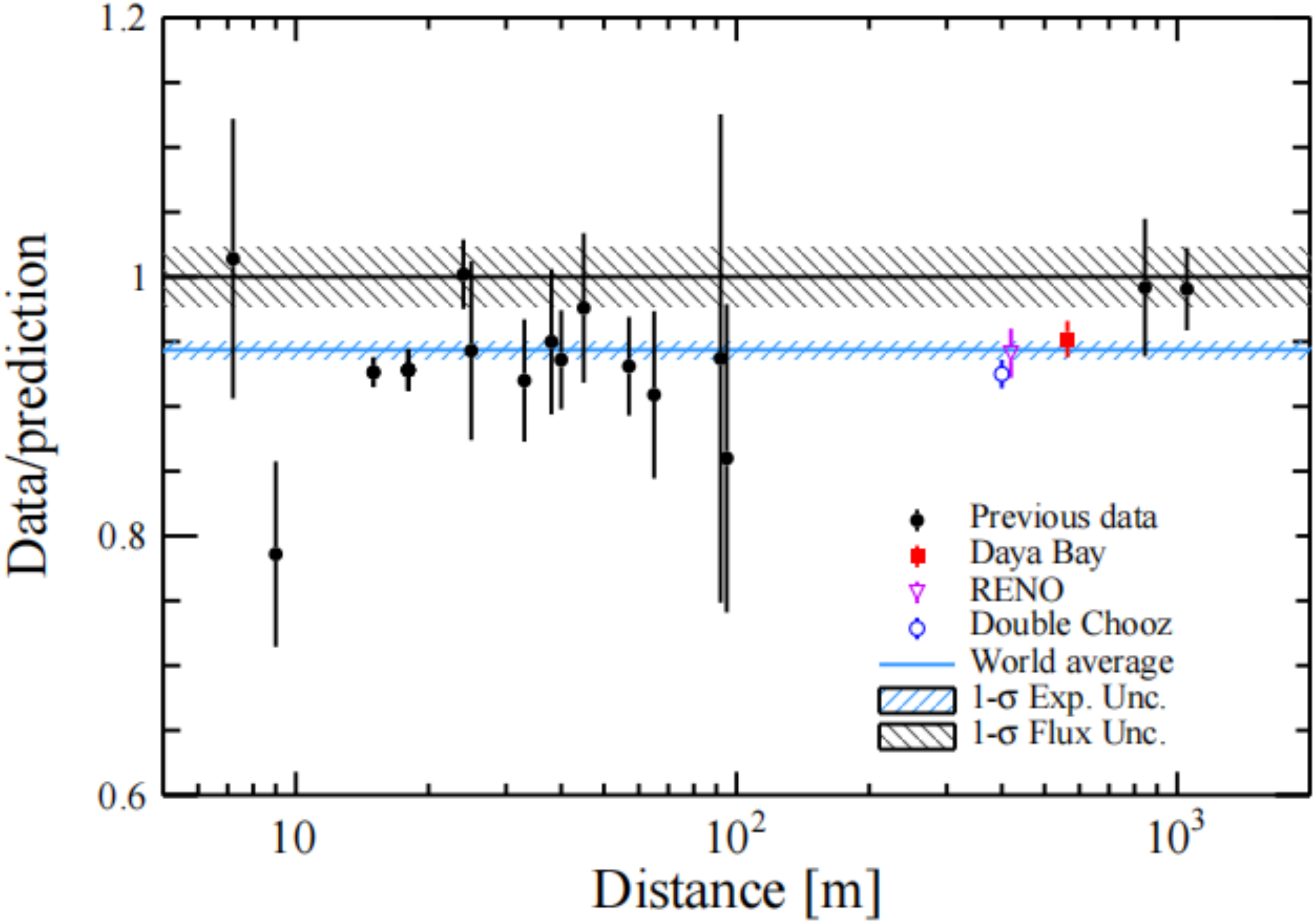
Note: A new software framework for evaluation of the reactor spectra, CONFLUX, is being developed, see the poster #272.



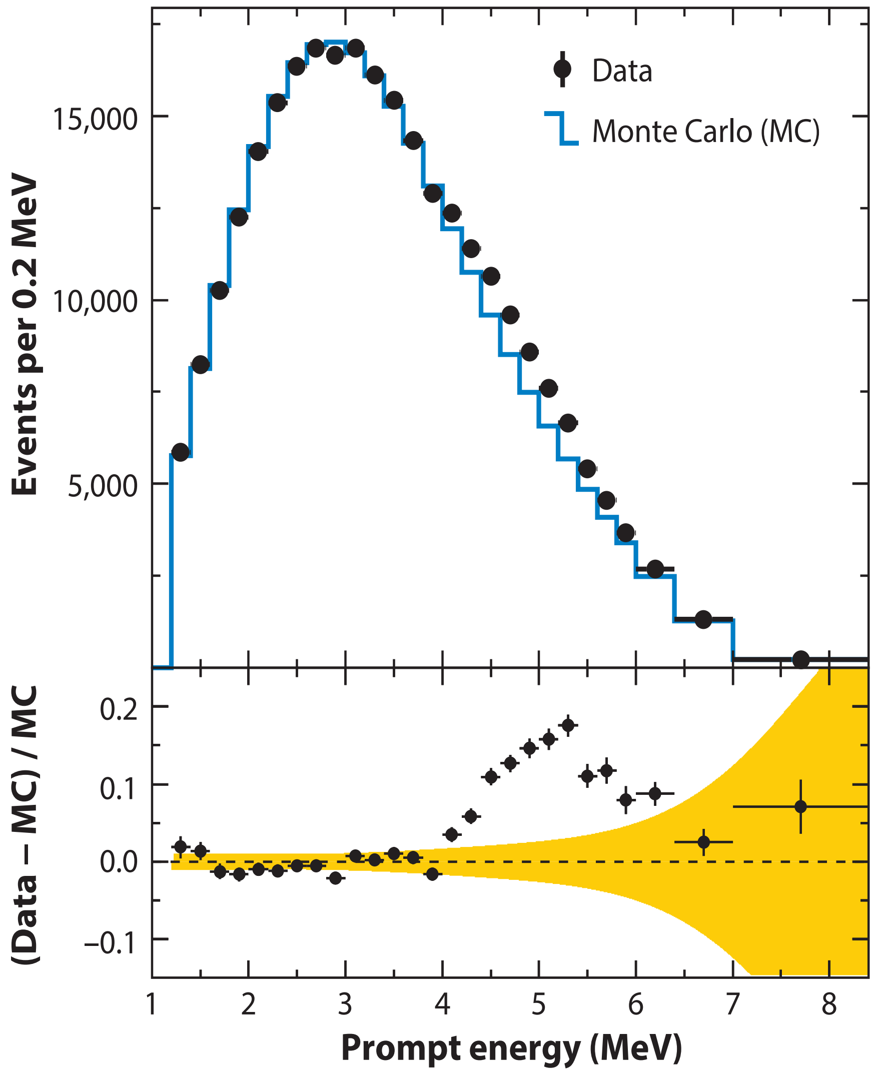
In the summation ~ 10% of the electrons are missed compared to ILL data. This is likely due to the missing decay data and thus were added.

Figure from Mueller et al. PRC **83**, 054615(2011)

Reactor anomaly (RAA): Measured reactor neutrino yields are ~6% lower than the Huber-Mueller prediction. (The results in figure were corrected for the known effect of the θ_{13} oscillations)

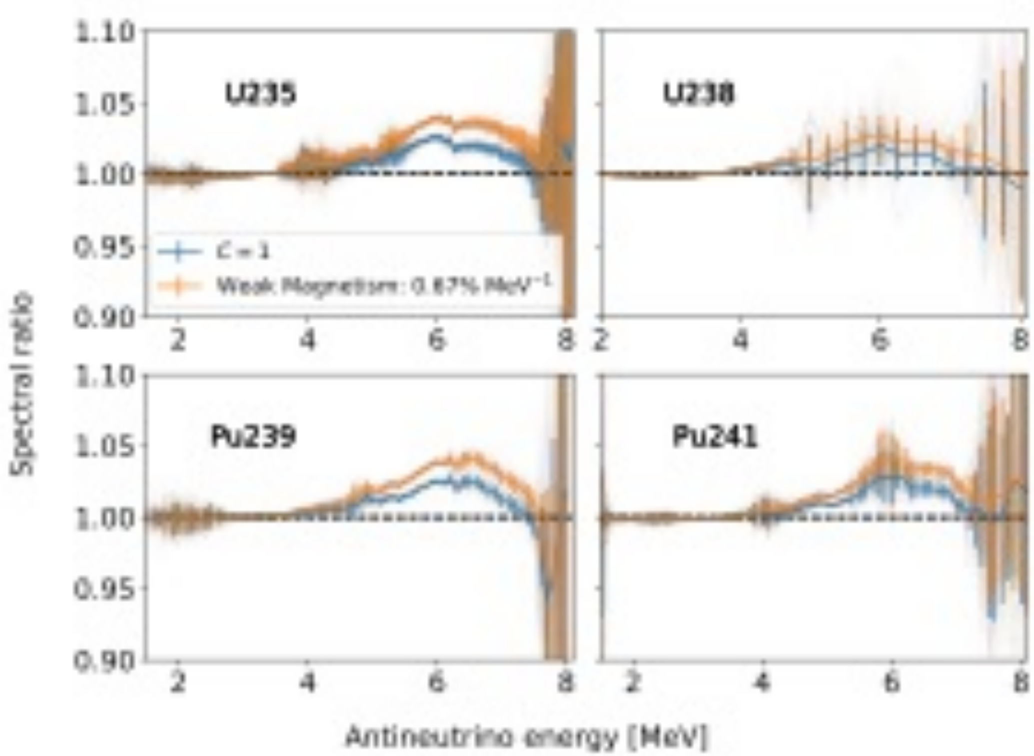


The shoulder (so-called bump) in the neutrino spectrum:
Analogous features were observed in all three high statistics experiments (Daya-Bay, RENO, Double Chooz) ; the RENO result is shown as an illustration. No feature like this is present in the ILL electron spectra.



The existence of the `bump' does not affect extraction of the oscillation parameters significantly. Nevertheless, it is important to explain this feature. Since in the 4-6 MeV energy range the first forbidden decays account for ~40% of the rate, their proper description is clearly desirable.

In Hayen et al, PRC **100**, 054323 (2019), nuclear shell model is used and the shape factors, i.e. the spectrum shapes of 36 individual first forbidden b decays, were evaluated. All these decays have a large Q values and account for substantial part of the rate in `bump' region. When plotted as ratios, the prediction indeed suggests the existence of the `bump'. However, its magnitude is only about half of the experimental result. Interestingly, the calculations suggest that the effect on the electron spectrum is substantially less that for neutrinos. This might explain its absence in the ILL spectrum.

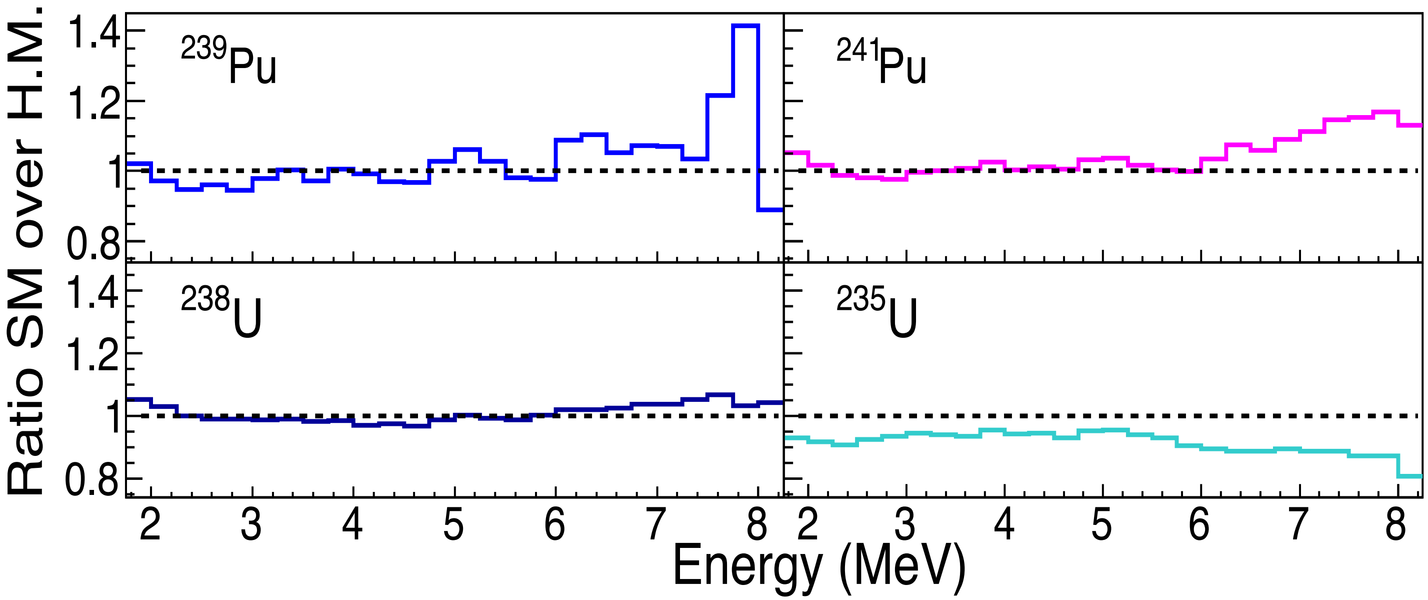


Possible explanations:

a) Physics beyond the standard model, i.e. the existence of ~eV mass sterile neutrinos, with oscillation length of a few meters. (see the talks yesterday dedicated to that possibility)
b) Some issues with the predicted spectrum (rest of this talk).

In this context let me mention the *gallium anomaly* (see the talk by S. Elliott yesterday). In the BEST experiment, 20-24% deficit of neutrino interactions with gallium, compared with the expectation, was found. If electron neutrinos interacting with ^{71}Ga, and thus by implication, with neutrons, are affected, then electron antineutrinos interacting with protons in reactor experiments, should be affected as well. We would thus expect a deficit of 20-24% in all reactor neutrino experiments as well. There is clearly presently a `tension' with this expectation.

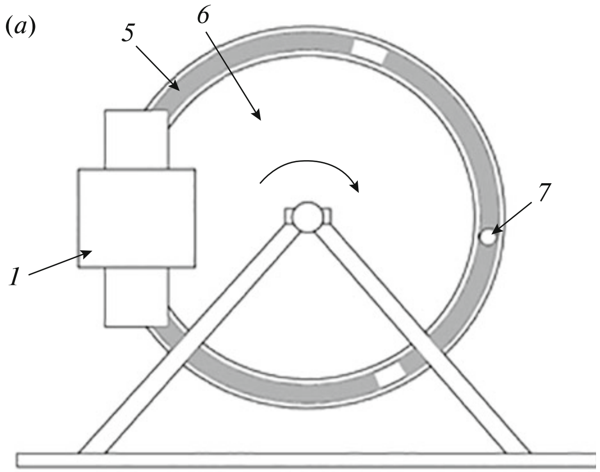
The **summation** method is free from dependence on the electron spectra measurements. However, it is known that the b decay data are vulnerable to the so-called *Pandemonium effect* resulting in an overestimate of the high energy part of the antineutrino spectra, particularly for the high Q value fission fragments. The Total Absorption Gamma-ray Spectroscopy (TAGS) technique avoids these issues. It has been applied to more and more isotopes, see e.g. Estienne et al., PRL **123**, 022502 (2019). Including the most recent (2018) available TAGS data results in spectra in a good agreement with the Huber-Mueller ones for ^{239}Pu, ^{241}Pu, and ^{238}U, but in a noticeable reduction for ^{235}U. With these results the *reactor anomaly* discrepancy is reduced to less than 2%. (The SM2018 model also describes reasonably the highest reactor energies (> 8 MeV)).



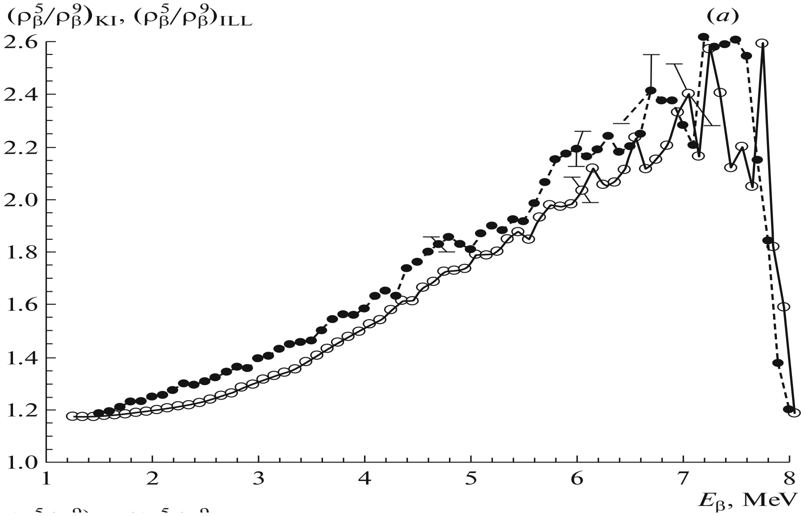
Determination of the ratio of the β spectra of ^{235}U to ^{239}Pu by Kopeikin et al., (Phys.At.Nucl.**84**,1 (2021))

It turns out that the spectrum ratio $^{235}\rho(E_\beta)\,/\,^{239}\rho(E_\beta)$ *as well as the same ratio for the antineutrinos are fairly independent on the (reasonable) way the spectra* $\rho(E_\beta)$ *and* $\rho(E_\nu)$ *are evaluated.*

In this work this ratio was determined by measuring both spectra simultaneously:



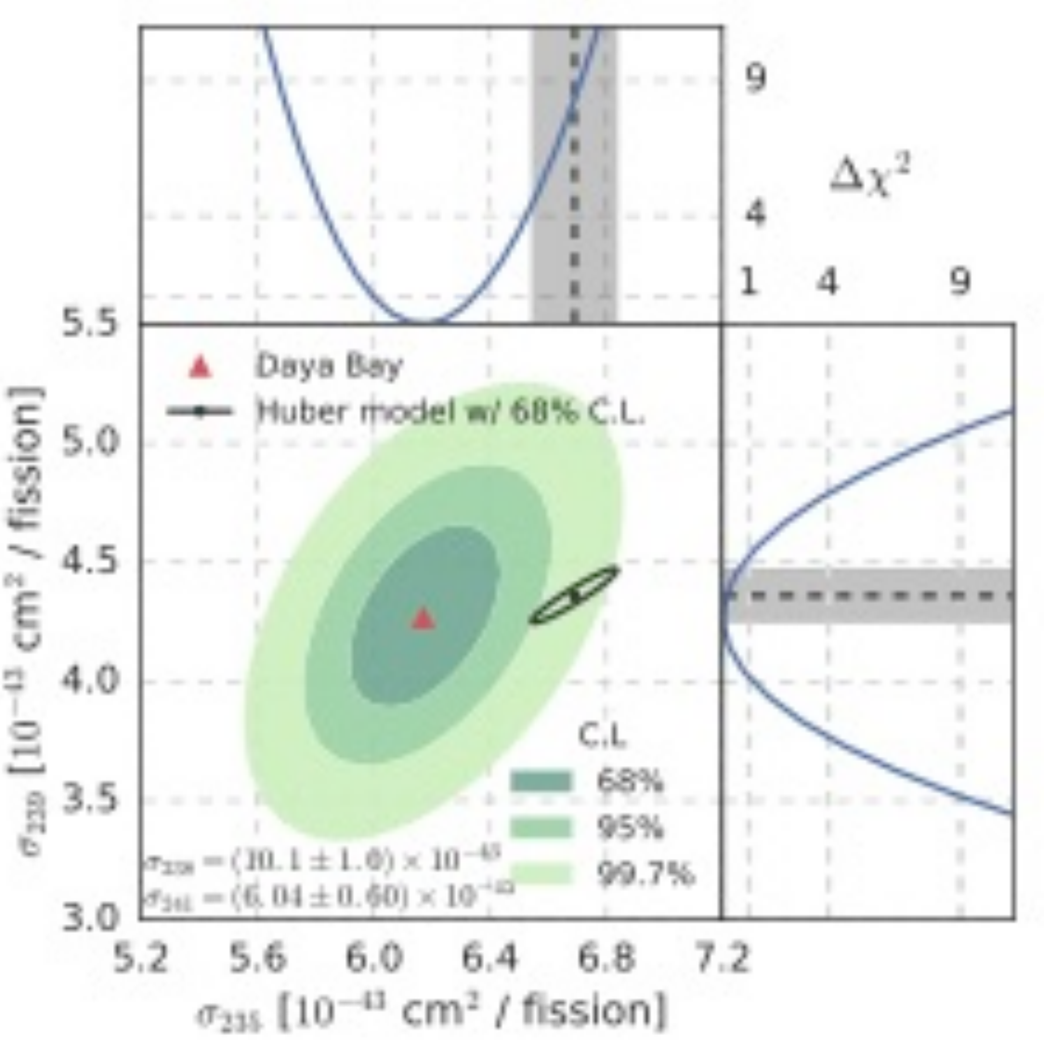
Foils of ^{235}U and ^{239}Pu are put on the rotating wheel, exposed to the neutron flux at (7) and the electrons are detected in the spectrometer (1).



Ratio of the present results (empty circles) to the earlier results by Schereckenbach et al. (full circles).

Conclusions: The ILL spectrum of ^{235}U need to be corrected downwards by ~5%

Contributions of ^{235}U and ^{239}Pu (as well as of ^{241}Pu and ^{238}U) fission to the reactor power changes with time in a well known manner. With a sufficient statistics it is therefore possible to disentangle their total cross sections per fission separately.



Analysis of the Daya-Bay experiment suggests that the σ_{235} is less than the prediction of the H-M model by about 8%, while σ_{239} agrees with the H-M prediction.

Fig. from An et al, PRL **118**, 251801 (2017)

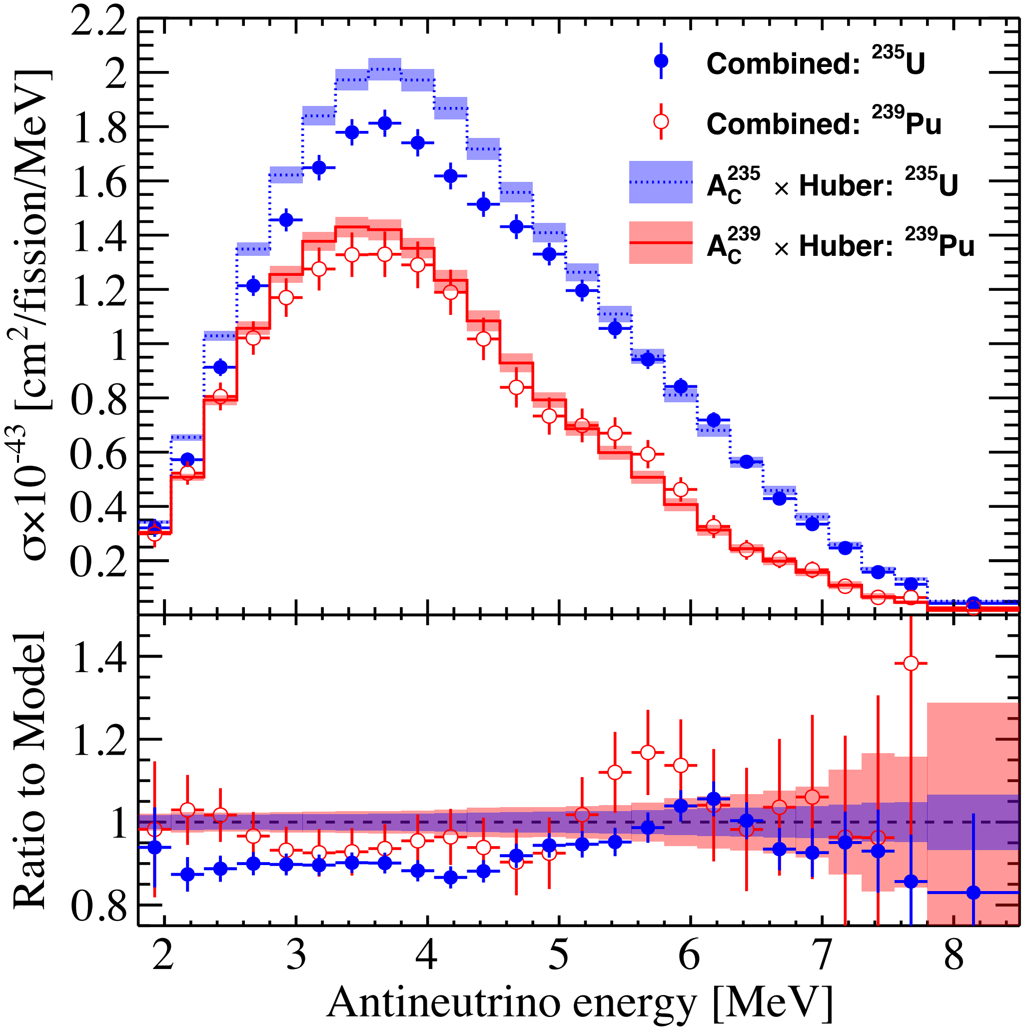


FIG. 5. (Top) ^{235}U and ^{239}Pu antineutrino spectra unfolded from the jointly deconvolved Daya Bay and PROSPECT measurements. (Bottom) Ratio of the measurements to their respective models, which are corrected by the smearing matrices $\boldsymbol{A}_c$ in both panels.

Another view of the Daya-Bay result, now in combination with data from the PROSPECT research reactor. Again, ^{235}U is noticeably less than the H-M prediction, while ^{239}Pu is much closer. Both spectra exhibit the `bump'.

Figure from An et al., PRL **128**,081801(2022)

Analogous result was obtained by analysis of the RENO data. Again, ^{239}Pu basically agrees with the prediction of the H-M model, while the ^{235}U cross section per fission is by about 8% smaller than predicted.

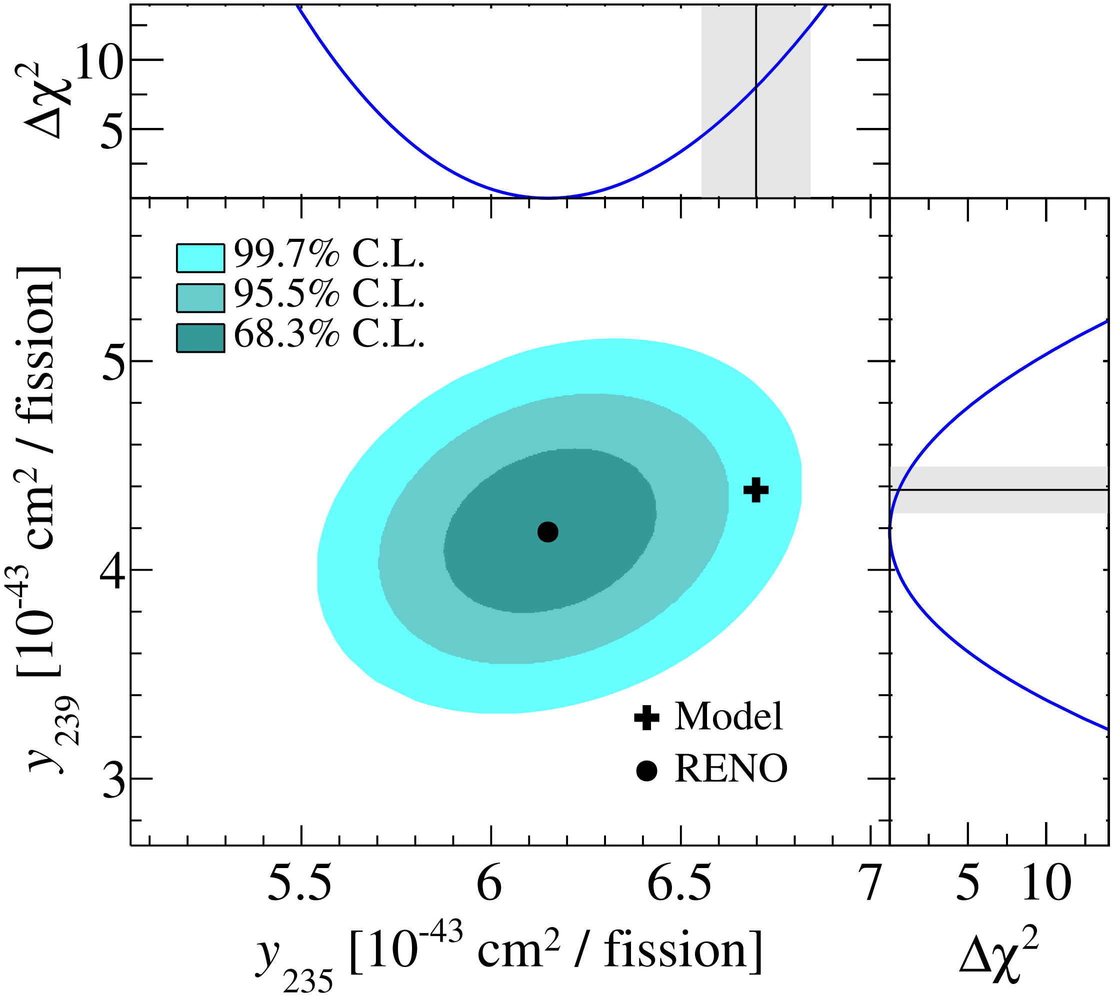
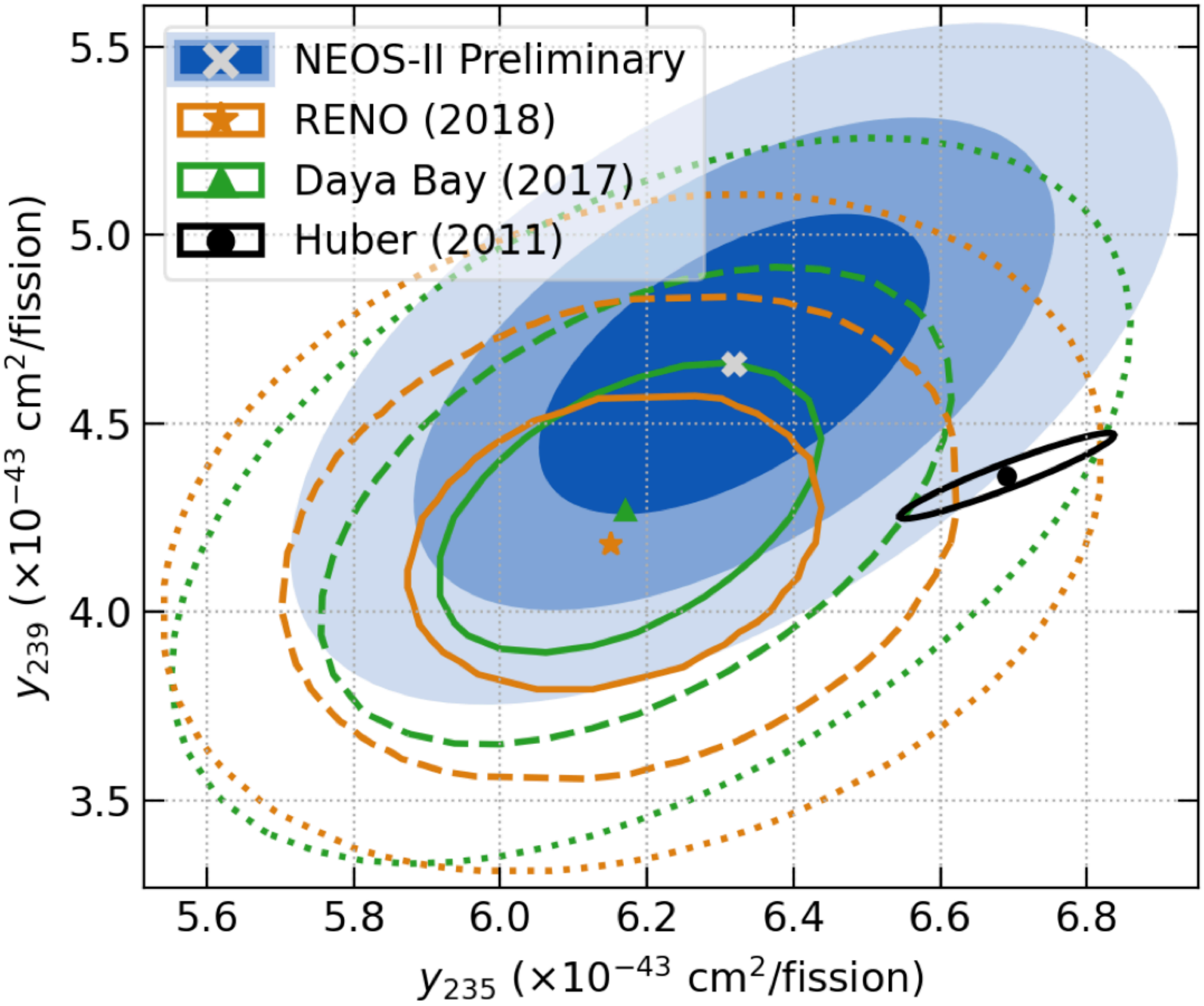


Figure from Bak et al., PRL **122, 232501 (2019)**

Analogous results obtained by NEOSS-II. See the talk by J. Kim at Neutrino 2022

- IBD Yields for ^{235}U & ^{239}Pu



Again, ^{239}Pu basically agrees with the H-M model, but ^{235}U is overestimated in the H-M model

Thus there are five independent determinations of the ^{235}U neutrino flux, suggesting that the prediction of the H-M model should be revised. The corresponding cross section per fission (in units of 10^{-43} cm^2/fission) are

Daya-Bay	6.17 ± 0.17
RENO	6.15 ± 0.19
NEOSS(prelim)	6.32 ± 0.18
EF model	6.29 ± 0.31
KI model	6.27 ± 0.13

They are thus perfectly consistent with each other. The same cross section in the H-M model is 6.74 ± 0.17, see Giunti et al., Phys. Lett. B**829**, 137054(2022). See also the talk by J. Kopp at Neutrino 2022.

Note:
The EF model is based on the work Estienne et al., PRL **123**, 022502 (2019).
The KI model is based on Kopeikin et al., (Phys.At.Nucl.**84**,1 (2021)) and Kopeikin et al, Phys. Rev.D **104**, L071301 (2021).

Summary:

1) There are five indications, consistent with each other, that the neutrino flux for ^{235}U in the H-M model should be reduced by 5-10 %, while the flux for ^{239}Pu seems to be reasonably well described by the H-M model.
2) All these findings are only at the 2-3 σ level. But taken together they strongly suggest that the standard H-M model fails for ^{235}U.
3) Likely explanation for this is some problem with the intensity normalization of the ILL electron spectrum for ^{235}U. Given the elapsed time it is unlikely that this assumption could be confirmed or rejected.
4) Accepting the need of reducing the ^{235}U flux in H-M model would essentially explain the reactor neutrino anomaly. Modified model would agree with the well determined total flux of reactor neutrinos.
5) The tension, or discrepancy, between the reactor neutrino flux and the gallium anomaly becomes even more pronounced.

spares

Experiments using nuclear reactors contributed significantly to the establishment of the current 3-oscillating neutrino flavor phenomenology, among other things.

Knowledge of reactor neutrino spectrum is essential for this success

Parameter	Main method(s)	Source(s)	Status
θ_{12}	Oscillations	solar, **reactor**	known
θ_{23}	Oscillations	atmospheric, accelerator	known
θ_{13}	Oscillations	**reactor**, accelerator	known
δ_{CP}	Oscillations	accelerator	hints
Δm^2_{21}	Oscillations	**reactor,** solar	known
$\|\Delta m^2_{31}\|$	Oscillations	**reactor**, accelerator, atmospheric	known
sign of Δm^2_{31}	Oscillations	**reactor**, accelerator, atmospheric	hints
mass $m_{1,2,3}$	Kinematics	β decay, cosmology	limits

(see Athar et al. arxiv 2111.07586)

Recent Very Short Baseline (VLBL) reactor neutrino experiments
(from Ahbar et al. 2111.07586)

Experiment	Power [$\mathrm{MW_{th}}$]	Baseline [m]	Target mass or volume	Target material	Segmentation
NEOS	2800	24	~1 m^3	GdLS	No
DANSS	3100	11-13	1 m^3	PS(Gd layer)	quasi 3D
Neutrino-4	100	6-12	1.8 ton	GDLS	2D
PROSPECT	85	7-12	4 ton	^{6}LiLS	2D
SoLid	72	6-9	1.6 ton	PS(^{6}Li layer)	3D
STEREO	57	9-11	2.4 m^3	GDLS	2D
NuLat*	any	any	0.9 ton	^{6}LiPS	3D
CHANDLER*	any	any	~1 ton	PS($^\wedge$Li layer)	3D
iDREAM*	3100	20	1 m^3	GDLS	No

* These are primarily reactor monitors

Neutrino-4 claims (at 2.7 σ) evidence for oscillations into sterile neutrinos, with Δm^2_{41} = 7.3 +- 1.17 eV^2 and $\sin^2 2\theta_{14}$ = 0.36 +- 0.12_{stat}. This is in tension with the results of Daya Bay, Bugey-3 and RENO, however agrees with the BEST ^{51}Cr ν_e source experiment with large Ga detectors.

Electron and antineutrino spectrum associated with fission is composed of ~6000 beta decay branches. At higher energies, above about 6 MeV, the number of important branches is greatly reduced, and individual shapes become relevant.

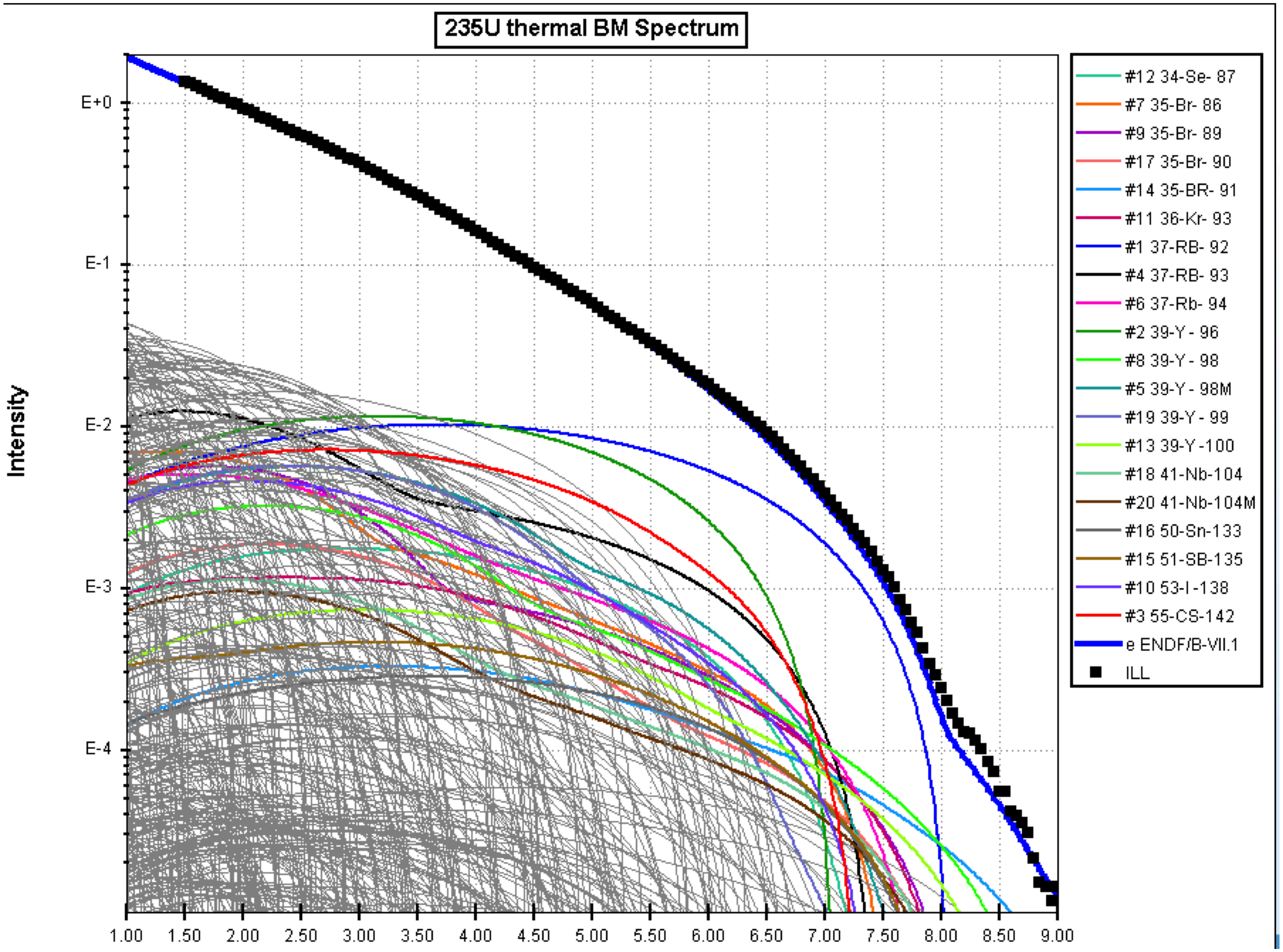
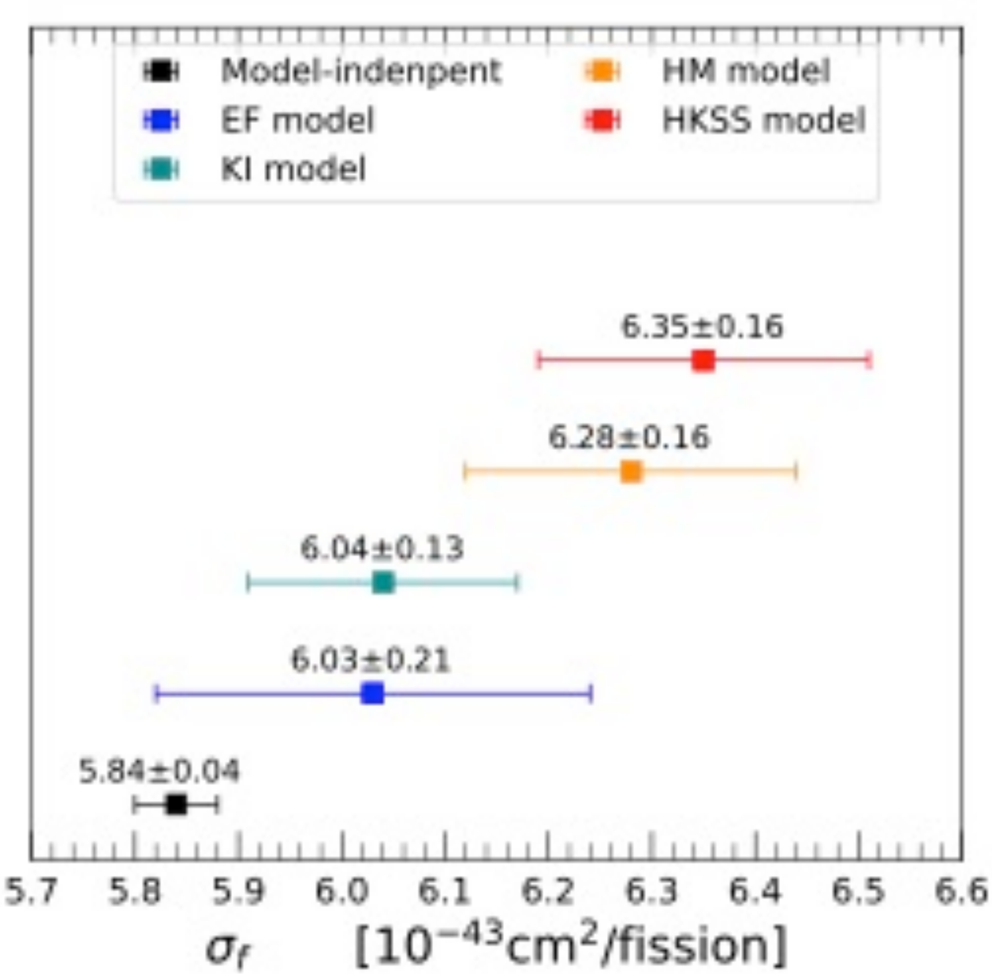


Figure from Sonzogni et al, PRC 91,011301

Determination of the cross section per fission from global analysis of all (power + research) reactor data.



for typical power reactor fuel composition

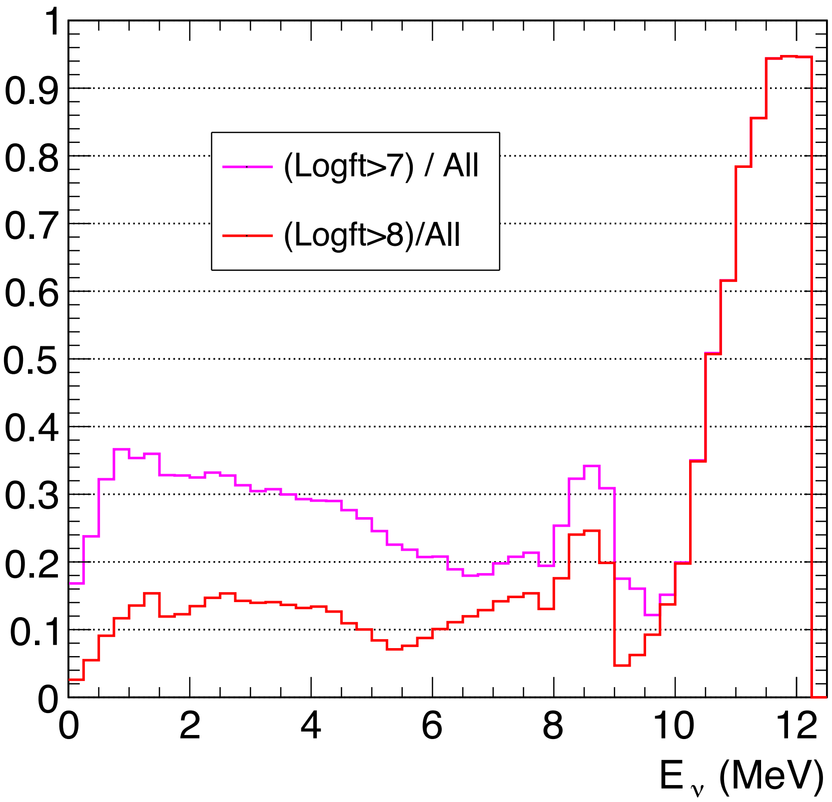
σ_{235} = 6.37 +- 0.08

σ_{235}^{HM} = 6.74 +- 0.17 (~2σ excess)

σ_{Pu} = 5.64 +- 0.20

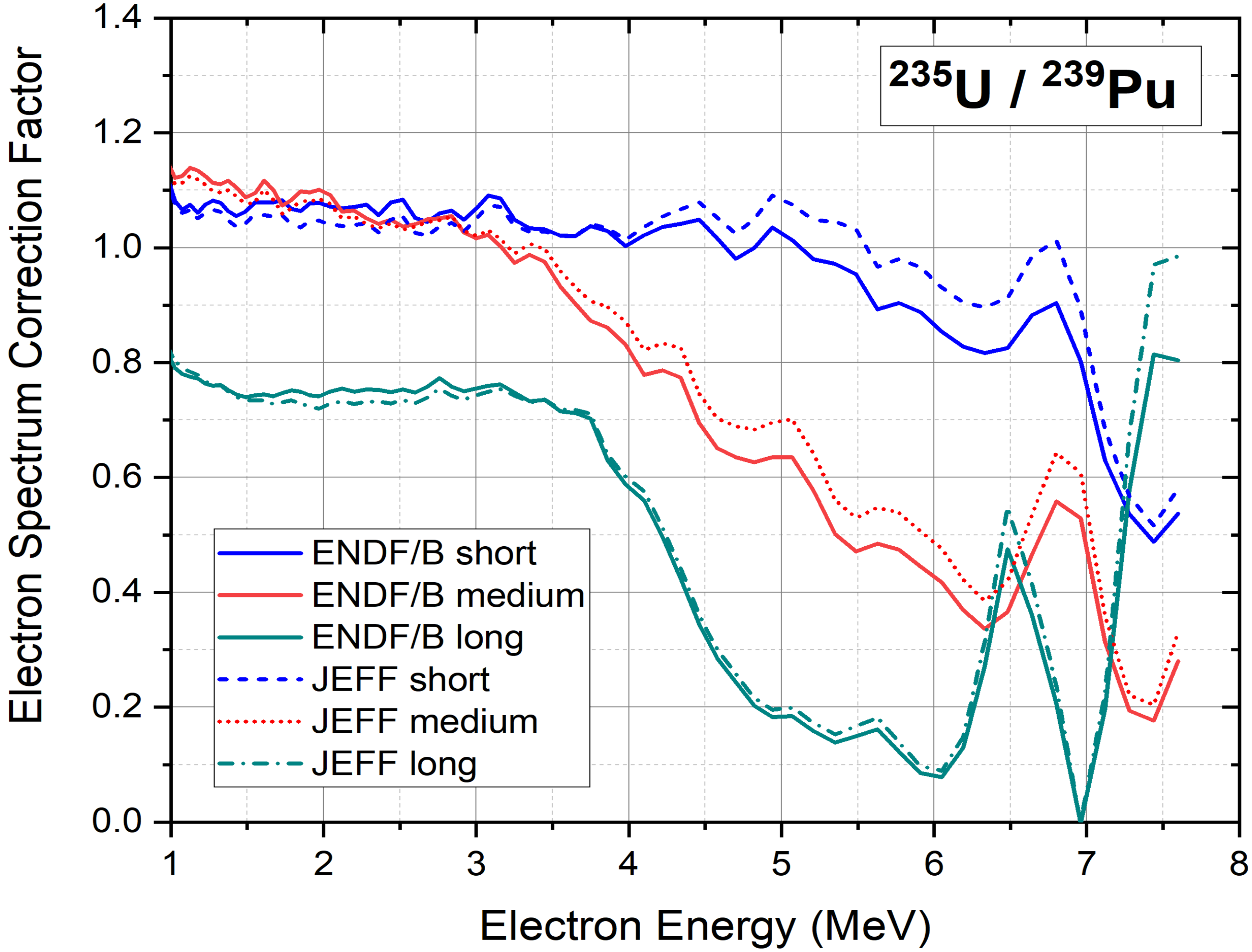
σ_{Pu}^{HM} = 5.48 +- 0.18 (within 1σ)

From Li and Xin,2112. 11386



β−decays with high log(ft) values represent a sizeable part of the fission ν spectra across all E_ν values (this indicates the large contribution of forbidden decays).

(D. Lhuillier, private communication)



Electron Spectrum Correction Factor
Electron Energy (MeV)
^{235}U / ^{239}Pu
ENDF/B short
ENDF/B medium
ENDF/B long
JEFF short
JEFF medium
JEFF long
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1
2
3
4
5
6
7
8