Reactor neutrino anomalies and possible solutions

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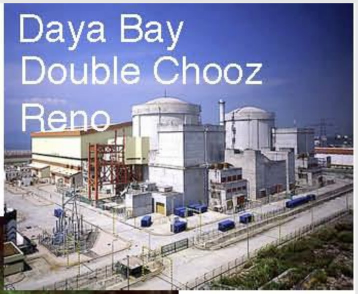
A history of reactor neutrino experiments

Neutrino Physics at Reactors

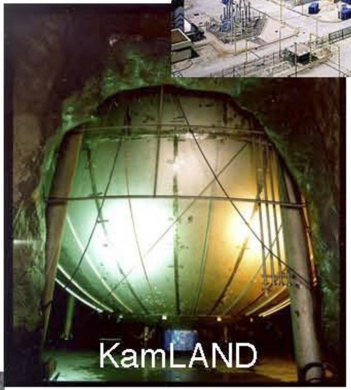
Next - Discovery and precision measurement of θ_{13}



2008 - Precision measurement of Δm_{12}^2 . Evidence for oscillation

2004 - Evidence for spectral distortion

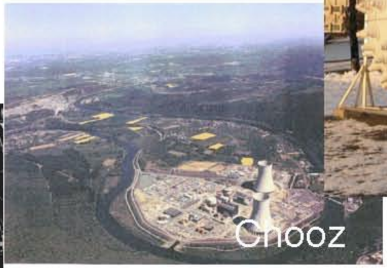
2003 - First observation of reactor antineutrino disappearance



1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

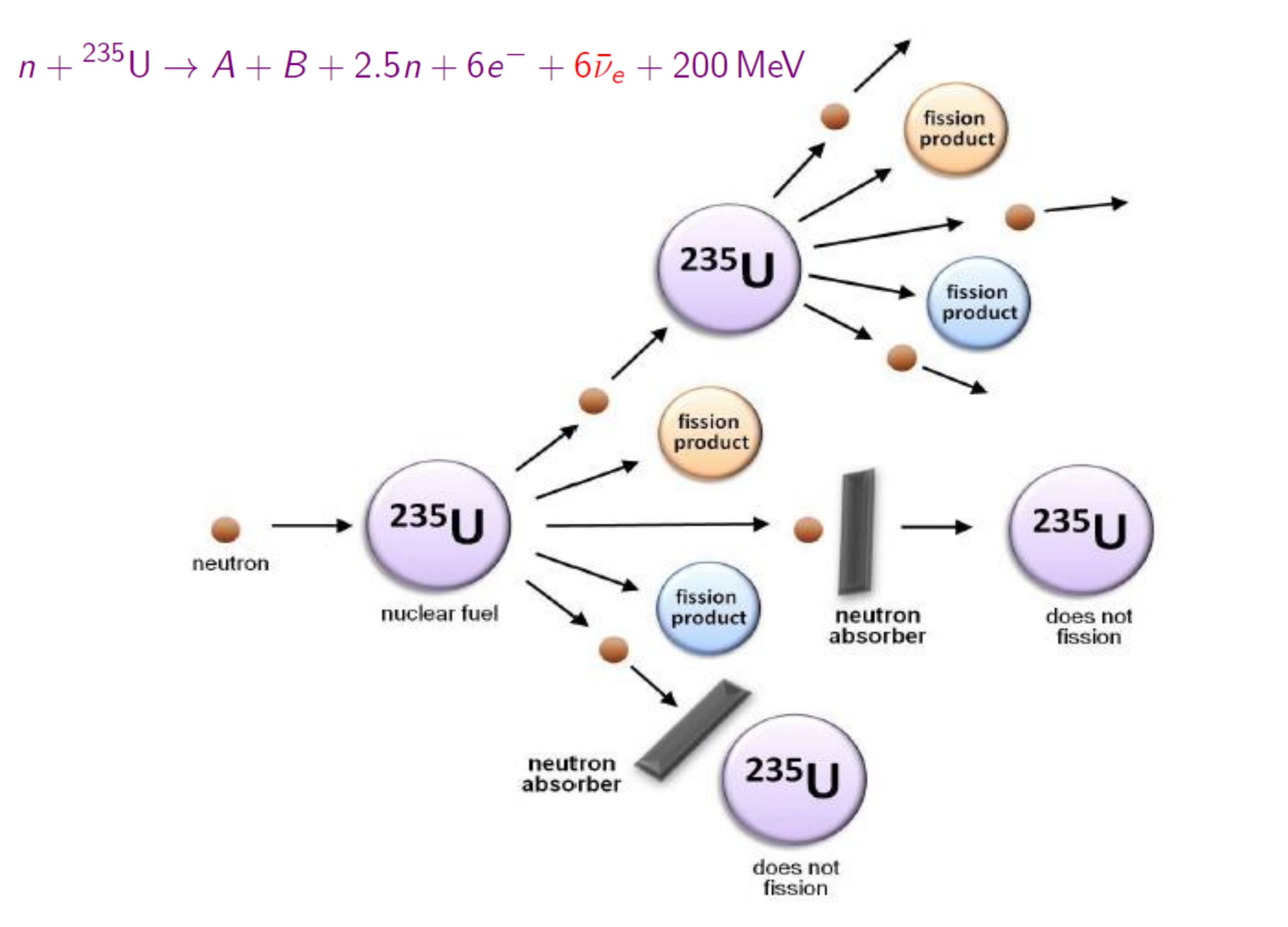


Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

slide of K. Heeger

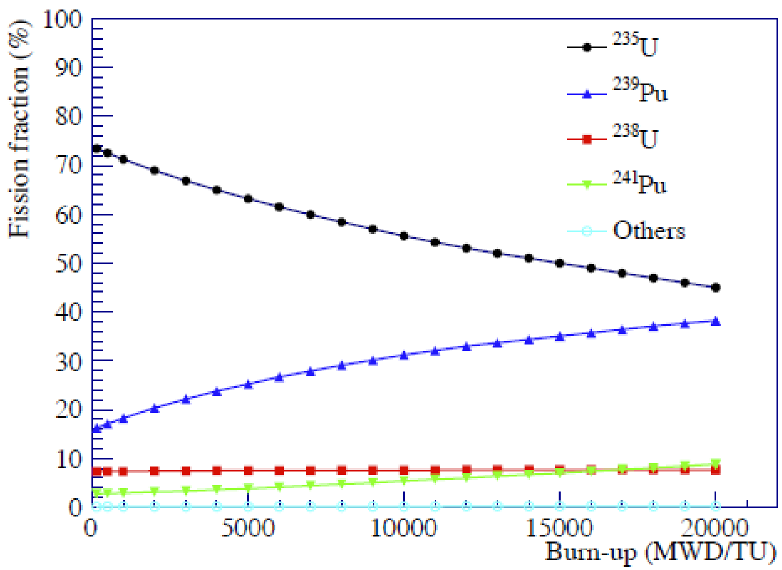
Neutrino emission from reactors

- **Reactor neutrinos (electron antineutrinos) are produced from beta decays of the neutron-rich fission products**



Commercial or Research reactors

- **Commercial reactors (Daya Bay as LWR): 4 main fission isotopes**



[Daya Bay, Chin. Phys. C 41 (2017) 013002]

- ^{239}Pu is generated from ^{238}U:

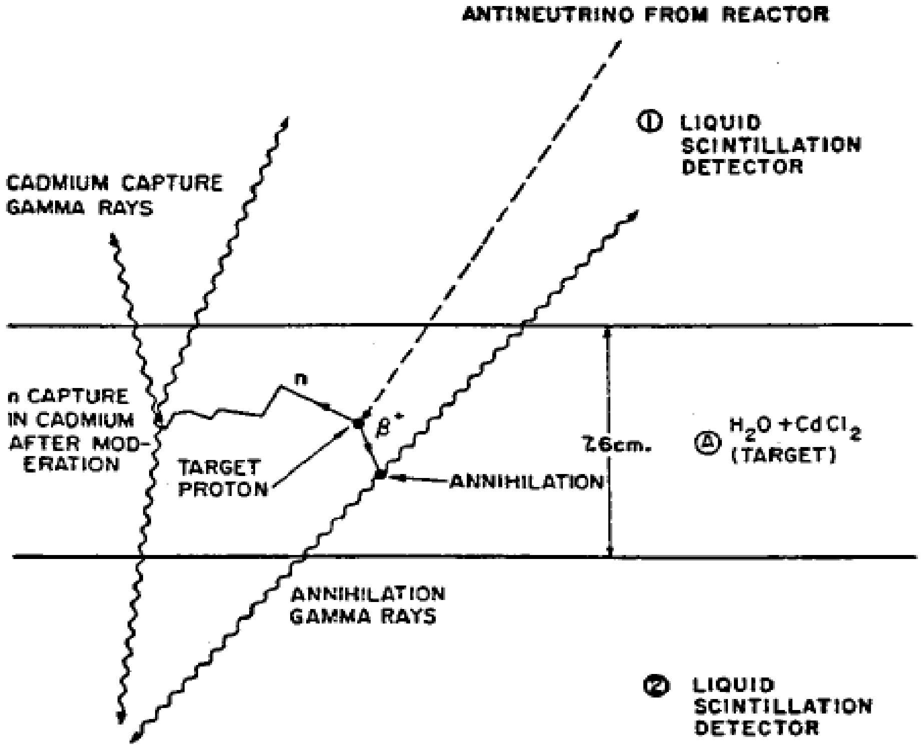
$$n + {}^{238}\text{U} \rightarrow {}^{239}\text{U} + \gamma$$
$$\downarrow$$
$${}^{239}\text{Np} + e^- + \bar{\nu}_e$$
$$\downarrow$$
$${}^{239}\text{Pu} + e^- + \bar{\nu}_e$$

- ^{241}Pu is generated from ^{239}Pu:

$$n + {}^{239}\text{Pu} \rightarrow {}^{240}\text{Pu} + \gamma$$
$$n + {}^{240}\text{Pu} \rightarrow {}^{241}\text{Pu} + \gamma$$

- **Research reactors:**
- **Use Highly Enriched Uranium (HEU): >90% ^{235}U**
- **Burning cycle is short (about 1 month): ^{235}U fission fraction >99%**

Detection: Inverse beta Decay



$$\bar{\nu}_e + p \to n + e^+$$

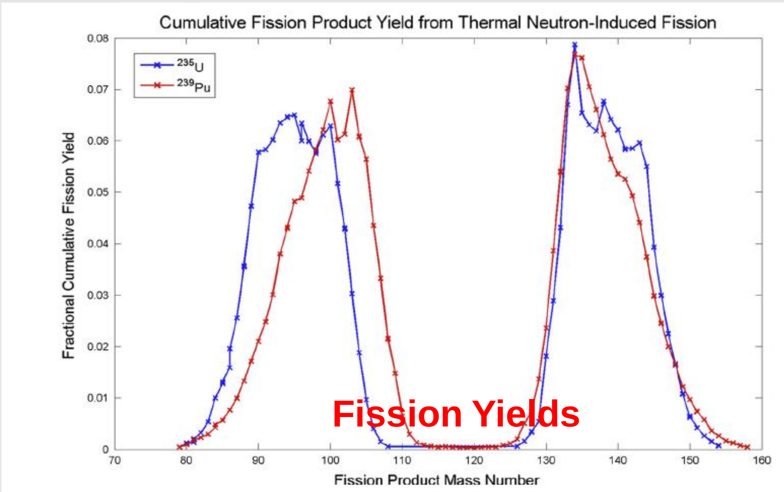
Cowan and Reines 1956

- The delayed ($\lesssim 200\,\mu$s) neutron capture signal is crucial for the background suppression.
- Well-known cross section obtained by crossing from the neutron lifetime.
- Neutrino energy measurement: $E_{\bar{\nu}_e} \simeq T_e + 1.8\,\text{MeV}$

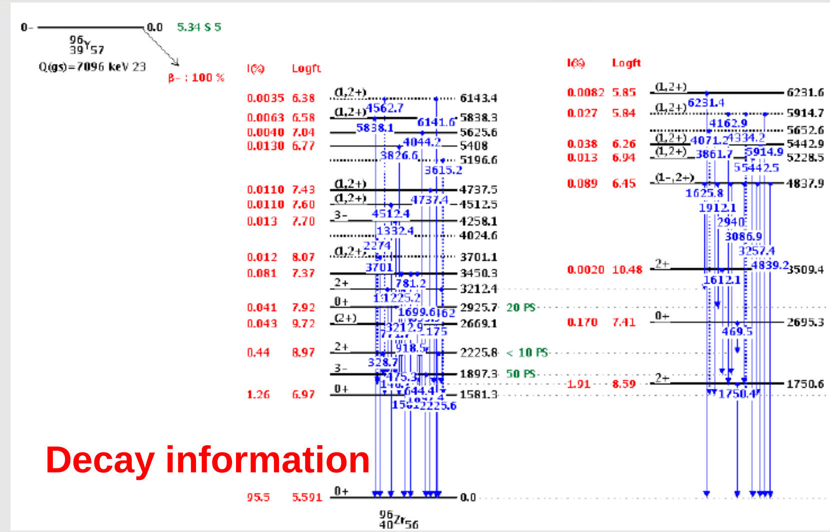
$$T_e = E_{\text{prompt}} - 2m_e$$

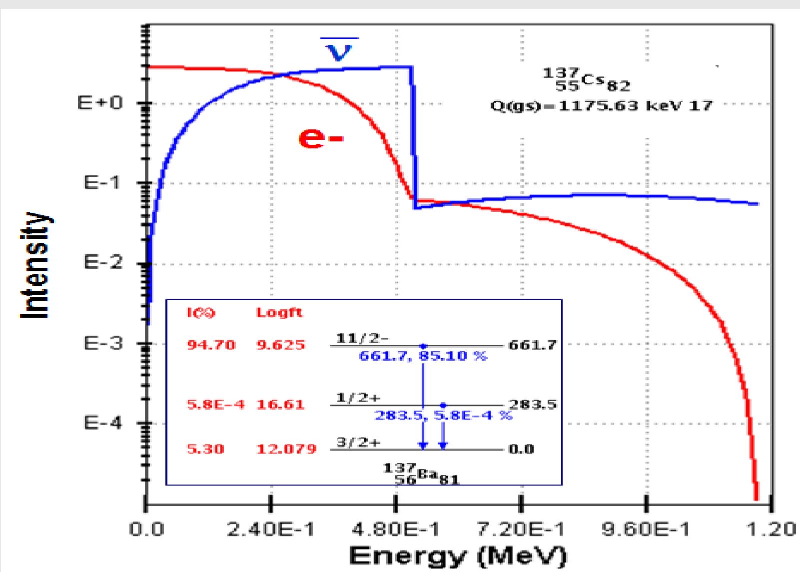
E_{prompt} is total visible prompt energy from positron annihilation

How to calculate the neutrino flux?



[Dayman, Biegalski, Haas, Rad. Nucl. Chem. 305 (2015) 213]





To calculate the neutrino flux, we need:

(a) Fission yields + decay information (nuclear data)

(b) Single beta-decay spectrum

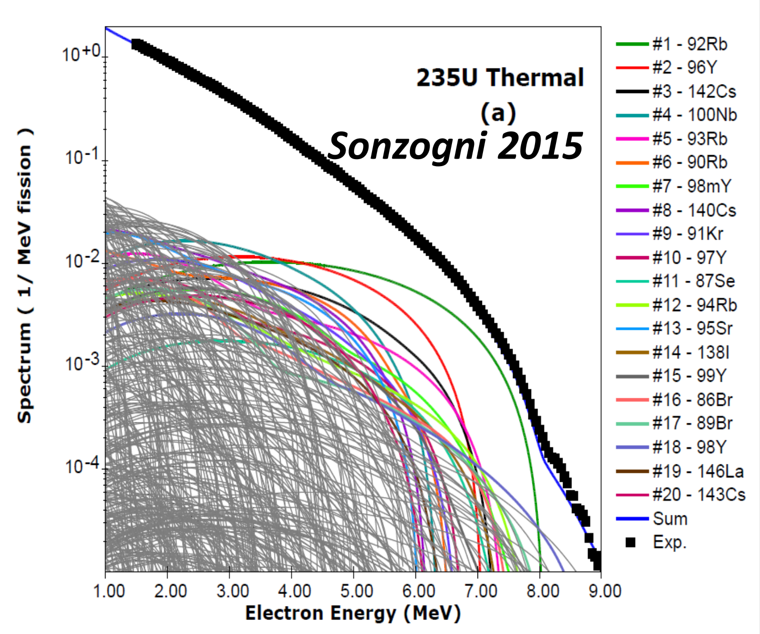
The ab initio method:

Take nuclear data, and then make the summation:

$$S_k(E) = \sum_{f=1}^{N_f} \mathcal{A}_f \times S_f(E),$$

$$S_f(E) = \sum_{b=1}^{N_b} BR_f^b \times S_f^b(Z_f, A_f, E_{0f}^b, E),$$

$$S_f^b(E_e, Z_f, A_f) = S_0(E_e)F(E_e, Z_f, A_f)C(E_e)(1 + \delta(E_e, Z_f, A_f)),$$



~1000 isotopes, ~6000 branches

Different nuclear databases have different reliability:

JEFF (Europe), ENDF (US), JENDL (Japan), CENDL (China) etc.

(a) Missing information or isotopes

(b) Pandemonium Problem (TAGS)

(c) Single beta spectrum investigation

Reactor neutrino prediction in 1980s

First ab-initio calculations were done in late 1970 and early 1980 (*Davis et al. 1979, Vogel et al. 1981, Klapdor & Metzinger 1982*)

PHYSICAL REVIEW C VOLUME 19, NUMBER 6 JUNE 1979

Reactor antineutrino spectra and their application to antineutrino-induced reactions

B. R. Davis and P. Vogel
California Institute of Technology, Pasadena, California 91125

F. M. Mann and R. E. Schenter
Hanford Engineering Development Laboratory, Richland, Washington 99352

(Received 13 December 1978)

The knowledge of reactor antineutrino spectra is necessary for the interpretation of weak-interaction
experiments located at nuclear reactors. We calcu
thermal neutron fission of ^{235}U and ^{239}Pu for var
part ($E \gtrsim 4$ MeV) of the spectra depends sensitiv
experimentally unknown decay schemes. We also
electron spectrum into the antineutrino spectrum.
and reaction rates for the inverse neutron β de
disintegration, and the antineutrino-electron scatte

PHYSICAL REVIEW C VOLUME 24, NUMBER 4 OCTOBER 1981

Reactor antineutrino spectra and their application to antineutrino-induced reactions. II

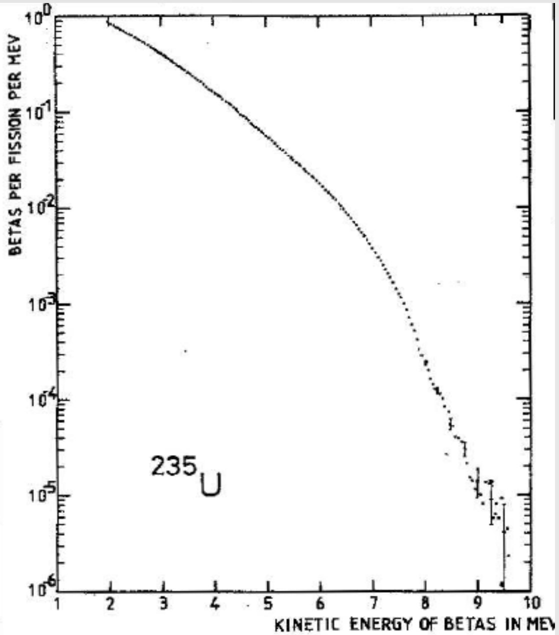
P. Vogel and G. K. Schenter
California Institute of Technology, Pasadena, California 91125

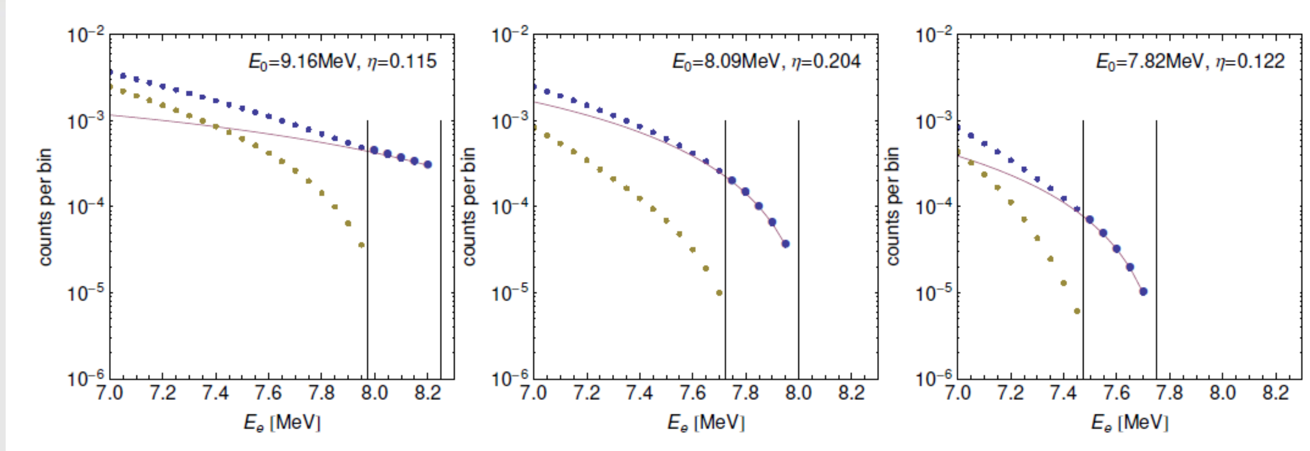
F. M. Mann and R. E. Schenter
Hanford Engineering Development Laboratory, Richland, Washington 99352

(Received 29 January 1981)

The antineutrino and electron spectra associated with various nuclear fuels are calculated. While there are substantial differences between the spectra of different uranium and plutonium isotopes, the dependence on the energy and flux of the fission-inducing neutrons is very weak. The resulting spectra can be used for the calculation of the antineutrino and electron spectra of an arbitrary nuclear reactor at various stages of its refueling cycle. The sources of uncertainties in the spectrum are identified and analyzed in detail. The exposure time dependence of the spectrum is also discussed. The averaged cross sections of the inverse neutron β decay, weak charged and neutral-current-induced deuteron disintegration, and the antineutrino-electron scattering are then evaluated using the resulting $\bar{\nu}_e$ spectra.

Reactor neutrino prediction in 1980s





(1) Beta measurements of the ^{235}U foil with a magnetic spectrometer at the ILL reactor:

Schreckenbach, et al. 1980s **(first 235, then 239, 241)**

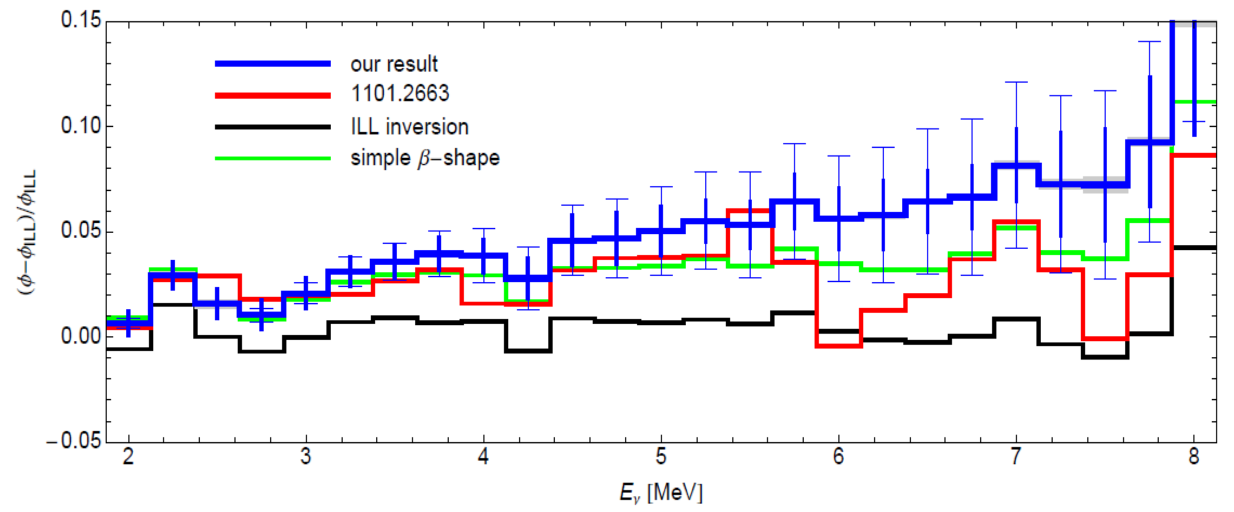
(2) Using dozens of virtual branches to fit the beta spectra, then obtain the neutrino spectra

(3) For ^{238}U, first measurement in Haag et al., 2013

The ILL + Vogel model had been used until 2011, and was consistent with measurement

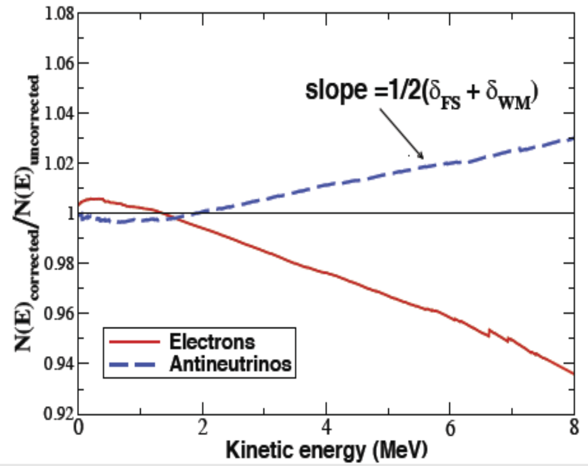
New conversion evaluations in 2011

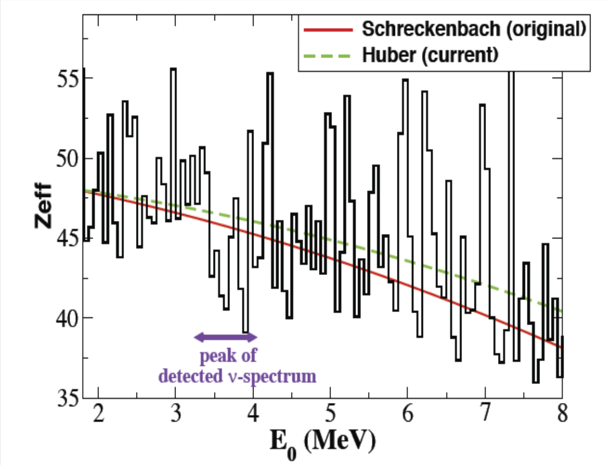
T. Mueller et al., Phys. Rev. C83, 054615 (2011); P. Huber, Phys. Rev. C84, 024617 (2011)

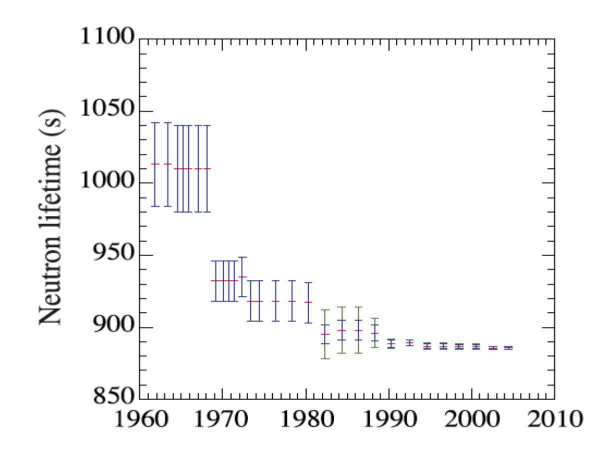


A strange conspiracy: **several small (1%-2%), but same-sign increases** of the reactor neutrino flux.

→ Reactor anomaly



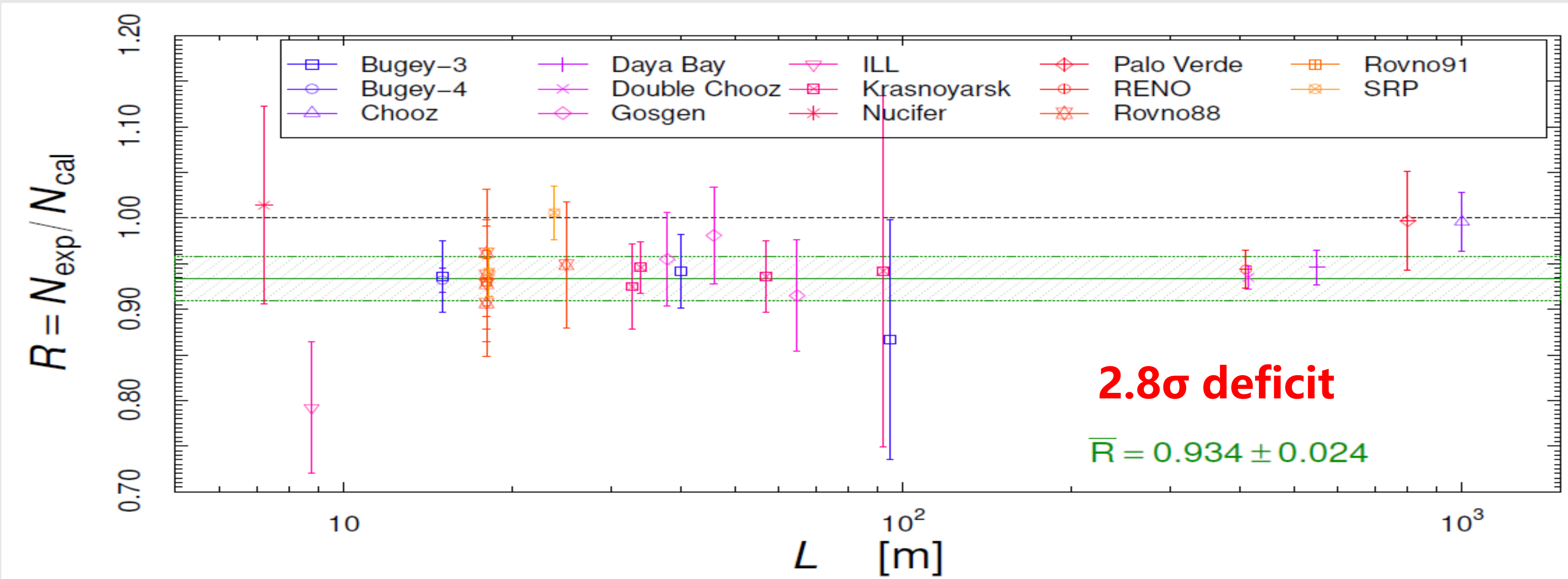




Reactor Rate Anomaly

[Mention et al, PRD 83 (2011) 073006]

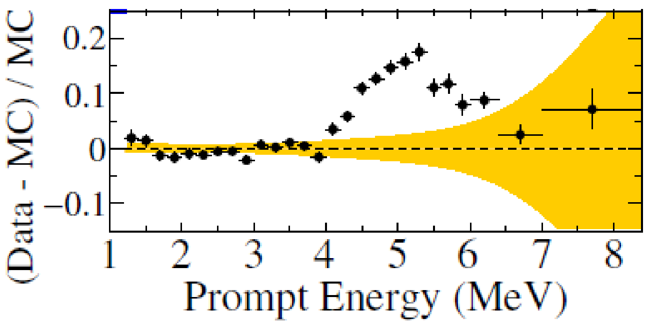
New reactor $\bar{\nu}_e$ fluxes [Mueller et al, PRC 83 (2011) 054615; Huber, PRC 84 (2011) 024617]



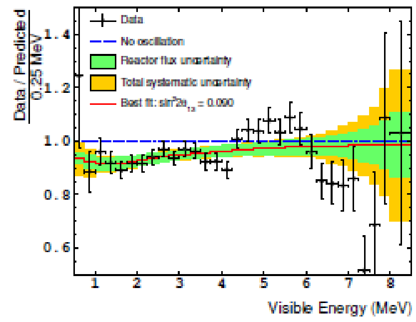
Possible causes:

- **An excess of the reactor antineutrino flux estimation**
- **Short-Baseline neutrino oscillations**
- **Any combination of the above two (hybrid solution)**

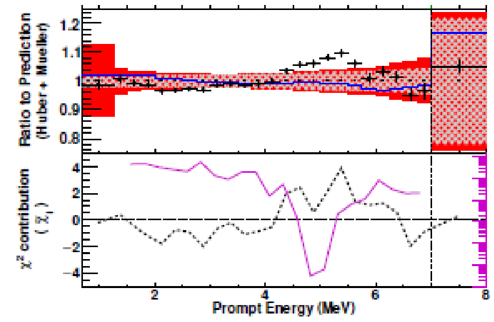
Reactor Spectrum Anomaly (Bump!)



[RENO, arXiv:1511.05849]



[Double Chooz, arXiv:1406.7763]



[Daya Bay, arXiv:1508.04233]

How to understand the BUMP?

(1) Is it observed in ALL the experiments? (next page)

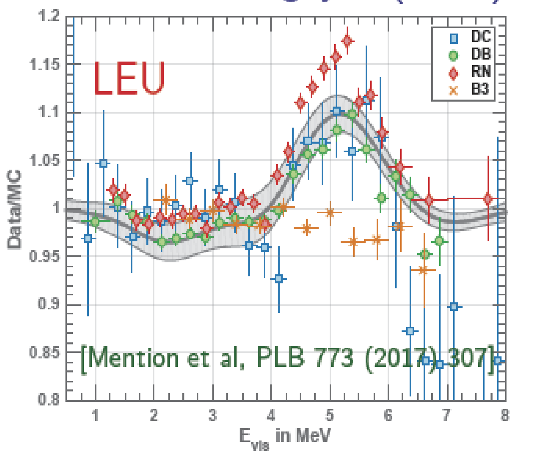
(2) Other backgrounds or other neutrino source? No, it is correlated with the reactor power.

(3) Cannot be explained by neutrino oscillations (averaged in RENO, Double CHOOZ and Daya Bay)

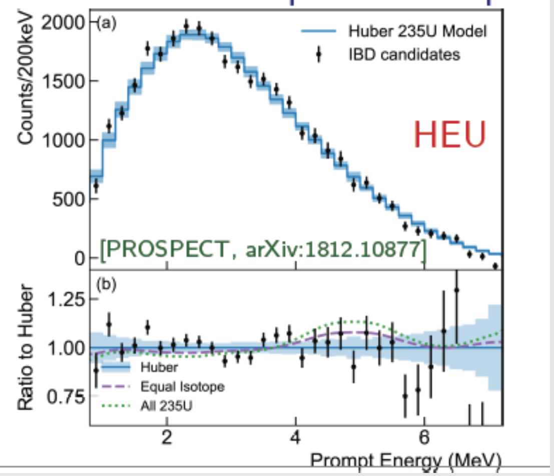
Need to re-evaluate the flux calculation before claim new physics

Observation of other experiments

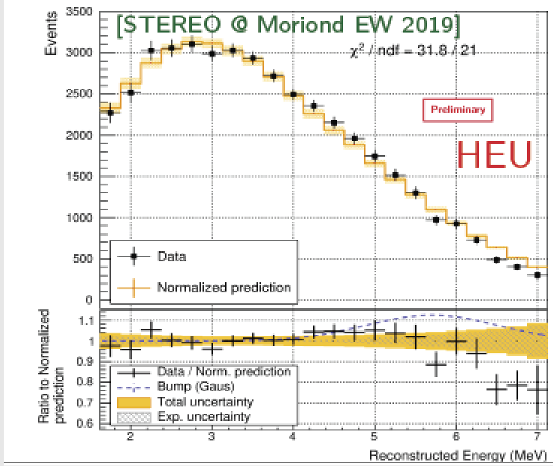
Not seen at Bugey-3 (1995)

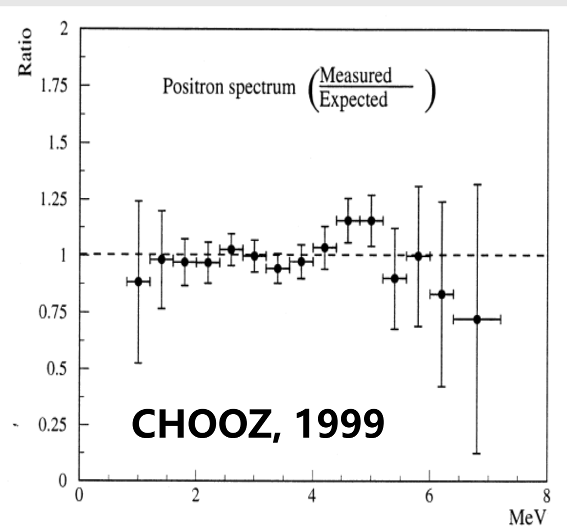


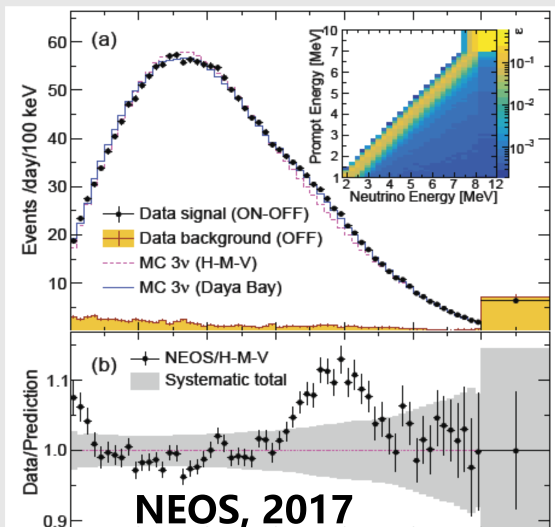
PROSPECT: bump or no bump?



STEREO: no bump







BUMP Puzzle:

(a) Related to the reactor type?

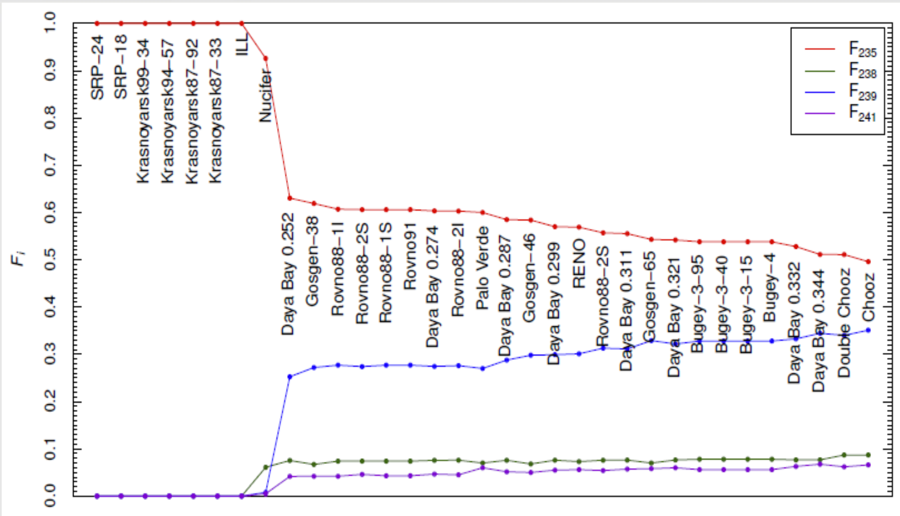
(b) Related to the detector type?

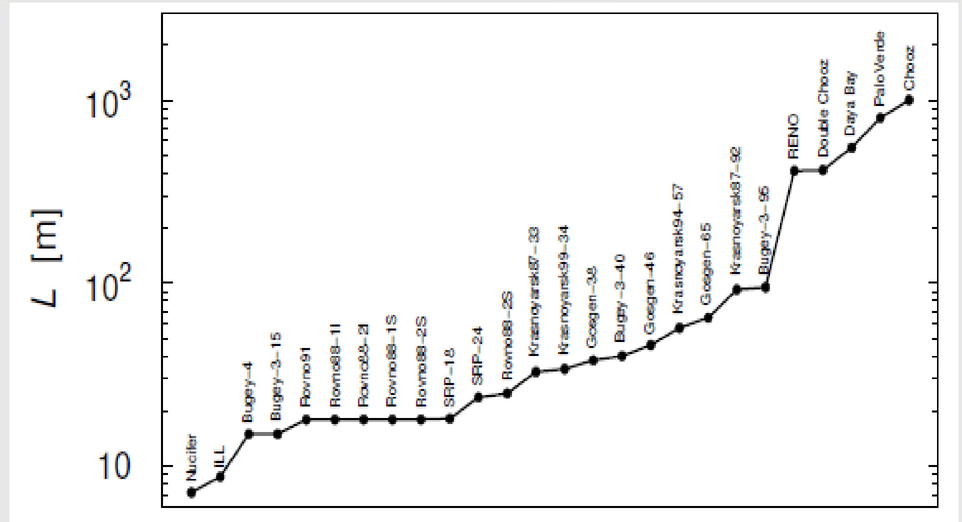
(A) Attempts for the reactor rate anomaly

Reactor Rates Data

a	Experiment	f^a_{235}	f^a_{238}	f^a_{239}	f^a_{241}	$R^{exp}_{a,SH}$	σ^{exp}_a [%]	σ^{cor}_a [%]	L_a [m]
1	Bugey-4	0.538	0.078	0.328	0.056	0.932	1.4	1.4	15
2	Rovno91	0.606	0.074	0.277	0.043	0.930	2.8		18
3	Rovno88-1I	0.607	0.074	0.277	0.042	0.907	6.4	3.8	18
4	Rovno88-2I	0.603	0.076	0.276	0.045	0.938	6.4		18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	2.2	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.8	25
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8		18
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2		15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.0	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2		95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4		37.9
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4	2.0	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7	3.8	64.7
14	ILL	1	0	0	0	0.792	9.1		8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.1	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4		92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	0	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	0	34
19	SRP-18	1	0	0	0	0.941	2.8	0	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0	≈ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	≈ 415

Classification as fission fraction or distance





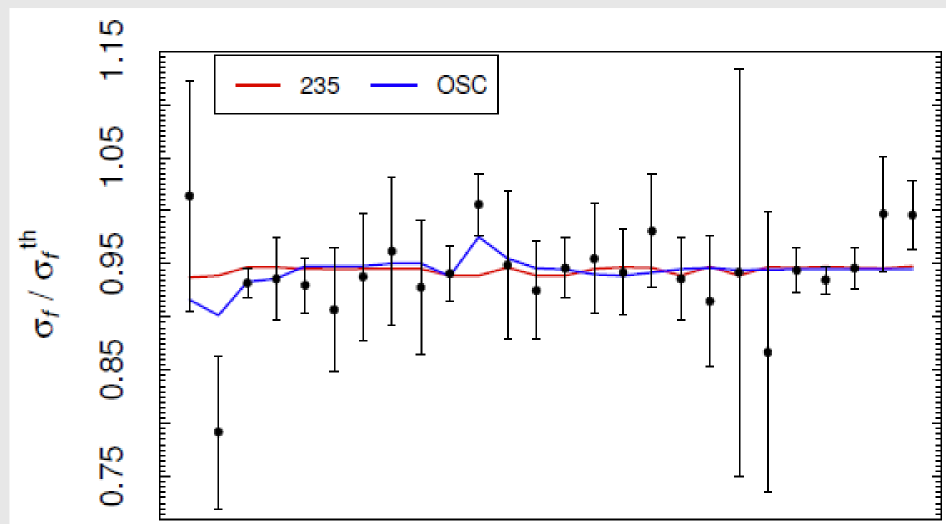
Non-nested model comparison between these two models.

Need MC simulation to do the statistical assessment.

	r_{235}	OSC
χ^2_{min}	25.3	23.0
NDF	32	31
GoF	79%	85%

Best fit: OSC

MC: r_{235} disfavored at 1.7σ



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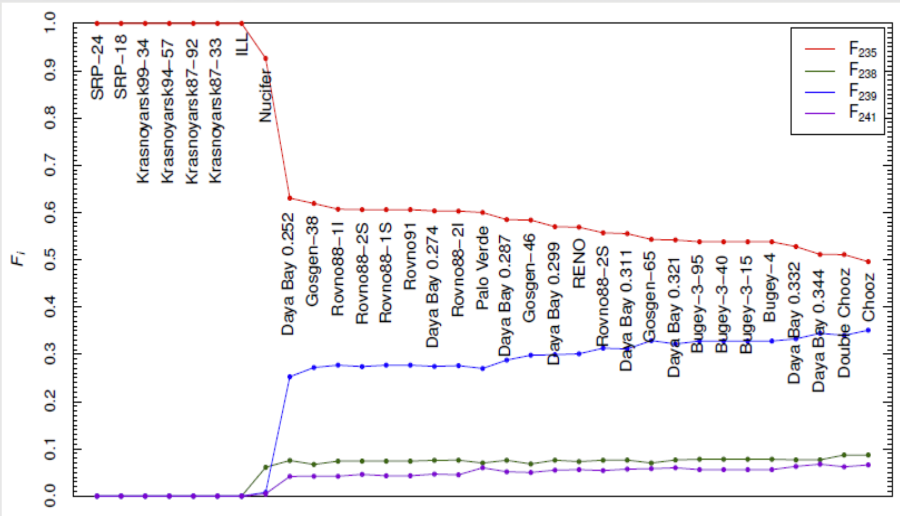

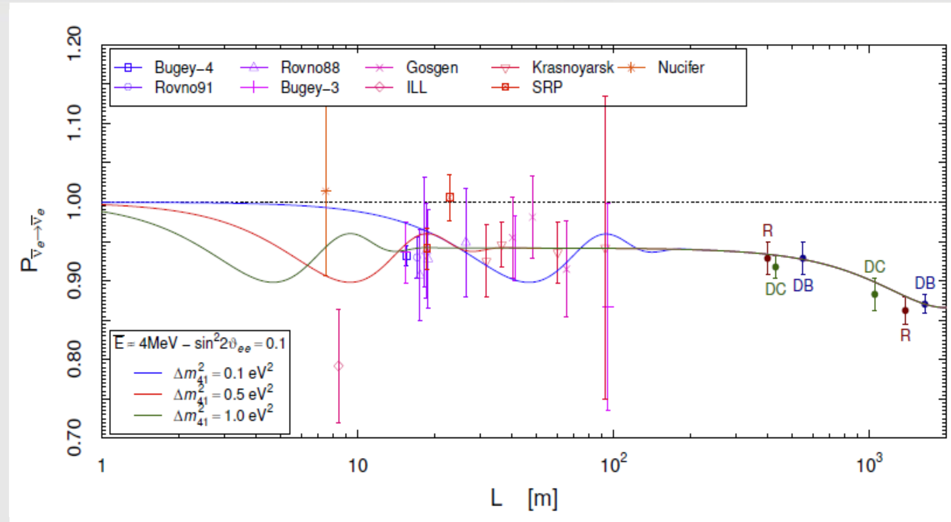

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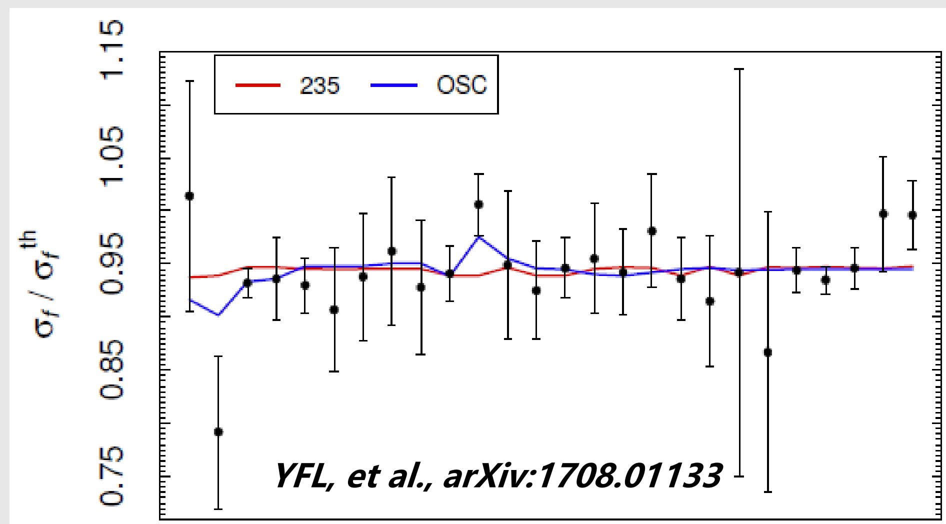
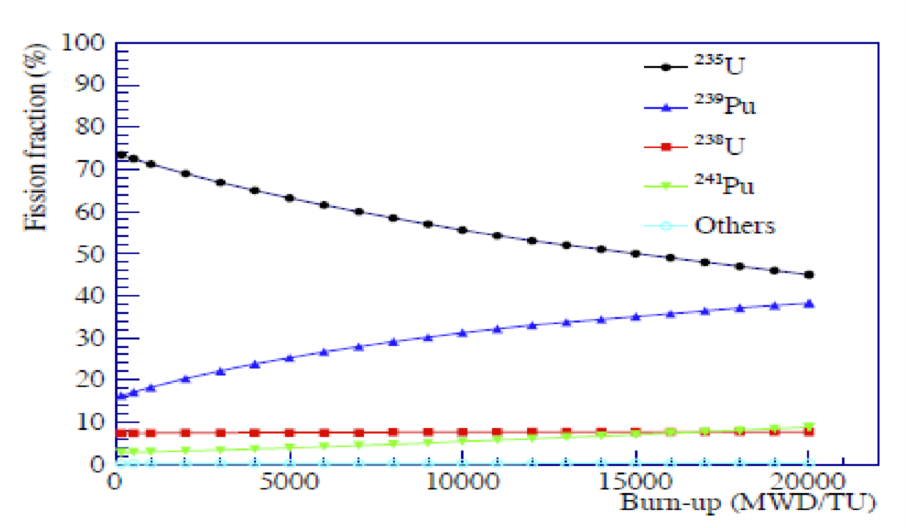
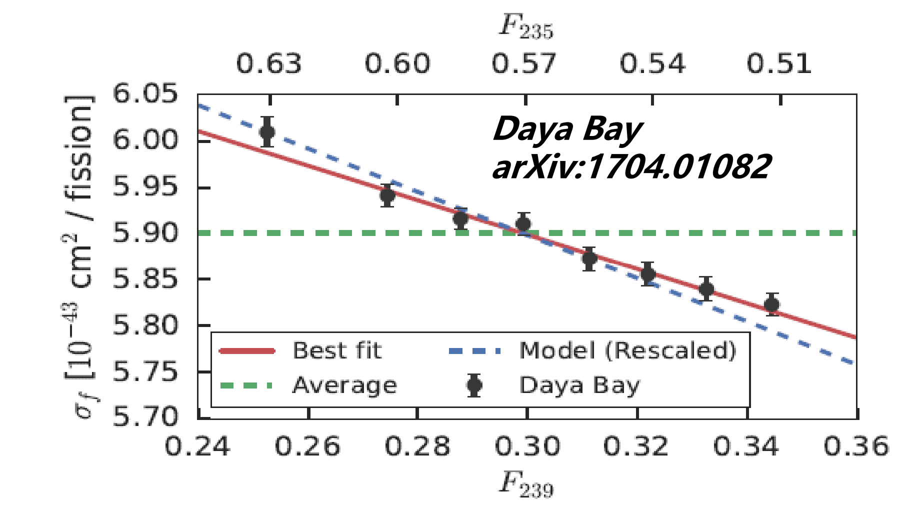
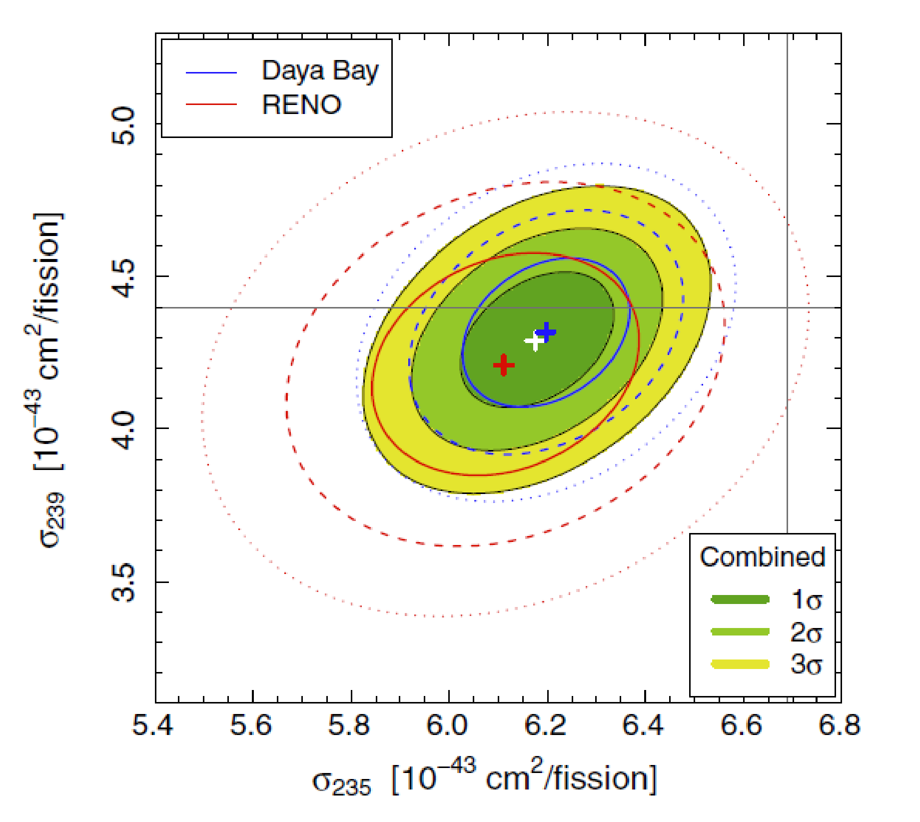


New Fuel Evolution Data







Reactor rates as function of the fuel fraction: A new information (slope)!

In consistent with model prediction

Global flux data (rates + evolution)

	235	239	235+239	235+238+239	235=239=241+238	OSC	235+OSC	239+OSC
$\chi^2_{\min}$	34.6	41.6	34.1	29.9	38.6	33.1	29.5	26.9
NDF	39	39	38	37	38	38	37	37
GoF	67%	36%	65%	79%	44%	69%	80%	89%
r_5	0.933± 0.010	(0.941)	0.932± 0.009	0.952± 0.014	0.941± 0.013	(1.014)	0.984± 0.025	(1.014)
r_8	(0.890)	(0.868)	(0.914)	0.672± 0.135	0.926± 0.096	(1.021)	(0.969)	(0.956)
r_9	(0.987)	0.997± 0.029	0.969± 0.030	1.042± 0.046	0.944± 0.015	(1.019)	(1.026)	1.099± 0.040
r_1	(0.989)	(0.938)	(1.003)	(1.001)	0.942± 0.013	(1.015)	(1.024)	(1.015)
Δm^2_{41}						$0.49^{+0.02}_{-0.03}$	$0.48^{+0.05}_{-0.03}$	0.49± 0.02
$\sin^2 2\vartheta_{ee}$						0.15± 0.04	$0.10^{+0.05}_{-0.04}$	0.16± 0.04

arXiv:1901.01807

Global Flux Data (rates + evolution):

a) A common inaccuracy of all beta conversion predictions: disfavored at 3.0σ

b) A deficit for the U235 rate is always obtained.

c) Oscillation-including hypothesis is favored over the oscillation-including one: moderately at 1-2σ

Problem in ab initio calculation (1)

There is a known "Pandemonium" problem in the nuclear data measurements:

Before the 90s, conventional detection techniques used high resolution γ-ray spectroscopy:

(1) Excellent resolution but efficiency which strongly decreases at high energy

(2) Danger of overlooking the existence of β-feeding into the high energy nuclear levels of daughter nuclei

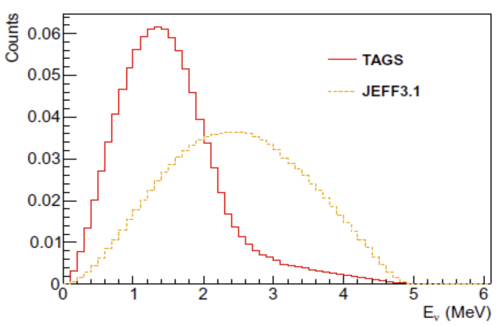


FIG. 1. Illustration of the pandemonium effect on the ^{105}Mo nucleus anti-ν energy spectrum presents in the JEFF3.1 data base and corrected in the TAS data.

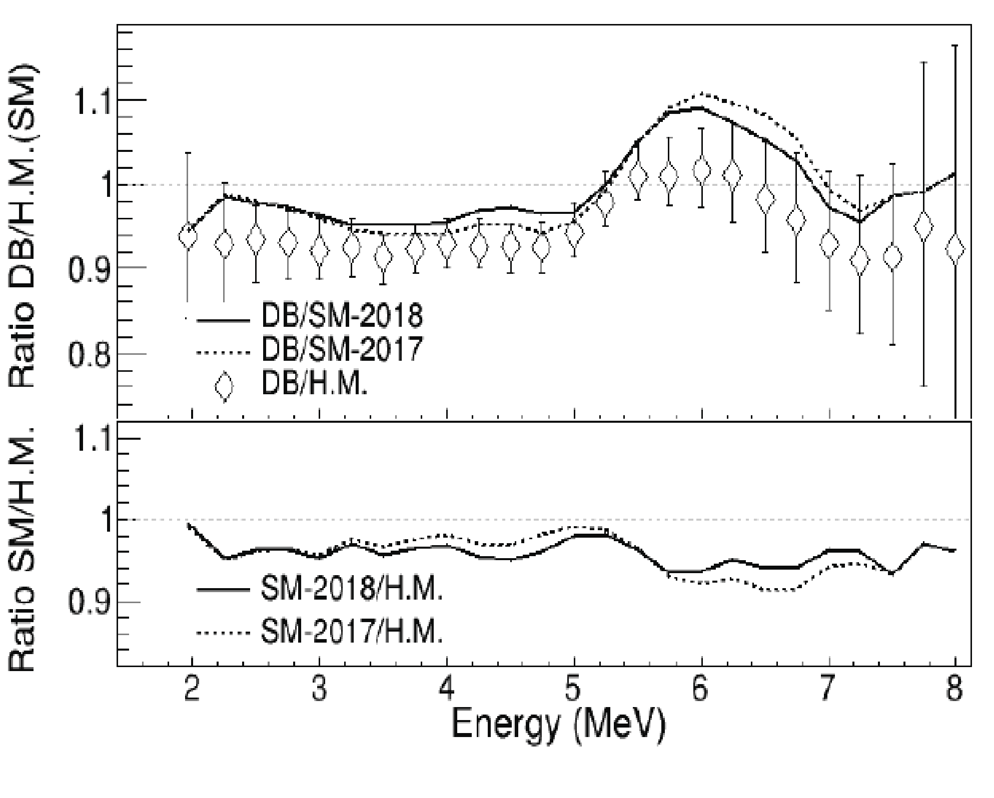
Phenomenon commonly called « pandemonium effect » by J. C Hardy in 1977

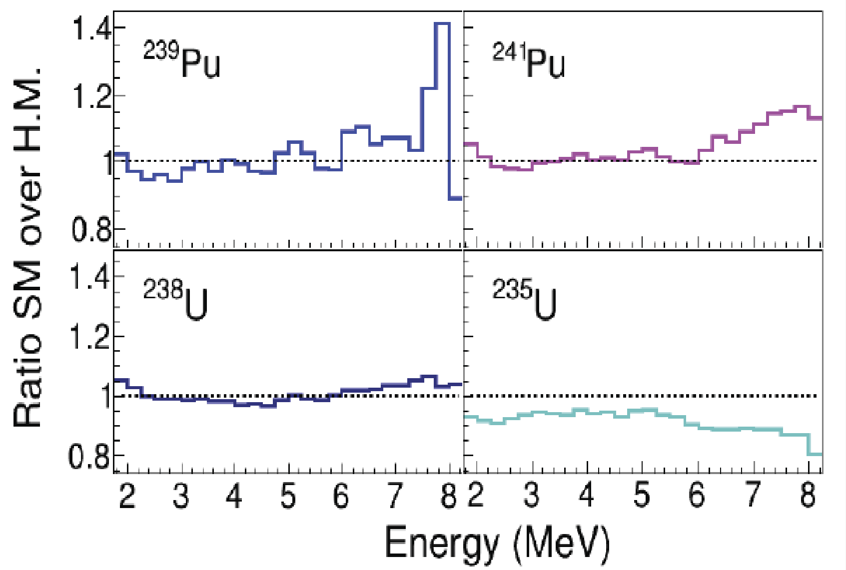
Need pandemonium-free data: **Total Absorption γ-ray Spectroscopy (TAGS)**

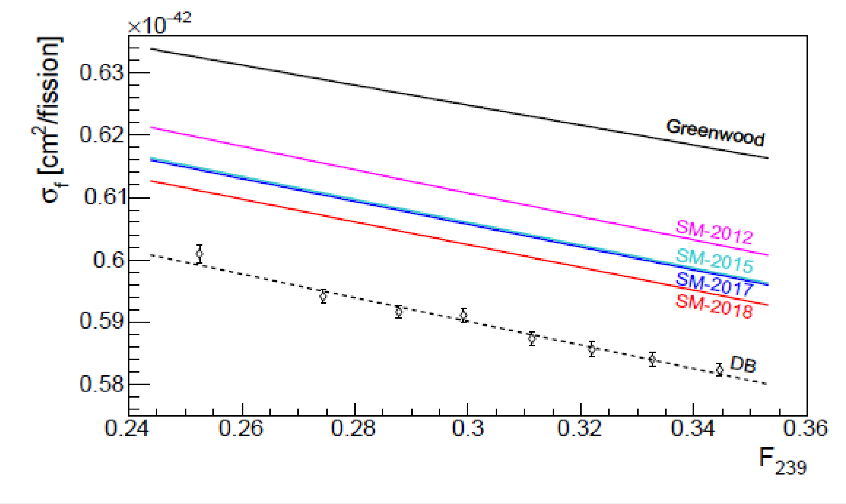
Model with Pandemonium free nuclear data

Estienne et al. 1904.09358:

Updated beta-feeding functions **from total absorption spectroscopy for key isotopes.**





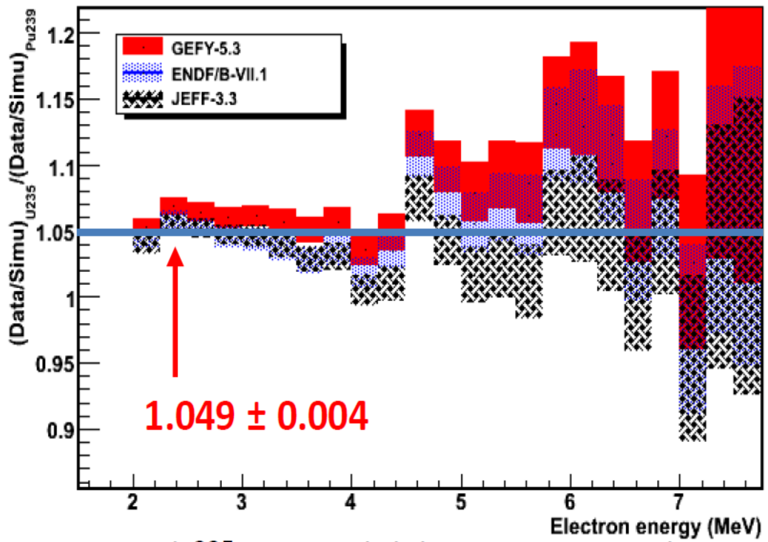


Another hint for the U235 issue

In the conversion method based on ILL beta spectra:

Four measurement performed at the ILL in the 80's

- **^{235}U(1):** [1] *K. Schreckenbach et al., PLB99 (1981) 251*
  ↳ Normalized on: **^{197}Au(n,e$^-$)^{198}Au**
- **^{235}U(2):** [2] *K. Schreckenbach et al.", PLB160 (1985) 325*
  ↳ Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and**
  β-decay following ^{115}In(n, γ)^{116m}In
- **^{239}Pu:** [3] *F. Feilitzch et al.", PLB118 (1982) 162*
  ↳ Normalized on: **^{197}Au(n,e$^-$)^{198}Au and ^{115}In(n,γ)^{116}In**
- **^{241}Pu:** [4] *A.A Hahn et al., PLB218 (1989) 365*
  ↳ Normalized on: **^{207}Pb(n,e$^-$)^{208}Pb and ^{115}In(n,e$^-$)^{116m}In**



b) ^{235}U from (2) (M-H reference)

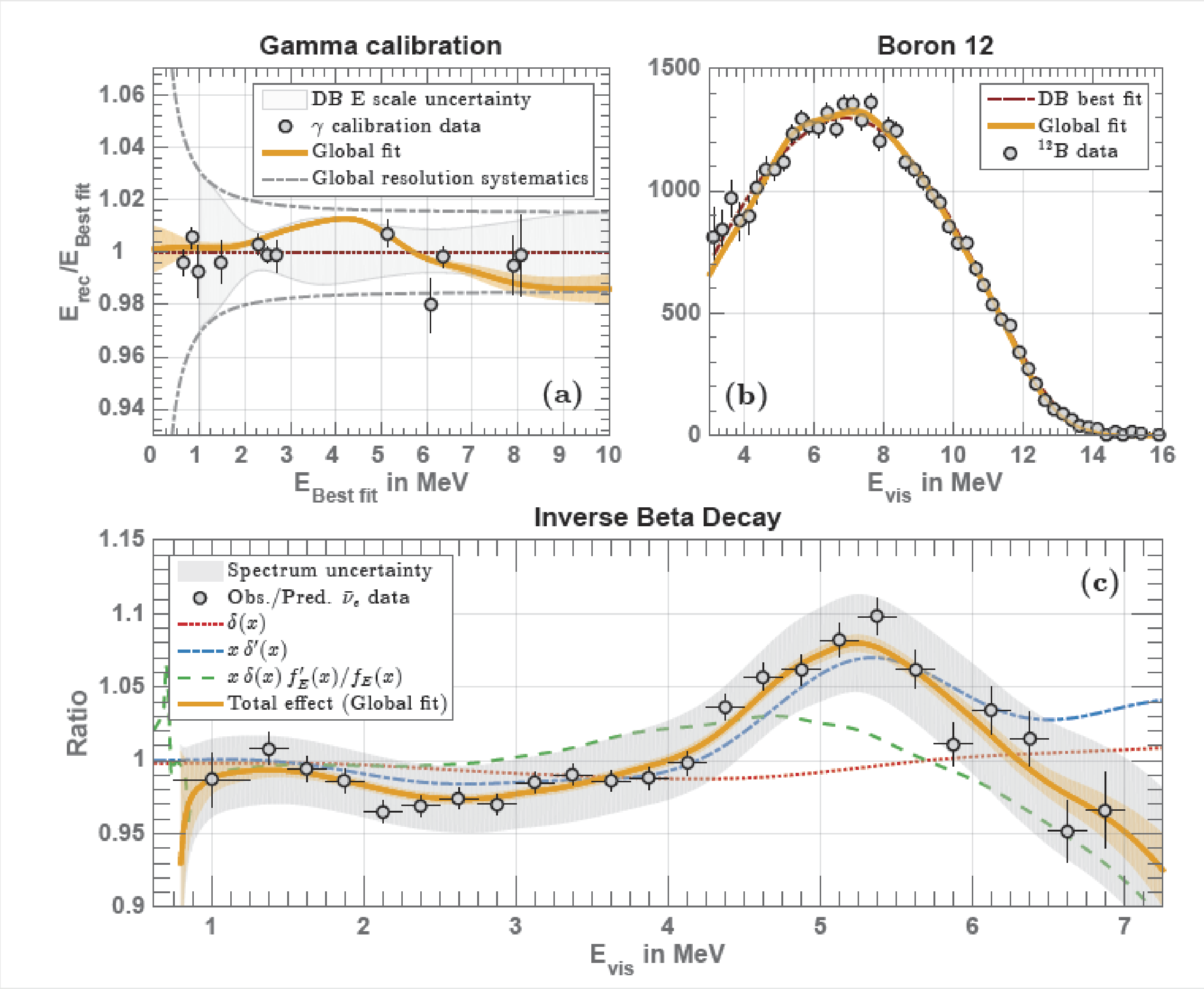
It seems there is inconsistency between 235U(2) and 239Pu: ~5% shift

Preliminary analysis by Anthony Onillon @ Applied Antineutrino Physics Workshop 2018 (AAP2018).

(B) Attempts for the reactor spectrum anomaly

Detector energy nonlinearity ?

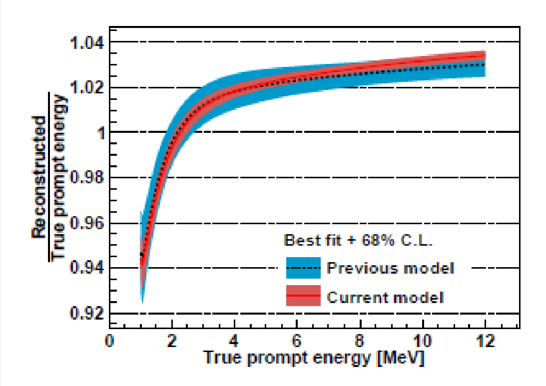
Mention et al, PLB 773 (2017) 307: is it possible to have detector effect ?



Disfavored by the new measurement:

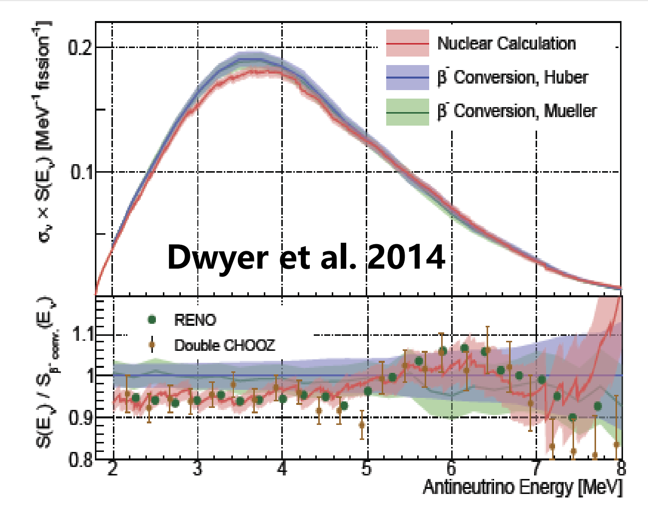
In the latest publication from Daya Bay: (arXiv: 1902.08241)

A new FADC system can reduce the detector nonlinearity to 0.5% level.

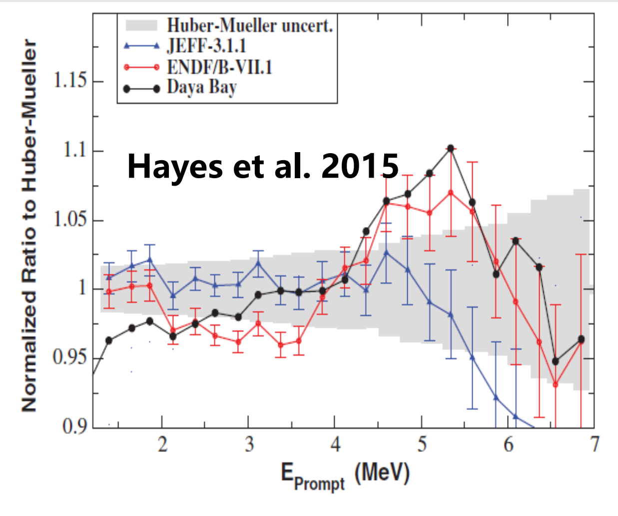


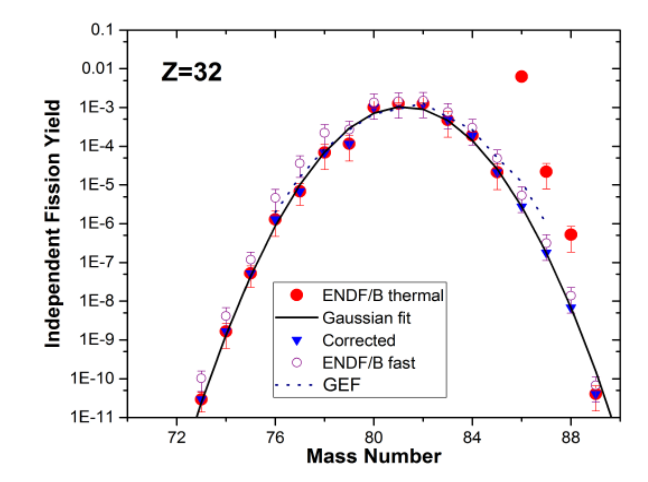
Problem of ab initio calculation (2)

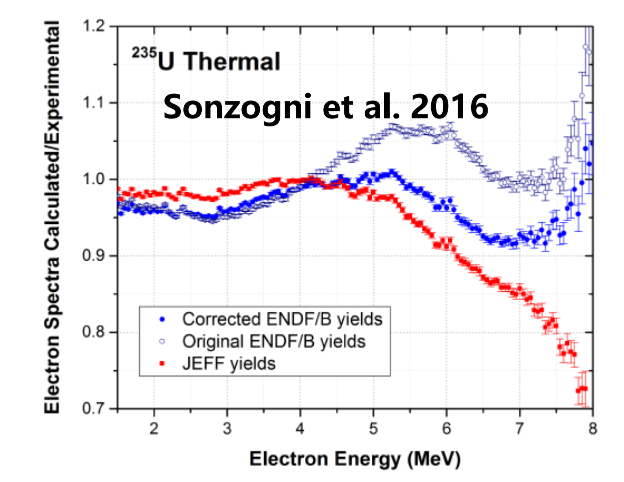
Inaccuracy or errors in the nuclear database: ENDF v.s. JEFF



Nucleus	JEFF Y_{F_t} (%)		ENDF Y_{F_t} (%)	
	^{235}U	^{239}Pu	^{235}U	^{239}Pu
^{89}Br	1.36	0.50	1.08	0.35
^{90}Br	0.49	0.10	0.56	0.25
^{95}Rb	0.66	0.26	0.77	0.44
^{96}Y	4.72	2.88	6.0	4.35
^{97}Y	2.08	1.22	4.89	3.75
^{98}Y	1.07	0.68	1.92	1.52
^{98m}Y	1.97	1.87	1.11	1.19
^{100}Y	0.30	0.21	0.61	0.35
^{134m}Sb	0.52	0.19	0.36	0.20







ENDF predicted a bump structure, but it turned out that some errors in the fission yield data therein.

Problem of ab initio calculation (3)

Analytical calculation of single beta decay can reproduce the lifetime very well, but no test for the energy spectrum!

$$N_\beta(E_e) = K p_e E_e (E_0 - E_e)^2 F(Z, E_e) C(Z, E_e) \times [1 + \delta(Z, A, E_e)],$$

$$F(Z, E_e) = 2(\gamma + 1)(2 p_e R)^{2(\gamma - 1)} e^{\pi y} \left| \frac{\Gamma(\gamma + iy)}{\Gamma(2\gamma + 1)} \right|^2$$

(1) The energy spectrum is investigated using a numerical calculation of exact lepton wave-functions.

(2)Three effects are considered:

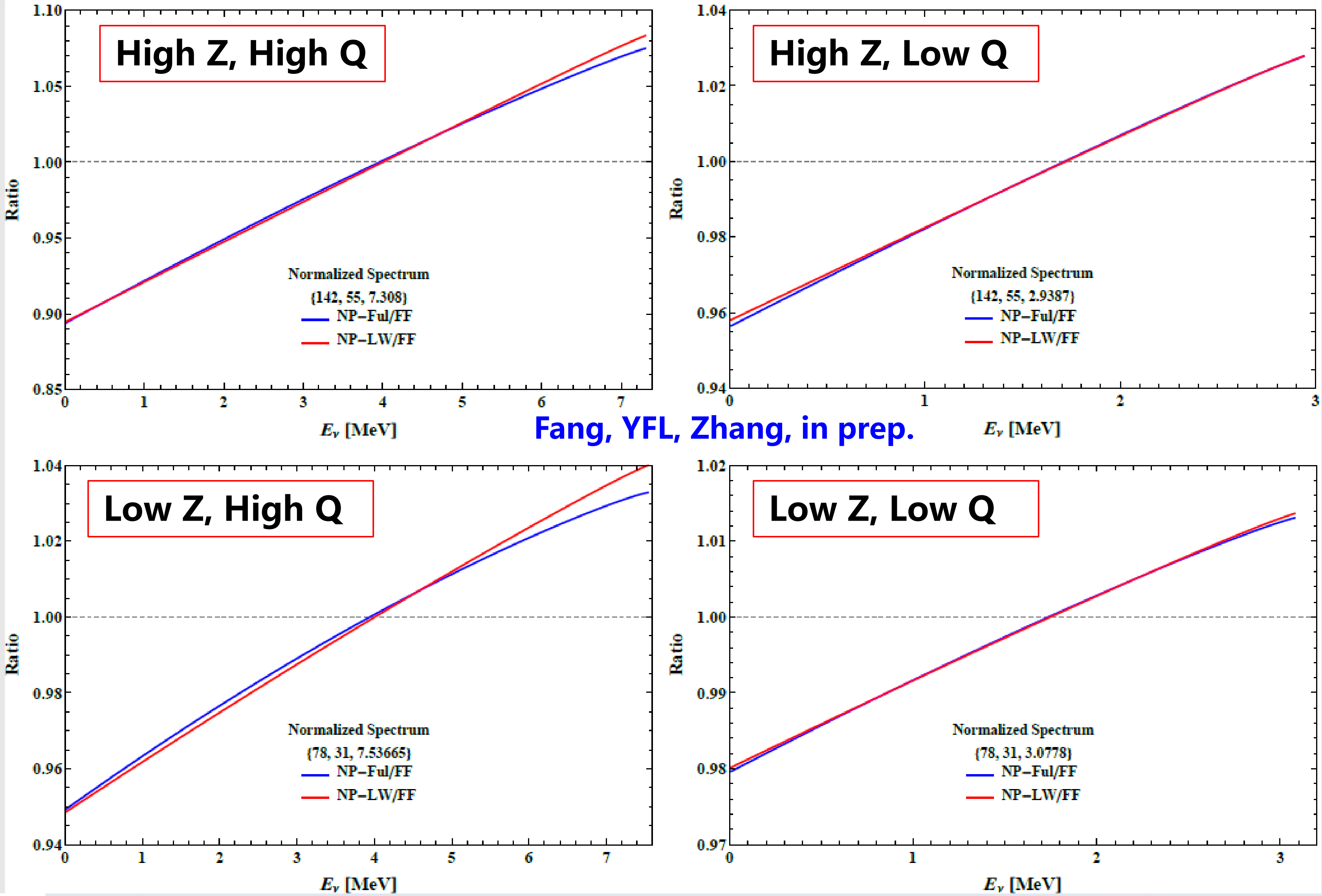
(a) Fermi function of point charge,

(b) Finite size corrections,

(c) neutrino long wave approximation.

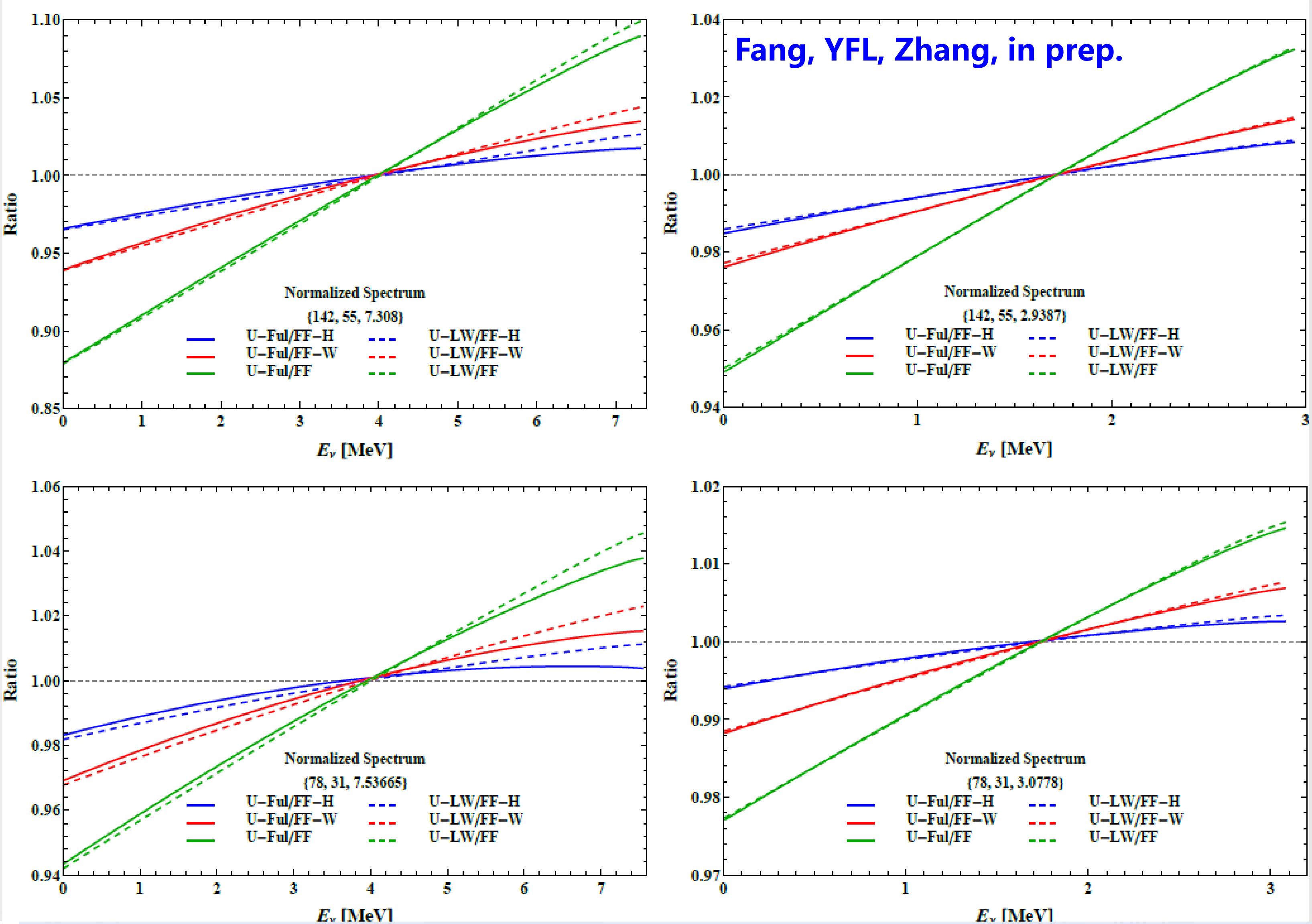
Fang, YFL, Zhang, in prep.

Numerical calculation with point charge



Fang, YFL, Zhang, in prep.

Numerical calculation with Uniform charge

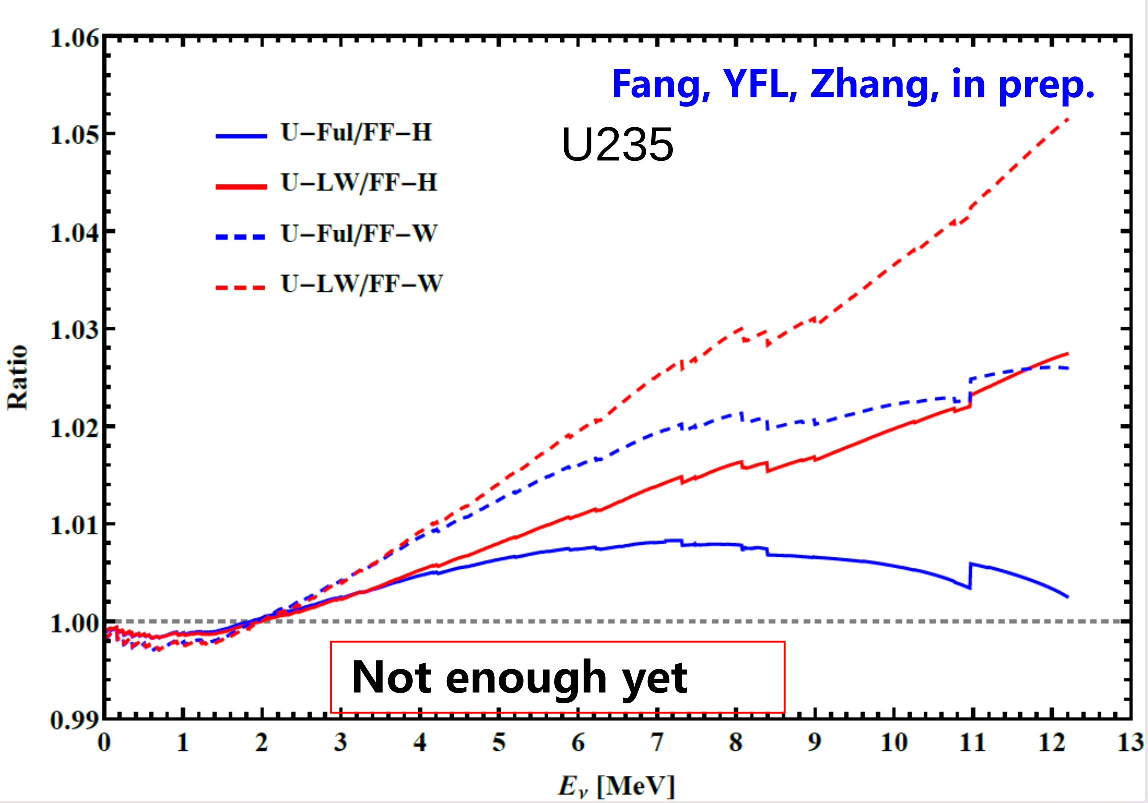


Ab initio calculation of U235

(a) Evaluated Nuclear Data File B.VIII.0, for fission yield data

(b) Evaluated Nuclear Structure Data Files for the decay data

(c) Full numerical calculation of single beta spectrum



First forbidden decay

The second model is to investigate the first forbidden decay effect in the conversion calculation: shape factor

YFL, Zhang PRD (2019)

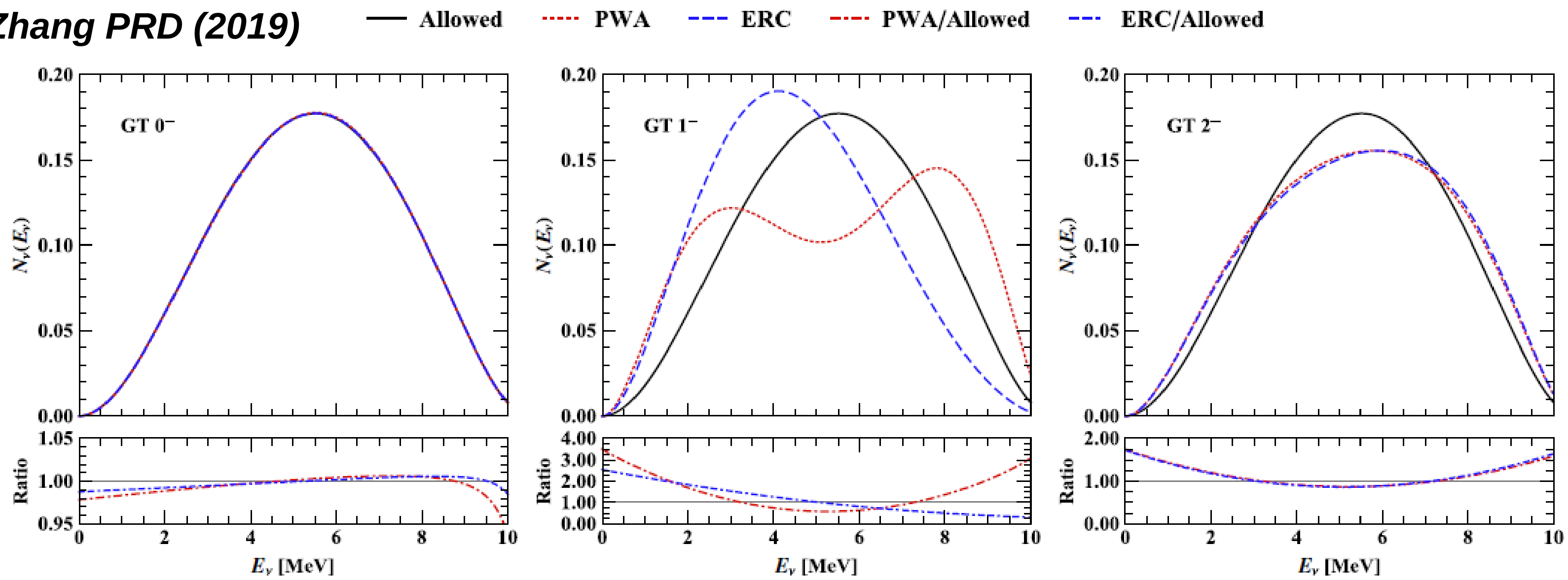
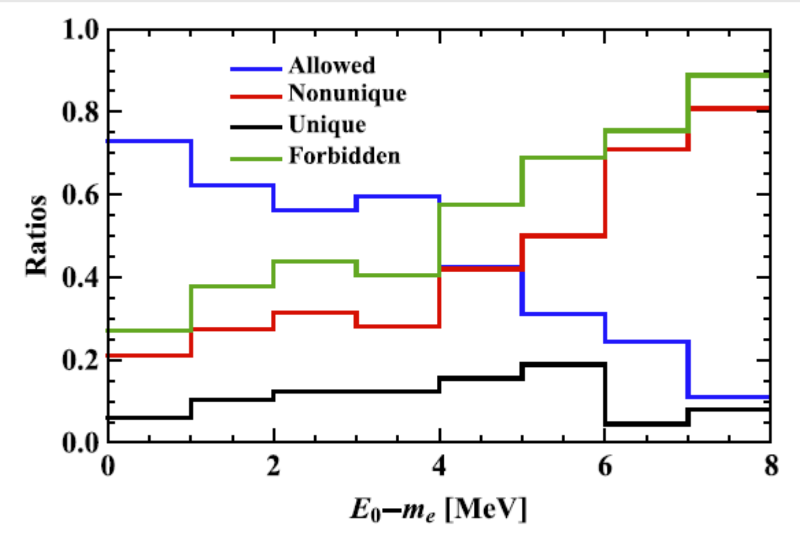


FIG. 1. The antineutrino spectra with different decay transition types with $Z = 47$, $A = 117$ for the daughter nucleus and $E_0 - m_e = 10$ MeV. The left, middle and right panels are for the cases of forbidden GT transitions of 0^-, 1^- and 2^- respectively. The black lines are the shape of allowed GT transitions. The red dotted and blue dashed lines stand for the spectra obtained in the plane wave approximation (PWA) and the exact relativistic calculation (ERC) of the Dirac wave function respectively. The ratios between the allowed and forbidden spectra are also shown in the corresponding lower panels.

Nuclear database properties

ENDFB.VIII.0 + ENSDF: statistical information

YFL, Zhang PRD (2019)



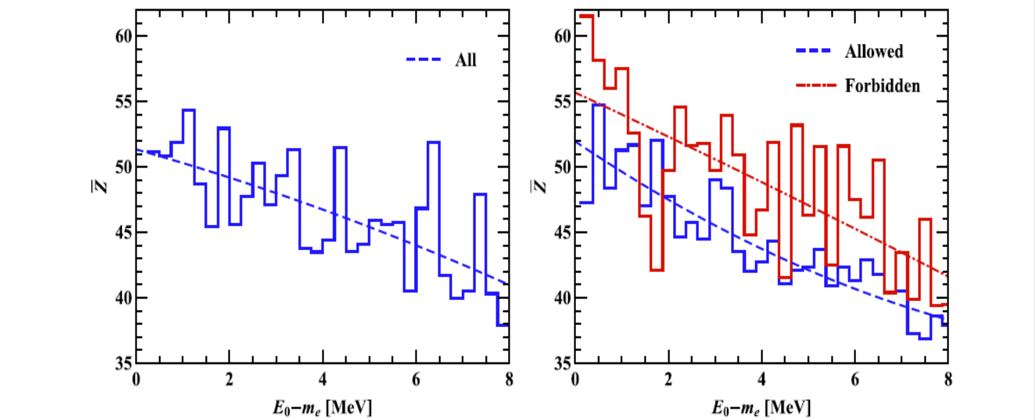


FIG. 3. The relation between the effective nuclear charge number $\bar{Z}$ and end point energy $E_0 - m_e$ for the ^{235}U fission isotope. All the decay branches are assumed to be the allowed GT transition in the left panel, and the results for the allowed and forbidden transitions are illustrated separately in the right panel. The second-order polynomial curves are fitted as the dashed or dashed and dash-dotted lines in the left and right panels.

$$\bar{Z}(E_0) = \frac{\sum_{A,Z} Y(A, Z-1) \sum_i b_i(E_0^i) Z}{\sum_{A,Z} Y(A, Z-1) \sum_i b_i(E_0^i)},$$

$$\bar{Z}(E_0) = a_0 + a_1(E_0 - m_e) + a_2(E_0 - m_e)^2,$$

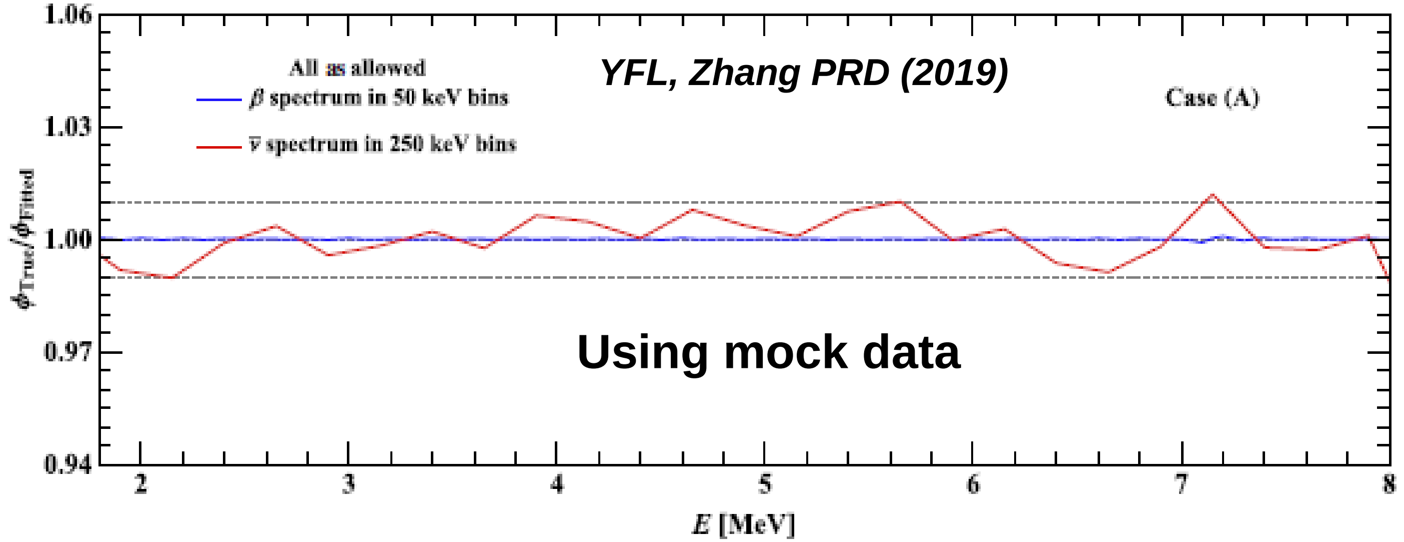
TABLE II. The coefficients for the polynomial fit of the effective nuclear charge number as the function of the end point energy $E_0 - m_e$.

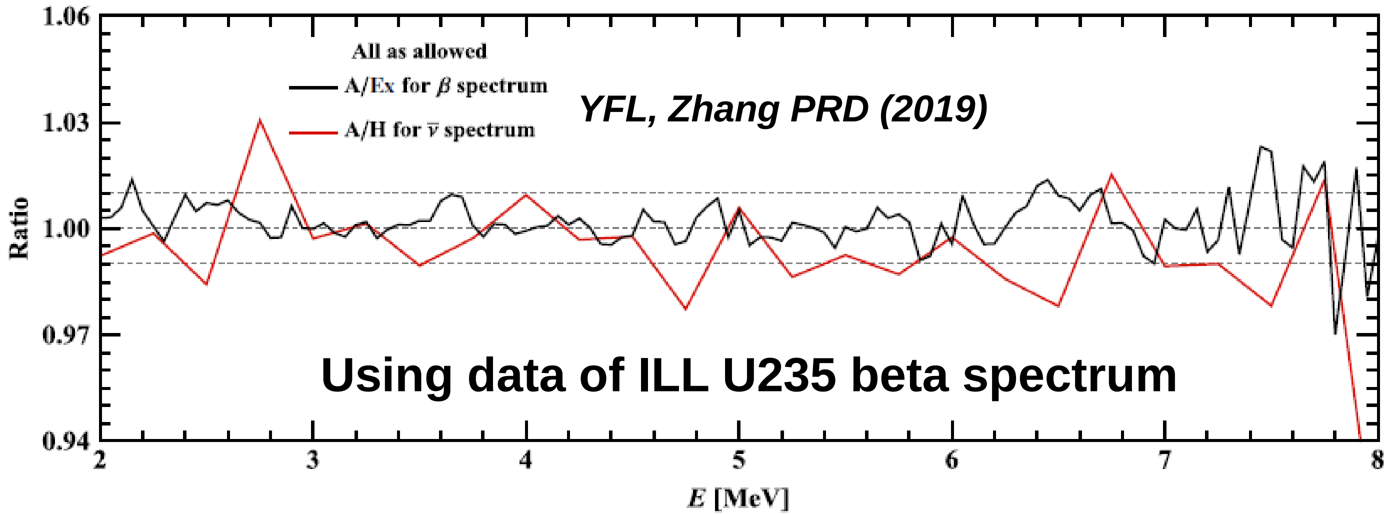
	a_0	a_1 (MeV^{-1})	a_2 (MeV^{-2})
All	51.3374	−1.00324	−0.0363509
Allowed	51.9464	−2.40159	0.0873305
Forbidden	55.6795	−1.66458	−0.0116643

More first forbidden decay for higher Q branches

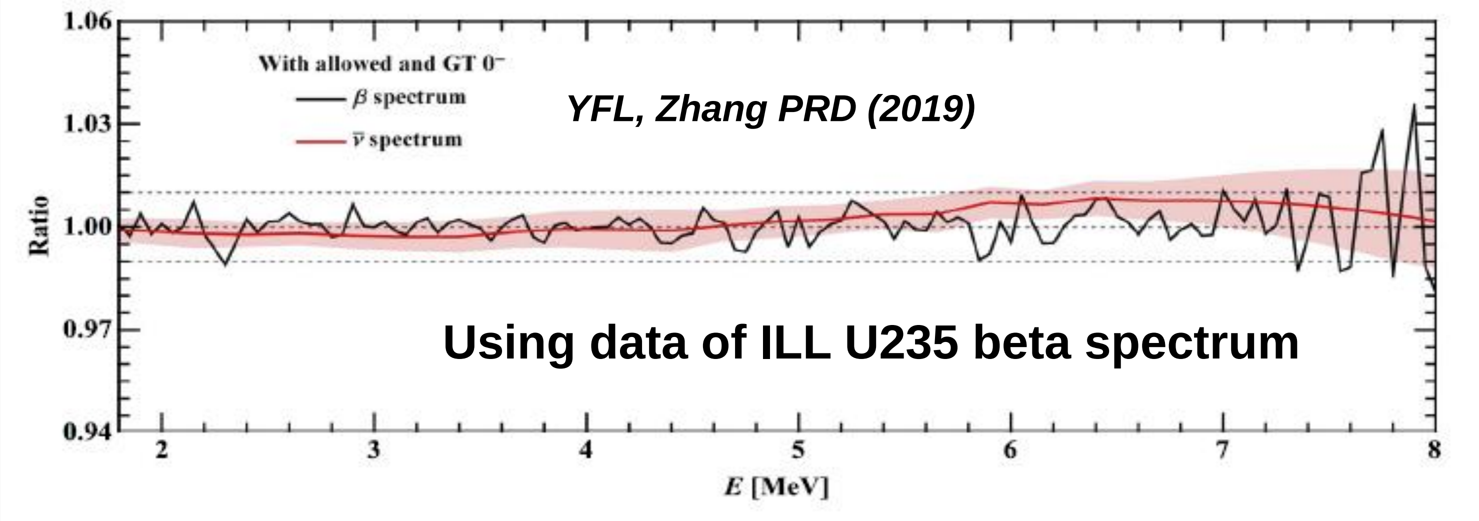
Forbidden branches tend to have larger effective charges

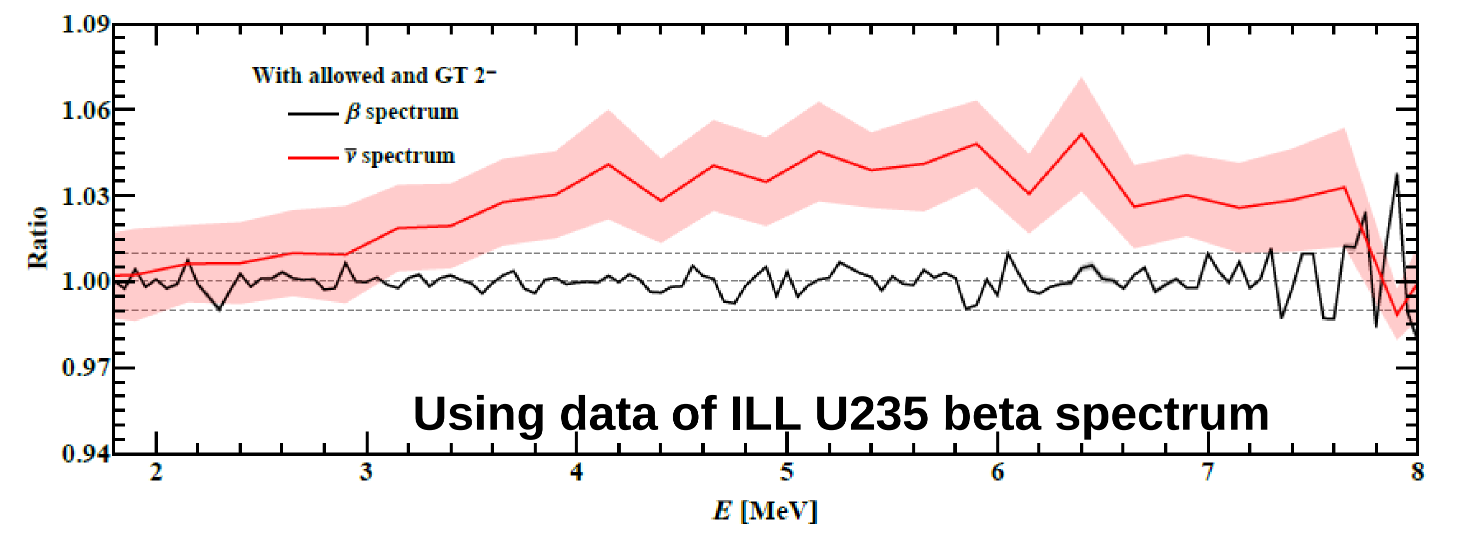
Conversion calculation: Validation





With allowed and forbidden decays

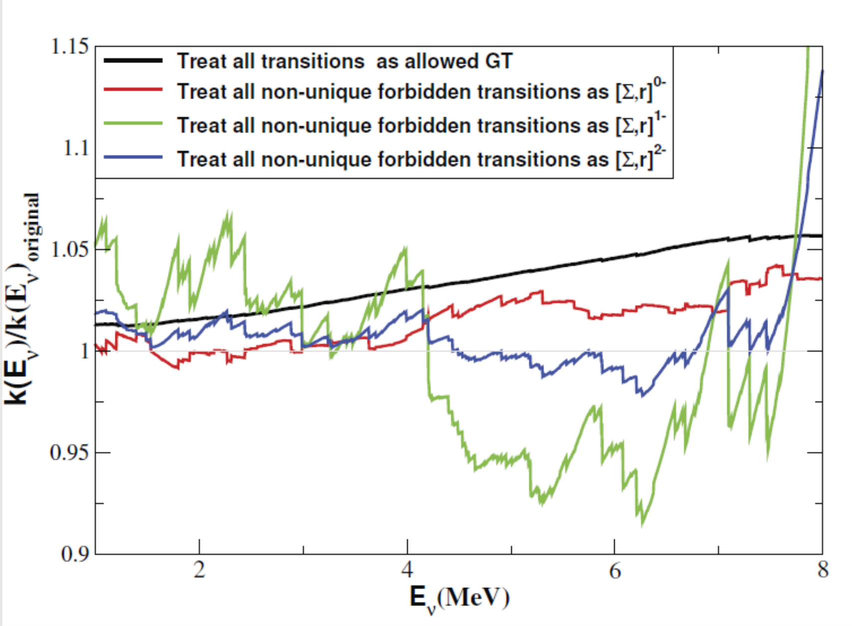


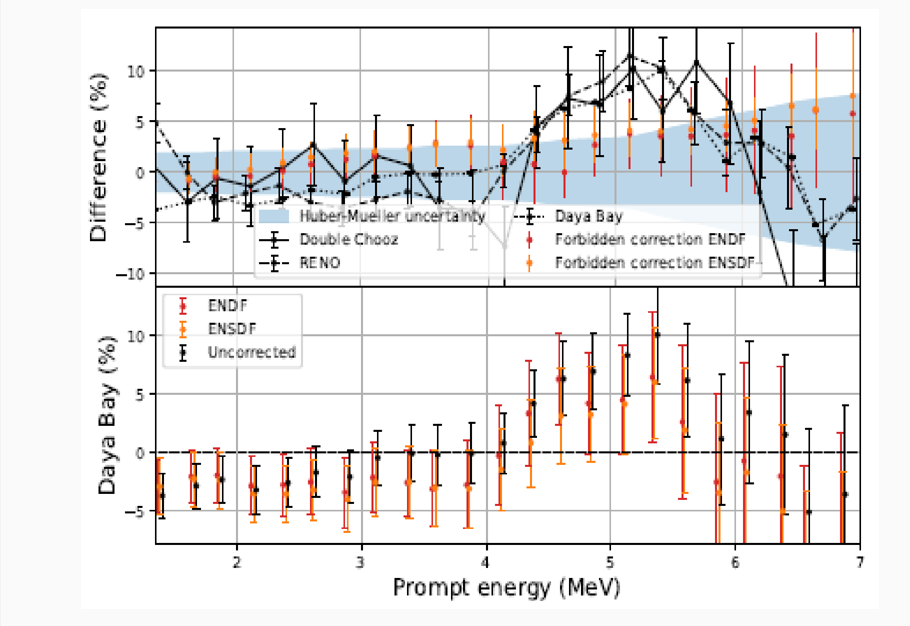


Other studies of forbidden decays

Including the first forbidden decay (analytical) in ab initio method, but using plain wave approximation
Hayes et al. (2014)

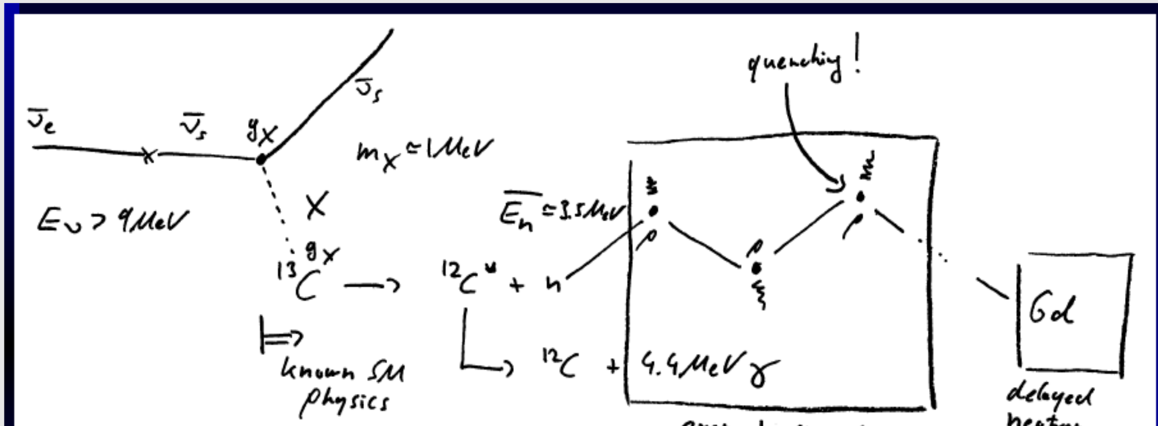
Including the first forbidden decay (using shell model) in ab initio method
Hayen et al. (2018)





- **Quantitatively agreed, but still** **cannot fully accommodate** **the bump of around 10% size!**
- **Need a** **self-consistent** **uncertainty evaluation!**

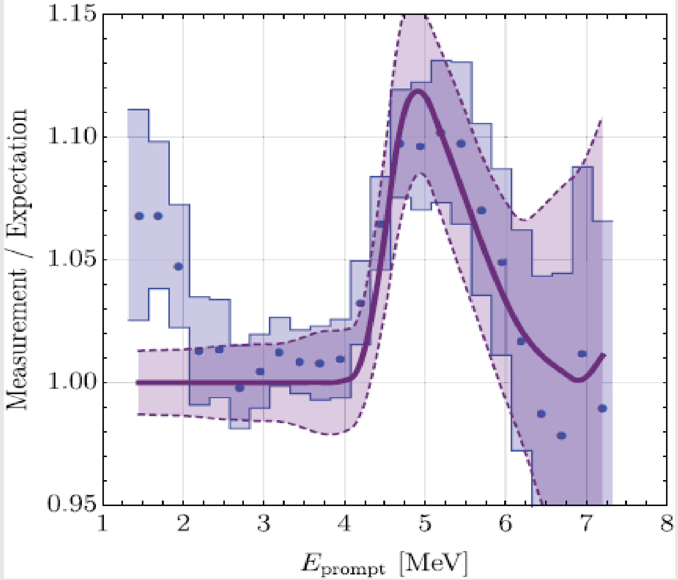
A brave new-physics idea?

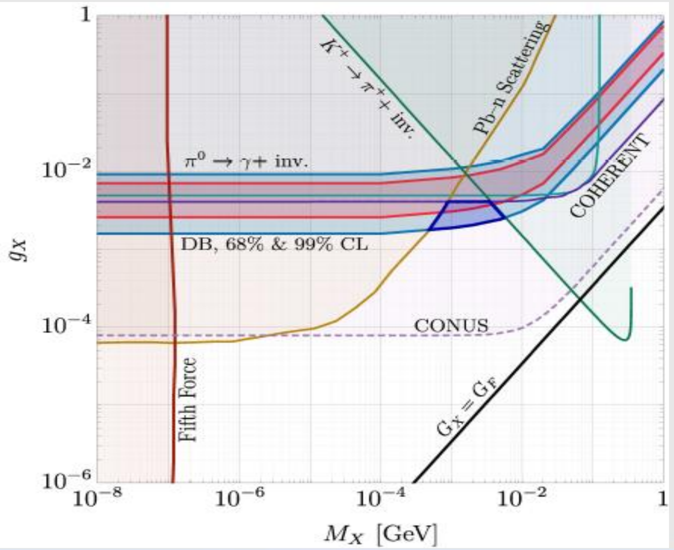


From Huber (2018)

Berryman, Brdar, PH, 2018

Requires a sterile neutrino consistent with the reactor anomaly and a new vector state X coupling to quarks.





- Need sterile neutrino oscillation and a light vector state
- The spectrum feature is determined by SM physics
- Not easy to avoid all the limits

Final Remarks-1

Reactor rate and spectrum anomalies are based on models in 2011 (a.k.a. Huber+ Mueller Model): new physics or not?

(1) Rate Anomaly:

- **Data driven global flux analysis, ab initio and conversion calculations, all raise a possible common problem in the U235 calculation**
- **Still need reactor spectral ratio measurement to test the sterile neutrino contributions**

Final Remarks-2

(2) Spectrum Anomaly: still an open question

- **Many nuclear physics issues are examined,**

Nuclear database, Fission yields,

Fermi Function, Finite Size, Forbidden decay, … …

- **Some can contribute to high energy excess; new physics explanations are not easy.**

(3) Our future improvements:

ab initio: a) Include latest TAGS data, b) test other analytical descriptions

Conversion: a) more accurate classification of FF transitions, b) complete uncertainty evaluation

Thanks!