

# Reactor neutrino anomalies and possible solutions

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**ICHEP 2020 | PRAGUE**

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ON HIGH ENERGY PHYSICS

**VIRTUAL  
CONFERENCE**

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**2020-07-30**

# Outline

- Fundamentals of reactor neutrinos
- **Rate anomaly:**  
**Data driven analysis**
- **Spectrum anomaly:**  
**Summation v.s. conversion method**
- **Summary**

# Summation or conversion method

## (1) Summation method (ab initio method):

- Rely on nuclear database:  
**Incomplete and/or bias**
- Rely on single beta decay:  
**accuracy or forbidden decay**
- ENDF, JEFF, and new data

## (2) Conversion method:

- Convert the aggregate  $\beta$  spectra measured at ILL in the 80' s **using 30 virtual branches**.
- Applied to  $^{235}\text{U}$ ,  $^{239}\text{Pu}$ ,  $^{241}\text{Pu}$  [Huber (2011)]
- $^{238}\text{U}$  using SM method [Mueller et al. (2011)]

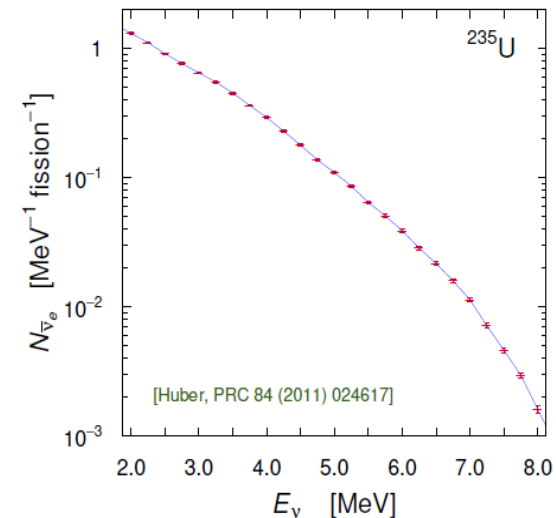
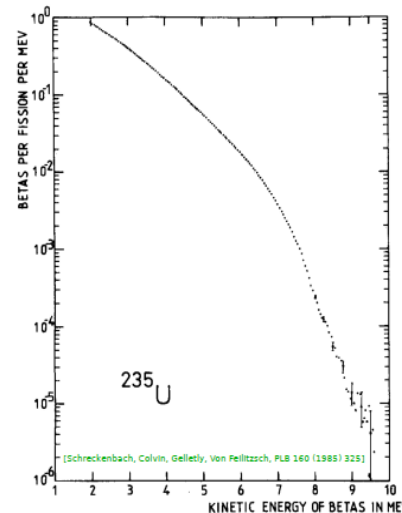
Aggregate reactor spectrum (electron or neutrino):

$$S_{\text{tot}}(E, t) = \sum_k F_k(t) S_k(E) \quad (k = 235, 238, 239, 241)$$

↑  
fission fractions

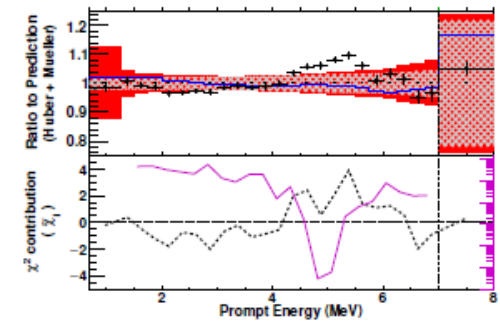
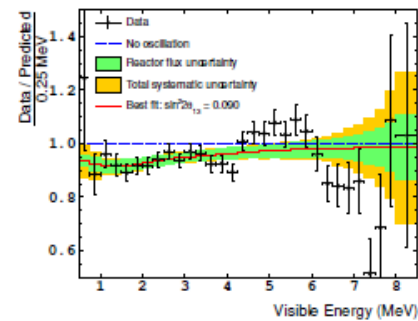
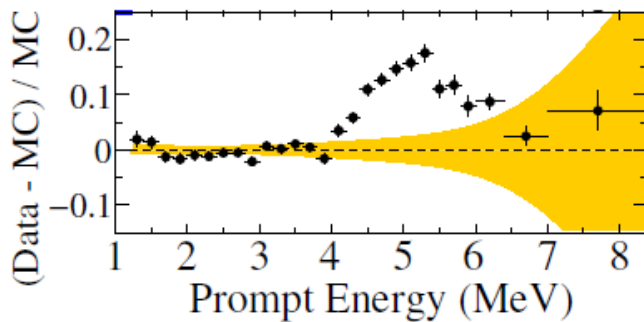
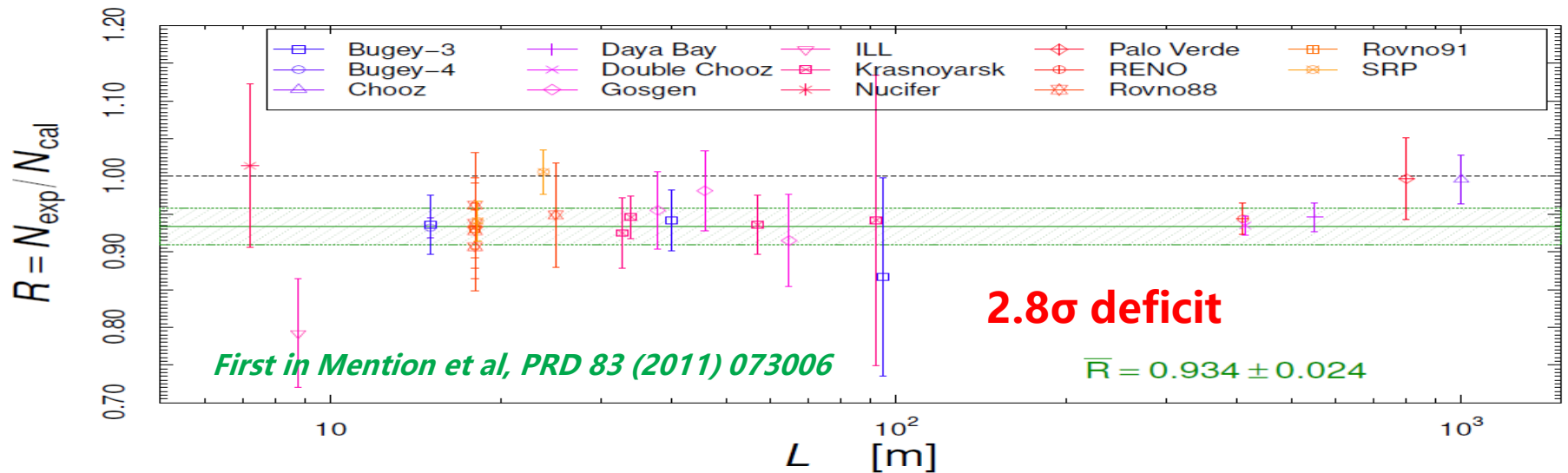
$$S_k(E) = \sum_n Y_n^k \sum_b \text{BR}_n^b S_n^b(E)$$

↑  
cumulative  
fission yield



# Reminder: Reactor Anomalies ?

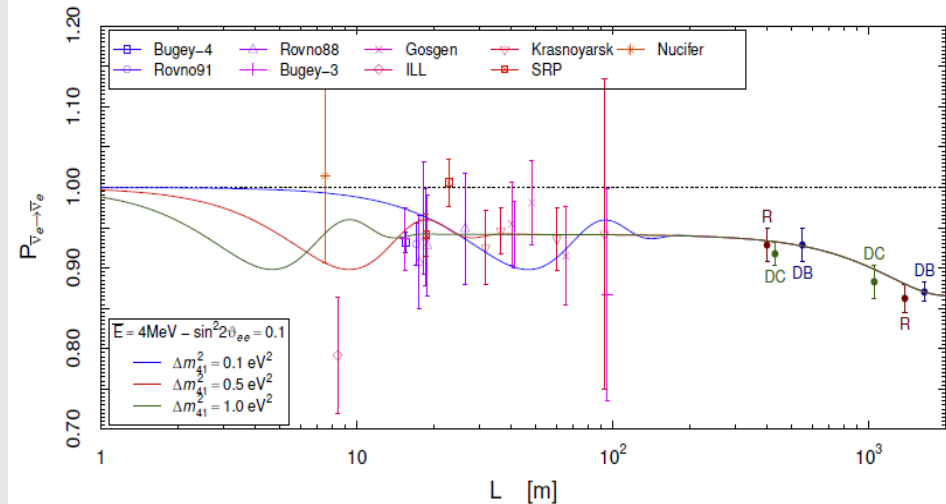
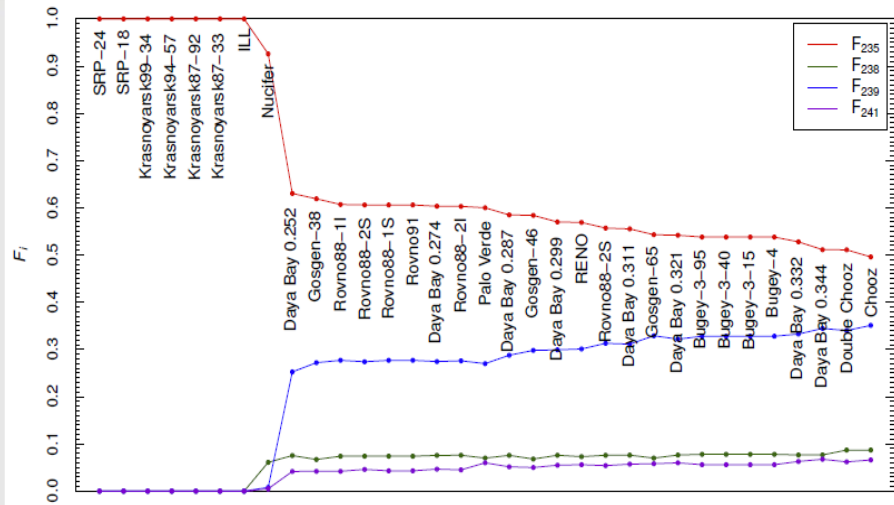
➤ New calculations of reactor  $\nu$  fluxes lead to rate and spectrum anomalies:



# (A) Reactor Rates Data

$a$	Experiment	$f_{235}^a$	$f_{238}^a$	$f_{239}^a$	$f_{241}^a$	$R_{a,SH}^{exp}$	$\sigma_a^{exp}$ [%]	$\sigma_a^{cor}$ [%]	$L_a$ [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	25		
7	Rovno88-2S	0.606	0.074	0.274	0.046	0.928	6.8	} 3.8	18	
8	Bugey-3-15	0.538	0.078	0.328	0.056	0.936	4.2	} 4.0	15	
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3		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	} 2.0	37.9	
12	Gosgen-46	0.584	0.068	0.298	0.050	0.981	5.4		} 3.8	45.9
13	Gosgen-65	0.543	0.070	0.329	0.058	0.915	6.7			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	$\approx 1000$	
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0	$\approx 800$	
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0	$\approx 550$	
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0	$\approx 410$	
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0	$\approx 415$	

# (A) Classification as fission fraction or distance



➤ Non-nested model comparison

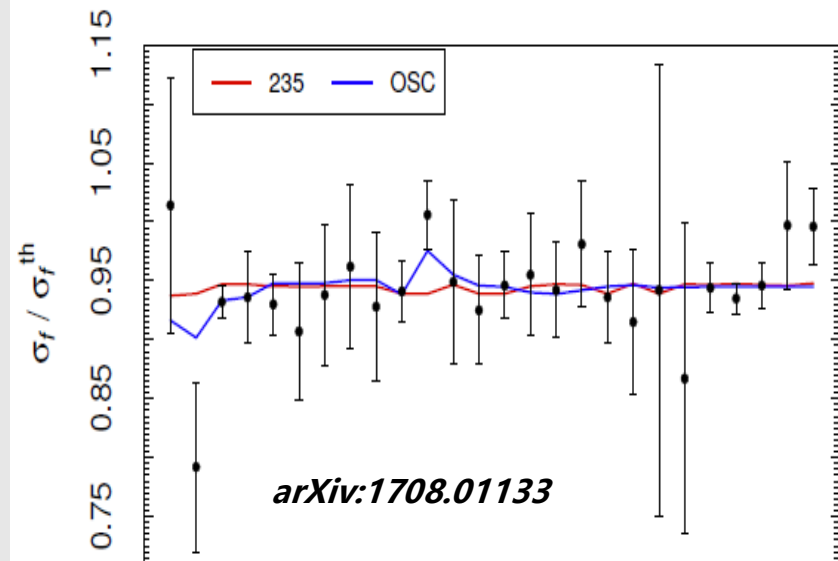
➤ Need simulation to do the statistical assessment

➤ Equal suppression (OSC): **slightly favored**

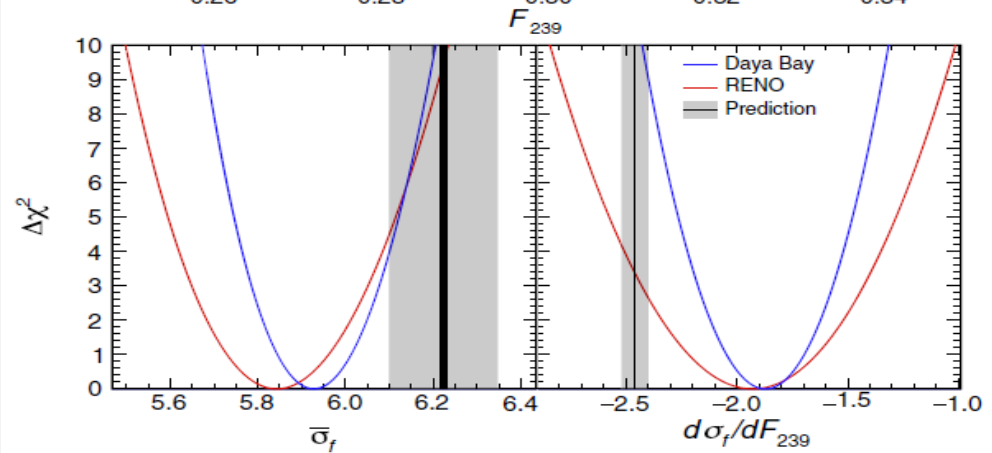
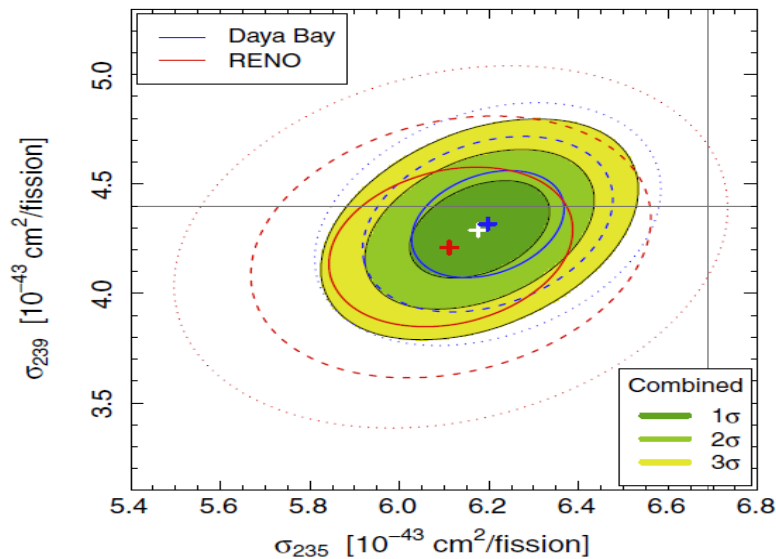
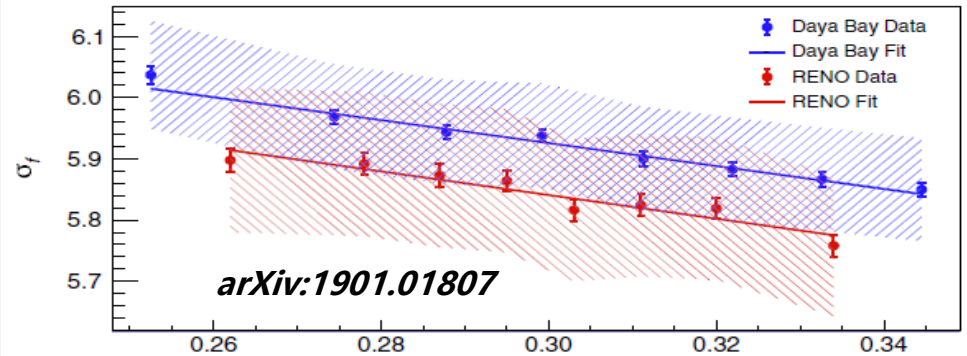
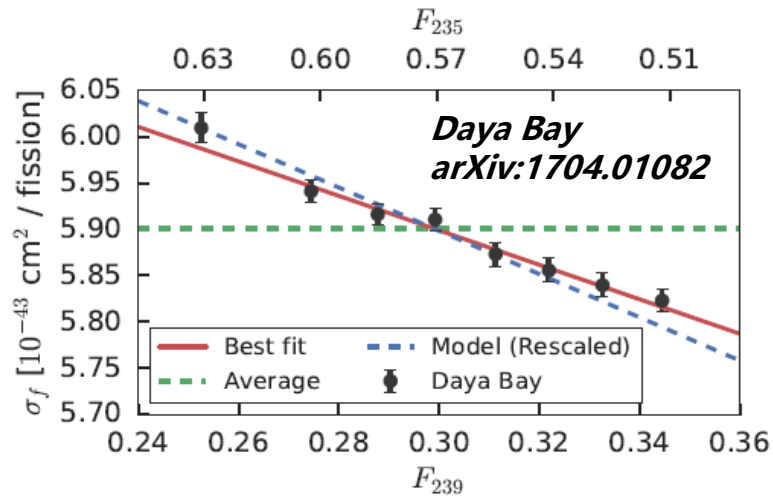
	$r_{235}$	OSC
$\chi^2_{\min}$	25.3	23.0
NDF	32	31
GoF	79%	85%

Best fit: OSC

MC:  $r_{235}$  disfavored at  $1.7\sigma$



# (A) New Fuel Evolution Data



- Reactor rates as function of the fuel fraction: **A new information (slope)!**
- **Inconsistent** with model prediction at around **3σ**

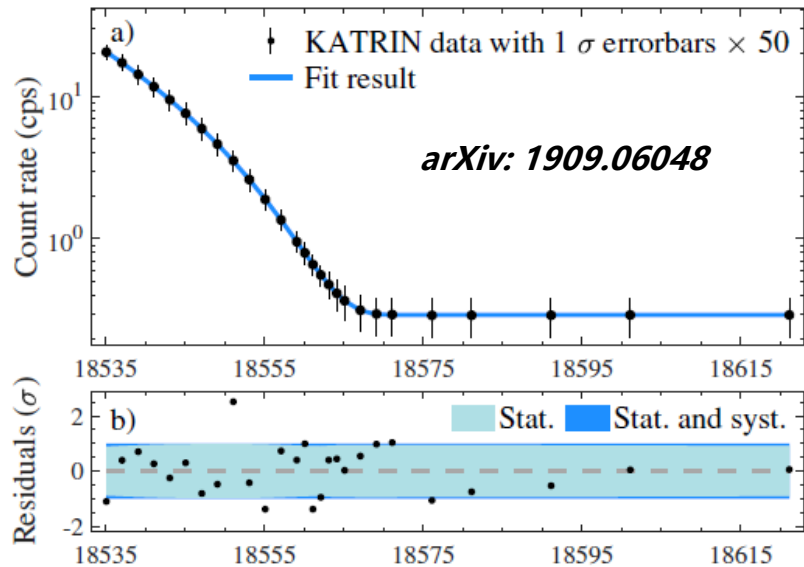
# (A) Global flux data (rates + evolution)

	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%
$r_5$	$0.933 \pm 0.010$	$(0.941)$	$0.932 \pm 0.009$	$0.952 \pm 0.014$	$0.941 \pm 0.013$	$(1.014)$	$0.984 \pm 0.025$	$(1.014)$
$r_8$	$(0.890)$	$(0.868)$	$(0.914)$	$0.672 \pm 0.135$	$0.926 \pm 0.096$	$(1.021)$	$(0.969)$	$(0.956)$
$r_9$	$(0.987)$	$0.997 \pm 0.029$	$0.969 \pm 0.030$	$1.042 \pm 0.046$	$0.944 \pm 0.015$	$(1.019)$	$(1.026)$	$1.099 \pm 0.040$
$r_1$	$(0.989)$	$(0.938)$	$(1.003)$	$(1.001)$	$0.942 \pm 0.013$	$(1.015)$	$(1.024)$	$(1.015)$
$\Delta m_{41}^2$						$0.49^{+0.02}_{-0.03}$	$0.48^{+0.05}_{-0.03}$	$0.49 \pm 0.02$
$\sin^2 2\theta_{ee}$	<i>arXiv:1901.01807</i>					$0.15 \pm 0.04$	$0.10^{+0.05}_{-0.04}$	$0.16 \pm 0.04$

## Global Flux Data (rates + evolution):

- A common inaccuracy of all beta conversion predictions: **disfavored at  $3.0\sigma$**
- A deficit for the U235 rate is **always favored**.
- Oscillation-including hypothesis is favored over the oscillation-excluding one: **moderately at  $1-2\sigma$**

# (A) Beta decay data



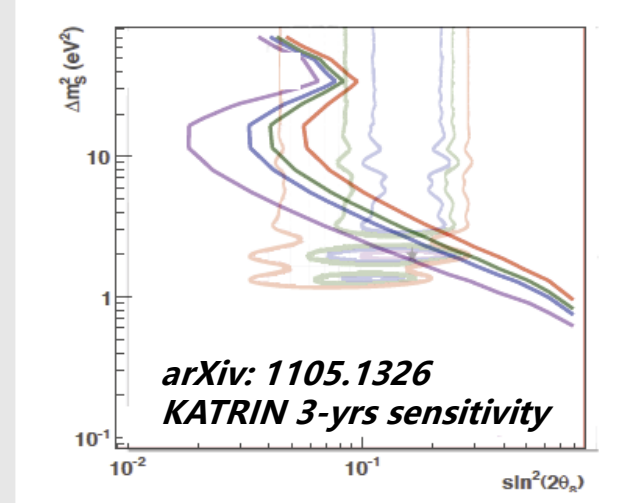
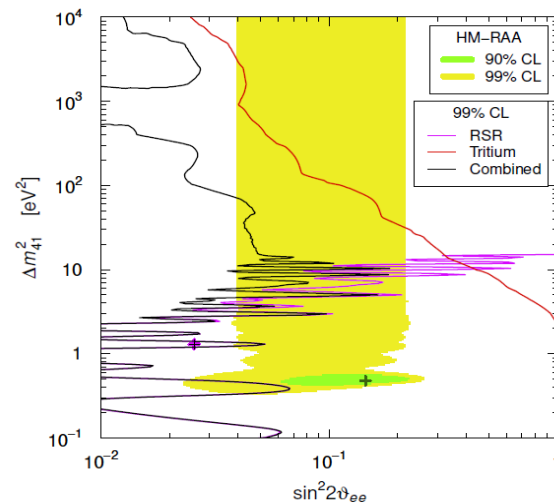
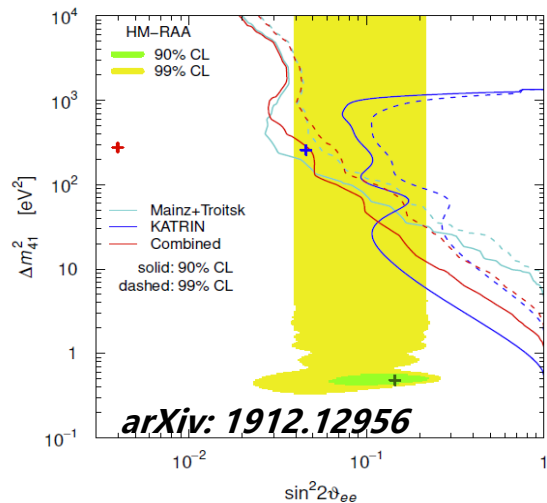
- Spectrum of  $\beta$  decay provide information on neutrino masses:

**KATRIN  $\rightarrow < 1.1$  eV (90%)**

- It can also test the oscillation explanation of RAA:

**Complementary to  
 Reactor Spectral Ratio measurements**

- High mass-squared region is disfavored



# (B) Possible Problems in SM method

## (1) Incomplete or biased nuclear database

- JEFF v.s. ENDF;
- pandemonium effect

## (2) Single $\beta$ decay spectrum

- Forbidden decay
- Accuracy of approximations

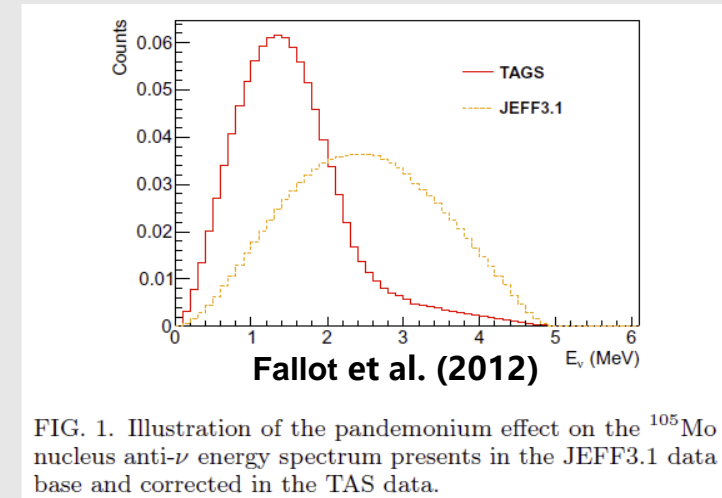
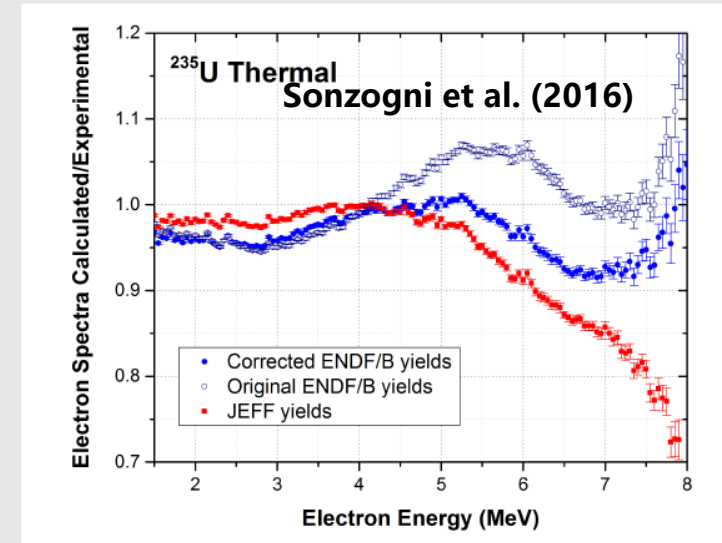
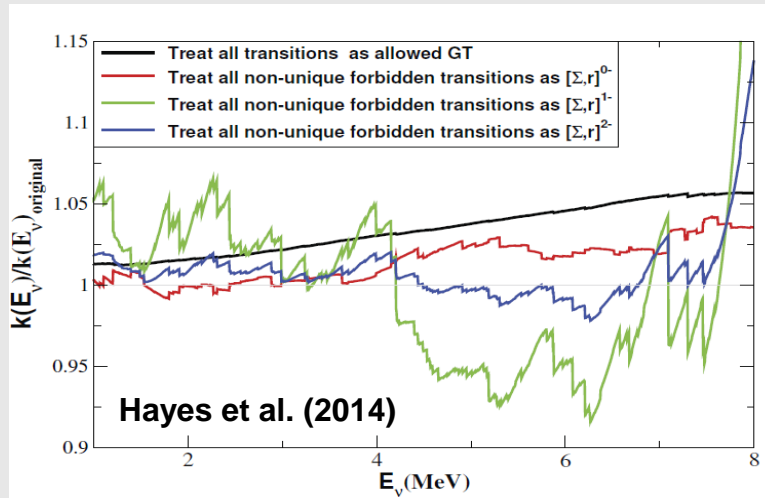


FIG. 1. Illustration of the pandemonium effect on the <sup>105</sup>Mo nucleus anti- $\nu$  energy spectrum presents in the JEFF3.1 data base and corrected in the TAGS data.

## (B) Are the approximations valid?

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

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

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

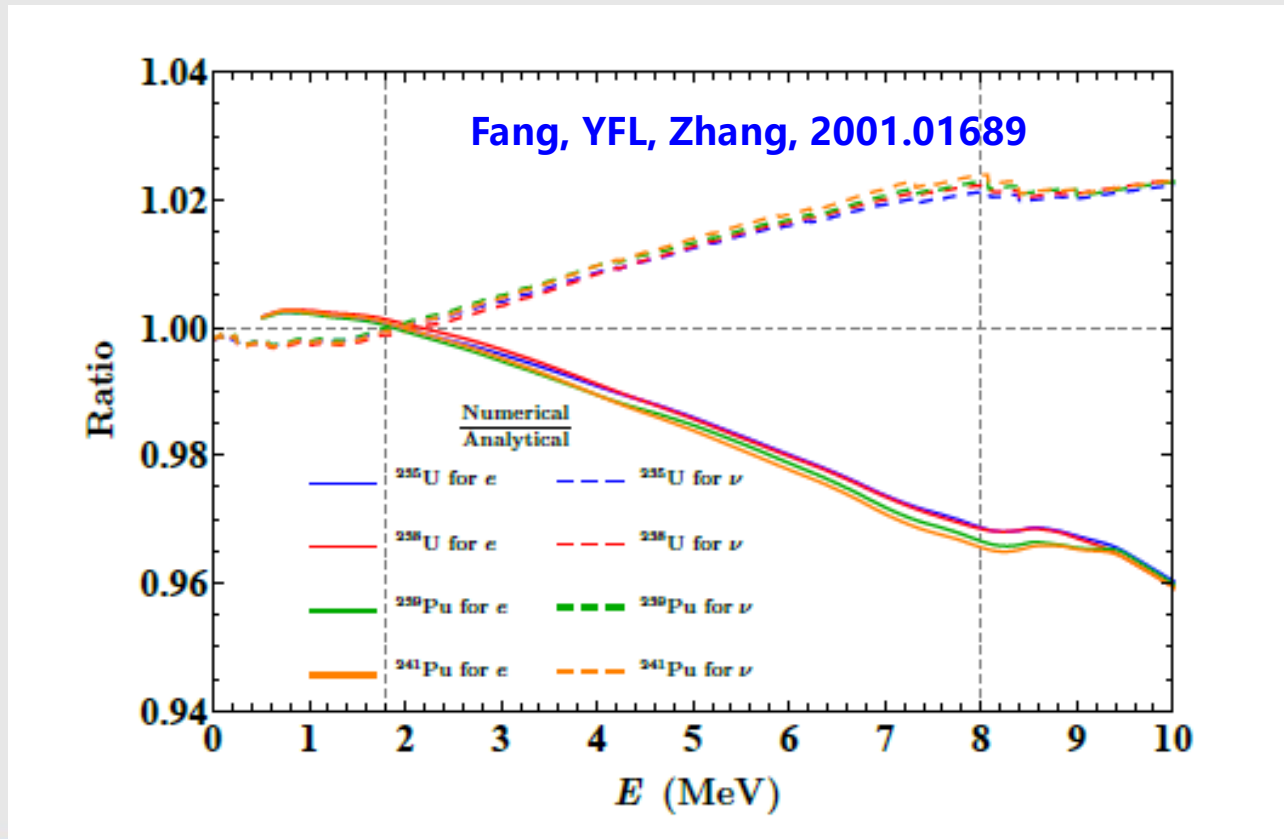
Fang, YFL, Zhang, 2001.01689

Three effects are considered:

- (a) Fermi function of point charge
- (b) Finite size corrections
- (c) neutrino long-wave approximation

## (B) New SM method

- (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



# (C) Conversion method

Our second model is to investigate the forbidden decay effect in the conversion calculation: **shape factor**

YFL, Zhang, 1904.07791

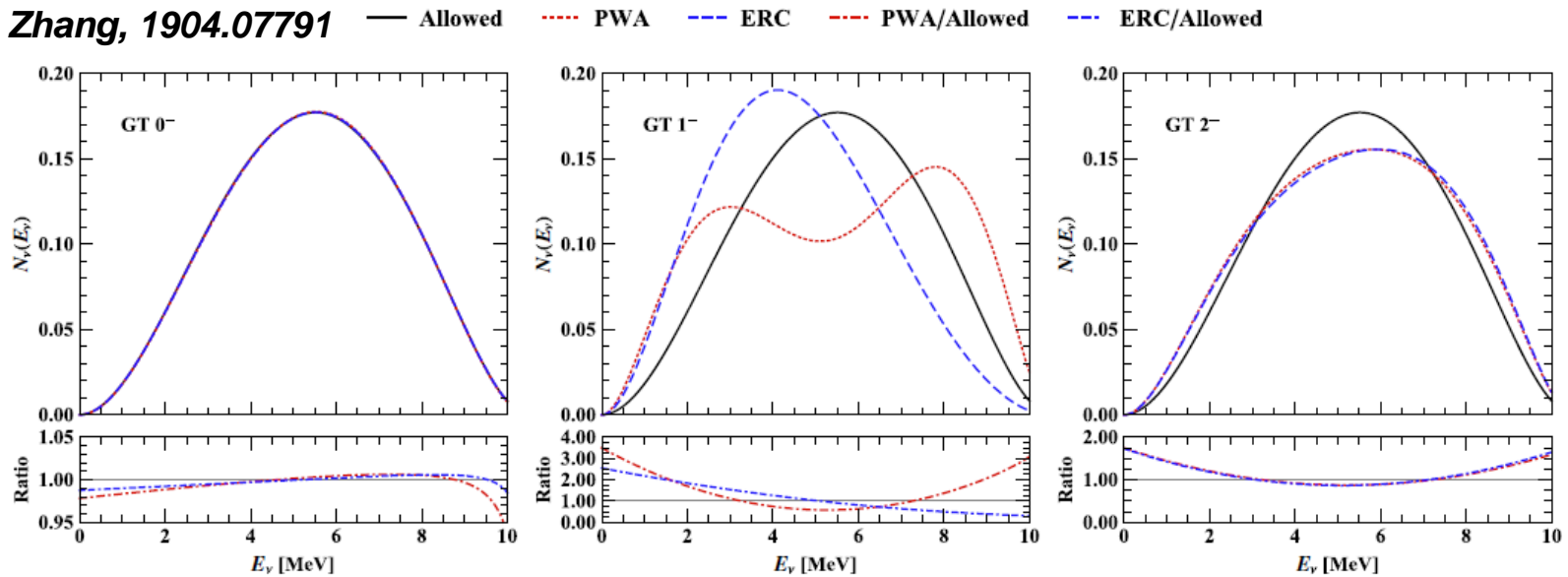


FIG. 1. The antineutrino spectra with different decay transition types with  $Z = 47$ ,  $A = 117$  for the daughter nucleus and  $E_0 - m_e = 10$  MeV. The left, middle and right panels are for the cases of forbidden GT transitions of  $0^-$ ,  $1^-$  and  $2^-$  respectively. The black lines are the 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.

# (C) Nuclear database properties

ENDFB.VIII.0 + ENSDF: **statistical information**

YFL, Zhang, 1904.07791

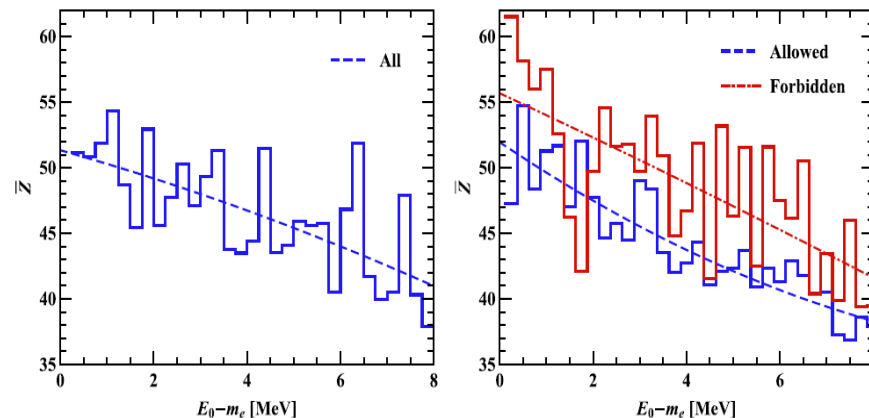
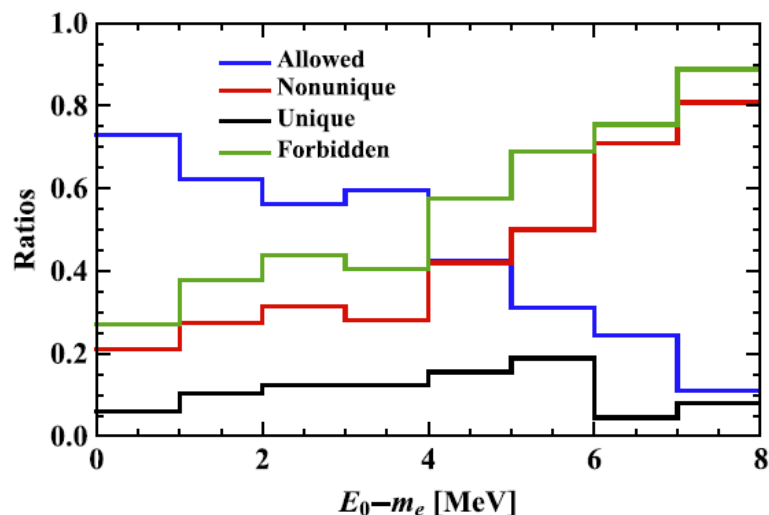


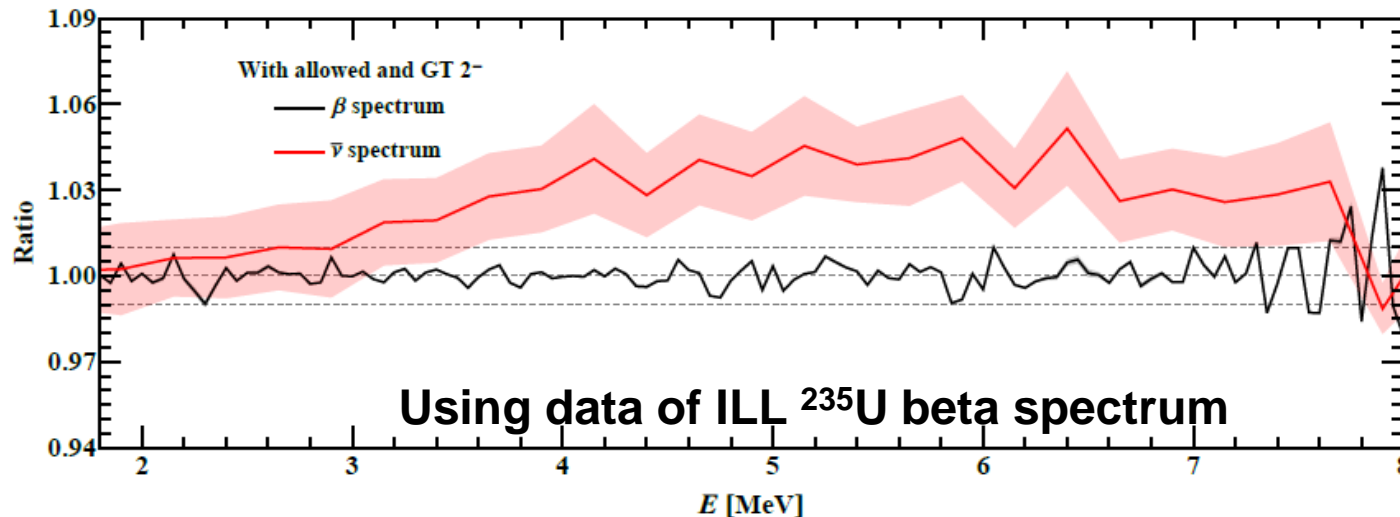
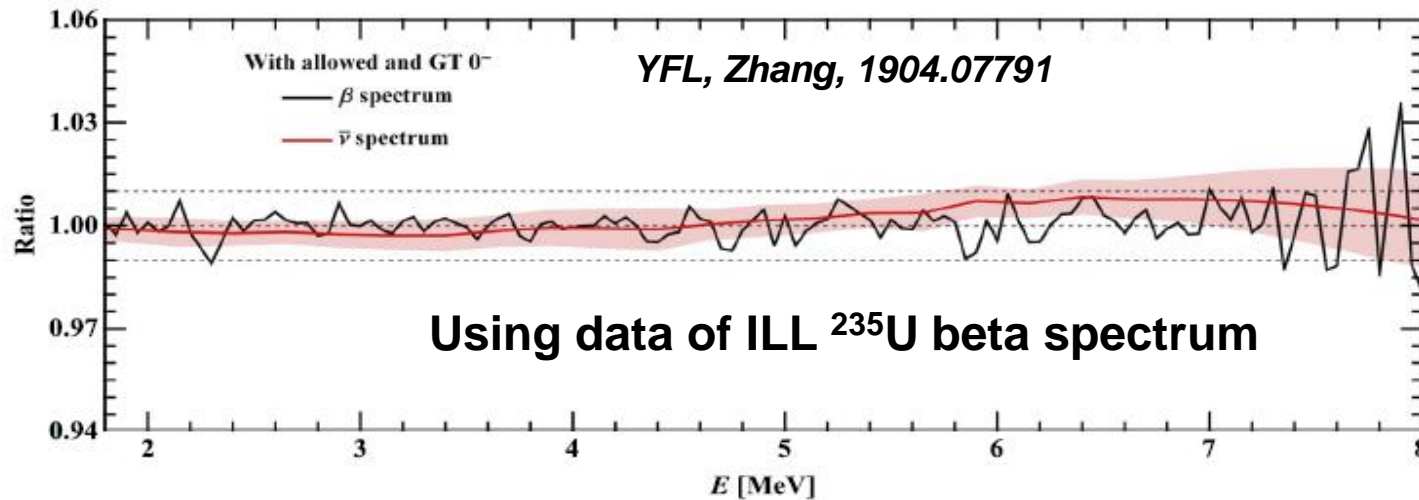
FIG. 3. The relation between the effective nuclear charge number  $\bar{Z}$  and end point energy  $E_0 - m_e$  for the  $^{235}\text{U}$  fission isotope. All the decay branches are assumed to be the allowed GT transition in the left panel, and the results for the allowed and forbidden transitions are 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.

**Two observations:**

- **More first forbidden decay for higher Q branches**
- **Forbidden branches tend to have larger effective charges**

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

# (C) With allowed and forbidden decays



Other studies of forbidden decay in Hayes et al. (2014) and Hayen et al. (2018)

# Summary

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

## **(1) Rate Anomaly:**

- **Data driven global flux analysis: Problem in the  $^{235}\text{U}$  flux calculation? Other contributions?**
- **Model independent method to test oscillations**

## **(2) Spectrum Anomaly:**

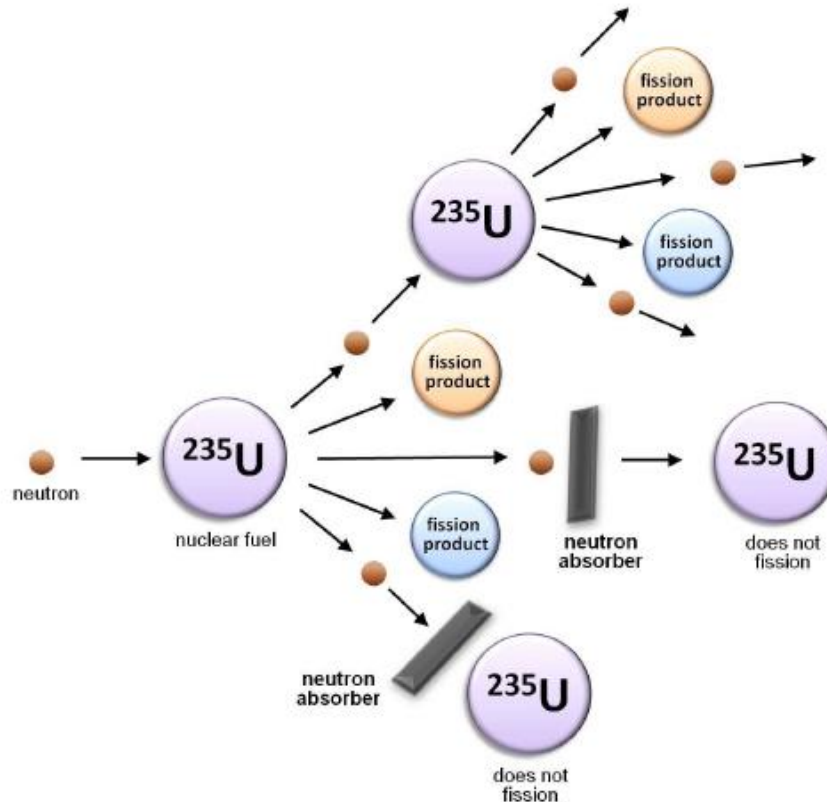
- **Many nuclear-physics issues are examined**
- **See some trend, but still an open question**

**Thanks!**

# Backup

# Neutrinos from reactors

- Nuclear reactors are the most intense terrestrial sources of electron antineutrinos
- Reactor neutrinos are produced from beta decay of fission products



- Within one fission:

**a) 2 or 3 neutrons**

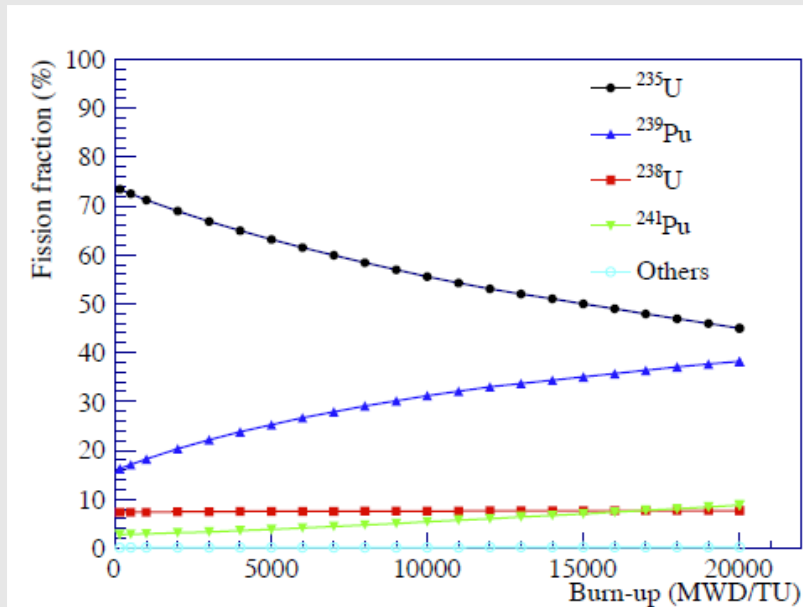
**b) 6 antineutrinos**

**c) 200 MeV energy**

are produced in the reactors.

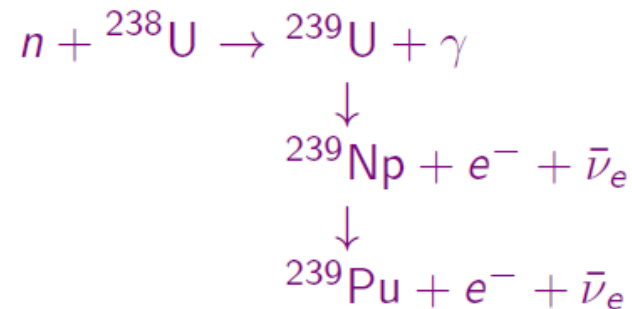
# Commercial or Research reactors

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

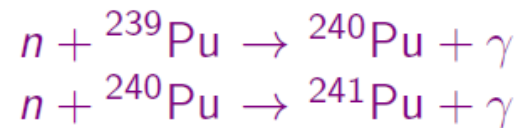


[Daya Bay, Chin. Phys. C 41 (2017) 013002]

- ▶ <sup>239</sup>Pu is generated from <sup>238</sup>U:



- ▶ <sup>241</sup>Pu is generated from <sup>239</sup>Pu:



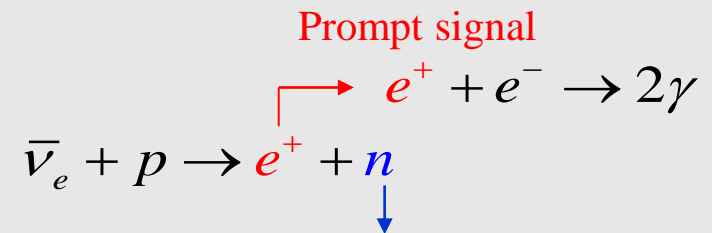
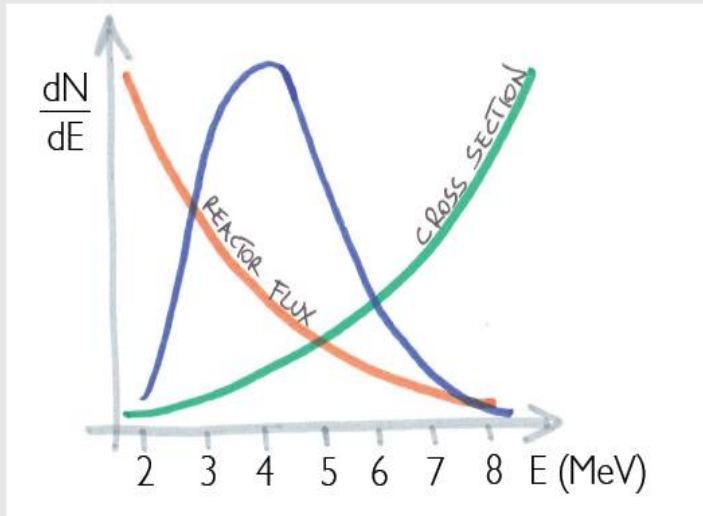
- Research reactors:

Use Highly Enriched Uranium (HEU): **>90% <sup>235</sup>U**

Burning cycle is short (about 1 month): **<sup>235</sup>U fission fraction >99%**

# Detection: Inverse beta decay

- Has been used in 1956 for the neutrino detection



Capture on H or Gd, Delayed signal, 2.2 or 8 MeV

- Coincidence of prompt and delayed signals: powerful for background suppression!
- Direct measurement of neutrino energies with the deposit energy of positron

# 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 calculate thermal neutron fission of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  for various parts ( $E \gtrsim 4$  MeV) of the spectra depends sensitively on experimentally unknown decay schemes. We also calculate the electron spectrum into the antineutrino spectrum, and reaction rates for the inverse neutron  $\beta$  decay disintegration, and the antineutrino-electron scattering.

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*

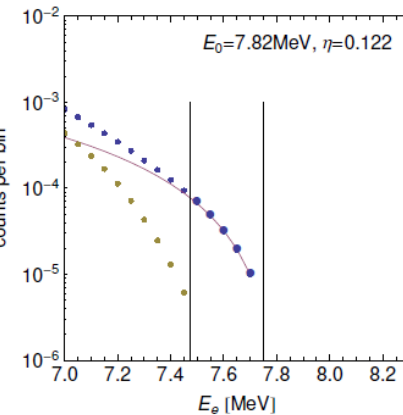
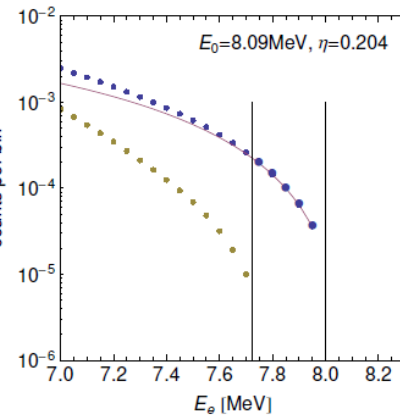
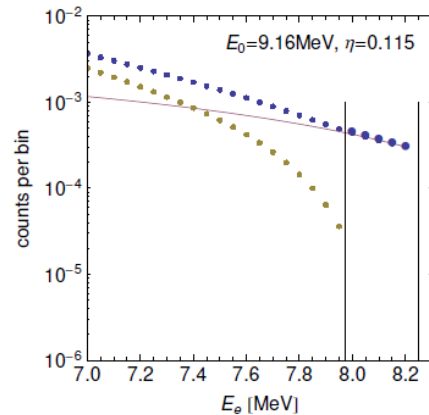
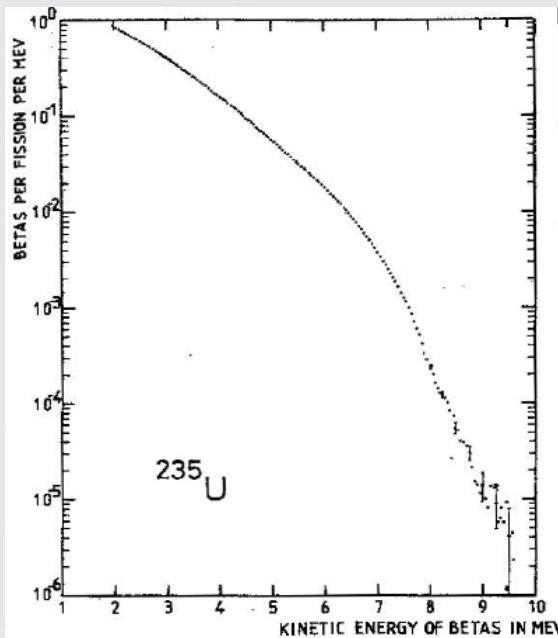
F. M. Mann and R. E. Schenter

*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  $\beta$  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  $^{235}\text{U}$  foil with a magnetic spectrometer at the ILL reactor:

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

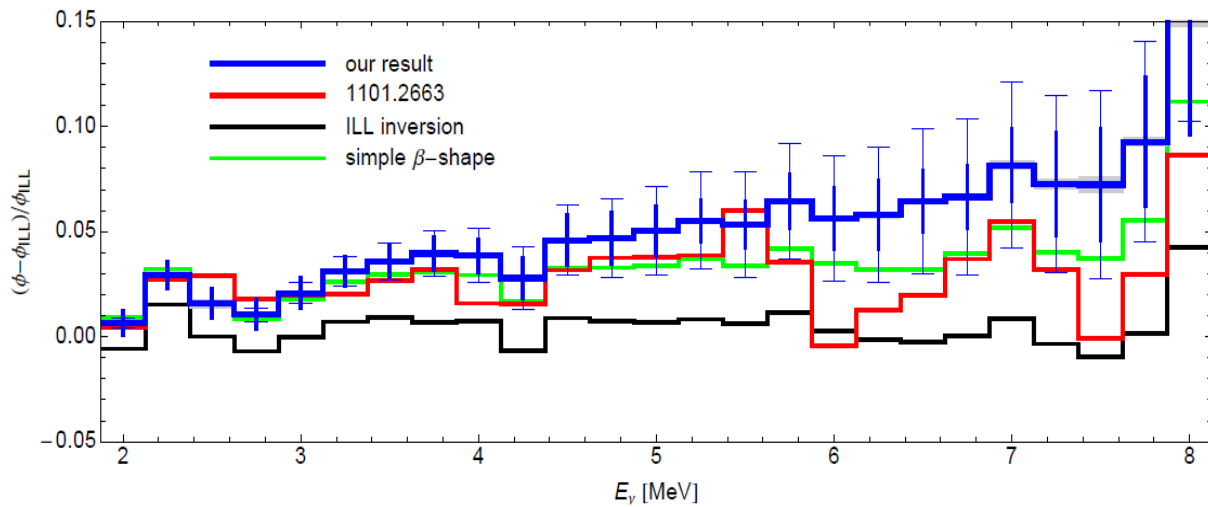
(2) Using dozens of virtual branches to fit the beta spectra, then obtain the neutrino spectra

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

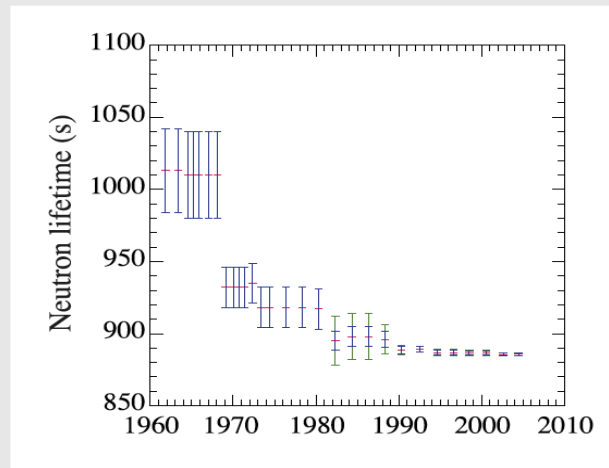
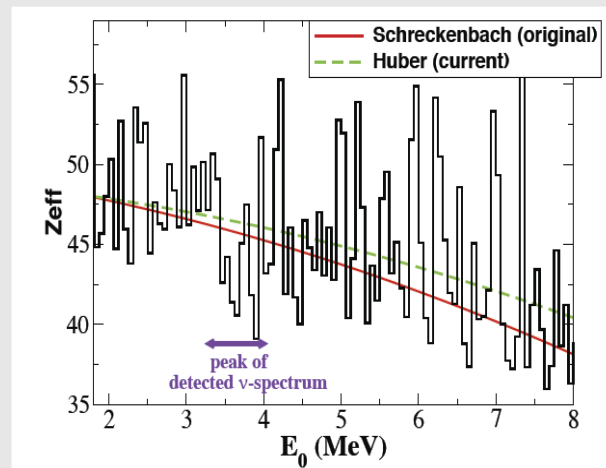
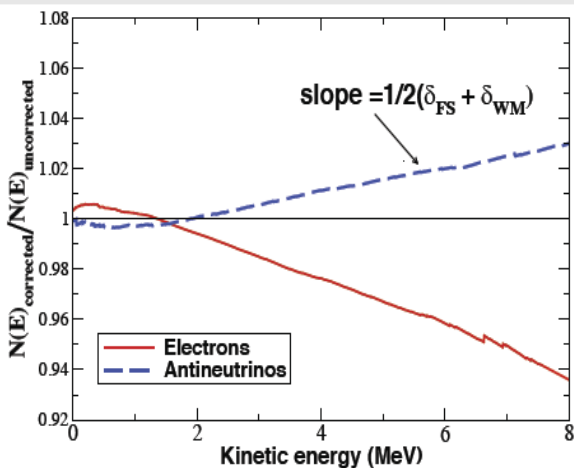
The ILL + Vogel model had been used until 2011, and was **consistent with** measurements

# New conversion evaluation in 2011

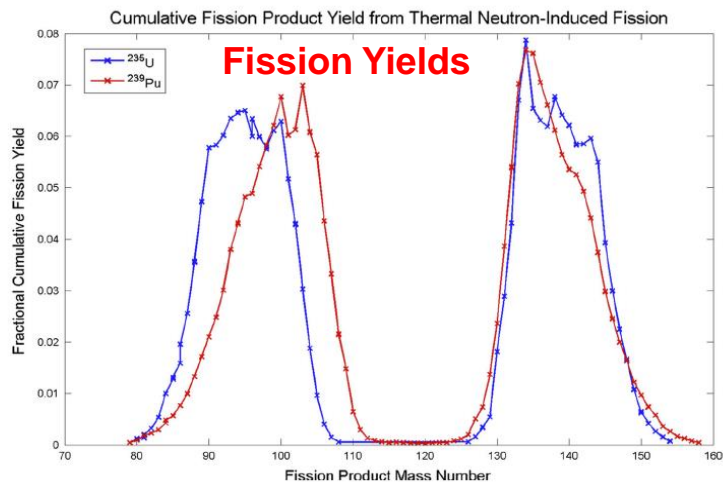
T. Mueller et al., Phys. Rev. C83, 054615 (2011); P. Huber, Phys. Rev. C84, 024617 (2011)



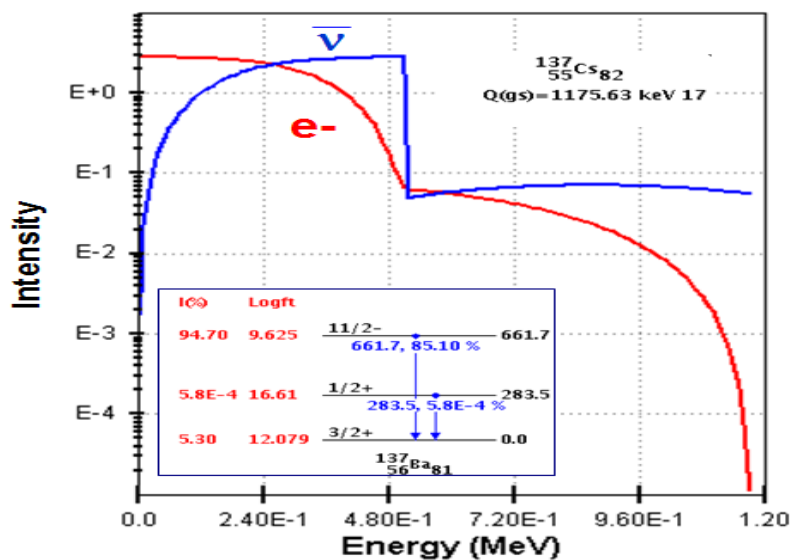
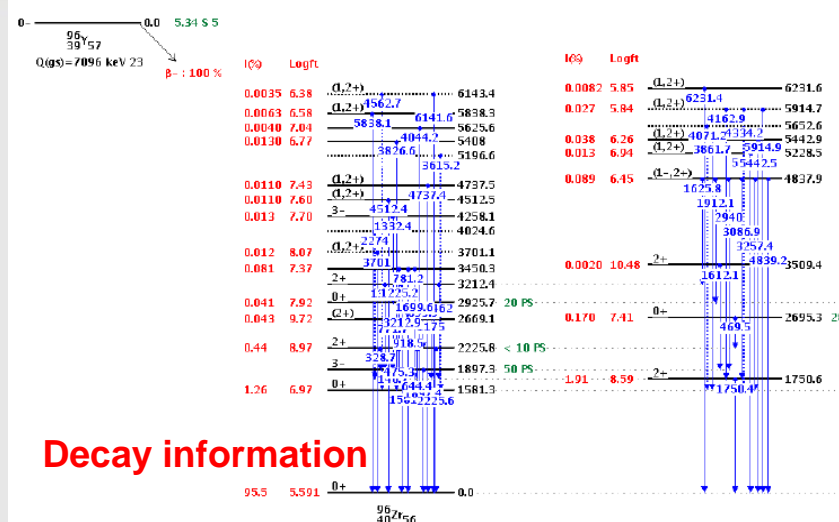
**A strange conspiracy:**  
**several small (1%-2%), but same-sign increases of the reactor neutrino flux.**  
**→ Reactor anomaly**



# How to calculate reactor neutrino flux?



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



To calculate the neutrino flux, we need:

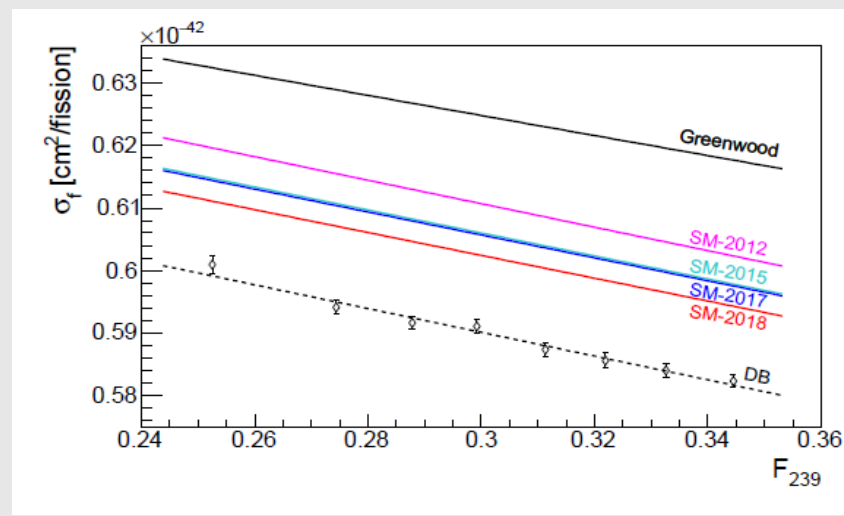
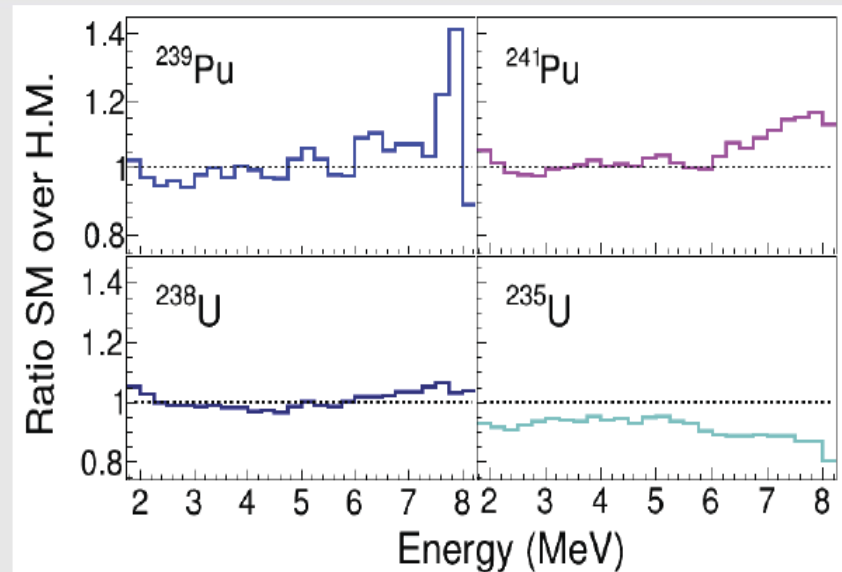
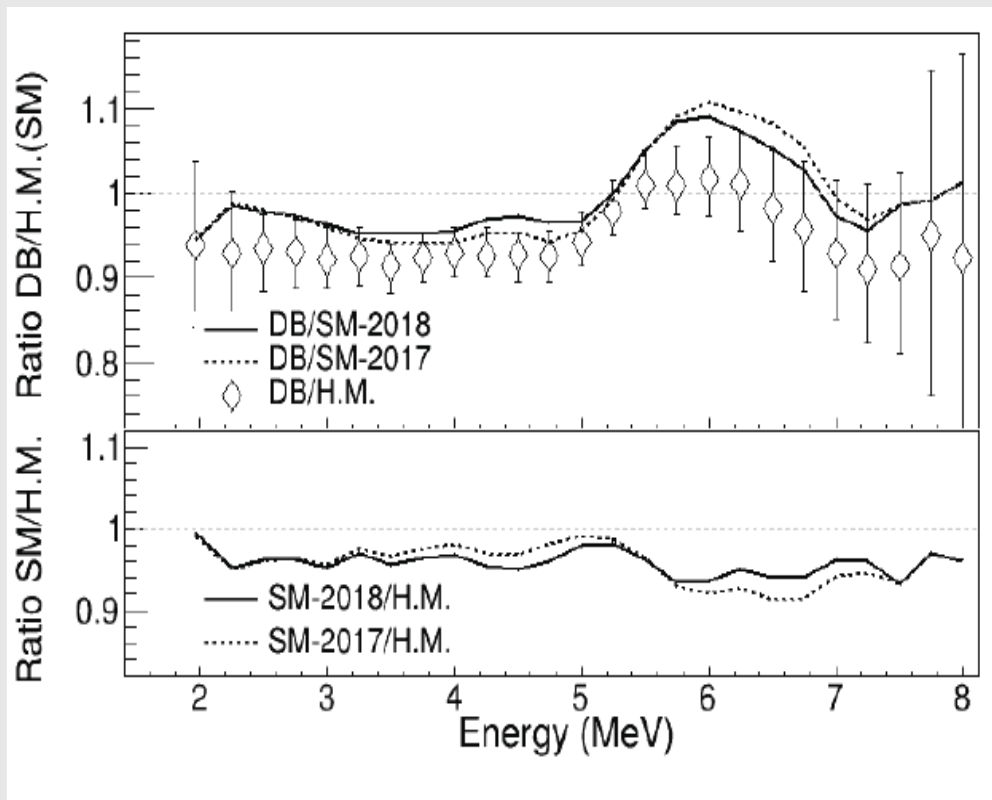
(a) Fission yields plus decay information (nuclear data)

(b) Single beta-decay spectrum

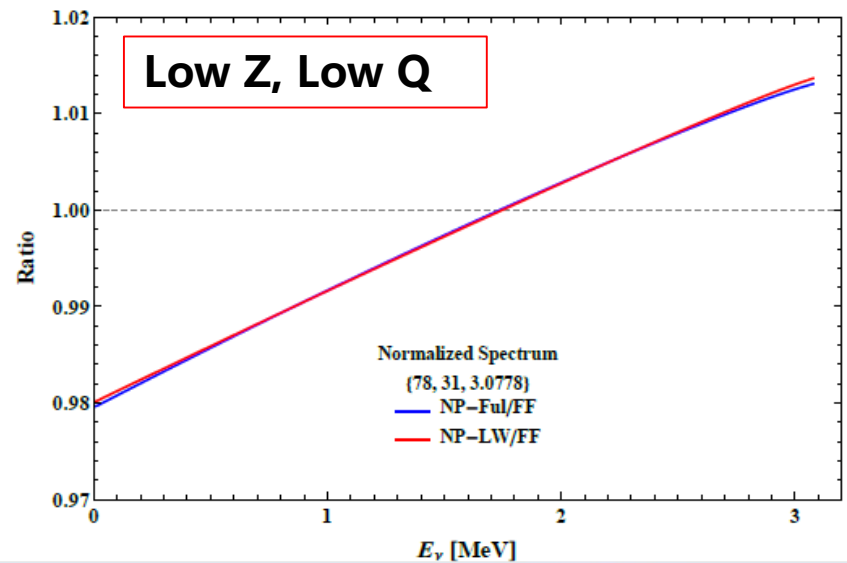
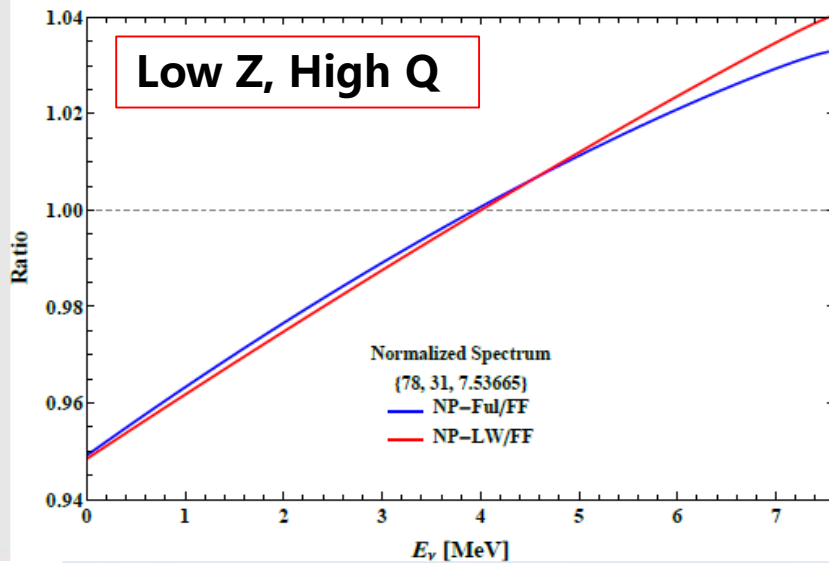
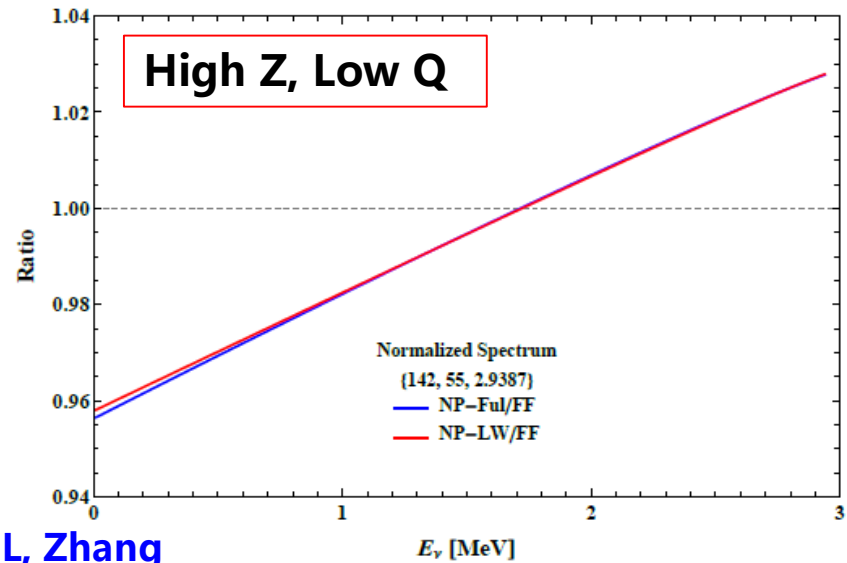
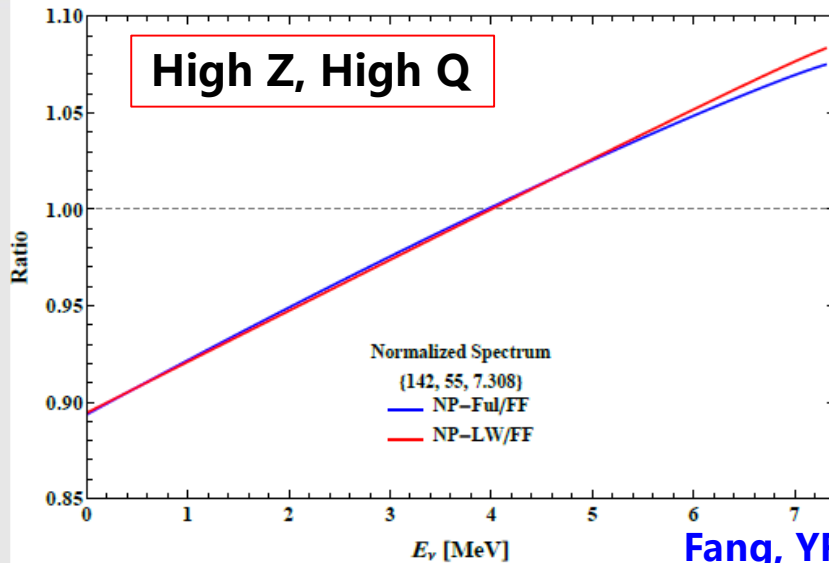
# SM Model with Pandemonium free data

Estienne et al. 1904.09358:

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

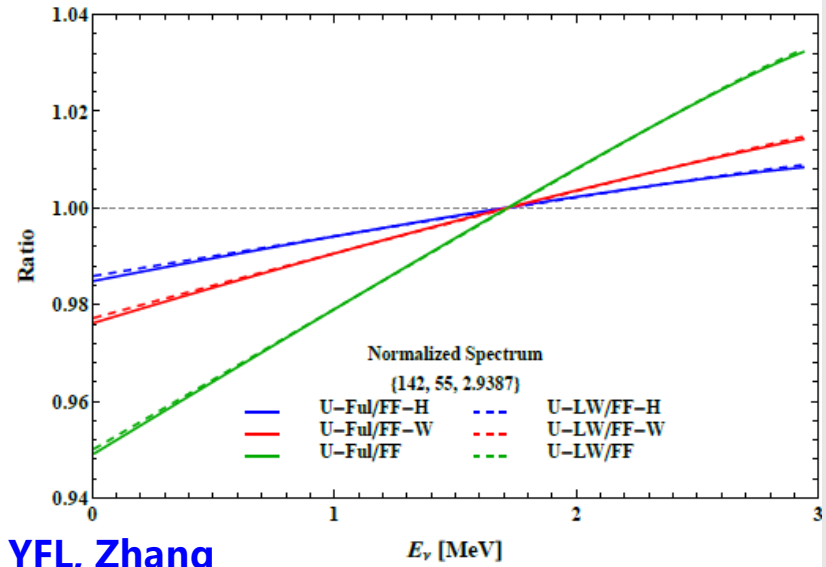
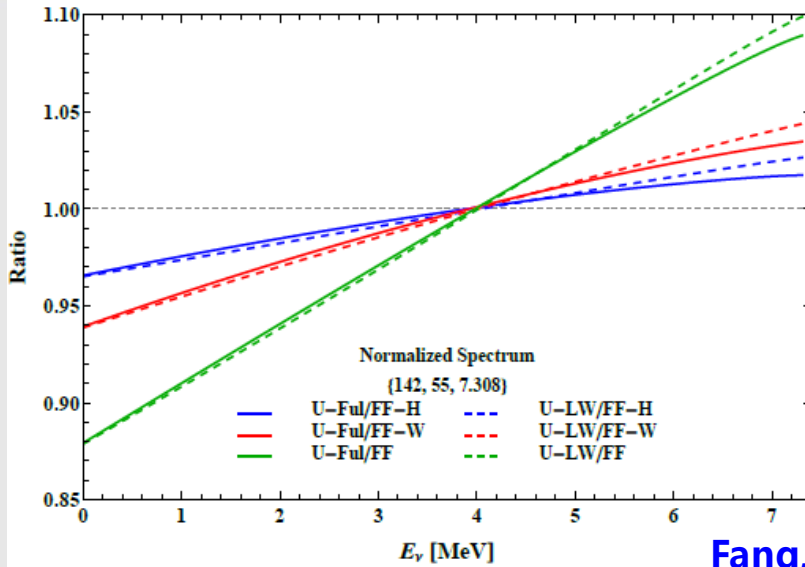


# Numerical calculation with point charge

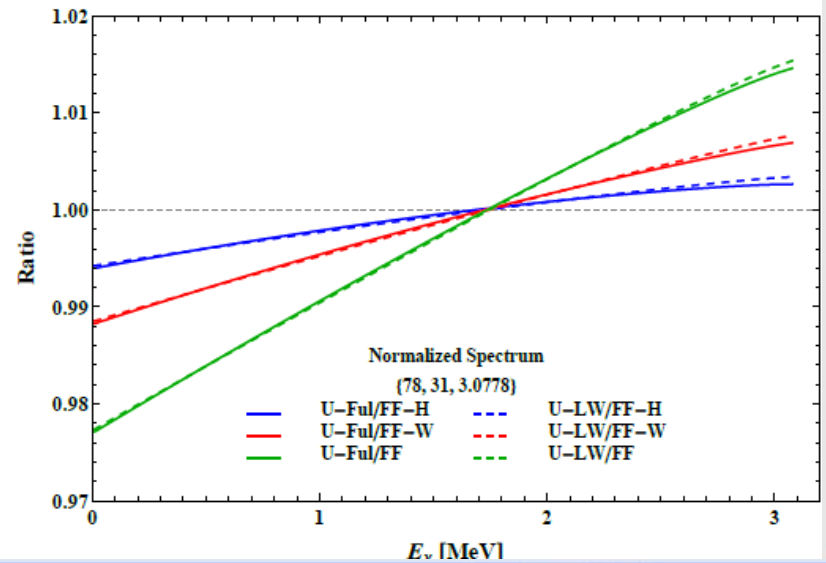
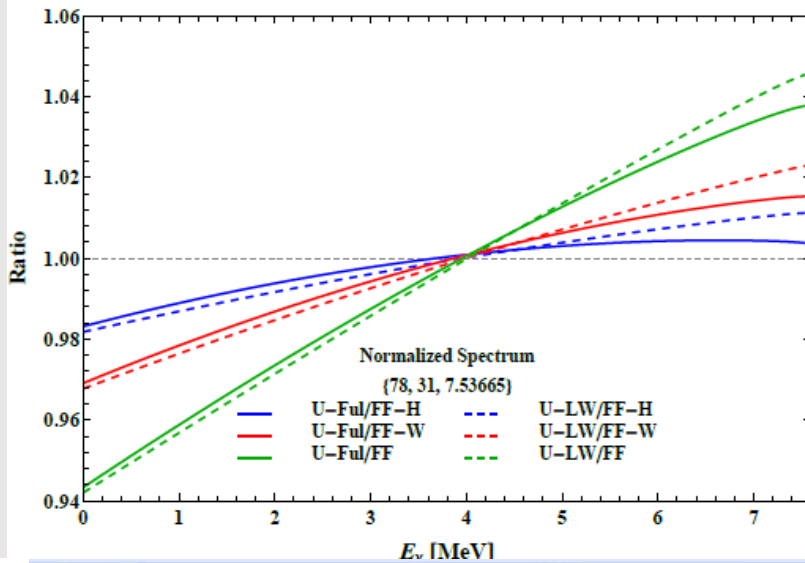


Fang, YFL, Zhang

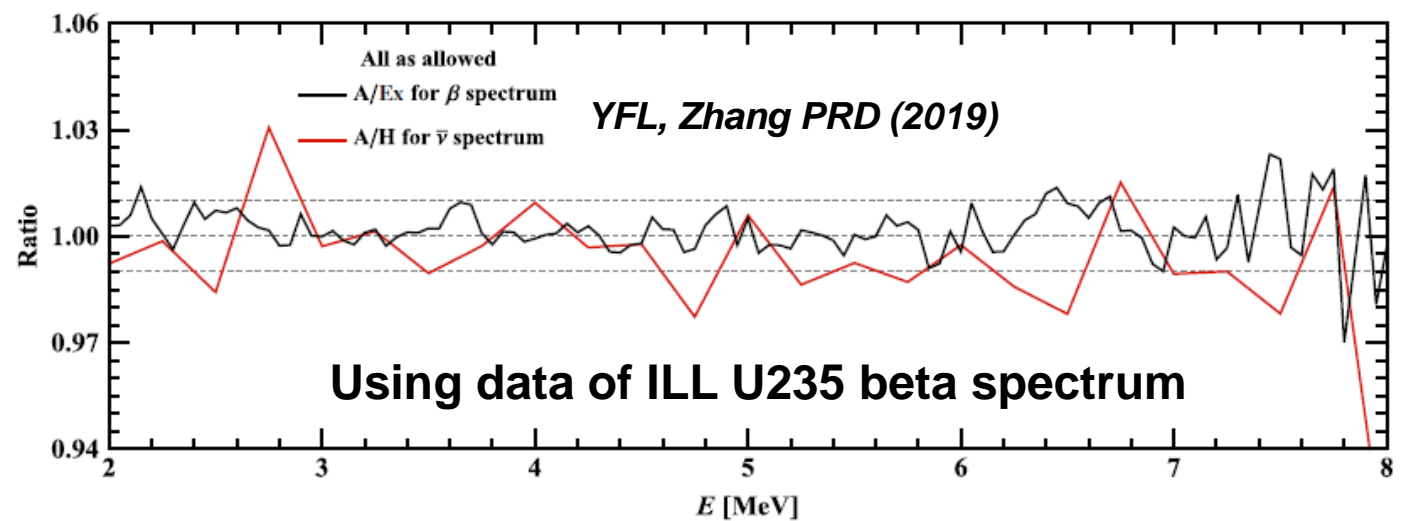
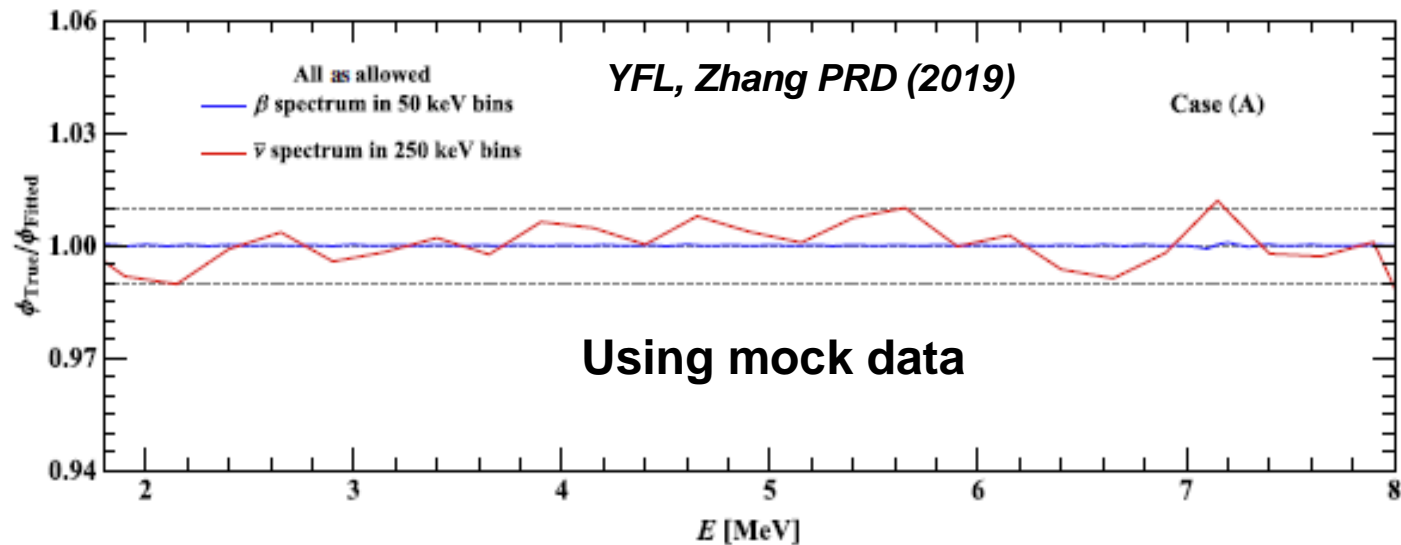
# Numerical calculation with uniform charge



Fang, YFL, Zhang



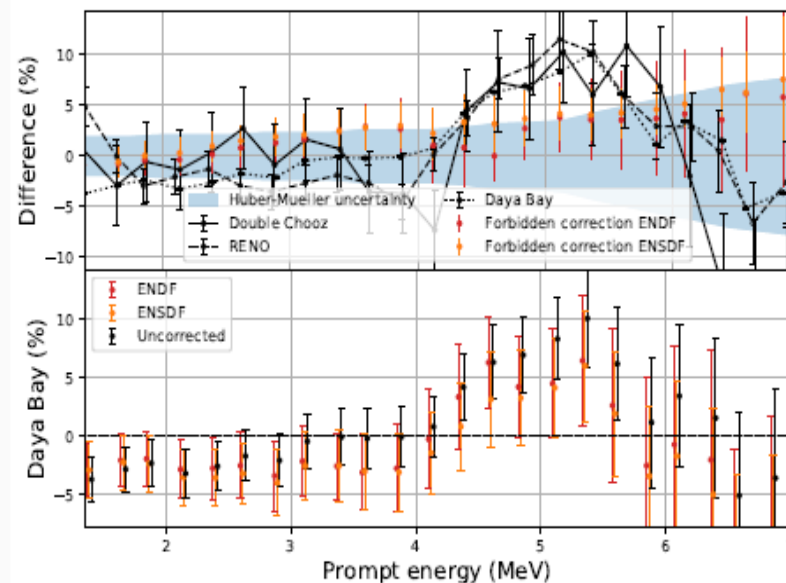
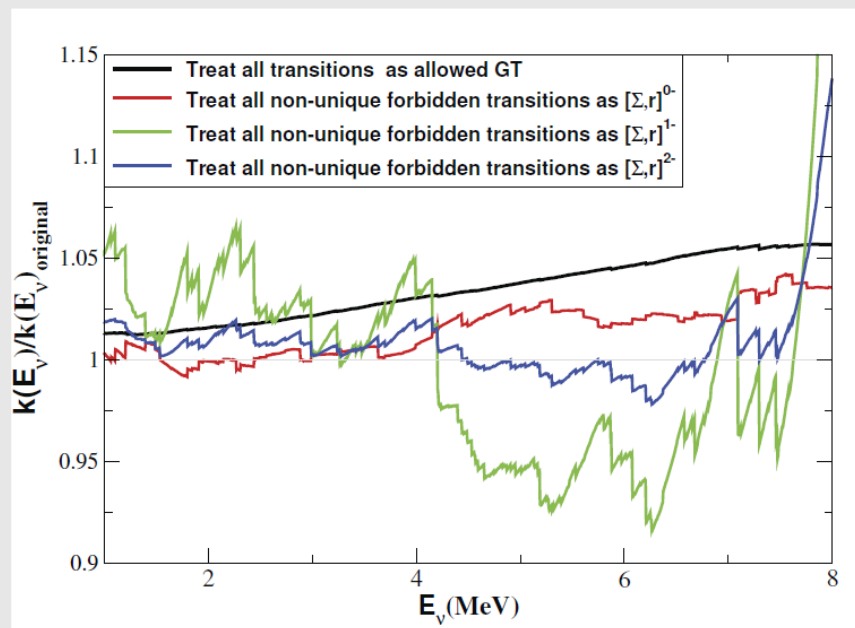
# Conversion calculation: Validation



# Other studies of forbidden decays

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

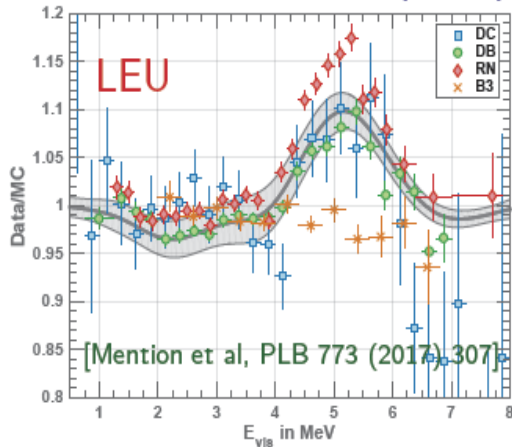
Including the first forbidden decay (using shell model) in summation method  
Hayes et al. (2018)



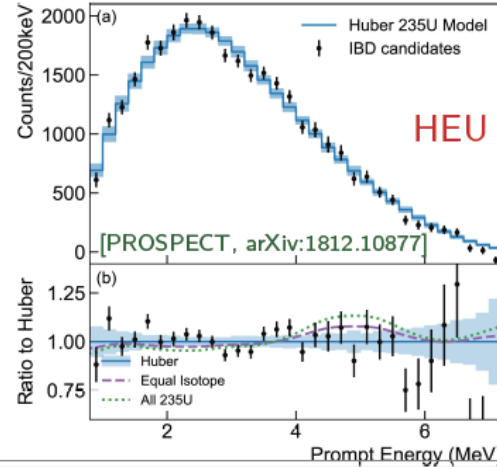
- Quantitatively agreed, but still **cannot fully accommodate** the bump of around 10% size!
- Need a **self-consistent** uncertainty evaluation!

# Observation of other experiments

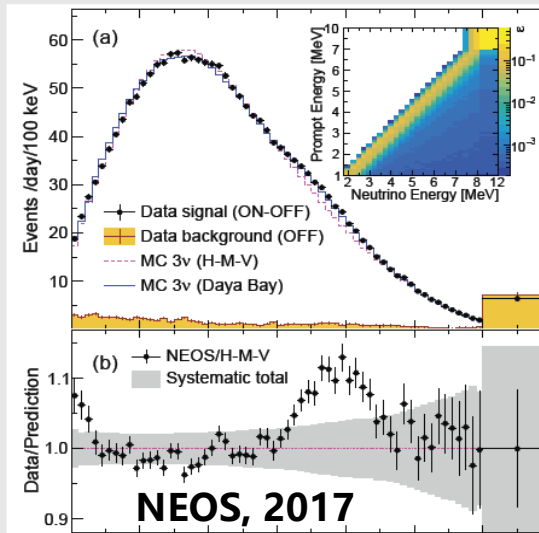
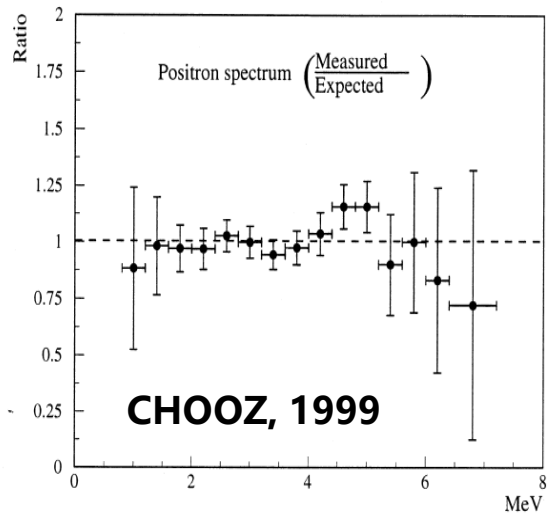
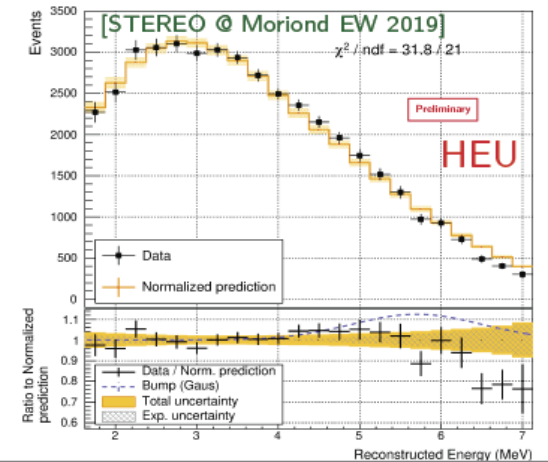
Not seen at Bugey-3 (1995)



PROSPECT: bump or no bump?



STEREO: no bump

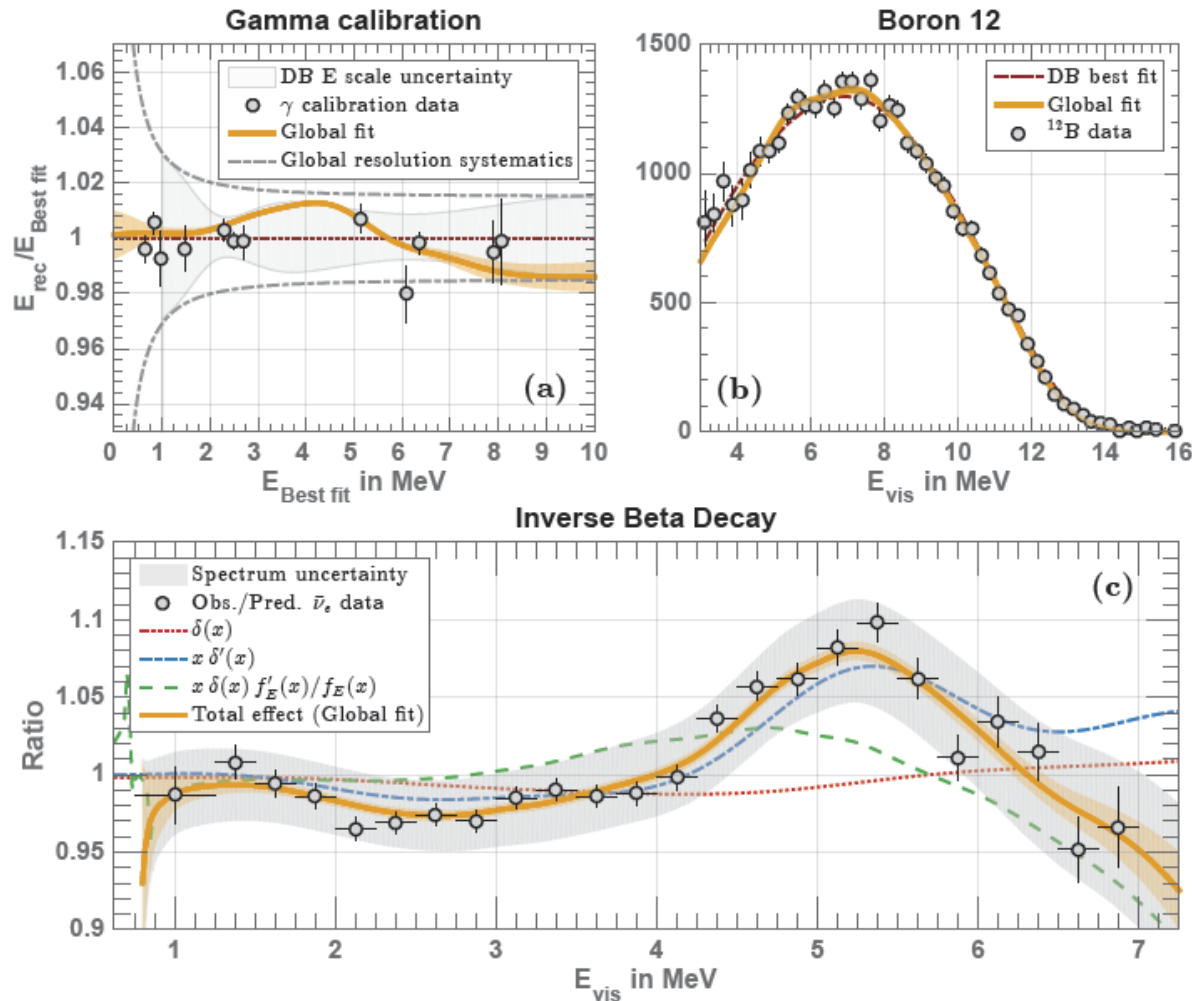


## BUMP Puzzle:

- (a) Related to the reactor type?
- (b) Related to the detector type?

# Problem: Detector energy nonlinearity ?

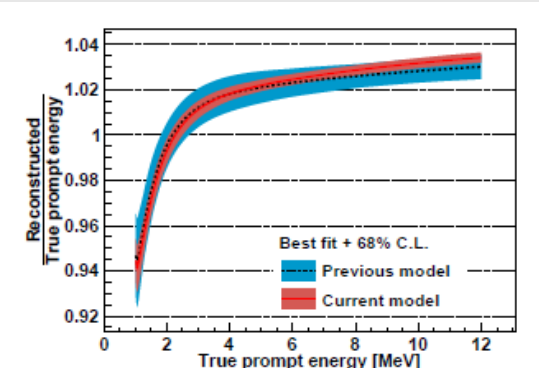
Mention et al, PLB 773 (2017) 307: is it possible to have detector effects ?



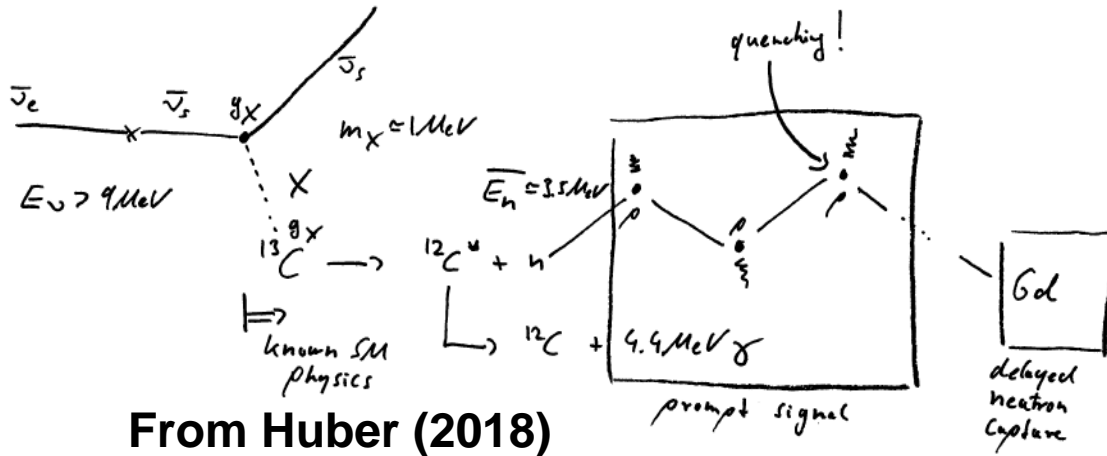
Disfavored by the new measurement:

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

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



# A brave new-physics idea?



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

