Neutrino Fits, Tensions and Puzzles

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All theorists are liars

Neutrino physics has a rich history of anomalies:

It took 40 years for Ray Davis and John Bahcall to be taken seriously with the solar neutrino anomaly.

The atmospheric neutrino anomaly did not last quite that long, but still was labeled an anomaly till Super-K came around in 1998.

Much of the anomalous nature stemmed from theoretical prejudice: neutrinos are massless, neutrino mixing angles are small, astrophysics isn't an exact science, chemistry is really scary asf.

Of course, I happen to be a theorist . . .

Why sterile?

We have measured in neutrino oscillation:

- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

This implies a lower bound on the mass of the heaviest neutrino

$\sqrt{2 \cdot 10^{-3}\,\mathrm{eV}^2} \sim 0.04\,\mathrm{eV}$ This IS BSM physics!

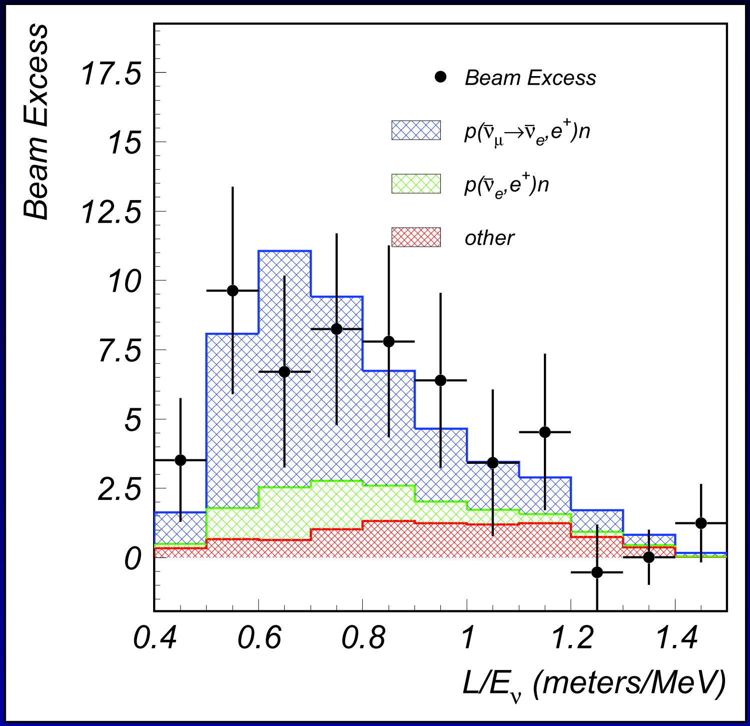
Any $\Delta m^2 \gg \Delta m^2_{21}, \Delta m^2_{31}$ requires a 4^{th} neutrino, BUT only three neutrinos with $m_\nu \leq m_Z$ couple to the Z $\Rightarrow$ "sterile" neutrino.

Evidence in favor

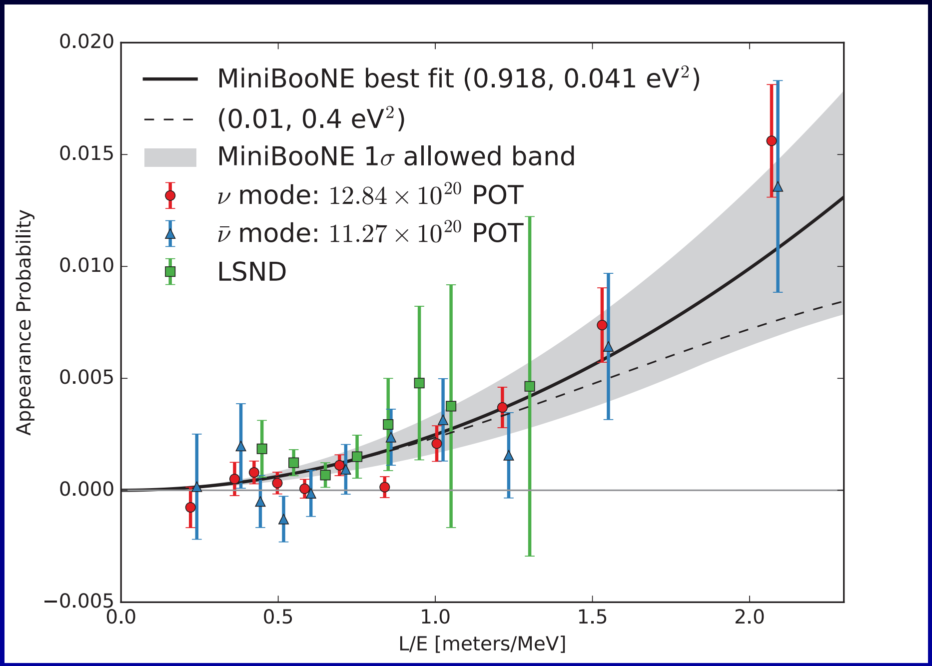
Or at least at odds with a simple 3-flavor framework

- LSND $\bar{\nu}_\mu \to \bar{\nu}_e$
- MiniBooNE $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$
- Reactors $\nu_e \to \nu_e$
- Gallium $\nu_e \to \nu_e$

LSND and MiniBooNE



LSND 1995



MiniBooNE 2018

$$P(\bar\nu_\mu \to \bar\nu_e) \simeq 0.003$$

Statistically significant: $4 - 6\sigma$

Fermilab SBN

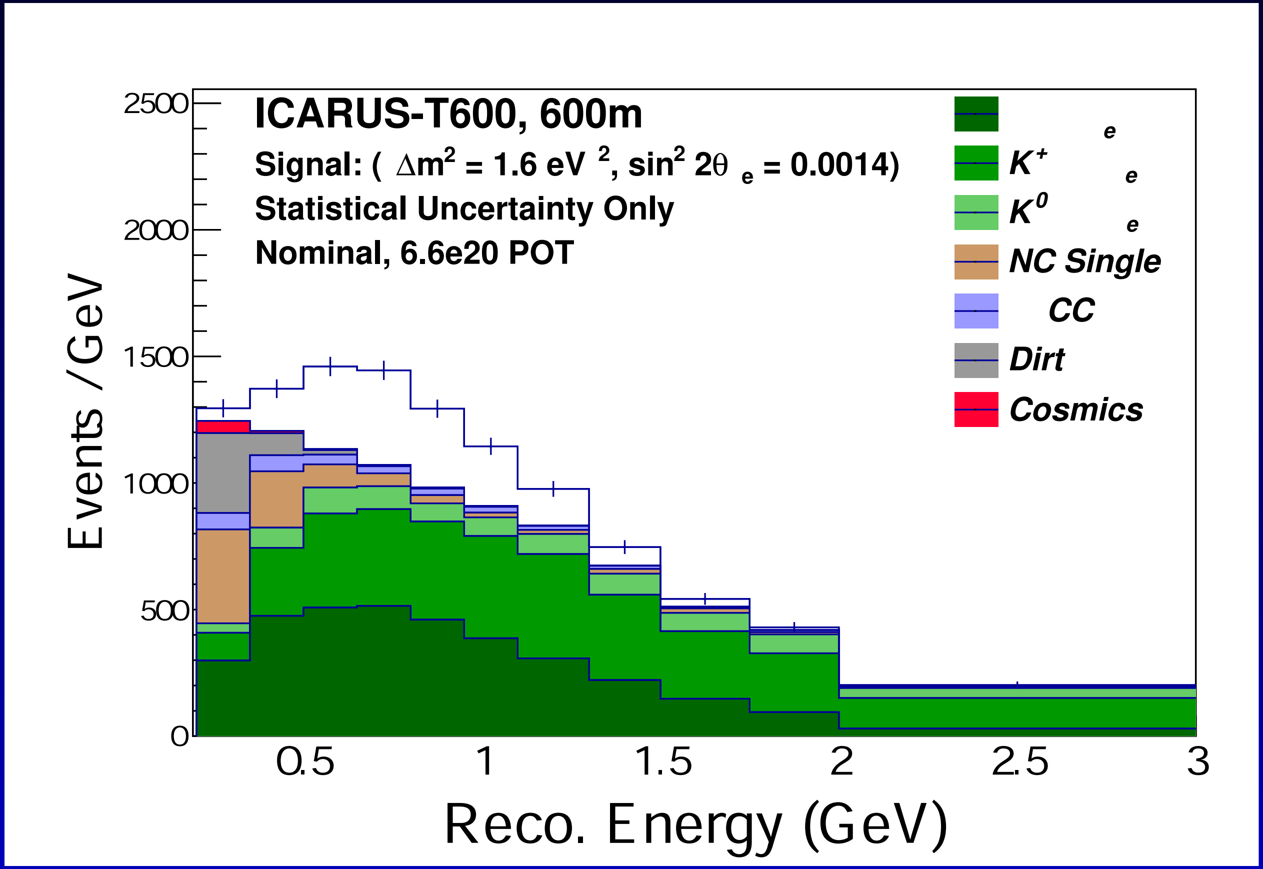
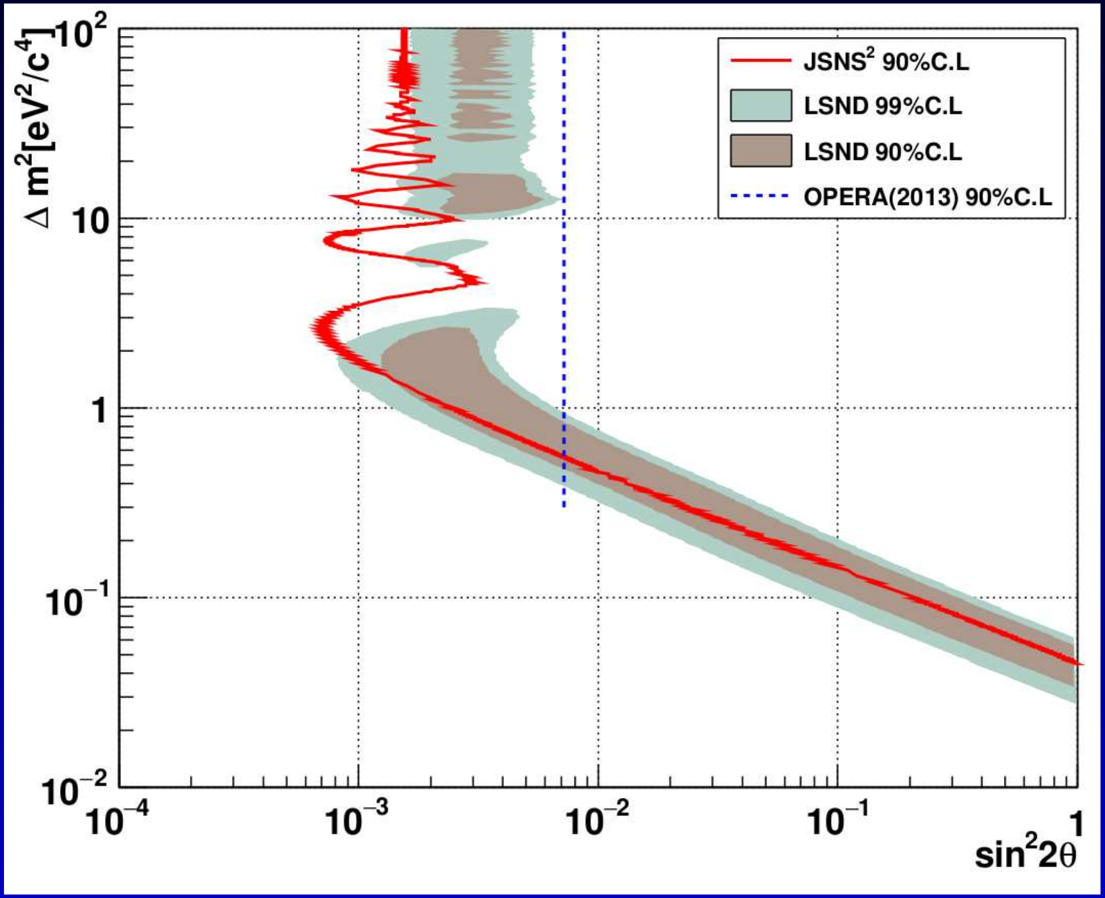


Figure courtesy D. Schmitz and C. Adams

Signal to noise not so different from LSND. . . will a near detector of completely different design help?

JSNS2

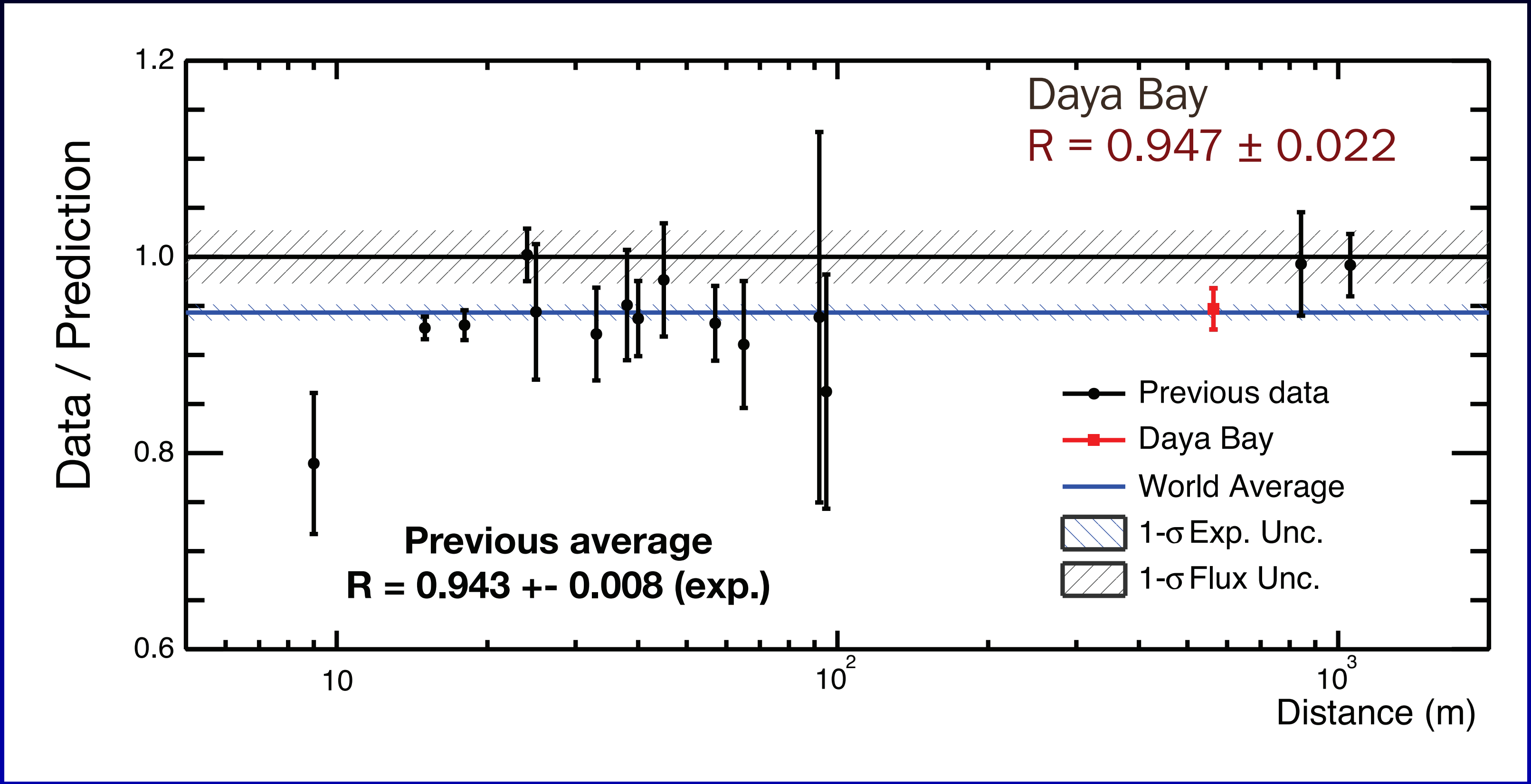


Pion decay at rest at JSNS, Gd-doped scintillator.

JSNS2, 2017

Direct test of the LSND result → should have been done 20 years ago!

The reactor anomaly



Daya Bay, 2014

Mueller *et al.*, 2011, 2012 – where are all the neutrinos gone?

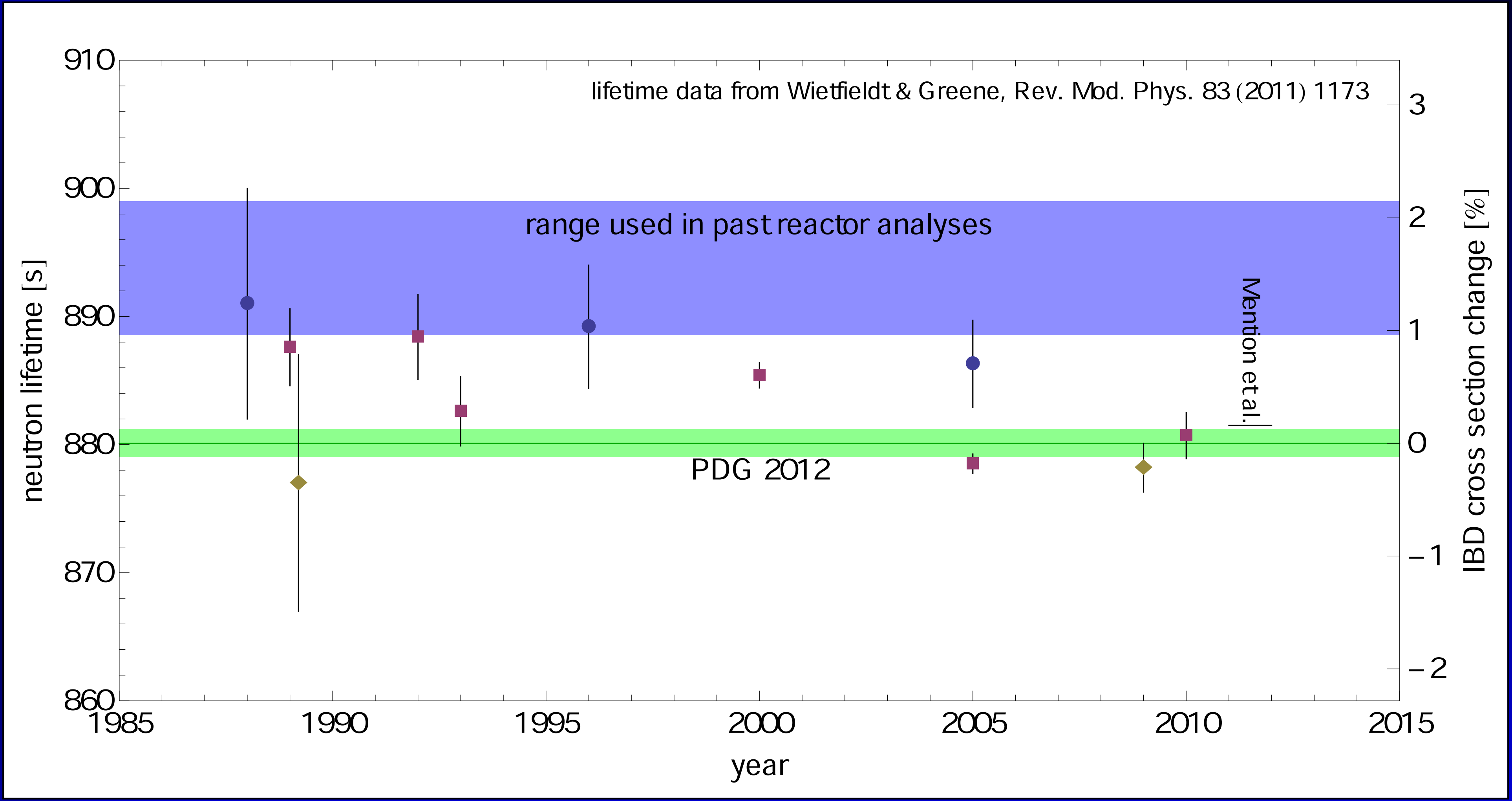
Contributors to the anomaly

6% deficit of $\bar{\nu}_e$ from nuclear reactors at short distances

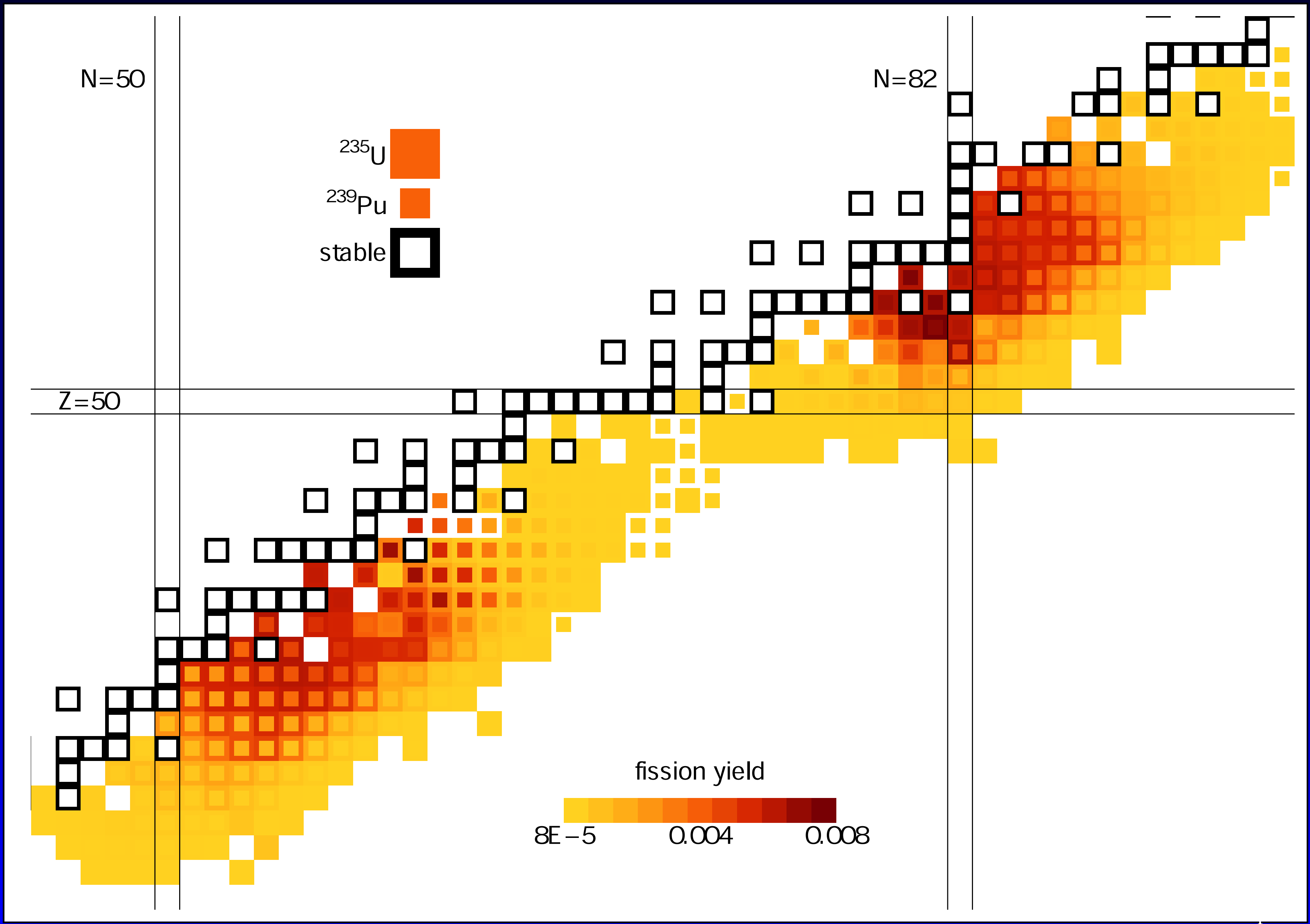
- 3% increase in reactor neutrino fluxes
- decrease in neutron lifetime
- inclusion of long-lived isotopes (non-equilibrium correction)

The effects is therefore only partially due to the fluxes, but the error budget is clearly dominated by the fluxes.

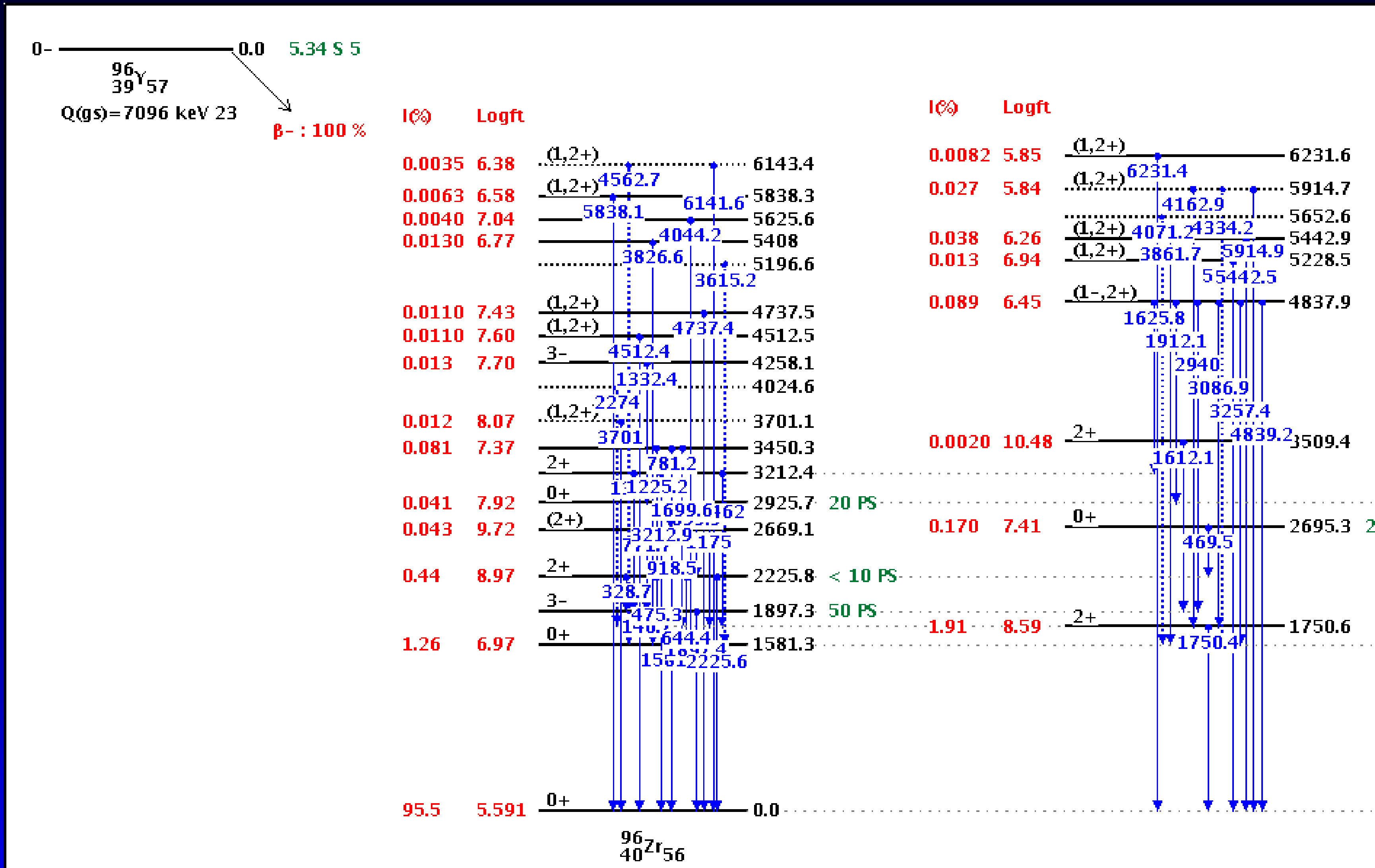
Neutron lifetime



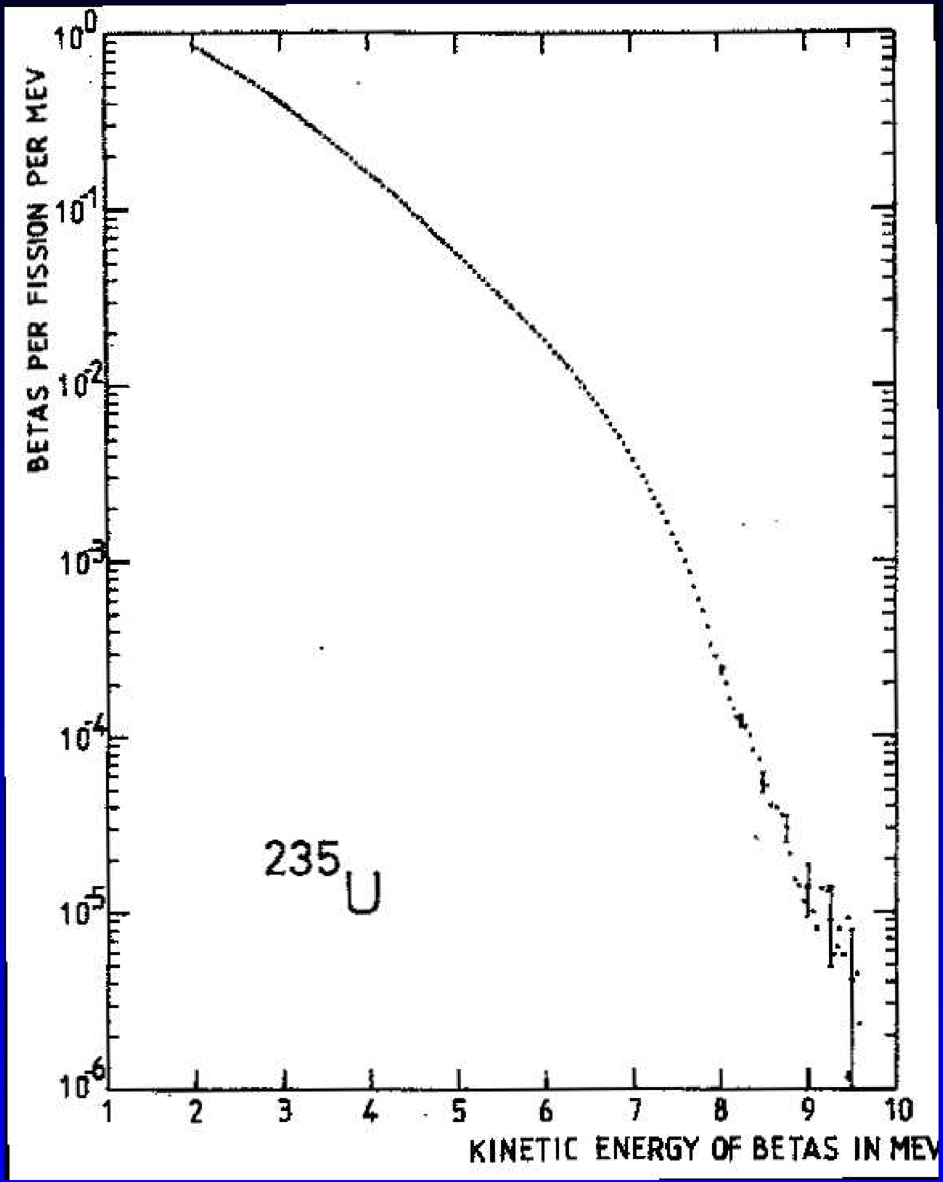
Neutrinos from fission



β-branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

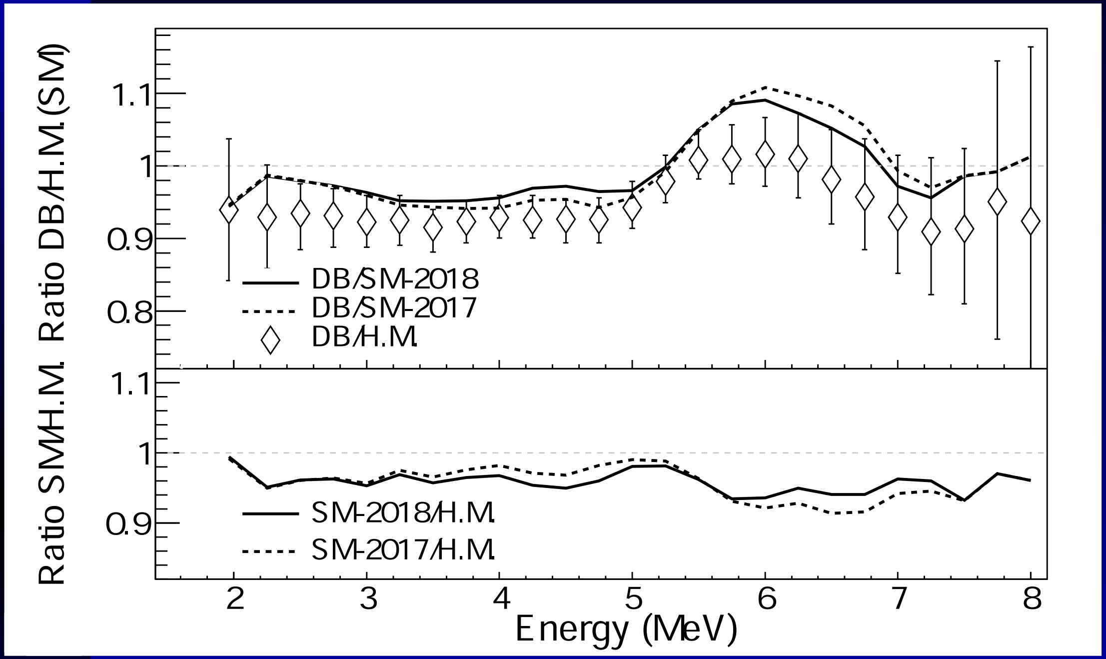
^{235}U foil inside the High Flux Reactor at ILL

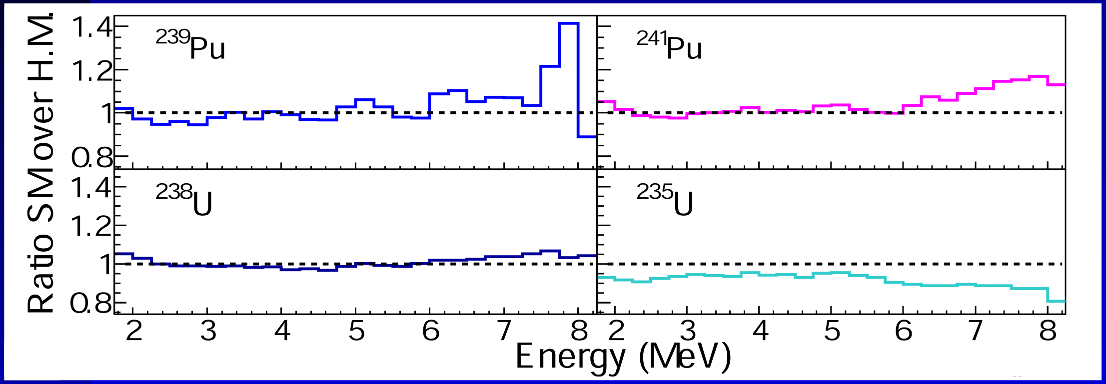
Electron spectroscopy with a magnetic spectrometer

Same method used for ^{239}Pu and ^{241}Pu

For ^{238}U recent measurement by Haag *et al.*, 2013

A priori calculations





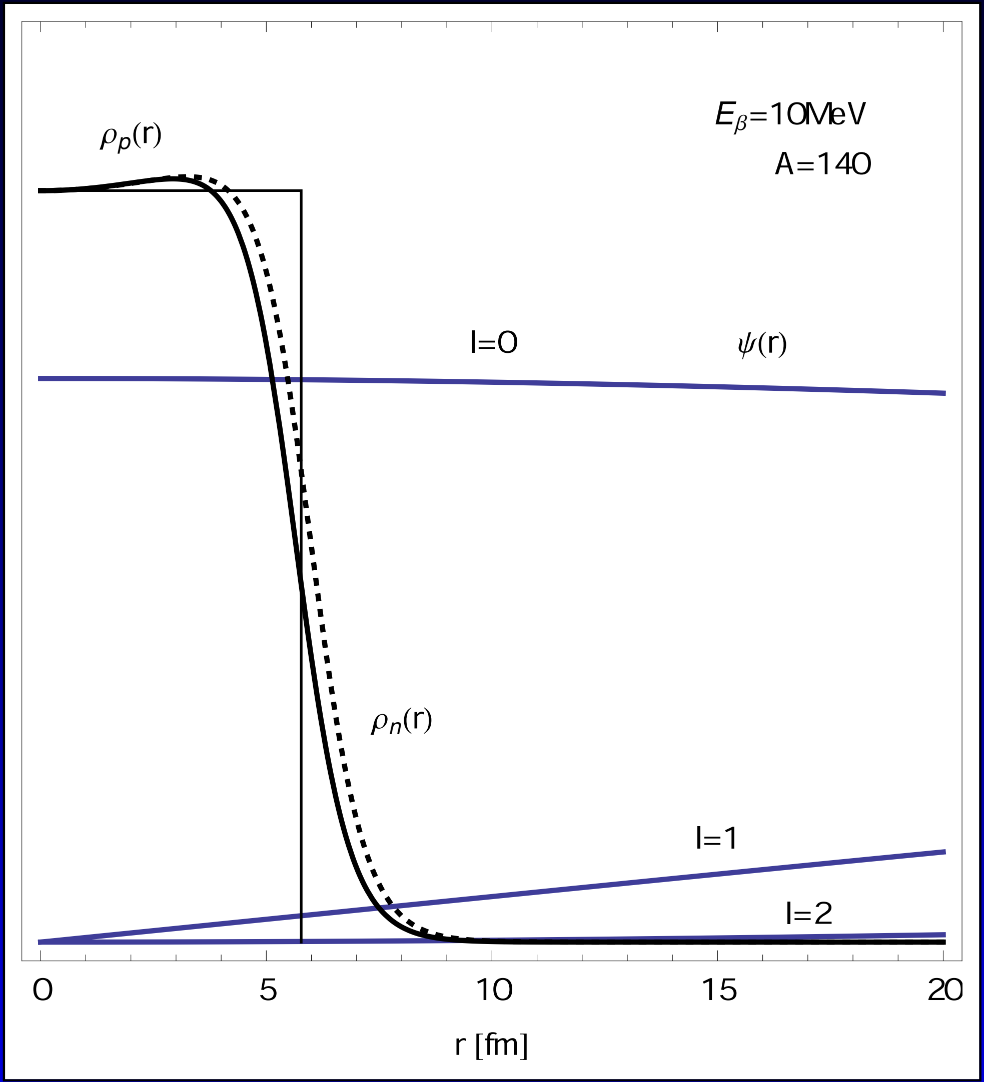
Estienne *et al.*, 2019

Updated β-feeding functions from total absorption γ spectroscopy (safe from pandemonium) for key isotopes.

For ^{238}, ^{239}Pu and ^{241}Pu better than 5% agreement with beta decay data

^{235}U, the odd-one-out?

Forbidden decays



$e,\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

Allowed:
s-wave emission ($l = 0$)

Forbidden:
p-wave emission ($l = 1$) or $l > 1$

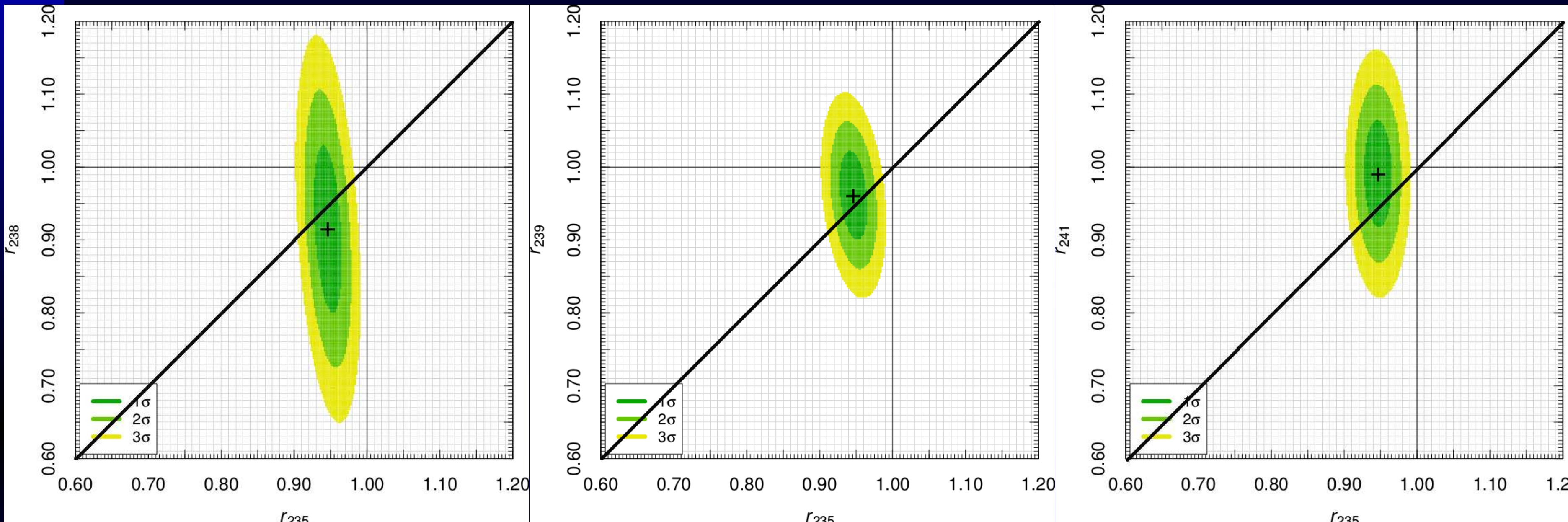
Significant nuclear structure dependence in forbidden decays$\rightarrow$ **large unquantifiable uncertainties!**

Look at past data

a	Experiment	f_{235}^a	f_{238}^a	f_{239}^a	f_{241}^a	$R_{a,\mathrm{SH}}^{\mathrm{exp}}$	σ_a^{exp} [%]	σ_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	1.8	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	3.8	18
5	Rovno88-1S	0.606	0.074	0.277	0.043	0.962	7.3	3.8	18
6	Rovno88-2S	0.557	0.076	0.313	0.054	0.949	7.3	3.8	25
7	Rovno88-3S	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	4.1	15
9	Bugey-3-40	0.538	0.078	0.328	0.056	0.942	4.3	4.1	40
10	Bugey-3-95	0.538	0.078	0.328	0.056	0.867	15.2	4.1	95
11	Gosgen-38	0.619	0.067	0.272	0.042	0.955	5.4	3.8	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	3.8	64.7
14	ILL	1	0	0	0	0.792	9.1	8.0	8.76
15	Krasnoyarsk87-33	1	0	0	0	0.925	5.0	4.8	32.8
16	Krasnoyarsk87-92	1	0	0	0	0.942	20.4	4.8	92.3
17	Krasnoyarsk94-57	1	0	0	0	0.936	4.2	2.5	57
18	Krasnoyarsk99-34	1	0	0	0	0.946	3.0	2.5	34
19	SRP-18	1	0	0	0	0.941	2.8	0.0	18.2
20	SRP-24	1	0	0	0	1.006	2.9	0.0	23.8
21	Nucifer	0.926	0.061	0.008	0.005	1.014	10.7	0.0	7.2
22	Chooz	0.496	0.087	0.351	0.066	0.996	3.2	0.0	≈ 1000
23	Palo Verde	0.600	0.070	0.270	0.060	0.997	5.4	0.0	≈ 800
24	Daya Bay	0.561	0.076	0.307	0.056	0.946	2.0	0.0	≈ 550
25	RENO	0.569	0.073	0.301	0.056	0.946	2.1	0.0	≈ 410
26	Double Chooz	0.511	0.087	0.340	0.062	0.935	1.4	0.0	≈ 415

Giunti, 2016

What does this tell us?

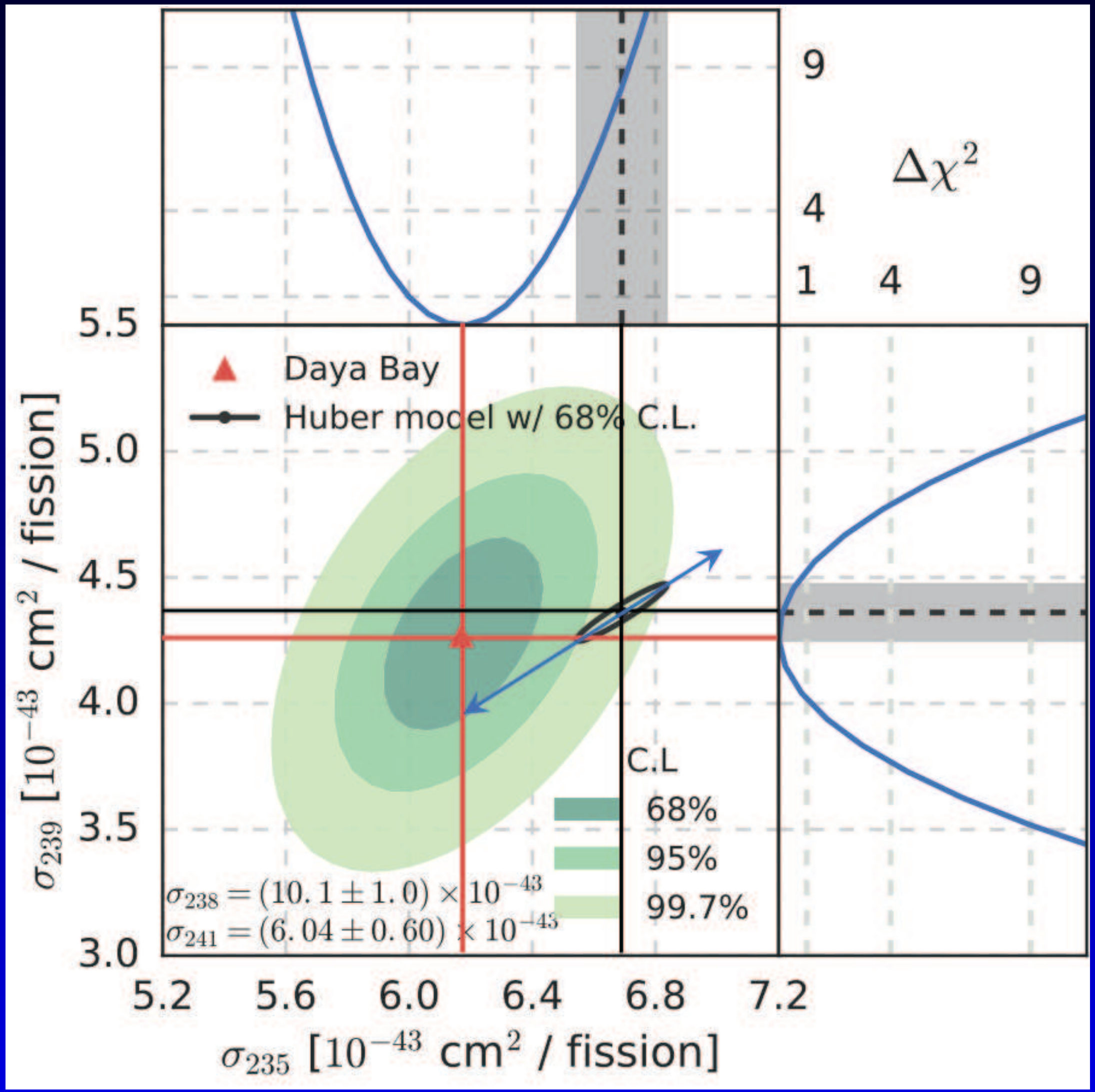


Giunti, 2016

Is ^{235}U odd?

Are the error bars for ^{235}U just smaller?

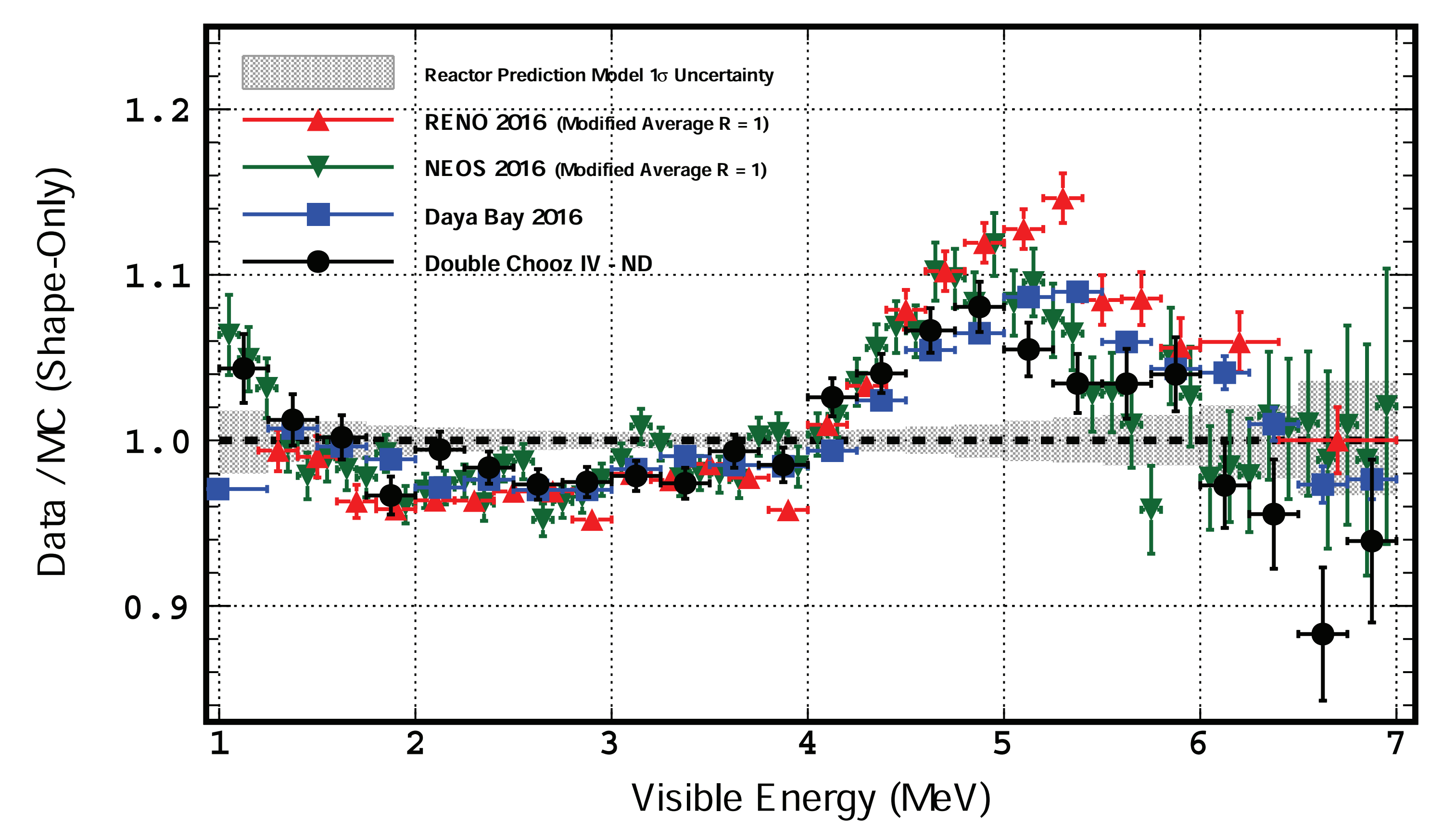
Latest result of Daya Bay



Only an issue if the prediction of Pu239 in the Huber+Mueller model is correct.
Hayes *et al.*, 2017

Daya Bay, 2017 and Diaz *et al.*, 2019

The 5 MeV bump

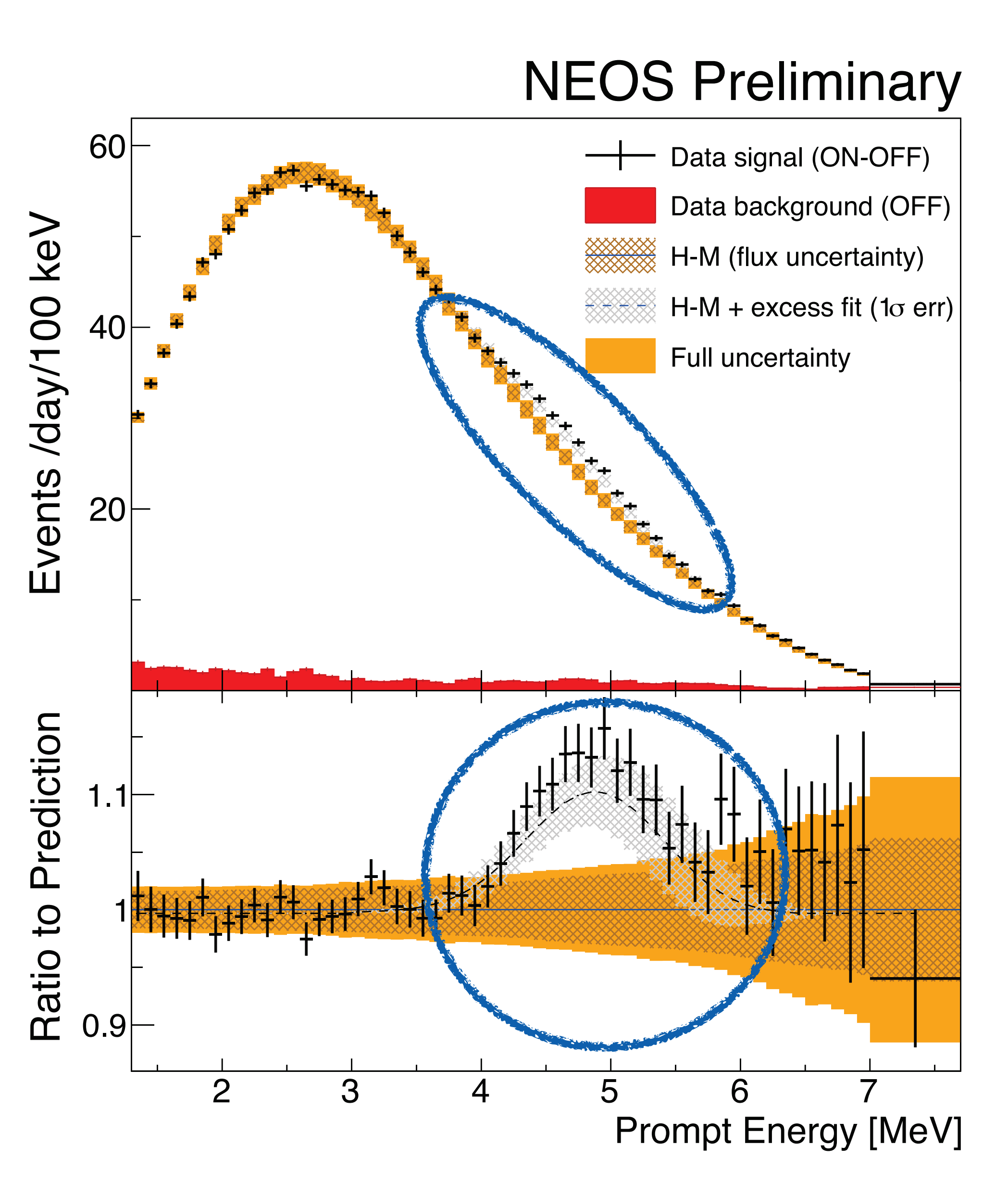


Double Chooz 2019

Seen by all three reactor experiments

Tracks reactor power

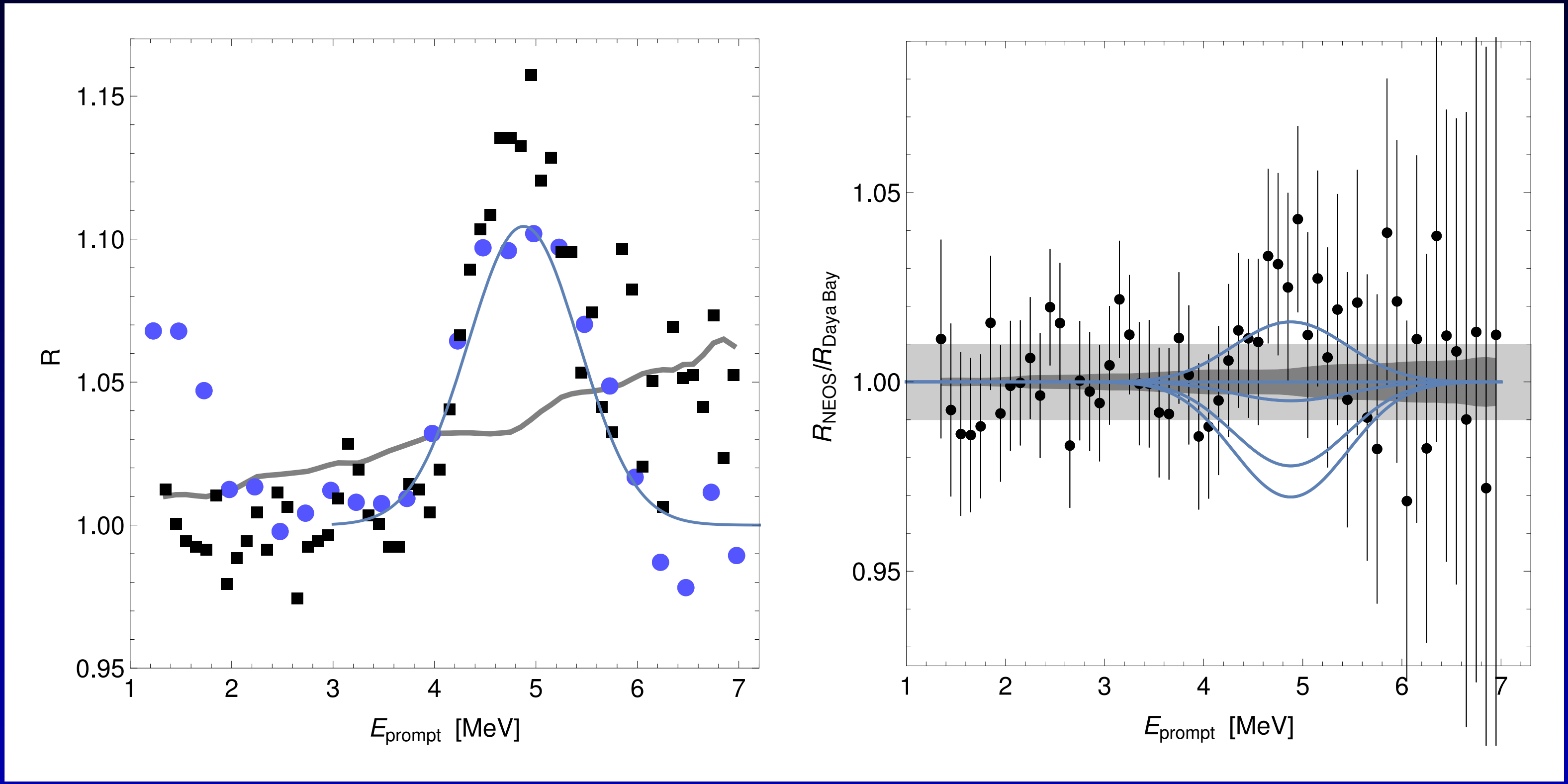
NEOS



NEOS, 2016

24m from a large core (power reactor), confirms bump

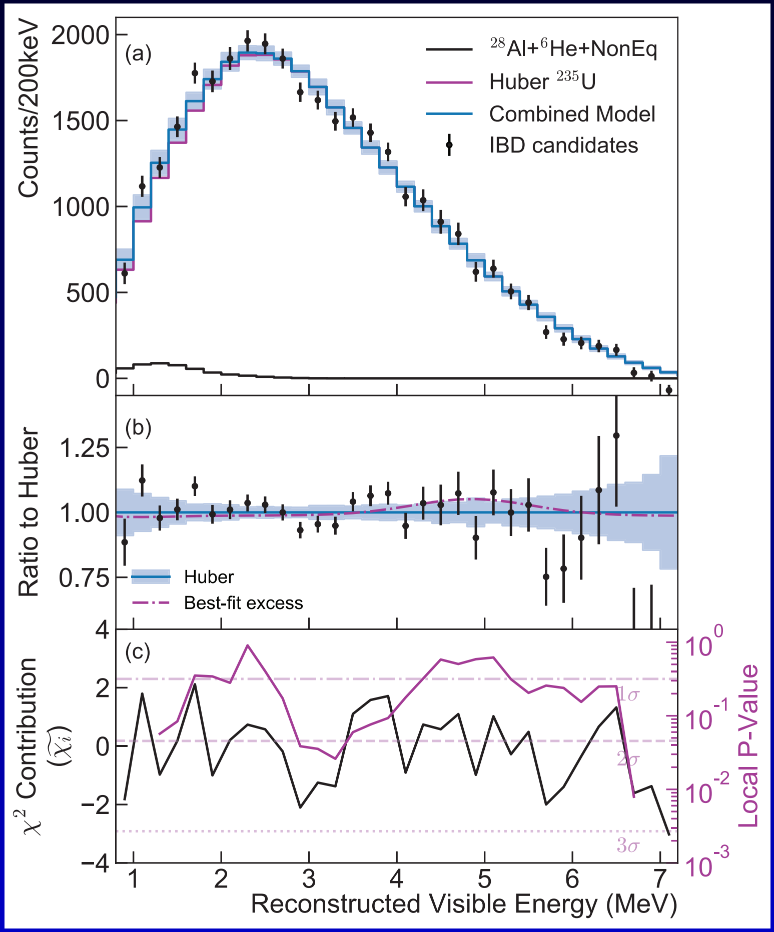
NEOS vs Daya Bay

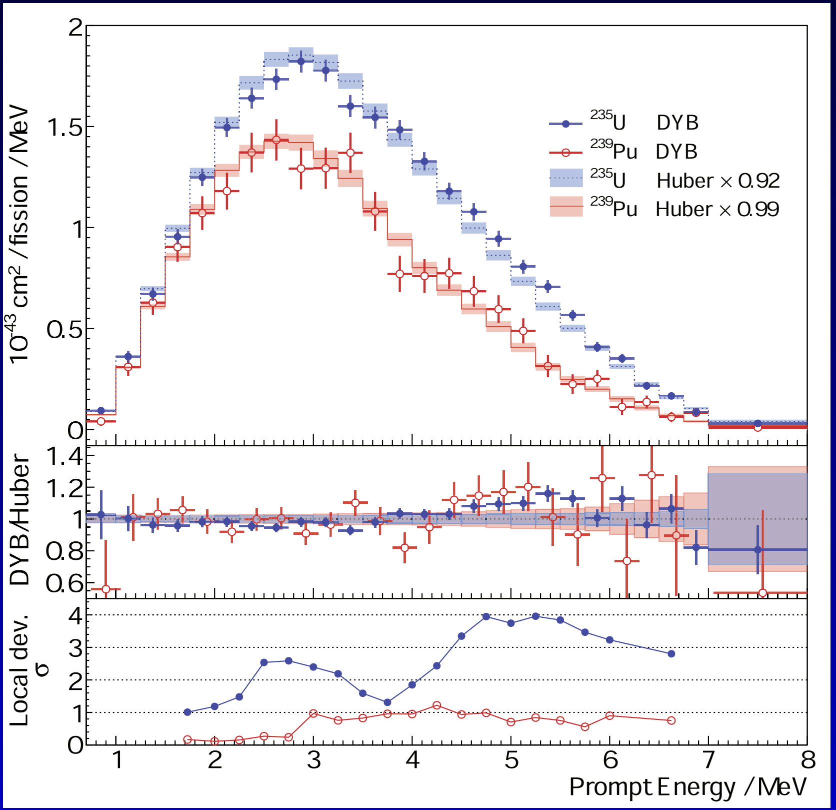


Huber, 2017

There is more U235 in NEOS, since core is fresh $\Rightarrow$ $3 - 4\,\sigma$ evidence against Pu as sole source of bump, but equal bump size is still allowed at better than $2\,\sigma$.

Latest data vs bump





PROSPECT 2018

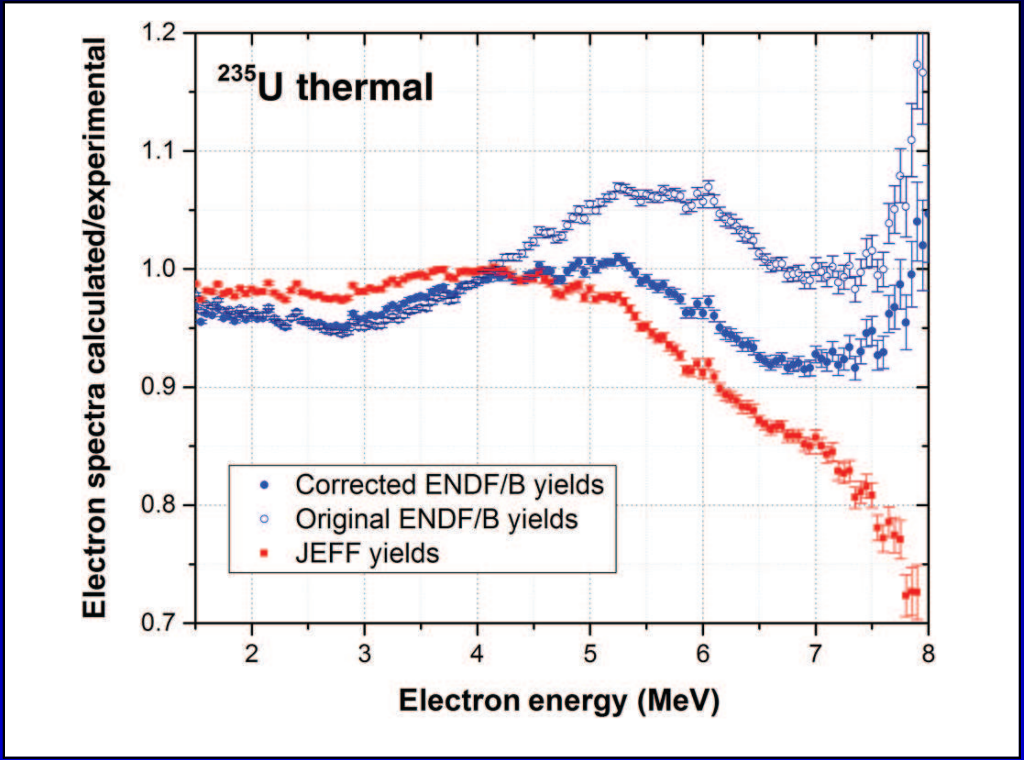
Disfavors ^{235}U as sole culprit at 2.1 σ

Daya Bay 2019

Requires a bump in ^{235}U at 4 σ

Explanations?

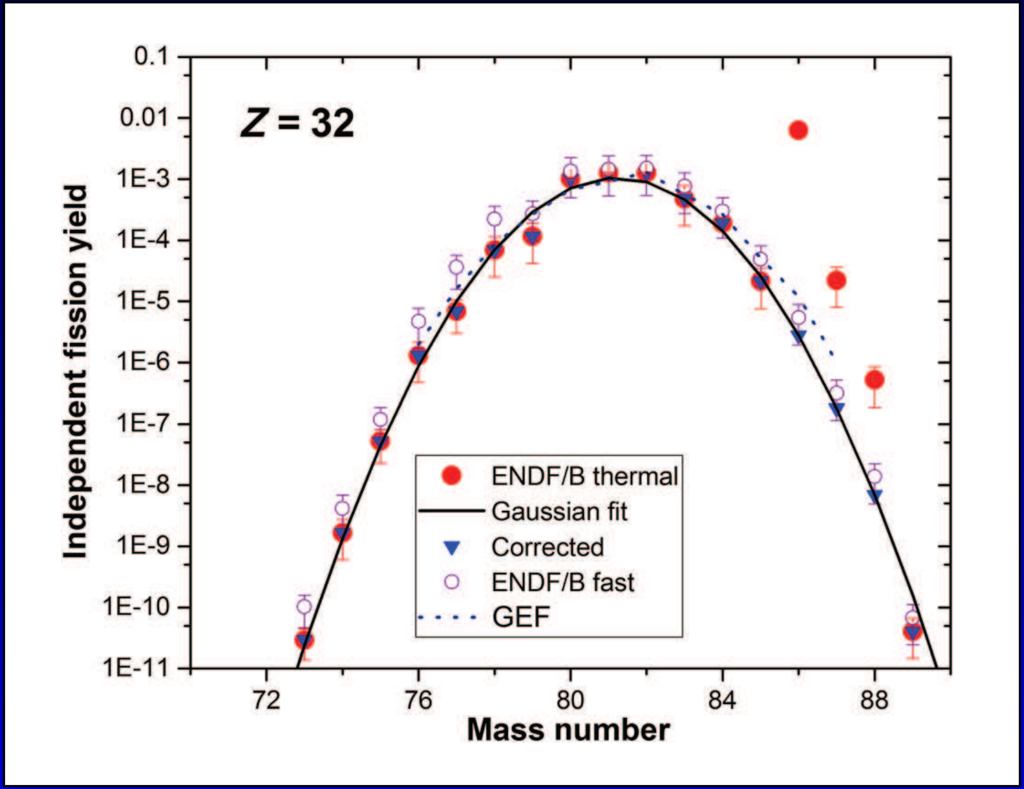
Direct summation of latest ENSDF database with allowed beta-spectrum shape Sonzogni *et al.*, 2016



This direct summation, as all other direct summations, does not agree with the Schreckenbach measurement.

What happened?

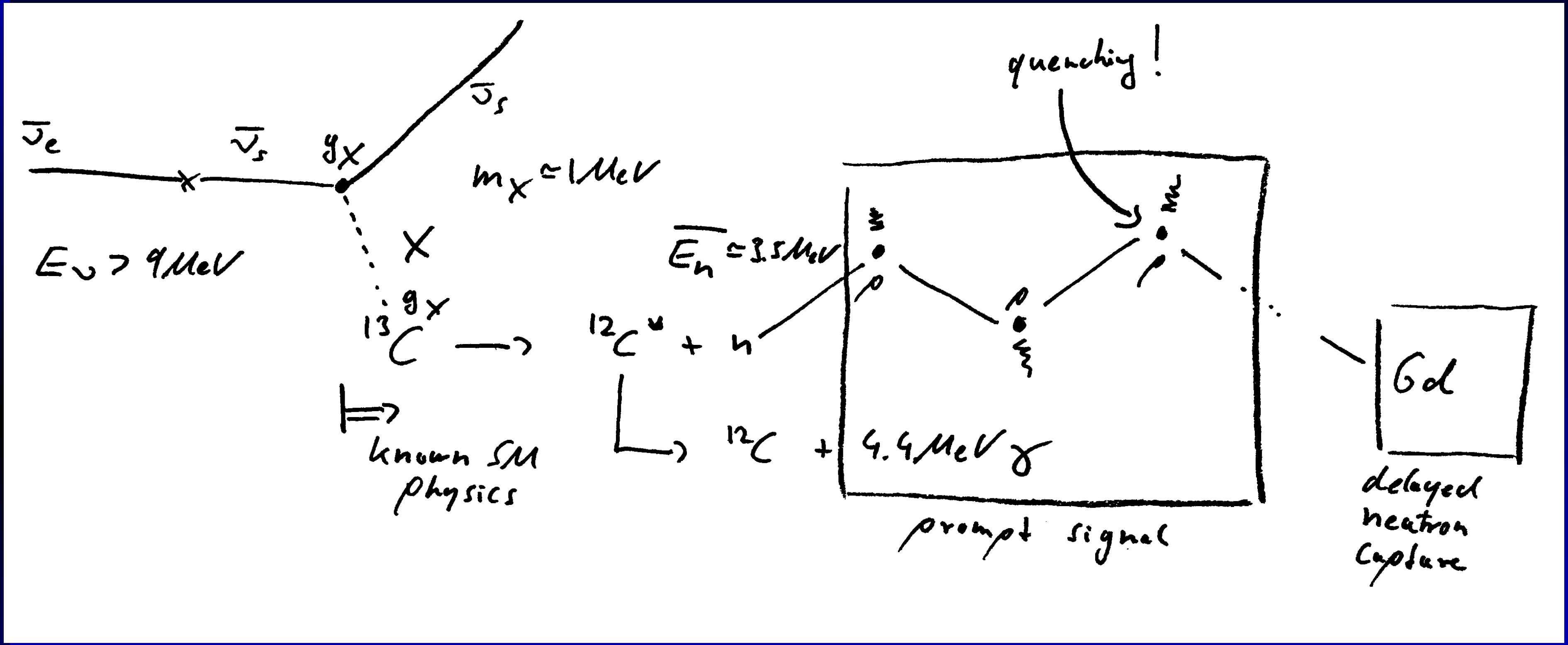
Fission yield data has been suspected previously Hayes *et al.* 2015 and this what Sonzogni *et al.*, 2016 found:



Who is the odd-one-out?

Fission yields for germanium-86 wrong in ENDF/B but not in JEFF.

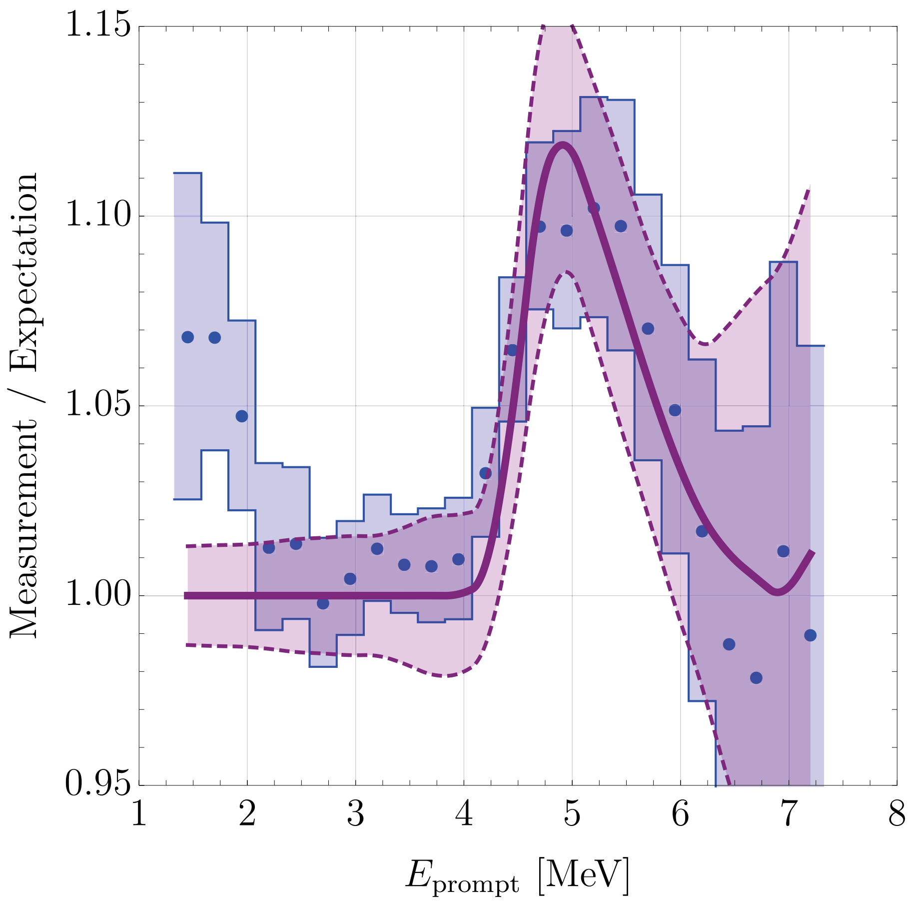
BSM explanation for the bump



Berryman, Brdar, PH, 2018

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

Does it work?



Berryman, Brdar, PH, 2018

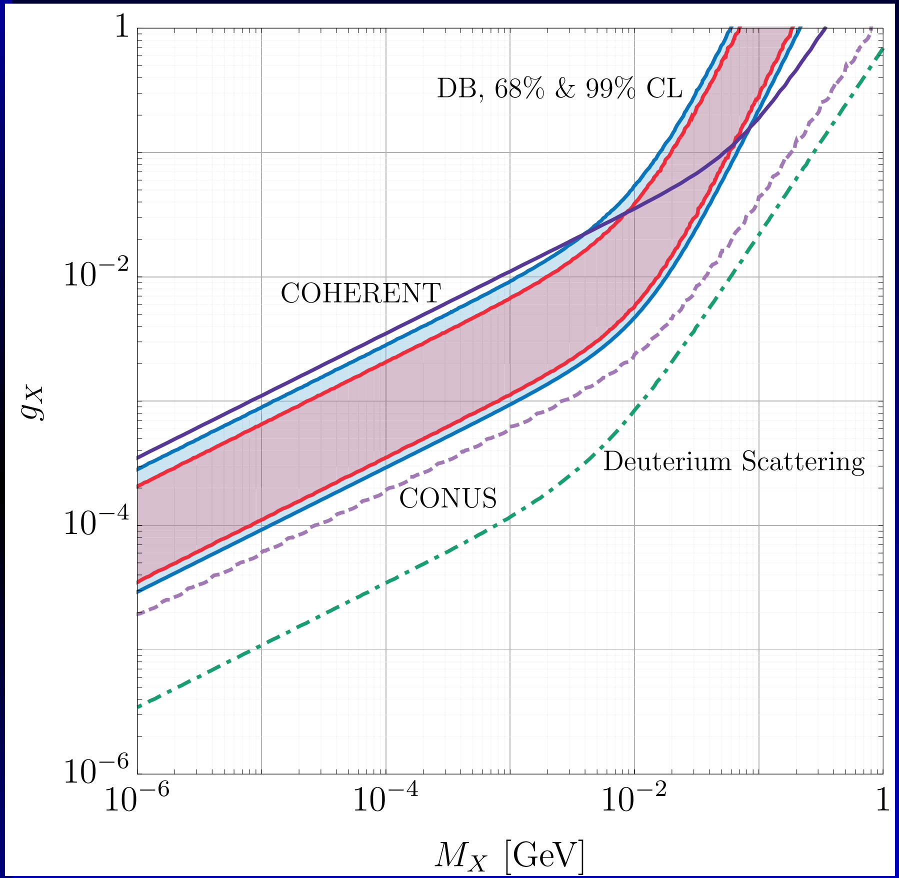
Excellent fit

Existence of high-energy neutrino flux is predicted

High energy flux is in agreement with Daya Bay bounds

Position and width of bump entirely determined by SM physics

Is it allowed?



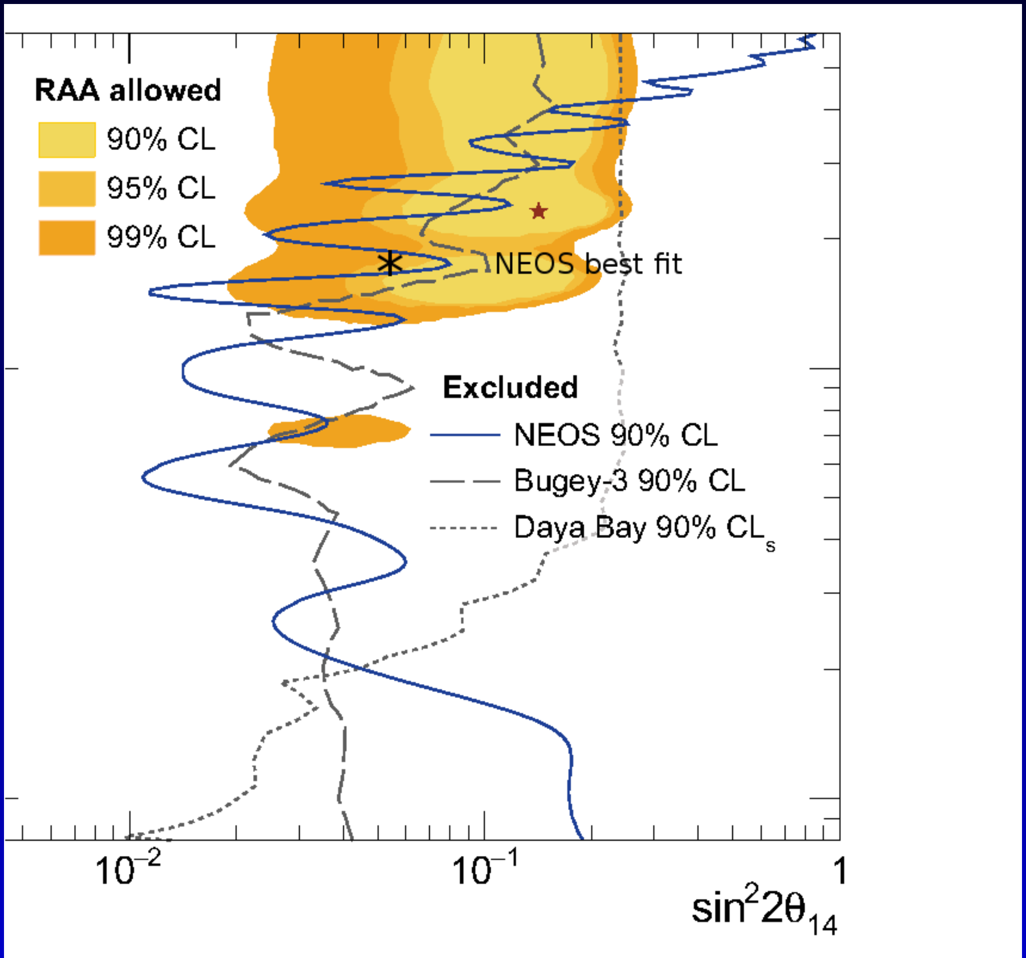
Berryman, Brdar, PH, 2018

Shown is axial coupling case, vector case even worse.

COHERENT data and old D_2O reactor data can not be reconciled with this model.

The bump remains unexplained with either BSM or nuclear physics!

NEOS and sterile neutrinos

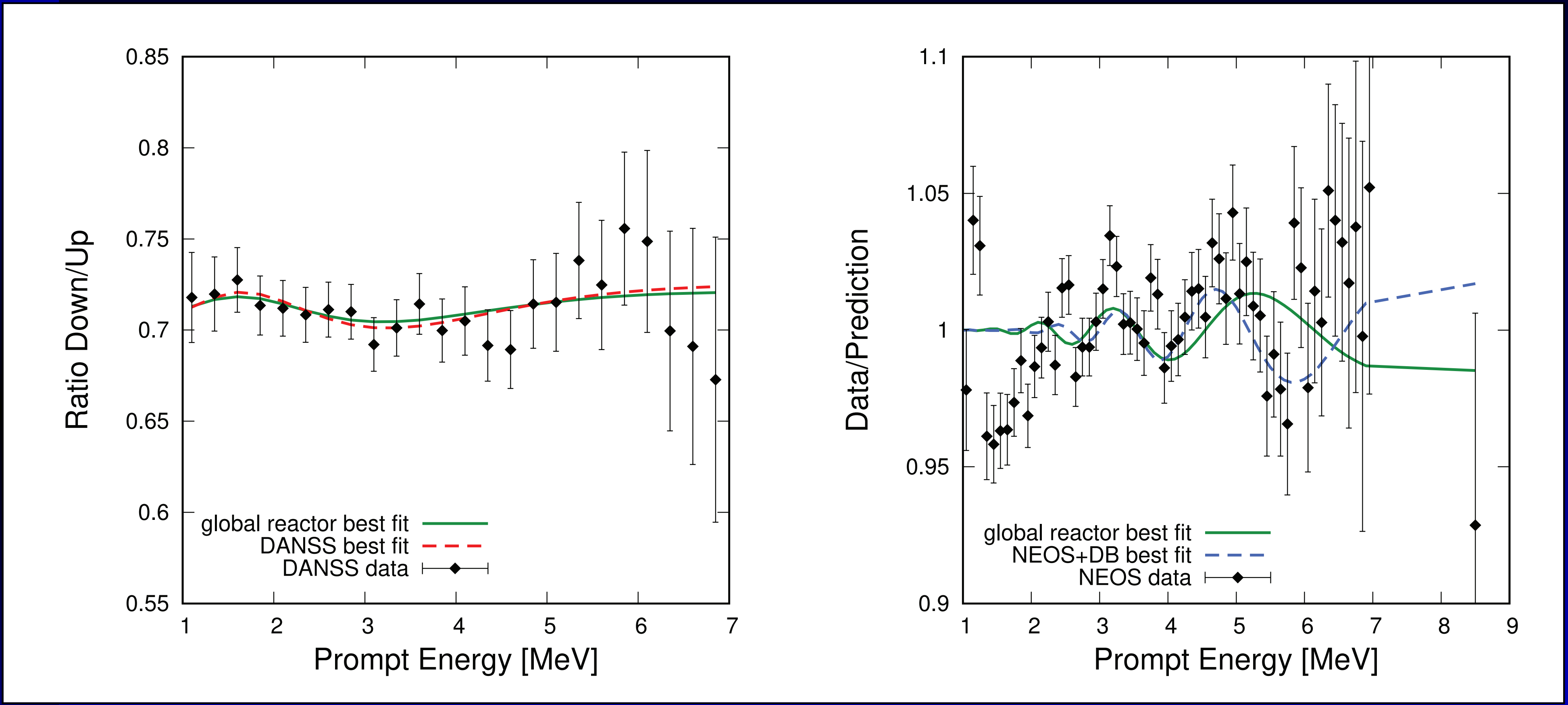


NEOS reports a limit, but their best fit occurs at $\sin^2 2\theta = 0.05$ and $\Delta m^2 = 1.73\,\mathrm{eV}^2$ with a χ^2 value 6.5 below the no-oscillation hypothesis.

adapted from NEOS, 2016

DANSS has a similar result.

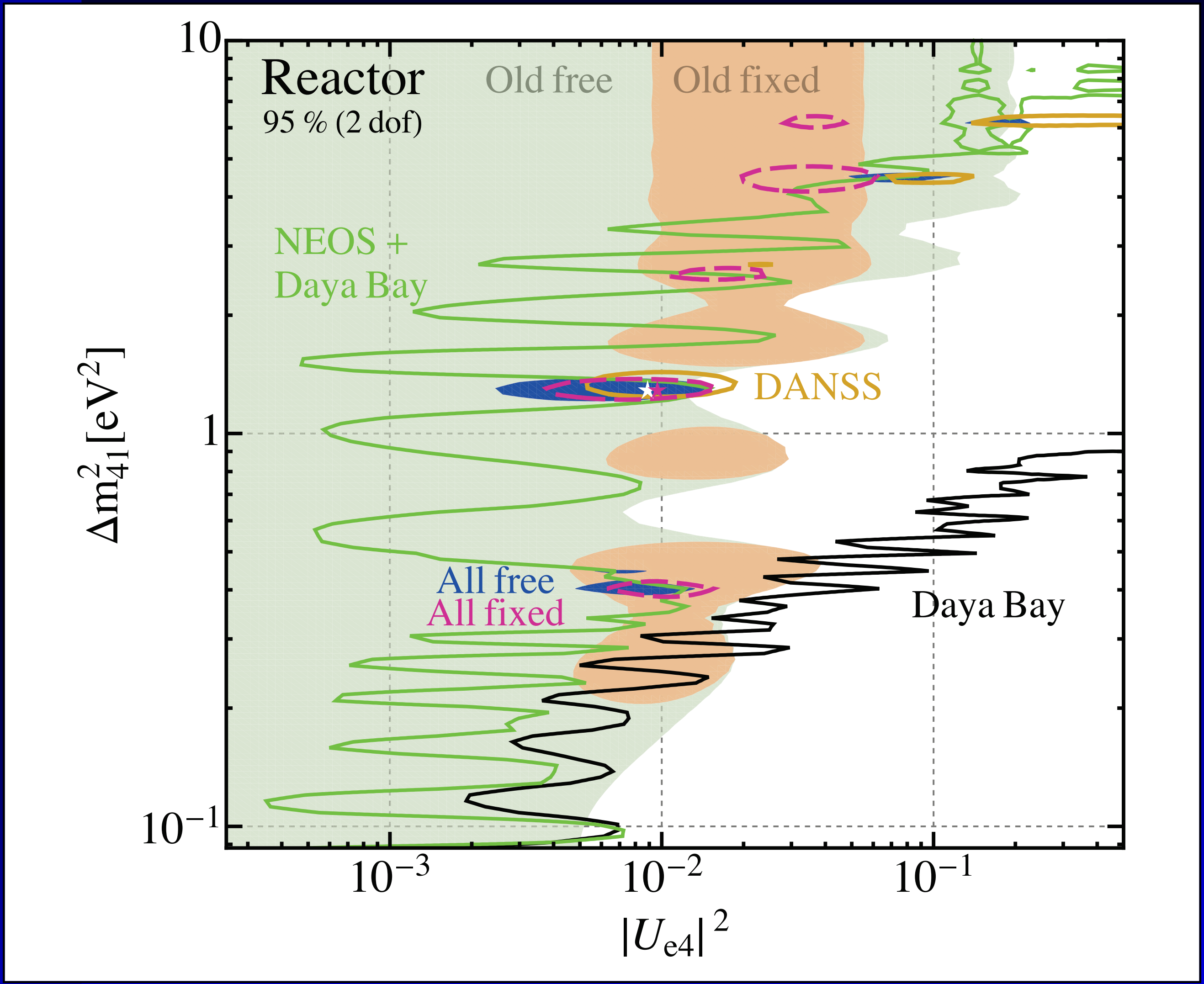
DANSS and NEOS



Dentler et al. 2018

This is a spectral effect independent of rate and shape predictions!

Reactor fit



Dentler et al. 2018

More than $3\,\sigma$ evidence for oscillation even without using a flux prediction!

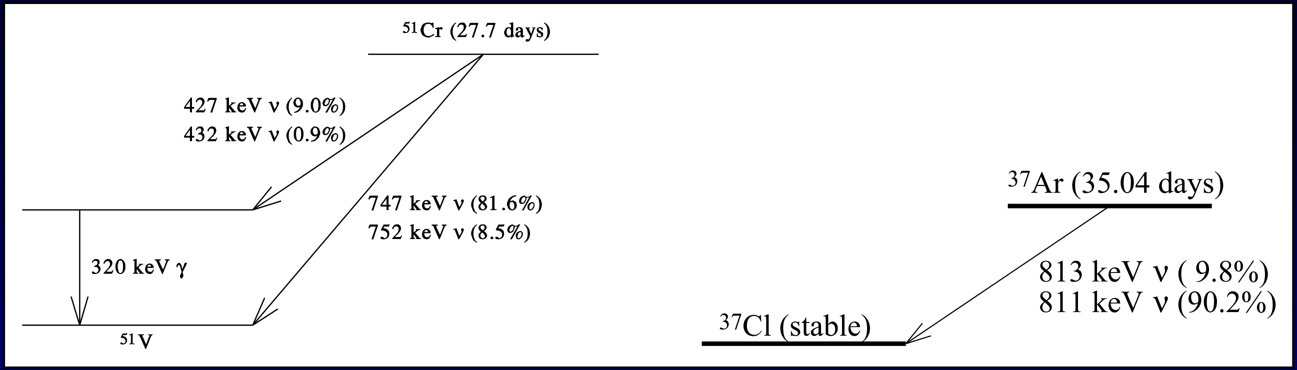
Gallium anomaly

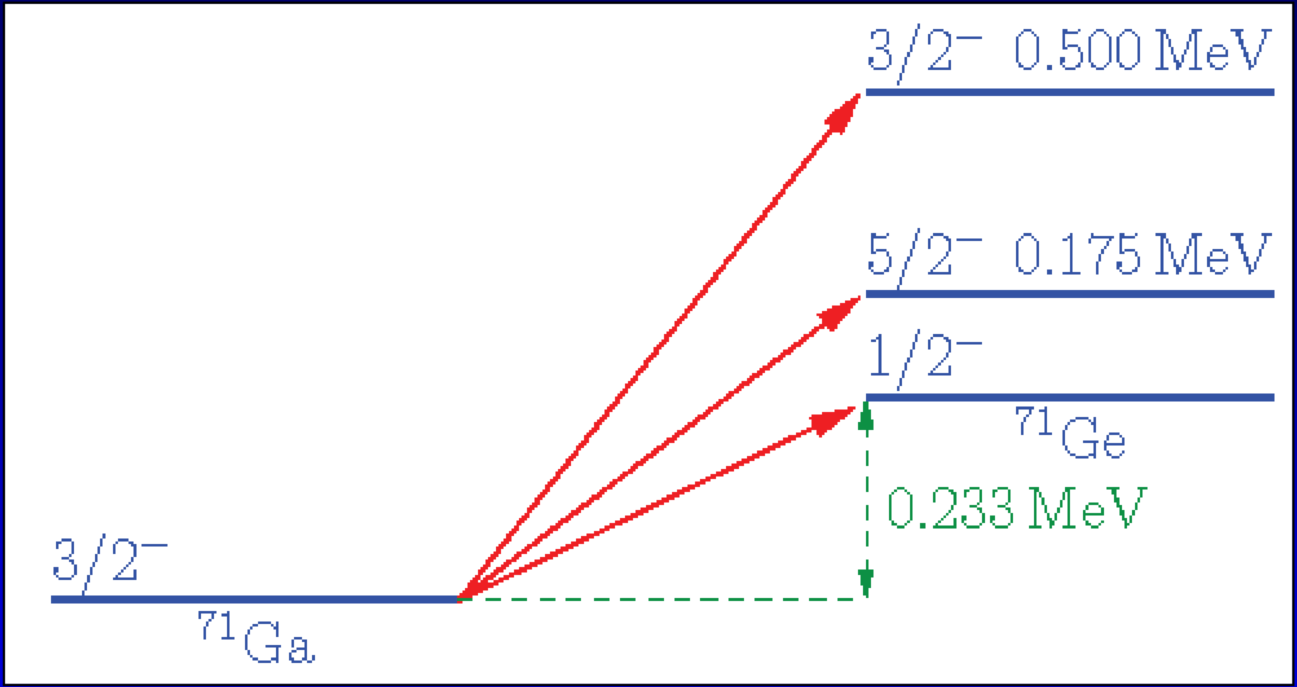
	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R_B^k	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm {}^{+0.084}_{-0.078}$
R_H^k	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm {}^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47	
source height [m]	2.7	2.38	0.72	

25% deficit of ν_e from radioactive sources at short distances

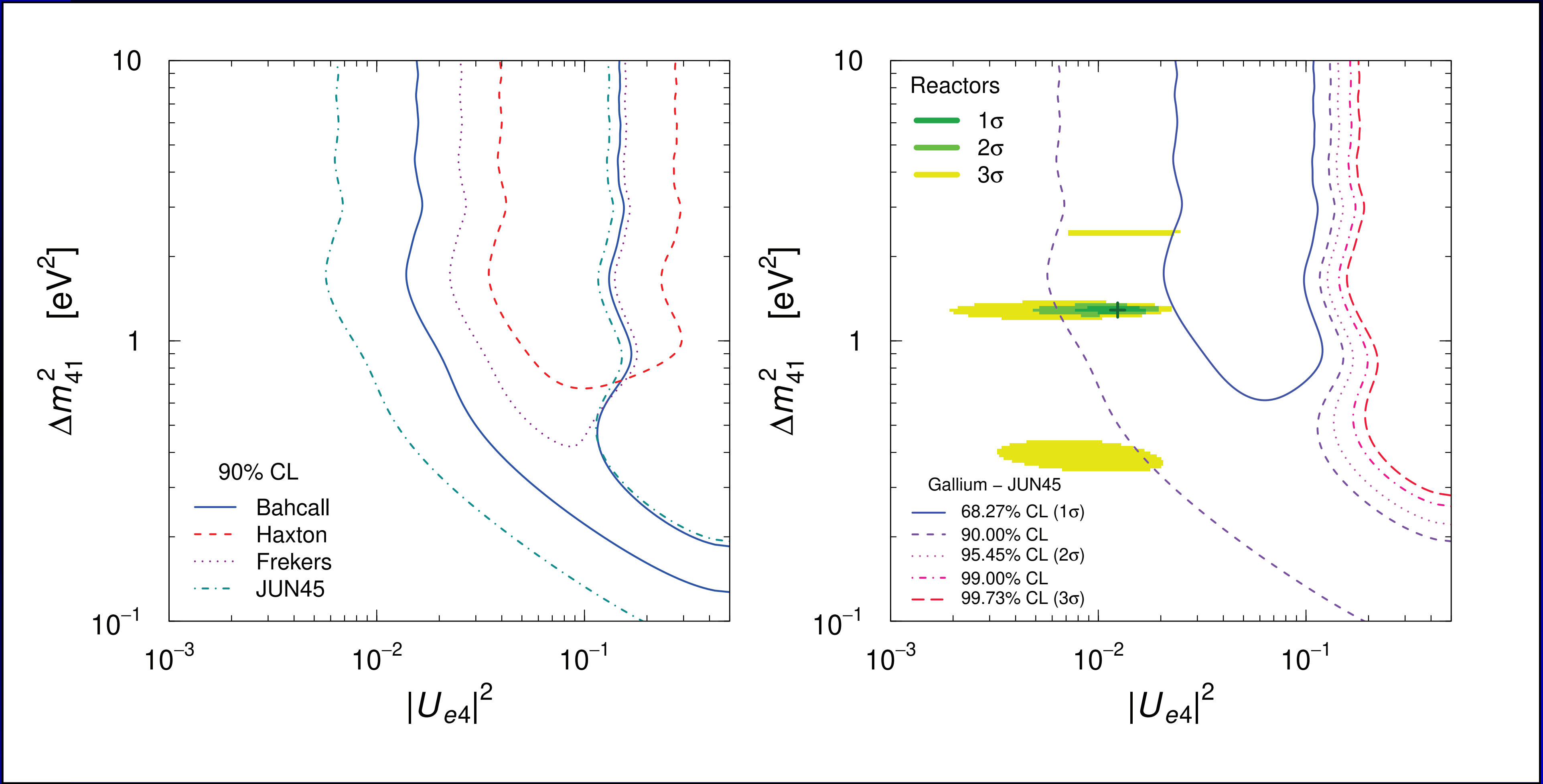
- Effect depends on nuclear matrix element
- R is a calibration constant

Nuclear matrix elements





Nuclear matrix elements – II



Kostensalo *et al.* 2019

Significance decreases from 3.0 σ to 2.3 σ, but all results in the $\nu_e/\bar{\nu}_e$ sector are fully consistent!

Disappearance and appearance

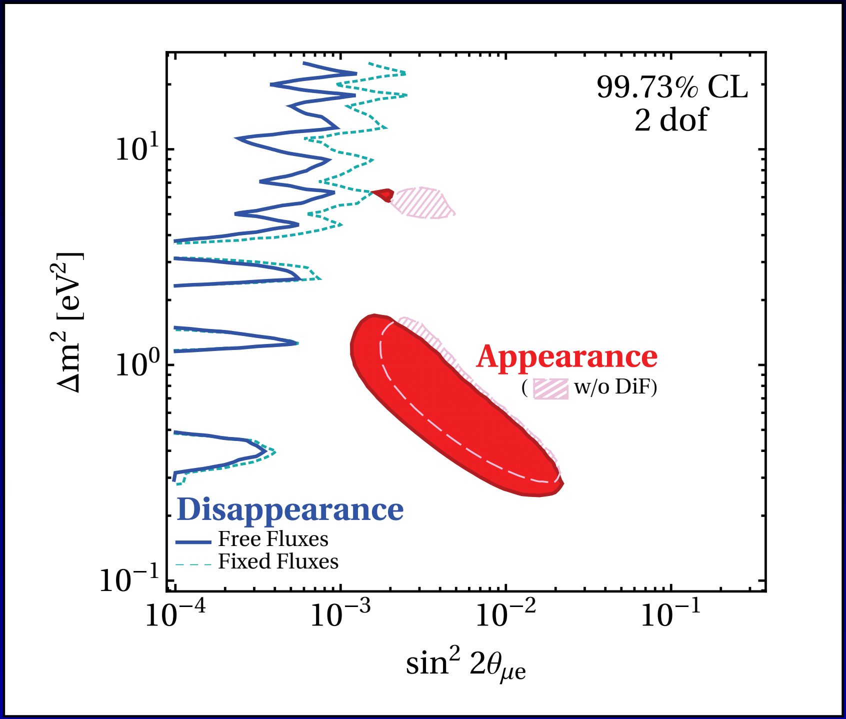
$\nu_\mu \to \nu_e$ requires that the sterile neutrino mixes with both ν_e and ν_μ

$\Rightarrow$ there must be effects in *both* $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$

Up to factors of 2, the energy averaged probabilities obey

$$P_{\mu e} \lesssim (1 - P_{\mu\mu})(1 - P_{ee})$$

Disappearance data



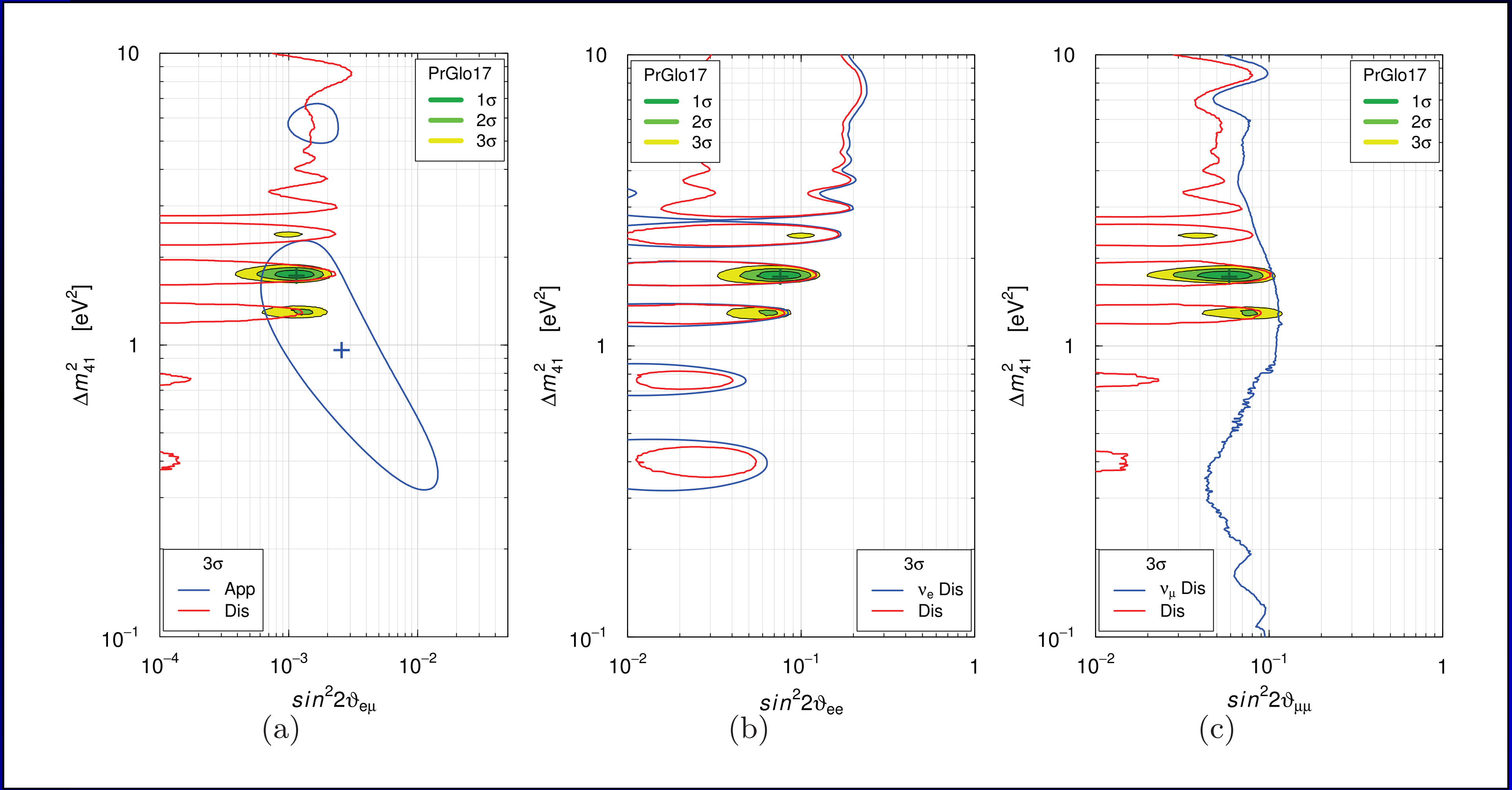
$$\sin^2 2\theta_{e\mu} = 4|U_{e4}U_{\mu 4}|^2$$

with $1 - P_{ee} \propto |U_{e4}|^2$
and $1 - P_{\mu\mu} \propto |U_{\mu 4}|^2$

Dentler, *et al.*, 2018

There is (and has been for decades) a strong tension between global appearance data and disappearance data.

Global fit



Gariazzo *et al.*, 2017

Caveat: not entirely up-to-date.

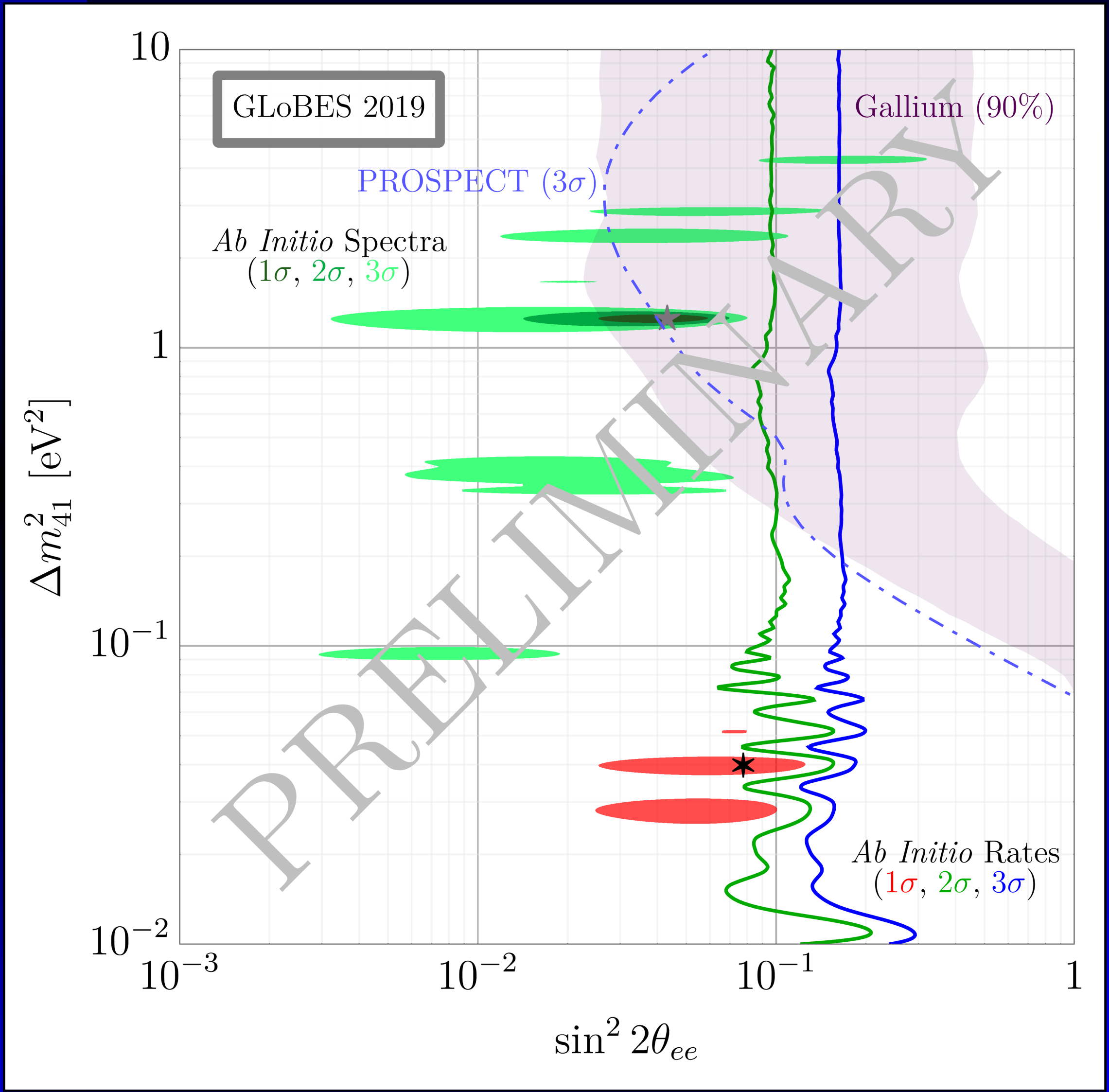
Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5 σ effects and they may be all due to the extraordinary difficulty of performing neutrino experiments, if not:

- N sterile neutrinos are the simplest explanation
- Tension with null results in disappearance remains

Due to their special nature as SM gauge singlets sterile neutrinos are strong candidates for being a portal to a hidden sector – significant experimental activity.

ν_e outlook



Current $\nu_e/\bar{\nu}_e$ data points to a region at the edge of the sensitivity current reactor experiments.

Berryman, PH, in preparation

Shown are the allowed regions from a fit to reactor data after the year 2010 separated into rate and spectrum. The reactor flux model uses the latest *ab initio* results from Estienne *et al.* for the central value and the Huber-Mueller results for the error bars. The gallium region is from Kostensalo *et al.*.

Summary

Tension in global fits

- Maybe more complicated than sterile neutrino
- And/or not all data is right
- Lots of nuclear physics uncertainties

With NEOS and DANSS we have a positive indication from reactors independent of flux predictions.

In combination, light sterile neutrinos are one of the best cases for New Physics, anywhere!

Questions?