The 5 MeV reactor neutrino excess

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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 . . .

The big question

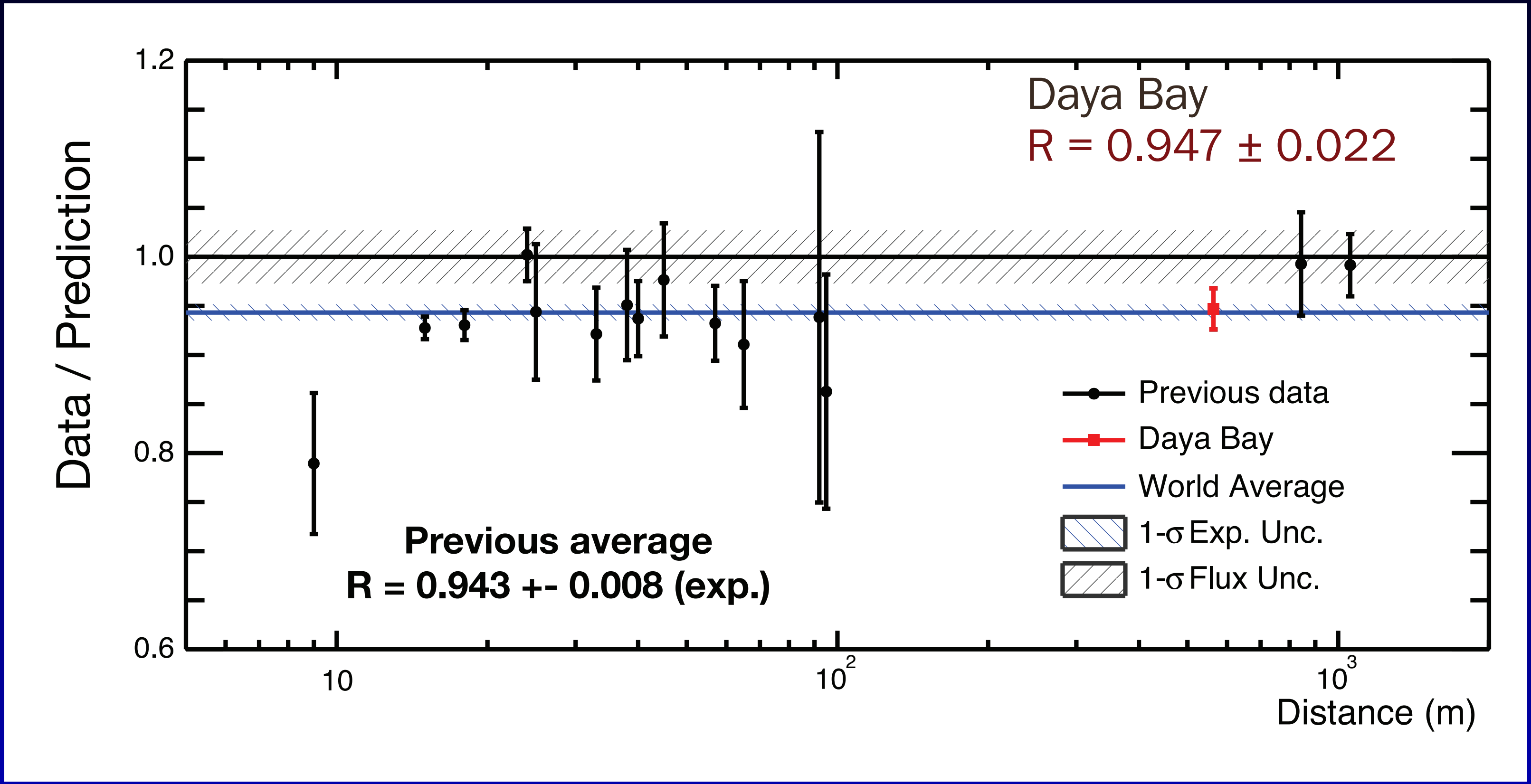
Things the Standard Model does NOT explain

- Neutrino mass
- Dark matter
- Baryon asymmetry
- Dark energy
- Gravity

50 years of ideas, most have been retired by LHC results, but NO hard experimental evidence to lead the way and no indication of what energy scale to look at.

Is there anything within our means we can find?

RAA – The reactor anomaly



Daya Bay, 2014

Mueller *et al.*, 2011, 2012

$$1.27\frac{10\,\mathrm{m}}{4\,\mathrm{MeV}}\Delta m^2 = \pi \Leftrightarrow \Delta m^2 \simeq 1\,\mathrm{eV}^2$$

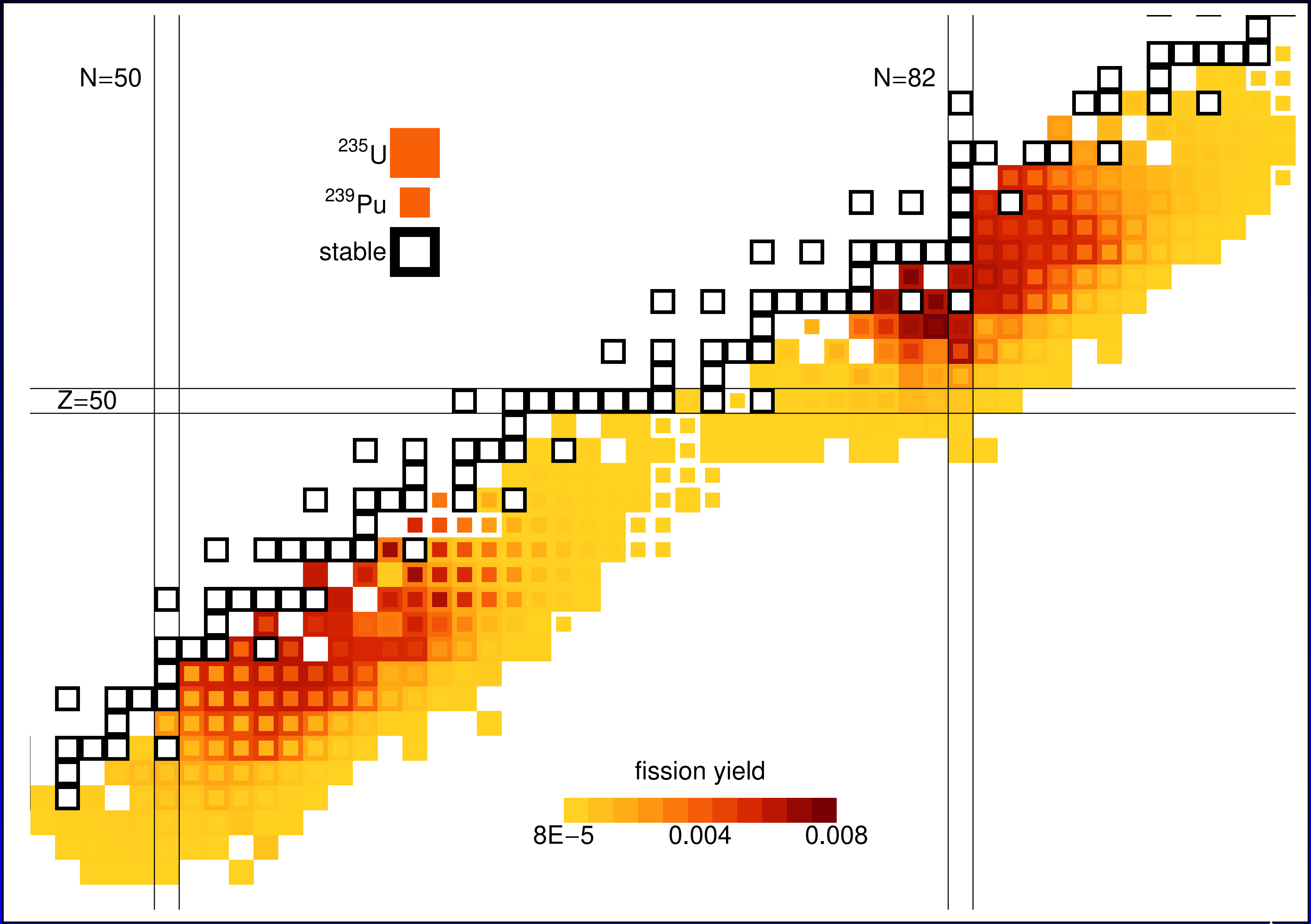
Sterile neutrinos

We have measured in neutrino oscillation:

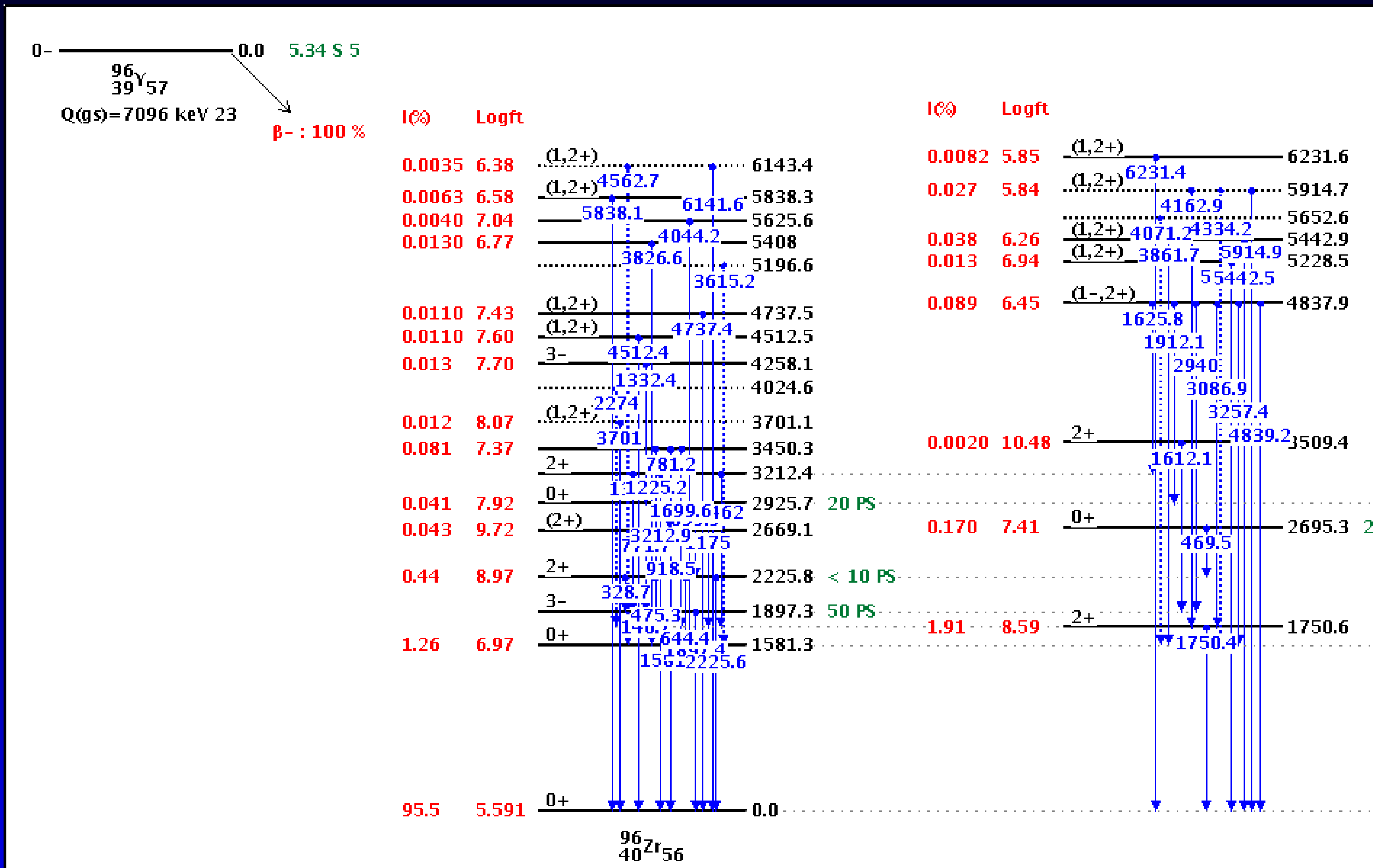
- $\Delta m^2_{21} \sim 8 \cdot 10^{-5}\,\mathrm{eV}^2$ and $\theta_{12} \sim 1/2$
- $\Delta m^2_{31} \sim 2 \cdot 10^{-3}\,\mathrm{eV}^2$ and $\theta_{23} \sim \pi/4$
- $\theta_{13} \sim 0.16$

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

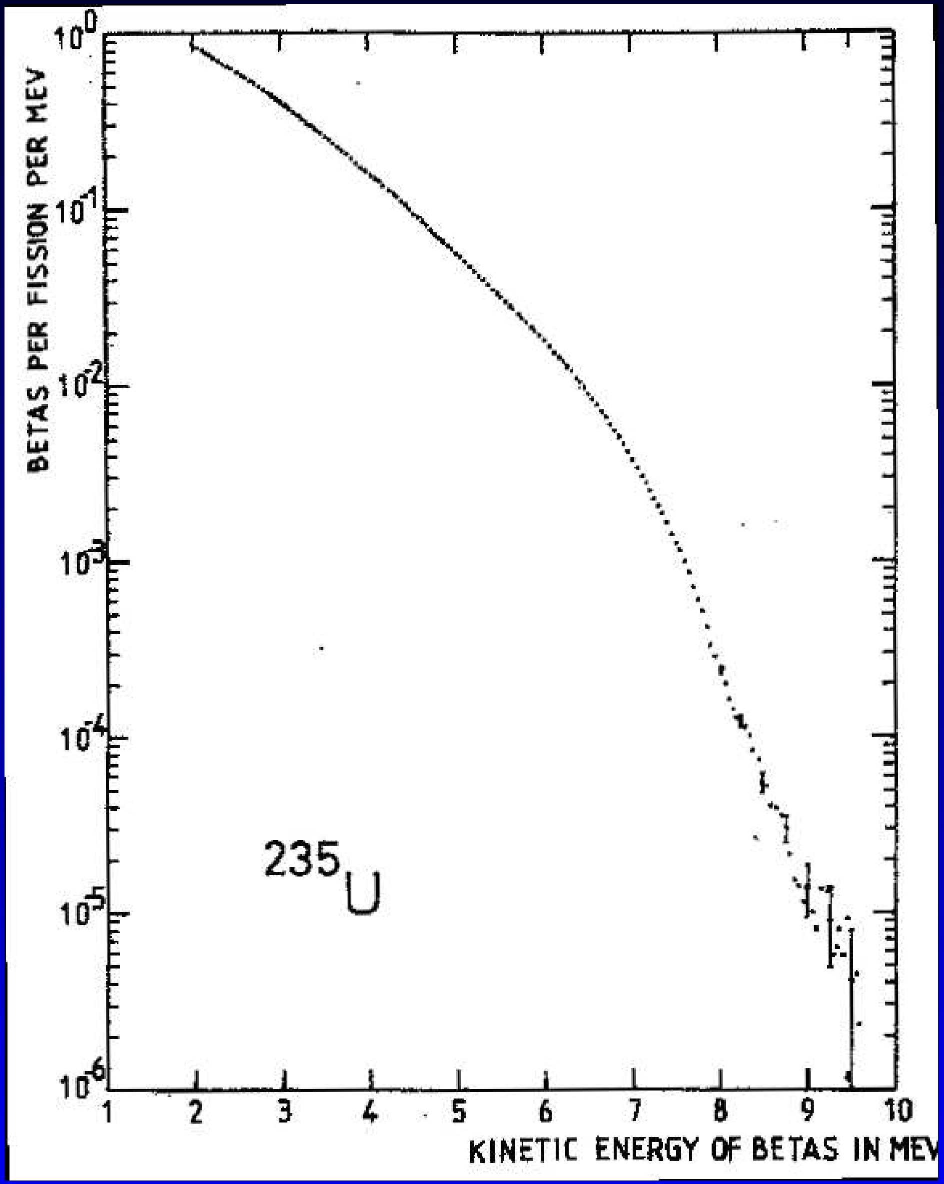
Neutrinos from fission



β-branches



β-spectrum from fission



Schreckenbach, *et al.* 1985.

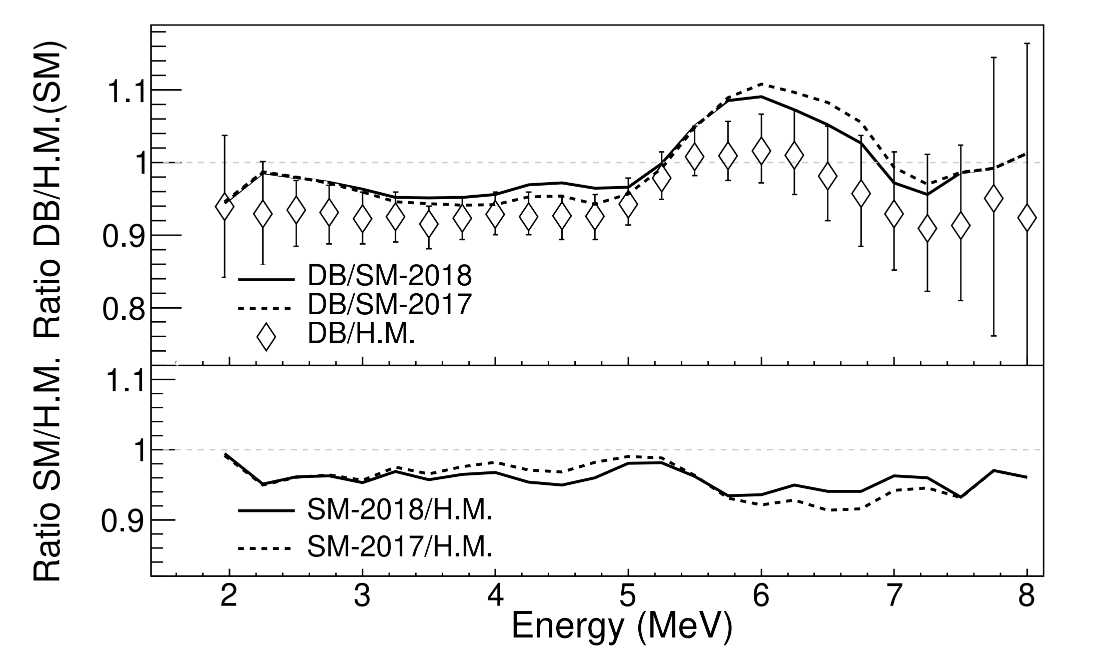
^{235}U foil inside the High Flux Reactor at ILL

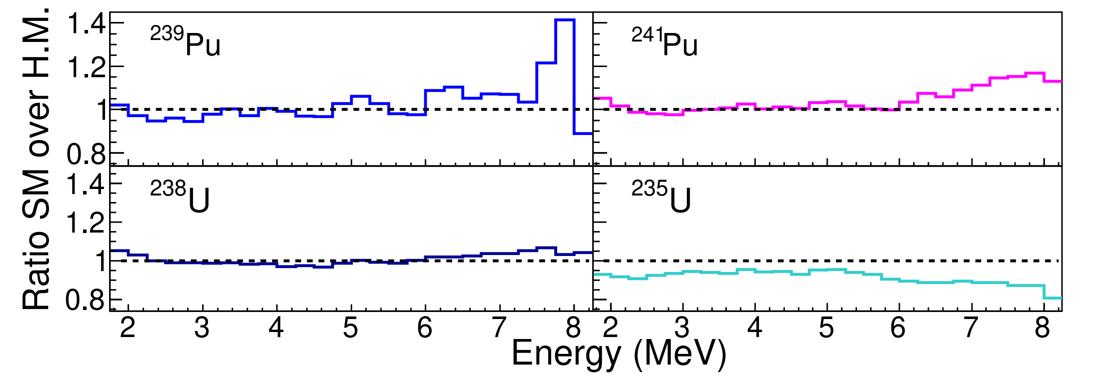
Electron spectroscopy with a magnetic spectrometer

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

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

A priori calculations





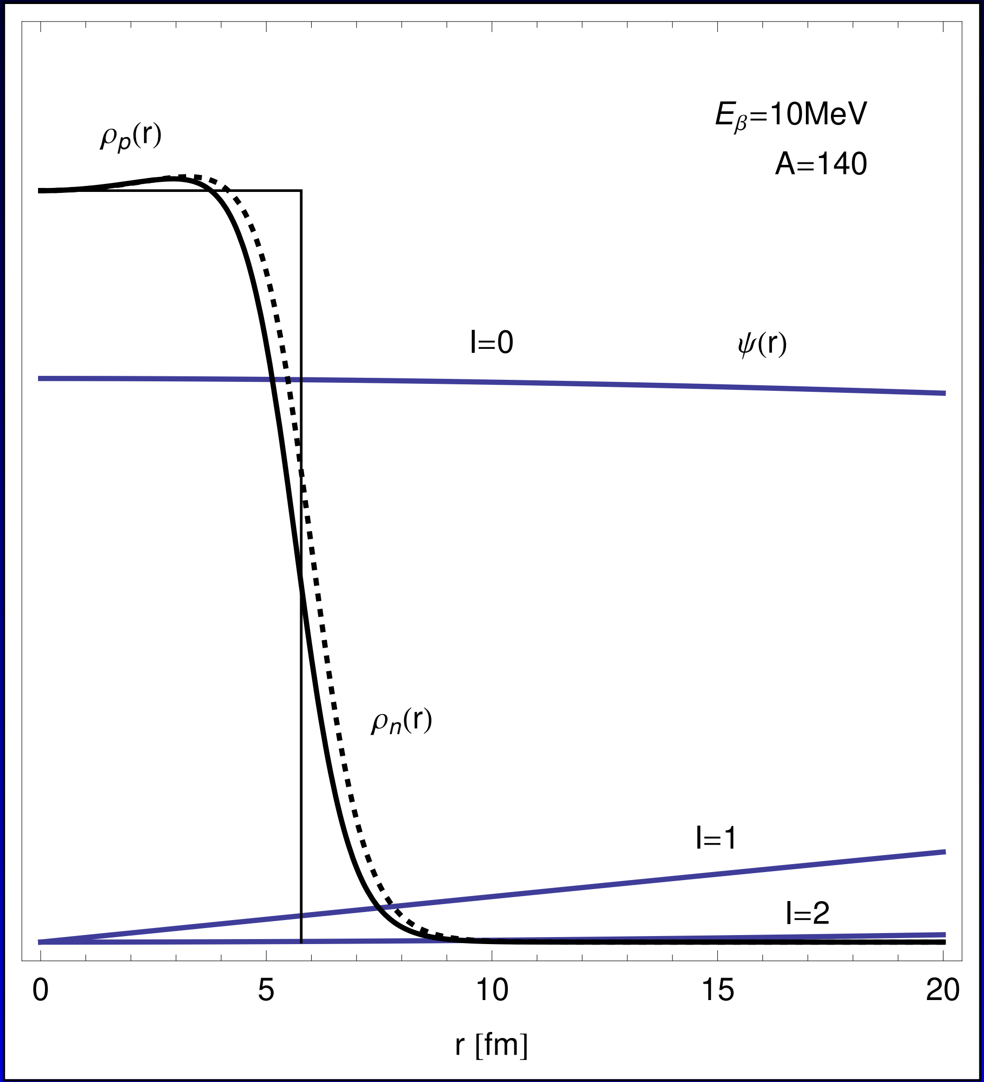
Estienne *et al.*, 2019

Using known fission yields and databases.

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 $\Rightarrow$ **reduces significance of RAA**

Forbidden decays



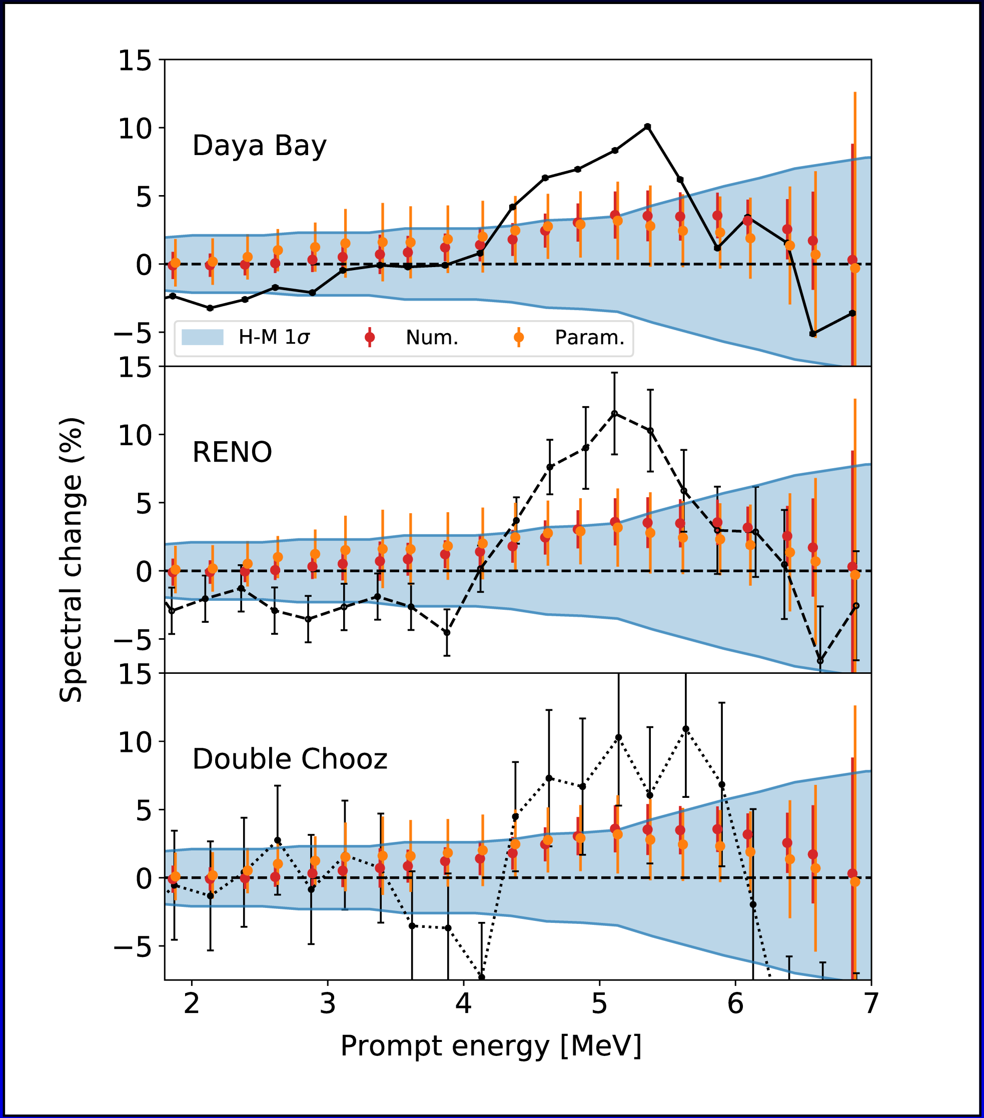
$e,\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

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!**

Shell model



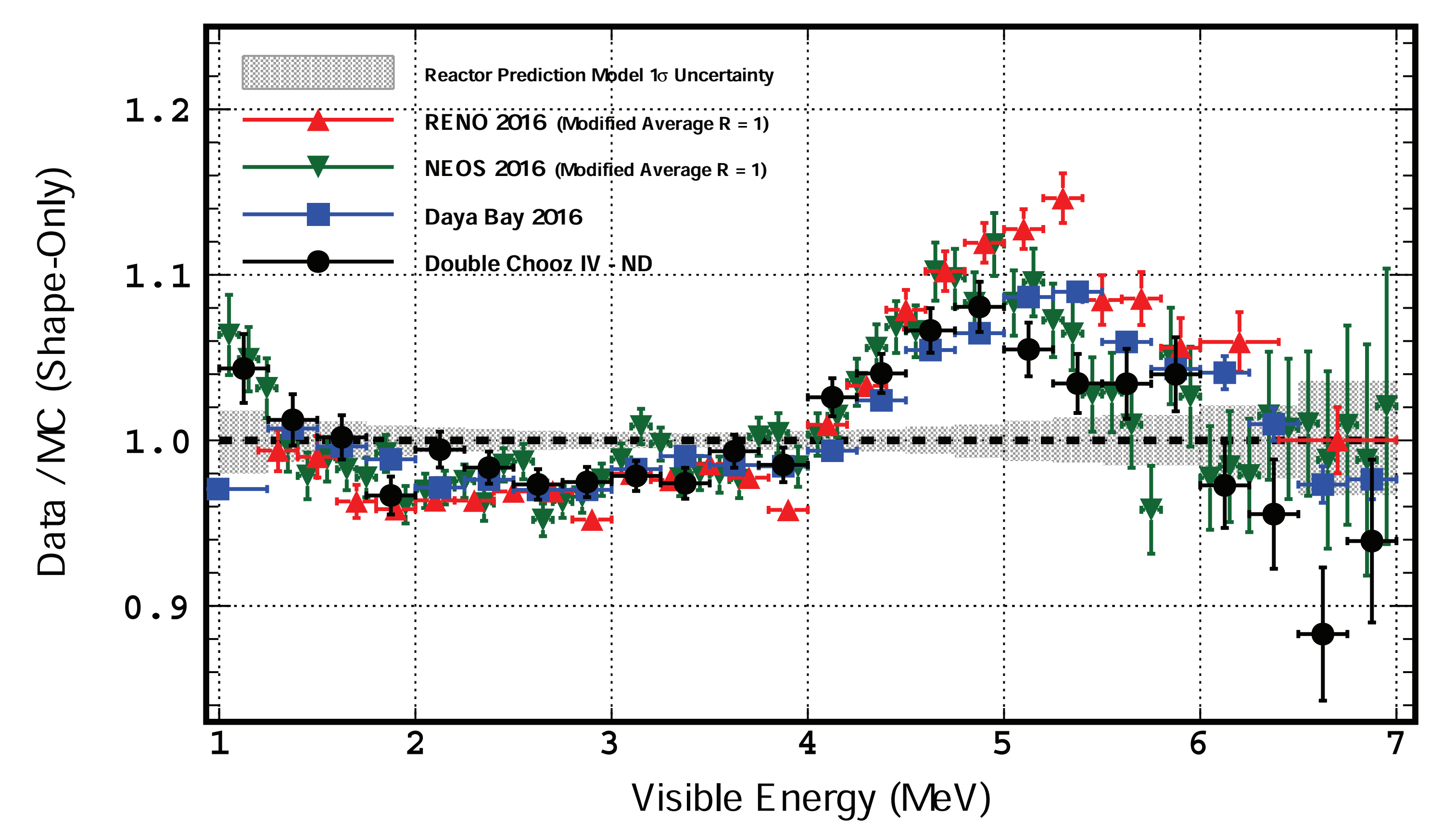
Hayen, *et al.* 2019

Microscopic shell model calculation of 36 forbidden isotopes.

Parameterization of the resulting shape factors for all other branches.

Increases the IBD rate anomaly by 40%, but the uncertainty increases by only 13% relative to HM $\Rightarrow$ **increases significance of RAA by** $\sim 20\%$

The 5 MeV bump

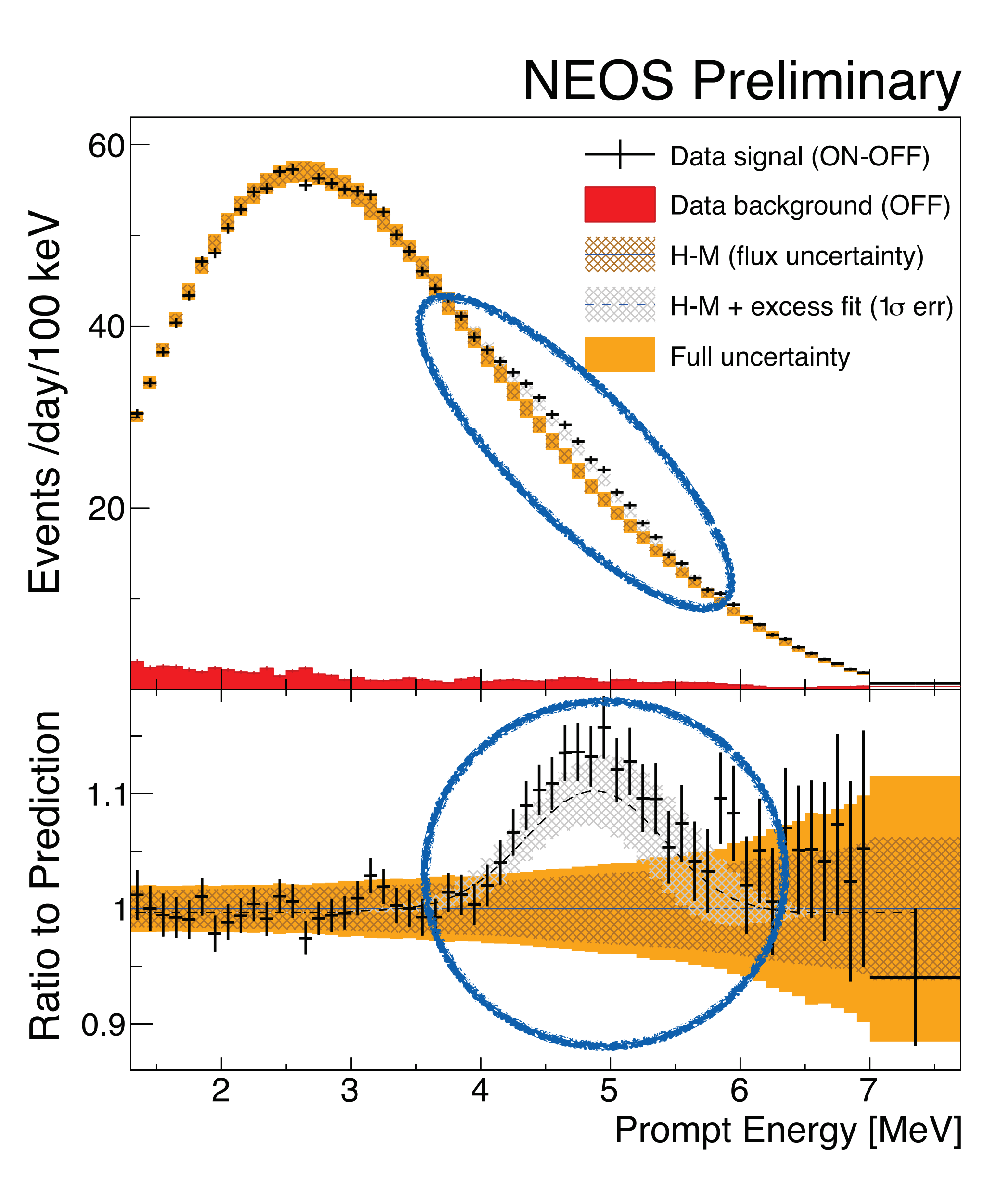


Double Chooz 2019

Seen by all three reactor experiments

Tracks reactor power

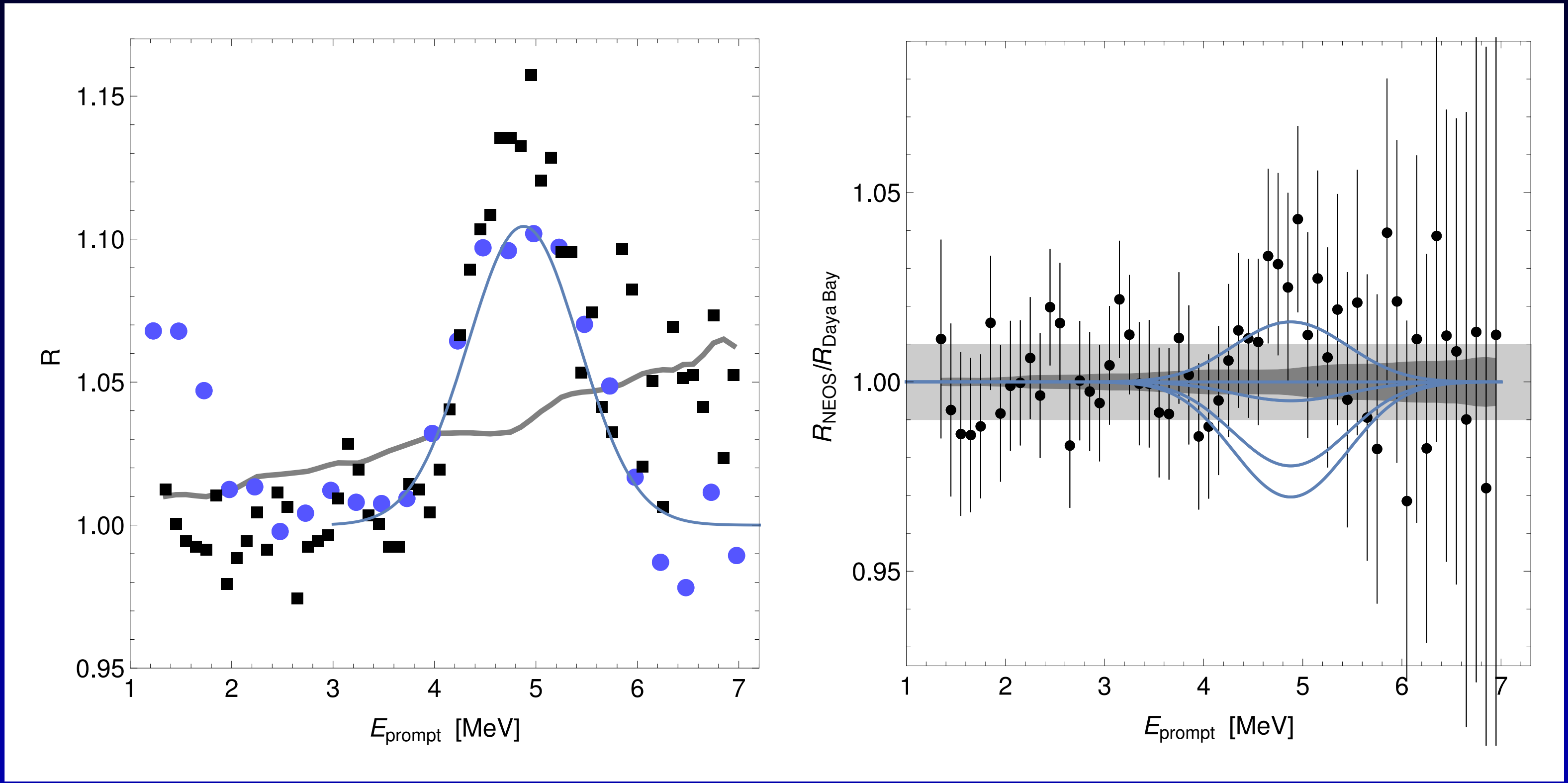
NEOS



NEOS, 2016

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

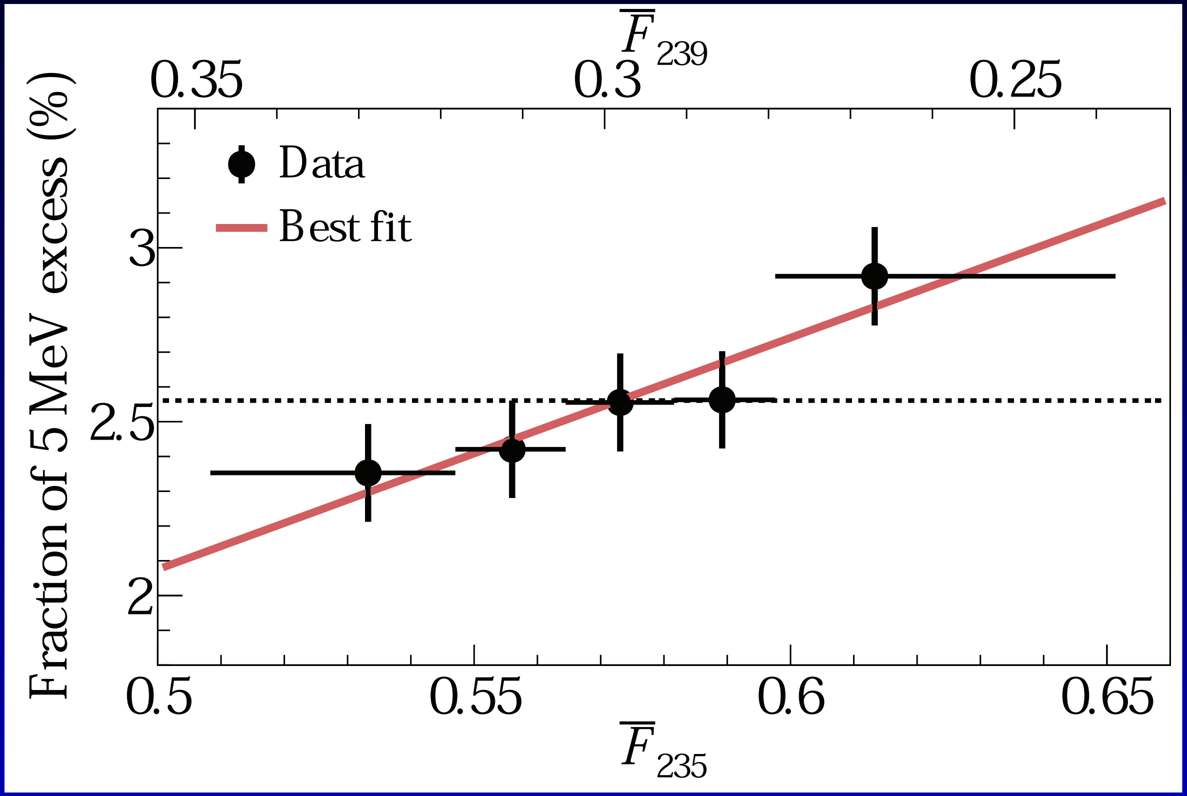
NEOS vs Daya Bay



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 $2\,\sigma$.

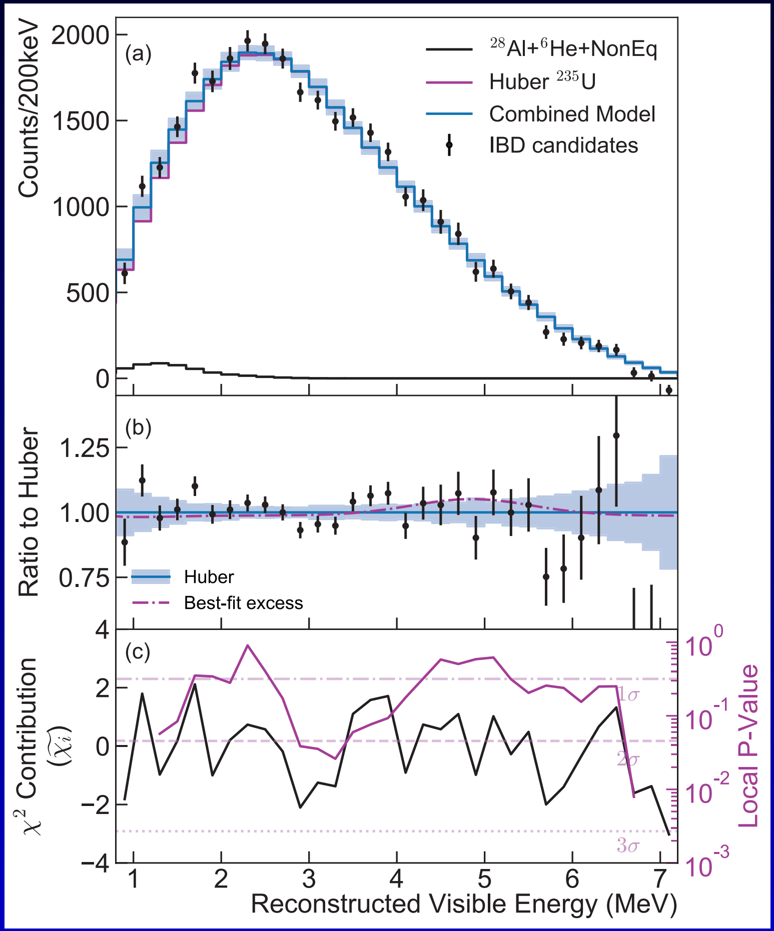
RENO and the bump



RENO, 2018

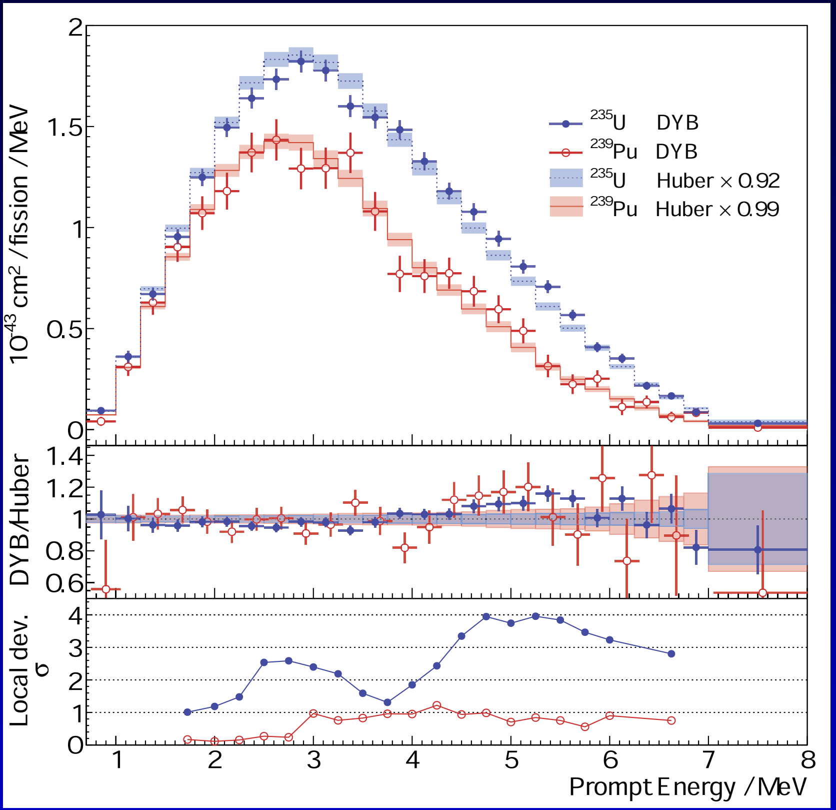
Slight correlation of bump amplitude with ^{235}U fission fraction disfavors the 'all fissiles contribute equally' hypothesis.

Latest data vs bump



PROSPECT 2018

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



Daya Bay 2019

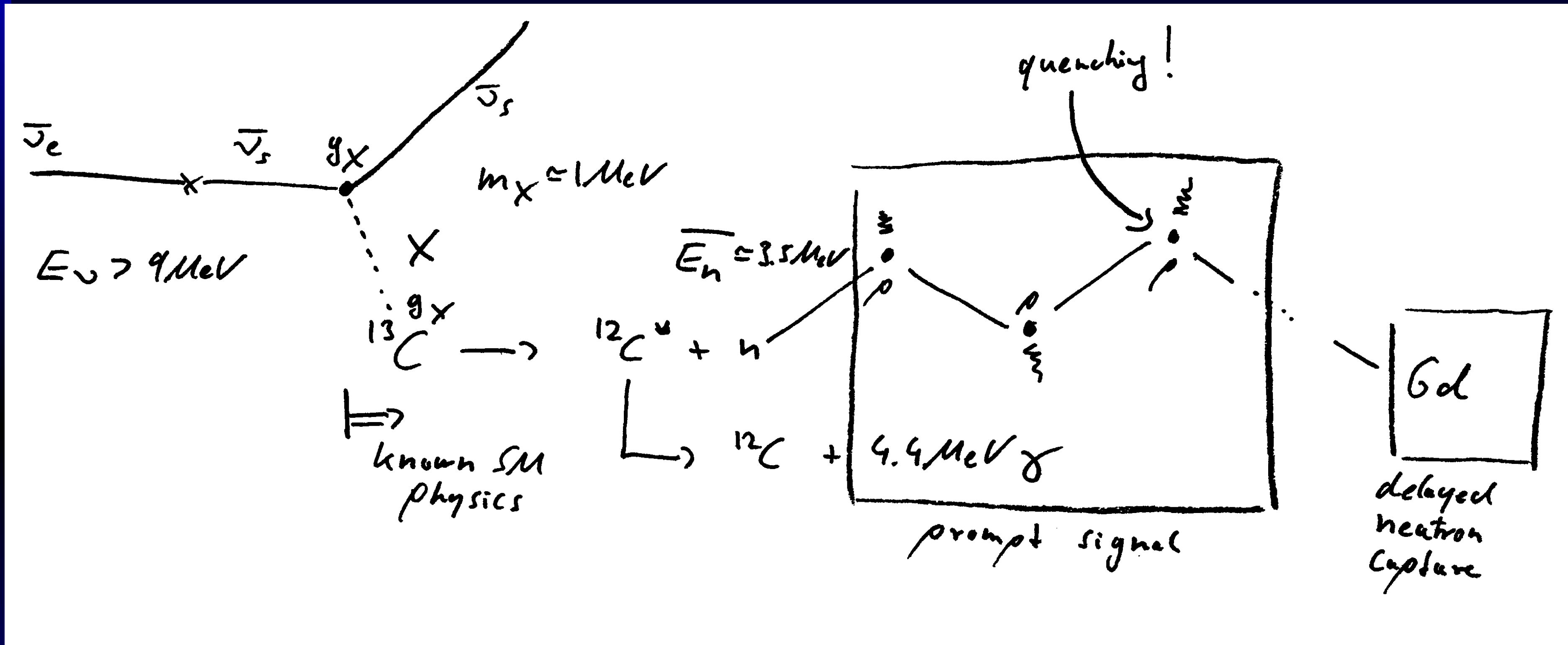
Requires a bump in ^{235}U at 4 σ

Explanations?

- Specific high yield beta emitters Dywer, Langford 2015 and many others, very sensitive to quality of nuclear input data Hayes *et al.* 2015, Sonzogni *et al.* 2016, difficult to reconcile with Schreckenbach data.
- Hayes *et al.* proposed neutron spectrum, disfavored by Littlejohn *et al.*, 2018.
- Hayen *et al.*, 2019 show that forbidden decays alone are an unlikely solution.

The bump remains unexplained by nuclear physics at this point.

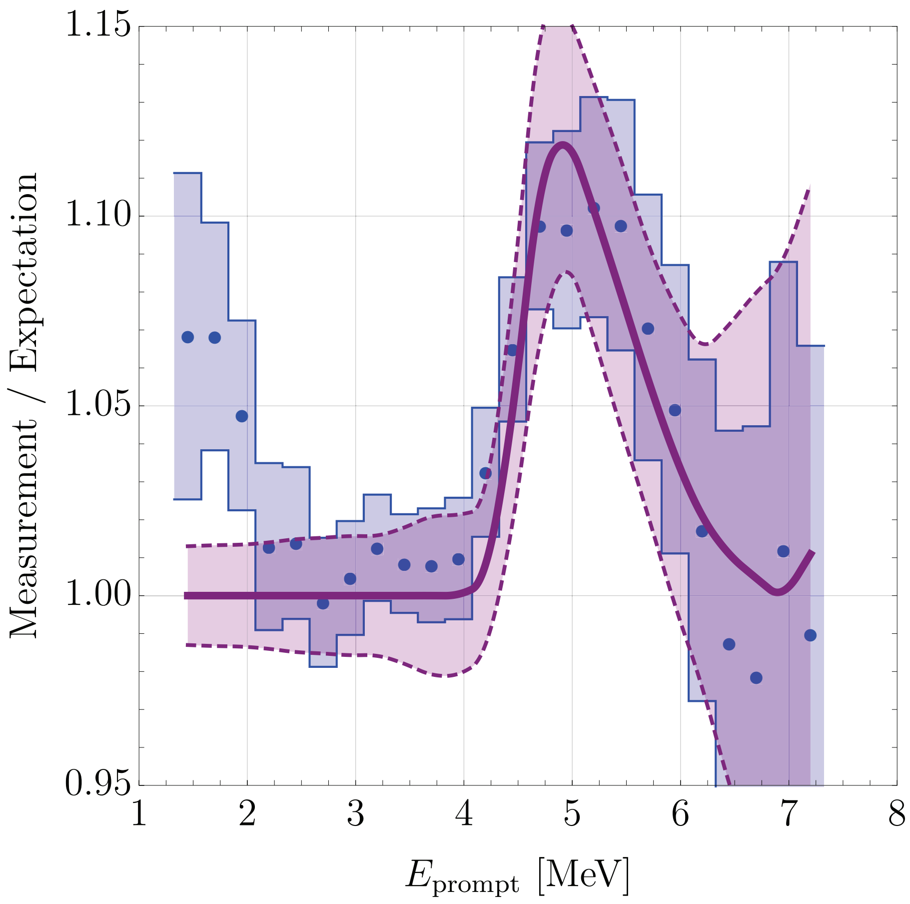
BSM model for the bump



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

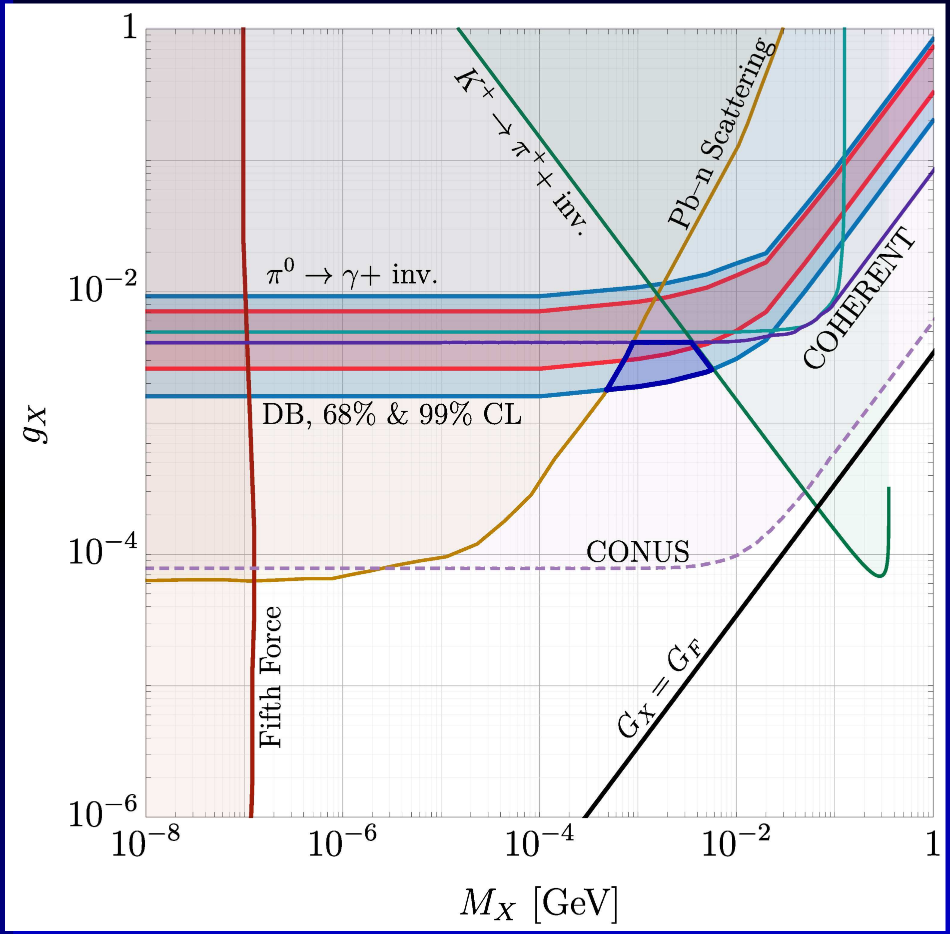
Excellent fit

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?



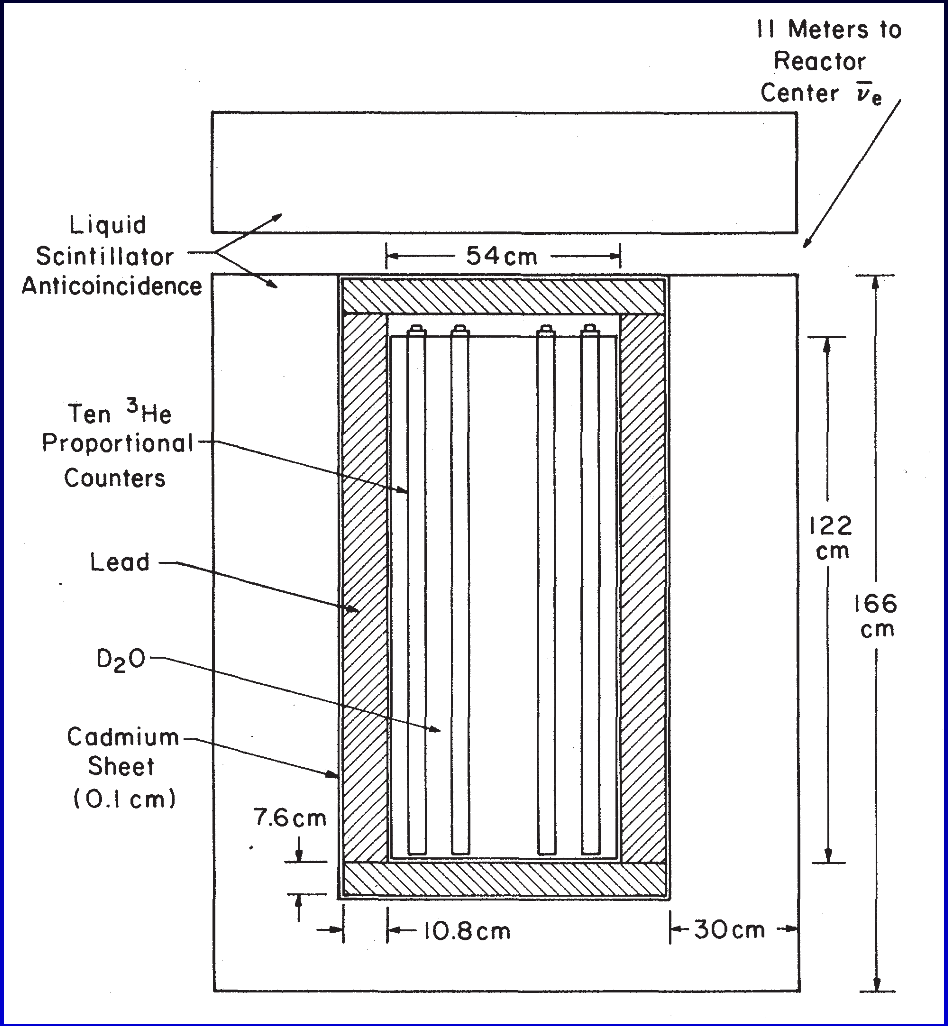
Berryman, Brdar, PH, 2018

Pb-n scattering and COHERENT data are most difficult to satisfy:

Choosing $Y_p = +1$ and $Y_n = -0.65$ exploits the different proton/neutron ration between light nuclei ^{13}C and heavy nuclei ^{208}Pb, ^{135}Cs and ^{127}I.

CONUS bound is avoidable with axial coupling.

Heavy water reactor experiment



268 kg D_2O at 11 m at the Savannah River Reactor (2 GW)

3 month data taking

Neutron counting with ^{3}He detectors

$$\bar{\nu}_e + d \stackrel{\text{CC}}{\rightarrow} n + n + e^+$$
$$\bar{\nu}_e + d \stackrel{\text{NC}}{\rightarrow} n + p + \bar{\nu}_e$$

Pasierb *et al.*, 1979

Heavy water data

Depending on the used reactor spectrum they find

$$\frac{\sigma_{\rm NC}^{\rm exp}}{\sigma_{\rm NC}^{SM}} = (0.83 - 1.3) \pm (0.13 - 0.22)$$

$$\frac{\sigma_{\rm CC}^{\rm exp}}{\sigma_{\rm CC}^{SM}} = (0.32 - 0.61) \pm (0.14 - 0.29)$$

Reines, Sobel, Pasierb 1980

For our model this matters because d is iso-scalar and we would predict a large enhancement (> 100) of the NC cross section.

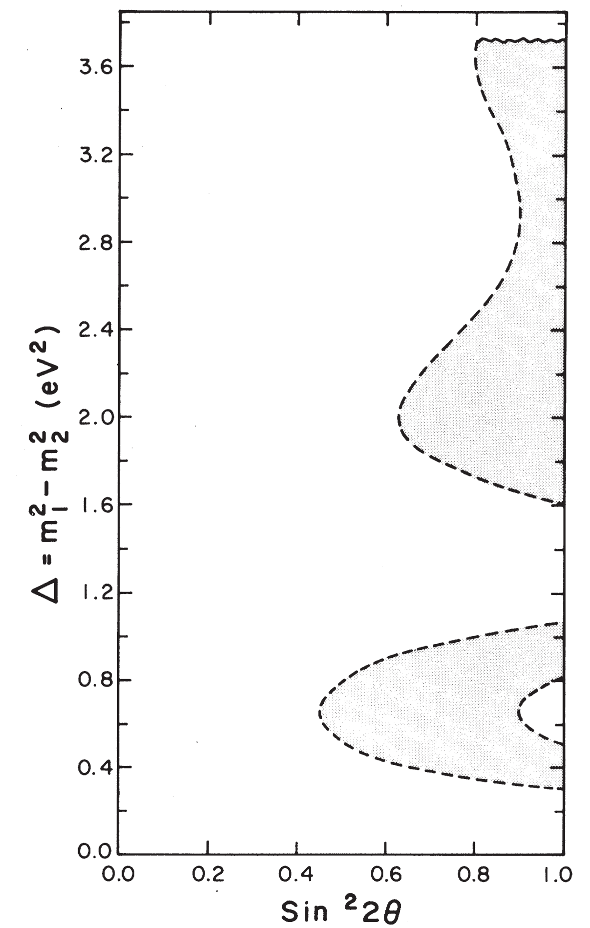
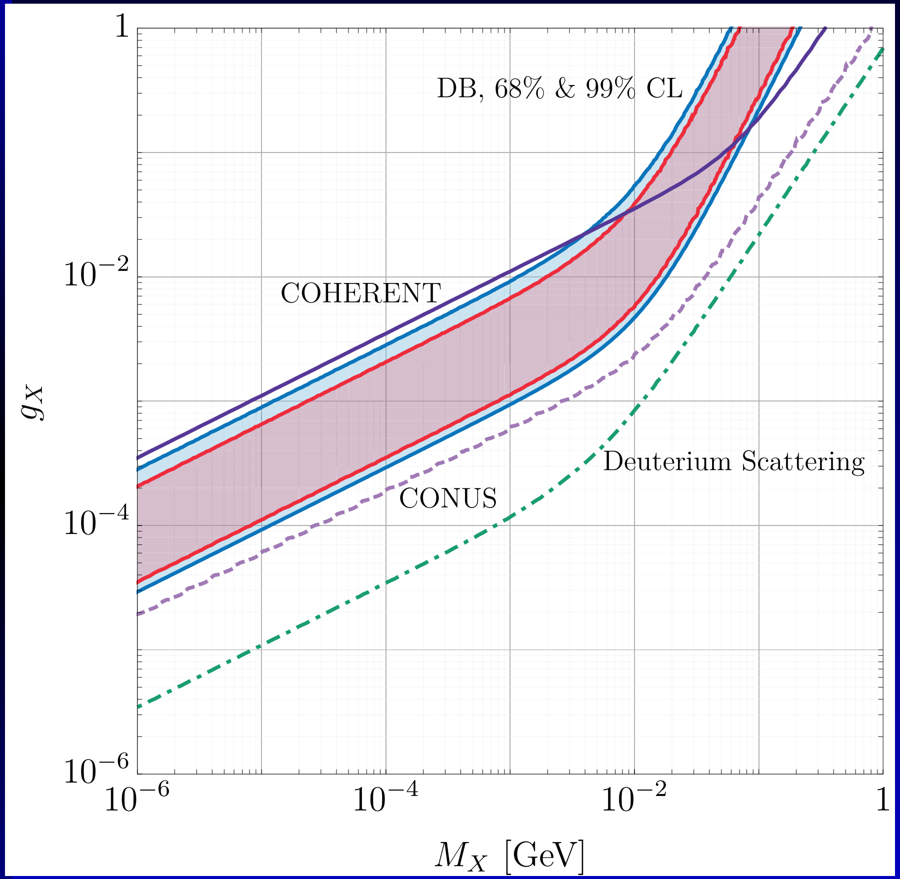


FIG. 1. Allowed regions of Δ and $\sin^2 2\theta$ for $\mathcal{R} = 0.38 \pm 0.21$.

Is it really allowed?



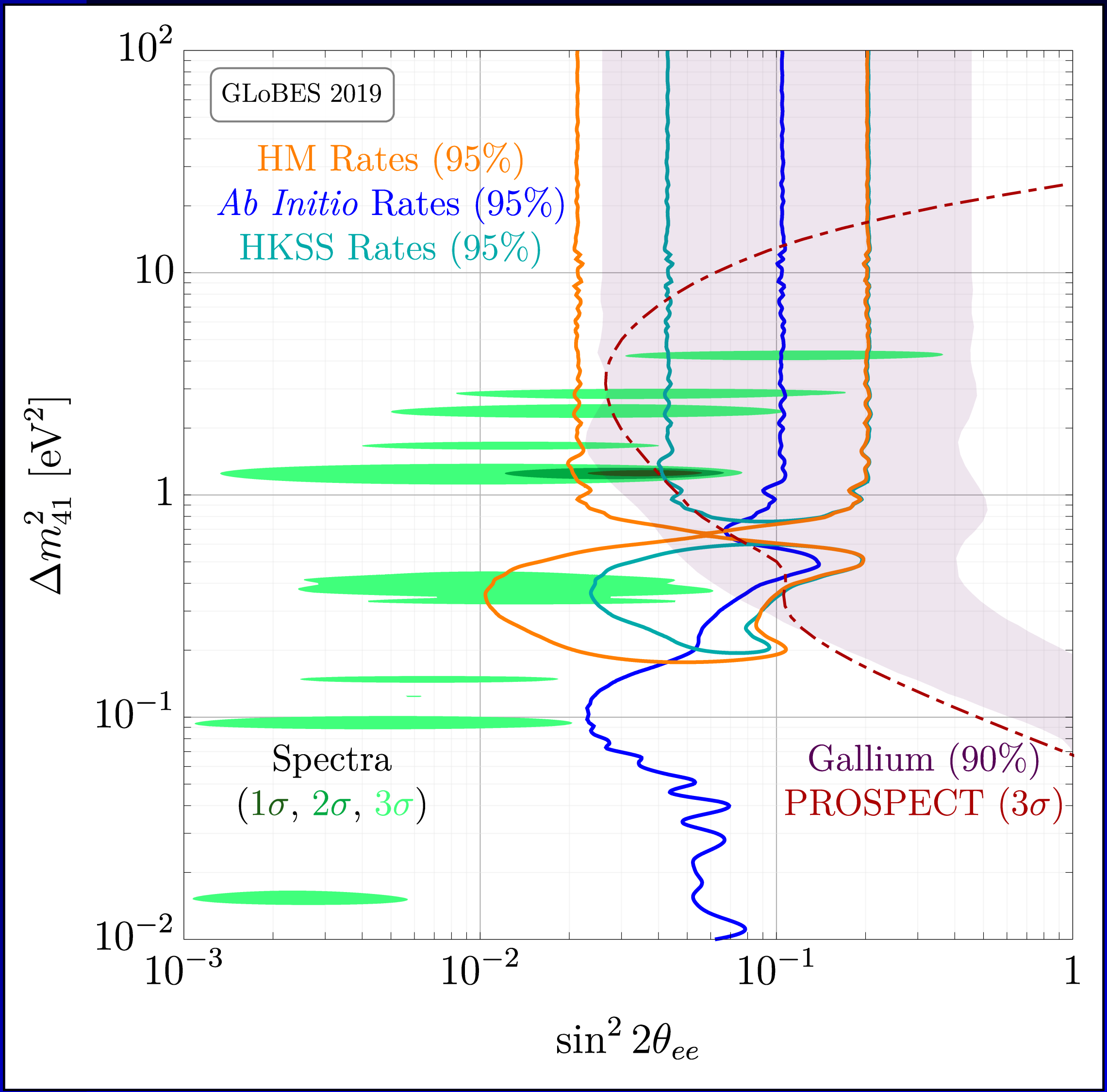
Berryman, Brdar, PH, 2018

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!

$\bar{\nu}_e$ oscillation present



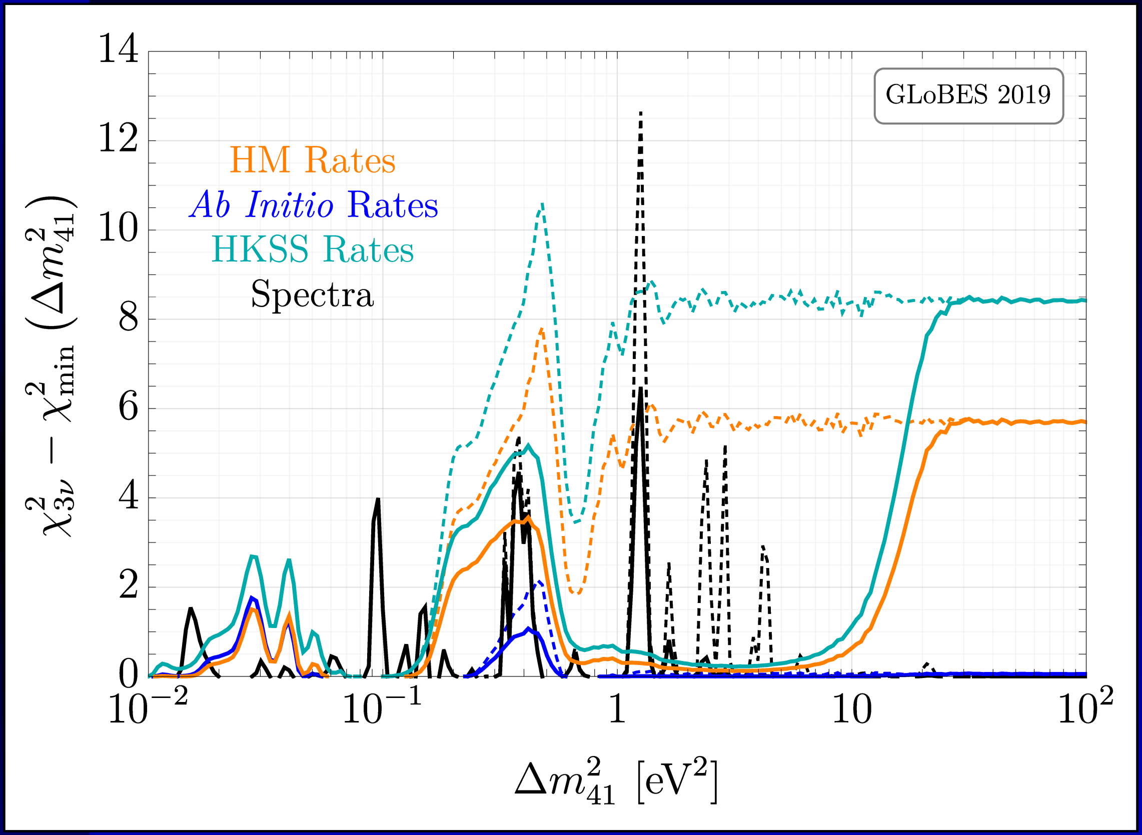
Berryman, PH, 1909.09267

Current $\nu_e/\bar{\nu}_e$ data **fully consistent** with a 1 eV sterile neutrino.

Allowed region at the edge of the sensitivity of current reactor experiments.

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

$\bar{\nu}_e$ oscillation future



Berryman, PH, 1909.09267

χ^2-difference between no-oscillation and best-fit oscillation at fixed Δm^2 – measures preference for oscillation.

Dashed – current data
Solid – after a hypothetical null result of 3 years of PROSPECT

Significant parameter space will remain for a while.

Note, global fit based on GLoBES: code and data will be made public soon.

Summary

- Reactors are very bright and complex neutrino sources – flux predictions agree at the 10%-level with data
- Anomalies in both rate and shape at the 5%-level – latest flux predictions are inconclusive
- 5 MeV excess is eluding an explanation from both BSM and nuclear physics
- $\sim 3\,\sigma$ hint for eV-scale sterile neutrino independent of flux models – this hint can not be fully tested by current experiments