Sterile neutrinos: fact or fiction?

Patrick Huber

Center for Neutrino Physics at Virginia Tech

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Online

All neutrino theorists are liars

Neutrino physics has a rich history of anomalies:

- solar anomaly, atmospheric anomaly
- 17keV neutrino, super-luminal, etc.

Solar and atmospheric neutrino oscillation a real, but their anomalous nature was supported by theoretical prejudice:

- neutrinos are massless
- neutrino mixing angles are small

Of course, I happen to be a neutrino 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 flavor physics and LHC results

Is there anything within our means we can find?

Neutrinos are massive – so what?

Neutrinos in the Standard Model (SM) are strictly massless ⇔ neutrino oscillation is BSM physics!

…yes, this is not SUSY, large extra dimensions or anyone's favorite BSM model, but it **IS the only** laboratory-based proof for the incompleteness of the SM.

It also makes them the fermion portal to the dark sector

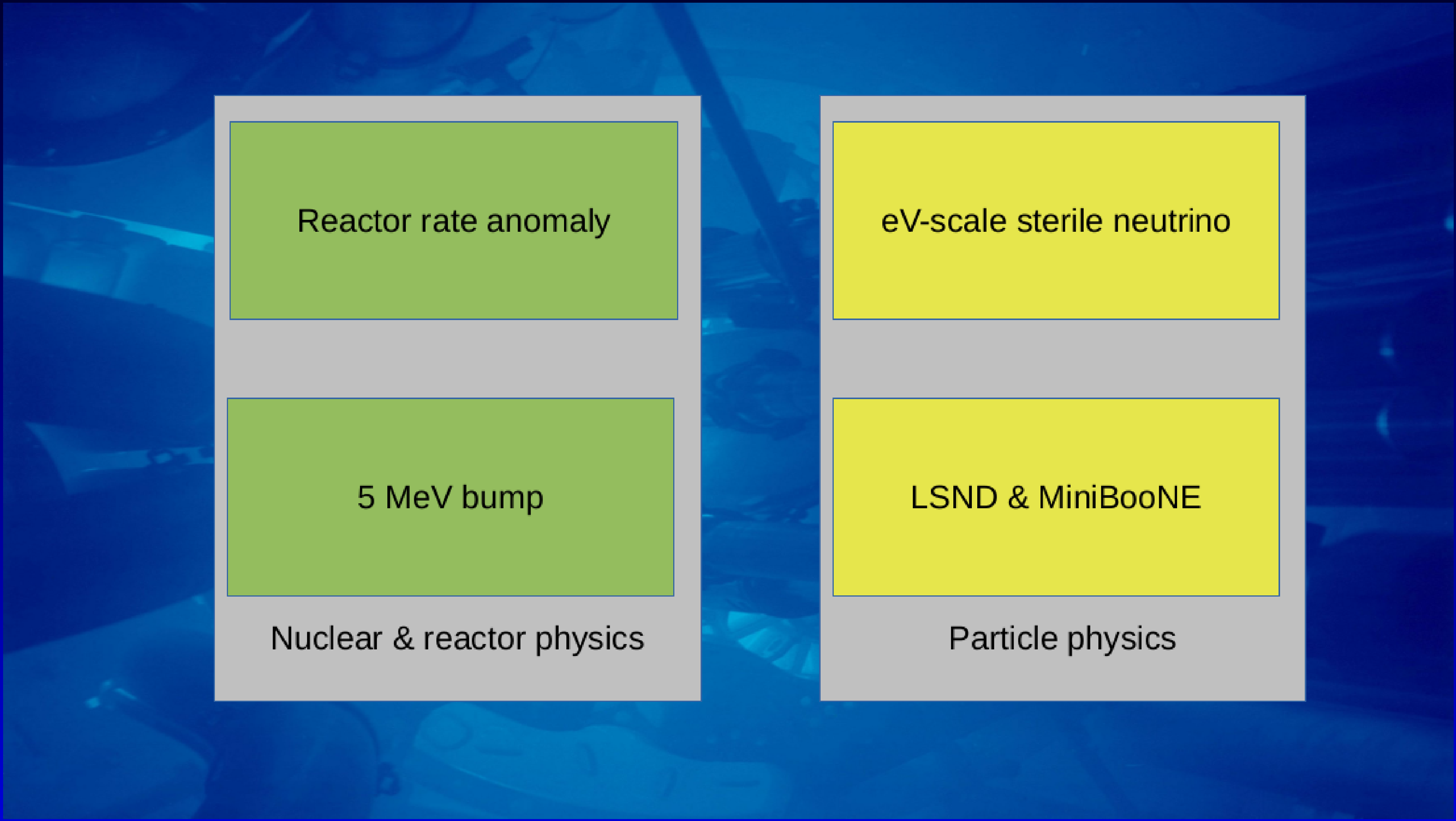
Alas, it is indirect evidence: no energy scale, no symmetry, no new interaction, no new particles are seen in the laboratory.

The remainder of this talk is all about searching below the lamp post.

Evidence in favor

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

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



Reactor rate anomaly

5 MeV bump

Nuclear & reactor physics

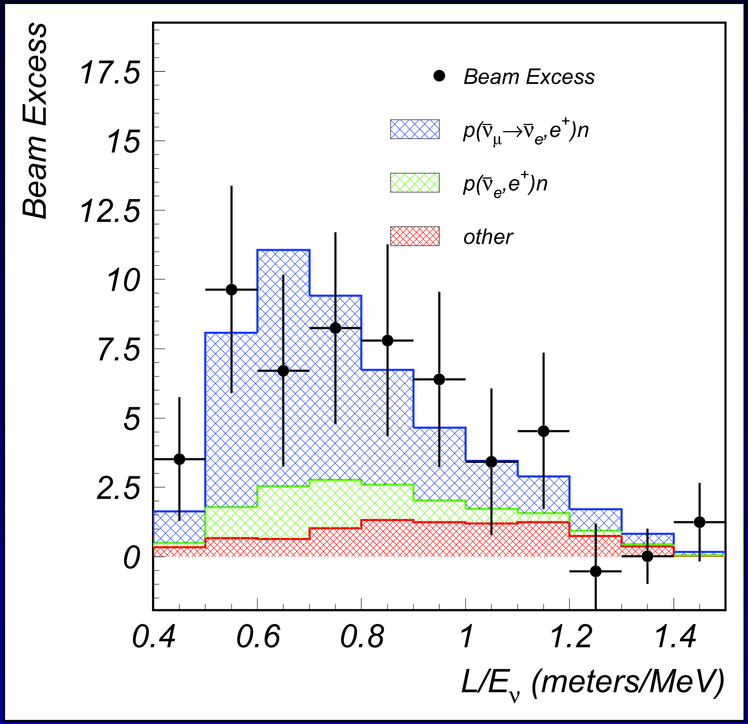
eV-scale sterile neutrino

LSND & MiniBooNE

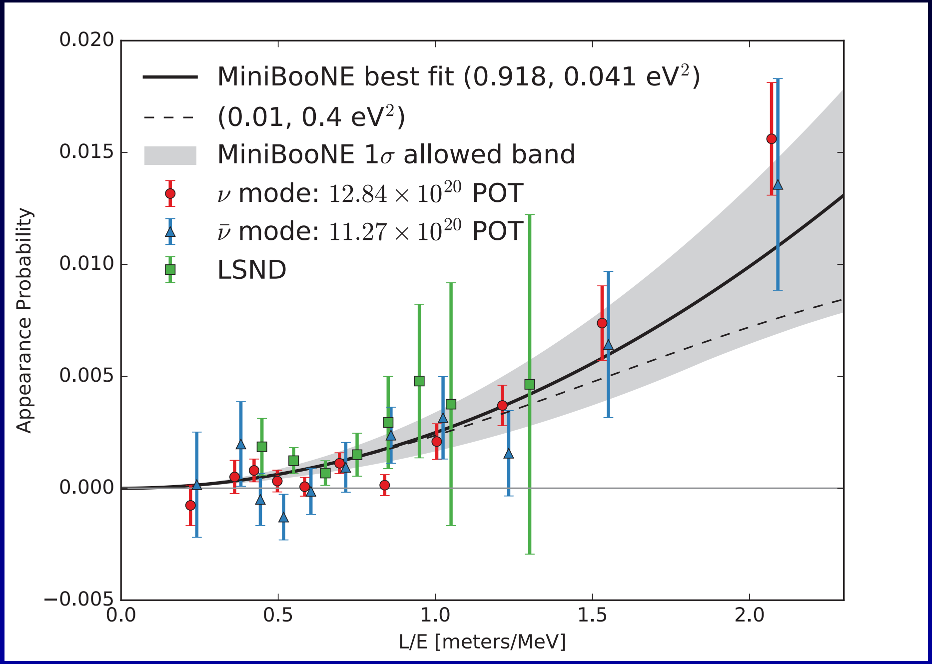
Particle physics

These four topics are related but distinct!

LSND and MiniBooNE



LSND 1995

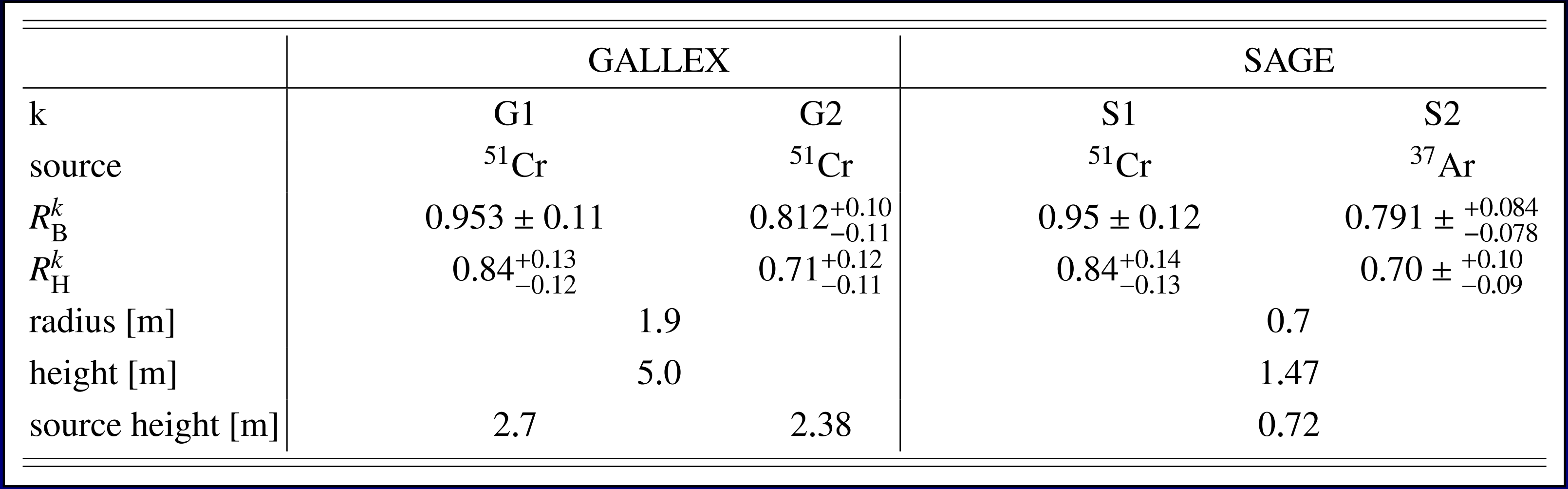


MiniBooNE 2018

$$P(\bar{\nu}_\mu \to \bar{\nu}_e) \simeq 0.003$$

Statistically significant: $4 - 6\sigma$

Gallium anomaly

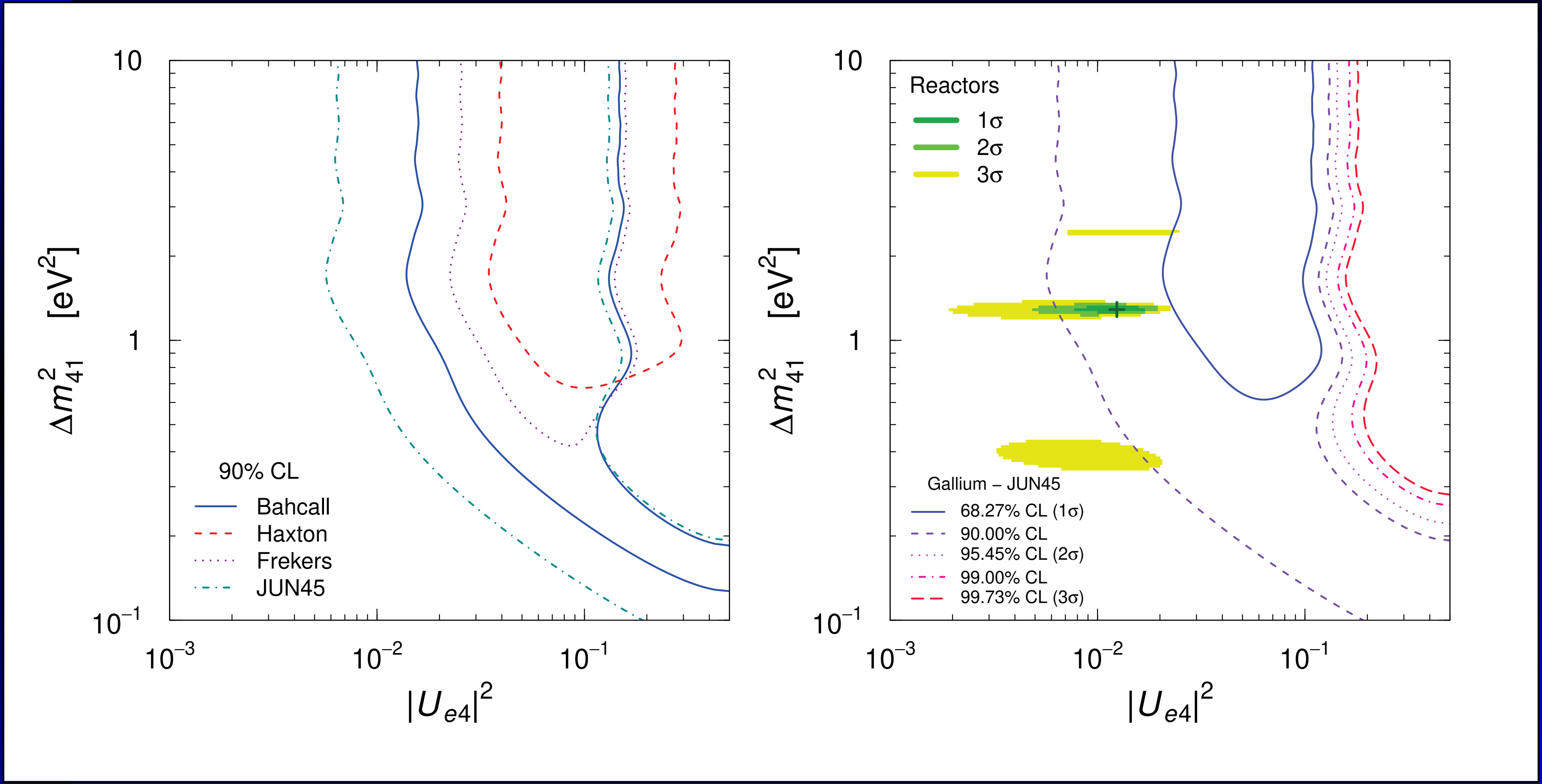


	GALLEX		SAGE	
k	G1	G2	S1	S2
source	^{51}Cr	^{51}Cr	^{51}Cr	^{37}Ar
R^k_{B}	0.953 ± 0.11	$0.812^{+0.10}_{-0.11}$	0.95 ± 0.12	$0.791 \pm ^{+0.084}_{-0.078}$
R^k_{H}	$0.84^{+0.13}_{-0.12}$	$0.71^{+0.12}_{-0.11}$	$0.84^{+0.14}_{-0.13}$	$0.70 \pm ^{+0.10}_{-0.09}$
radius [m]	1.9		0.7	
height [m]	5.0		1.47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

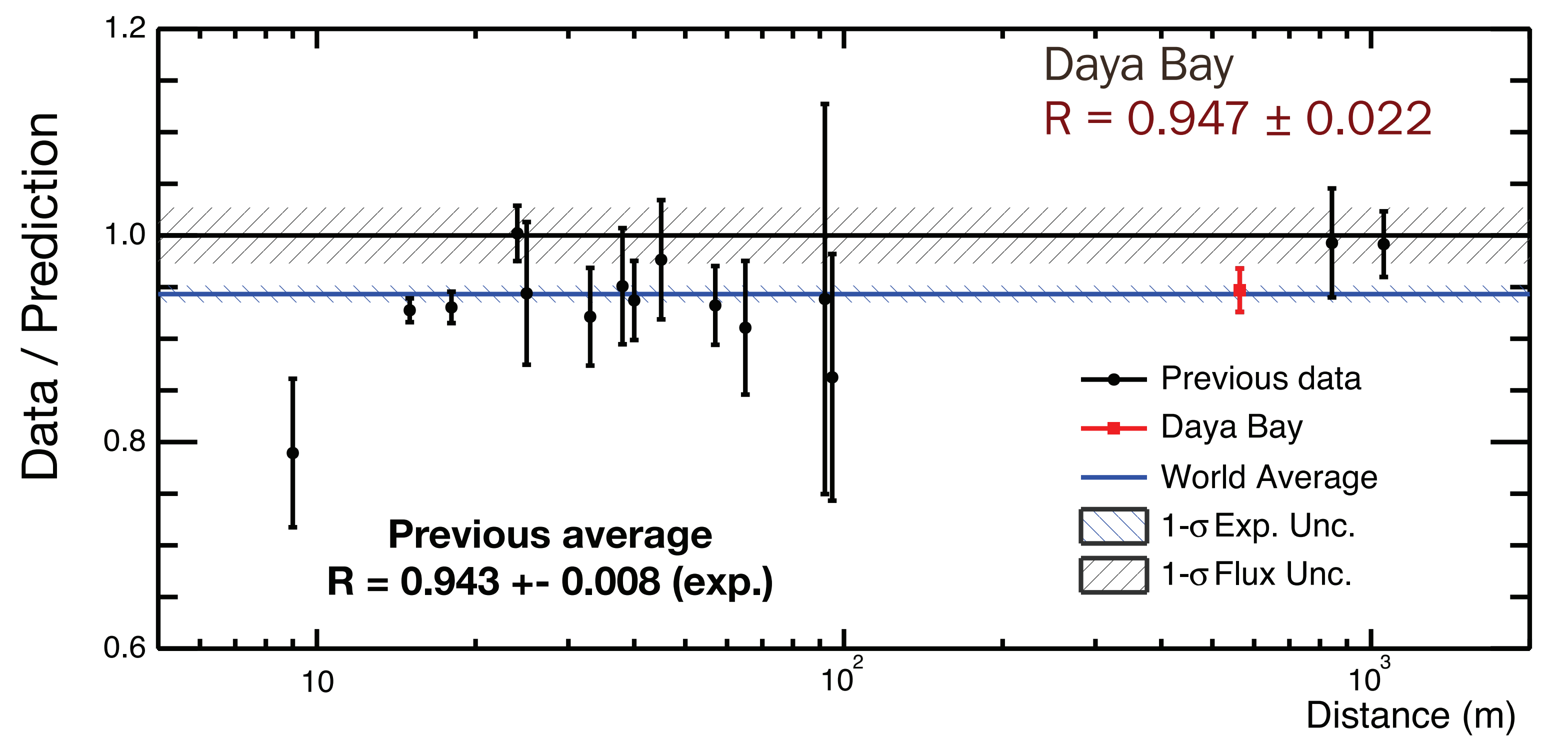
Nuclear matrix element update



Kostensalo *et al.* 2019

Significance decreases from $3.0\,\sigma$ to $2.3\,\sigma$.

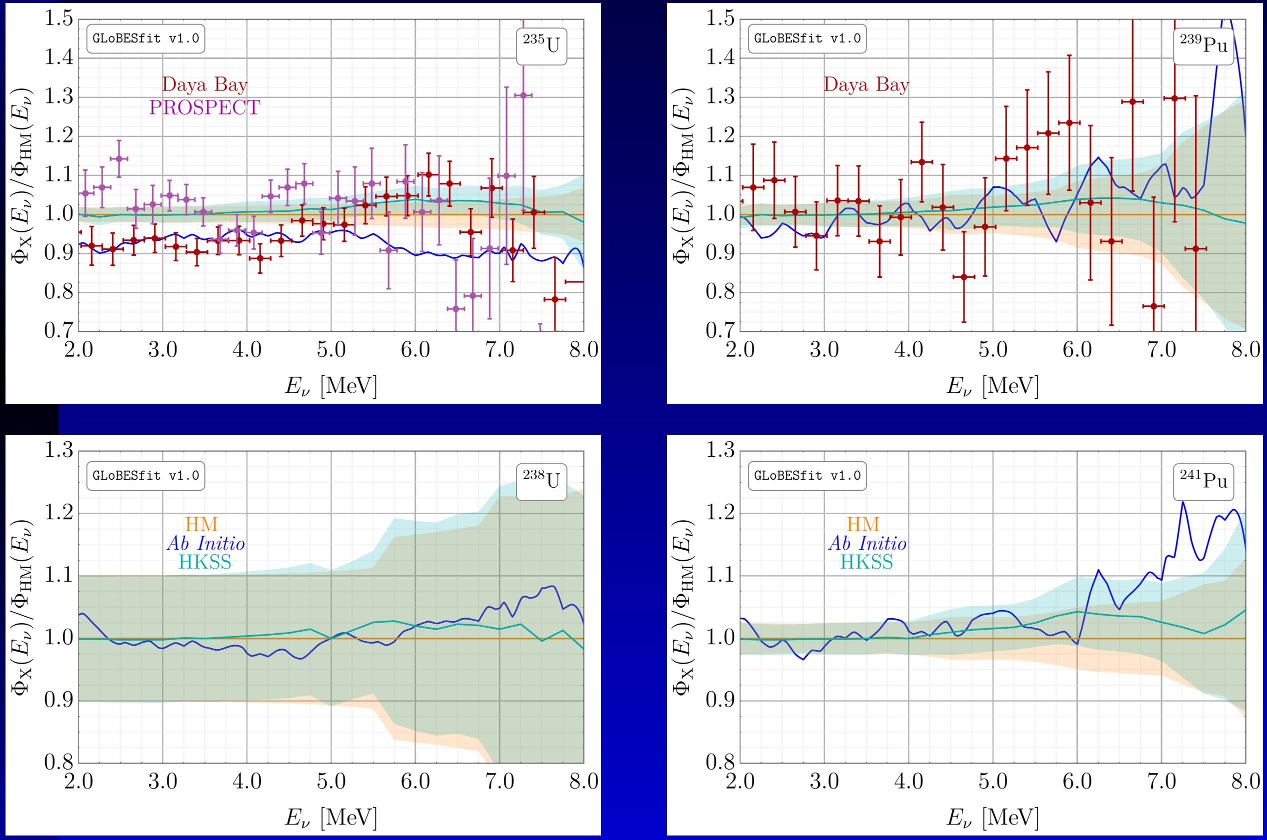
The reactor anomaly



Daya Bay, 2014

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

Where we are



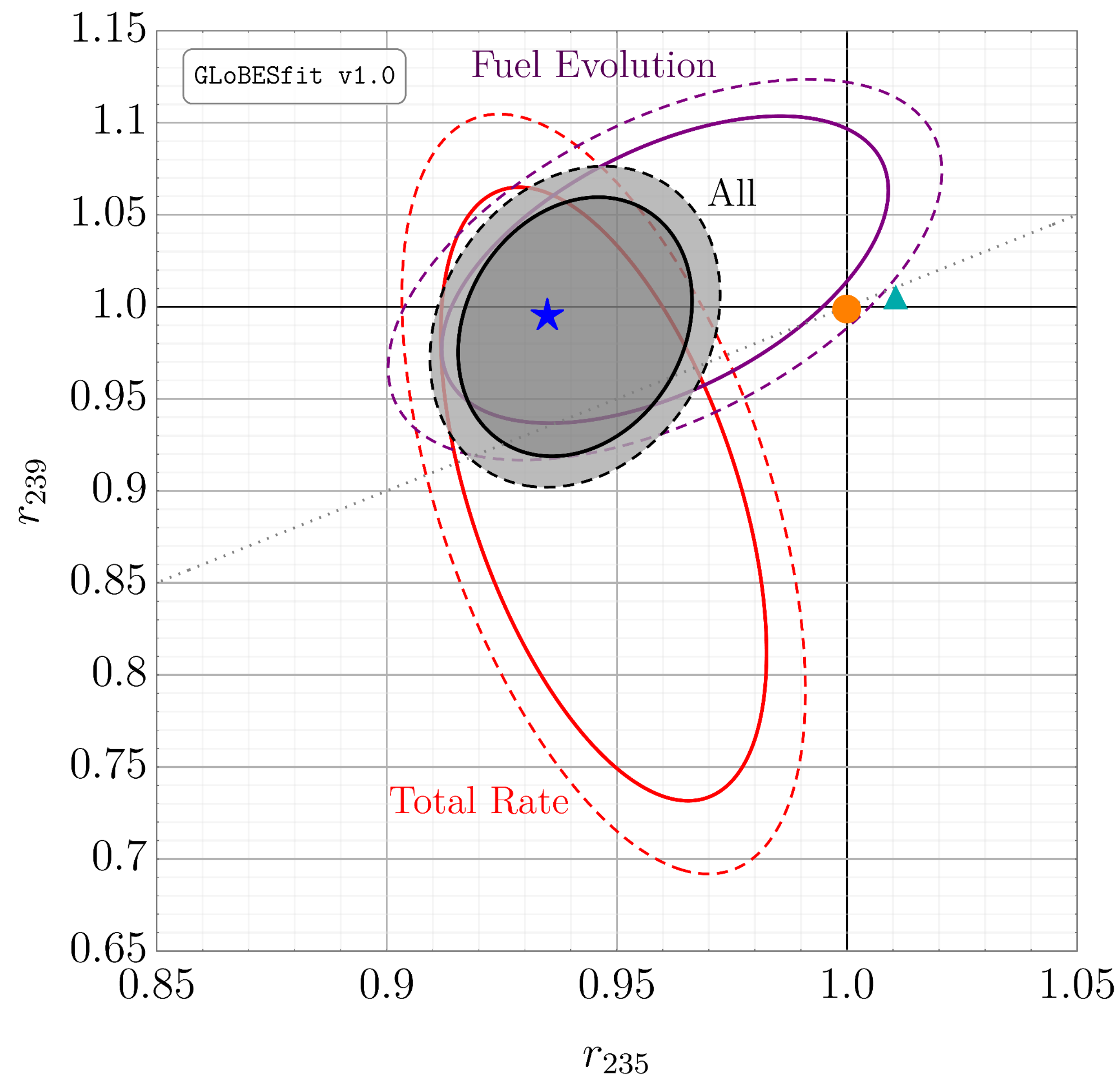
3 different flux models, data from 2 different experiments

Except for U235:
+ the models agree within error bars
+ the models agree with neutrino data

U235 has smallest error bars, not surprising that discrepancies show up first.

Berryman, PH, 2020

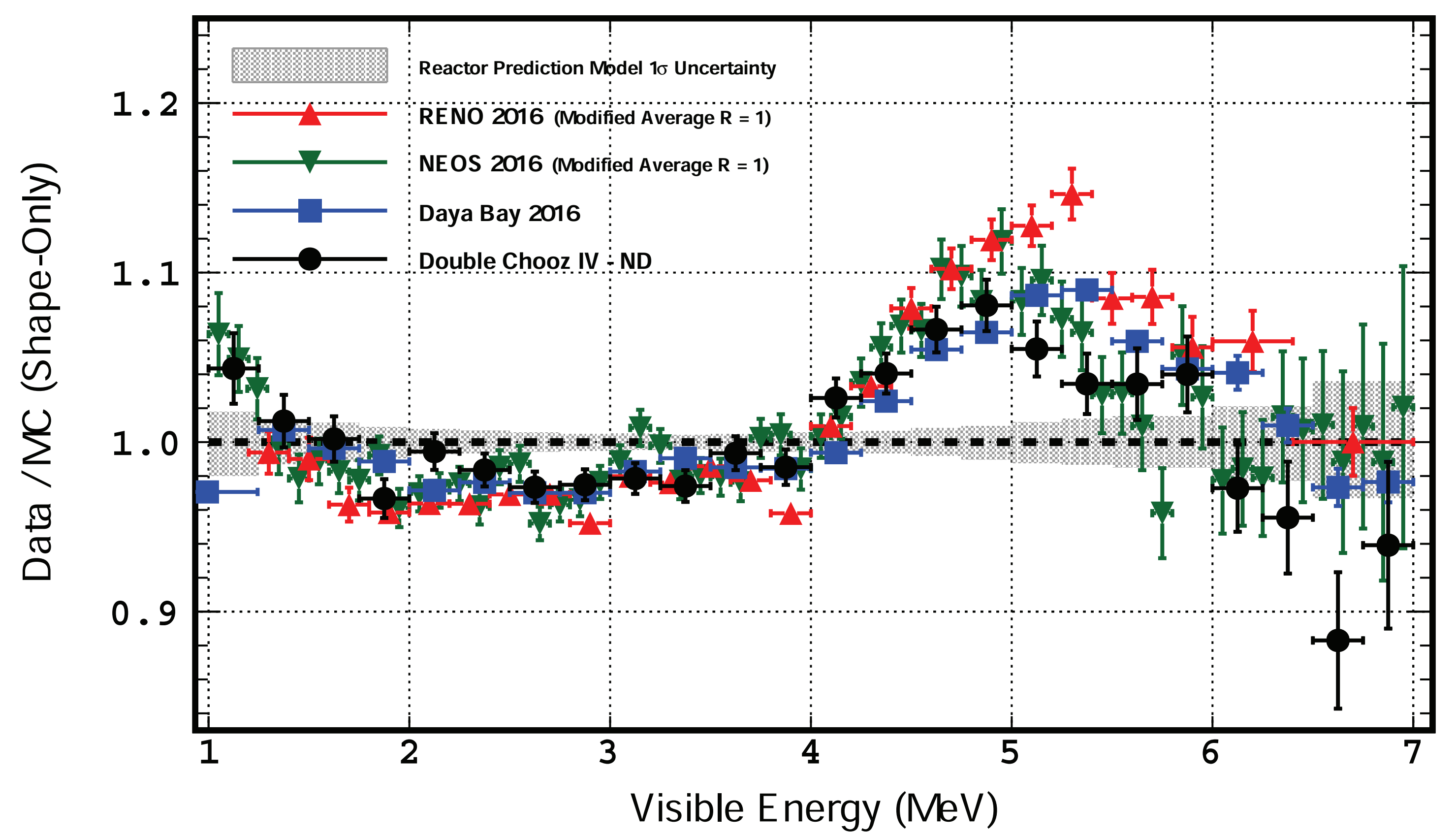
Fuel evolution



$r_{235} \neq 1$, there are not enough neutrinos from 235U.

Berryman, PH, 2020

The 5 MeV bump

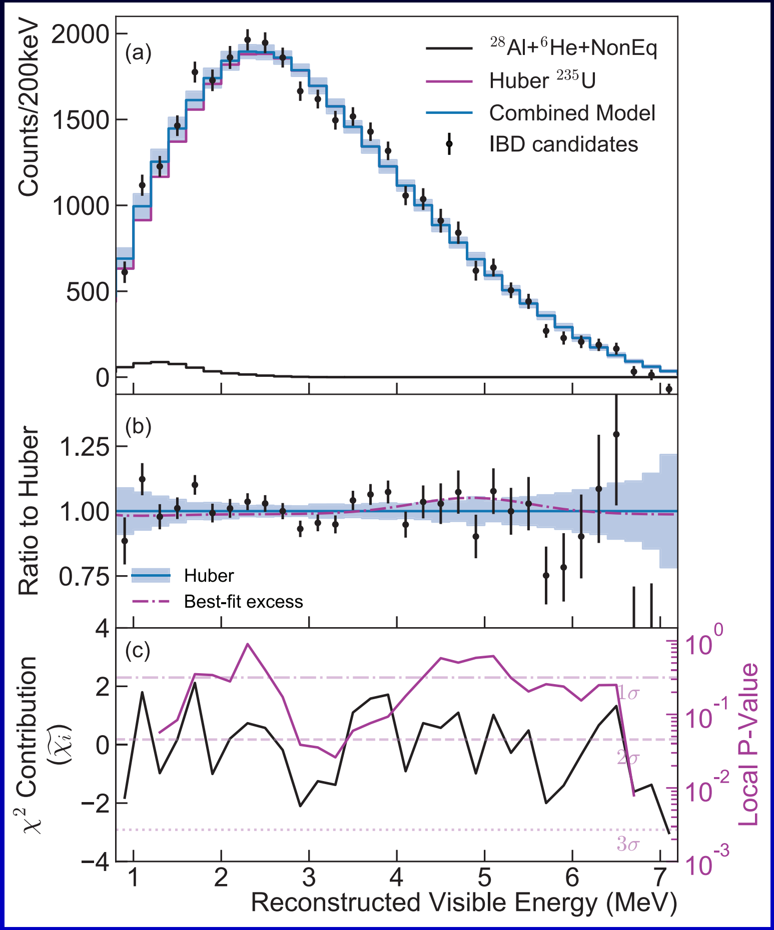


Double Chooz 2019

Contains only 0.5% of all neutrino events – not important for sterile neutrinos

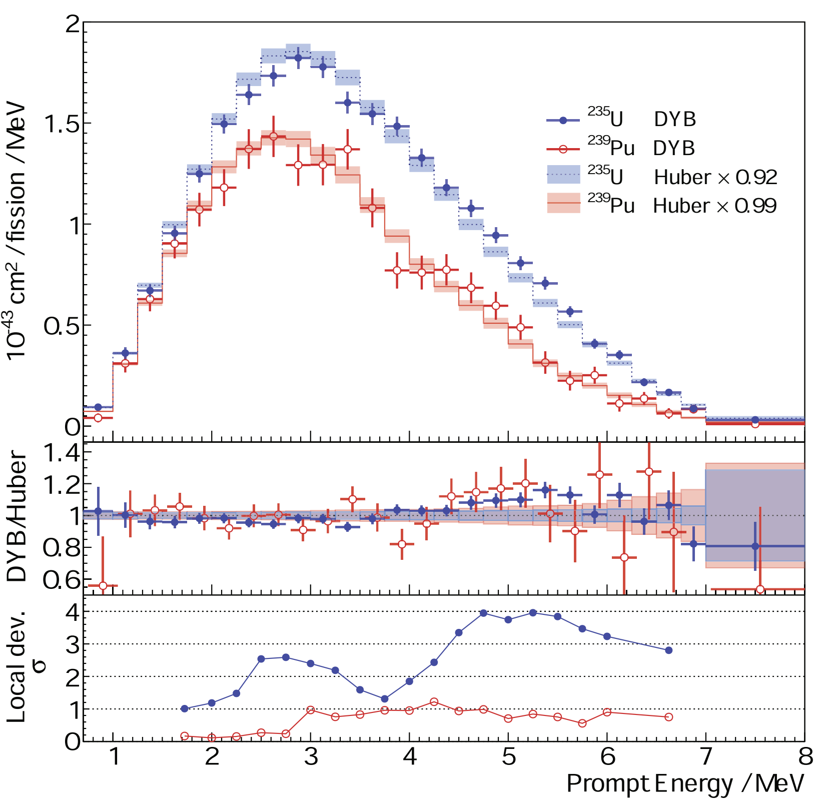
Yet, statistically more significant than the RAA!

Latest data vs bump



PROSPECT 2018

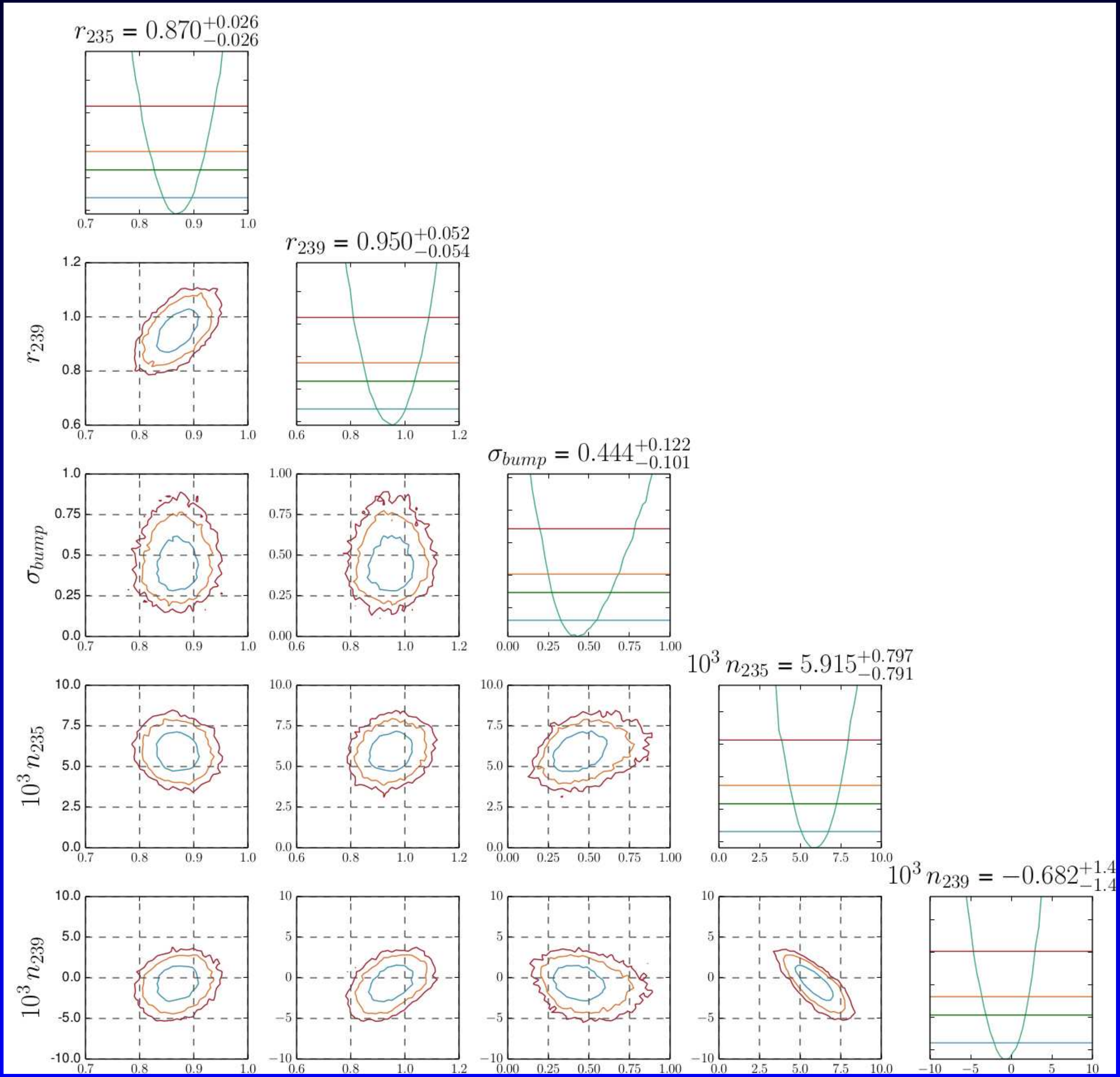
Disfavors ^{235}U as sole culprit at 2.1 σ



Daya Bay 2019, 2021

Requires a bump in ^{235}U at 4 σ

Bumpology

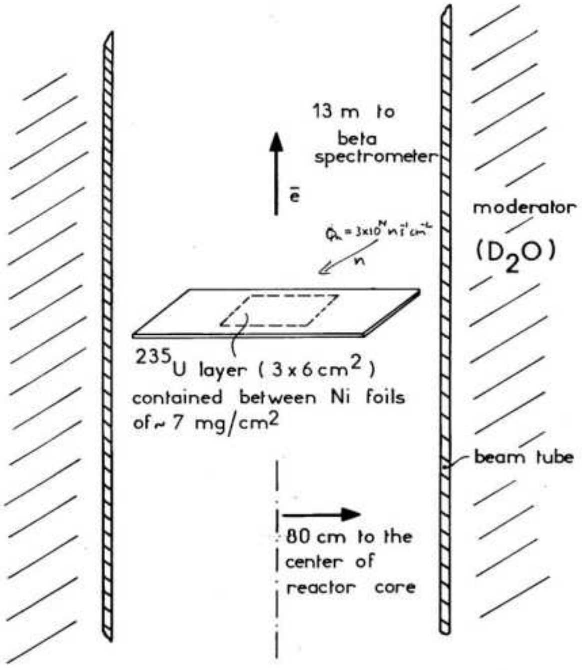


Daya Bay, RENO and PROSPECT as of 2019

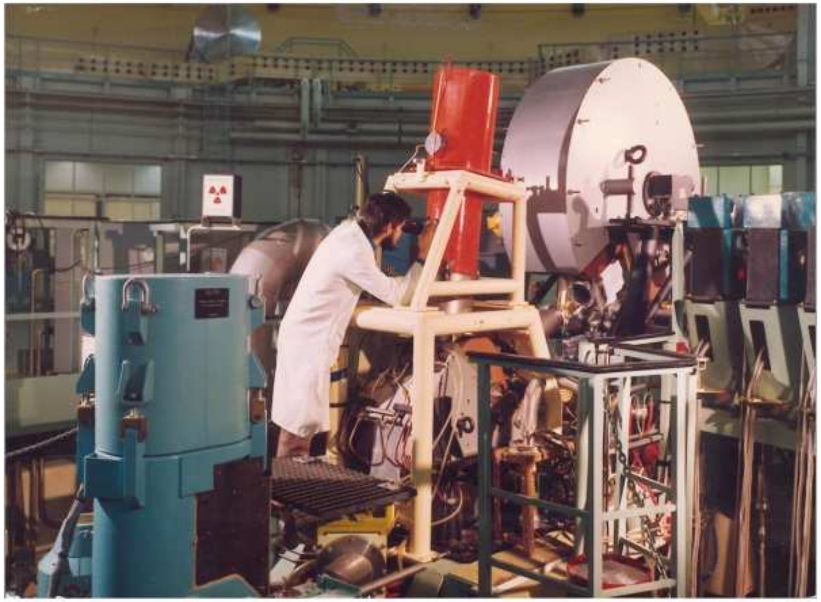
Only $n_{235} \neq 0$ with any significance

Berryman, PH, 2020

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

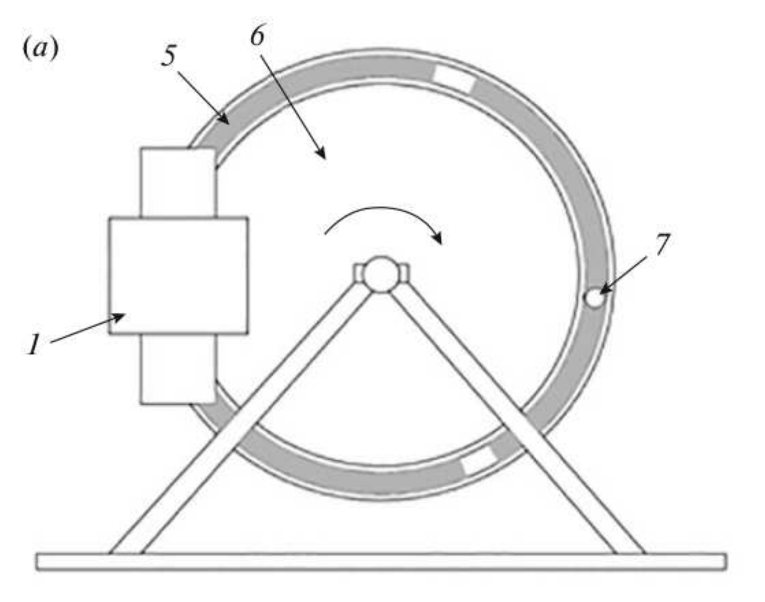
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

Neutron flux calibration standards different for U235 and Pu239: 207Pb and 197Au respectively.

Combined with potential differences in neutron spectrum – room for a 5% shift of U235 normalization?

A. Letourneau, A. Onillon, AAP 2018

2021 beta measurement

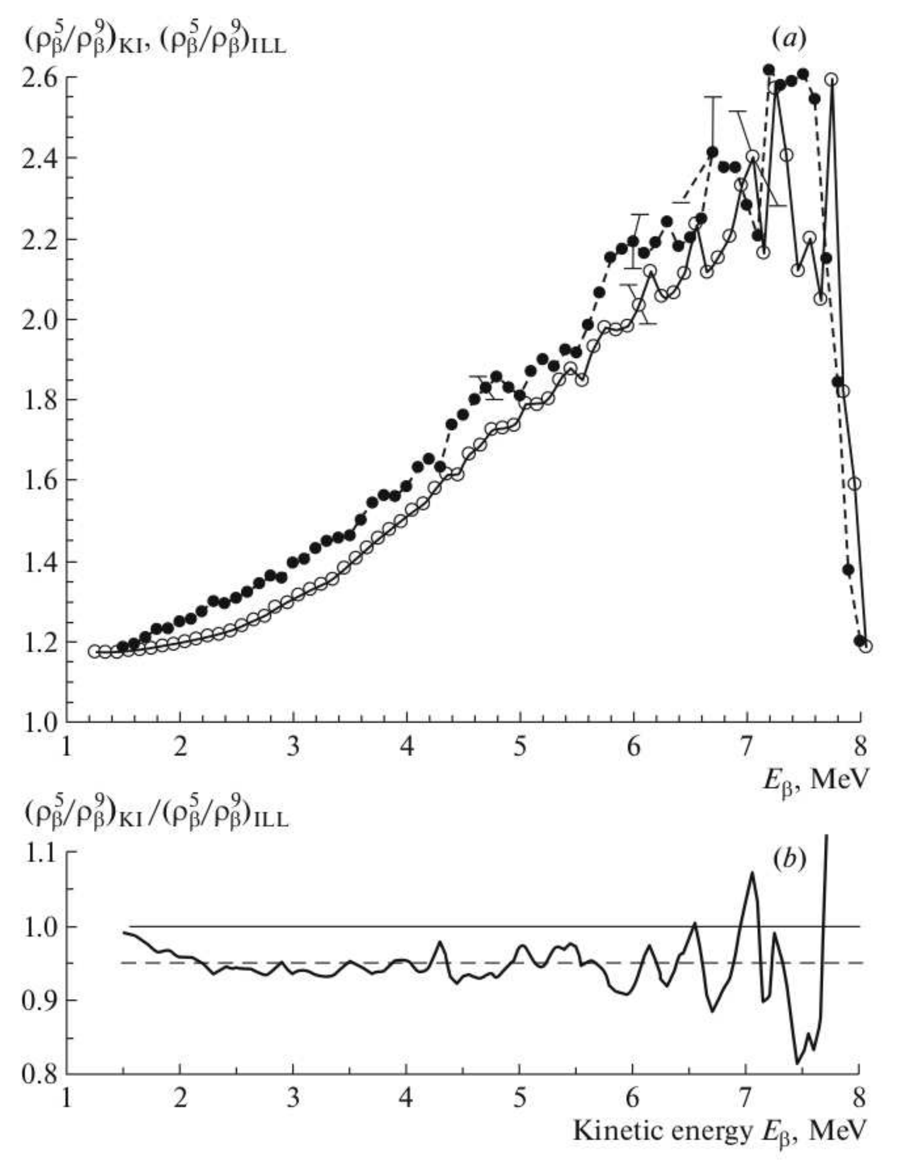


Relative measurement of U235 and Pu239 targets under identical conditions.

Beta detection with stilbene.

This slide and the following are based on V. Kopeikin, M. Skorokhvatov, O. Titov (2021) and V. Kopeikin , Yu. Panin, A. Sabelnikov (2020)

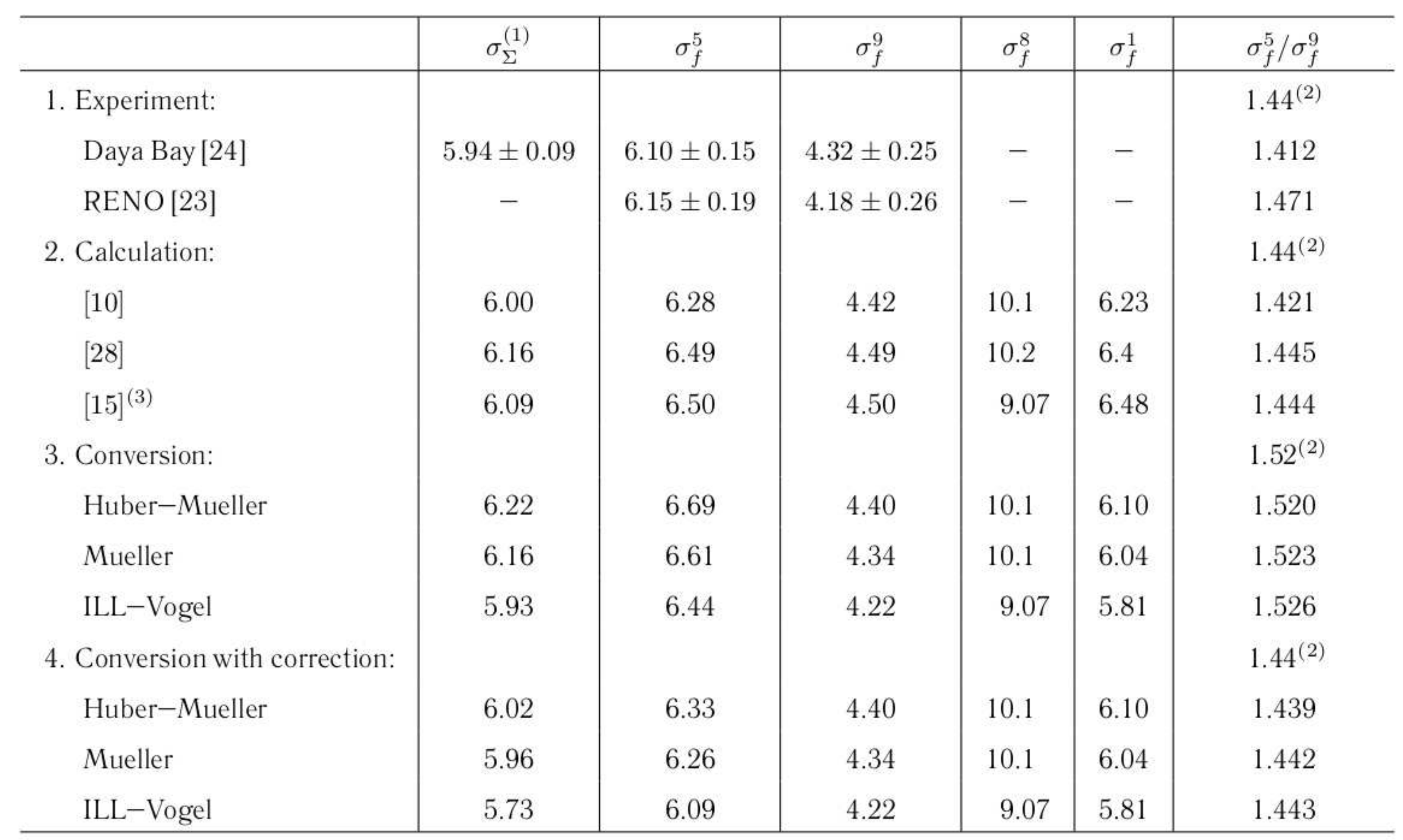
2021 beta results



At relevant energies the new measurement is about 5% below the previous one

Systematics is difficult in these measurements, but no obvious issues.

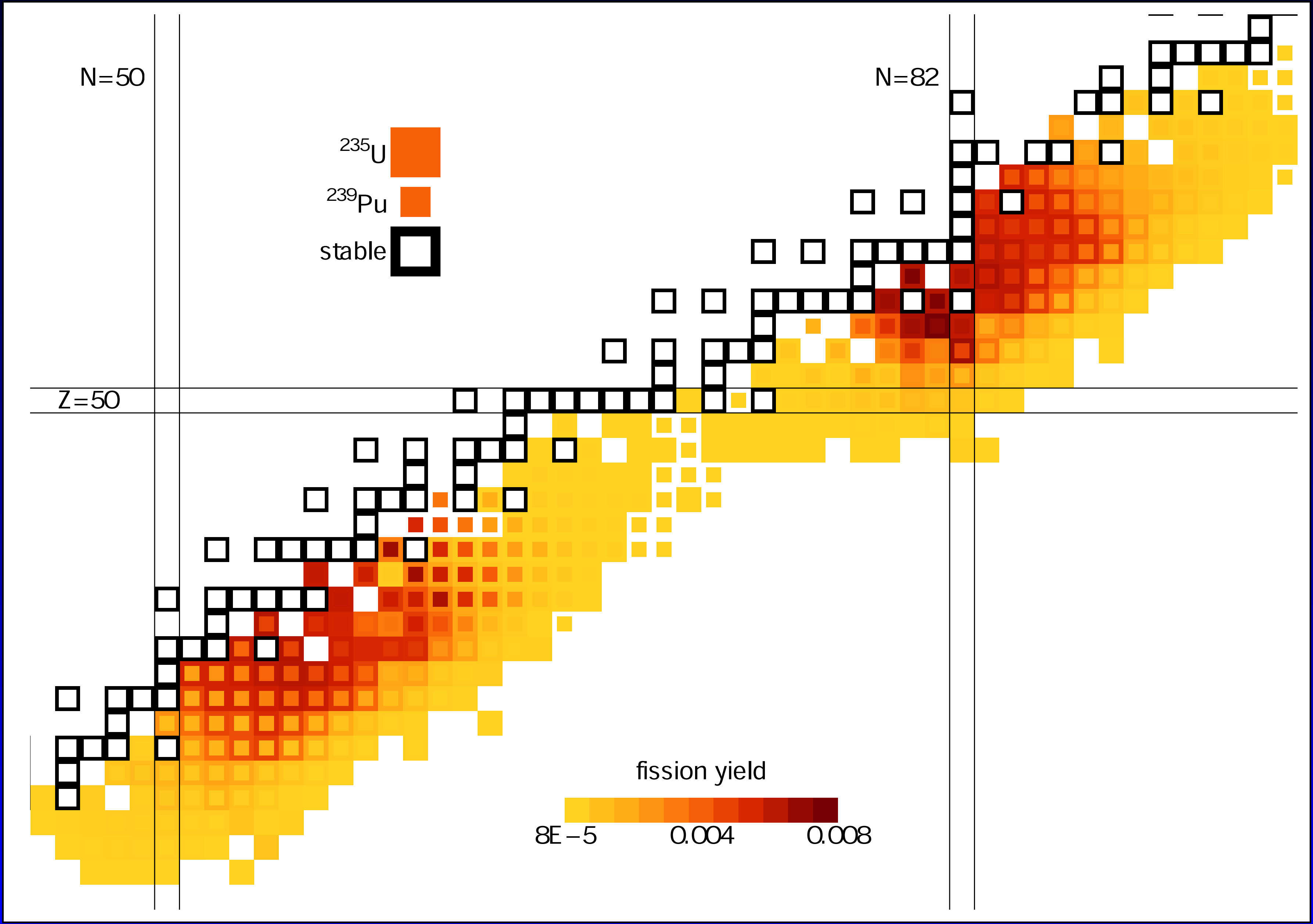
2021 beta impact



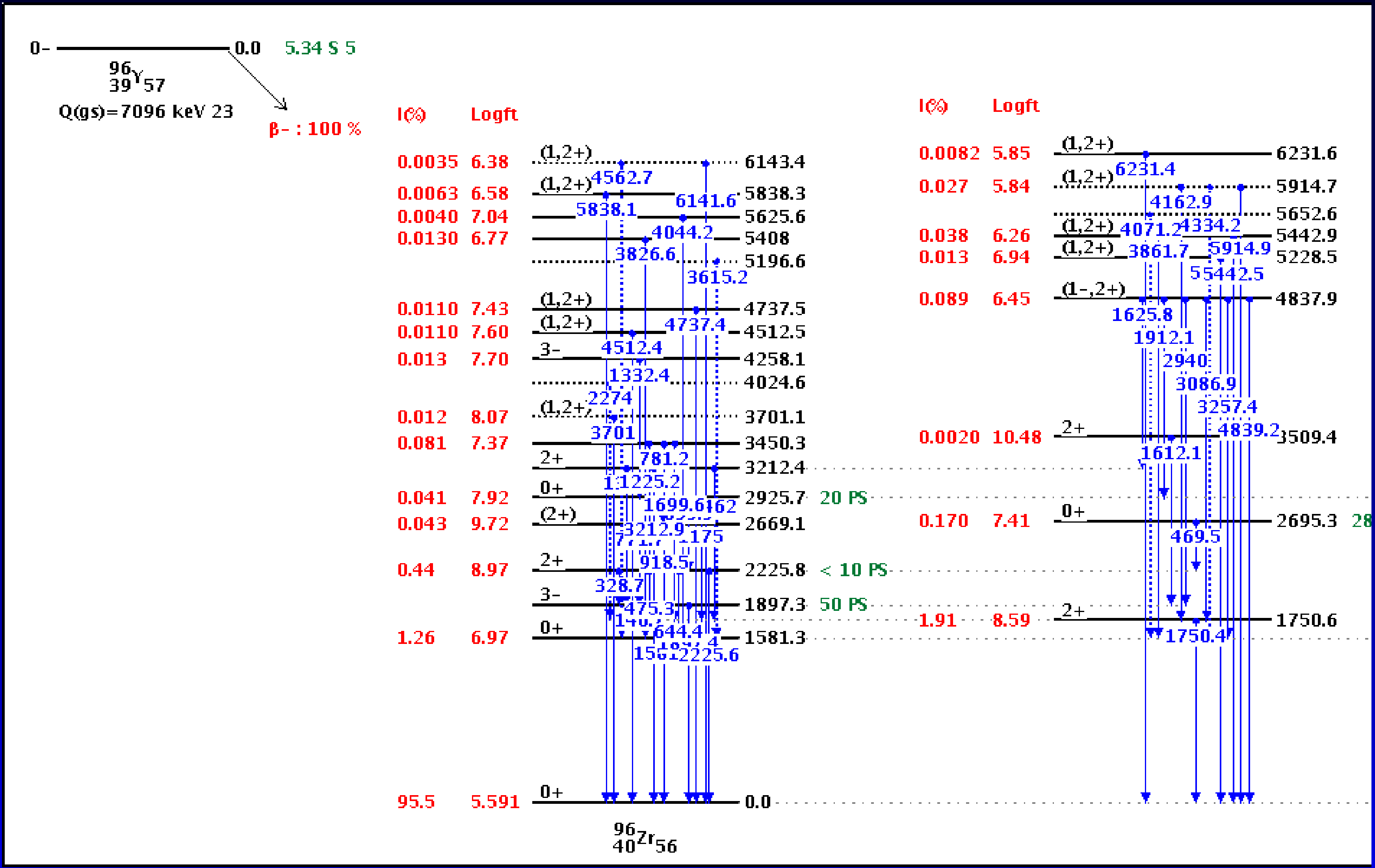
	$\sigma_\Sigma^{(1)}$	σ_f^5	σ_f^9	σ_f^8	σ_f^1	σ_f^5/σ_f^9
1. Experiment:						$1.44^{(2)}$
Daya Bay [24]	5.94 ± 0.09	6.10 ± 0.15	4.32 ± 0.25	–	–	1.412
RENO [23]	–	6.15 ± 0.19	4.18 ± 0.26	–	–	1.471
2. Calculation:						$1.44^{(2)}$
[10]	6.00	6.28	4.42	10.1	6.23	1.421
[28]	6.16	6.49	4.49	10.2	6.4	1.445
$[15]^{(3)}$	6.09	6.50	4.50	9.07	6.48	1.444
3. Conversion:						$1.52^{(2)}$
Huber–Mueller	6.22	6.69	4.40	10.1	6.10	1.520
Mueller	6.16	6.61	4.34	10.1	6.04	1.523
ILL–Vogel	5.93	6.44	4.22	9.07	5.81	1.526
4. Conversion with correction:						$1.44^{(2)}$
Huber–Mueller	6.02	6.33	4.40	10.1	6.10	1.439
Mueller	5.96	6.26	4.34	10.1	6.04	1.442
ILL–Vogel	5.73	6.09	4.22	9.07	5.81	1.443

Now the predicted and measured U235/Pu235 IBD ratio agree well. IF confirmed, no RAA!

Why is this so complicated?



β-branches



Two ways to predict

Summation calculations

Fission yields
Beta yields

Problem: databases are insufficient & difficulty of assigning an error budget

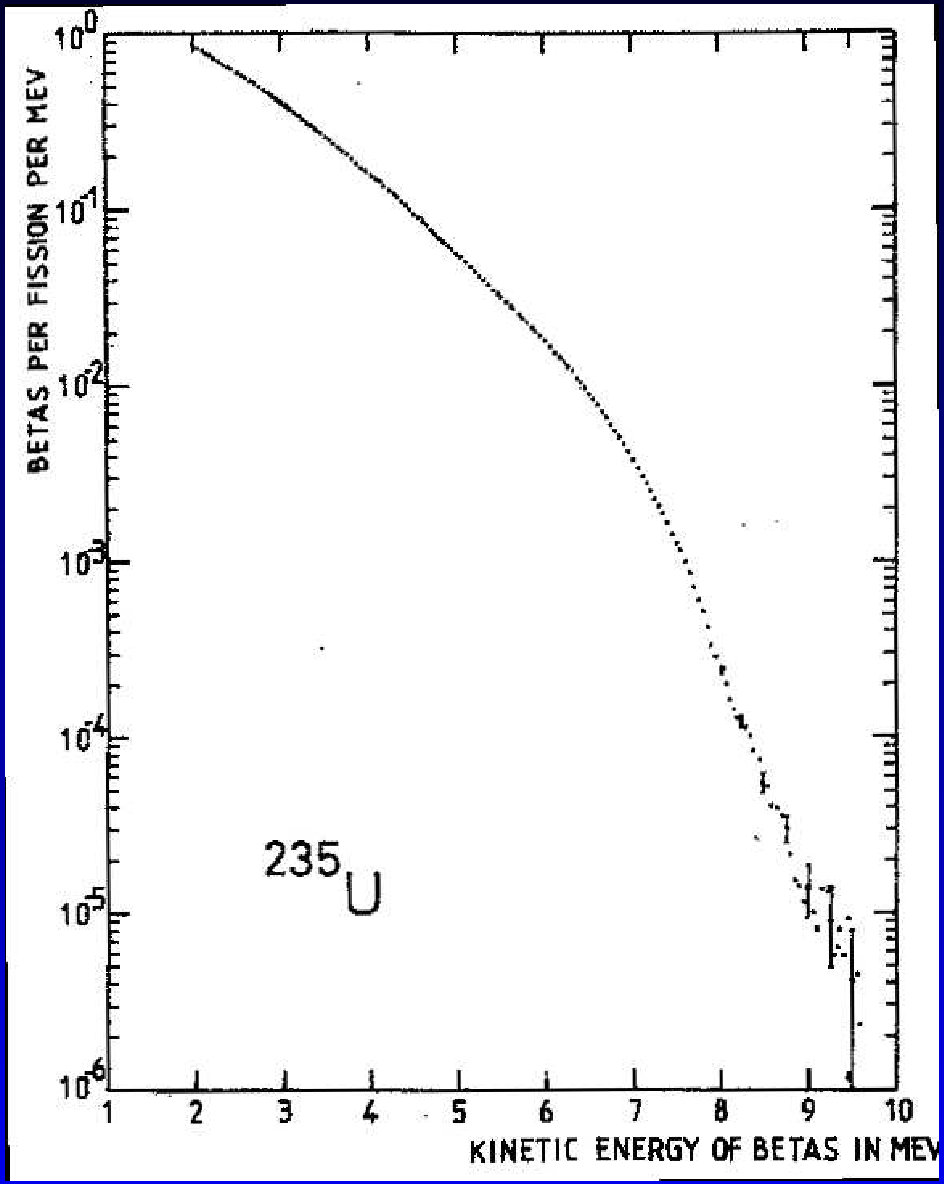
Conversion calculations

Cumulative beta spectra
Z_{eff} from databases

Problem: single set of cumulative beta spectra & forbidden corrections have to rely on databases

In both approaches, one has to deal with:
Forbidden decays
Weak magnetism corrections
Non-equilibrium corrections
Structural materials in the reactor

Conversion method



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

Extraction of ν-spectrum

We can measure the total β-spectrum

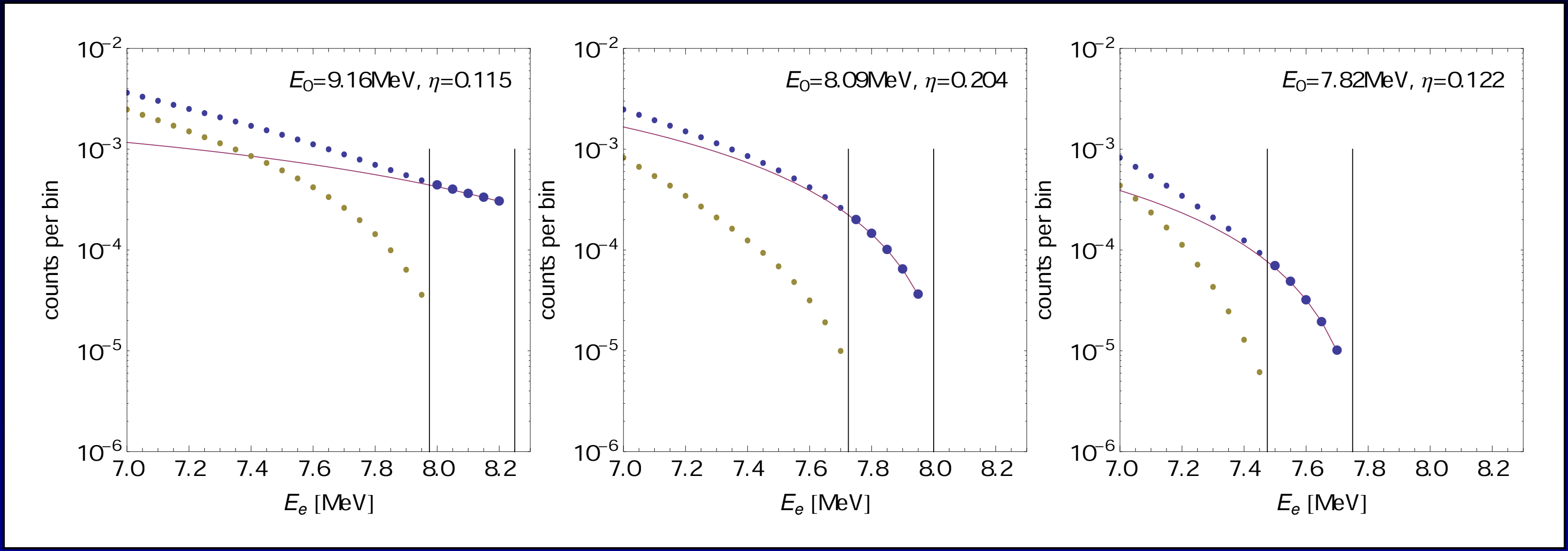
$$\mathcal{N}_\beta(E_e) = \int dE_0 N_\beta(E_e, E_0; \bar{Z})\, \eta(E_0)\,. \qquad (1)$$

with $\bar{Z}$ effective nuclear charge and try to "fit" the underlying distribution of endpoints, $\eta(E_0)$.

This is a so called Fredholm integral equation of the first kind – mathematically ill-posed, *i.e.* solutions tend to oscillate, needs regulator (typically energy average), however that will introduce a bias.

This approach is know as "virtual branches"

Virtual branches



1 – fit an allowed β-spectrum with free normalization η and endpoint energy E_0 the last s data points

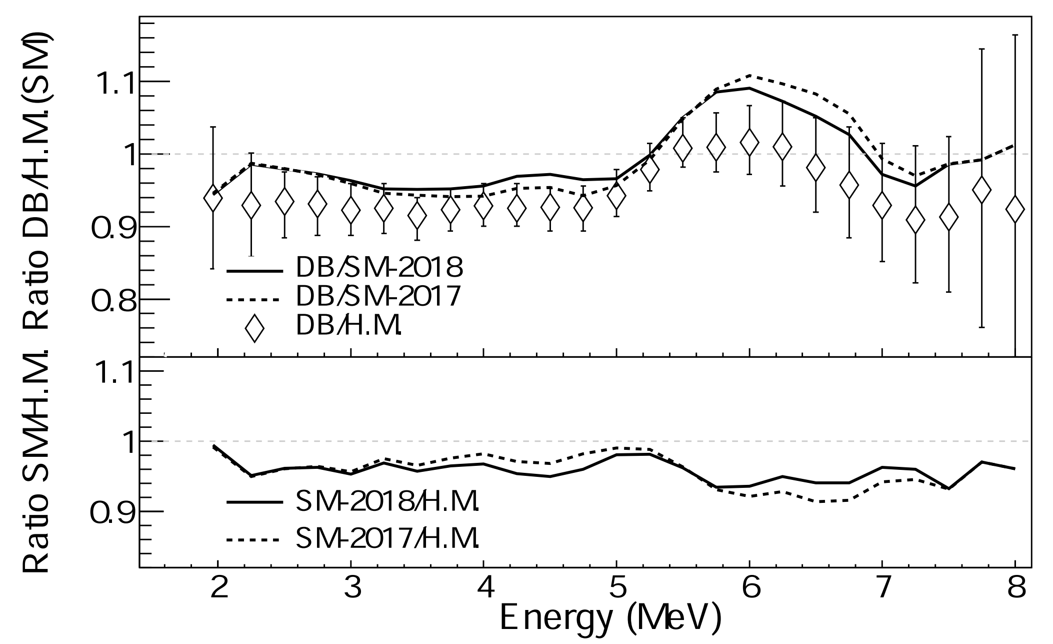
2 – delete the last s data points

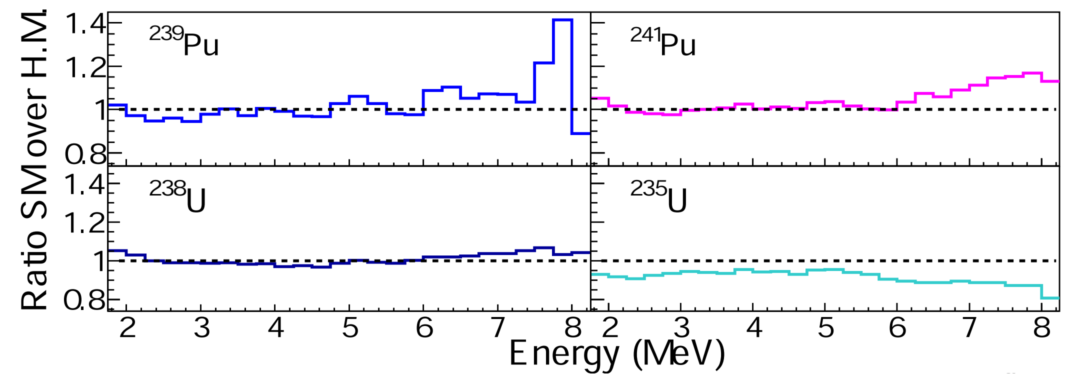
3 – subtract the fitted spectrum from the data

4 – goto 1

Invert each virtual branch using energy conservation into a neutrino spectrum and add them all.

Summation method





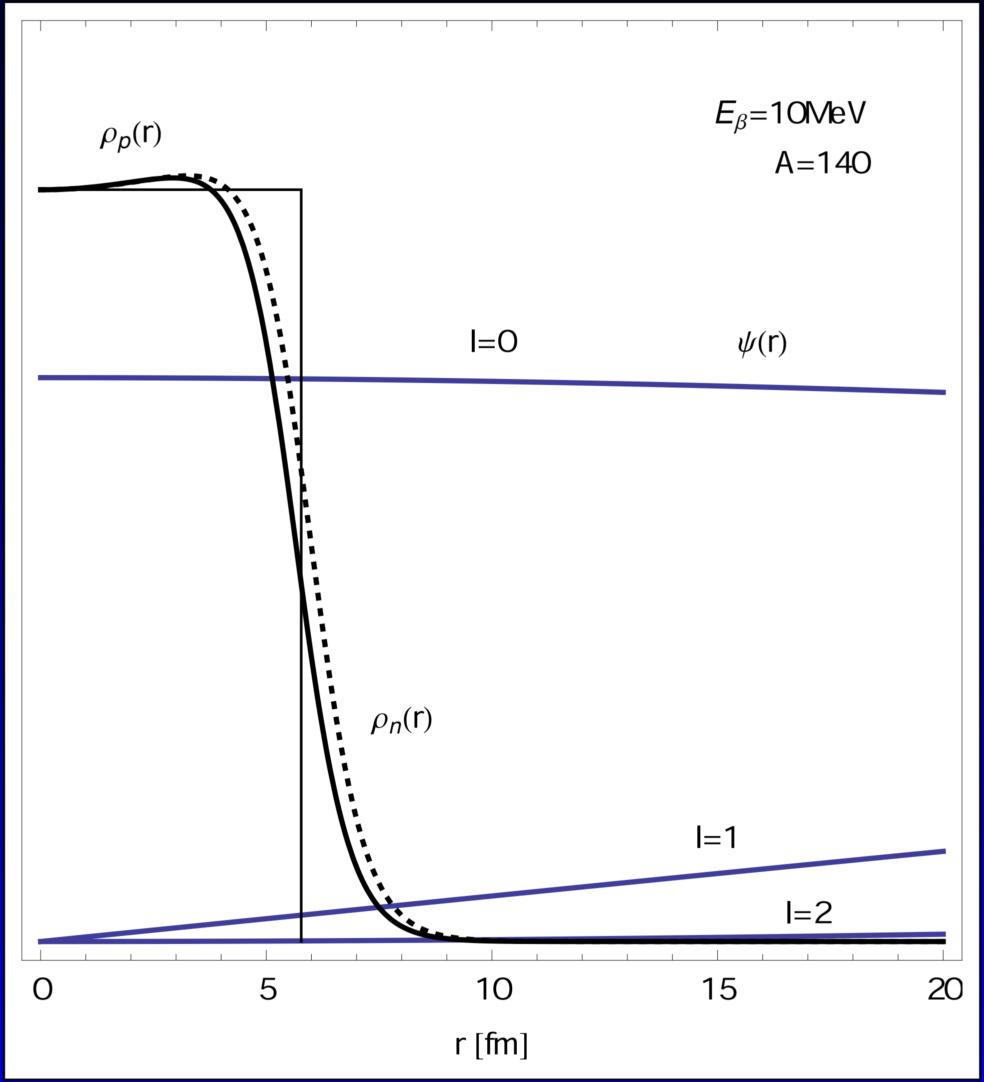
Estienne *et al.*, 2019

Take fission yields from database.

Take beta decay information from database.

For the most crucial isotopes use β-feeding functions from total absorption γ spectroscopy.

Forbidden decays



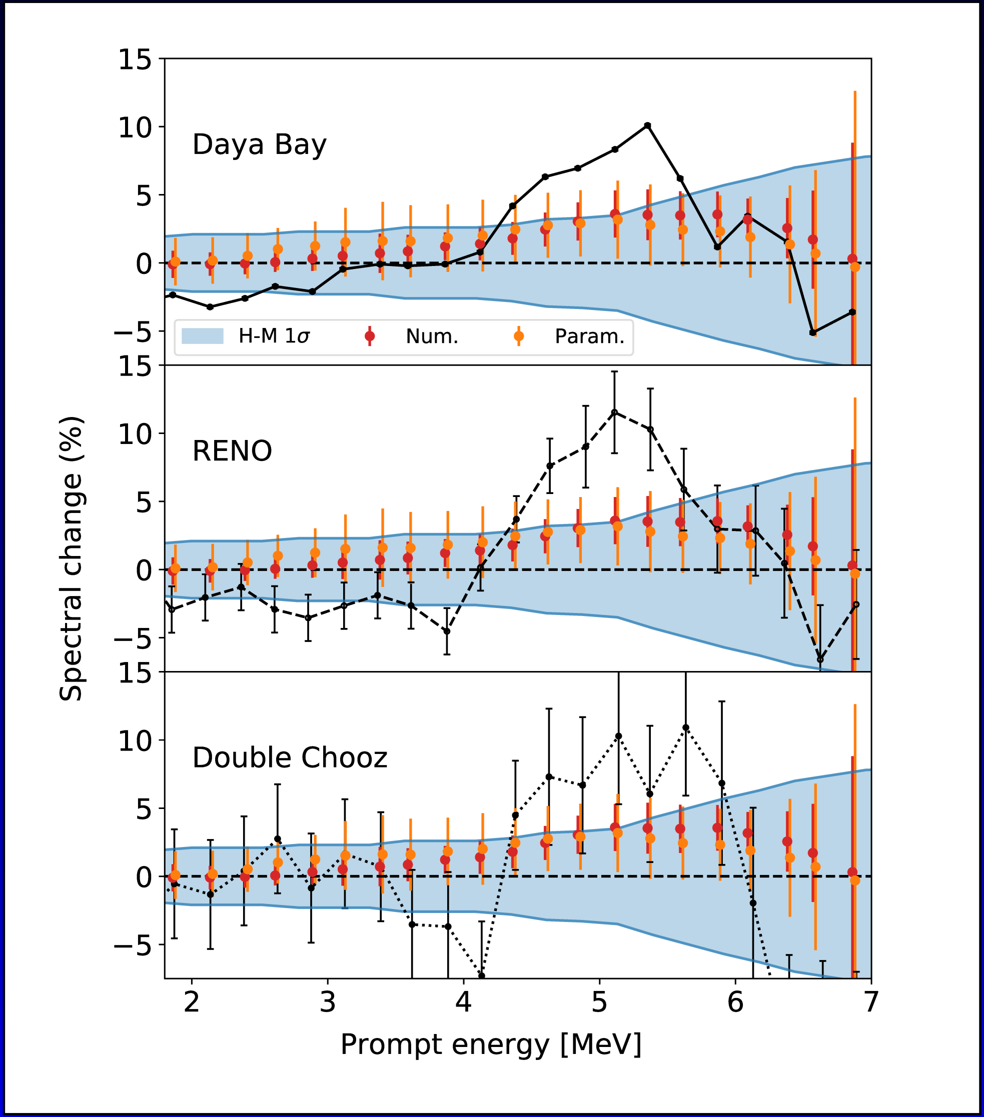
e,$\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

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

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

Significant nuclear structure dependence in forbidden decays→ **sizable uncertainties?**

Forbidden decays – shell model



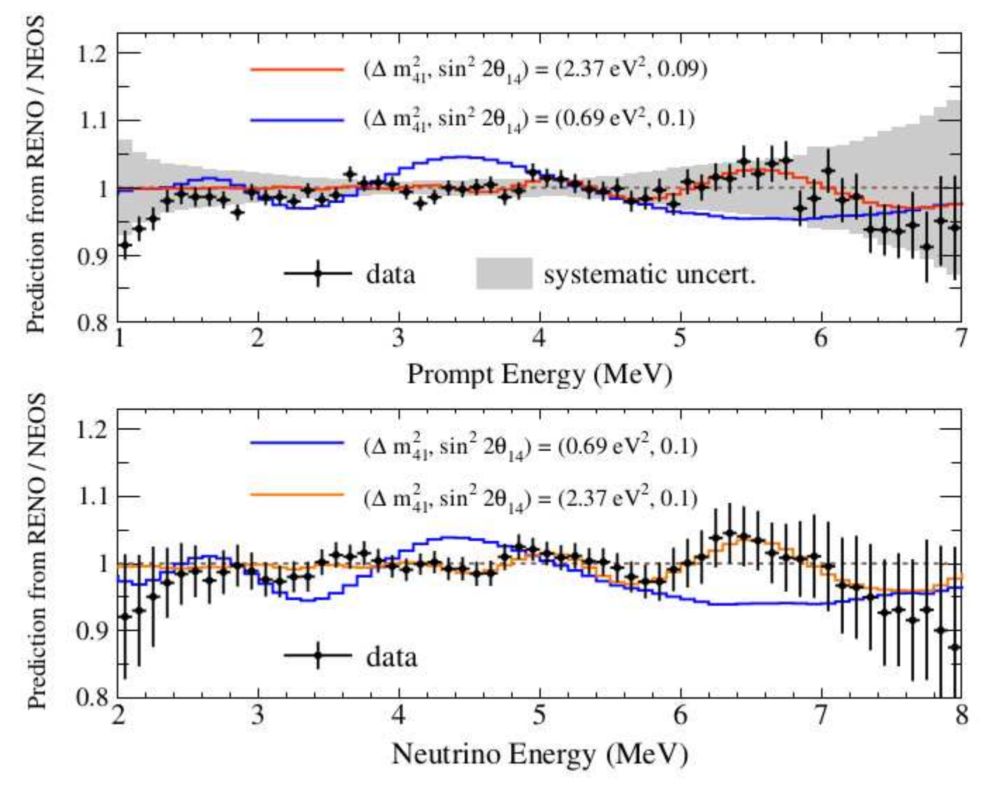
Hayen, *et al.* 2019

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

NEOS and sterile neutrinos



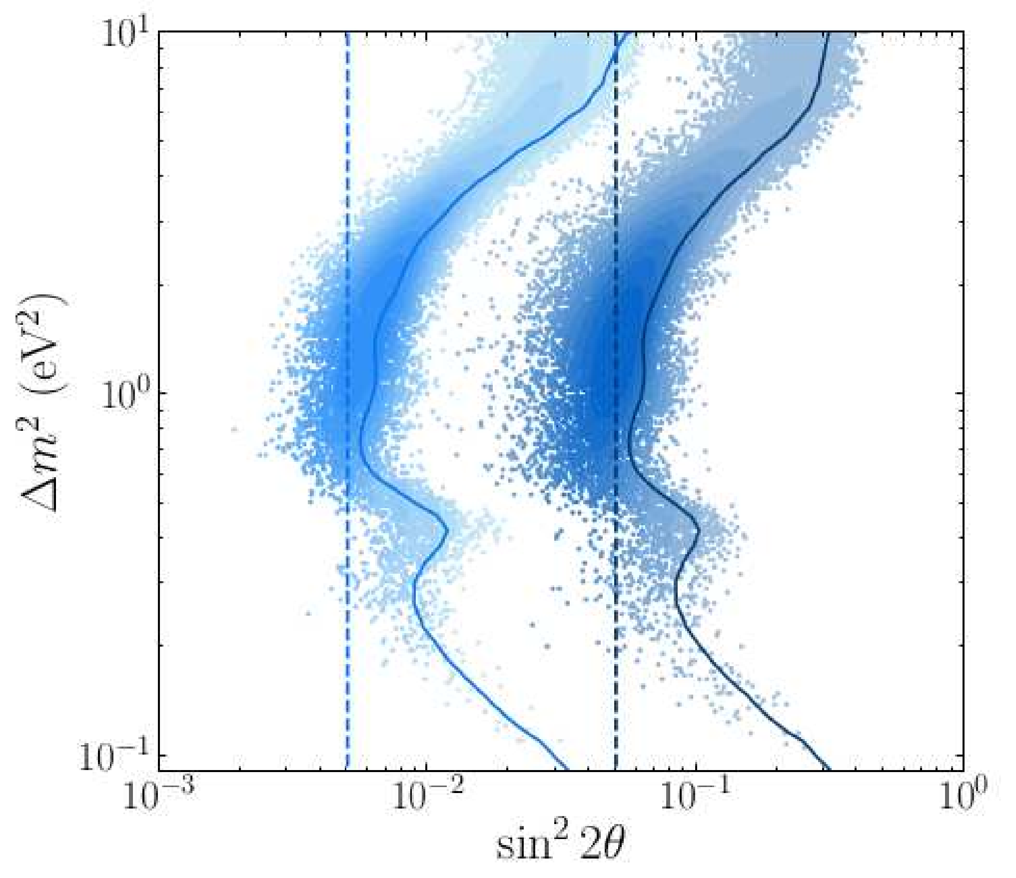
Ratio of observations, independent of reactor fluxes!

$\Delta\chi^2 = 11.6$ for oscillations, the p-value is however only 0.13.

2011.00896

This break down of Wilks' theorem has been observed by many authors: Agostini, Neumair, 2019; Silaeva, Sinev, 2020; Giunti, 2020] [PROSPECT+STEREO, 2020; Coloma, PH, Schwetz, 2020

Oscillations are everywhere



Hypothetical two baseline experiment

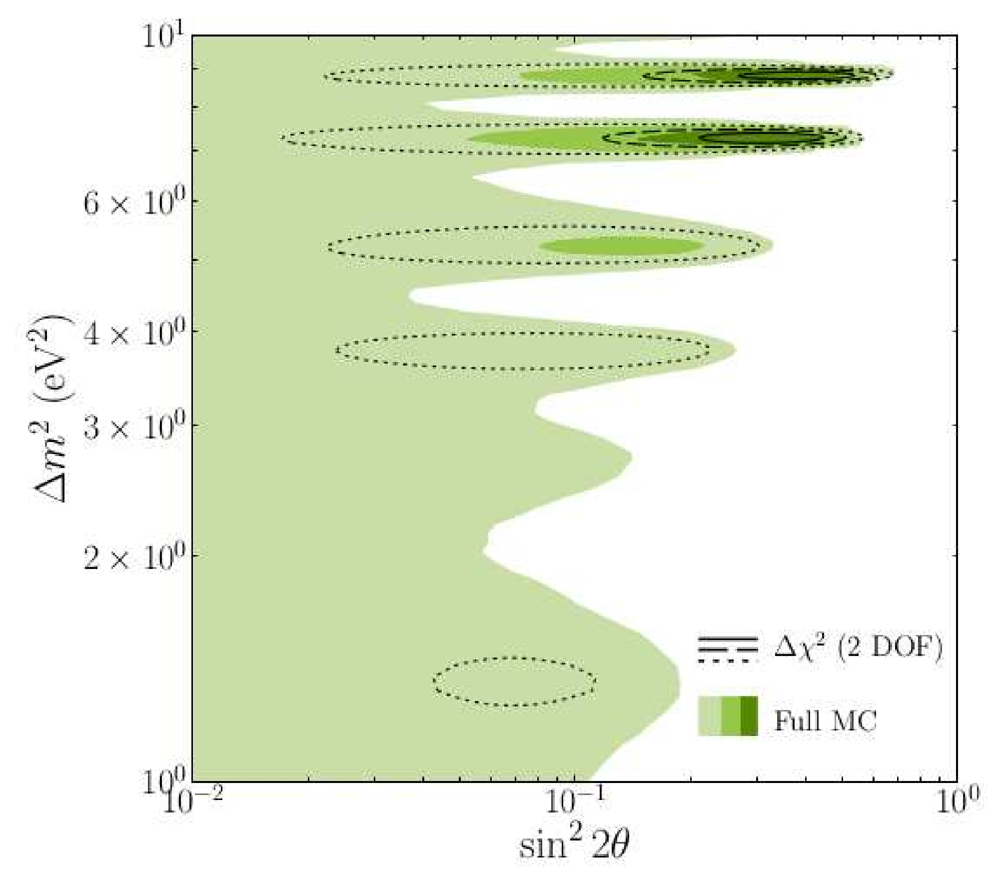
Maximum likelhood estimate is biased and not consistent.

Wilks' theorem does not apply

Coloma, PH, Schwetz, 2020

The reason is that some oscillation with some frequency always fits fluctuations better than no oscillation

Neutrino-4



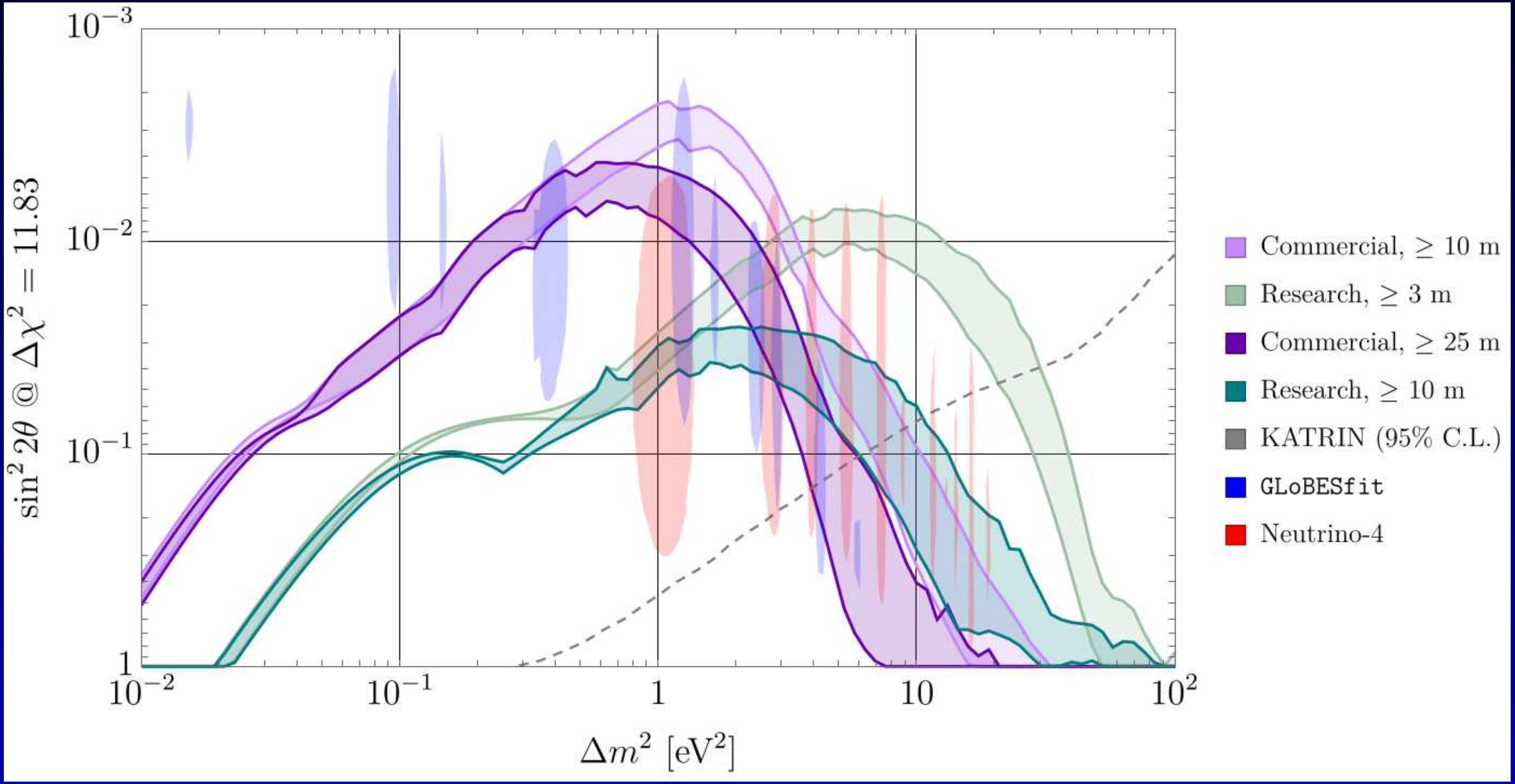
Significance goes from $3.2\,\sigma$ down to $2.6\,\sigma$

Here we assume that all systematics has been treated correctly.

Coloma, PH, Schwetz, 2020

Giunti, Li, Ternes, Zhang, 2021 following Danilov, Skrobova 2020 find that energy resolution modeling could reduce this to $2.2\,\sigma$ and would shift $\sin^2 2\theta \rightarrow 1$.

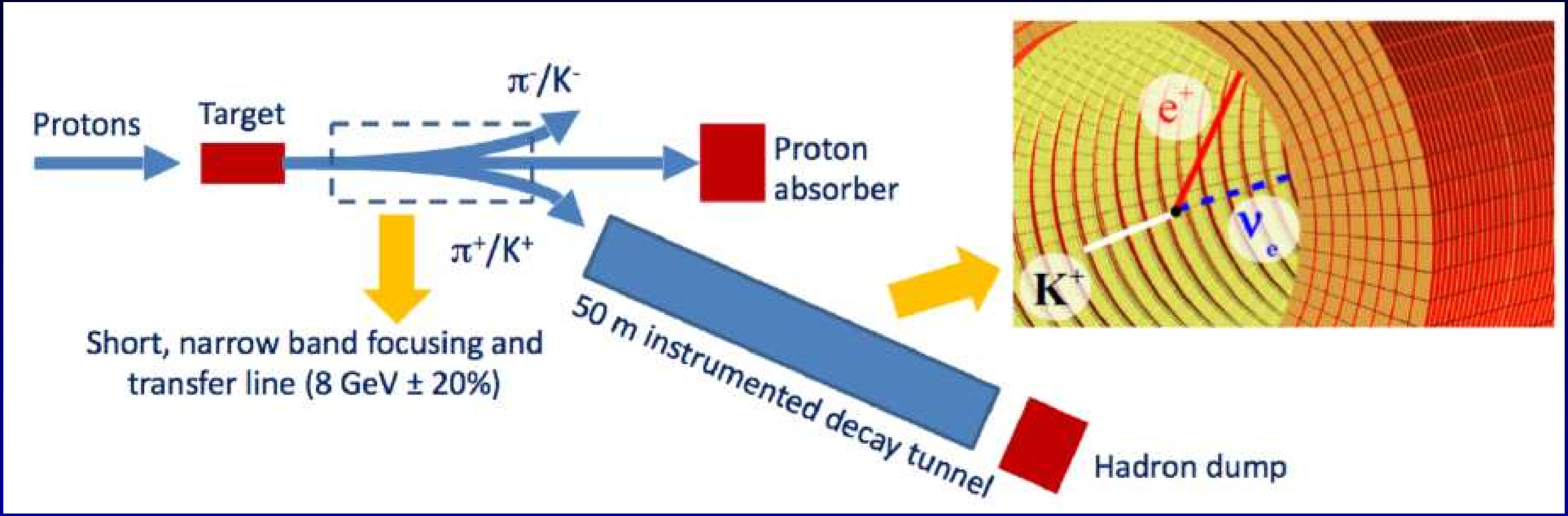
Resolving high Δm^2 oscillations



Berryman, Delgadillo, PH, 2021

- Green field study, optimized two-baseline setup, 5 tons, 1 year
- Key is to get very close

ENUBET – setup

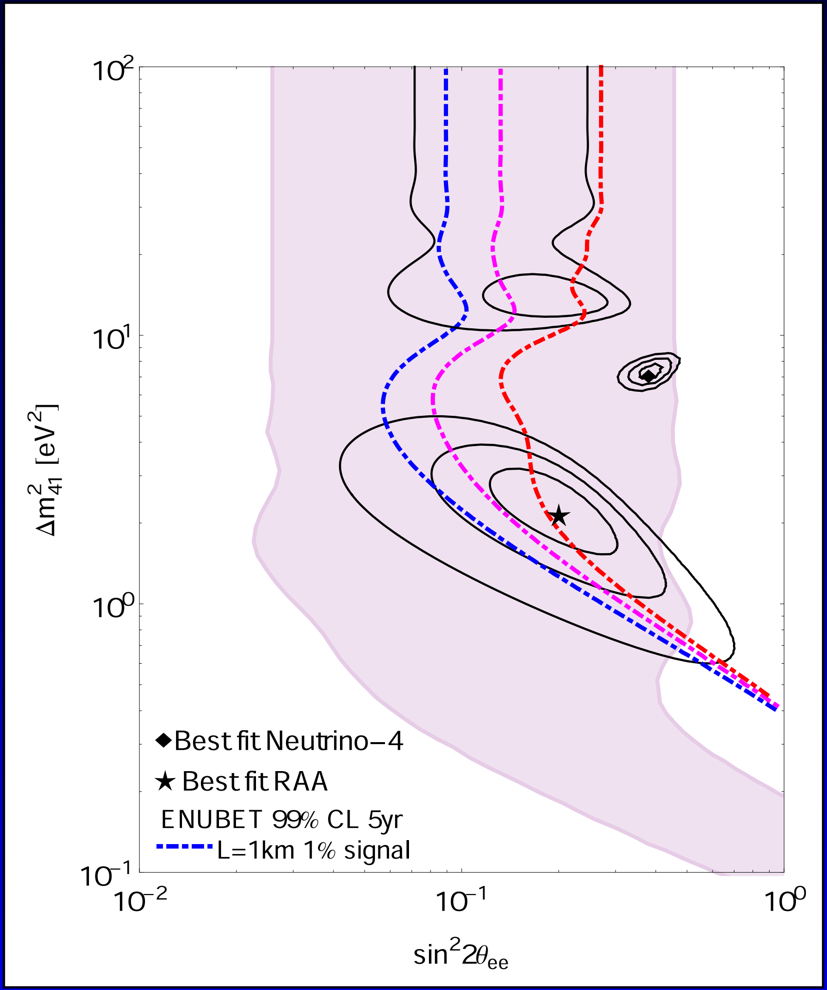


- provides a tagged ν_e beam
- provides an anti-tagged ν_μ beam (from pion decay mostly)
- precise normalization $\sim 1\%$

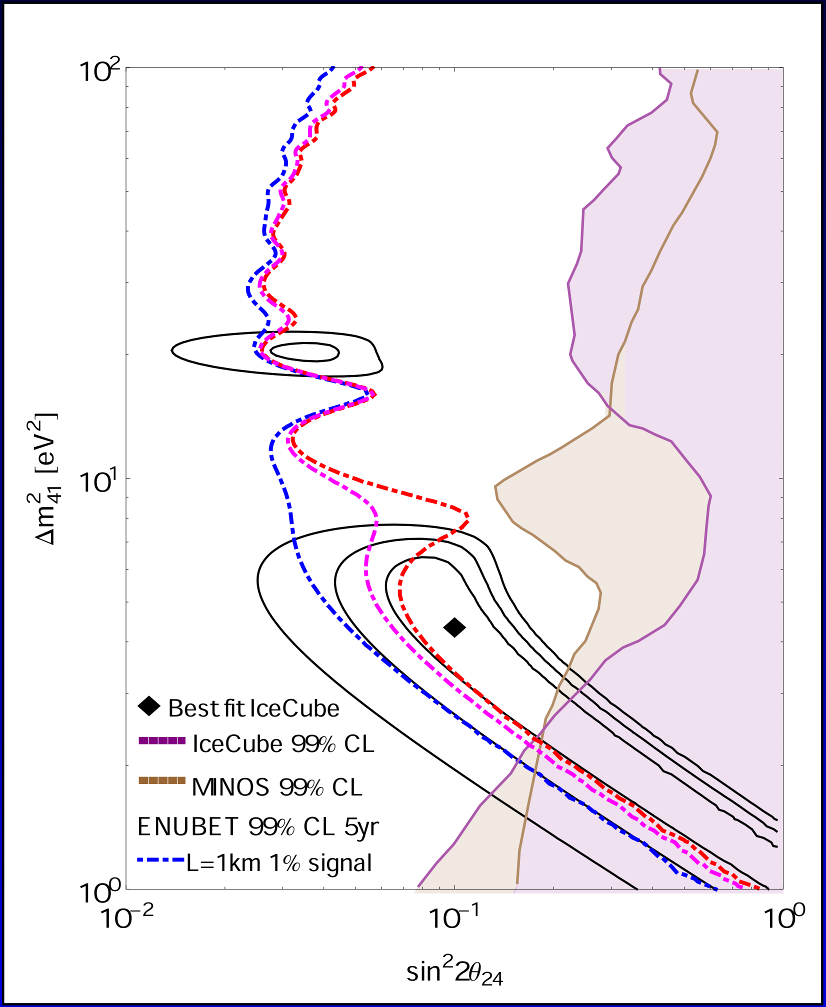
We propose a 1 kton LArTPC at a baseline of 1 km.

ENUBET – results

ν_e disappearance

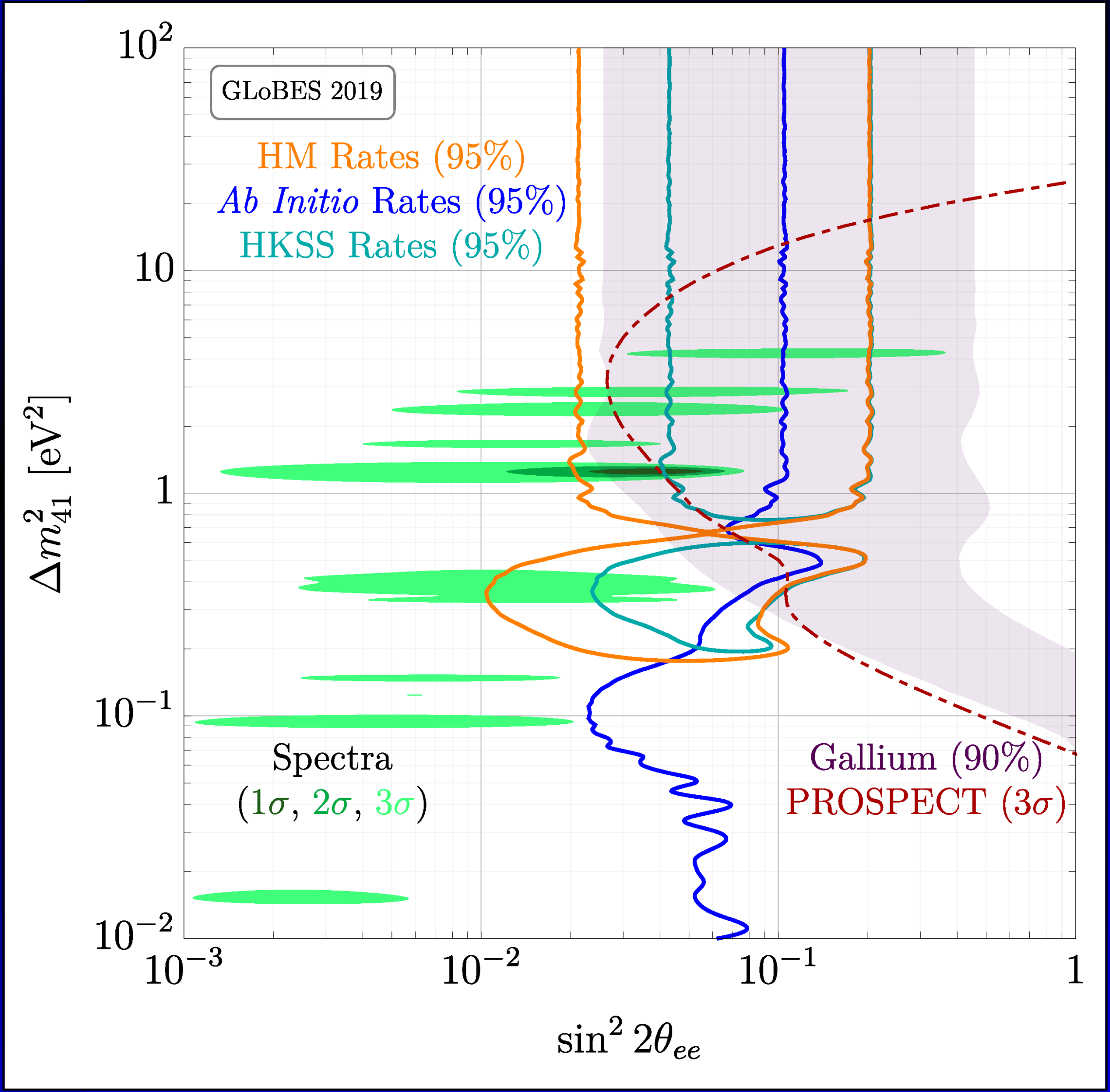


ν_μ disappearance



Delgadillo, PH, 2020

ν_e status 2019

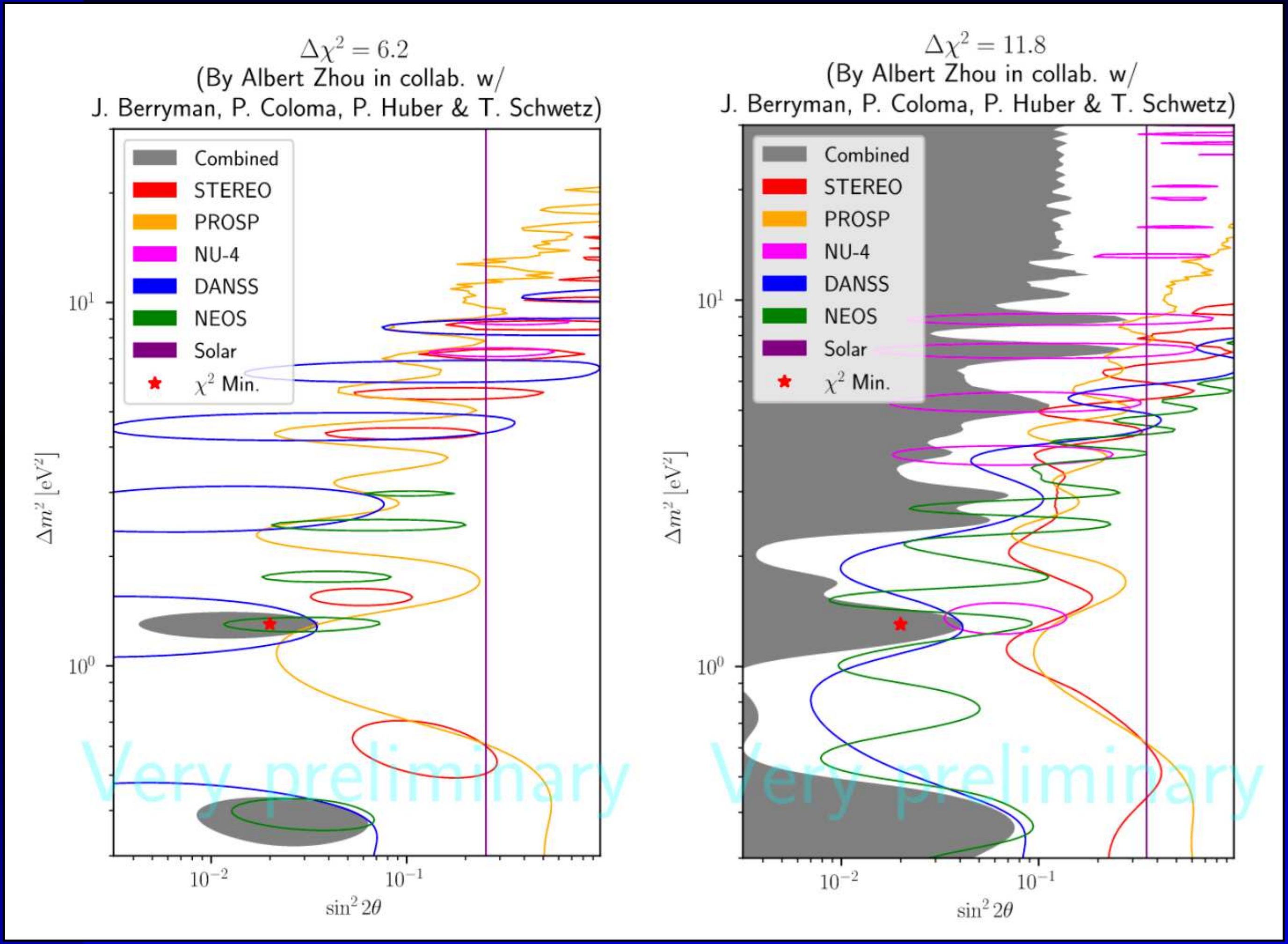


Berryman, PH, 2019

$\Delta\chi^2 = 13.8$ evidence for oscillation, flux model-independent, driven by NEOS and DANSS

Consistent with Gallium anomaly.

ν_{e} status 2021



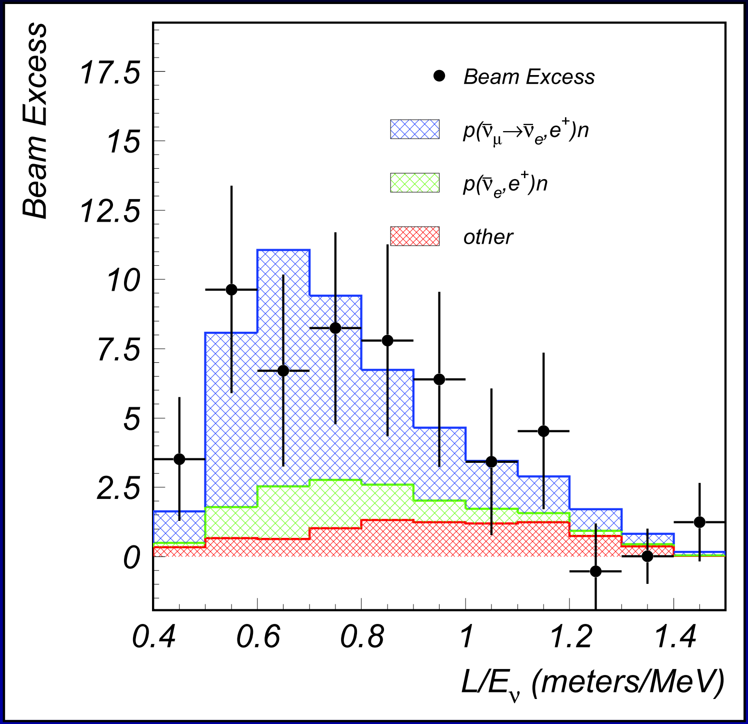
$$\Delta\chi^2 = 9.9$$

Neutrino-4 not inconsistent

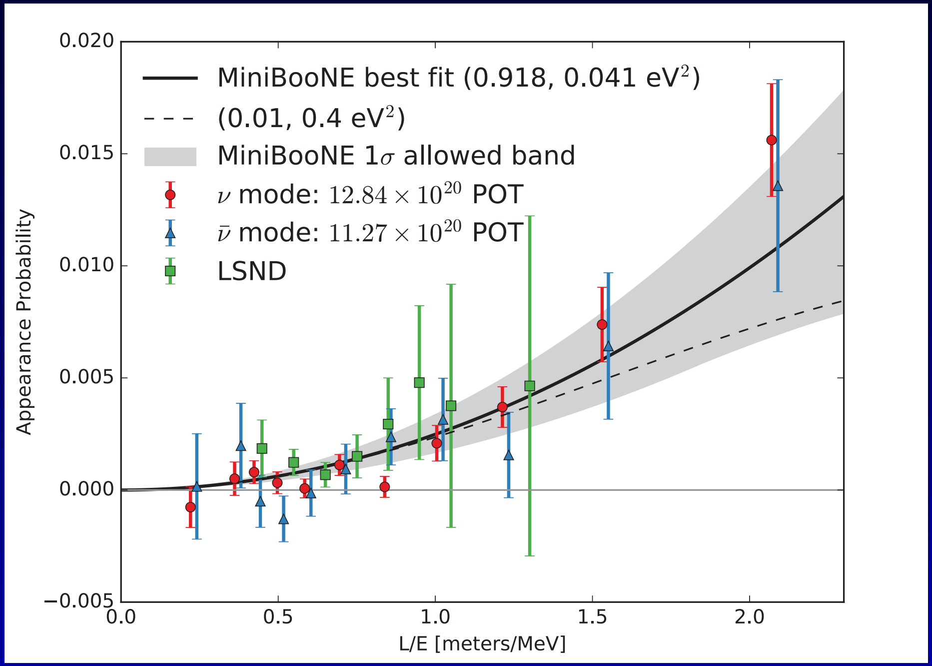
Still consistent with Gallium anomaly

But overall significance?

LSND & MiniBooNE



LSND 1995

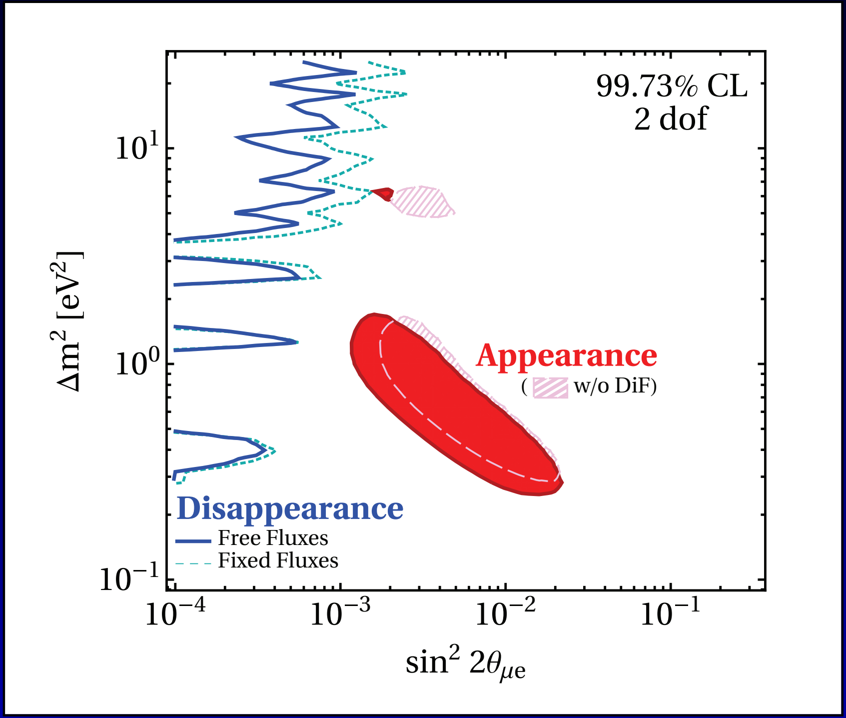


MiniBooNE 2018

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq 0.003$$

$\nu_\mu \rightarrow \nu_e$ requires that the sterile neutrino mixes with both ν_e and ν_μ, so there must be an effect in ν_μ disappearance.

Disappearance data



Dentler, *et al.*, 2018

$$\sin^2 2\theta_{e\mu} = 4|U_{e4}U_{\mu4}|^2$$

with $1 - P_{ee} \propto |U_{e4}|^2$
and $1 - P_{\mu\mu} \propto |U_{\mu4}|^2$

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

Decaying sterile neutrinos?

e.g., 1910.13456, 1911.01427, 1911.01447

Finding a sterile neutrino

All pieces of evidence have in common that they are less than 5 σ effects:

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

Reactor rate and spectrum anomalies likely are due to nuclear physics, but this does not impact reactor sterile results much $\Rightarrow$ need to understand integral beta spectrum measurements.