Reactor Neutrinos

Patrick Huber

Center for Neutrino Physics at Virginia Tech

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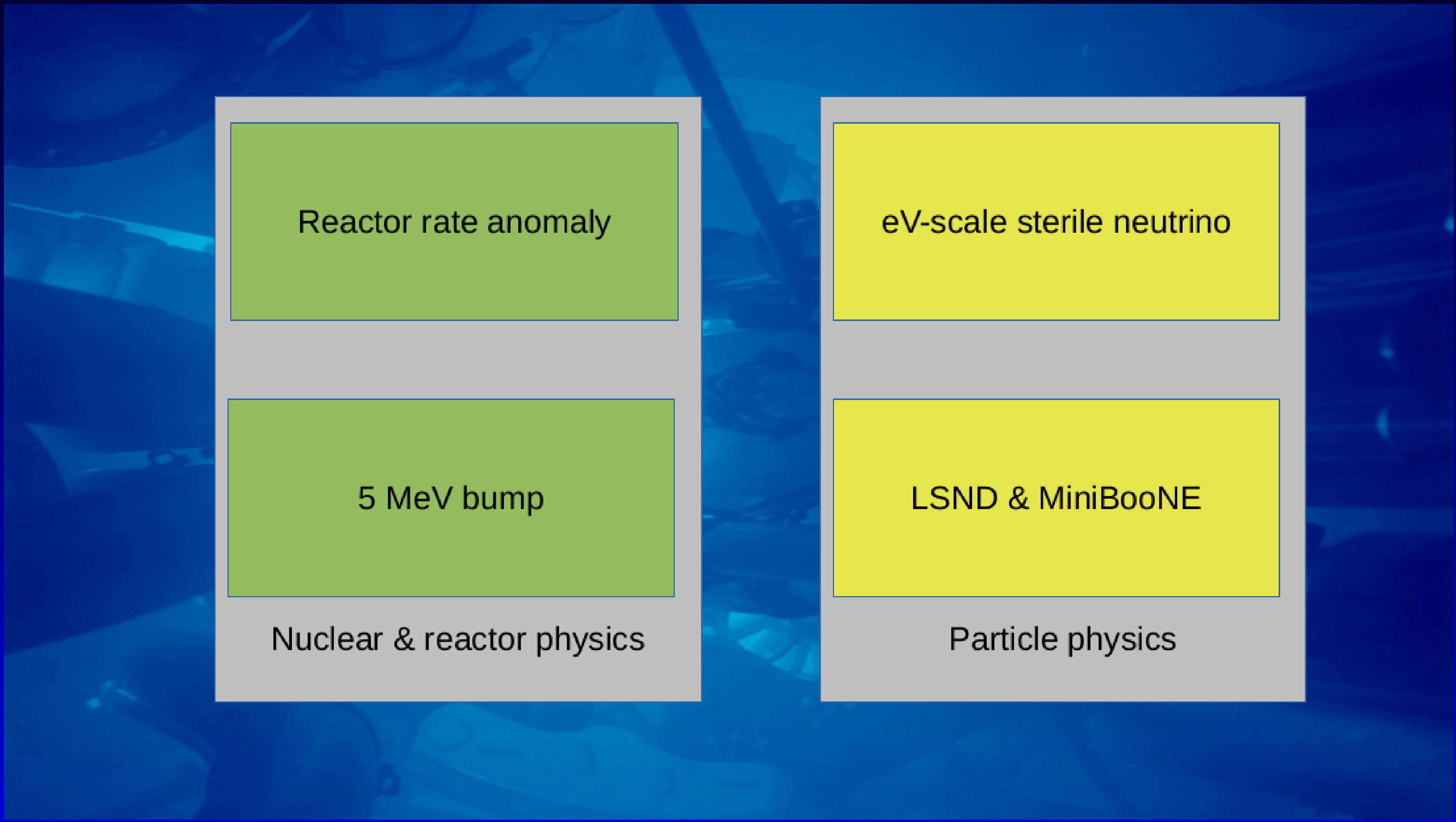
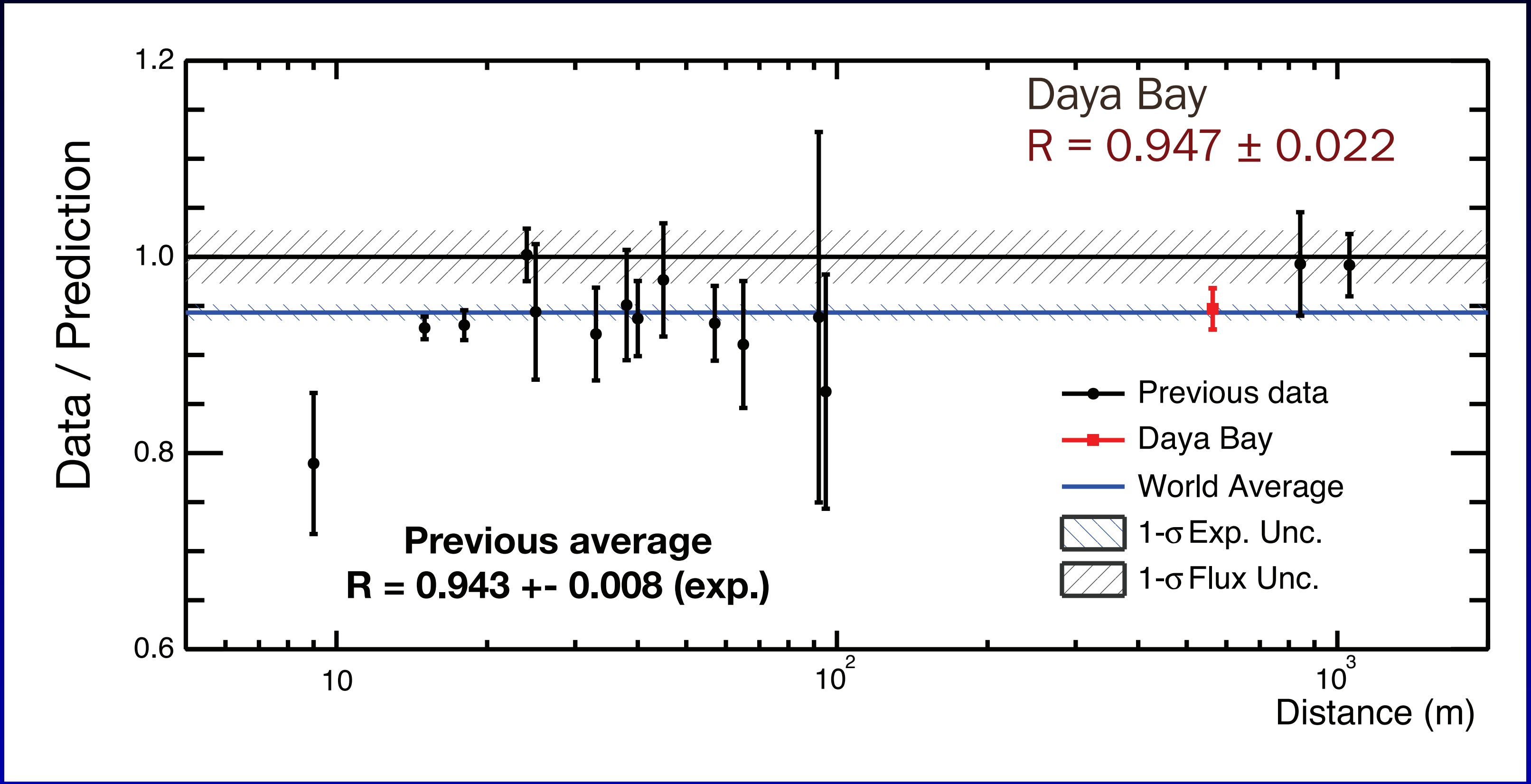


These four topics are related but distinct!

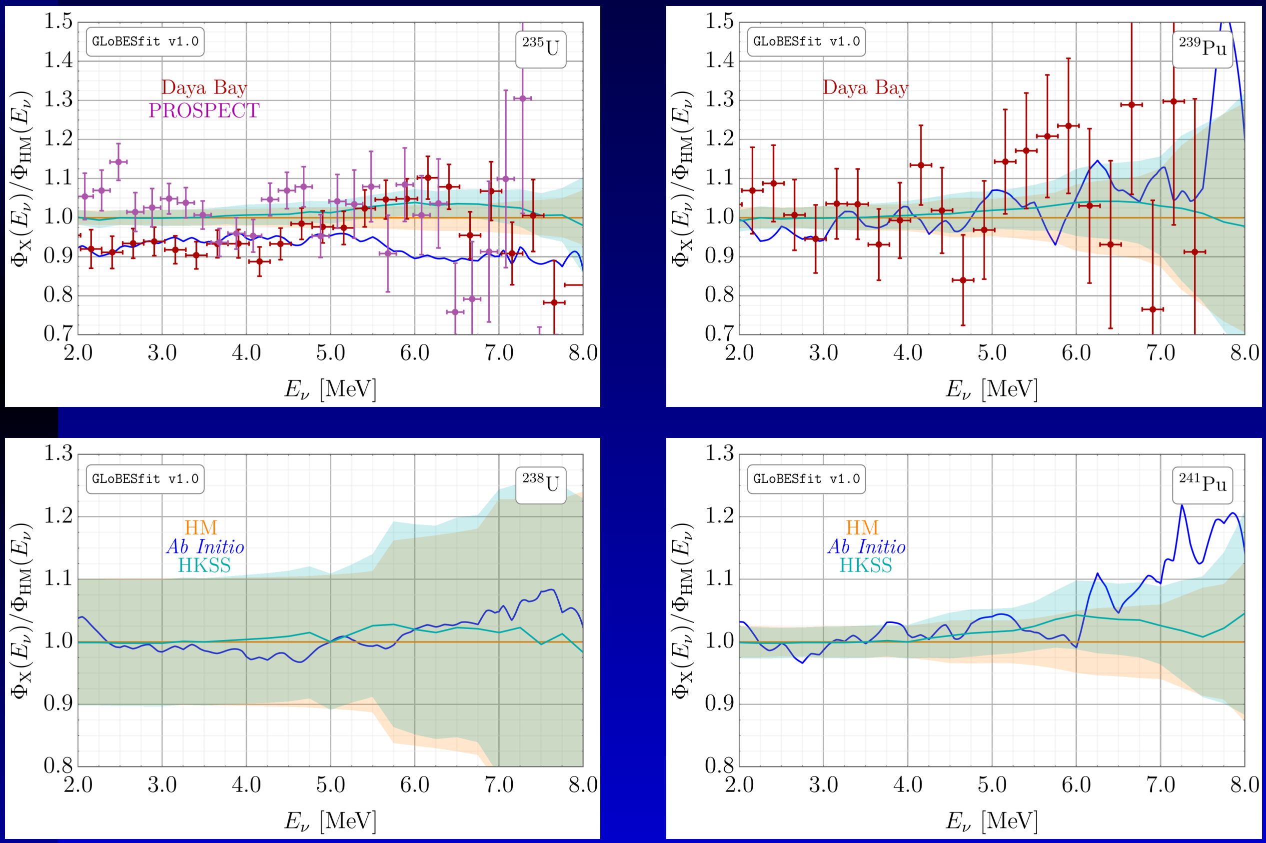
The reactor anomaly



Daya Bay, 2014

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

Where we are



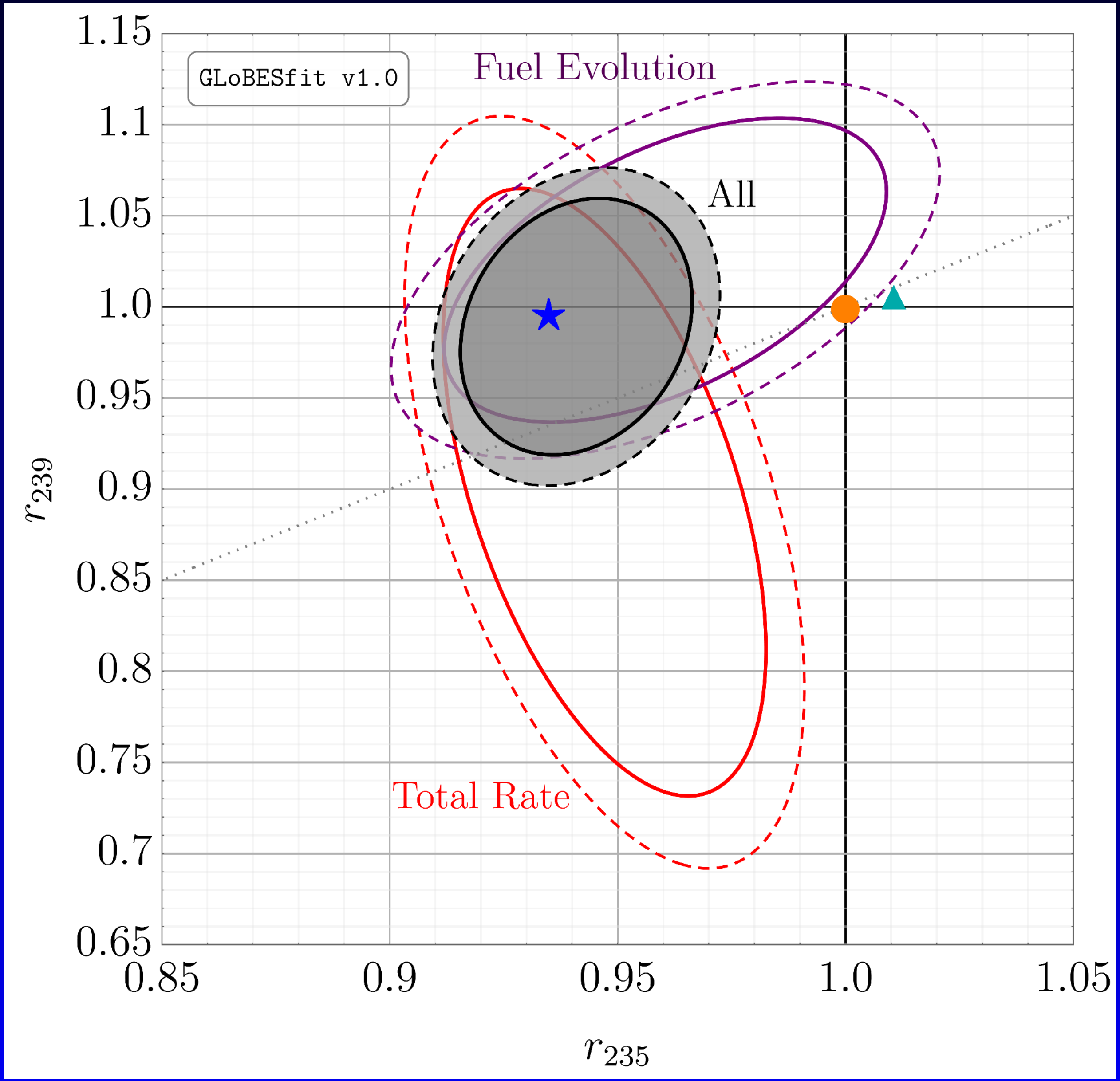
3 different flux models, data from 2 different experiments

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

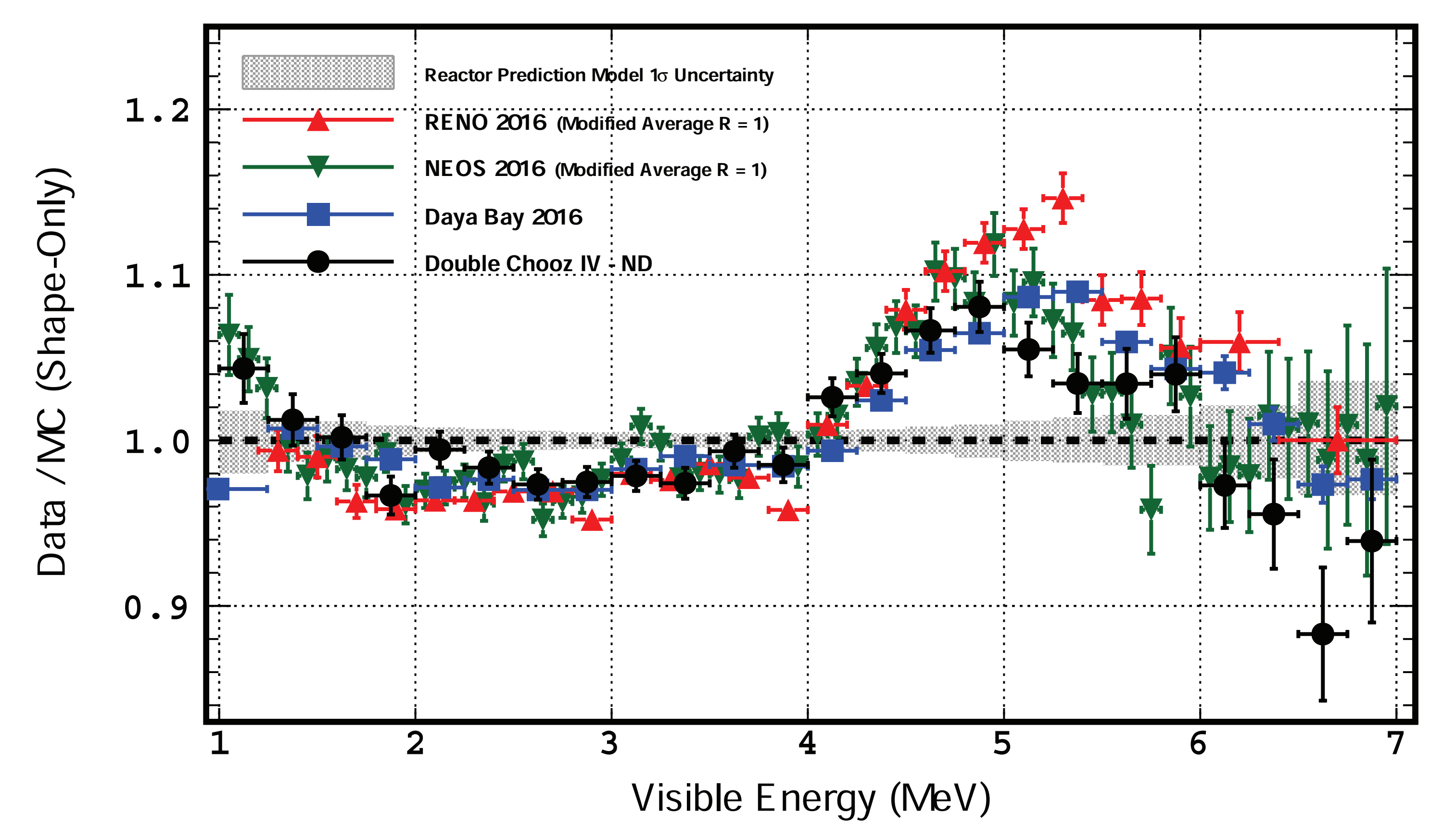
Fuel evolution



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

Berryman, PH, 2020

The 5 MeV bump

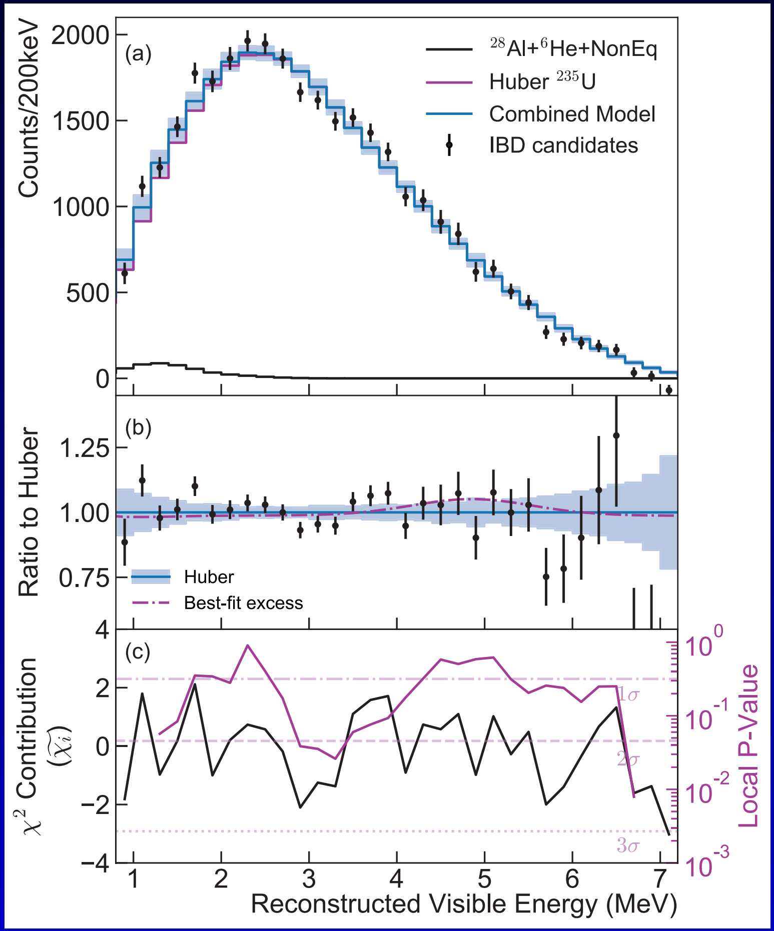


Double Chooz 2019

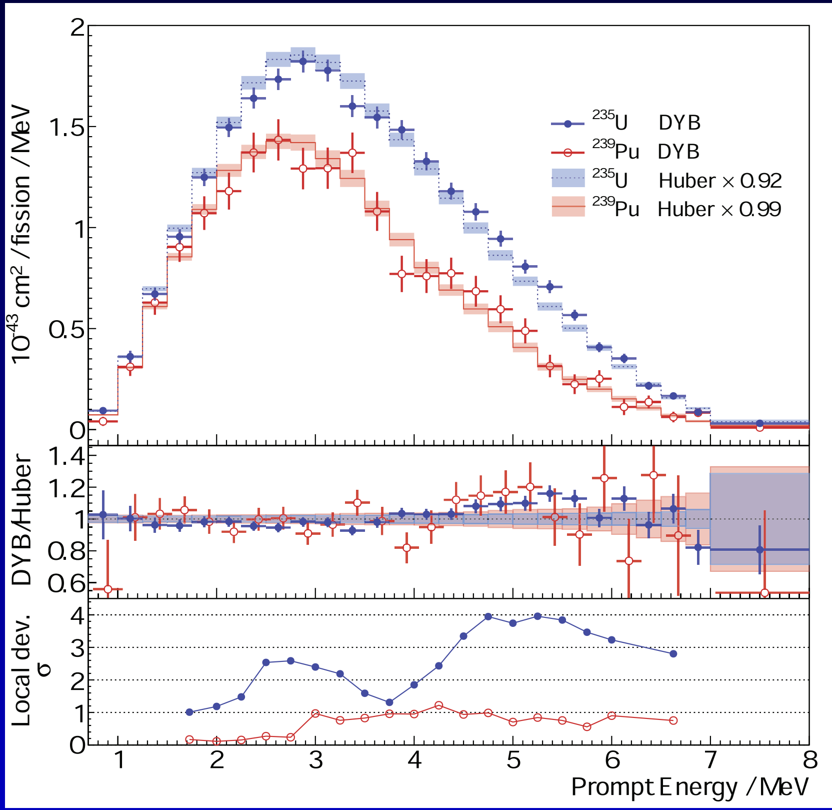
Contains only 0.5% of all neutrino events – not important for sterile neutrinos

Yet, statistically more significant than the RAA!

Latest data vs bump

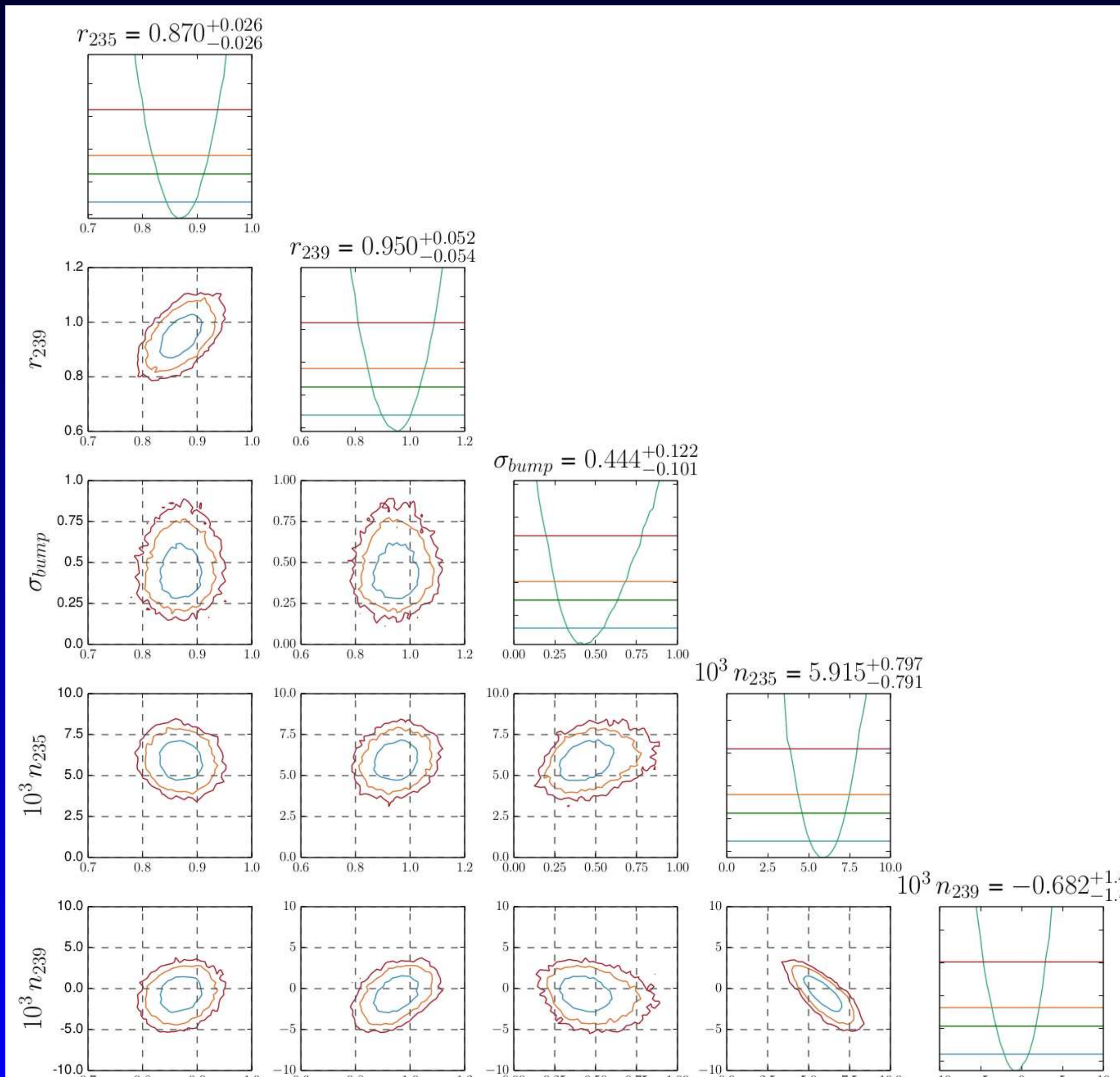


PROSPECT 2018
Disfavors ^{235}U as sole culprit at 2.1 σ



Daya Bay 2019, 2021
Requires a bump in ^{235}U at 4 σ

Bumpology

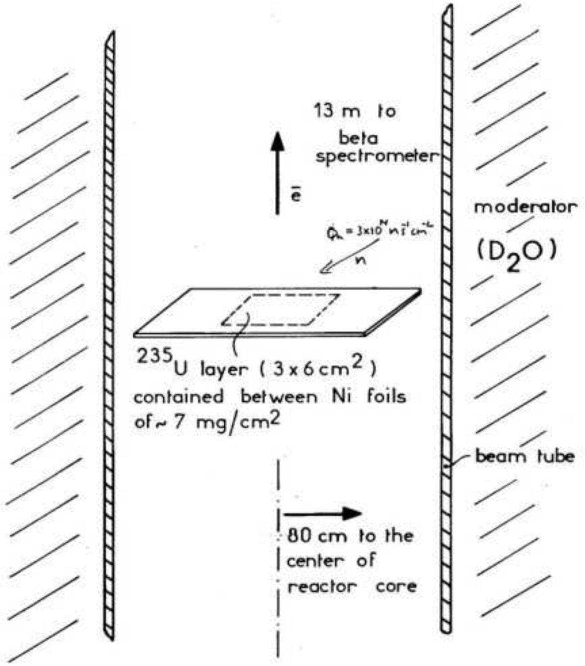


Daya Bay, RENO and PROSPECT as of 2019

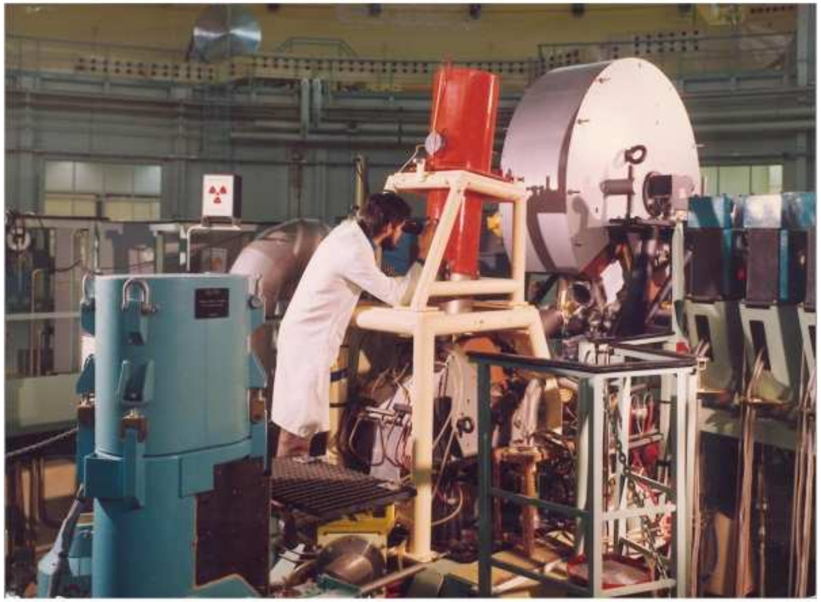
Only $n_{235} \neq 0$ with any significance

Berryman, PH, 2020

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

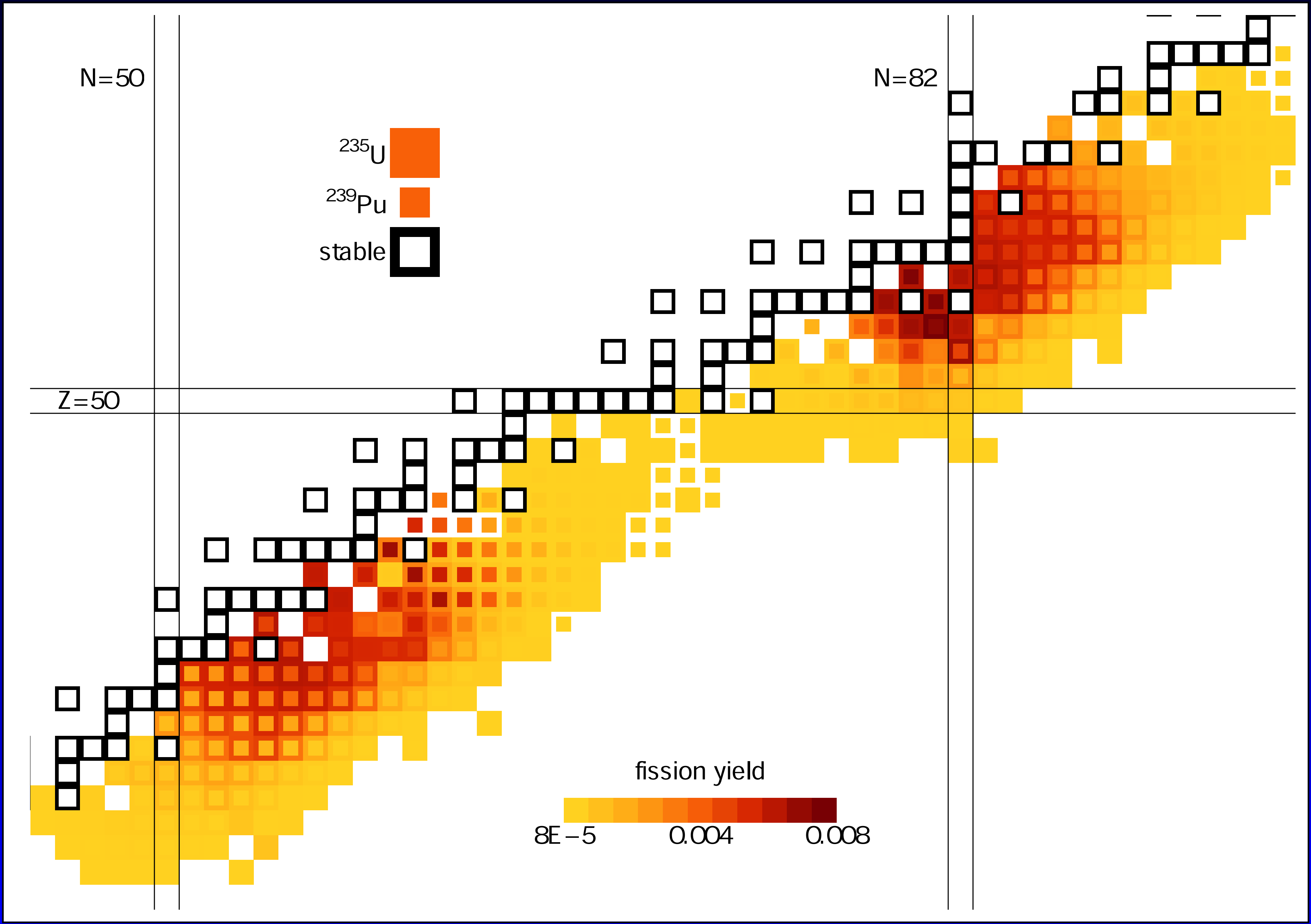
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

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

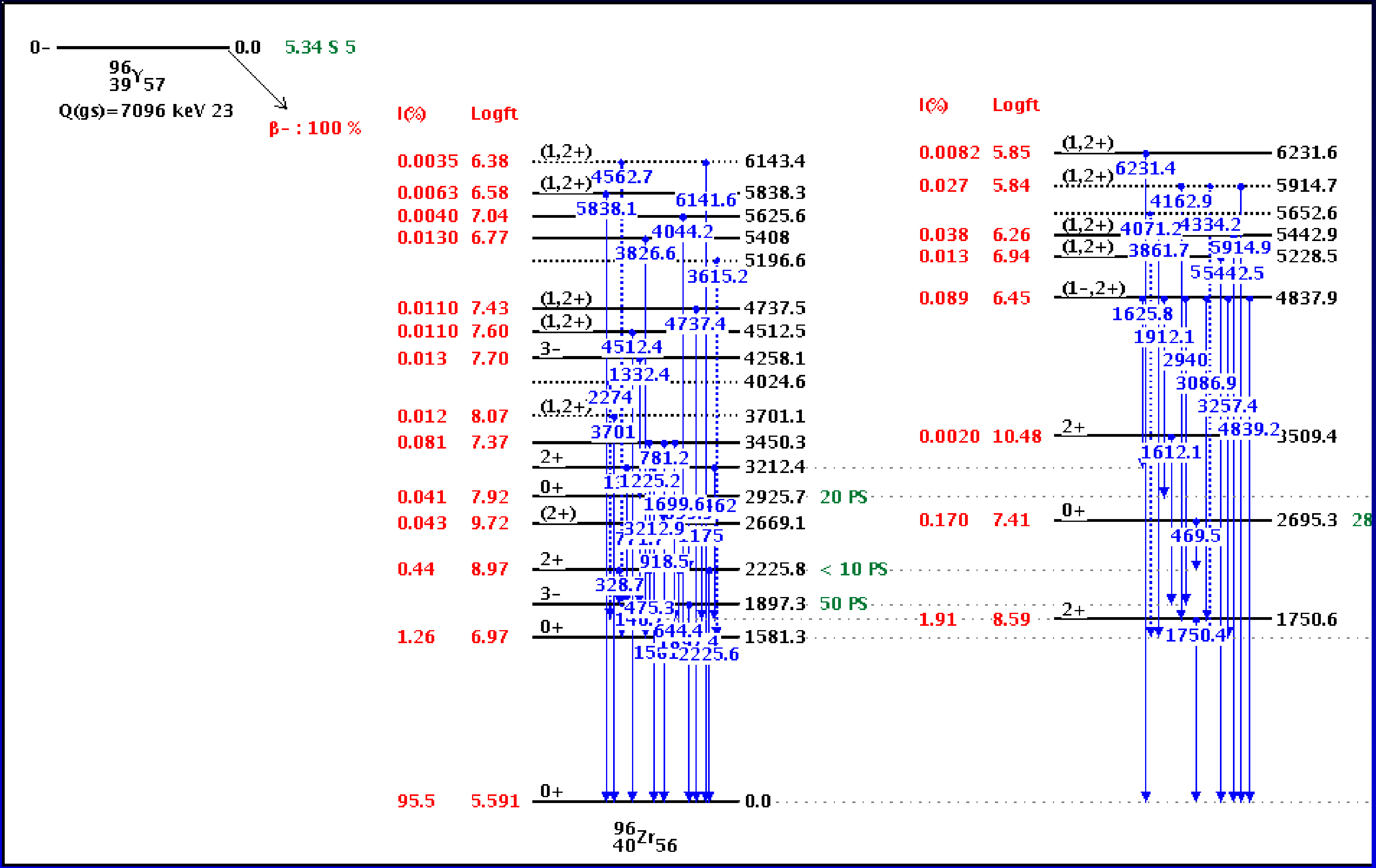
Combined with potential differences in neutron spectrum – room for a 5% shift of U235 normalization?

A. Letourneau, A. Onillon, AAP 2018

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

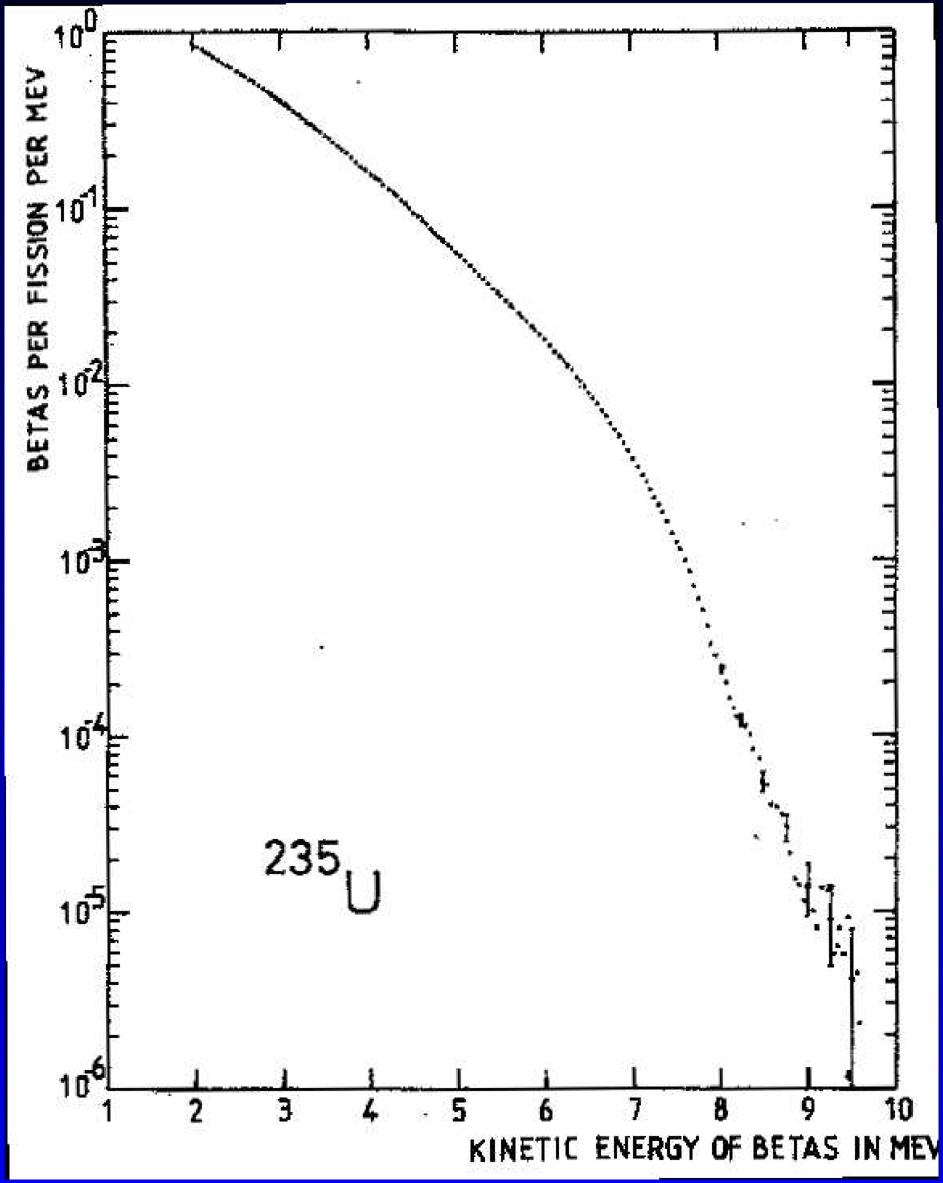
Conversion calculations

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.

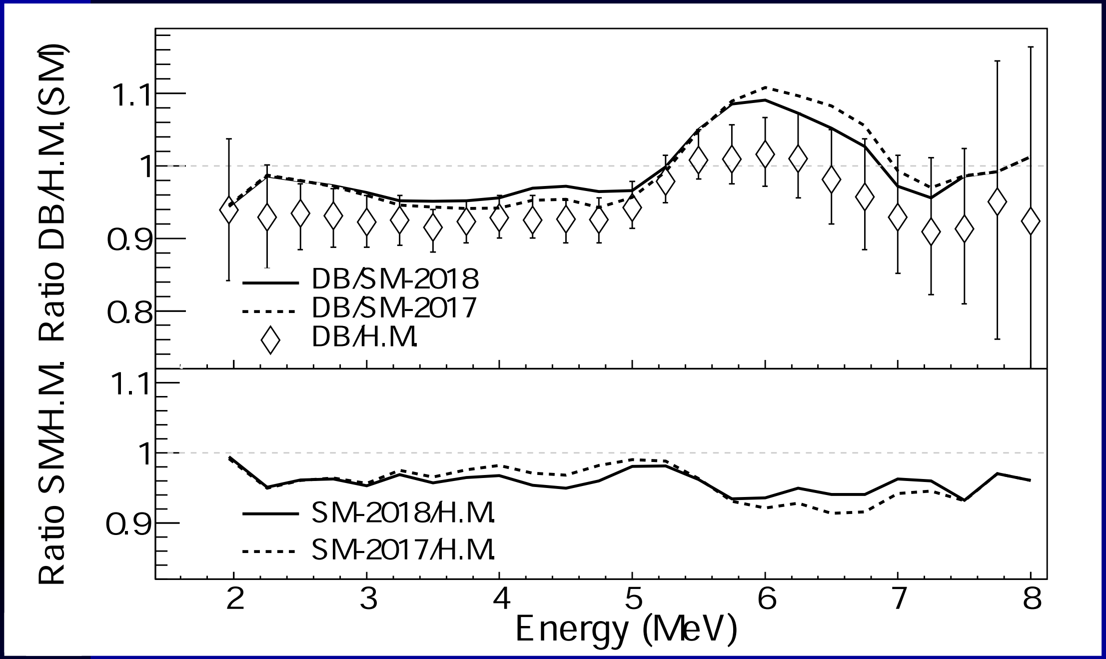
^{235}U foil inside the High Flux Reactor at ILL

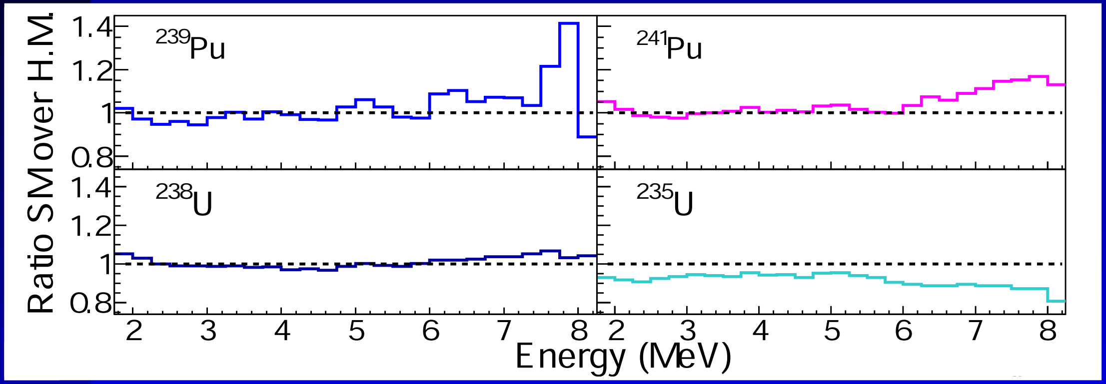
Electron spectroscopy with a magnetic spectrometer

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

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

Summation method





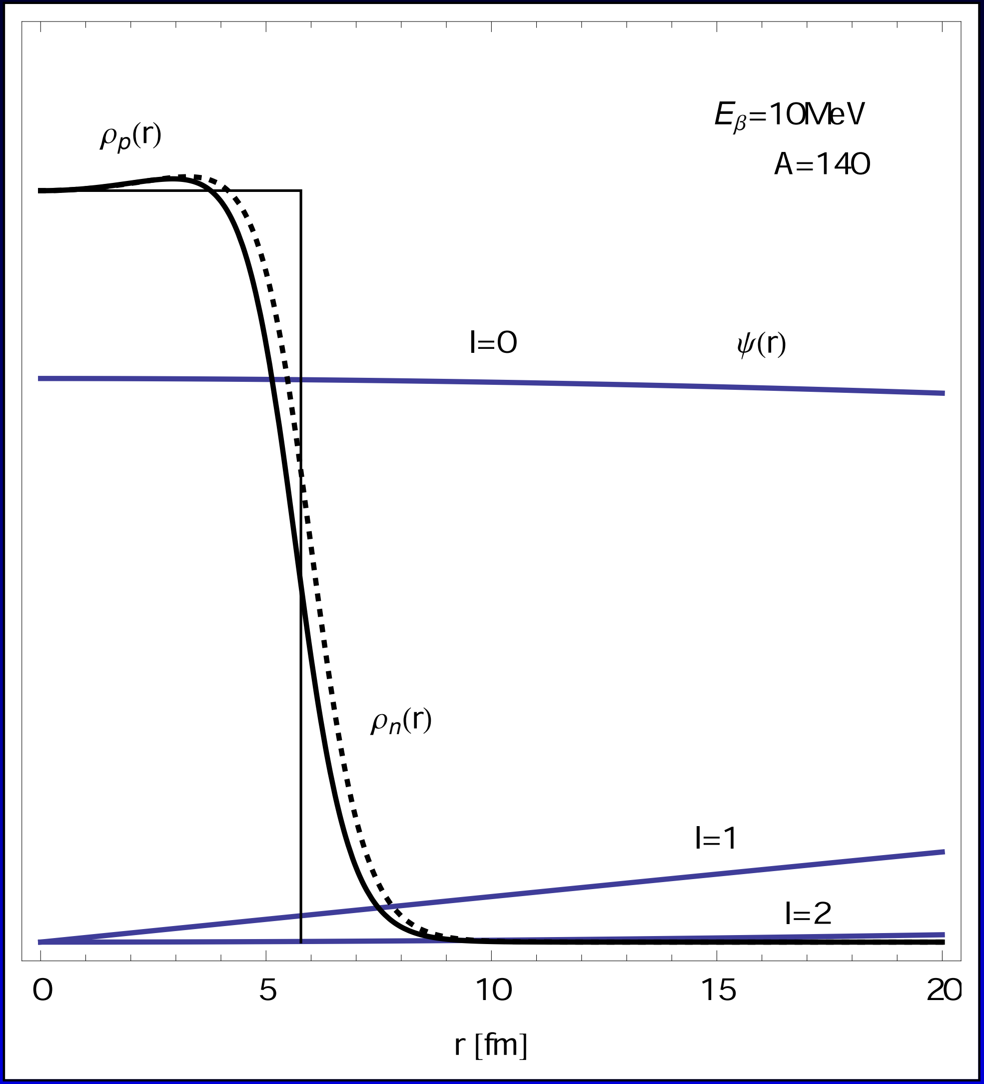
Estienne *et al.*, 2019

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



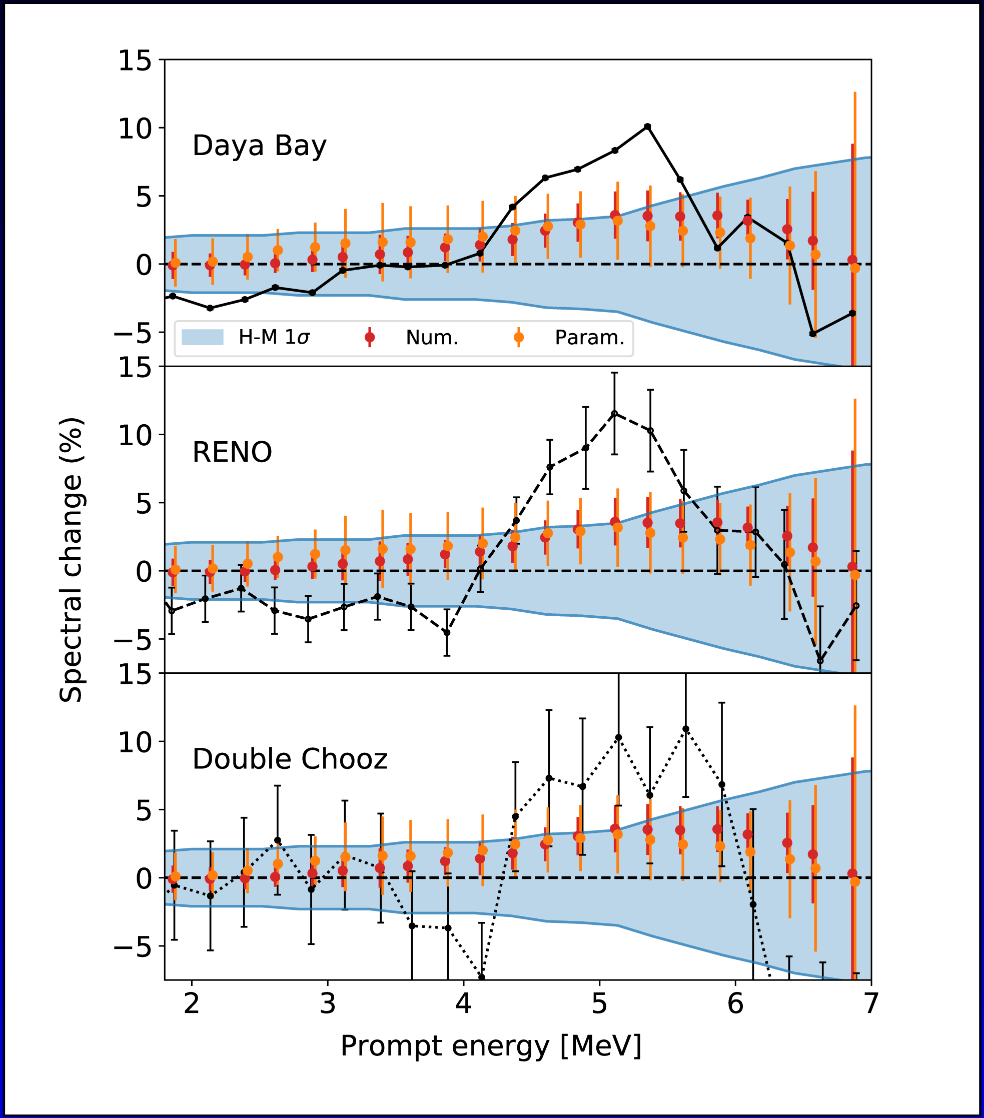
$e,\bar{\nu}$ final state can form a singlet or triplet spin state J=0 or J=1

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

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

Significant nuclear structure dependence in forbidden decays$\rightarrow$ **sizable uncertainties?**

Forbidden decays – shell model



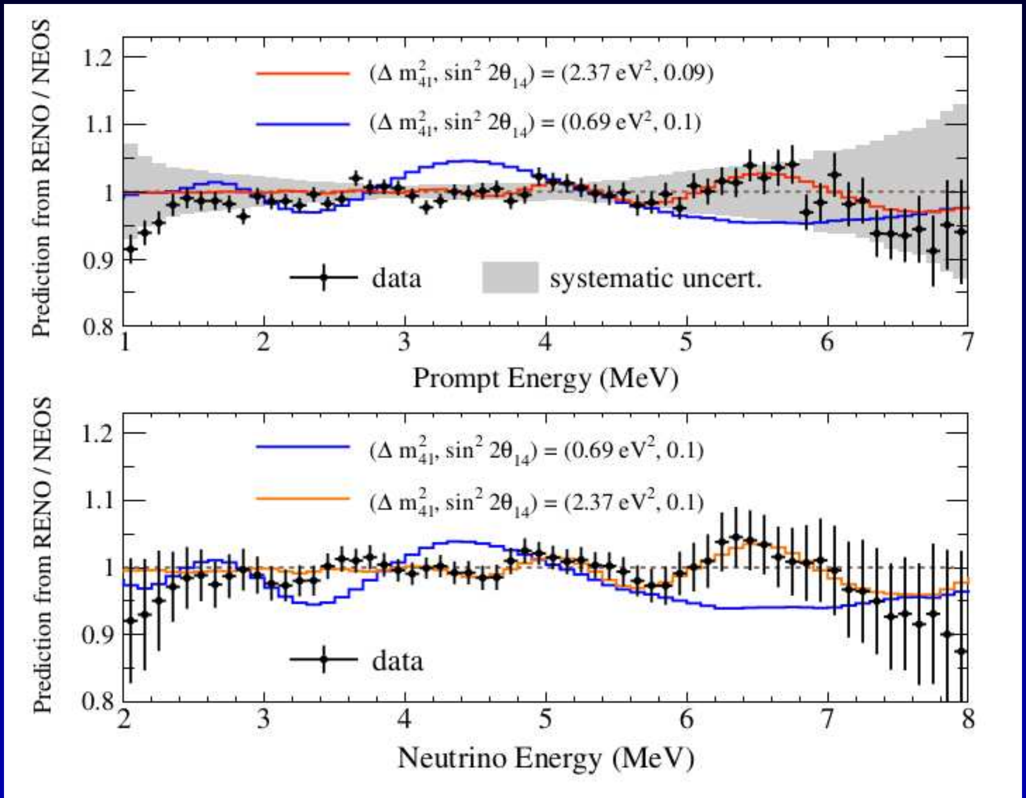
Hayen, *et al.* 2019

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



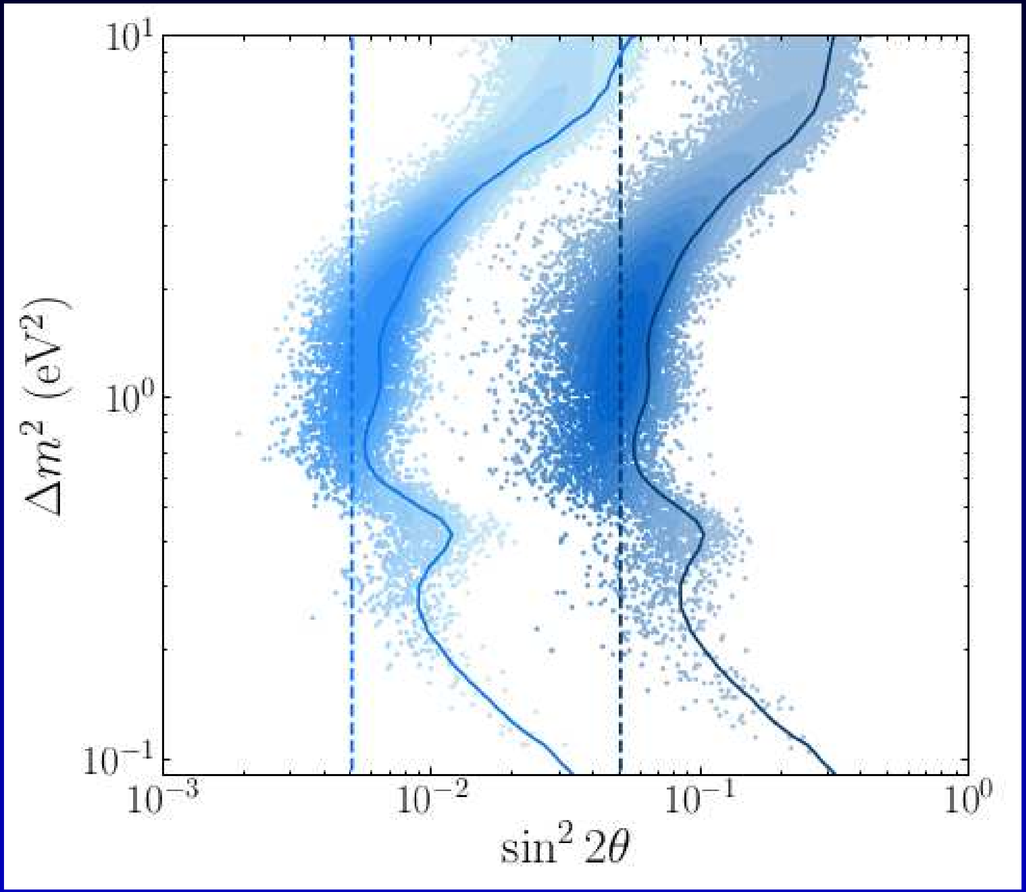
Ratio of observations, independent of reactor fluxes!

$\Delta\chi^2 = 11.6$ 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

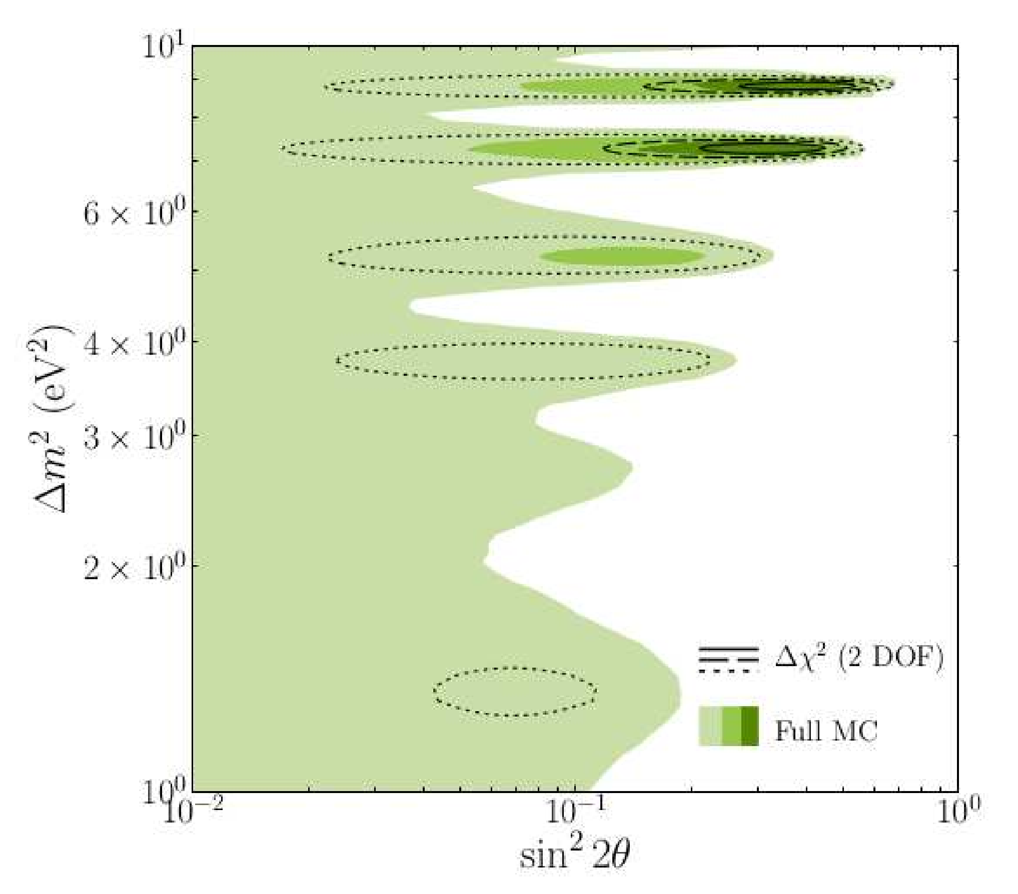
Maximum likelihood estimate is biased and not consistent.

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



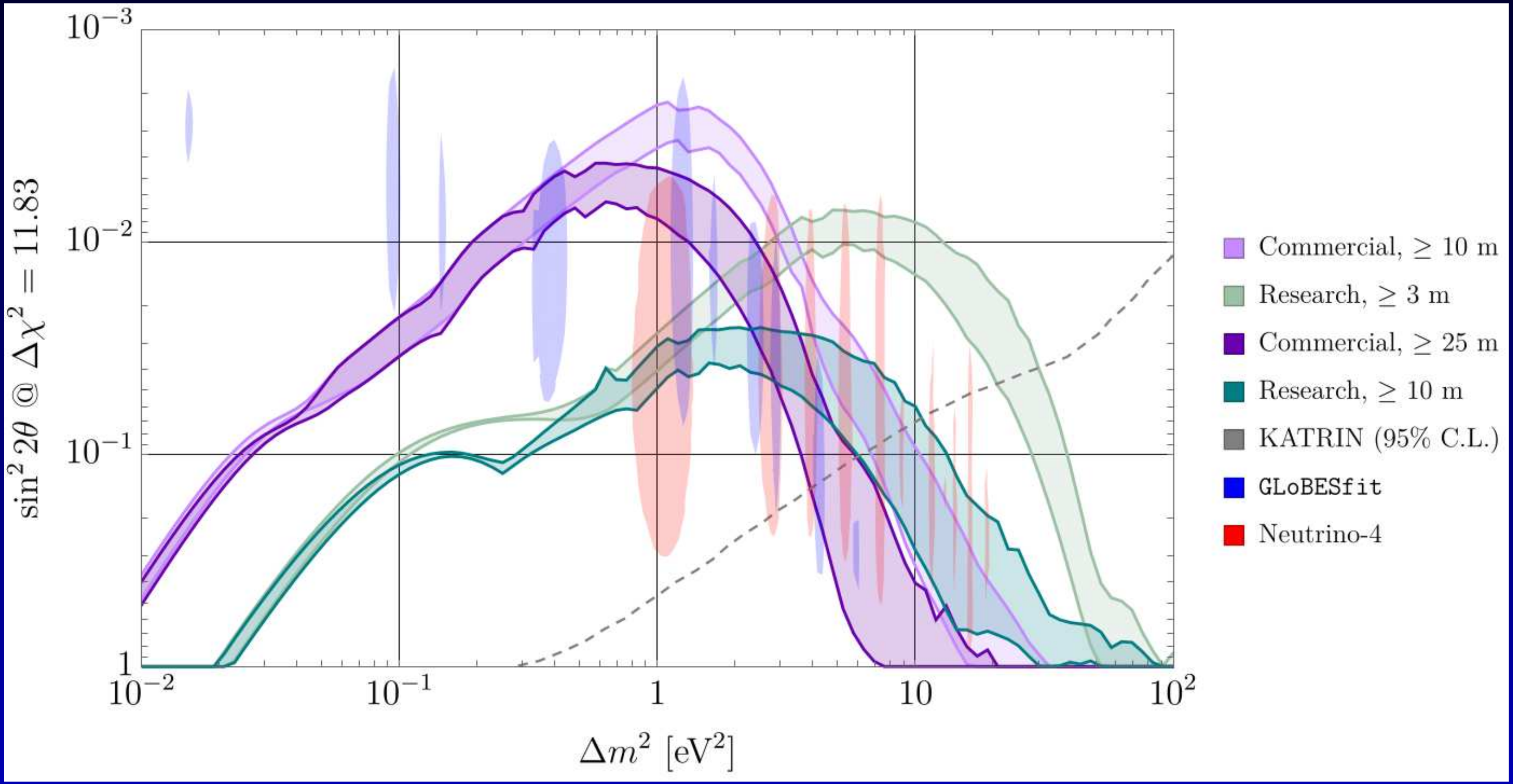
Significance goes from $3.2\,\sigma$ down to $2.6\,\sigma$

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 $\sin^2 2\theta \to 1$.

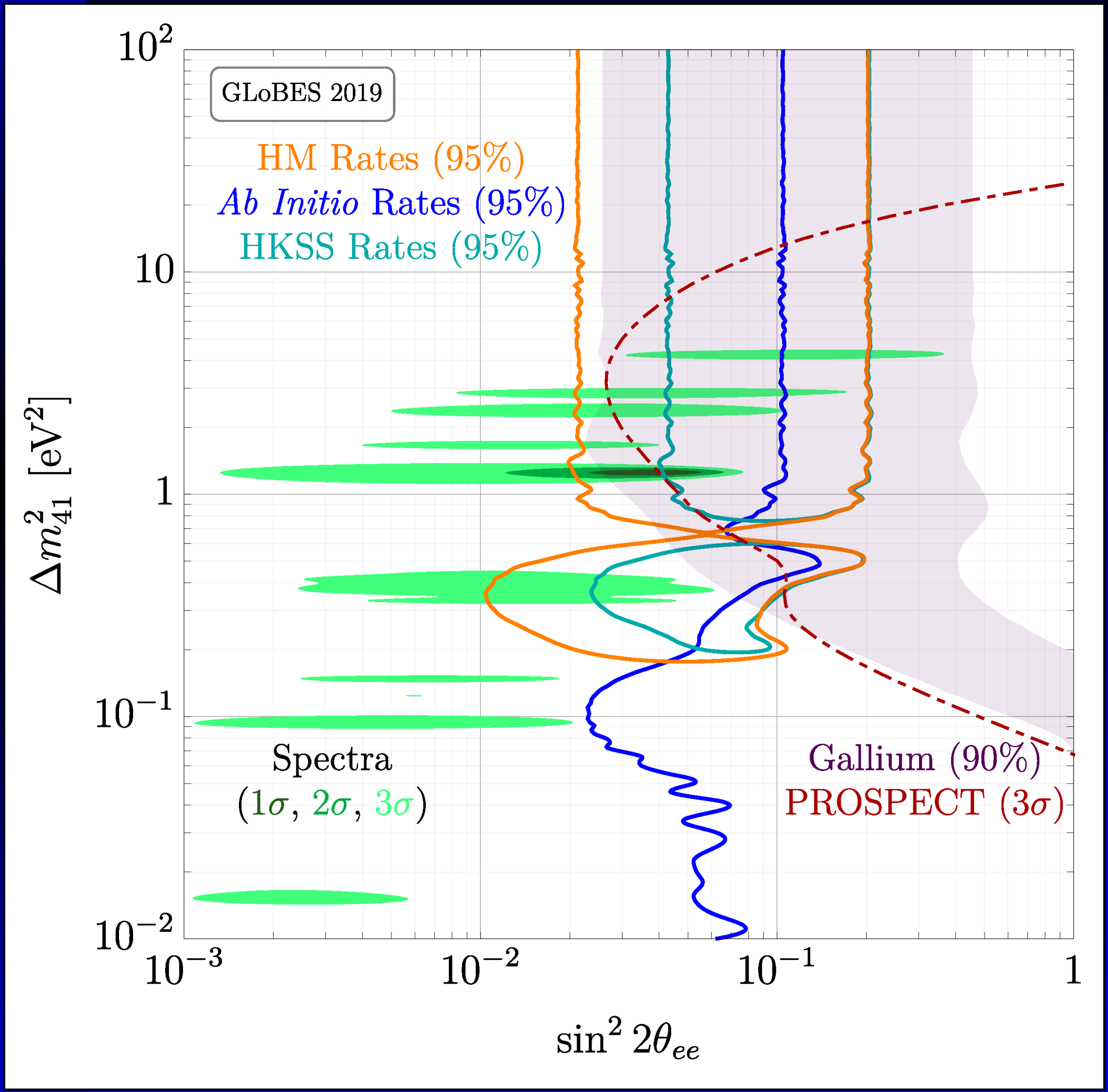
Resolving high Δm^2 oscillations



Berryman, Delgadillo, PH, preliminary

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

ν_e status 2019

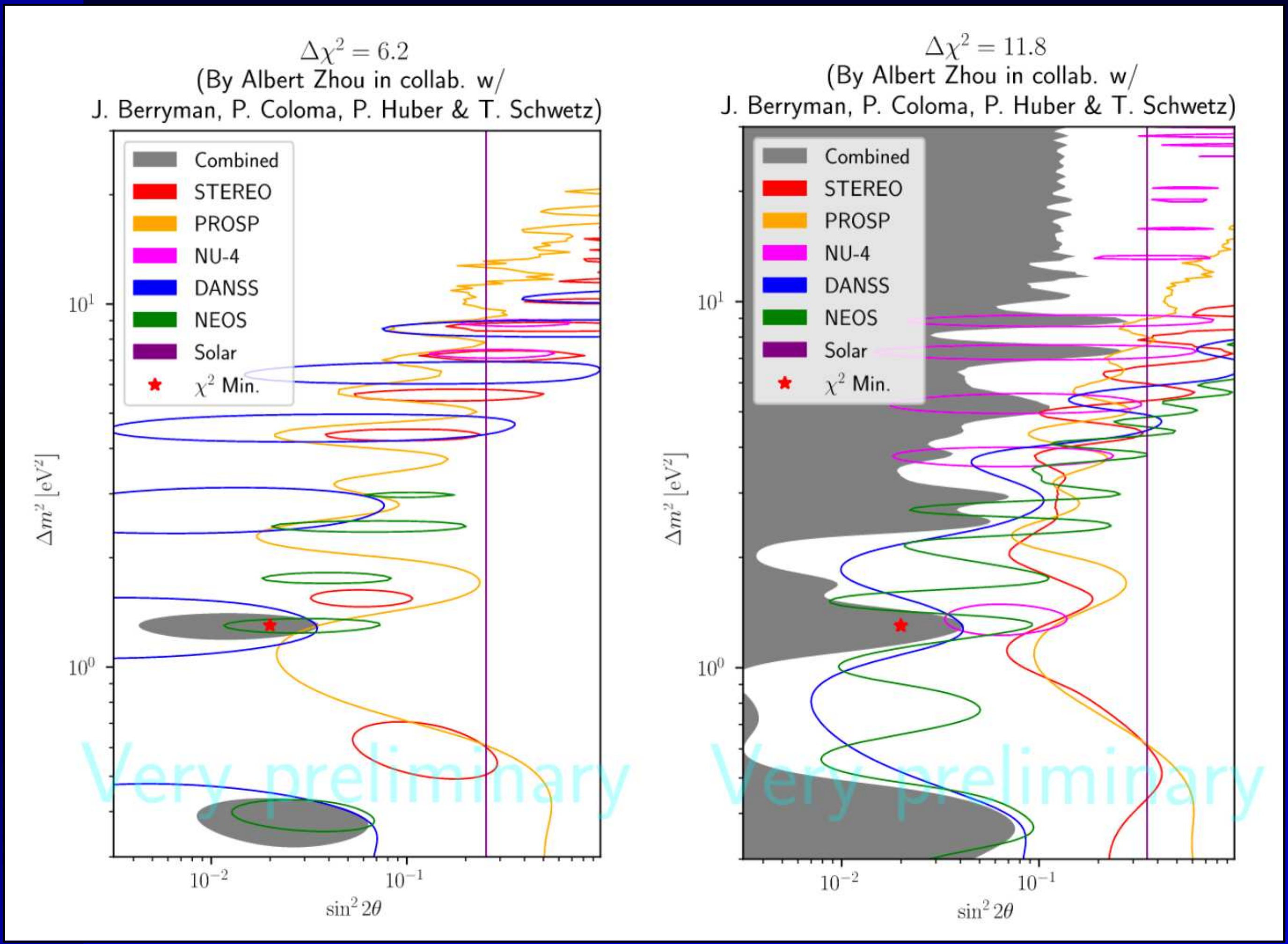


$\Delta\chi^2 = 13.8$ evidence for oscillation, flux model-independent, driven by NEOS and DANSS

Consistent with Gallium anomaly.

Berryman, PH, 2019

ν_e status 2021



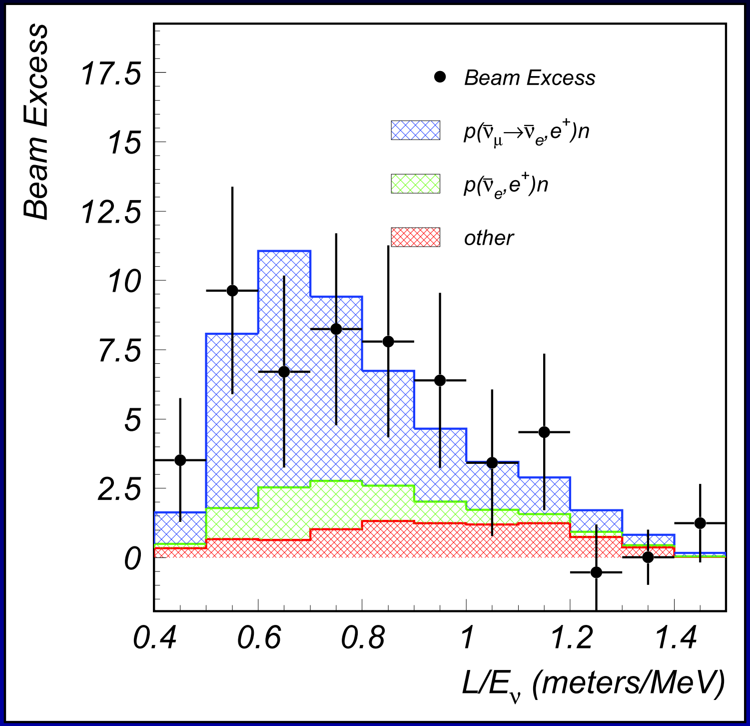
$\Delta\chi^2 = 9.9$

Neutrino-4 not inconsistent

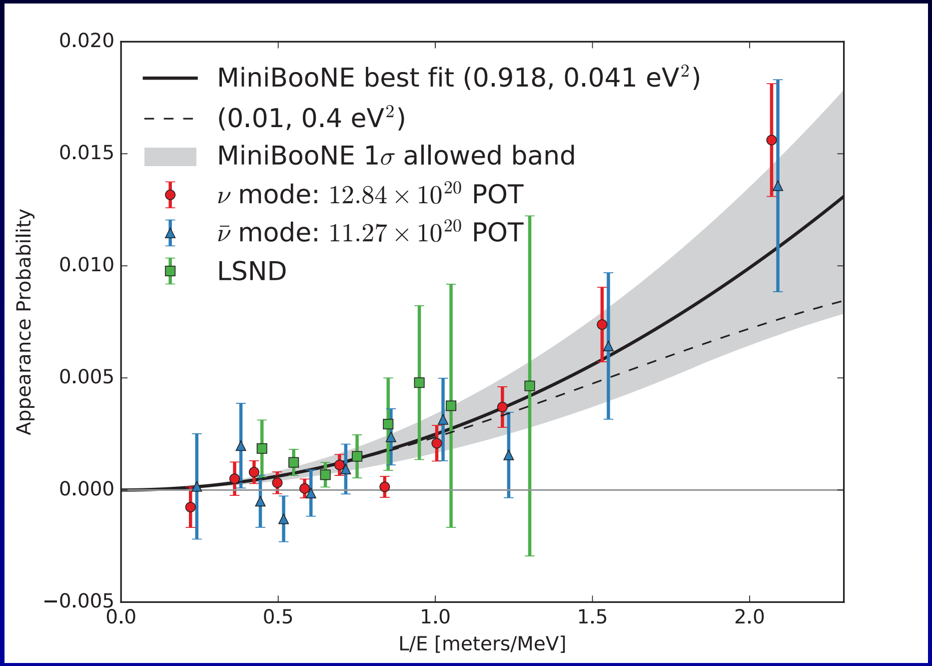
Still consistent with Gallium anomaly

But overall significance?

LSND & MiniBooNE



LSND 1995

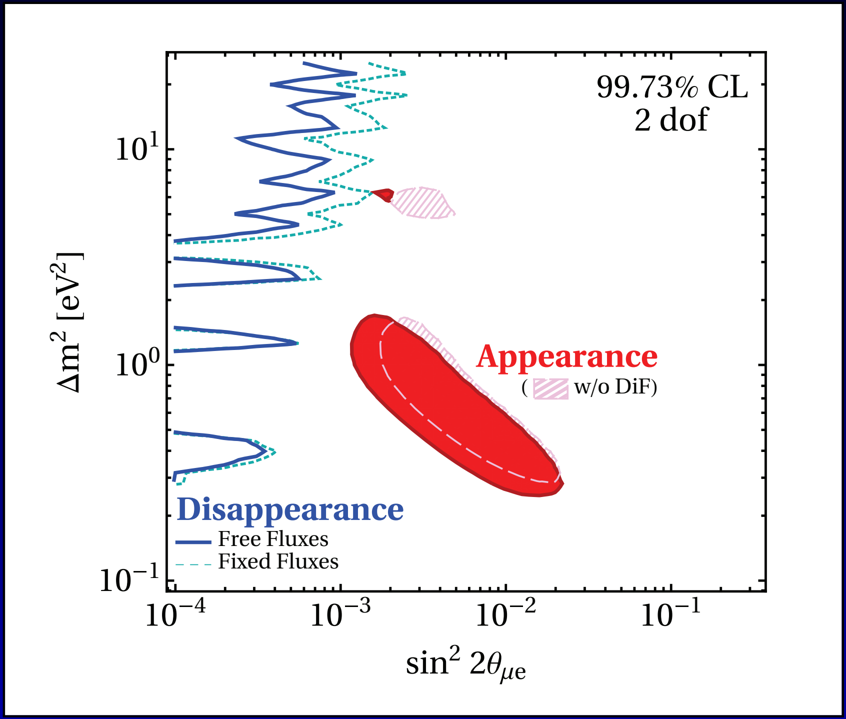


MiniBooNE 2018

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

$\nu_\mu \rightarrow \nu_e$ 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

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

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

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

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

Reactor rate and spectrum anomalies likely are due to nuclear physics, but this does not impact reactor sterile results AT ALL.