Reactor neutrinos: spectra and oscillations

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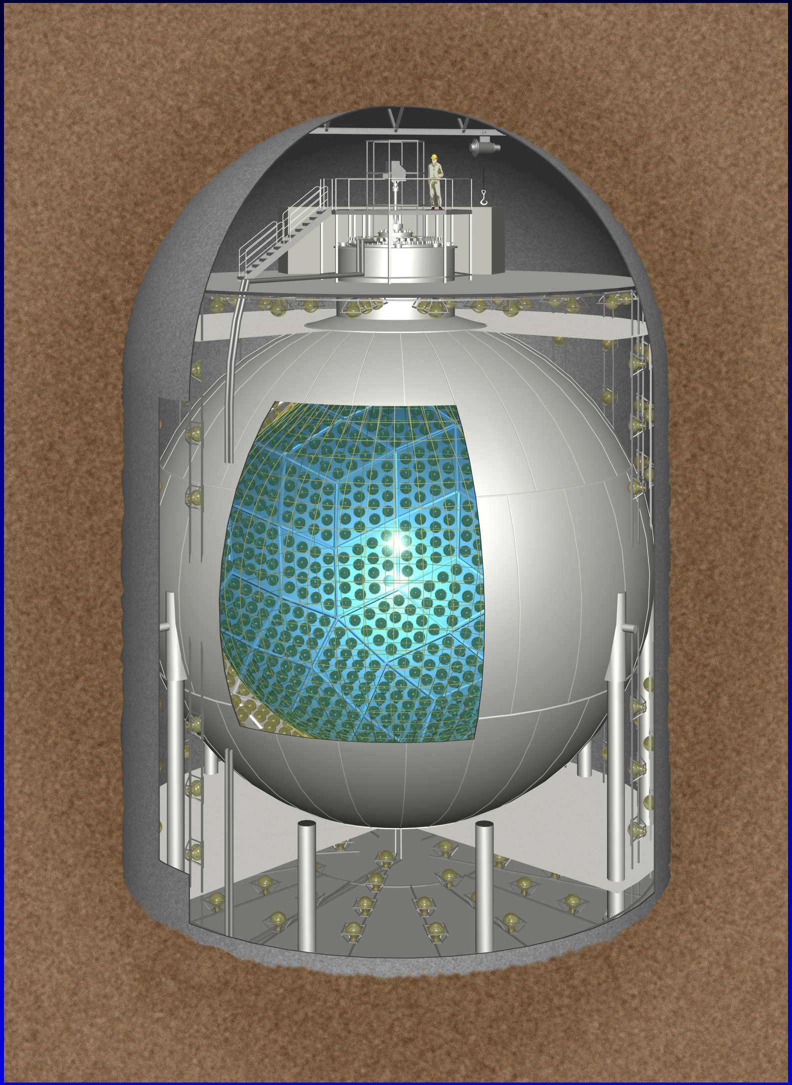
Why reactors?

- 3% of the energy release in fission is in neutrinos – 100 MW for a power reactor or about $10^{21}\,\mathrm{s}^{-1}$ neutrinos.
- Built for weapons, energy, . . .
  – not paid from physics budget
- Flavor pure source with well understood flux and energy spectrum
- Inverse beta decay provides a well understood, flavor tagging detection reaction with a “large” cross section
- Inverse beta decay has a clean experimental signature – delayed coincidence

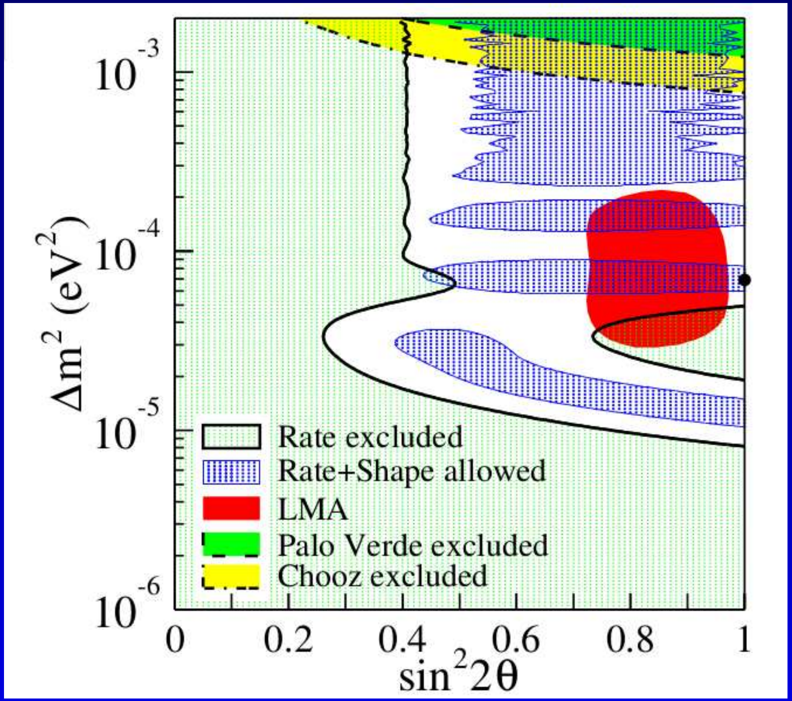
KamLAND – 2002

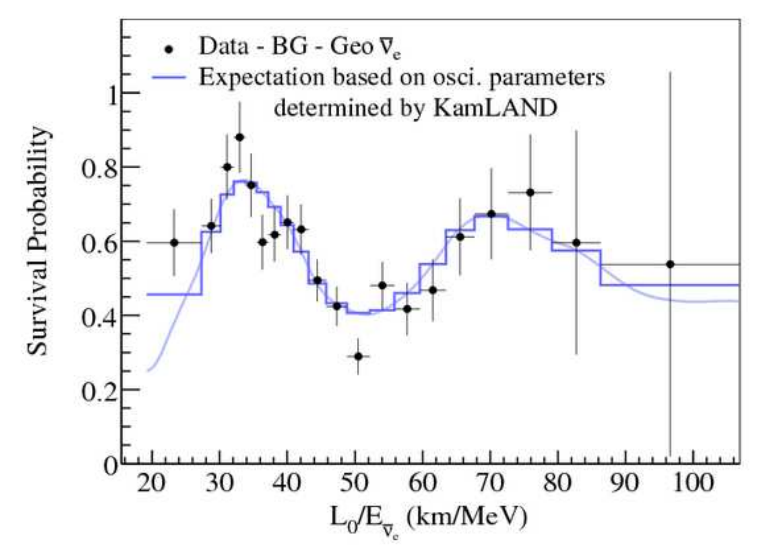


1000 t of liquid organic scintillator, undoped, deep underground.

KamLAND – results

KamLAND confirmed the oscillation interpretation of the solar neutrino results and “picked” the so-called LMA solution.

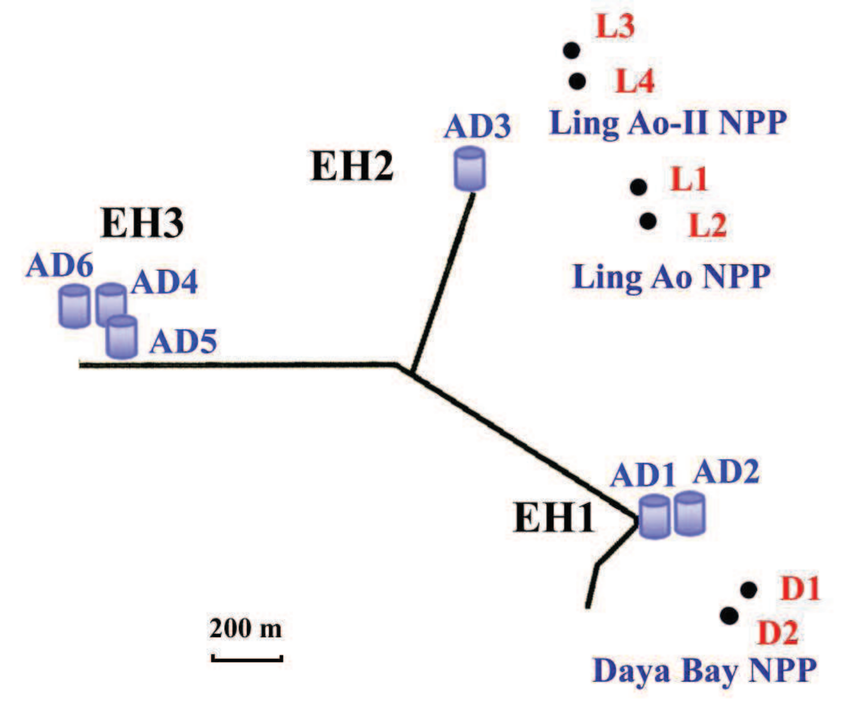




Later it was the first experiment to see an oscillatory pattern.

Daya Bay – 2011

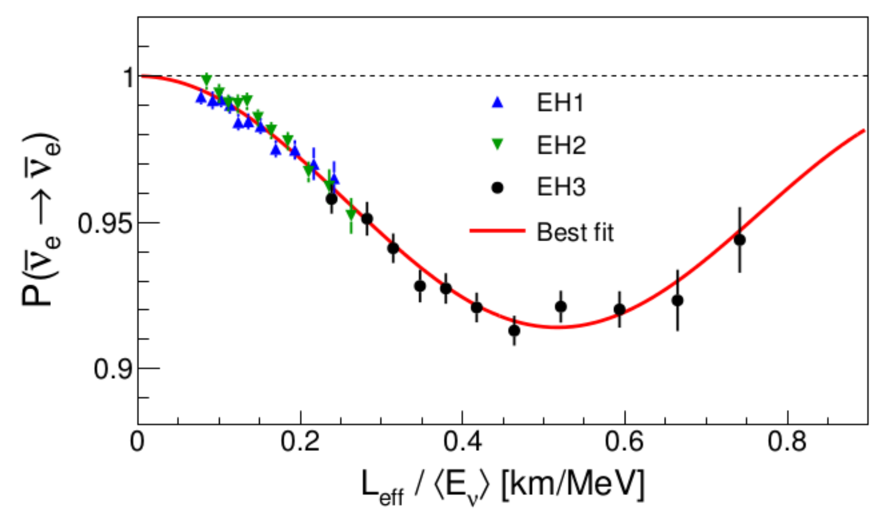
In a 1 reactor, 2 detector setup all flux related errors cancel completely in the near-to-far ratio.

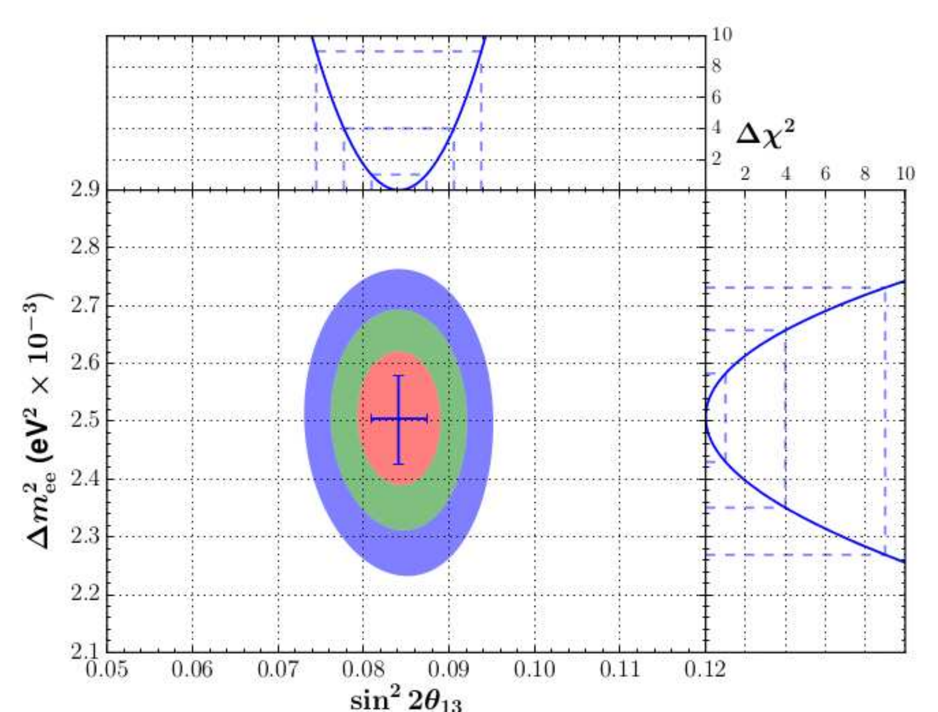


A careful choice of detector locations mitigates the complexity of the Daya Bay layout.

AD3 sees the same ratio of Ling Ao I to Ling Ao II events as do the far detectors.

Daya Bay – results





More than 2.5 million IBD events.

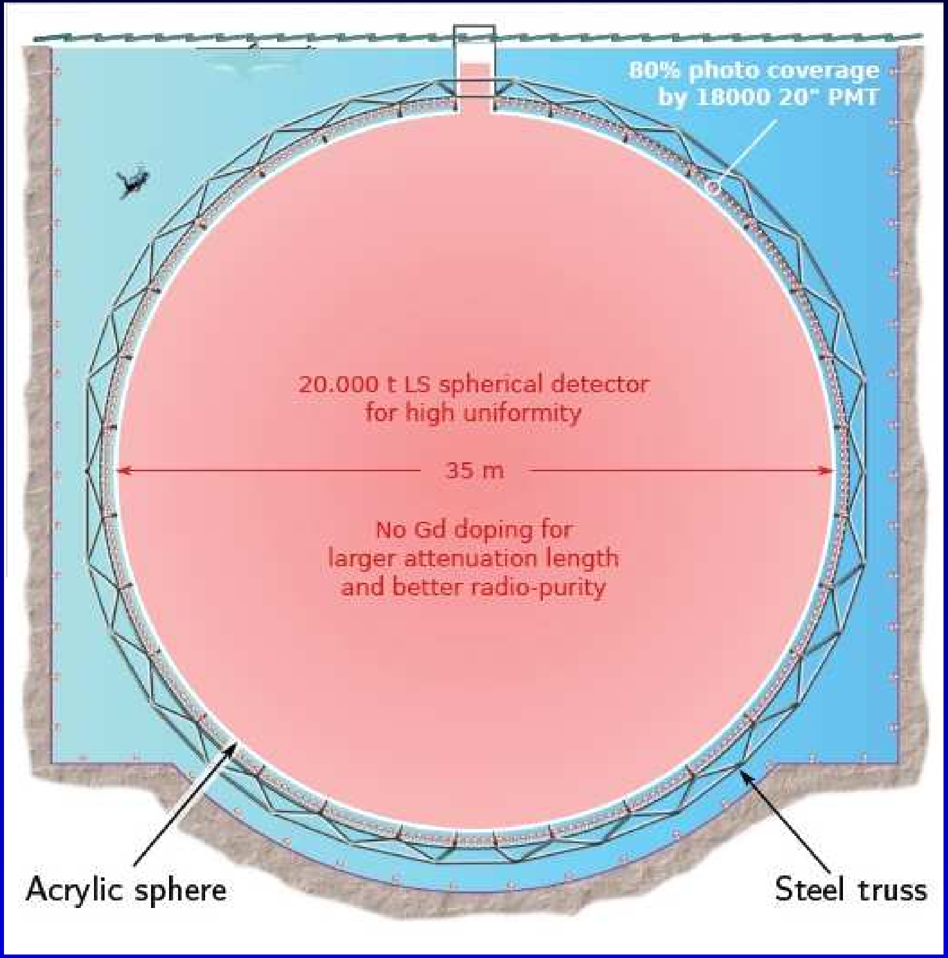
Most precise measurement of θ_{13}

Precise measurement of Δm^2_{32}

RENO and Double Chooz are very similar in concept and results between agree very well.

JUNO – under construction

Jiangmen Underground Neutrino Observatory

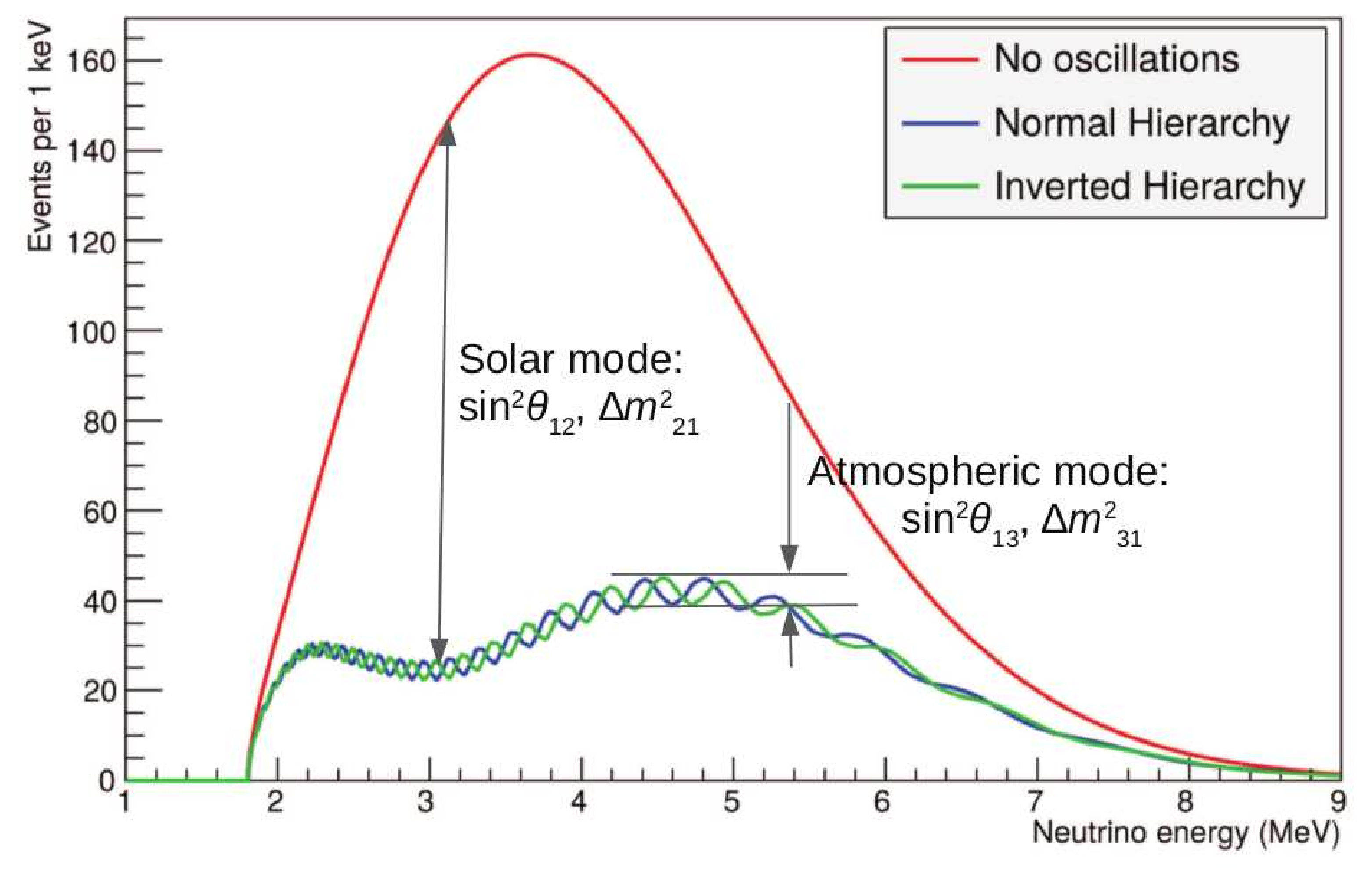


20,000 ton undoped liquid scintillator

53 km from two powerful reactor complexes, 18 GW each

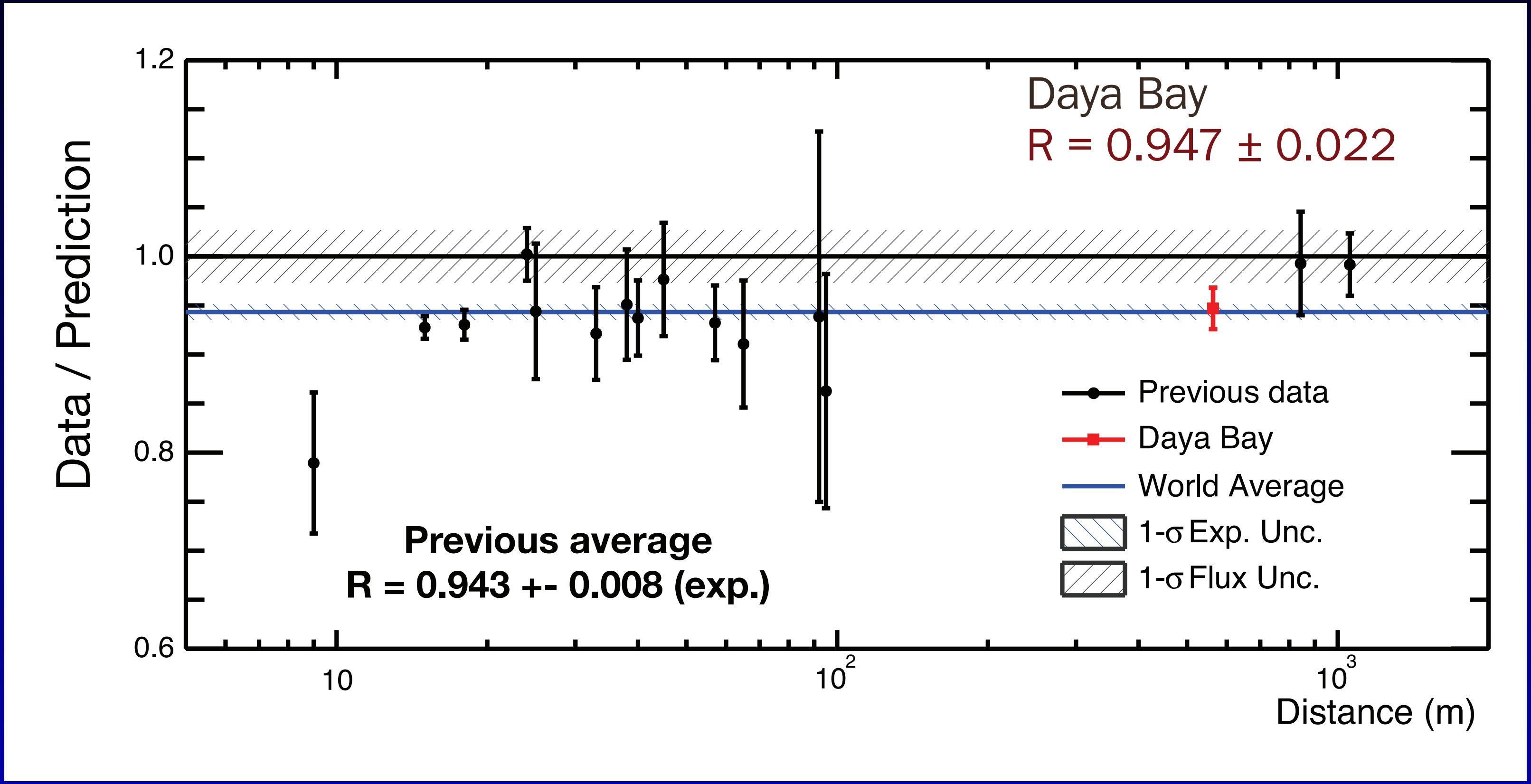
Start of data taking ∼ 2024.

JUNO – physics goals



Measurement of mass hierarchy w/o matter effects
1% level measurement of solar mixing parameters

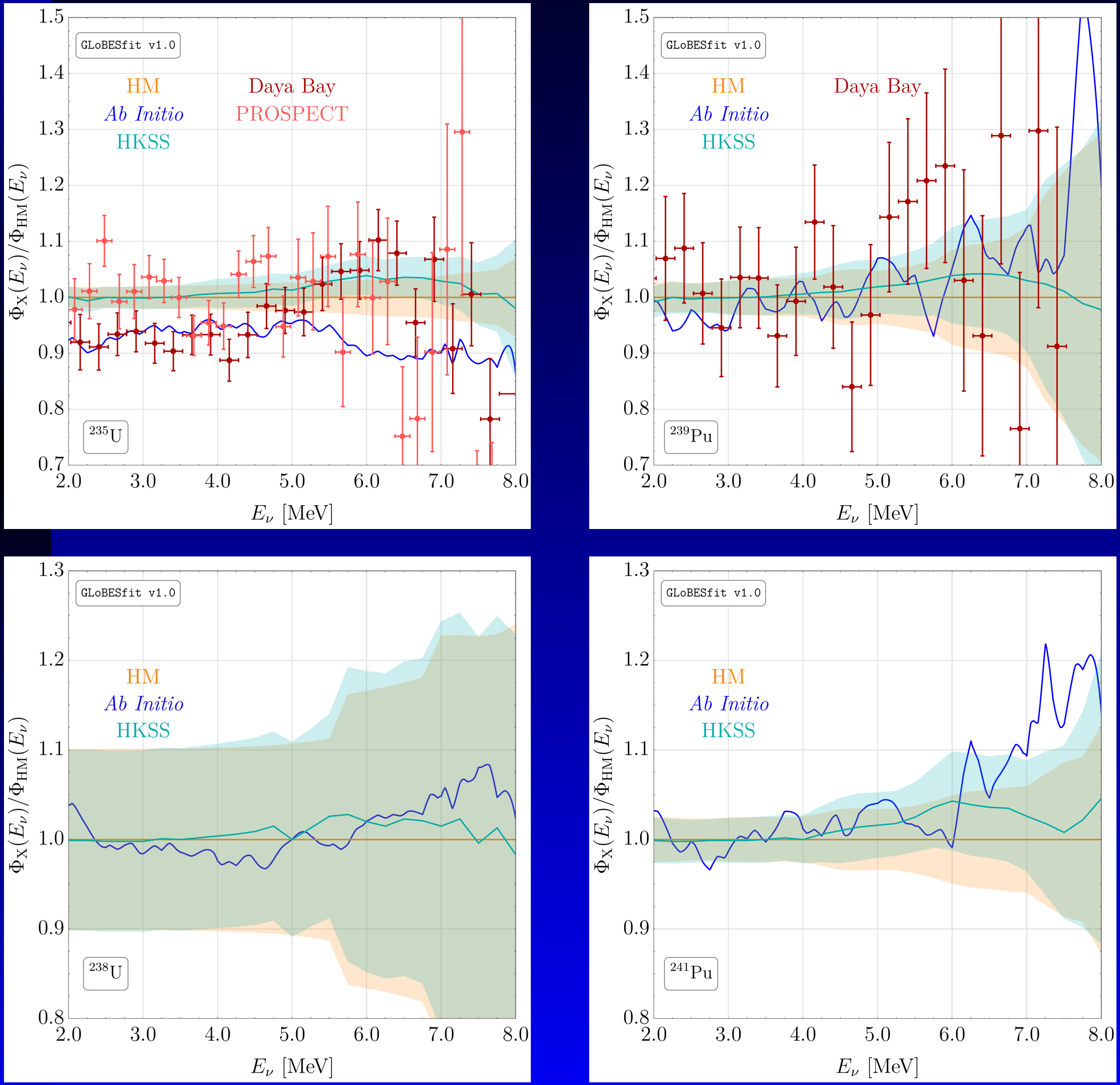
The reactor anomaly



Daya Bay, 2014

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

Status quo early 2021



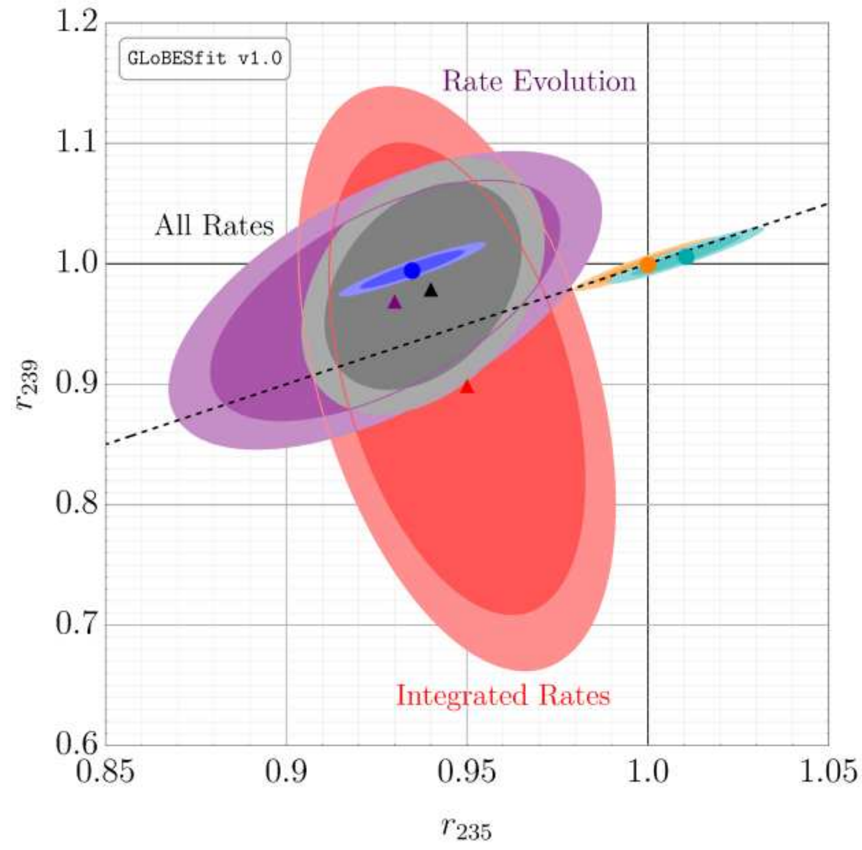
3 different flux models, data from 2 different experiments

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

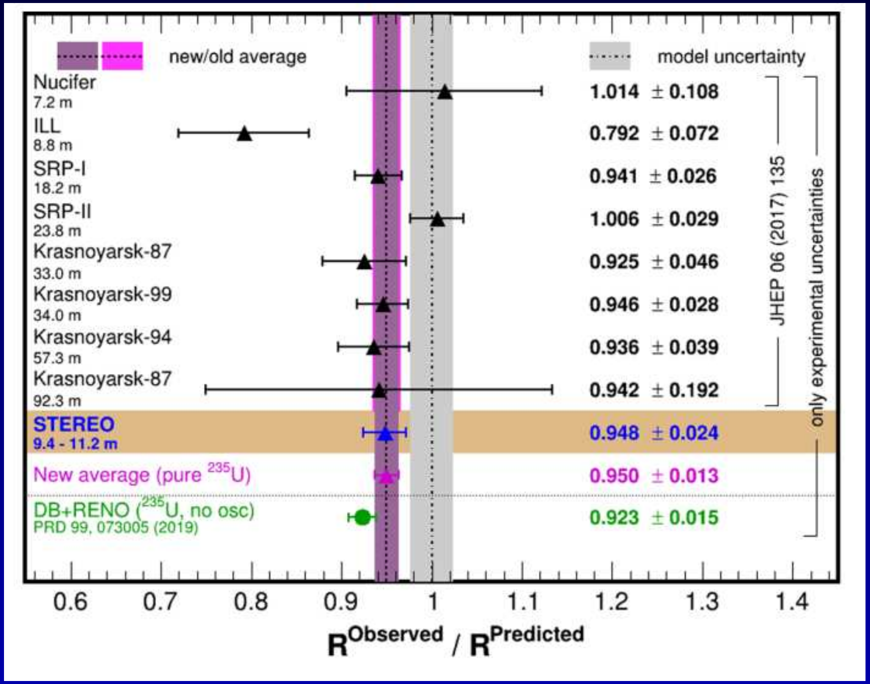
U235 has smallest error bars, not surprising that discrepancies show up first.

Berryman, PH, 2020

Fuel evolution



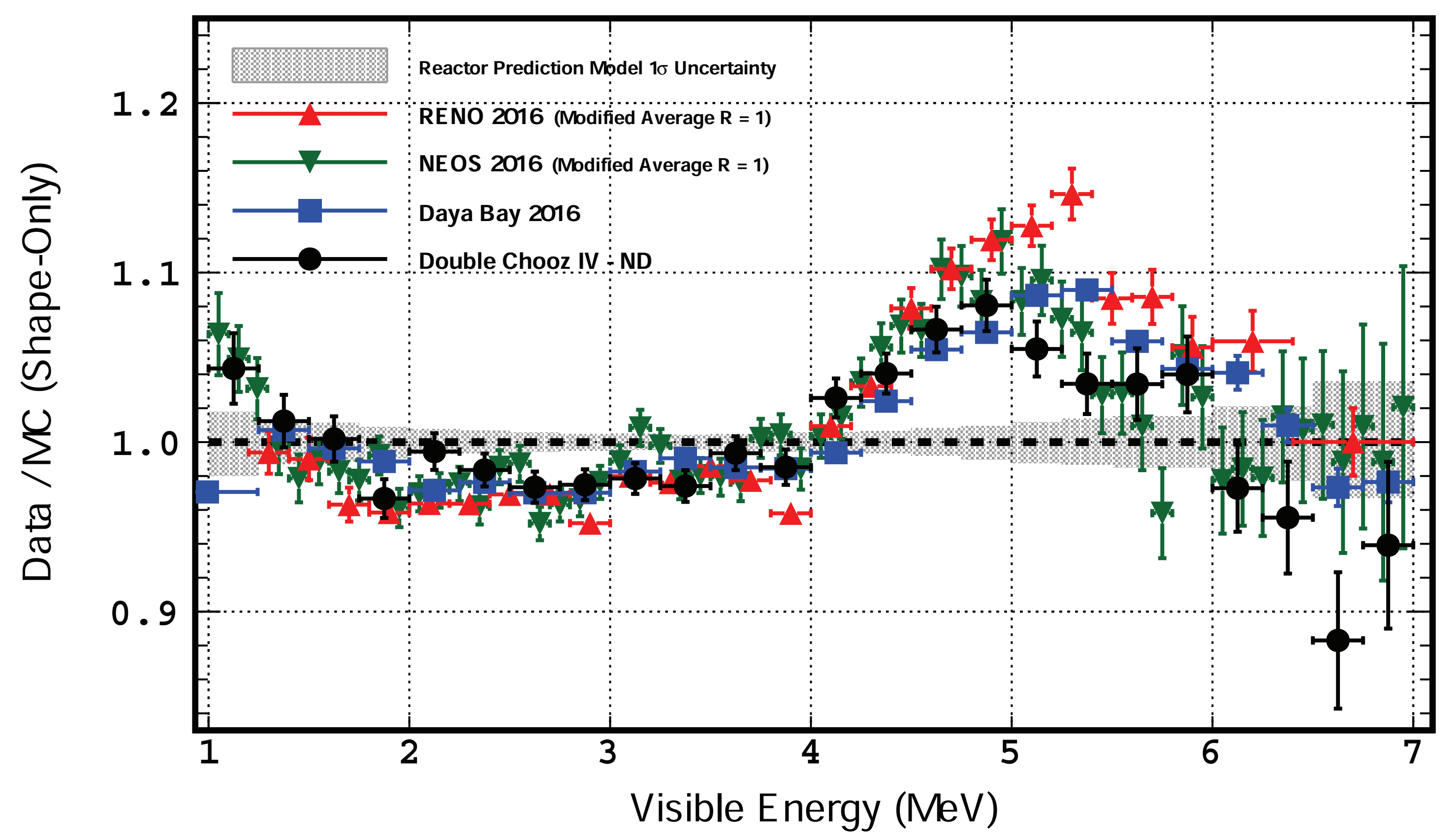
Berryman, PH, 2020



STEREO, 2020

U235 seems to “own” all of the deficit.

The 5 MeV bump

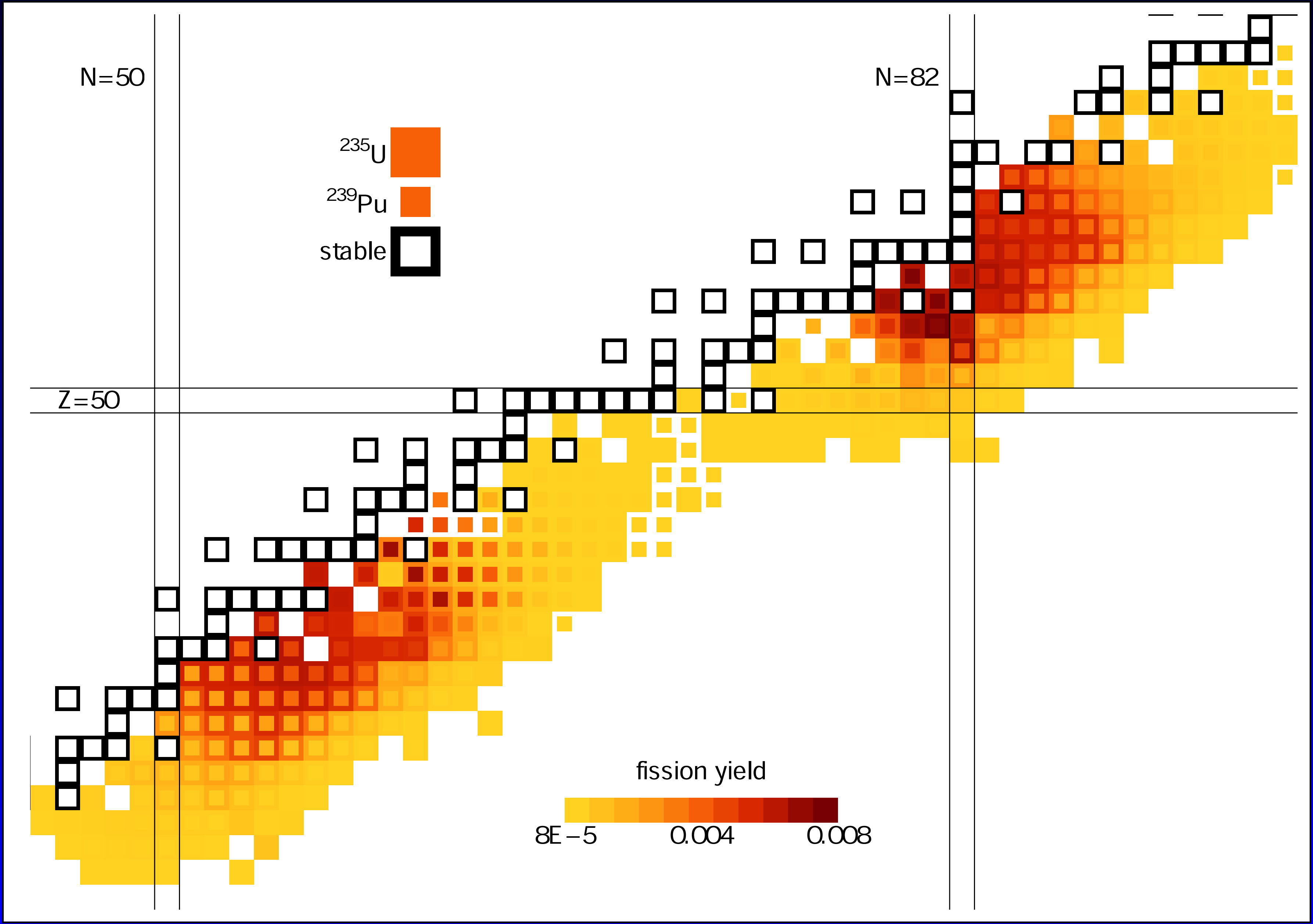


Double Chooz 2019

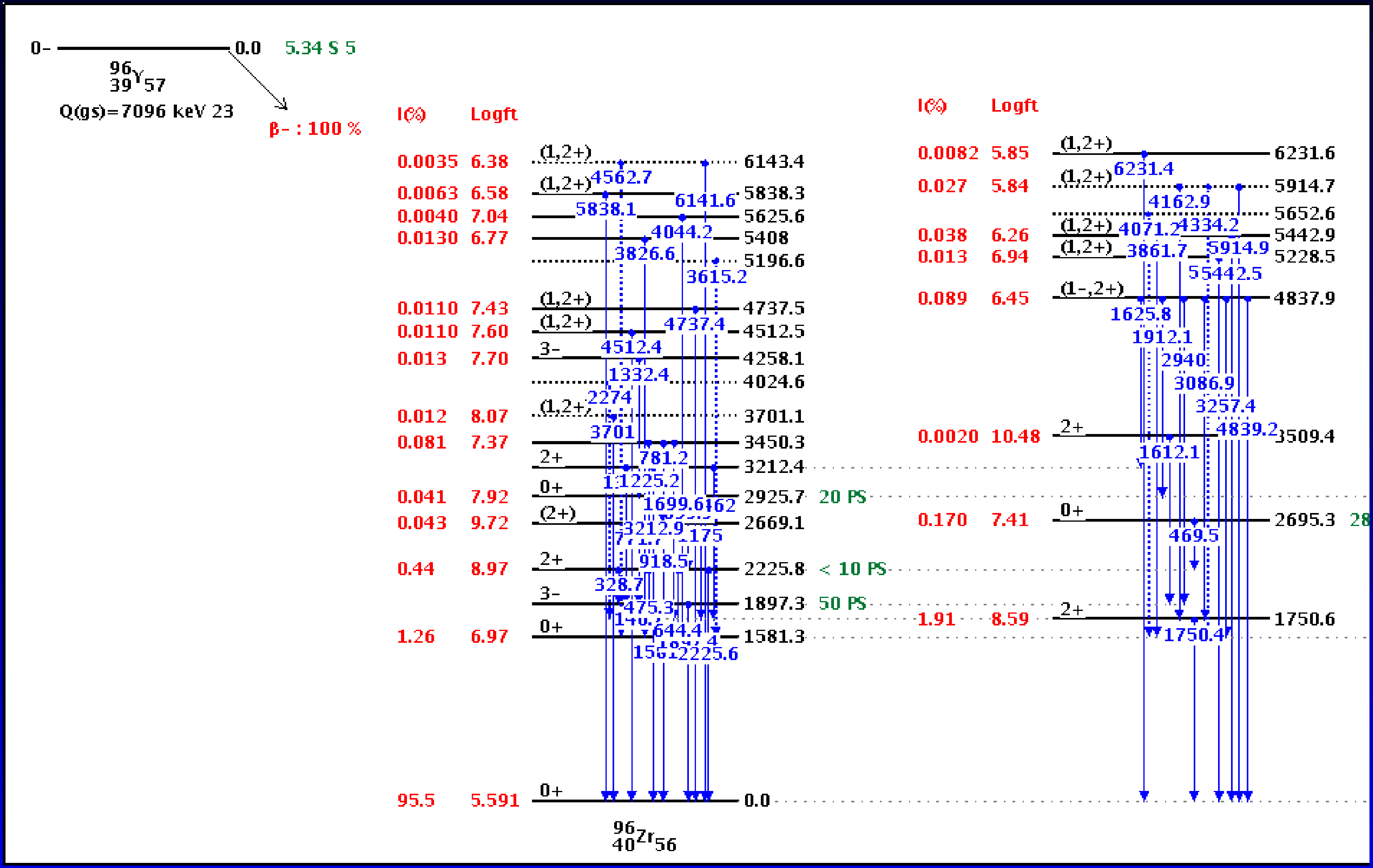
Contains only 0.5% of all neutrino events – not important for sterile neutrinos

Yet, statistically more significant than the RAA!

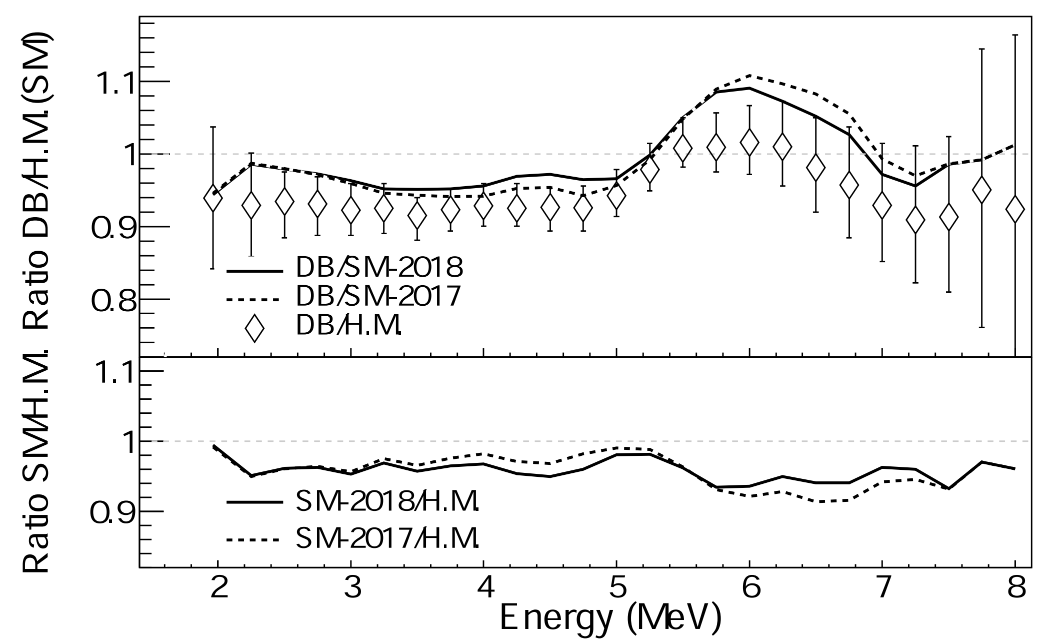
Why is this so complicated?

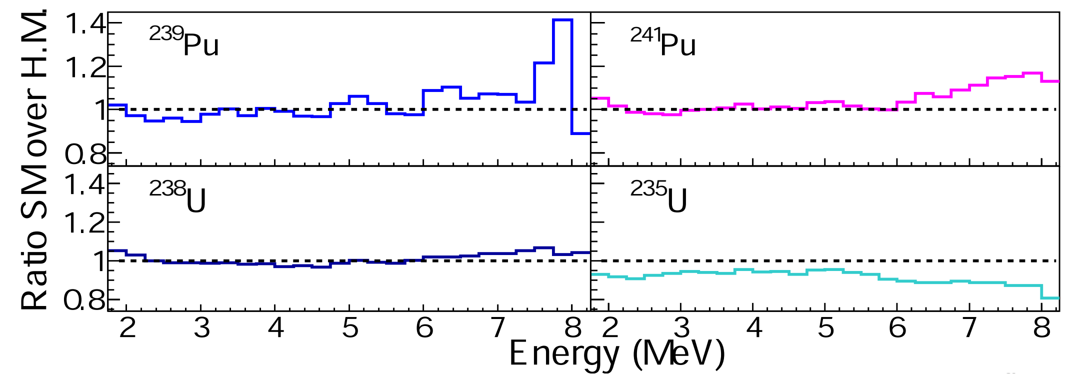


β-branches



Summation method – EF





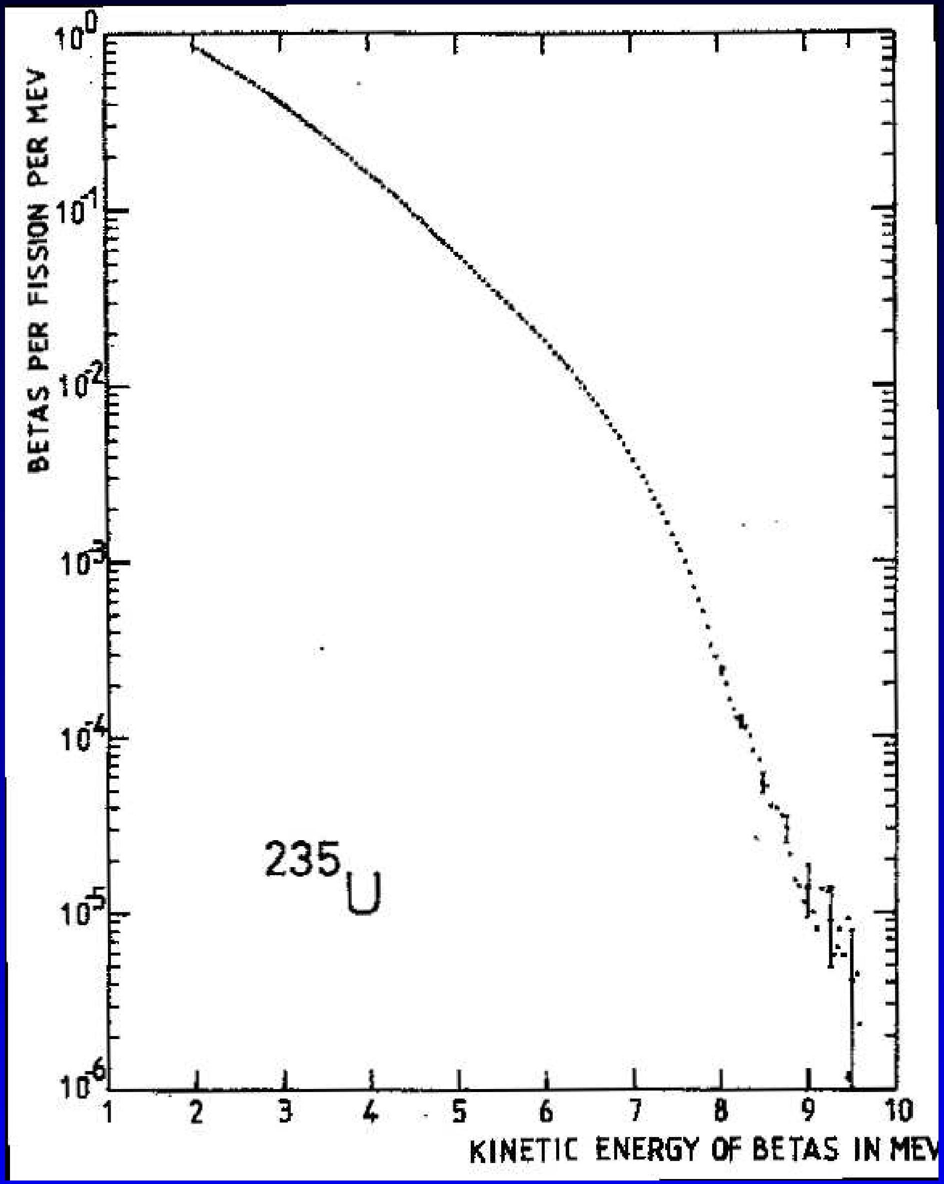
Estienne *et al.*, 2019

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.

Conversion method – HM



Schreckenbach, *et al.* 1985.

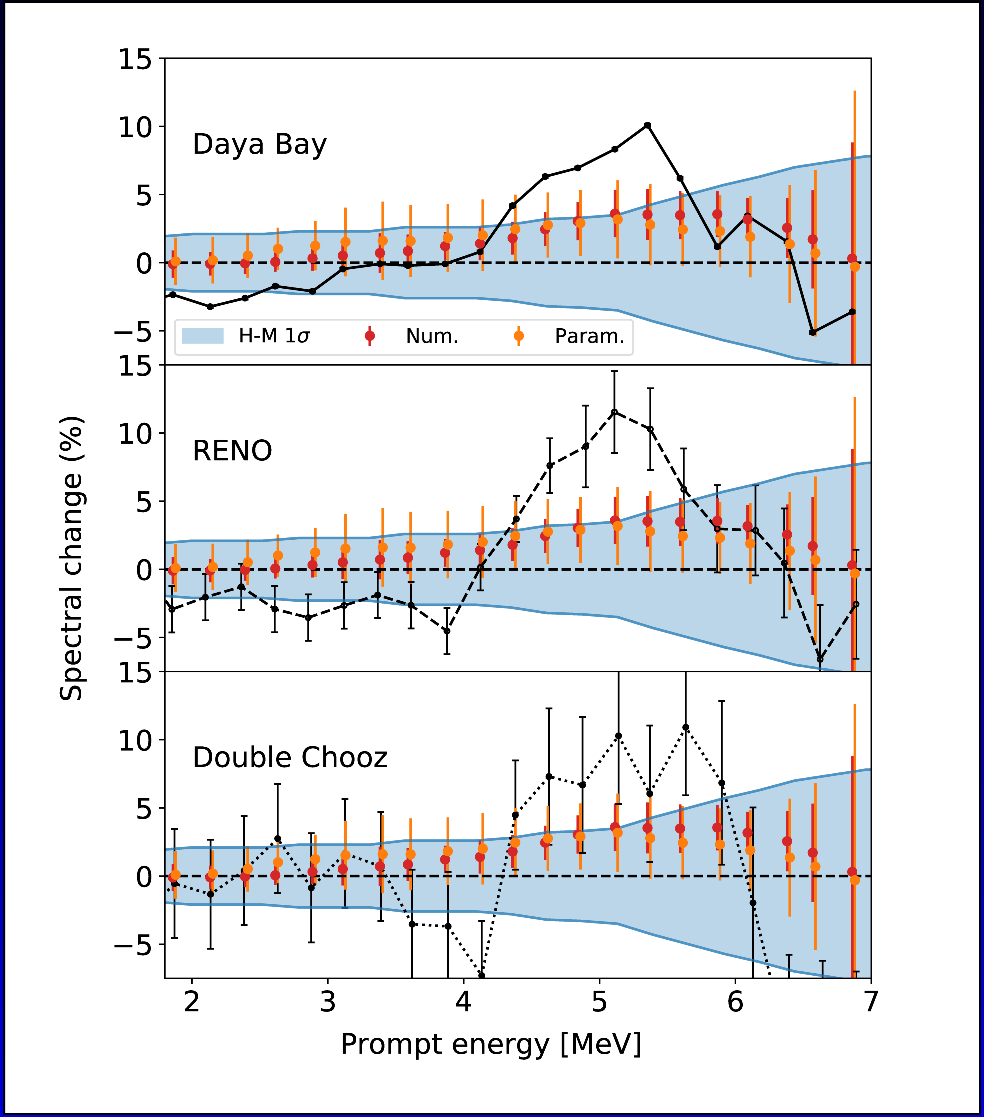
^{235}U foil inside the High Flux Reactor at ILL

Electron spectroscopy with a magnetic spectrometer

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

Mueller *et al.*, 2011; PH, 2011

Shell model – HKSS



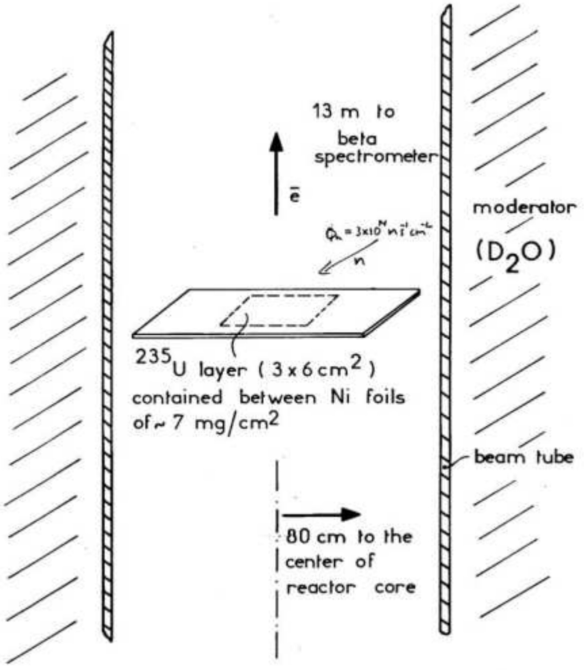
Hayen, *et al.* 2019

Forbidden decays major source of systematic.

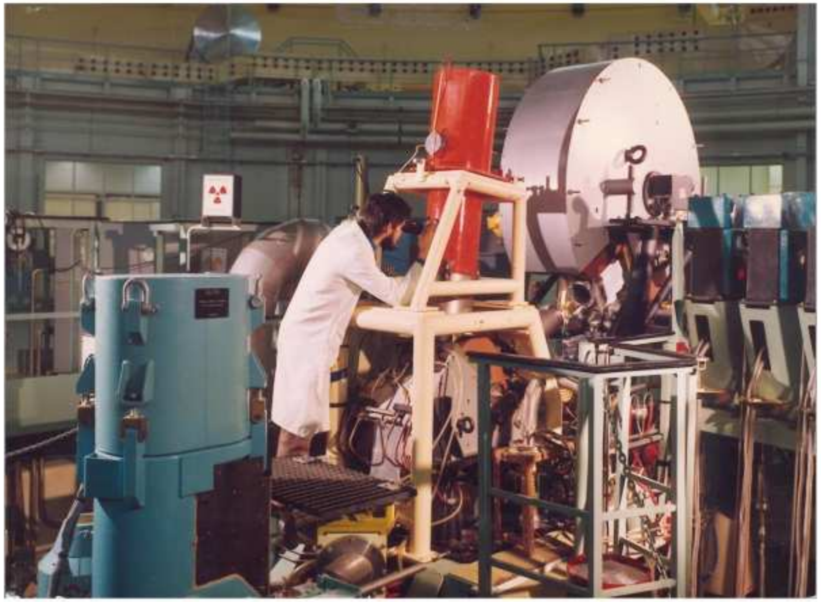
Microscopic shell model calculation of 36 forbidden isotopes, otherwise similar to HM.

Increases the IBD rate anomaly by 40%, but the uncertainty increases by only 13% relative to HM

Kill BILL?



SCHEMATIC VIEW OF THE TARGET SITE



Magnetic BILL spectrometer at ILL, 1972-1991

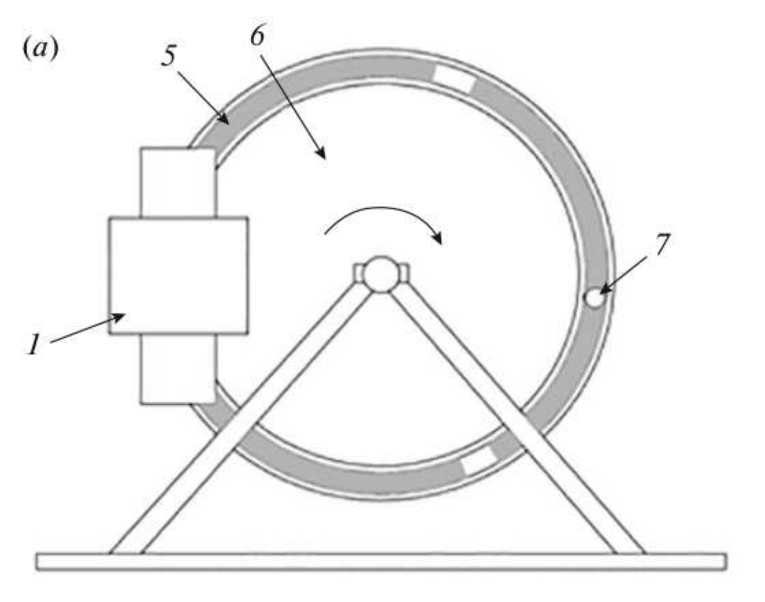
(Electron detector in focal plane: multi chamber proportional counter in transmission, rear mounted scintillator in coincidence)

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

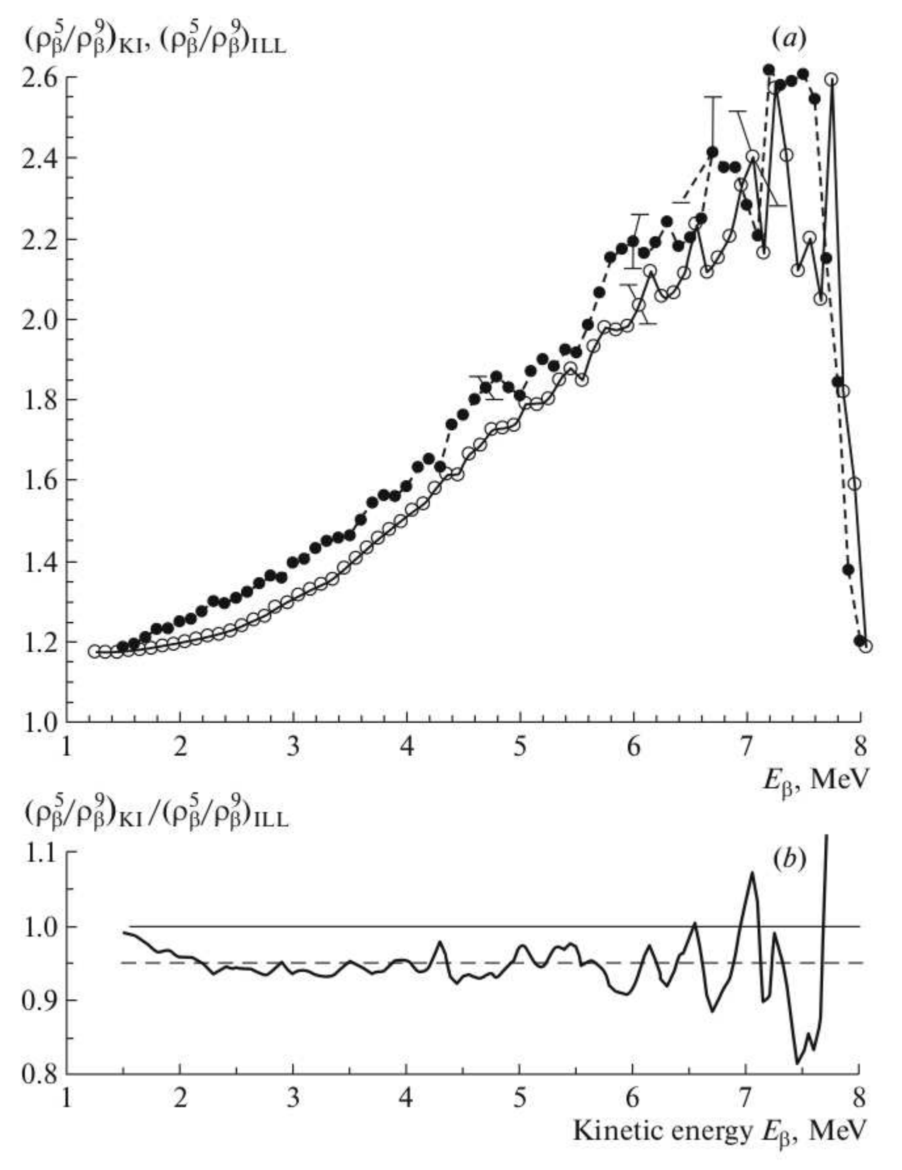


Relative measurement of U235 and Pu239 targets under identical conditions.

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) and we will refer to this as the Kurchatov Institute (KI) data.

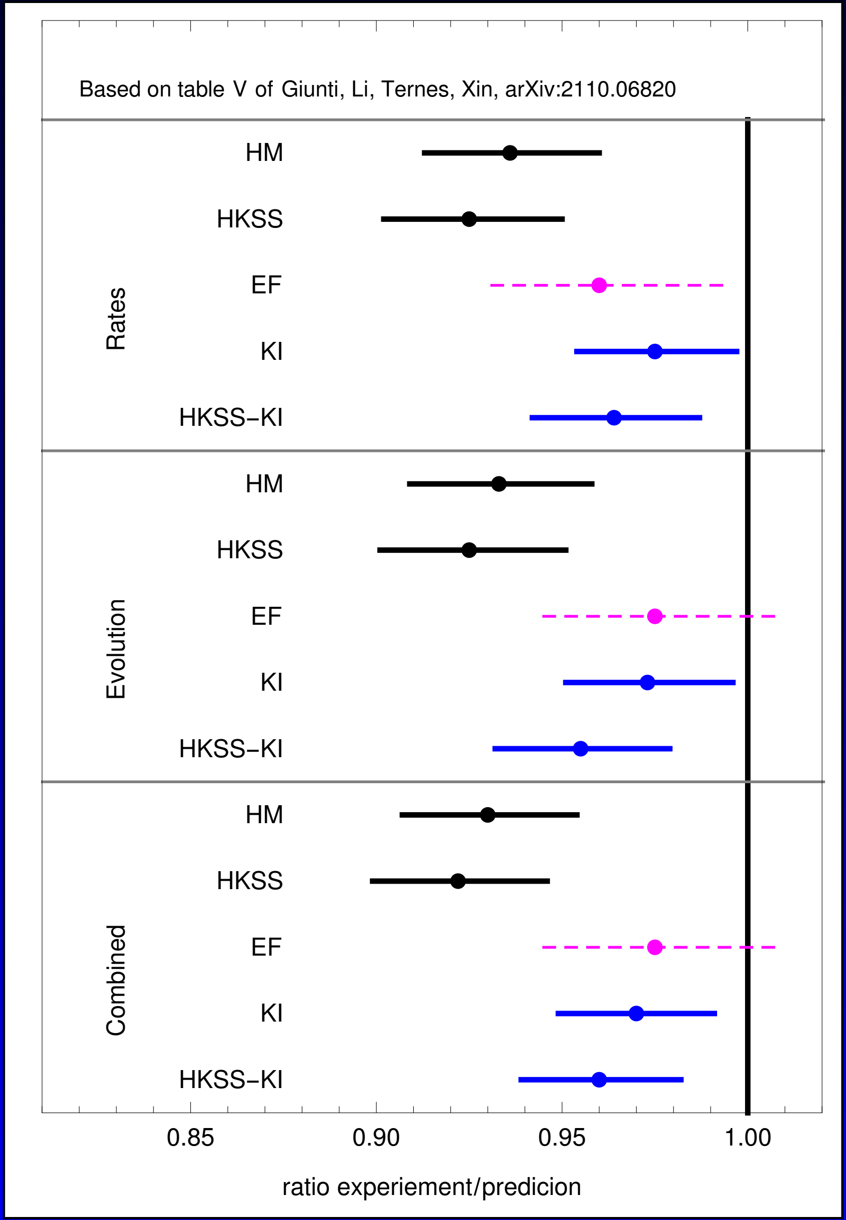
2021 beta results



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

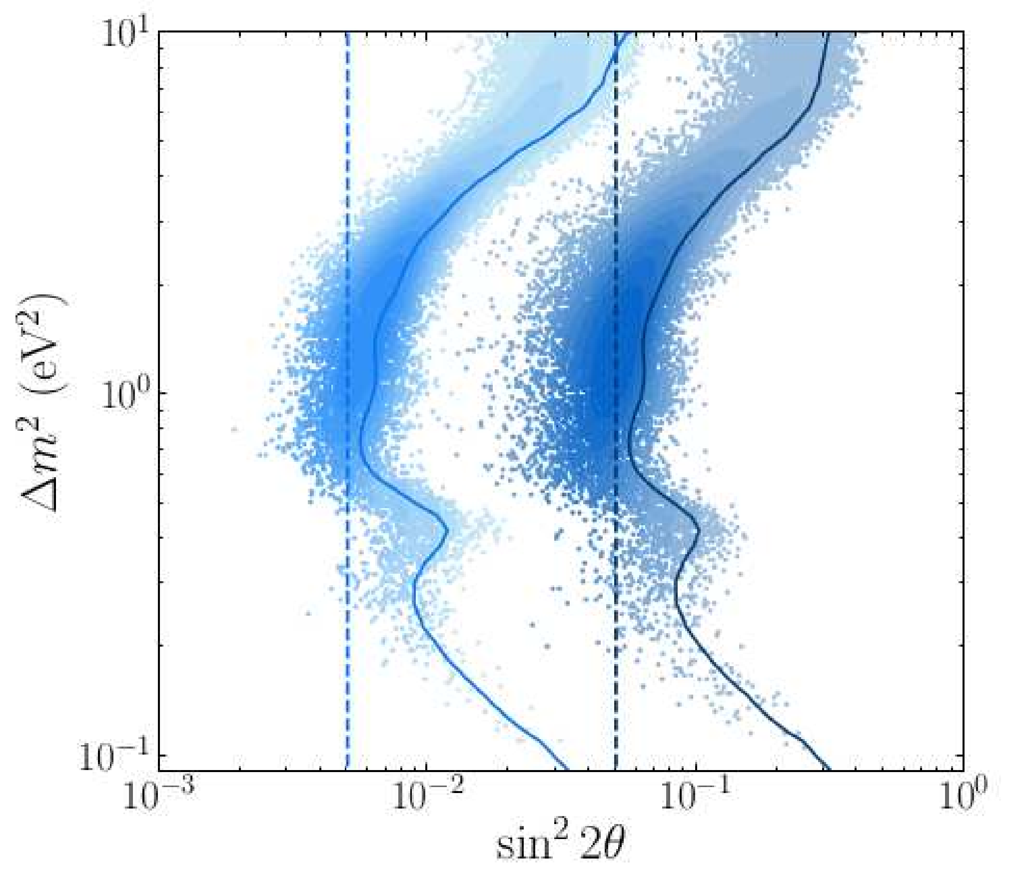


HM – conversion
HKSS – conversion
+ forbidden decays
EF – summation
unclear theory error
KI – HM + KI data
HKSS+KI – HKSS +KI

With the KI correction agreement between summation and conversion improved.

RAA significance reduced to less than 2σ

Oscillations are everywhere



Hypothetical two baseline experiment

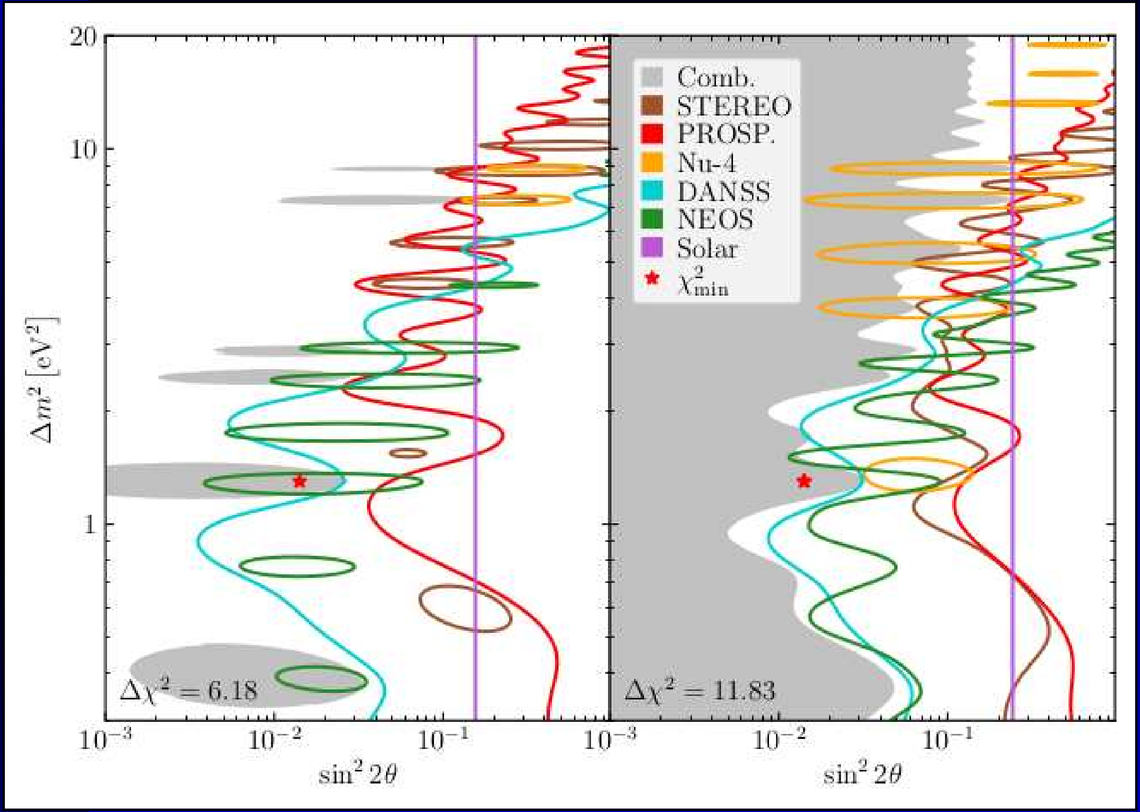
Maximum likelihood estimate is biased and not consistent.

Wilks' theorem does not apply

Coloma, PH, Schwetz, 2020

Agostini, Neumair, 2019; Silaeva, Sinev, 2020; Giunti, 2020
PROSPECT+STEREO, 2020

Global reactor data



Berryman, Coloma, PH, Schwetz, Zhou 2021

$\Delta\chi^2 = 7.3$ for no-oscillation hypothesis, flux model-independent

Solar data provides a strong constraint at large $\sin^2 2\theta$

Feldman-Cousins p-value 24.7% (1.1σ)
$\Rightarrow$ no evidence for oscillation

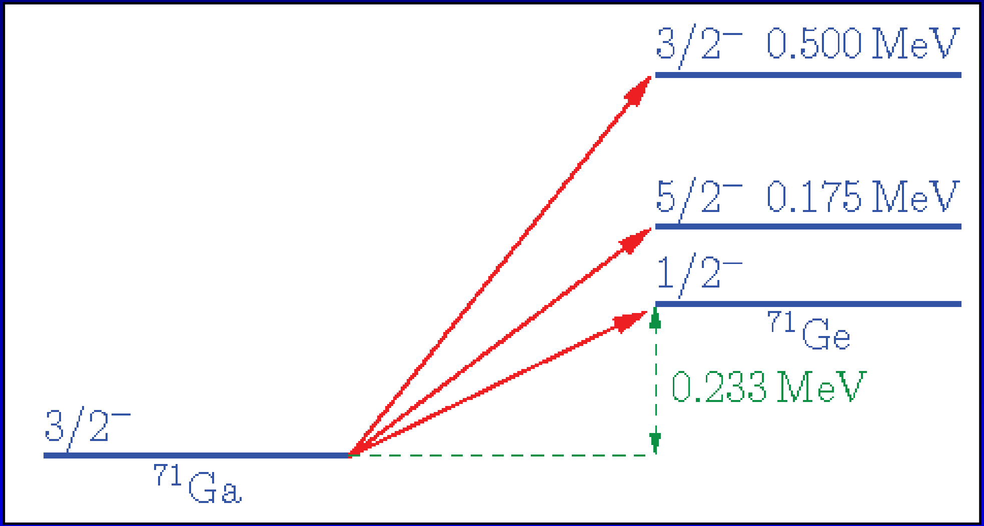
No tension with Neutrino-4

Gallium anomaly

Radioactive source experiments

GALLEX	GALLEX	SAGE	SAGE	BEST (inner)	BEST (outer)
0.953 ± 0.11	0.812 ± 0.10	0.95 ± 0.12	0.791 ± 0.084	0.791 ± 0.044	0.766 ± 0.045

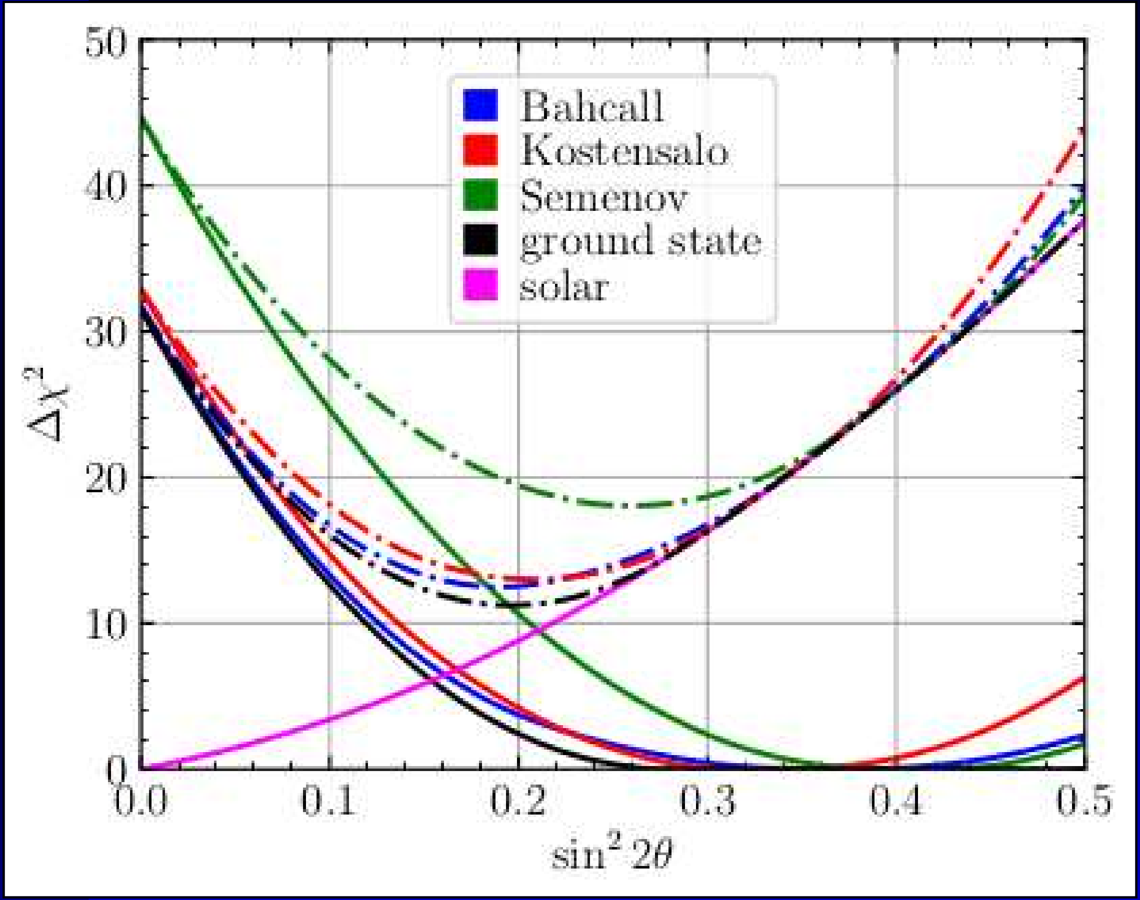
Nuclear matrix elements



ground state follows from beta decay of ^{71}Ge

excited states?

Gallium and solar



BCHSZ 2021

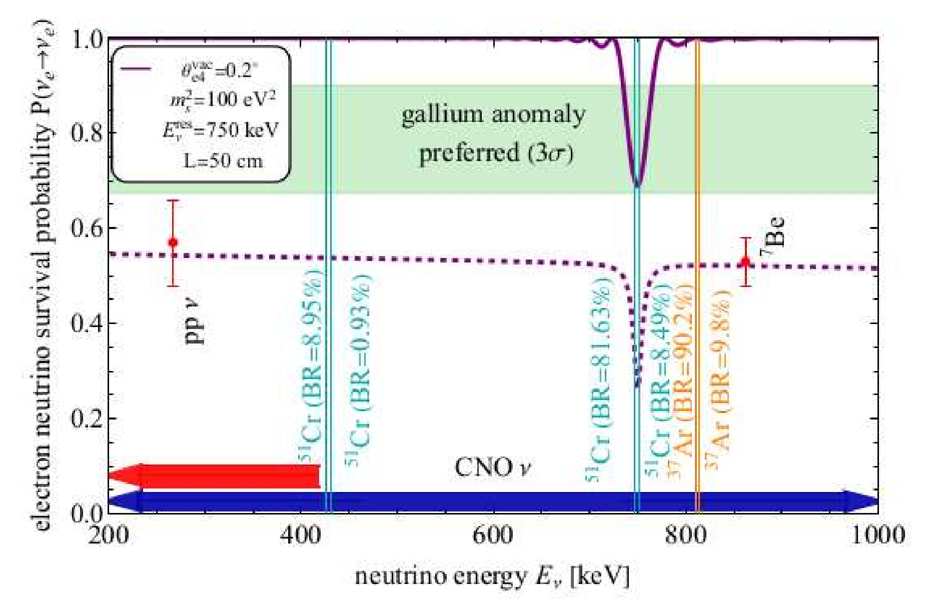
Any model for the matrix element yields more than 5σ for the gallium anomaly, even the ground state contribution by itself.

BUT, there is a more than 3σ tension with solar data.

Explanations?

Experimental reasons (all disfavored)

longer ^{71}Ge halflife	smaller matrix element, smaller cross section see also Giunti 2023
new excited state in ^{71}Ga	would change the matrix element
larger BR($^{51}\mathrm{Cr} \to {}^{51}\mathrm{V}^*$)	changes relation between decay heat and source strength
^{71}Ge extraction efficiency	some ^{71}Ge does not get extracted



Engineer a MSW resonance at the ^{51}Cr neutrino energy.

Brdar, Gehrlein, Kopp, 2023

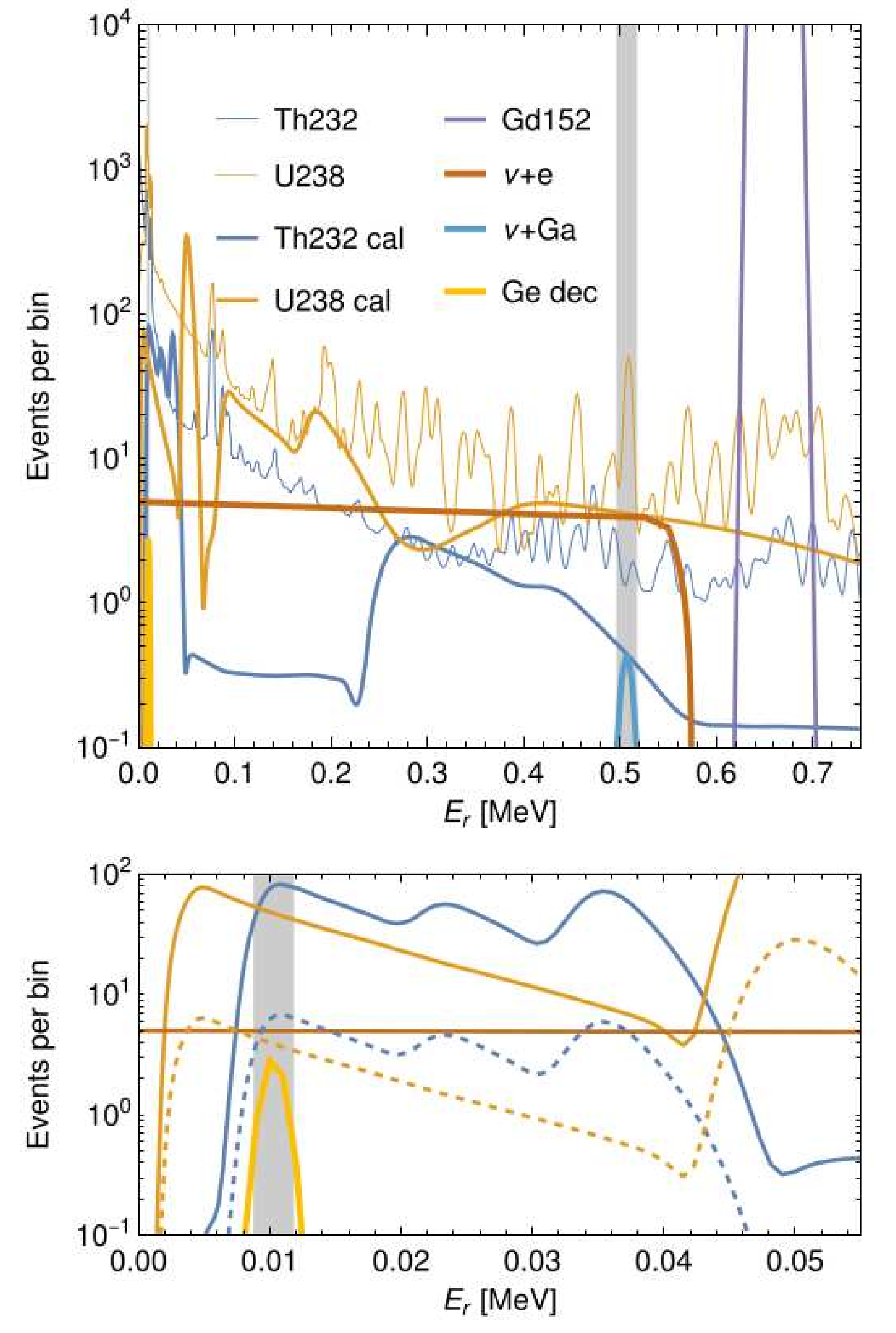
Other tests of gallium data?

Ce:GAGG
contains 21% by weight gallium
has a density of 6.6 g cm^3
has a light yield 50,000 ph/MeV

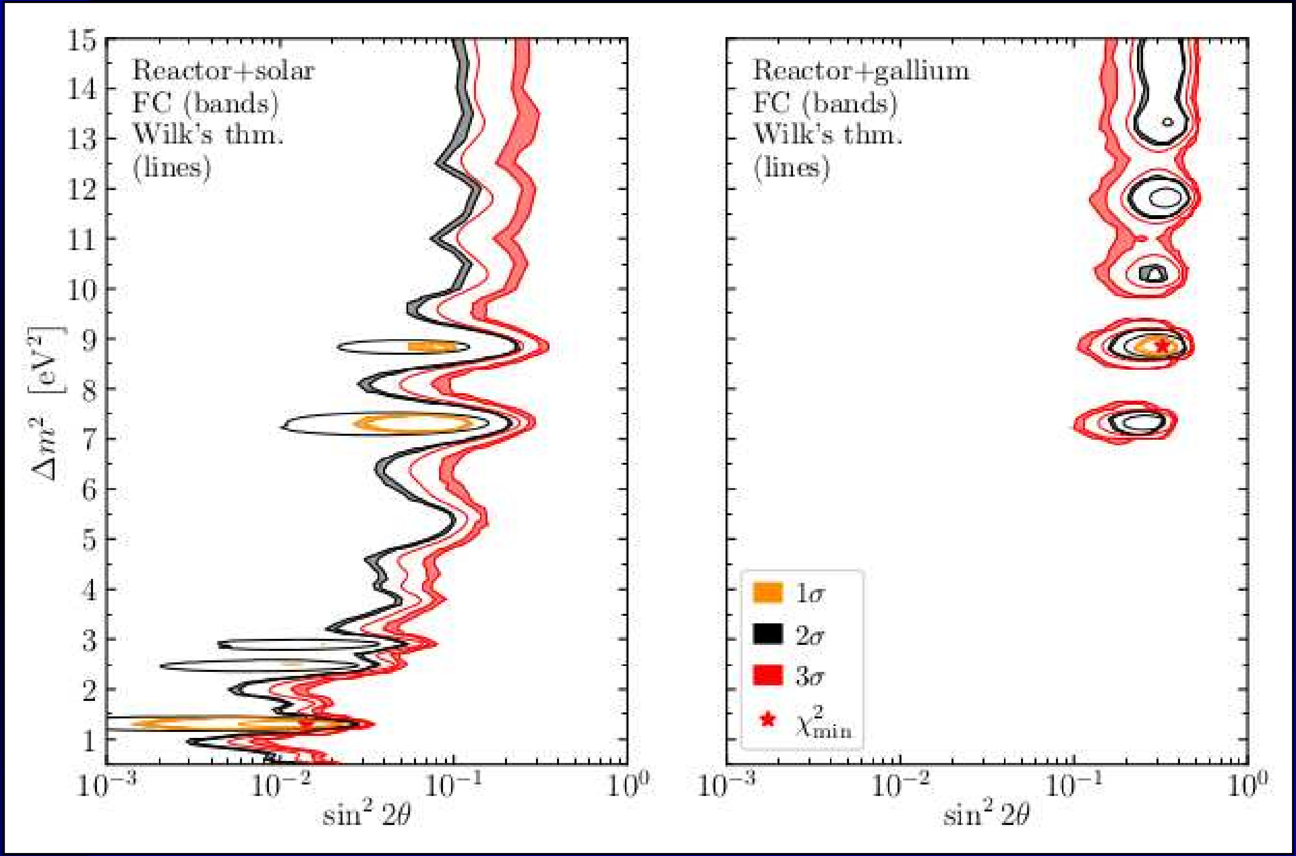
Few tons of Ce:GAGG and a 4π high-QE light detection system à la JUNO-TAO allow for **Ge-tagging**, which when combined with several multi-MCi ^{51}Cr source runs could provide a $> 5\sigma$ test.

Key challenges:
U/Th content of Ce:GAGG,
10-100 improvement needed
High-energy γs from source require a thick shield ($\sim$ 40 cm), which can be offset be using enriched ^{71}Ga.

PH, 2022



All together now



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Full FC analysis

Reactor+solar: 1.1σ

Reactor+gallium: 5.3-5.7σ

Evidence for neutrino disappearance entirely driven by gallium results,
only tension gallium vs solar at $> 3\sigma$.

Outlook

Reactors as neutrino source are cheap, bright and clean.

The reactor antineutrino anomaly is likely due to flawed input data and not due to new or nuclear physics.

No evidence for $\bar{\nu}_e$ disappearance from reactors, but from gallium, $> 5\sigma$!

Rich potential for applications