Searches for Nonstandard Neutrino Oscillations at Nuclear Reactors

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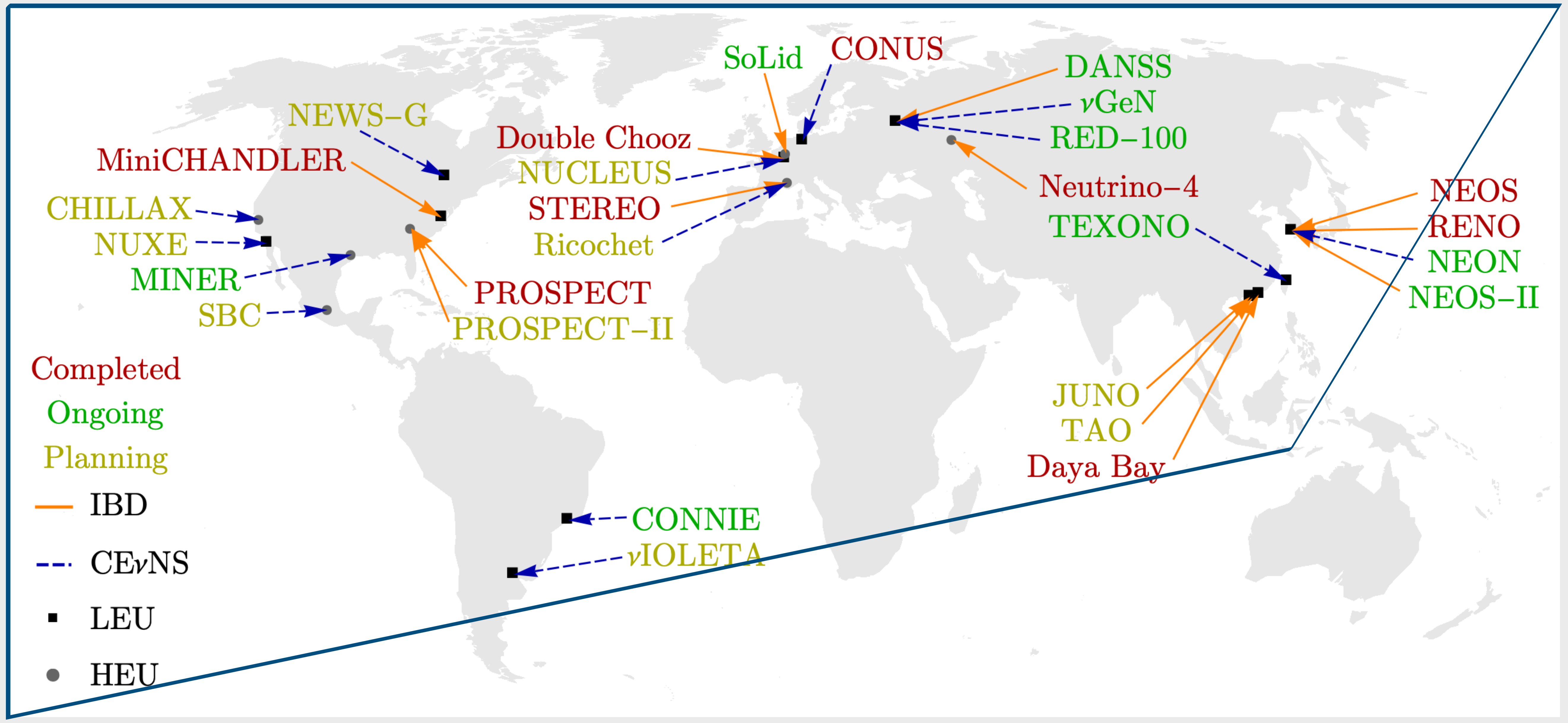
Antineutrinos from Nuclear Reactors

Nuclear reactors are an important part of the international neutrino program and connect to a number of NF topical groups: **NF01, NF02, NF03, NF05, NF07, NF09, NF10**.

The reactor community has been working on a comprehensive White Paper to summarize the importance of reactors to neutrino physics specifically and to the broader US HEP program.

I can only dedicate time to a small part of a much larger whole: *using nuclear reactors to search for nonstandard oscillations*, particularly *sterile neutrinos* [1-4].



HEP Physics Opportunities Using Reactor Antineutrinos

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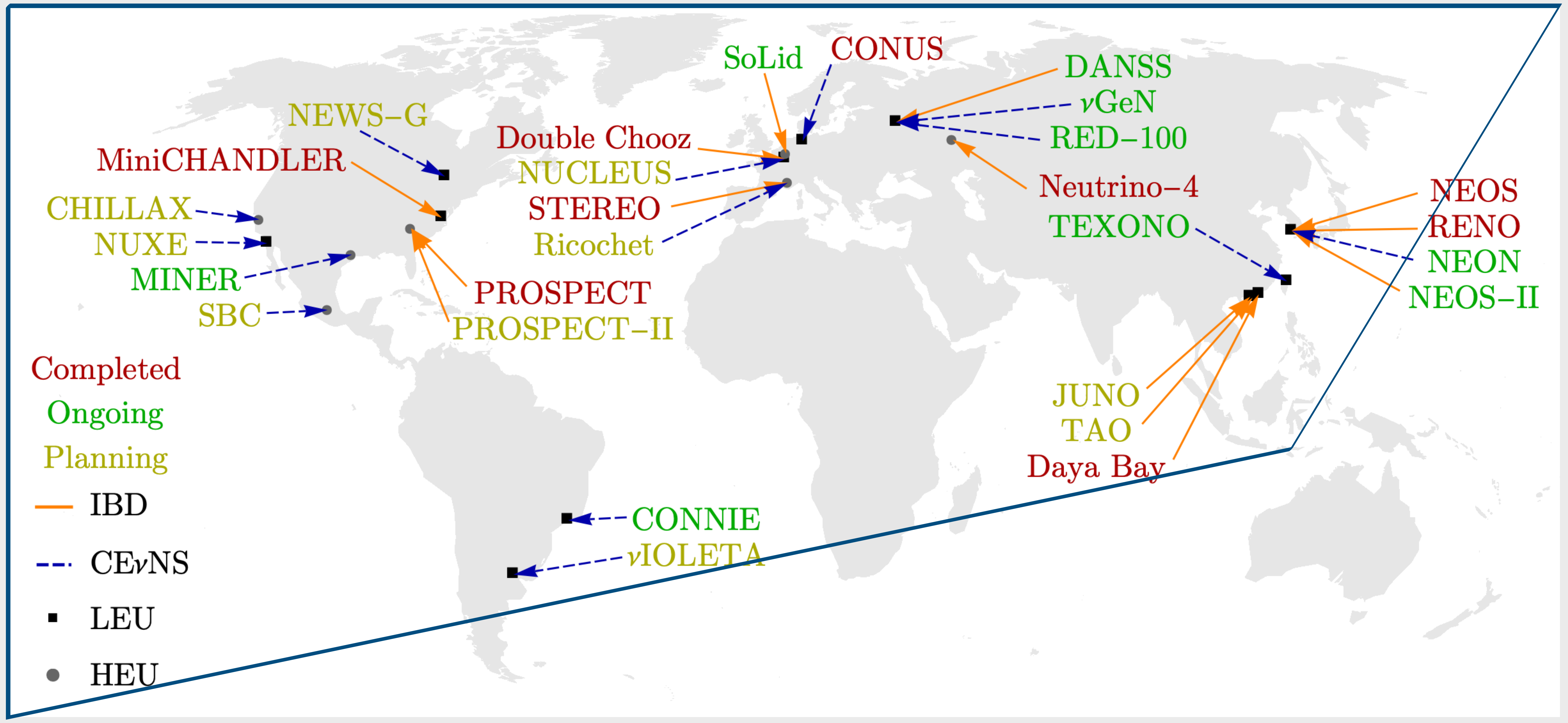


HEP Physics Opportunities Using Reactor Antineutrinos

The Reactor Antineutrino Anomaly

In 2011, short-baseline reactor experiments were reinterpreted [5] with updated predictions for the antineutrino flux [6,7] — and came up 5.7(2.3)% short! This is the *Reactor Antineutrino Anomaly (RAA)*. This can be interpreted as *modest* evidence in favor of a sterile neutrino.

The antineutrino fluxes have been intensely scrutinized. Models based on different techniques [8,9] disagree in the level of discrepancy — but recent measurements from Kurchatov Institute (KI) [10,11] imply that these *may* be starting to converge.

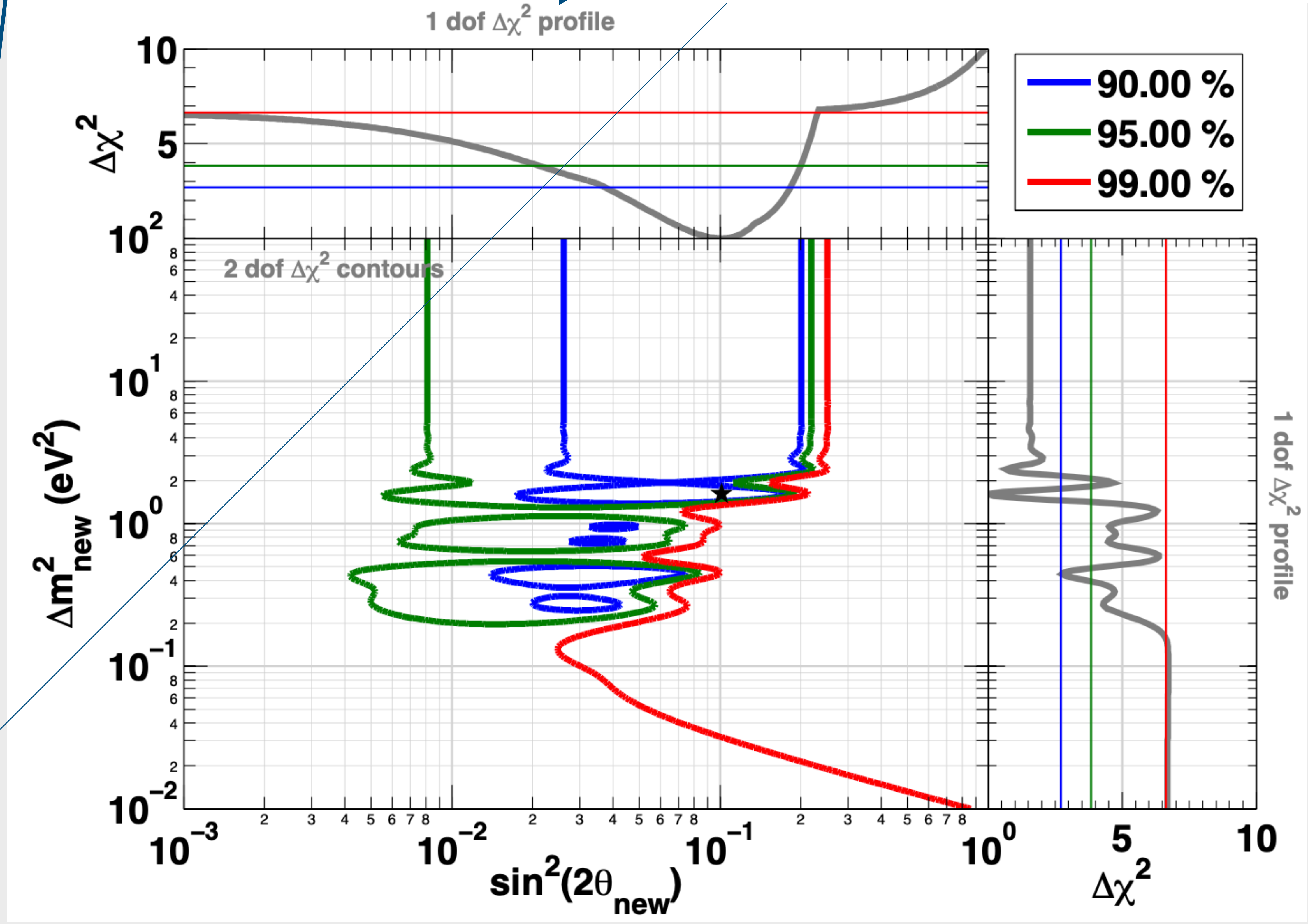
A recent study [12] has explicitly calculated the severity of the RAA for several flux models and finds that

A. flux models based on modern data imply *no significant deficit*; and

B. there still exists room for a nonstandard contribution at the level ~5-10%.

The punchline: *the RAA is not quite dead, but it's probably on life support!*

$$P_{ee} \simeq 1 - \sin^2 2\theta_{ee} \sin^2\left(\frac{\Delta m^2_{41} L}{4E_\nu}\right)$$



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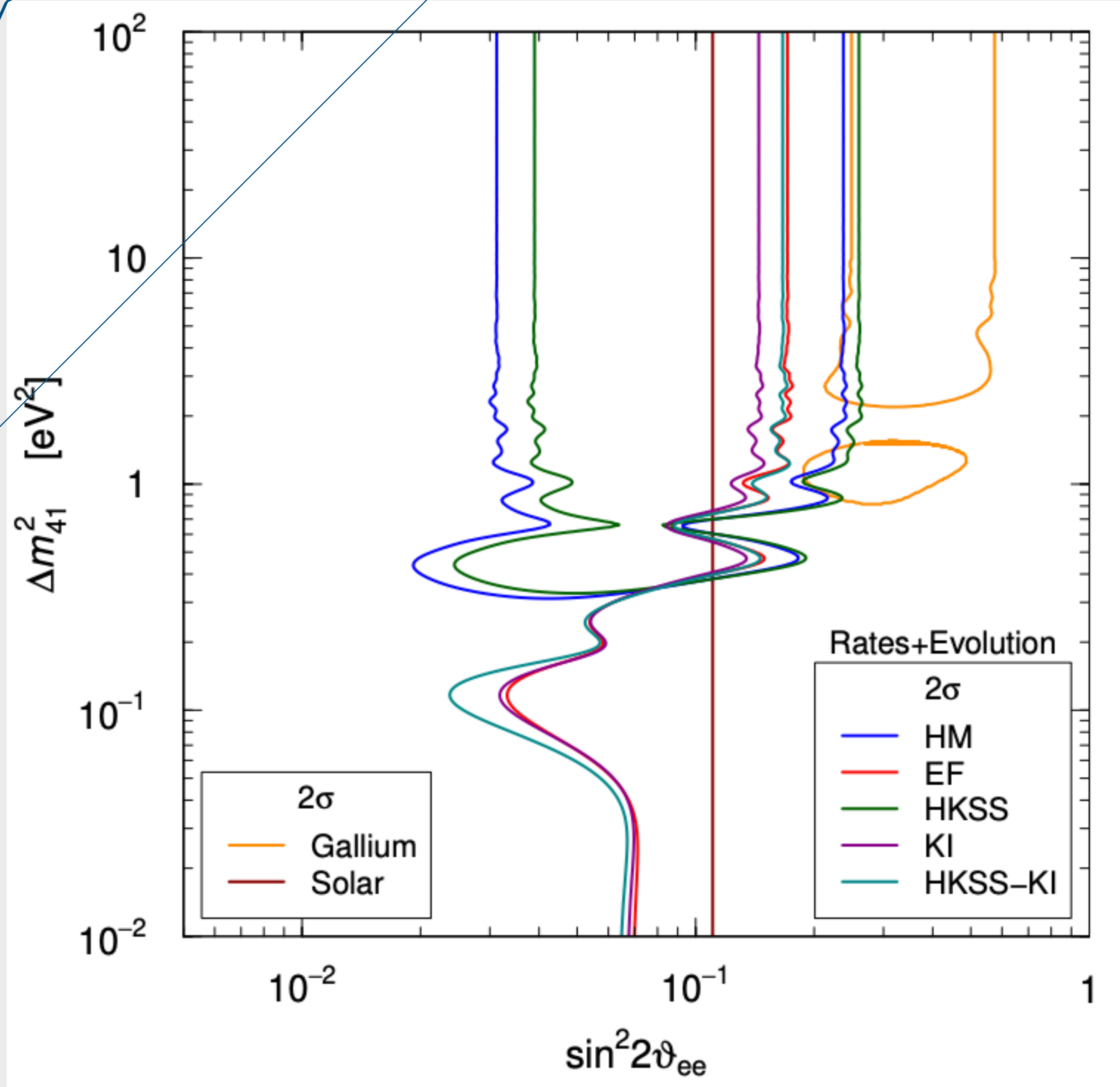
	Flux Model	R	Significance	2σ Limit on $\sin^2 2\theta_{ee}$
[6,7]	HM	$0.930^{+0.024}_{-0.023}$	2.8σ	[0.031, 0.236]
[8]	EF	$0.975^{+0.032}_{-0.030}$	0.8σ	< 0.170
[9]	HKSS	$0.922^{+0.024}_{-0.023}$	3.0σ	[0.039, 0.259]
[10,11]	KI	0.970 ± 0.021	1.4σ	< 0.144
[12]	HKSS-KI	$0.960^{+0.022}_{-0.021}$	1.8σ	< 0.166



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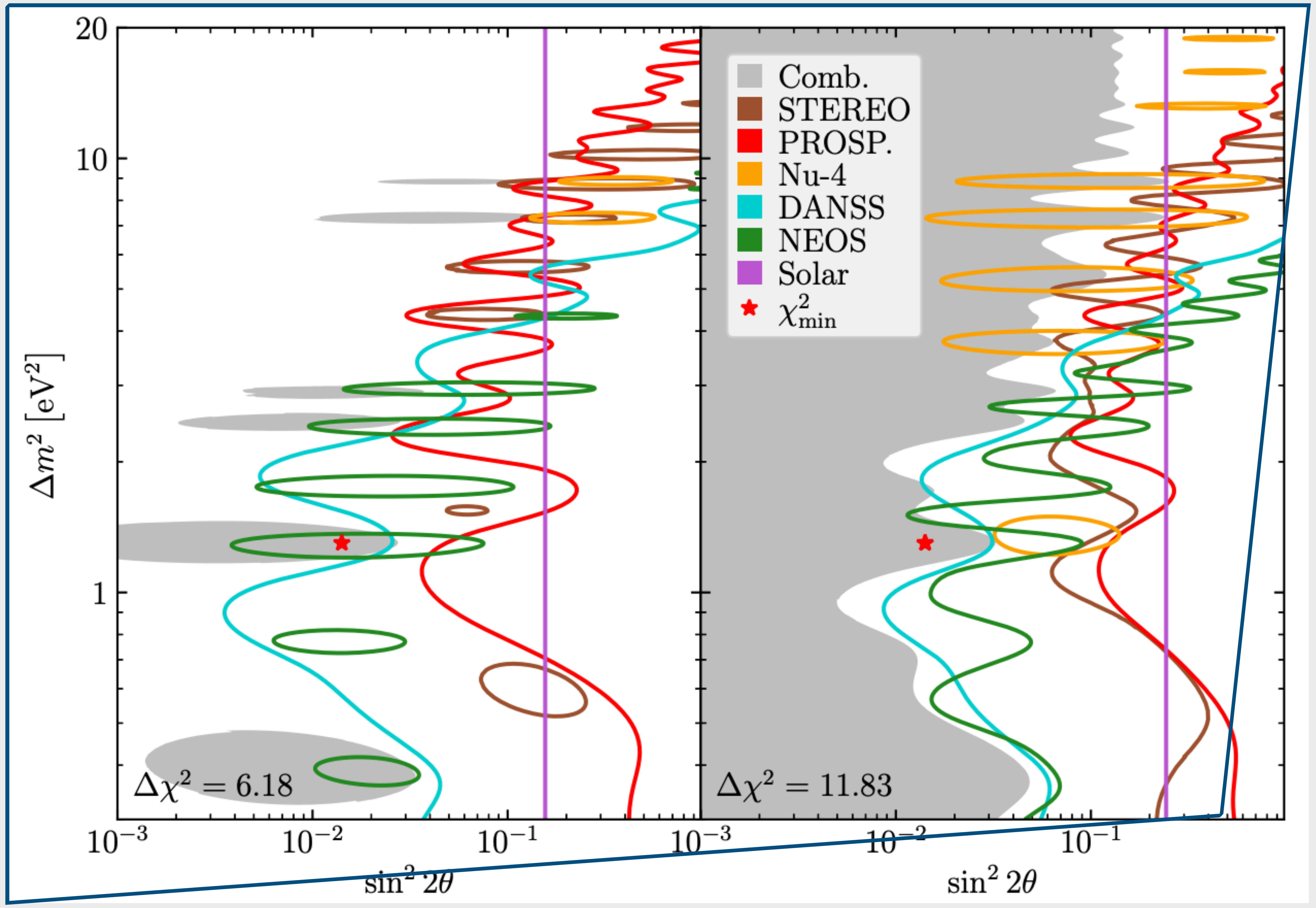
Reactor Spectral Ratios



That said, anomalous ν_e appearance at LSND and MiniBooNE can be interpreted as indications of new oscillations at the eV scale. This hypothesis can be more robustly tested at reactors using *ratios of measured spectra* at *short baselines* (L ≲ 25 m).

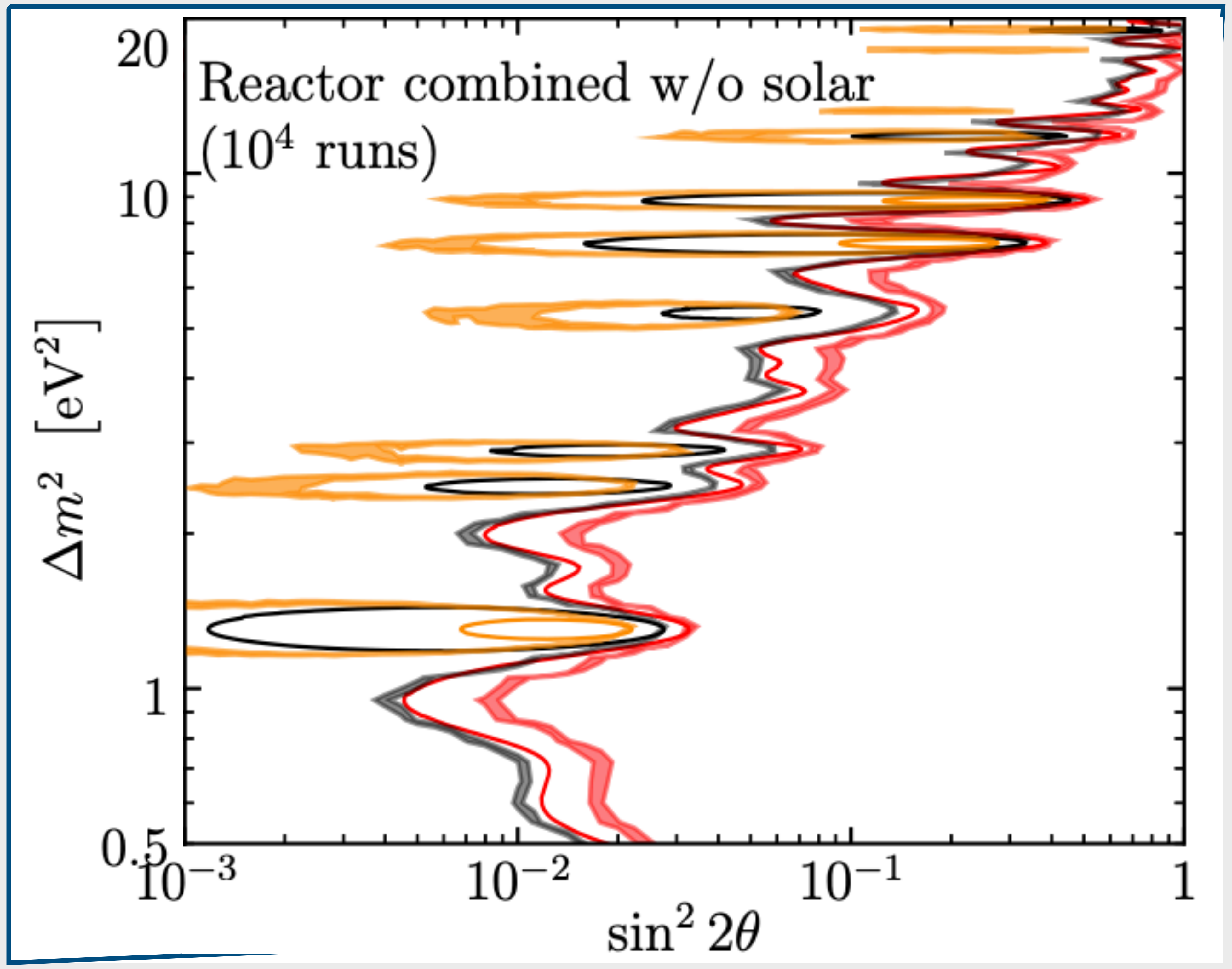
Prior to 2021, combined analyses of spectral ratios yielded ≳3σ hints of nonstandard oscillations [13-16]. However, a combination of more data from more experiments and improved statistical methods [17-20] implies that this is more appropriately ≳1σ — *which is obviously quite a bit less*!

Therefore, *reactor spectral ratios place a strong constraint on sterile-neutrino interpretations of LSND and MiniBooNE!*

JMB et al., arXiv:2111.12530

Reactor Spectral Ratios

	$\chi^2_{\rm min}/{\rm dof}$	$\Delta m^2_{\rm min}$	$\sin^2(2\theta_{\rm min})$	$\Delta\chi^2_{3\nu}$	p_0	$\#\sigma$	$\#\sigma^{(W)}$
REACTORS	428/421	8.86 eV^2	0.26	7.3	27.4%	1.1	2.2
W/ Solar	432/425	1.30 eV^2	0.014	6.6	17.8%	1.3	2.1



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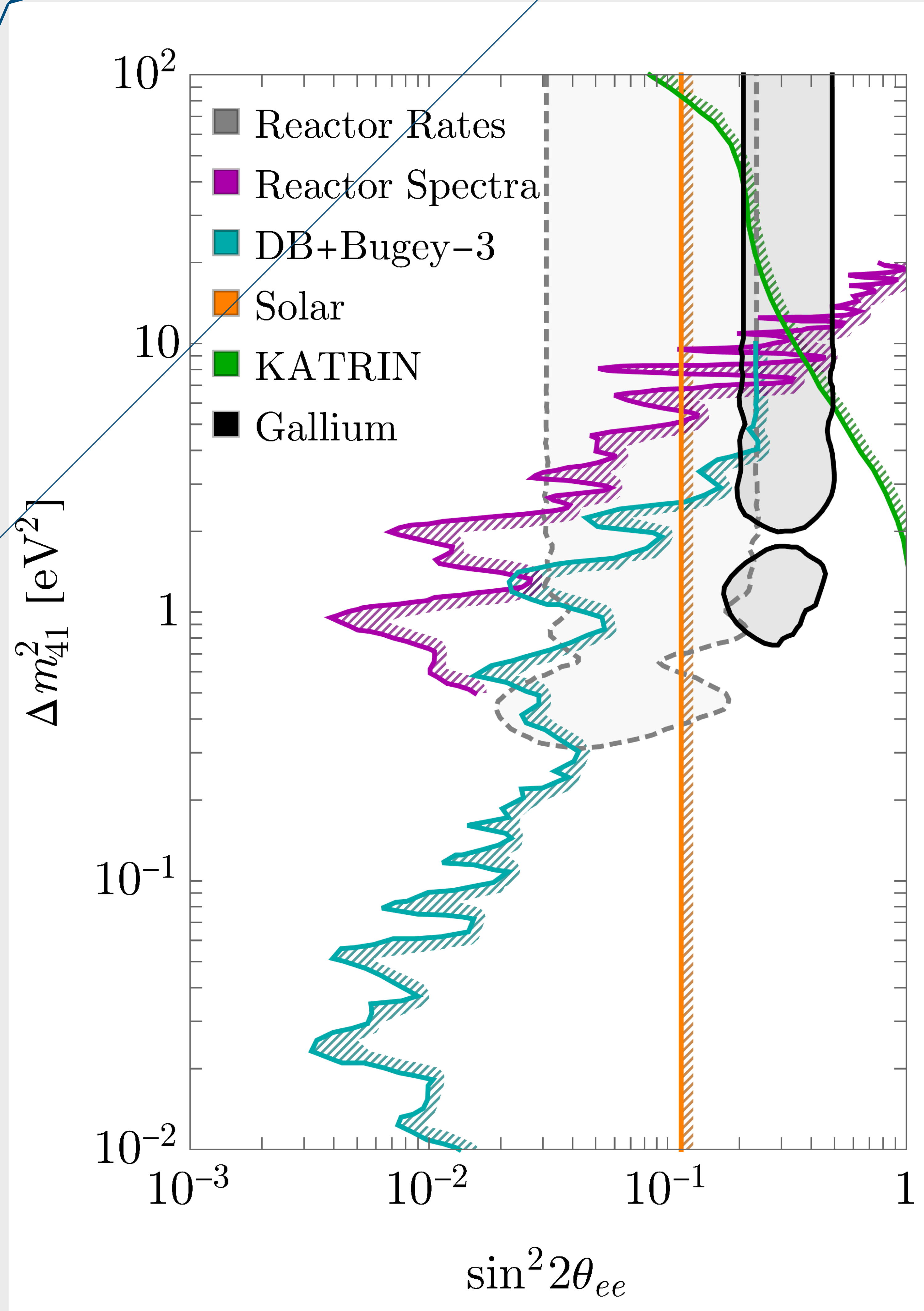
The Status of ν_e Disappearance Searches

Here's a full(ish) picture of ν_e disappearance:

- Reactors are fully consistent with solar experiments [21] — push towards smaller values of $\sin^2 2\vartheta_{ee}$.
- Reactors are *also* fully consistent with anomalous signal from BEST [22-24] and other gallium experiments — push towards larger Δm^2_{41}.
- Clearly, *solar and gallium experiments are quite unhappy with one another!* This tension amounts to ≳3σ [20].
- KATRIN [25] constrains the high-Δm^2_{41} space (≳ 20 eV²) — the gallium region is under *even more* tension!
- Also some pressure from ν_e–^{12}C scattering, T2K and MicroBooNE; these are a bit more complicated to interpret because they receive ν_μ contributions.
- By the way, cosmology is *very* unhappy for sterile neutrinos to exist in this range of masses and mixings [26].



A coherent explanation of the anomalies has yet to emerge, but it's clear that 3+1 doesn't cut it!

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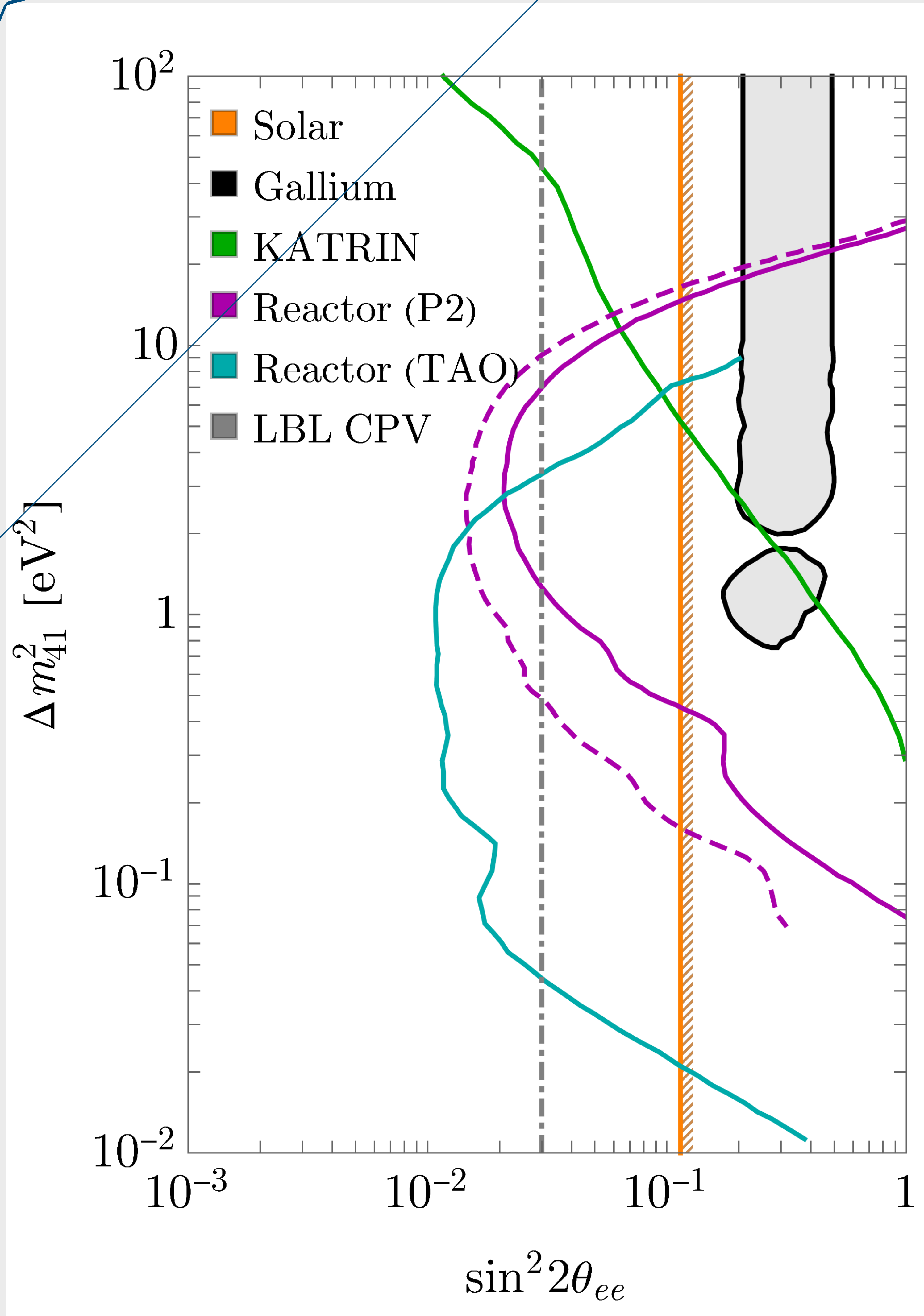

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Looking to the Future

What else could possibly explain the anomalies?

- *Additional sterile species?*
- *Decay of the sterile neutrino?*
- *Nonstandard interactions?*
- *Coupling to hidden sector/dark matter?*
- *Assuredly many, many others!*

Aside from the *existing* anomalies, what other (new) physics scenarios can be probed with reactors?

- *Decoherence of the neutrino wave packet [27-29]*
- *Violation of CPT, Lorentz invariance [30,31]*
- *The existence of large extra dimensions [32]*
- *Again, many others!*

More broadly, *what is it about nuclear reactors that makes them well suited to study neutrino physics, both new and old*?

A. They're a *flavor-pure* source of (anti)neutrinos.

B. They're (largely) uninfluenced by *matter effects*, even at (and beyond) medium baselines.

C. The *low energies* allow oscillations to develop more prominently over shorter distances, and make the final states relatively simple to characterize.

D. They're relatively *inexpensive* — the reactors are built for other purposes (e.g., power generation), so one really only needs to procure a detector.

These features have made – and will continue to make – reactors an important piece of the overall puzzle of neutrino physics!

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