The Sterile Neutrino is Dead; Long Live the Sterile Neutrino!

Jeff Berryman, University of Kentucky & University of California, Berkeley
N3AS Weekly Seminar
18 August, 2020

Prologue

The literature concerning sterile neutrinos is *incredibly vast* — and I only have a half an hour to cover the most interesting parts! Let me point the curious attendee to the following reviews and references therein:

C. Giunti & T. Lasserre, Ann. Rev. Nucl. Part. Sci. 69 (2019) 163
A. Diaz, et al., arXiv:1906.00045
S. Böser, et al., Prog. Part. Nucl. Phys. 111 (2020) 103736

Moreover, check the Neutrino 2020 Indico page if you're interested in more up-to-date information on sterile neutrino searches and other aspects of neutrino physics:

https://indico.fnal.gov/event/43209/

Also consider reading https://physics.aps.org/articles/v13/123 (V. Niro and P. A. N. Machado)

Where are We and How Did We Get Here?

Motivation

We have *empirical evidence* that there must be more to Nature than what is described by the Standard Model — dark matter, dark energy, etc. — but we only know how to study *one such phenomenon* in the laboratory:

The existence of nonzero neutrino masses!

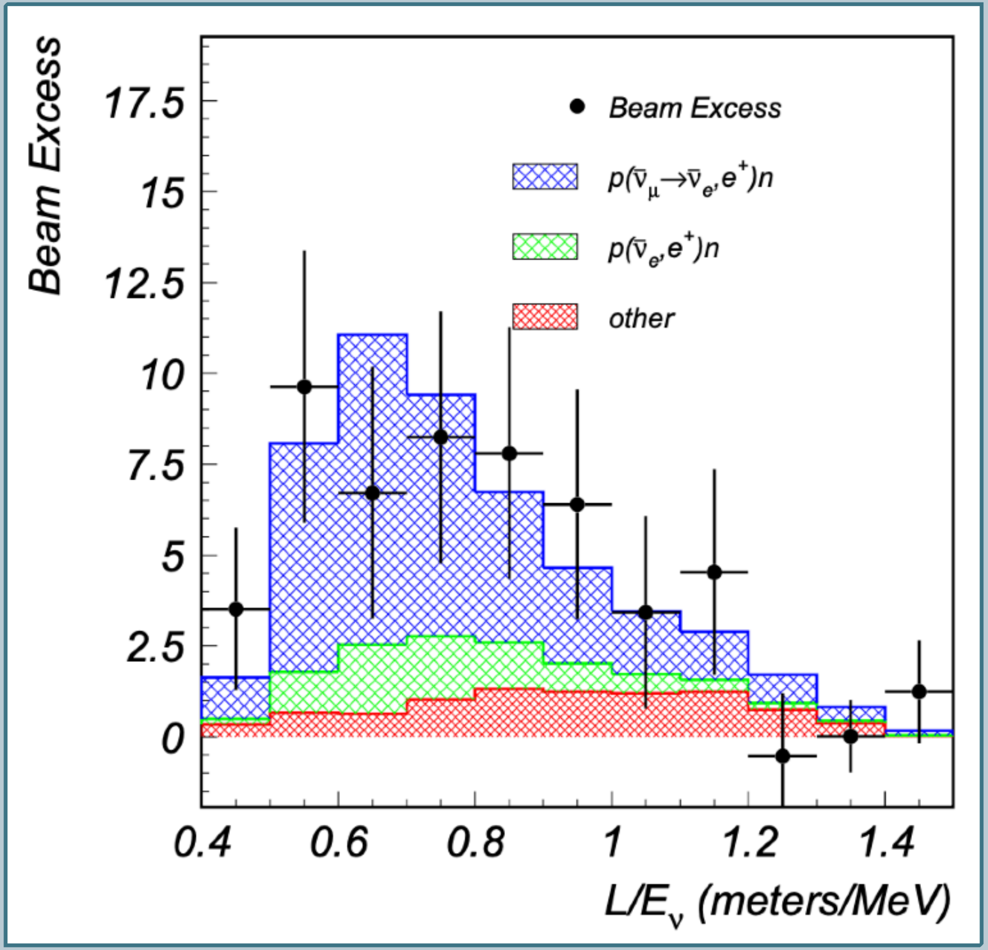
The big question is: Are neutrino masses generated by a *qualitatively different mechanism* than those of the other fermions?

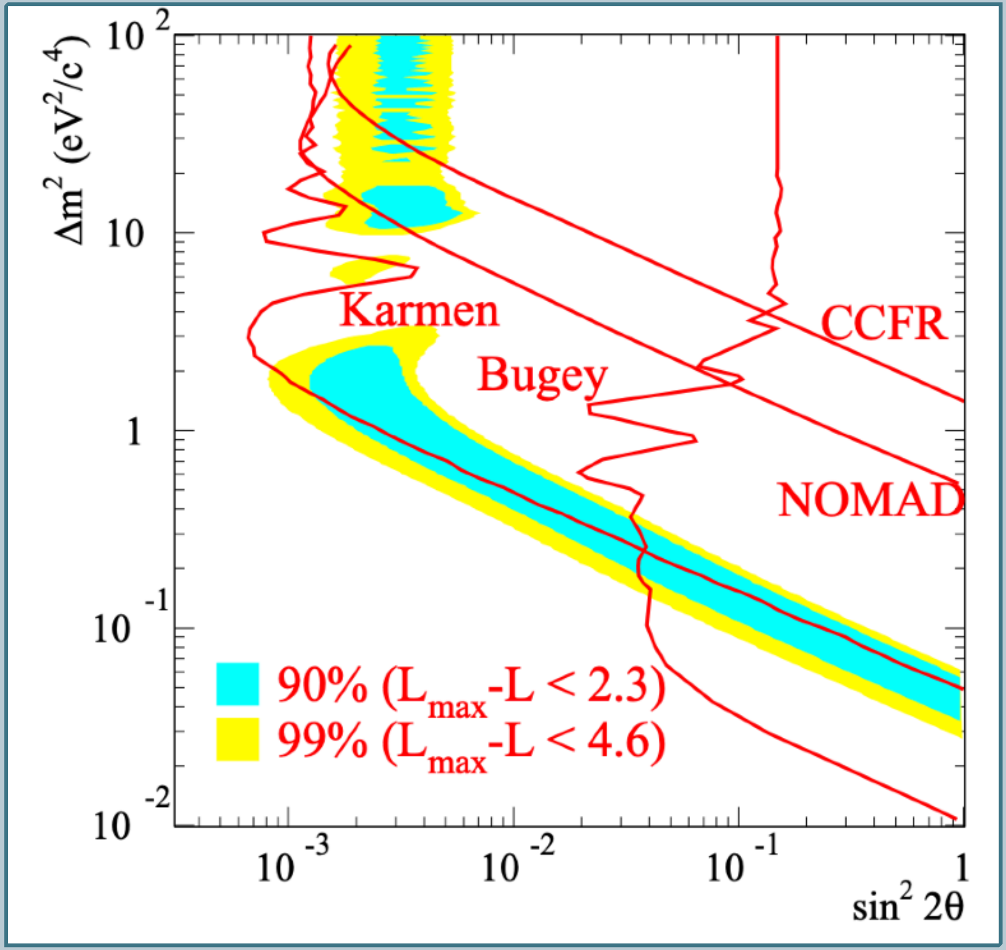
If the answer is *yes*, then there ought to be *related phenomena* which we can probe by studying neutrinos in enough different ways

One possible such phenomenon (which need not necessarily be realized!) is the existence of *additional neutrino states* that are visible at the energy scales accessible in our terrestrial experiment

Some History – LSND

LSND searched for ~eV-scale neutrino oscillations using an intense proton beam and pion decays — and *claims* to have a positive signal at 3.8σ!





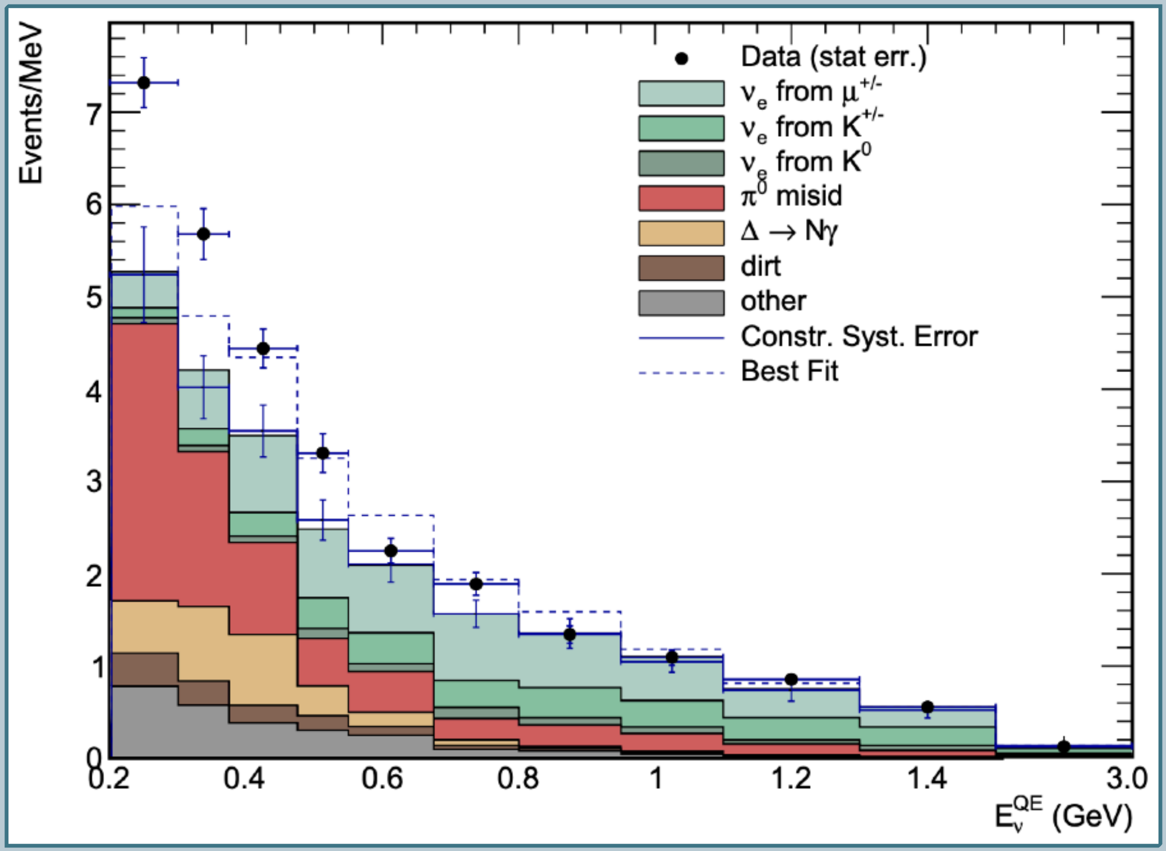
NB: In the *two-neutrino limit*, the *appearance* probability is given by

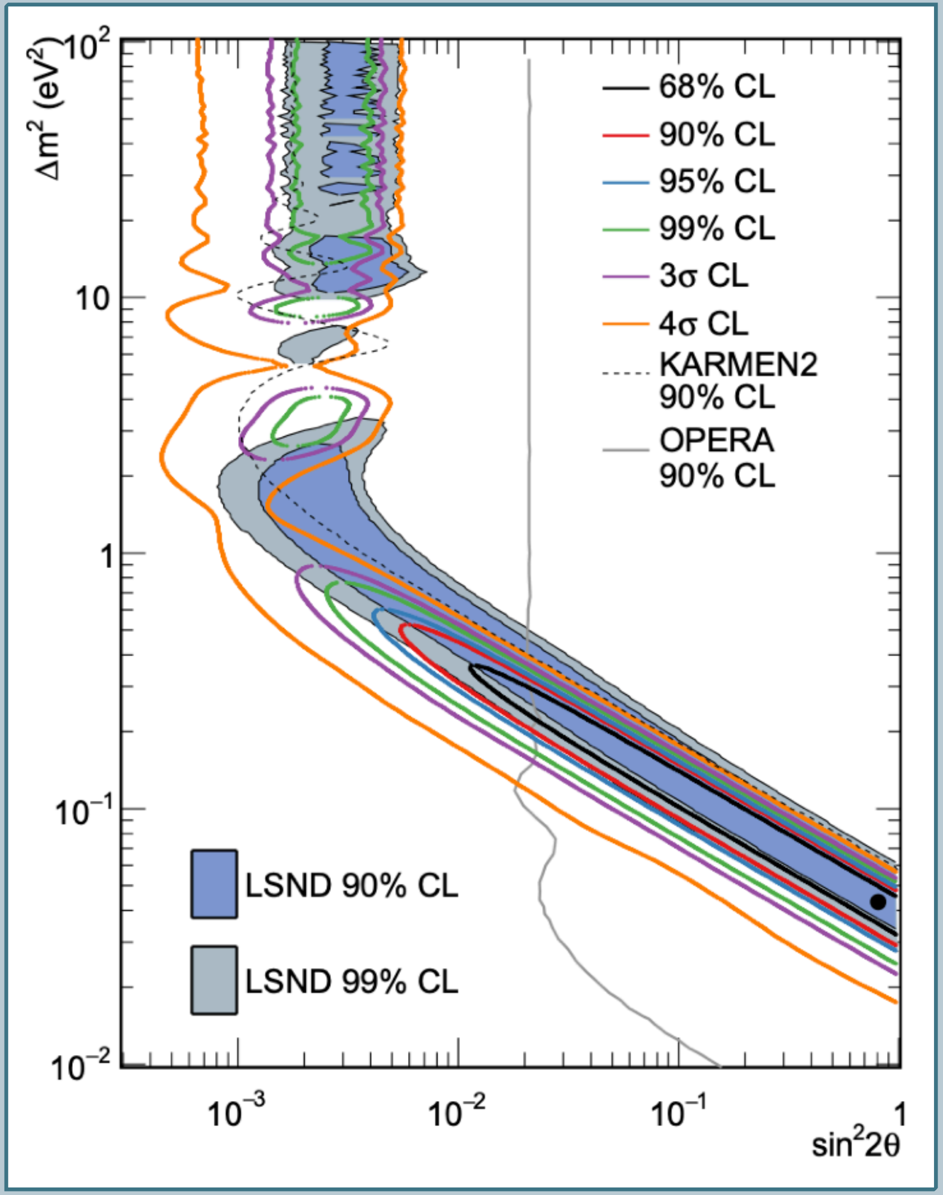
$$P\left(\nu_\alpha \to \nu_\beta\right) = 4|U_{\alpha 4}|^2|U_{\beta 4}|^2 \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right) \equiv \sin^2 2\theta_{\alpha\beta} \sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

LSND Collaboration, PRD 64 (2001) 112007

MiniBooNE

MiniBooNE has been the successor to LSND — different technology (accelerator neutrinos vs. πDAR), but *same regime of L/E!*





The upshot: MiniBooNE data contain an anomaly at the level of 4.8σ!

Largely consistent with LSND — for better or worse!

MiniBooNE Collaboration, arXiv:2006.16883;
A. Hourlier @ Neutrino 2020

Gallium Anomalies

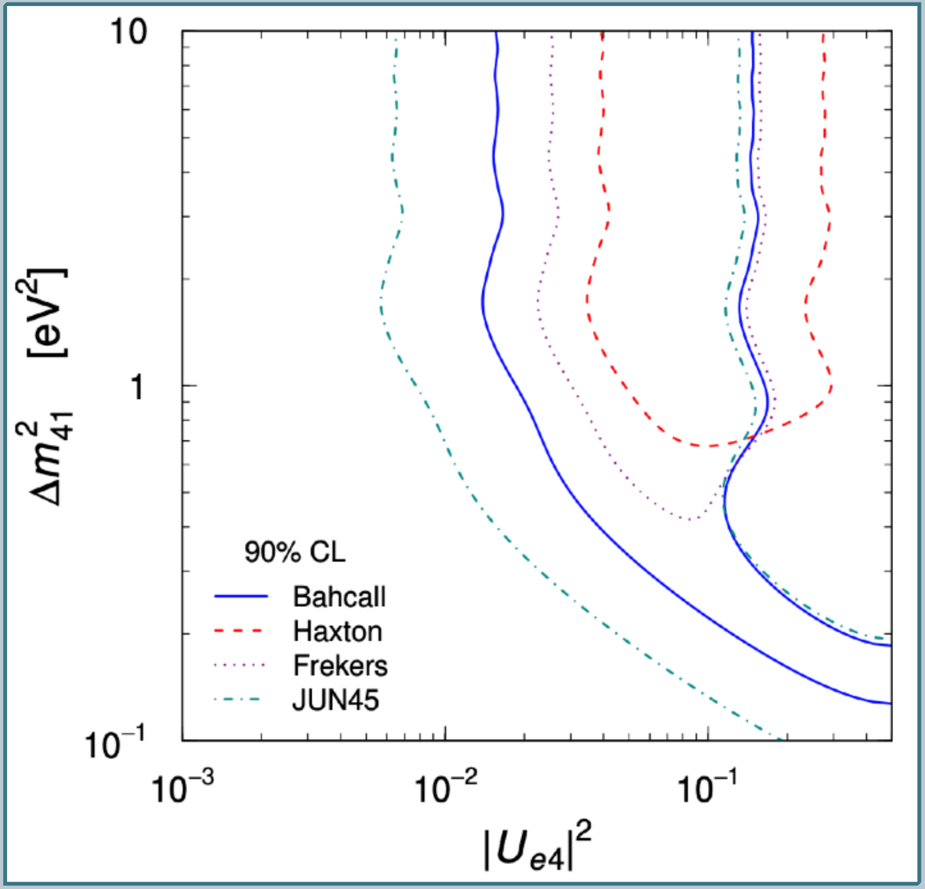
In preparation for their use as solar neutrino experiments, SAGE and GALLEX used ^{37}Ar and ^{51}Cr electron-capture sources for calibration

	GALLEX-1	GALLEX-2	SAGE-1	SAGE-2	Average	Anomaly
R_{Bahcall}	0.95 ± 0.11	0.81 ± 0.11	0.95 ± 0.12	0.79 ± 0.08	0.85 ± 0.06	2.6σ
R_{Haxton}	0.86 ± 0.13	0.74 ± 0.12	0.86 ± 0.14	0.72 ± 0.10	0.76 ± 0.10	2.5σ
R_{Frekers}	0.93 ± 0.11	0.79 ± 0.11	0.93 ± 0.12	0.77 ± 0.08	0.84 ± 0.05	3.0σ
R_{JUN45}	0.97 ± 0.11	0.83 ± 0.11	0.97 ± 0.12	0.81 ± 0.08	0.88 ± 0.05	2.3σ

The rows correspond to different predictions of the signal cross section:

$$^{71}\text{Ga}\left(\nu_e, e^-\right)^{71}\text{Ge}$$

The dominant theoretical uncertainty involves relative transition strengths to excited states of ^{71}Ge



$$P(\nu_\alpha \to \nu_\alpha) = 1 - 4|U_{\alpha 4}|^2(1 - |U_{\alpha 4}|^2)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

$$\equiv 1 - \sin^2 2\theta_{\alpha\alpha}\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

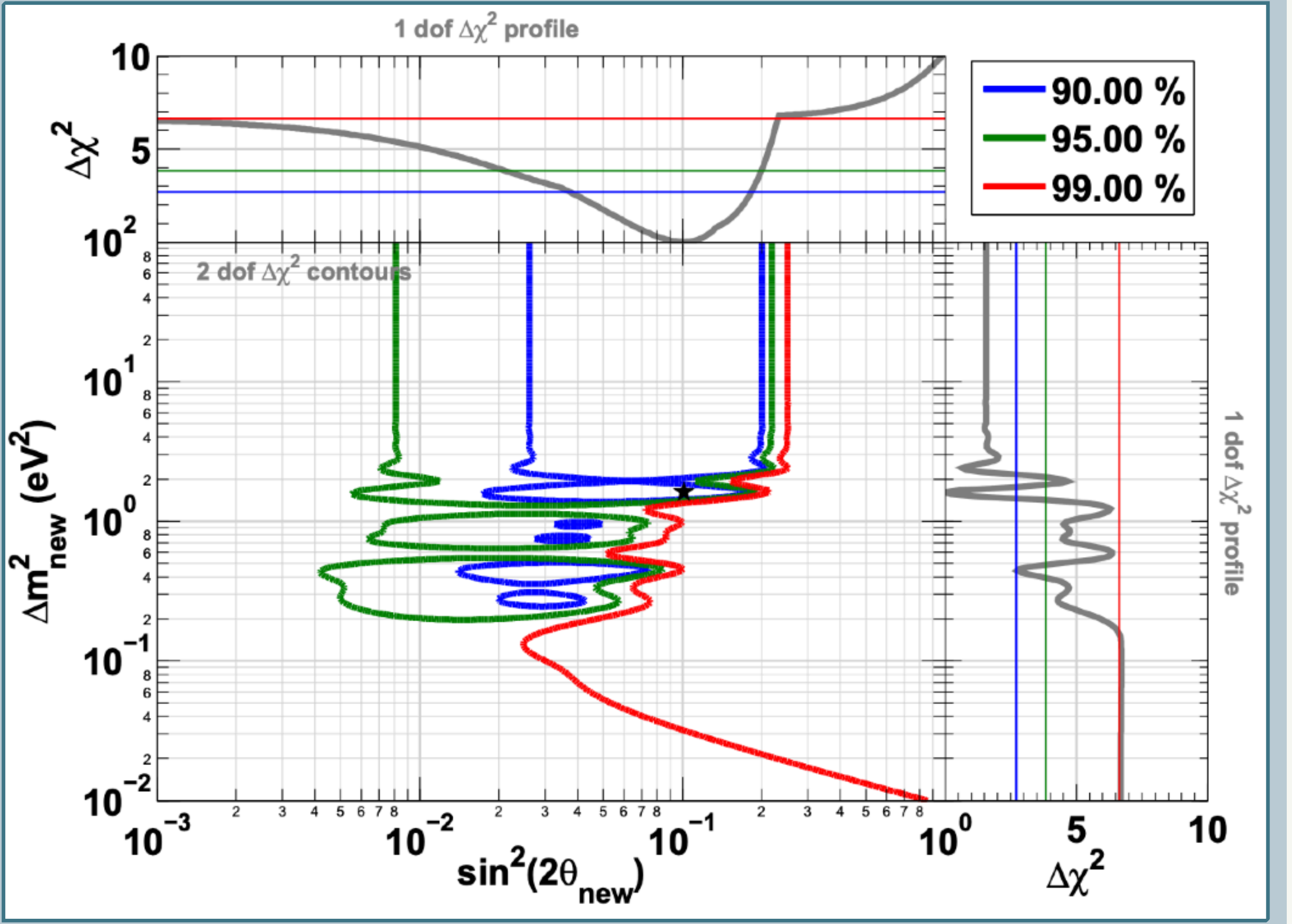
J. Kostensalo, et al., Phys. Lett. B 795 (2019) 542

Legacy Reactor Experiments

Nuclear reactors produce electron antineutrinos in abundance; a typical power reactor produces ~$O(10^{20})$ per second. The price, however, is that our knowledge of the flux of these antineutrinos is *relatively uncertain* (~2-3% level)

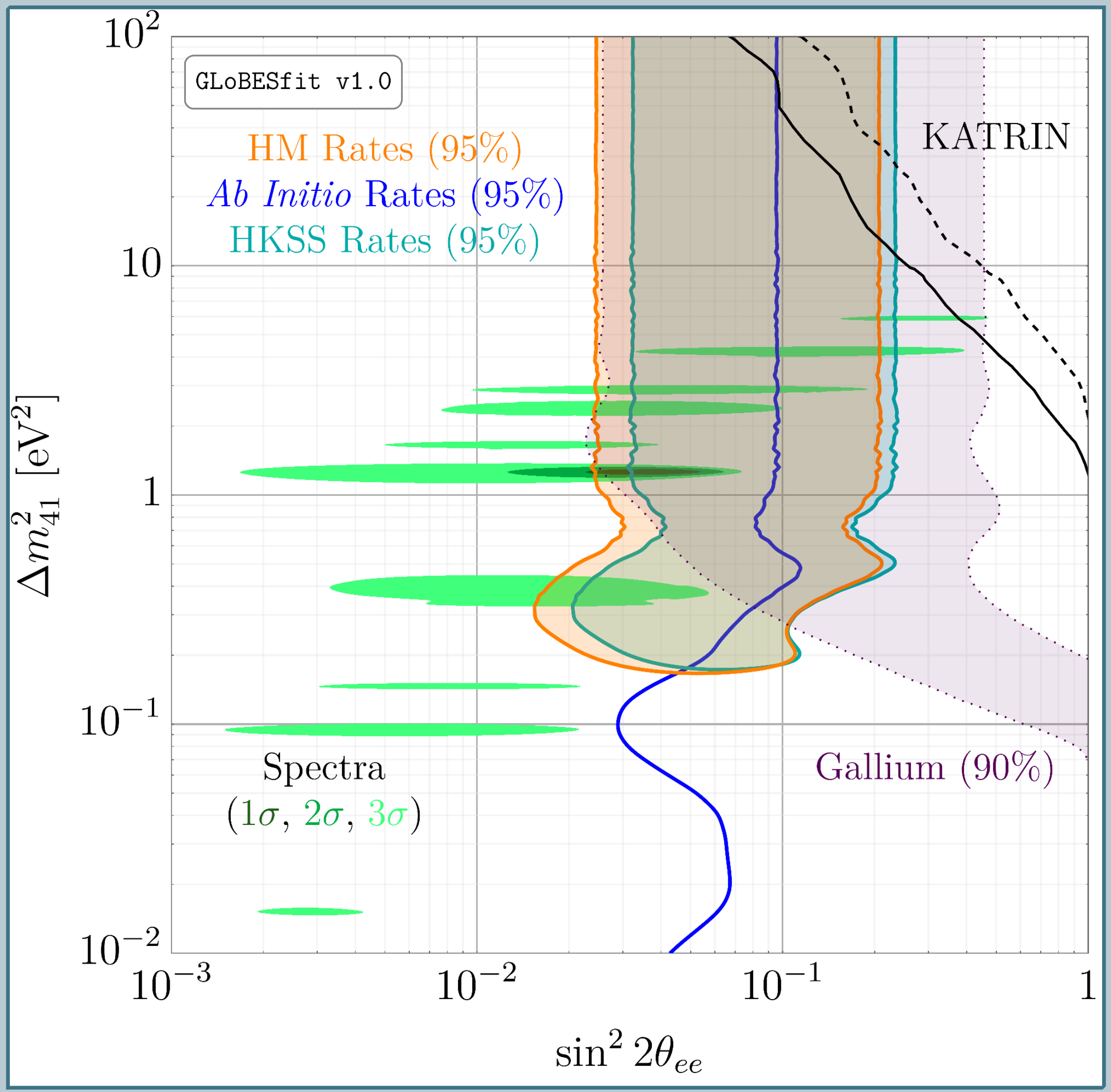
Reactor experiments from the 1980s-1990s show a *clear* deficit with respect to older predictions (but how good are these predictions?)

This is referred to as *the reactor antineutrino anomaly*



G. Mention, et al., PRD 83 (2011) 073006;

Modern Reactor Experiments



In addition to measurements of *absolute event rates*, modern detectors can measure *event spectra*

Looking at *ratios* of the spectra measured at two positions mitigates uncertainties stemming from the reactor flux

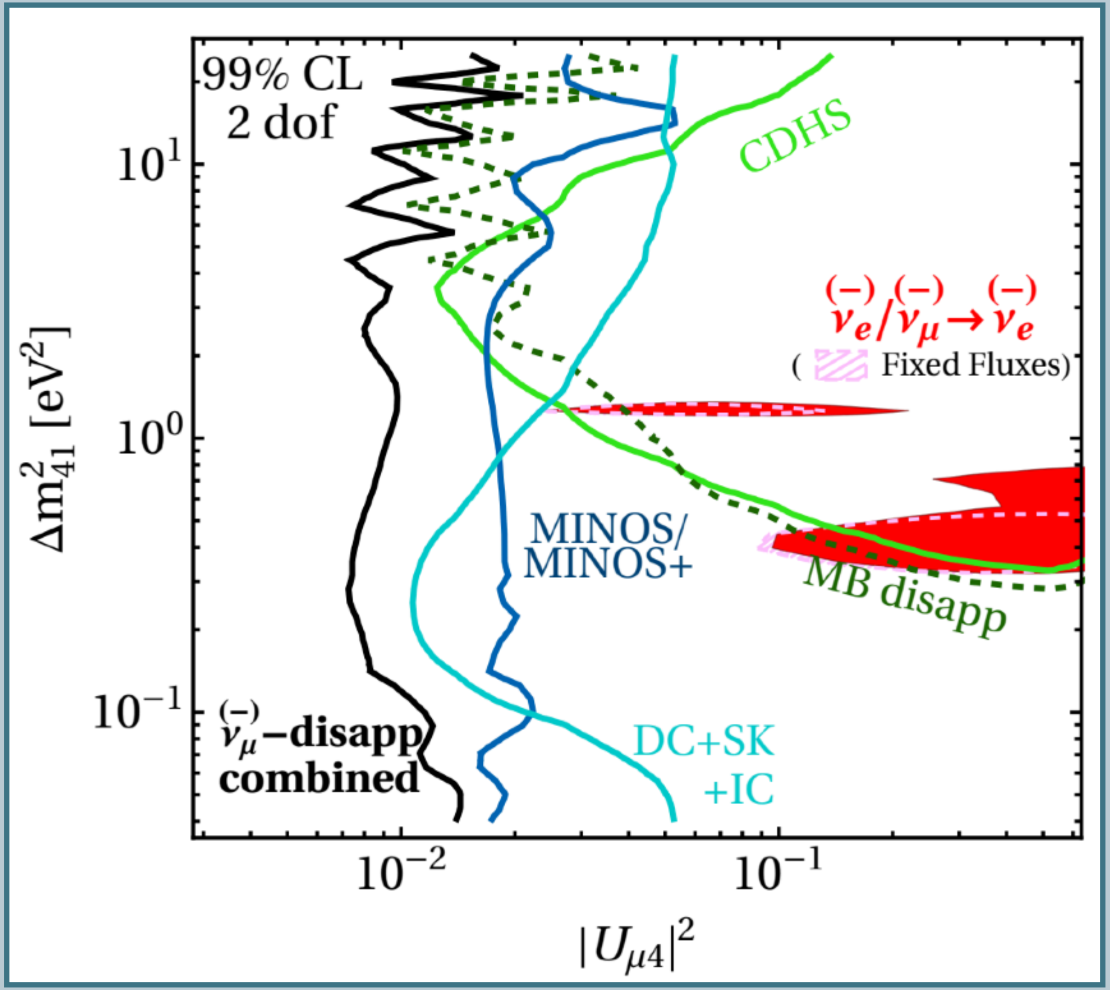
These *seem* to suggest a moderate preference for a sterile neutrino, but there are issues with the statistical interpretation of these data – more on this later…

NB: This analysis does not account for recent results from PROSPECT, STEREO, Neutrino-4 — check back soon!
NB: Constraints from solar and ^{12}C experiments also exist, but no positive signals

JMB & P. Huber, PRD 101 (2020) 015008 & arXiv:2005.01756;
J. Kostensalo, et al., Phys. Lett. B 795 (2019) 542; C. Giunti, et al., JHEP 05 (2020) 061

So What's the Problem?

The appearance anomalies are *inconsistent* with the disappearance anomalies — particularly due to the lack of any anomalous ν_μ disappearance!



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M. Dentler, et al., JHEP 08 (2018) 010;
see also MINOS+ and Daya Bay Collaborations, PRL 125 (2020) 071801

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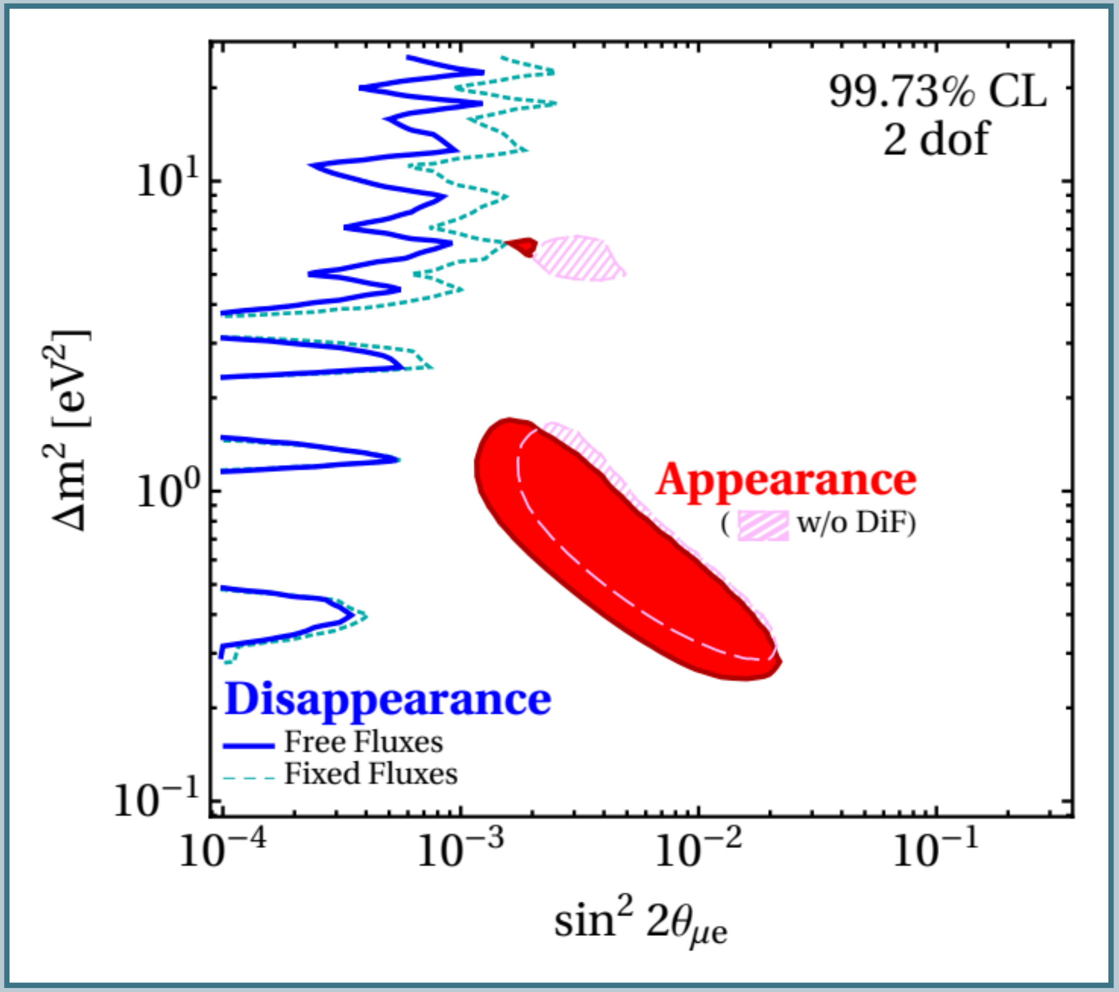

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Global	1120.9	79.1	11.9	1012.2	17.7	29.6/2	3.71×10^{-7}
Removing anomalous data sets							
w/o LSND	1099.2	86.8	12.8	1012.2	0.1	12.9/2	1.6×10^{-3}
w/o MiniBooNE	1012.2	40.7	8.3	947.2	16.1	24.4/2	5.2×10^{-6}
w/o reactors	925.1	79.1	12.2	833.8	8.1	20.3/2	3.8×10^{-5}
w/o gallium	1116.0	79.1	13.8	1003.1	20.1	33.9/2	4.4×10^{-8}
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w/o IceCube	920.8	79.1	11.9	812.4	17.5	29.4/2	4.2×10^{-7}
w/o MINOS(+)	1052.1	79.1	15.6	948.6	8.94	24.5/2	4.7×10^{-6}
w/o MB disapp	1054.9	79.1	14.7	947.2	13.9	28.7/2	6.0×10^{-7}
w/o CDHS	1104.8	79.1	11.9	997.5	16.3	28.2/2	7.5×10^{-7}
Removing classes of data							
$\overset{(-)}{\nu}_e$ dis vs app	628.6	79.1	0.8	542.9	5.8	6.6/2	3.6×10^{-2}
$\overset{(-)}{\nu}_\mu$ dis vs app	564.7	79.1	12.0	468.9	4.7	16.7/2	2.3×10^{-4}
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	13.9	781.7	9.7	23.6/2	7.4×10^{-6}

M. Dentler, et al., JHEP 08 (2018) 010;
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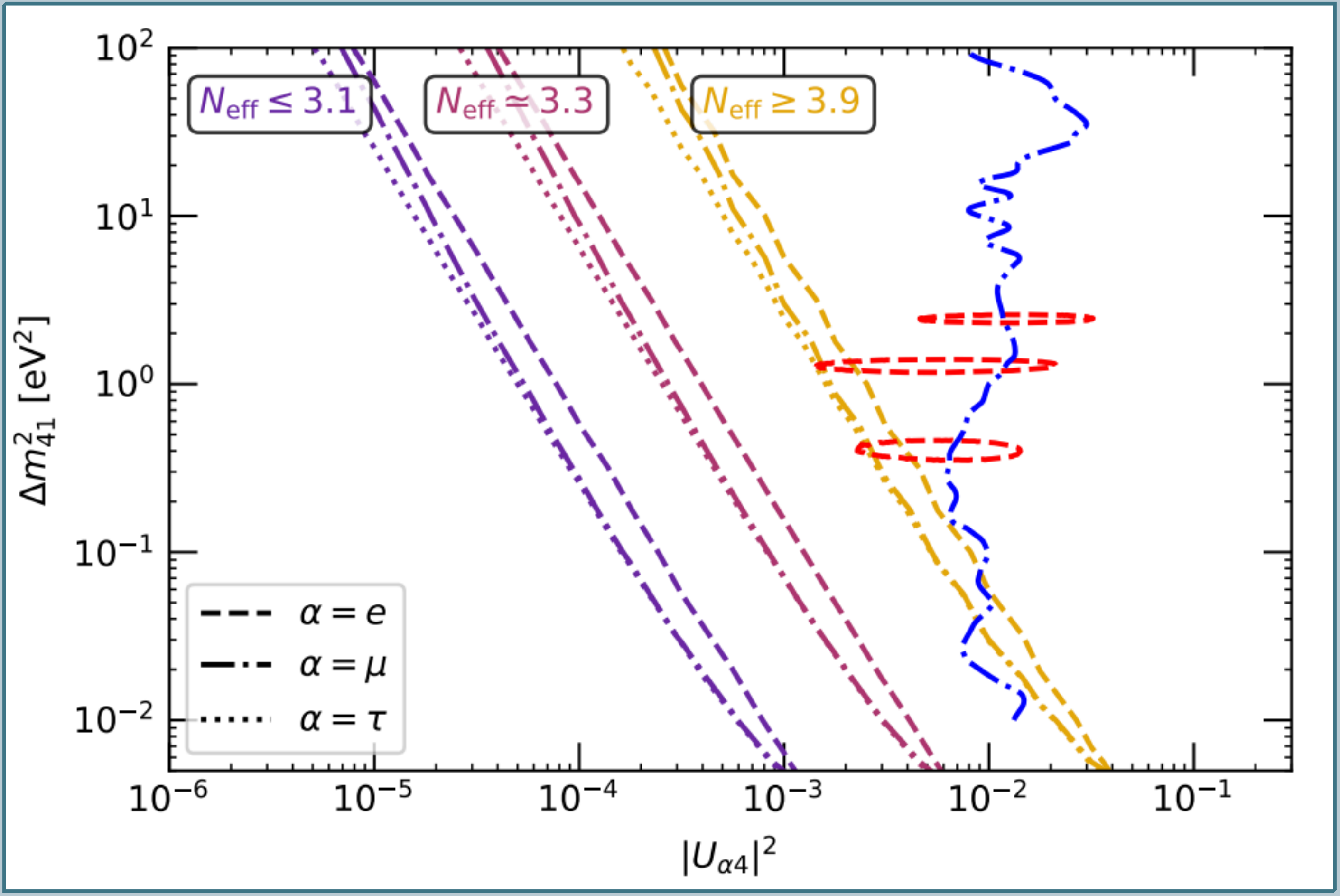
$\overset{(-)}{\nu}_\mu$ dis + solar vs app	884.4	79.1	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

This analysis is a few years old already, but a recent joint analysis of MINOS(+), Bugey and Daya Bay data shows this tension persists!

M. Dentler, et al., JHEP 08 (2018) 010;
see also MINOS+ and Daya Bay Collaborations, PRL 125 (2020) 071801

But Wait, There's More!

If a sterile neutrino with mixings this large existed, then we would expect to have already seen it through its impact on cosmology!



It's not *impossible* to imagine modifications to the thermal history of the universe — but it certainly suggests that *something is amiss* with this picture!

S. Gariazzo, P. F. de Salas & S. Pastore, JCAP 07 (2019) 014; S. Hagstotz, et al., arXiv:2003.02289; JMB, PRD 100 (2019) 023540;

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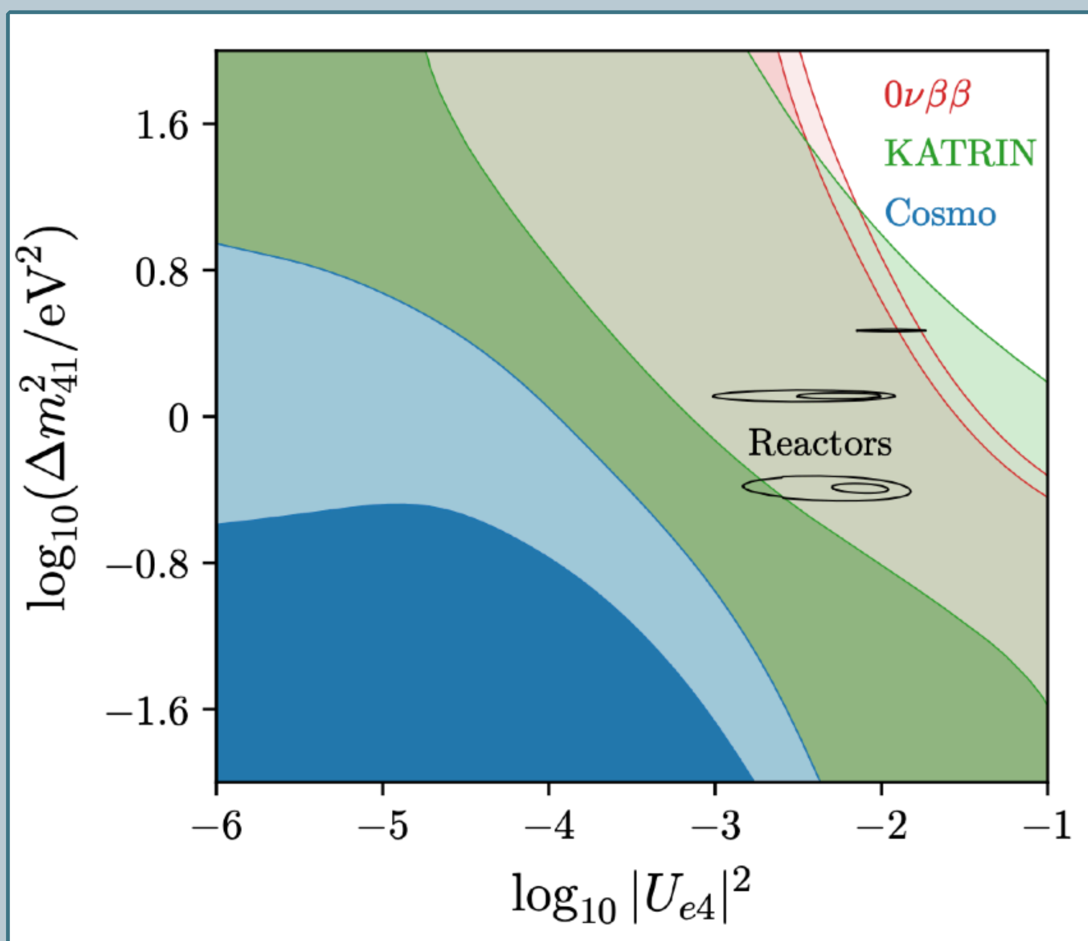

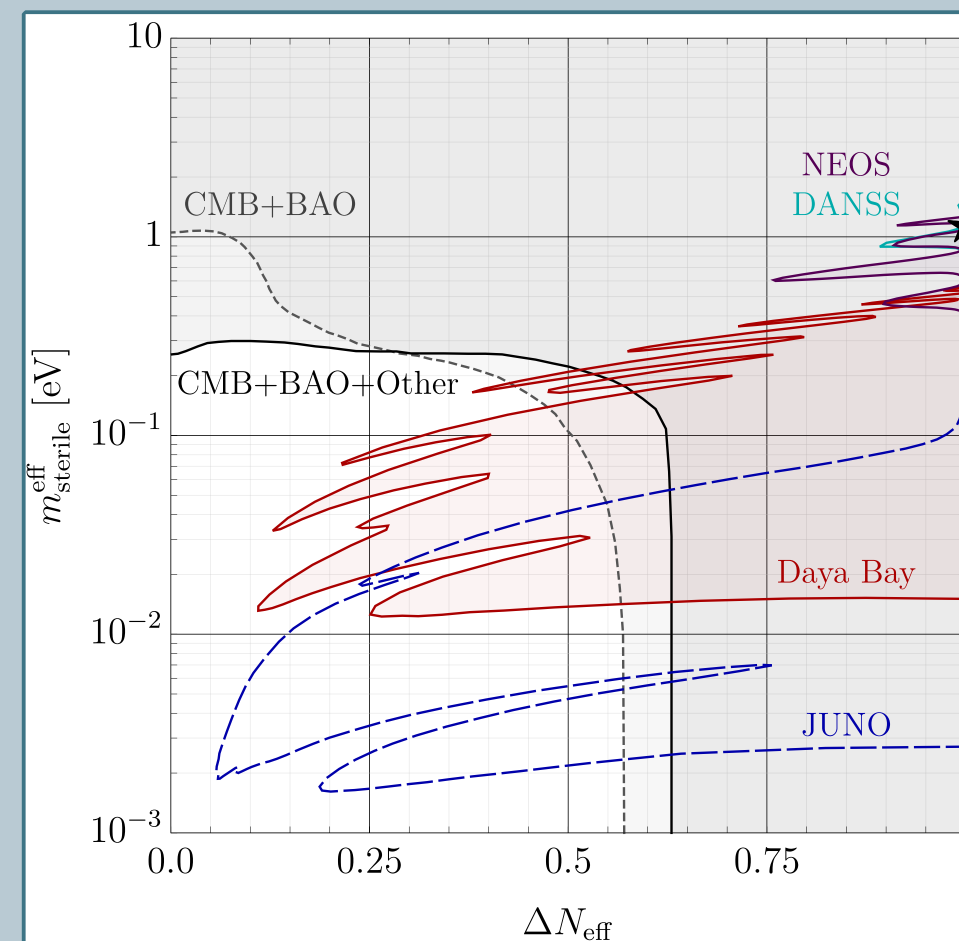

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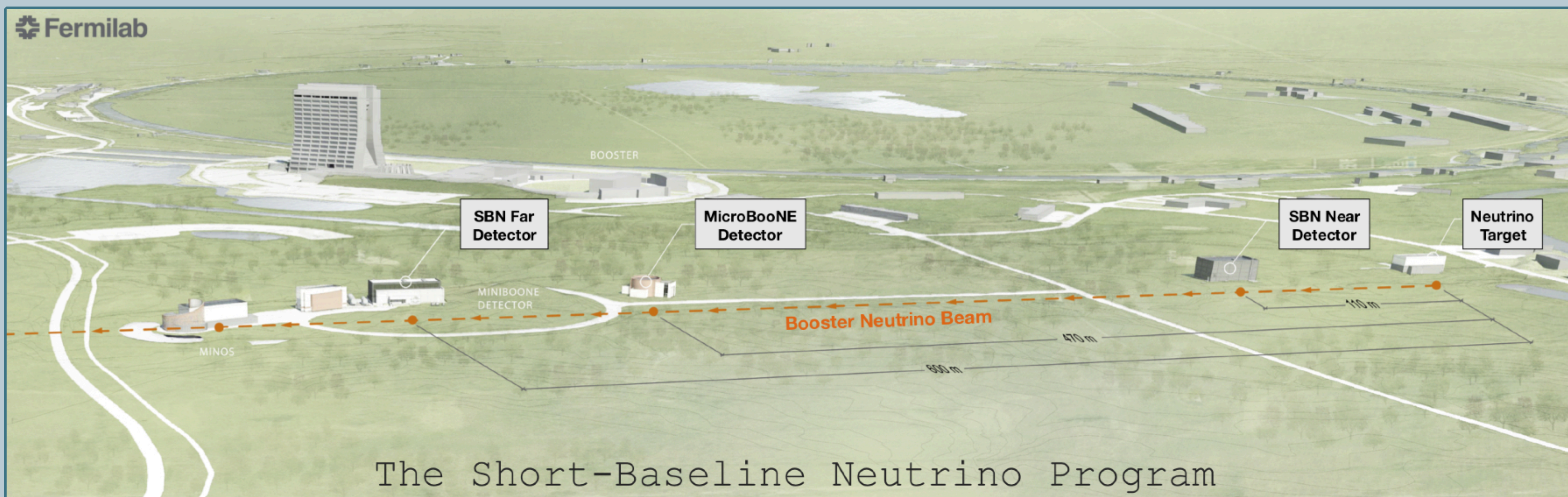
So Now What?

Fermilab Short Baseline Program



Three detectors: SBND (100 m), MicroBooNE (470 m) and ICARUS (600 m)

This may be the best chance we're going to have to probe the LSND anomaly — but it's not our only chance!

P. A. N. Machado, O. Palamara & D. W. Schmitz, Ann. Rev. Nucl. Part. Sci. 69 (2019) 363; see also G. Karagiorgi @ Neutrino 2020

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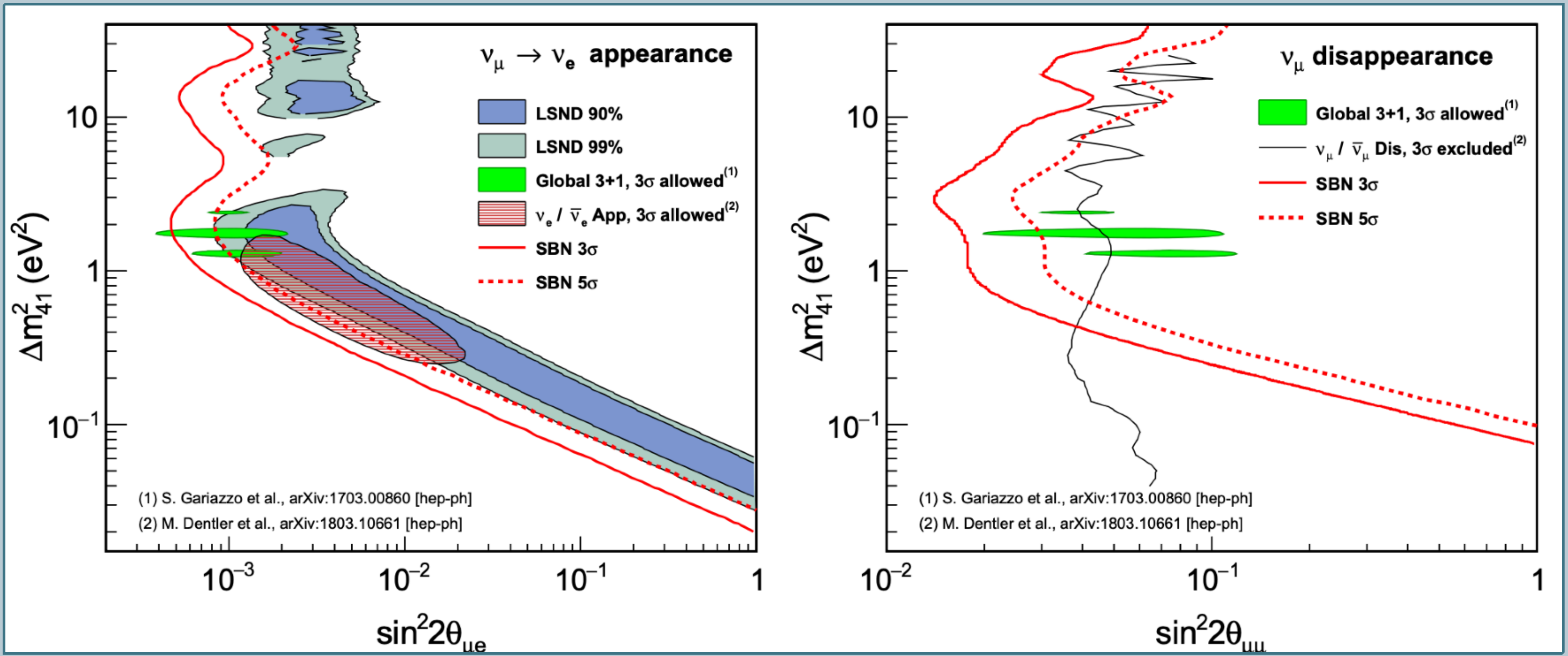

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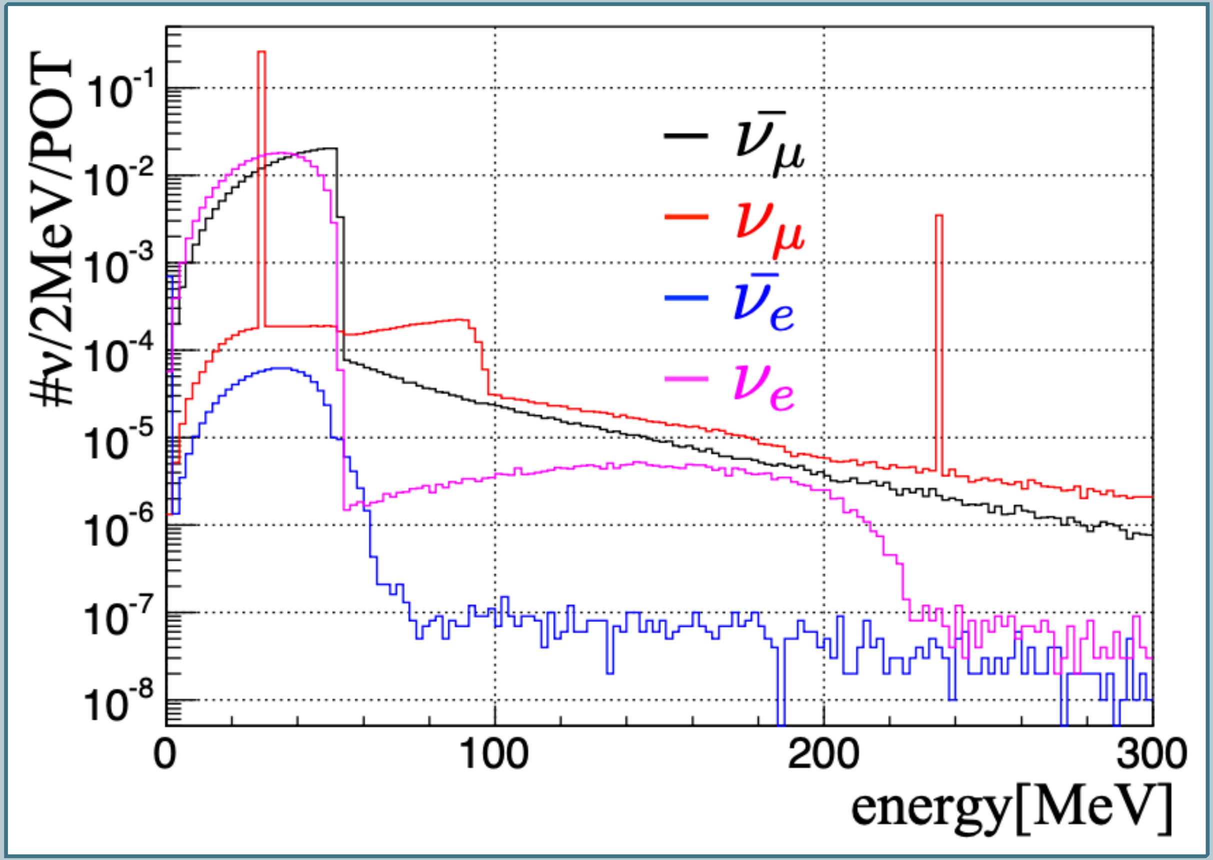
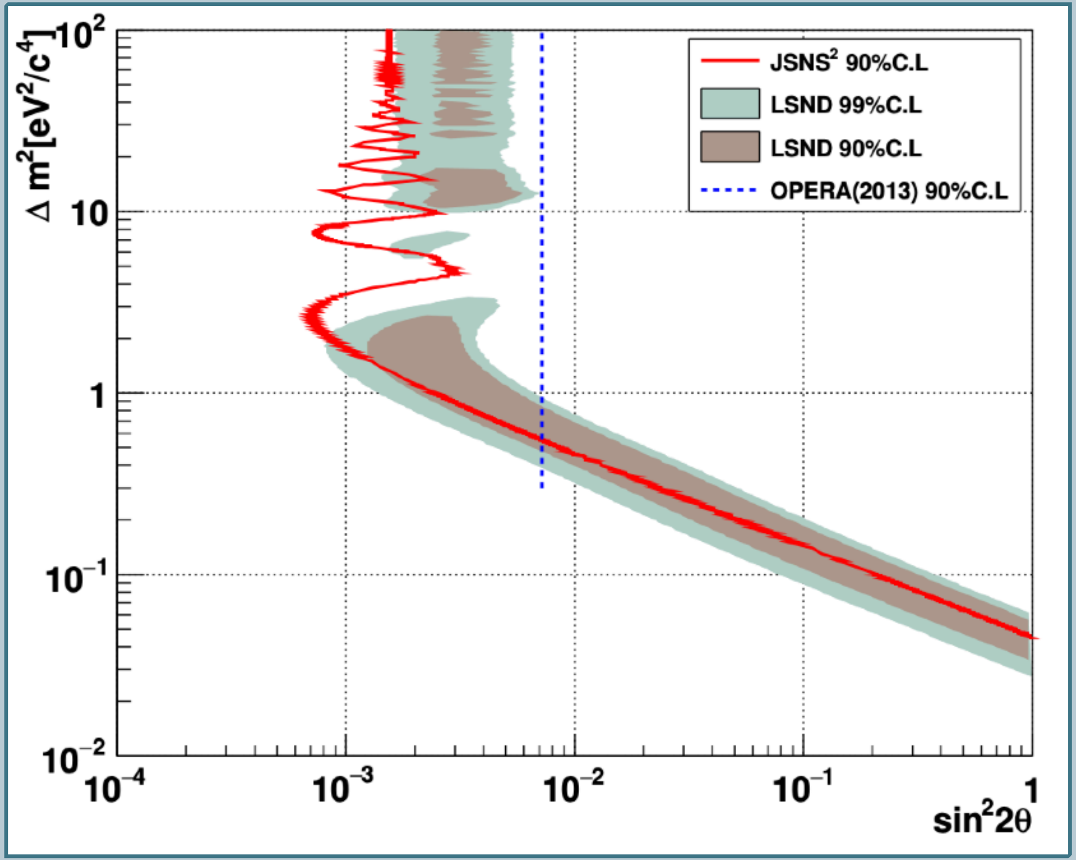
JSNS²

An independent accelerator-based search for sterile neutrinos; similar to the original LSND experiment, but higher beam energy

Data taking is ongoing and the collaboration is looking to secure funds for a second detector!





S. Ajimura, et al., arXiv:1705.08629;
T. Maruyama @ Neutrino 2020

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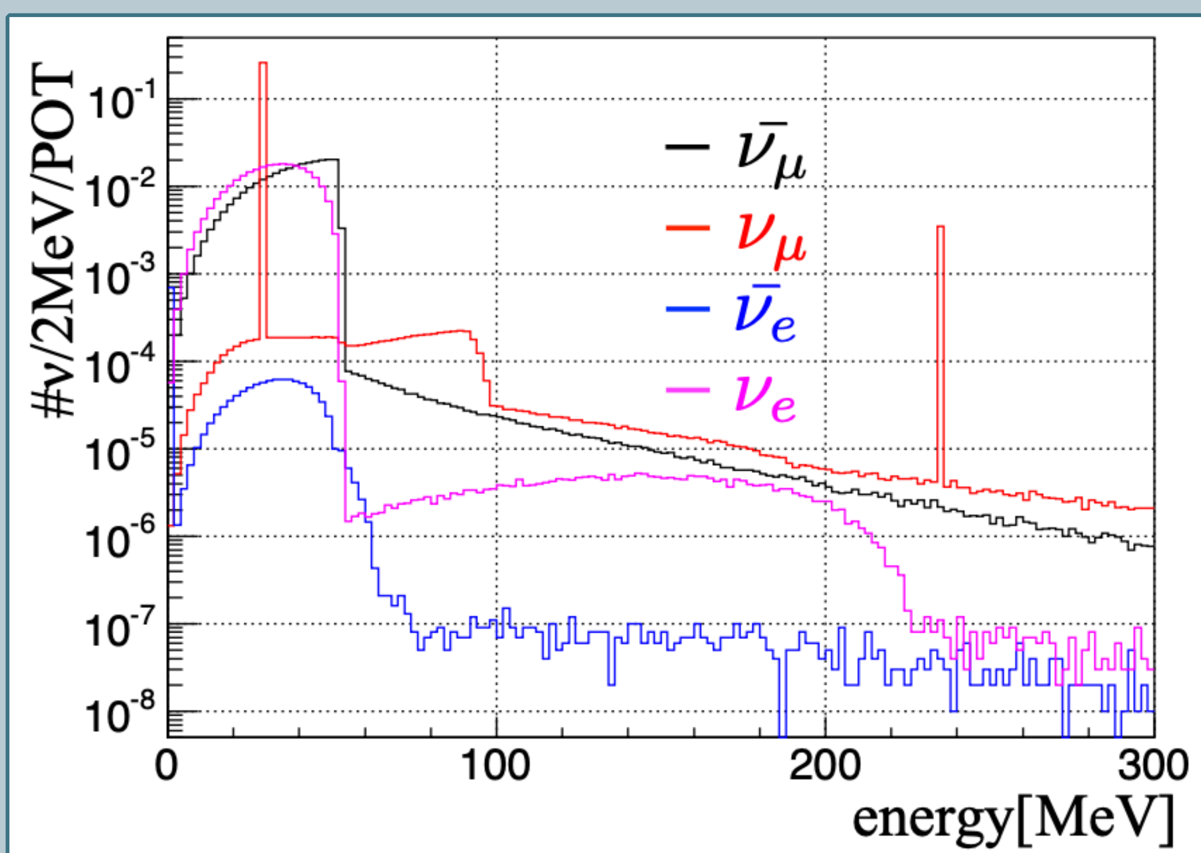
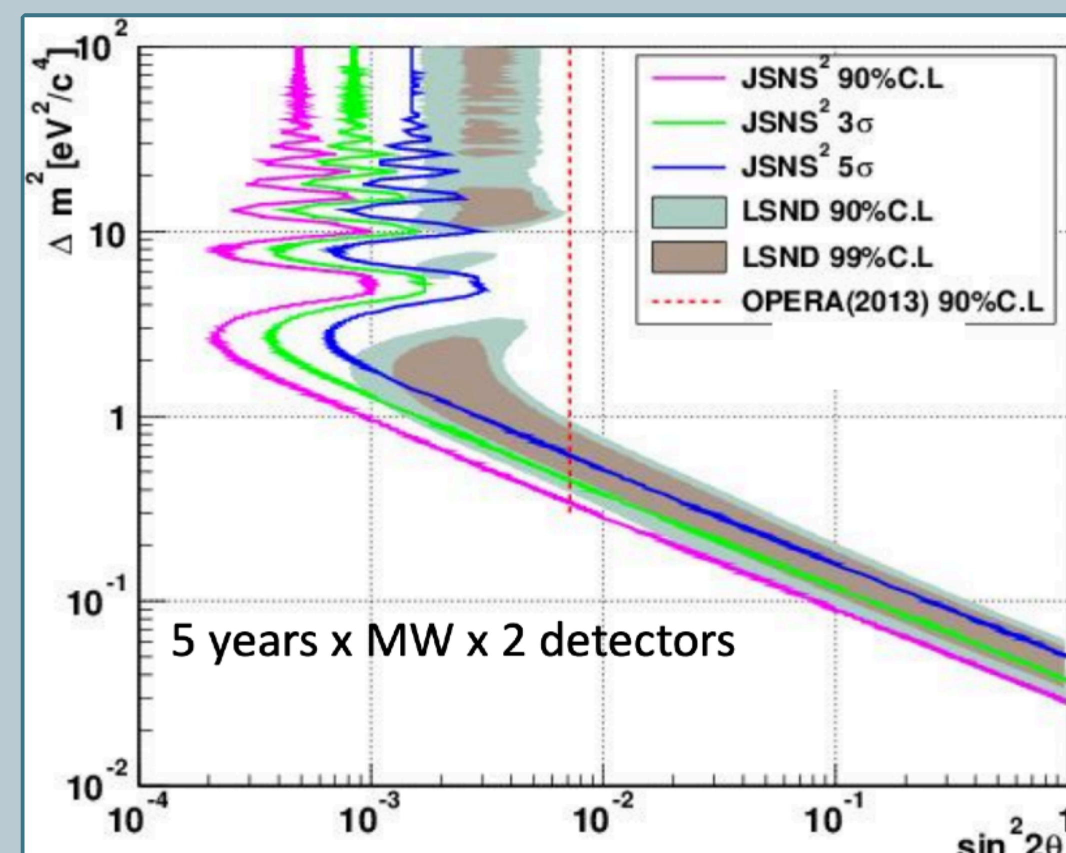
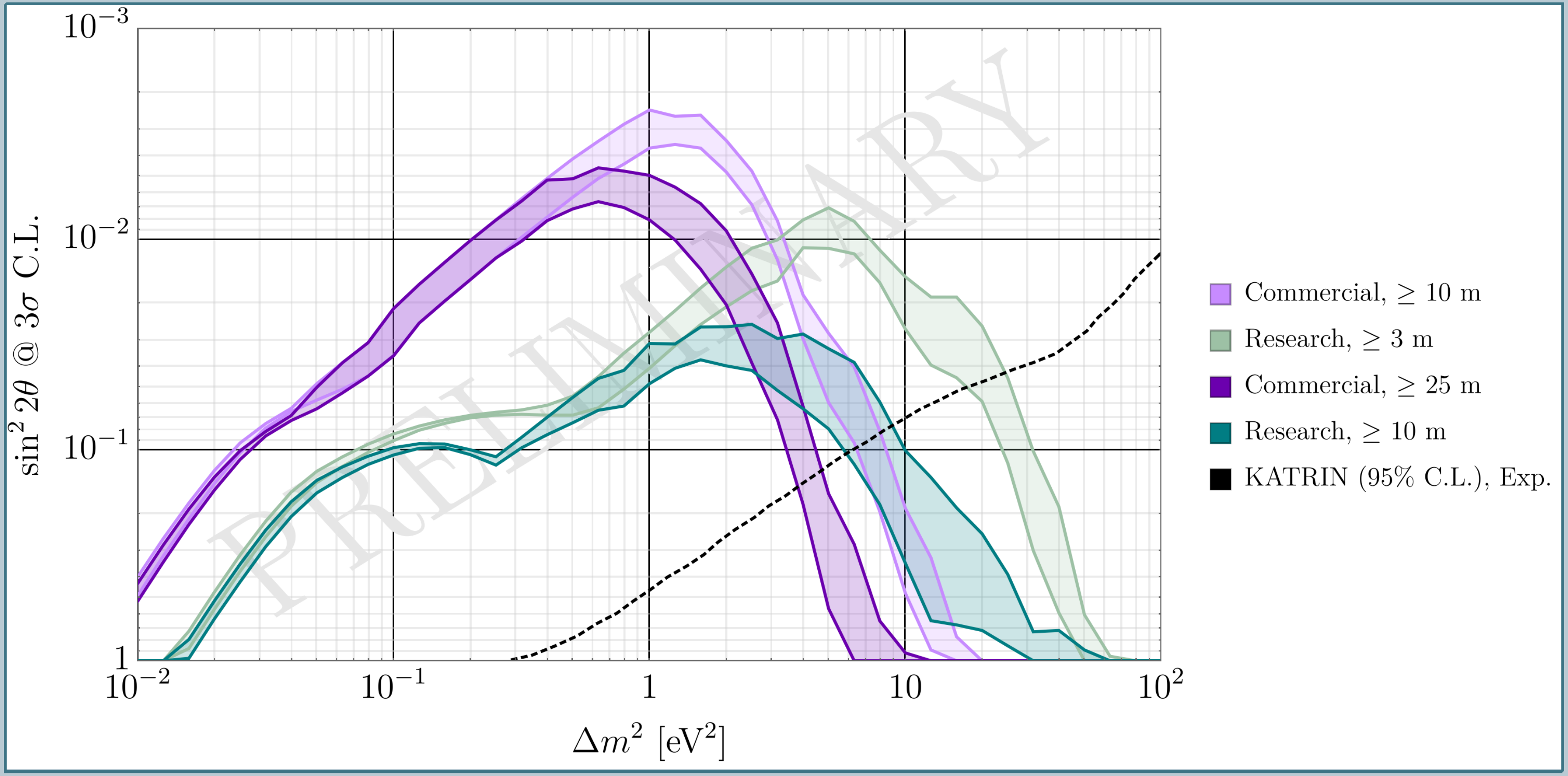




S. Ajimura, et al., arXiv:1705.08629;
T. Maruyama @ Neutrino 2020

Future Reactor Experiments



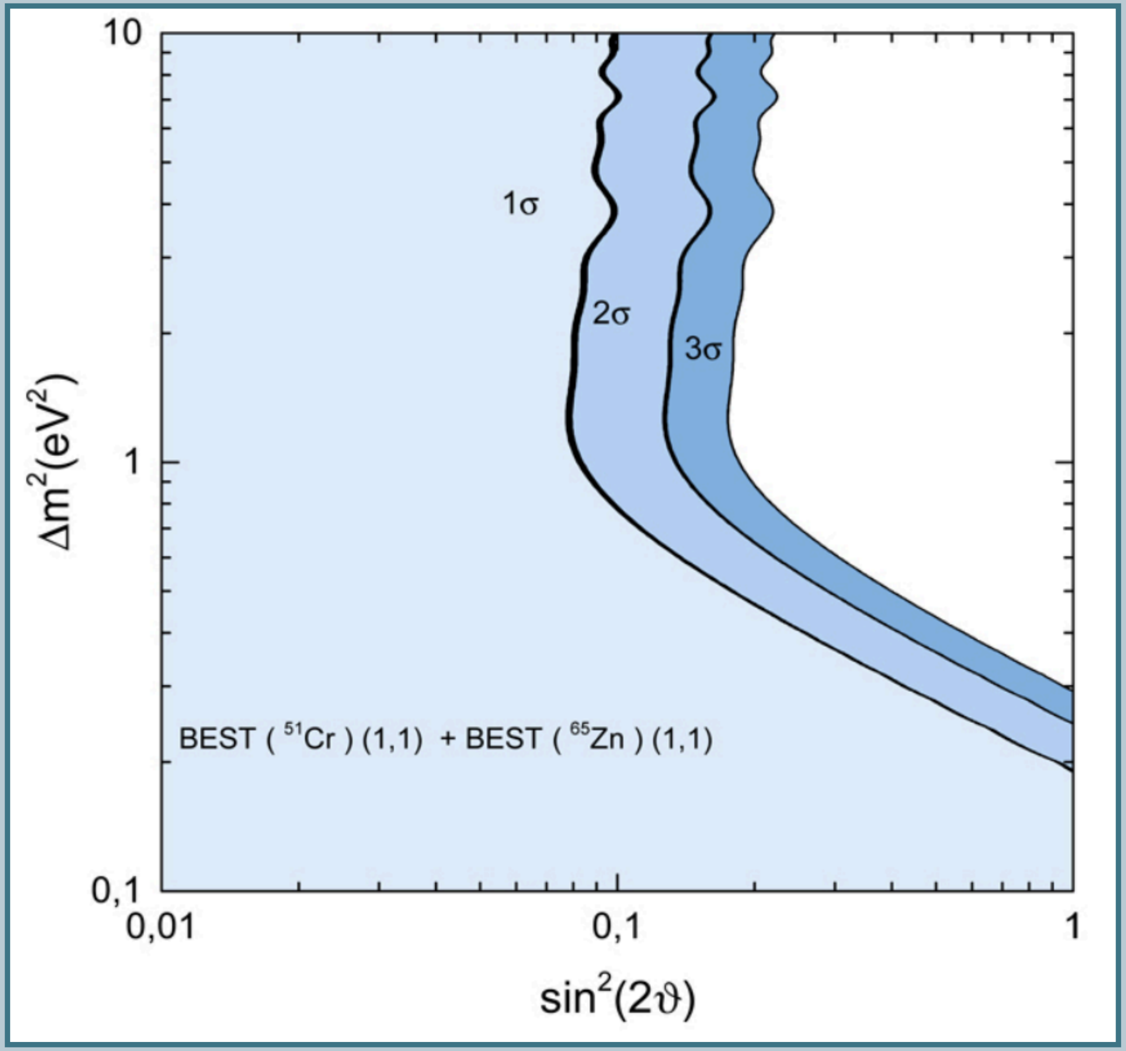
By the end of the next generation, we'll have *just about saturated* how well reactor experiments can perform in the search for sterile neutrinos, barring *significant* improvements in detector design and technology

New ideas will be needed!

JMB, L. Delgadillo Franco & P. Huber, In Preparation

Isotopic Decays

- *Isotopic* sources may have some advantages over reactors (e.g., spectrum of neutrinos is better known), but are not without challenges
- General types of experiments:
  - Gallium experiments – BEST
  - ^{8}Li decay – IsoDAR
  - ^{144}Ce – ~~SOX~~



BEST Collaboration, PRD 97 (2018) 073001; IsoDAR Collaboration, arXiv:1710.09325; Borexino Collaboration, JHEP 08 (2013) 038

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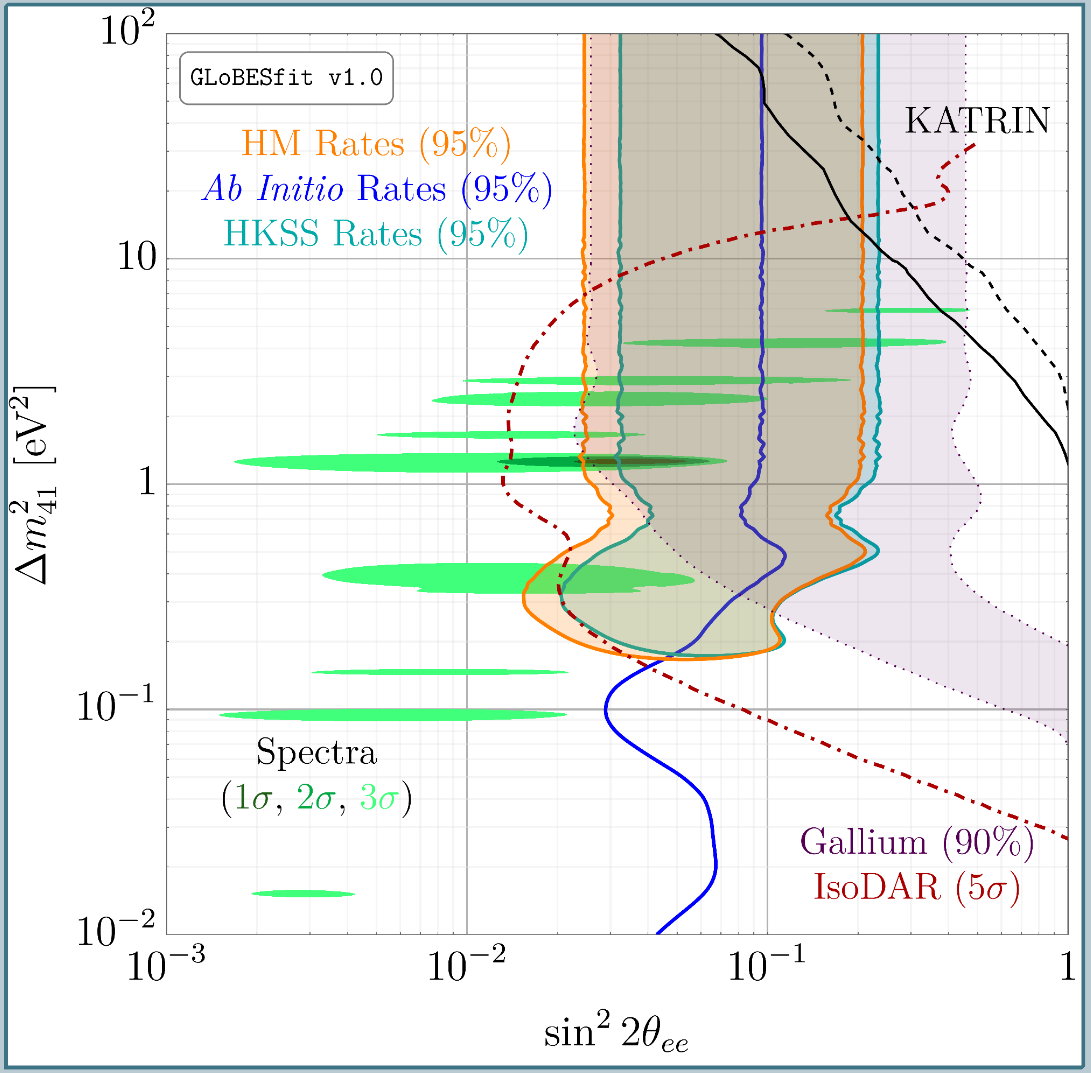

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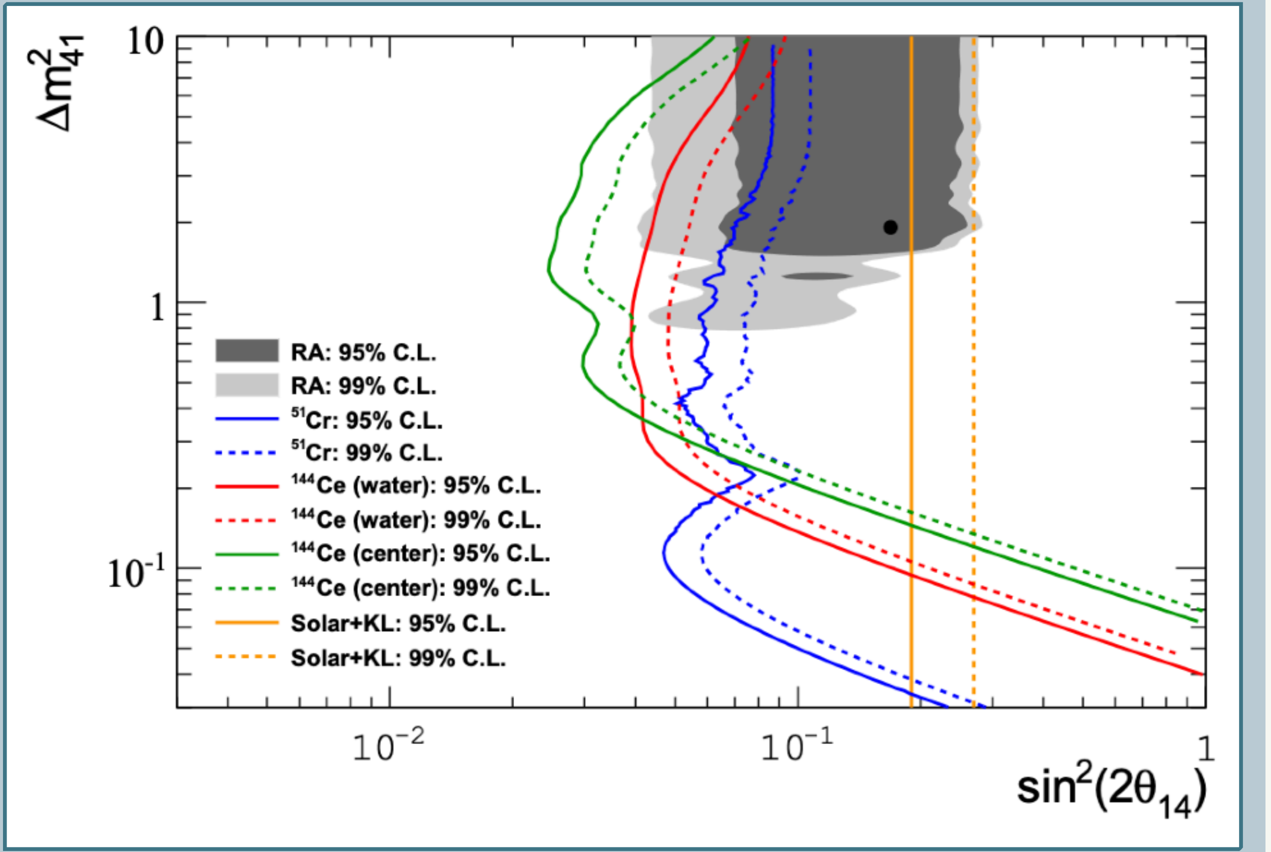

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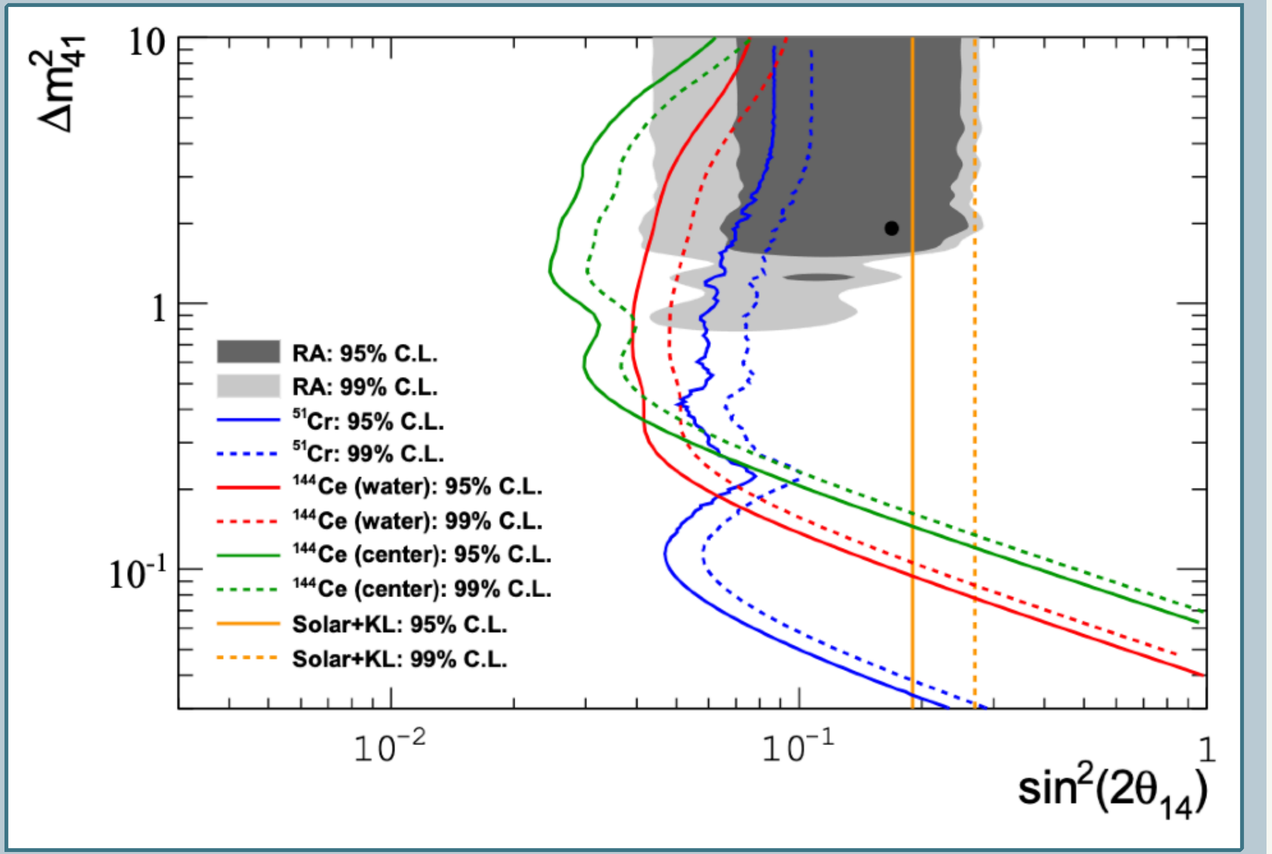


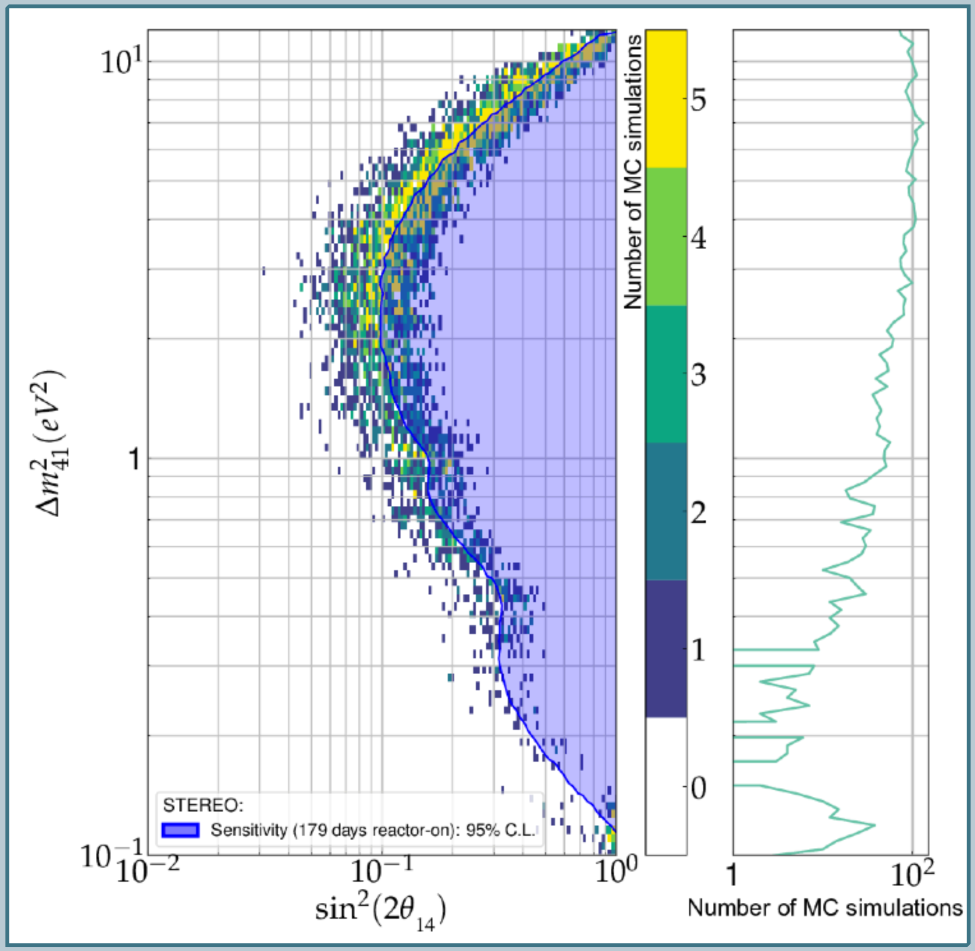
New ideas would certainly be welcome here!

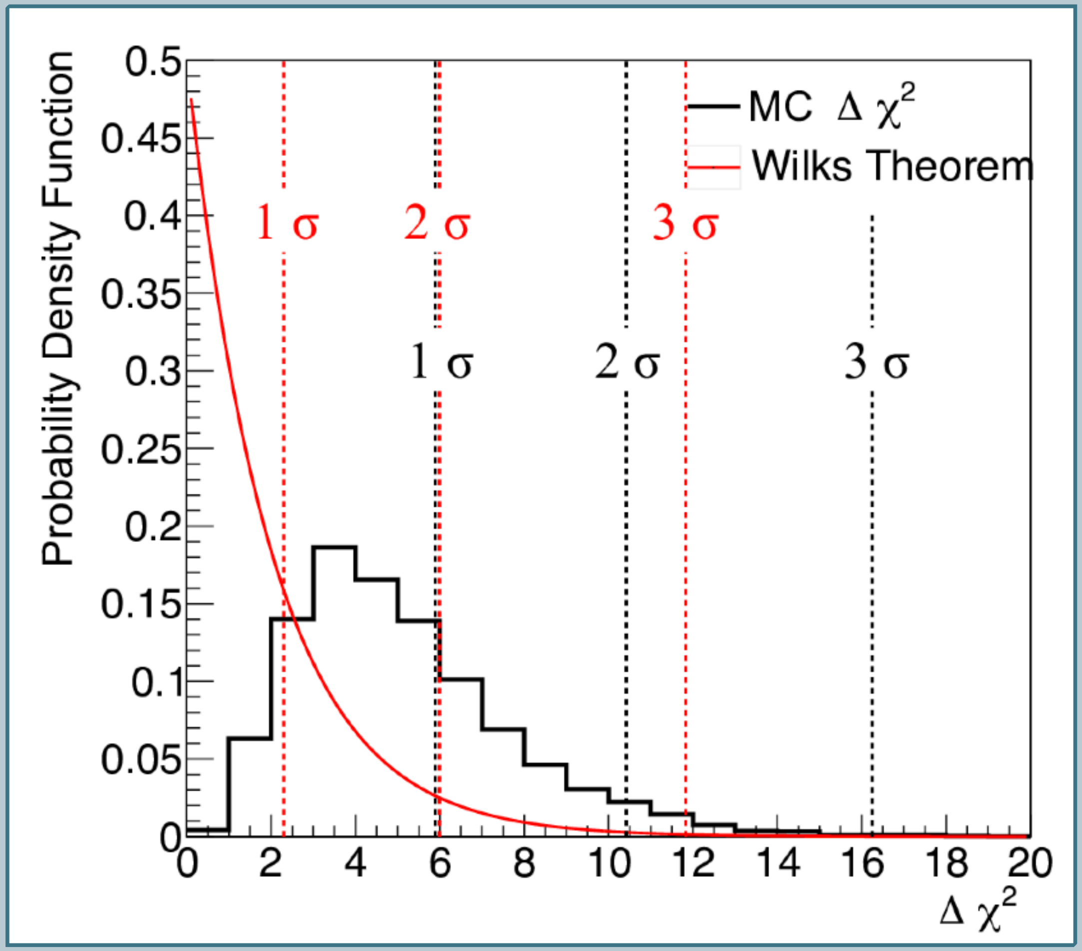
BEST Collaboration, PRD 97 (2018) 073001; IsoDAR Collaboration, arXiv:1710.09325; Borexino Collaboration, JHEP 08 (2013) 038

The Importance of Statistics

Going from test statistic (e.g., $\Delta\chi^2$) to confidence level is not always a trivial endeavor! Some types of observables show sizable deviations from *Wilks' theorem* — Monte Carlo methods are needed to determine what the correct confidence levels *should* be!

BTW: This has been known for some time – Feldman-Cousins!





PROSPECT & STEREO Collaborations, arXiv:2006.13147;
G. J. Feldman & R. D. Cousins, PRD 57 (1998) 3873

A Case Study: Neutrino-4

Neutrino-4 *claims* to see an oscillation signal at the level of $\Delta\chi^2 \approx 13$!
How *robust* is this result?

P. Coloma, P. Huber & T. Schwetz, arXiv:2008.06083

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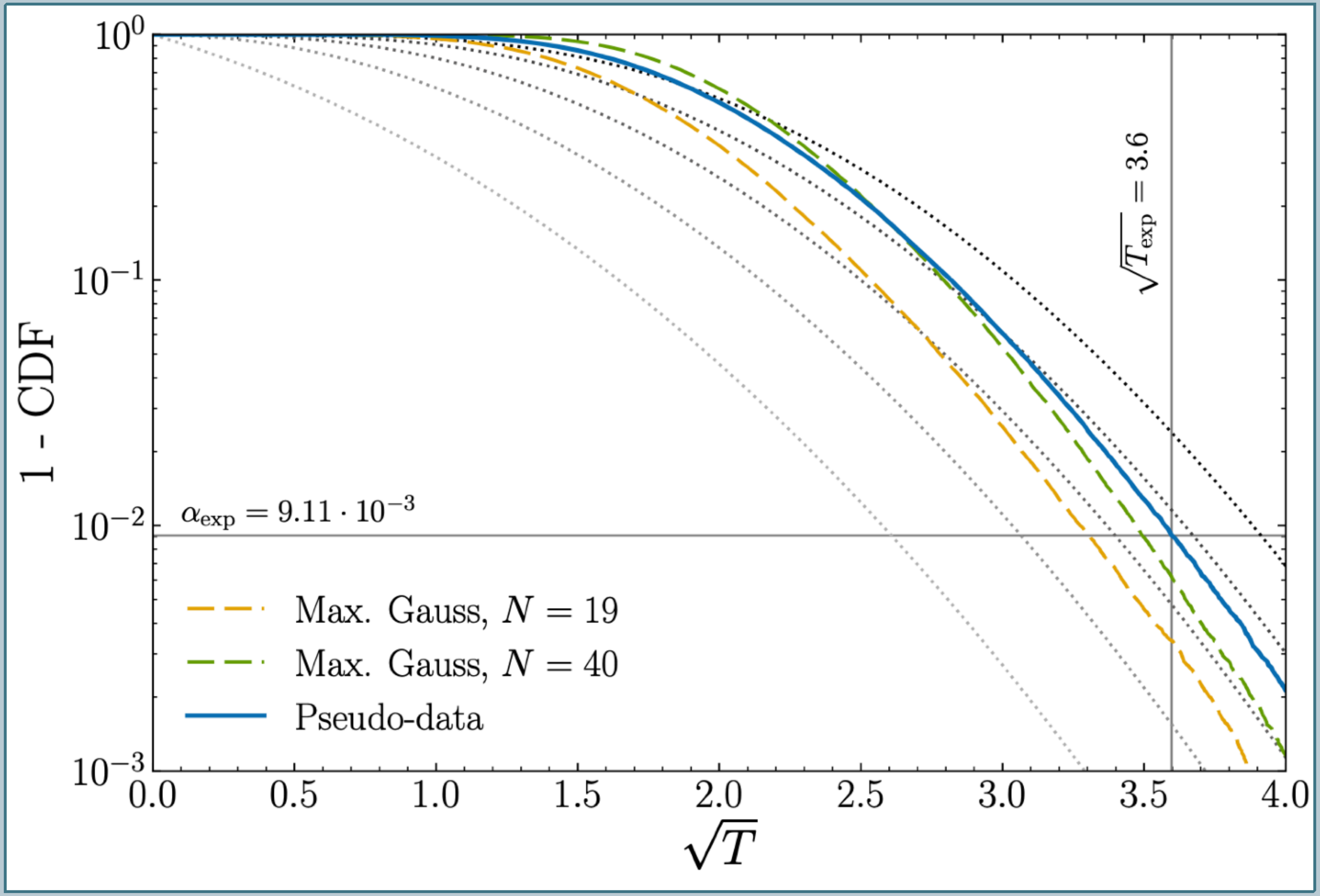

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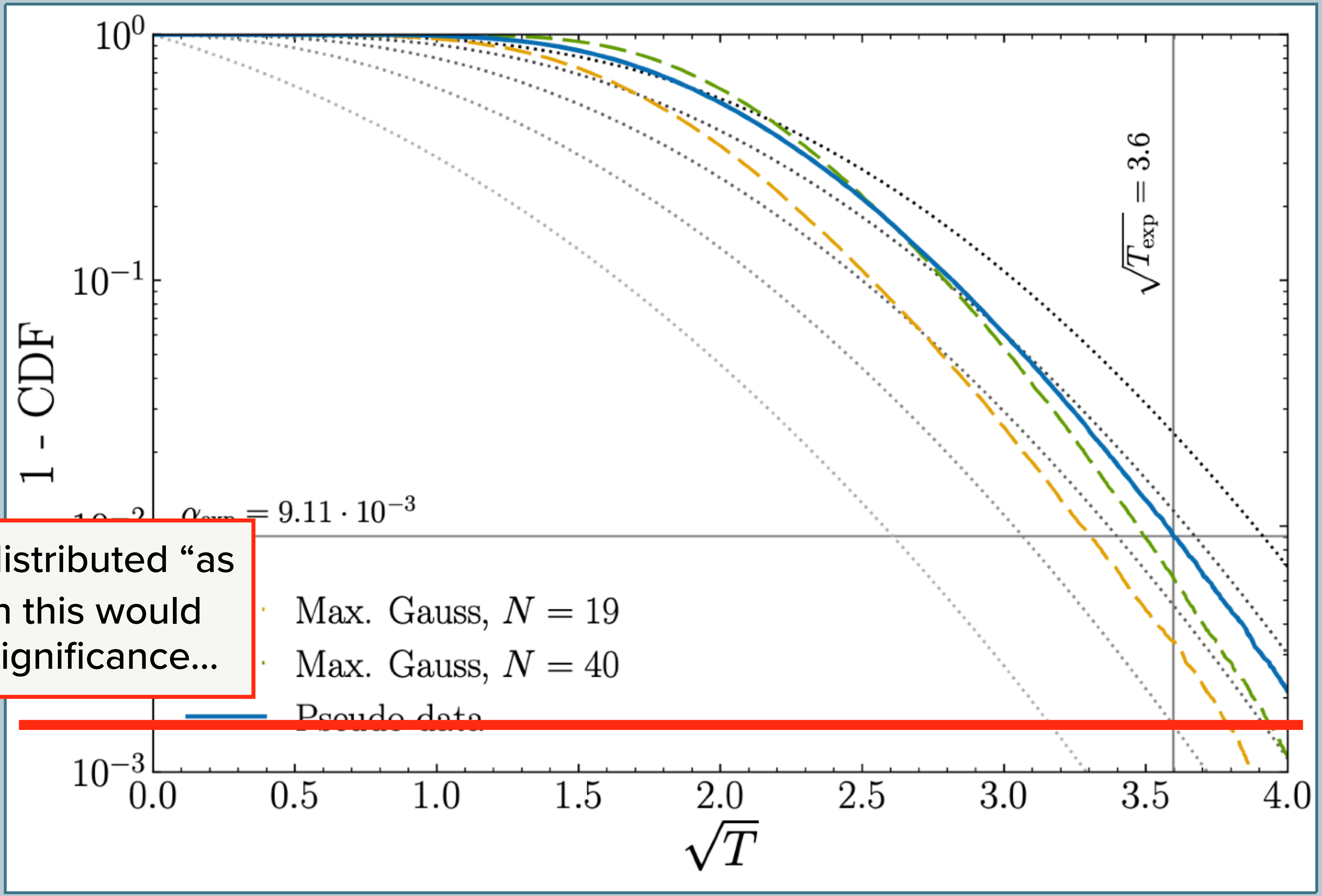

If $\Delta\chi^2$ were distributed "as usual," then this would imply 3.2σ significance…

P. Coloma, P. Huber & T. Schwetz, arXiv:2008.06083

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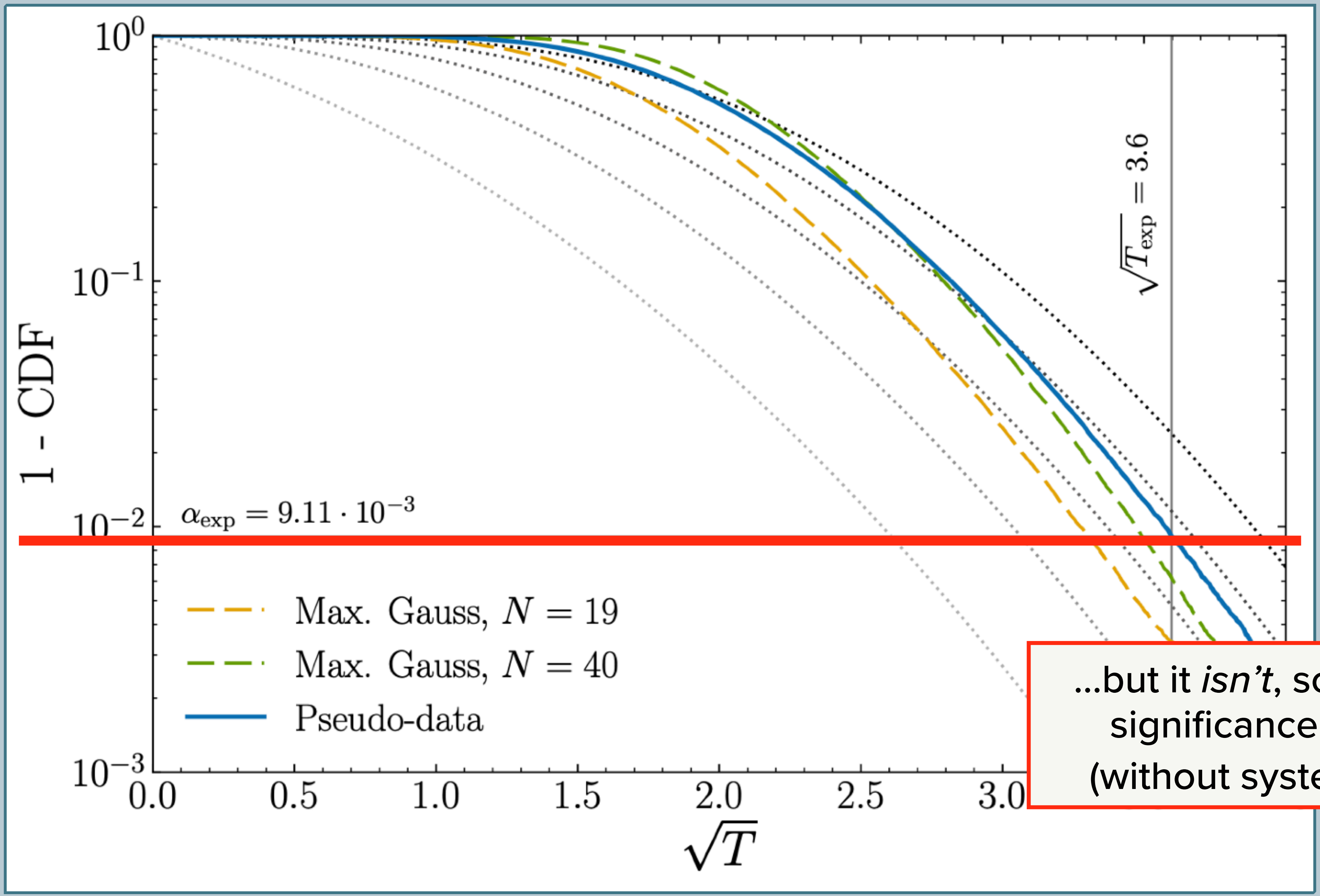

…but it *isn't*, so the *true* significance is 2.6σ (without systematics)!

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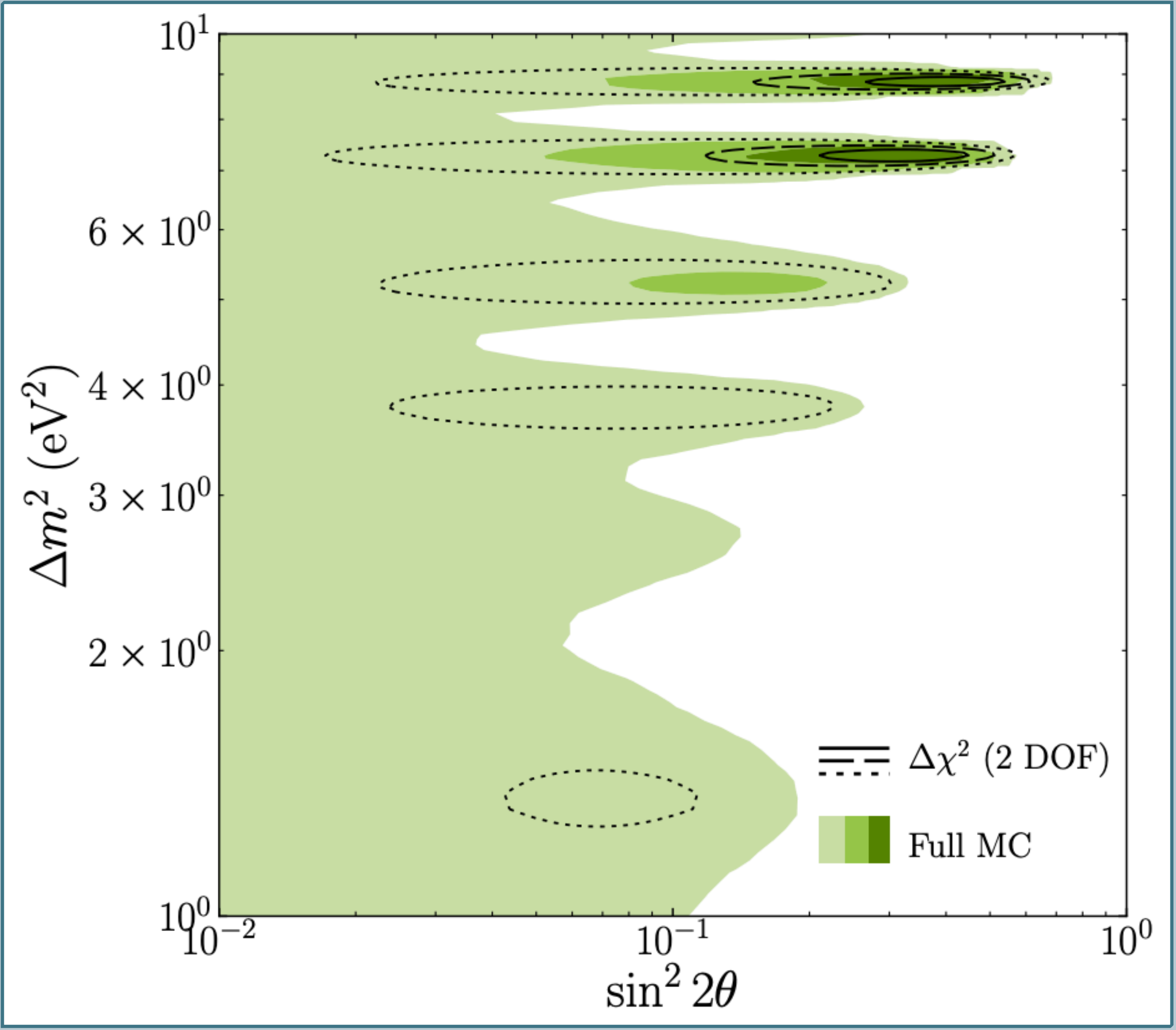
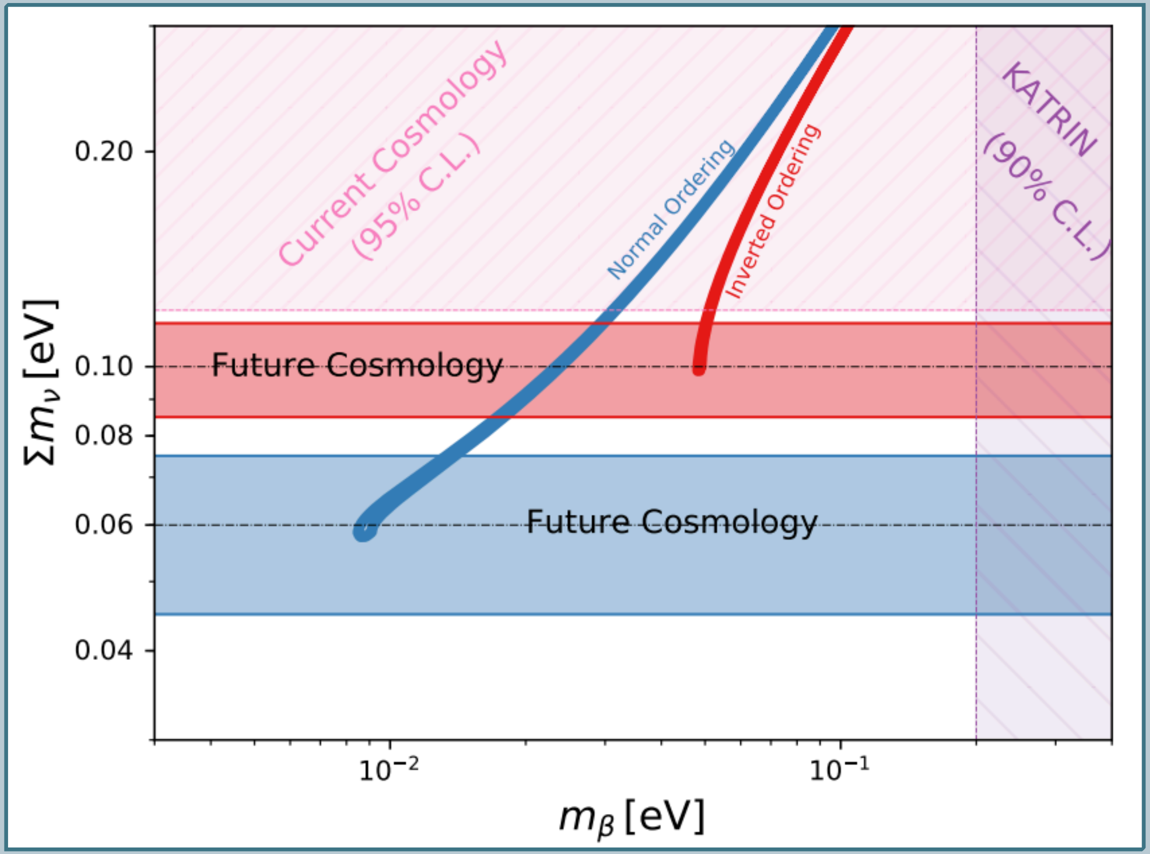
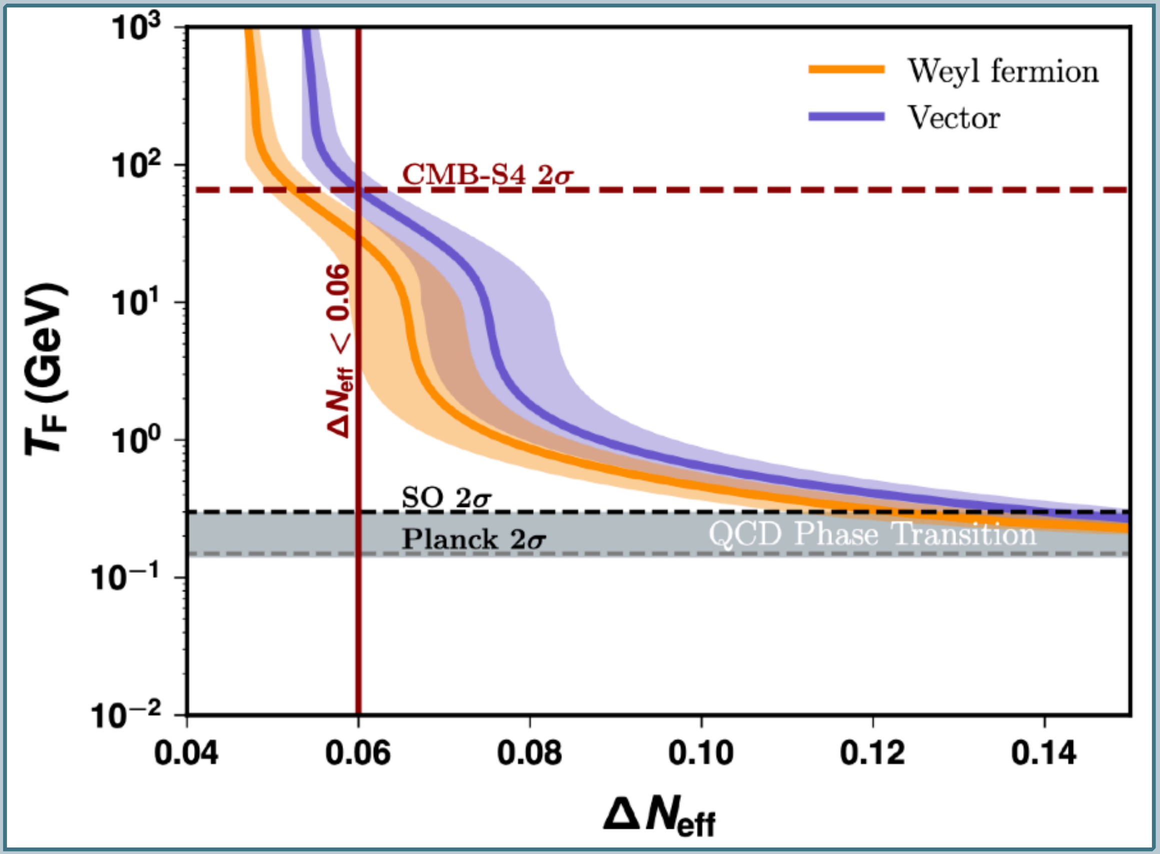


P. Coloma, P. Huber & T. Schwetz, arXiv:2008.06083

Cosmology in the Future

Efforts like CMB-S4 and DESI will continue to pare down the available parameter space in the standard cosmology…





…but since the standard cosmology is already *strongly opposed* to the introduction of truly sterile neutrinos, these will need to be used to constrain more exotic scenarios!

CMB-S4 Collaboration, arXiv:1907.04473; L. Knox @ Neutrino 2020

Less-Than-Sterile Neutrinos

Light, self-interacting neutrinos *may* be able to reconcile tensions with, e.g., differing measurements of the Hubble parameter (assuming this is of physical origins) while avoiding the classic constraints, e.g., ΔN_{eff}

	Planck TT			Planck TTTEEE			Planck TTTEEE + R19		
Dataset	Vanilla	Pseudo	Thermal	Vanilla	Pseudo	Thermal	Vanilla	Pseudo	Thermal
Planck low-ℓ TT	23.6	21.4	20.2	23.5	24.0	20.3	21.5	23.3	20.3
Planck low-ℓ EE	395.7	396.4	395.9	395.8	396.6	396.6	396.9	395.9	397.3
Planck high-ℓ TT	760.6	767.3	774.0	−−	−−	−−	−−	−−	−−
Planck high-ℓ TTTEEE	−−	−−	−−	2346.3	2357.6	2380.5	2355.1	2358.6	2378.5
R19	−−	−−	−−	−−	−−	−−	6.4	1.05	0.0
Total χ^2	1180.0	1185.0	1190.1	2765.6	2778.1	2797.3	2779.8	2778.8	2796.0
Total $\Delta\chi^2$	0	5	10	0	12.5	31.5	0	−1.0	16.2

	Planck TT			Planck TTTEEE			Planck TTTEEE + R19		
Parameter	Vanilla	Pseudo	Thermal	Vanilla	Pseudo	Thermal	Vanilla	Pseudo	Thermal
$\Delta N_{\rm eff}$	< 0.28	< 0.86	1	< 0.20	< 0.56	1	< 0.47	$0.38^{+0.15}_{-0.15}$	1
m_s [eV]	< 8.77	$3.1^{+1.3}_{-1.1}$	< 0.44	n.c.	< 1.14	< 0.91	< 7.58	< 1.19	< 0.22
H_0 [km/s/Mpc]	$67.5^{+1.0}_{-1.1}$	$72.2^{+1.7}_{-2.9}$	$74.2^{+2.1}_{-1.2}$	$67.8^{+0.7}_{-0.7}$	$71.6^{+1.1}_{-1.6}$	$73.3^{+2.1}_{-0.5}$	$69.6^{+0.8}_{-1.3}$	$72.8^{+1.1}_{-1.2}$	$74.1^{+0.9}_{-0.7}$
n_s	$0.964^{+0.007}_{-0.007}$	$0.971^{+0.014}_{-0.013}$	$1.002^{+0.007}_{-0.006}$	$0.965^{+0.005}_{-0.005}$	$0.951^{+0.006}_{-0.008}$	$0.999^{+0.007}_{-0.004}$	$0.975^{+0.006}_{-0.008}$	$0.957^{+0.006}_{-0.006}$	$1.001^{+0.004}_{-0.004}$

"Vanilla" — Standard, truly sterile neutrino
"Pseudo" — Sterile coupled to (effectively massless) pseudoscalar
"Thermal" — Same as vanilla, but $\Delta N_{eff} \equiv 1$

M. Archidiacono, et al., arXiv:2006.12885

Less-Than-Sterile Neutrinos

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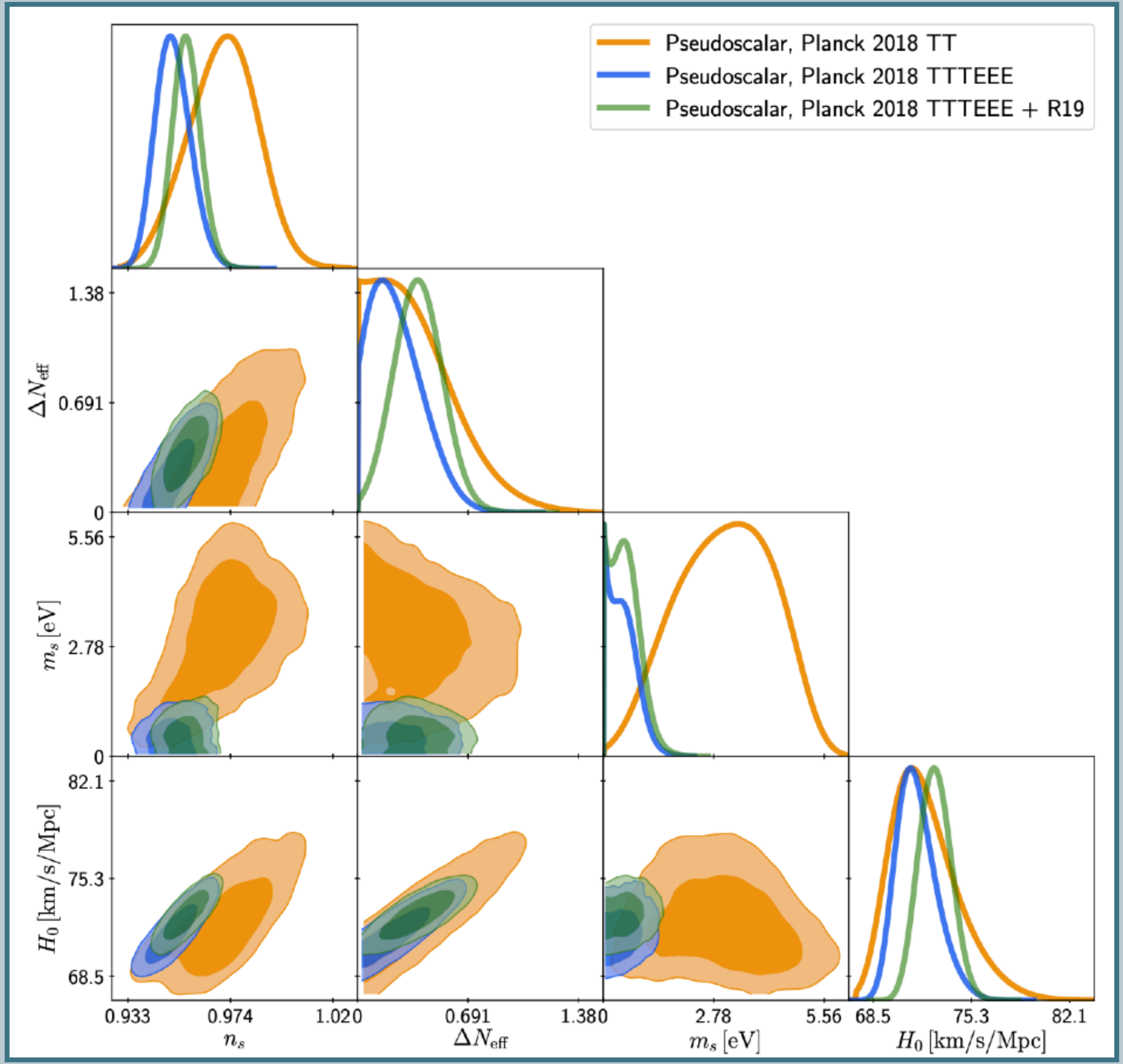
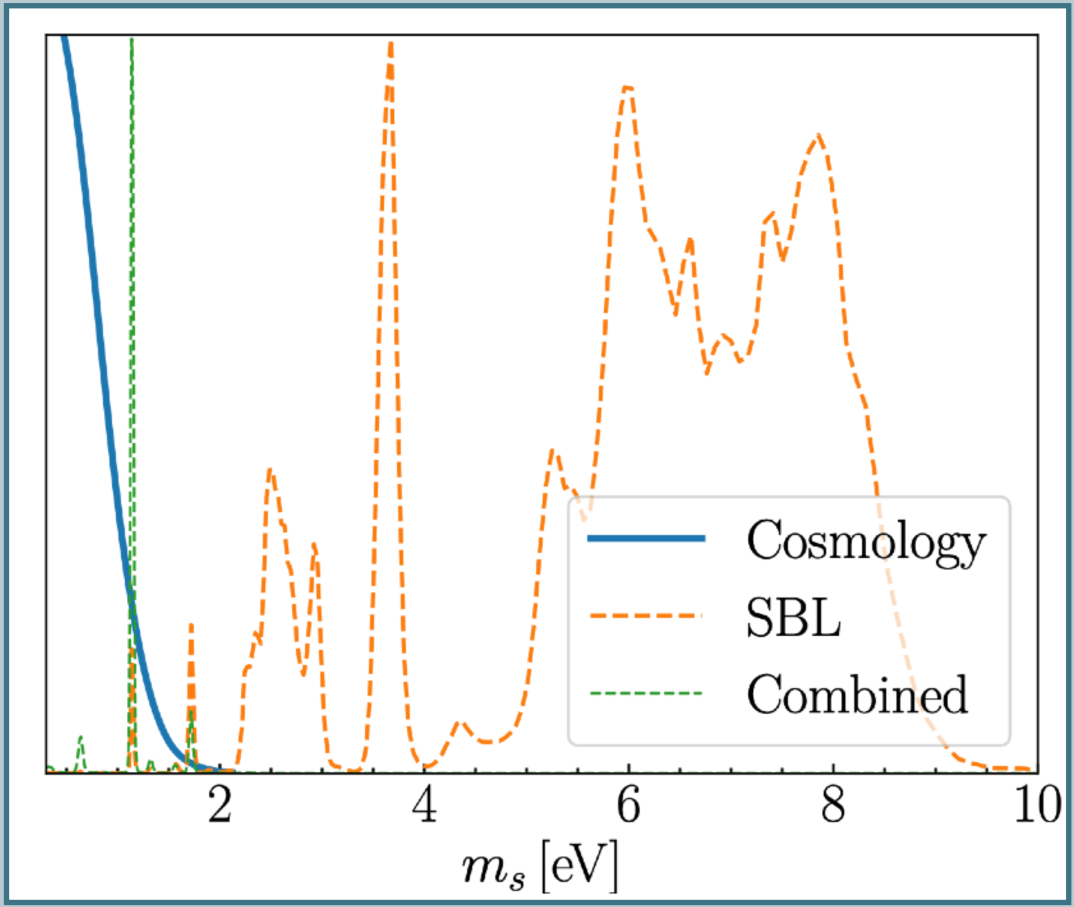
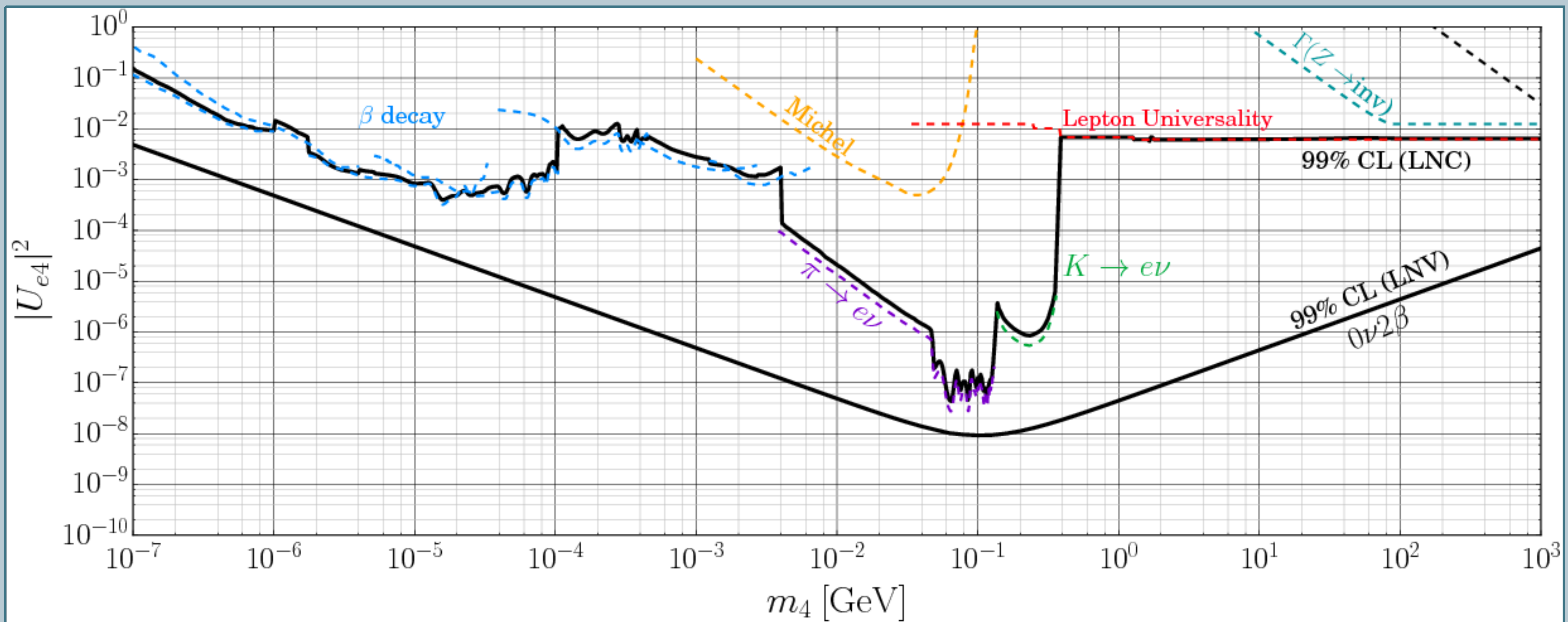




M. Archidiacono, et al., arXiv:2006.12885

Beyond the eV Scale

A (Very) Broad View

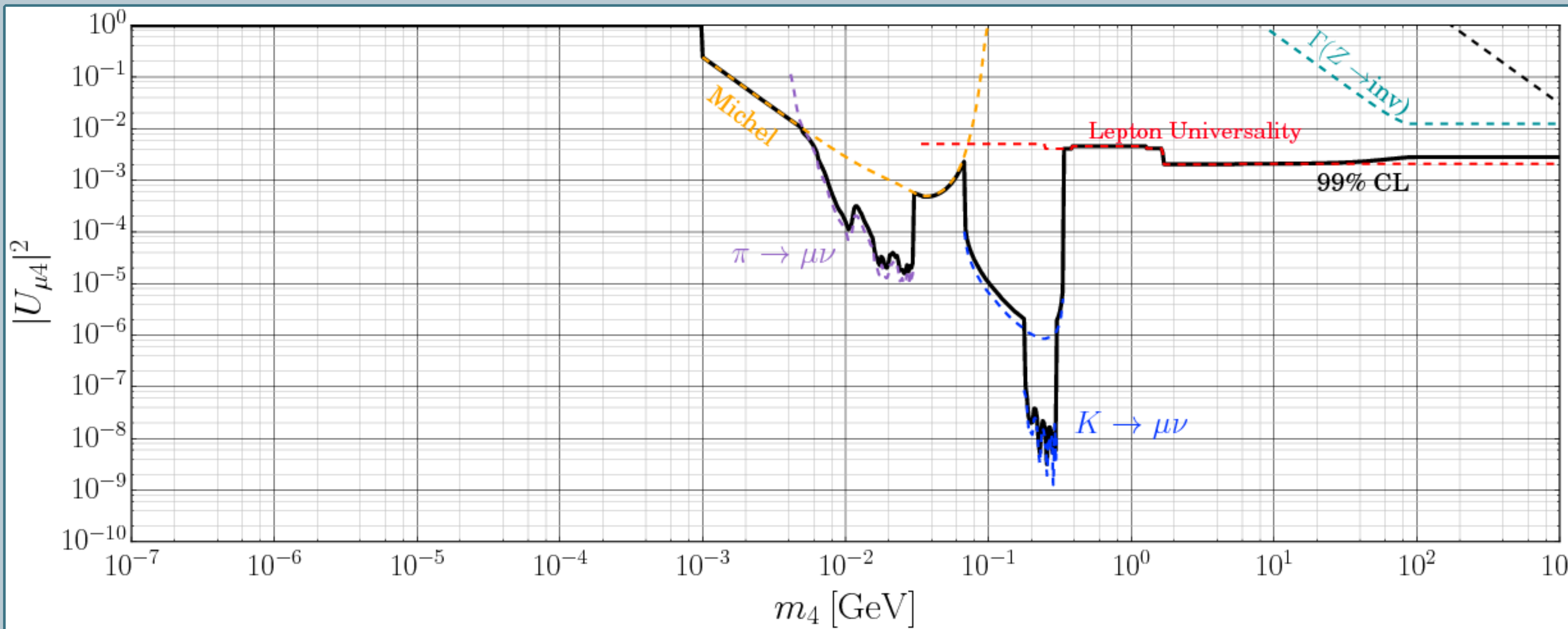


Nobody ever said that a new neutrino *absolutely must* be light enough to participate in oscillations!

There are plenty of ways in which new, gauge-singlet fermions could appear over a *wide range* of mass scales

A. de Gouvêa & A. Kobach, PRD 93 (2016) 033005

A (Very) Broad View



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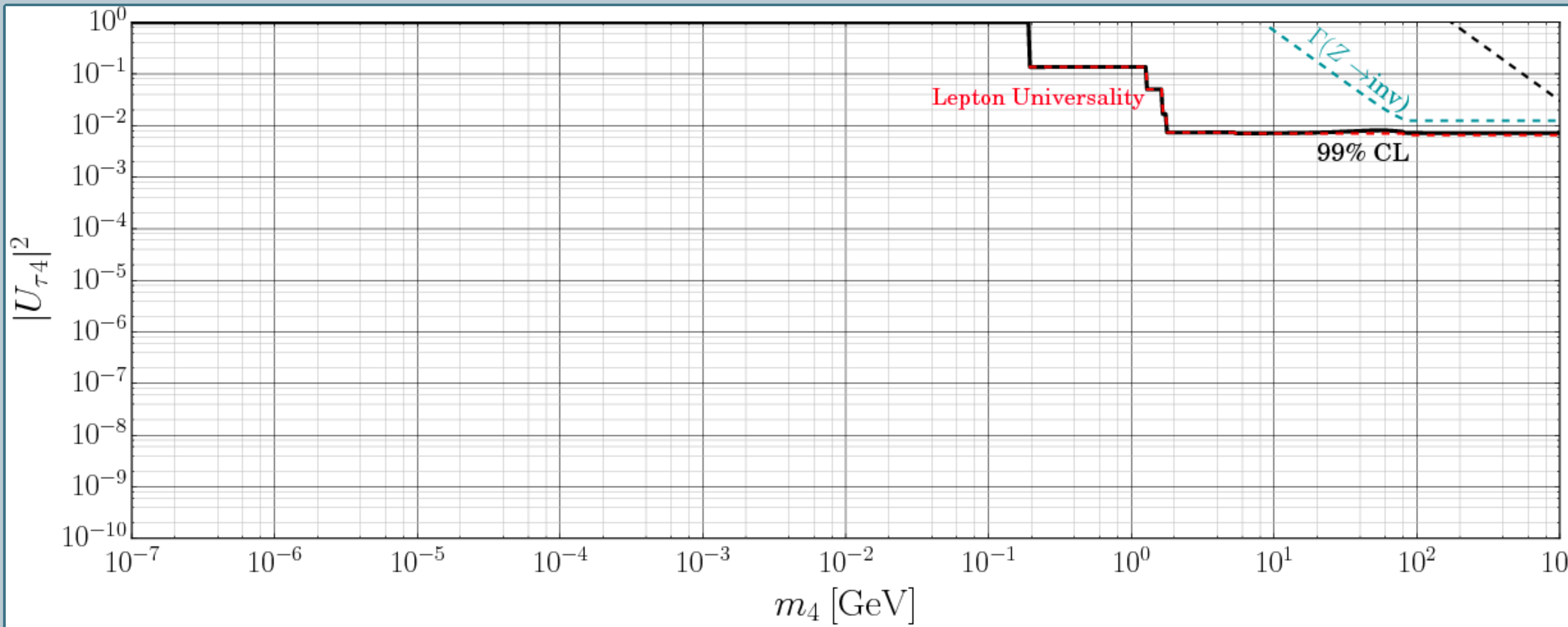

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A. de Gouvêa & A. Kobach, PRD 93 (2016) 033005

keV-Scale Neutrinos

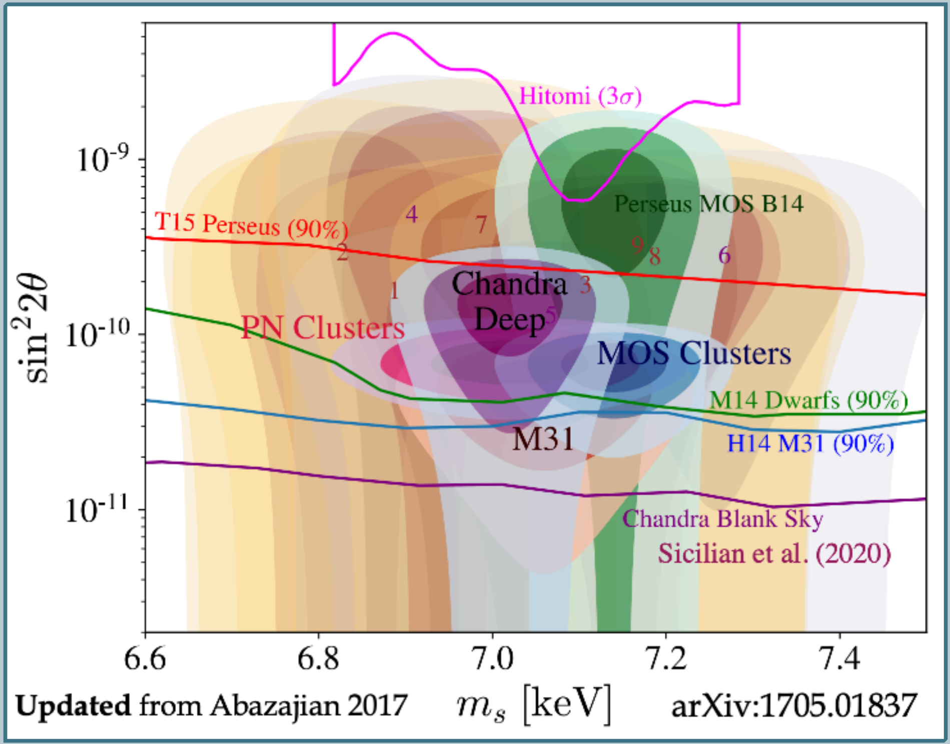
The existence of dark matter *requires* that we add more ingredients to the SM — perhaps an extra neutrino fits the bill?

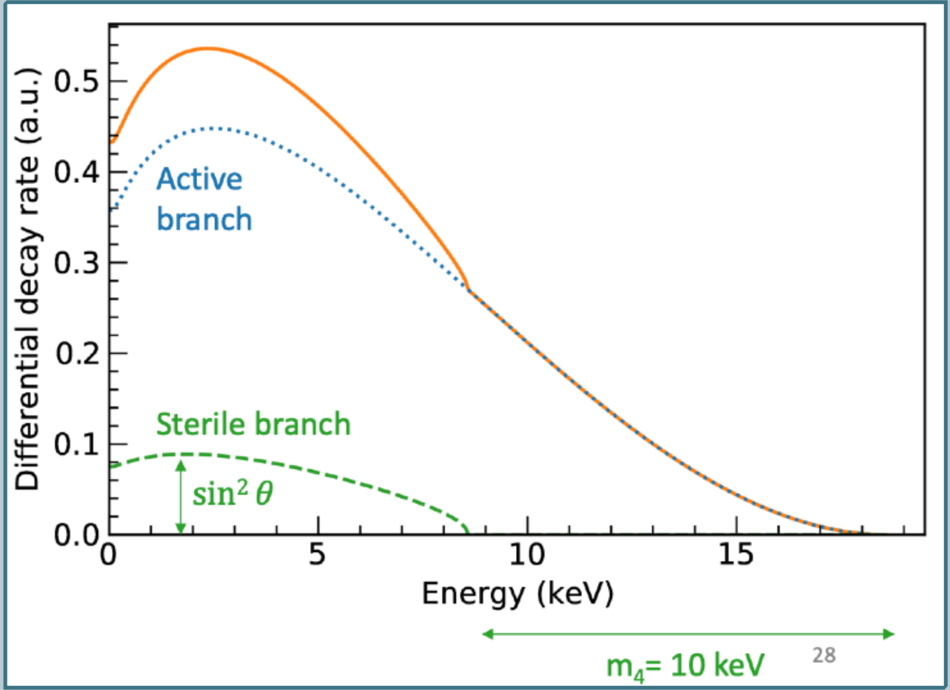
One-loop decay to light neutrino and photon:

$$\Gamma \approx 1.4 \times 10^{-30} \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1\ \mathrm{keV}}\right)^5$$

Stable on cosmological time scales, but may produce an *observable* signature! (Unexplained ~3.5 keV line?)

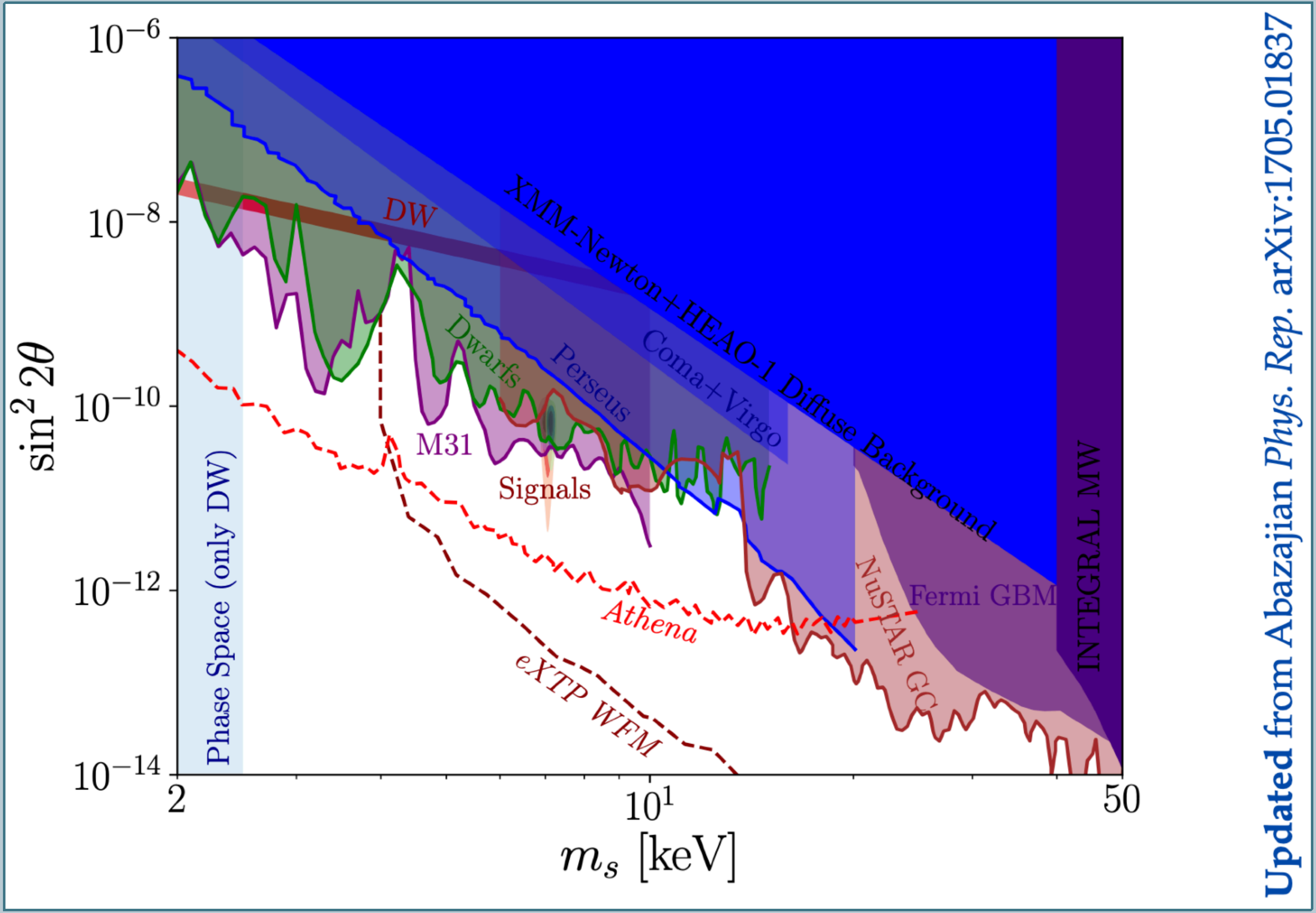
Can be probed at *terrestrial* experiments, too — TRISTAN, Project 8, HUNTER, ECHo, HOLMES





K. Abazajian, Phys. Rept. 711-712 (2017) 1 & Neutrino 2020;
S. Mertens @ Neutrino 2020

keV-Scale Sterile Neutrinos



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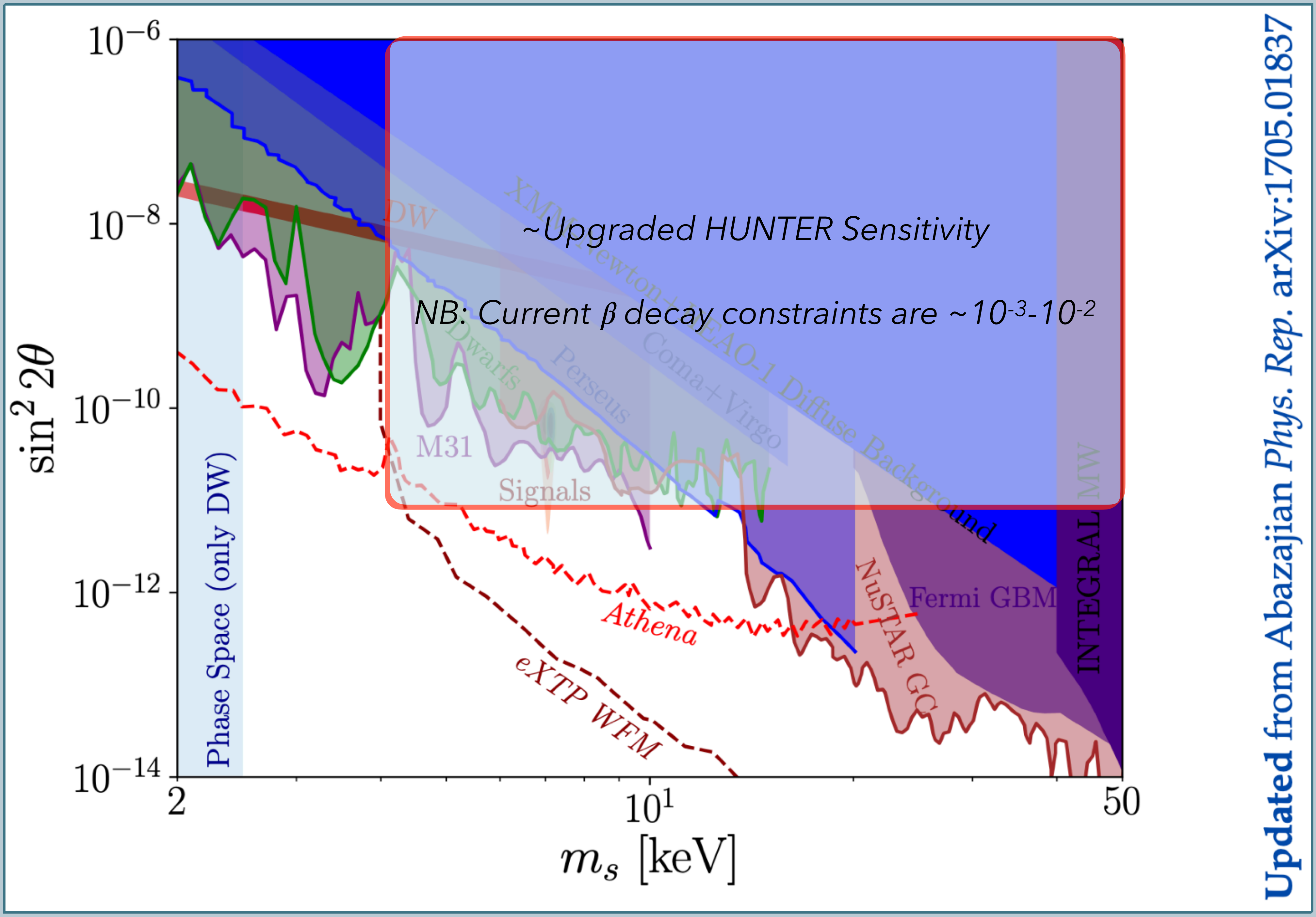


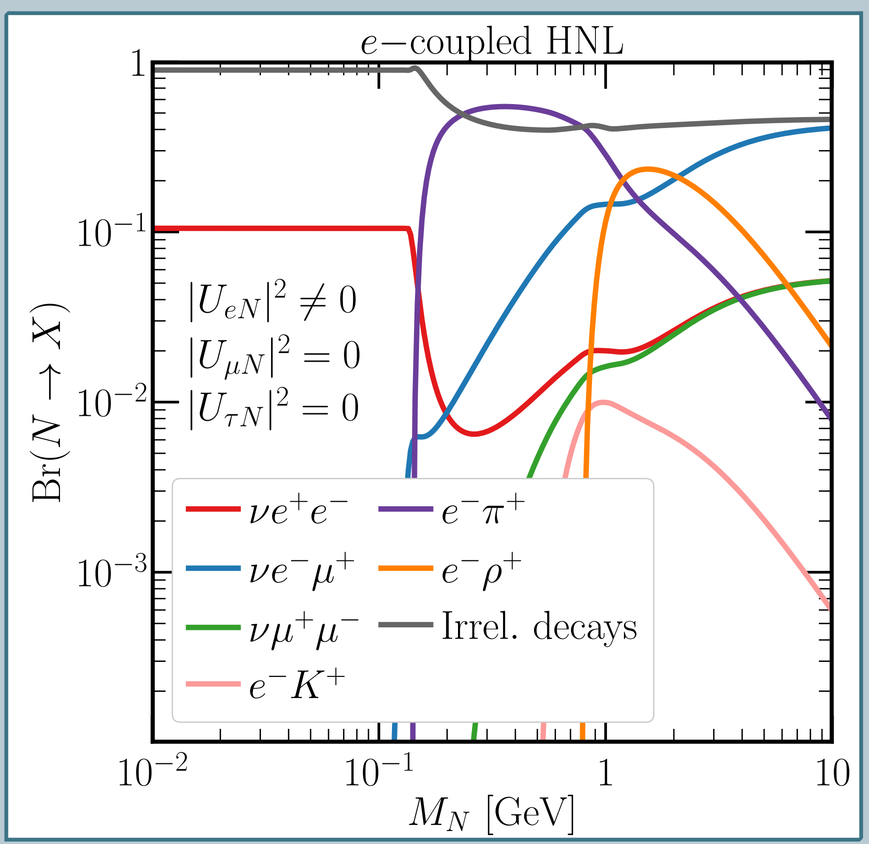
K. Abazajian, Phys. Rept. 711-712 (2017) 1 & Neutrino 2020;
J. Mertoff @ U.S. Cosmic Visions 2017

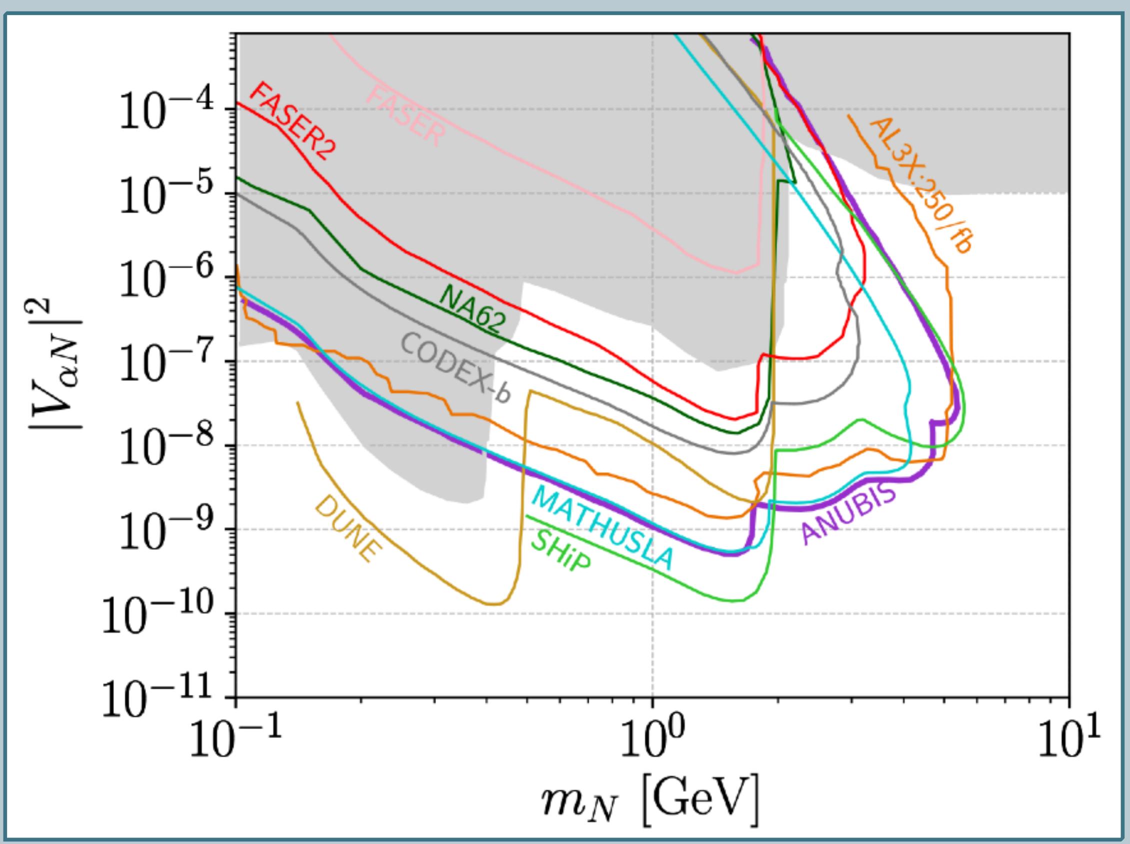
MeV/GeV-scale Neutrinos

If heavy neutrinos — a.k.a. heavy neutral leptons (HNLs) — *do* exist, then they may modify some (semi-)leptonic decays

Several types of experiments can search for HNL decays to visible SM particles:

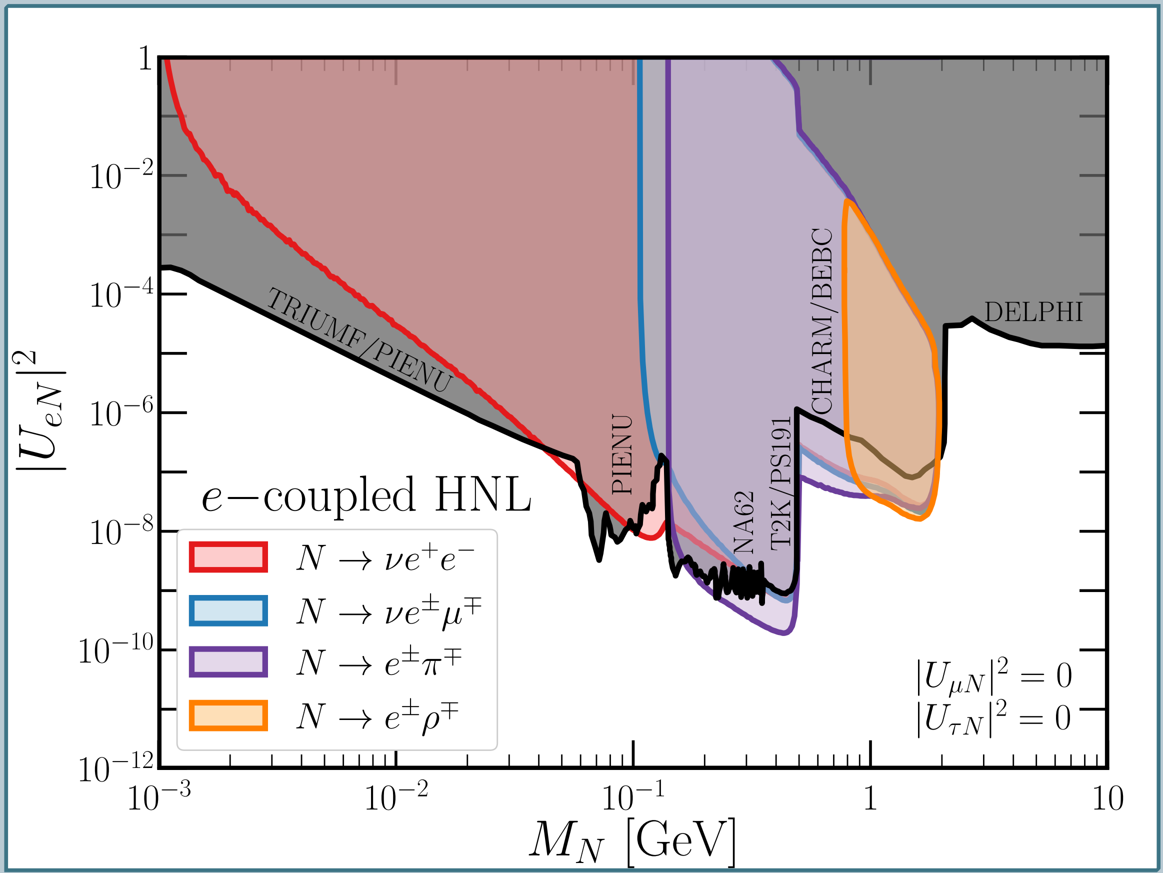
- Proton-proton collisions: DELPHI, L3, *MATHUSLA*, NA62…
- Proton beam dump/neutrino beams: *DUNE*, NuTeV, *SHiP*, T2K…

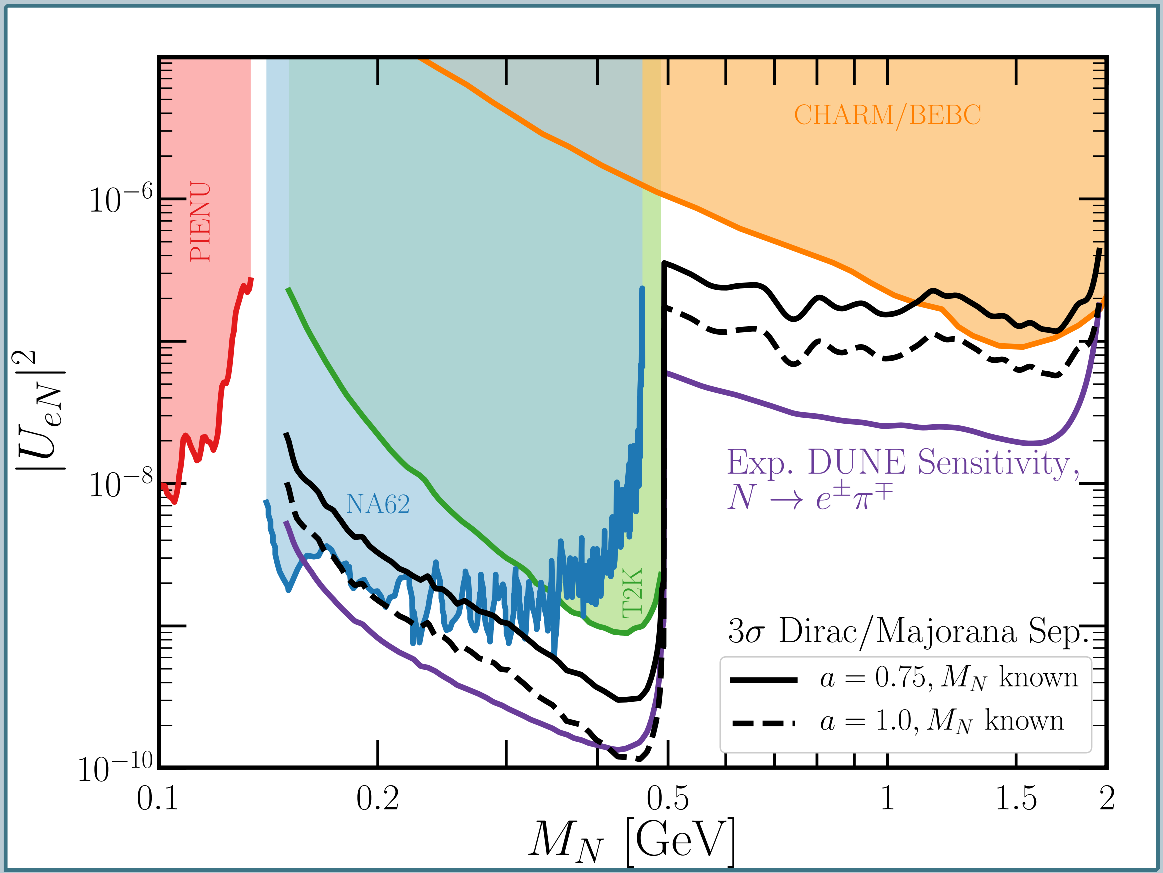




JMB, et al., JHEP 02 (2020) 174; M. Hirsch & Z. S. Wang, PRD 101 (2020) 055034

MeV/GeV-scale Neutrinos





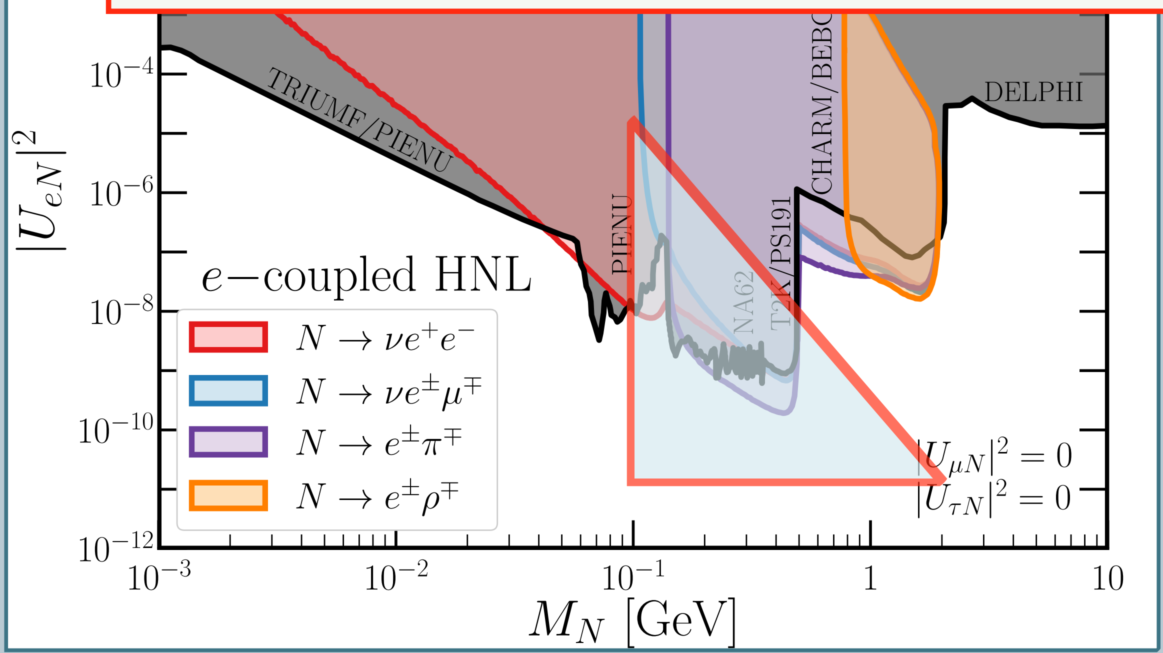
DUNE offers a unique opportunity — its near detector complex will contain a *gaseous* argon detector, which can be used for precise particle and charge identification

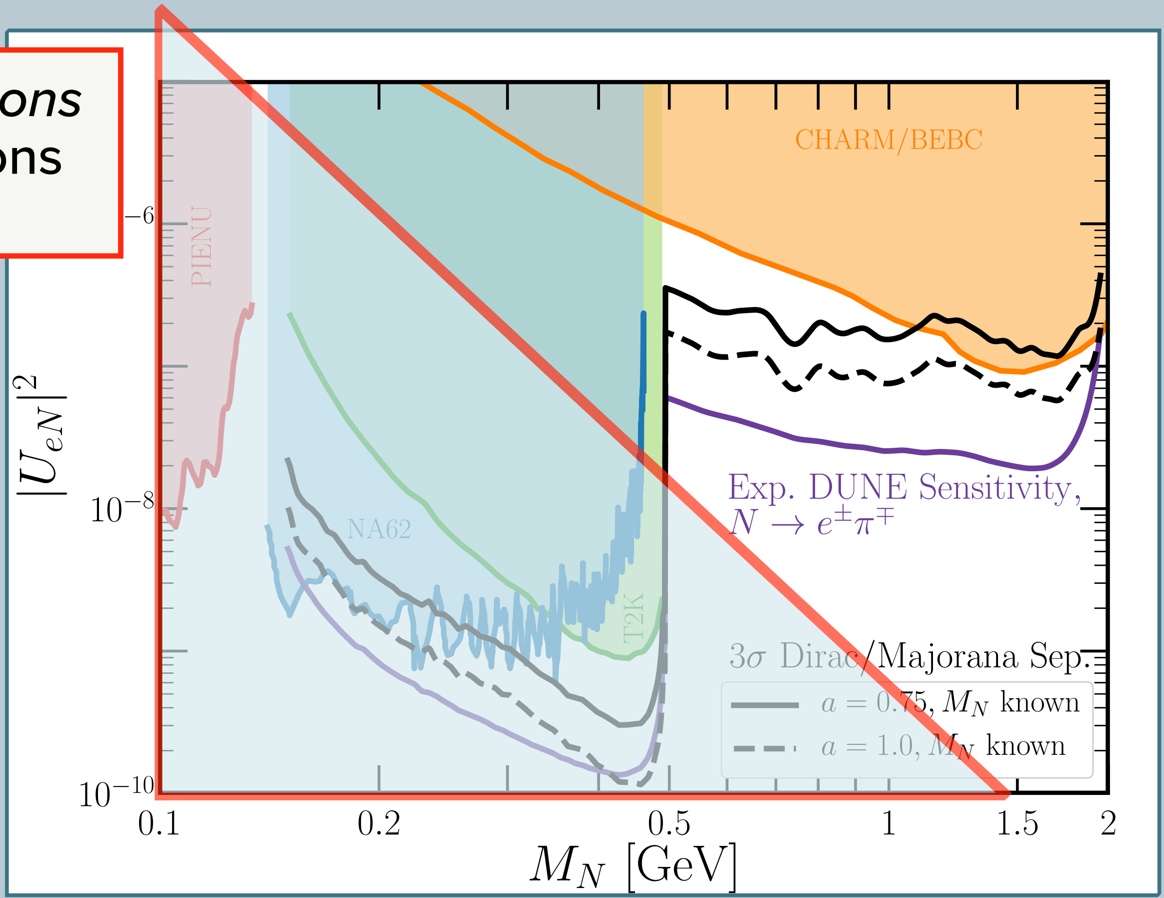
Might be able to distinguish *Dirac* from *Majorana* HNLs!

JMB, et al., JHEP 02 (2020) 174; A. Boyarsky, et al., arXiv:2008.00749

MeV/GeV-scale Neutrinos

BTW: HNLs in the early universe produce *mesons* from their decays; these can equilibrate protons and neutrons *too efficiently* for BBN





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JMB, et al., JHEP 02 (2020) 174; A. Boyarsky, et al., arXiv:2008.00749

The Things I Missed

Obviously, there are *a ton* of possible ways to resolve these anomalies that I didn't have time to get into — with and without the introduction of new physics!

New signatures:
Gninenko 1107.0279 *No LSND*
Heavy neutrino O(MeV), magnetic moment, decay

Bertuzzo et al 1807.09877, Ballett et al 1808.02916, Arguelles et al 1812.08768
Heavy neutrino O(1-100MeV), light Z', decay *No LSND*

Oscillations+:
Asaadi et al 1712.08019
Resonant matter effect *UV challenge*

Doring et al 1808.07460, Barenboim et al 1911.02329
eV steriles and extra dimensional shortcuts *not clear*

Liao et al 1810.01000
Steriles + NCNSI + CCNSI *Baroque*

Decay:
Bai et al 1512.05357, Dentler et al 1911.01427, de Gouvêa et al 1911.01447
Heavy sterile O(keV-MeV) decay to ν_e *May work...*

Reactor fluxes:

A. C. Hayes, et al., PRL 112 (2014) 202501;
A.C. Hayes & P. Vogel, Ann. Rev. Nucl. Part. Sci. 66 (2016) 219;
M. Estienne et al. PRL 123, (2019) 022502;
L. Hayen, et al., PRC 99 (2019) 031301
JMB & P. Huber, arXiv:2005.0175

Nonstandard Neutrino Cosmology:

J. F. Cherry, et al., arXiv:1605.06506;
N. Blinov, PRL 123 (2019), 191102;
C. D. Kreisch, et al., PRD 101 (2020) 123505
A. de Gouvêa, et al., PRL 124 (2020), 081802;
Y. Y. Y. Wong @ Neutrino 2020 & references therein

And a lot more!

Advertisement: Snowmass and P5

The particle physics community is currently in the long-term planning process

Snowmass is going on now; *P5* will be convening next calendar year

Any and all input is helpful!

If you're interested in participating, please feel free to reach out: jeffberryman[AT]berkeley[DOT]edu

Letters of interest (LOIs; LsOI?) are (nominally) due *31 August*

Conclusions

- The evidence for the existence of additional neutrinos is *ambiguous*; the hints keep piling up, but a *consistent picture* has yet to emerge
  - That there are numerous independent methods to search for them is an asset — but we need to decipher what these hints are telling us
- Whether or not you believe that sterile neutrinos exist is ultimately up to you, but *you should care deeply about how we go about searching for it*
  - Funding is essentially a zero-sum game; money spent on hunting for sterile neutrinos is money that *isn't spent doing something else*
- With long-term planning underway, now is a great time to start thinking about where we go from here
  - If you're interested in this question, now's the time to *speak up!*

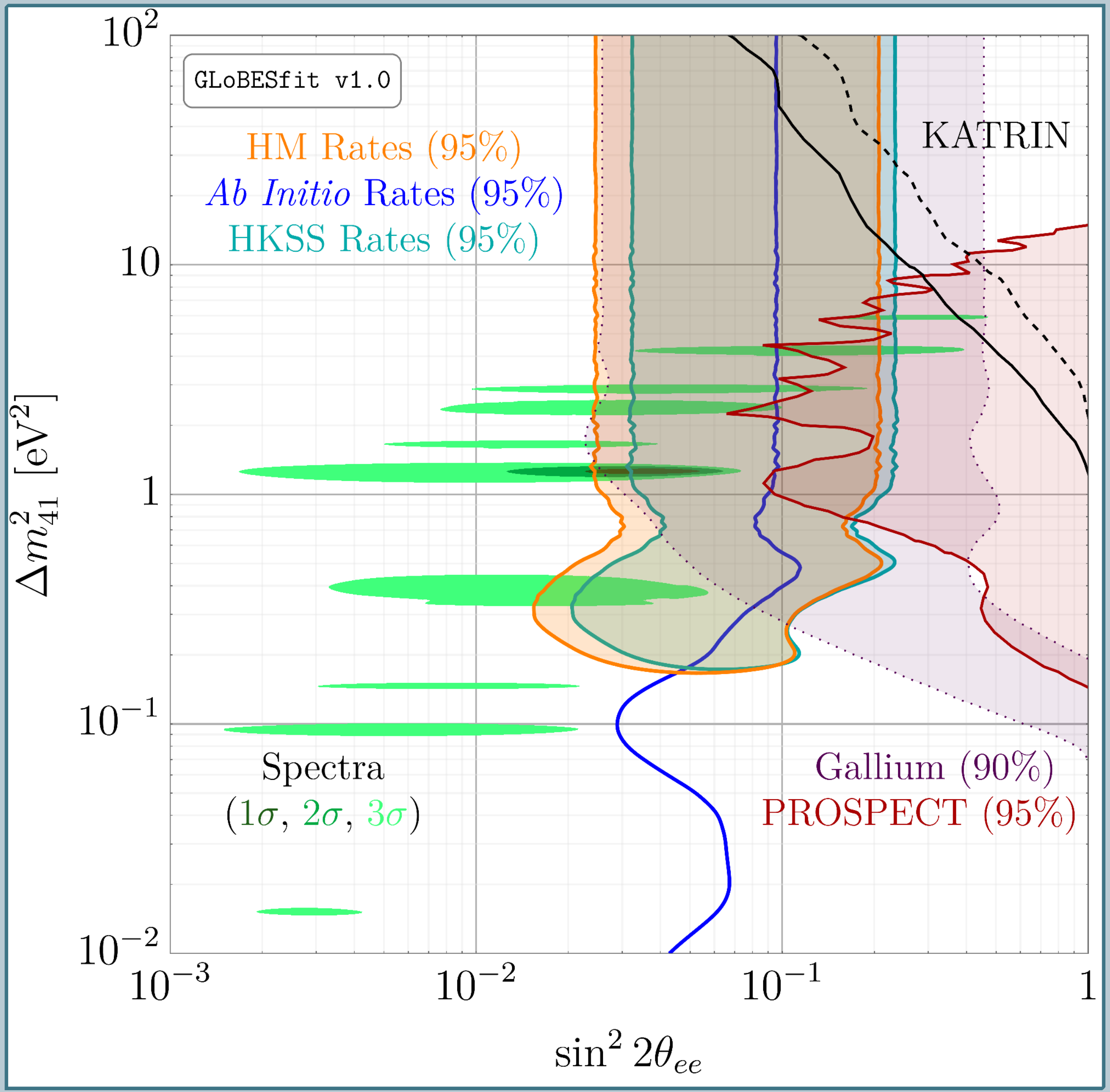
We'll See What Happens!

Thank you for your attention!

Backup

Comparison with PROSPECT

Current constraints from PROSPECT do not appear to be as competitive in the hunt for a sterile neutrino – perhaps opportunities for improvement?

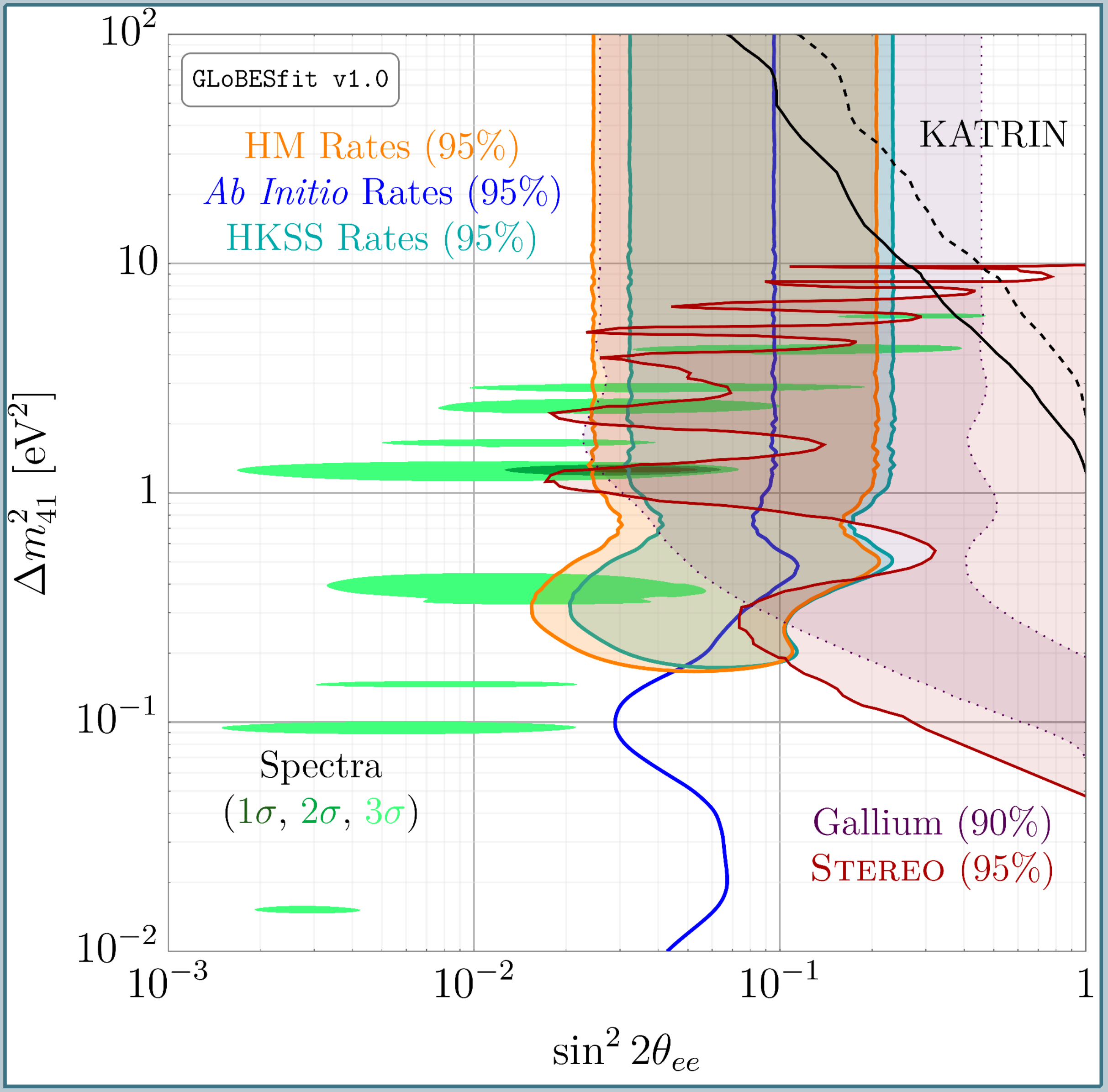


PROSPECT Collaboration, arXiv:2006.11210

Comparison with STEREO

The latest result from STEREO (179 days) is already challenging the results of our spectral analysis!

This (and PROSPECT) will be included in future updates to our code, **`GLoBESfit`**



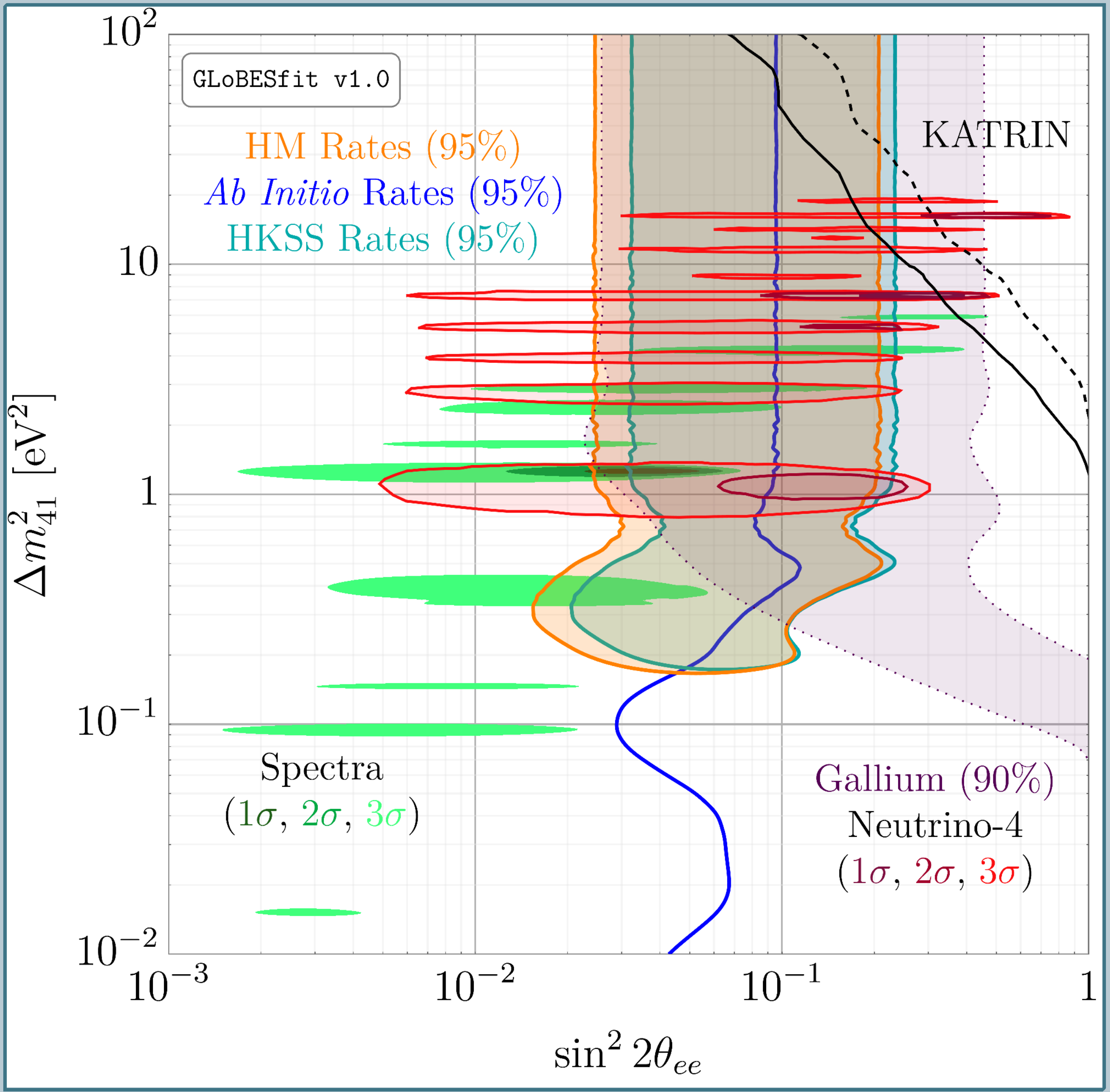
STEREO Collaboration, arXiv:1912.06582; S. Schoppmann @ Neutrino 2020

Comparison with Neutrino-4

Neutrino-4 has been…*controversial*

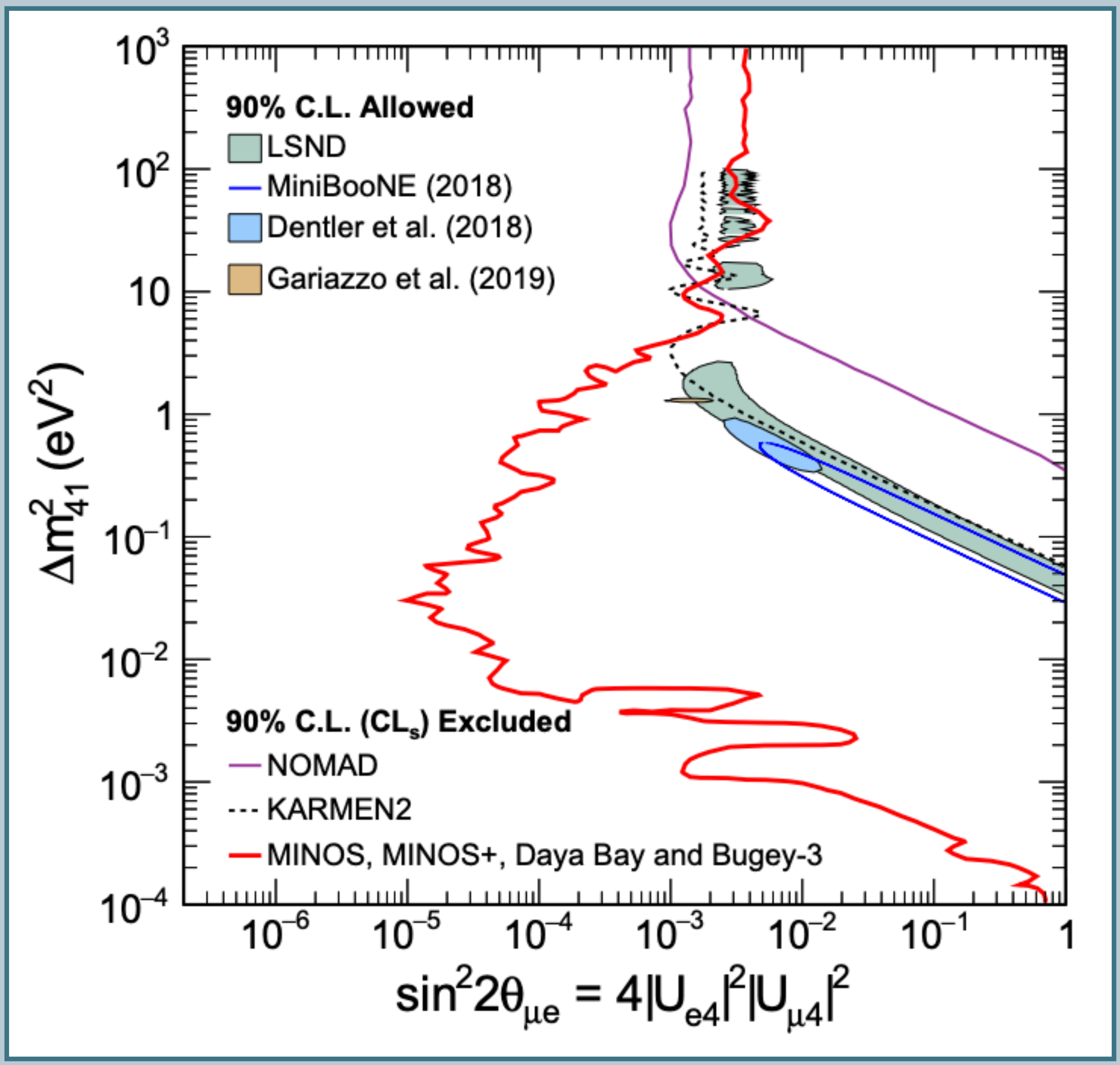
See *arXiv:2006.13147* (PROSPECT & STEREO Collaborations) for discussion on the deficiencies of Neutrino-4's analysis

See *arXiv:2006.13639* for Neutrino-4's response



A. Serebrov @ AAP 2019

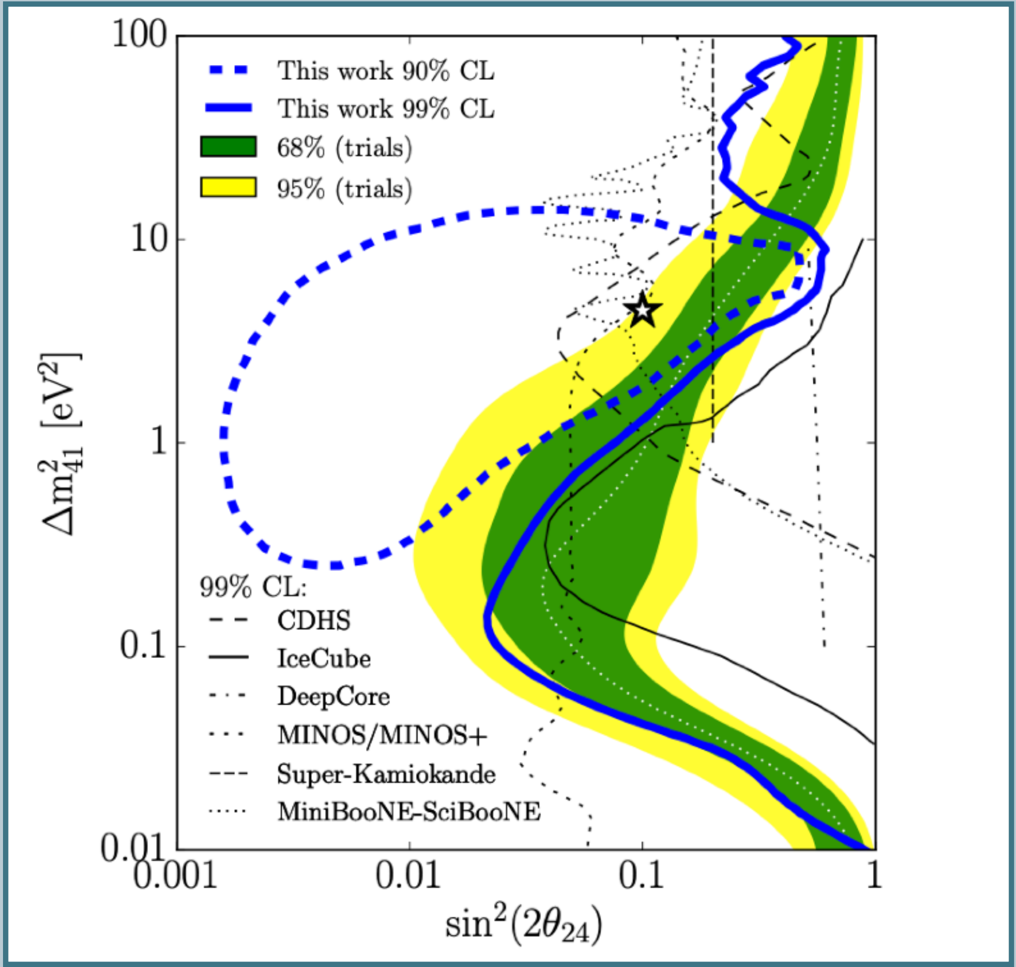
MINOS(+), Daya Bay & Bugey

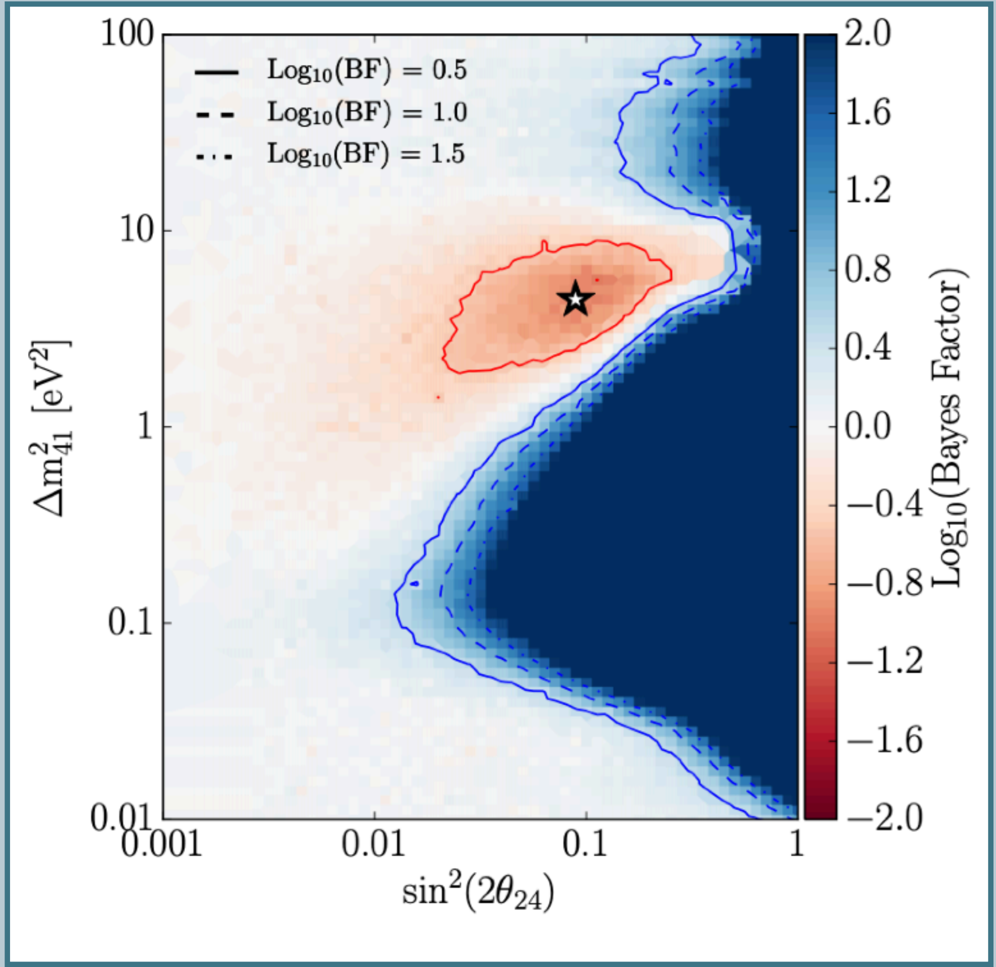


The conclusion is inescapable: the appearance and disappearance data don't play nicely together!

MINOS+ and Daya Bay Collaborations, PRL 125 (2020) 071801

IceCube

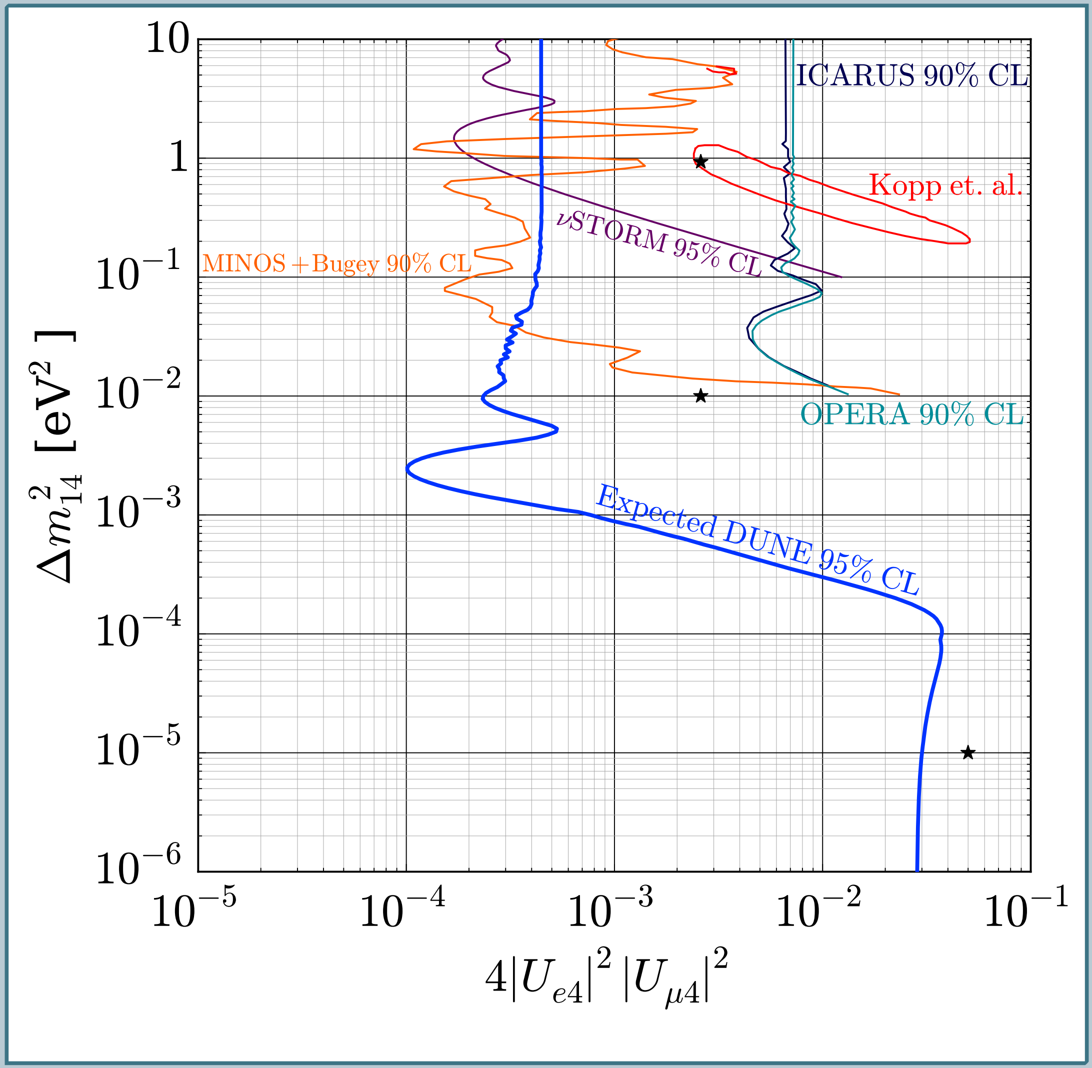


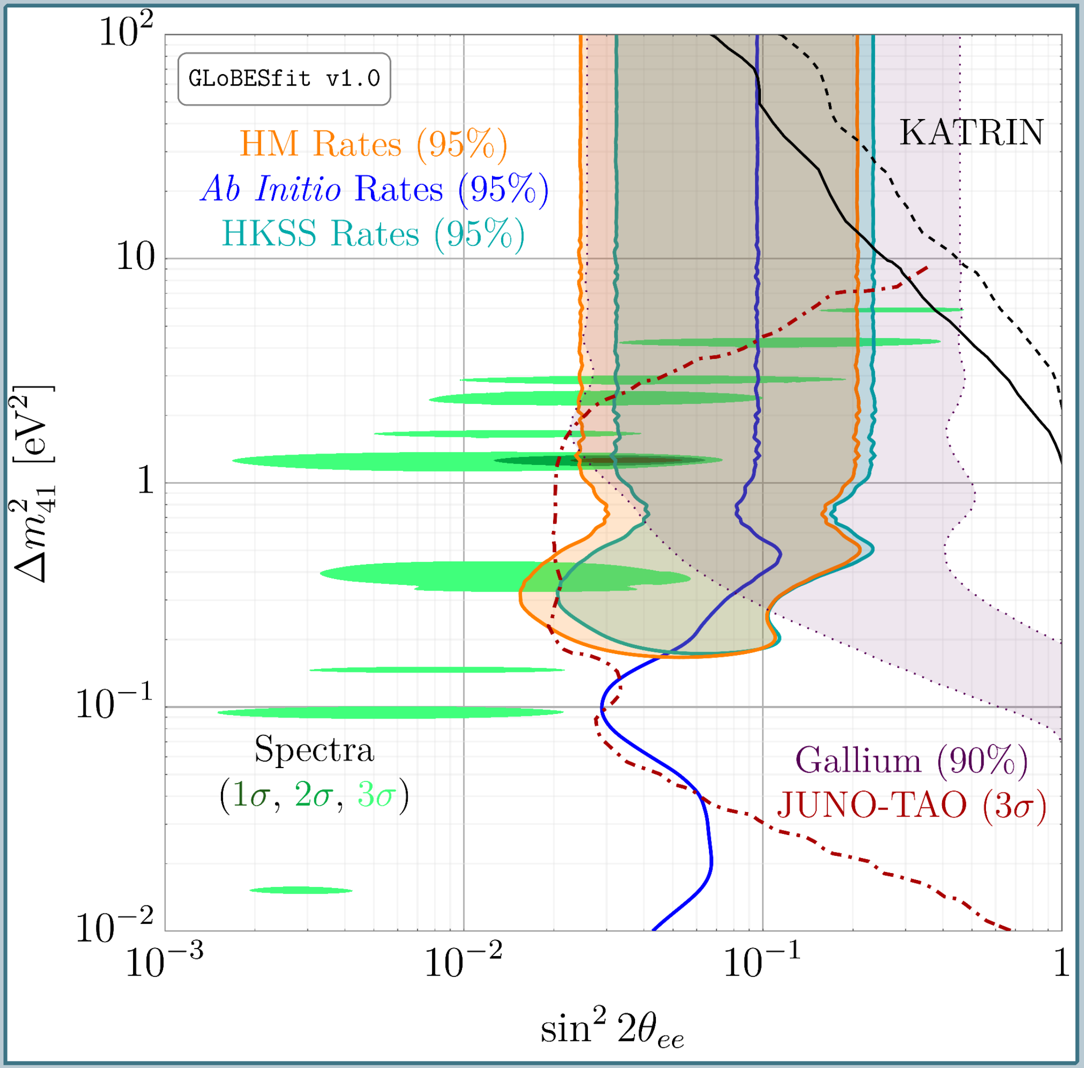


The IceCube collaboration has performed both a frequentist (left) and Bayesian (right) search for a sterile neutrino. They show *very mild* preference for nonzero ν_μ disappearance, *but this is not worth getting excited over*

IceCube Collaboration, arXiv:2005.12942 & 2005.12943

Long-Baseline Experiments





Long-baseline experimental programs will also have some sensitivity

See also: HyperKamiokande, T2HK(K), INO, ESSνSB, Theia

JMB, A. de Gouvêa, A. Kobach & K. J. Kelly, PRD 92 (2015) 073012;
JUNO Collaboration, arXiv:2005.08745