Sterile neutrinos

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Breaking news: neutrinos have mass!

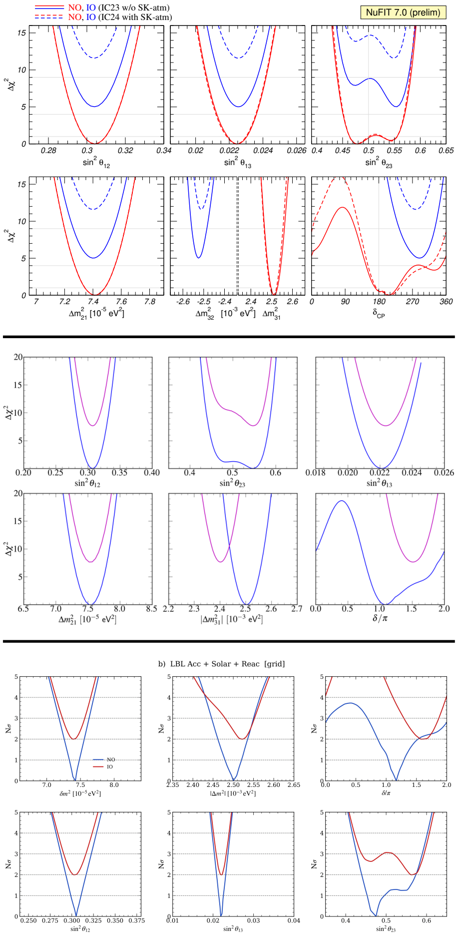
- 3ν global fits: non-zero $\Delta m^2_{ji} \Rightarrow$ non-zero m_i;
- however, in the original SM there is no ν_R:

$(1,2)_{-1}$	$(3,2)_{1/3}$	$(1,1)_{-2}$	$(3,1)_{4/3}$	$(3,1)_{-2/3}$
$\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L$	$\begin{pmatrix}u^i\\ d^i\end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix}\nu_\mu\\ \mu\end{pmatrix}_L$	$\begin{pmatrix}c^i\\ s^i\end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix}\nu_\tau\\ \tau\end{pmatrix}_L$	$\begin{pmatrix}t^i\\ b^i\end{pmatrix}_L$	τ_R	t^i_R	b^i_R

with $SU(3)_C \times SU(2)_L \times U(1)_Y \Rightarrow SU(3)_C \times U(1)_{EM}$;

- SM birth: $\begin{cases} m_{\nu_e} < 2.2 \text{ eV} & ({}^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e) \\ m_{\nu_\mu} < 190 \text{ KeV} & (\pi \to \mu + \nu_\mu) \\ m_{\nu_\tau} < 18.2 \text{ MeV} & (\tau \to n\pi + \nu_\tau, \text{ with } n > 3) \end{cases}$

$\Rightarrow$ neutrinos are conjured to be **massless** and **left-handed**.



NuFIT [1]

Valencia [2]

Bari [3]

[1] I. Esteban *et al.*, NuFIT 7.0 (in preparation)

[2] M. Beccaria, talk NOW 2026, Otranto, Italy, 31/08–6/09/2026

[3] F. Marcone, talk NOW 2026, Otranto, Italy, 31/08–6/09/2026

Adding neutrino masses to the SM: Dirac or Majorana?

- How to write a mass term for a fermion field? Two possibilities:

Dirac

$$\mathscr{L}^{\text{D}} = -m\,(\overline{\nu_R}\,\nu_L + \overline{\nu_L}\,\nu_R)$$

- can be implemented in the SM via SSB as for up-type quarks:

$$\mathscr{L}^{\text{D}} = -Y^\ell\,\overline{L_L}\,\Phi\,\ell_R - Y^\nu\,\overline{L_L}\,\tilde{\Phi}\,\nu_R + \text{h.c.}$$

- however, it requires a **new** field ν_R $\Longrightarrow$ SM extension!

Majorana

$$\mathscr{L}^{\text{M}} = -\frac{1}{2}m\left(\overline{\nu_L^C}\,\nu_L + \overline{\nu_L}\,\nu_L^C\right)$$

- only ν_L used $\Longrightarrow$ no new field required;
- breaks gauge symmetries $\Longrightarrow$ unthinkable for **charged** particles (Q is conserved);
- can't be written explicitly in the SM $\Longrightarrow$ should be generated by some *effective* mechanism $\Longrightarrow$ SM extension!

- both possibilities are phenomenologically viable $\Longrightarrow$ most general case is to use both:

$$\mathscr{L} = -Y^\ell\,\overline{L_L}\,\Phi\,\ell_R - Y^\nu\,\overline{L_L}\,\tilde{\Phi}\,\nu_R - \frac{1}{2}M\,\overline{\nu_R^C}\,\nu_R + \text{h.c.}$$

- ν_R is a singlet under SM symmetries $\Longrightarrow$ can have an explicit Majorana mass;
- now we have 6 mass eigenstates, furthermore ν_R gauge singlets need not be three…

Neutrino oscillations in the presence of extra mass states

- Equation of motion: same as usual, but only in the mass basis (identified by suffix “mb”):

$$i\frac{d\vec{\nu}_{\text{mb}}}{dt} = \boldsymbol{H}_{\text{mb}}\,\vec{\nu}_{\text{mb}}; \qquad \boldsymbol{H}_{\text{mb}} = \boldsymbol{D}_{\text{vac}} \pm \boldsymbol{U}_{\text{vac}}^{\dagger} \cdot \boldsymbol{V}_{\text{mat}} \cdot \boldsymbol{U}_{\text{vac}};$$

$$\boldsymbol{U}_{\text{vac}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \dots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \dots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \dots \end{pmatrix}, \qquad \vec{\nu}_{\text{mb}} = \left(\nu_1,\ \nu_2,\ \nu_3,\ \nu_4,\ \dots\right)^T;$$

$$\boldsymbol{D}_{\text{vac}} = \frac{1}{2E_\nu}\,\textbf{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31},\ \Delta m^2_{41},\ \dots\right), \qquad \boldsymbol{V}_{\text{mat}} = \sqrt{2}G_F\left[N_e\,\textbf{diag}\left(1,\ 0,\ 0\right) - \frac{N_n}{2}\boldsymbol{I}_3\right];$$

- notice that $\boldsymbol{U}_{\text{vac}}$ is a rectangular $3 \times N$ matrix, fulfilling unitarity relation $\boldsymbol{U}_{\text{vac}} \cdot \boldsymbol{U}_{\text{vac}}^{\dagger} = \boldsymbol{I}_3$;
- formally, we can extend $\boldsymbol{U}_{\text{vac}}$ to a full $N \times N$ unitary matrix $\boldsymbol{U}$ by considering $N-3$ “flavor” states $\{\nu_{s_1}, \dots, \nu_{s_{N-3}}\}$. In this case $\boldsymbol{V}_{\text{mat}}$ is extended with null diagonal entries, and:

$$\boldsymbol{U} = \begin{pmatrix} & & \boldsymbol{U}_{\text{vac}} & & \\ U_{s_i 1} & U_{s_i 2} & U_{s_i 3} & U_{s_i 4} & \dots \end{pmatrix}, \qquad \vec{\nu} = \left(\nu_e,\ \nu_\mu,\ \nu_\tau,\ \nu_{s_1},\ \dots\right)^T;$$

- but notice that ν_{s_i} states are defined arbitrarily, hence mixing among them is unphysical.

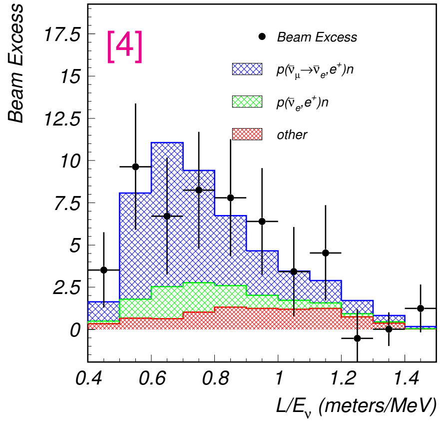
¿? do current experimental data show any indication that extra sterile states may exist?

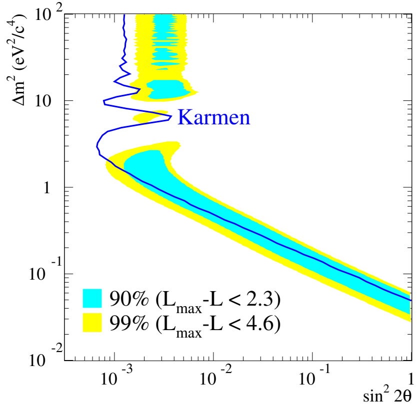
A long time ago… the LSND anomaly

- Back in the 90's, the LSND experiment observed an excess of $\bar\nu_e$ events in a $\bar\nu_\mu$ beam ($E_\nu \sim 30$ MeV, $L \simeq 35$ m) [4];
- the signal is compatible with $\bar\nu_\mu \to \bar\nu_e$ oscillations provided that $\Delta m^2 \gtrsim 0.1$ eV^2;
- on the other hand, global neutrino data give (at 3σ):

$$\Delta m^2_{\text{SOL}} \simeq [7.2 \to 7.6] \times 10^{-5}\ \text{eV}^2\,,$$
$$|\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3}\ \text{eV}^2\,;$$

- hence, to explain LSND with mass-induced ν oscillations one needs **new** neutrino mass eigenstates;
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [5];
- since then, lots of searches have tried to shed light on the issue.





[4] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049]

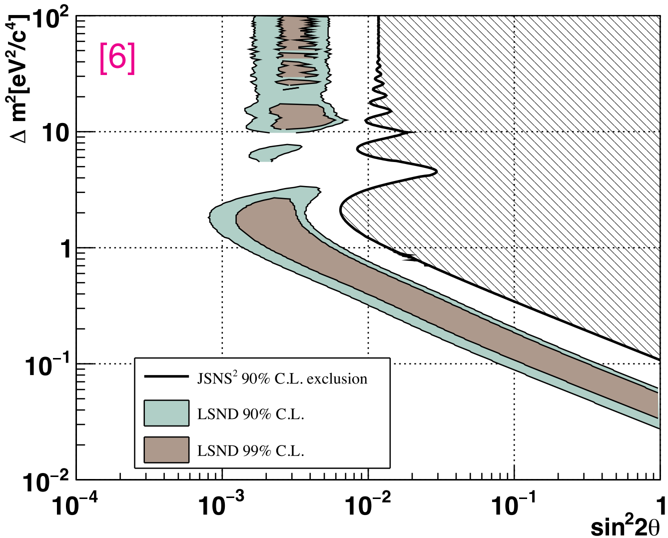
[5] B. Armbruster *et al.* [KARMEN collab], Phys. Rev. D **65** (2002) 112001 [hep-ex/0203021]

Testing the LSND finding: JSNS^2

- To really check the LSND finding in a model-independent way, one need an experiment with the same physics configuration (and possibly different detector technology);
- Karmen not powerful enough. Since then no new experiment of this kind – until now;
- JSNS^2 just presented first data [6]: events $= 8$, background $= 6.1 \pm 1.0$, LSND-bf $= 2.8 \pm 1.3$ $\Rightarrow$ still far from required sensitivity;
- statistics: $\times\, 3$ already available, $\times\, 6$ expected. Also: far detector under commissioning, larger fiducial volume & better efficiency expected;
- will it be enough to probe LSND? Maybe.

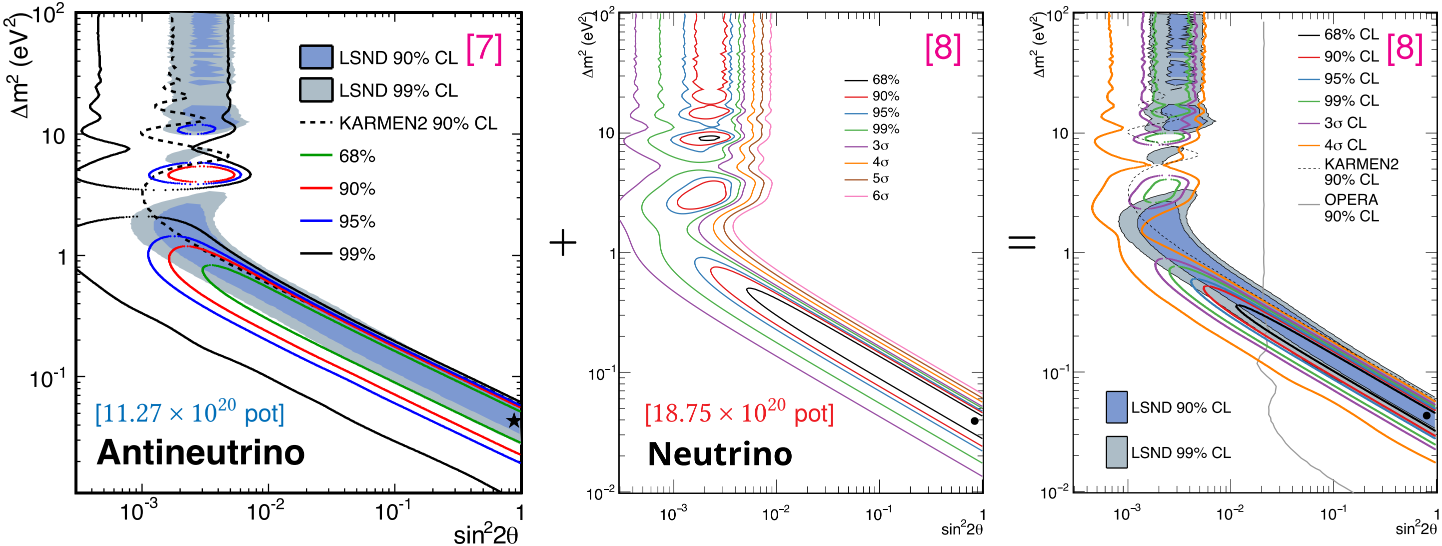
[6] D. Lee [JSNS^2], talk at NuFact 2026, Tsung-Dao Lee Institute, Shanghai, China, 31/08–5/09/2026

	LSND	JSNS²/JSNS²-II
Target Mass	167 tons	17 tons (Near) , 32tons (Far)
Baseline	30 m	24 m (Near) , 48m (Far)
Beam Energy	0.8 GeV proton	3 GeV proton
# μ / p	0.079	0.48 +- 0.17 (*)
Beam duty factor	1/14 (by Linac)	8/40000 (by Synchrotron)
Energy Resolution	7% @ 45MeV	3% @ 53MeV
Liquid scintillator	Scintillation light	Gd-loaded Scintillation light + DIN is added
Delayed signal	E ~ 2.2MeV, Δt ~ 200μs	E ~ 8MeV, Δt ~ 30μs



Testing the LSND interpretation: the MiniBooNE experiment

- MiniBooNE: probe $\bar{\nu}_\mu \to \bar{\nu}_e$ conversion ($E = 200 \to 1250$ MeV, $L \simeq 541$ m, $L/E \sim$ LSND);
- excess in both $\bar{\nu}$ and ν $\Rightarrow$ oscillations compatible with LSND (ev $= 4.8\sigma$, gof $= 12.3\%$);
- however, the low energy part of the excess **cannot** be accounted just by oscillations…

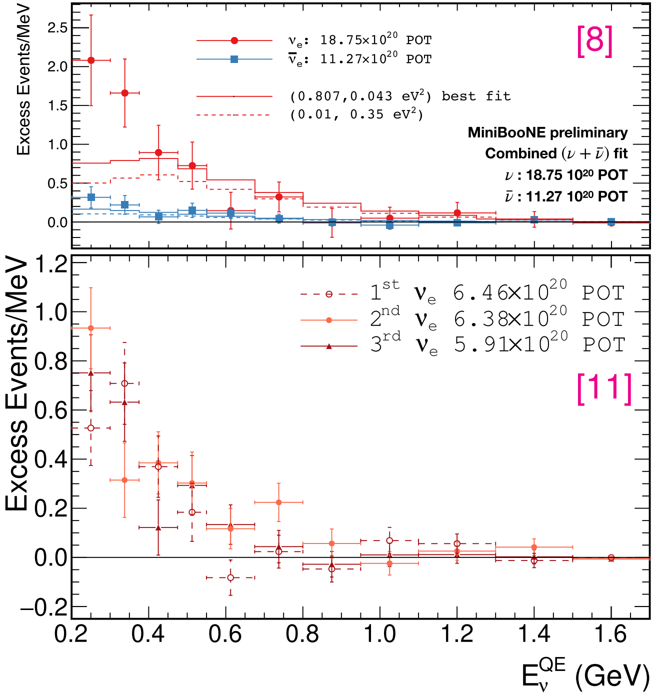


[7] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [arXiv:1303.2588]

[8] A. Hourlier [MiniBooNE], talk at Neutrino 2020, Fermilab (online), USA, 22/6-2/7/2020

MiniBooNE low-energy excess

- Excess present from the very beginning;
- 2007 (ν): low-E excess too steep for oscillation fit ($P_{\text{osc}} \simeq 1\%$) $\Rightarrow$ set $E \geq 475$ MeV $\Rightarrow$ no signal left $\Rightarrow$ **reject** LSND [9];
- 2013 ($\bar{\nu}$): low-E not so steep + mid-E excess observed $\Rightarrow$ good oscillation fit ($P_{\text{osc}} \simeq 66\%$) $\Rightarrow$ **confirm** LSND [7];
- 2018 (ν): low-E softened + mid-E excess seen also in ν $\Rightarrow$ mild oscillation fit ($P_{\text{osc}} \simeq 15\%$) [10];
- 2020 (ν): more data released [11], oscillations confirmed but low-E excess definitely there.



[8] A. Hourlier [MiniBooNE], talk at Neutrino 2020, Fermilab (online), USA, 22/6-2/7/2020

[9] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **98** (2007) 231801 [arXiv:0704.1500]

[7] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **110** (2013) 161801 [arXiv:1303.2588]

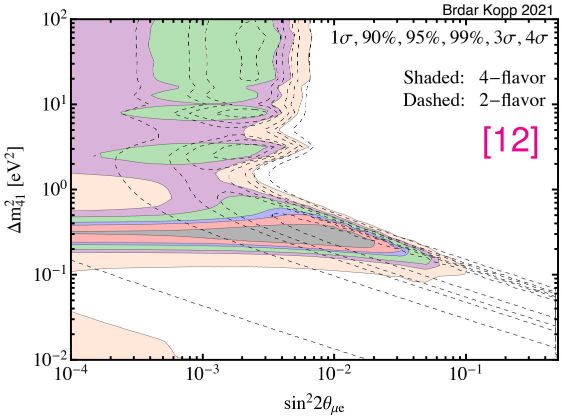
[10] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **121** (2018) 221801 [arXiv:1805.12028]

[11] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. D **103** (2021) 052002 [arXiv:2006.16883]

Final results of MiniBooNE

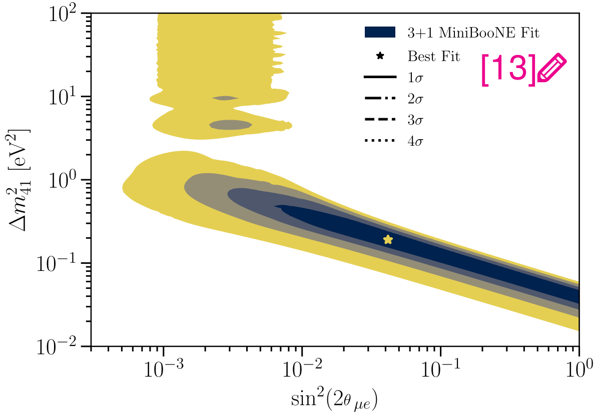
- Possible systematics related to the low-E excess:
  - misreconstruction of neutrino energy;
  - π^0 from NC reconstructed as ν_e;
  - single photon from NC misidentified as ν_e;
- extensive studies performed by the collaboration;
- present status: no combination of known systematics could account for the whole excess [12];

⇒ independent experimental confirmation is required.



2ν versus 4ν oscillations

- Former MB studies overlooked oscillations of $\overset{(-)}{\nu}_e$ beam contamination and $\overset{(-)}{\nu}_\mu$ calibration sample [12];
- such effects can be very important. Omission corrected in final analysis [13].



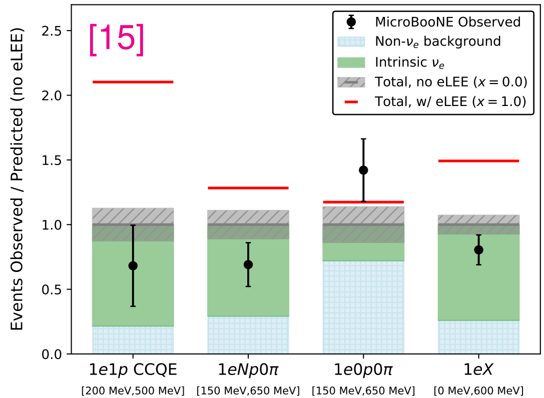
[12] V. Brdar and J. Kopp, Phys. Rev. D **105** (2022) 115024 [arXiv:2109.08157]
[13] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]

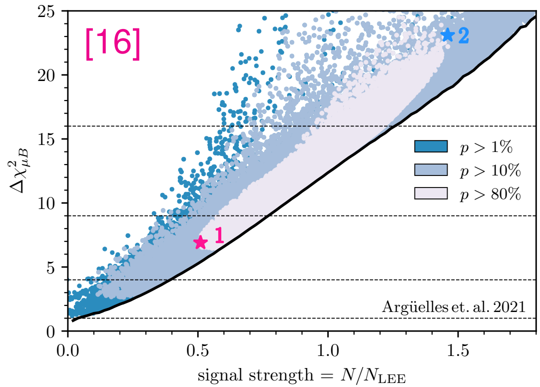
The MicroBooNE experiment

- Baseline $= 468.5$ m (72.5 m upstream of MiniBooNE);
- LArTPC ⇒ imaging with mm-scale spatial resolution;

⇒ perfectly suited to cross-check MiniBooNE excess;

- first results presented in fall 2021:
  - no evidence of enhanced π^0 or γ production [14];
  - no evidence of ν_e excess over SM prediction [15];
- however, rejection of MB signal in [15] based on the assumption that the entire ν_e excess matches the difference between data and best-fit MB background;
- but in [16] it was noticed that various signal/background compositions can fit MB equally well, but lead to different μB sensitivity ⇒ rejection **not** model-independent…

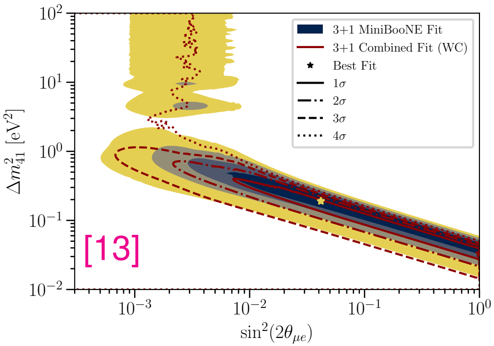


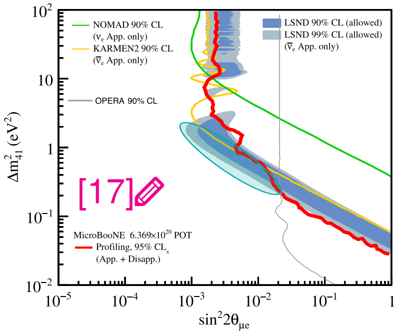


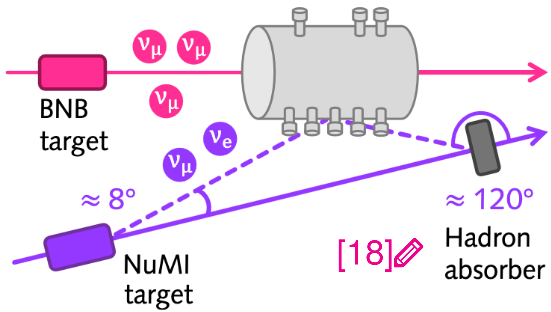
[14] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 111801 [arXiv:2110.00409]
[15] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801 [arXiv:2110.14054]
[16] C.A. Argüelles *et al.*, Phys. Rev. Lett. **128** (2022) 241802 [arXiv:2111.10359]

First comparison of MicroBooNE and MicroBooNE results

- MiniBooNE: updated analysis including μB bounds [13] $\Rightarrow 3\sigma$ region at $\Delta m^2_{41} \lesssim 1$ eV;
- MicroBooNE: global 4ν analysis [17] disfavors MB/LSND but does not rule it out completely;
- other experiments exclude large Δm^2 (NOMAD) and large $\theta_{\mu e}$ (ICARUS, OPERA);
- remaining allowed region at $0.1 \lesssim \Delta m^2_{41}/\text{eV}^2 \lesssim 1$ and $10^{-3} \lesssim \sin^2\theta_{\mu e} \lesssim \text{few} \times 10^{-2}$;
- these results have been obtained using only ν from the BNB beam (on-axis, 0.5% intrinsic ν_e);
- but μBooNE is also exposed to the very different NuMI beam (8° off-axis, 5% intrinsic ν_e, ...).



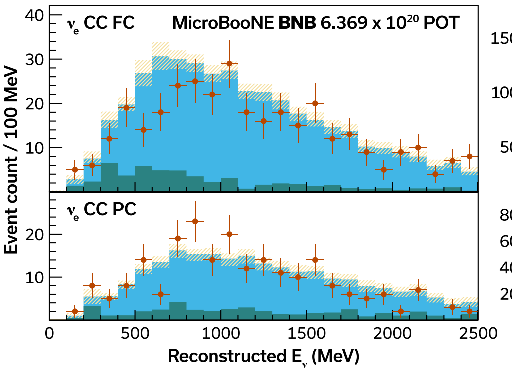


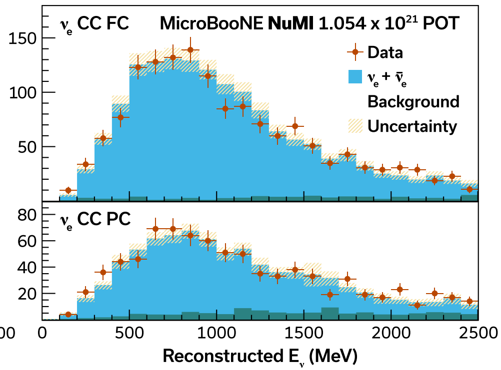


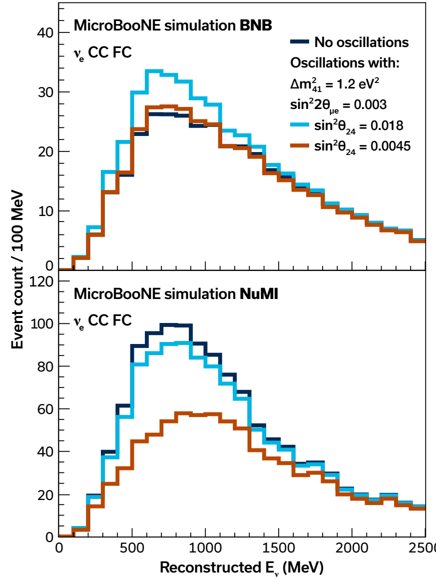
[13] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]
[17] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **130** (2023) 011801 [arXiv:2210.10216]
[18] D. Caratelli [MicroBooNE], talk at NuFact 2026, Shanghai, China, 31/08–5/09/2026

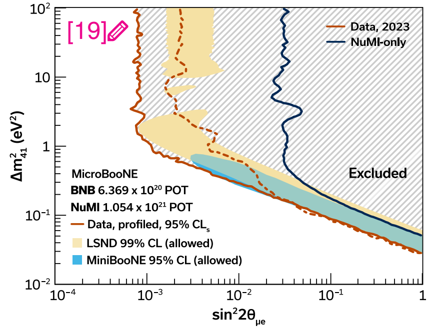
Latest MicroBooNE results: ν_e appearance

- New results: no evidence of ν_e appearance, neither in BNB nor in NuMI events $\Rightarrow$ no-oscillation solution favored;
- joint BNB + NuMI fit break 4ν degeneracies $\Rightarrow$ μBooNE can now exclude the entire 95% MiniBooNE & LSND regions [19];
- also, profiling over 4ν parameters hides information $\Rightarrow$ real rejection potentially larger than it appears in 2ν plot [20].







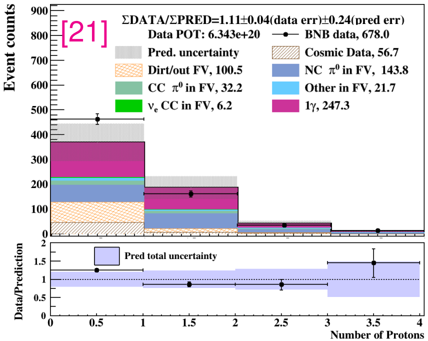


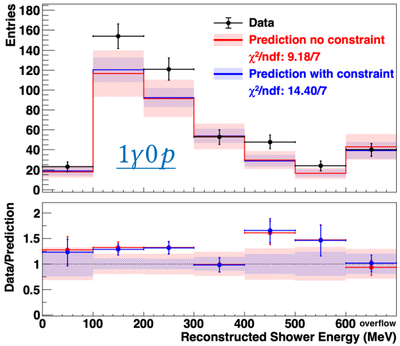
[19] P. Abratenko *et al.* [μB], Nature **648** (2025) 64 [arXiv:2512.07159]

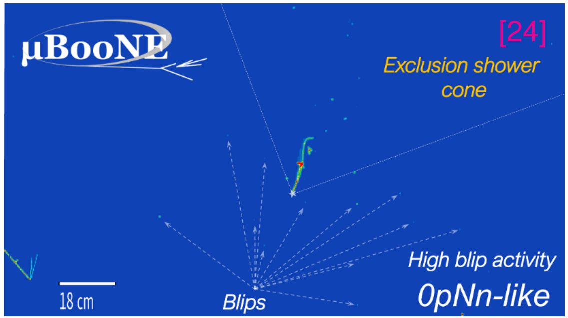
[20] O. B. Rodrigues *et al.*, PRL **135** (2025) 081801 [arXiv:2503.13594]

MicroBooNE update: dissecting the MiniBooNE low-energy excess

- In a search for 1γ events compatible with MB-LEE, μB itself found an excess [21];
- prime-suspects NC $\Delta \to N\gamma$ [22] and NC coherent 1γ [23] already disfavored;
- analysis show that the excess involves events without visible protons ($1\gamma 0p$) [21];
- recent idea: surrounding "blips" may reveal neutrons or other final-state particles [24];
- work is ongoing to establish if this excess and the MiniBooNE LEE one are related.







[21] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **136** (2026) 181806 [`arXiv:2502.06064`]

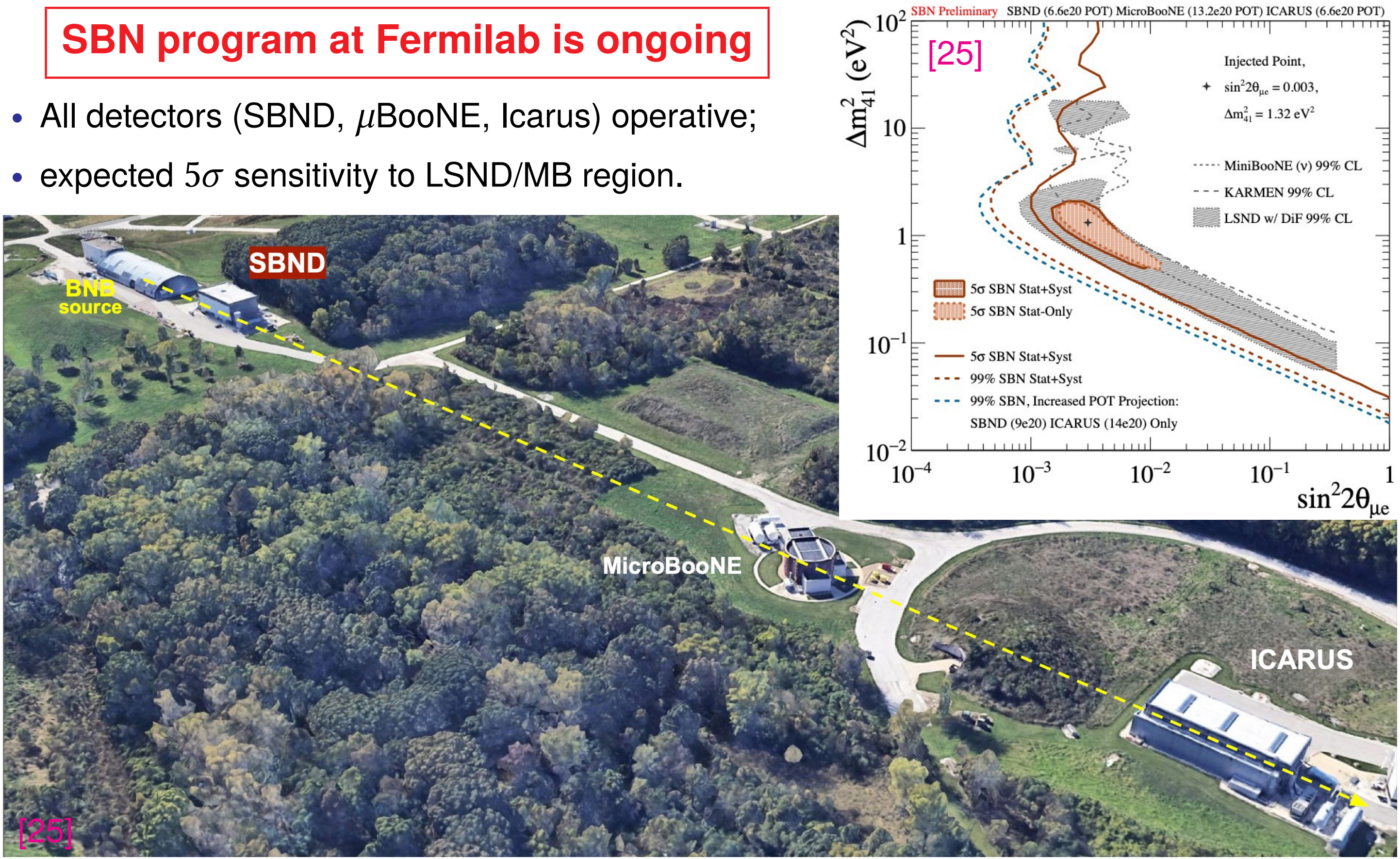
[22] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. D **112** (2025) L091101 [`arXiv:2502.05750`]

[23] P. Abratenko *et al.* [MicroBooNE], `arXiv:2502.06091`

[24] J. Hyun Jo [MicroBooNE], talk at Neutrino 2026, Irvine, USA, 21-26/06/2026

SBN program at Fermilab is ongoing

- All detectors (SBND, μBooNE, Icarus) operative;
- expected 5σ sensitivity to LSND/MB region.

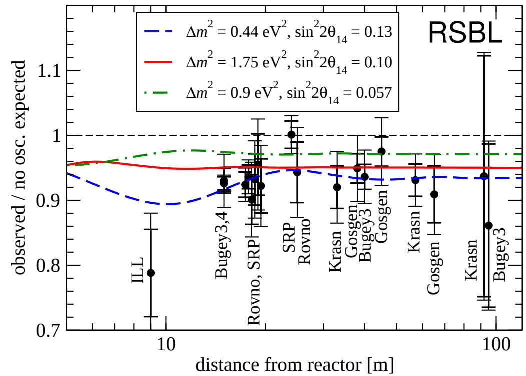


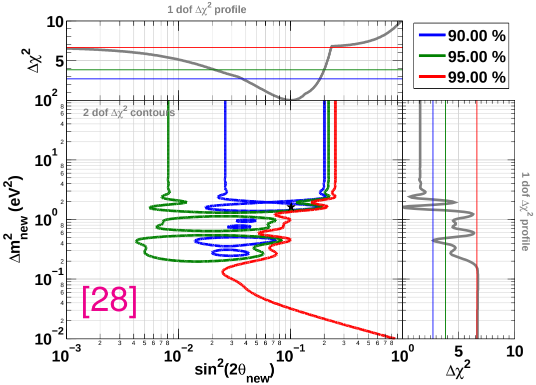
[25] S. Berkman, talk NOW 2026, Otranto, Italy, 31/08–6/09/2026

$\bar{\nu}_e$ disappearance: the reactor anomaly

- In [26, 27] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1~\text{eV}^2$;
- global data (3σ): $\begin{cases} \Delta m^2_\text{SOL} \simeq [7.2 \to 7.6] \times 10^{-5}~\text{eV}^2\,, \\ |\Delta m^2_\text{ATM}| \simeq [2.4 \to 2.6] \times 10^{-3}~\text{eV}^2\,; \end{cases}$

$\Rightarrow$ solutions: **add new neutrinos** or **revise fluxes**.





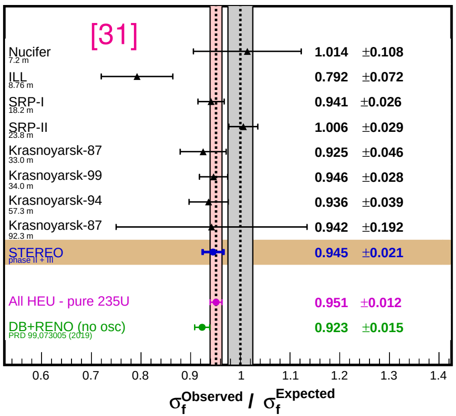
[26] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663]

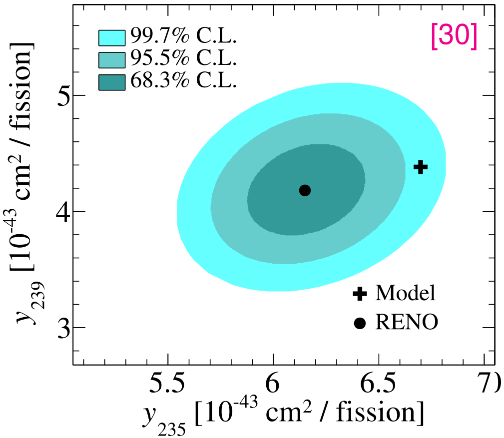
[27] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687]

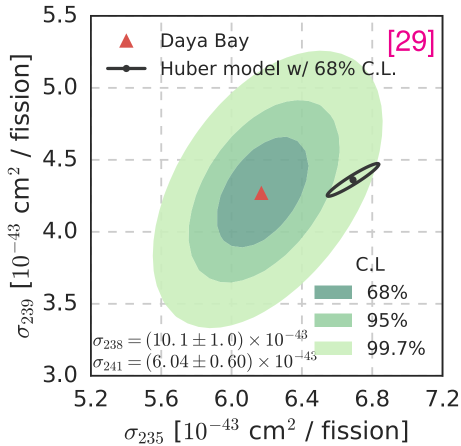
[28] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755]

Reactor anomaly: sterile ν or wrong fluxes?

- DB [29] and RENO [30]: fuel burnup cycle $\Rightarrow$ reconstruct contribution of main isotopes;
- Results: ^{239}Pu mostly agrees with Huber-Mueller model, while ^{235}U substantially below;
- STEREO data [31] (pure ^{235}U reactor) indicate a deficit similar to DB and RENO ones;
- sterile ν: deficit should be the same for all isotopes $\Rightarrow$ disagrees with observations.







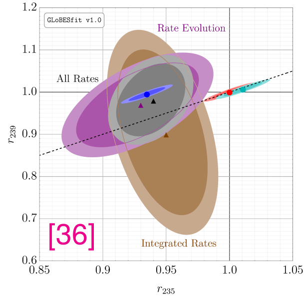
[29] F.P. An *et al.* [Daya-Bay], Phys. Rev. Lett. **118** (2017) 251801 [arXiv:1704.01082]

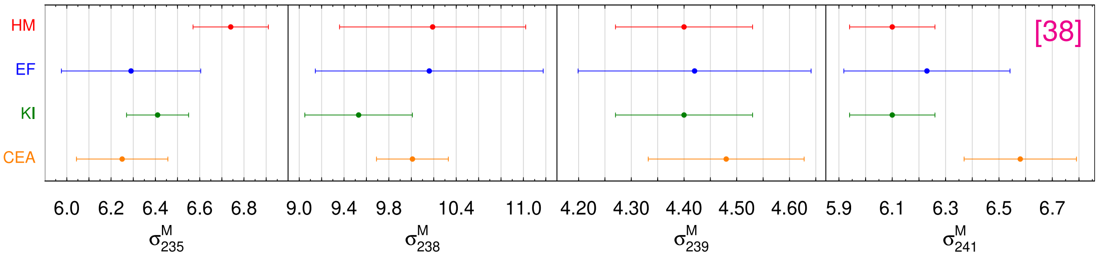
[30] G. Bak *et al.* [RENO], Phys. Rev. Lett. **122** (2019) 232501 [arXiv:1806.00574]

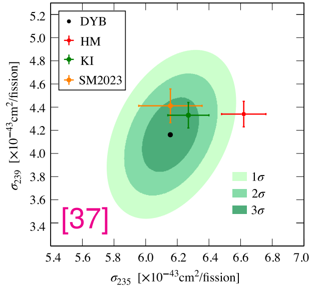
[31] H. Almazán *et al.* [STEREO], Nature **613** (2023) 257-261 [arXiv:2210.07664]

Recent developments in reactor flux models

- New reactor flux calculations: EF [32], HKSS [33], KI [34], CEA [35];
- EF and CEA (summation) in good agreement with observed rates;
- KI model (conversion) yields very similar results to EF;
- conversely, HKSS (conversion) gives rates similar to HM.







[32] M. Estienne *et al.* [EF model], Phys. Rev. Lett. **123** (2019) 022502 [arXiv:1904.09358]

[33] L. Hayen *et al.* [HKSS model], Phys. Rev. C **100** (2019) 054323 [arXiv:1908.08302]

[34] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [arXiv:2103.01684]

[35] L. Perissé *et al.* [CEA model], Phys. Rev. C **108** (2023) 055501 [arXiv:2304.14992]

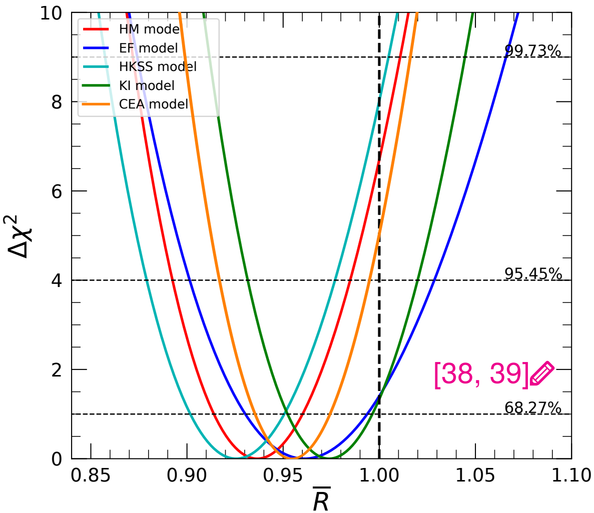
[36] J.M. Berryman and P. Huber, JHEP **01** (2021) 167 [arXiv:2005.01756]

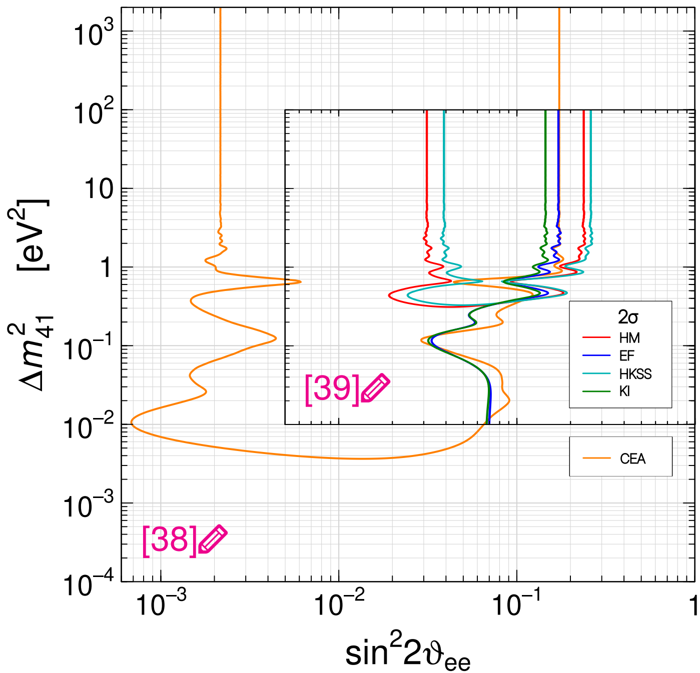
[37] F.P. An *et al.* [Daya-Bay], Phys. Rev. Lett. **134** (2025) 201802 [arXiv:2501.00746]

[38] C. Giunti, Y.F. Li, R.P. Zhang, arXiv:2605.10353

Status of the reactor anomaly

- Sterile ν hint [38, 39]: sizable (HM, HKSS) → weak (EF, KI) → sizable (CEA);
- reason: CEA agrees with (EF, KI) in *value*, but has smaller *errors* ⇒ tension reappear.



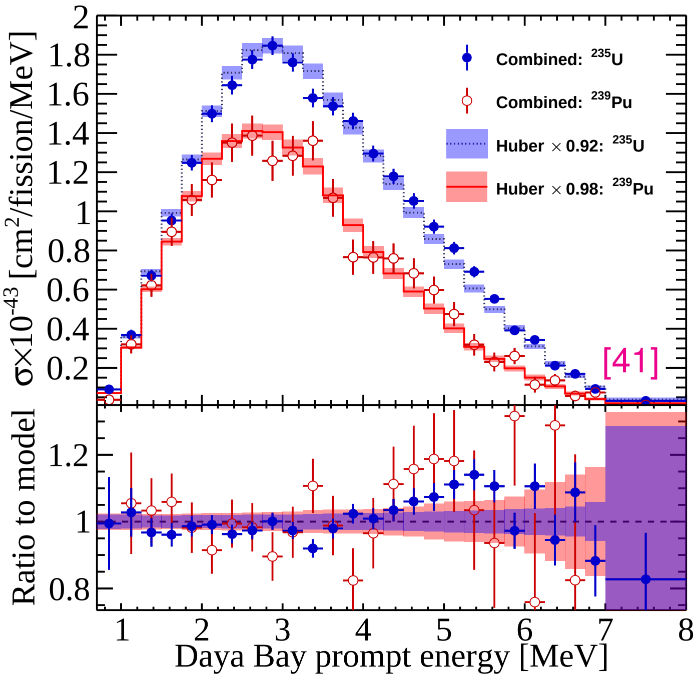


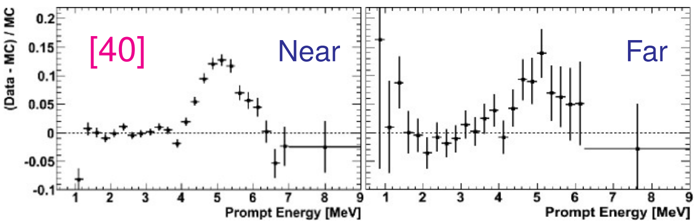
RAA/rates	HM	EF	HKSS	KI	CEA
Ref. [39]	2.5σ	1.2σ	2.9σ	1.1σ	—
Ref. [38]	2.6σ	1.2σ	—	0.6σ	2.2σ

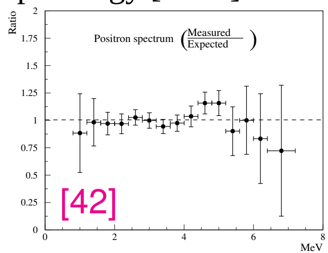
[38] C. Giunti, Y.F. Li, R.P. Zhang, arXiv:2605.10353
[39] C. Giunti *et al.*, Phys. Lett. B **829** (2022) 137054 [arXiv:2110.06820]

$\bar{\nu}_e$ disapp: 5 MeV excess

- Neutrino 2014: RENO [40] reported an excess of events around 5 MeV;
- seen by most reactors (also old Chooz [42]);
- DB+Prospect [41]: affect both ^{235}U & ^{239}Pu;
- excess (not deficit) & independent of $L \Rightarrow$ **flux feature**, not ~~**sterile oscillations**~~;
- accounted by HKSS, but not by EF and KI $\Rightarrow$ reactor fluxes require further scrutiny.



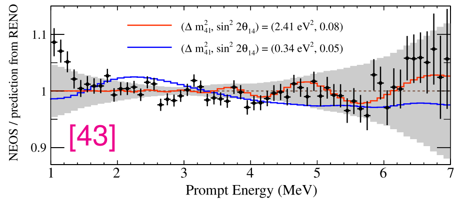


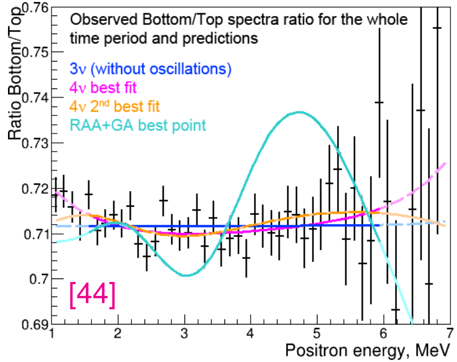


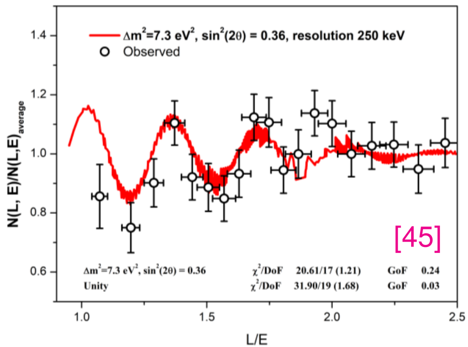
[40] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014
[41] F.P. An *et al.* [DB+Prospect], PRL **128** (2022) 081801 [arXiv:2106.12251]
[42] M. Apollonio *et al.* [Chooz], PLB **466** (1999) 415 [hep-ex/9907037]

Sterile ν: spectra and baselines

- New detectors with spectral capability and baseline range:
  - NEOS (Korea), commercial, $L = 23.7$ m;
  - STEREO (France), enriched, $L = 9 \to 11$ m;
  - PROSPECT (USA), enriched, $L = 7 \to 12$ m;
  - DANSS (Russia) commercial, $L = 10.9 \to 12.9$ m;
  - SOLID (Belgium), enriched, $L = 5.5 \to 12$ m;
  - Neutrino4 (Russia), enriched, $L = 6 \to 12$ m;
- goals: { – accurate study of reactor ν spectrum; – flux-independent osc. by near/far ratio;
- results: most experiments report no evidence, a few observe wiggles at low significance (DANSS, NEOS);
- exception: Neutrino4 reports 3σ signal with $\Delta m^2 \sim 7$ eV^2.



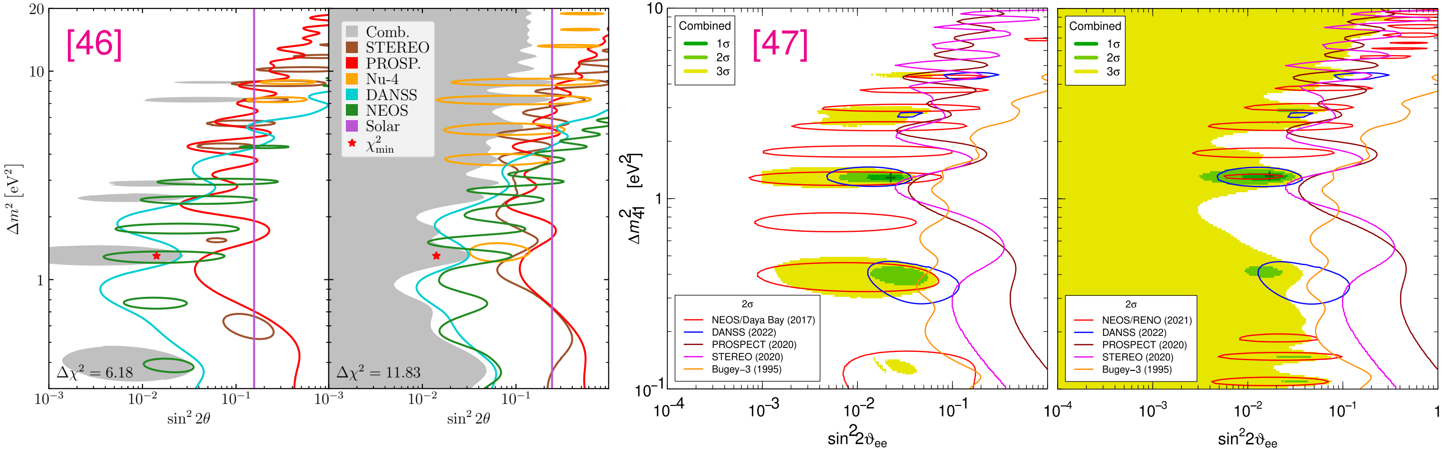




[43] Z. Atif *et al.* [NEOS & RENO], Phys. Rev. D **105** (2022) L111101 [arXiv:2011.00896]
[44] E. Samigullin [DANSS], talk at NuFact 23, Seoul, Korea, 25/08/2023
[45] A.P. Serebrov *et al.* [NEUTRINO4], arXiv:2302.09958

Flux-independent fits of reactor $\bar{\nu}_e$ disappearance data

- Fits based on spectral ratios at various distances are independent of the reactor ν spectrum;
- NEOS + Daya-Bay exhibits stronger wiggles than NEOS + RENO [47];
- no consistent pattern from various "hints". Combined fit weakly prefers $\Delta m^2 \sim 1.3$ eV^2;
- SOLID's first results [48] (not included in these fits) don't find any indication of sterile ν.



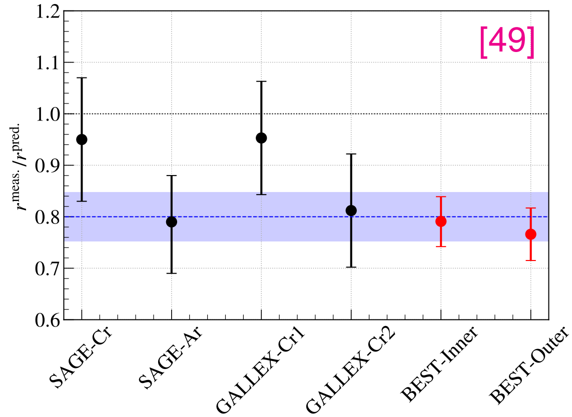
[46] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]
[47] C. Giunti *et al.*, JHEP **10** (2022) 164 [arXiv:2209.00916]
[48] Y. Abreu *et al.* [SoLid], Phys. Rev. D **111** (2025) 072005 [arXiv:2407.14382]

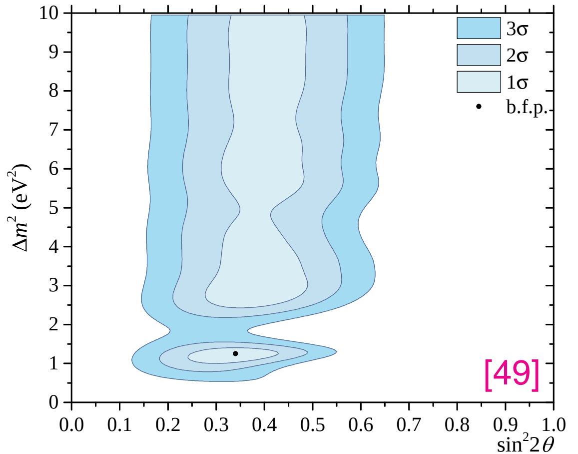
ν_e disappearance: the gallium anomaly

- ${}^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}\,\nu$ capture cross-section was calibrated with intense ${}^{51}\mathrm{Cr}$ and ${}^{37}\mathrm{Ar}$ sources by GALLEX & SAGE (20 years ago) as well as BEST (2022);
- these measurements show a significant deficit with respect to the predicted values [49]:

$$\left.\begin{array}{rl} \text{GALLEX:} & \begin{cases} R_1(\mathrm{Cr}) = 0.953 \pm 0.11 \\ R_2(\mathrm{Cr}) = 0.812 \pm 0.11 \end{cases} \\ \text{SAGE:} & \begin{cases} R_3(\mathrm{Cr}) = 0.95 \pm 0.12 \\ R_4(\mathrm{Ar}) = 0.79 \pm 0.095 \end{cases} \\ \text{BEST:} & \begin{cases} R_5(\mathrm{I}) = 0.791 \pm 0.05 \\ R_6(\mathrm{O}) = 0.766 \pm 0.05 \end{cases} \end{array}\right\} \Rightarrow \boxed{0.80 \pm 0.047}$$

- such deficit can be interpreted in terms of oscillations;
- data suggest $\Delta m^2 \gtrsim 1\ \mathrm{eV}^2$ but require very large θ_{ee}.



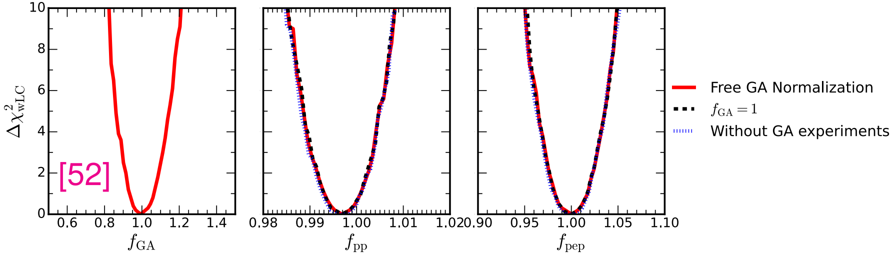


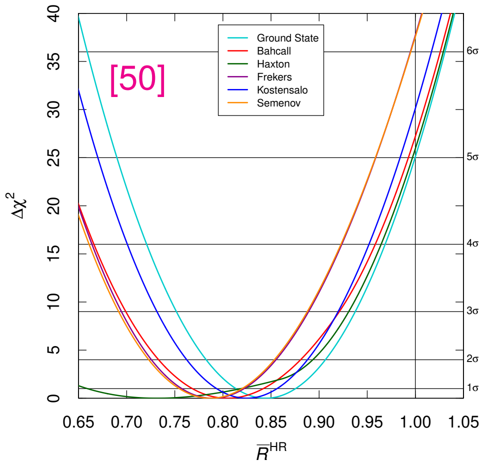
[49] V.V. Barinov *et al.* [BEST], Phys. Rev. C **105** (2022) no.6, 065502 [arXiv:2201.07364]

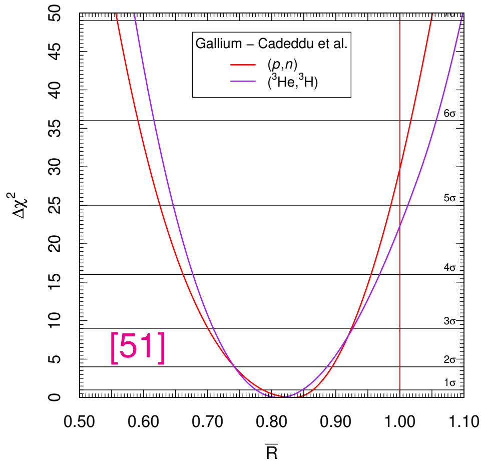
Origin of the gallium anomaly

- Large θ_{ee} required by Gallium ν_e oscill. clashes with:
  - reactor $\bar{\nu}_e$ data, as seen in previous slides;
  - solar ν_e data, which don't tolerate a large ν_s fraction;
- can the Gallium cross-section be overestimated?
  - well-known ground-state suffices for the tension [50];
  - recent recalculations do not alleviate the problem [51];
  - solar data agree well with current cross-section [52];

⇒ no obvious solution to the Gallium puzzle.



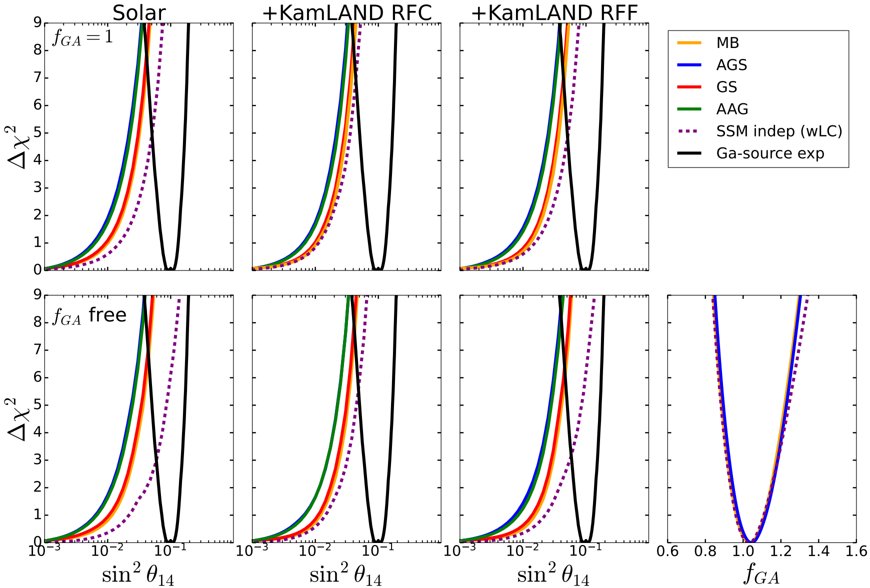


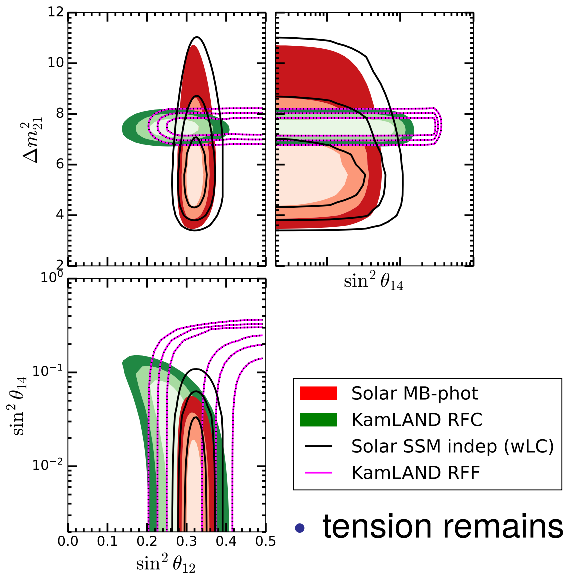


[50] C. Giunti *et al.*, Phys. Lett. B **842** (2023) 137983 [2212.09722]
[51] M. Cadeddu *et al.*, Phys. Rev. D **113** (2026) 033006 [2507.13103]
[52] M.C. Gonzalez-Garcia *et al.*, JHEP **02** (2024) 064 [2311.16226]

Tension between solar and gallium data: some insight

- Can SSM fluxes be the problem? $\to$ Try various options, or even leave the fluxes free;
- can we trust Gallium *solar* measurements? $\to$ Both fixed or free f_{Ga} normalization;
- can we trust reactor fluxes? $\to$ Both constrained and free KamLAND (+ DB) scale;





- tension remains.

[53] M. C. Gonzalez-Garcia *et al.*, Phys. Lett. B **862** (2025) 139297 [arXiv:2411.16840]

Tension between solar and gallium data: results

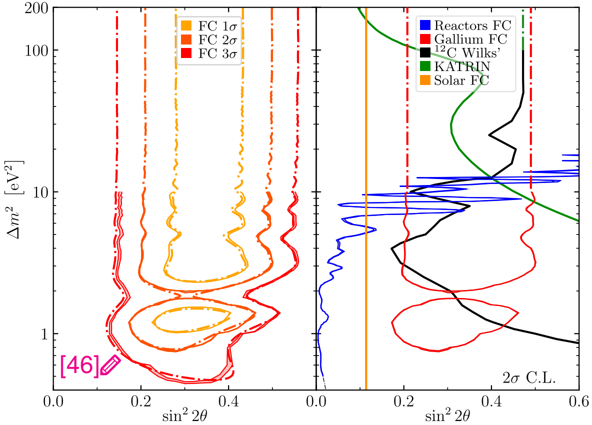
- Solar+KL data favor $\theta_{14} = 0$ irrespective of SSM model, KL reactor fluxes, or inclusion of f_{Ga};
- even the least constraining scenario (everything free) has a p-value no better than 2.9%;
- only way to further reduce the tension acting on solar data is to relax the Luminosity Constraint. An increase larger than 10% is required, despite the current precision being 0.34%.

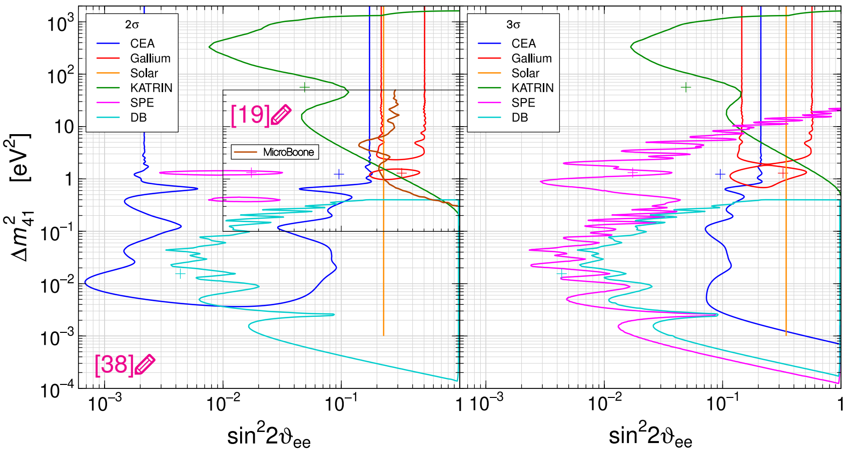
		$f_{\text{Ga}} = 1$			f_{Ga} free		
	SSM	χ^2_{PG}/n	p-value ($\times 10^{-3}$)	$\#\sigma$	χ^2_{PG}/n	p-value ($\times 10^{-3}$)	$\#\sigma$
Solar	MB-phot/GS98	14.9	0.11	3.9	13.1	0.3	3.6
	AAG21/AGSS09	18.7	0.2	4.3	17.3	0.03	4.2
	SSM indep (wLC)	9.1	2.6	3.0	4.9	27	2.2
Solar + KL-RFC	MB-phot/GS98	15.9	0.07	4.0	15.1	0.1	3.9
	AAG21/AGSS09	19.4	0.1	4.4	18.7	0.01	4.3
	SSM indep (wLC)	13.5	0.23	3.7	10.5	1.2	3.2
Solar + KL-RFF	MB-phot/GS98	13.2	0.28	3.6	11.7	0.64	3.4
	AAG21/AGSS09	17.3	0.03	4.2	16.0	0.06	4.0
	SSM indep (wLC)	8.7	3.1	2.9	4.8	29	2.2

[53] M. C. Gonzalez-Garcia *et al.*, Phys. Lett. B **862** (2025) 139297 [arXiv:2411.16840]

Comparison of all ν_e and $\bar\nu_e$ disappearance data

- Reactors: proper FC statistics relaxes bounds by about 1σ w.r.t. Wilk's limits [46];
- Gallium: FC not so important [46], but it cannot be reconciled with other data [46, 38];
- solar and μBooNE also disfavor large mixing angle, and Katrin does so at large Δm^2;
- "least tension" among $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ at $\Delta m^2 \gtrsim 10^3$ eV^2, far from $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ "hints" at $\Delta m^2 \sim 1$ eV^2.

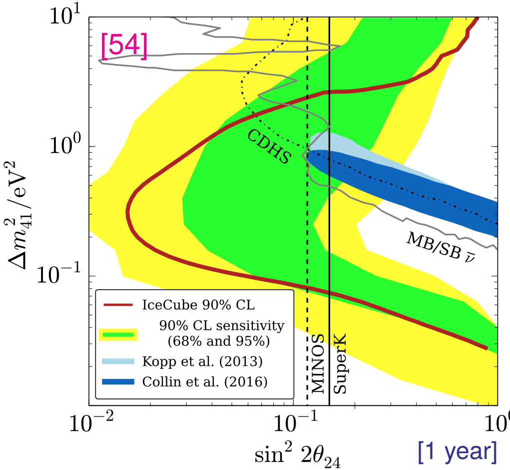


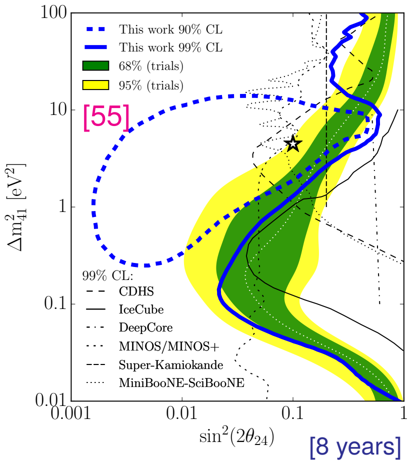


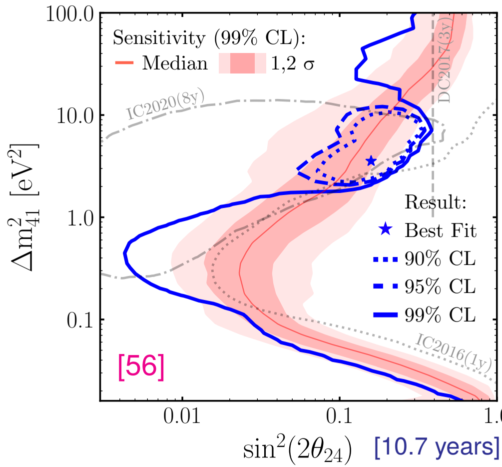
[19] P. Abratenko *et al.* [MicroBooNE], Nature **648** (2025) 64 [arXiv:2512.07159]
[38] C. Giunti, Y.F. Li, R.P. Zhang, arXiv:2605.10353
[46] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]

Search for ν_μ disappearance at IceCube

- Since oscillations only depend on $\Delta m^2/E$, larger Δm^2 produce visible effects at larger E;
- IceCube has been detecting high-energy ($\sim$ TeV) atmos. neutrinos since its construction;
- a small "island" around $\Delta m^2 \sim$ few eV^2 and $\sin^2 2\theta_{\mu\mu} \sim 0.1$ has been gaining prominence;
- p-value for no-oscillation: of 47% (1 year), 8% (8 years), 3.1% (10.7 years) $\Rightarrow$ trend?







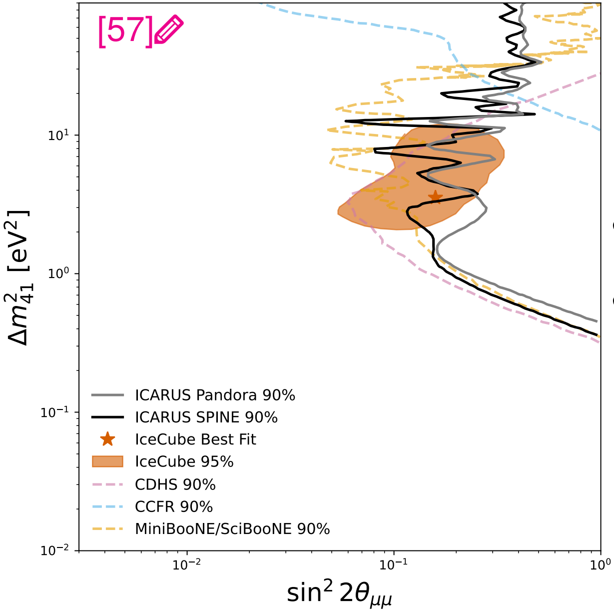
[54] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **117** (2016) 071801 [arXiv:1605.01990]

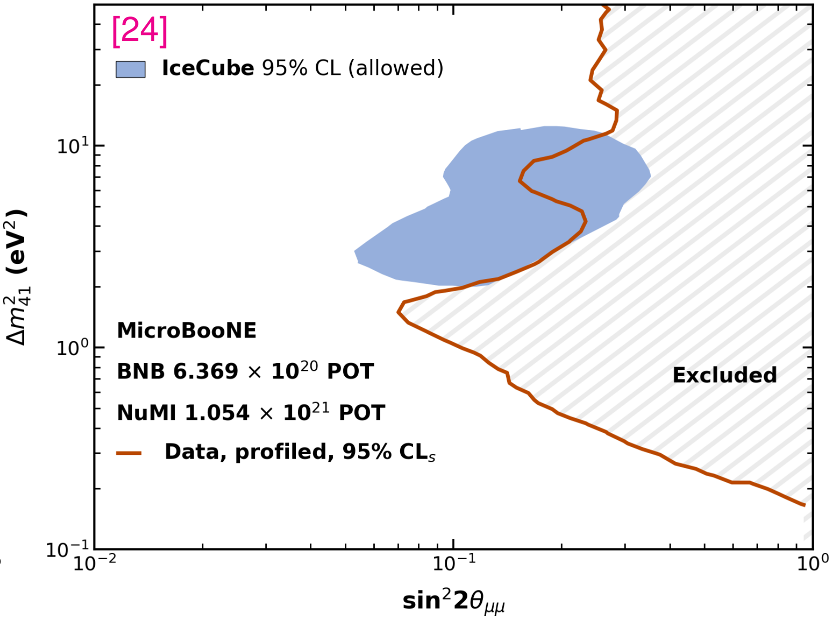
[55] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **125** (2020) 141801 [arXiv:2005.12942]

[56] R. Abbasi *et al.* [IceCube], Phys. Rev. Lett. **133** (2024) 201804 [arXiv:2405.08070]

Recent searches for ν_μ disappearance at SBL experiments

- Results on ν_μ disappearance have been presented by ICARUS [57] and MicroBooNE [24];
- no deficit was observed ⇒ IceCube region partially probed and disfavored.



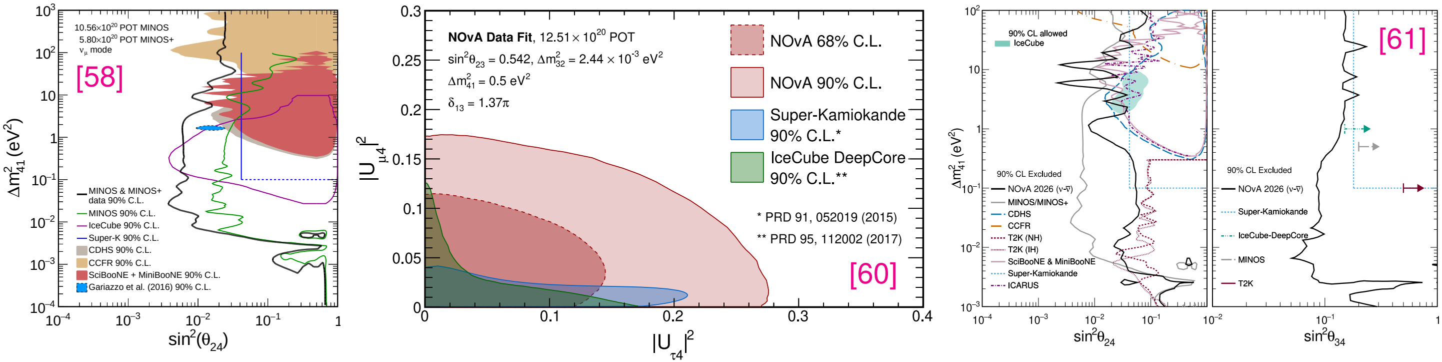


[24] J. Hyun Jo [MicroBooNE], talk at Neutrino 2026, Irvine, USA, 21-26/06/2026

[57] F.A. Alrahman *et al.* [ICARUS], arXiv:2603.22557

Search for ν_μ disappearance at LBL experiments

- Sterile ν can be searched at LBL experiments by “switching” the roles of near & far detectors:
  - far detector observes fully averaged oscillations $\Rightarrow$ fixes the *energy shape* of the beam;
  - near detector looks for spectral distortions which would indicate SBL oscillations;
- data collected by MINOS/MINOS+ [58], T2K [59], and NOvA (both NC [60] & CC [61]);
- IceCube region completely excluded by MINOS/MINOS+ as well as latest NOvA/CC data.



[58] P. Adamson *et al.* [MINOS+], Phys. Rev. Lett. **122** (2019) no.9, 091803 [arXiv:1710.06488]

[59] K. Abe *et al.* [T2K], Phys. Rev. D **99** (2019) no.7, 071103 [arXiv:1902.06529]

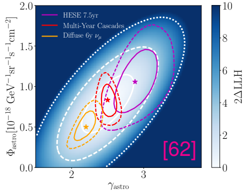
[60] M.A. Acero *et al.* [NOvA], Phys. Rev. Lett. **127** (2021) no.20, 201801 [arXiv:2106.04673]

[61] S. Abubakar *et al.* [NOvA], arXiv:2609.08900

Insights from IceCube 8-year data

- deviation from no-osc led by high-E data [62]:
  - removing these bins weakens the hint;
  - impact of astro-ν is comparable in size;
- astro-ν important $\Rightarrow$ are they reliable?
  - simulation: ratio $(\nu_e : \nu_\mu : \nu_\tau : \nu_s) = (1 : 1 : 1 : 0)$ at Earth surface [56, 62] based on data;
  - physics: flavor ν_α at far source $\to$ mass ν_i at Earth, ratio depends on mixings (also θ_{24});
  - no test using 'distant source' mentioned;

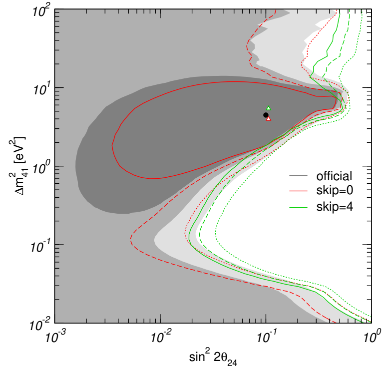
$\Rightarrow$ recent results may require more scrutiny.

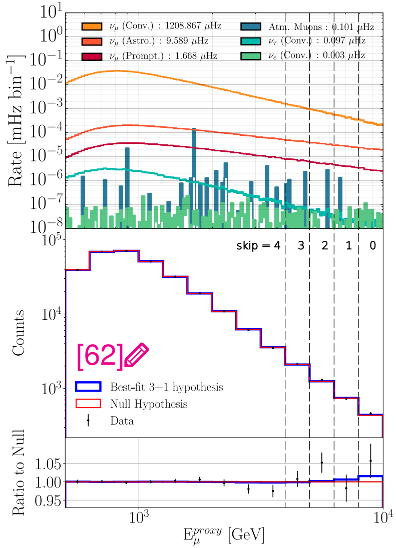


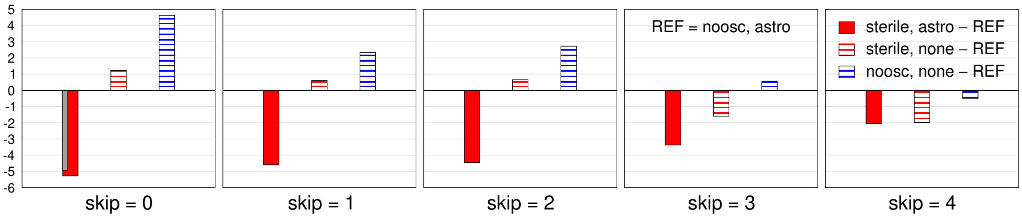
[56] The expected number of events is computed by convolving the simulated detector response with the expected neutrino flux at the detector. The neutrino flux at the Earth's surface is calculated using DAEMONFLUX [48] for neutrinos generated in the atmosphere. The astrophysical neutrino flux is assumed to have an equal flavor composition and be symmetric for neutrinos and antineutrinos [49–52]; it has an isotropic angular spectrum and an energy spectrum consistent with previous IceCube measurements [53–55]. All these fluxes are propagated to the detector using nuSQuIDS [56], assuming the PREM model (using 200 radial layers) [57] and CSMS cross sections [58] to model the Earth's density profile and neutrino cross sections, respectively. This propagation is conducted independently for each choice of sterile neutrino parameters.

Non-conventional neutrino flux: With the maximum reconstructed energy extended from 10 to 100 TeV compared to the previous analysis [20], a more conservative approach has been adopted for the high-energy flux, consisting of astrophysical and prompt components. This analysis represents these fluxes by a broken power law, with uncorrelated Gaussian priors assigned to the normalization and two spectral indices. The prior for the normalization at 100 TeV and both spectral indices are centered at $0.787 \times 10^{-18}\ \mathrm{GeV^{-1}sr^{-1}s^{-1}cm^{-2}}$ and -2.5, respectively, and the width of the priors is 46% and 36%. A uniform prior is assumed for the energy pivot point. These priors were chosen to encompass all IceCube astrophysical neutrino flux measurements to date.

Mismodeling tests incorporated a galactic component [64], increasing the prompt component by an order of magnitude or removing it altogether, and considering ν- and $\bar{\nu}$-only astrophysical contributions. Our investigations revealed a significance for spurious sterile-like signals below 0.3σ in all test cases.







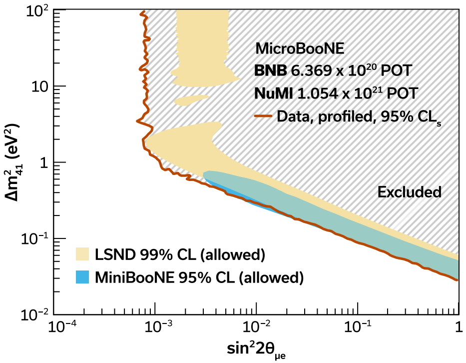
[56] R. Abbasi *et al.* [IceCube], PRL **133** (2024) 201804 [2405.08070]

[62] M.G. Aartsen *et al.* [IceCube], PRD **102** (2020) 052009 [2005.12943]

Summary of the observed anomalies

- a number of anomalies (hinting at new ν states) have been observed in various channels:

$\nu_\mu \to \nu_e$

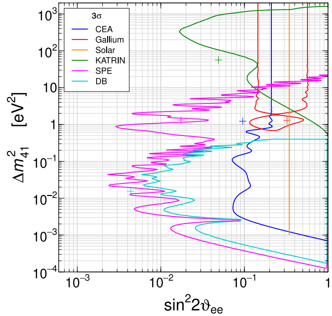


— strong: LSND, MB;

— reject: μBooNE, others;

— problem: low-E excess;

$\nu_e \to \nu_e$



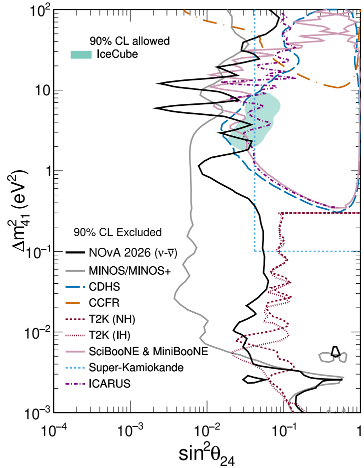
— strong: Neutrino4, Gallium;

— mild: reactor anomaly;

— reject: reactor, Sun, Katrin;

— problem: 5 MeV bump;

$\nu_\mu \to \nu_\mu$

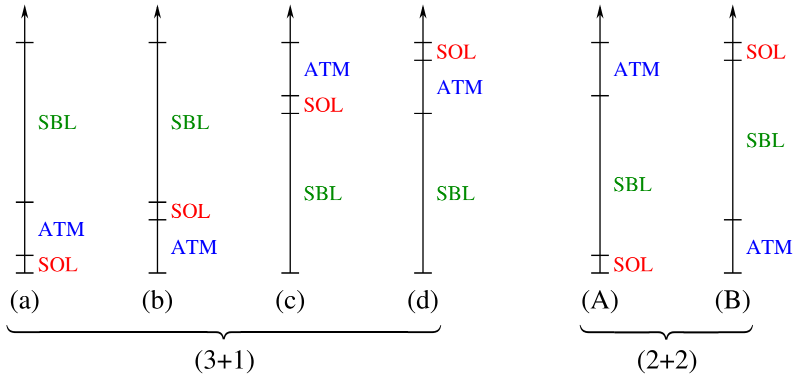


— no evidence (IC: weak);

- each anomaly is in tension with other data within the same oscillation channel $\Rightarrow$ not viable;
- hence, there is no need to inquire if different channels are mutually compatible;
- but since this is a lecture as well as a talk, we will briefly discuss this aspect anyway.

Four neutrino mass models

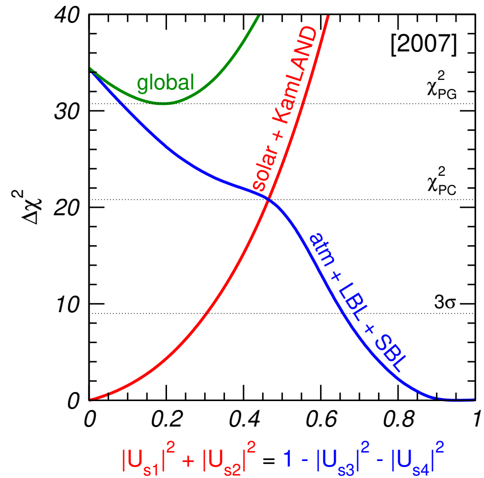
- Hierarchy of splittings: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{SBL}} \Rightarrow$ 6 different mass schemes:



$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

(2+2) models

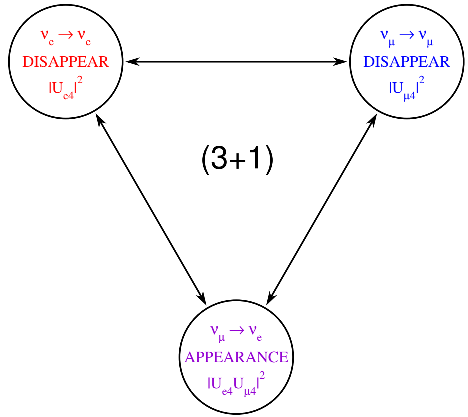
- **not** continuous perturbation of 3ν models;
- unitarity of U requires $|U_{s1}|^2 + |U_{s2}|^2 + |U_{s3}|^2 + |U_{s4}|^2 = 1$;
- however, at 3σ: $\begin{cases} |U_{s1}|^2 + |U_{s2}|^2 \lesssim 0.31 \text{ from solar data,} \\ |U_{s3}|^2 + |U_{s4}|^2 \lesssim 0.37 \text{ from atmos data;} \end{cases}$
- hence, this class of models is not viable.

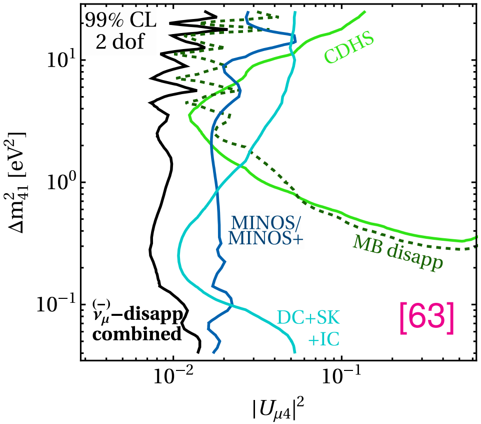


(3+1): appearance versus disappearance

- (3+1): $P_{\nu_\mu\to\nu_e} \propto |U_{e4}U_{\mu4}|^2$ with $\begin{cases} |U_{e4}|^2 \propto P_{\nu_e\to\nu_e}\,, \\ |U_{\mu4}|^2 \propto P_{\nu_\mu\to\nu_\mu}\,; \end{cases}$
- hence, $P_{\nu_\mu\to\nu_e} > 0$ requires $\begin{cases} P_{\nu_e\to\nu_e} > 0\,, \\ P_{\nu_\mu\to\nu_\mu} > 0\,; \end{cases}$

¿? are $\nu_e \to \nu_e$, $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$ data mutually compatible?





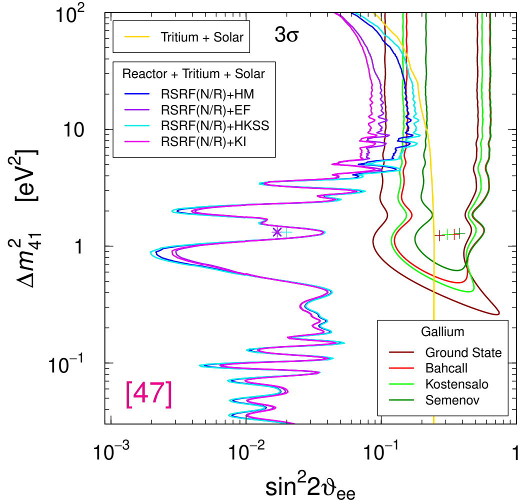
ν_μ disappearance: long-term situation

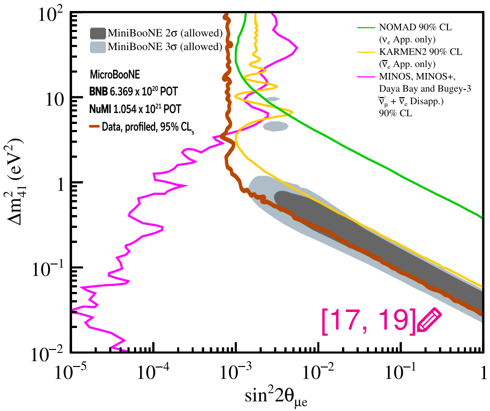
- Many searches have been performed across decades:
  - CDHS (ν)
  - Sci/MiniBooNE $(\nu, \bar\nu)$
  - μBooNE, Icarus (ν)
  - LBL accelerator $(\nu, \bar\nu)$
  - SK atmospheric $(\nu + \bar\nu)$
  - IC atmospheric $(\nu + \bar\nu)$
- no serious hint of ν_μ disappearance has been observed;
- bound on $|U_{\mu4}|^2$ may be in tension with other data.

[63] M. Dentler *et al.*, JHEP **08** (2018) 010 [arXiv:1803.10661]

(3+1): tension among data samples

- Inconsistency between Reactors and Gallium results **prevents** a combined fit of all $\nu_e \to \nu_e$ data;
- limits on a subset of $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_\mu$ disappearance [64] imply a bound on $\nu_\mu \to \nu_e$ **stronger** than what required to explain the LSND and MiniBooNe excesses;
- such tension between **APP** and **DIS** data was first pointed out in 1999 [65]. Full global fit in 2001 [66] cornered (3+1) models. No conceptual change since then…





[17] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **130** (2023) 011801 [arXiv:2210.10216]

[19] P. Abratenko *et al.* [MicroBooNE], Nature **648** (2025) 64 [arXiv:2512.07159]

[47] C. Giunti *et al.*, JHEP **10** (2022) 164 [arXiv:2209.00916]

[64] P. Adamson *et al.* [MINOS+ and Daya-Bay], Phys. Rev. Lett. **125** (2020) 071801 [arXiv:2002.00301]

[65] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454]

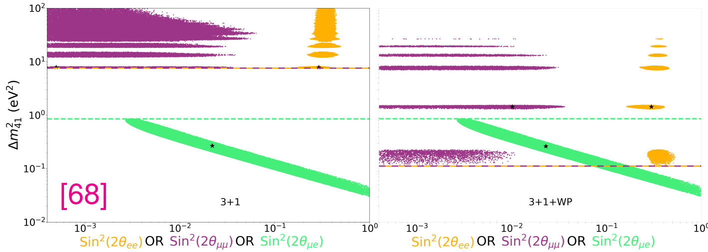
[66] MM, Schwetz, Valle, PLB **518** (2001) 252 [hep-ph/0107150]

IV. Global fits of eV sterile data: combining everything together

Beyond (3+1) oscillations

- If (3+1) models do not work (and never did), why do we keep discussing them?
  - they are a natural extension of 3ν;
  - they individually explain each anomaly;
  - hence, they make a great starting point;
- can we do better than this?
  - more steriles (3+2, 3+3, …) not enough;
  - recent trend towards "dumping" [68] (first noted in [67]), but tensions remain;
  - alternatives explain some (not all) data;
  - usually very "exotic" and "ad-hoc";

⇒ "vanilla ν_s" still best working tool.



Explanations beyond the Standard Model [Goal: account for the Gallium anomaly]

ν_s coupled to ultralight DM (MSW resonance, Sec. 5.1.1)	several exotic ingredients; somewhat tuned MSW resonance; new ν_4 decay channel required for cosmology.	★★★★☆
ν_s coupled to dark energy (MSW resonance, Sec. 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, Sec. 5.1.3)	several exotic ingredients; somewhat tuned parametric resonance; cosmology requires post-BBN DM production via misalignment.	★★★★☆
decaying ν_s (Section 5.2)	difficult to reconcile with reactor and solar data; regeneration of active neutrinos in ν_s decays alleviates tension, but does not resolve it.	★★☆☆☆
vanilla eV-scale ν_s (Refs. [17, 18])	preferred parameter space is strongly disfavored by solar and reactor data.	★☆☆☆☆
ν_s with CPT violation (Refs. [130])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (Refs. [131–133])	neutrinos oscillate into sterile Kaluza–Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (Ref. [134])	based on a difference between sterile neutrino mixing angles at production and detection (see also [135, 136]); fit worse than for vanilla ν_s.	
decoherence (Refs. [137, 138])	non-standard source of decoherence needed; known experimental energy resolutions constrain wave packet length, making an explanation by wave packet separation alone challenging.	
ν_s coupled to ultralight scalar (Ref. [139])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	

[69]

[67] S. Palomares-Ruiz *et al.*, JHEP **09** (2005) 048 [hep-ph/0505216]

[68] J.M. Hardin *et al.*, JHEP **09** (2023) 058 [arXiv:2211.02610]

[69] V. Brdar *et al.*, JHEP **05** (2023) 143 [arXiv:2303.05528]

- Anomalies in $\nu_e \to \nu_e$ disappearance and $\nu_\mu \to \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3ν oscillation paradigm;
- each of these anomalies can be **individually** explained by sterile neutrinos ($\Delta m^2 \sim 1$ eV^2);
- unlike a few years ago, sterile neutrinos **no longer succeed** in simultaneously explaining groups of anomalies sharing the same oscillation channel. Concretely:
  - $\nu_e \to \nu_e$ disappearance data exhibit a serious tension in solar/reactor vs gallium results, as well as some issue between different "spectral shape" reactor experiments;
  - $\nu_\mu \to \nu_e$ appearance data show a growing discrepancy between LSND/MiniBooNE and μBooNE, as well an excess in low-E neutrino data which cannot be explained by oscillations alone and so far has eluded the searches for new systematics;
- the quest for a "global" model reconciling $\nu_e \to \nu_e$, $\nu_\mu \to \nu_e$, $\nu_\mu \to \nu_\mu$ data is now secondary: it is more urgent to clarify the "local" inconsistencies within each of these classes;
- to this aim, new experimental data are required. A number of experiments are under way;
- if the $\nu_e \to \nu_e$ and $\nu_\mu \to \nu_e$ anomalies are confirmed, new physics will be needed. Such new physics will probably involve extra sterile states, but together with "something else". At present, however, **no model is known** which can convincingly explain everything.