(eV) sterile neutrinos: global picture and local views

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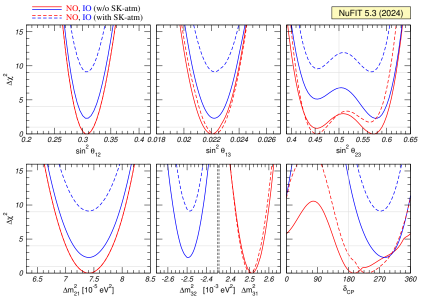
Status of three neutrino oscillations (before this conference)

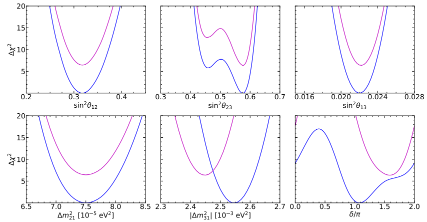
NuFIT group [1]



		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.66^{+0.73}_{-0.70}$	$31.60 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.11}$	$8.19 \to 8.89$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+41}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

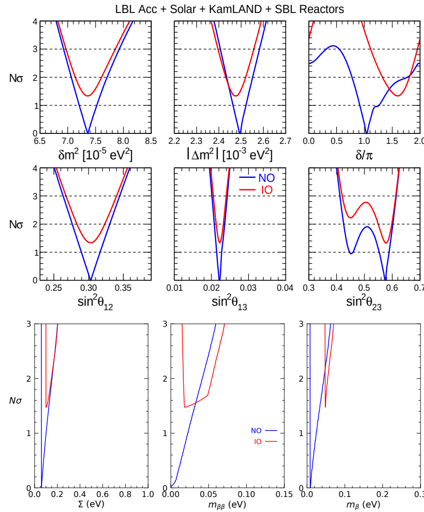
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 9.1$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$	$0.307^{+0.012}_{-0.011}$	$0.275 \to 0.344$
	$\theta_{12}/^\circ$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$	$33.67^{+0.73}_{-0.71}$	$31.61 \to 35.94$
	$\sin^2\theta_{23}$	$0.454^{+0.019}_{-0.016}$	$0.411 \to 0.606$	$0.568^{+0.016}_{-0.021}$	$0.412 \to 0.611$
	$\theta_{23}/^\circ$	$42.3^{+1.1}_{-0.9}$	$39.9 \to 51.1$	$48.9^{+0.9}_{-1.2}$	$39.9 \to 51.4$
	$\sin^2\theta_{13}$	$0.02224^{+0.00056}_{-0.00057}$	$0.02047 \to 0.02397$	$0.02222^{+0.00069}_{-0.00057}$	$0.02049 \to 0.02420$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.13}_{-0.11}$	$8.23 \to 8.95$
	$\delta_{CP}/^\circ$	232^{+39}_{-25}	$139 \to 350$	273^{+24}_{-26}	$195 \to 342$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.81 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.505^{+0.024}_{-0.026}$	$+2.426 \to +2.586$	$-2.487^{+0.027}_{-0.024}$	$-2.566 \to -2.407$

Valencia group [2]



parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m^2_{21}[10^{-5}eV^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$\lvert\Delta m^2_{31}\rvert[10^{-3}eV^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$\lvert\Delta m^2_{31}\rvert[10^{-3}eV^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2\theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2\theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

Bari group [3]



Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
$\delta m^2/10^{-5}\ eV^2$	NO, IO	7.36	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.90 – 3.16	2.77 – 3.30	2.63 – 3.45	4.5
$\lvert\Delta m^2\rvert/10^{-3}\ eV^2$	NO	2.485	2.454 – 2.508	2.427 – 2.537	2.401 – 2.565	1.1
	IO	2.455	2.430 – 2.485	2.403 – 2.513	2.376 – 2.541	1.1
$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.30	2.11 – 2.37	2.04 – 2.44	3.0
	IO	2.23	2.17 – 2.29	2.10 – 2.38	2.03 – 2.45	3.1
$\sin^2\theta_{23}/10^{-1}$	NO	4.55	4.40 – 4.73	4.27 – 5.81	4.16 – 5.99	6.7
	IO	5.69	5.48 – 5.82	4.30 – 5.94	4.17 – 6.06	5.5
δ/π	NO	1.24	1.11 – 1.42	0.94 – 1.74	0.77 – 1.97	16
	IO	1.52	1.37 – 1.66	1.22 – 1.78	1.07 – 1.90	9
$\Delta\chi^2_{IO-NO}$	IO−NO	+6.5				

[1] I. Esteban *et al.*, JHEP **09** (2020) 178 [arXiv:2007.14792] & NuFIT 5.3 [http://www.nu-fit.org]

[2] P.F. de Salas *et al.*, JHEP **02** (2021) 071 [arXiv:2006.11237] ⇝ [Tortola]

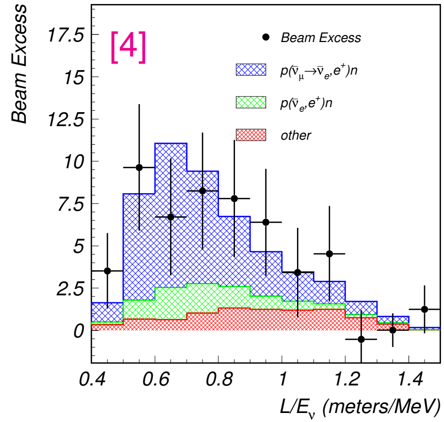
[3] F. Capozzi *et al.*, Phys. Rev. D **104** (2021) 083031 [arXiv:2107.00532]

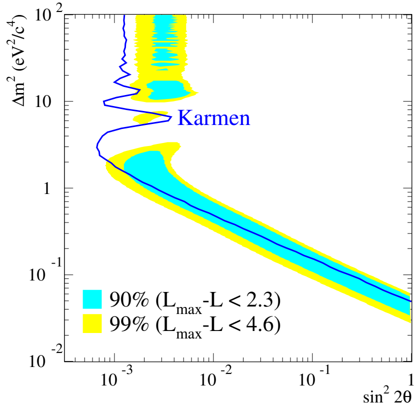
A long time ago... the LSND anomaly

- 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 Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [5];
- 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):

$$\Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5}\ \text{eV}^2\,,$$
$$|\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3}\ \text{eV}^2\,;$$

- hence, to explain LSND with mass-induced ν oscillations one needs **new** neutrino mass eigenstates;
- MiniBooNE: much larger E_ν and L but similar L/E_ν.



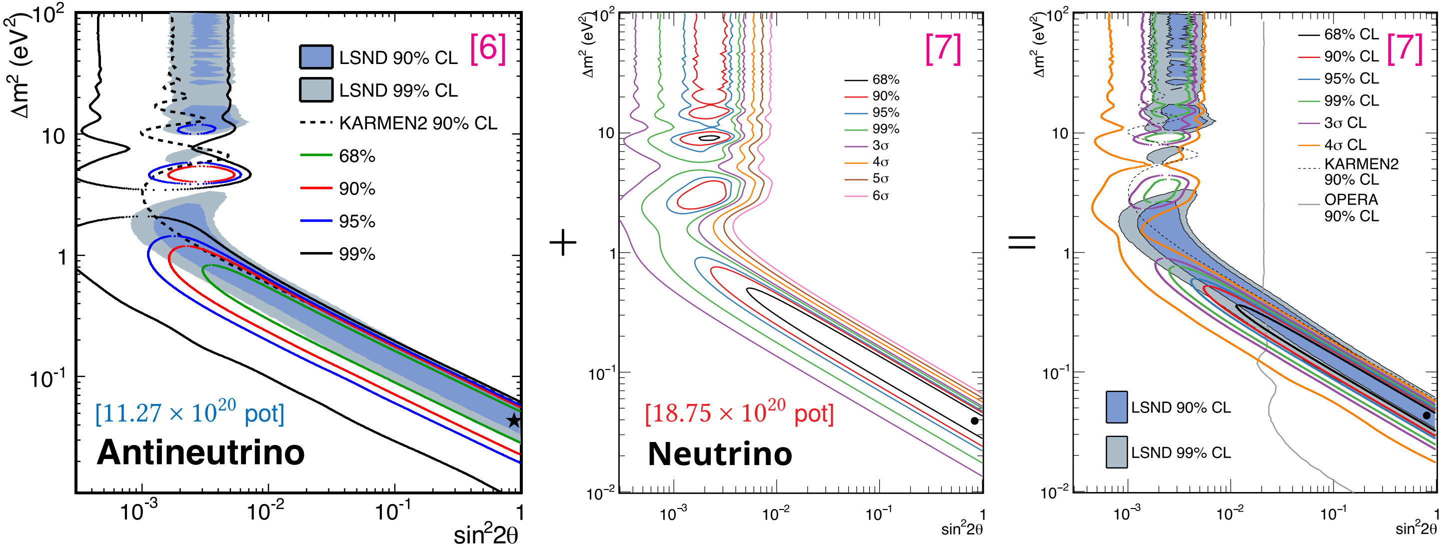


[4] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049]

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

The MiniBooNE experiment

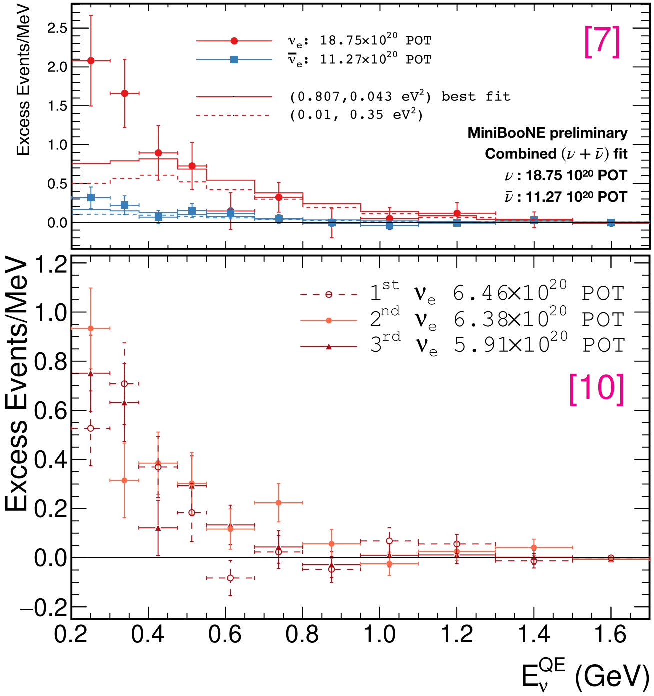
- MiniBooNE searched for $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$ conversion ($E = 200 \to 1250$ MeV, $L \simeq 541$ m);
- excess in both $\bar\nu$ and $\nu \Rightarrow$ oscillations compatible with LSND (ev $= 4.8\sigma$, gof $= 12.3\%$);
- however, the low energy part of the excess **cannot**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



[6] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [arXiv:1303.2588]
[7] A. Hourlier, 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 [8];
- 2013 ($\bar{\nu}$): low-E not so steep + mid-E excess observed $\Rightarrow$ good oscillation fit ($P_\text{osc} \simeq 66\%$) $\Rightarrow$ **confirm** LSND [6];
- 2018 (ν): low-E softened + mid-E excess seen also in ν $\Rightarrow$ mild oscillation fit ($P_\text{osc} \simeq 15\%$) [9];
- 2020 (ν): more data released [10], oscillations confirmed but low-E excess definitely there.



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

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

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

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

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

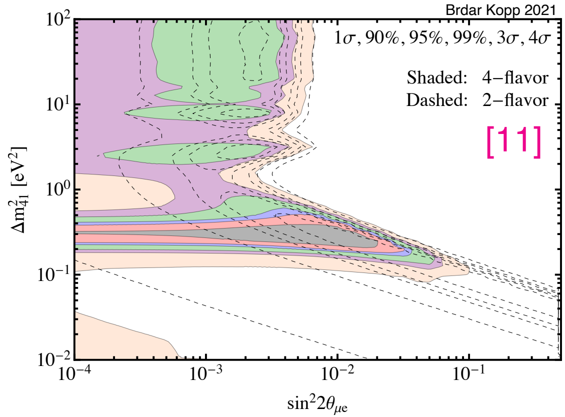
Present status of MiniBooNE

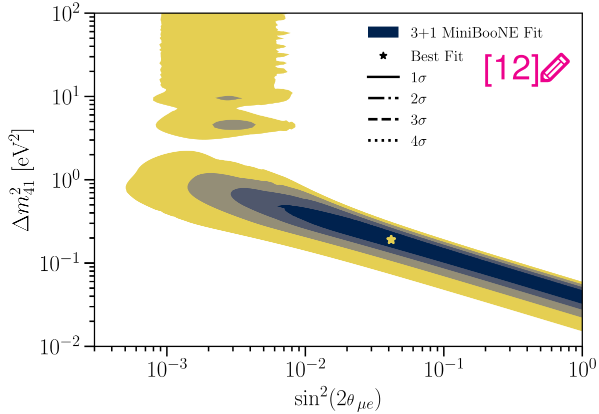
- Possible systematics related to the low-E excess:
  - misreconstruction of neutrino energy;
  - π^0 from NC reconstructed as ν_e;
  - single photon from NC misidentified as ν_e;
- extensive studies performed by the collaboration;
- present status: no combination of known systematics could account for the whole excess [11];

⇒ 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 [11];
- such effects can be very important. Omission corrected in recent reanalysis [12].





[11] V. Brdar and J. Kopp, Phys. Rev. D **105** (2022) 115024 [arXiv:2109.08157]

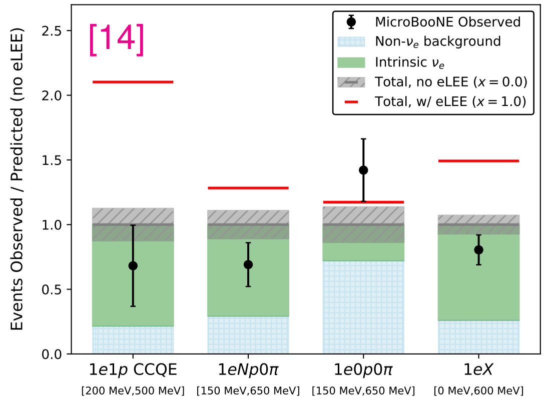
[12] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]

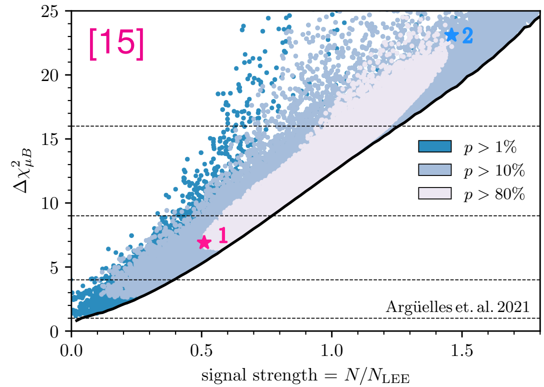
The MicroBooNE experiment

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

$\Rightarrow$ perfectly suited to cross-check MiniBooNE excess;

- first results presented in fall 2021:
  - no evidence of enhanced π^0 or γ production [13];
  - no evidence of ν_e excess over SM prediction [14];
- however, rejection of MB signal in [14] based on the assumption that the entire ν_e excess matches the difference between data and best-fit MB background;
- but in [15] it was noticed that various signal/background compositions can fit MB equally well, but lead to different μB sensitivity $\Rightarrow$ rejection **not** model-independent…





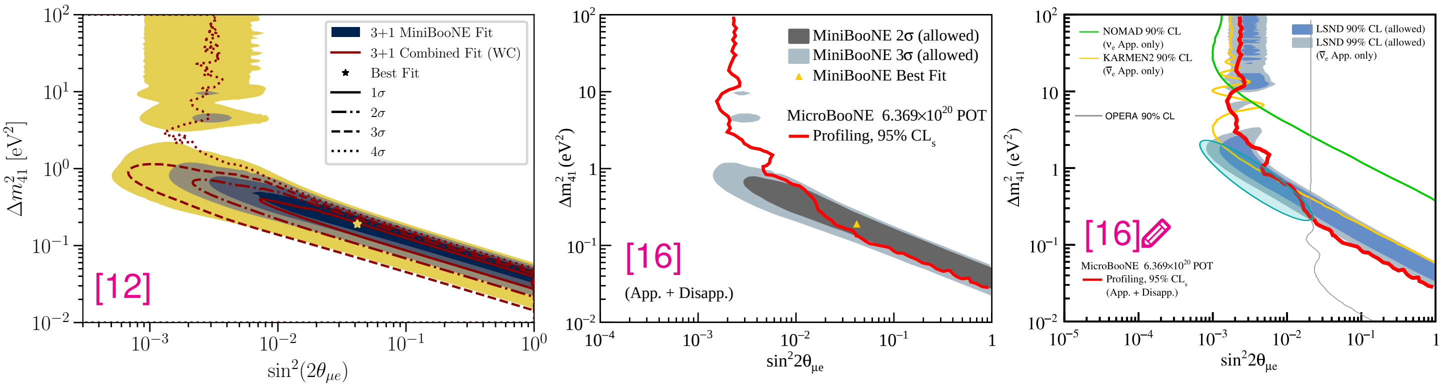
[13] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 111801 [arXiv:2110.00409]

[14] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801 [arXiv:2110.14054]

[15] C.A. Argüelles *et al.*, Phys. Rev. Lett. **128** (2022) 241802 [arXiv:2111.10359]

Comparison of MicroBooNE and MicroBooNE results

- MiniBooNE: updated analysis including μB bounds [12] $\Rightarrow$ 3σ region at $\Delta m^2_{41} \lesssim 1$ eV;
- MicroBooNE: global 4ν analysis [16] 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 $10^{-3} \lesssim \sin^2\theta_{\mu e} \lesssim \text{few} \times 10^{-2}$;
- Short Baseline Neutrino Program @ Fermilab: see next talks; $\rightsquigarrow$ [Caratelli, Gibin, ...]
- Japan: JSNS^2 will provide an independent check of LSND/MiniBooNE excess. $\rightsquigarrow$ [Marzec]



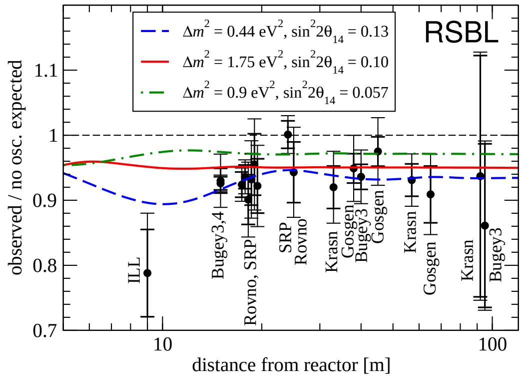
[12] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]

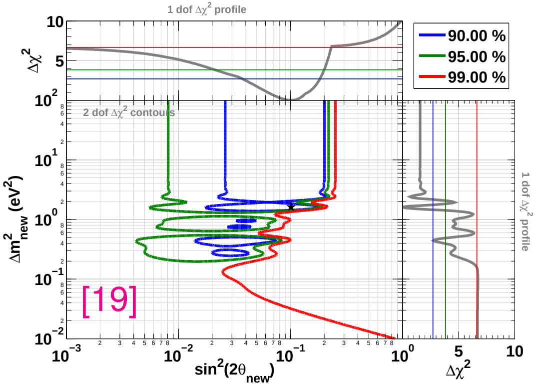
[16] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **130** (2023) 011801 [arXiv:2210.10216]

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

- In [17, 18] 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; ⇝ [Sonzogni]
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- global data (3σ): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5} \text{ eV}^2, \\ |\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3} \text{ eV}^2; \end{cases}$

⇒ solutions: **add new neutrinos** or **revise fluxes**.

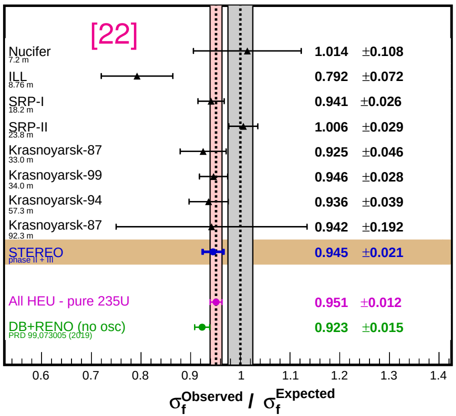


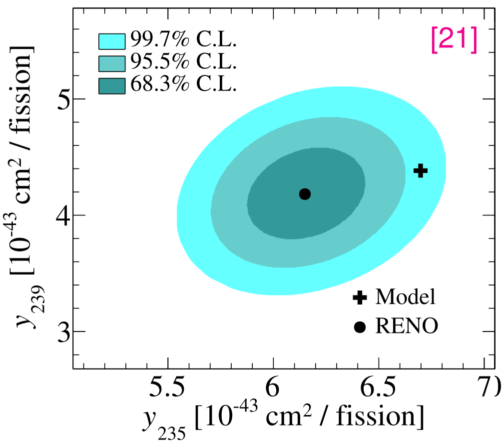


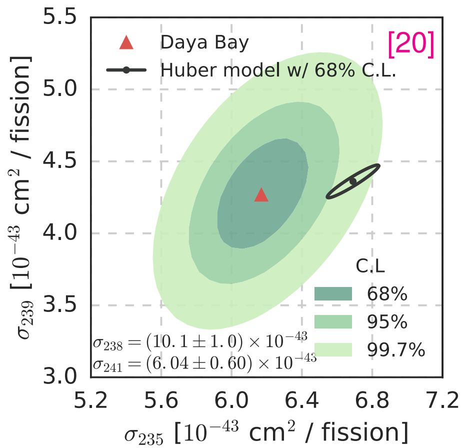
[17] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663]
[18] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687]
[19] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755]

Reactor anomaly: sterile ν or wrong fluxes?

- DB [20] and RENO [21]: 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 [22] (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.







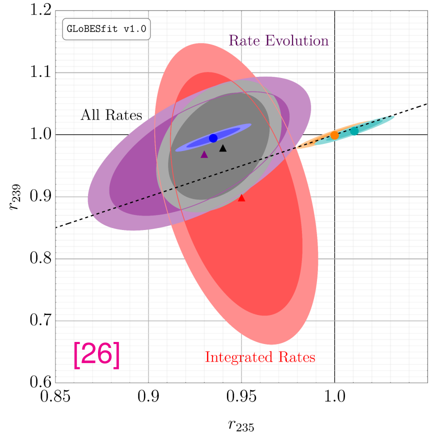
[20] F.P. An *et al.* [Daya-Bay], Phys. Rev. Lett. **118** (2017) 251801 [arXiv:1704.01082]

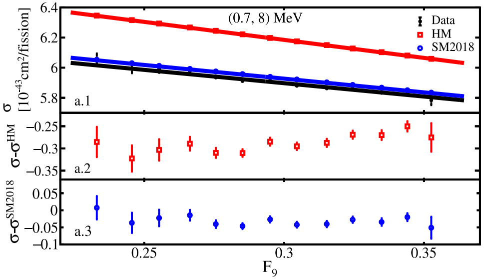
[21] G. Bak *et al.* [RENO], Phys. Rev. Lett. **122** (2019) 232501 [arXiv:1806.00574]

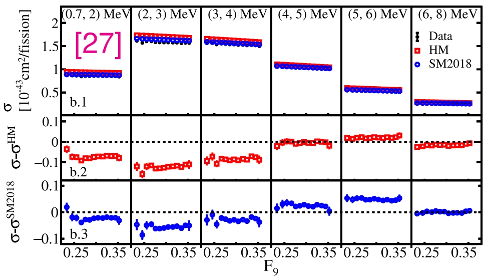
[22] H. Almazán *et al.* [STEREO], Nature **613** (2023) 257-261 [arXiv:2210.07664]

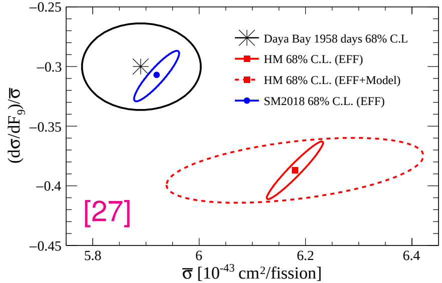
Recent improvements in reactor flux models

- New reactor flux calculations: EF [23], HKSS [24], KI [25];
- EF model (summation) in good agreement with total rates, although the spectral shape is still not optimal;
- KI model (conversion) yields very similar results to EF;
- conversely, HKSS (conversion) gives rates similar to HM.









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

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

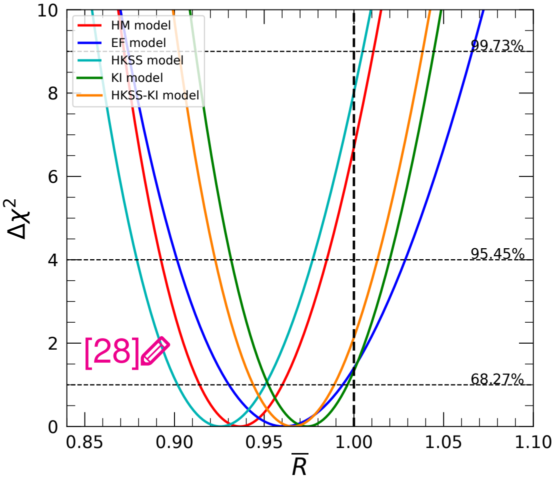
[25] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [2103.01684]

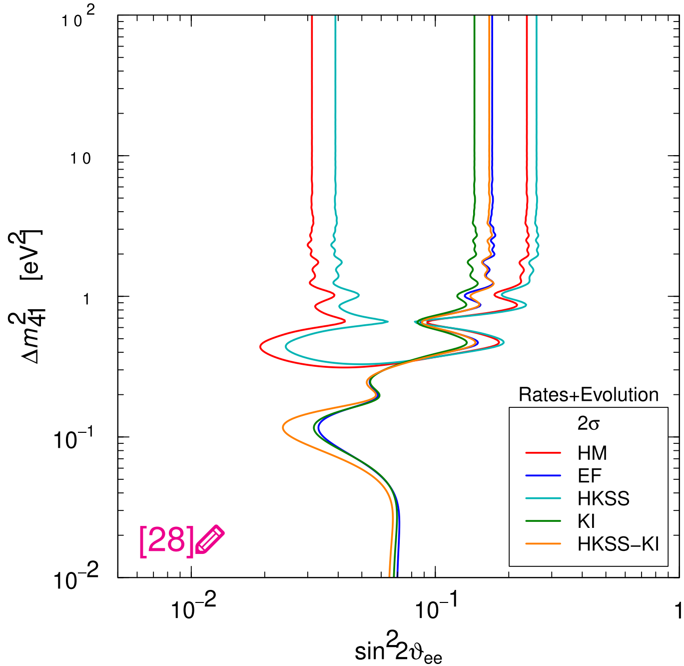
[26] J.M. Berryman and P. Huber, JHEP **01** (2021) 167 [arXiv:2005.01756]

[27] F.P. An *et al.* [Daya-Bay], Phys. Rev. Lett. **130** (2023) 211801 [arXiv:2210.01068]

Global fit of reactor $\bar{\nu}_e$ disappearance (total rates)

- From Ref. [28]: hint of sterile ν strongly reduced for EF (0.8σ) and KI (1.4σ);
- hint sizable for HM (2.8σ) and HKSS (3.0σ).

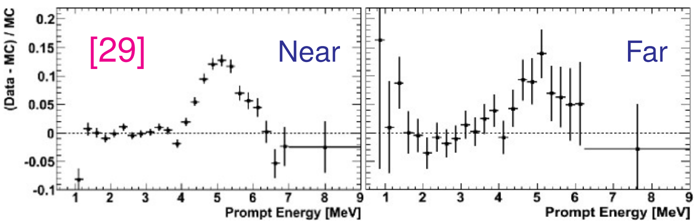


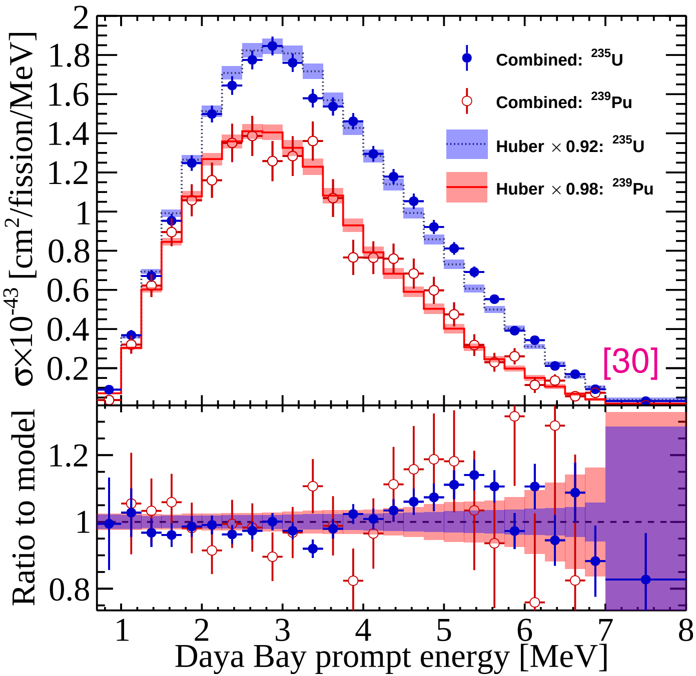


[23] M. Estienne *et al.* [EF model], Phys. Rev. Lett. **123** (2019) 022502 [arXiv:1904.09358]
[24] L. Hayen *et al.* [HKSS model], Phys. Rev. C **100** (2019) 054323 [arXiv:1908.08302]
[25] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [2103.01684]
[28] C. Giunti *et al.*, Phys. Lett. B **829** (2022) 137054 [arXiv:2110.06820]

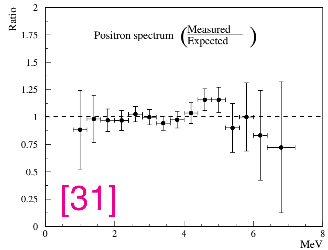
$\bar{\nu}_e$ disapp: 5 MeV excess

- Neutrino 2014: RENO [29] reported an excess of events around 5 MeV;
- seen by most reactors (also old Chooz [31]);
- DB+Prospect [30]: 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.





⇝ [Sonzogni]



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

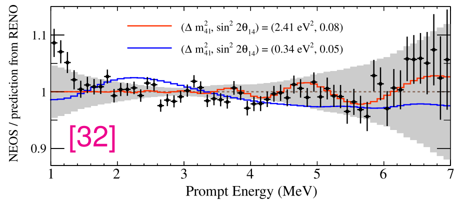
Sterile ν: spectra and baselines

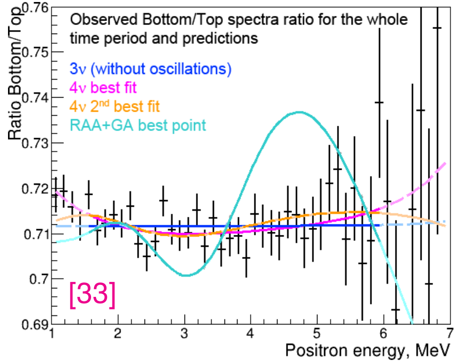
- New detectors with spectral capability and baseline range:
  - NEOS (Korea), commercial, $L = 23.7$ m;
  - STEREO (France), enriched, $L = 9 \to 11$ m;
  - PROSPECT (USA), enriched, $L = 7 \to 12$ m;
  - DANSS (Russia) commercial, $L = 10.9 \to 12.9$ m;
  - SOLID (Belgium), enriched, $L = 5.5 \to 12$ 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); ⇝ [Danilov]
- exception: Neutrino4 reports 3σ signal with $\Delta m^2 \sim 7$ eV^2.

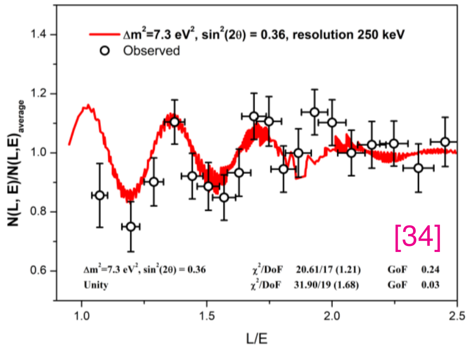
[32] Z. Atif *et al.* [NEOS & RENO], Phys. Rev. D **105** (2022) L111101 [arXiv:2011.00896]

[33] E. Samigullin [DANSS], talk at NuFact 23, Seoul, Korea, 25/08/2023

[34] A.P. Serebrov *et al.* [NEUTRINO4], arXiv:2302.09958

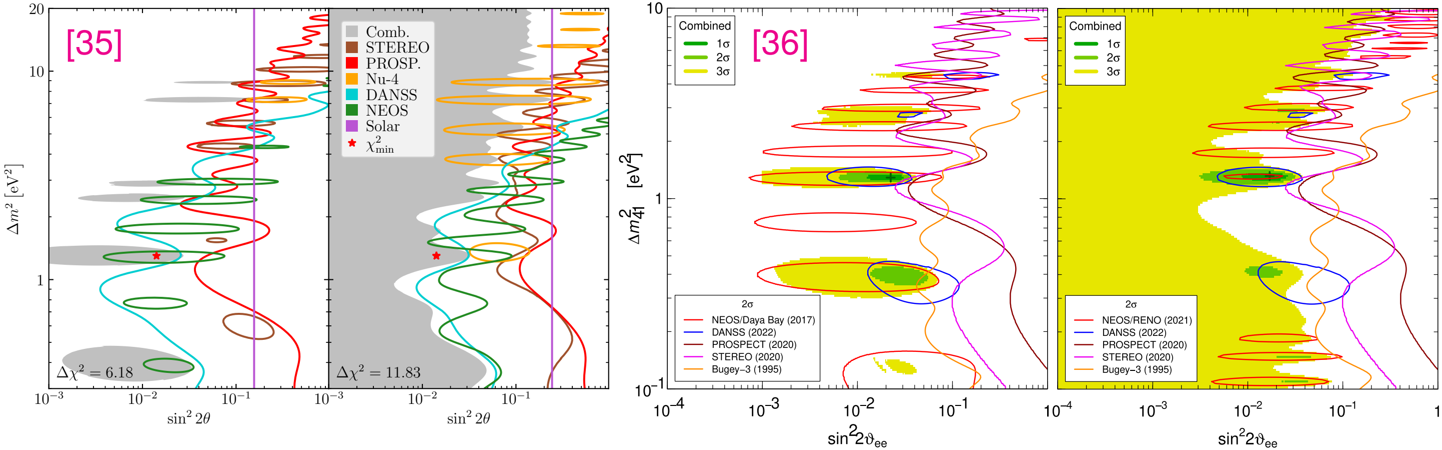






Flux-independent fits of reactor $\bar{\nu}_e$ disappearance data

- Fits based on spectral ratios at various distances are independent of the reactor ν spectrum;
- NEOS + Daya-Bay exhibits stronger wiggles than NEOS + RENO [36];
- no consistent pattern from various "hints". Combined fit weakly prefers $\Delta m^2 \sim 1.3$ eV^2;
- SOLID's first results presented at TAUP'23 [37] not included here.



[35] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]
[36] C. Giunti *et al.*, JHEP **10** (2022) 164 [arXiv:2209.00916]
[37] D. Galbinski [SOLID], talk at TAUP 23, Vienna, Austria, 30/08/2023

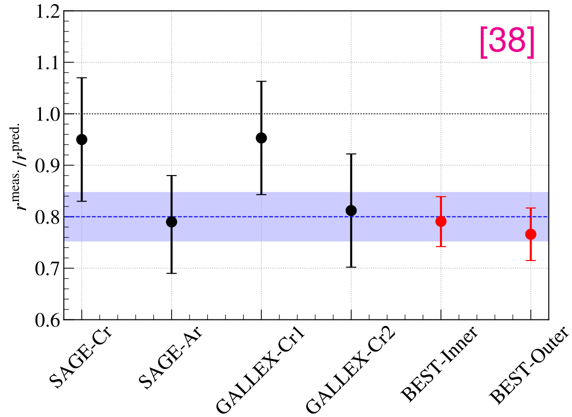
ν_e disappearance: the gallium anomaly

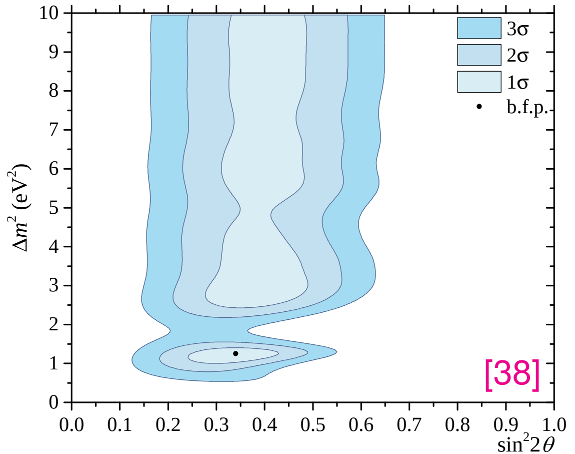
- $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}\,\nu$ capture cross-section was calibrated with intense $^{51}\mathrm{Cr}$ and $^{37}\mathrm{Ar}$ sources by GALLEX & SAGE (20 years ago) as well as BEST (2022);
- these measurements show a significant deficit with respect to the predicted values [38]:

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

⇝ [Gorbunov]

- 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}.



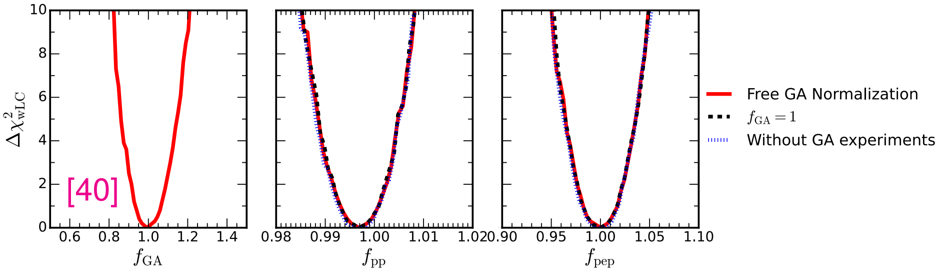


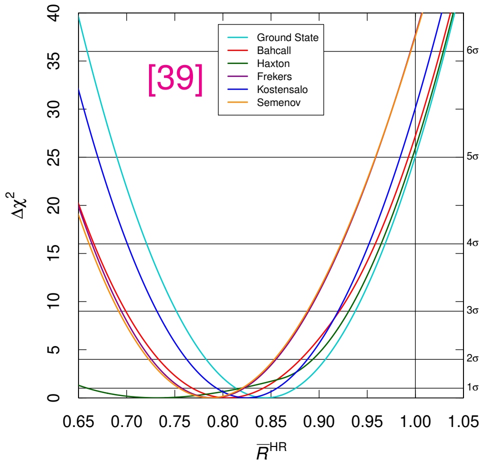
[38] V.V. Barinov *et al.* [BEST], Phys. Rev. C **105** (2022) no.6, 065502 [arXiv:2201.07364]

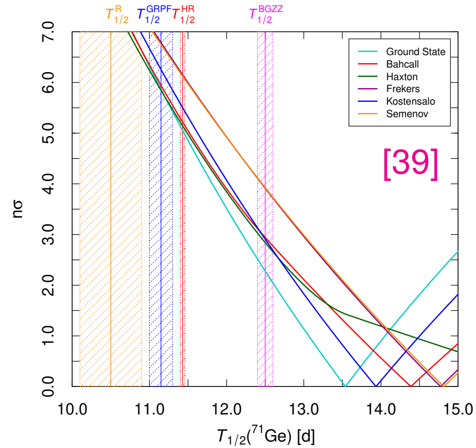
Origin of the gallium anomaly

- 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;
  - ^{71}Ge half-life may be wrong, but needed "error" very large;
  - solar data show no tension with current cross-section;

$\Longrightarrow$ no obvious solution to the Gallium puzzle.





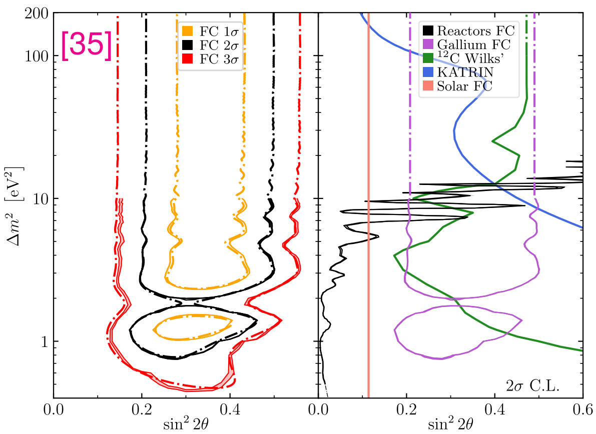


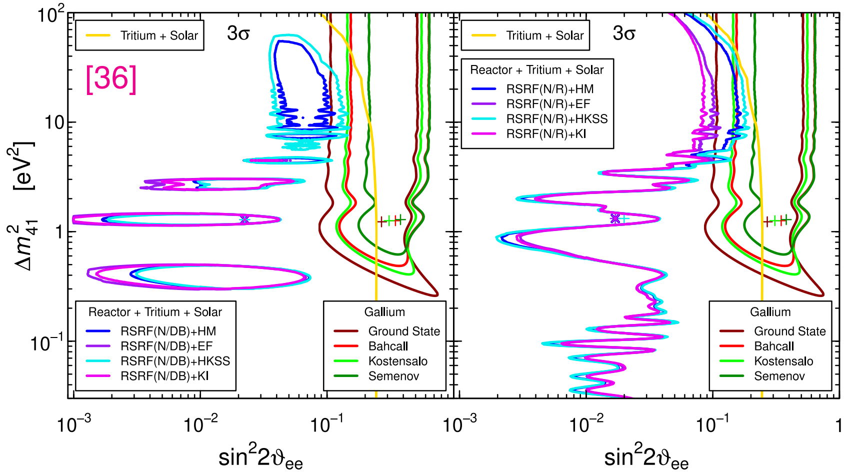
[39] C. Giunti *et al.*, Phys. Lett. B **842** (2023) 137983 [2212.09722]

[40] M.C. Gonzalez-Garcia *et al.*, JHEP **02** (2024) 064 [2311.16226]

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 [35];
- Gallium: FC not so important [35], but it cannot be reconciled with other data [35, 36];
- "least tension" $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ at $\Delta m^2 \sim 10\ \text{eV}^2$, **in tension** with $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ value $\Delta m^2 \sim 1\ \text{eV}^2$;
- solar data also disfavor large mixing angle, and tritium does so at large Δm^2.

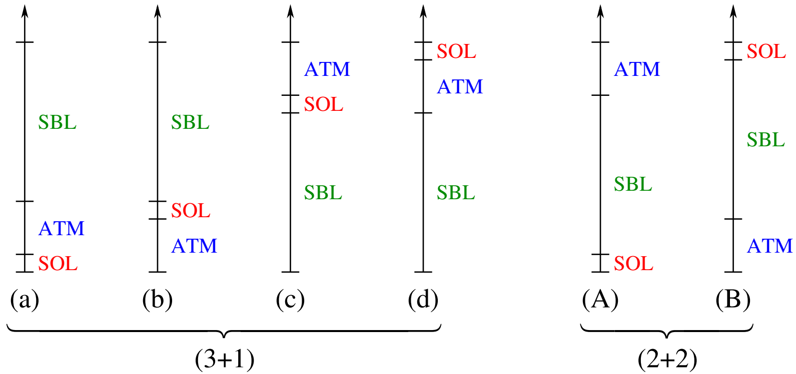




[35] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]
[36] C. Giunti *et al.*, JHEP **10** (2022) 164 [arXiv:2209.00916]

Four neutrino mass models

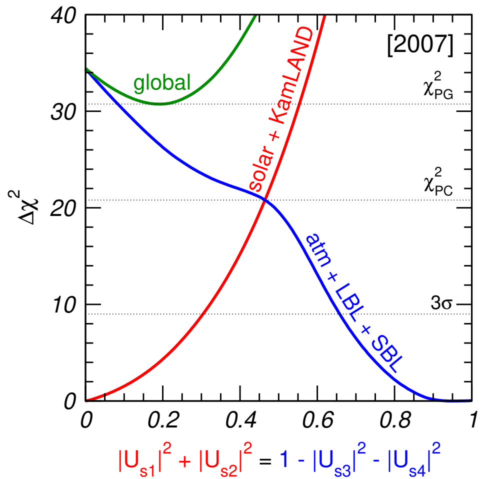
- Hierarchy of splittings: $\Delta m^2_{\text{SOL}} \ll \Delta m^2_{\text{ATM}} \ll \Delta m^2_{\text{SBL}} \Rightarrow$ 6 different mass schemes:



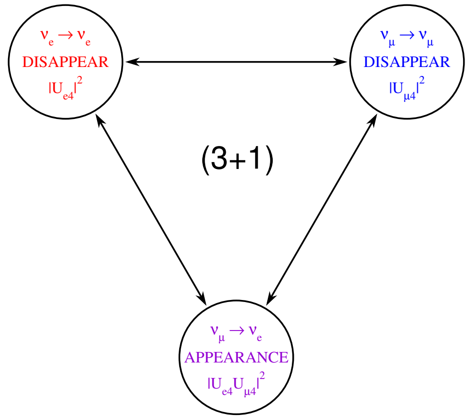
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

(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.

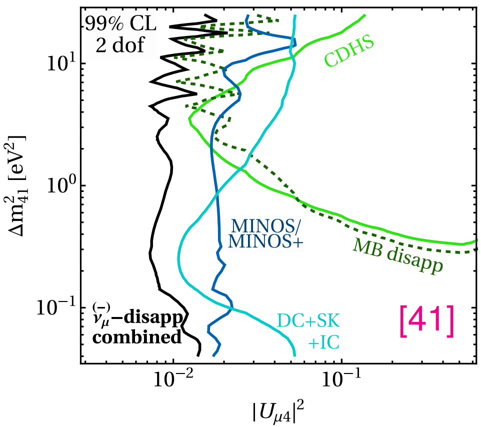


(3+1): appearance versus disappearance



- (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 $\nu_\mu \to \nu_\mu$ searches compatible with this?



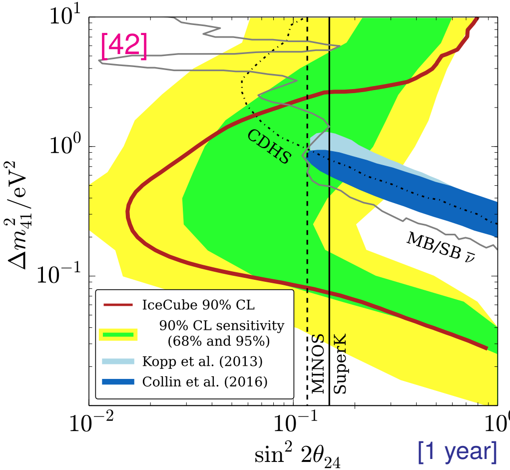
ν_μ disappearance: long-term situation

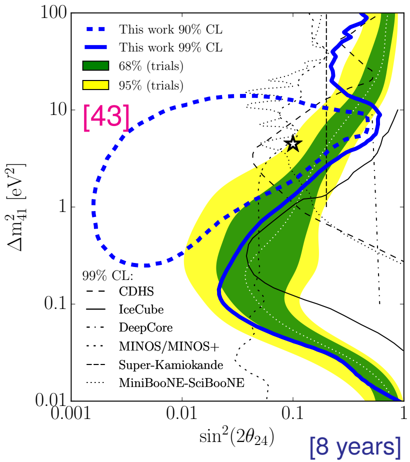
- Many experiments have been performed:
  - CDHS (ν)
  - MiniBooNE $(\nu, \bar\nu)$
  - SciBooNE $(\nu, \bar\nu)$
  - MINOS (ν)
  - NOνA (ν)
  - SK atmos $(\nu, \bar\nu)$
- no hint of ν_μ disappearance has been observed;
- bound on $|U_{\mu4}|^2$ may be in tension with other data...

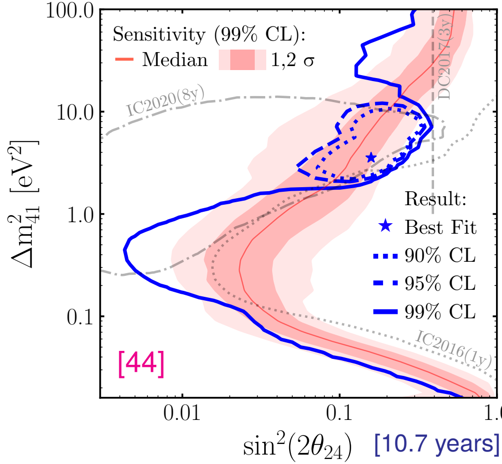
[41] M. Dentler *et al.*, JHEP **08** (2018) 010 [arXiv:1803.10661]

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) $\Rightarrow$ still OK.







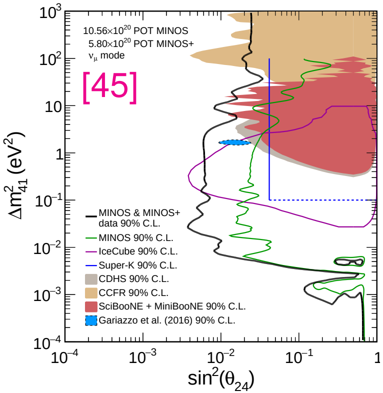
[42] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **117** (2016) 071801 [arXiv:1605.01990]

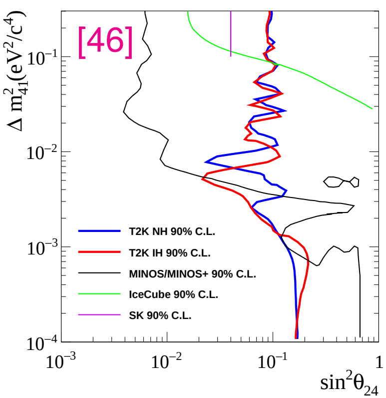
[43] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **125** (2020) 141801 [arXiv:2005.12942]

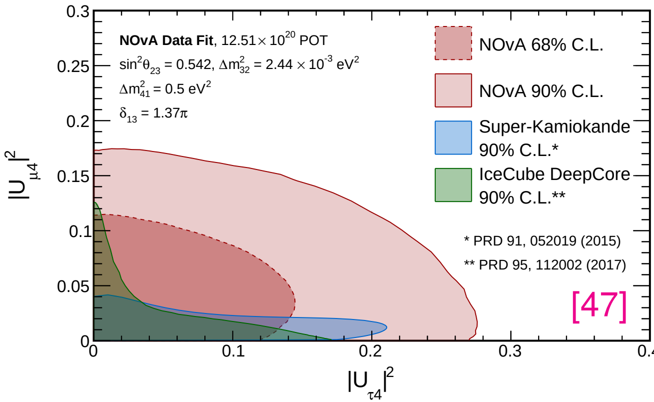
[44] R. Abbasi *et al.* [IceCube], arXiv:2405.08070 ⇝ [Yañez]

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;
- results presented by MINOS/MINOS+ [45], T2K [46], and NOvA [47] collaborations;
- sterile oscillations can also be studied by looking for deficit in neutral-current data [47].







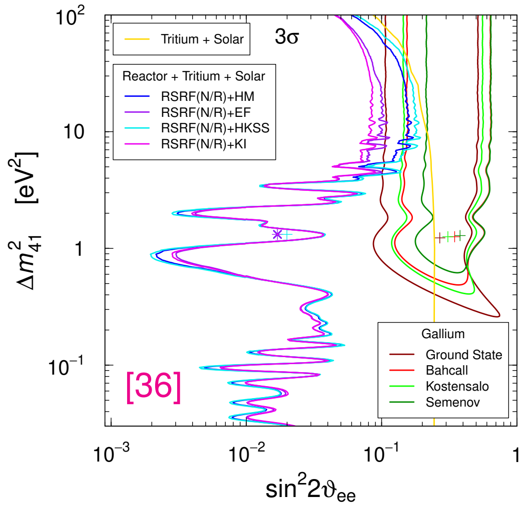
[45] P. Adamson *et al.* [MINOS+], Phys. Rev. Lett. **122** (2019) no.9, 091803 [arXiv:1710.06488]

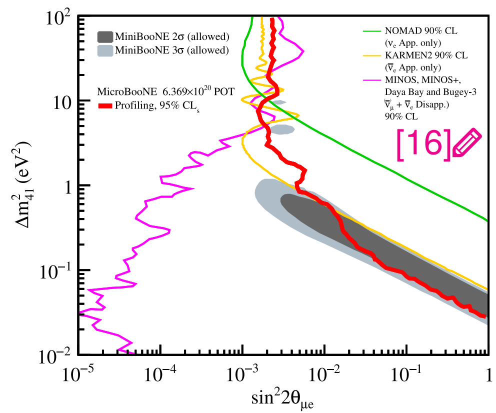
[46] K. Abe *et al.* [T2K], Phys. Rev. D **99** (2019) no.7, 071103 [arXiv:1902.06529]

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

(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 [48] 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 [49]. Full global fit in 2001 [50] cornered (3+1) models. No conceptual change since then…





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

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

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

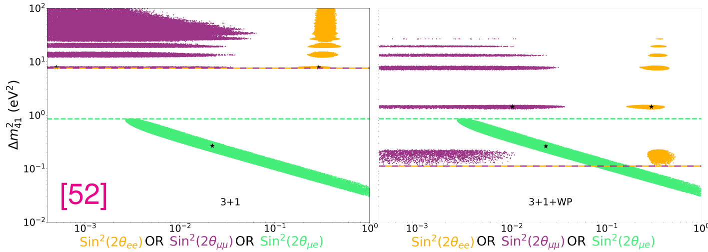
[49] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454]

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

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" [52] (first noted in [51]), but tensions remain;
  – alternatives explain some (not all) data;
  – usually very "exotic" and "ad-hoc";

$\Rightarrow$ "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	[53]

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

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

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

Summary

- 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;
- 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 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, we will hear about them during this conference;
- 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.