Beyond three-neutrino oscillations: sterile neutrinos, NSI, and others

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2nd school on "Multi-Aspect Young-ORiented Advanced Neutrino Academy (MAYORANA)"

Palazzo Grimaldi, Modica, Italy – June 24th & 25th, 2025

Instituto de Física Teórica UAM-CSIC

EXCELENCIA SEVERO OCHOA

UNIVERSIDAD AUTONOMA DE MADRID

CSIC Consejo Superior de Investigaciones Científicas

Gobierno de España Ministerio de Ciencia e Innovación

Agencia Estatal de Investigación

Project PID2022-142545NB-C21 funded by MCIN/AEI/10.13039/501100011033/ FEDER, UE

Neutrino oscillations: where we are

- Global 6-parameter fit (including δ_{CP}):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + BX(1–3);
  - **Atmospheric**: IC19 | IC24 + SK(1–5);
  - **Reactor**: KamLAND + SNOplus + IC + DB + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- best-fit point and 1σ (3σ) ranges:

$$\theta_{12} = 33.68\,^{+0.73}_{-0.70}\,\left(^{+2.27}_{-2.05}\right), \qquad \Delta m^2_{21} = 7.49\,^{+0.19}_{-0.19}\,\left(^{+0.56}_{-0.57}\right) \times 10^{-5}\ \text{eV}^2,$$

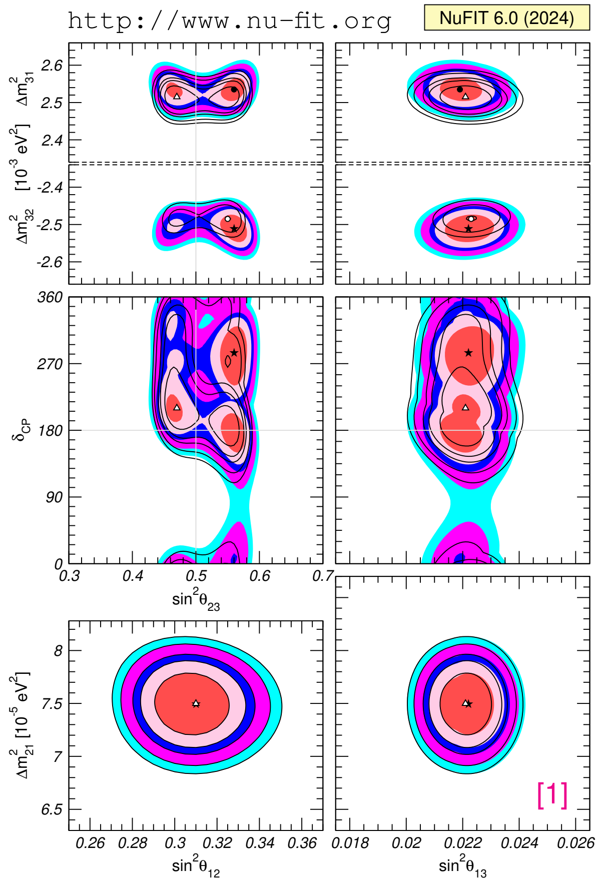
$$\theta_{23} = \begin{cases} 48.5\,^{+0.7}_{-0.9}\,\left(^{+2.0}_{-7.6}\right), \\ 48.6\,^{+0.7}_{-0.9}\,\left(^{+2.0}_{-7.2}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.534\,^{+0.025}_{-0.023}\,\left(^{+0.072}_{-0.071}\right) \times 10^{-3}\ \text{eV}^2, \\ -2.510\,^{+0.024}_{-0.025}\,\left(^{+0.072}_{-0.073}\right) \times 10^{-3}\ \text{eV}^2, \end{cases}$$

$$\theta_{13} = 8.58\,^{+0.11}_{-0.13}\,\left(^{+0.33}_{-0.39}\right), \qquad \delta_{\text{CP}} = 285\,^{+25}_{-28}\,\left(^{+129}_{-182}\right);$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.842 & 0.519 \to 0.580 & 0.142 \to 0.155 \\ 0.248 \to 0.505 & 0.473 \to 0.682 & 0.649 \to 0.764 \\ 0.270 \to 0.521 & 0.483 \to 0.690 & 0.628 \to 0.746 \end{pmatrix};$$

- ordering: $\Delta\chi^2_{\text{IO-NO}} = -0.6$ (IC19) | $+6.1$ (IC24 + SK).

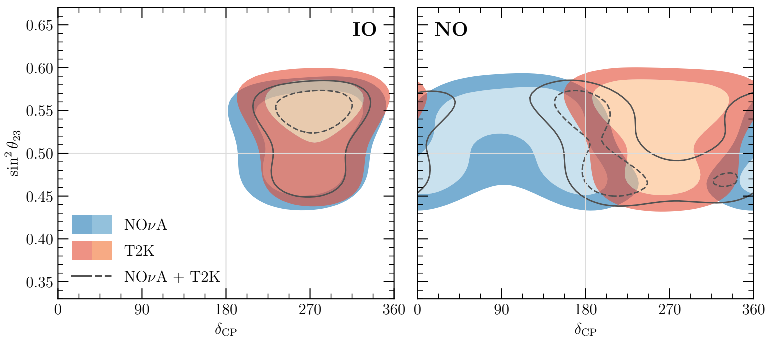


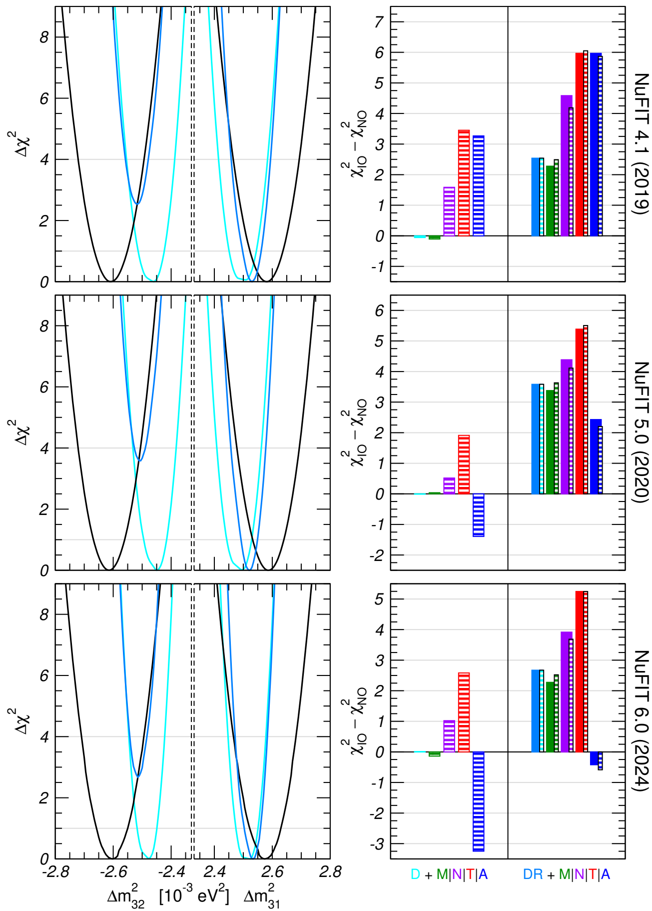
[1] I. Esteban *et al.*, JHEP **12** (2024) 216 [arXiv:2410.05380] & NuFIT 6.0 [http://www.nu-fit.org]

Open issues in 3ν oscillations

- 3ν picture is **robust**! But we still don't know:
  - **CP violation**: $\delta_{CP} \approx 180^\circ$ (NO) | 270° (IO);
  - **ordering**: Rea+Dis → NO, T2K+NOvA → IO;
  - **θ_{23} octant**: hints, but no clear indication;
- weak tensions in 3ν data (T2K/NOvA for NO);
- anomalies in some ~~3ν~~ data (LSND, MB, BEST);
- future experiments expected to shed light;

¿? can New Physics play a role in their task?





SM with ν masses: general three-neutrino framework

- Equation of motion: **6 parameters** (including Dirac and neglecting Majorana phases):

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

$$\boldsymbol{U}_{\text{vac}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}\, e^{-i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -s_{13}\, e^{i\delta_{\text{CP}}} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \xcancel{\begin{pmatrix} e^{i\eta_1} & 0 & 0 \\ 0 & e^{i\eta_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}}, \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix};$$

$$\boldsymbol{D}_{\text{vac}} = \frac{1}{2E_\nu}\left[\,\mathbf{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right) + \xcancel{m_1^2 \boldsymbol{I}}\right]; \qquad \boldsymbol{V}_{\text{mat}} = \sqrt{2} G_F N_e\, \mathbf{diag}\left(1,\ 0,\ 0\right).$$

Paradigms hardcoded in this construction

- Only the three neutrino flavors of the SM take part to the oscillation process;
- mixing angles in vacuum do not depend on energy;
- oscillation frequency in vacuum scales as $1/E$;
- matter contributions are flavor-diagonal and determined by the SM (no parameters);
- neutrino production and detection processes occur as described by the SM.

Neutrinos in the Standard Model

- The SM is a gauge theory based on the symmetry group

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

- LEP tested this symmetry to 1% precision and the missing particles t, ν_τ were found:

$(1,2)_{-1}$	$(3,2)_{1/3}$	$(1,1)_{-2}$	$(3,1)_{4/3}$	$(3,1)_{-2/3}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	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

Notice there is no ν_R

$\Rightarrow$ Accidental global symmetry:

$$B \times L_e \times L_\mu \times L_\tau$$

- When SM was invented upper bounds on m_ν:

$m_{\nu_e} < 2.2$ eV $\quad (^3H \to {}^3He + e^- + \bar{\nu}_e)$

$m_{\nu_\mu} < 190$ KeV $\quad (\pi \to \mu + \nu_\mu)$

$m_{\nu_\tau} < 18.2$ MeV $\quad (\tau \to n\pi + \nu_\tau$, with $n > 3)$

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

Neutrino masses: Dirac or Majorana?

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

Dirac

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

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

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

- however, it requires a **new** field ν_R ⇒ SM extension!

Majorana

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

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

- both possibilities are phenomenologically viable ⇒ 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 ⇒ can have an explicit Majorana mass;
- but in any case, once we introduce new gauge singlets… why to stop at 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"):

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

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

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

- 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:

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

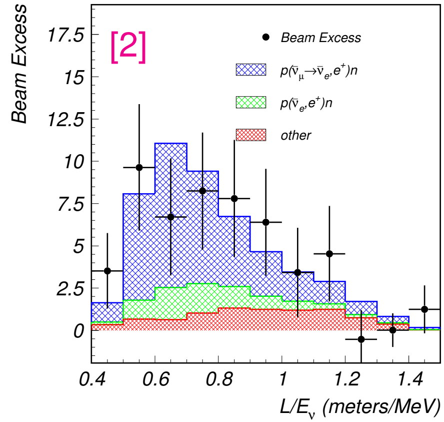
- but notice that ν_{s_i} states are defined arbitrarily, hence mixing among them is unphysical.

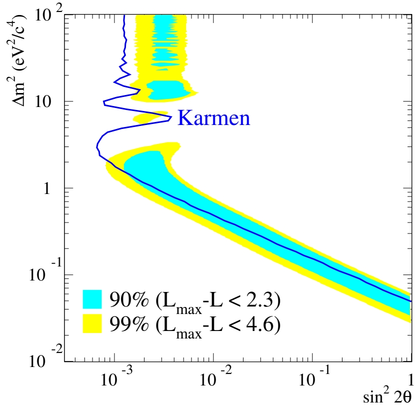
A long time ago... the LSND anomaly

- 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) [2];
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [3];
- 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.

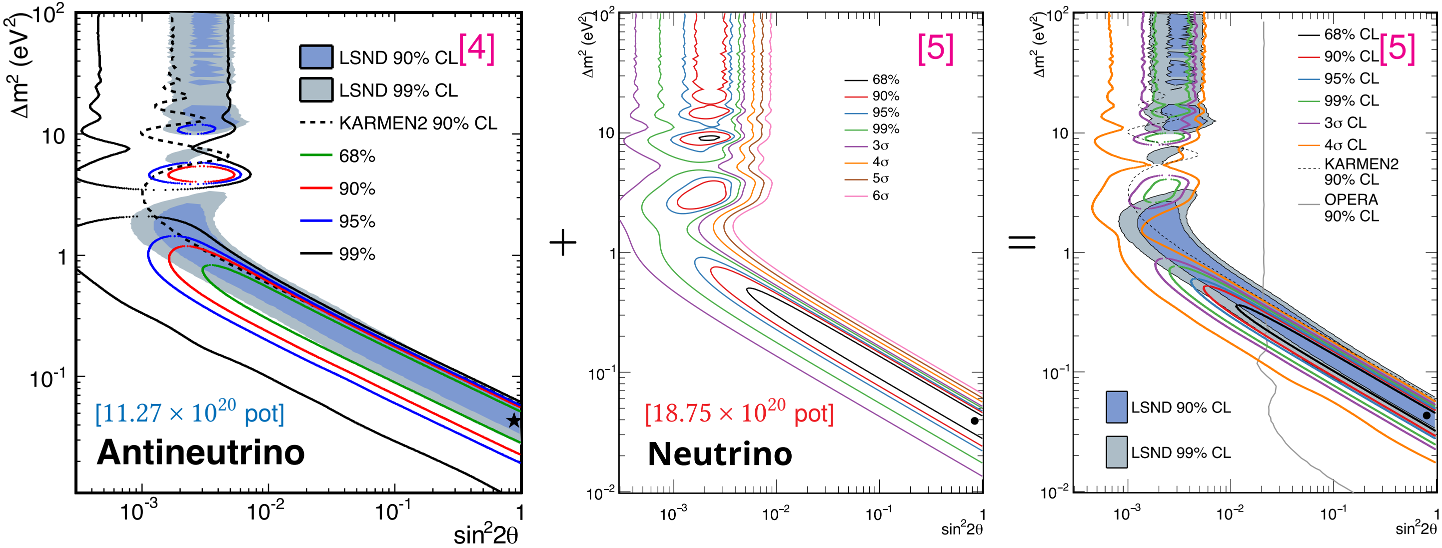




[2] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049]
[3] B. Armbruster *et al.* [KARMEN collab], Phys. Rev. D **65** (2002) 112001 [hep-ex/0203021]

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…

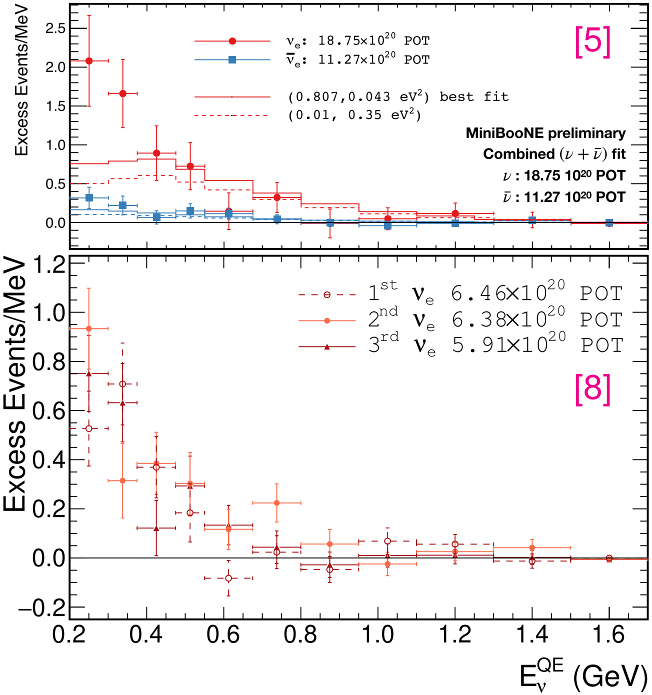


[4] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [arXiv:1303.2588]

[5] 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 [6];
- 2013 ($\bar\nu$): low-E not so steep + mid-E excess observed $\Rightarrow$ good oscillation fit ($P_\text{osc} \simeq 66\%$) $\Rightarrow$ **confirm** LSND [4];
- 2018 (ν): low-E softened + mid-E excess seen also in ν $\Rightarrow$ mild oscillation fit ($P_\text{osc} \simeq 15\%$) [7];
- 2020 (ν): more data released [8], oscillations confirmed but low-E excess definitely there.



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

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

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

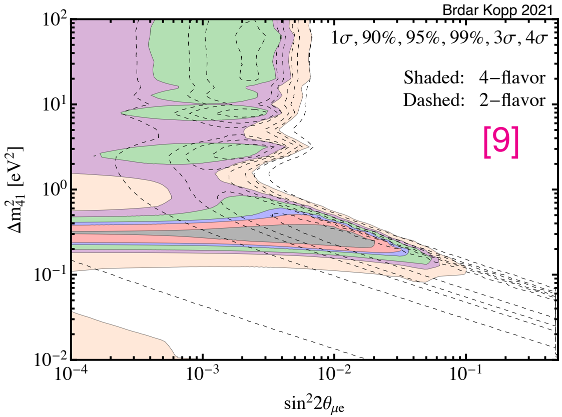
[7] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **121** (2018) 221801 [arXiv:1805.12028]

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

Present status of MiniBooNE

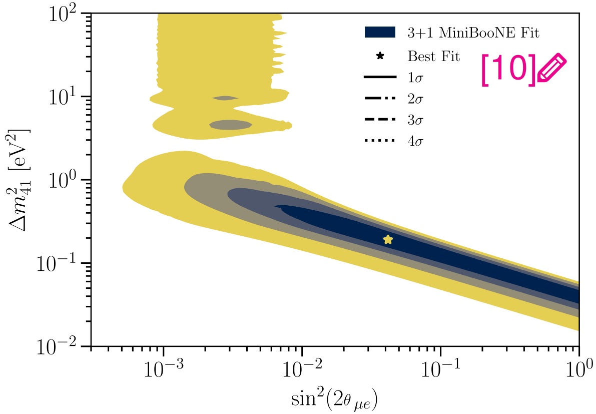
- Possible systematics related to the low-E excess:
  - misreconstruction of neutrino energy;
  - π^0 from NC reconstructed as ν_e;
  - single photon from NC misidentified as ν_e;
- extensive studies performed by the collaboration;
- present status: no combination of known systematics could account for the whole excess [9];

$\Rightarrow$ 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 [9];
- such effects can be very important. Omission corrected in recent reanalysis [10].



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

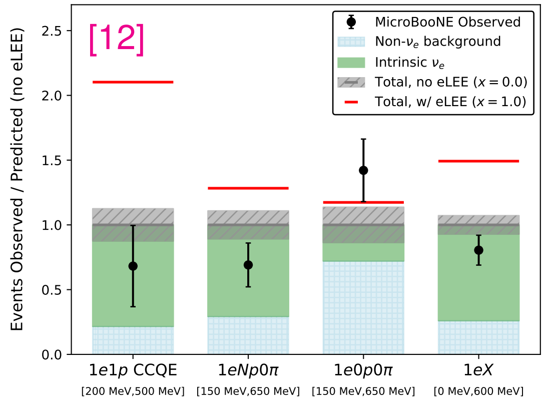
[10] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]

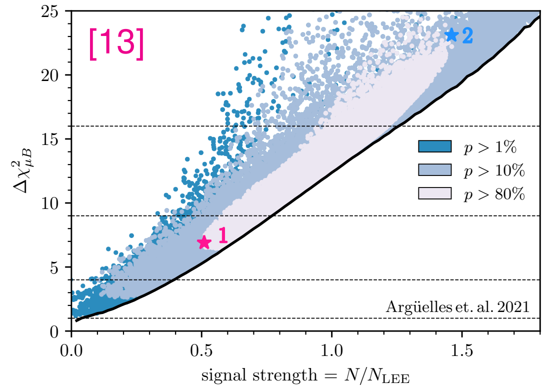
The MicroBooNE experiment

- 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 [11];
  - no evidence of ν_e excess over SM prediction [12];
- however, rejection of MB signal in [12] based on the assumption that the entire ν_e excess matches the difference between data and best-fit MB background;
- but in [13] it was noticed that various signal/background compositions can fit MB equally well, but lead to different μB sensitivity $\Rightarrow$ rejection **not** model-independent...

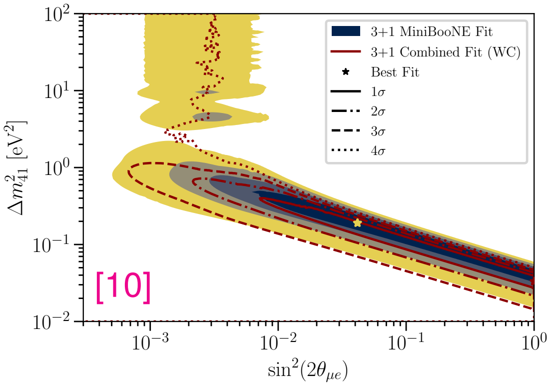


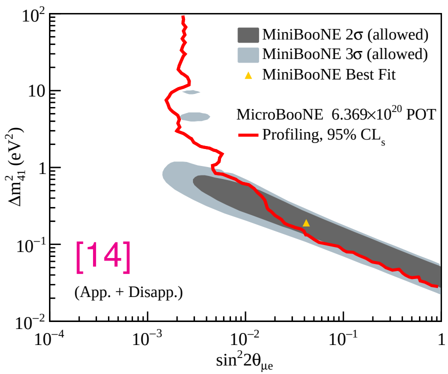


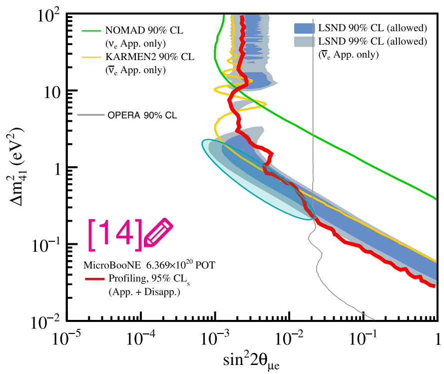
[11] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 111801 [arXiv:2110.00409]
[12] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801 [arXiv:2110.14054]
[13] C.A. Argüelles *et al.*, Phys. Rev. Lett. **128** (2022) 241802 [arXiv:2111.10359]

Comparison of MicroBooNE and MicroBooNE results

- MiniBooNE: updated analysis including μB bounds [10] $\Rightarrow 3\sigma$ region at $\Delta m^2_{41} \lesssim 1$ eV;
- MicroBooNE: global 4ν analysis [14] 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: currently in progress;
- Japan: JSNS^2 will provide an independent check of LSND/MiniBooNE excess.

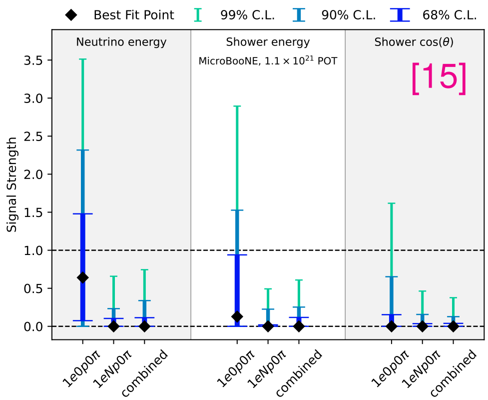




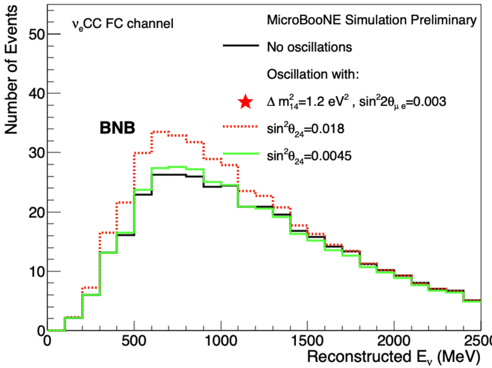


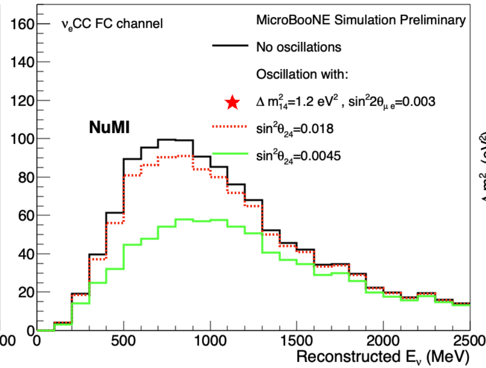
[10] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]
[14] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **130** (2023) 011801 [arXiv:2210.10216]

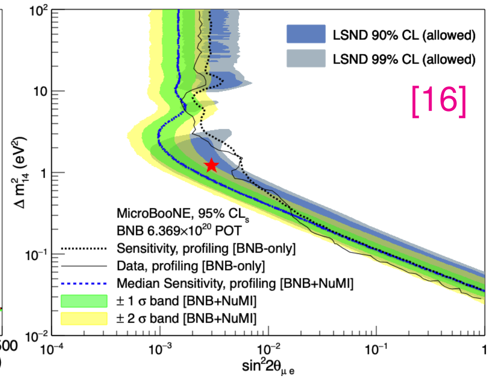
MicroBooNE update: ν_e appearance



- New analysis [15]: 5 year of data, 2 topologies, 3 observables $\Rightarrow$ ν_e interpretation of MB excess ruled out at 99.5%;
- in progress [16]: extra 4ν parameters degrade 2ν exclusion plot $\Rightarrow$ off-axis ν from NuMI beam can break degeneracy;
- Ref. [17]: profiling over 4ν parameters hides information, real tension larger than it appears in 2ν plot.



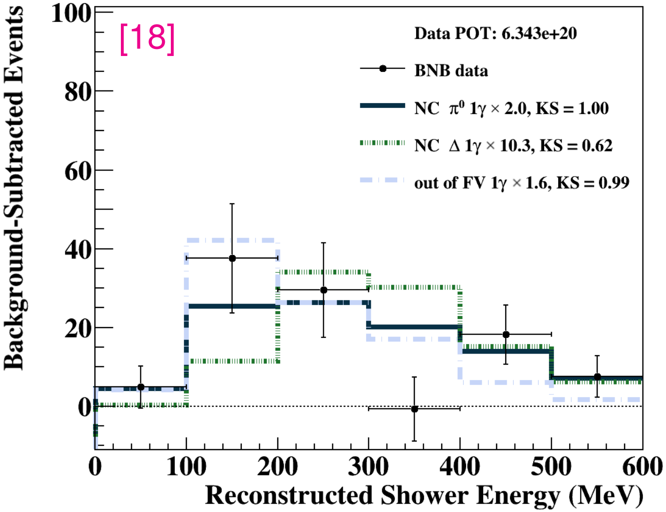


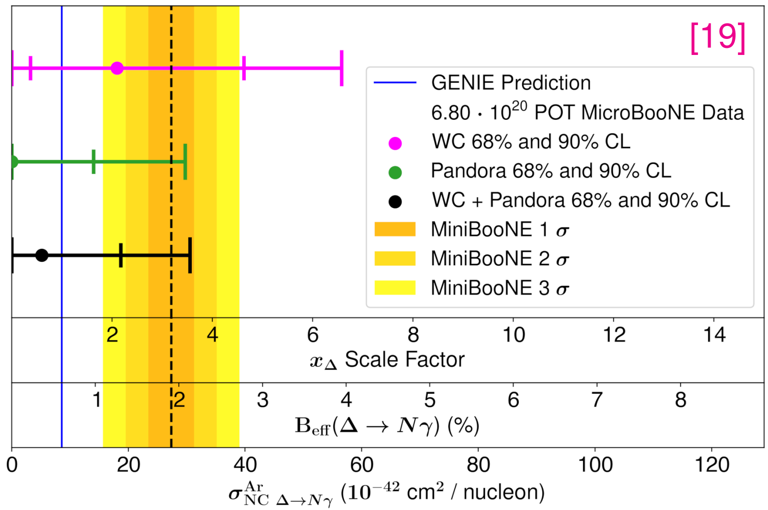


[15] P. Abratenko *et al.* [MicroBooNE collaboration], arXiv:2412.14407.
[16] MicroBooNe collab., public note MICROBOONE-NOTE-1132-PUB, FERMILAB-FN-1255-PPD.
[17] O.B. Rodrigues, M. Hostert, K.J. Kelly, B. Littlejohn *et al.*, arXiv:2503.13594.

MicroBooNE update: dissecting the MiniBooNE low-energy excess

- In a search for 1γ events compatible with MB-LEE, μB itself found an excess [18];
- prime-suspect NC $\Delta \to N\gamma$ already disfavored [19] and incompatible with E shape;
- instead, NC $\pi^0 1\gamma$ and ν interactions outside the detector show reasonable compatibility;
- presently no guarantee that this excess and the MB-LEE one are the same, but it's a start.



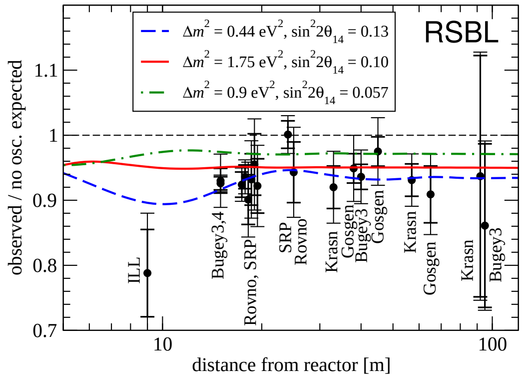


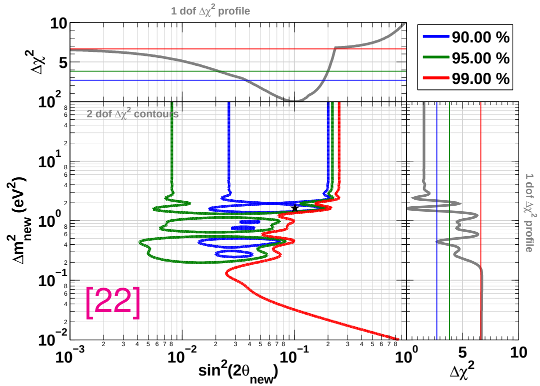
[18] P. Abratenko *et al.* [MicroBooNE collaboration], arXiv:2502.06064.
[19] P. Abratenko *et al.* [MicroBooNE collaboration], arXiv:2502.05750.

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

- In [20, 21] 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 $L \Rightarrow \Delta m^2 \gtrsim 1$ eV^2;
- global data (3σ): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5}\ \text{eV}^2, \\ |\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3}\ \text{eV}^2; \end{cases}$

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

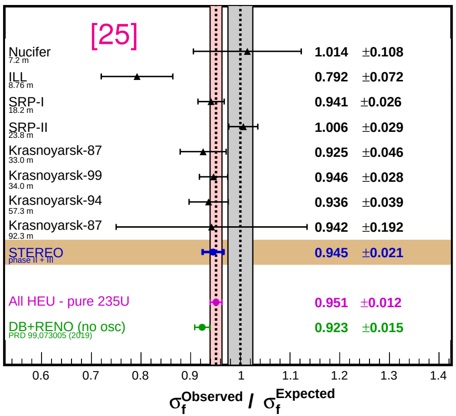


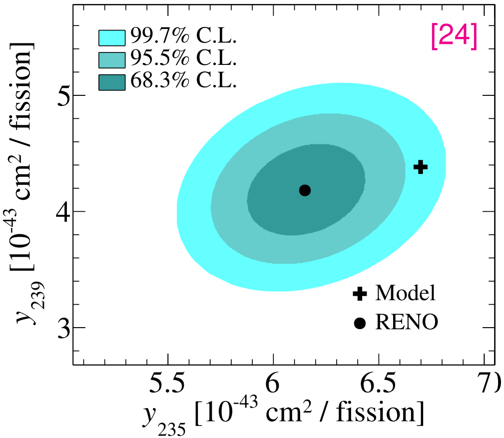


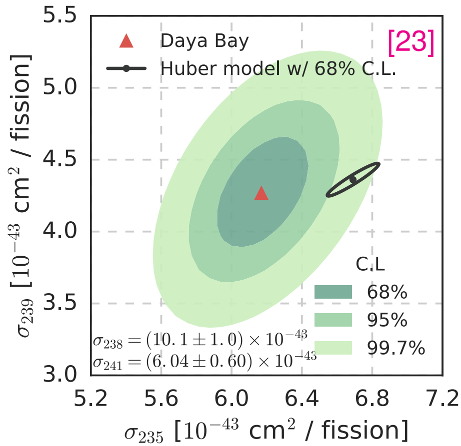
[20] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663]
[21] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687]
[22] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755]

Reactor anomaly: sterile ν or wrong fluxes?

- DB [23] and RENO [24]: 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 [25] (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.







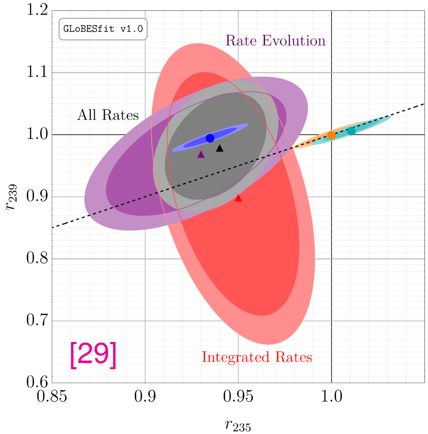
[23] F.P. An *et al.* [Daya-Bay], Phys. Rev. Lett. **118** (2017) 251801 [arXiv:1704.01082]

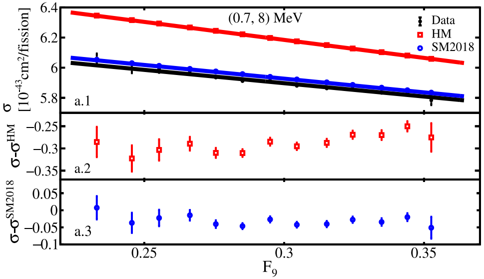
[24] G. Bak *et al.* [RENO], Phys. Rev. Lett. **122** (2019) 232501 [arXiv:1806.00574]

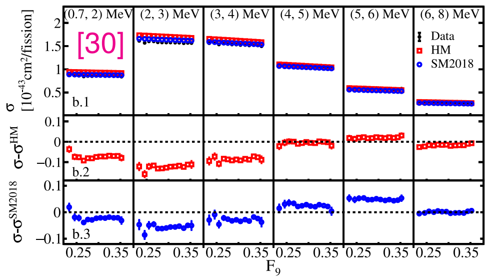
[25] H. Almazán *et al.* [STEREO], Nature **613** (2023) 257-261 [arXiv:2210.07664]

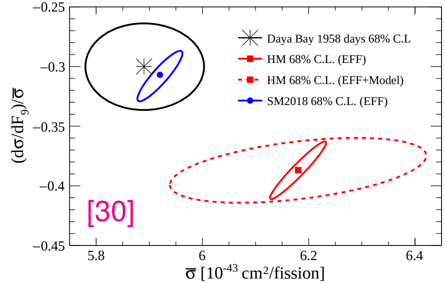
Recent improvements in reactor flux models

- New reactor flux calculations: EF [26], HKSS [27], KI [28];
- 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.









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

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

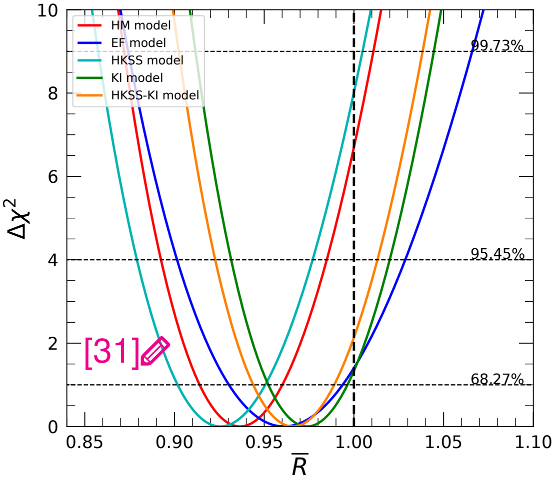
[28] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [2103.01684]

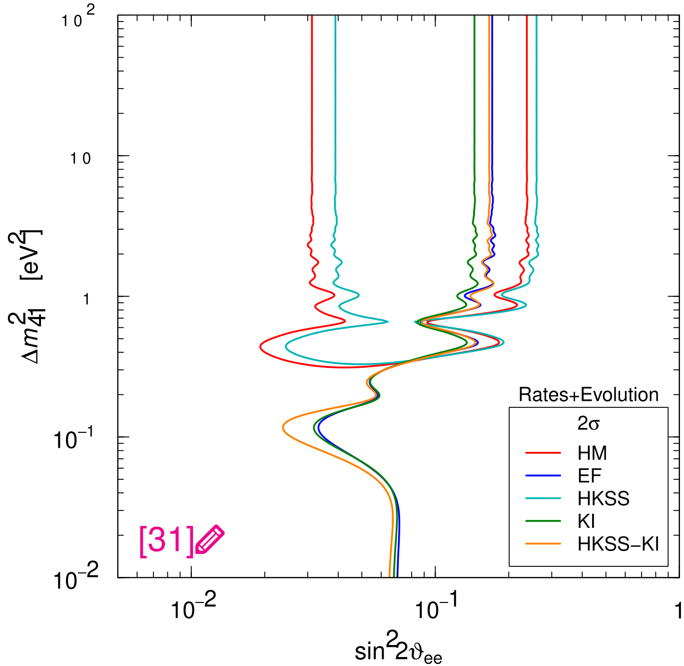
[29] J.M. Berryman and P. Huber, JHEP **01** (2021) 167 [arXiv:2005.01756]

[30] 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. [31]: hint of sterile ν strongly reduced for EF (0.8σ) and KI (1.4σ);
- hint sizable for HM (2.8σ) and HKSS (3.0σ).





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

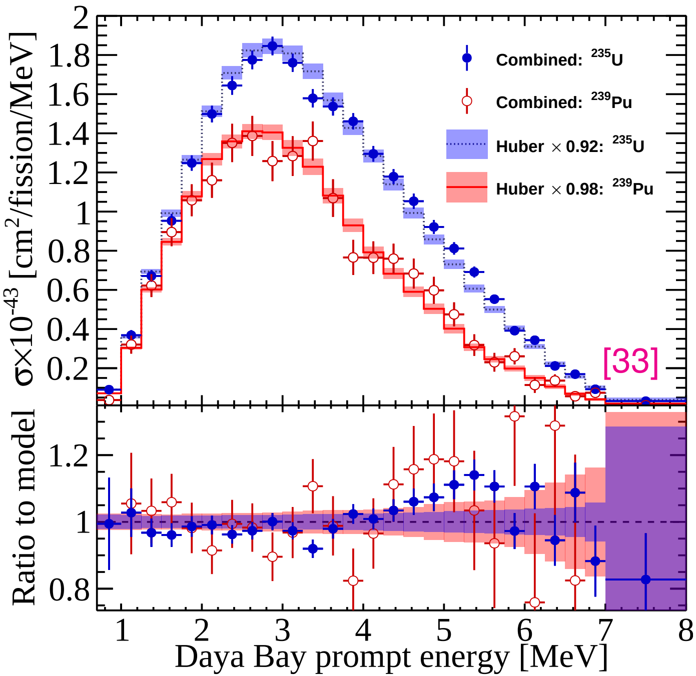
[27] L. Hayen *et al.* [HKSS model], Phys. Rev. C **100** (2019) 054323 [arXiv:1908.08302]

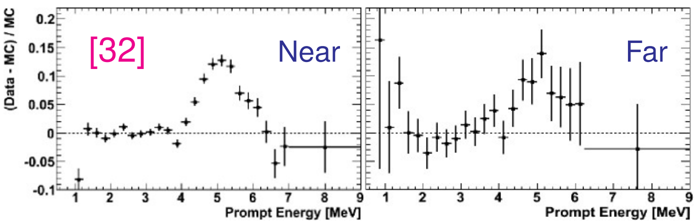
[28] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [2103.01684]

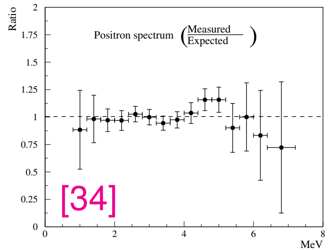
[31] C. Giunti *et al.*, Phys. Lett. B **829** (2022) 137054 [arXiv:2110.06820]

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

- Neutrino 2014: RENO [32] reported an excess of events around 5 MeV;
- seen by most reactors (also old Chooz [34]);
- DB+Prospect [33]: affect both $^{235}\mathrm{U}$ & $^{239}\mathrm{Pu}$;
- 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.







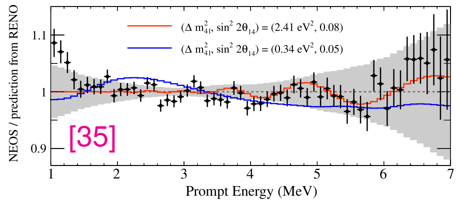
[32] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014

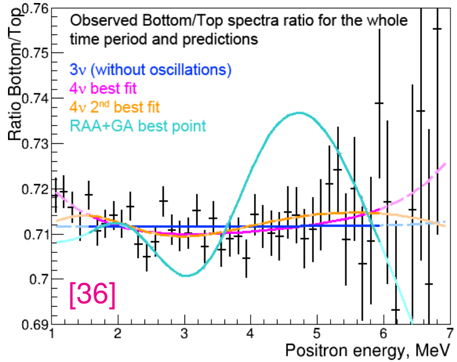
[33] F.P. An *et al.* [DB+Prospect], PRL **128** (2022) 081801 [arXiv:2106.12251]

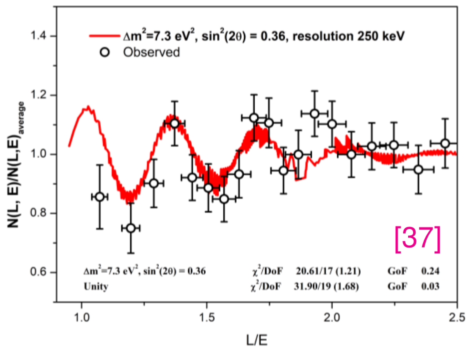
[34] M. Apollonio *et al.* [Chooz], PLB **466** (1999) 415 [hep-ex/9907037]

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.







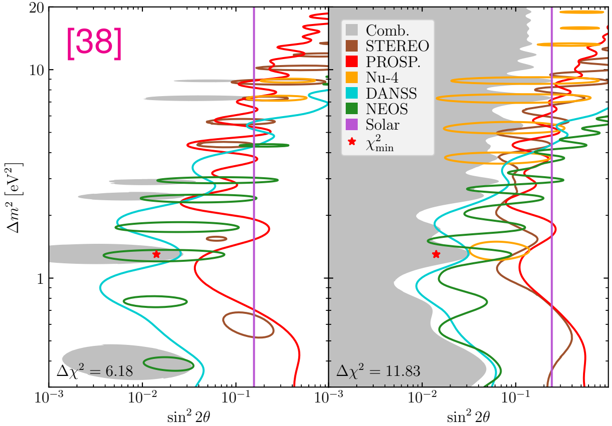
[35] Z. Atif *et al.* [NEOS & RENO], Phys. Rev. D **105** (2022) L111101 [arXiv:2011.00896]

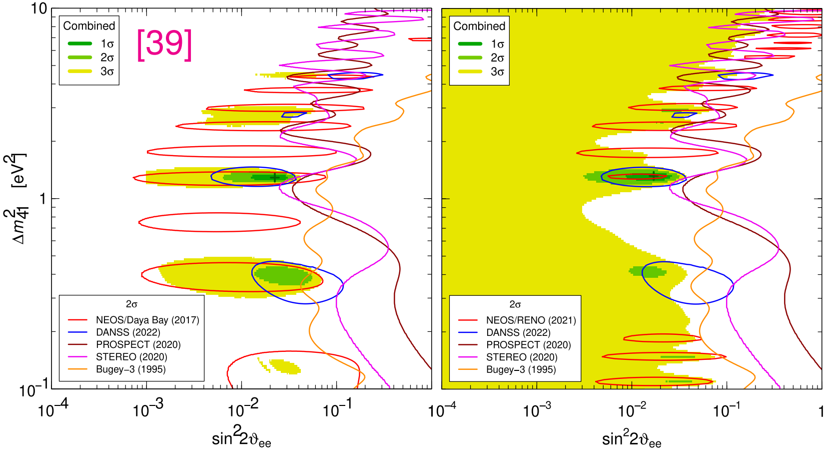
[36] E. Samigullin [DANSS], talk at NuFact 23, Seoul, Korea, 25/08/2023

[37] 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 [39];
- 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 [40] not included here.





[38] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]

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

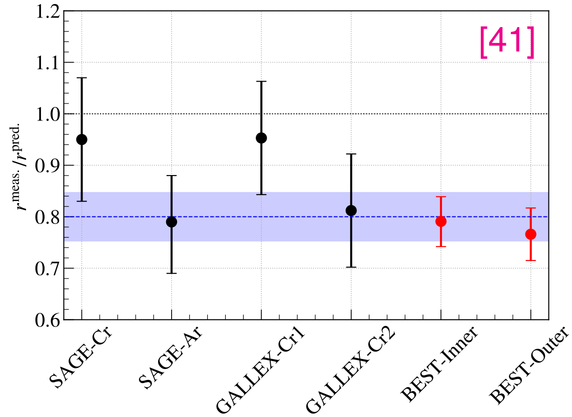
[40] D. Galbinski [SOLID], talk at TAUP 23, Vienna, Austria, 30/08/2023

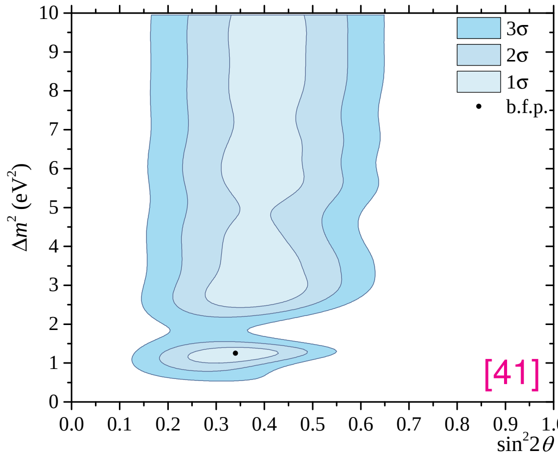
ν_e disappearance: the gallium anomaly

- $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}\,\nu$ 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 [41]:

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

- 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}.



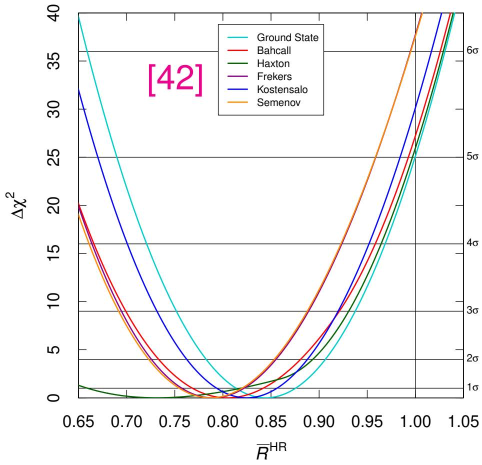


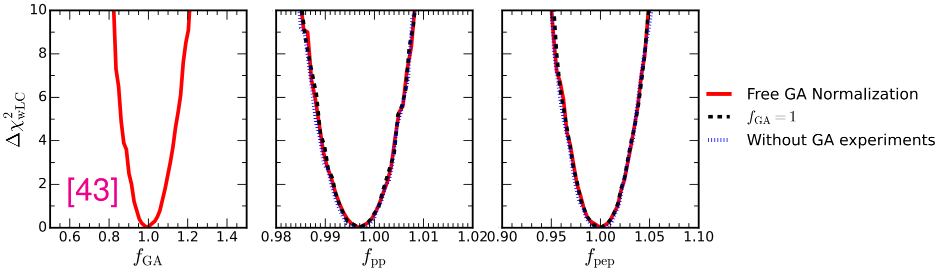
[41] V.V. Barinov *et al.* [BEST], Phys. Rev. C **105** (2022) no.6, 065502 [arXiv:2201.07364]

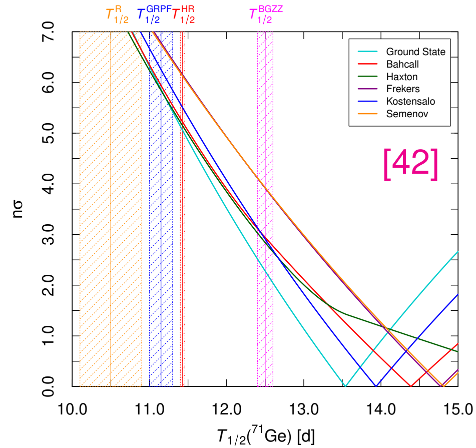
Origin of the gallium anomaly

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

⇒ no obvious solution to the Gallium puzzle.





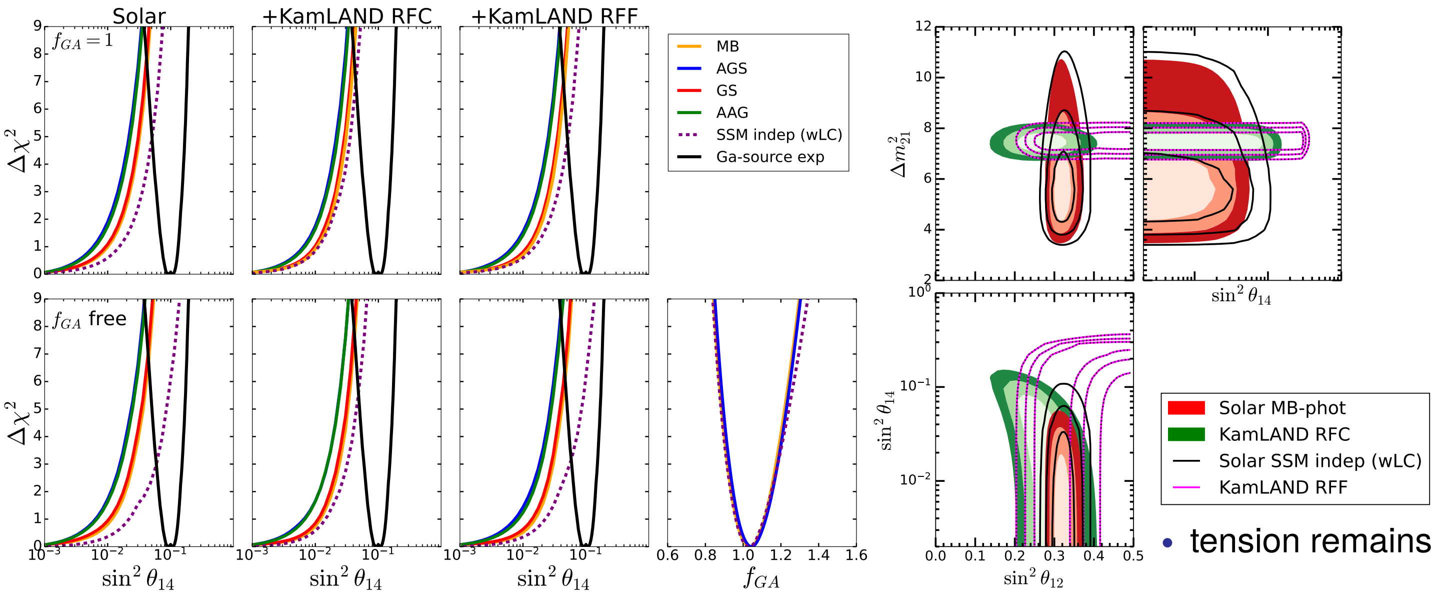


[42] C. Giunti *et al.*, Phys. Lett. B **842** (2023) 137983 [2212.09722]

[43] 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? → Try various options, or even leave the fluxes free;
- can we trust Gallium *solar* measurements? → Both fixed or free f_{Ga} normalization;
- can we trust reactor fluxes? → Both constrained and free KamLAND (+ DB) scale;



- tension remains.

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

Tension between solar and gallium data: results

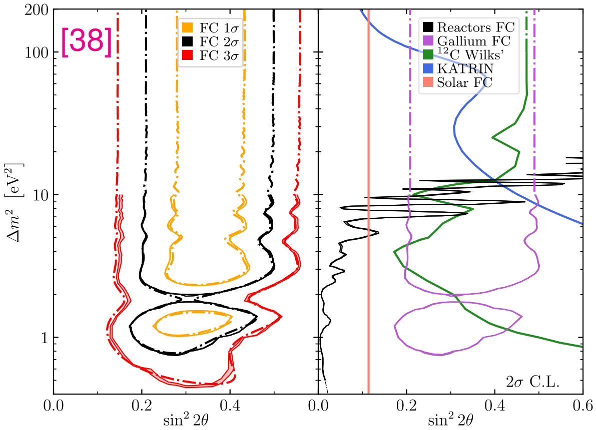
- Solar+KL data favor $\theta_{14} = 0$ irrespective of SSM model, KL reactor fluxes, or inclusion of f_{Ga};
- even the least constraining scenario (everything free) has a p-value no better than 0.29%;
- only way to further reduce the tension acting on solar data is to relax the Luminosity Constraint. An increase larger than 10% is required, despite the current precision being 0.34%.

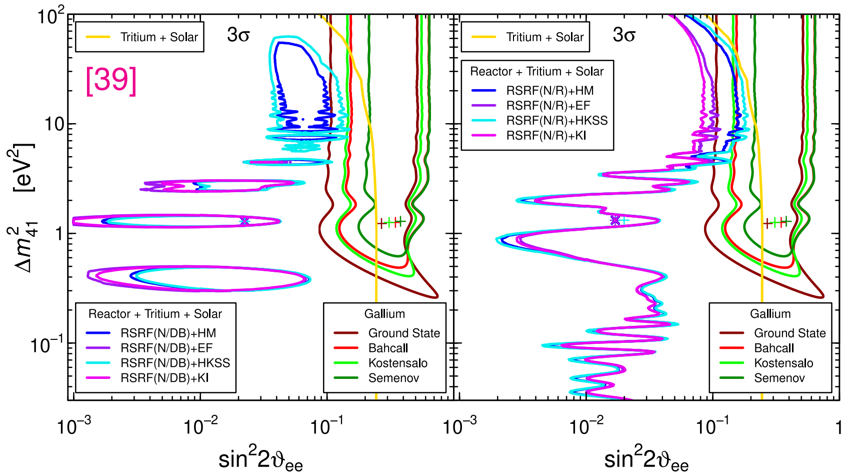
		$f_{\text{Ga}} = 1$			f_{Ga} free		
	SSM	χ^2_{PG}/n	p-value ($\times 10^{-3}$)	$\#\sigma$	χ^2_{PG}/n	p-value ($\times 10^{-3}$)	$\#\sigma$
Solar	MB-phot/GS98	14.9	0.11	3.9	13.1	0.3	3.6
	AAG21/AGSS09	18.7	0.2	4.3	17.3	0.03	4.2
	SSM indep (wLC)	9.1	2.6	3.0	4.9	27	2.2
Solar + KL-RFC	MB-phot/GS98	15.9	0.07	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

[44] 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 [38];
- Gallium: FC not so important [38], but it cannot be reconciled with other data [38, 39];
- "least tension" $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$ at $\Delta m^2 \sim 10$ eV^2, **in tension** with $\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e$ value $\Delta m^2 \sim 1$ eV^2;
- solar data also disfavor large mixing angle, and tritium does so at large Δm^2.



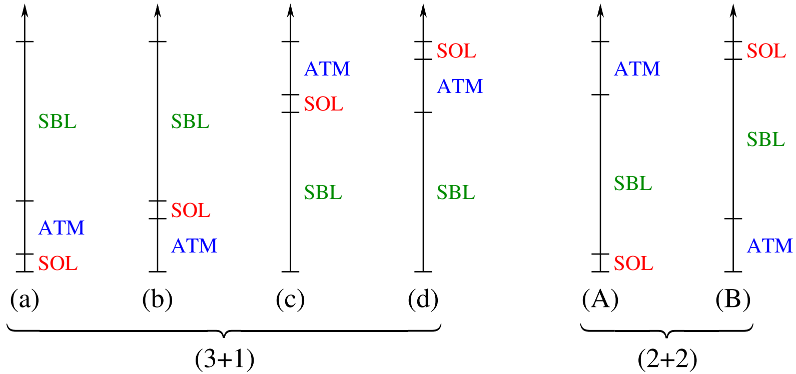


[38] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]

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

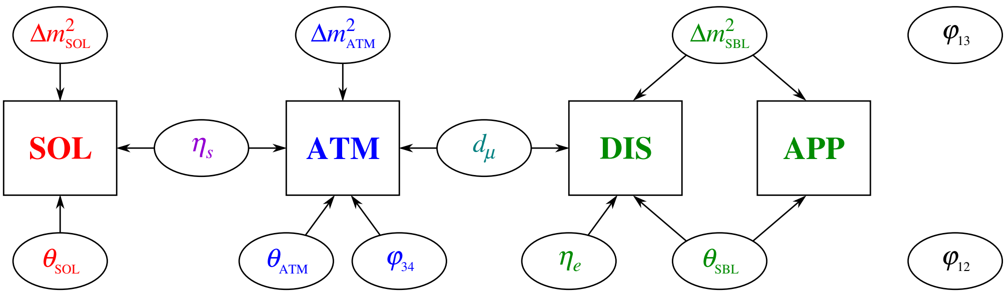
Four neutrino mass models

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

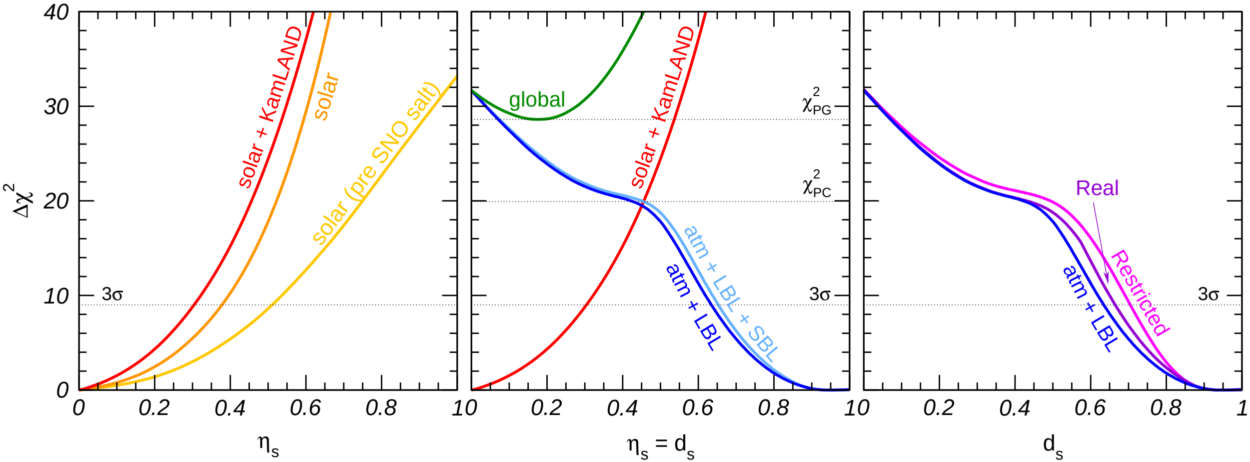


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

- Total: 3 Δm^2, 6 angles, 3 phases. Different set of experimental data *partially decouple*:



(2+2): ruled out by solar and atmospheric data



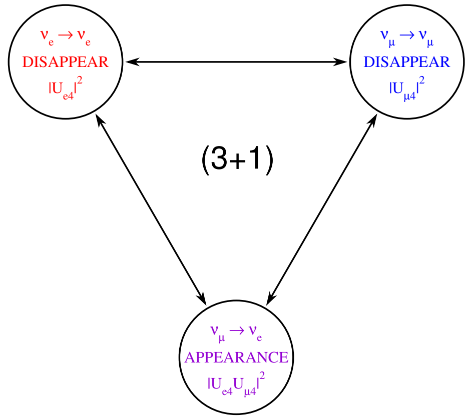
- in (2+2) models, fractions of ν_s in solar (η_s) and atmos ($1 - d_s$) add to one $\Rightarrow$ $\boxed{\eta_s = d_s}$;
- 3σ allowed regions $\eta_s \equiv\leq 0.31$ (solar) and $d_s \geq 0.63$ (atmos) do not overlap; superposition occurs only above 4.5σ ($\chi^2_{\text{PC}} = 19.9$);
- the χ^2 increase from the combination of solar and atmos data is $\chi^2_{\text{PG}} = 28.6$ (1 dof), corresponding to a PG $= 9 \times 10^{-8}$ [45].

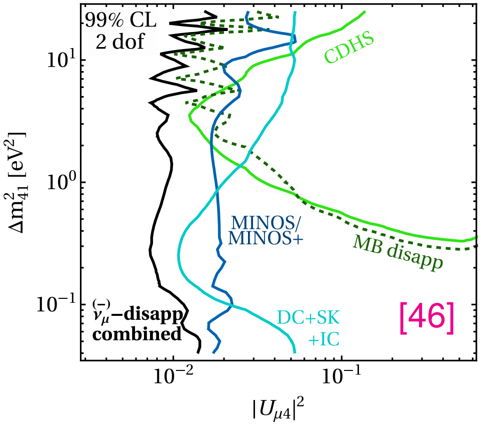
[45] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157]

(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?





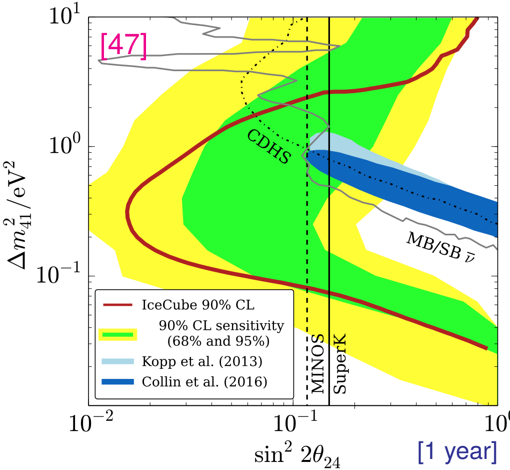
ν_μ disappearance: long-term situation

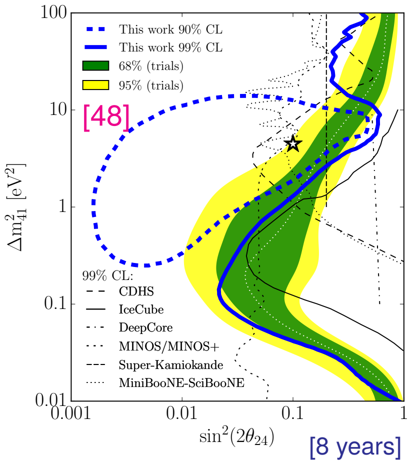
- Many experiments have been performed:
  - CDHS (ν)
  - MiniBooNE $(\nu, \bar\nu)$
  - SciBooNE $(\nu, \bar\nu)$
  - MINOS (ν)
  - NOνA (ν)
  - SK atmos $(\nu, \bar\nu)$
- no hint of ν_μ disappearance has been observed;
- bound on $|U_{\mu4}|^2$ may be in tension with other data…

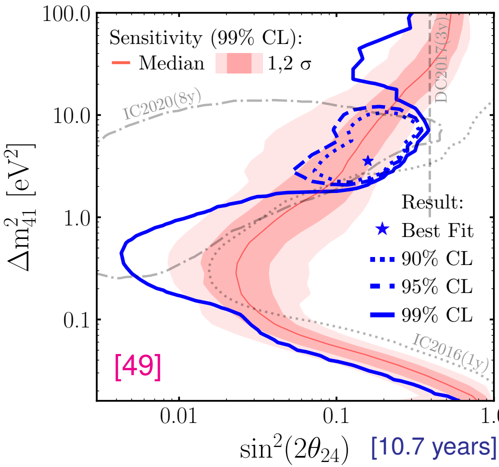
[46] M. Dentler *et al.*, JHEP **08** (2018) 010 [arXiv:1803.10661]

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.







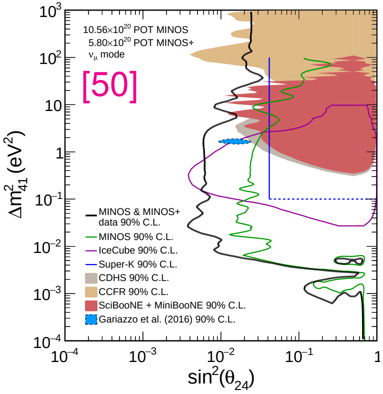
[47] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **117** (2016) 071801 [arXiv:1605.01990]

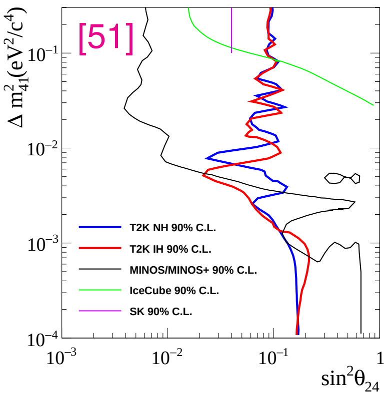
[48] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **125** (2020) 141801 [arXiv:2005.12942]

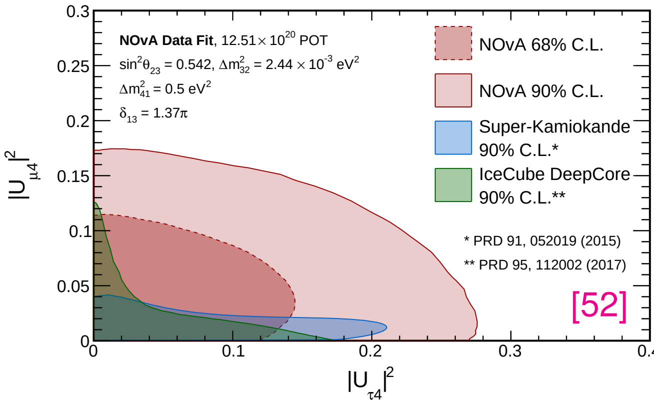
[49] R. Abbasi *et al.* [IceCube], Phys. Rev. Lett. **133** (2024) 201804 [arXiv:2405.08070]

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+ [50], T2K [51], and NOvA [52] collaborations;
- sterile oscillations can also be studied by looking for deficit in neutral-current data [52].



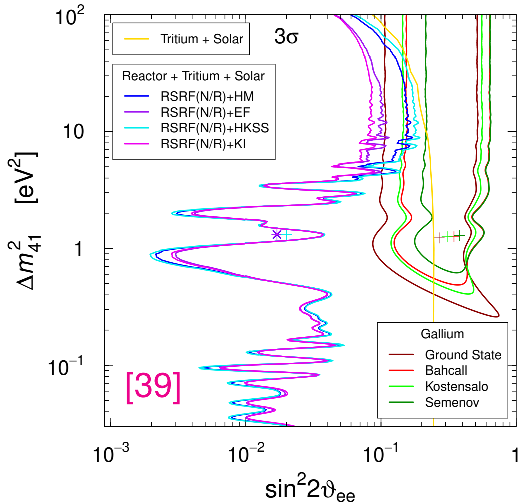


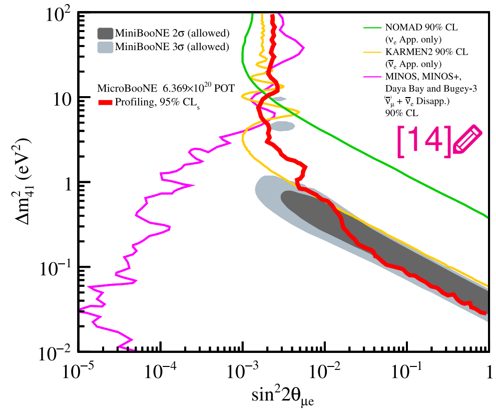


[50] P. Adamson *et al.* [MINOS+], Phys. Rev. Lett. **122** (2019) no.9, 091803 [arXiv:1710.06488]
[51] K. Abe *et al.* [T2K], Phys. Rev. D **99** (2019) no.7, 071103 [arXiv:1902.06529]
[52] M.A. Acero *et al.* [NOvA], Phys. Rev. Lett. **127** (2021) no.20, 201801 [arXiv:2106.04673]

(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 [53] 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 [54]. Full global fit in 2001 [55] cornered (3+1) models. No conceptual change since then…





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

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

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

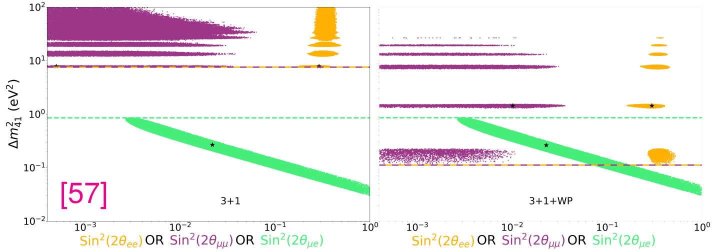
[54] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454]

[55] 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" [57] (first noted in [56]), 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	[58]

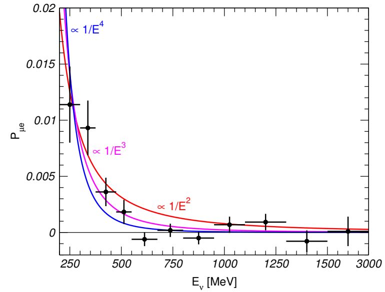
[56] S. Palomares-Ruiz *et al.*, JHEP **09** (2005) 048 [hep-ph/0505216]
[57] J.M. Hardin *et al.*, JHEP **09** (2023) 058 [arXiv:2211.02610]
[58] V. Brdar *et al.*, JHEP **05** (2023) 143 [arXiv:2303.05528]

I/d. Global fits with eV steriles: ν_μ disappearance

More sterile neutrinos? The case of (3+2) models

- With *one* extra sterile neutrino, m_4:

$$P_{\mu e}^{4\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} \quad \text{with} \quad \phi_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \,;$$



- for large energy $P_{\mu e}^{4\nu}$ drops as $1/E^2$;
- however, the low-energy MB excess is much sharper ($\sim 1/E^3$);
- On the other hand, with *two* extra neutrinos, m_4 and m_5:

$$P_{\mu e}^{5\nu} = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2\phi_{41} + 4|U_{e5}|^2|U_{\mu 5}|^2 \sin^2\phi_{51} + 8|U_{e4}U_{e5}U_{\mu 4}U_{\mu 5}| \sin\phi_{41} \sin\phi_{51} \cos(\phi_{54} - \delta) \,;$$

- terms of order $1/E^2$ suppressed if $\delta \approx \pi$ and $|U_{e4}U_{\mu 4}|\Delta m_{41}^2 \approx |U_{e5}U_{\mu 5}|\Delta m_{51}^2$;

⇒ two extra sterile states provide a better desciption of the MB low-energy ν data [59].

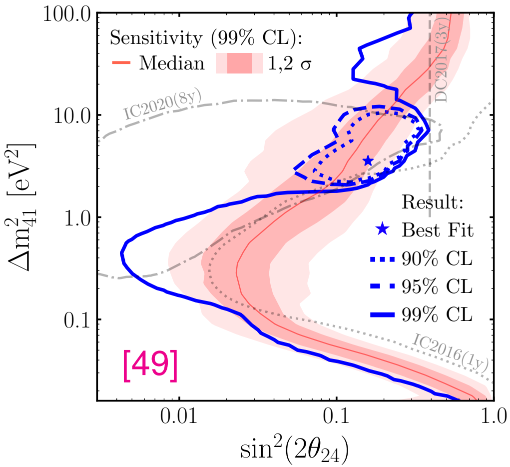
- also, $\delta = \arg(U_{e4}^* U_{\mu 4} U_{e5} U_{\mu 5}^*)$ differentiates between ν (MB) from $\bar\nu$ (MB/LSND);
- however, (3+2) models suffer from **the same APP/DIS tension** as (3+1) models;
- also, (3+2) models have stronger problems with cosmology since $\sum m_\nu$ is larger;

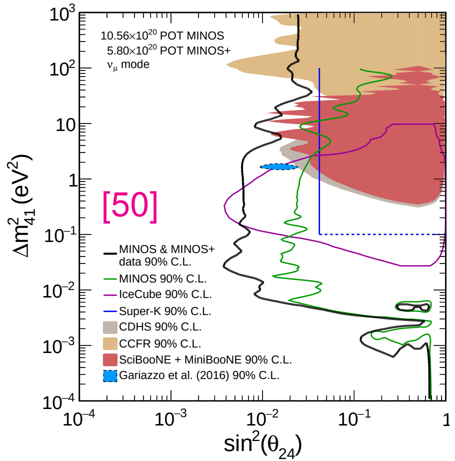
⇒ (3+N) models **do not present substantial advantages** over the simpler (3+1) model.

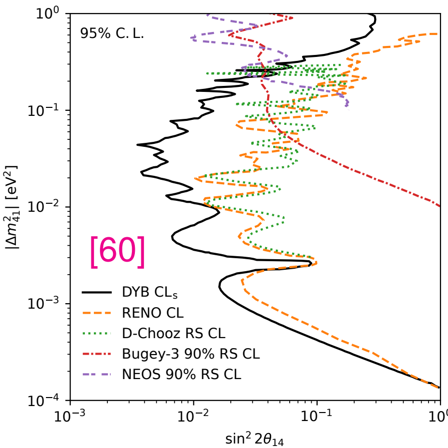
[59] M. Maltoni, T. Schwetz, Phys. Rev. **D76** (2007) 093005 [arXiv:0705.0107]

General bounds on sterile neutrinos

- Reactors & accelerator: weak matter effects ⇒ mass window determined by baseline;
- experiments with near & far detectors reach max sensitivity between the two scales, but drop considerably when oscillations become averaged at both sites;
- atmospheric: important contributions to sensitivity from resonant conversion in matter.



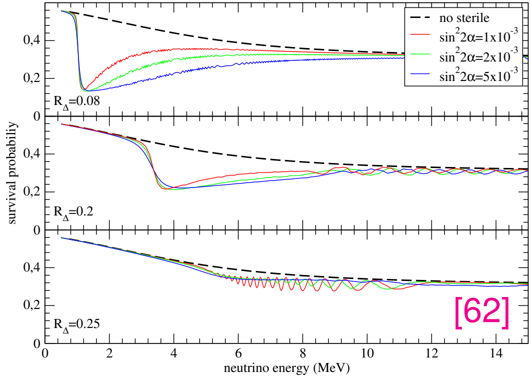


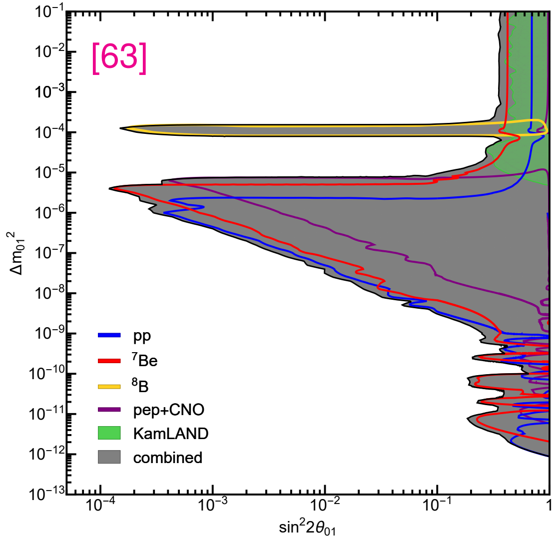


[49] R. Abbasi *et al.* [IceCube], Phys. Rev. Lett. **133** (2024) 201804 [arXiv:2405.08070]
[50] P. Adamson *et al.* [MINOS+], Phys. Rev. Lett. **122** (2019) no.9, 091803 [arXiv:1710.06488]
[60] F.P. An *et al.* [Daya Bay], Phys. Rev. Lett. **133** (2024) 051801 [arXiv:2404.01687]

Sterile neutrinos and solar data

- Notation: $\vec{\nu} = (\nu_s, \nu_e, \nu_\mu, \nu_\tau)$, $\vec{\nu}_{\text{mb}} = (\nu_0, \nu_1, \nu_2, \nu_3)$, $D_{\text{vac}} \propto \textbf{diag}\left(\Delta m^2_{01}, 0, \Delta m^2_{21}, \Delta m^2_{31}\right)$, $\boldsymbol{U} \equiv \boldsymbol{U}_{\text{SM}} \boldsymbol{R}^{\alpha}_{01}$;
- as noted in [61], a sterile with $R_\Delta \equiv \Delta m^2_{01} / \Delta m^2_{21} \sim 0.2$ and small mixing α modifies the vacuum-matter transition $\Rightarrow$ explain why low-E turn-up not so prominent;
- for very small values of Δm^2_{01}, the oscillation length becomes larger than Earth eccentricity, and then comparable with the Sun-Earth distance;
- excluded region determined by a number of different phenomena, and exhibits a rich phenomenology.





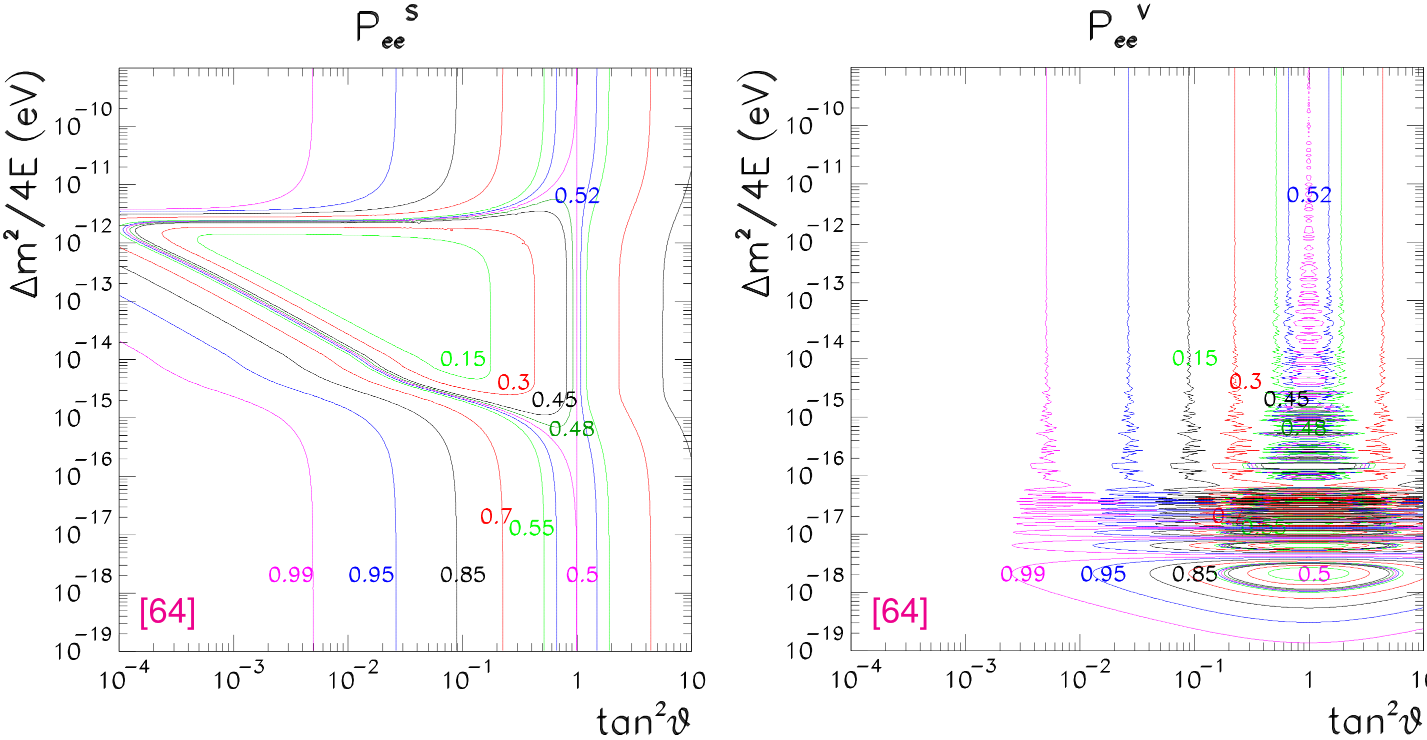
[61] P.C. de Holanda and A.Yu. Smirnov, Phys. Rev. D **69** (2004) 113002 [hep-ph/0307266]

[62] P.C. de Holanda and A.Yu. Smirnov, Phys. Rev. D **83** (2011) 113011 [arXiv:1012.5627]

[63] Z. Chen, J. Liao, J. Ling and B. Yue, JHEP **09** (2022) 004 [arXiv:2205.07574]

Connection with two-neutrino solar oscillations

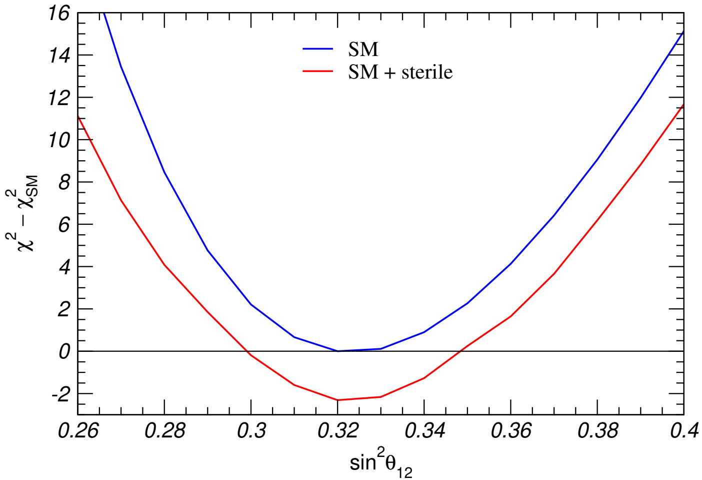
- The sterile bounds shows the same features as old-times pure-2ν ($\theta_{13} = 0$) solar studies.

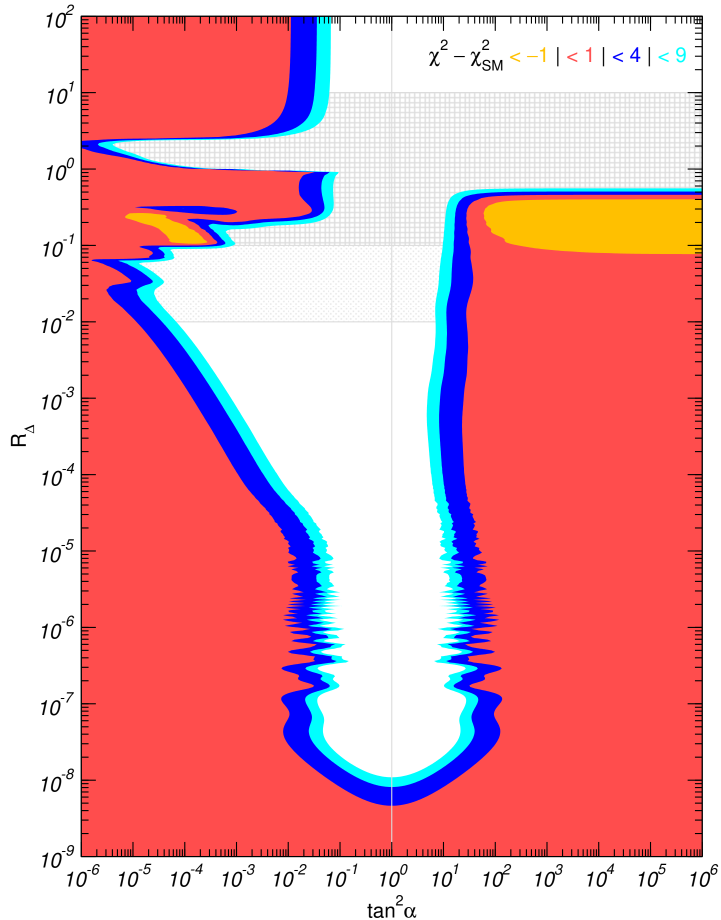


[64] C. Peña-Garay, Master's thesis, University of Valencia (Spain), 2001.

Bounds from current solar data

- Warning: we set $\Delta m^2_{21} = 7.5 \times 10^{-5}$ eV^2:
  - outside gray bands: KL fixes Δm^2_{21};
  - light band: KL fixes $\Delta m^2_{ee} \sim \Delta m^2_{21}$;
  - dark band: allowed OK, excluded not;
- orange regions: slighly better than SM;
- θ_{12} range moslty unaffected by steriles.





- 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 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.

Neutrino interactions in the Standard Model

- Effective low-energy Lagrangian for **standard** neutrino interactions with matter:

$$\mathcal{L}_{\text{SM}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{f,\beta} \left([\bar{\nu}_\beta \gamma_\mu P_L \ell_\beta][\bar{f}\gamma^\mu P_L f'] + \text{h.c.} \right) - 2\sqrt{2}G_F \sum_{f,P,\beta} g_P^f [\bar{\nu}_\beta \gamma_\mu P_L \nu_\beta][\bar{f}\gamma^\mu P f]$$

where $P \in \{P_L, P_R\}$, (f, f') form an SU(2) doublet, and g_P^f is the Z coupling to fermion f:

$$g_L^\nu = \frac{1}{2}, \qquad g_L^\ell = \sin^2\theta_W - \frac{1}{2}, \qquad g_L^u = -\frac{2}{3}\sin^2\theta_W + \frac{1}{2}, \qquad g_L^d = \frac{1}{3}\sin^2\theta_W - \frac{1}{2},$$

$$g_R^\nu = 0, \qquad g_R^\ell = \sin^2\theta_W, \qquad g_R^u = -\frac{2}{3}\sin^2\theta_W, \qquad g_R^d = \frac{1}{3}\sin^2\theta_W;$$

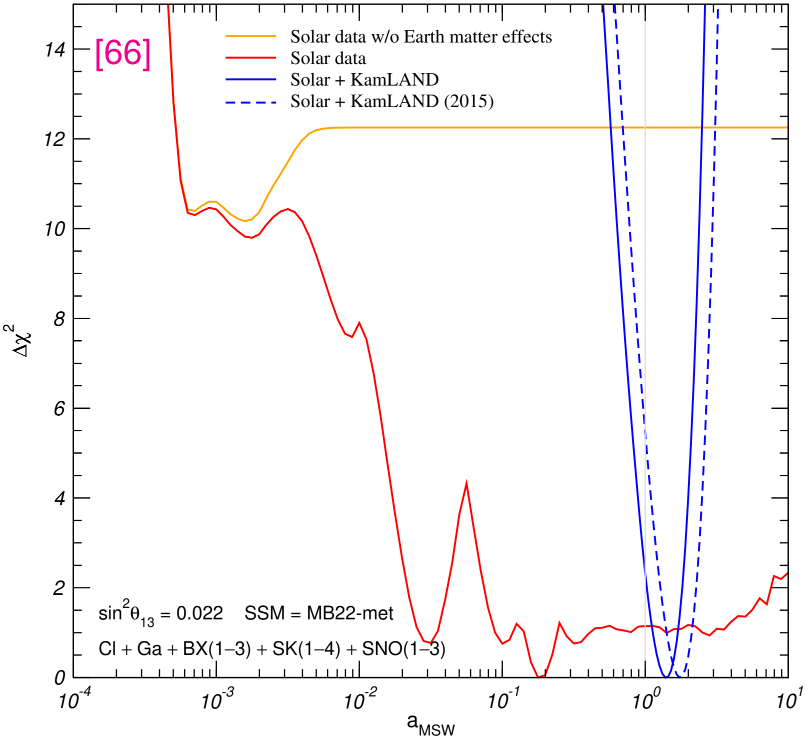
- this form of the Lagrangian and expressions for the couplings lead to:
  - matter potentials: $V_{\text{CC}} = \sqrt{2}\, G_F\, N_e\, \mathbf{diag}(1, 0, 0)$ and $V_{\text{NC}} = -\sqrt{2}\big/2\, G_F\, N_n\, \mathbf{diag}(1, 1, 1)$;
  - the usual neutrino cross-sections, in particular the *neutrino-electron elastic scattering*

$$\frac{d\sigma_\beta^{\text{SM}}}{dT_e}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi} \left\{ c_{L\beta}^2 \left[1 + \frac{\alpha}{\pi} f_-(y)\right] + c_{R\beta}^2 (1-y)^2 \left[1 + \frac{\alpha}{\pi} f_+(y)\right] - 2\, c_{L\beta}\, c_{R\beta} \frac{m_e y}{2E_\nu} \left[1 + \frac{\alpha}{\pi} f_\pm(y)\right] \right\}$$

where $c_{Le} = g_L^\ell + 1$, $c_{L\mu} = c_{L\tau} = g_L^\ell$, and $c_{Re} = c_{R\mu} = c_{R\tau} = g_R^\ell$ (at tree level). Here f_+, f_-, $f_\pm$ are loop functions and $y \equiv T_e / E_\nu$. We will return on this later.

Non-standard neutrino interactions: a first example

- Ref. [65]: is solar MSW as expected?
- model: $V_e \to a_{\text{MSW}} V_e$ (a kind of NSI);
- Sun: lots of matter, yet no bound as:
  - P invariant if Δm^2 & L also scaled;
  - MSW regime insensitive to L;
- including Earth D/N effects set a scale for L, but a_{MSW} still unconstrained;
- KamLAND: almost no matter, thus no sensitivity to a_{MSW}, but fixes Δm^2;
- together: $0.67 < a_{\text{MSW}} < 2.32$ at 3σ;
- in brief: { – **degeneracies** arise; – **synergies** solve them.



[65] G. L. Fogli, E. Lisi, A. Marrone, A. Palazzo, Phys. Lett. B **583** (2004) 149 [hep-ph/0309100]
[66] M. Maltoni, A. Yu. Smirnov, Eur. Phys. J. A **52** (2016) 87 [arXiv:1507.05287]

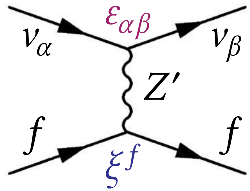
Non-standard neutrino interactions: general formalism

- Let us extend the SM by a NC-like **non-standard** neutrino-matter term:

$$\mathscr{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \sum_{f,P,\alpha,\beta} \varepsilon_{\alpha\beta}^{fP} [\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta][\bar{f}\gamma^\mu P f];$$

  where $P \in \{P_L, P_R\}$ and $f \in \{e, u, d\}$ is a fermion present in ordinary matter;
- however, most general parameter space too large to handle $\Rightarrow$ simplifications needed;
- here we assume that the ν flavor structure is **independent** of the charged fermion type:

$$\varepsilon_{\alpha\beta}^{fP} \equiv \varepsilon_{\alpha\beta}\, \xi^f \chi^P, \quad \Rightarrow \quad \mathscr{L}_{\text{NSI}}^{\text{eff}} = -2\sqrt{2}G_F \Big[\sum_{\alpha,\beta} \varepsilon_{\alpha\beta} (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta) \Big] \Big[\sum_{fP} \xi^f \chi^P (\bar{f}\gamma_\mu P f) \Big];$$



- quarks always confined inside nucleons $\Rightarrow$ introduce effective couplings:

$$\xi^p = 2\xi^u + \xi^d, \qquad \xi^n = 2\xi^d + 2\xi^u;$$

- length of $\vec{\xi} \equiv (\xi^e, \xi^p, \xi^n)$ degenerate with $|\varepsilon_{\alpha\beta}| \Rightarrow$ fix $|\vec{\xi}| = \sqrt{5} \Rightarrow$ half-sphere;
- strenght of various effects (matter potential, scattering, ...) controlled by mediator mass $m_{Z'}$ [67].

[67] Y. Farzan, Phys. Lett. B **748** (2015) 311 [arXiv:1505.06906]

Non-standard neutrino interactions: propagation effects

- Typical oscillation length $\gg$ km $\Rightarrow$ contact-interaction regime for $m_{Z'} \gg 10^{-11}$ eV;
- most neutrino detection occur through CC interactions $\Rightarrow$ unaffected by our NC-like NSI;
- some experiments sensitive to elastic scattering $\Rightarrow$ affected by NC-like NSI with e, but effects suppressed for $m_{Z'} \ll \mathcal{O}(500\ \text{keV})$ [Borexino] or $m_{Z'} \ll \mathcal{O}(5{-}10\ \text{MeV})$ [SK, SNO];
- hence, for a large range of $m_{Z'}$, our NC-like NSI only manifest themselves in ν propagation;
- matter potential sensitive to vector couplings $\Rightarrow$ only $\chi^V \equiv \chi^L + \chi^R$ combination relevant;
- NSI effects controlled by fermion $N_f(\vec{x})$, but matter neutrality implies $N_e(\vec{x}) = N_p(\vec{x})$, hence:

$$V_{\text{NSI}} \propto \sum_f N_f(\vec{x})\, \varepsilon_{\alpha\beta}^{fV} = \varepsilon_{\alpha\beta}\, \chi^V \sum_f N_f(\vec{x})\, \xi^f = \varepsilon_{\alpha\beta}\, \chi^V \left[N_{e=p}(\vec{x}) \left(\xi^e + \xi^p \right) + N_n(\vec{x})\, \xi^n \right];$$

- only the direction in the $(\xi^e + \xi^p,\ \xi^n)$ plane probed by ν oscillations $\Rightarrow$ define an angle η':

$$\xi^e + \xi^p \equiv \sqrt{5}\, \mathcal{N} \cos\eta', \quad \xi^n \equiv \sqrt{5}\, \mathcal{N} \sin\eta', \quad \varepsilon'_{\alpha\beta} \equiv \mathcal{N}\, \varepsilon_{\alpha\beta} \text{ with } \mathcal{N} \equiv \left| (\xi^e + \xi^p,\ \xi^n) \right| \big/ \left| \vec{\xi} \right|;$$

- special cases: $\eta' = \pm 90^\circ\ (n)$, $\eta' = 0\ (p + e)$, $\eta' \approx 26.6^\circ\ (u)$, $\eta' \approx 63.4^\circ\ (d)$.

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI-ν) + **1** (NSI-f) = **15** parameters [68]:

$$i\frac{d\vec{\nu}}{dt} = \boldsymbol{H}\,\vec{\nu}; \qquad \boldsymbol{H} = \boldsymbol{U}_{\text{vac}} \cdot \boldsymbol{D}_{\text{vac}} \cdot \boldsymbol{U}_{\text{vac}}^{\dagger} \pm \boldsymbol{V}_{\text{mat}}; \qquad \boldsymbol{D}_{\text{vac}} = \frac{1}{2E_\nu}\,\mathbf{diag}\left(0,\ \Delta m^2_{21},\ \Delta m^2_{31}\right);$$

$$\boldsymbol{U}_{\text{vac}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12}\,e^{i\delta_{\text{CP}}} & 0 \\ -s_{12}\,e^{-i\delta_{\text{CP}}} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \qquad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix},$$

$$\mathcal{E}_{\alpha\beta}(\vec{x}) \equiv \sum_f \frac{N_f(\vec{x})}{N_e(\vec{x})}\,\varepsilon^{fV}_{\alpha\beta} = \sqrt{5}\,\varepsilon'_{\alpha\beta}\,\chi^V\left[\cos\eta' + Y_n(\vec{x})\sin\eta'\right], \qquad Y_n(\vec{x}) \equiv \frac{N_n(\vec{x})}{N_e(\vec{x})},$$

$$\boldsymbol{V}_{\text{mat}} \equiv \boldsymbol{V}_{\text{SM}} + \boldsymbol{V}_{\text{NSI}} = \sqrt{2}G_F N_e(\vec{x}) \begin{pmatrix} 1 + \mathcal{E}_{ee}(\vec{x}) & \mathcal{E}_{e\mu}(\vec{x}) & \mathcal{E}_{e\tau}(\vec{x}) \\ \mathcal{E}^\star_{e\mu}(\vec{x}) & \mathcal{E}_{\mu\mu}(\vec{x}) & \mathcal{E}_{\mu\tau}(\vec{x}) \\ \mathcal{E}^\star_{e\tau}(\vec{x}) & \mathcal{E}^\star_{\mu\tau}(\vec{x}) & \mathcal{E}_{\tau\tau}(\vec{x}) \end{pmatrix};$$

- notice that our definition of $\boldsymbol{U}_{\text{vac}}$ differ by the "usual" one by an overall rephasing, $\boldsymbol{U}_{\text{vac}} = \boldsymbol{\Phi} \cdot \boldsymbol{U} \cdot \boldsymbol{\Phi}^\star$ with $\boldsymbol{\Phi} \equiv \mathbf{diag}\left(e^{i\delta_{\text{CP}}}, 1, 1\right)$, which is irrelevant in the standard case of no-NSI.

[68] I. Esteban *et al.*, JHEP **08** (2018) 180 [arXiv:1805.04530]

The generalized mass ordering degeneracy

- General symmetry: $\boldsymbol{H} \to -\boldsymbol{H}^\star$ does not affect the neutrino probabilities;
- we have $\boldsymbol{H} = \boldsymbol{H}_\text{vac} \pm \boldsymbol{V}_\text{mat}$. For vacuum, $\boldsymbol{H}_\text{vac} \to -\boldsymbol{H}_\text{vac}^\star$ occurs if: $\begin{cases} \Delta m^2_{31} \to -\Delta m^2_{32}\,, \\ \theta_{12} \to \pi/2 - \theta_{12}\,, \\ \delta_\text{CP} \to \pi - \delta_\text{CP}\,, \end{cases}$
- notice how this transformation links together mass ordering and solar octant [69, 70, 71];
- for matter, $\boldsymbol{V}_\text{mat} \to -\boldsymbol{V}_\text{mat}^\star$ requires: $\begin{cases} \left[\mathcal{E}_{ee}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right] \to -\left[\mathcal{E}_{ee}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right] - 2\,, \\ \left[\mathcal{E}_{\tau\tau}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right] \to -\left[\mathcal{E}_{\tau\tau}(\vec{x}) - \mathcal{E}_{\mu\mu}(\vec{x})\right]\,, \\ \mathcal{E}_{\alpha\beta}(\vec{x}) \to -\mathcal{E}_{\alpha\beta}^\star(\vec{x}) \qquad (\alpha \neq \beta)\,, \end{cases}$
- since $\boldsymbol{V}_\text{mat} = \boldsymbol{V}_\text{SM} + \boldsymbol{V}_\text{NSI}$ and $\boldsymbol{V}_\text{SM}$ is fixed, this symmetry requires NSI;
- in general, $\mathcal{E}_{\alpha\beta}(\vec{x})$ varies along trajectory $\Rightarrow$ symmetry only approximate, **unless**:
  - NSI proportional to electric charge ($\eta' = 0$), so same matter profile for SM and NSI;
  - neutron/proton ratio $Y_n(\vec{x})$ is constant, and same for all the neutrino trajectories.

[69] M.C. Gonzalez-Garcia, M. Maltoni, JHEP **09** (2013) 152 [arXiv:1307.3092]
[70] P. Bakhti, Y. Farzan, JHEP **07** (2014) 064 [arXiv:1403.0744]
[71] P. Coloma, T. Schwetz, Phys. Rev. D **94** (2016) 055005 [arXiv:1604.05772]

Matter potential for solar and KamLAND neutrinos

- One mass dominance ($\Delta m^2_{31} \to \infty$) $\Rightarrow$ $P_{ee} = c_{13}^4 P_{\text{eff}} + s_{13}^4$ with the probability P_{eff} determined by an effective 2ν model (as in the SM):

$$i\frac{d\vec{\nu}}{dt} = \left[\boldsymbol{H}^{\text{eff}}_{\text{vac}} + \boldsymbol{H}^{\text{eff}}_{\text{mat}}\right]\vec{\nu}, \qquad \vec{\nu} = \begin{pmatrix}\nu_e \\ \nu_a\end{pmatrix}, \qquad \boldsymbol{H}^{\text{eff}}_{\text{vac}} \equiv \frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix}-\cos 2\theta_{12} & \sin 2\theta_{12}\, e^{i\delta_{\text{CP}}} \\ \sin 2\theta_{12}\, e^{-i\delta_{\text{CP}}} & \cos 2\theta_{12}\end{pmatrix},$$

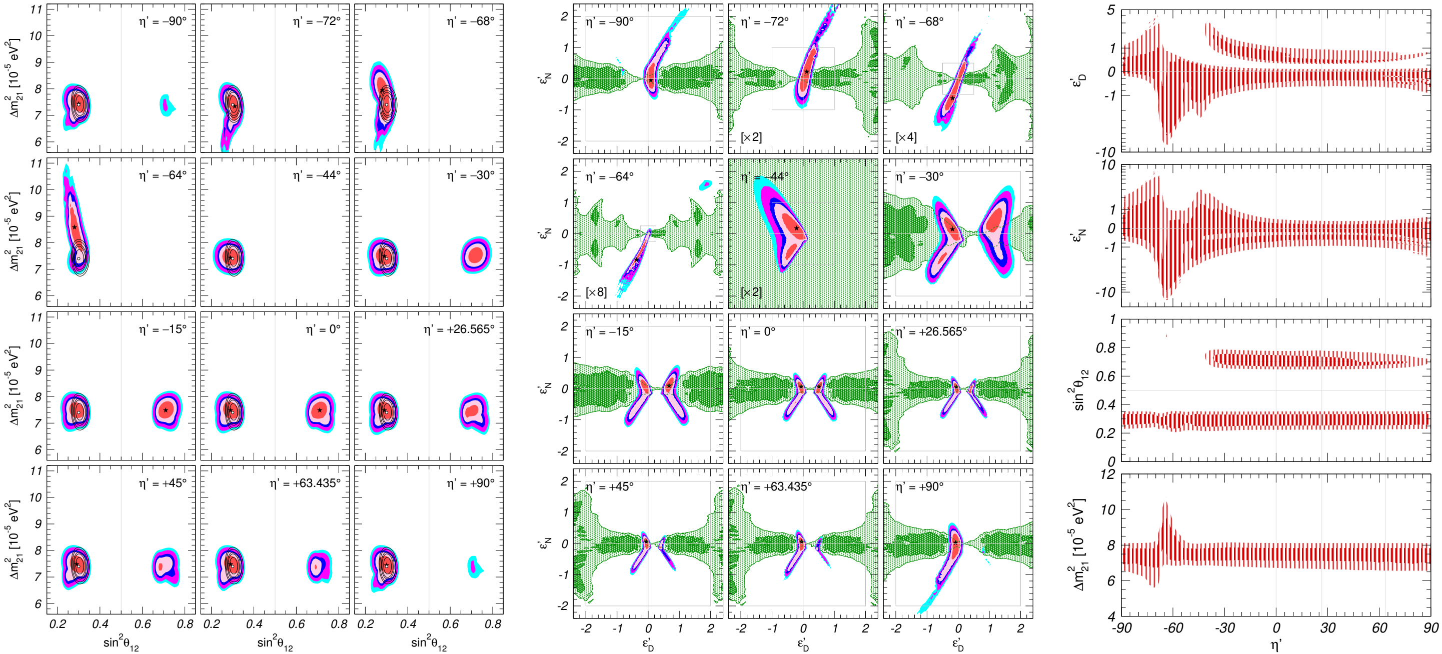
$$\boldsymbol{H}^{\text{eff}}_{\text{mat}} \equiv \sqrt{2}\, G_F N_e(\vec{x}) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0\end{pmatrix} + \sqrt{5}\,\chi^V \left[\cos\eta' + Y_n(\vec{x})\sin\eta'\right]\begin{pmatrix}-\varepsilon'_D & \varepsilon'_N \\ \varepsilon'^{\star}_N & \varepsilon'_D\end{pmatrix}\right],$$

$$\begin{cases} \varepsilon'_D = c_{13}s_{13}\,\text{Re}\big(s_{23}\,\varepsilon'_{e\mu} + c_{23}\,\varepsilon'_{e\tau}\big) - \big(1 + s_{13}^2\big)c_{23}s_{23}\,\text{Re}\big(\varepsilon'_{\mu\tau}\big) \\ \qquad\quad - c_{13}^2\big(\varepsilon'_{ee} - \varepsilon'_{\mu\mu}\big)\big/\,2 + \big(s_{23}^2 - s_{13}^2 c_{23}^2\big)\big(\varepsilon'_{\tau\tau} - \varepsilon'_{\mu\mu}\big)\big/\,2\,, \\ \varepsilon'_N = c_{13}\big(c_{23}\,\varepsilon'_{e\mu} - s_{23}\,\varepsilon'_{e\tau}\big) + s_{13}\Big[s_{23}^2\,\varepsilon'_{\mu\tau} - c_{23}^2\,\varepsilon'^{\star}_{\mu\tau} + c_{23}s_{23}\big(\varepsilon'_{\tau\tau} - \varepsilon'_{\mu\mu}\big)\Big]; \end{cases}$$

- solar data can be perfectly fitted by NSI only $\Rightarrow$ solar LMA solution **is unstable** with respect to the introduction of NSI;
- KamLAND **requires** Δm^2_{21} but only weakly sensitive to NSI $\Rightarrow$ it **determines** Δm^2_{21};
- in the solar core $Y_n(\vec{x}) \in [1/6, 1/2]$ $\Rightarrow$ approximate cancellation of NSI for $\eta' \in [-80^\circ, -63^\circ]$.

Oscillation results for solar and KamLAND neutrinos

- Generalized mass-ordering degeneracy $\Rightarrow$ new LMA-D solution with $\theta_{12} > 45^\circ$ [72];
- $\eta' = 0 \Rightarrow$ NSI terms proportional to $N_p(\vec{x}) \equiv N_e(\vec{x}) \Rightarrow$ the degeneracy becomes exact.



[72] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280]

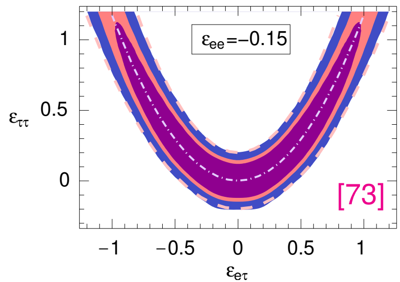
Matter potential for atmospheric and long-baseline neutrinos

- In Earth matter: $Y_n(\vec{x}) \to Y_n^\oplus \approx 1.051 \Rightarrow \mathcal{E}_{\alpha\beta}(\vec{x}) \to \varepsilon_{\alpha\beta}^\oplus$ becomes an effective parameter:

$$\varepsilon_{\alpha\beta}^\oplus \equiv \sqrt{5}\left[\cos\eta' + Y_n^\oplus \sin\eta'\right] \varepsilon'_{\alpha\beta} ,$$

- the bounds on $\varepsilon_{\alpha\beta}^\oplus$ are independent of the fermion couplings (*i.e.*, of η');
- for $\eta' = \arctan(-1/Y_n^\oplus) \approx -43.6^\circ$ ATM+LBL data imply **no** bound on $\varepsilon'_{\alpha\beta}$;
- the NSI parameter space is too big to be properly studied $\Rightarrow$ simplification needed;
- bounds on $\varepsilon_{\alpha\beta}^\oplus$ are weakest when $V_{\text{mat}} \propto \delta_{e\alpha}\delta_{e\beta} + \varepsilon_{\alpha\beta}^\oplus$ has two degenerate eigenvalues [73] $\Rightarrow$ focus on such case $\Rightarrow$ introduce parameters ($\varepsilon_\oplus$, φ_{12}, φ_{13}, α_1, α_2) and define:

$$\begin{aligned}
\varepsilon_{ee}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \varepsilon_\oplus \left(\cos^2\varphi_{12} - \sin^2\varphi_{12}\right)\cos^2\varphi_{13} - 1 ,\\
\varepsilon_{\tau\tau}^\oplus - \varepsilon_{\mu\mu}^\oplus &= \varepsilon_\oplus \left(\sin^2\varphi_{13} - \sin^2\varphi_{12}\cos^2\varphi_{13}\right) ,\\
\varepsilon_{e\mu}^\oplus &= -\varepsilon_\oplus \cos\varphi_{12}\sin\varphi_{12}\cos^2\varphi_{13}\, e^{i(\alpha_1-\alpha_2)} ,\\
\varepsilon_{e\tau}^\oplus &= -\varepsilon_\oplus \cos\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}\, e^{i(2\alpha_1+\alpha_2)} ,\\
\varepsilon_{\mu\tau}^\oplus &= \varepsilon_\oplus \sin\varphi_{12}\cos\varphi_{13}\sin\varphi_{13}\, e^{i(\alpha_1+2\alpha_2)} .
\end{aligned}$$

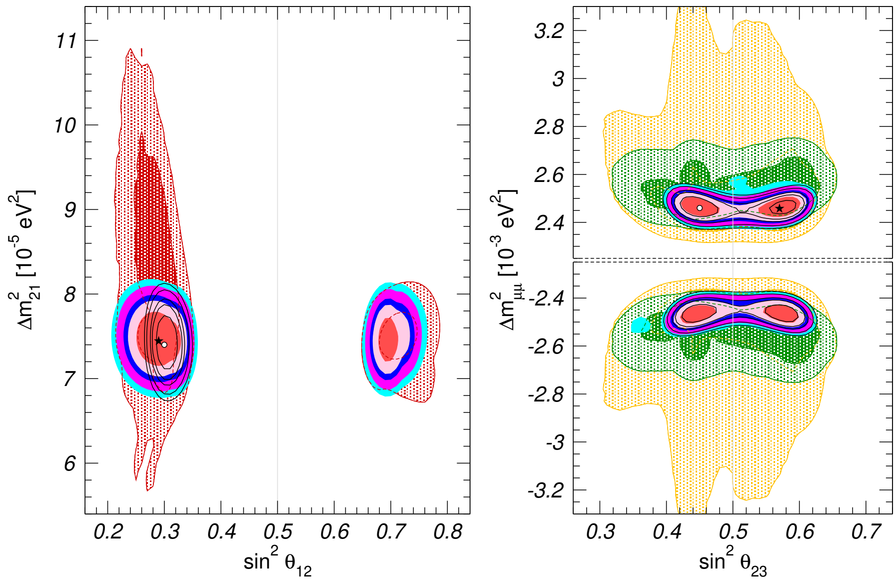


- for definiteness we also assume on CP conservation and set $\delta_{\text{CP}} = \alpha_1 = \alpha_2 = 0$.

[73] A. Friedland, C. Lunardini, M. Maltoni, Phys. Rev. D **70** (2004) 111301 [hep-ph/0408264]

Impact of NSI on the oscillation parameters

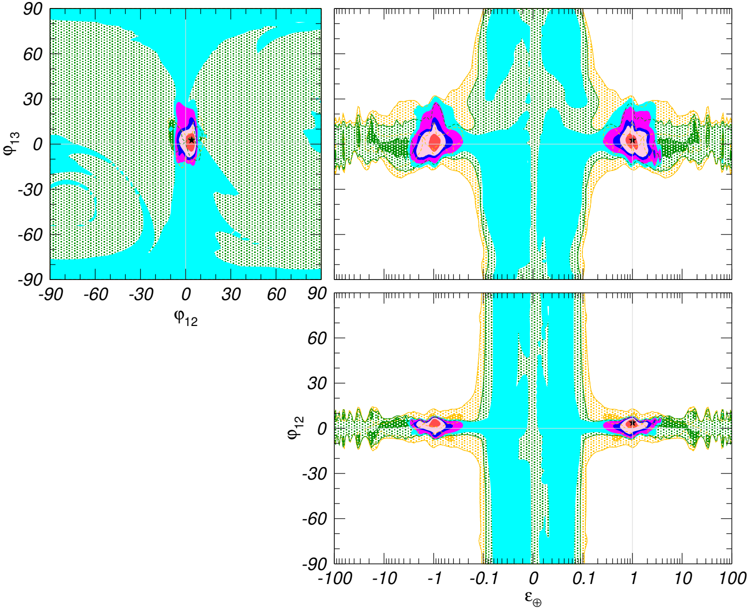
- Once marginalized over η', analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}, as well as the appearance of the LMA-D solution [72];
- a similar worsening appears in ATM + LBL-dis + LBL-app + IceCUBE + MBL-rea analysis;
- synergies between solar and atmospheric sectors allow to recover the SM accuracy on most parameters (except θ_{12});
- notice that the LMA-D solution persists also in the global fit;
- high-energy atmos. IceCUBE data have no sensitivity to oscillations ($P_{\mu\mu} \propto 1/E^2$), hence they contribute little.

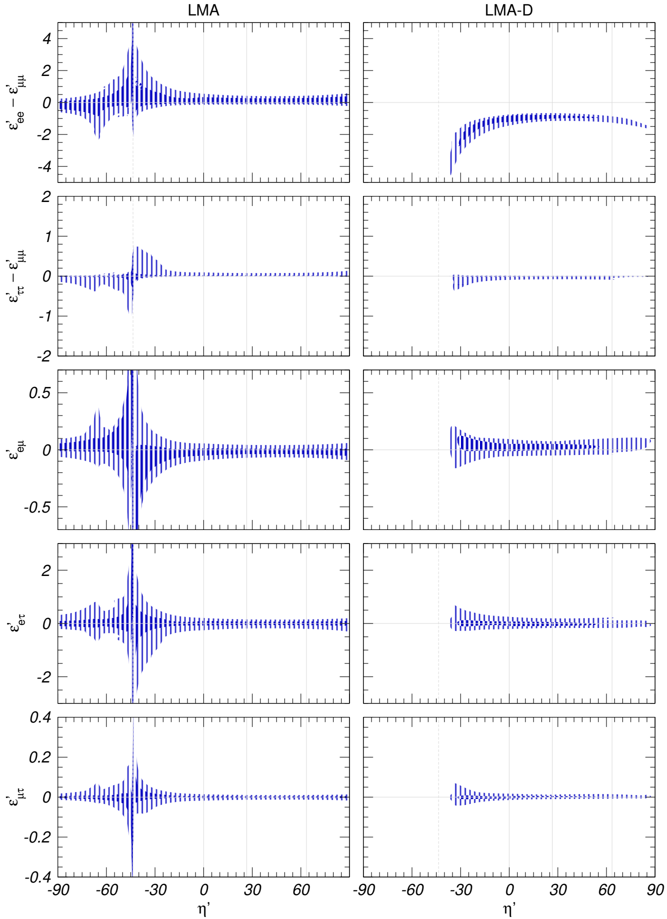


[72] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280]

Determination of NSI parameters

- Reduced ($\varepsilon_\oplus$, φ_{12}, φ_{13}) parameter space can be constrained by joint solar+KamLAND and ATM+LBL analysis;
- bounds can then be recast in term of $\varepsilon'_{\alpha\beta}$.





Non-standard interactions with electrons: formalism

- Let's focus on solar ν and assume $m_{Z'} \gtrsim \mathcal{O}(\text{MeV})$. In the presence of NC-like NSI with e, elastic scattering is modified $\Rightarrow$ detection process (SK, SNO, Borexino) is affected;
- in the SM, ν interactions (both CC and NC) are diagonal in the flavor basis. Hence:

$$N_{\text{ev}} \propto \sum_\beta P_{e\beta}\, \sigma_\beta^{\text{SM}} \quad \text{with} \quad P_{e\beta} \equiv |S_{\beta e}|^2 \quad (\nu_e \to \nu_\beta \text{ transition probabilities})$$

- this expression is only valid in the flavor basis. Unitary rotation $\boldsymbol{U} \Rightarrow$ arbitrary basis:

$$S_{\beta e} = \sum_i U_{\beta i}\, S_{ie} \quad \Rightarrow \quad P_{e\beta} = \sum_{ij} U_{\beta i}\, \rho_{ij}^{(e)}\, U_{j\beta}^\dagger \quad \text{with} \quad \rho_{ij}^{(e)} \equiv S_{ie}\, S_{ej}^\dagger = \left[\boldsymbol{S}\, \boldsymbol{\Pi}^{(e)}\, \boldsymbol{S}^\dagger\right]_{ij}$$

- where $\boldsymbol{\rho}^{(e)}$ is the ν density matrix at the detector (for a ν_e at the source). Substituting:

$$N_{\text{ev}} \propto \sum_{ij} \rho_{ij}^{(e)} \sum_\beta U_{j\beta}^\dagger\, \sigma_\beta^{\text{SM}}\, U_{\beta i} = \boxed{\text{Tr}\left[\boldsymbol{\rho}^{(e)}\, \boldsymbol{\sigma}^{\text{SM}}\right]} \quad \text{with} \quad \sigma_{ji}^{\text{SM}} \equiv \left[\boldsymbol{U}^\dagger \textbf{diag}\left\{\sigma_\beta^{\text{SM}}\right\} \boldsymbol{U}\right]_{ji};$$

- here $\boldsymbol{\sigma}^{\text{SM}}$ is a matrix in flavor space, containing enough information to describe the ES interaction of *any* neutrino state without the need to explicitly project it onto the interaction eigenstates: such projection is now implicitly encoded into $\boldsymbol{\sigma}^{\text{SM}}$.

Neutrino-electron cross-section in the presence of NSI

- In the presence of flavor-changing NSI, the SM flavor basis no longer coincides with the interaction eigenstates. Hence, the general formula $N_{\text{ev}} \propto \mathrm{Tr}\left[\boldsymbol{\rho}^{(e)}\, \boldsymbol{\sigma}^{\text{NSI}}\right]$ must be used;
- the cross-section matrix $\boldsymbol{\sigma}^{\text{NSI}}$ is the integral over T_e of the following expression:

$$\frac{\mathrm{d}\boldsymbol{\sigma}^{\text{NSI}}}{\mathrm{d}T_e}(E_\nu, T_e) = \frac{2G_F^2 m_e}{\pi}\left\{ C_L^2 \left[1 + \frac{\alpha}{\pi} f_-(y)\right] + C_R^2 (1-y)^2 \left[1 + \frac{\alpha}{\pi} f_+(y)\right] - \left\{C_L, C_R\right\} \frac{m_e y}{2E_\nu}\left[1 + \frac{\alpha}{\pi} f_\pm(y)\right]\right\}$$

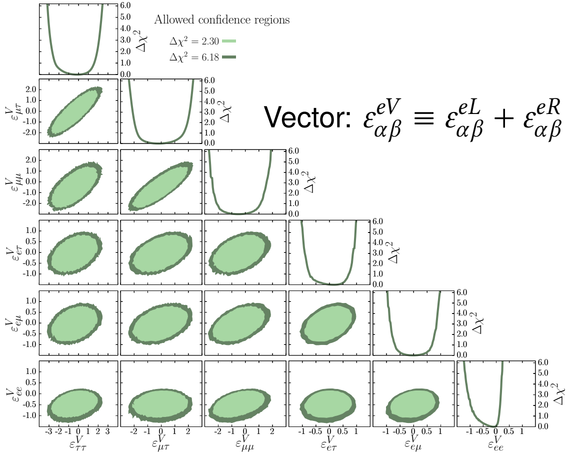
where f_+, f_-, $f_\pm$ are loop functions, $y \equiv T_e / E_\nu$, and C_L, C_R are 3×3 hermitian matrices:

$$\begin{cases} C^L_{\alpha\beta} \equiv c_{L\beta}\, \delta_{\alpha\beta} + \varepsilon^{eL}_{\alpha\beta} \\ C^R_{\alpha\beta} \equiv c_{L\beta}\, \delta_{\alpha\beta} + \varepsilon^{Re}_{\alpha\beta} \end{cases} \quad \text{with} \quad \begin{cases} c_{L\tau} = c_{L\mu} = g^\ell_L \quad \text{and} \quad c_{Le} = g^\ell_L + 1\,, \\ c_{R\tau} = c_{R\mu} = c_{Re} = g^\ell_R \quad \text{(at tree level)}\,; \end{cases}$$

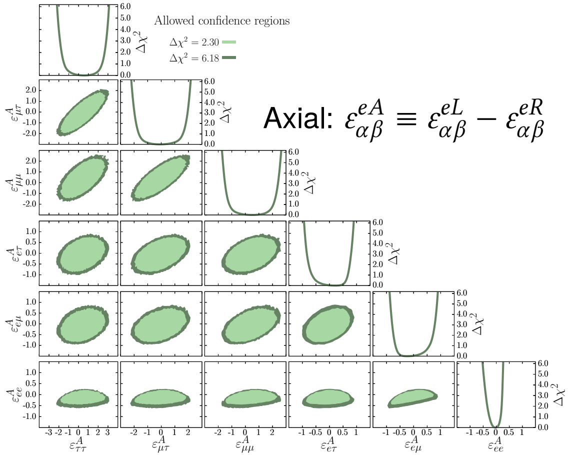
- when the NSI terms $\varepsilon^{eL}_{\alpha\beta}$ and $\varepsilon^{eR}_{\alpha\beta}$ are set to zero, the matrix $\mathrm{d}\boldsymbol{\sigma}^{\text{NSI}} / \mathrm{d}T_e$ becomes diagonal and the SM expressions are recovered;
- the cross section for antineutrinos can be obtained by interchanging $C_L \leftrightarrow C_R^\star$;
- NSI effects on neutrino propagation are the same as in the previous section (with $\eta' = 0$ for $\xi^p = \xi^n = 0$) and are accounted by the density matrix $\boldsymbol{\rho}^{(e)}$.

Bounds on NSI-e from Borexino

- $m_{Z'} \gtrsim \mathcal{O}(500\text{ keV}) \Rightarrow$ Borexino sensitive to NSI-e;
- Ref. [74]: { – only diagonal NSI considered; – only 1 or 2 NSI varied at-a-time;
- in [75] we studied the general case. We found:
  - degeneracies strongly weakens the bounds;
  - yet a definite $\mathcal{O}(1)$ bound is always found.



	Allowed regions at 90% CL ($\Delta\chi^2 = 2.71$)			
	Vector		Axial Vector	
	1 Parameter	Marginalized	1 Parameter	Marginalized
ε_{ee}	$[-0.09, +0.14]$	$[-1.05, +0.17]$	$[-0.05, +0.10]$	$[-0.38, +0.24]$
$\varepsilon_{\mu\mu}$	$[-0.51, +0.35]$	$[-2.38, +1.54]$	$[-0.29, +0.19] \oplus [+0.68, +1.45]$	$[-1.47, +2.37]$
$\varepsilon_{\tau\tau}$	$[-0.66, +0.52]$	$[-2.85, +2.04]$	$[-0.40, +0.36] \oplus [+0.69, +1.44]$	$[-1.82, +2.81]$
$\varepsilon_{e\mu}$	$[-0.34, +0.61]$	$[-0.83, +0.84]$	$[-0.30, +0.43]$	$[-0.79, +0.76]$
$\varepsilon_{e\tau}$	$[-0.48, +0.47]$	$[-0.90, +0.85]$	$[-0.40, +0.38]$	$[-0.81, +0.78]$
$\varepsilon_{\mu\tau}$	$[-0.25, +0.36]$	$[-2.07, +2.06]$	$[-1.10, -0.75] \oplus [-0.13, +0.22]$	$[-1.95, +1.91]$

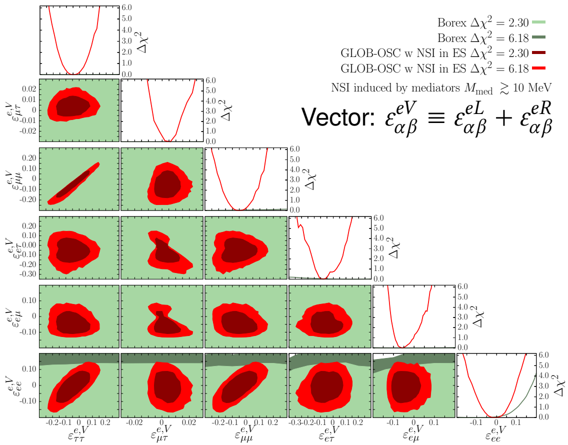


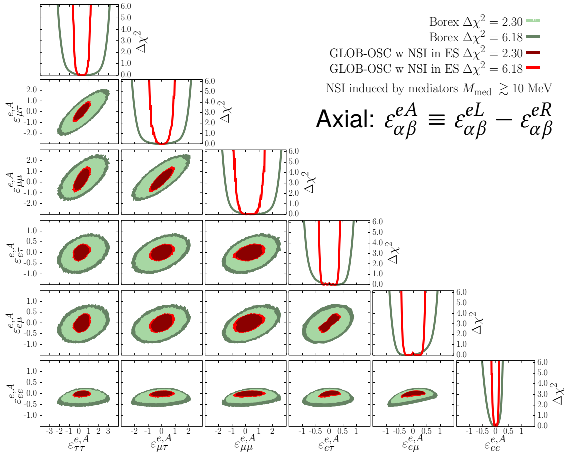
[74] Borexino coll., JHEP **02** (2020) 038 [arXiv:1905.03512]
[75] Coloma *et al.*, JHEP **07** (2022) 138 [arXiv:2204.03011]

Bounds on NSI-e from global data

- $m_{Z'} \gtrsim \mathcal{O}(10\text{ MeV}) \Rightarrow$ SK & SNO sensitive to NSI-e:
  - SK measures ES events with high statistics;
  - SNO determines the $^{8}\mathrm{B}$ flux accurately via NC;
- bounds from Borexino alone greatly enhanced [76];
- limits dominated by NSI contributions to the ES cross-section, which allow to derive separate bounds on diagonal $\varepsilon^{eV}_{\alpha\alpha}$ and $\varepsilon^{eA}_{\alpha\alpha}$ couplings.

	Allowed ranges at 90% CL (marginalized)			
	Vector ($X = V$)		Axial-vector ($X = A$)	
	Borexino	GLOB-OSC w NSI in ES	Borexino	GLOB-OSC w NSI in ES
$\varepsilon^{e,X}_{ee}$	$[-1.1, +0.17]$	$[-0.13, +0.10]$	$[-0.38, +0.24]$	$[-0.13, +0.11]$
$\varepsilon^{e,X}_{\mu\mu}$	$[-2.4, +1.5]$	$[-0.20, +0.10]$	$[-1.5, +2.4]$	$[-0.70, +1.2]$
$\varepsilon^{e,X}_{\tau\tau}$	$[-2.8, +2.1]$	$[-0.17, +0.093]$	$[-1.8, +2.8]$	$[-0.53, +1.0]$
$\varepsilon^{e,X}_{e\mu}$	$[-0.83, +0.84]$	$[-0.097, +0.011]$	$[-0.79, +0.76]$	$[-0.41, +0.40]$
$\varepsilon^{e,X}_{e\tau}$	$[-0.90, +0.85]$	$[-0.18, +0.080]$	$[-0.81, +0.78]$	$[-0.36, +0.36]$
$\varepsilon^{e,X}_{\mu\tau}$	$[-2.1, +2.1]$	$[-0.0063, +0.016]$	$[-1.9, +1.9]$	$[-0.79, +0.81]$





[76] Coloma *et al.*, JHEP **08** (2023) 032 [arXiv:2305.07698]

Neutrino-nucleus cross-section in the presence of NSI

- At $m_{Z'} \gtrsim \mathcal{O}(50\text{ MeV})$, coherent neutrino-nucleus scattering becomes senstive to NSI;
- the cross-section matrix $\boldsymbol{\sigma}^{\text{coh}}$ is the integral over the recoil energy of the nucleus E_R of:

$$\frac{\mathrm{d}\boldsymbol{\sigma}^{\text{coh}}}{\mathrm{d}E_R}(E_\nu, E_R) = \frac{G_F^2}{2\pi}\, \mathcal{Q}^2\, F^2(2m_A E_R)\, m_A\left(2 - \frac{m_A E_R}{E_\nu^2}\right)$$

where m_A is the nucleus' mass, $F(q^2)$ its nuclear form factor, and $\mathcal{Q}$ an hermitian matrix:

$$\mathcal{Q}_{\alpha\beta} = Z\left(g_V^p\, \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{pV}\right) + N\left(g_V^n\, \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{nV}\right);$$

- here g_V^p and g_V^n are the SM vector couplings to protons and neutrons. We can rewrite:

$$\mathcal{Q}_{\alpha\beta} = Z\left[(g_p^V + Y_n^{\text{coh}}\, g_n^V)\,\delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{\text{coh}}\right] \quad \text{with} \quad \varepsilon_{\alpha\beta}^{\text{coh}} \equiv \varepsilon_{\alpha\beta}^{pV} + Y_n^{\text{coh}}\, \varepsilon_{\alpha\beta}^{nV} \quad \text{and} \quad Y_n^{\text{coh}} \equiv N/Z\,;$$

- notice that only vector couplings matter, as for oscillations. Assuming factorization:

$$\varepsilon_{\alpha\beta}^{\text{coh}} = \varepsilon_{\alpha\beta}\, \chi^V\left(\xi^p + Y_n^{\text{coh}}\, \xi^n\right) = \sqrt{5}\, \varepsilon''_{\alpha\beta}\, \chi^V\left[\cos\eta'' + Y_n^{\text{coh}} \sin\eta''\right]$$

were we have used that only the direction η'' in the (ξ^p, ξ^n) plane is probed by coherent:

$$\xi^p \equiv \sqrt{5}\,\mathcal{N}\cos\eta''\,, \quad \xi^n \equiv \sqrt{5}\,\mathcal{N}\sin\eta''\,, \quad \varepsilon''_{\alpha\beta} \equiv \mathcal{N}\,\varepsilon_{\alpha\beta} \quad \text{with} \quad \mathcal{N} \equiv \left|(\xi^p, \xi^n)\right| / \left|\vec{\xi}\right|.$$

The COHERENT experiment

- Observation of coherent neutrino-nucleus scattering [77] allows to put bounds on vector NSI:

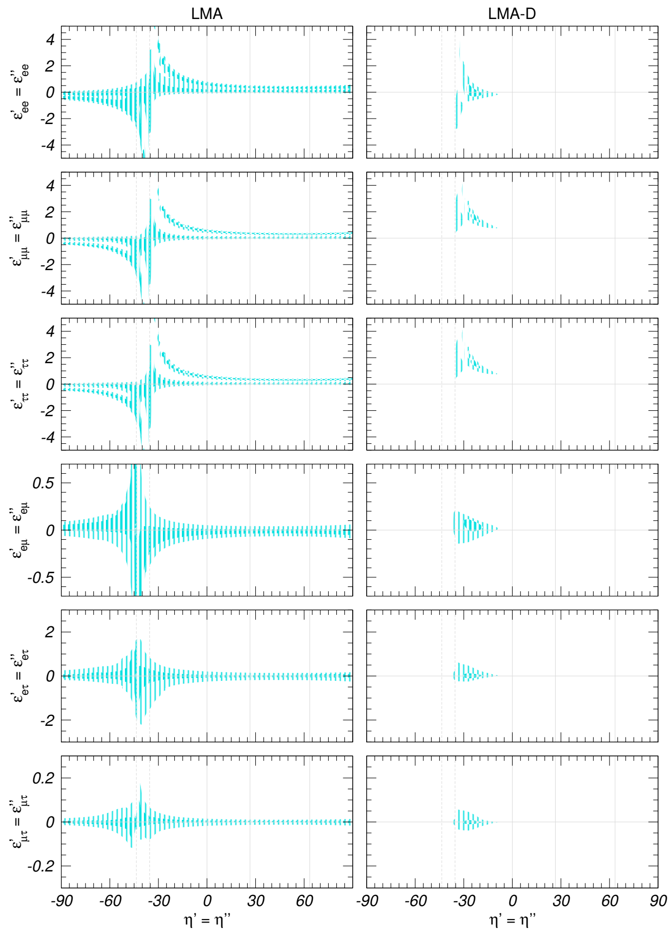
$$\varepsilon^{\text{coh}}_{\alpha\beta} = \sqrt{5}\,\varepsilon''_{\alpha\beta}\,\chi^V\left[\cos\eta'' + Y_n^{\text{coh}}\sin\eta''\right];$$

- $Y_n^{\text{coh}} \approx 1.407 \Rightarrow$ no bound on $\varepsilon''_{\alpha\beta}$ is implied for $\eta'' = \arctan(-1/Y_n^{\text{coh}}) \approx -35.4°$;

- combination: $\begin{cases} \text{oscillation effects} \to \eta', \\ \text{coherent scattering} \to \eta'', \\ \text{elastic scattering} \to \xi^e; \end{cases}$

- NSI with quarks $\Rightarrow \xi^e = 0 \Rightarrow \eta' = \eta''$;

- separate bounds on diagonal $\varepsilon_{\alpha\alpha}$ $(= \varepsilon'_{\alpha\alpha} = \varepsilon''_{\alpha\alpha})$ couplings can be placed.



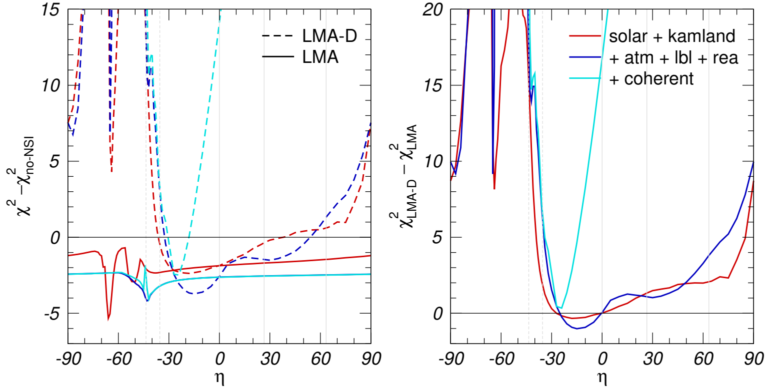
[77] D. Akimov *et al.* [COHERENT], Science **357** (2017) 1123 [arXiv:1708.01294]

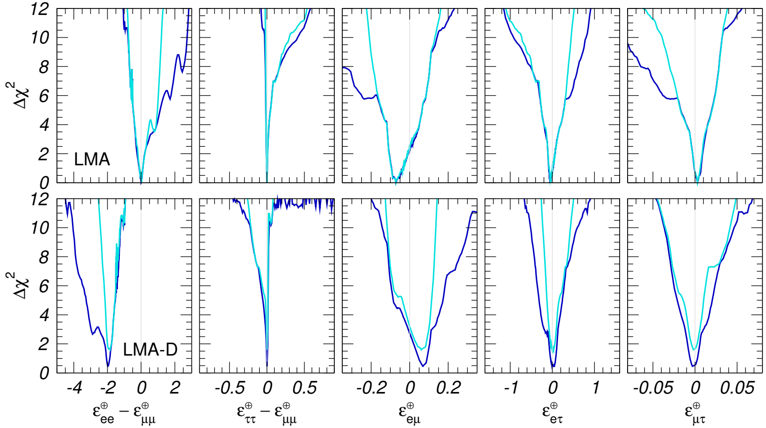
Bounds on NSI with quarks

- Inclusion of COHERENT data rules out LMA-D for NSI with u, d, or p, but **not** in the general case;
- our general 2σ bounds [78]:

	OSCILLATIONS			+ COHERENT (t+E Duke)
	LMA	LMA ⊕ LMA-D		LMA = LMA ⊕ LMA-D
$\varepsilon^u_{ee} - \varepsilon^u_{\mu\mu}$	[−0.072, +0.321]	⊕[−1.042, −0.743]	ε^u_{ee}	[−0.031, +0.476]
$\varepsilon^u_{\tau\tau} - \varepsilon^u_{\mu\mu}$	[−0.001, +0.018]	[−0.016, +0.018]	$\varepsilon^u_{\mu\mu}$	[−0.029, +0.068] ⊕ [+0.309, +0.415]
			$\varepsilon^u_{\tau\tau}$	[−0.029, +0.068] ⊕ [+0.309, +0.414]
$\varepsilon^u_{e\mu}$	[−0.050, +0.020]	[−0.050, +0.059]	$\varepsilon^u_{e\mu}$	[−0.048, +0.020]
$\varepsilon^u_{e\tau}$	[−0.077, +0.098]	[−0.111, +0.098]	$\varepsilon^u_{e\tau}$	[−0.077, +0.095]
$\varepsilon^u_{\mu\tau}$	[−0.006, +0.007]	[−0.006, +0.007]	$\varepsilon^u_{\mu\tau}$	[−0.006, +0.007]
$\varepsilon^d_{ee} - \varepsilon^d_{\mu\mu}$	[−0.084, +0.326]	⊕[−1.081, −1.026]	ε^d_{ee}	[−0.034, +0.426]
$\varepsilon^d_{\tau\tau} - \varepsilon^d_{\mu\mu}$	[−0.001, +0.018]	[−0.001, +0.018]	$\varepsilon^d_{\mu\mu}$	[−0.027, +0.063] ⊕ [+0.275, +0.371]
			$\varepsilon^d_{\tau\tau}$	[−0.027, +0.067] ⊕ [+0.274, +0.372]
$\varepsilon^d_{e\mu}$	[−0.051, +0.020]	[−0.051, +0.038]	$\varepsilon^d_{e\mu}$	[−0.050, +0.020]
$\varepsilon^d_{e\tau}$	[−0.077, +0.098]	[−0.077, −0.098]	$\varepsilon^d_{e\tau}$	[−0.076, +0.097]
$\varepsilon^d_{\mu\tau}$	[−0.006, +0.007]	[−0.006, +0.007]	$\varepsilon^d_{\mu\tau}$	[−0.006, +0.007]
$\varepsilon^p_{ee} - \varepsilon^p_{\mu\mu}$	[−0.190, +0.927]	⊕[−2.927, −1.814]	ε^p_{ee}	[−0.086, +0.884] ⊕ [+1.083, +1.605]
$\varepsilon^p_{\tau\tau} - \varepsilon^p_{\mu\mu}$	[−0.001, +0.053]	[−0.052, +0.053]	$\varepsilon^p_{\mu\mu}$	[−0.097, +0.220] ⊕ [+1.063, +1.410]
			$\varepsilon^p_{\tau\tau}$	[−0.098, +0.221] ⊕ [+1.063, +1.408]
$\varepsilon^p_{e\mu}$	[−0.145, +0.058]	[−0.145, +0.145]	$\varepsilon^p_{e\mu}$	[−0.124, +0.058]
$\varepsilon^p_{e\tau}$	[−0.238, +0.292]	[−0.292, +0.292]	$\varepsilon^p_{e\tau}$	[−0.239, +0.244]
$\varepsilon^p_{\mu\tau}$	[−0.019, +0.021]	[−0.021, +0.021]	$\varepsilon^p_{\mu\tau}$	[−0.013, +0.021]

- Argon data add further $\Delta\chi^2 \sim 4$ [79].





[78] P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, JHEP **02** (2020) 023 [arXiv:1911.09109]

[79] M. Chaves and T. Schwetz, JHEP **05** (2021), 042 [arXiv:2102.11981]

Vector NSI in the general case

- Direction of $(\xi^e, \xi^u, \xi^d) \leftrightarrow$ half-sphere $|\vec{\xi}| = \sqrt{5}$;
- choose *two* angles (η, ζ) and define:

$$\varepsilon_{\alpha\beta}^{fV} \equiv \varepsilon_{\alpha\beta}\, \xi^f \chi^V \quad \text{with} \begin{cases} \xi^e = \sqrt{5}\cos\eta\sin\zeta\,, \\ \xi^p = \sqrt{5}\cos\eta\cos\zeta\,, \\ \xi^n = \sqrt{5}\sin\eta\,; \end{cases}$$

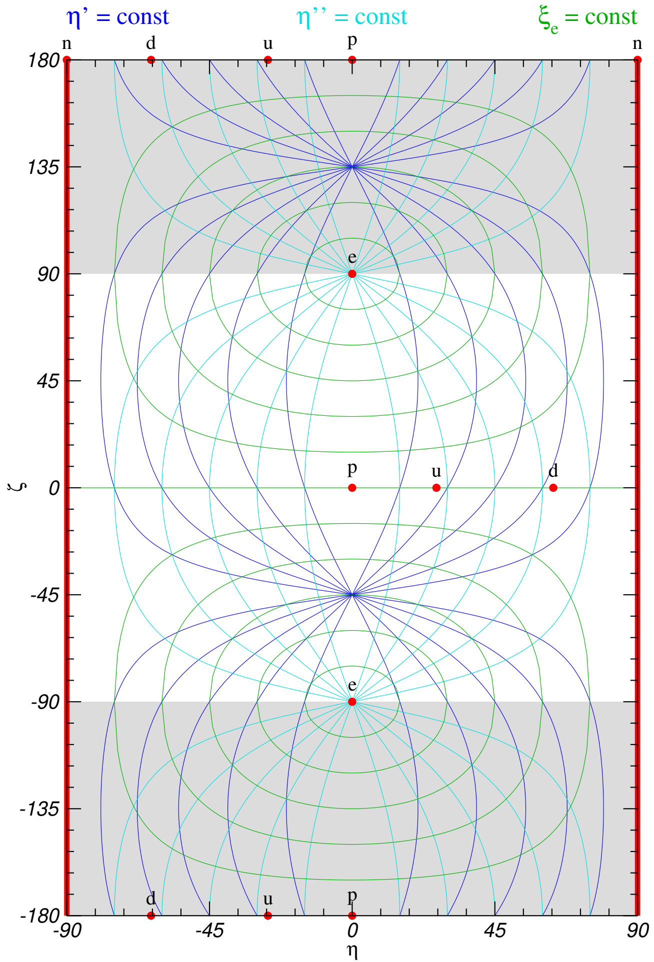
- each type of "effect" is constant on given lines:

oscillations: $\tan\eta' = \tan\eta \,/\, (\cos\zeta + \sin\zeta)$,

coherent sc.: $\tan\eta'' = \tan\eta \,/\, \cos\zeta$,

elastic sc.: $\xi^e \,/\, |\vec{\xi}| = \cos\eta\sin\zeta$;

- combining different sets breaks degeneracy;
- special case: $\zeta = 0 \Rightarrow \xi^e = 0 \Rightarrow \eta' = \eta'' = \eta$.



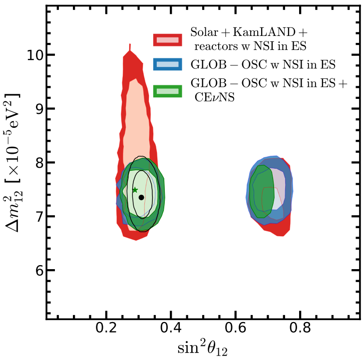
[76] Coloma *et al.*, JHEP [arXiv:2305.07698]

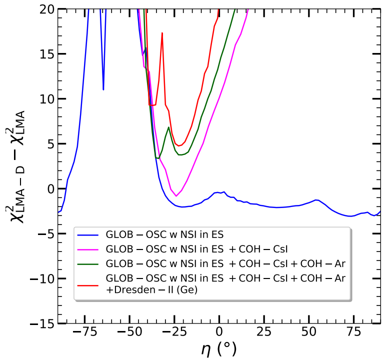
Bounds on vector NSI

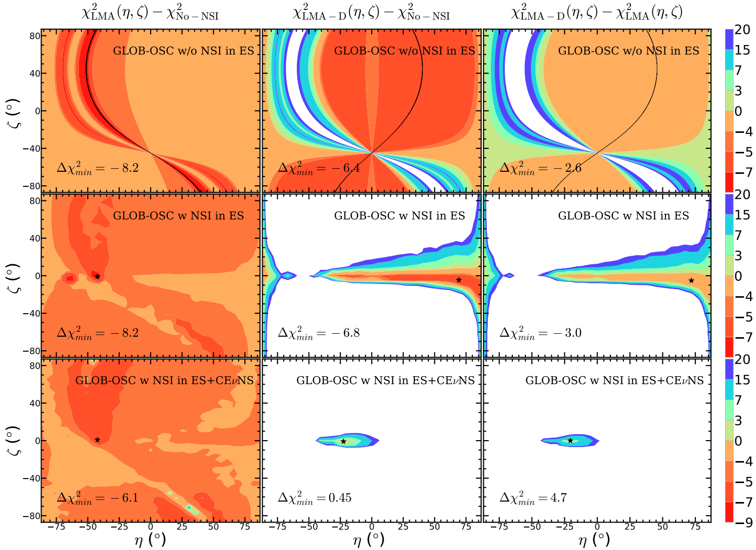
- Determination of oscillation parameters remain stable under NSI (except θ_{12});
- ES effects disfavor region at large ξ^e (roughly $|\zeta| \gtrsim 45^\circ$) but have little impact on rejection of LMA-D;
- inclusion of coherent scattering data rules out LMA-D (except in a small region).

Allowed ranges at 90% CL / 99% CL marginalized

GLOB-OSC w/o NSI in ES		GLOB-OSC w NSI in ES + CEνNS	
$\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu}$	$[-3.1, -2.8] \oplus [-2.1, -1.88] \oplus [-0.15, +0.17]$ $[-4.8, -1.6] \oplus [-0.40, +2.6]$	$^{\oplus}_{ee}$	$[-0.19, +0.20] \oplus [+0.95, +1.3]$ $[-0.23, +0.25] \oplus [+0.81, +1.3]$
		$^{\oplus}_{\mu\mu}$	$[-0.43, +0.14] \oplus [+0.91, +1.3]$ $[-0.29, +0.20] \oplus [+0.83, +1.4]$
$^{\oplus}_{\tau\tau} - \varepsilon^{\oplus}_{\mu\mu}$	$[-0.0215, +0.0122]$ $[-0.075, +0.080]$	$^{\oplus}_{\tau\tau}$	$[-0.43, +0.14] \oplus [+0.91, +1.3]$ $[-0.29, +0.20] \oplus [+0.83, +1.4]$
$^{\oplus}_{e\mu}$	$[-0.11, -0.021] \oplus [+0.045, +0.135]$ $[-0.32, +0.40]$	$^{\oplus}_{e\mu}$	$[-0.12, +0.011]$ $[-0.18, +0.08]$
$^{\oplus}_{\mu\tau}$	$[-0.22, +0.088]$ $[-0.49, +0.45]$	$^{\oplus}_{e\tau}$	$[-0.16, +0.083]$ $[-0.25, +0.33]$
$^{\oplus}_{\mu\tau}$	$[-0.0063, +0.013]$ $[-0.043, +0.039]$	$^{\oplus}_{\mu\tau}$	$[-0.0047, +0.012]$ $[-0.020, +0.021]$







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- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. The three-neutrino scenario is nowadays well proven and **robust**;
- however, the possibility of physics beyond the 3ν paradigm remains open. Here we have focused on NC-like non-standard neutrino-matter interactions;
- we have extended previous studies by considering NSI with an arbitrary ratio of couplings to the constituents of ordinary matter (parametrized by coefficients ξ^e, ξ^u, ξ^d) and a lepton-flavor structure independent of the fermion type (parametrized by a matrix $\varepsilon_{\alpha\beta}$);
- we have found that NSI can spoil the precise determination of the oscillation parameters offered by **specific** class of experiments, but the 3ν precision is recovered once all the data are combined **together** – except for θ_{12} where a new region (LMA-D) appears;
- for $m_{Z'} \gtrsim \mathcal{O}(10\text{ MeV})$ NSI with electrons also affect ES interactions in solar data. Interference between oscillation and scattering effects requires careful treatment;
- the degeneracy between LMA-D and the ν mass ordering cannot be resolved by oscillation data alone. Combination with scattering experiments (*e.g.*, COHERENT) is essential, but requires a sufficiently large mediator mass $m_{Z'} \gtrsim \mathcal{O}(50\text{ MeV})$.