Beyond the Standard Model Physics with Neutrinos

Michele Maltoni

Instituto de Física Teórica UAM/CSIC

YETI 2024 – The 3 Neutrino Problem

IPPP, Durham University, UK – July 31st, 2024

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**: SK(1–4) + DeepCore;
  - **Reactor**: KamLAND + Dbl-Chooz + Daya-Bay + Reno;
  - **Accelerator**: Minos + T2K + NOvA;

- best-fit point and 1σ (3σ) ranges:

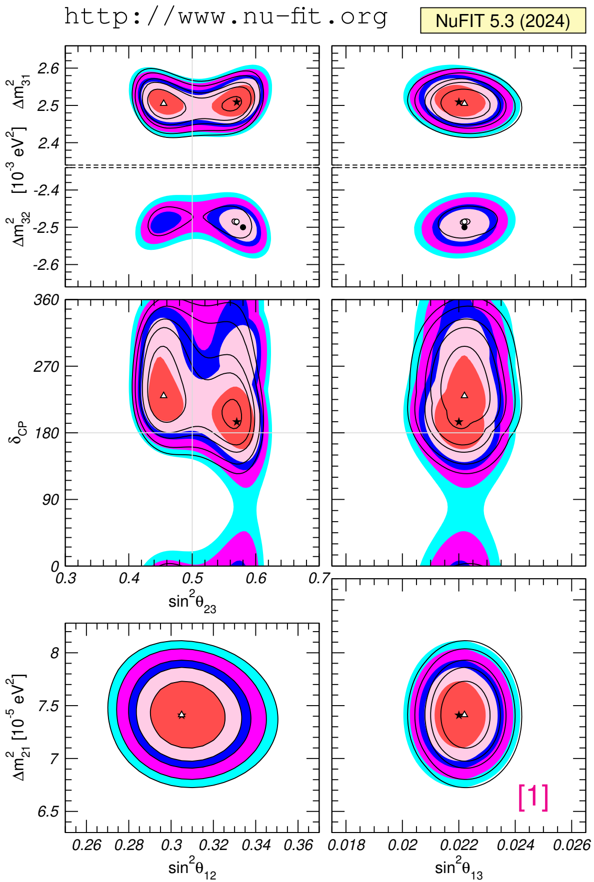
$$\theta_{12} = 33.66\,^{+0.73}_{-0.70}\,\left(^{+2.28}_{-2.06}\right), \qquad \Delta m^2_{21} = 7.41\,^{+0.21}_{-0.20}\,\left(^{+0.62}_{-0.60}\right) \times 10^{-5}\ \mathrm{eV}^2,$$

$$\theta_{23} = \begin{cases} 49.1\,^{+1.0}_{-1.3}\,\left(^{+2.8}_{-9.5}\right), \\ 49.5\,^{+0.9}_{-1.2}\,\left(^{+2.6}_{-9.5}\right), \end{cases} \qquad \Delta m^2_{31} = \begin{cases} +2.511\,^{+0.027}_{-0.027}\,\left(^{+0.085}_{-0.084}\right) \times 10^{-3}\ \mathrm{eV}^2, \\ -2.498\,^{+0.032}_{-0.024}\,\left(^{+0.090}_{-0.083}\right) \times 10^{-3}\ \mathrm{eV}^2, \end{cases}$$

$$\theta_{13} = 8.54\,^{+0.11}_{-0.11}\,\left(^{+0.36}_{-0.35}\right), \qquad \delta_{\mathrm{CP}} = 197\,^{+41}_{-25}\,\left(^{+207}_{-89}\right);$$

- neutrino mixing matrix:

$$|U|_{3\sigma} = \begin{pmatrix} 0.801 \to 0.842 & 0.518 \to 0.580 & 0.143 \to 0.155 \\ 0.244 \to 0.500 & 0.498 \to 0.690 & 0.634 \to 0.770 \\ 0.276 \to 0.521 & 0.473 \to 0.672 & 0.621 \to 0.759 \end{pmatrix}.$$

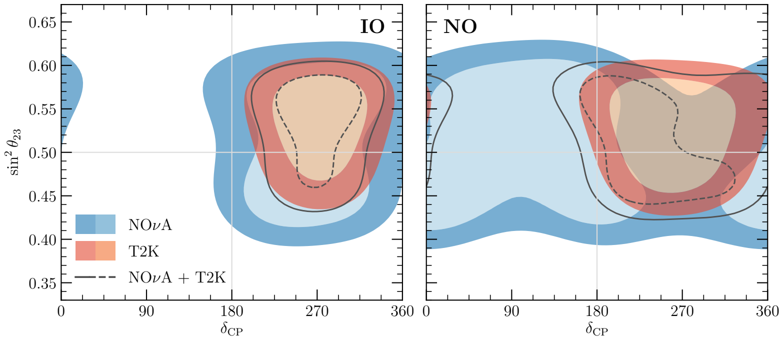


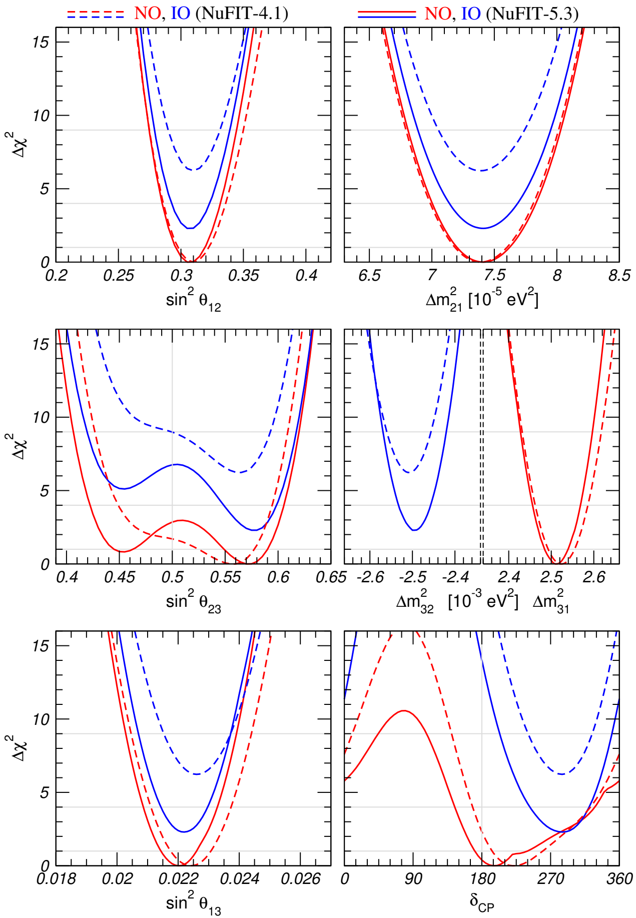
[1] I. Esteban *et al.*, JHEP **09** (2020) 178 [arXiv:2007.14792] & NuFIT 5.3 [http://www.nu-fit.org].

Open issues in 3ν oscillations

- **CP violation**: tension on δ_{CP} between T2K and NOvA for the case of normal ordering (NO);
- **Mass ordering**: due to such tension, long-standing hints in favor of NO is now reduced;
- **θ_{23} octant**: still no clue on deviation of θ_{23} from maximal, and (if so) in which direction;
  - future experiments expected to shed light;

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





Non-standard neutrino interactions: formalism

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

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

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:

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

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

- here we consider NC-like **non-standard** neutrino-matter described by:

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

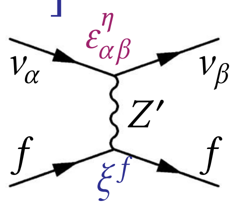
- ordinary matter composed by $\{e, u, d\}$ ⟹ ν propagation sensitive to NSI with them;
- some experiments sensitive to $\nu - e$ elastic scattering ⟹ NC-like NSI with e affect both propagation and interactions ⟹ require dedicated treatment ⟹ ignored for now;
- conversely, NC-like NSI's with quarks do **not** affect processes such as lepton appearance, which involve quarks through CC interactions ⟹ only ν propagation affected.

Non-standard neutrino interactions: formalism

- Conventionally, only NSI with either u or d quarks have been considered;
- still, both cases can appear simultaneously, and produce consequences (*e.g.*, cancellations) which invalidate the u-only or d-only bounds;
- however, most general parameter space too large to handle ⇒ simplifications needed;
- here we assume that the ν flavor structure is **independent** of the charged fermion type:

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

- since neutrino **propagation** is only sensitive to the vector couplings:



$$\varepsilon_{\alpha\beta}^{f} \equiv \varepsilon_{\alpha\beta}^{fL} + \varepsilon_{\alpha\beta}^{fR} = \varepsilon_{\alpha\beta}^{\eta}\, \xi^f \quad \text{with} \quad \xi^f = \xi^{fL} + \xi^{fR} ;$$

- only the direction in the (ξ^u, ξ^d) plane is non-trivial for ν oscillations ⇒ define an angle η:

$$\xi^u = \frac{\sqrt{5}}{3}(2\cos\eta - \sin\eta)\,, \qquad \xi^d = \frac{\sqrt{5}}{3}(2\sin\eta - \cos\eta)\,;$$

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

Non-standard interactions and 3ν oscillations

- Equation of motion: **6** (vac) + **8** (NSI-ν) + **1** (NSI-q) = **15** parameters [2]:

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

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

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

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

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

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

The generalized mass ordering degeneracy

- General symmetry: $H \to -H^\star$ does not affect the neutrino probabilities;
- we have $H = H_\text{vac} \pm V_\text{mat}$. For vacuum, $H_\text{vac} \to -H^\star_\text{vac}$ 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 [3, 4, 5];
- for matter, $V_\text{mat} \to -V^\star_\text{mat}$ requires: $\begin{cases} [\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{ee}(x) - \mathcal{E}_{\mu\mu}(x)] - 2\,, \\ [\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)] \to -[\mathcal{E}_{\tau\tau}(x) - \mathcal{E}_{\mu\mu}(x)]\,, \\ \mathcal{E}_{\alpha\beta}(x) \to -\mathcal{E}^\star_{\alpha\beta}(x) \qquad (\alpha \neq \beta)\,, \end{cases}$
- since $V_\text{mat} = V_\text{SM} + V_\text{NSI}$ and V_SM is fixed, this symmetry requires NSI;
- in general, $\mathcal{E}_{\alpha\beta}(x)$ 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 $Y_n(x)$ is constant, and same for all the neutrino trajectories.

[3] M.C. Gonzalez-Garcia, M. Maltoni, JHEP **09** (2013) 152 [arXiv:1307.3092]
[4] P. Bakhti, Y. Farzan, JHEP **07** (2014) 064 [arXiv:1403.0744].
[5] 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):

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

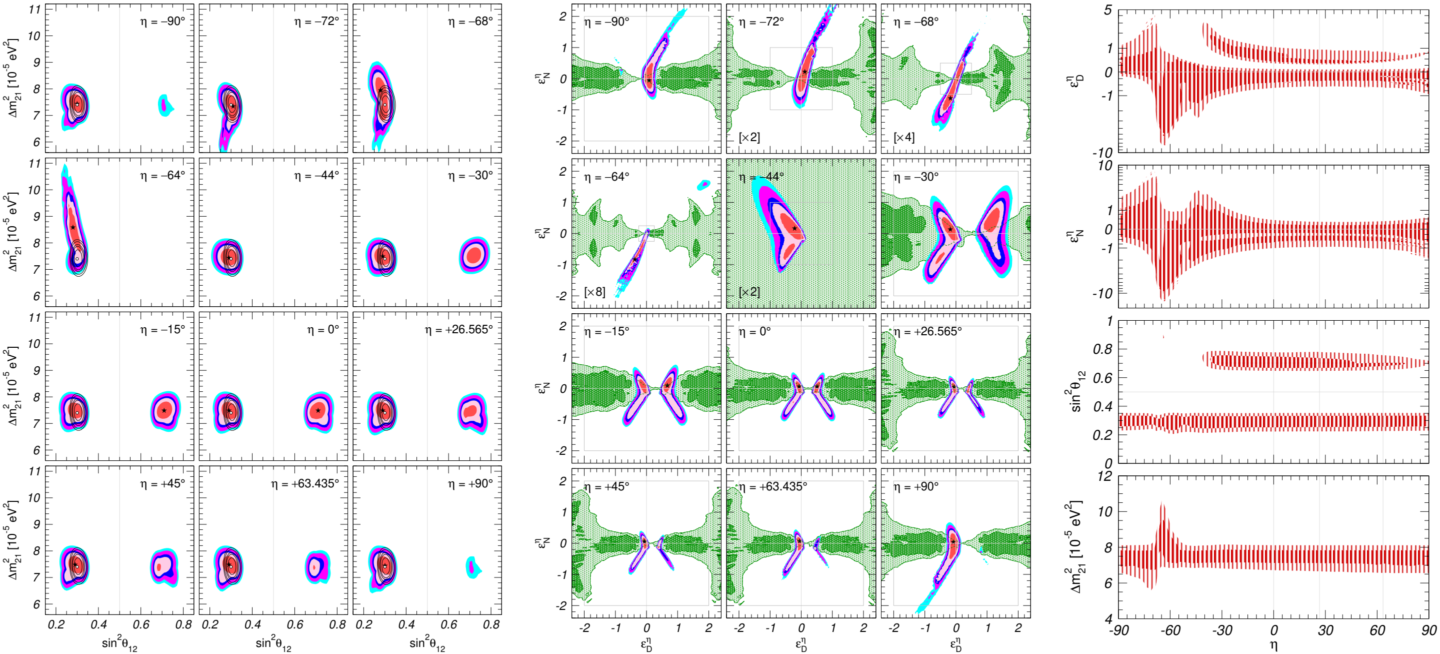
$$\boldsymbol{H}^{\text{eff}}_{\text{mat}} \equiv \sqrt{2}\, G_F N_e(r) \left[\begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix} + \sqrt{5}\left[\cos\eta + Y_n(x)\sin\eta\right] \begin{pmatrix} -\varepsilon_D^\eta & \varepsilon_N^\eta \\ \varepsilon_N^{\eta\star} & \varepsilon_D^\eta \end{pmatrix}\right],$$

$$\begin{cases} \varepsilon_D^\eta = c_{13}s_{13}\,\text{Re}\left(s_{23}\,\varepsilon_{e\mu}^\eta + c_{23}\,\varepsilon_{e\tau}^\eta\right) - \left(1+s_{13}^2\right)c_{23}s_{23}\,\text{Re}\left(\varepsilon_{\mu\tau}^\eta\right) \\ \qquad\quad - c_{13}^2\left(\varepsilon_{ee}^\eta - \varepsilon_{\mu\mu}^\eta\right)/\,2 + \left(s_{23}^2 - s_{13}^2 c_{23}^2\right)\left(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta\right)/\,2\,, \\ \varepsilon_N^\eta = c_{13}\left(c_{23}\,\varepsilon_{e\mu}^\eta - s_{23}\,\varepsilon_{e\tau}^\eta\right) + s_{13}\left[s_{23}^2\,\varepsilon_{\mu\tau}^\eta - c_{23}^2\,\varepsilon_{\mu\tau}^{\eta\star} + c_{23}s_{23}\left(\varepsilon_{\tau\tau}^\eta - \varepsilon_{\mu\mu}^\eta\right)\right]; \end{cases}$$

- 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 $Y_n(x) \in [1/6, 1/2]$ $\Rightarrow$ approximate cancellation of NSI for $\eta \in [-80^\circ, -63^\circ]$.

Oscillation results for solar and KamLAND neutrinos

- Generalized mass-ordering degeneracy ⇒ new LMA-D solution with $\theta_{12} > 45^\circ$ [6];
- $\eta = 0$ ⇒ NSI terms proportional to $N_p(x) \equiv N_e(x)$ ⇒ the degeneracy becomes exact.

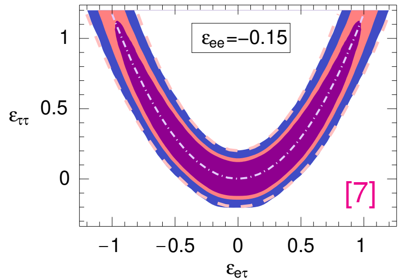


[6] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

Matter potential for atmospheric and long-baseline neutrinos

- In Earth matter: $Y_n(x) \to Y_n^\oplus \approx 1.051 \Rightarrow \mathcal{E}_{\alpha\beta}(x) \to \varepsilon_{\alpha\beta}^\oplus$ becomes an effective parameter:
$$\varepsilon_{\alpha\beta}^\oplus \equiv \sqrt{5}\left[\cos\eta + Y_n^\oplus \sin\eta\right] \varepsilon_{\alpha\beta}^\eta ,$$
- the bounds on $\varepsilon_{\alpha\beta}^\oplus$ are independent of the quark couplings (*i.e.*, of η);
- for $\eta = \arctan(-1/Y_n^\oplus) \approx -43.6^\circ$ ATM+LBL data imply **no** bound on $\varepsilon_{\alpha\beta}^\eta$;
- 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 [7] $\Rightarrow$ focus on such case $\Rightarrow$ introduce parameters ($\varepsilon_\oplus$, φ_{12}, φ_{13}, α_1, α_2) and define:

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

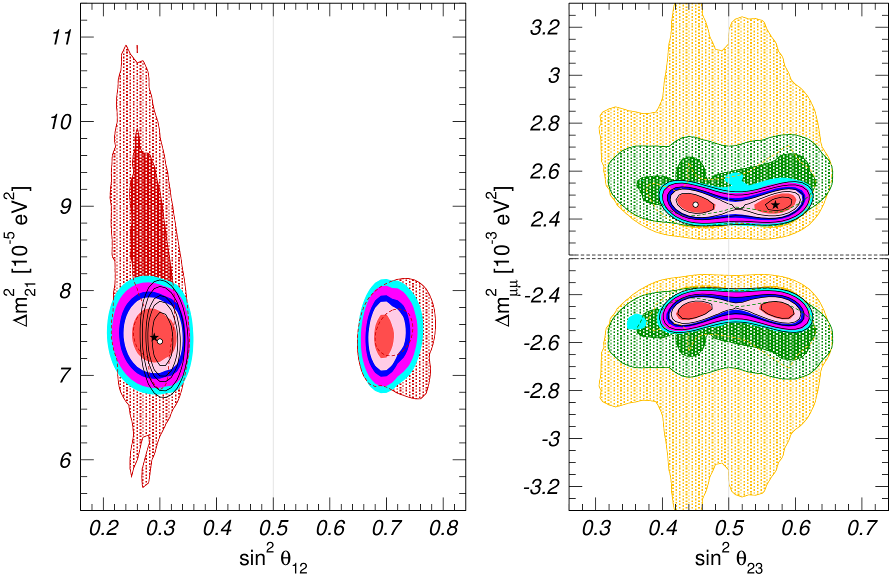


- for definiteness we also assume on CP conservation and set $\delta_\text{CP} = \alpha_1 = \alpha_2 = 0$.

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

Impact of NSI on the oscillation parameters

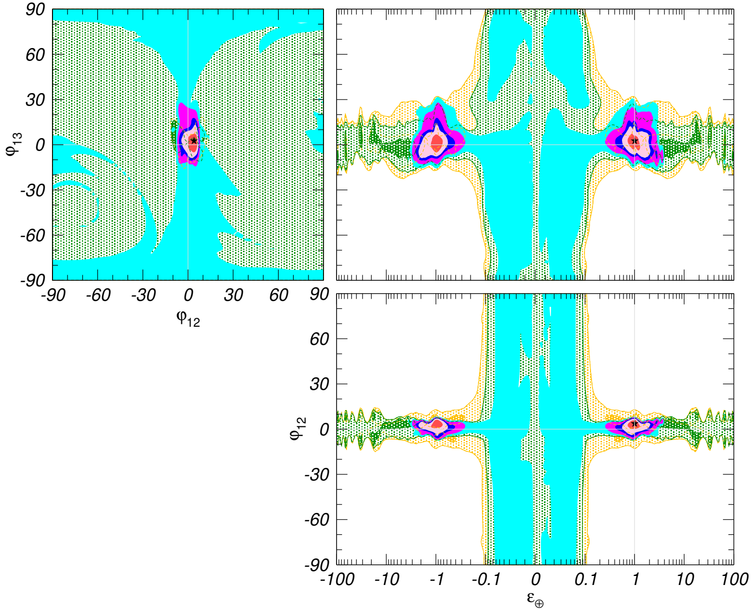
- Once marginalized over η, analysis of solar + KamLAND data shows strong deterioration of the precision on Δm^2_{21} and θ_{12}, as well as the appearance of the LMA-D solution [6];
- a similar worsening appears in ATM + LBL-dis + LBL-app + IceCUBE + MBL-rea analysis;
- synergies between solar and atmospheric 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.

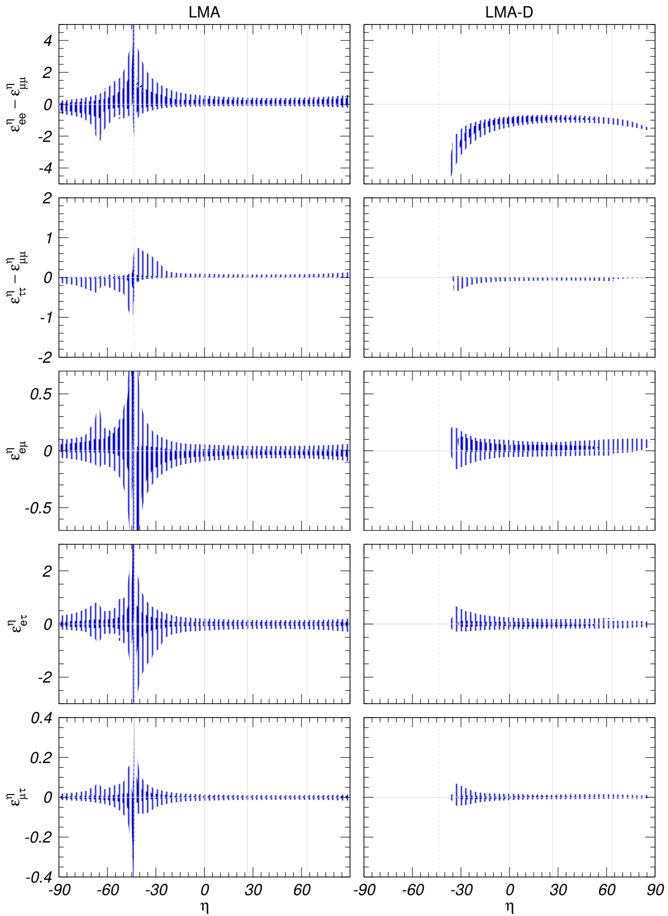


[6] O.G. Miranda, M.A. Tortola, J.W.F. Valle, JHEP **10** (2006) 008 [hep-ph/0406280].

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 $\varepsilon^\eta_{\alpha\beta}$.





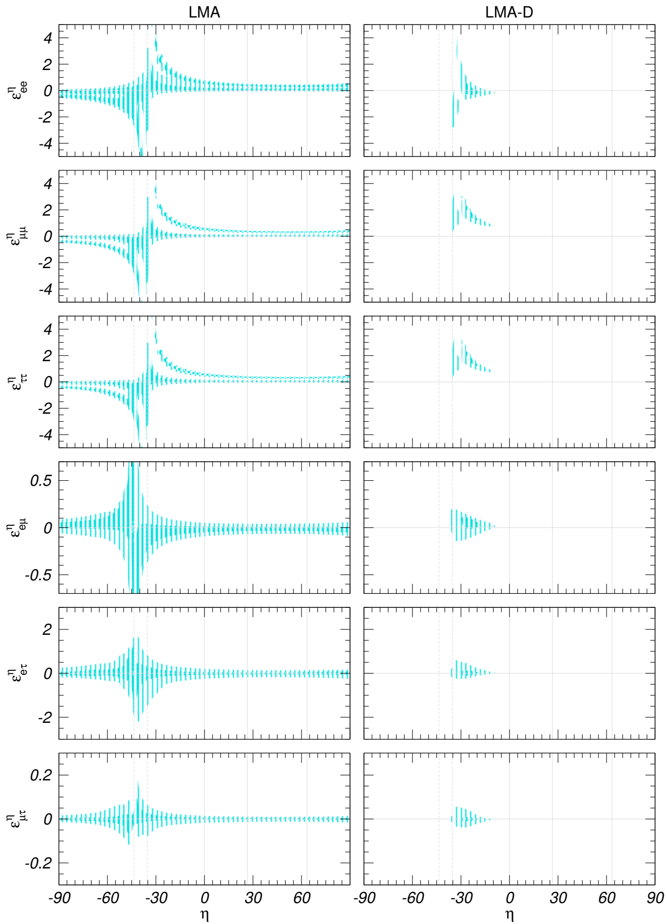
The COHERENT experiment

- Observation of coherent neutrino-nucleus scattering [8] allows to put bounds on NSI through the effective charges ($Y_n^{\text{coh}} \approx 1.407$):

$$\mathcal{Q}_\alpha^2 \propto \left[(g_p^V + Y_n^{\text{coh}} g_n^V) + \varepsilon_{\alpha\alpha}^{\text{coh}}\right]^2 + \sum_{\beta\neq\alpha} \left(\varepsilon_{\alpha\beta}^{\text{coh}}\right)^2$$

$$\text{with} \quad \varepsilon_{\alpha\beta}^{\text{coh}} = \sqrt{5}\left[\cos\eta + Y_n^{\text{coh}} \sin\eta\right] \varepsilon_{\alpha\beta}^{\eta}\,;$$

- for $\eta = \arctan(-1/Y_n^{\text{coh}}) \approx -35.4^\circ$ no bound on $\varepsilon_{\alpha\beta}^{\eta}$ is implied;
- separate bounds on diagonal $\varepsilon_{\alpha\alpha}^{\eta}$ couplings can be placed.



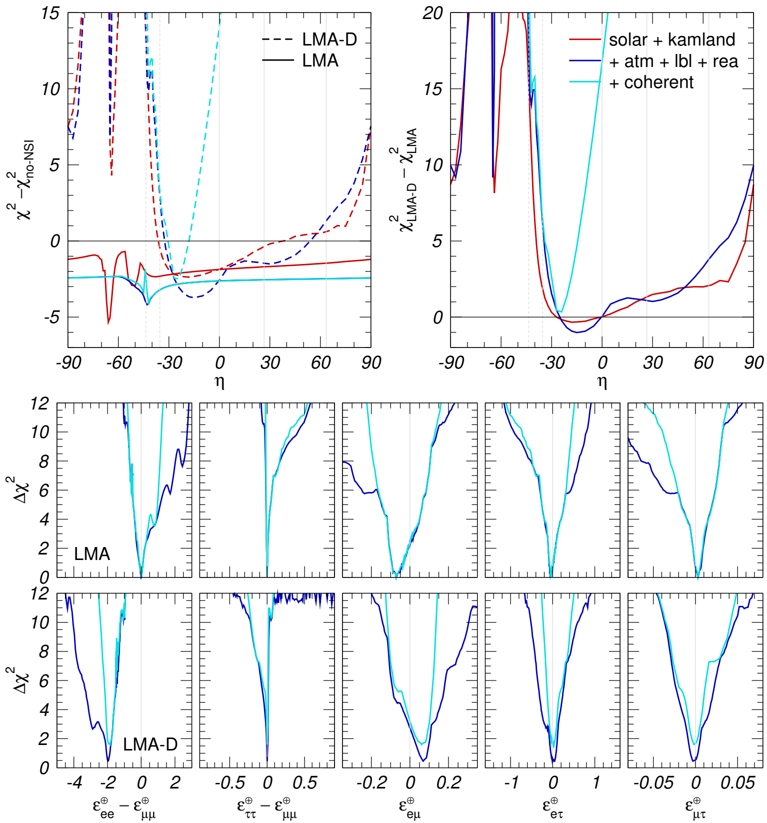
[8] D. Akimov *et al.* [COHERENT], Science **357** (2017) 1123 [arXiv:1708.01294]
[9] P. Coloma, I. Esteban *et al.*, JHEP **02** (2020) 023 [arXiv:1911.09109].

General NSI bounds

- 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 [9]:

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 $\Delta\chi^2 \sim 4$ [10].

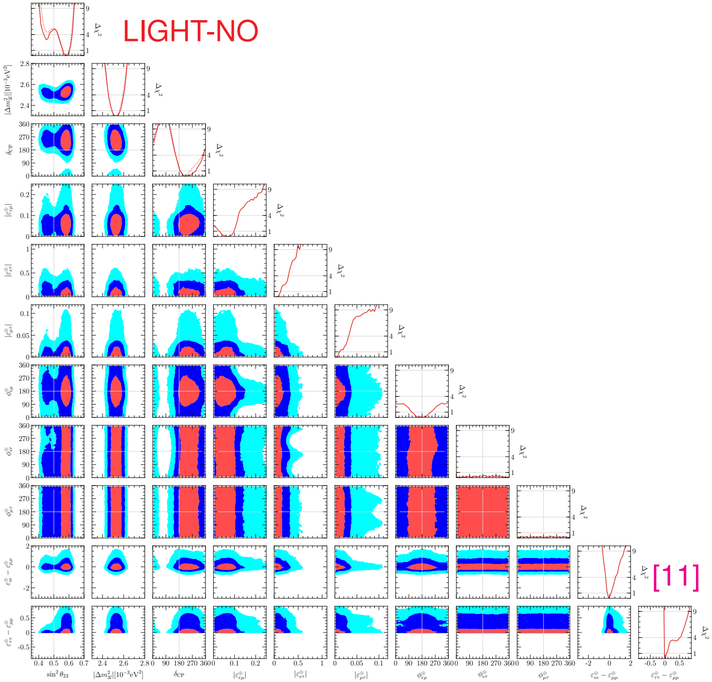


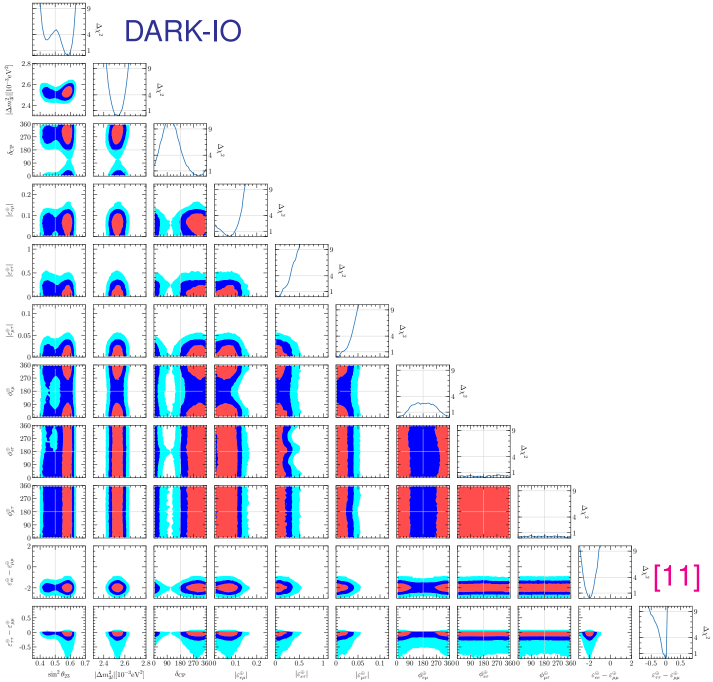
[9] P. Coloma, I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, JHEP **02** (2020) 023 [arXiv:1911.09109].

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

CP violation in the presence of NSI

- NSI introduce three additional phases $\phi^{\oplus}_{\alpha\beta}$, associated to the non-diagonal elements $\varepsilon^{\oplus}_{\alpha\beta}$.





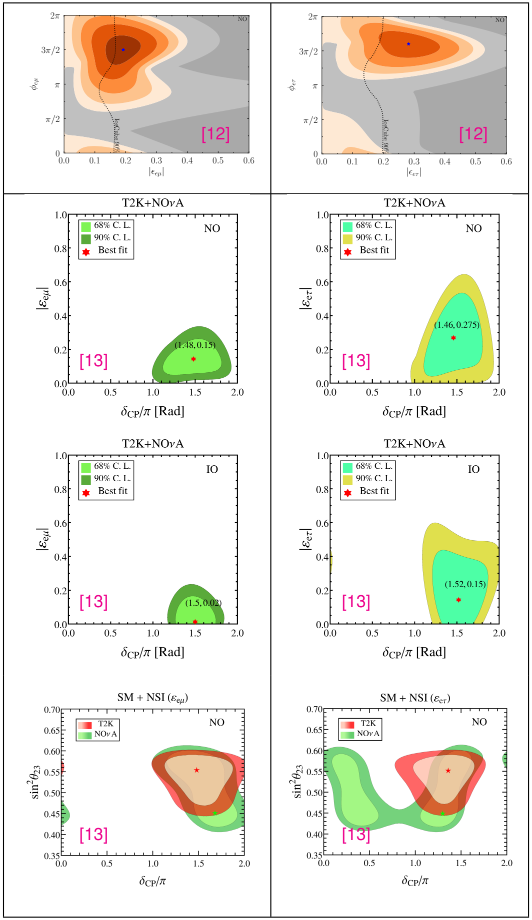
[11] I. Esteban *et al.*, JHEP **06** (2019) 055 [arXiv:1905.05203].

Impact of NSI on T2K and NOvA

- It has been noted [12, 13] that tension between T2K and NOvA in the determination of δ_{CP} for Normal Ordering can be alleviated by NSI;
- both papers suggest two alternative mechanisms: $|\varepsilon_{e\mu}^{\oplus}| \sim 0.15$ and $|\varepsilon_{e\tau}^{\oplus}| \sim 0.3$, yielding similar improvements ($\Delta\chi^2_{e\mu} \sim 4.5$ and $\Delta\chi^2_{e\tau} \sim 3.7$) w.r.t. SM for NO;
- no significant NSI contribution is found for IO;
- both mechanisms favor maximal CP violation ($\delta_{CP} \sim 270^\circ$) in the presence of NSI;
- by alleviating the T2K–NOvA tension, the worsening of NO w.r.t. IO does **not** take place.

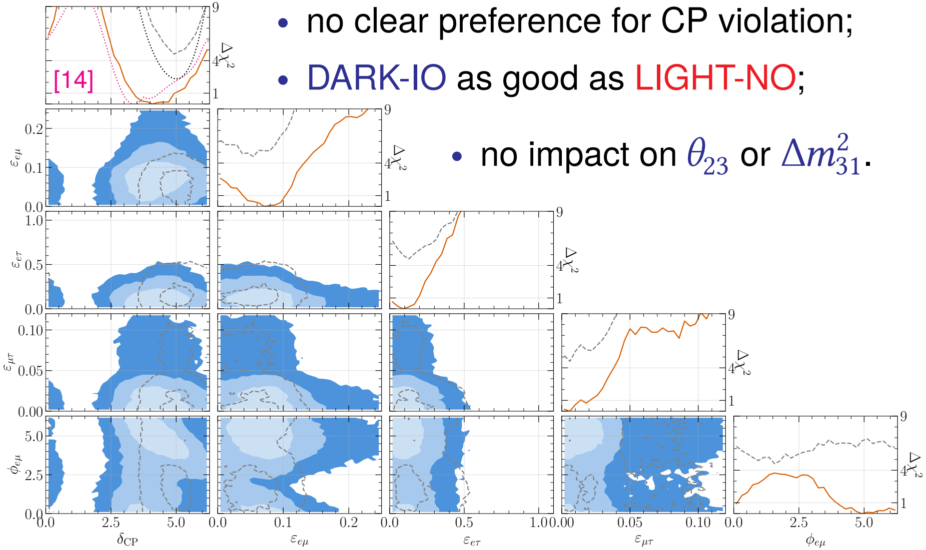
[12] P.B. Denton, J. Gehrlein, R. Pestes, Phys. Rev. Lett. **126** (2021) 051801 [arXiv:2008.01110].

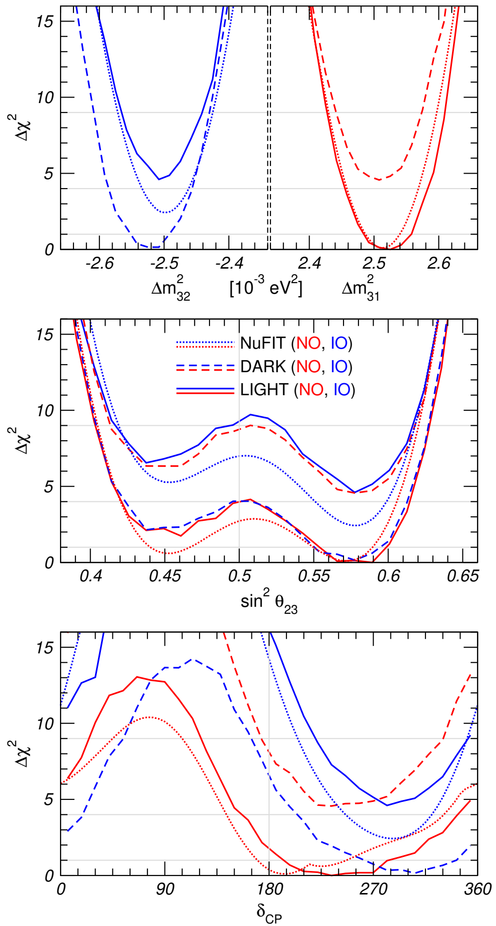
[13] S.S. Chatterjee, A. Palazzo, Phys. Rev. Lett. **126** (2021) 051802 [arXiv:2008.04161].



Impact of NSI on oscillation parameters

- Global fits of **all** neutrino data indicate that:
  - $\varepsilon^{\oplus}_{e\mu}$ mechanism OK, but with smaller $|\varepsilon^{\oplus}_{e\mu}| \simeq 0.08$;
  - $\varepsilon^{\oplus}_{e\tau}$ mechanism severely constrained;
- preference of NO over IO increases by $\Delta\chi^2 \sim 2.3$;
  - no clear preference for CP violation;
  - DARK-IO as good as LIGHT-NO;
  - no impact on θ_{23} or Δm^2_{31}.





[14] I. Esteban, private communication & arXiv:2004.04745.

Non-standard interactions with electrons: formalism

- Let's focus here on solar neutrinos. In the presence of NC-like NSI with e, elastic scattering is modified ⇒ detection process (*e.g.*, in 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 $\boldsymbol{U}$ ⇒ 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:

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

- 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 $N_{\text{ev}} \propto \text{Tr}\left[\boldsymbol{\rho}^{(e)}\, \boldsymbol{\sigma}^{\text{NSI}}\right]$ must be used;
- the cross-section matrix $\boldsymbol{\sigma}^{\text{NSI}}$ is the integral over T_e of the following expression:

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

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

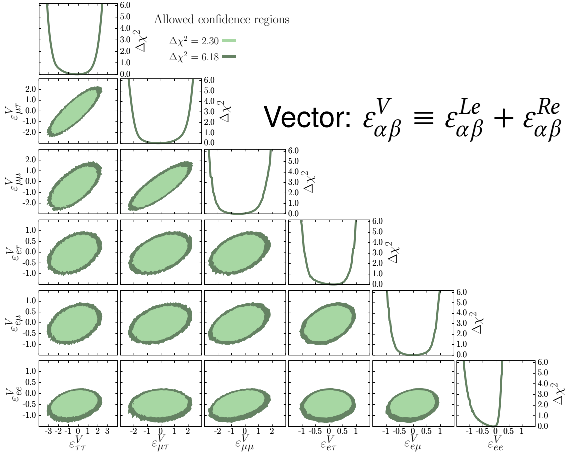
$$\begin{cases} C^L_{\alpha\beta} \equiv c_{L\beta}\,\delta_{\alpha\beta} + \varepsilon^{Le}_{\alpha\beta} \\ C^R_{\alpha\beta} \equiv c_{L\beta}\,\delta_{\alpha\beta} + \varepsilon^{Re}_{\alpha\beta} \end{cases} \quad \text{with} \quad \begin{cases} c_{L\tau} = c_{L\mu} = g_L^\ell \quad \text{and} \quad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

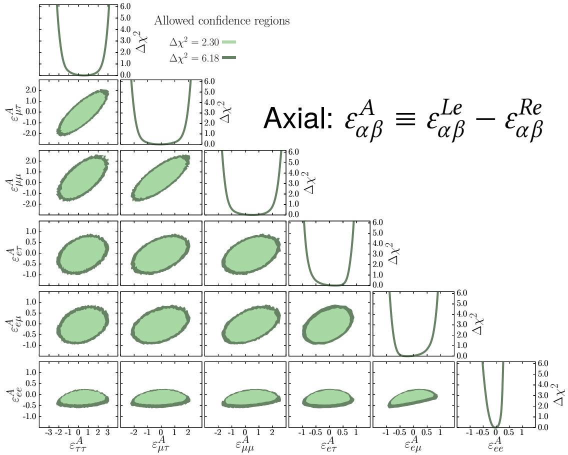
- when the NSI terms $\varepsilon^{Le}_{\alpha\beta}$ and $\varepsilon^{Re}_{\alpha\beta}$ are set to zero, the matrix $d\boldsymbol{\sigma}^{\text{NSI}}/dT_e$ becomes diagonal and the SM expressions are recovered;
- the cross section for antineutrinos can be obtained by interchanging $C_L \leftrightarrow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

Bounds on NSI-e from Borexino II

- Ref. [15]: analysis of NSI-e with Borexino. Caveats:
  - only diagonal NSI considered;
  - only 1 or 2 NSI parameters varied at-a-time;
- in [16] 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}	$[-0.09, +0.14]$	$[-1.05, +0.17]$	$[-0.05, +0.10]$	$[-0.38, +0.24]$
$\varepsilon_{\mu\mu}$	$[-0.51, +0.35]$	$[-2.38, +1.54]$	$[-0.29, +0.19] \oplus [+0.68, +1.45]$	$[-1.47, +2.37]$
$\varepsilon_{\tau\tau}$	$[-0.66, +0.52]$	$[-2.85, +2.04]$	$[-0.40, +0.36] \oplus [+0.69, +1.44]$	$[-1.82, +2.81]$
$\varepsilon_{e\mu}$	$[-0.34, +0.61]$	$[-0.83, +0.84]$	$[-0.30, +0.43]$	$[-0.79, +0.76]$
$\varepsilon_{e\tau}$	$[-0.48, +0.47]$	$[-0.90, +0.85]$	$[-0.40, +0.38]$	$[-0.81, +0.78]$
$\varepsilon_{\mu\tau}$	$[-0.25, +0.36]$	$[-2.07, +2.06]$	$[-1.10, -0.75] \oplus [-0.13, +0.22]$	$[-1.95, +1.91]$

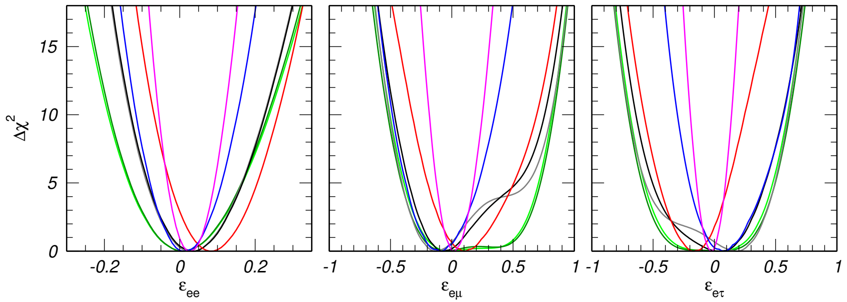




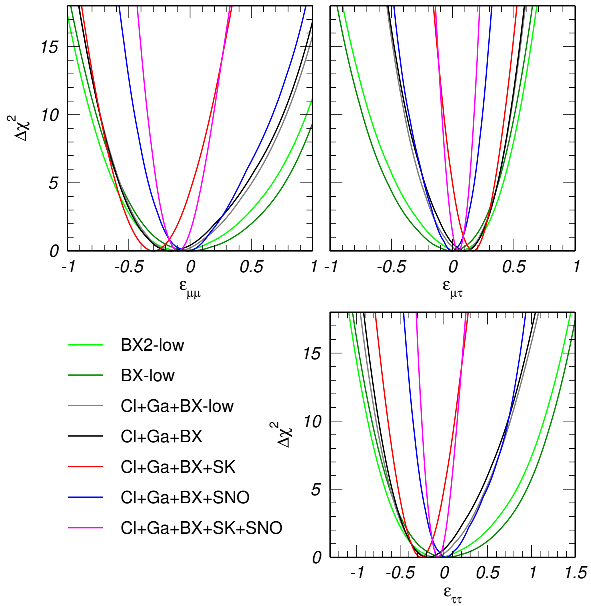
[15] Borexino coll., JHEP **02** (2020) 038 [arXiv:1905.03512]
[16] Coloma *et al.*, JHEP **07** (2022) 138 [arXiv:2204.03011]

I/e. Non-standard neutrino interactions with electrons

NSI-*e* from all solar data



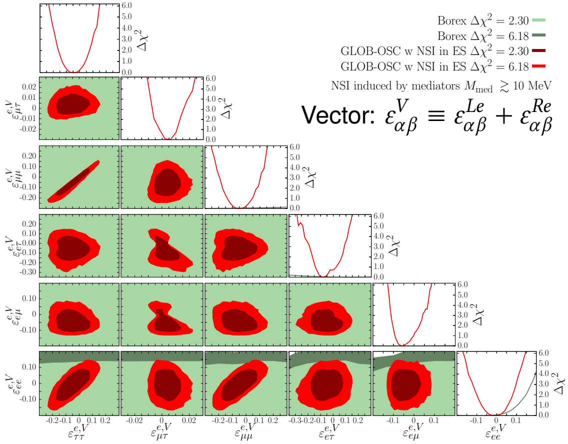
- Caveat: in this slide we vary only 1 NSI parameter at-a-time;
- other low-E data such as BX1 and Cl+Ga have little impact;
- however, SK and SNO contribute significantly:
  - SK measures ES events with high statistics;
  - SNO is only weakly sensitive to ES, however it accurately determines the $^8\mathrm{B}$ flux through NC;
  - SK+SNO combination yield strong bounds;
- of course, degeneracies among different NSI parameters will weaken the bounds, but improvement over BX2-only data still expected;
- global analysis is tough because of the large number of parameters, but not impossible…

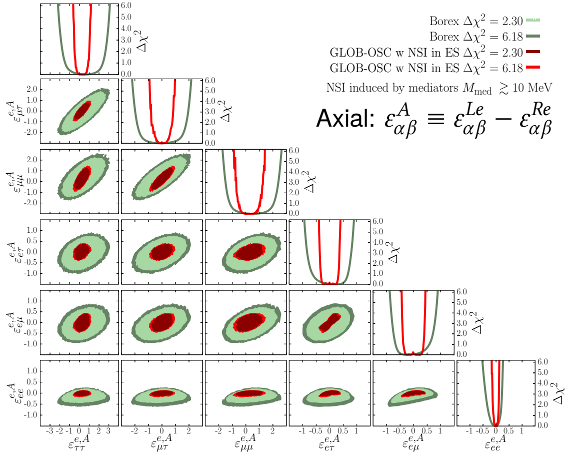


Bounds on NSI-e from global data

- In [17] we performed a global analysis of all solar data, varying all parameters simultaneously;
- indeed, the bounds from Borexino alone are greatly enhanced, both for vector and axial couplings;
- the limits are dominated by NSI contributions to the ES cross-section, which allow to derive separate bounds on diagonal $\varepsilon^{e,V}_{\alpha\alpha}$ and $\varepsilon^{e,A}_{\alpha\alpha}$ 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
$\varepsilon^{e,X}_{ee}$	$[-1.1, +0.17]$	$[-0.13, +0.10]$	$[-0.38, +0.24]$	$[-0.13, +0.11]$
$\varepsilon^{e,X}_{\mu\mu}$	$[-2.4, +1.5]$	$[-0.20, +0.10]$	$[-1.5, +2.4]$	$[-0.70, +1.2]$
$\varepsilon^{e,X}_{\tau\tau}$	$[-2.8, +2.1]$	$[-0.17, +0.093]$	$[-1.8, +2.8]$	$[-0.53, +1.0]$
$\varepsilon^{e,X}_{e\mu}$	$[-0.83, +0.84]$	$[-0.097, +0.011]$	$[-0.79, +0.76]$	$[-0.41, +0.40]$
$\varepsilon^{e,X}_{e\tau}$	$[-0.90, +0.85]$	$[-0.18, +0.080]$	$[-0.81, +0.78]$	$[-0.36, +0.36]$
$\varepsilon^{e,X}_{\mu\tau}$	$[-2.1, +2.1]$	$[-0.0063, +0.016]$	$[-1.9, +1.9]$	$[-0.79, +0.81]$





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

Bounds on generic NSI

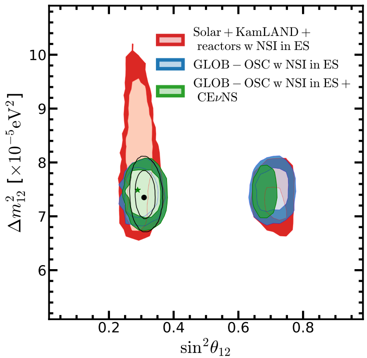
- Choose *two* angles (η, ζ) and define:

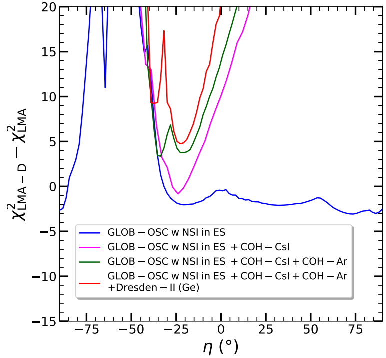
$$\varepsilon_{\alpha\beta}^{fP} \equiv \varepsilon_{\alpha\beta}^{\eta}\, \xi^{f} \chi^{P}\,, \quad \begin{cases} \xi^{e} = \sqrt{5}\cos\eta\sin\zeta\,, \\ \xi^{p} = \sqrt{5}\cos\eta\cos\zeta\,, \\ \xi^{n} = \sqrt{5}\sin\eta\,; \end{cases}$$

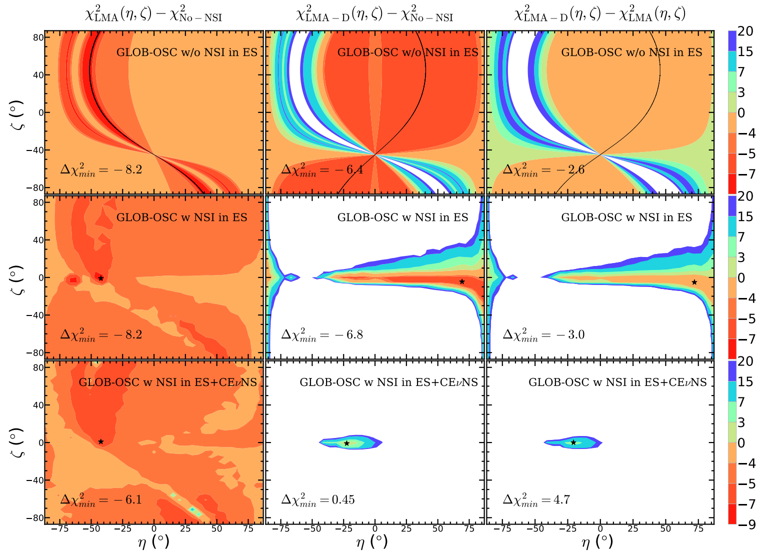
- direction of $(\xi^e, \xi^u, \xi^d) \leftrightarrow$ half-sphere.

Allowed ranges at 90% CL / 99% CL marginalized

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







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

Neutrino oscillations in the presence of extra mass states

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

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

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

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

- 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:

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

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

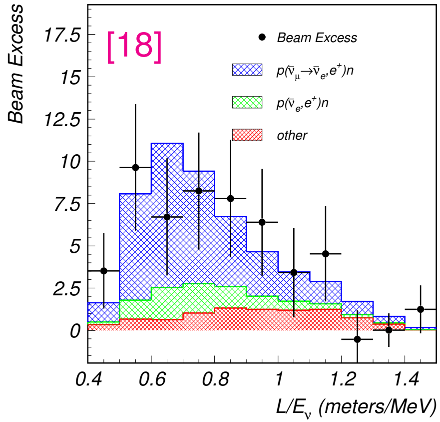
II/b. Oscillation anomalies: $\nu_\mu \to \nu_e$ appearance

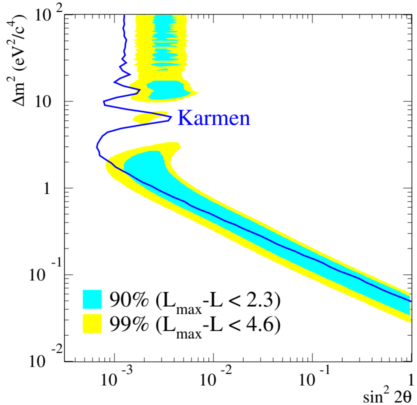
A long time ago... the LSND anomaly

- 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) [18];
- the Karmen collaboration did not confirm the claim, but couldn't fully exclude it either [19];
- 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.



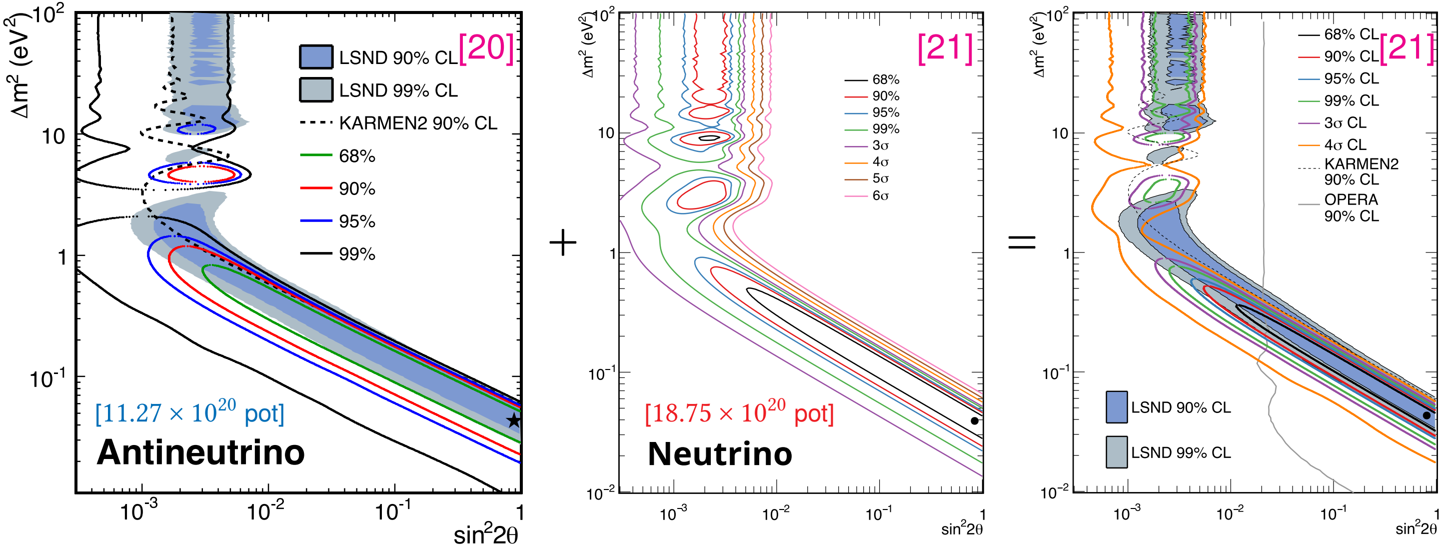


[18] A. Aguilar-Arevalo *et al.* [LSND collab], Phys. Rev. D **64** (2001) 112007 [hep-ex/0104049]

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

The MiniBooNE experiment

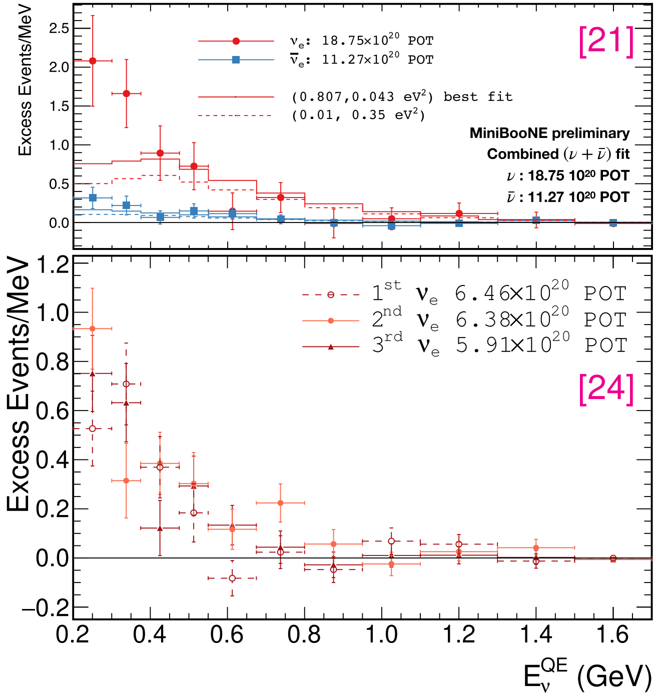
- MiniBooNE searched for $\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_\mu$ conversion ($E = 200 \to 1250$ MeV, $L \simeq 541$ m);
- excess in both $\bar\nu$ and $\nu \Rightarrow$ oscillations compatible with LSND (ev $= 4.8\sigma$, gof $= 12.3\%$);
- however, the low energy part of the excess **cannot**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



[20] A.A. Aguilar-Arevalo *et al.* [MiniBooNE collab], PRL **110** (2013) 161801 [arXiv:1303.2588]
[21] 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 [22];
- 2013 ($\bar\nu$): low-E not so steep + mid-E excess observed $\Rightarrow$ good oscillation fit ($P_{\text{osc}} \simeq 66\%$) $\Rightarrow$ **confirm** LSND [20];
- 2018 (ν): low-E softened + mid-E excess seen also in ν $\Rightarrow$ mild oscillation fit ($P_{\text{osc}} \simeq 15\%$) [23];
- 2020 (ν): more data released [24], oscillations confirmed but low-E excess definitely there.



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

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

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

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

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

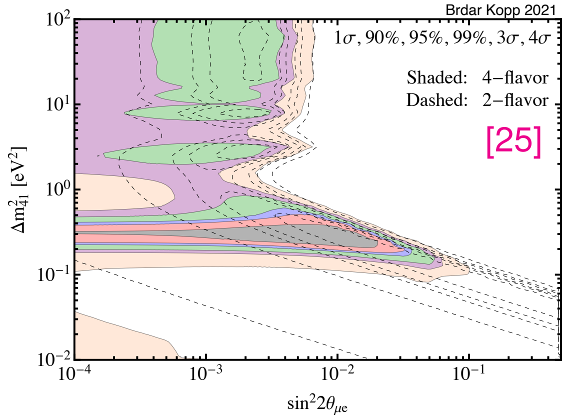
Present status of MiniBooNE

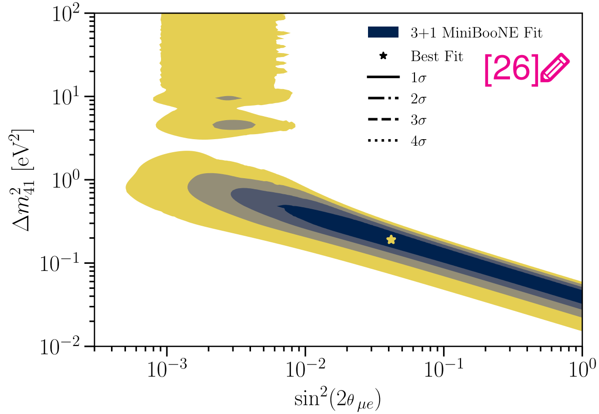
- Possible systematics related to the low-E excess:
  - misreconstruction of neutrino energy;
  - π^0 from NC reconstructed as ν_e;
  - single photon from NC misidentified as ν_e;
- extensive studies performed by the collaboration;
- present status: no combination of known systematics could account for the whole excess [25];

⇒ 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 [25];
- such effects can be very important. Omission corrected in recent reanalysis [26].





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

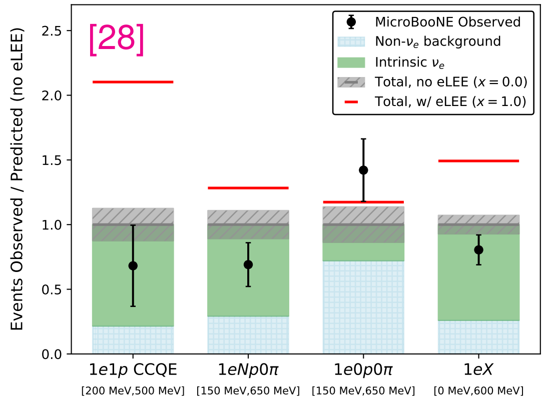
[26] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]

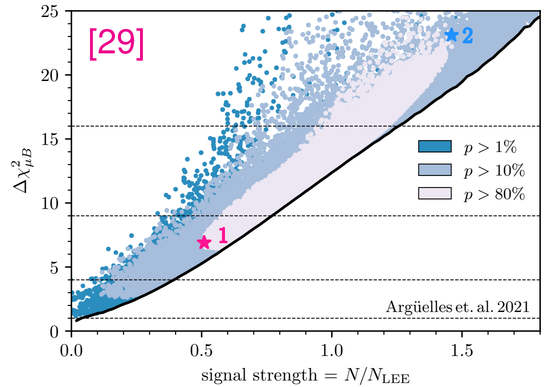
The MicroBooNE experiment

- 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 [27];
  - no evidence of ν_e excess over SM prediction [28];
- however, rejection of MB signal in [28] based on the assumption that the entire ν_e excess matches the difference between data and best-fit MB background;
- but in [29] it was noticed that various signal/background compositions can fit MB equally well, but lead to different μB sensitivity $\Rightarrow$ rejection **not** model-independent...

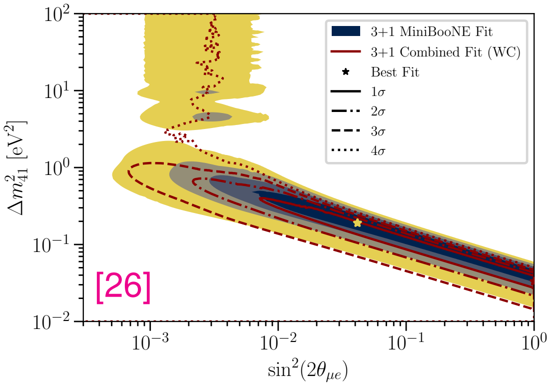


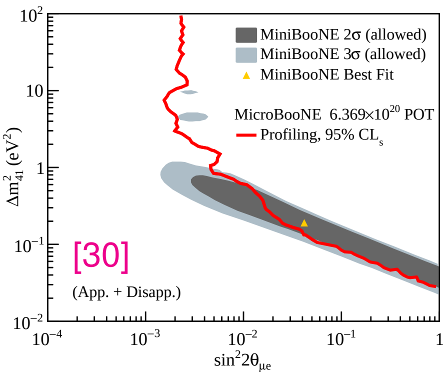


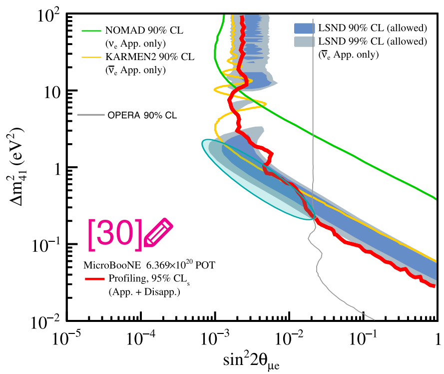
[27] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 111801 [arXiv:2110.00409]
[28] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **128** (2022) 241801 [arXiv:2110.14054]
[29] C.A. Argüelles *et al.*, Phys. Rev. Lett. **128** (2022) 241802 [arXiv:2111.10359]

Comparison of MicroBooNE and MicroBooNE results

- MiniBooNE: updated analysis including μB bounds [26] $\Rightarrow$ 3σ region at $\Delta m^2_{41} \lesssim 1$ eV;
- MicroBooNE: global 4ν analysis [30] 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;
- Japan: JSNS^2 will provide an independent check of LSND/MiniBooNE excess.





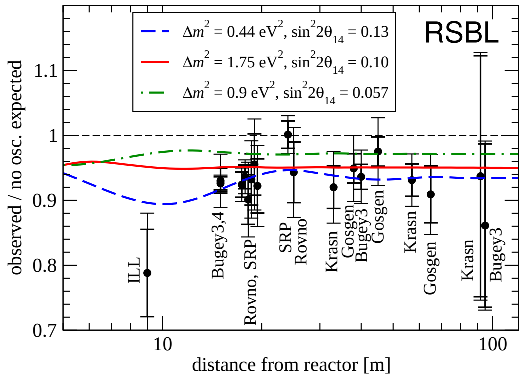


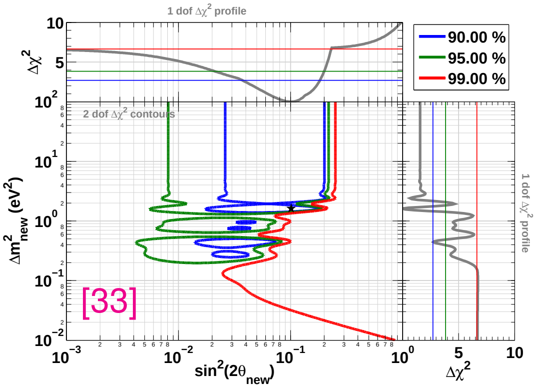
[26] A.A. Aguilar-Arevalo *et al.* [MiniBooNE], Phys. Rev. Lett. **129** (2022) 201801 [arXiv:2201.01724]
[30] P. Abratenko *et al.* [MicroBooNE], Phys. Rev. Lett. **130** (2023) 011801 [arXiv:2210.10216]

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

- In [31, 32] the reactor $\bar{\nu}$ fluxes was reevaluated;
- the new calculations result in a small increase of the flux by about **3.5%**;
- hence, **all** reactor short-baseline (RSBL) finding no evidence are actually observing a deficit;
- this deficit **could** be interpreted as being due to SBL neutrino oscillations;
- no visible dependence on $L \Rightarrow \Delta m^2 \gtrsim 1\ \text{eV}^2$;
- global data (3σ): $\begin{cases} \Delta m^2_{\text{SOL}} \simeq [6.8 \to 8.0] \times 10^{-5}\ \text{eV}^2\,, \\ |\Delta m^2_{\text{ATM}}| \simeq [2.4 \to 2.6] \times 10^{-3}\ \text{eV}^2\,; \end{cases}$

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

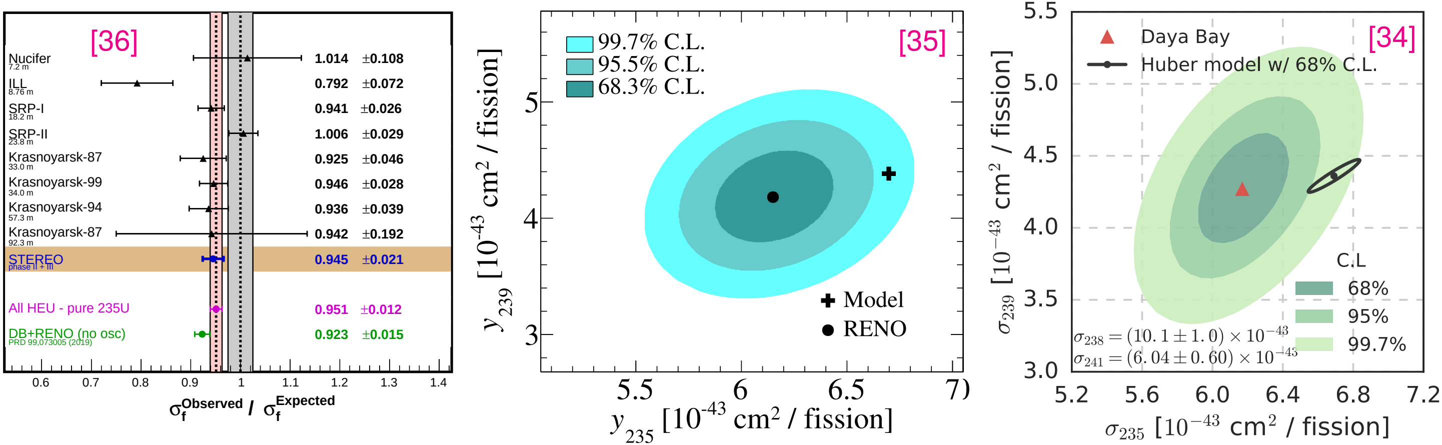




[31] T.A. Mueller *et al.*, Phys. Rev. **C83** (2011) 054615 [arXiv:1101.2663]
[32] P. Huber, Phys. Rev. C **84** (2011) 024617 [arXiv:1106.0687]
[33] G. Mention *et al.*, Phys. Rev. **D83** (2011) 073006 [arXiv:1101.2755]

Reactor anomaly: sterile ν or wrong fluxes?

- DB [34] and RENO [35]: fuel burnup cycle $\Rightarrow$ reconstruct contribution of main isotopes;
- Results: $^{239}\mathrm{Pu}$ mostly agrees with Huber-Mueller model, while $^{235}\mathrm{U}$ substantially below;
- STEREO data [36] (pure $^{235}\mathrm{U}$ reactor) indicate a deficit similar to DB and RENO ones;
- sterile ν: deficit should be the same for all isotopes $\Rightarrow$ disagrees with observations.



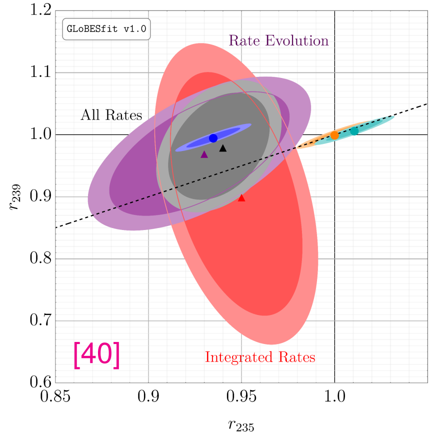
[34] F.P. An *et al.* [Daya-Bay], Phys. Rev. Lett. **118** (2017) 251801 [arXiv:1704.01082]

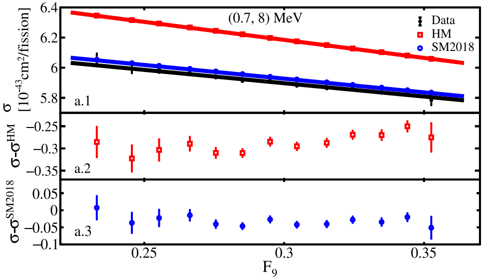
[35] G. Bak *et al.* [RENO], Phys. Rev. Lett. **122** (2019) 232501 [arXiv:1806.00574]

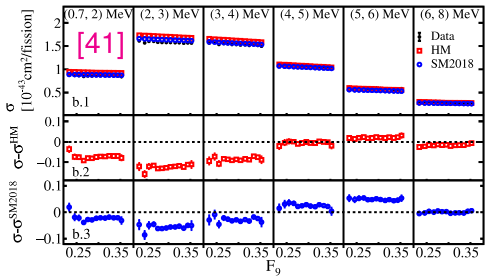
[36] H. Almazán *et al.* [STEREO], Nature **613** (2023) 257-261 [arXiv:2210.07664]

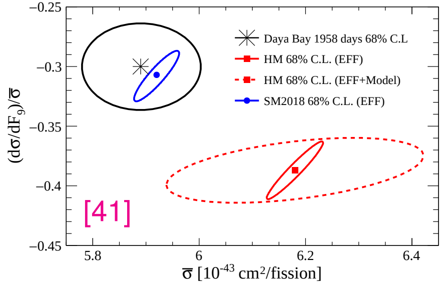
Recent improvements in reactor flux models

- New reactor flux calculations: EF [37], HKSS [38], KI [39];
- 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.





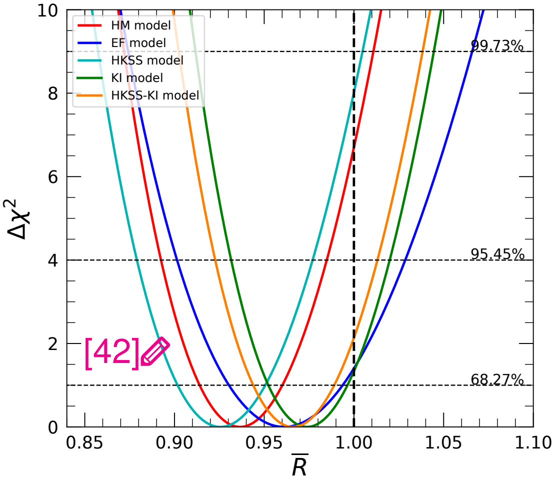


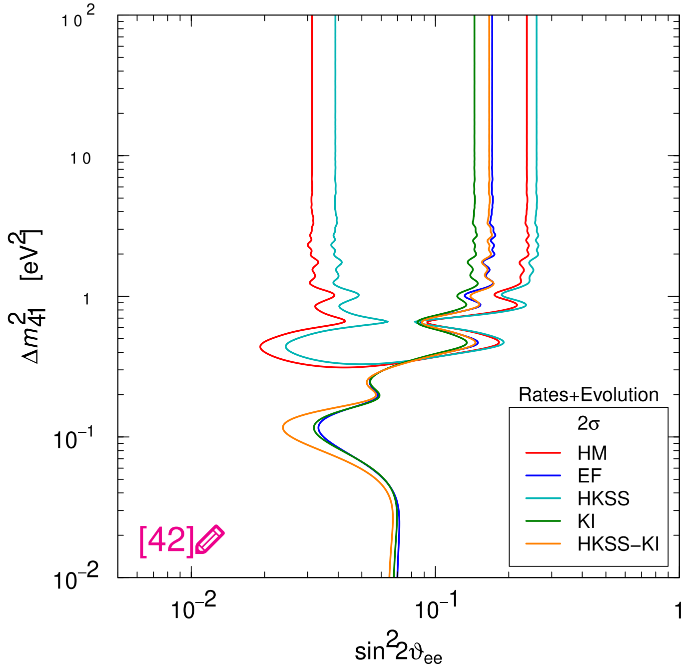


[37] M. Estienne *et al.* [EF model], Phys. Rev. Lett. **123** (2019) 022502 [arXiv:1904.09358]
[38] L. Hayen *et al.* [HKSS model], Phys. Rev. C **100** (2019) 054323 [arXiv:1908.08302]
[39] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [2103.01684]
[40] J.M. Berryman and P. Huber, JHEP **01** (2021) 167 [arXiv:2005.01756]
[41] 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. [42]: hint of sterile ν strongly reduced for EF (0.8σ) and KI (1.4σ);
- hint sizable for HM (2.8σ) and HKSS (3.0σ).





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

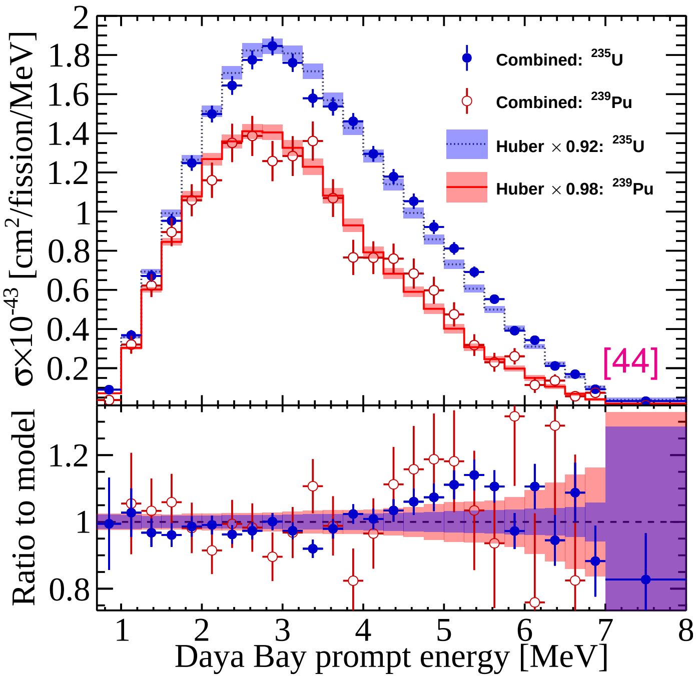
[38] L. Hayen *et al.* [HKSS model], Phys. Rev. C **100** (2019) 054323 [arXiv:1908.08302]

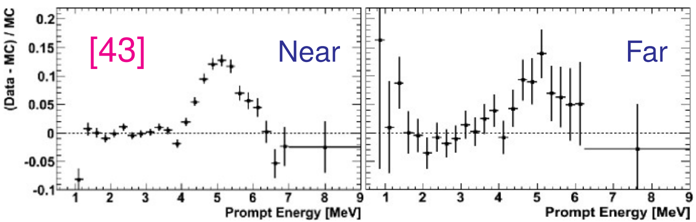
[39] V. Kopeikin *et al.* [KI model], Phys. Rev. D **104** (2021) L071301 [2103.01684]

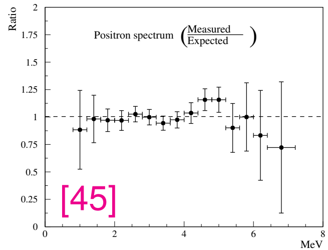
[42] C. Giunti *et al.*, Phys. Lett. B **829** (2022) 137054 [arXiv:2110.06820]

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

- Neutrino 2014: RENO [43] reported an excess of events around 5 MeV;
- seen by most reactors (also old Chooz [45]);
- DB+Prospect [44]: 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.



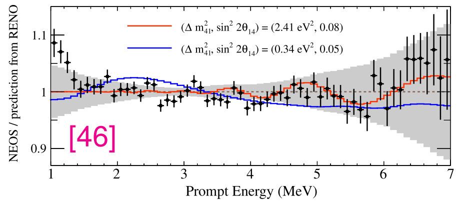


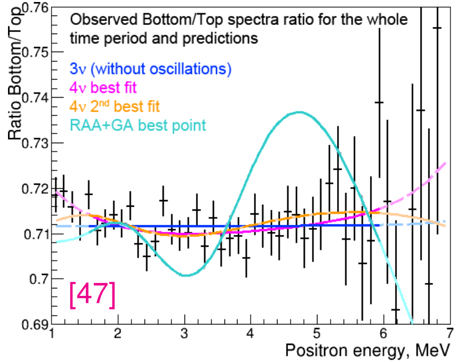


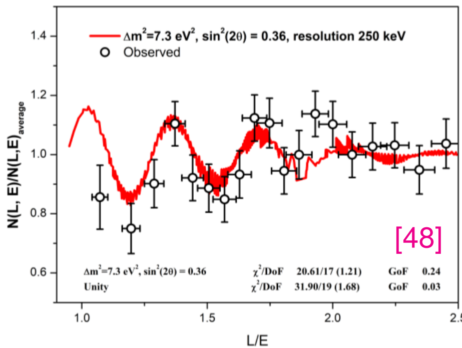
[43] S.H Seo [RENO], talk at Neutrino 2014, Boston, USA, June 2-7, 2014
[44] F.P. An *et al.* [DB+Prospect], PRL **128** (2022) 081801 [arXiv:2106.12251]
[45] M. Apollonio *et al.* [Chooz], PLB **466** (1999) 415 [hep-ex/9907037]

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.







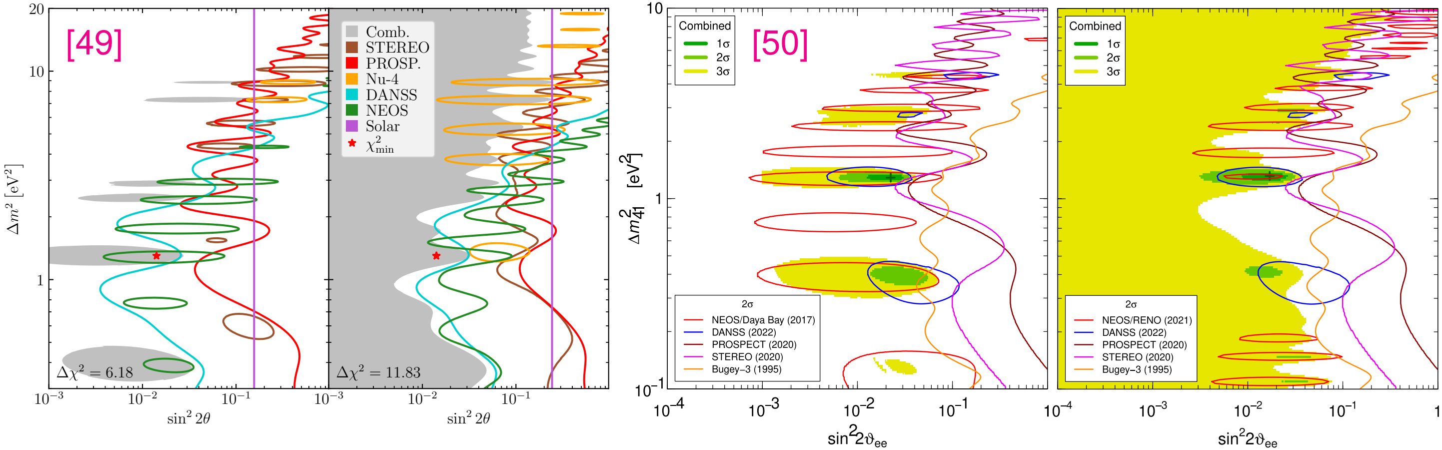
[46] Z. Atif *et al.* [NEOS & RENO], Phys. Rev. D **105** (2022) L111101 [arXiv:2011.00896]

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

[48] 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 [50];
- 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 [51] not included here.



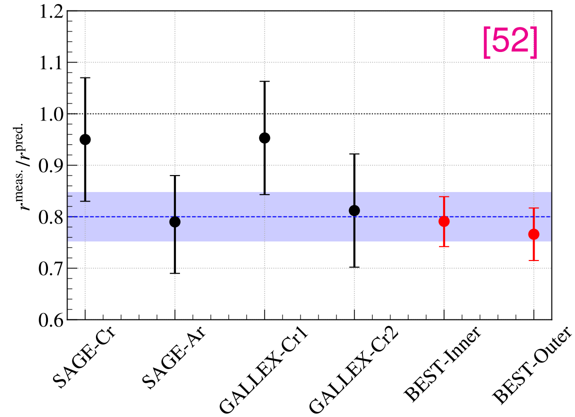
[49] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]
[50] C. Giunti *et al.*, JHEP **10** (2022) 164 [arXiv:2209.00916]
[51] D. Galbinski [SOLID], talk at TAUP 23, Vienna, Austria, 30/08/2023

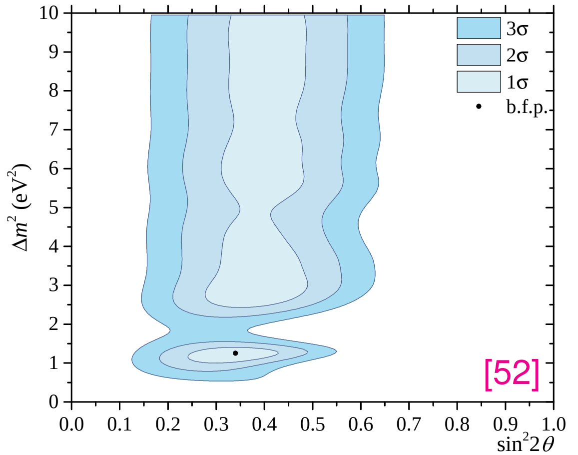
ν_e disappearance: the gallium anomaly

- $^{71}\mathrm{Ga} \to {}^{71}\mathrm{Ge}\,\nu$ 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 [52]:

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

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



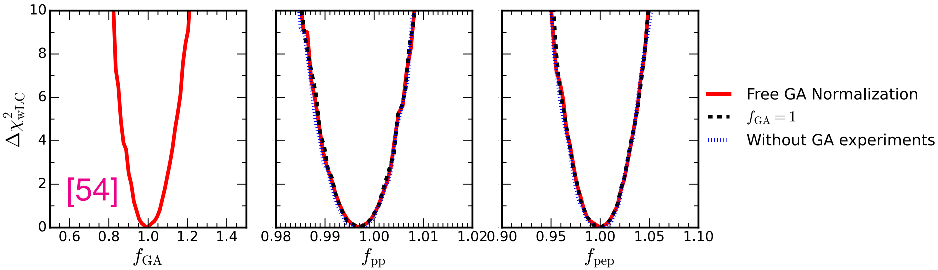


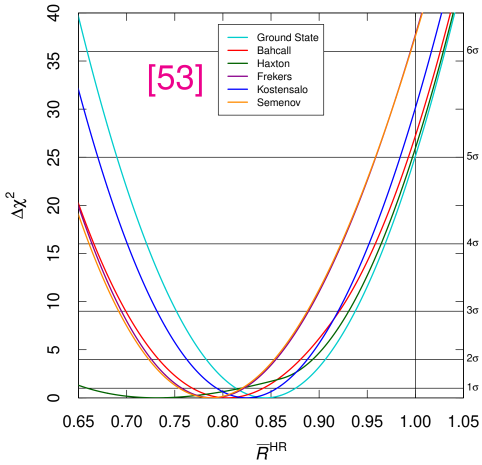
[52] V.V. Barinov *et al.* [BEST], Phys. Rev. C **105** (2022) no.6, 065502 [arXiv:2201.07364]

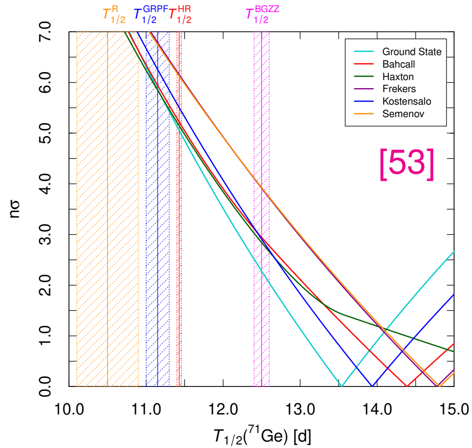
Origin of the gallium anomaly

- 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;

⇒ no obvious solution to the Gallium puzzle.





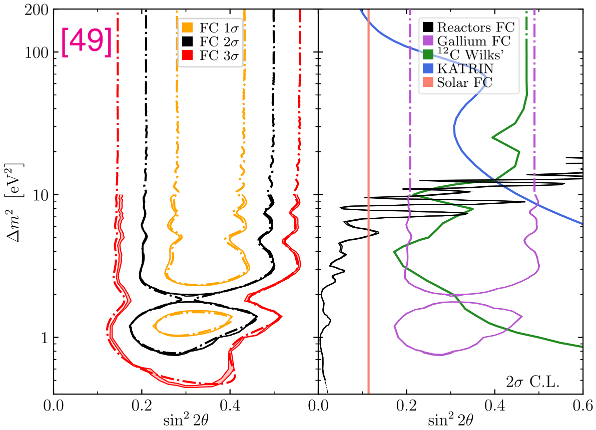


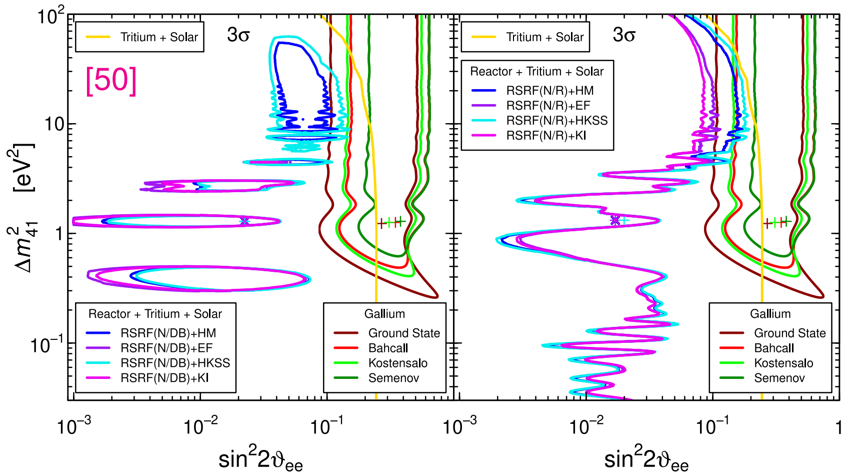
[53] C. Giunti *et al.*, Phys. Lett. B **842** (2023) 137983 [2212.09722]

[54] 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 [49];
- Gallium: FC not so important [49], but it cannot be reconciled with other data [49, 50];
- "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.



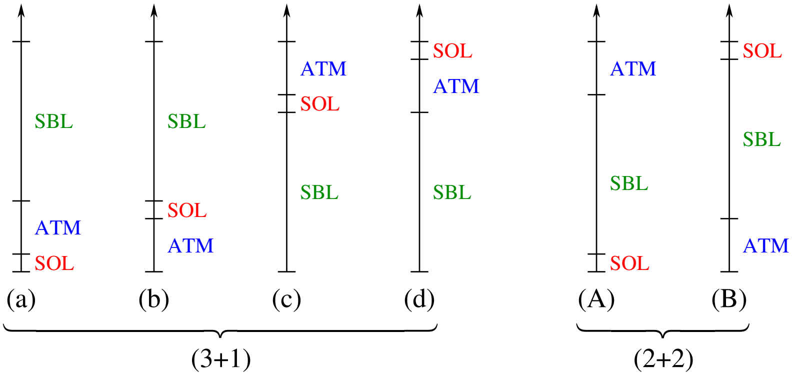


[49] J.M. Berryman *et al.*, JHEP **02** (2022) 055 [arXiv:2111.12530]

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

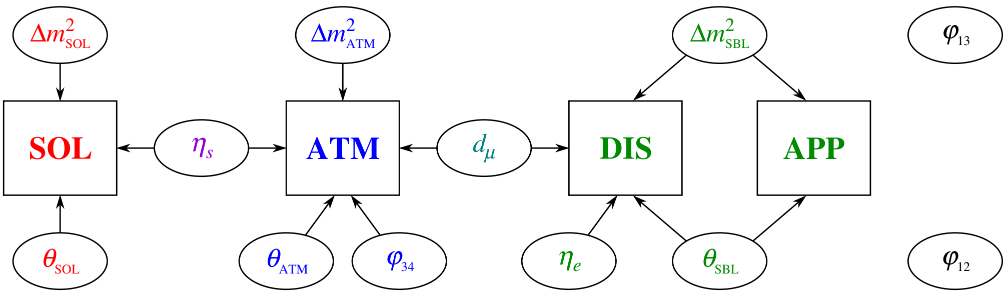
Four neutrino mass models

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

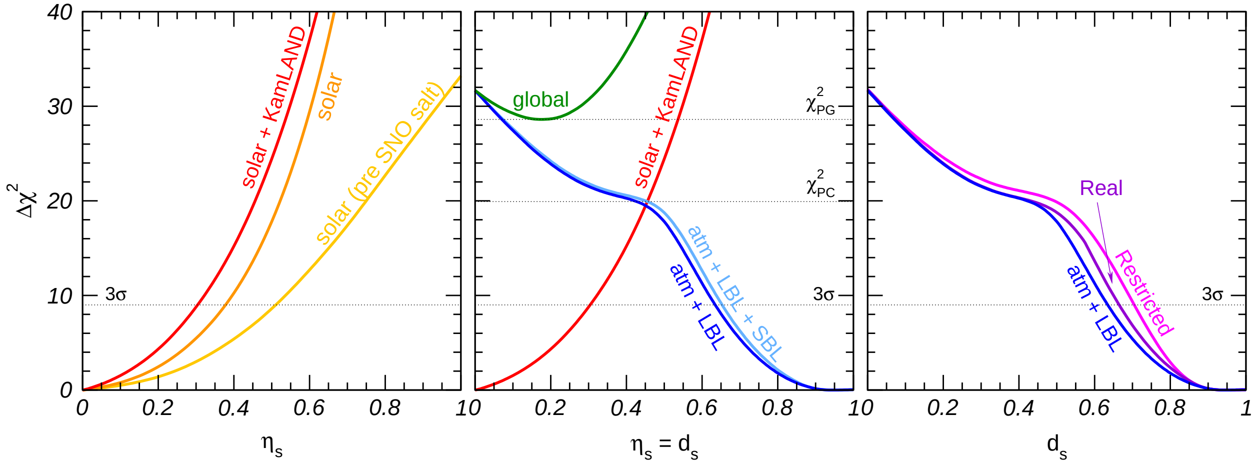


$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix}$$

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



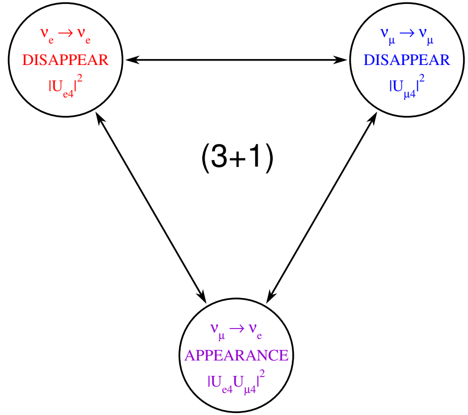
(2+2): ruled out by solar and atmospheric data



- 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 $= 9 \times 10^{-8}$ [55].

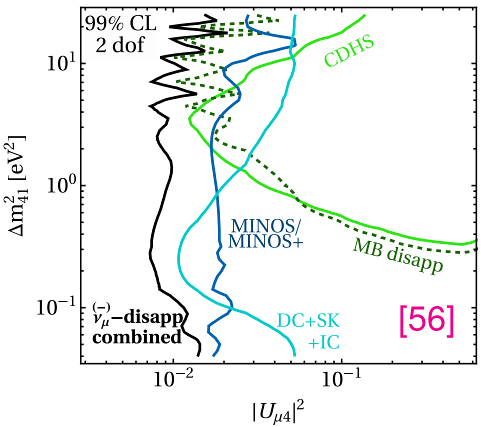
[55] M. Maltoni, T. Schwetz, M.A. Tortola, J.W.F. Valle, Nucl. Phys. **B643** (2002) 321 [hep-ph/0207157].

(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?



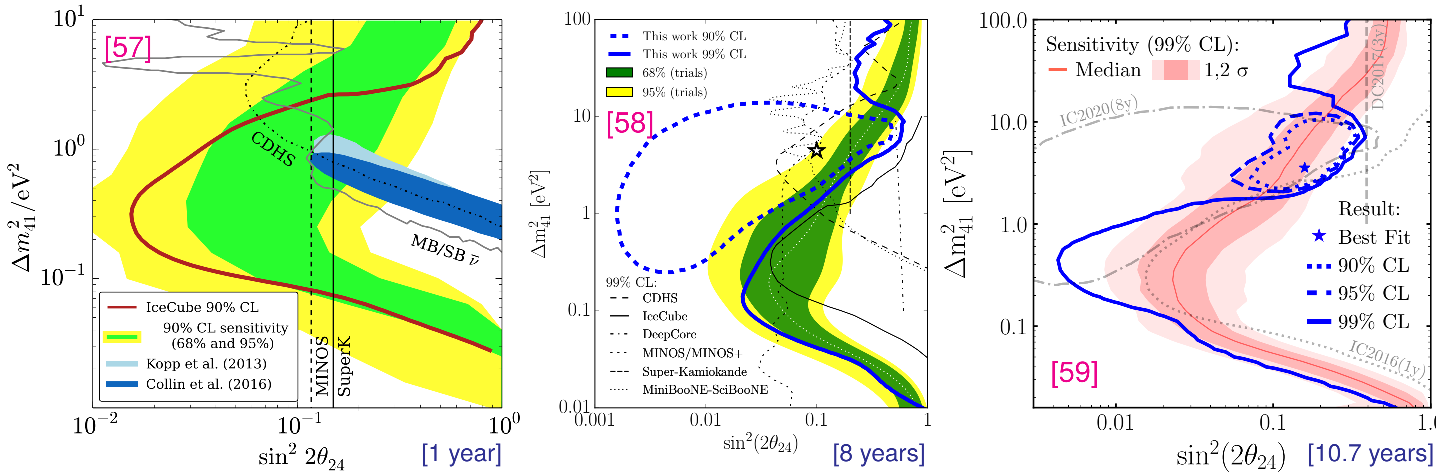
ν_μ disappearance: long-term situation

- 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…

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

Search for ν_μ disappearance at IceCube

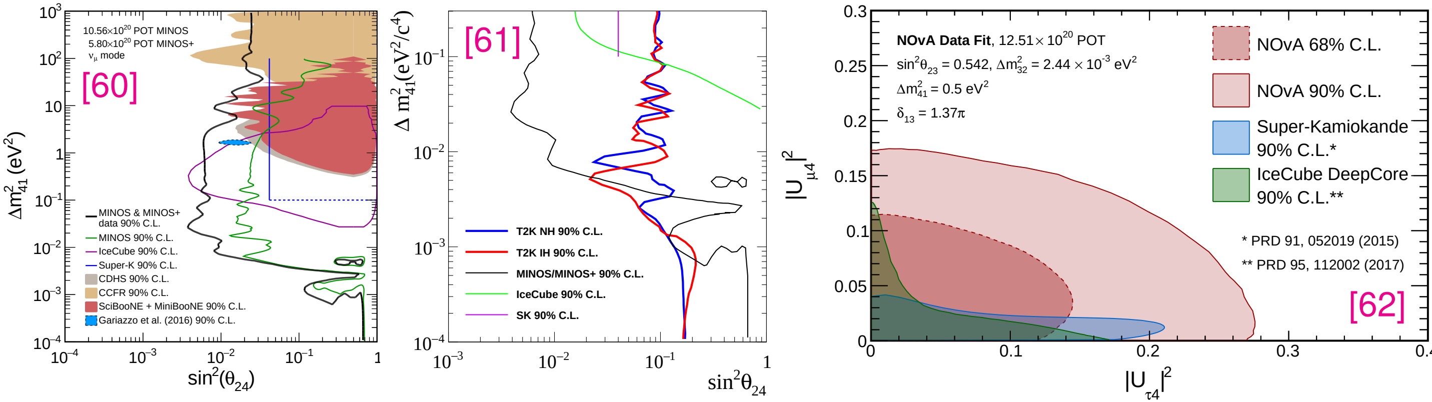
- Since oscillations only depend on $\Delta m^2/E$, larger Δm^2 produce visible effects at larger E;
- IceCube has been detecting high-energy ($\sim$ TeV) atmos. neutrinos since its construction;
- a small "island" around $\Delta m^2 \sim$ few eV^2 and $\sin^2 2\theta_{\mu\mu} \sim 0.1$ has been gaining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



[57] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **117** (2016) 071801 [arXiv:1605.01990]
[58] M.G. Aartsen *et al.* [IceCube], Phys. Rev. Lett. **125** (2020) 141801 [arXiv:2005.12942]
[59] R. Abbasi *et al.* [IceCube], arXiv:2405.08070

Search for ν_μ disappearance at LBL experiments

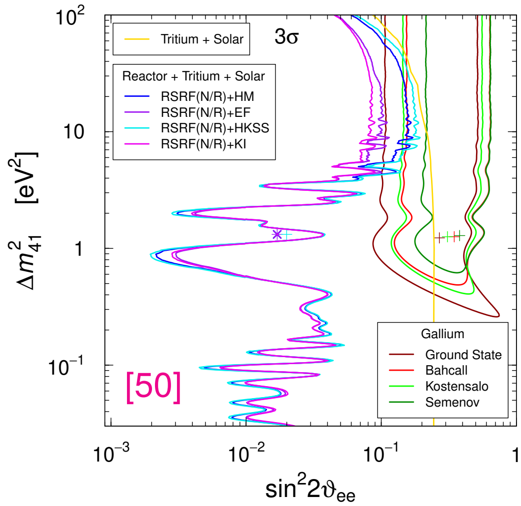
- Sterile ν can be searched at LBL experiments by "switching" the roles of near & far detectors:
  - far detector observes fully averaged oscillations $\Rightarrow$ fixes the *energy shape* of the beam;
  - near detector looks for spectral distortions which would indicate SBL oscillations;
- results presented by MINOS/MINOS+ [60], T2K [61], and NOvA [62] collaborations;
- sterile oscillations can also be studied by looking for deficit in neutral-current data [62].

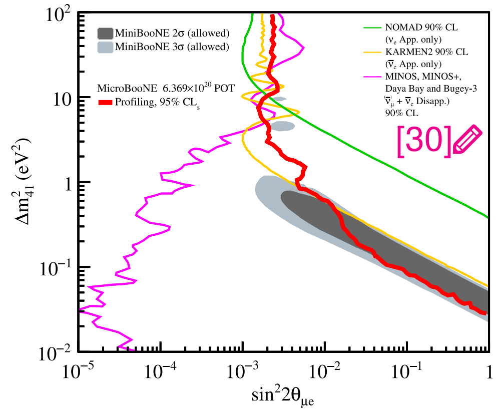


[60] P. Adamson *et al.* [MINOS+], Phys. Rev. Lett. **122** (2019) no.9, 091803 [arXiv:1710.06488]
[61] K. Abe *et al.* [T2K], Phys. Rev. D **99** (2019) no.7, 071103 [arXiv:1902.06529]
[62] M.A. Acero *et al.* [NOvA], Phys. Rev. Lett. **127** (2021) no.20, 201801 [arXiv:2106.04673]

(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 [63] 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 [64]. Full global fit in 2001 [65] cornered (3+1) models. No conceptual change since then…





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

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

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

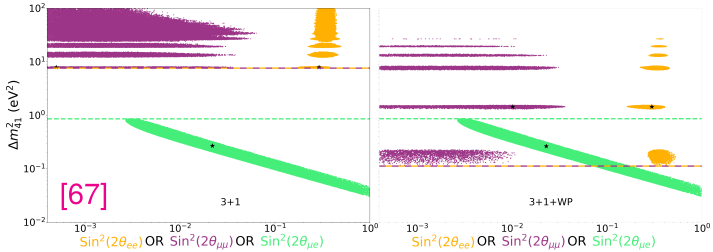
[64] S.M. Bilenky *et al.*, PRD **60** (1999) 073007 [hep-ph/9903454]

[65] 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" [67] (first noted in [66]), but tensions remain;
  - alternatives explain some (not all) data;
  - usually very "exotic" and "ad-hoc";

⇒ "vanilla ν_s" still best working tool.



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

ν_s coupled to ultralight DM (MSW resonance, Sec. 5.1.1)	several exotic ingredients; somewhat tuned MSW resonance; new ν_4 decay channel required for cosmology.	★★★★☆
ν_s coupled to dark energy (MSW resonance, Sec. 5.1.2)	several exotic ingredients; somewhat tuned MSW resonance; cosmology similar to the previous scenario.	★★★☆☆
ν_s coupled to ultralight DM (param. resonance, Sec. 5.1.3)	several exotic ingredients; somewhat tuned parametric resonance; cosmology requires post-BBN DM production via misalignment.	★★★★☆
decaying ν_s (Section 5.2)	difficult to reconcile with reactor and solar data; regeneration of active neutrinos in ν_s decays alleviates tension, but does not resolve it.	★★☆☆☆
vanilla eV-scale ν_s (Refs. [17, 18])	preferred parameter space is strongly disfavored by solar and reactor data.	★☆☆☆☆
ν_s with CPT violation (Refs. [130])	avoids constraints from reactor experiments, but those from solar neutrinos cannot be alleviated.	
extra dimensions (Refs. [131–133])	neutrinos oscillate into sterile Kaluza–Klein modes that propagate in extra dimensions; in tension with reactor data.	
stochastic neutrino mixing (Ref. [134])	based on a difference between sterile neutrino mixing angles at production and detection (see also [135, 136]); fit worse than for vanilla ν_s.	
decoherence (Refs. [137, 138])	non-standard source of decoherence needed; known experimental energy resolutions constrain wave packet length, making an explanation by wave packet separation alone challenging.	
ν_s coupled to ultralight scalar (Ref. [139])	ultralight scalar coupling to ν_s and to ordinary matter affects sterile neutrino parameters; can not avoid reactor constraints	[68]

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

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

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

Summary

- Most of the present data from solar, atmospheric, reactor and accelerator experiments are well explained by the 3ν oscillation hypothesis. The 3ν scenario is well proven and **robust**;
- however, the possibility of physics beyond the 3ν paradigm remains open (and it is even supported by a few anomalies, albeit inconclusive). Here we have focused on two mechanisms:

NC-like non-standard neutrino-matter interactions

- we have considered NSI with arbitrary ratios of couplings to e, u, d (parametrized by angles η and ζ) and a common structure of the lepton-flavor vertex (parametrized by a matrix $\varepsilon^{\eta}_{\alpha\beta}$);
- we have found that NSI **cannot** spoil the precise determination of the oscillation parameters once all the data are combined together – except for θ_{12} where a new region (LMA-D) appears;
- a 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;

Sterile neutrinos with masses in the eV range

- $\nu_e \to \nu_e$ 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;
- each anomalous data set can be **individually** explained by sterile neutrinos, but no **global** explanation of all data (or even data sharing the same oscillation channel) is possible.