Global Status of Neutrino Mixing as of Winter 2025

Rencontres de Moriond

Ivan Esteban

25st March 2025

With NuFIT: M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J.P. Pinheiro & T. Schwetz

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Introduction

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See arXiv:2410.05380 [JHEP 12(2025) 216]

Standard Model

The Standard Model is a gauge theory based on

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

and three fermion generations

$(SU(3), SU(2))_Y$				
$(1,2)_{-\frac{1}{2}}$	$(3,2)_{\frac{1}{6}}$	$(1,1)_{-1}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$\begin{pmatrix} u^i \\ d^i \end{pmatrix}_L$	e_R	u^i_R	d^i_R
$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$	$\begin{pmatrix} c^i \\ s^i \end{pmatrix}_L$	μ_R	c^i_R	s^i_R
$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$	$\begin{pmatrix} t^i \\ b^i \end{pmatrix}_L$	τ_R	t^i_R	b^i_R

with no $\nu_R \implies$ lepton flavours are *accidentally* conserved and $\boldsymbol{m_\nu = 0}$.

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There is New Physics in the lepton sector

We have observed neutrino flavour changes:

- Atmospheric ν_μ & $\bar{\nu}_\mu$ disappear, most likely to ν_τ (SK, MINOS, ICECUBE).
- Accelerator ν_μ & $\bar{\nu}_\mu$ disappear at $L \sim 300/800$ km (K2K, T2K, MINOS, NOνA).
- Some accelerator ν_μ & $\bar{\nu}_\mu$ appear as ν_e at $L \sim 300/800$ km (T2K, MINOS, NOνA).
- Some accelerator ν_μ appear as ν_τ at $L \sim 300/800$ km (OPERA).
- Solar ν_e convert to ν_μ & ν_τ (Cl, Ga, SK, SNO, Borexino).
- Reactor $\bar{\nu}_e$ disappear at $L \sim 200$ km (KamLAND).
- Reactor $\bar{\nu}_e$ disappear at $L \sim 1$ km (D-Chooz, Daya Bay, Reno).

Each lepton number is violated: **there is physics beyond the SM**.

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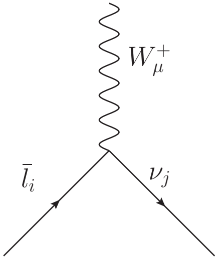
There is New Physics in the lepton sector

We have observed neutrino flavour changes (Sun, atmosphere, human-made). The minimal explanation is to give neutrinos a mass. As a consequence, leptons mix:

$$-\mathcal{L}_{CC} = \frac{g}{\sqrt{2}} W_\mu^+ \sum_{ij} \left(\boldsymbol{U_{ij}^{\text{lep}}} \bar{\ell}_{iL} \gamma^\mu \nu_{jL} + U_{ij}^{\text{CKM}} \bar{u}_{iL} \gamma^\mu d_{jL} \right) + \text{h.c.}$$



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Neutrino flavour oscillations

To parametrise the new physics, **flavour oscillations** are a unique experimental window.

$$|\nu_\alpha(0)\rangle = \sum_i U^{\text{lep}\,*}_{\alpha i} |\nu_i\rangle \Rightarrow |\nu_\alpha(L)\rangle \simeq \sum_i U^{\text{lep}\,*}_{\alpha i} e^{-i\frac{m_i^2 L}{2E}} |\nu_i\rangle$$

$|\nu_i\rangle$ interfere:

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_{i<j}^{n} \mathrm{Re}\left[U^{\text{lep}}_{\alpha i} U^{\text{lep}*}_{\beta i} U^{\text{lep}*}_{\alpha j} U^{\text{lep}}_{\beta j}\right] \sin^2\frac{\Delta m^2_{ij} L}{4E} + 2\sum_{i<j}^{n} \mathrm{Im}\left[U^{\text{lep}}_{\alpha i} U^{\text{lep}*}_{\beta i} U^{\text{lep}*}_{\alpha j} U^{\text{lep}}_{\beta j}\right] \sin\frac{\Delta m^2_{ij} L}{2E}$$

For 2ν, $P_{\text{osc}} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$, **insensitive to $\boldsymbol{\theta}$ octant and $\boldsymbol{\Delta m^2}$ sign**.

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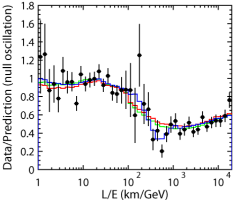
Travelling in matter, ν_e get a potential $V_{\nu_e} = \sqrt{2} G_F n_e$,

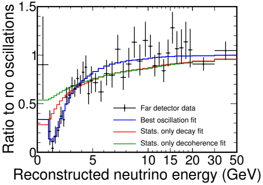
$$i\frac{d}{dx}\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle\end{pmatrix} = H_{\text{eff}}\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle\end{pmatrix} \;;\; H_{\text{eff}} = \begin{pmatrix}\sqrt{2}G_F n_e & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0\end{pmatrix} + \frac{1}{2E} U^{\text{lep}} \begin{pmatrix} m_1^2 & 0 & \\ 0 & m_2^2 & \\ & & \ddots \end{pmatrix} U^{\text{lep}\dagger}$$

Experimental knowledge

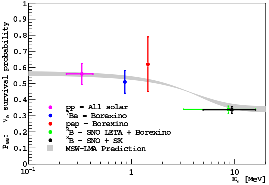
We need 3 light neutrinos



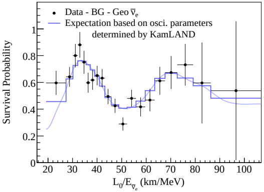
Atmospheric ν in SK



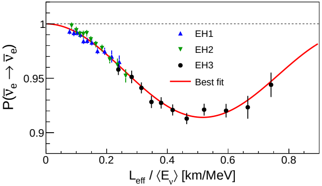
Accelerator ν in MINOS (L=735 km)



Solar ν (MSW conversion)



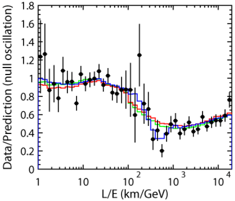
Reactor $\bar{\nu}$ in KamLAND



Reactor $\bar{\nu}$ in Daya Bay

Experimental knowledge

We need 3 light neutrinos



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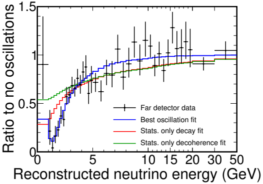

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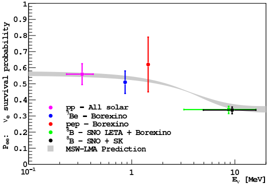

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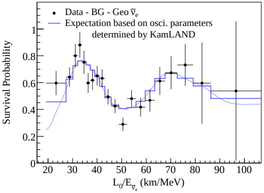
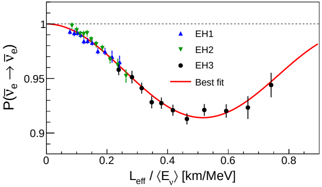


Reactor $\bar{\nu}$ in KamLAND



Reactor $\bar{\nu}$ in Daya Bay

Sun
$$\begin{cases} \Delta m^2 \sim 10^{-5}\text{eV}^2 \\ \theta \sim 30^\circ \end{cases}$$

Atm. Accel.
$$\begin{cases} \Delta m^2 \sim 10^{-3}\text{eV}^2 \\ \theta \sim 45^\circ \end{cases}$$

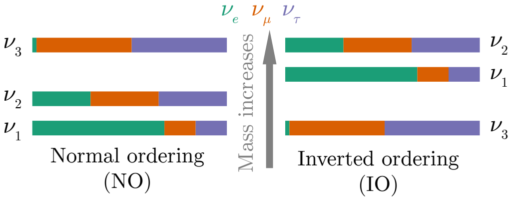
Reac.
$$\begin{cases} \Delta m^2 \sim 10^{-5}\text{eV}^2 \\ \theta \sim 30^\circ \\ \Delta m^2 \sim 10^{-3}\text{eV}^2 \\ \theta \sim 9^\circ \end{cases}$$

Experimental knowledge

Parametrisation and open questions

Gonzalez-Garcia, Maltoni, Martinez-Soler, Pinheiro, Schwetz, **IE** *JHEP* **12**(2025) 216. NuFIT 6.0, www.nu-fit.org.

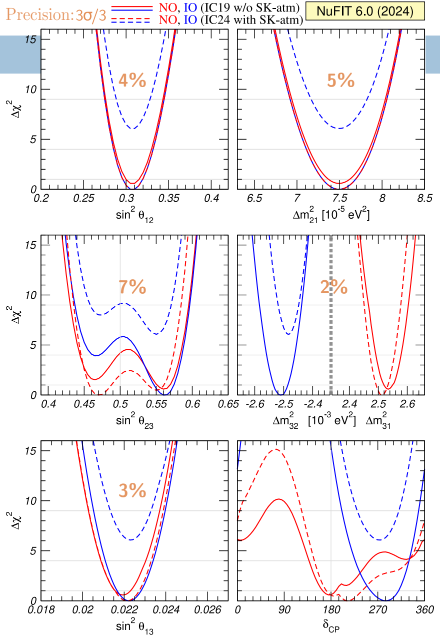
We are now measuring three-neutrino effects,



- $\theta_{23} < 45°$? $\theta_{23} > 45°$?
- CP violation?

$$P_{\nu_\alpha \to \nu_\beta} - P_{\bar\nu_\alpha \to \bar\nu_\beta} \propto J_{\text{lep}} = c_{12} c_{23} c_{13}^2 s_{12} s_{23} s_{13} \sin\delta_{\text{CP}} = (0.0333 \pm 0.0006) \sin\delta_{\text{CP}}$$

which also assess **the global consistency of the framework**.



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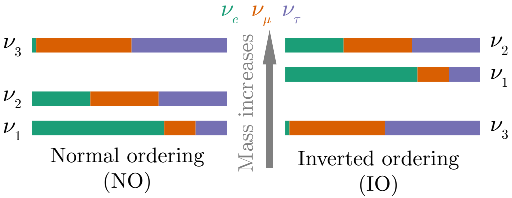

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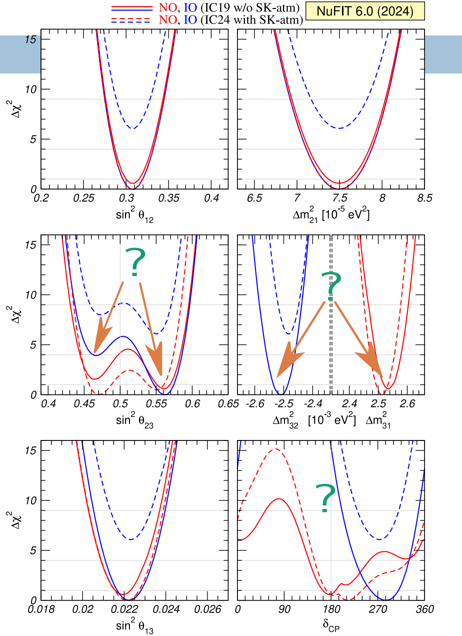

1-2 sector

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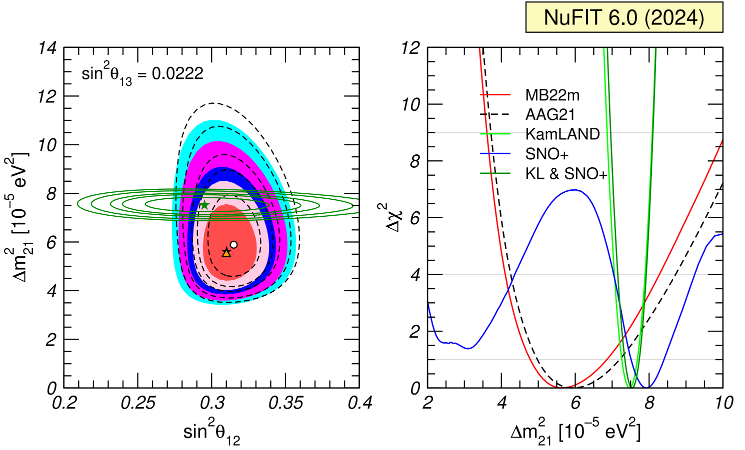
Dominated by solar neutrinos & long baseline reactors (KamLAND).

Very different environments!

- Solar neutrino modeling updated
  Modern methodology, in agreement with helioseismology (Magg et al, 2203.02255)
- SNO+ data!



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Mass ordering

We can determine $\Delta m^2_{3\ell}$ in

- LBL, through $\nu_\mu \to \nu_\mu$

$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{\mu\mu} L}{4E}\right)$$

$$\Delta m^2_{\mu\mu} \simeq \Delta m^2_{3\ell} + \begin{cases} -\cos^2\theta_{12}\Delta m^2_{21} & \text{for NO} \\ \sin^2\theta_{12}\Delta m^2_{21} & \text{for IO} \end{cases}$$

- Reactors, through $\bar{\nu}_e \to \bar{\nu}_e$

$$P_{ee} \simeq 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

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Petcov, Piai, hep-ph/0112074 (2002)
Choubey, Petcov, Piai, hep-ph/0306017 (2003)
Nunokawa, Parke, Zukanovich-Funchal, hep-ph/0503283 (2005)

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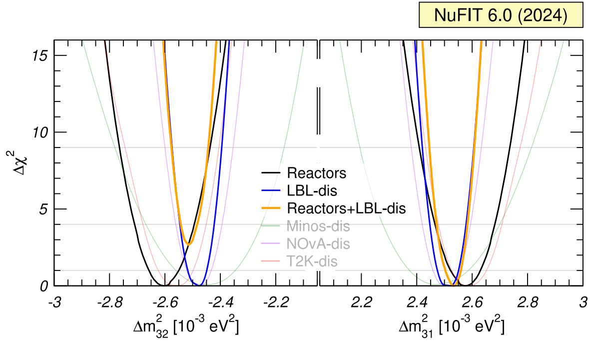

3ν effects

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Mass ordering, δ_{CP}, θ_{23} octant

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta_{31}(1-A)}{(1-A)^2} + \frac{\Delta_{21}}{\Delta_{31}} 8J_{\text{lep}}^{\max}\cos(\Delta_{31}+\delta_{\text{CP}})\frac{\sin\Delta_{31}A}{A}\frac{\sin\Delta_{31}(1-A)}{(1-A)} + \mathcal{O}\left(\frac{\Delta_{21}}{\Delta_{31}}\right)^2$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

$$(\Delta_{31}\sim 1, \Delta_{21}\sim 10^{-2})$$

$$A = 2\sqrt{2}G_F n_e\frac{E}{\Delta m_{31}^2}$$

$$J_{\text{lep}}^{\max} = \frac{1}{8}c_{13}^2 s_{13} c_{12} s_{12} c_{23} s_{23}$$

Strongly correlated: we need as much data and independent determinations as possible!

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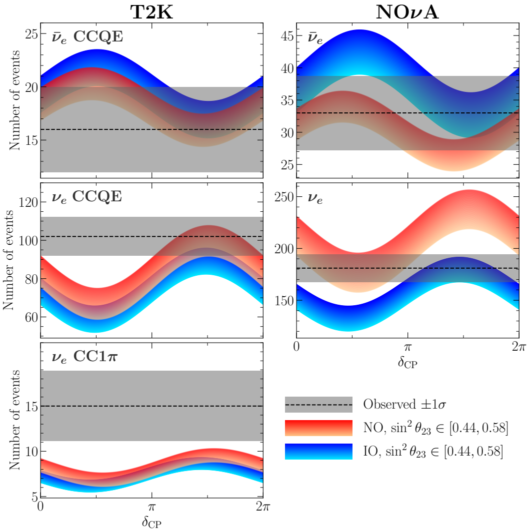
T2K vs NOνA



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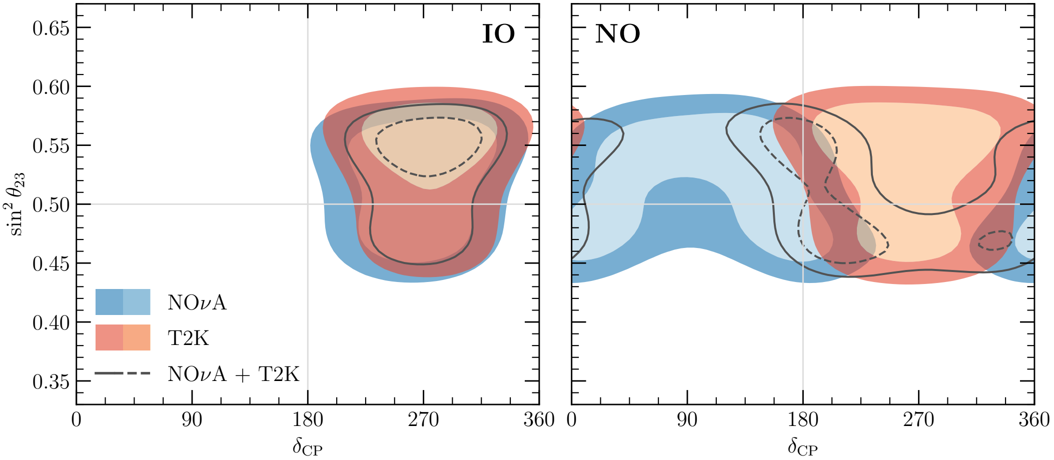

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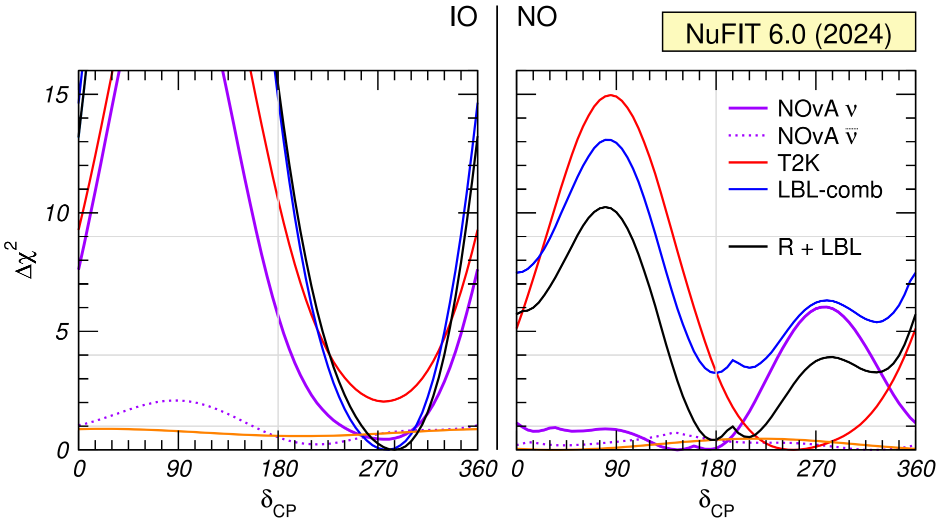

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T2K vs NOνA: is there a tension?

There are two main "tensions" in the data:

- Reactors vs accelerators *in IO*
- NOνA vs T2K *in NO*

Can we claim that the 3ν framework does not consistently explain all data?

Do we need additional New Physics?

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M. Maltoni and T. Schwetz, "Testing the statistical compatibility of independent data sets," Phys. Rev. D **68**, 033020 (2003) arXiv:hep-ph/0304176.

- T2K vs NOνA, *NO*: 2σ ($\mathbf{p \sim 0.045}$)
- Reactors vs (T2K+NOνA), *IO*: 1.4σ ($\mathbf{p \sim 0.16}$)

At most 2σ. But there's many other data combinations (see the paper)

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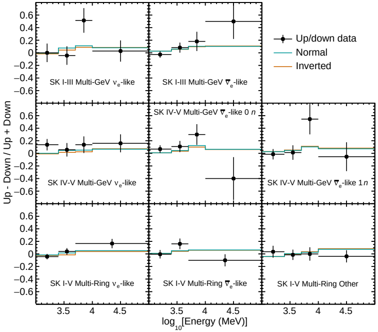
Atmospheric neutrino samples, and more on the mass ordering

For atmospheric neutrinos, we do not have enough information to reproduce the analysis. We have to use χ^2 tables.

- **Super-K** (arXiv:2311.05105): $\sim 2\sigma$ rejection of IO.



But data is not particularly compatible with NO either

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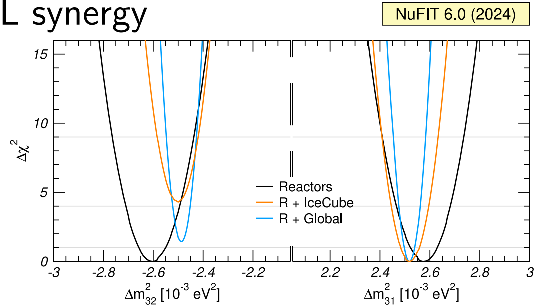
- **Super-K** (arXiv:2311.05105): $\sim 2\sigma$ rejection of IO.
- **IceCube** (arXiv:2405.02163): the determination of Δm^2_{32} adds up to the reactor-LBL synergy



With *both* tables, NO is preferred with $\sim 2.5\sigma$.

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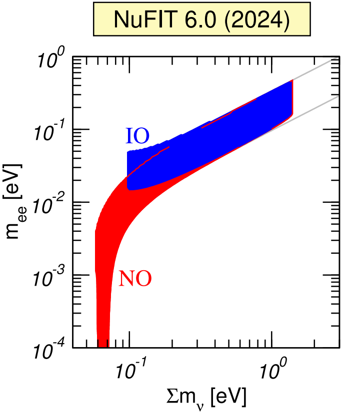
Some consequences for the global picture

The mass ordering is relevant for absolute neutrino mass searches.



- **$0\nu\beta\beta$**: depending on nuclear matrix elements,
  $m_{ee} \lesssim 0.08$–$0.18\,\text{eV}$ (Ge, GERDA, 2009.06079)
  $m_{ee} \lesssim 0.028$–$0.12\,\text{eV}$ (Xe, KamLAND-Zen, 2406.11438)
- **Cosmology**: depending on datasets and modeling, $\sum m_\nu \lesssim 0.04$–$0.3\,\text{eV}$.

Conclusions

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- We are currently testing and **overconstraining** the 3ν paradigm.
  Either a robust understanding of Nature or a surprise awaits!
- Most parameters are determined within $\sim 5\%$.
- A reactors + LBL tension in $\Delta m^2_{3\ell}$ *within IO* gives a $\sim 2\sigma$ preference for NO.
- A NOνA + T2K tension in $\delta_{\rm CP}$ *within NO* gives a $\sim 2\sigma$ preference for IO.
- The global analysis is at the *maximal confusion level*, with 1σ–2σ hints not pointing in the same direction,
  - Only after adding IceCube and *Super-K* tables, there is preference for NO.
  - For NO, CP conservation is favored. For IO, maximal CP violation.
  - No clear preference for θ_{23} octant.
- Stay tuned!

Thanks to the rest of the NuFIT collaboration: M.C. Gonzalez-Garcia, M. Maltoni, I. Martinez-Soler, J. P. Pinheiro, T. Schwetz. And thanks to the great work by the experimental collaborations!