Status of neutrino masses and mixings

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Phenomenology of Lepton Masses and Mixing with Discrete Flavor Symmetries

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From neutrino hypothesis to oscillations

1. Neutrino hypothesis:
   - W.Pauli (1930): β-decay, a three-body process - proposal of "neutron";
   - J.Chadwick (1932): discovery of neutron;
   - E.Fermi (1934): $n \longrightarrow p + e^{-} + \bar{\nu}$;
2. Neutrino detection:
   - F.Reines and C.L. Cowan experiments (1953-59): $\bar{\nu} + p \longrightarrow e^{+} + n$;
3. Solar neutrino problem:
   - R. Davis et al. (1972): flux of the solar ν_e's was (2-3) times smaller than expected;
4. Neutrino oscillations:
   - $P(\nu_f \rightarrow \nu_f) < 1$;

arXiv:1210.3065

Nobel Prize in Physics for 2015 to Takaaki Kajita and Arthur B. McDonald
"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

Neutrino mixing

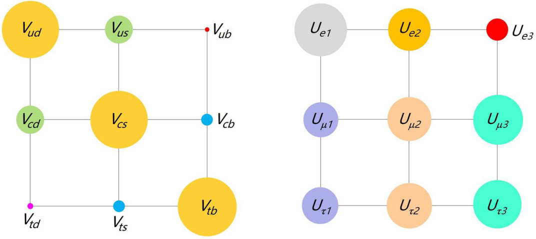
Neutrino flavor and mass eigenstates are related by

$$|\nu_\alpha\rangle = \mathrm{U}_{\alpha i}\,|\nu_i\rangle$$

Pontecorvo–Maki–Nakagawa–Sakata parametrization of mixing matrix

$$\mathrm{U}_{\mathrm{PMNS}} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{i\delta} \\ s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{s3} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{bmatrix} \begin{bmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

where $c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $\delta \equiv \delta_{\mathrm{CP}}$.

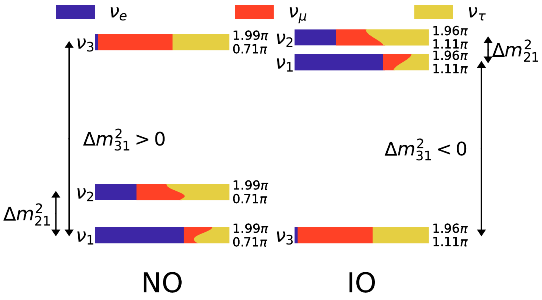


(a) CKM quark flavor mixing (b) PMNS lepton flavor mixing

Taken from arXiv:2210.11922, Figure 2.

Mass ordering, $m_0 = m_{lightest}$

Normal mass ordering (NO)	Inverted mass ordering (IO)
$m_1 = m_0,$	$m_1 = \sqrt{m_0^2 - \Delta m_{21}^2} - \Delta m_{32}^2,$
$m_2 = \sqrt{m_0^2 + \Delta m_{21}^2},$	$m_2 = \sqrt{m_0^2 - \Delta m_{32}^2},$
$m_3 = \sqrt{m_0^2 + \Delta m_{31}^2},$	$m_3 = m_0,$



Taken from https://globalfit.astroparticles.es, updated arXiv:1806.11051, Figure 1

Oscillation data, with SK

Parameter	Ordering	NuFIT 5.2 (2022)		de Salas et al. (2021)		Capozzi et al. (2021)	
		bf$\pm 1\sigma$	3σ range	bf$\pm 1\sigma$	3σ range	bf$\pm 1\sigma$	3σ range
$\sin^2\theta_{12}/10^{-1}$	NO, IO	$3.03^{+0.12}_{-0.12}$	2.70 — 3.41	$3.18^{+0.16}_{-0.16}$	2.71 — 3.69	$3.03^{+0.13}_{-0.13}$	2.63 — 3.45
$\sin^2\theta_{23}/10^{-1}$	NO	$4.51^{+0.19}_{-0.16}$	4.08 — 6.03	$5.74^{+0.14}_{-0.14}$	4.34 — 6.10	$4.55^{+0.18}_{-0.15}$	4.16 — 5.99
θ_{23} octant	IO	$5.69^{+0.16}_{-0.21}$	4.12 — 6.13	$5.78^{+0.10}_{-0.17}$	4.33 — 6.08	$5.69^{+0.12}_{-0.21}$	4.17 — 6.06
$\sin^2\theta_{13}/10^{-2}$	NO	$2.225^{+0.056}_{-0.059}$	2.052 — 2.398	$2.200^{+0.069}_{-0.062}$	2.000 — 2.405	$2.23^{+0.07}_{-0.06}$	2.04 — 2.44
$\neq 0$	IO	$2.223^{+0.058}_{-0.058}$	2.048 — 2.416	$2.225^{+0.064}_{-0.070}$	2.018 — 2.424	$2.23^{+0.06}_{-0.06}$	2.03 — 2.45
δ_{CP}/π	NO	$1.29^{+0.20}_{-0.14}$	0.80 — 1.94	$1.08^{+0.13}_{-0.12}$	0.71 — 1.99	$1.24^{+0.18}_{-0.13}$	0.77 — 1.97
can be 0?	IO	$1.53^{+0.12}_{-0.16}$	1.08 — 1.91	$1.58^{+0.15}_{-0.16}$	1.11 — 1.96	$1.52^{+0.15}_{-0.11}$	1.07 — 1.90
$\Delta m^2_{21}/10^{-5}\mathrm{eV}^2$	NO, IO	$7.41^{+0.21}_{-0.20}$	6.82 — 8.03	$7.50^{+0.22}_{-0.20}$	6.94 — 8.14	$7.36^{+0.16}_{-0.15}$	6.93 — 7.93
$\lvert\Delta m^2_{\mathrm{atm}}\rvert/10^{-3}\mathrm{eV}^2$	NO	$2.507^{+0.026}_{-0.027}$	2.427 — 2.590	$2.55^{+0.02}_{-0.03}$	2.47 — 2.63	$2.485^{+0.023}_{-0.031}$	2.401 — 2.565
	IO	$2.486^{+0.028}_{-0.025}$	2.406 — 2.570	$2.45^{+0.02}_{-0.03}$	2.37 — 2.53	$2.455^{+0.030}_{-0.025}$	2.376 — 2.541
$\Delta\chi^2$	IO - NO	6.4		6.4		6.5	

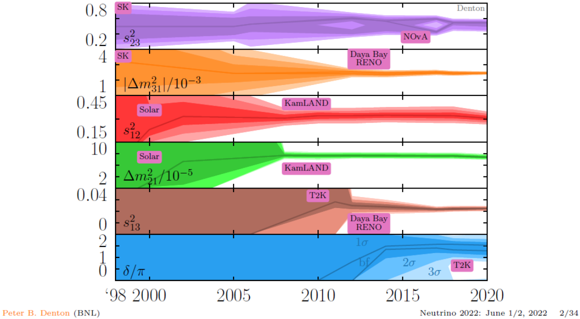
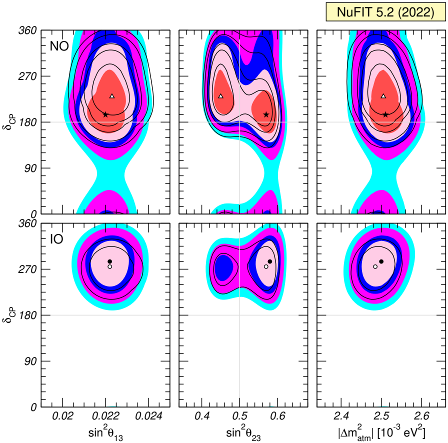


Figure taken form Peter B. Denton talk, link here.

NuFIT 5.2 (2022)

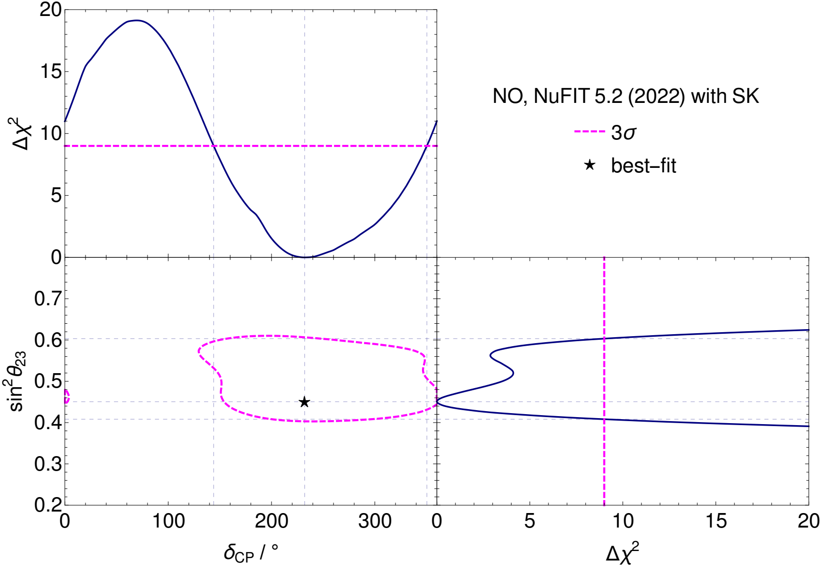
NuFIT 5.2 (2022)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
	$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
	$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
	$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
	$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
		bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
	$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
	$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
	$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
	$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
	$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
	$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$



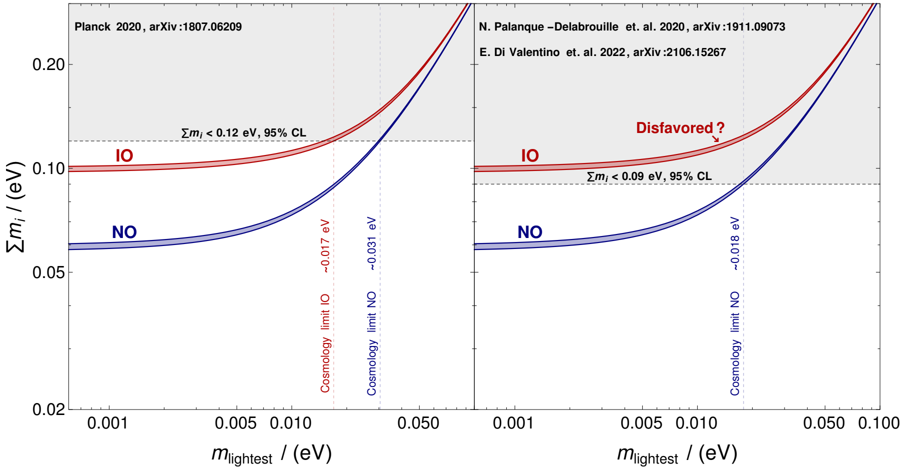
Taken from http://www.nu-fit.org, updated arXiv:2007.14792

NO, NuFIT 5.2 (2022) with SK, 3σ, 1 dof *vs.* 2 dof



3σ, nonzero $\delta_{\rm CP}$? 1 dof *vs.* 2 dof.

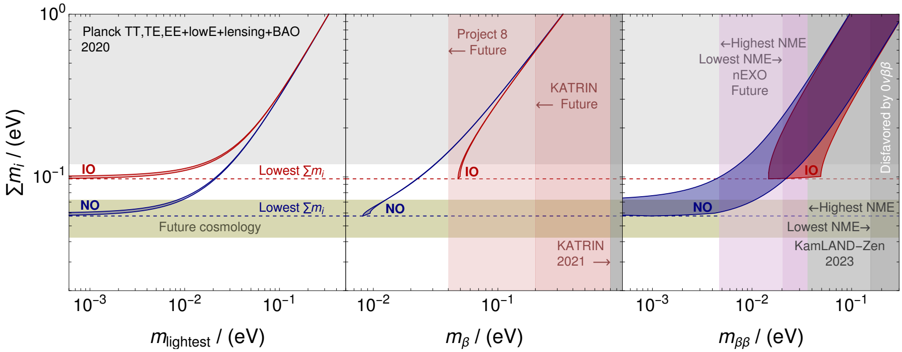
Neutrino mass - cosmology



Is IO disfavored?

see also: Peter B. Denton talk (link), Julien Lesgourgues talk (link).

Effective neutrino mass

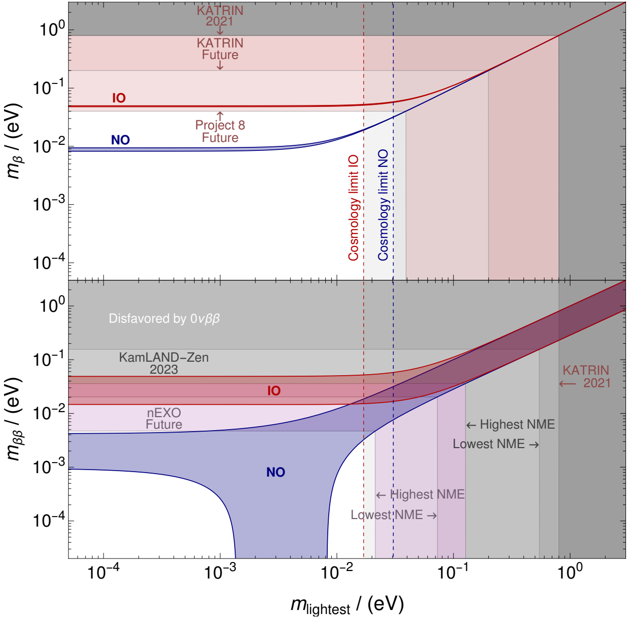


Planck: $\sum_i m_i < 0.12$ eV, 95% CL, arXiv:1807.06209

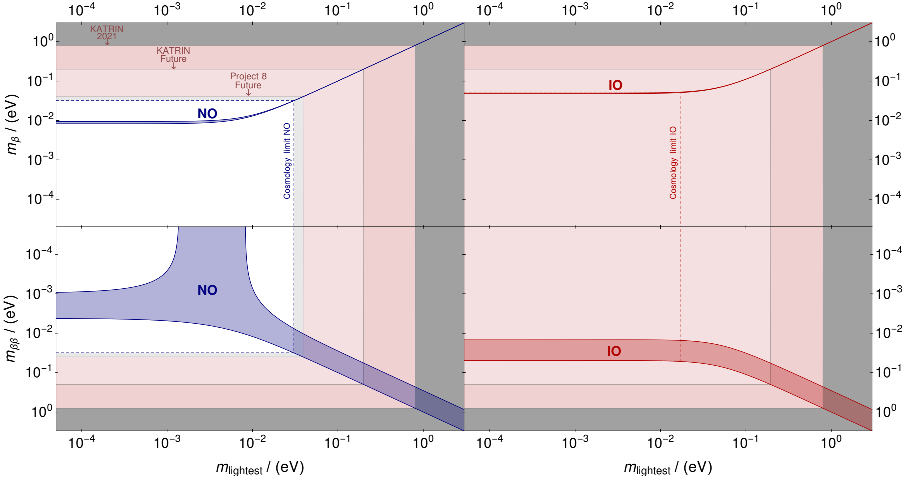
KATRIN: $m_\beta < 0.8$ eV, 90% CL, arXiv:2105.08533

KamLAND-Zen: $m_{\beta\beta} <$ (0.036 to) 0.156 eV, 90% CL, arXiv:2203.02139

Effective neutrino mass

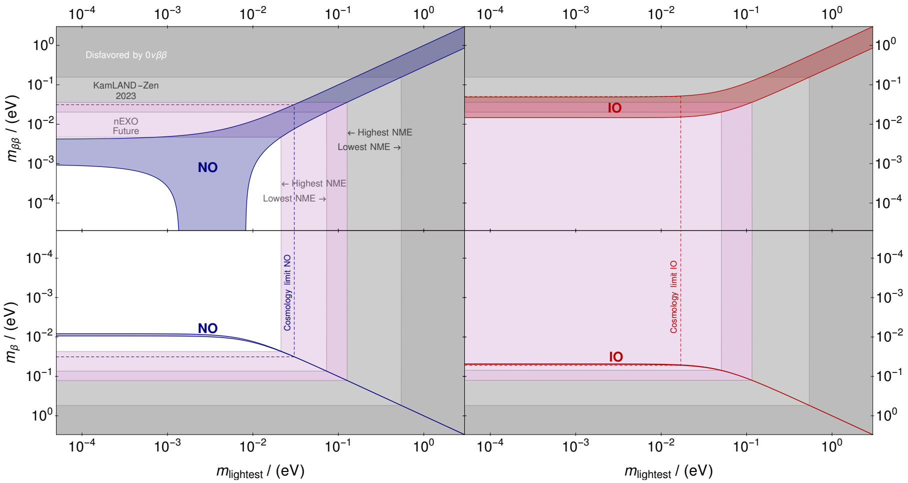


m_β projections



KATRIN limit $m_\beta < 0.8$ eV projection via $m_{lightest}$: $m_{\beta\beta} < 0.8$ eV for NO/IO.

$m_{\beta\beta}$ projections



KamLAND-Zen limit $m_{\beta\beta} <$ (0.036 to) 0.156 eV projection via $m_{lightest}$: $m_{\beta} <$(0.13 to) 0.55 eV for NO/IO.

Summary

1. Neutrino masses
   - general preference of NO over IO;
   - IO not (yet?) disfavored;
   - projections of experimental bounds for $\sum_i m_i$, m_β, $m_{\beta\beta}$;
2. Oscillation data:
   - δ_{CP} (still) can be 0;
   - $\theta_{13} \neq 0$;
   - IO/NO θ_{23} octant (with SK);

Neutrino masses and mixings play an important role in validating and constraining discrete symmetry neutrino flavor models.

See also, later today: Biswajit Karmakar talk - Phenomenology of flavor symmetric scoto-seesaw

Thank you
for your attention.

Effective electron neutrino mass:

$$m_\beta^2 = \frac{\sum_i m_i^2 |U_{ei}|^2}{\sum_i |U_{ei}|^2} = \sum_i m_i^2 |U_{ei}|^2 = c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2.$$

Effective Majorana mass:

$$m_{\beta\beta} = \left| \sum_i m_i U_{ei}^2 \right| = \left| m_1 c_{13}^2 c_{12}^2 e^{i2\alpha_1} + m_2 c_{13}^2 s_{12}^2 e^{i2\alpha_2} + m_3 s_{13}^2 e^{-i2\delta_{\rm CP}} \right|.$$

The half-life of $0\nu\beta\beta$:

$$[T_{1/2}^{0\nu}]^{-1} = \frac{m_{\beta\beta}^2}{m_e^2} G_{0\nu} g_A^4 |M^{0\nu}|^2.$$