Neutrino masses and mixing

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SM with ν masses: general three-neutrino framework

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

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

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

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

6 parameters $\Longleftrightarrow$ 6 types of experiments

- **MeV** sources:
  - – solar experiments (mainly SNO) $\longrightarrow \theta_{12}$
  - – rector LBL (KamLAND) $\longrightarrow \Delta m^2_{21}$
  - – rector MBL (Double-Chooz, Daya-Bay, Reno) $\longrightarrow \theta_{13}\ [\Delta m^2_{31}]$
- **GeV** sources:
  - – atmospheric experiments (SK, DC) $\longrightarrow \theta_{23}$
  - – accelerator LBL-DIS $\nu_\mu \to \nu_\mu$ (T2K, NOvA) $\longrightarrow \Delta m^2_{31}\ [\theta_{23}]$
  - – accelerator LBL-APP $\nu_\mu \to \nu_e$ (T2K, NOvA) $\longrightarrow \delta_{\text{CP}}$

I. MeV sources: solar and reactor experiments

Solar and reactor neutrinos

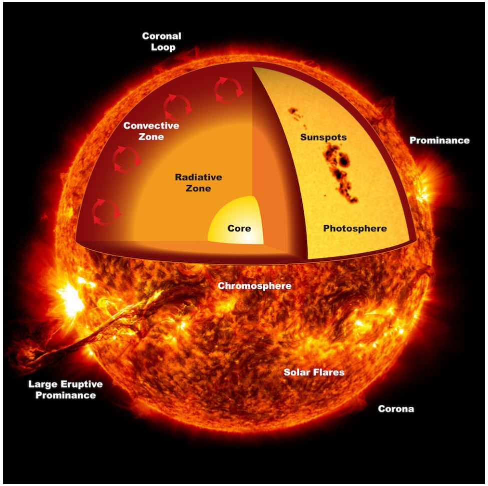
- ν_e from **nuclear** reactions $\Rightarrow$ energy in the MeV range;
- ν_μ and ν_τ indistinguishable $\Rightarrow$ no sensitivity to θ_{23} or δ_{CP}.

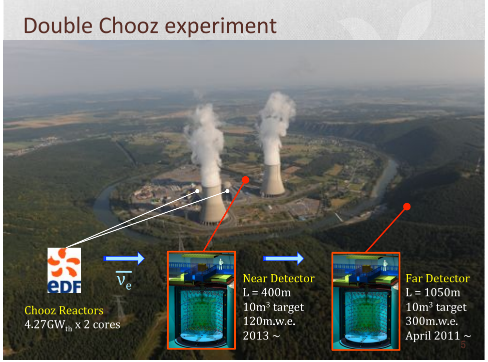
Reactor neutrinos

- $\bar{\nu}_e$ produced by nuclear **fission** in reactor's core;
- detection: inverse beta decay ($\bar{\nu}_e + p \to e^+ + n$), both e^+ and n observed in coincidence;
- negligible matter effects $\Rightarrow$ mostly vacuum params.

Solar neutrinos

- ν_e produced by nuclear **fusion** in the core of the Sun;
- two different mechanisms at work: p-p chain and CNO cycle. Both give $4p \to {}^4\text{He} + 2e^+ + 2\nu_e + \gamma \Rightarrow$ solar light and neutrinos in well-defined mutual proportions;
- detection: various processes (CC-ν_e, NC, ES);
- matter effects very important (MSW effect).

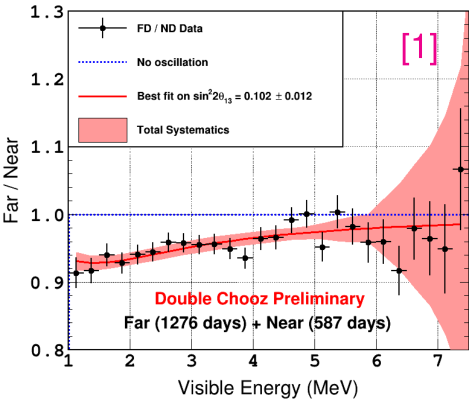


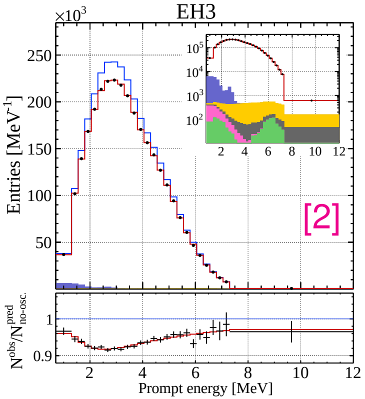

Double Chooz experiment

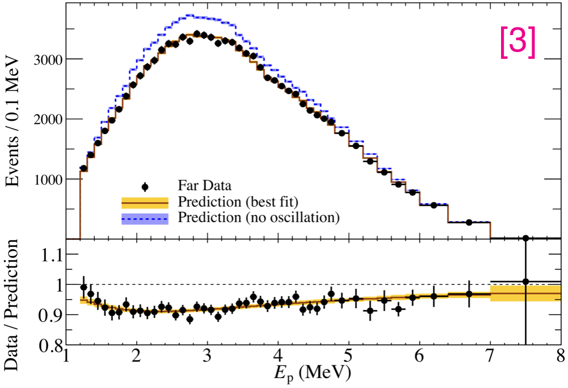
I. MeV sources: solar and reactor experiments

Medium-baseline reactor neutrino disappearance and θ_{13}

- Positive $\bar{\nu}_e$ disappearance ($\approx$ 1 km) in DOUBLE-CHOOZ [1], DAYA-BAY [2], RENO [3];
- experimental results are mutually consistent $\Rightarrow$ it is now a firmly established fact that $\theta_{13} \neq 0$ $\Rightarrow$ full 3ν oscillation phenomenology;
- all these experiments have spectral capabilities and detector units placed at different baselines $\Rightarrow$ uncertainties in the reactor flux predictions do **not** affect the results.







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[1] T. Bezerra [DOUBLE-CHOOZ], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

[2] F.P. An *et al.* [DAYA BAY], Phys. Rev. Lett. **130** (2023) 161802 [`arXiv:2211.14988`].

[3] J. Yoo [RENO], online talk presented at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

I. MeV sources: solar and reactor experiments

Troubles with reactor fluxes

Reactor antineutrino anomaly

- In [4, 5] the reactor $\bar{\nu}$ fluxes was reevaluated;
- new calculations: small increase by about **3.5%**;
- impact [6]: no evidence (before) → deficit (now);
- origin [8, 9]: $^{239}\mathrm{Pu}$ mostly OK, deficit from $^{235}\mathrm{U}$.

5 MeV excess

- RENO [7]: excess of events around 5 MeV;
- both in NEAR and FAR detector → independent of L;
- confirmed by Daya-Bay, Double-Chooz, and others;
- DB+Prospect [10]: affect **both** $^{235}\mathrm{U}$ & $^{239}\mathrm{Pu}$.

[4] T.A. Mueller *et al.*, PRC **83** 054615 [`arXiv:1101.2663`]

[5] P. Huber, PRC **84** 024617 [`arXiv:1106.0687`]

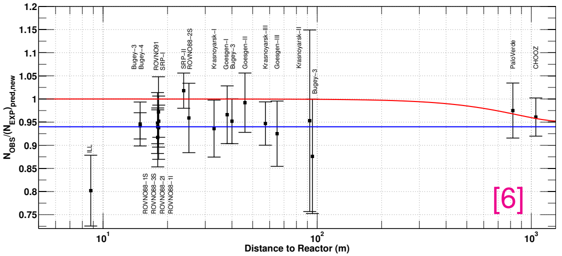
[6] G. Mention *et al.*, PRD **83** 073006 [`arXiv:1101.2755`]

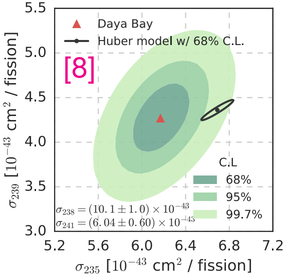
[7] S.H Seo [RENO], talk at Neutrino 2014, USA, 2–7/06/2014

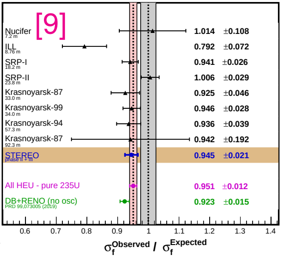
[8] [Daya-Bay], PRL **118** 251801 [`arXiv:1704.01082`]

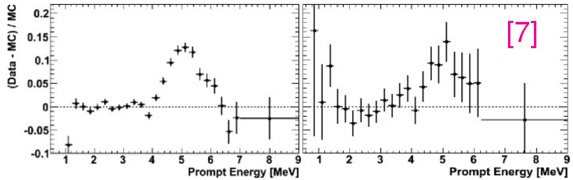
[9] [STEREO], Nature **613** 257 [`arXiv:2210.07664`]

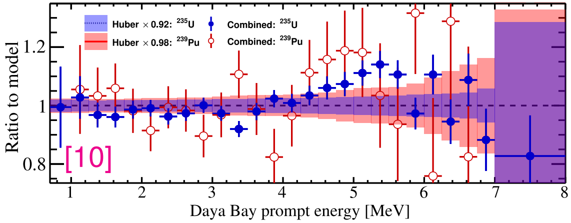
[10] [DB+Prospect], PRL **128** 081801 [`arXiv:2106.12251`]







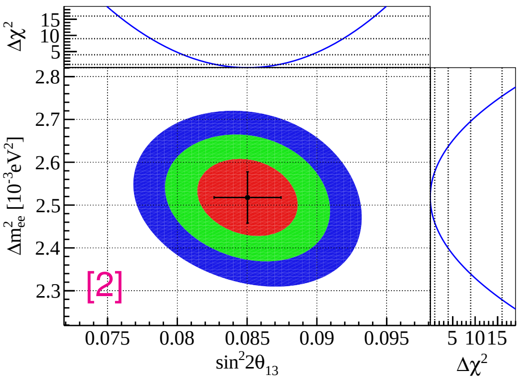


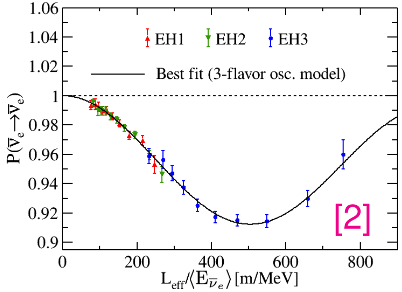


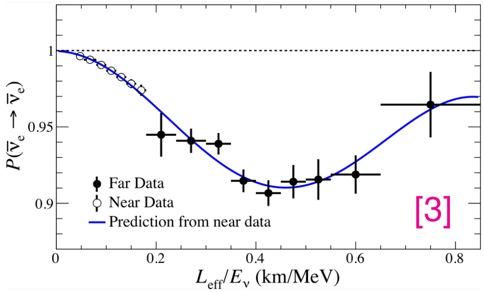
I. MeV sources: solar and reactor experiments

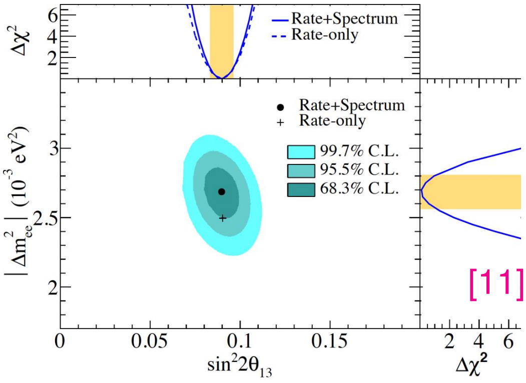
Measuring θ_{13} and Δm^2_{31} from reactor data

- FAR/NEAR spectral ratio ⇒ flux shape irrelevant;
- spectral information from Double-Chooz, Daya-Bay and Reno ⇒ oscillation pattern clearly visible ⇒ θ_{13} and Δm^2_{31} accurately determined by reactor data;
- accuracy from reactor $\nu_e \to \nu_e$ comparable with LBL $\nu_\mu \to \nu_\mu$, but oscillation channel is different ⇒ important **complementary** information available.









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[2] F.P. An *et al.* [DAYA BAY], Phys. Rev. Lett. **130** (2023) 161802 [`arXiv:2211.14988`].

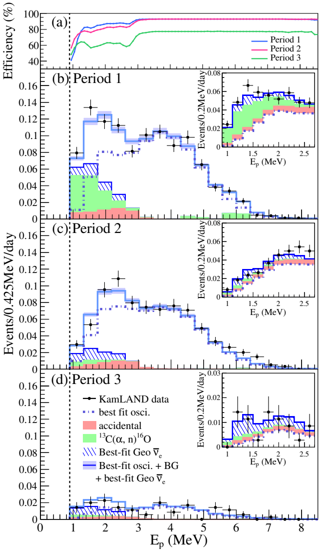
[3] J. Yoo [RENO], online talk at Neutrino 2020, Fermilab, USA, 22/06–2/07/2020.

[11] K.K. Joo [RENO], online talk at Neutrino 2022, Virtual Seoul, Korea, 30/05–4/06/2022.

I. MeV sources: solar and reactor experiments

Measuring θ_{12} and Δm^2_{21} with KamLAND data

- Much longer baseline ($\approx$ 180 km) $\Rightarrow$ sensitive to θ_{12} and Δm^2_{21};
- lack of a near detector $\Rightarrow$ spectral distortions may be an issue;
- problem discussed in [12, 13] $\Rightarrow$ impact on Δm^2_{21} found to be small;
- solution: bind KamLAND spectrum to Daya-Bay measurement [14].

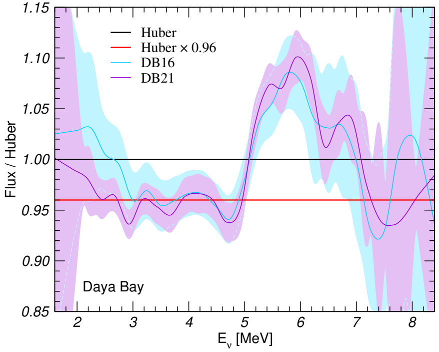


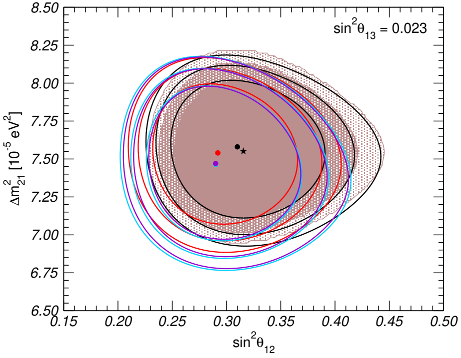
[12] M. Maltoni, A.Yu. Smirnov, EPJA **52** (2016) 87 [`arXiv:1507.05287`].

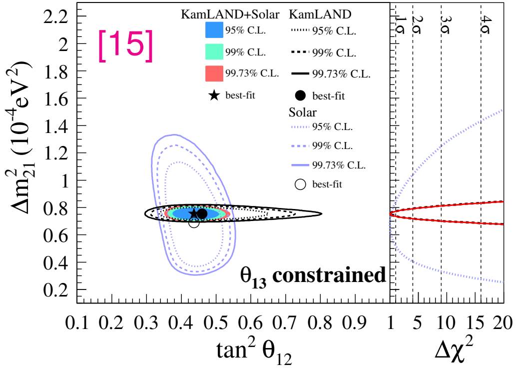
[13] F. Capozzi *et al.*, NPB **908** (2016) 218 [`arXiv:1601.07777`].

[14] F.P. An *et al.* [Daya-Bay], CPC **45** (2021) 073001 [`arXiv:2102.04614`].

[15] A. Gando *et al.* [KamLAND], PRD **88** (2013) 033001 [`arXiv:1303.4667`].







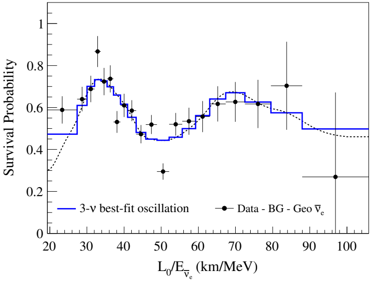
I. MeV sources: solar and reactor experiments

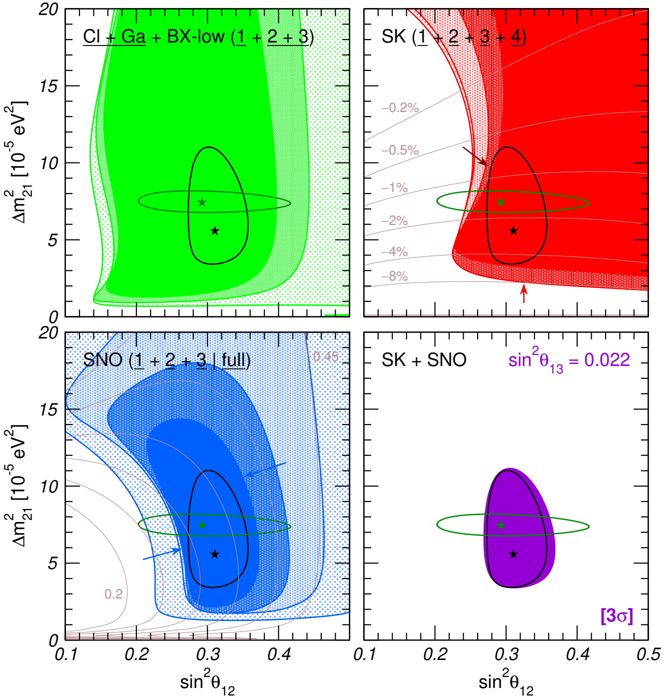
Determination of θ_{12} and Δm^2_{21} from solar neutrino data

- $P_{ee} = c_{13}^4 P_{\text{eff}} + s_{13}^4, \quad i\frac{d\vec{\nu}}{dt} = \left[\frac{\Delta m^2_{21}}{4E_\nu}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} \pm \sqrt{2} G_F N_e \begin{pmatrix} c_{13}^2 & 0 \\ 0 & 0 \end{pmatrix}\right]\vec{\nu}, \quad \vec{\nu} = \begin{pmatrix} \nu_e \\ \nu_a \end{pmatrix};$
- $\nu_\mu \equiv \nu_\tau \Rightarrow$ no sensitivity to θ_{23} and δ_{CP};
- $\Delta m^2_{31} \approx \infty \Rightarrow$ specific Δm^2_{31} value irrelevant;

$\Rightarrow$ data only depend on Δm^2_{21}, θ_{12} and θ_{13};

- param's: $\begin{cases} \theta_{12} \text{ dominated by SNO;} \\ \Delta m^2_{21} \text{ dominated by KamLAND;} \end{cases}$
- solar region determined by high-E data, low-E contribution marginal;
- SNO-NC measurement confirms SSM;
- KamLAND precisely determines the oscillation pattern.

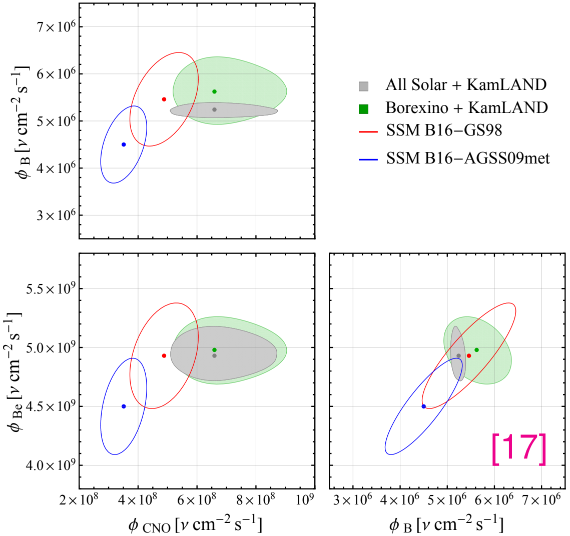




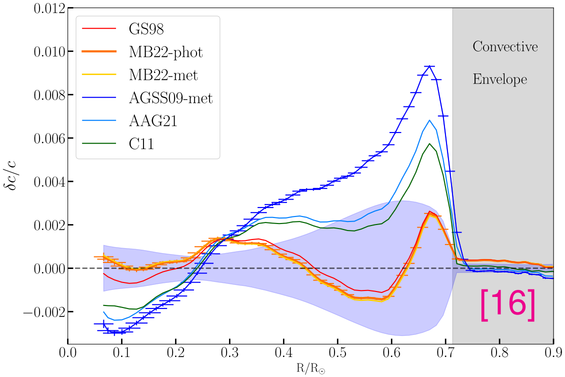
I. MeV sources: solar and reactor experiments

Uncertainties in the solar fluxes

- Long-standing tension between surface and internal composition of the Sun. Two types of models:
  - **high-metallicity** (GS98 → MB22): good agreement with *helioseismology*, but historically poor description of the *Sun's atmosphere*;
  - **low-metallicity** (AGSS09 → AAG21): solve issues with *surface* modelling, but fails to properly reproduce *helioseismic* results;
- recent CNO measurement by Borexino [17] ⇒ experimental determination of *all* solar fluxes ⇒ data indicate preference for **high-metallilticy** models;
- new MB22 model [16] reconciles *surface* data with the high metallicity required by *helioseismology*.



[17]



[16]

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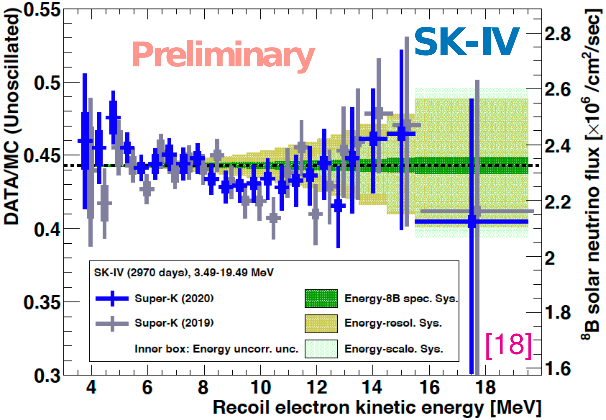
[16] E. Magg *et al.*, A&A **661** A140 [`arXiv:2203.02255`].

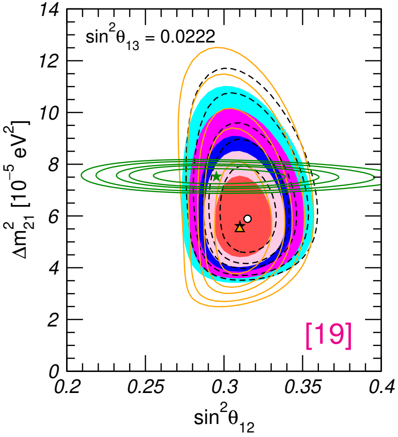
[17] S. Appel *et al.* [BOREXINO], PRL [`arXiv:2205.15975`].

Comparison between solar and KamLAND measurements

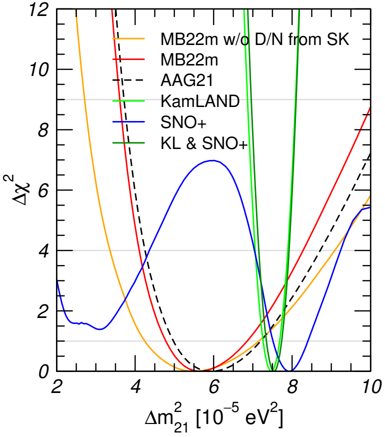
- Long-standing weak tension on preferred Δm^2_{21} from solar and KamLAND data;
- choice of the assumed solar model (GS, AGSS, MB22, …) has little impact on the issue;
- cause: { – too much D/N asymmetry in SK; – no indication of low-E turn-up }
- new data [18]: { – D/N: $3.6\% \to 2.1\%$, – "hints" of turn-up.}

⇒ tension considerably reduced after Neutrino 2020 conference.





NuFIT 6.0 (2024)



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[18] Y. Nakajima [SK], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

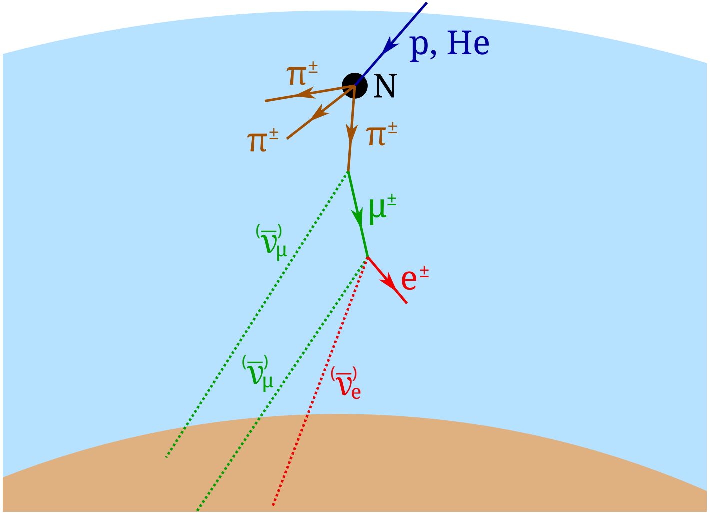
[19] I. Esteban *et al.*, `arXiv:2410.05380` & NuFIT 6.0 [`http://www.nu-fit.org`].

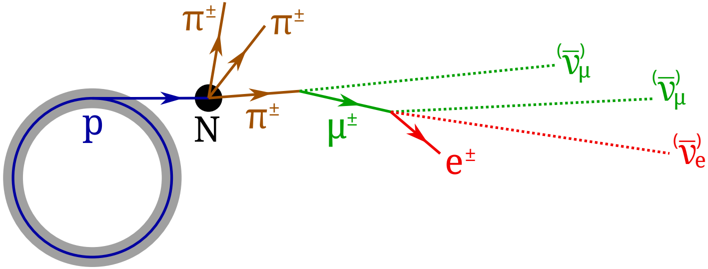
Atmospheric and accelerator neutrinos

- Atmospheric (accelerator) neutrinos are produced by the interaction of *cosmic rays* (*protons*) with the Earth's atmosphere (target):

$$
\begin{aligned}
&\boxed{1} \quad A_{\text{in}} + A_{\text{tgt}} \to \pi^\pm, K^\pm, K^0, \dots \\
&\boxed{2} \quad \pi^\pm \to \mu^\pm + \nu_\mu \,, \\
&\boxed{3} \quad \mu^\pm \to e^\pm + \nu_e + \nu_\mu \,;
\end{aligned}
$$

- at the detector, some ν interacts and produces a **charged lepton**, which is observed;
- atmospheric: fluxes of ν_μ and ν_e are known with poor precision ($\approx 20\%$), but the accuracy on the ν_μ/ν_e ratio is better ($\approx 5\%$);
- accelerator: a **near detector** allow to characterize the unoscillated ν flux.

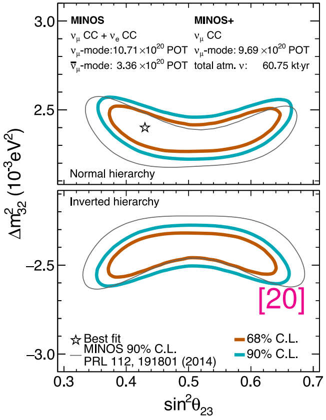


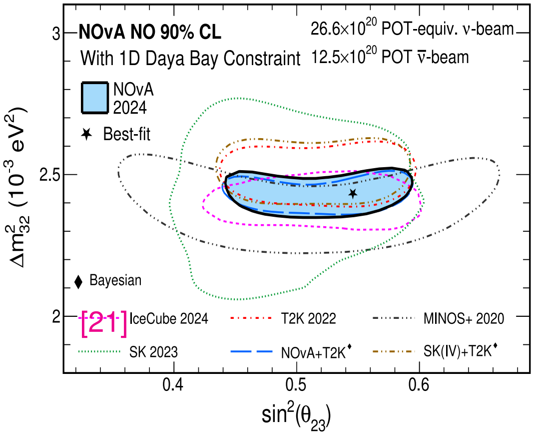


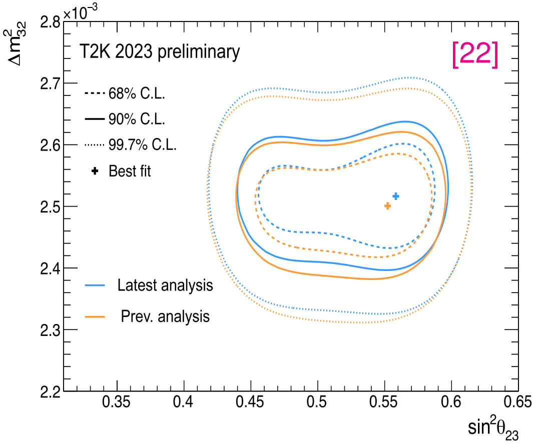
II. GeV sources: atmospheric and accelerator experiments

Determination of Δm^2_{31} and θ_{23} from accelerator data

- Δm^2_{31} & θ_{23} dominated by LBL disappearance ($\nu_\mu \to \nu_\mu$) data;
- Δm^2_{21} & θ_{12} subleading contributions to LBL appearance ($\nu_\mu \to \nu_e$) $\Rightarrow$ relevant for δ_{CP};
- reasonably good agreement between all experiments in the allowed regions, although some small differences are visible.







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[20] T. Carroll [MINOS], online talk at Neutrino 2020, Fermilab, USA, June 22–July 2, 2020.

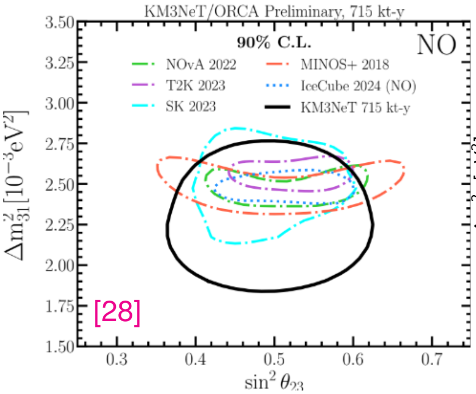
[21] J. Wolcott [NOvA], talk at Neutrino 2024, Milan, Italy, June 16–22, 2024.

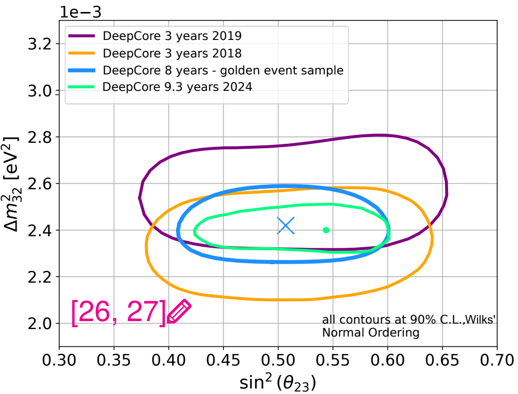
[22] D. Carabadjac [T2K], talk at ICHEP 2024, Prague, Czech Republic, July 17–24, 2024.

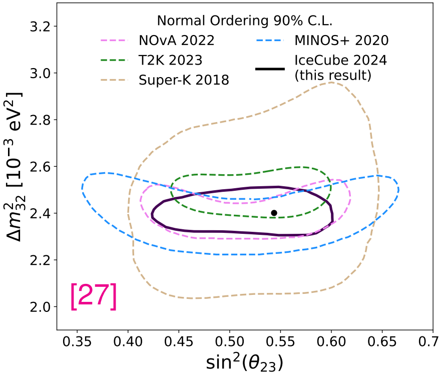
II. GeV sources: atmospheric and accelerator experiments

The contribution of neutrino telescopes through atmospheric data

- IceCUBE/DeepCore: after many 3-year "calibration" fits [23, 24, 25], updated 8-year [26] and 9.3-year [27] results presented (but not "released") ⇒ competitive with reactors and LBL;
- Km3NET/ORCA: under deployment (23/115 strings so far [28]), fit (ORCA6+11) catching up.







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[23] M.G. Aartsen *et al.* [ICECUBE], PRD **91** (2015) 072004 [`arXiv:1410.7227`], updated Oct. 2016. [IC16]

[24] M.G. Aartsen *et al.* [ICECUBE], PRL **120** (2018) 071801 [`arXiv:1707.07081`].

[25] M.G. Aartsen *et al.* [ICECUBE], PRD **99** (2019) 032007 [`arXiv:1901.05366`]. [IC19]

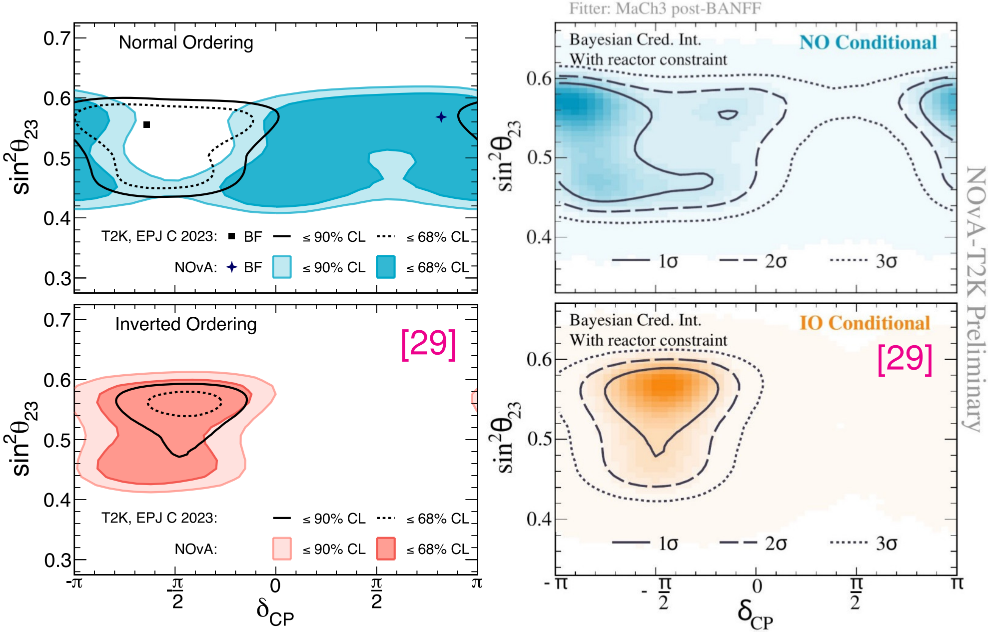
[26] R. Abbasi *et al.* [ICECUBE], PRD **108** (2023) 012014 [`arXiv:2304.12236`].

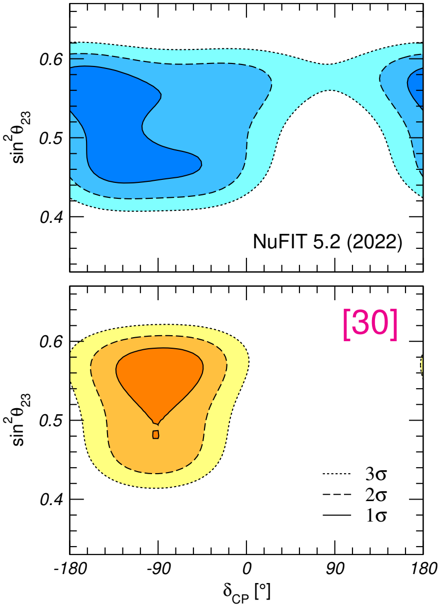
[27] R. Abbasi *et al.* [ICECUBE], `arXiv:2405.02163`. [IC24]

[28] J. Coelho [KM3NET], talk at Neutrino 2024, Milan, Italy, June 16–22, 2024.

Tension between NOvA and T2K data: summer 2020

- Neutrino 2020: tension on δ_{CP} between T2K and NOvA for **NO** (no problem for **IO**);
- official joint T2K/NOvA analysis finally presented [29], results very similar to estimates [30].





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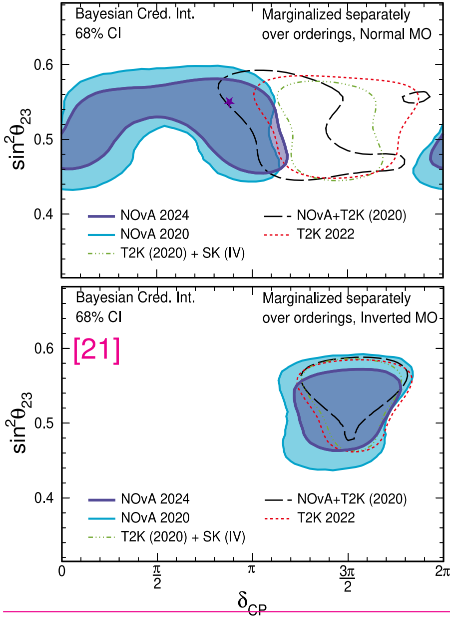
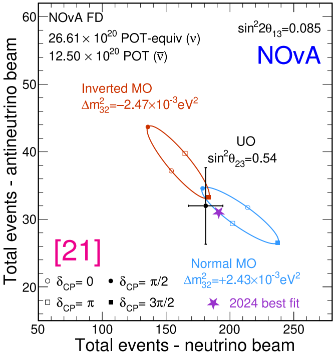
[29] M. Sanchez [NOvA], talk at Moriond-EW 2024, La Thuile, Italy, March 24–31, 2024.

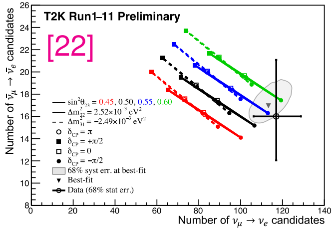
[30] I. Esteban *et al.*, JHEP **09** (2020) 178 [`arXiv:2007.14792`].

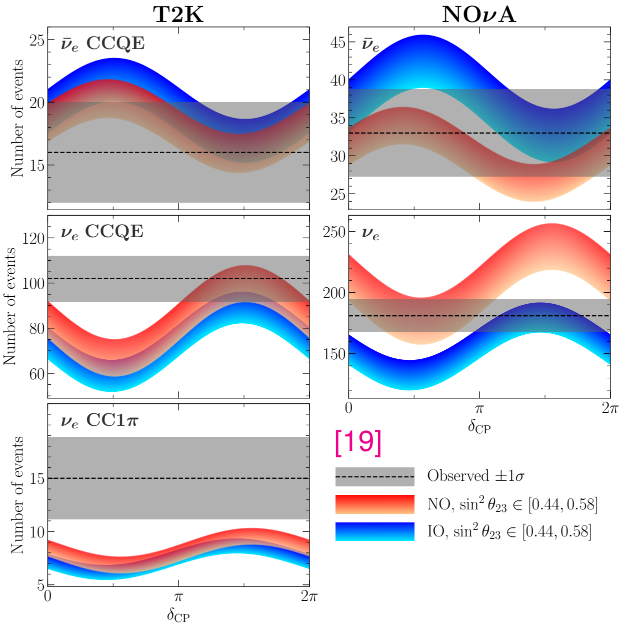
Tension between NOvA and T2K data: today

- Neutrino 2024: NOvA substantially increased ν statistics, but no qualitative change on δ_{CP}.









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[19] I. Esteban *et al.*, `arXiv:2410.05380` & NuFIT 6.0 [`http://www.nu-fit.org`].

[21] J. Wolcott [NOvA], talk at Neutrino 2024, Milan, Italy, June 16–22, 2024.

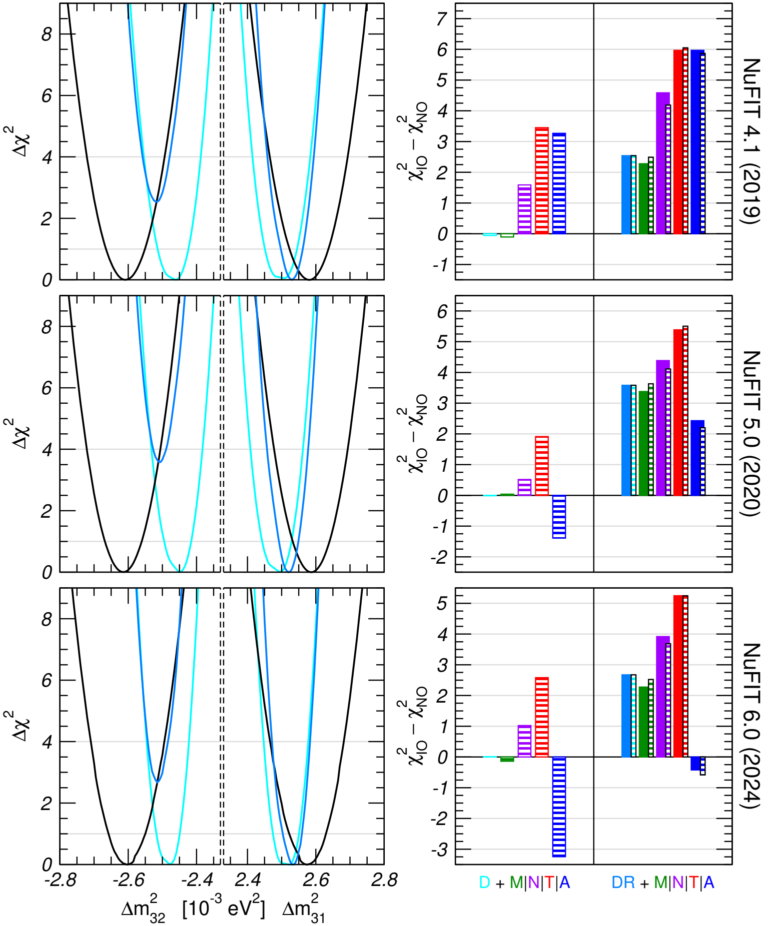
[22] D. Carabadjac [T2K], talk at ICHEP 2024, Prague, Czech Republic, July 17–24, 2024.

II. GeV sources: atmospheric and accelerator experiments

Δm^2_{31} and mass ordering

- *disappearance* data: → **NO**
  - Δm^2_{31} measured both by **reactor** (ν_e) and **accelerator** (ν_μ), but neither is sensitive to the ordering;
  - however, **combination** prefer **NO** due to better compatibility on Δm^2_{31} range;
- *appearance* data: → **IO**
  - taken by **themselves** both T2K and NOvA exhibit a preference for **NO**;
  - but the δ_{CP} tension among them (which has increased over time) implies than **joint** LBL-app data prefer **IO**;

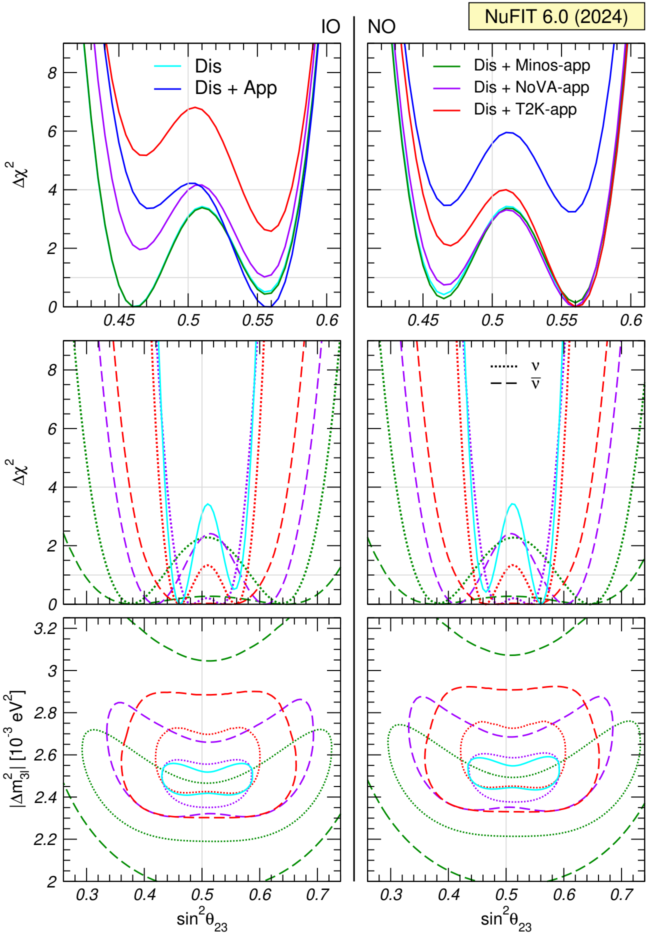
★ constrasting preferences of *dis.* and *app.* data mutually cancel ⇒ no indication.



II. GeV sources: atmospheric and accelerator experiments

θ_{23} mixing and octant

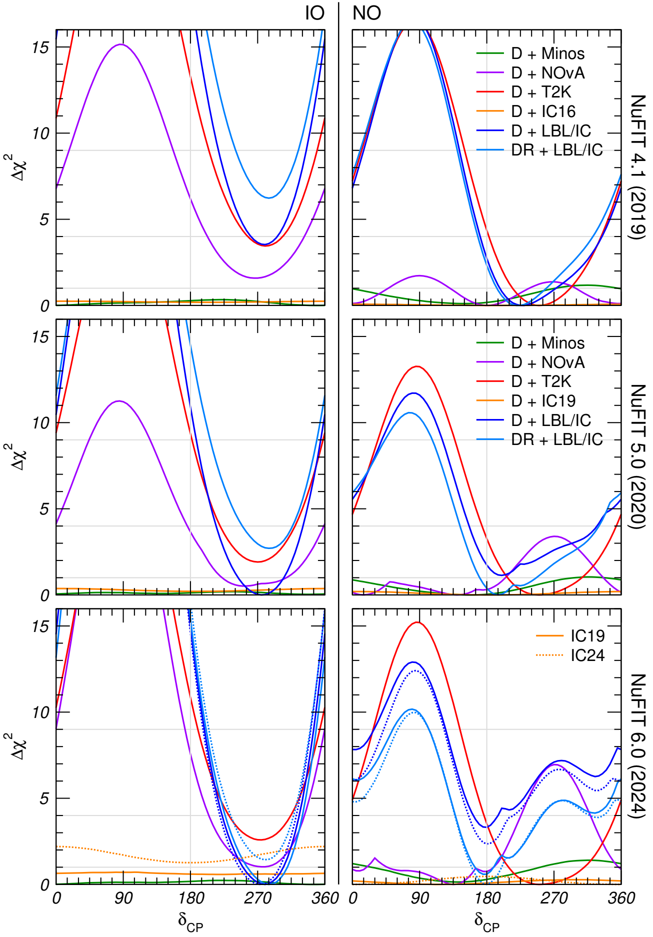
- *disappearance* data:
  - each individual LBL-dis ν or $\bar{\nu}$ data slightly favor deviation from maximal mixing, but without any preference for a given octant;
  - combined disapp. data disfavor maximal mixing at $\Delta\chi^2 \sim 3.4$, with marginal octant preference (**NO** $> 45^\circ$ & **IO** $< 45^\circ$ at $\Delta\chi^2 \sim 0.4$);
- adding *appearance* data:
  - Minos contribution practically irrelevant;
  - T2K (more) and NOvA (less) both push for $\theta_{23} > 45^\circ$, irrespective of the mass ordering;
  - combination confirms $\theta_{23} > 45^\circ$ for **IO**, but for **NO** the δ_{CP} tension between T2K and NOvA cancels this hint and lead to similar minima.



II. GeV sources: atmospheric and accelerator experiments

Status of the CP phase

- T2K data show a clear preference for maximal CP violation ($\delta_{CP} \simeq 270^\circ$), irrespective of the assumed mass ordering;
- NOvA data also favor such value for **IO**, but for **NO** it disfavors it, preferring instead the CP conserving value $\delta_{CP} \simeq 180^\circ$;
- NOvA rejection of $\delta_{CP} \simeq 270^\circ$ has steadingly increased over time: $1.2\sigma \to 1.8\sigma \to 2.6\sigma$ from the analysis of NuFIT 4.1 → 5.0 → 6.0 data;
- Minos & IceCube have practically no sensitivity to δ_{CP} and give negligible contribution;
- combined LBL+IC experiments indicate $\delta_{CP} \simeq \pi$ for **NO**, thus dominated by NOvA. Further inclusion of reactors does not change this picture.



Summary

Neutrino oscillations: where we are

- Global 6-parameter fit (including $\delta_{\rm CP}$):
  - **Solar**: Cl + Ga + SK(1–4) + SNO-full (I+II+III) + BX(1–3);
  - **Atmospheric**: IC19 | IC24 + SK(1–5);
  - **Reactor**: KamLAND + SNOplus + DC + DB + Reno;
  - **Accelerator**: Minos + T2K + NOvA;
- best-fit point and 1σ (3σ) ranges:

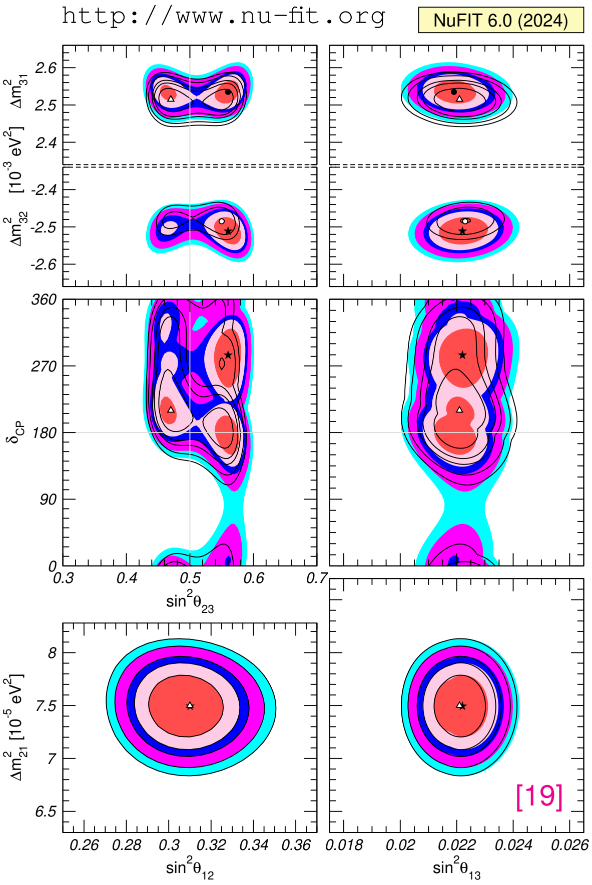
$$\theta_{12} = 33.68\,^{+0.73}_{-0.70}\,\left(^{+2.27}_{-2.05}\right), \qquad \Delta m^2_{21} = 7.49\,^{+0.19}_{-0.19}\,\left(^{+0.56}_{-0.57}\right) \times 10^{-5}~\text{eV}^2,$$

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

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

- neutrino mixing matrix:

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



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[19] I. Esteban *et al.*, `arXiv:2410.05380` & NuFIT 6.0 [`http://www.nu-fit.org`].

Summary

- 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 robust;
- the long-standing “hints” concerning the mass ordering, with **NO** favored over **IO** at the $2\sigma \div 3\sigma$ level, are cancelled by the T2K/NOvA tension;
- the discovery of large θ_{13} opened the road to searches for CP violation. However, results on this topic need further clarifications;
- deviation from maximal θ_{23} mixing is also still an open issue. The region $\theta_{23} > 45^\circ$ seems to be slightly preferred, especially for **IO**;
- synergies between different experiments will be crucial to increase the sensitivity.