Neutrino Phenomenology: Progress and Open Questions

Mariam Tórtola

IFIC, CSIC/Universitat de València

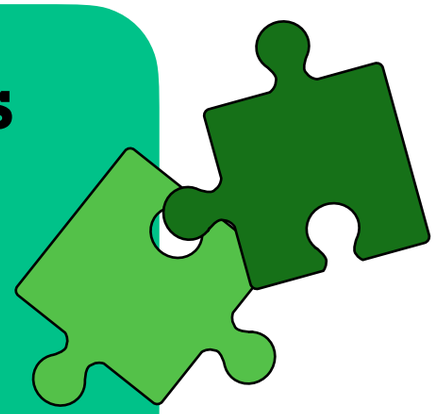


MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS
VNIVERSITAT DE VALÈNCIA
IFIC INSTITUT DE FÍSICA CORPUSCULAR
EXCELENCIA SEVERO OCHOA
GENERALITAT VALENCIANA Conselleria d'Educació, Universitats i Ocupació

Neutrino physics: open questions

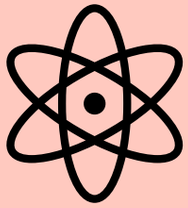
Neutrino masses and mixings

Established by oscillation experiments (almost)



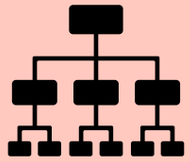
Origin of mass

Dirac or Majorana? Seesaw?
Radiative mechanisms?



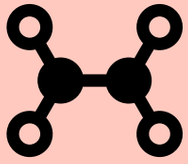
Flavour structure

Why these masses, mixing angles and CP phases?



Lepton-number violation

Are neutrinos Majorana particles?
Can 0νββ be observed?



New physics

Sterile states, new interactions
Connection to leptogenesis



Status of three-neutrino oscillations

The three-flavour framework

neutrino mixing

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13}e^{i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

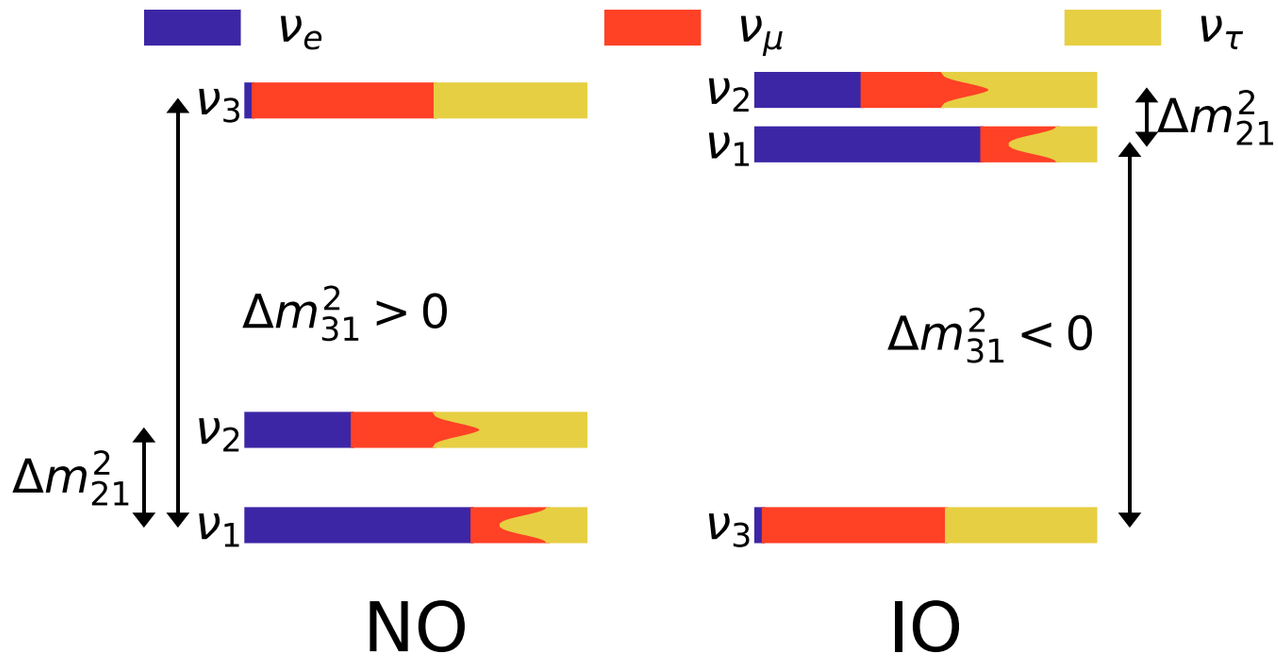
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

$$\Delta m^2_{21}, \Delta m^2_{31}$$

neutrino mass spectrum



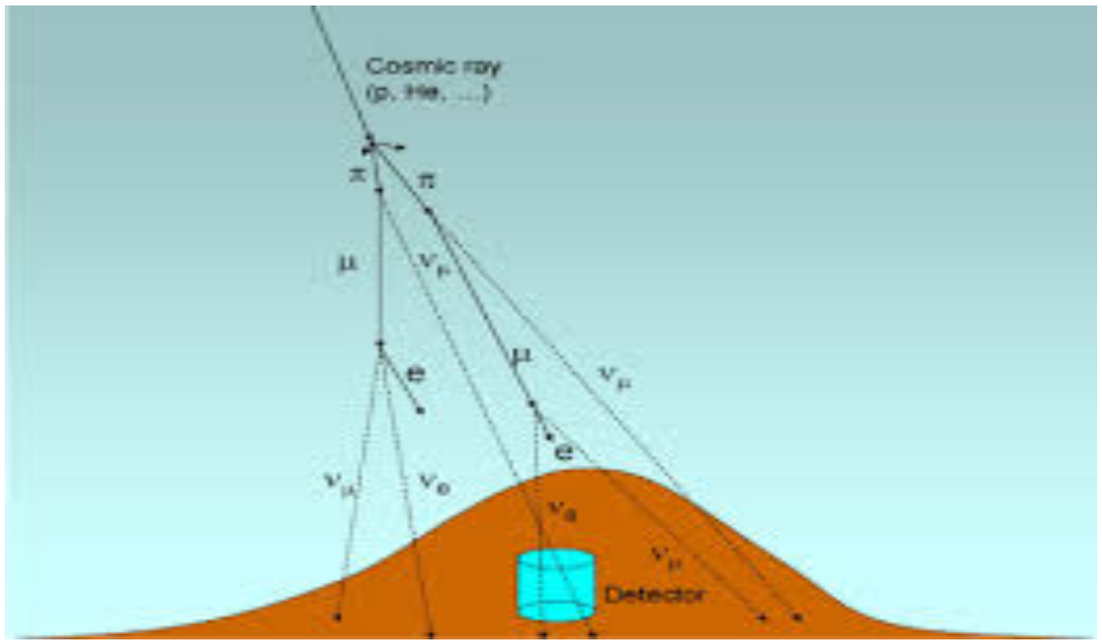
de Salas et al, 2018

Neutrino oscillations

Solar neutrinos



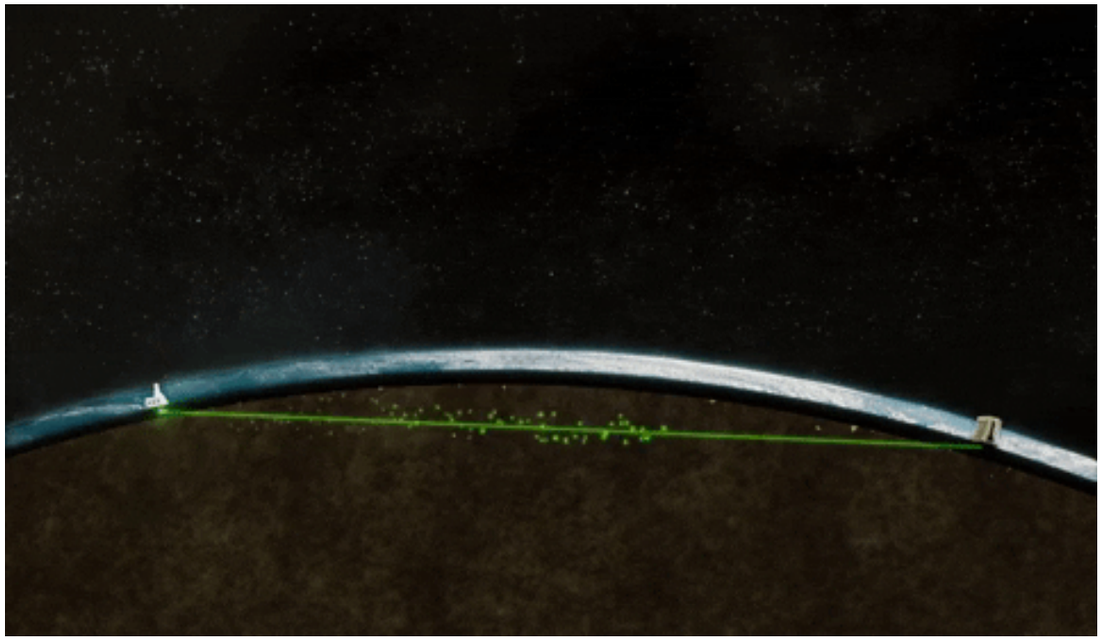
Atmospheric neutrinos



Reactor neutrinos



Accelerator neutrinos

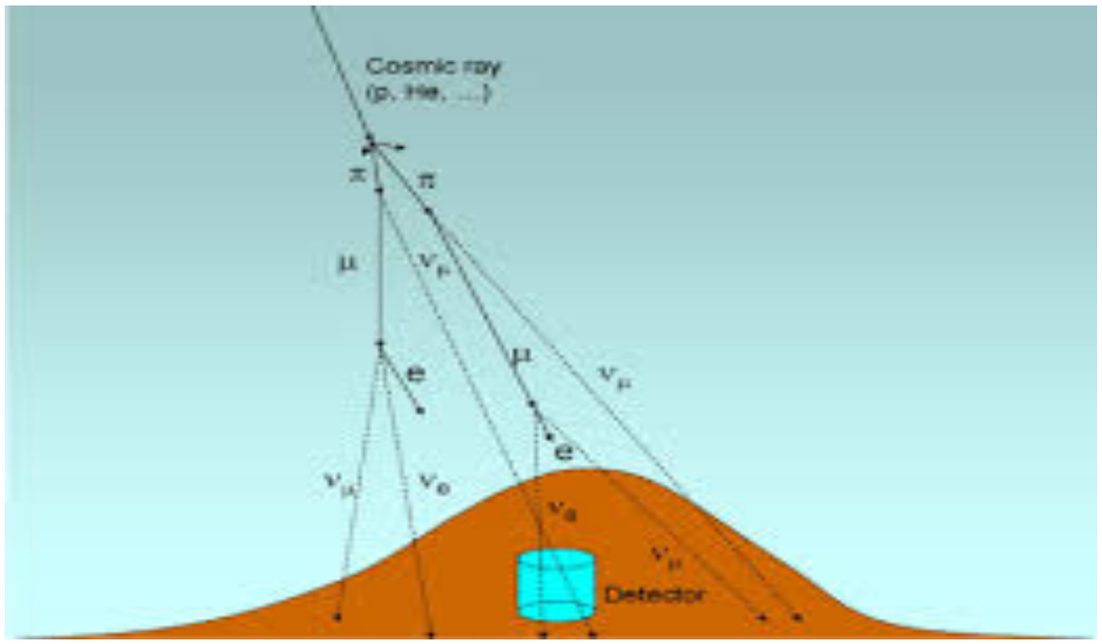


Neutrino oscillations

Solar neutrinos



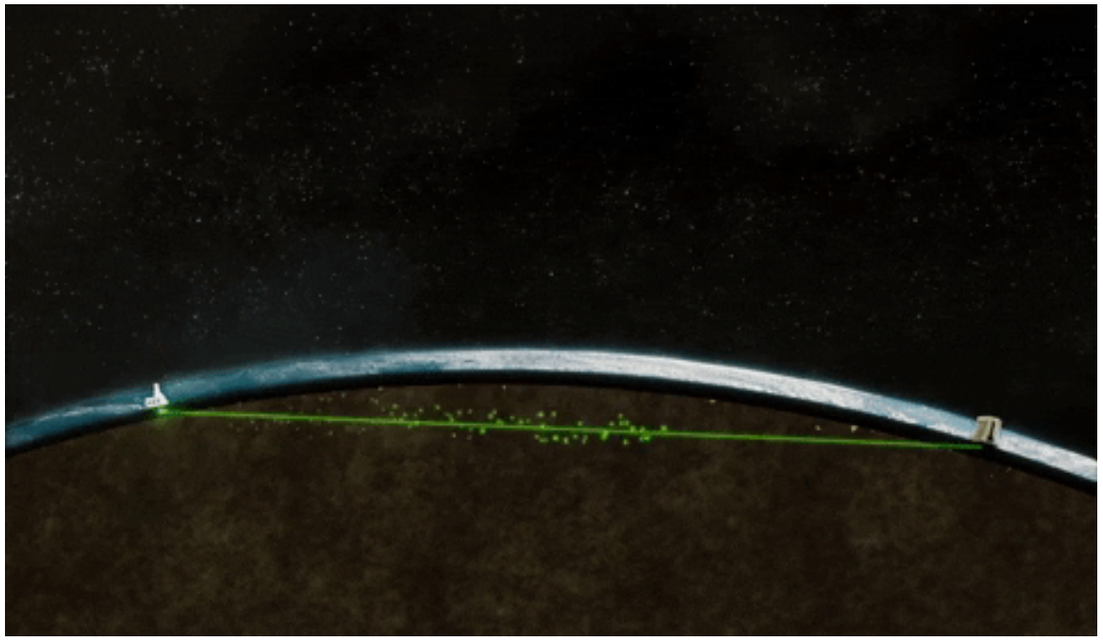
Atmospheric neutrinos



Reactor neutrinos



Accelerator neutrinos

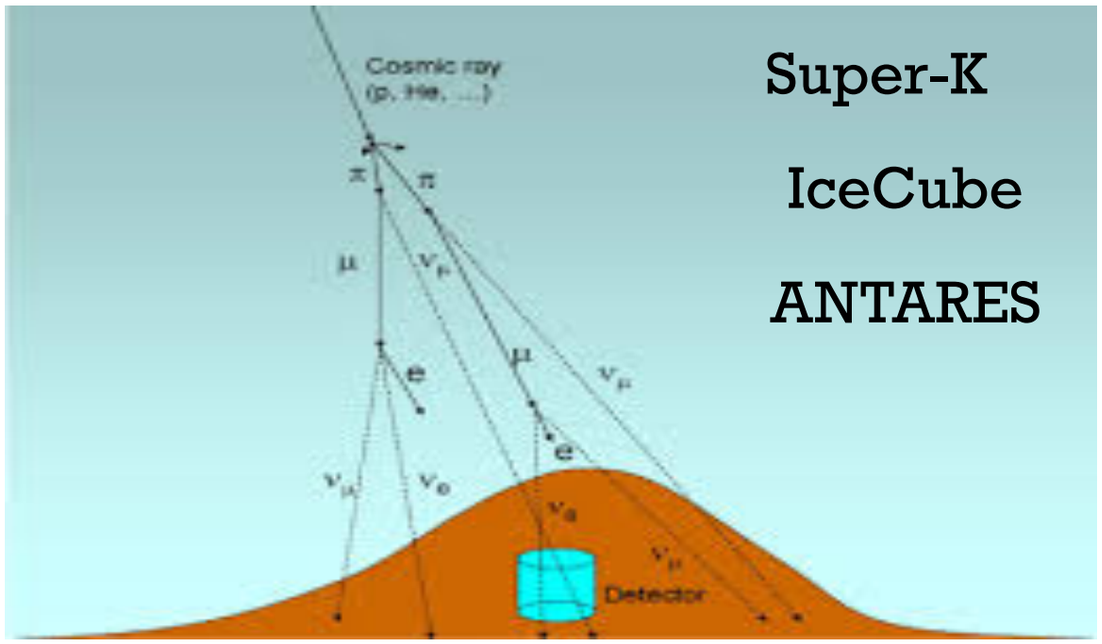


Neutrino oscillations

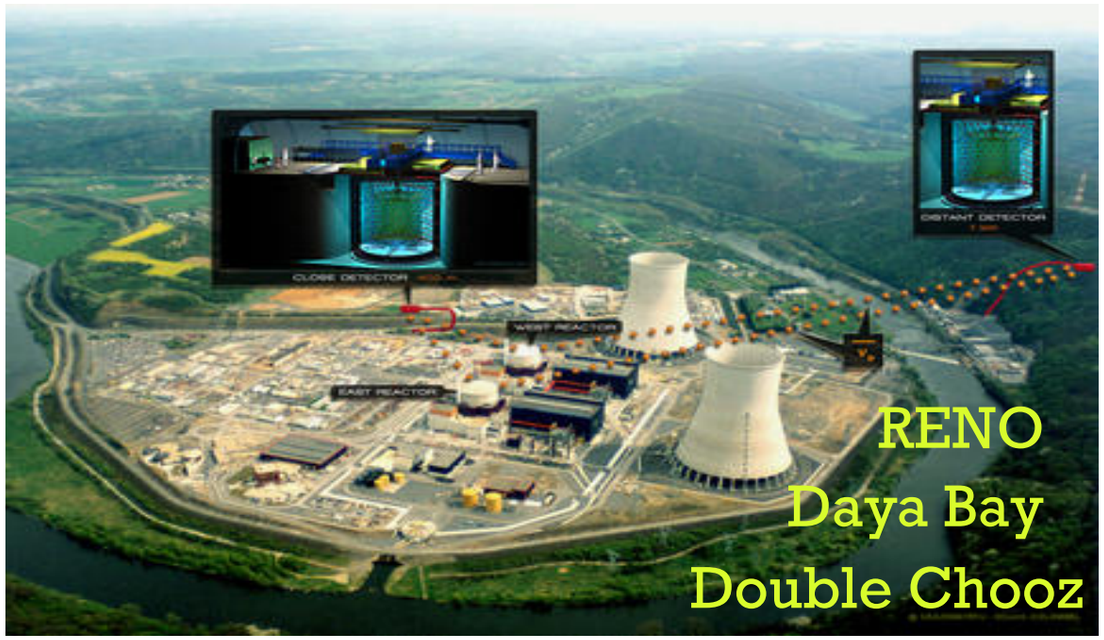
Solar sector: θ_{12}, θ_{13}, Δm^2_{21}



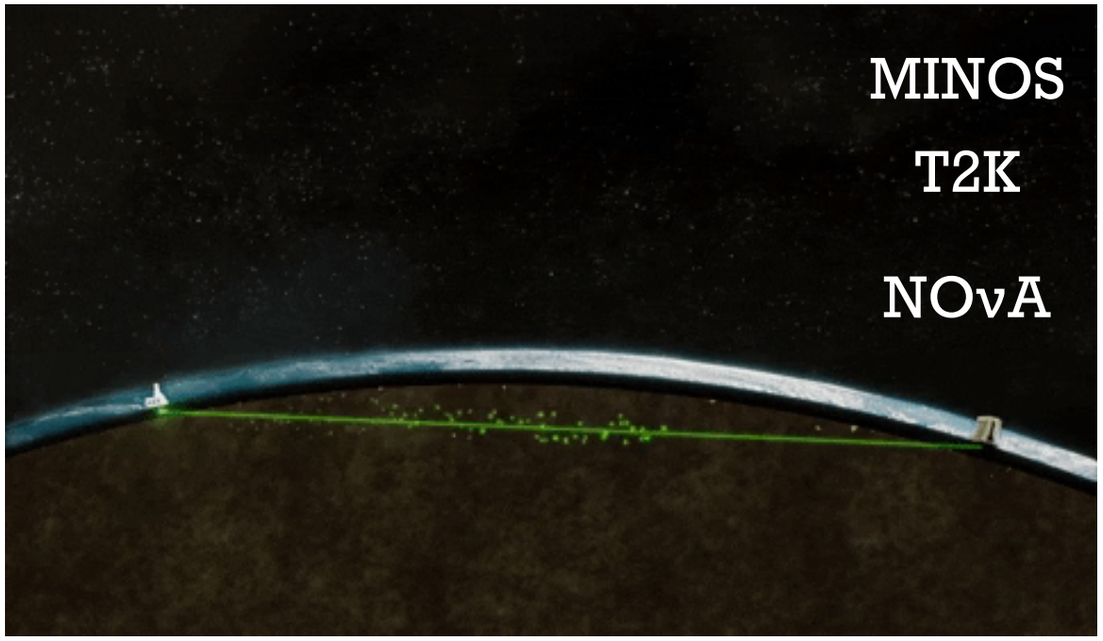
Atmospheric sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



Reactor sector: θ_{13}, Δm^2_{31}



Accelerator sector: θ_{23}, θ_{13}, Δm^2_{31}, δ

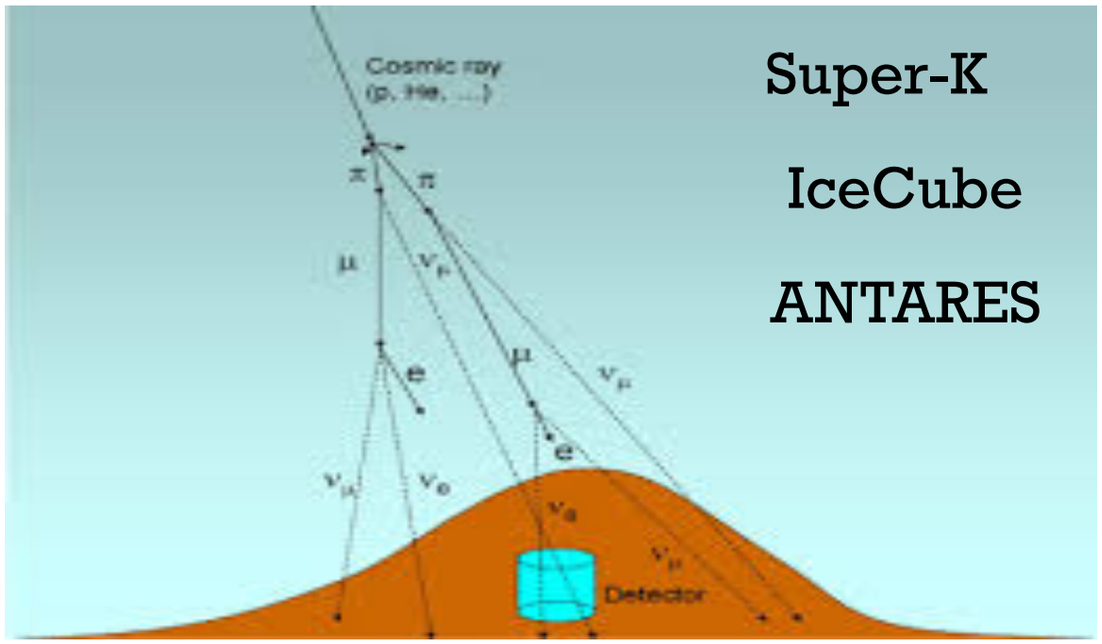


Neutrino oscillations

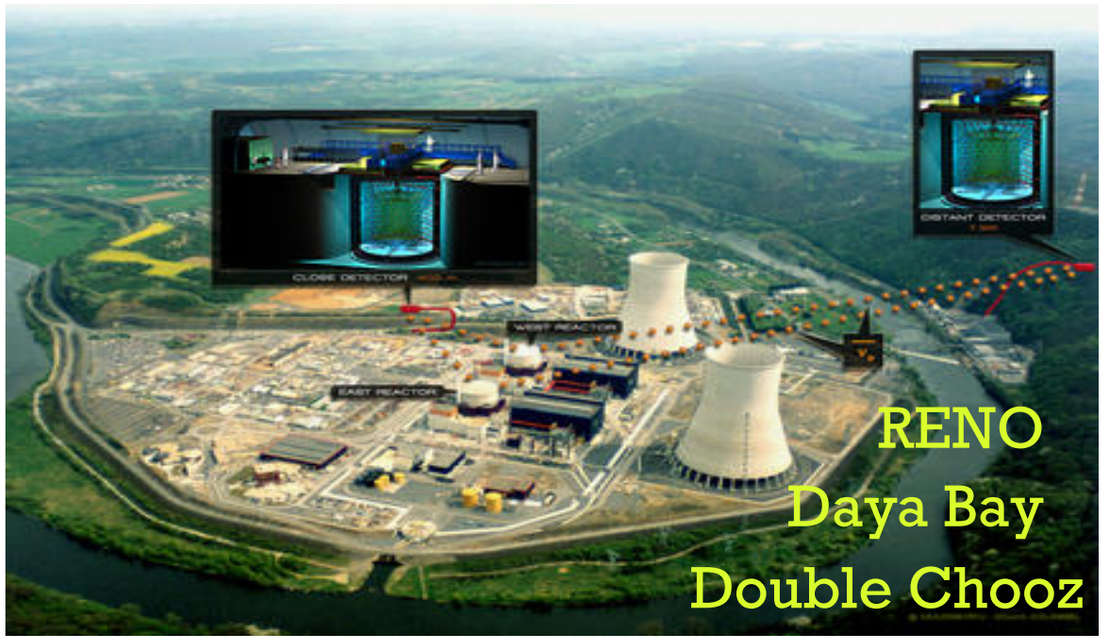
Solar sector: θ_{12}, θ_{13}, Δm^2_{21}



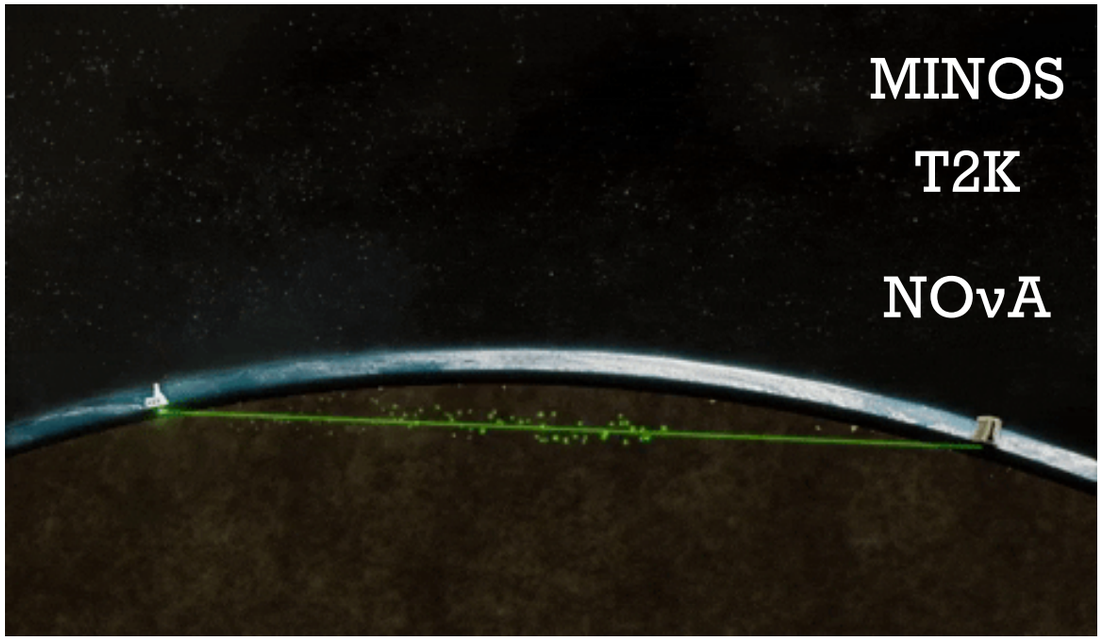
Atmospheric sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



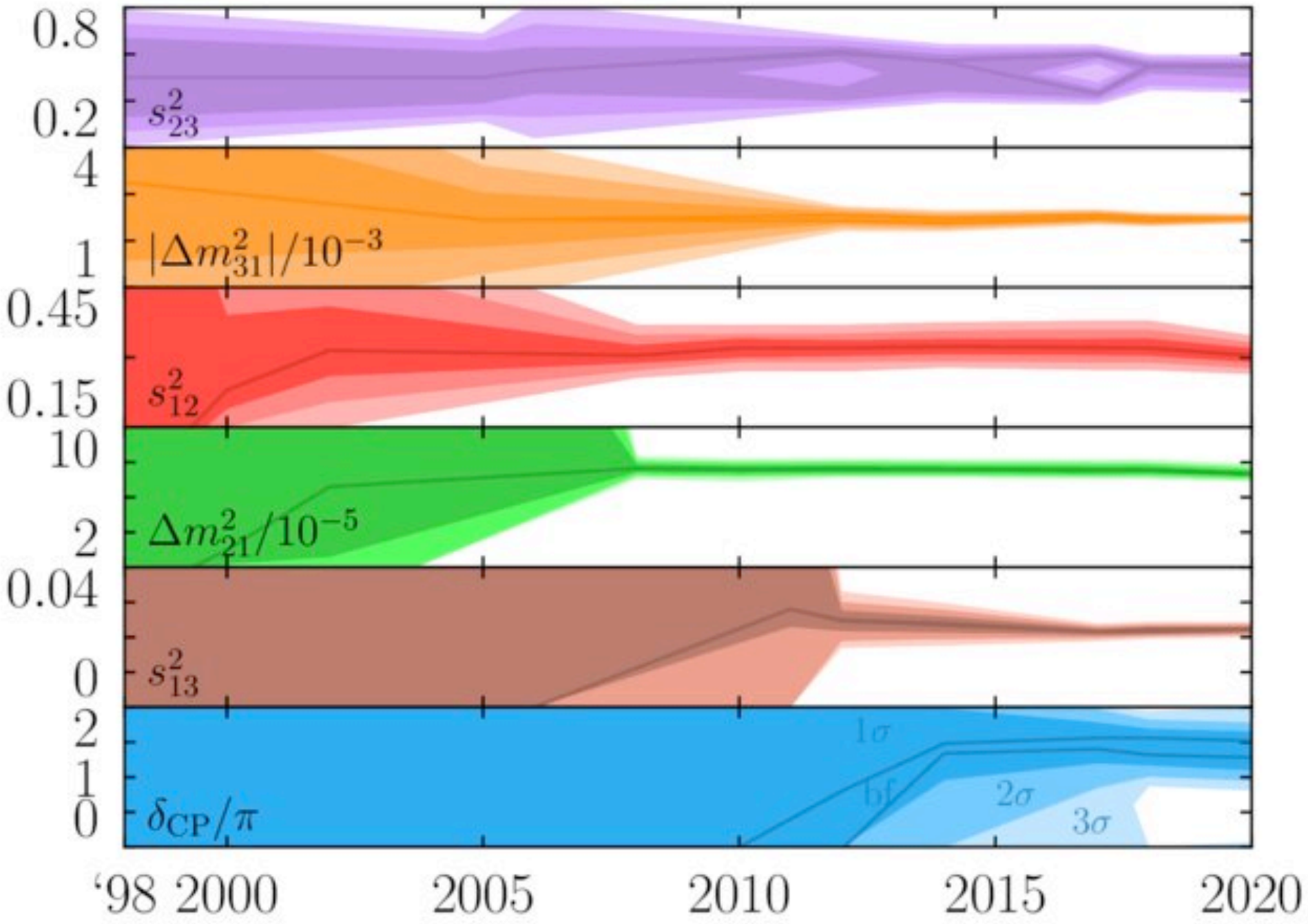
Reactor sector: θ_{13}, Δm^2_{31}



Accelerator sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



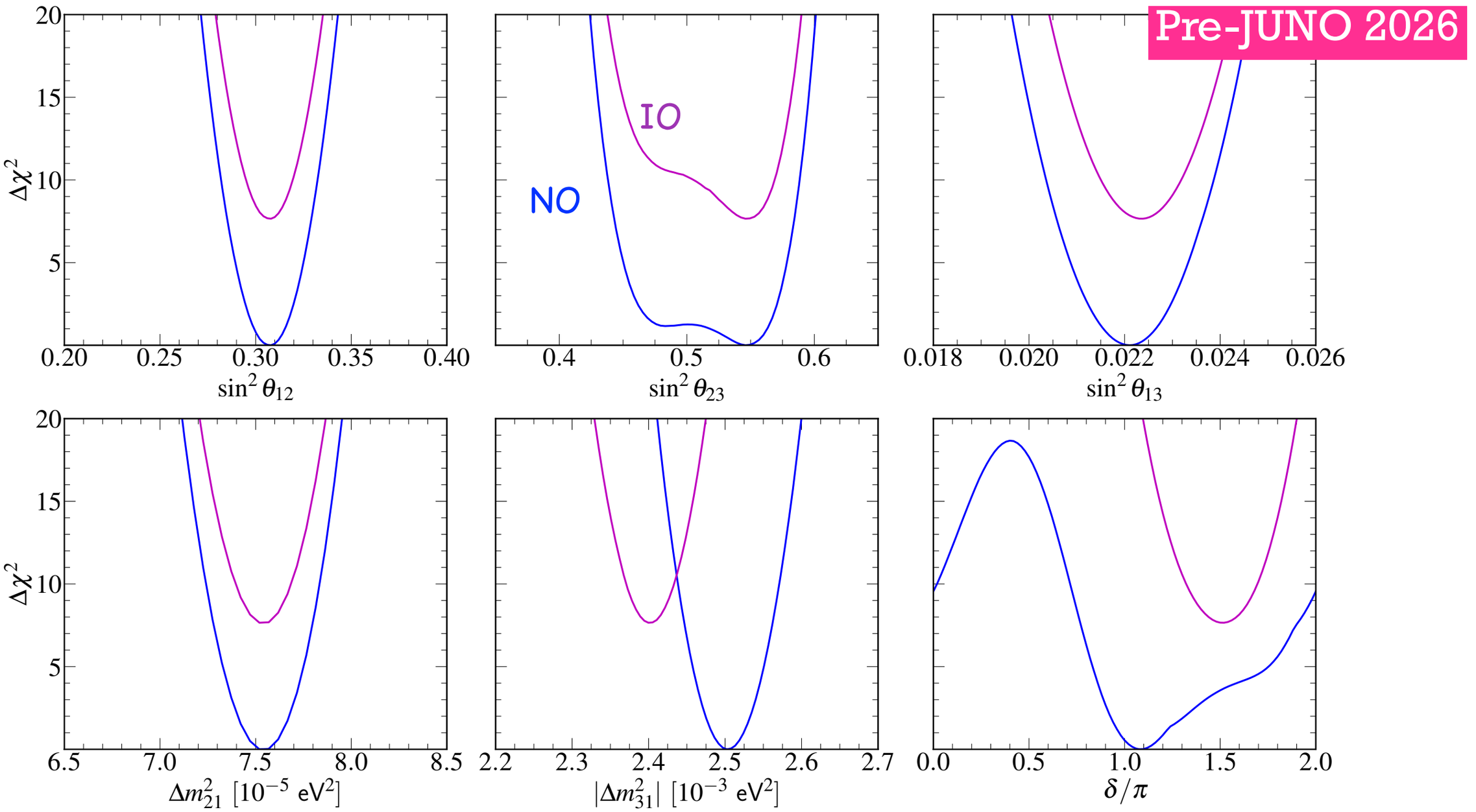
Three-neutrino oscillation parameters



Denton et al, Snowmass Neutrino Frontier: NF01 Report [arXiv:2212.00809]

Global fits to ν oscillations

de Salas et al, **JHEP 02 (2021) 071** https://globalfit.astroparticles.es/

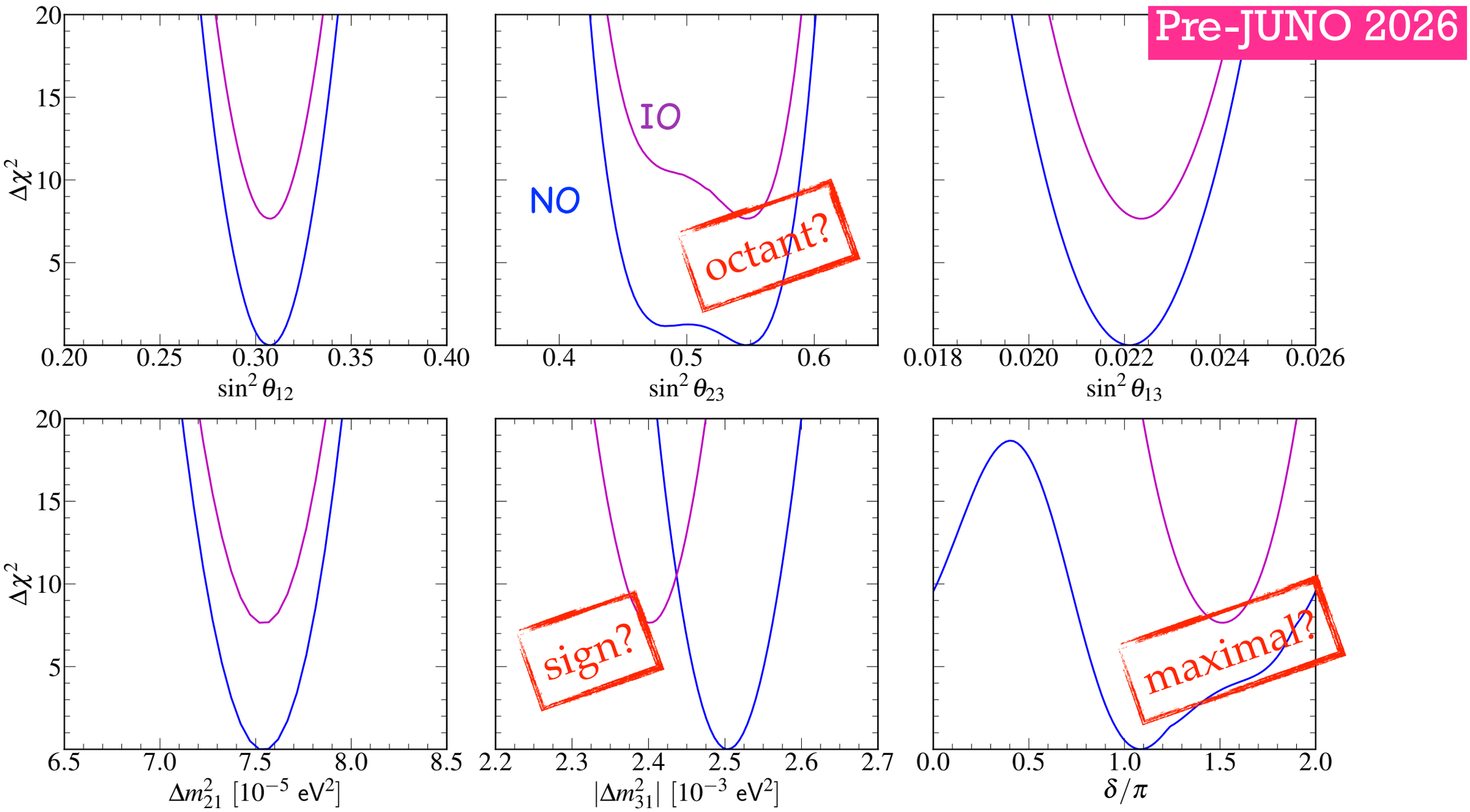


$\Delta\chi^2$(IO-NO) = 7.7

See also NuFIT and Bari analyses

Global fits to ν oscillations

de Salas et al, **JHEP 02 (2021) 071** https://globalfit.astroparticles.es/

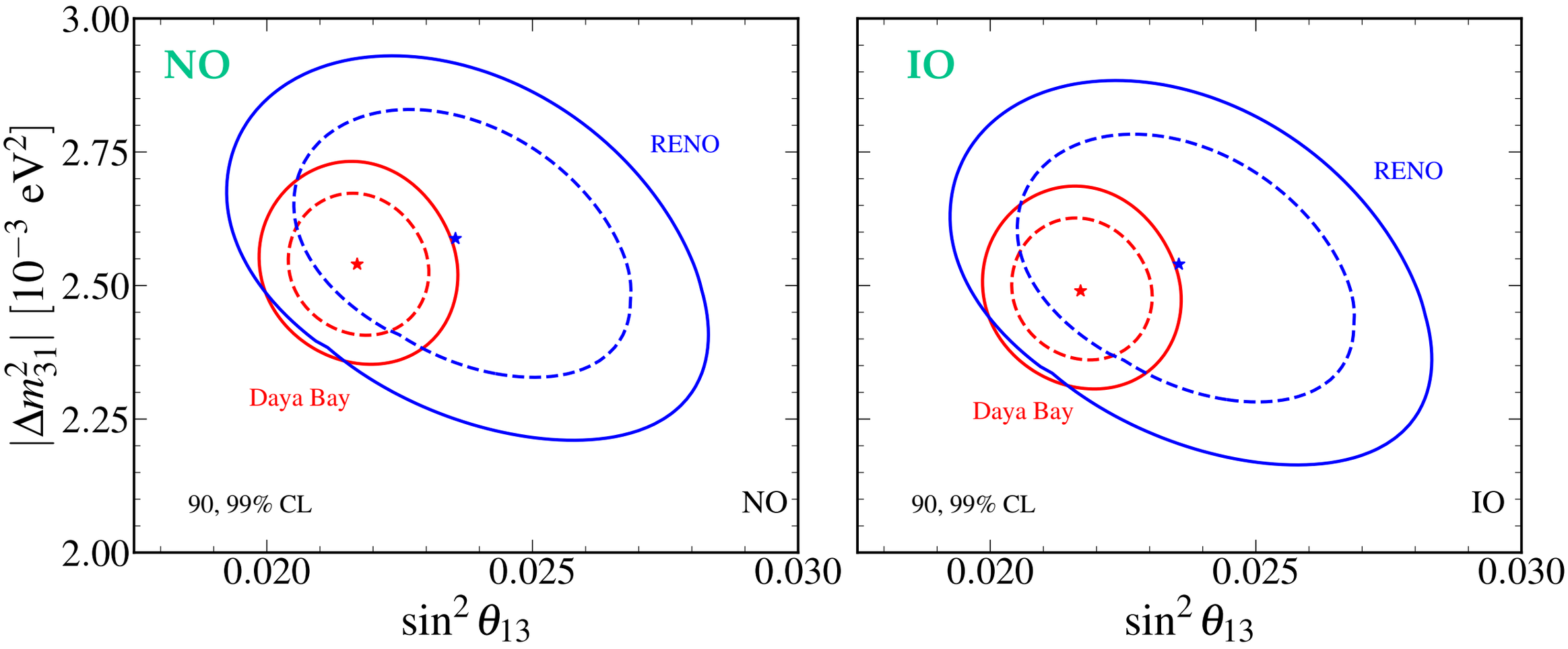


$\Delta\chi^2$(IO-NO) = 7.7

See also NuFIT and Bari analyses

The reactor sector

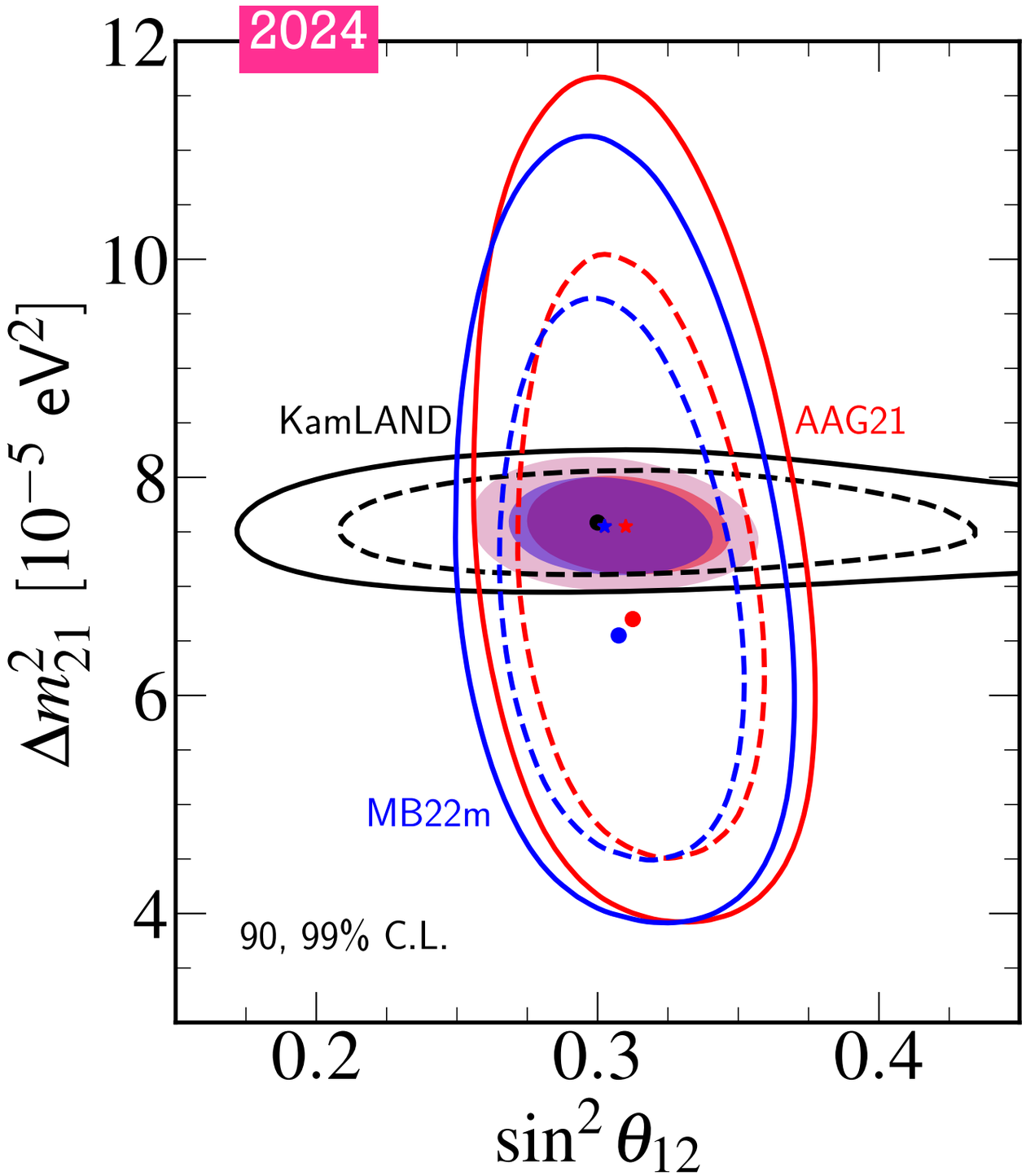
$$P_{ee} = 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m^2_{31} L}{4E} \right)$$



$\sin^2\theta_{13} = \left(2.20^{+0.07}_{-0.04}\right) \cdot 10^{-2}$

$\sin^2\theta_{13} = \left(2.23^{+0.05}_{-0.06}\right) \cdot 10^{-2}$

The solar sector

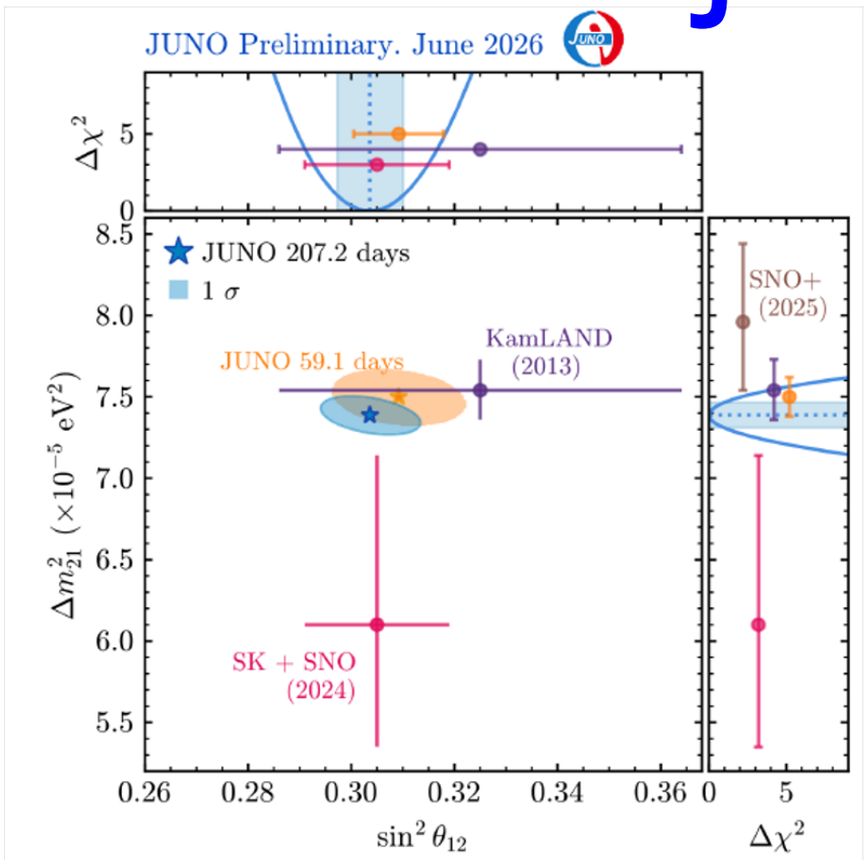


- θ_{12} measurement dominated by solar neutrino data
- Δm^2_{21} is better measured by KamLAND.
- 1.5σ mismatch between the values of Δm^2_{21} measured by solar and KamLAND

$$\sin^2\theta_{12} = 0.308^{+0.009}_{-0.007}$$

$$\Delta m^2_{21} = (7.52^{+0.11}_{-0.07}) \times 10^{-5}\text{eV}^2$$

Latest JUNO data (207.2 days)



Y. Wang (Neutrino 2026)

$\Delta m^2_{12} = (7.388 \pm 0.078) \times 10^{-5}$ eV^2 (1.6% to 1.1%)

$\sin^2\theta_{12} = 0.3036 \pm 0.0087$ (2.8% to 2.1%)

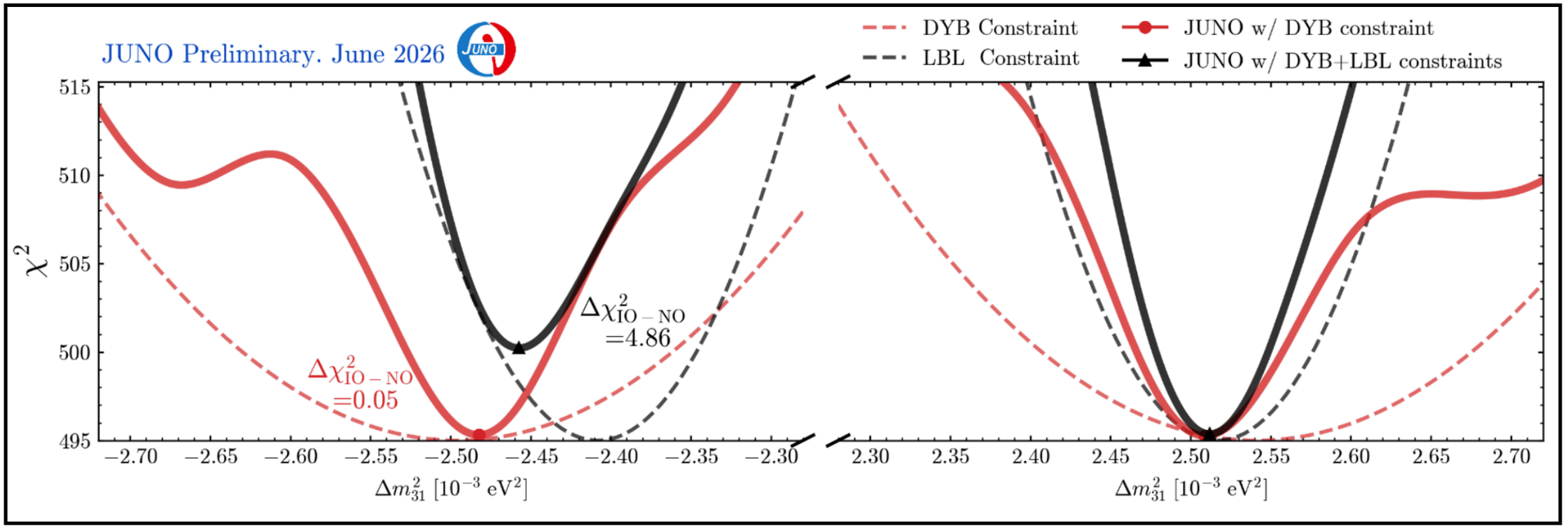
Global precision:

$\sigma(\Delta m^2_{21}) < 1\%$ and $\sigma(\sin^2\theta_{12}) < 2\%$

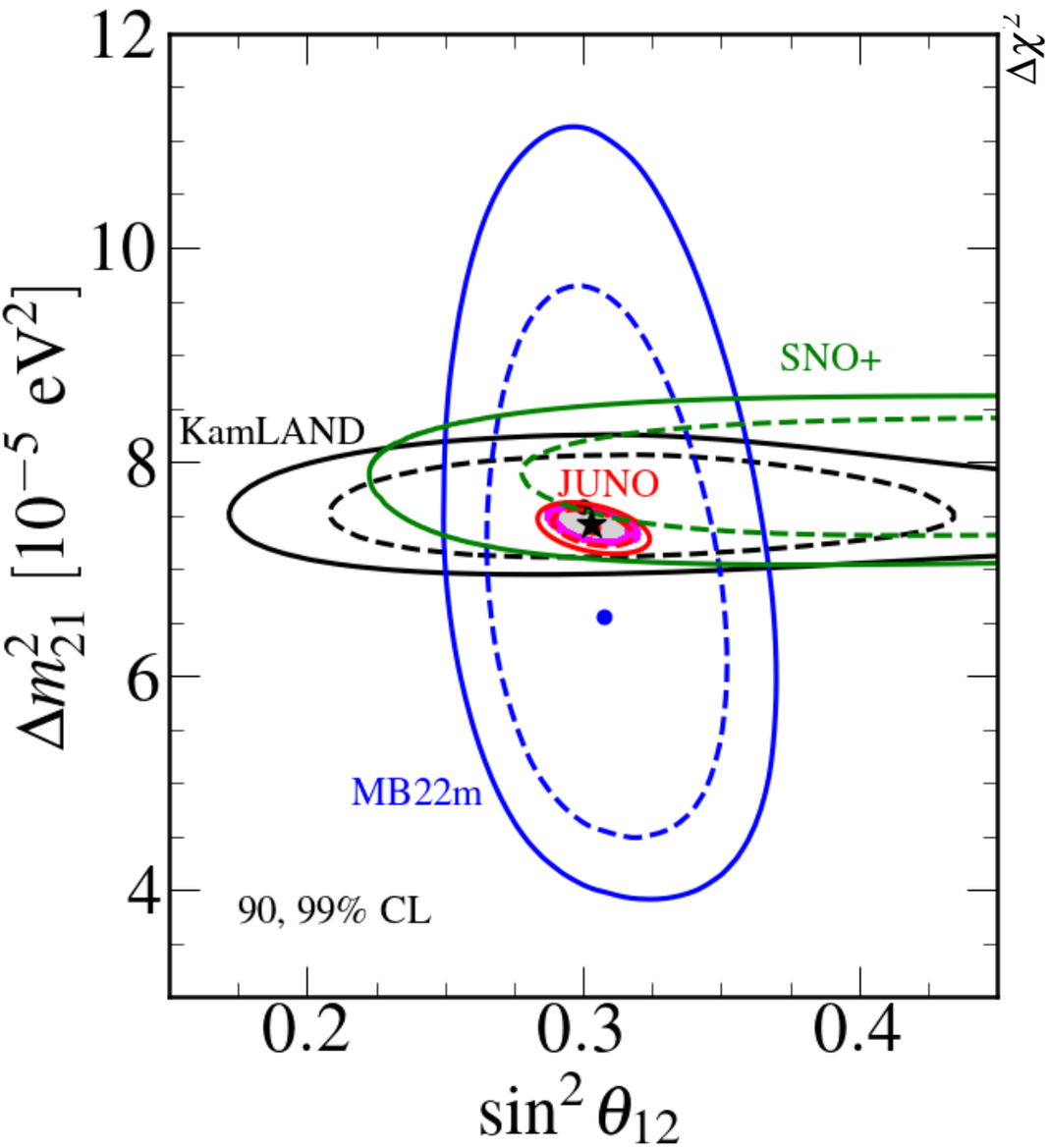
1% precision in Δm^2_{31}

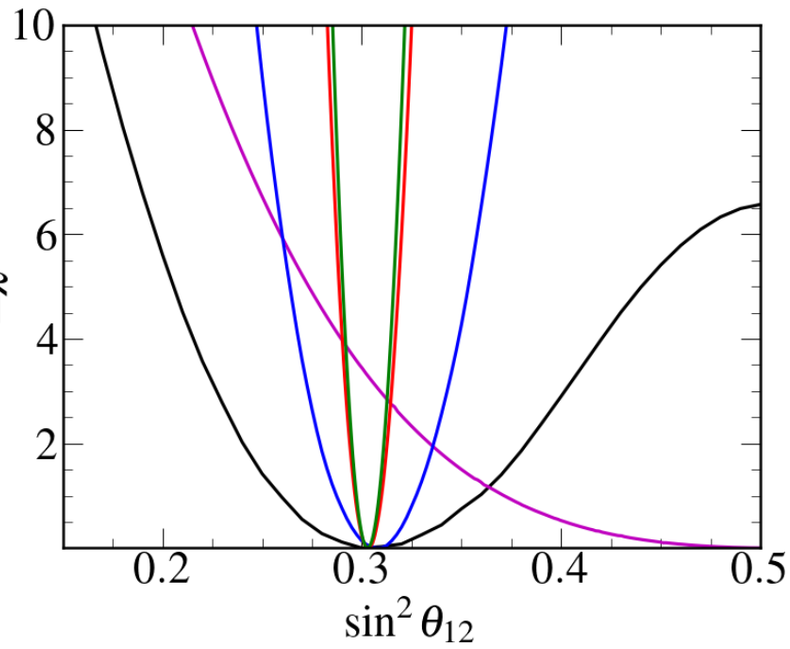
$$\Delta m^2_{31} = \left(2.509^{+0.027}_{-0.025}\right) \times 10^{-3}\text{eV}^2$$

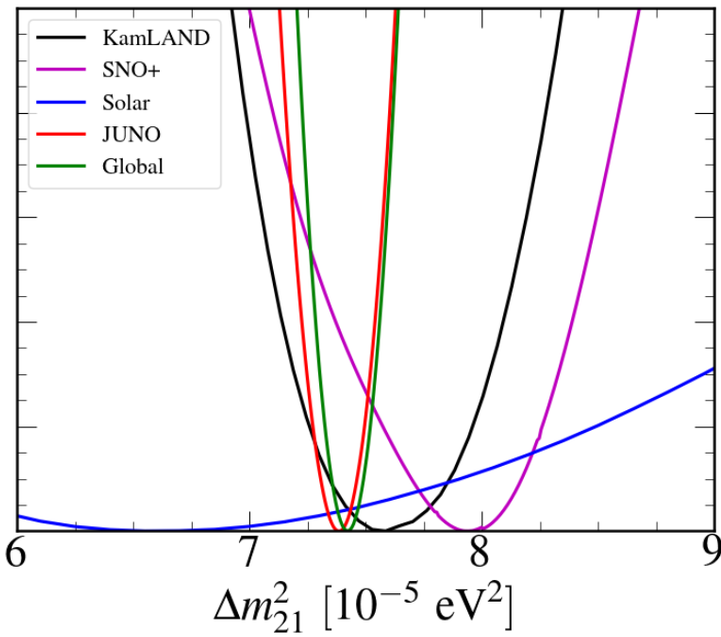
$$\Delta m^2_{31} = \left(-2.482^{+0.025}_{-0.026}\right) \times 10^{-3}\text{eV}^2$$



The solar sector in 2026







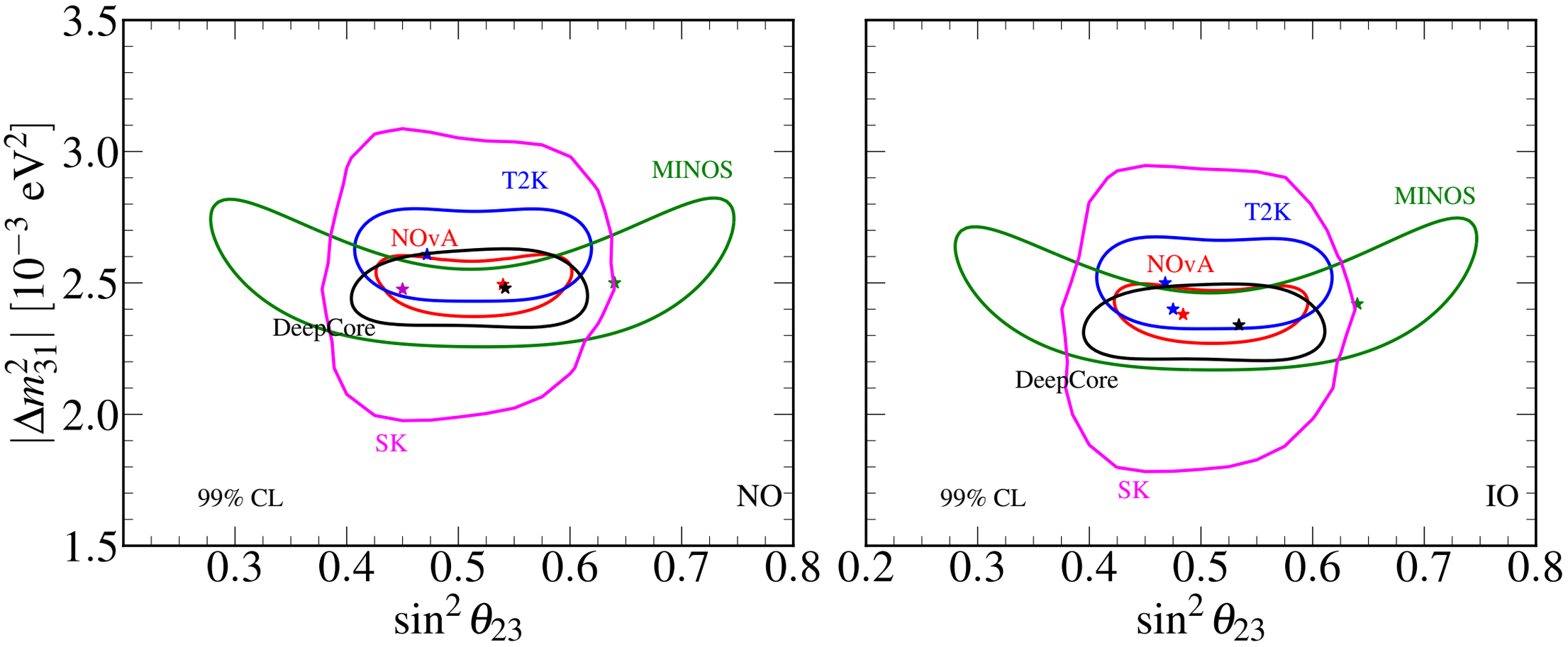
Best precision ever reached for Δm^2_{21} and θ_{12} thanks to JUNO

$$\frac{\sigma_{\Delta m^2_{21}}}{\Delta m^2_{12}} = 1.0\,\% \qquad \frac{\sigma_{\sin^2\theta_{12}}}{\sin^2\theta_{12}} = 2.0\,\%$$

$$\sin^2\theta_{12} = 0.303 \pm 0.006$$

$$\Delta m^2_{21} = (7.42 \pm 0.07) \times 10^{-5}\text{eV}^2$$

Atmospheric & accelerator sector



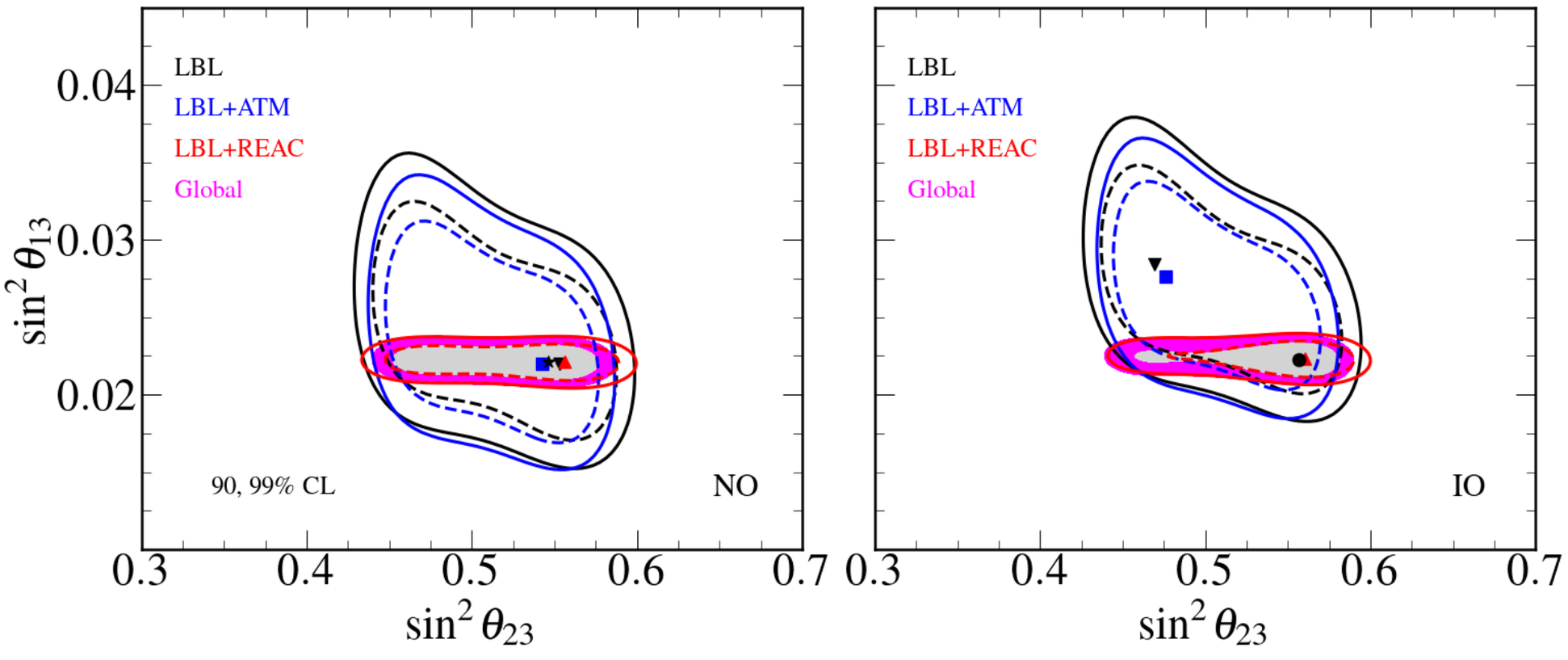
$$|\Delta m^2_{31}| = \left(2.502^{+0.022}_{-0.019}\right) \cdot 10^{-3}\,\text{eV}^2$$

$$|\Delta m^2_{31}| = \left(2.400^{+0.022}_{-0.018}\right) \cdot 10^{-3}\,\text{eV}^2$$

- Great agreement among all the experiments
- Best sensitivity obtained by T2K, NOvA and IC-DeepCore.
- Not possible to resolve the octant of the atmospheric angle.

The octant of θ_{23}

- **LBL** combination slightly prefer UO (NO) and LO(IO) with $\Delta\chi^2 = 0.2$ - 0.5
- LBL + ATM prefers UO (NO) and LO (IO) with $\Delta\chi^2 \sim 0.2$ - 0.7
- LBL + REAC favors UO (NO and IO) with $\Delta\chi^2 \sim 1.9$ - 4.3 over LO
- Global analysis shows a milder preference for UO with $\Delta\chi^2 \sim 1.2$ (2.7) for NO (IO)



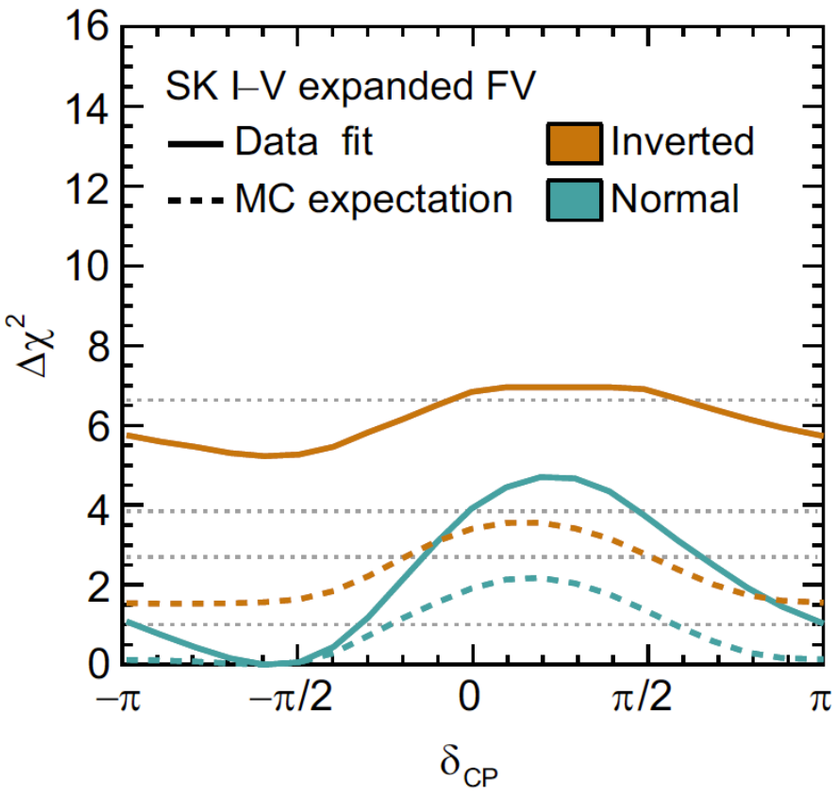
$$\sin^2\theta_{23} = 0.546^{+0.016}_{-0.019}$$

$$\sin^2\theta_{23} = 0.556^{+0.015}_{-0.018}$$

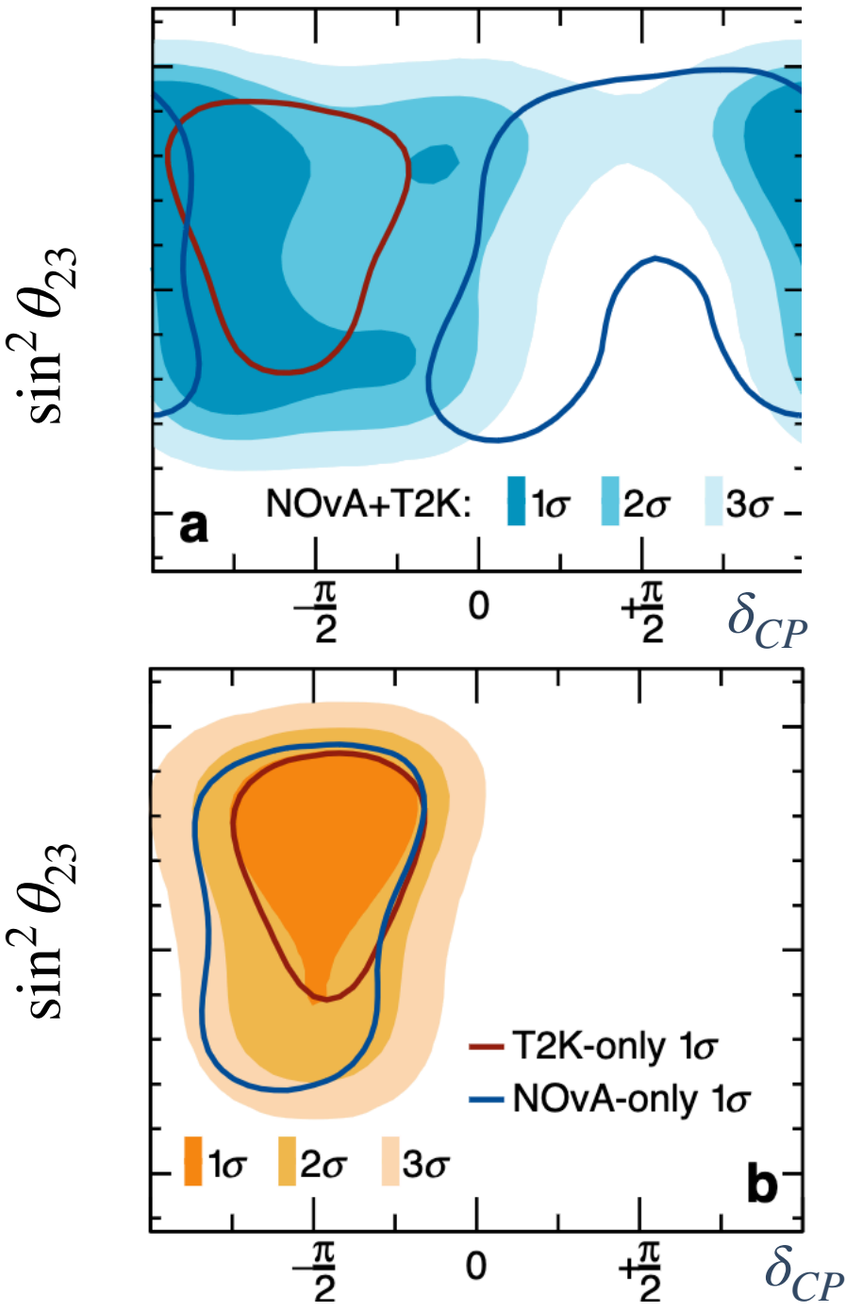
The CP phase

Observation of the appearance channels $\nu_\mu \to \nu_e$ in atmospheric and accelerator experiments allows to measure $\delta_{\rm CP}$

SK Collab, PRD 109 (2024) 072014



Super-Kamiokande observes a ν_e excess in agrement with maximal CP phase $\delta_{\rm CP} \sim 3\pi/2$

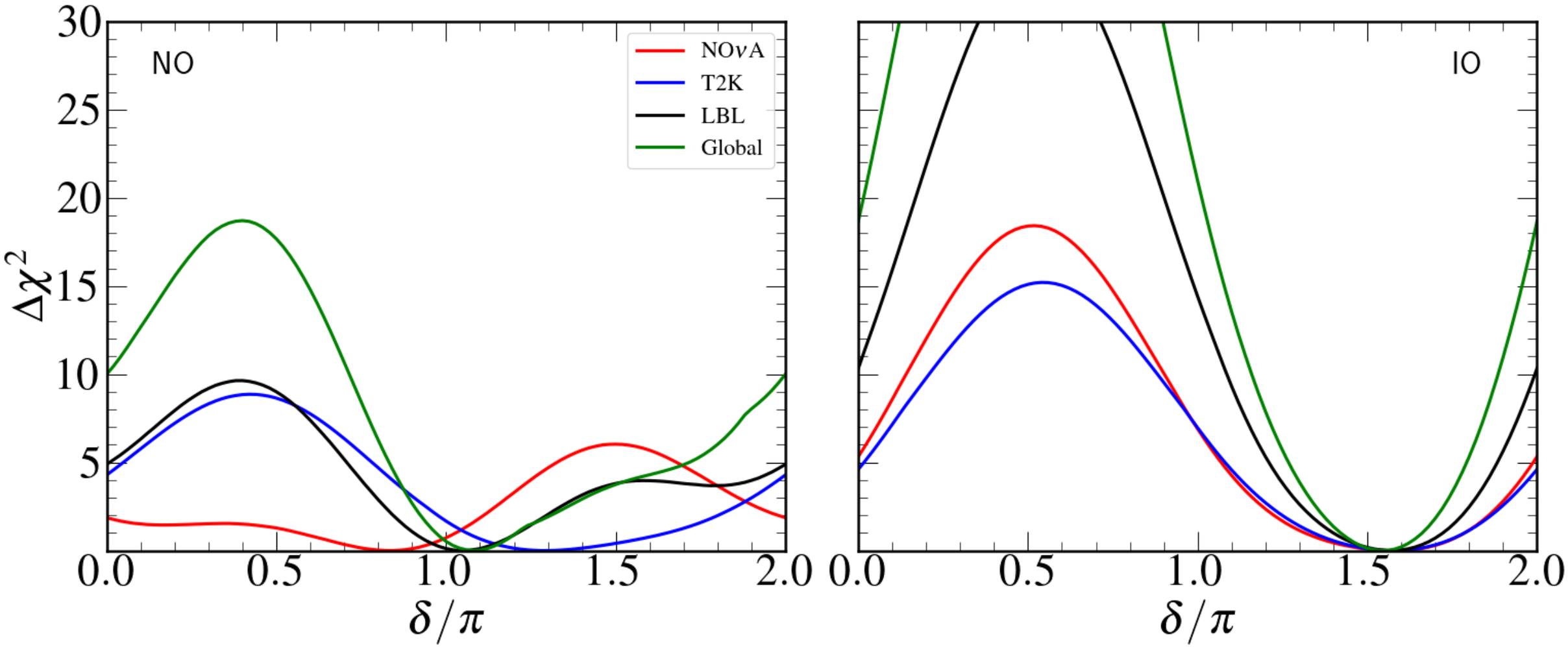


Joint T2K & NOvA analysis 2510.19888

T2K prefers also $\delta_{\rm CP} \sim 3\pi/2$

NOvA results depend on mass ordering

The CP phase



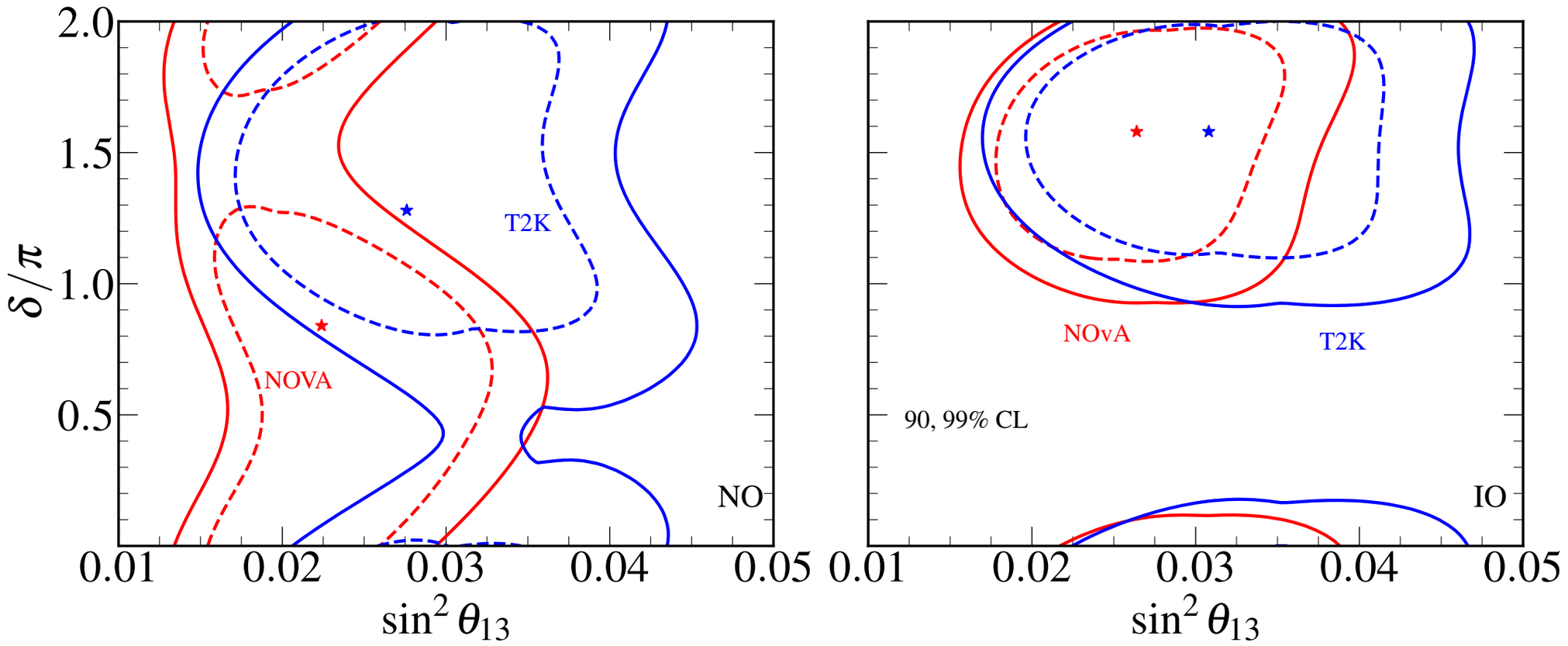
- NO: mismatch between NOvA and T2K and SK atmospheric results

  $\delta_{BF} = 1.08\pi$; $\delta = \pi/2$ (0) disfavored at 4.2σ (3.1σ)

- IO: all experiments prefer $\delta \approx 3\pi/2$

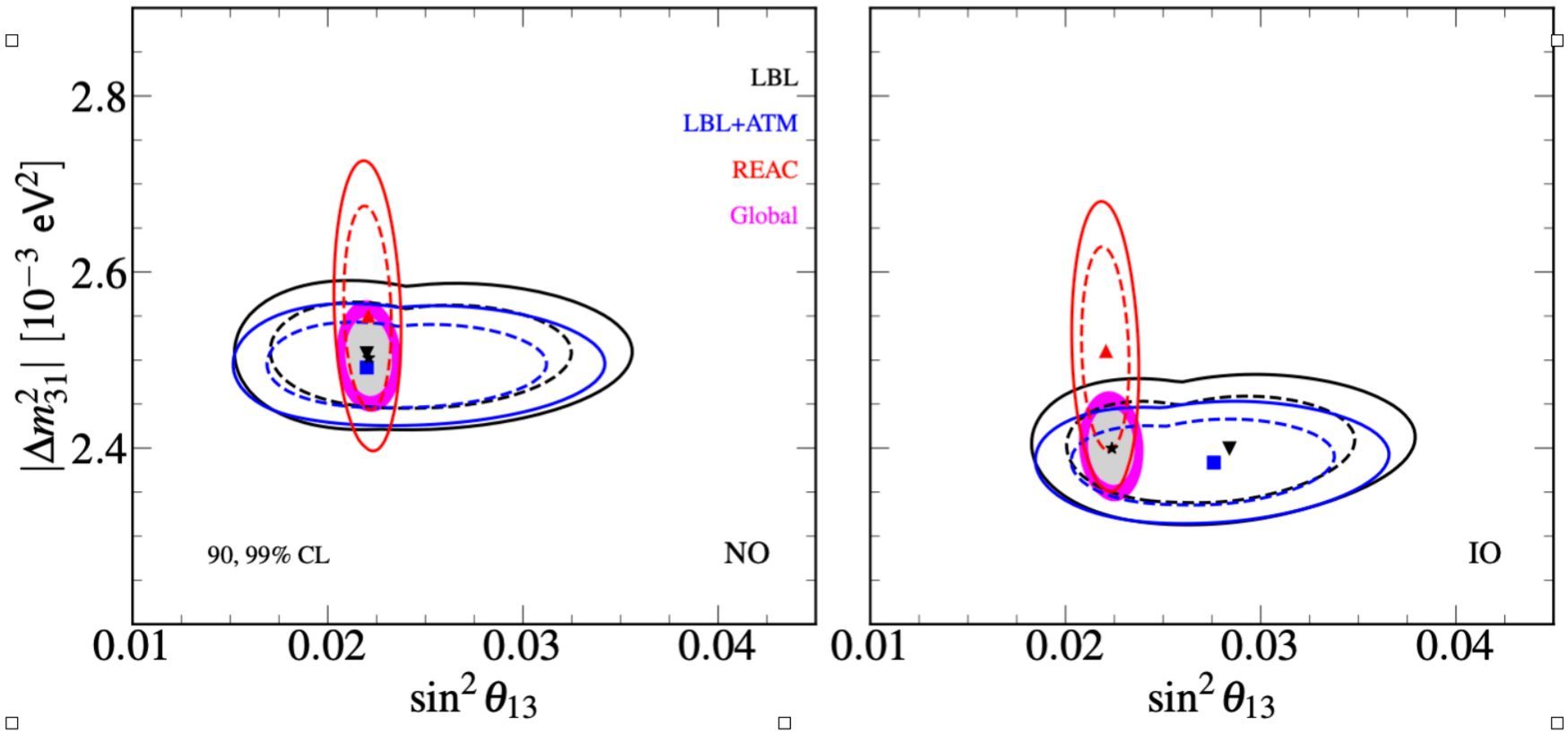
  $\delta_{BF} = 1.54\pi$; $\delta = \pi/2$ (π) disfavored at 7.5σ (4.4σ)

The mass ordering



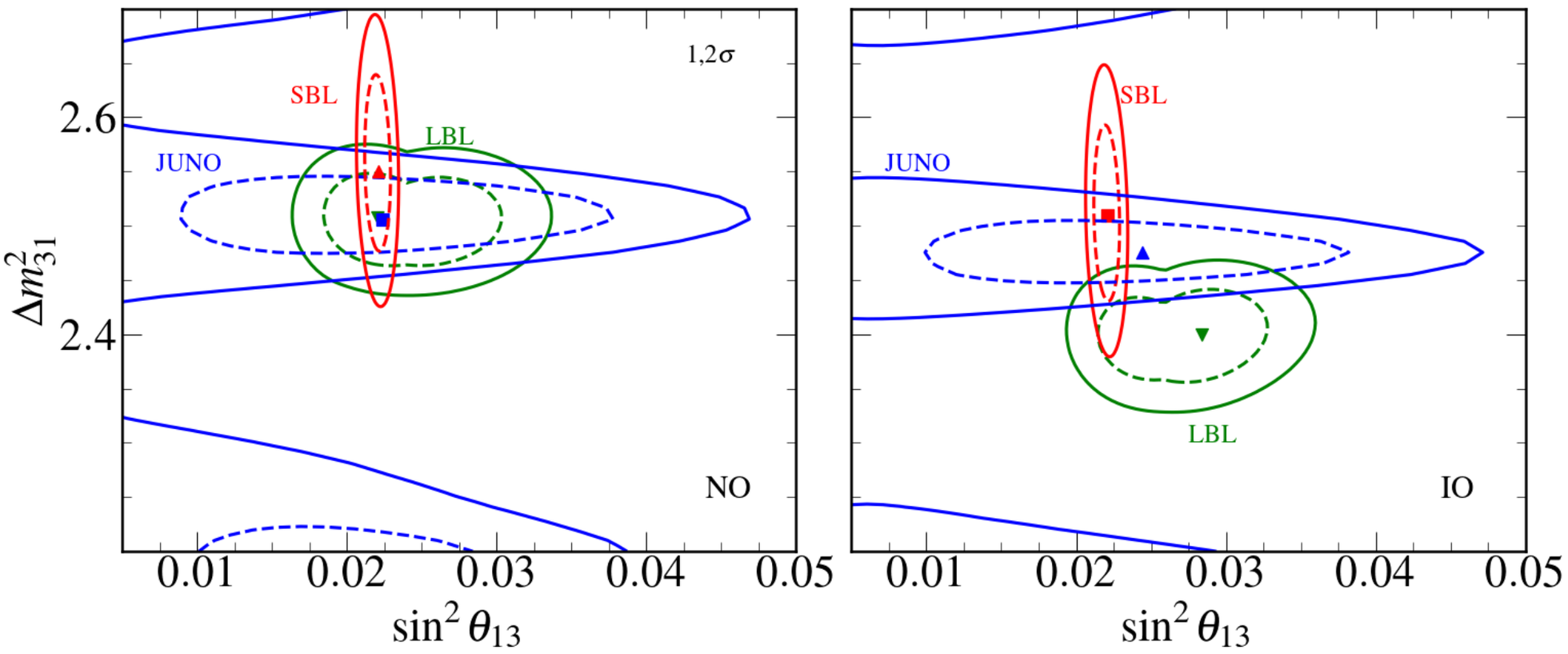
- **T2K** and **NOvA** separate analyses prefer NO with $\Delta\chi^2 \approx 1.1\text{-}1.3$
- **LBL** prefer IO with $\Delta\chi^2 \approx 2.9$ (T2K-NOvA tension in NO)

The mass ordering



- T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 1.1$-1.3
- LBL prefer IO with $\Delta\chi^2 \approx 2.9$ (T2K-NOvA tension in NO)
- LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.3$ (tension in Δm^2_{31} in IO)
- SK-atm prefers NO with $\Delta\chi^2 = 5.69$ (5.23) for θ_{13} constrained (free)

The mass ordering



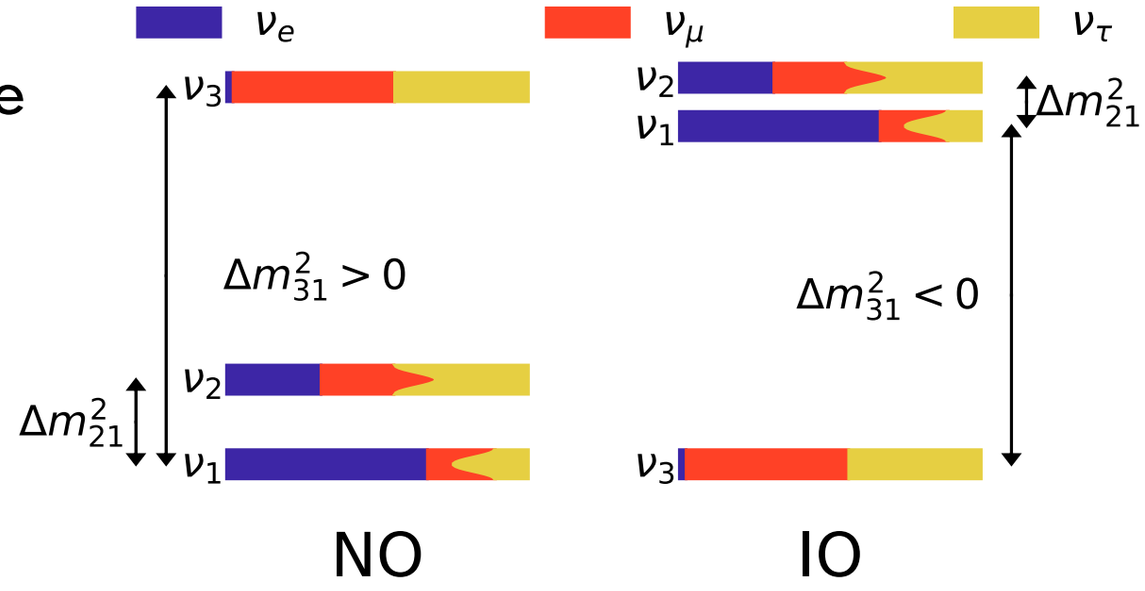
- T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 1.1$-1.3
- LBL prefer IO with $\Delta\chi^2 \approx 2.9$ (T2K-NOvA tension in NO)
- LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.3$ (tension in Δm^2_{31} in IO)
- SK-atm prefers NO with $\Delta\chi^2 = 5.69$ (5.23) for θ_{13} constrained (free)

Adding JUNO increases the preference for NO to $\Delta\chi^2$ (IO-NO)= 14.3

Neutrino masses: what do we know?

Neutrino oscillations establish non-zero neutrino masses

- Two independent mass-squared splittings are measured: Δm^2_{21} and Δm^2_{31}
- Two possible orderings remain under consideration: NO and IO
- The absolute mass scale remains unknown



de Salas et al, 2018

Three key open questions

1) What is the lightest neutrino mass?
2) What is the mass ordering?
3) What is the origin of the small neutrino masses?



Credit: Symmetry Magazine

Measuring the absolute ν mass

Neutrino oscillations

$$\sum m_\nu|_{\rm NO} \gtrsim 0.06\,{\rm eV}$$

$$\sum m_\nu|_{\rm IO} \gtrsim 0.1\,{\rm eV}$$

Direct kinematic constraints

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

$m_\beta < 0.45$ eV (90% CL)

KATRIN, 2025

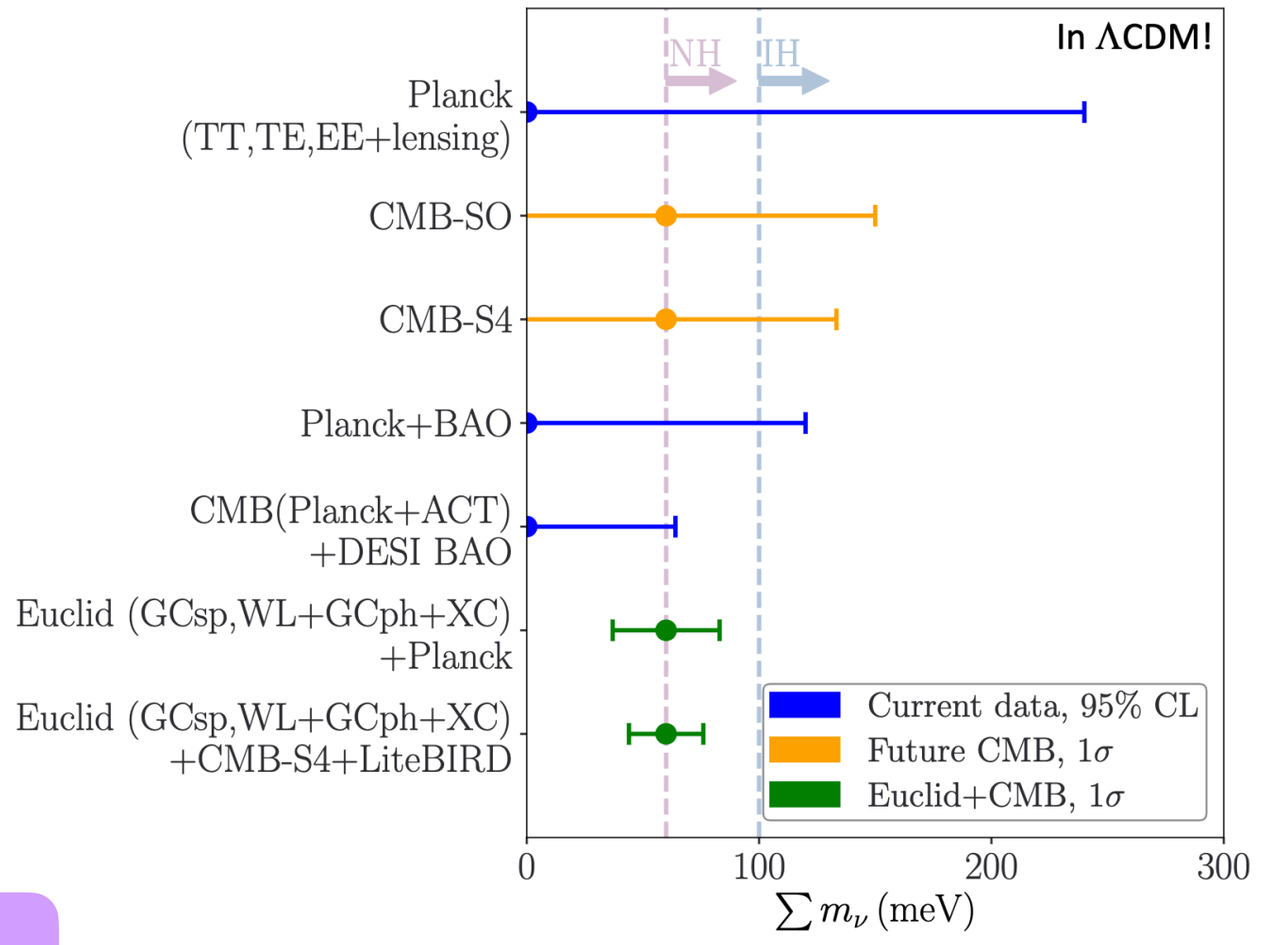
Neutrinoless double β decay

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$

See talks today

Cosmological constraints

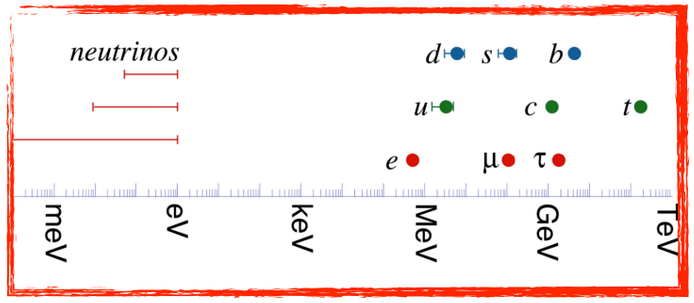
$$\Sigma m_\nu = m_1 + m_2 + m_3$$



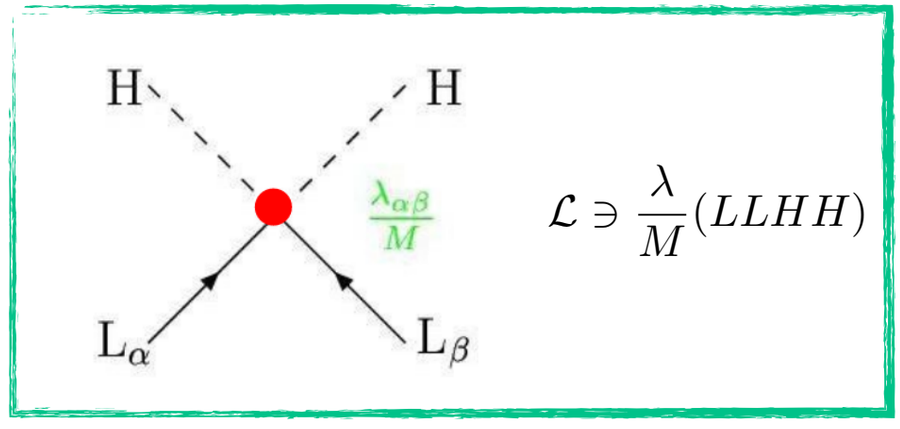
M. Archidiacono @ Erice 2026

The origin of neutrino masses

$m_\nu << m_f$: different origin?

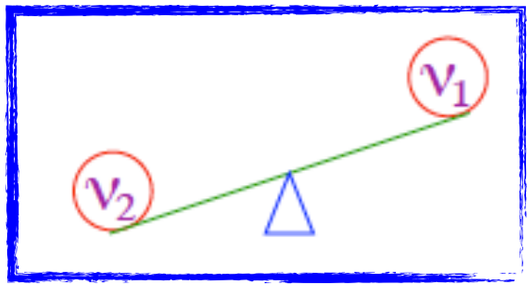


- Dirac masses: right-handed neutrinos & very small Yukawa couplings
- Majorana masses: violate lepton number and can arise through the dim5 **Weinberg** operator
- Seesaw mechanisms: smallness due to heavy states or other high-scale physics.
- Radiative models: generated through quantum corrections, involving new particles



For the **simplest type-I seesaw:** $m_\nu = -m_D M_R^{-1} m_D^T$

For $m_D \sim 100$ GeV, $m_\nu \sim 0.01 - 1$eV with $M_R \sim 10^{13} - 10^{15}$ GeV



Open questions

- What mechanism generates neutrino masses?
- Is lepton number violated?
- Can the mechanism be tested experimentally?
- Can it explain the baryon asymmetry through leptogenesis?

Beyond the 3ν paradigm

3ν framework: absence of any **new physics** besides neutrino masses

✦ Neutrino results suggest the presence of **physics BSM** to explain:

- ✓ light neutrino masses (mass generation mechanism)
- ✓ large neutrino mixing compared to quark sector (flavour problem)
- ✓ short-distance anomalies (LSND, reactor and Ga anomalies)

✦ Many different **BSM scenarios** analyzed in the literature:

- ✓ Non-standard interactions
- ✓ Non-unitary mixing
- ✓ CPT and Lorentz violation
- ✓ E.m. ν properties
- ✓ Light sterile neutrinos
- ✓ …

Are there experimentally accessible deviations from the standard 3ν picture?

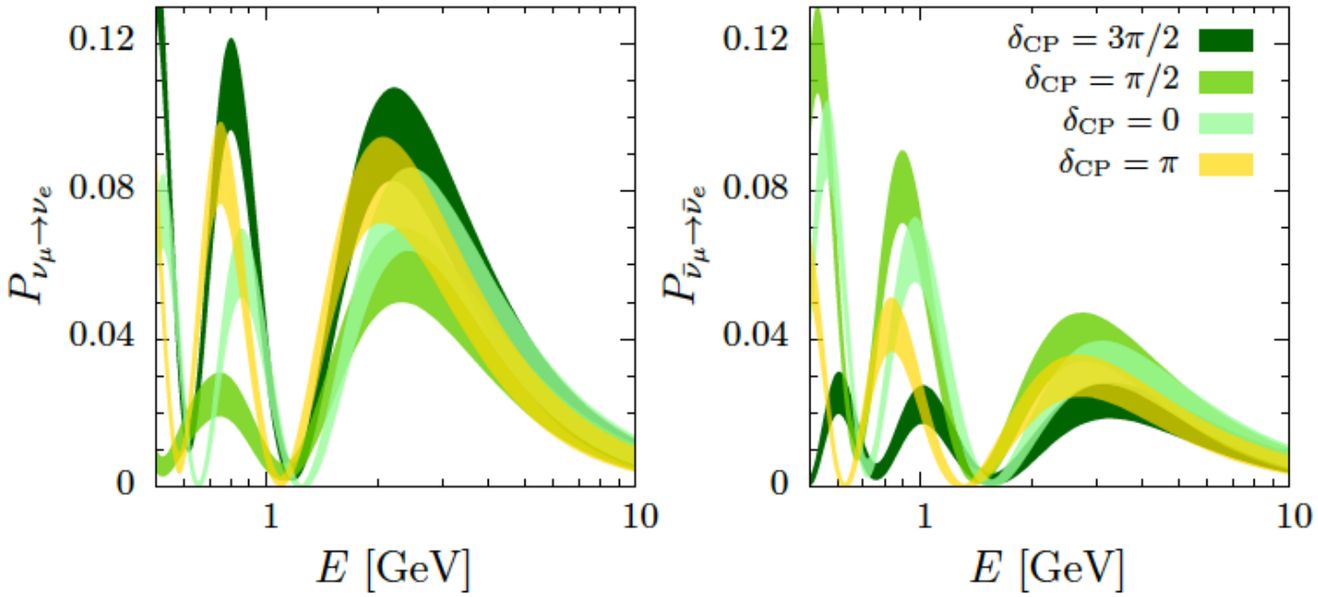
- limits on size of new physics effects
- Robustness of 3ν oscillations with NP
- Explain tensions among experiments

Robustness of 3ν oscillations

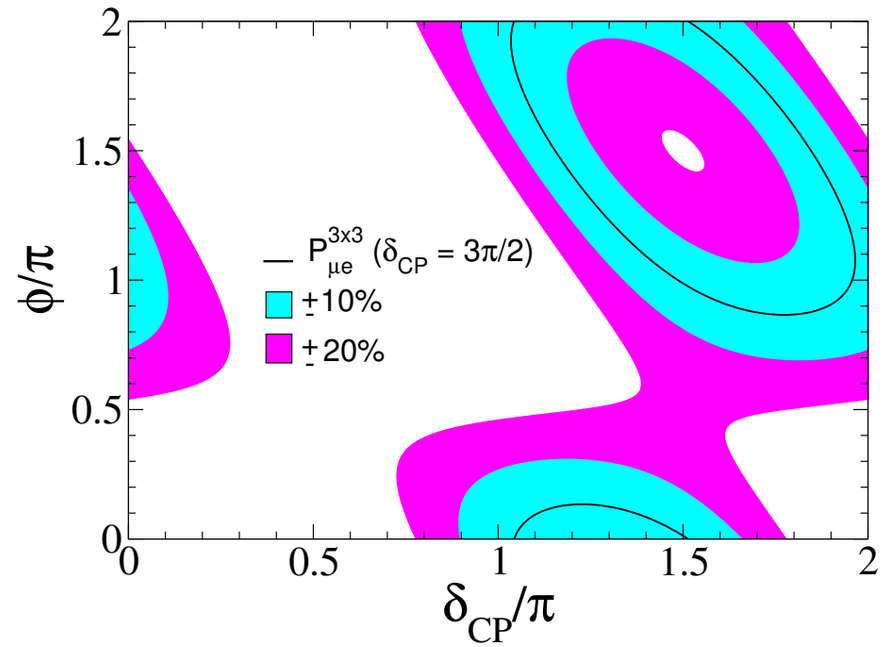
With non-unitary light neutrino mixing new complex phases may affect oscillations

$$N = N^{NP} U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times 3}_{\mu e} + \alpha^2_{11}\alpha_{22}|\alpha_{21}| P^{I}_{\mu e} + \alpha^2_{11}|\alpha_{21}|^2 \quad \textbf{with} \quad P^{I}_{\mu e}(\phi)$$



Escrihuela et al, NJP 2017



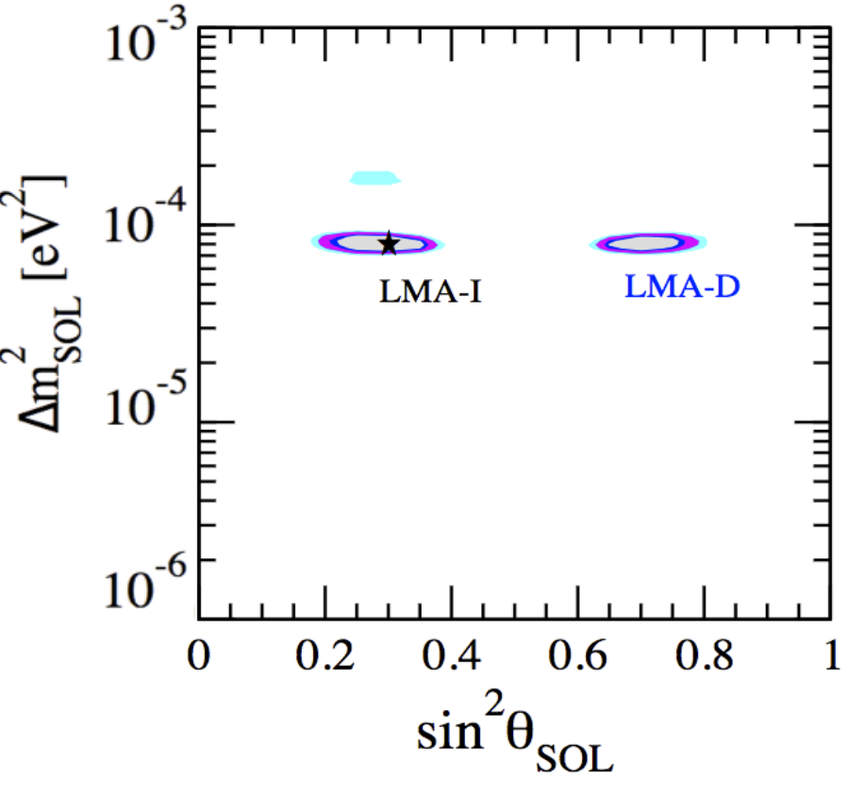
Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV may affect the sensitivity to δ in future LBL experiments

Robustness of 3ν oscillations

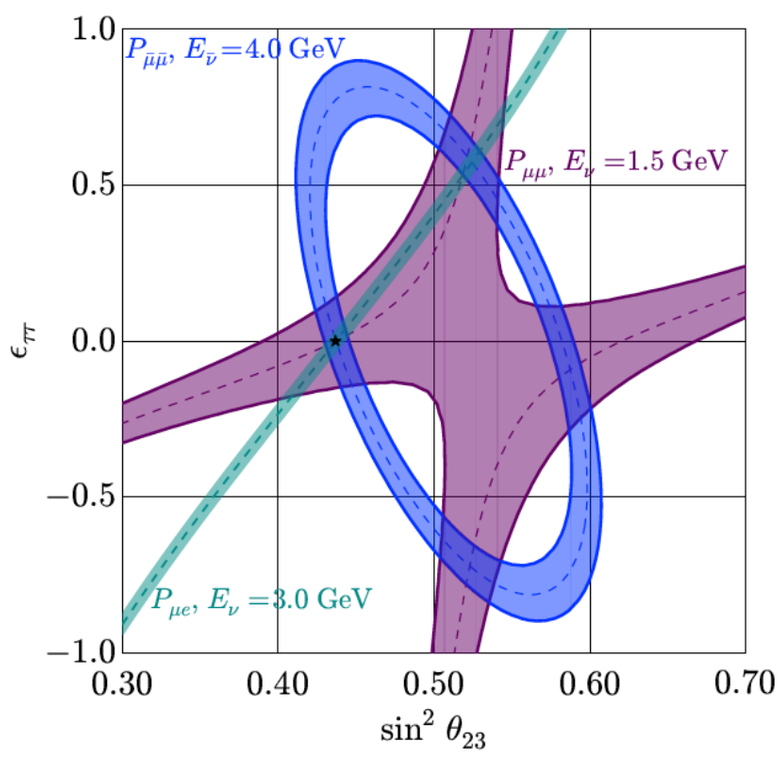
NSI can modify the neutrino propagation, production and detection and affecting the sensitivity of current and future experiments

Θ_{12} in solar experiments



Miranda et al, JHEP 2006

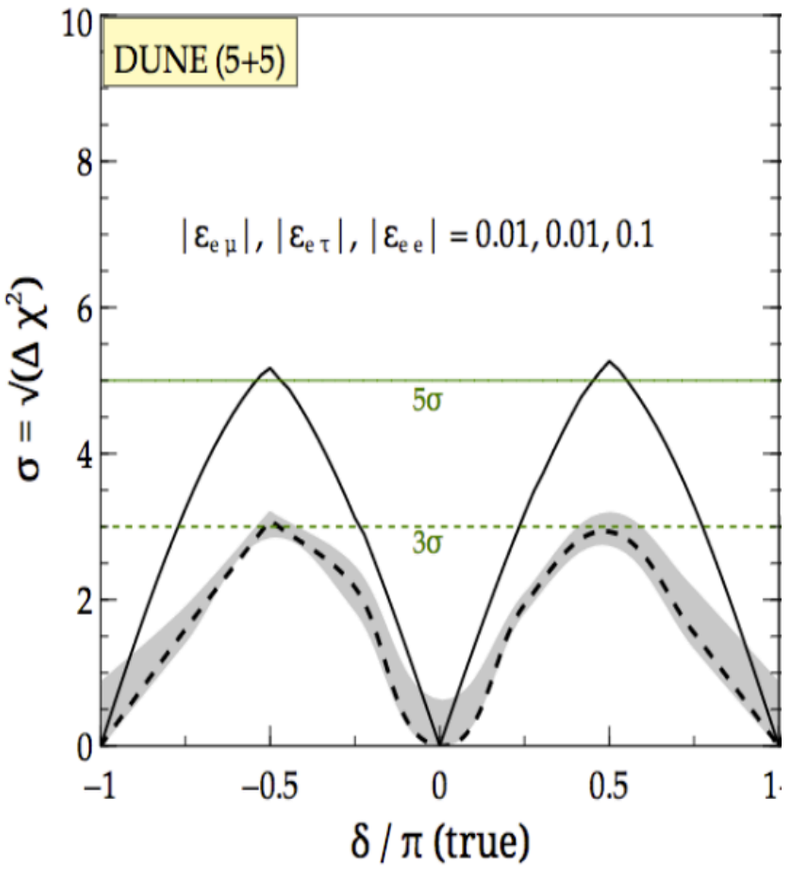
Θ_{23} sensitivity in DUNE



Gouvea and Kelly, NPB 2016

Coloma, JHEP 2016

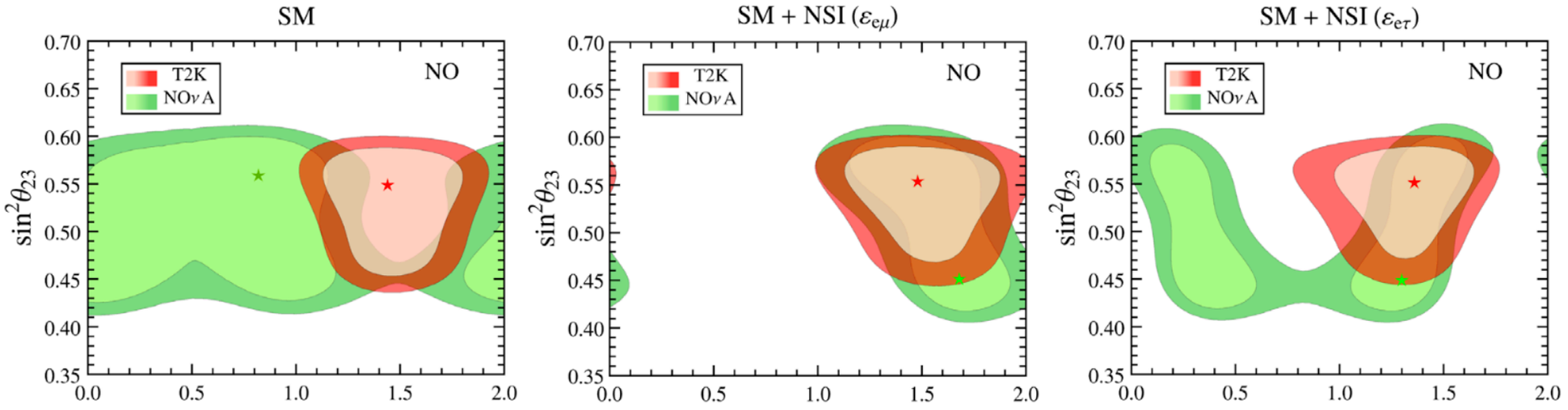
CP sensitivity in DUNE



Masud and Mehta, PRD 2016

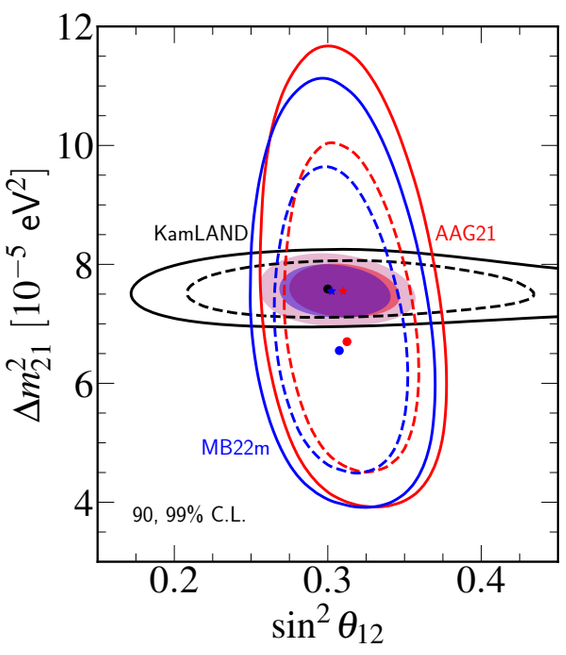
Alleviating tensions with BSM physics

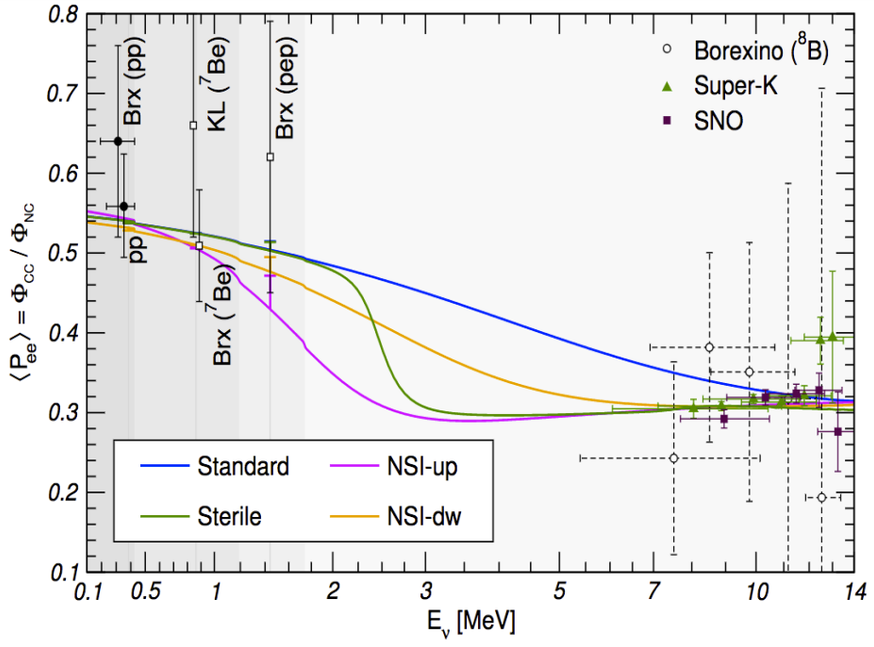
CP-violating NSI couplings may reconcile T2K and NOvA



Chatterjee & Palazzo, PRL 2021,
Denton et al, PRL 2021

NSI in the sun would reduce tension between solar and KamLAND



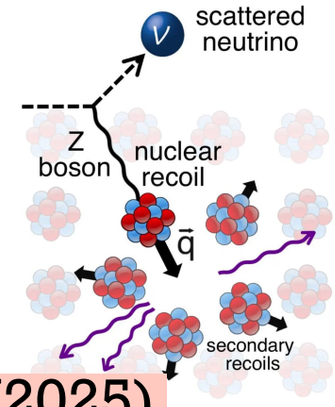


1.5σ mismatch between the measured of Δm^2_{21}

Escrihuela et al, PRD80 (2009)
Coloma et al, PRD96 (2017)
Maltoni & Smirnov, EPJ 2015

Searching for new physics with CEvNS

CEvNs experiments provide a very powerful tool to search for BSM physics with small size detectors



π-DAR neutrinos (2017) | Solar neutrinos (2024) | Reactor neutrinos (2025)

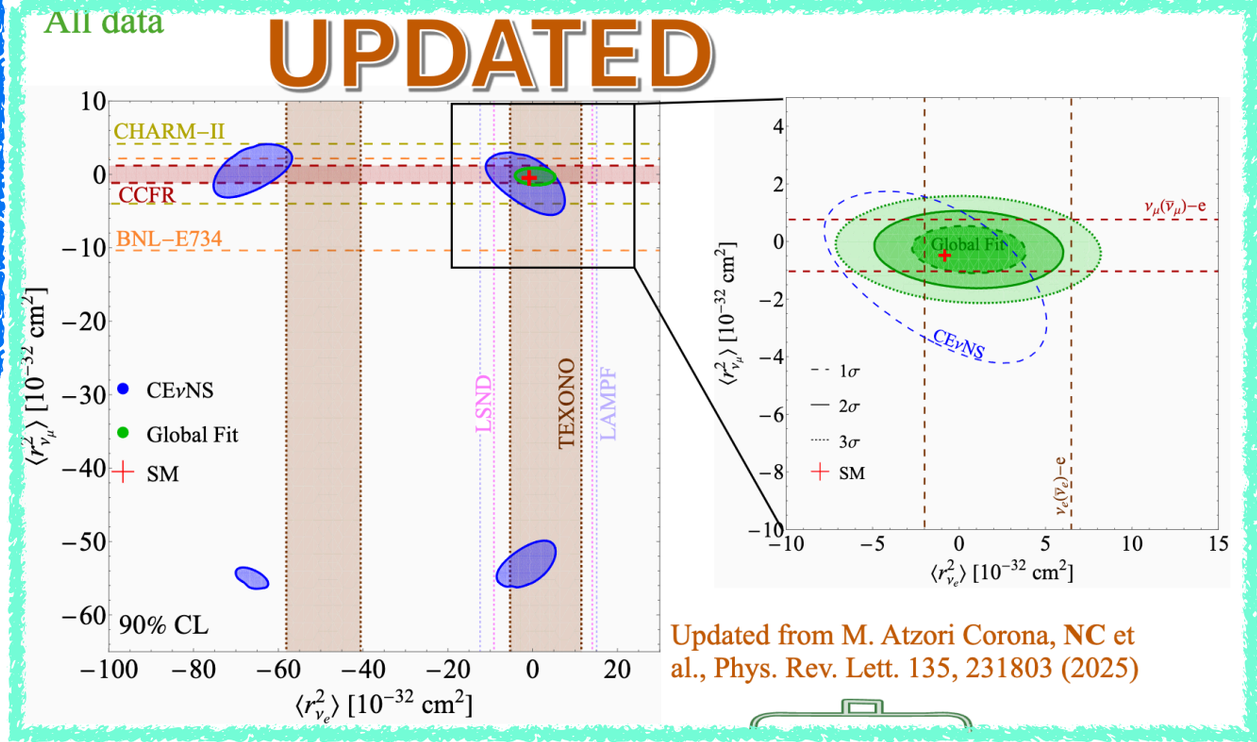
Bounds on neutrino magnetic moment (90% CL)

$$\mu_{\nu_e}^{\text{eff}} \leq 4.78 \times 10^{-10}\ \mu_B \qquad (\text{CE}\nu\text{NS only})\,,$$
$$\mu_{\nu_e}^{\text{eff}} \leq 1.10 \times 10^{-10}\ \mu_B \qquad (\text{CE}\nu\text{NS} + \text{E}\nu\text{ES})$$

De Romeri et al, PRD 2025

See talk by M. Meier about CONUS+

N. Cargioli @ Magnificent CEvNS 2026



Updated from M. Atzori Corona, **NC** et al., Phys. Rev. Lett. 135, 231803 (2025)

Conclusions & Outlook

Oscillation experiments have established a solid picture of ν mixing

- ✓ precise determinations for most parameters (~ 1 - 5%)
- ✓ slight preference for $\theta_{23} > 45°$, not conclusive
- ✓ normal ordering preferred over IO with $\Delta\chi^2 = 14.3$
- ✓ T2K & NOvA tension impacts on mass ordering and CP violation results
- ✓ JUNO data established leading precision in solar parameters.

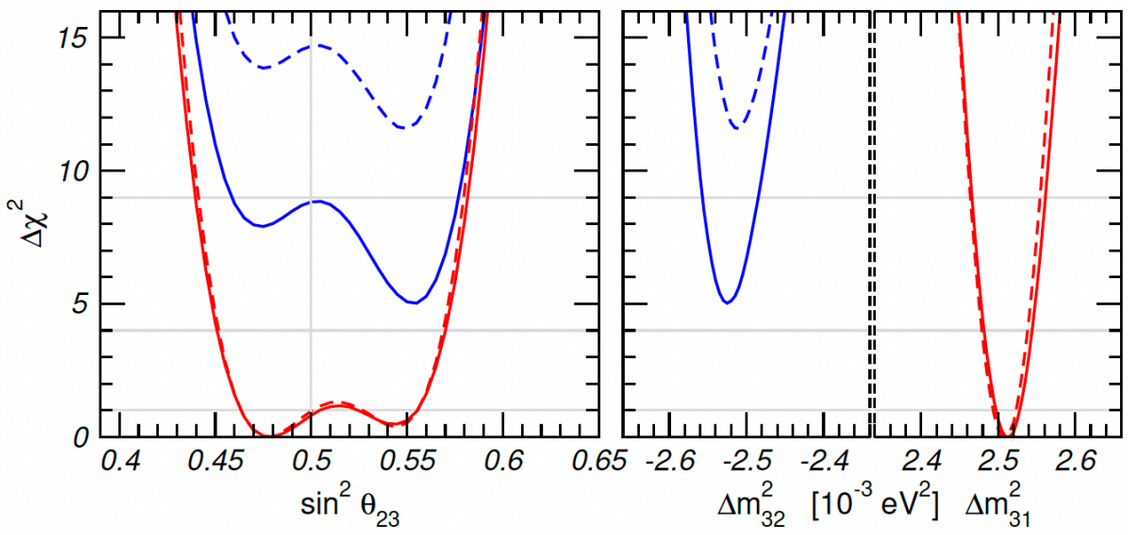
The origin of neutrino masses remains unknown:

Precision measurements and complementary searches are needed to answer these questions

Neutrinos remain a powerful tool to explore physics beyond the Standard Model

JUNO impact on MO at global fits

Our global analysis prefers NO with $\Delta\chi^2 = 14.3$

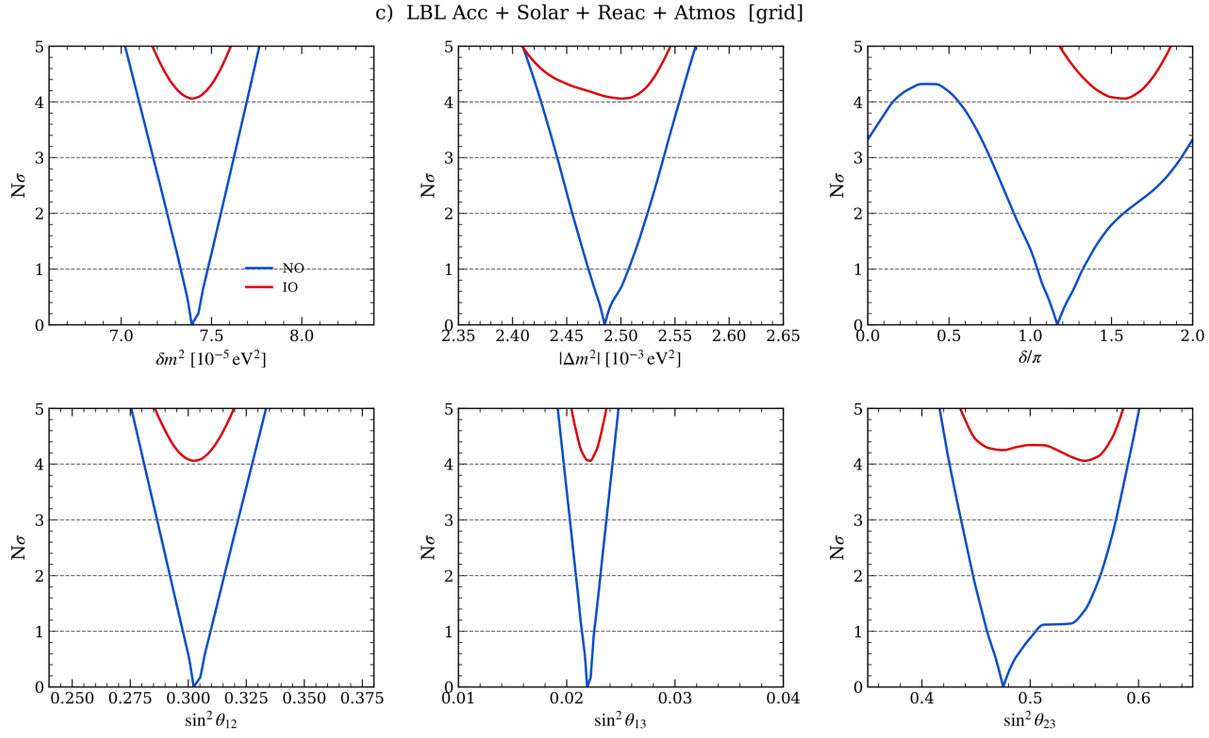


NO, IO (IC23 w/o SK-atm)
NO, IO (IC24 with SK-atm)

NuFIT 7.0 (prelim)

$\Delta\chi^2$(IO-NO) = 11.5

I. Martinez-Soler, NOW 2026



$\Delta\chi^2$(IO-NO) = 16

F. Marcone, NOW 2026