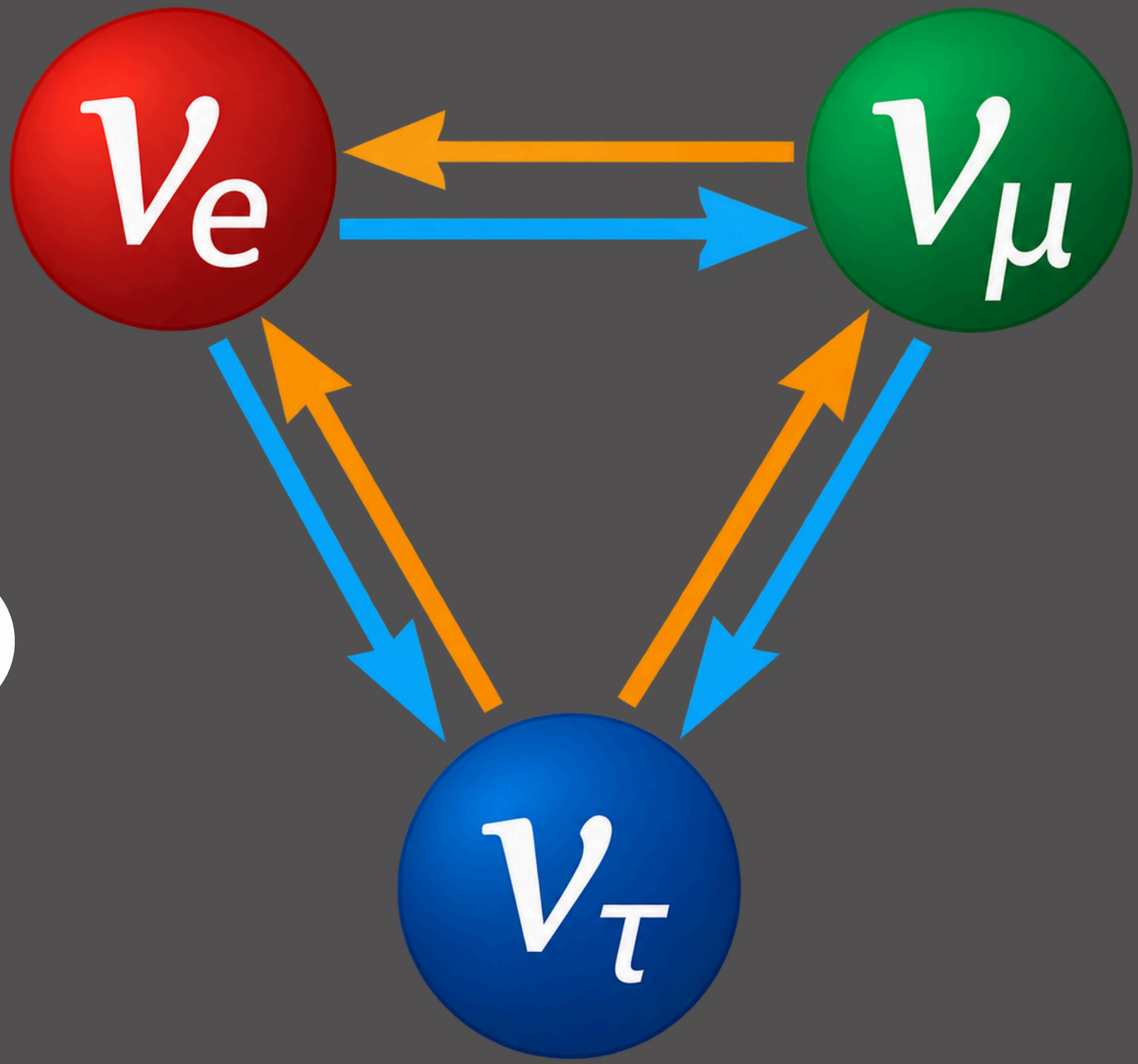
Probing Damping Effects in Neutrino Oscillations with JUNO

MARTINA BECCARIA

GSSI, L'Aquila-Italy
INFN-LNGS, Assergi (AQ)-Italy

DISCRETE 2026

Bratislava, 14 Nov 2026

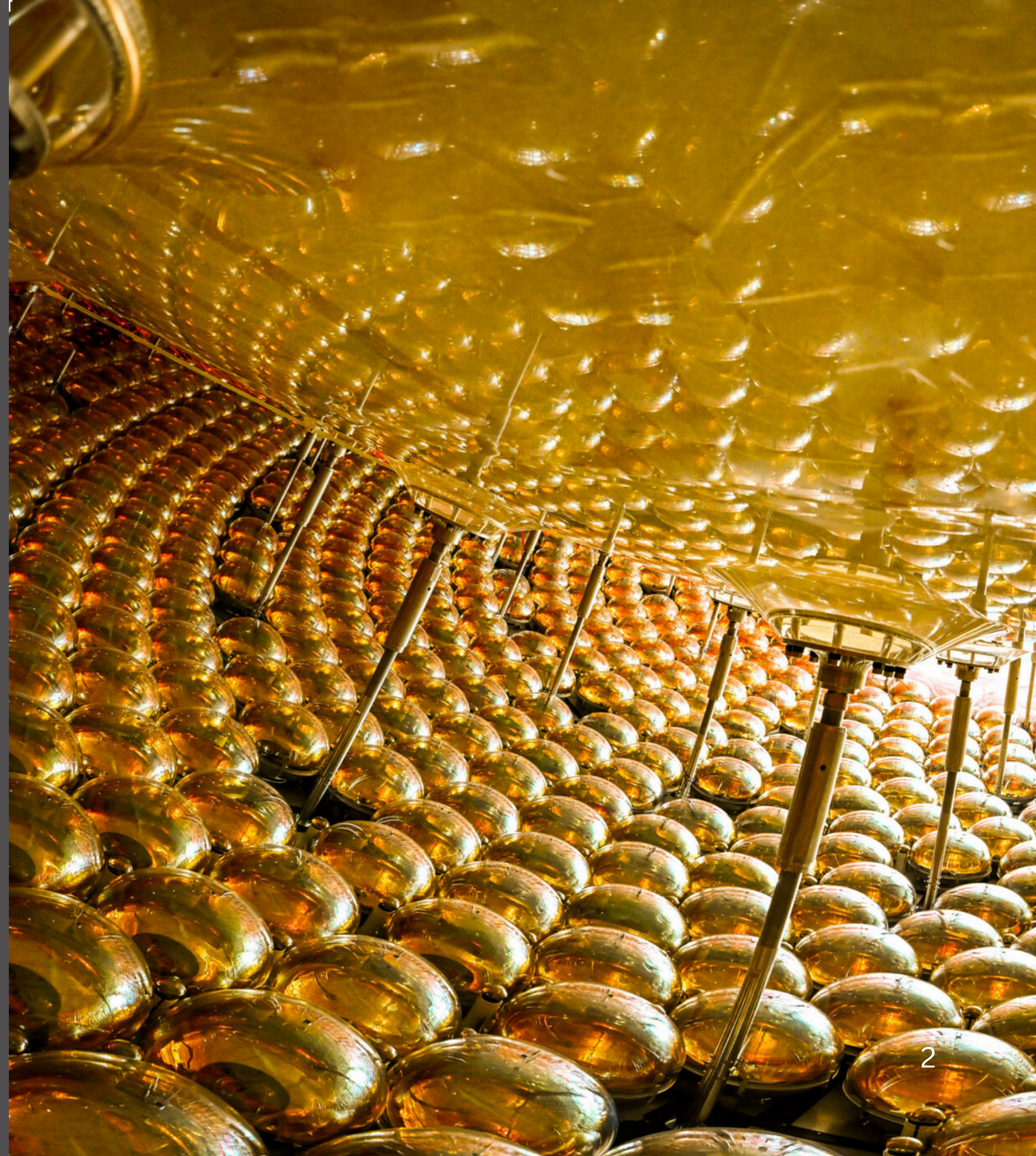


JUNO contribution to the Neutrino Global Fit

Based on updated version
(in preparation) of JHEP 02 (2021) 071

Damping effects on neutrino oscillations with JUNO

Based on
arXiv:2606.13362 [hep-ph]-M.Beccaria, C.A. Ternes

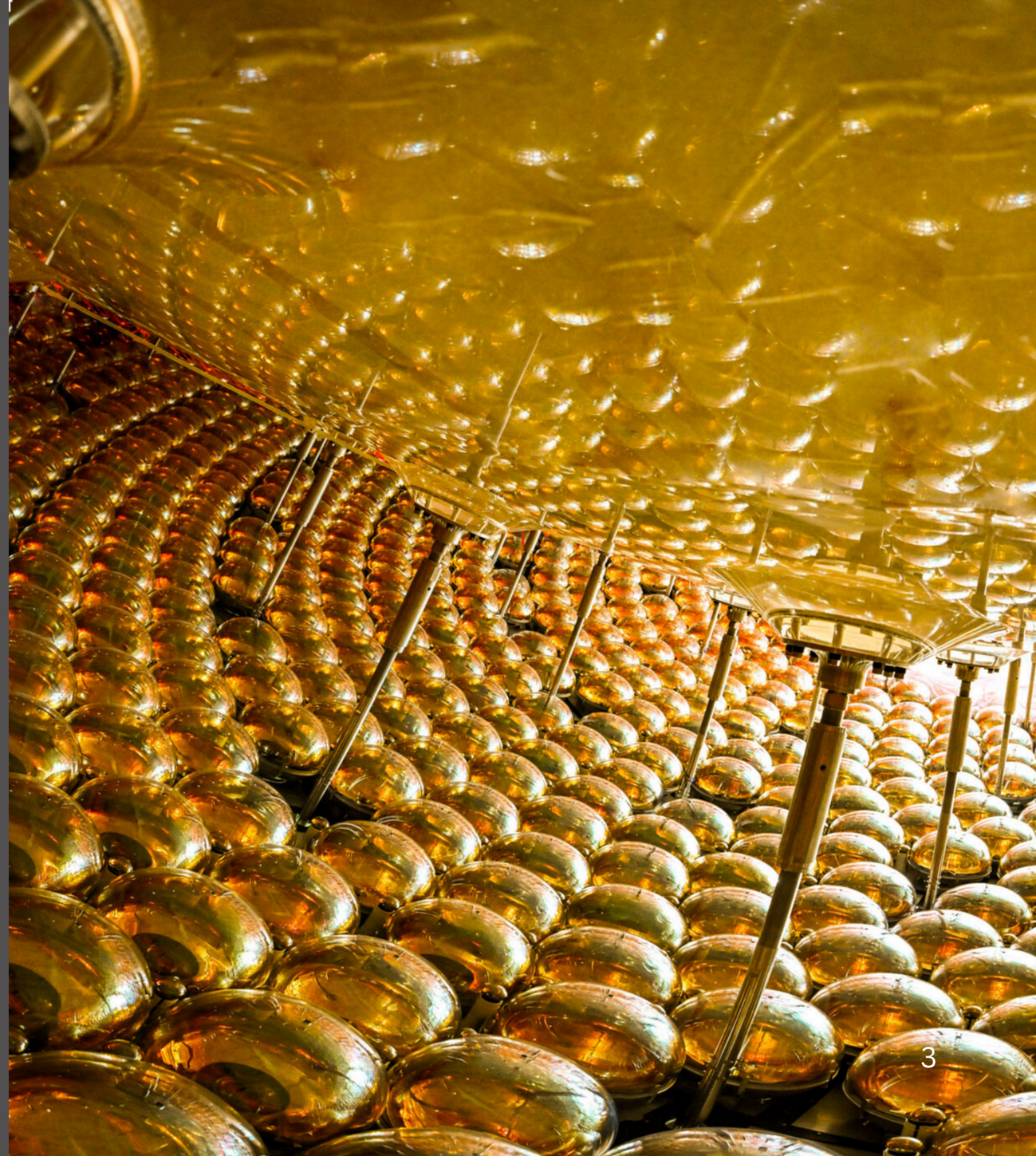


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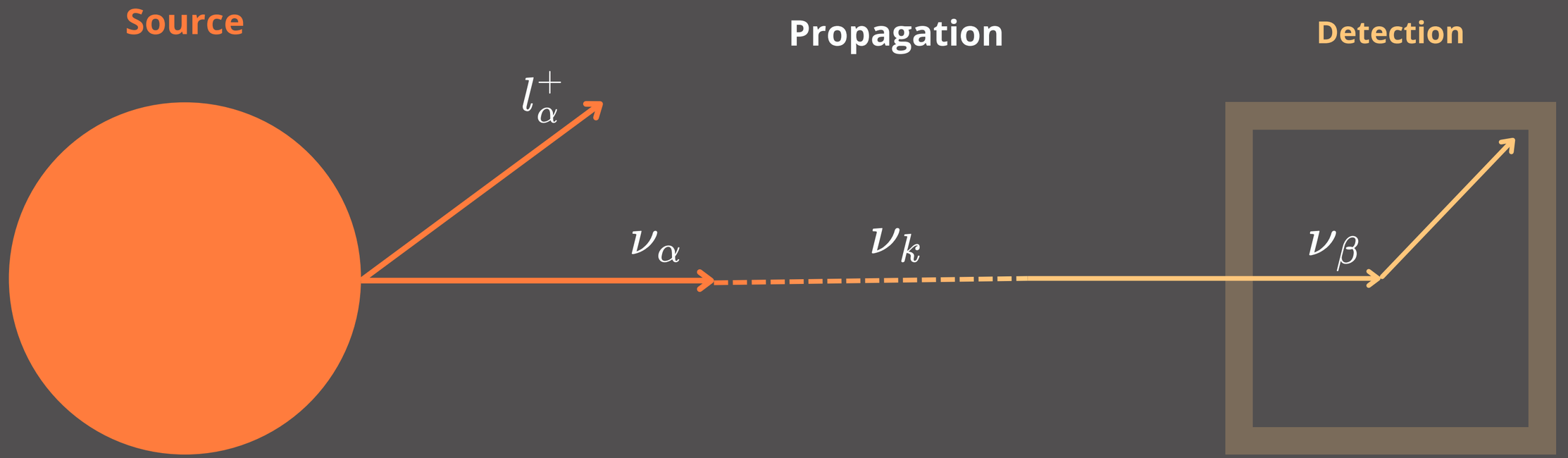
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Neutrino Oscillations

Probability

$$P(\alpha \to \beta; E, L) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta k} e^{-i \frac{\Delta m^2_{kj}}{2E} L}$$



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Lepton mixing matrix

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

where

- $c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$ ⟶ θ_{12}, θ_{13}, θ_{23} mixing angles
- δ Dirac phase
- α, β Majorana phases not involved in oscillations

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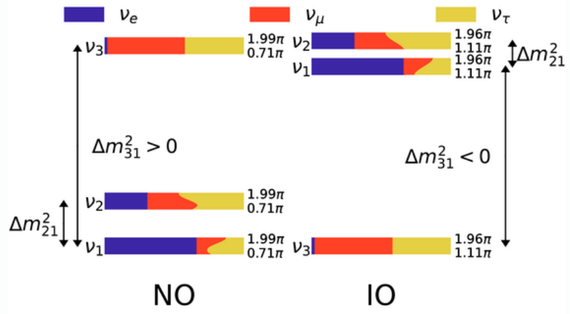
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Mass splittings

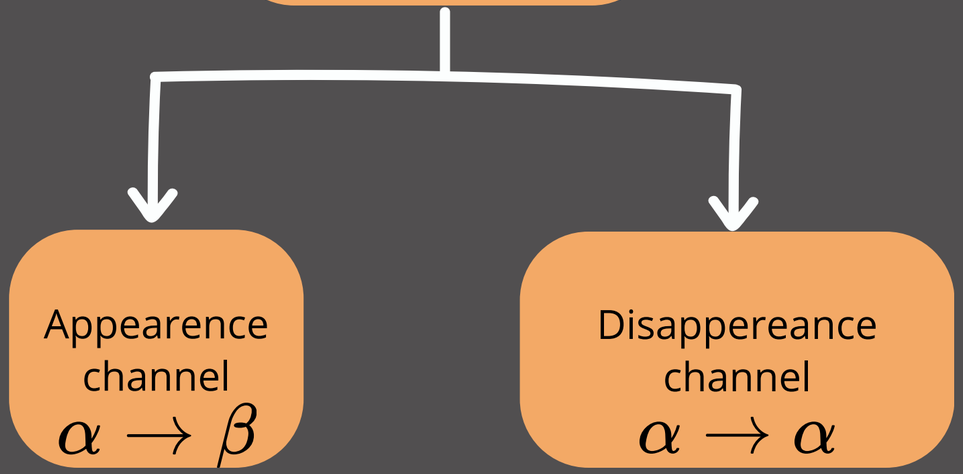
- The dependence is on $\Delta m_{kj}^2 = m_k^2 - m_j^2$, not on the three separate masses m_1, m_2, m_3: two possible situations



Different experiments are used to study the **different parameters**

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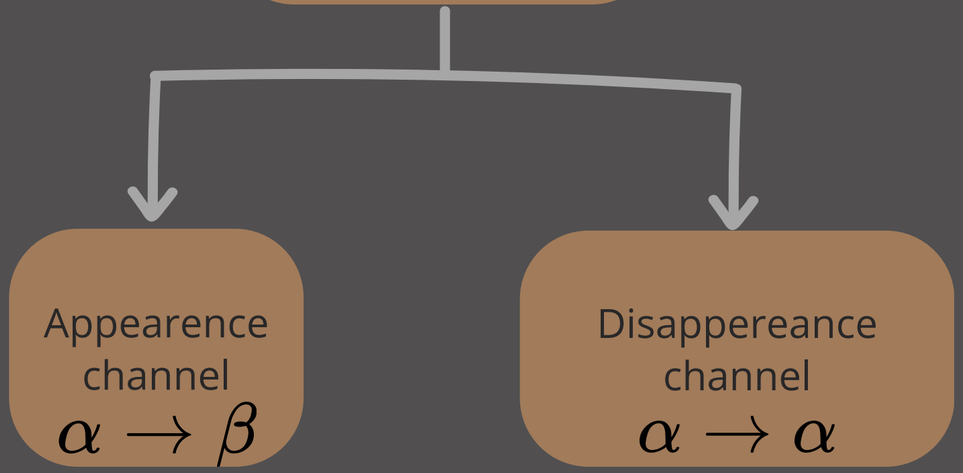
Different channels can be studied, with both neutrinos and anti-neutrinos



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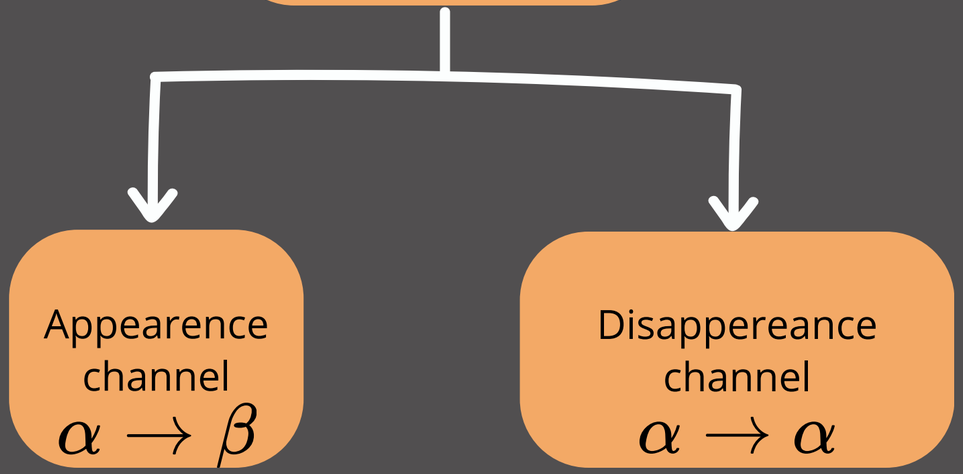
Combination of datasets from different experiments **enhances sensitivity**



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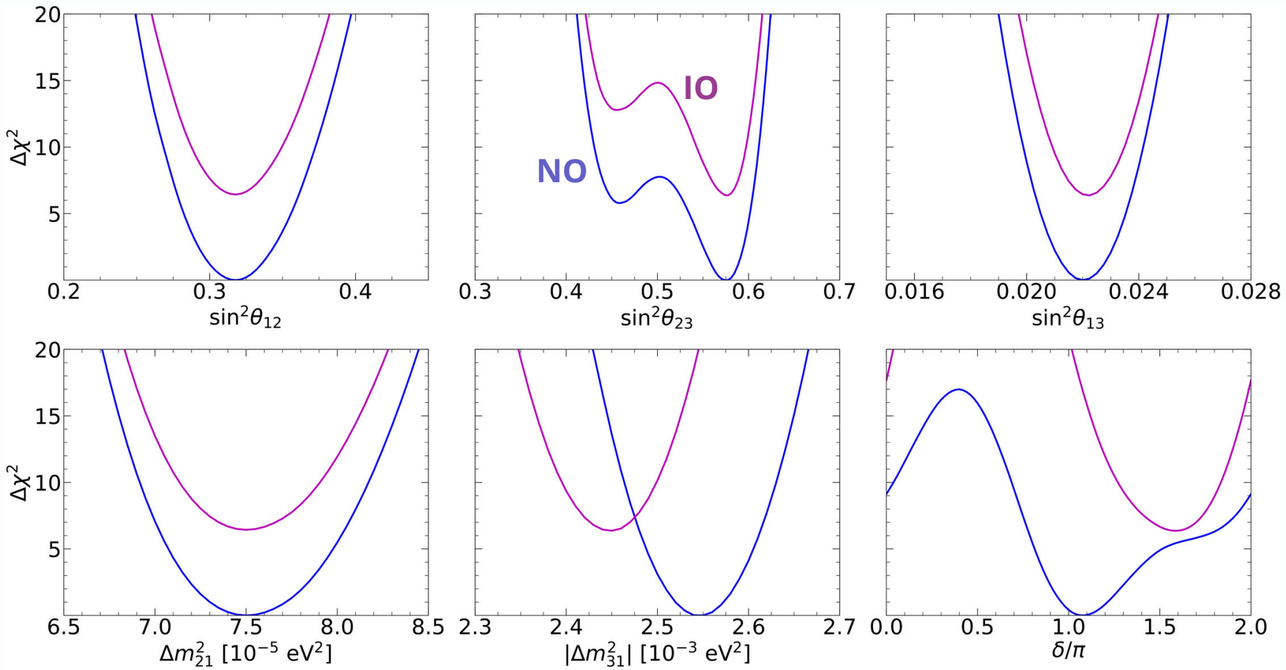
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Neutrino Global Fit

See also other groups' works:
M. C. Gonzalez-Garcia's talk: NuFit-JHEP 12 (2024) 216
A. Marrone's talk: Bari-PhysRevD.111.093006

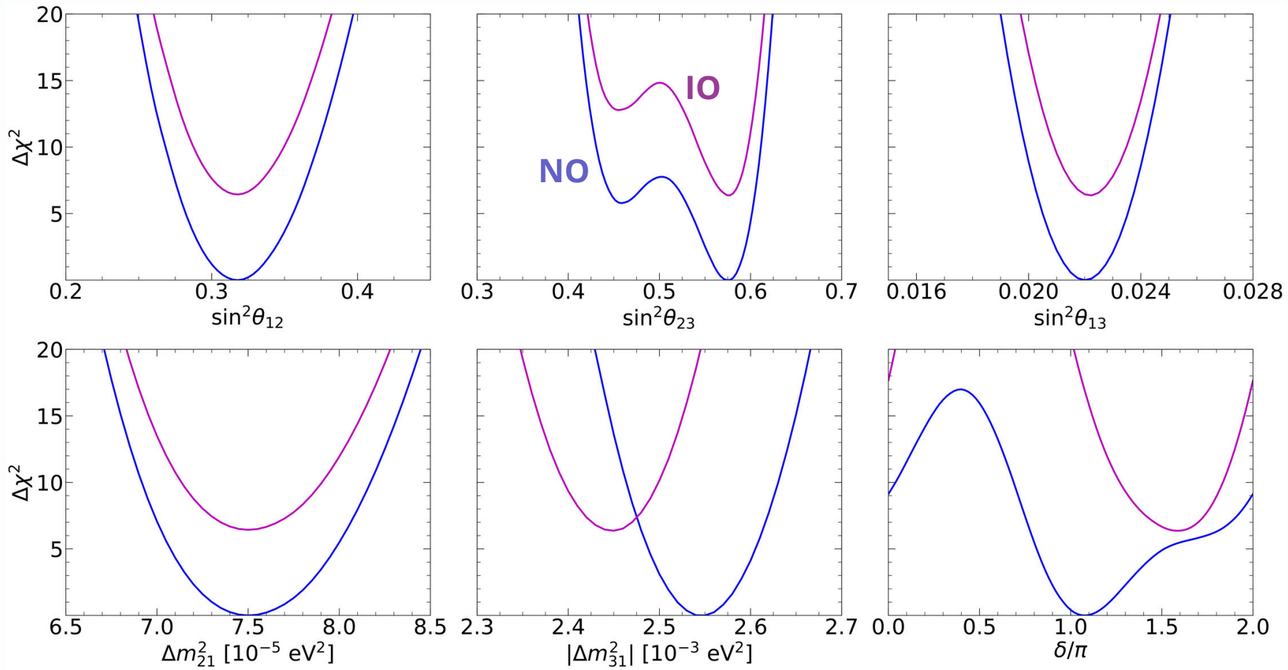
Valencia - Global Fit (2020)
JHEP 02 (2021) 071



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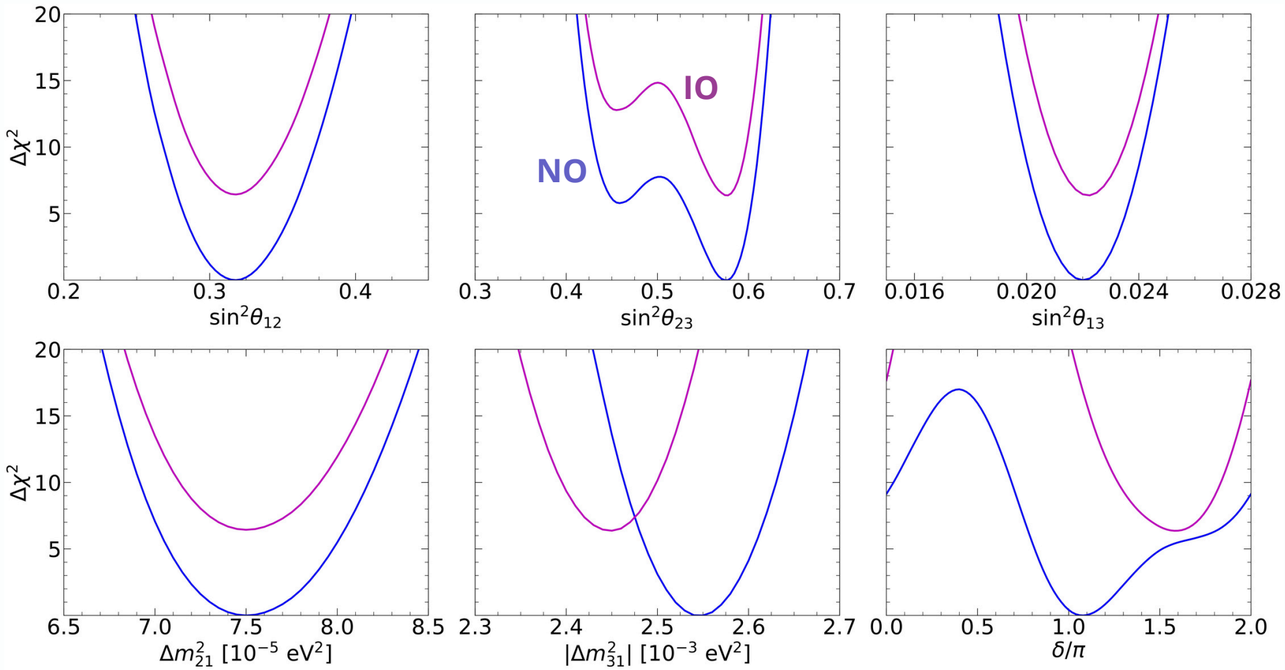
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Results updated in **2026**

Neutrino Global Fit

Valencia - Global Fit (2020)

JHEP 02 (2021) 071



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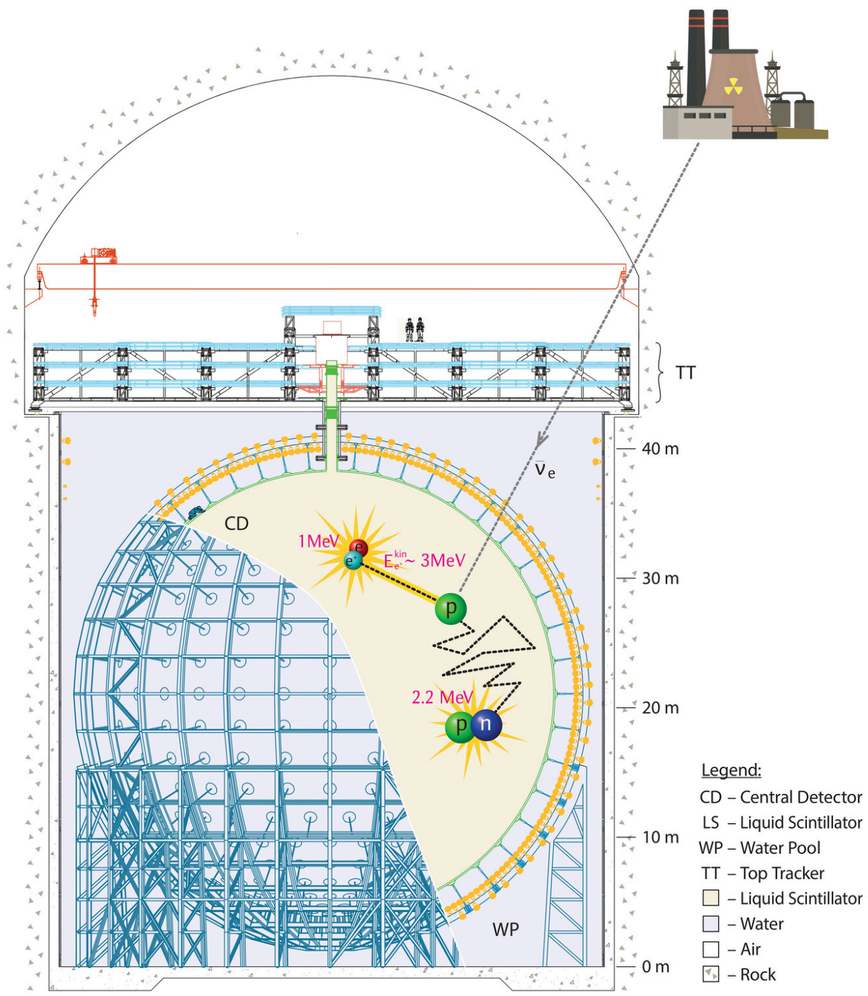
Results updated in **2026**

I will mainy focus on
JUNO contribution
to the Neutrino Global Fit

Neutrino Global Fit

JUNO

See also
Vit Vorobel and
Tomáš Tměj's talk

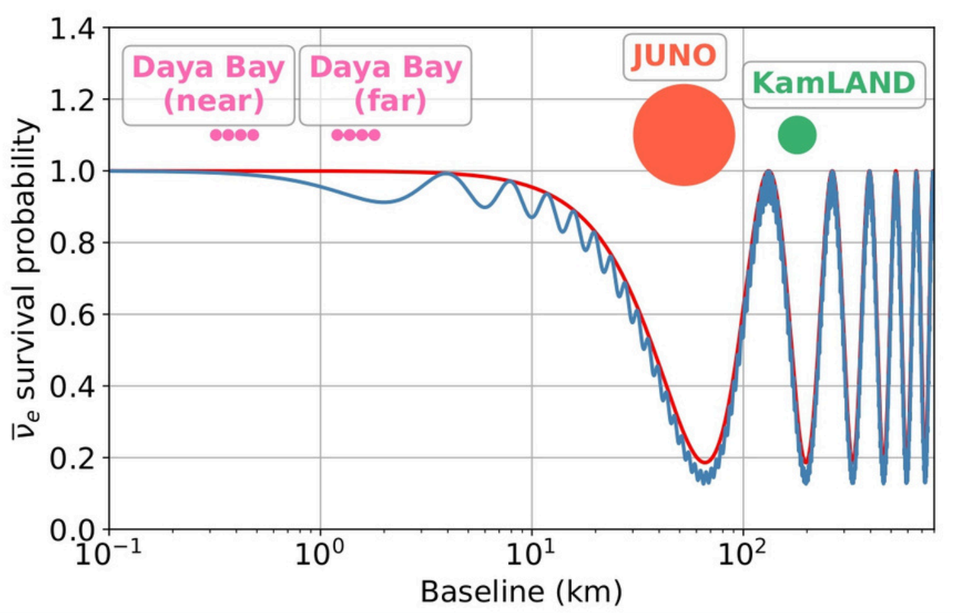


Credit: JUNO Collaboration, arXiv:2104.02565

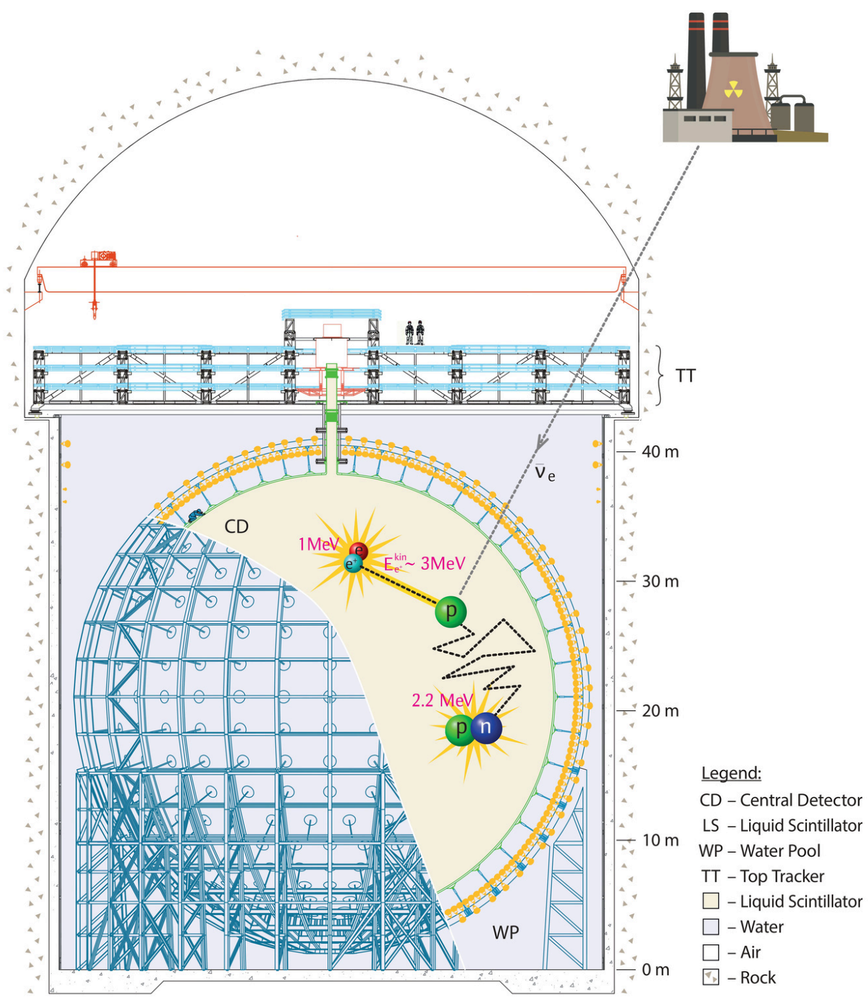
JUNO

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Position



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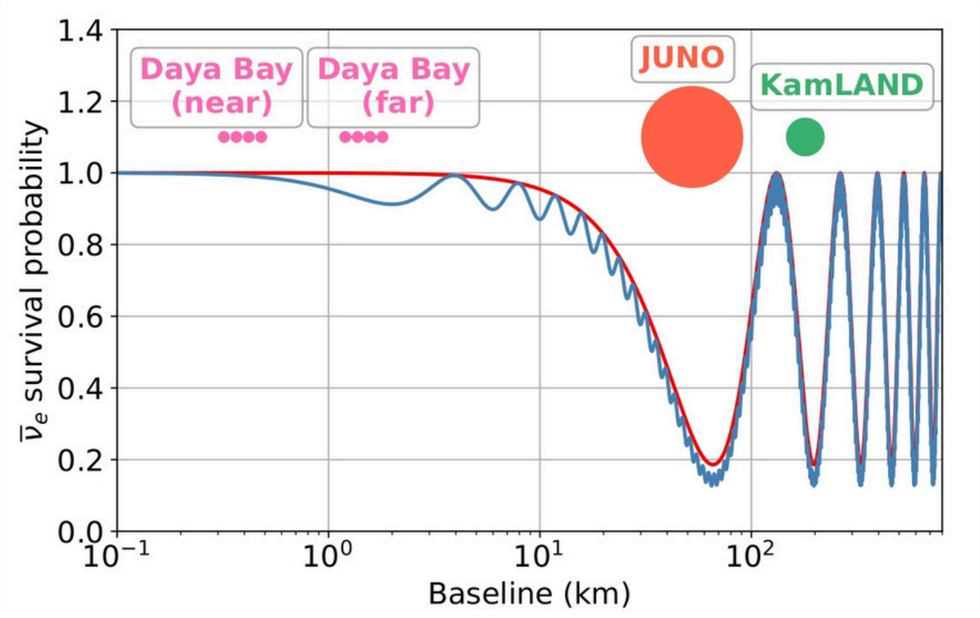
Excellent Energy Resolution

Dimensions

JUNO

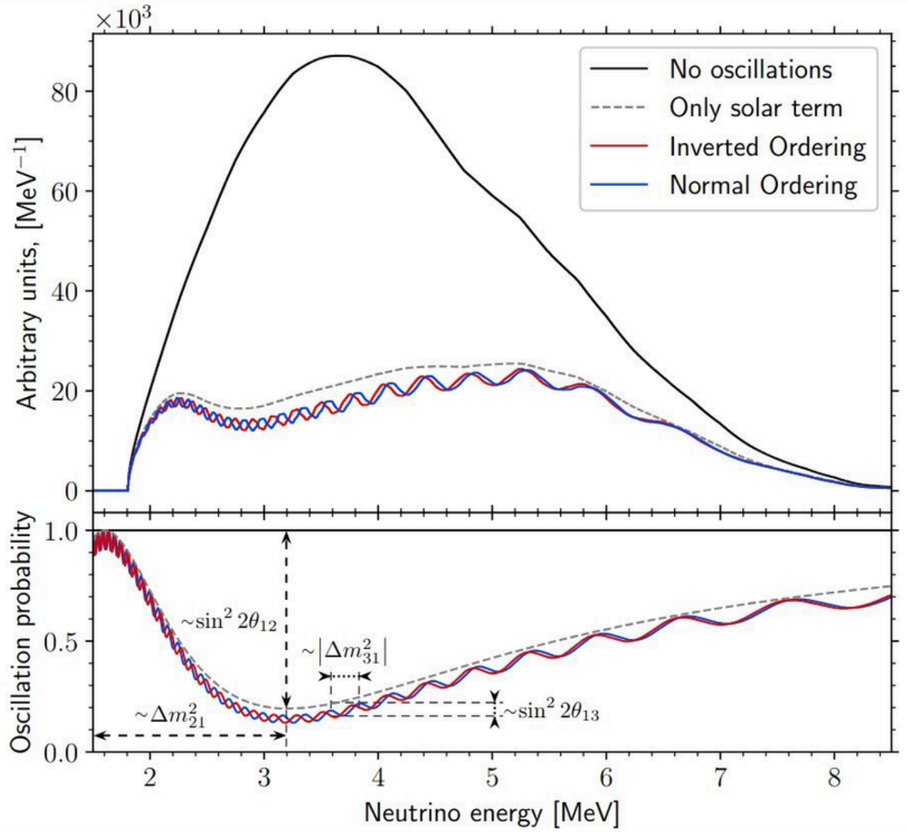
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Credit: JUNO Collaboration, arXiv:2104.02565

- **Slow oscillations:** Δm^2_{21} θ_{12}
- **Fast oscillations:** Δm^2_{31} (θ_{13})

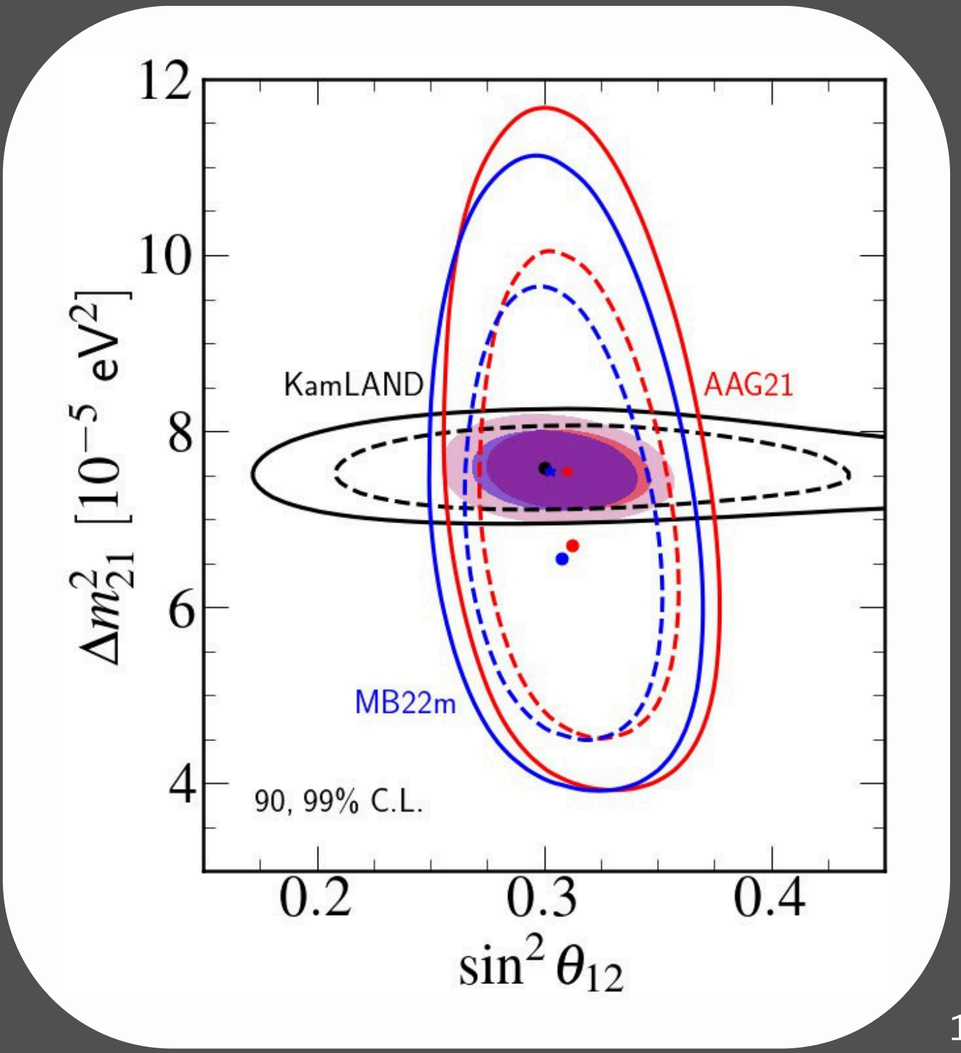


Credit: D. Basilico, LNGS Seminar

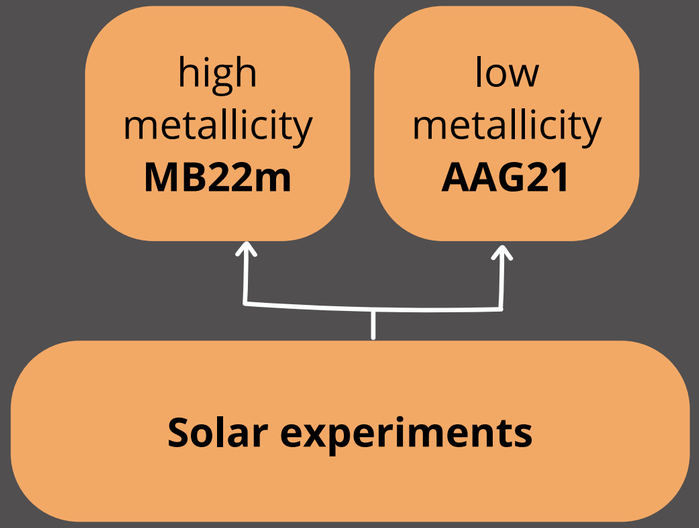
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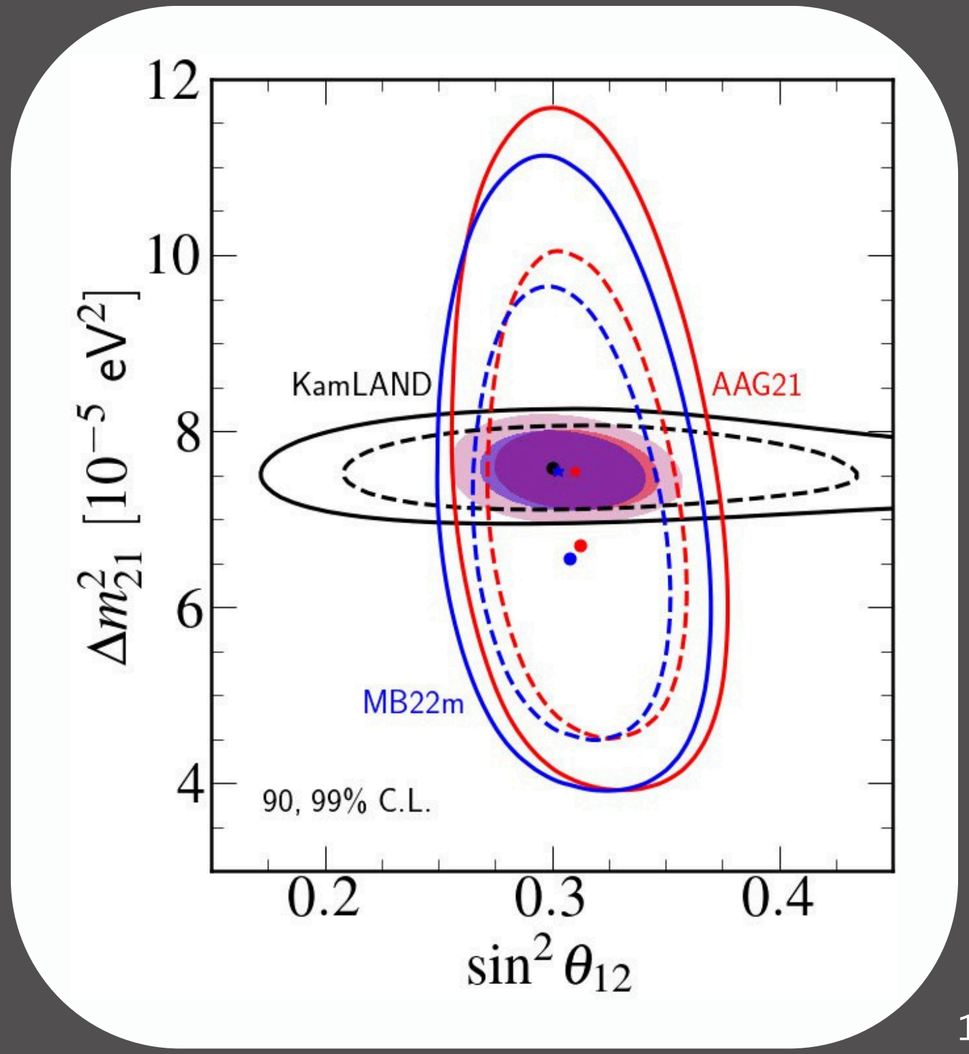
Dimensions

Solar sector: $\Delta m^2_{21}, \theta_{12}$ before 2025



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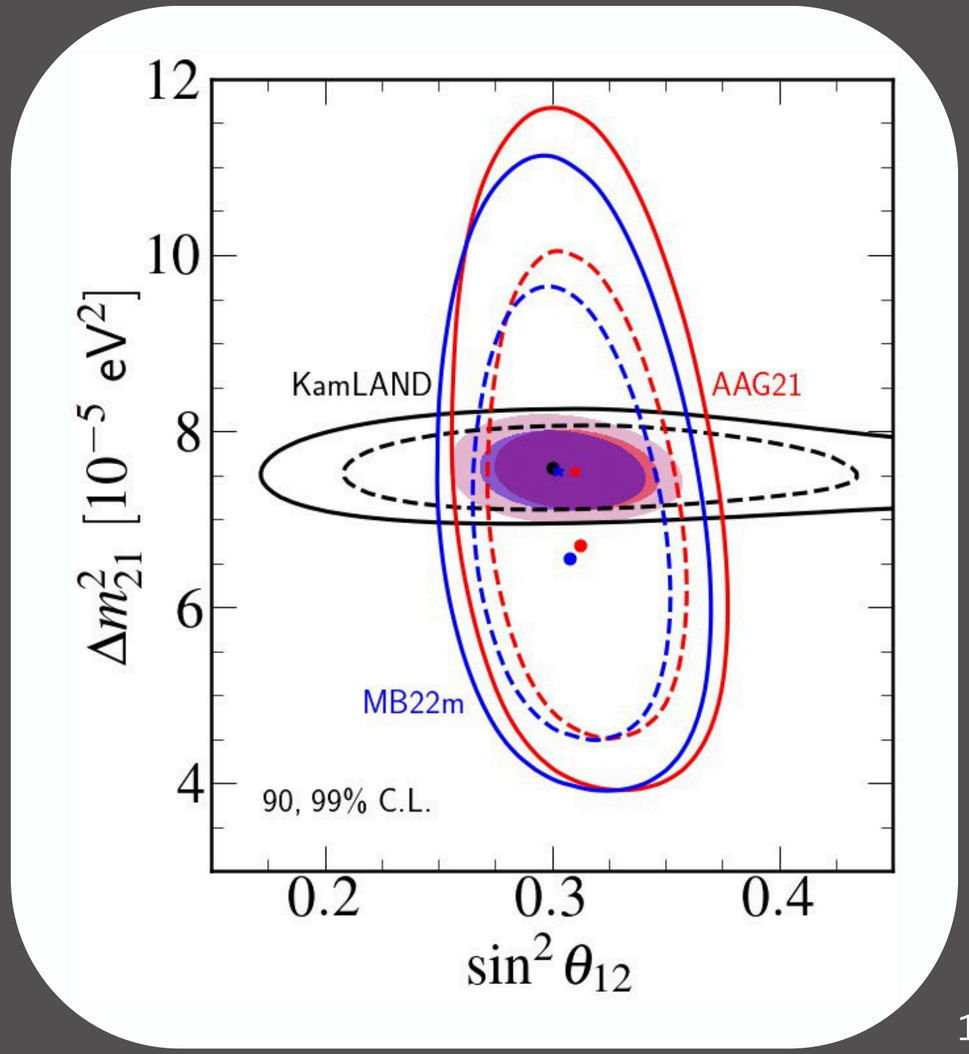
Solar sector: $\Delta m^2_{21}, \theta_{12}$ before 2025

high metallicity **MB22m**

low metallicity **AAG21**

Solar experiments

Long baseline reactor **KamLAND**



Solar sector: $\Delta m^2_{21}, \theta_{12}$ before 2025

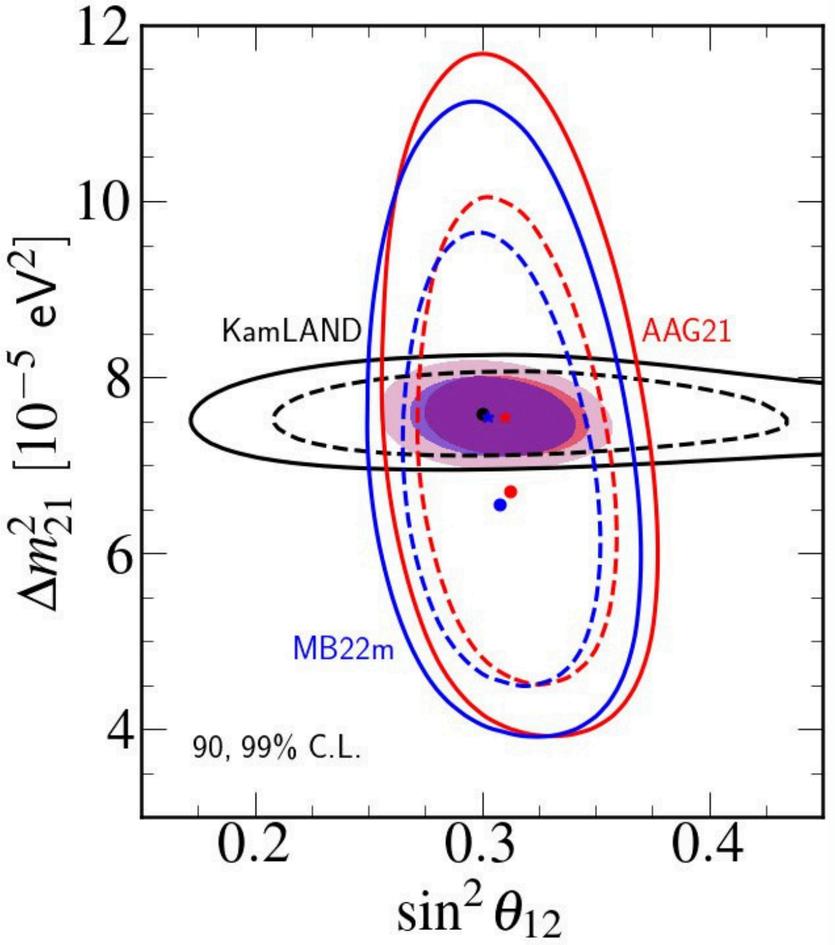
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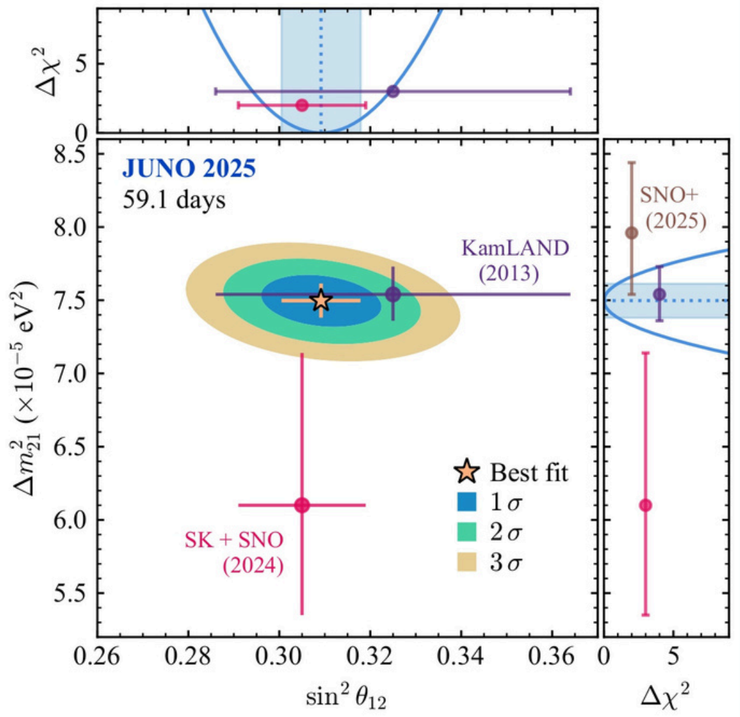
Long baseline reactor **KamLAND**

$$\sin^2\theta_{12} = (3.04 \pm 0.16) \cdot 10^{-1}$$
$$\Delta m^2_{21} = (7.55^{+0.22}_{-0.20}) \cdot 10^{-5}\text{eV}^2$$

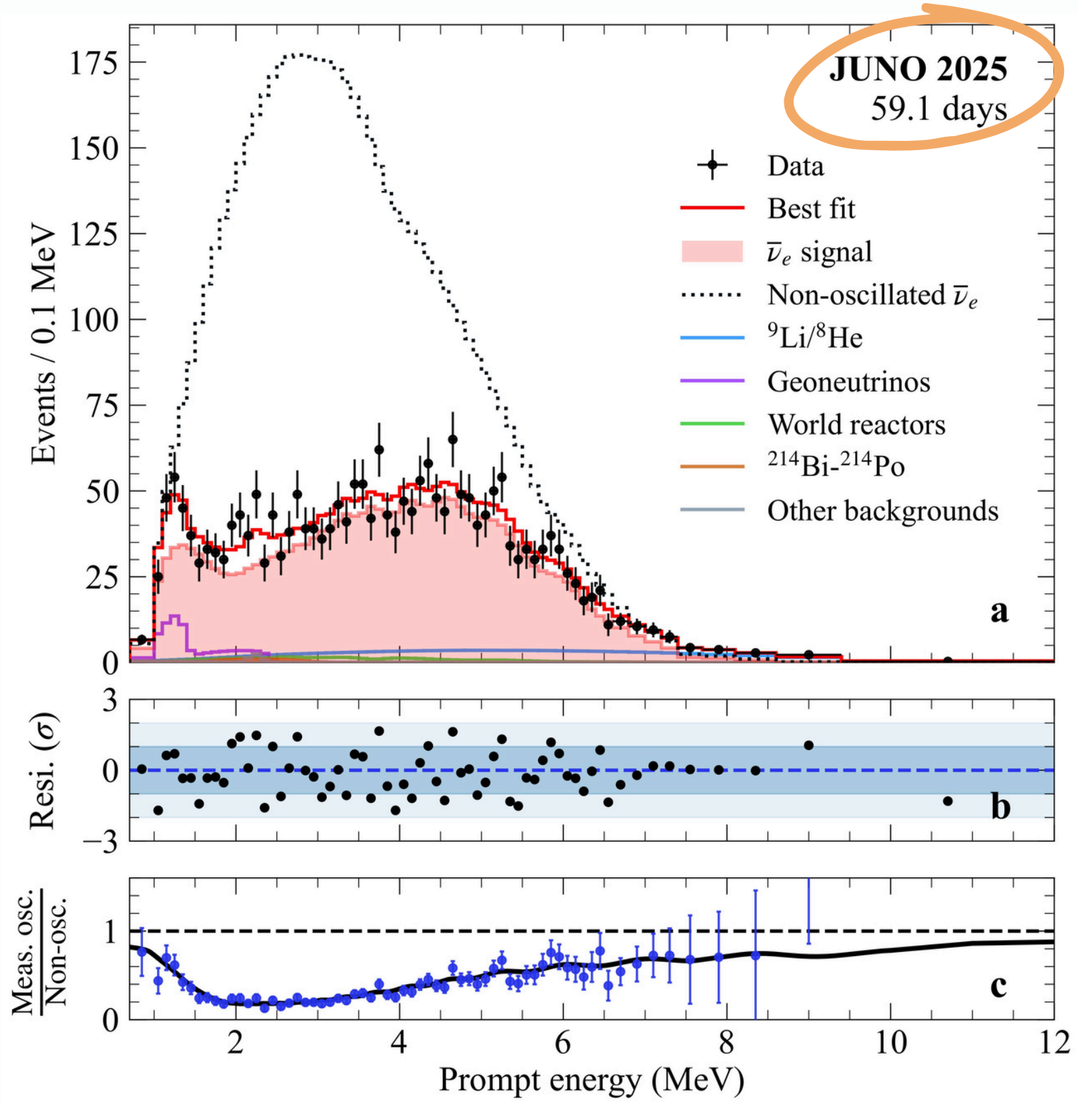


JUNO first results

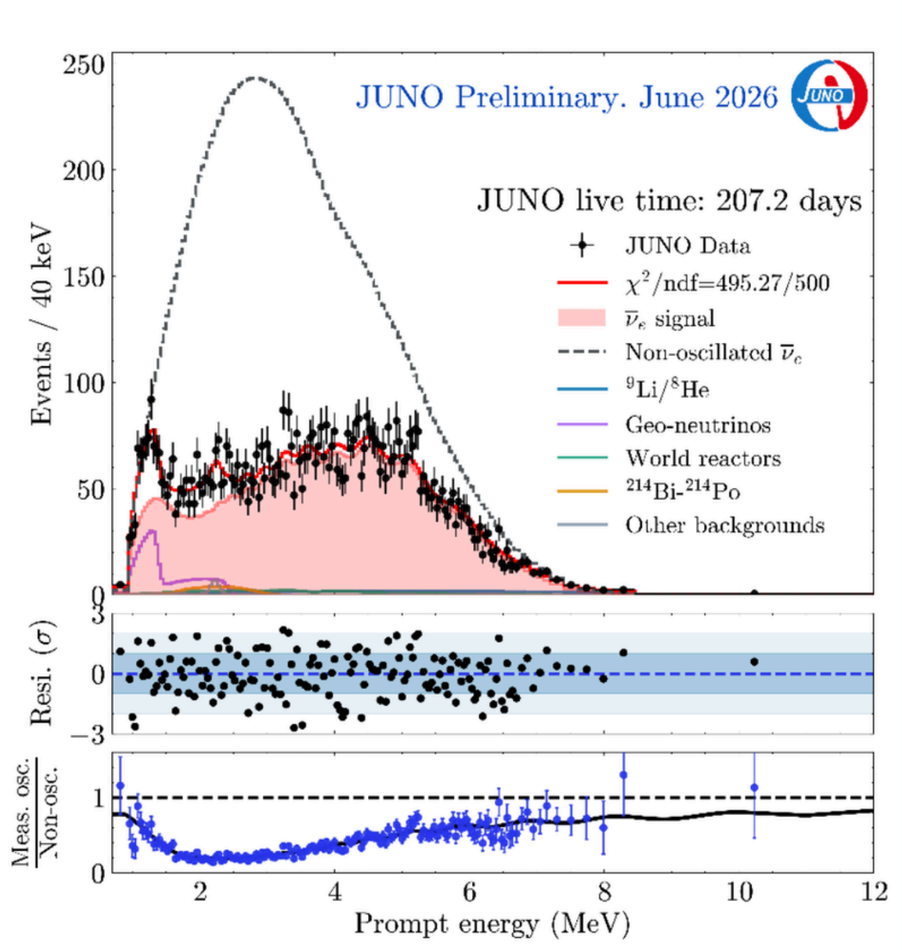
JUNO Collaboration,
Nature 654 (2026) 8118, 343-348



First oscillated energy spectrum published



JUNO second results



Antineutrinos ($\overline{\nu}_e$) Candidates Summary		
DAQ live time (days)	207.2	
$\overline{\nu}_e$ candidates	8294	
Selection Efficiencies (%)	ε	σ_{rel}
Fiducial volume	87.12%	0.96%
PMT flasher rejection	$> 99.9\%$	Negligible
μ veto	93.67%	0.02%
Multiplicity cut	95.94%	negligible
Prompt-delayed coinc.	95.50%	0.32%
Correlated discriminator	98.99%	0.15%
Total efficiency (ε_{tot})	74.01%	1.02%
$\overline{\nu}_e$ signal (cpd)		
w/o ε_{tot} corrected	36.02 ± 0.62	
w/ ε_{tot} corrected	48.67 ± 1.08	
Backgrounds (cpd)	Pre-fit	Best-fit
^{9}Li/^{8}He	1.05 ± 0.27	1.41 ± 0.26
Geoneutrinos	Free	2.12
World reactors	0.92 ± 0.09	0.92 ± 0.09
^{214}Bi-^{214}Po	0.42 ± 0.31	0.57 ± 0.34
^{13}C(α, n)^{16}O	0.05 ± 0.02	0.05 ± 0.02
Fast neutrons	0.02 ± 0.02	0.02 ± 0.02
Double neutrons	0.10 ± 0.10	0.13 ± 0.10
Atmospheric neutrinos	0.09 ± 0.04	0.11 ± 0.05
Accidentals	0.07 ± 0.01	0.07 ± 0.01

JUNO Collaboration, arxiv:2609.37895

Improved precision on the solar sector parameters

First results on Δm^2_{31} important for mass ordering determination

Credit: Yifang Wang, NEUTRINO2026

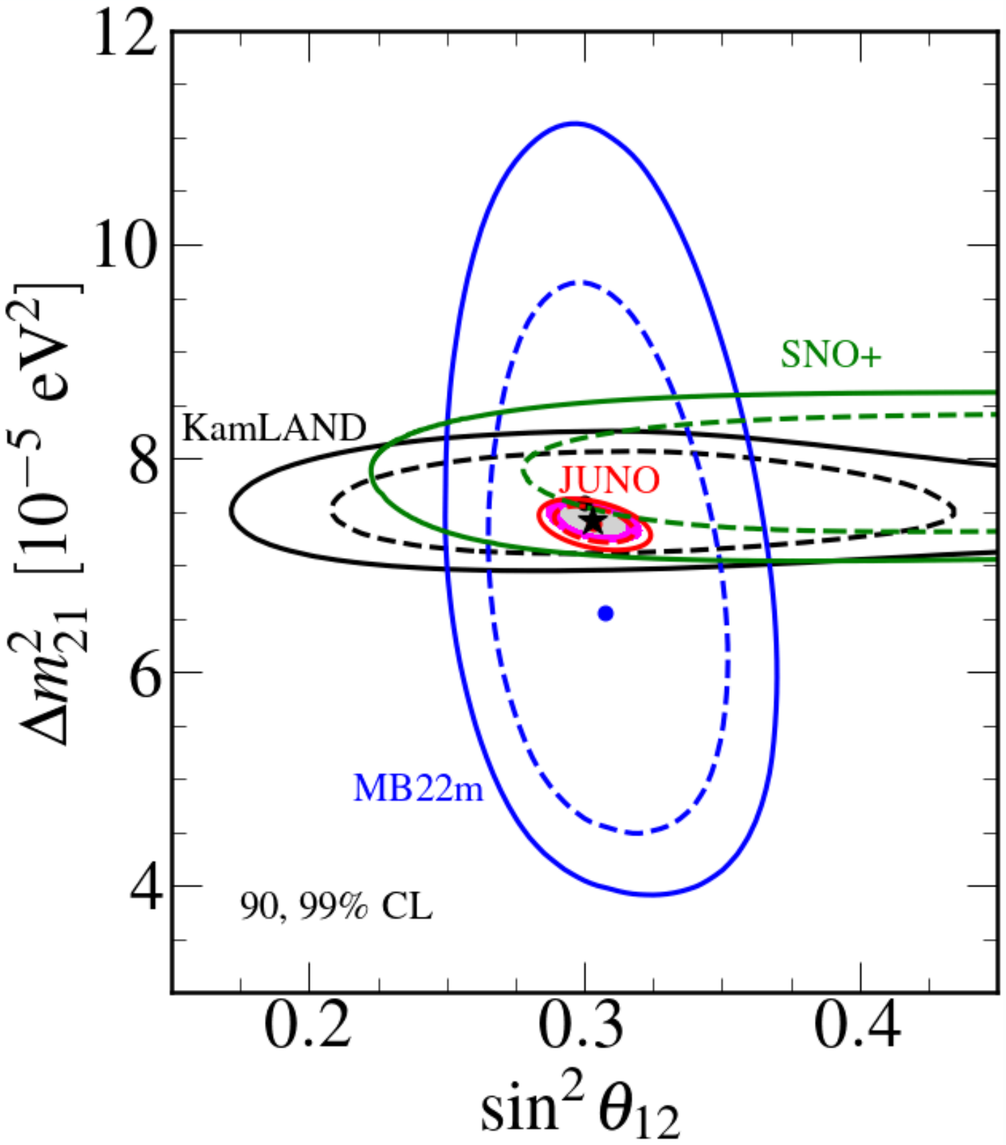
Updated solar sector

SNO+ first results

Second experiment after KamLAND to use **long baseline** reactor antineutrino

Data acquisition period
May 2022 -July 2025

SNO+ Collaboration,
Phys.Rev.Lett. 135 (2025) 12, 121801
arXiv:2511.11856v2 [hep-ex]

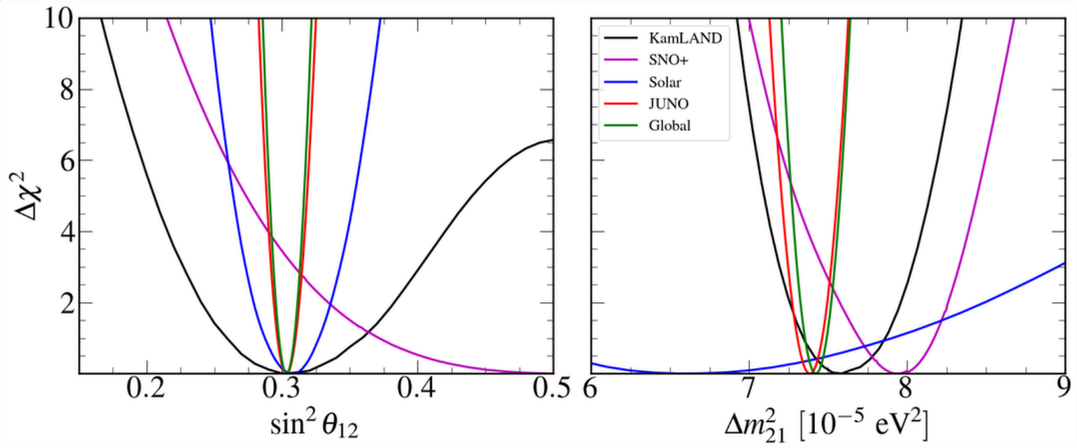


2026, preliminary

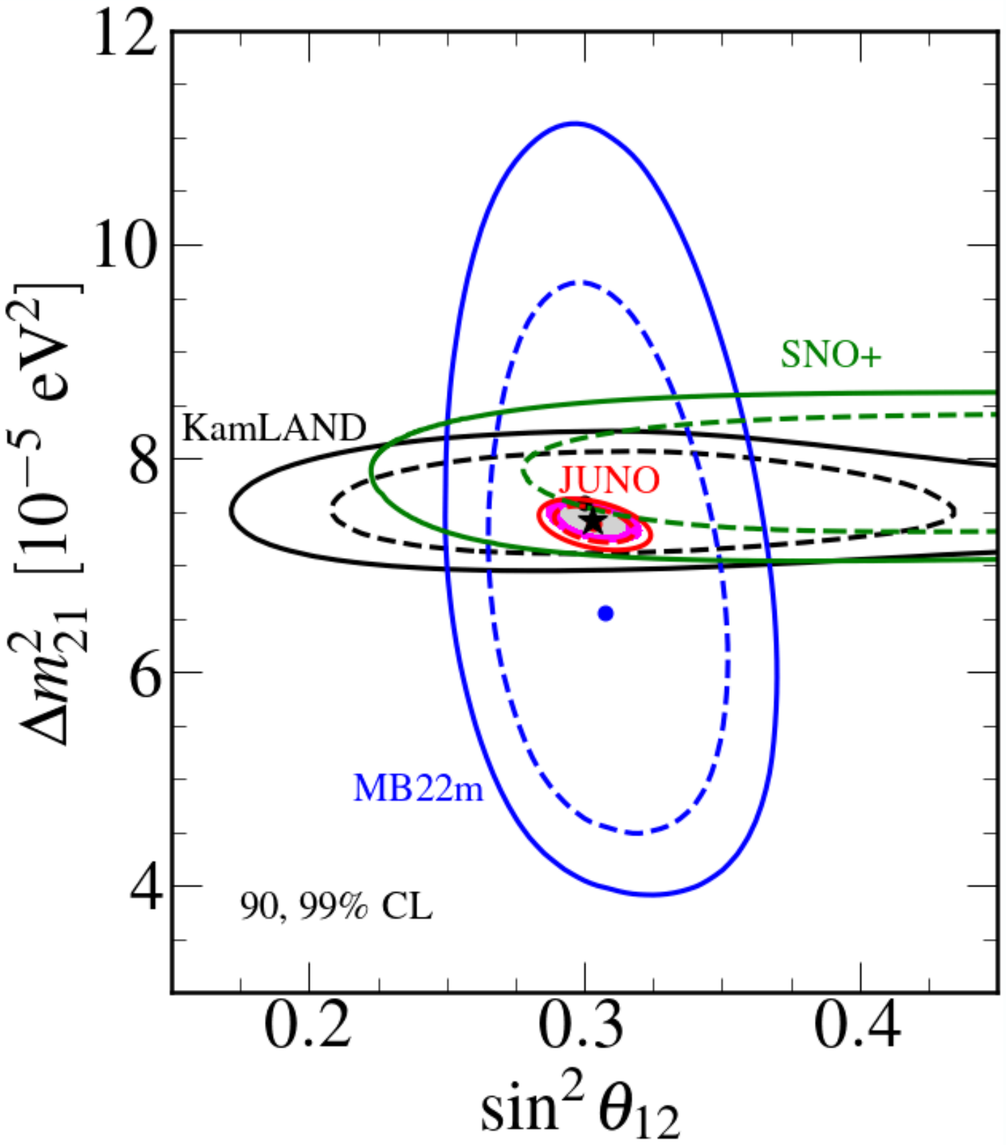
Updated solar sector

Best precision ever reached for Δm^2_{21} and $\sin^2\theta_{12}$ in JUNO:

$$\frac{\sigma_{\Delta m^2_{21}}}{\Delta m^2_{21}} = 1.1\% \qquad \frac{\sigma_{\sin^2\theta_{12}}}{\sin^2\theta_{12}} = 2.1\%$$



2026, preliminary

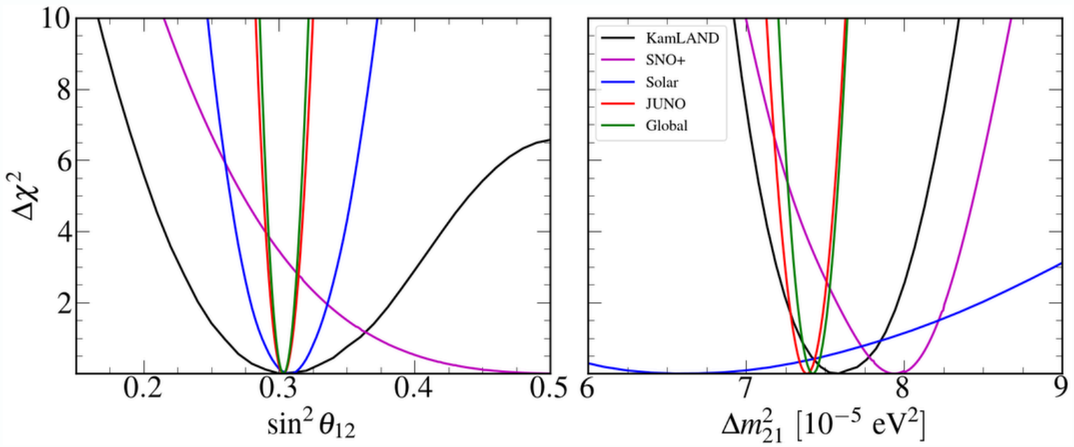


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Updated solar sector

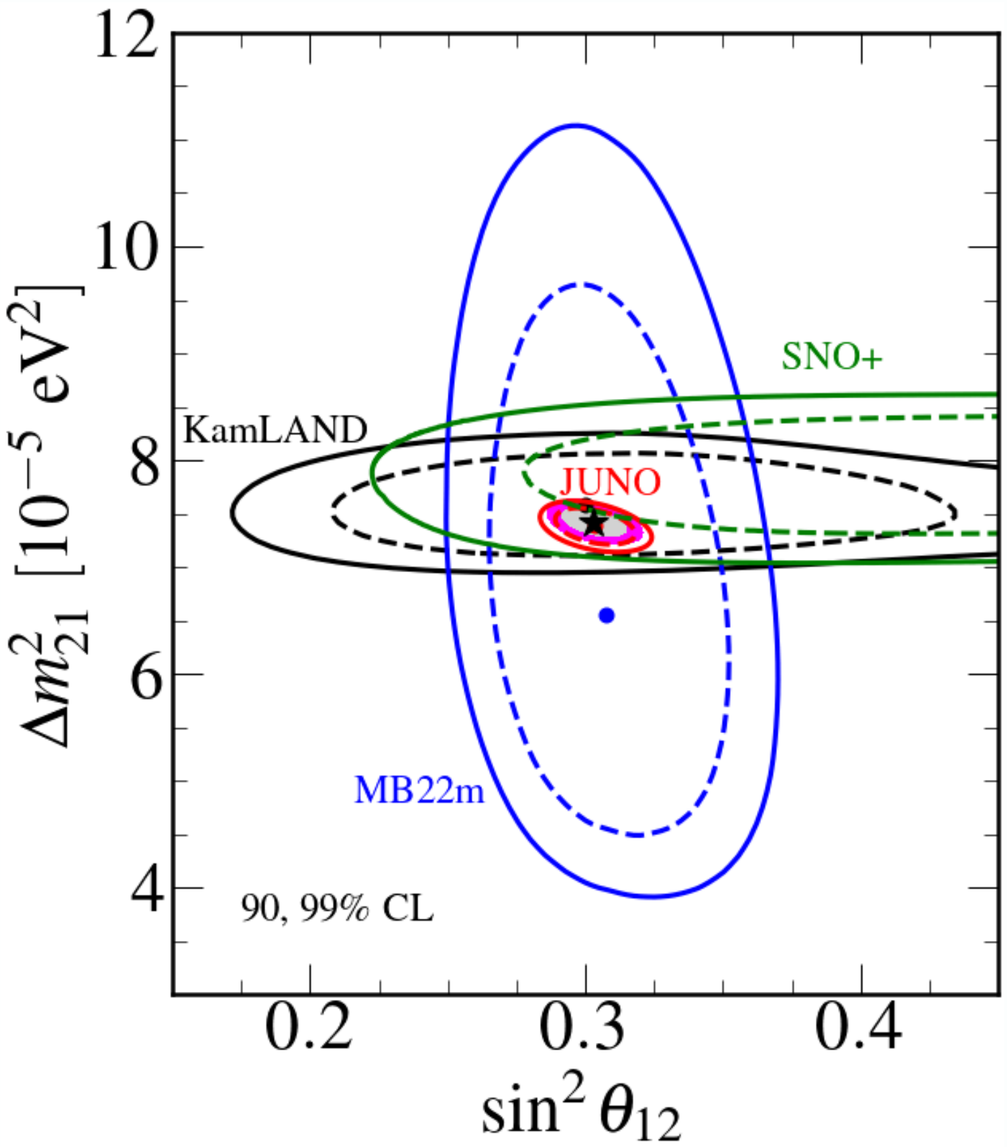
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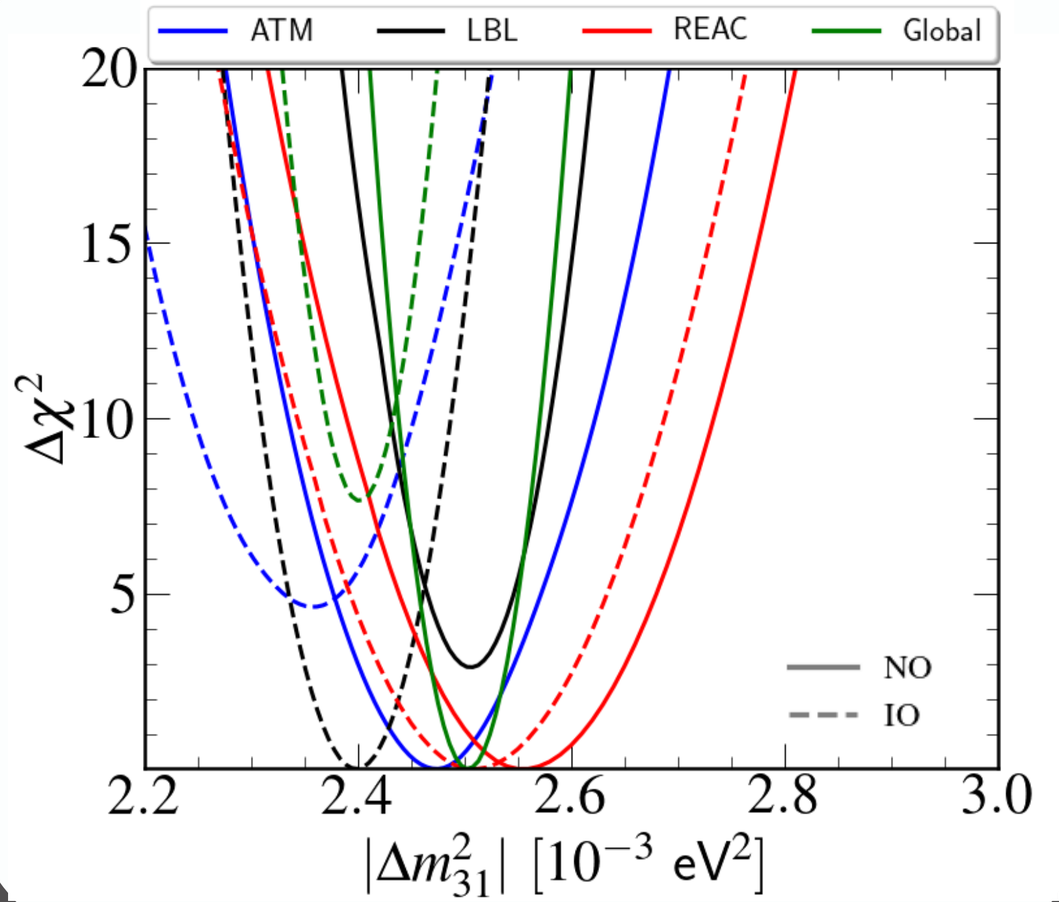
2026, preliminary

$$\sin^2\theta_{12} = (3.030 \pm 0.057)\cdot 10^{-1}$$
$$\Delta m^2_{21} = (7.42^{+0.37}_{-0.67})\cdot 10^{-5}\mathrm{eV}^2$$



2026, preliminary

Neutrino Mass ordering before 2026



Long baseline accelerators
NOvA, T2K

Inverted Ordering

Atmospheric data
IceCube-DC, SK

Normal Ordering

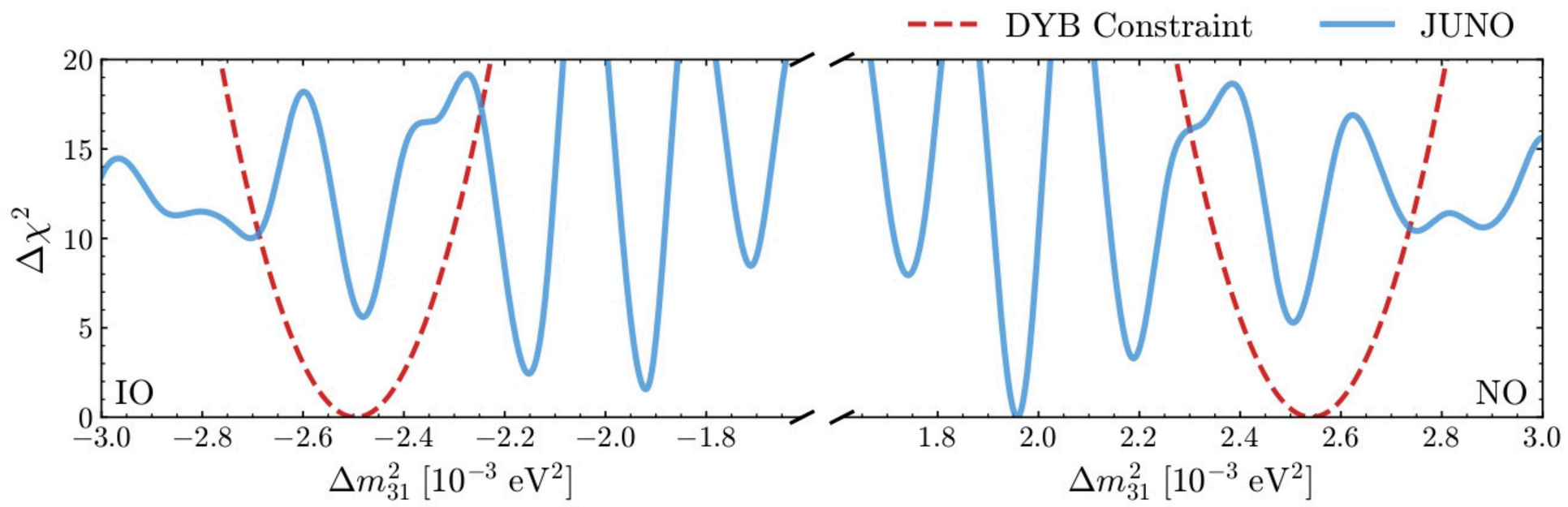
+Reactor data
Daya Bay, RENO

Normal Ordering

Global analysis
Preference for **normal ordering** at 2.7σ

$$|\Delta m^2_{31}| = (2.502^{+0.022}_{-0.019}) \cdot 10^{-3}\text{eV}^2 \text{ (NO)}$$
$$|\Delta m^2_{31}| = (2.400^{+0.022}_{-0.018}) \cdot 10^{-3}\text{eV}^2 \text{ (IO)}$$

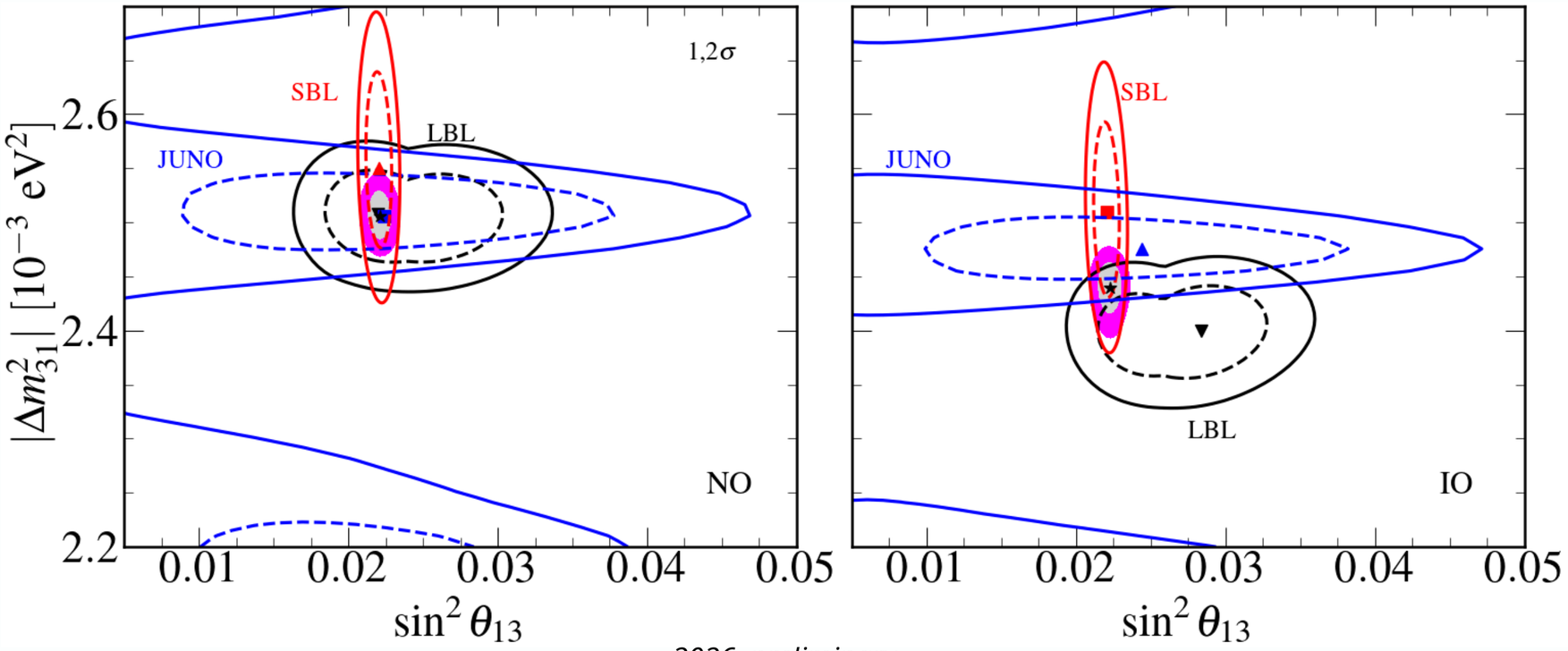
Neutrino Mass ordering after JUNO



Credit: JUNO Collaboration, arxiv:2609.37895

JUNO data exhibit
multiple local minima

Neutrino Mass ordering after JUNO

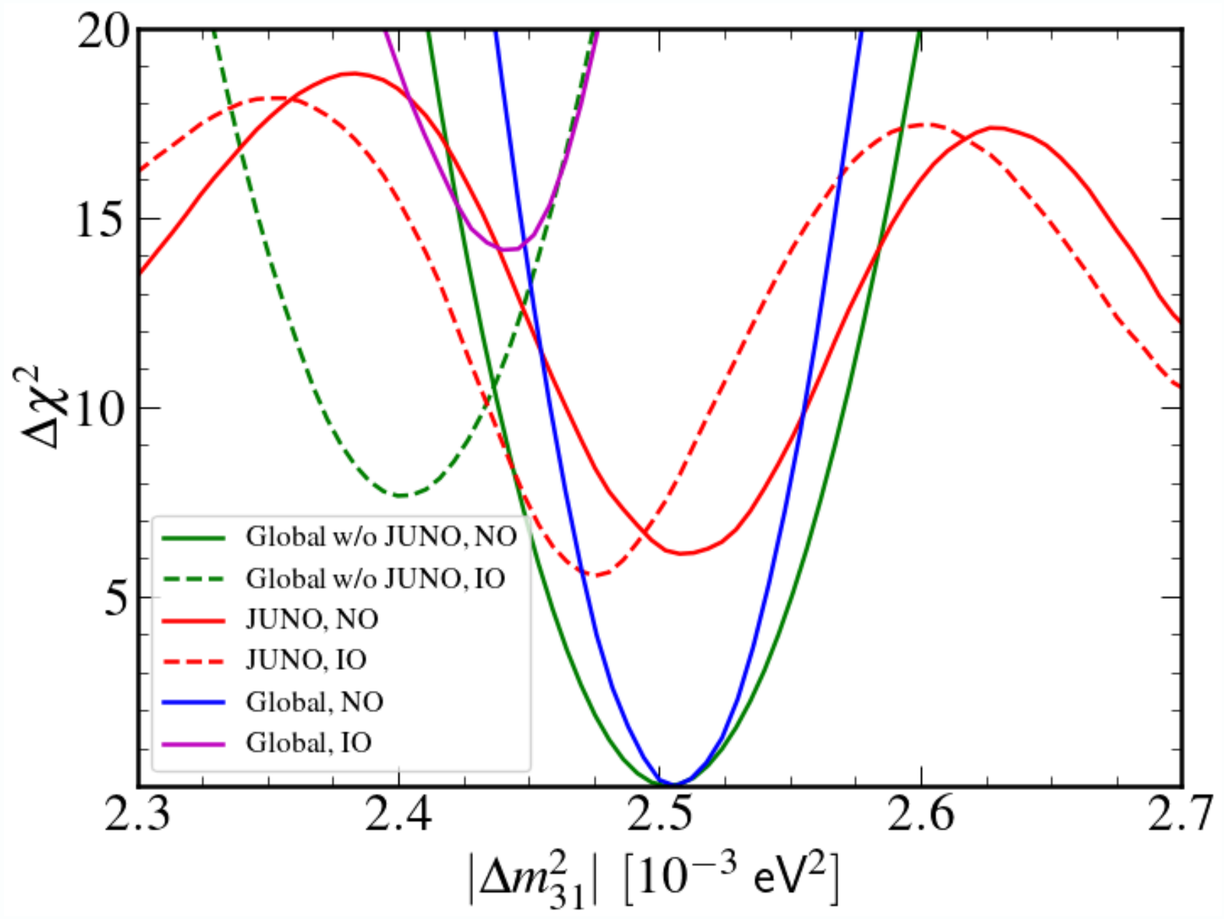


2026, preliminary

JUNO data exhibit
multiple local minima

Information on the neutrino mass ordering and $|\Delta m^2_{31}|$ value comes from a **combination with other datasets**

Neutrino Mass ordering after JUNO



2026, preliminary

Preference for
normal ordering
with
$\Delta\chi^2 = 14.14$

Precision improved:

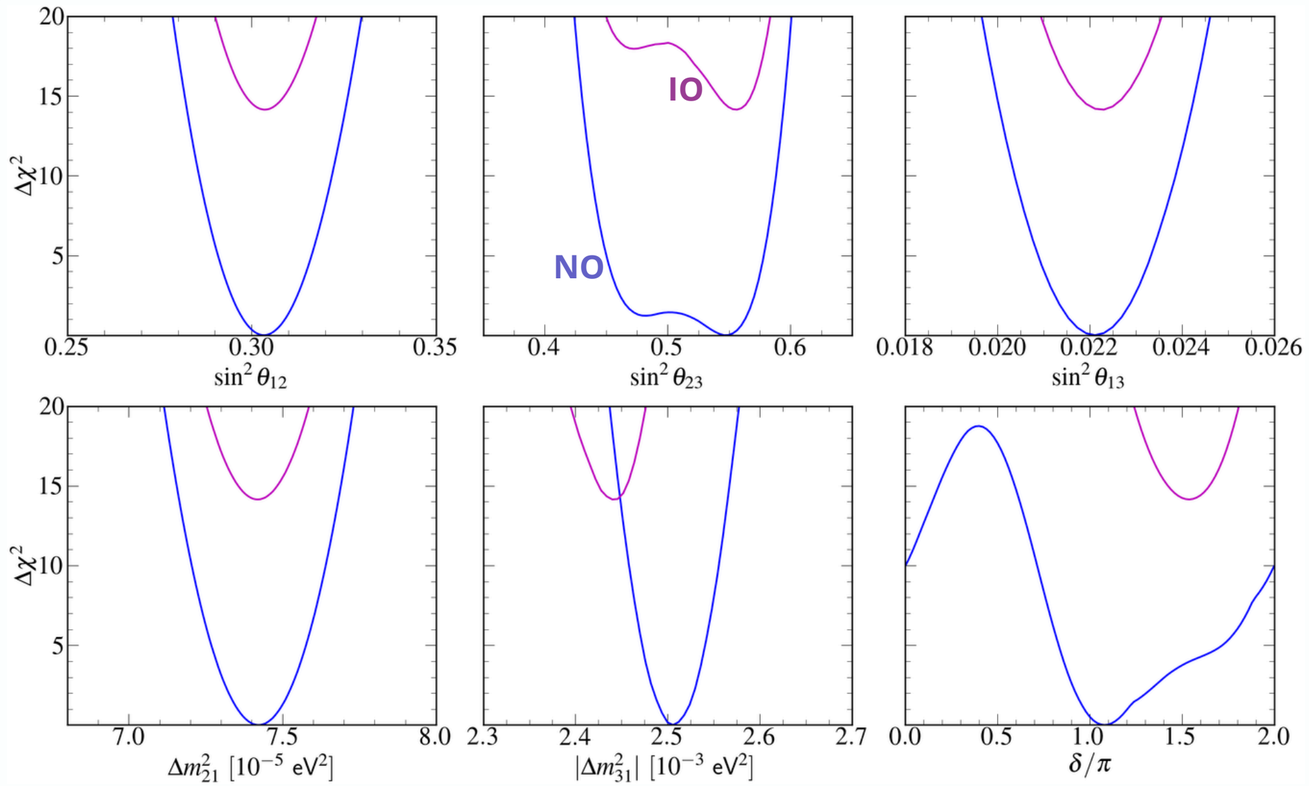
$|\Delta m^2_{31}| = (2.506^{+0.016}_{-0.014}) \times 10^{-3}$ eV^2 (NO)

$|\Delta m^2_{31}| = (2.440^{+0.017}_{-0.016}) \times 10^{-3}$ eV^2 (IO)

Valencia Global Fit-Updated

Parameter	Best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	7.42 ± 0.07
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.506^{+0.016}_{-0.014}$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.440^{+0.017}_{-0.016}$
$\sin^2\theta_{12}$	$0.3033^{+0.0057}_{-0.0056}$
$\sin^2\theta_{23}$ (NO)	$0.546^{+0.017}_{-0.024}$
$\sin^2\theta_{23}$ (IO)	$0.557^{+0.012}_{-0.017}$
$\sin^2\theta_{13}$ (NO)	$0.02212^{+0.00054}_{-0.00055}$
$\sin^2\theta_{13}$ (IO)	$0.02231^{+0.00048}_{-0.00060}$
δ/π (NO)	$1.08^{+0.13}_{-0.11}$
δ/π (IO)	$1.54^{+0.12}_{-0.13}$

2026 values, preliminary



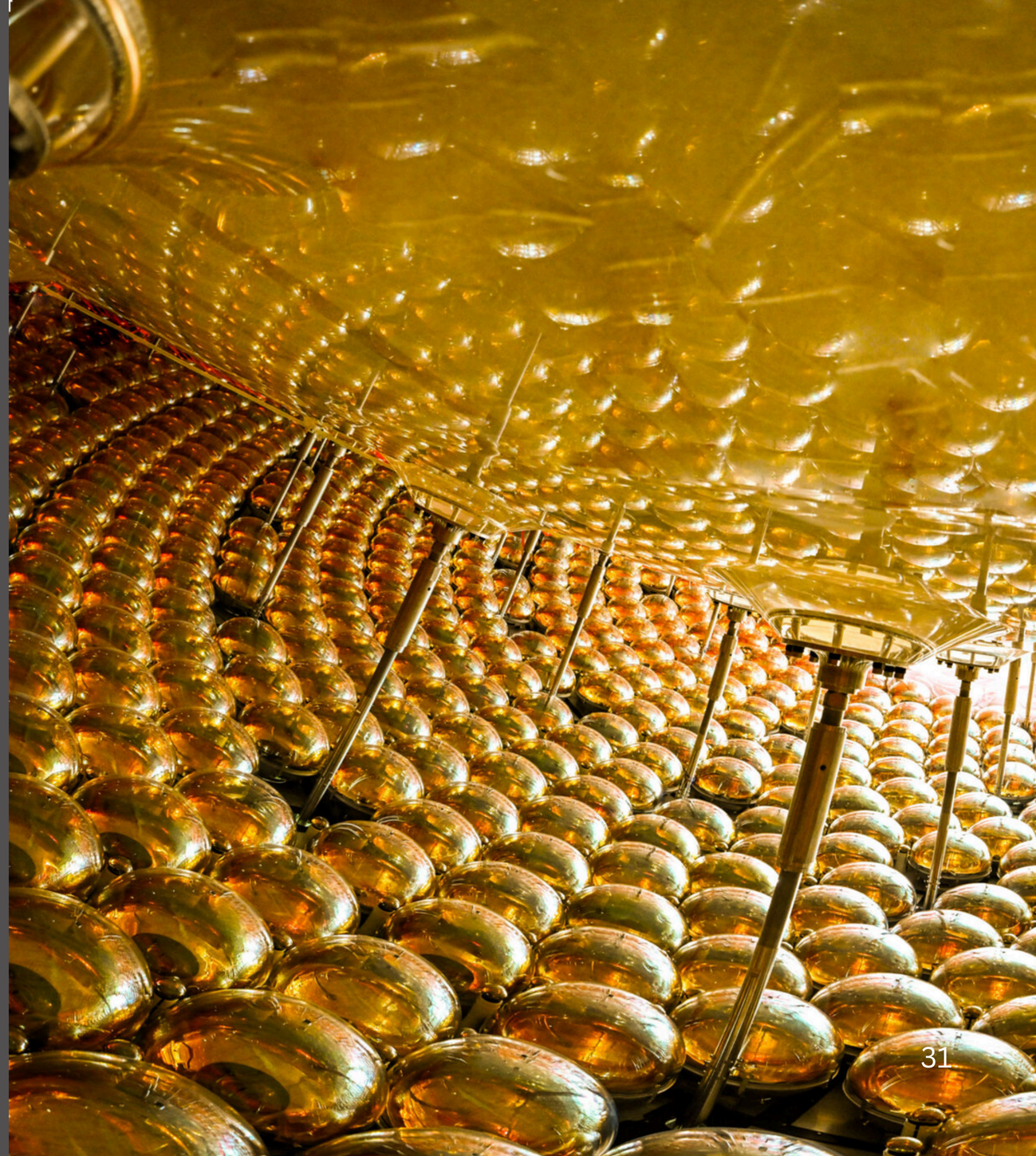
2026, preliminary

JUNO contribution to the Neutrino Global Fit

Based on updated version
(in preparation) of JHEP 02 (2021) 071

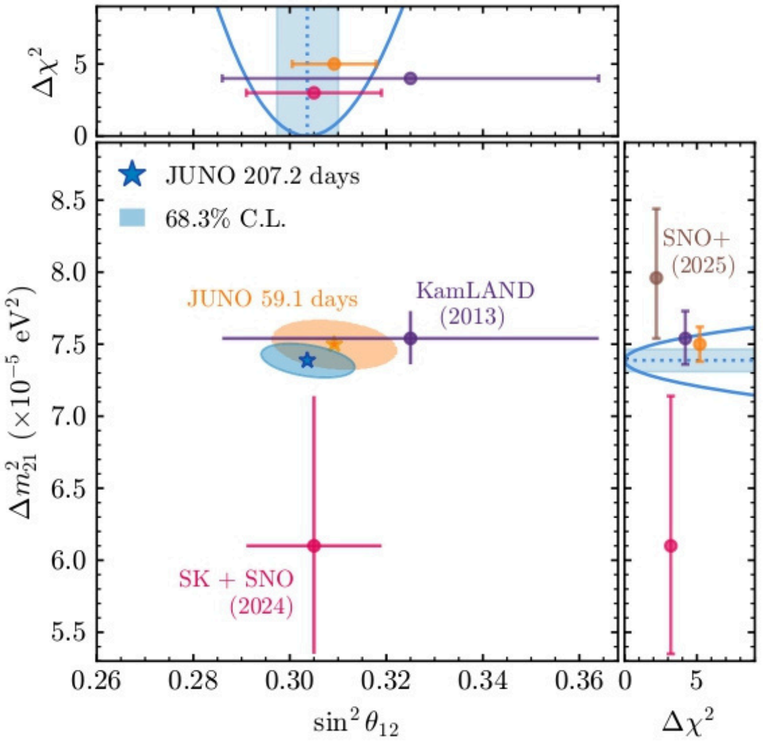
Damping effects on neutrino oscillations with JUNO

Based on
arXiv:2606.13362 [hep-ph]-M.Beccaria, C.A. Ternes



JUNO results

JUNO Collaboration, arxiv:2609.37895



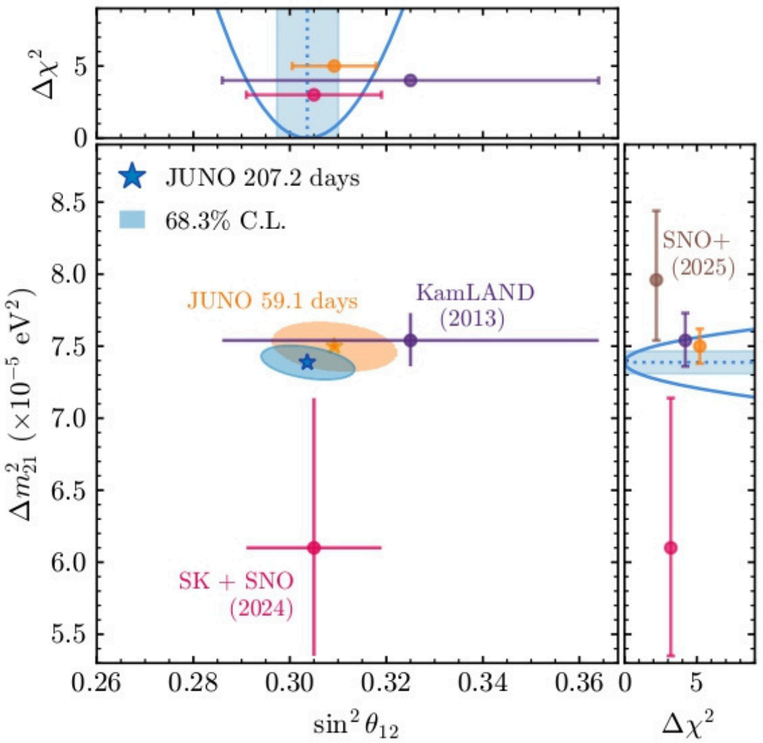
207.2 days:

$$\sin^2\theta_{12} = 0.3036 \pm 0.0064$$

$$\Delta m^2_{21} = (7.388 \pm 0.078) \cdot 10^{-5}\mathrm{eV}^2$$

JUNO results

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$$\sin^2\theta_{12} = 0.3036 \pm 0.0064$$

$$\Delta m^2_{21} = (7.388 \pm 0.078) \cdot 10^{-5}\text{eV}^2$$

DAMPING

How are these parameters affected?

Which constraints can we put on these phenomena?

Oscillation probability and damping effects

Probability

$$P(\alpha \to \beta; E, L) = \sum_{k,j} U^*_{\alpha k} U_{\beta k} U_{\alpha j} U^*_{\beta k} e^{-i \frac{\Delta m^2_{kj}}{2E} L}$$

Oscillation probability and damping effects

$$P^{JUNO}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2 \Delta_{21}$$
$$- \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

with

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

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Oscillation probability and damping effects

$$P^{JUNO}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

with

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

$$\begin{aligned} P_{ee} = {} & |U_{e1}|^4 + |U_{e2}|^4 + |U_{e3}|^4 \\ & + 2|U_{e1}|^2|U_{e2}|^2\cos 2\Delta_{21} \\ & + 2|U_{e1}|^2|U_{e3}|^2\cos 2\Delta_{31} \\ & + 2|U_{e2}|^2|U_{e3}|^2\cos 2\Delta_{32} \end{aligned}$$

STANDARD

Oscillation probability and damping effects

$$P^{JUNO}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

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STANDARD

$$P_{ee}^{\text{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2\cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2\cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2\cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

DAMPING

Oscillation probability and damping effects

$$P^{JUNO}(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12}\cos^4\theta_{13}\sin^2\Delta_{21} - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})$$

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STANDARD

Wave packets

Environmental decoherence

Invisible decay

$$P_{ee}^{\text{damp}} = |U_{e1}|^4 e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2\cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2\cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2\cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

DAMPING

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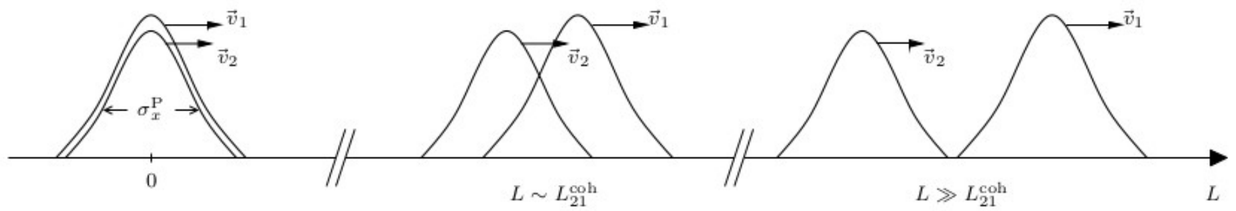
$$P_{ee}^{\text{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

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Theoretical motivations

- Abandoning the plane wave approximation and considering the wave packet description, the propagation depends on the coherence lenght, related to the wave packet size

$$L_{ij}^{coh} = \frac{4\sqrt{2}E^2}{|\Delta m_{ij}^2|}\sigma$$



Wave packets

Environmental decoherence

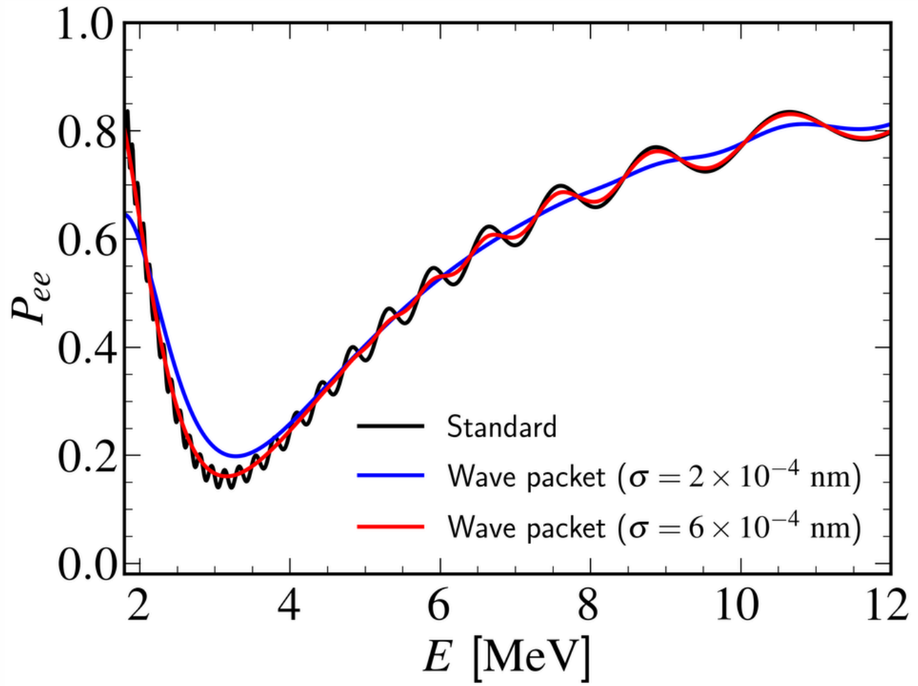
Invisible decay

$$P_{ee}^{\mathrm{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

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$$D_i(E,L) = 0 \ (i = 1,2,3)$$

$$D_{ij}(E,L) = \left(\frac{\Delta m^2_{ij} L}{4\sqrt{2}E^2\sigma}\right)^2 = \left(\frac{L}{L^{coh}_{ij}}\right)^2$$



MB, C.A. Ternes, 2606.13362

Wave packets

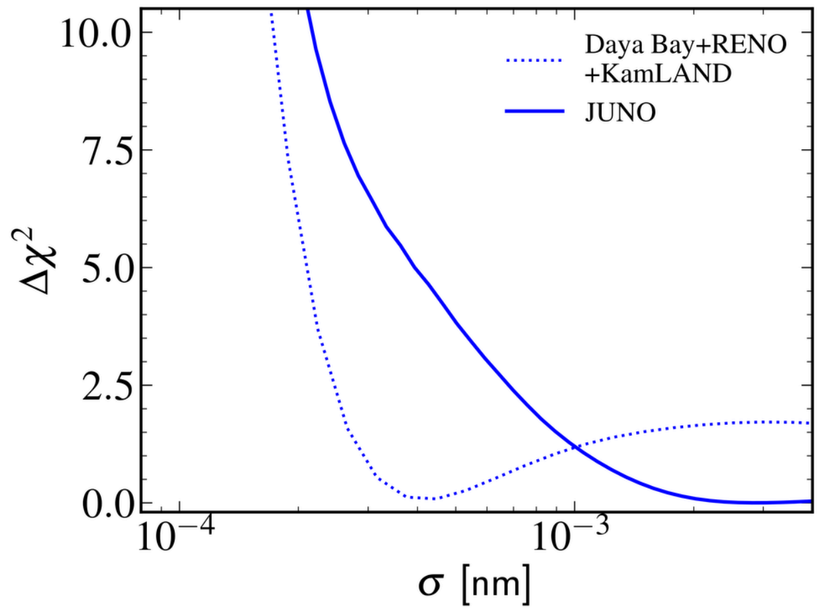
Environmental decoherence

Invisible decay

$$P^{\text{damp}}_{ee} = |U_{e1}|^4 e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)}$$
$$+ 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)}$$
$$+ 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)}$$
$$+ 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

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Bounds on neutrino wave packet width



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Minimization over the standard oscillation parameters with **priors** from

- solar data on $\Delta m^2_{21},\ \theta_{12}$
- Long baseline accelerators and atmospheric data on Δm^2_{31}

$$\sigma > 6.48 \times 10^{-4}\ \text{nm}\ @90\%\ \text{C.L.}$$

Stronger bound than DayaBay+RENO+KamLAND

(A. de Gouvêa, V. De Romeri, C. A. Ternes, 2410.01357)

$$\chi^2(\vec{p}) = \min_{\vec{\alpha}} \left\{ 2 \sum_i \left[N_{\text{exp},i}(\vec{p},\vec{\alpha}) - N_{\text{dat},i} + N_{\text{dat},i} \log \left(\frac{N_{\text{dat},i}}{N_{\text{exp},i}(\vec{p},\vec{\alpha})} \right) \right] + \sum_i \left(\frac{\alpha_i}{\sigma_i} \right)^2 \right\} + \chi^2_{\text{prior}}$$

Wave packets

Environmental decoherence

Invisible decay

$$P_{ee}^{\text{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

DAMPING

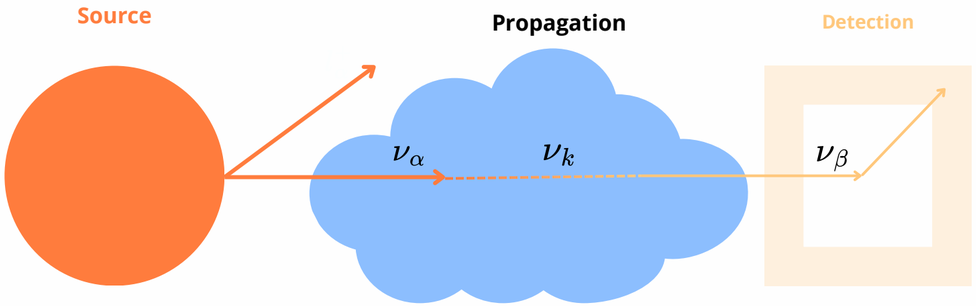
Theoretical motivations (1)

- Neutrinos can also lose coherence if they interact with some unknown environment: this can be described by the Lindblad Master equation:

$$\frac{\partial \rho_\nu(t)}{\partial t} = -i[H, \rho_\nu(t)] + \mathcal{D}[\rho_\nu(t)]$$

Hermitian density matrix that describes the neutrino states in the mass basis

Dissipative term that encodes the decoherence effects



Wave packets

Environmental decoherence

Invisible decay

$$P_{ee}^{\text{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

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Theoretical motivations (2)

- Under well-motivated assumptions, the dissipative term given by a 8x8 matrix can be rewritten as

$$\mathbf{D} = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

  which leads to the following damping parameters:

$$D_i(E,L) = 0 \ (i = 1,2,3) \qquad D_{ij}(E,L) = \Gamma_{ij} L = \gamma_{ij} L \left(\frac{E}{E_0}\right)^n \text{ with } E_0 = 1 \text{ GeV}$$

- Since for JUNO E<1 GeV, we consider
  - n=-2: gravitationally induced decoherence
  - n=-1: decay like decoherence
  - n=0: energy-independent model

Wave packets

Environmental decoherence

Invisible decay

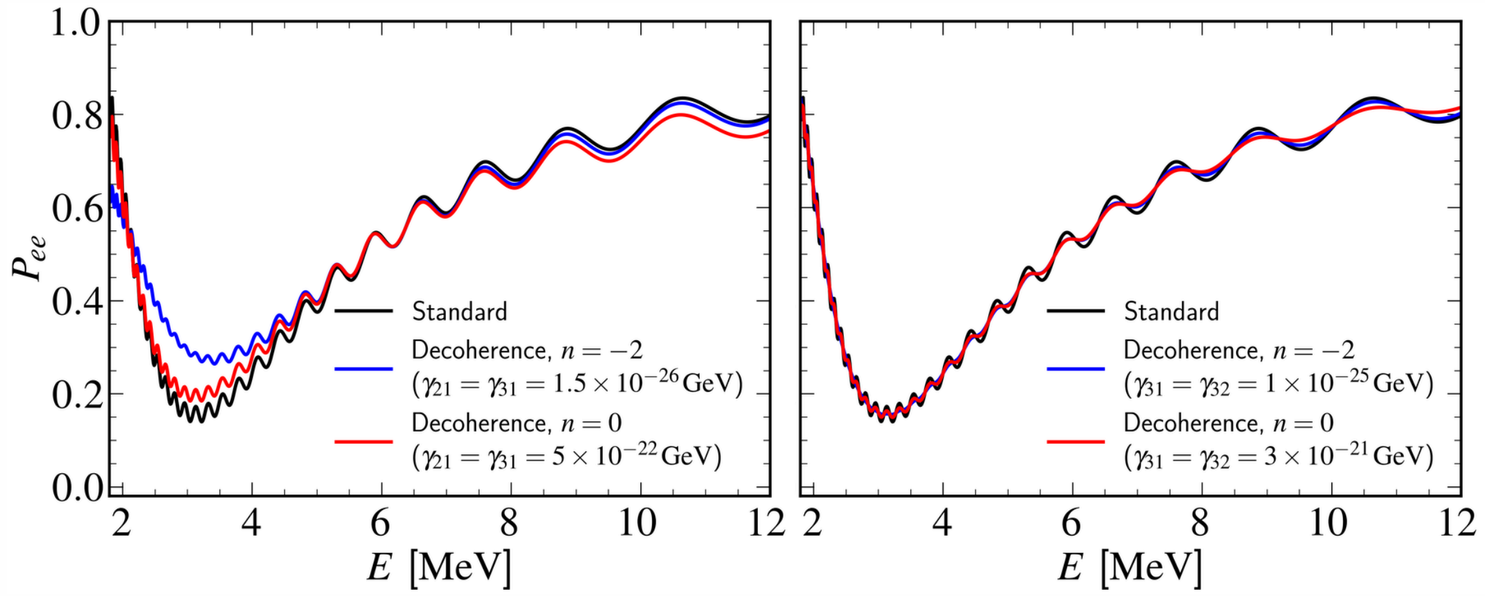
$$P_{ee}^{\text{damp}} = |U_{e1}|^4 \, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2 |U_{e2}|^2 \cos 2\Delta_{21} \, e^{-D_{21}(E,L)} + 2|U_{e1}|^2 |U_{e3}|^2 \cos 2\Delta_{31} \, e^{-D_{31}(E,L)} + 2|U_{e2}|^2 |U_{e3}|^2 \cos 2\Delta_{32} \, e^{-D_{32}(E,L)}$$

DAMPING

$$D_i(E,L) = 0 \ (i = 1,2,3)$$

$$D_{ij}(E,L) = \gamma_{ij} L \left(\frac{E}{E_0}\right)^n$$

with $E_0 = 1$ GeV, $n = -2, -1, 0$



MB, C.A. Ternes, 2606.13362

Wave packets

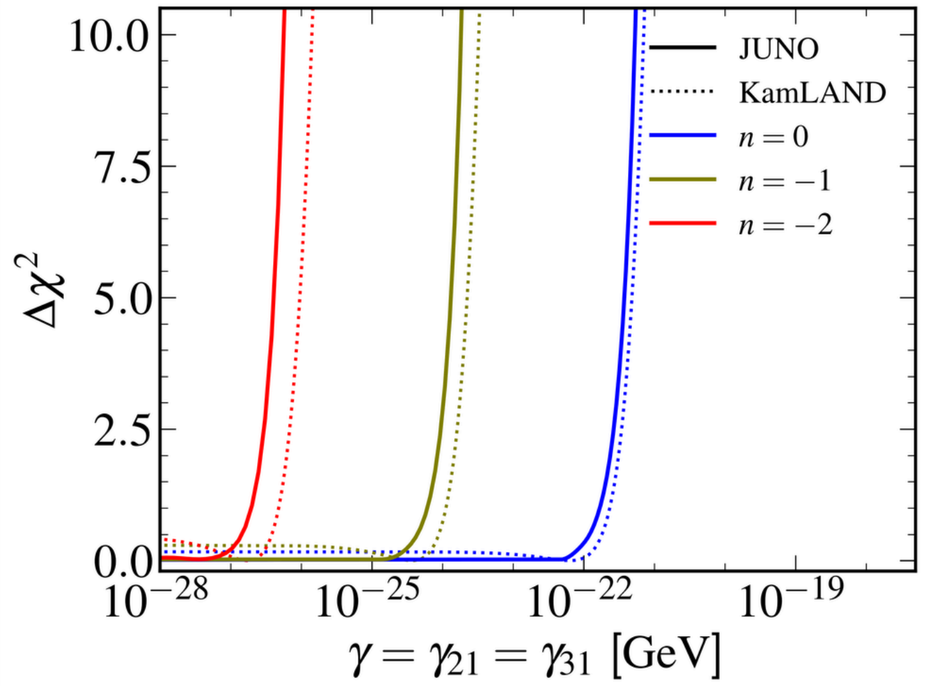
Environmental decoherence

Invisible decay

$$P_{ee}^{\text{damp}} = |U_{e1}|^4 \, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)}$$
$$+ 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21} \, e^{-D_{21}(E,L)}$$
$$+ 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31} \, e^{-D_{31}(E,L)}$$
$$+ 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32} \, e^{-D_{32}(E,L)}$$

DAMPING

Bounds on environmental decoherence: $\gamma_{21} = \gamma_{31}$



MB, C.A. Ternes, 2606.13362

Minimization over the standard oscillation parameters with **priors** from

- solar data on $\Delta m^2_{21},\ \theta_{12}$

$$\gamma := \gamma_{21} = \gamma_{31},\ \gamma_{32} = 0$$

90% C.L. limits:

$$\gamma < 2.87 \times 10^{-22}\ \text{GeV}\quad (n = 0)$$

$$\gamma < 1.10 \times 10^{-24}\ \text{GeV}\ (n = -1)$$

$$\gamma < 3.75 \times 10^{-27}\ \text{GeV}\ (n = -2)$$

Stronger than the full KamLAND dataset

(V. De Romeri et al., 2306.14699)

Bounds on environmental decoherence: $\gamma_{31} = \gamma_{32}$

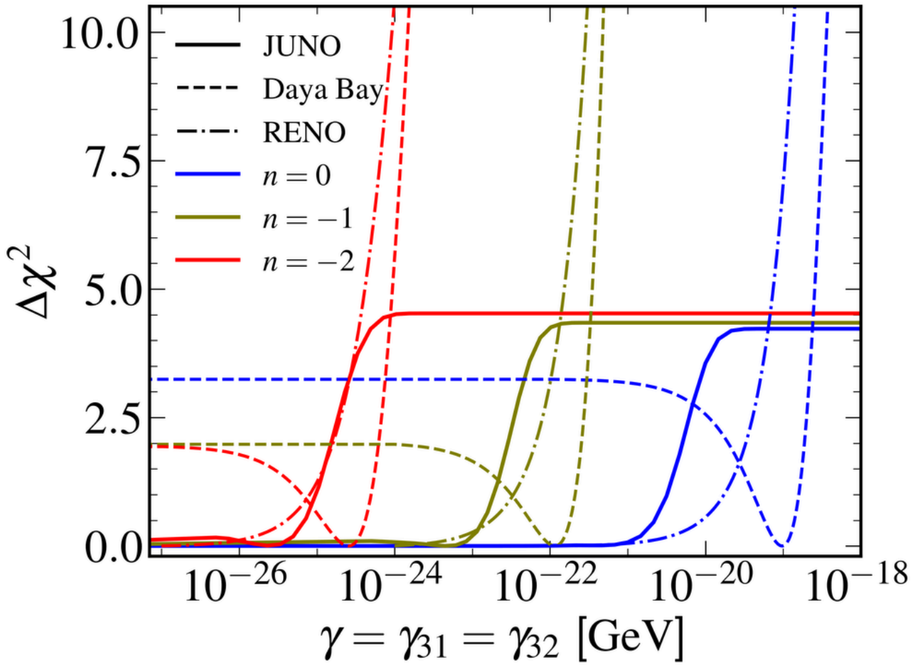
Minimization over the standard oscillation parameters with **priors** from
- solar data on $\Delta m^2_{21},\ \theta_{12}$

$$\gamma := \gamma_{31} = \gamma_{32},\ \gamma_{21} = 0$$

90% C.L. limits:

$$\gamma < 6.73 \times 10^{-21}\ \text{GeV} \quad (n = 0)$$
$$\gamma < 3.77 \times 10^{-23}\ \text{GeV}\ (n = -1)$$
$$\gamma < 2.07 \times 10^{-25}\ \text{GeV}\ (n = -2)$$

Sensitivity to fast oscillations still limited
- 90% CL bound slightly stronger than Daya Bay and RENO (MB, C.A. Ternes, 2606.13362)
- No bounds at larger confidence levels



MB, C.A. Ternes, 2606.13362

Wave packets

Environmental decoherence

Invisible decay

$$P_{ee}^{\text{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

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Theoretical motivations

- We can assume that active neutrinos are subject to both standard mixing and invisible decays, so the evolution for the flavour states is described by

$$H = \frac{1}{2E}\left[H_0 + H_M + H_D\right]$$

Vacuum Hamiltonian

Matter effect term

$$H_D = U\,\mathrm{diag}(-i\alpha_1, -i\alpha_2, -i\alpha_3)U^\dagger$$

where $\alpha_i = \dfrac{m_i}{\tau_i}$ depends on the mass and lifetime of the neutrino mass eigenstate.

Wave packets

Environmental decoherence

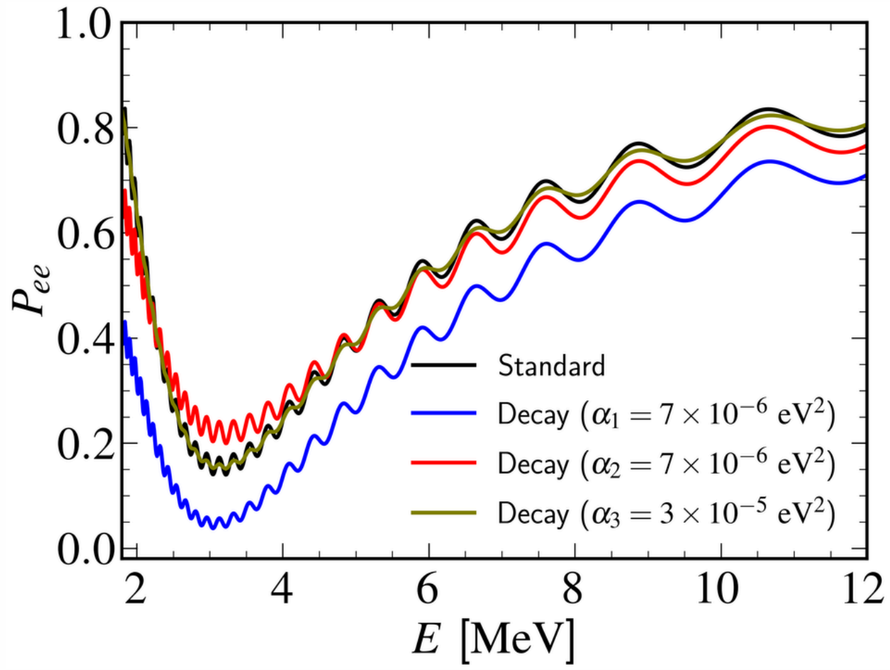
Invisible decay

$$\begin{aligned} P_{ee}^{\mathrm{damp}} = {} & |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} \\ & + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} \\ & + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} \\ & + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)} \end{aligned}$$

DAMPING

$$D_i(E,L) = \alpha_i \frac{L}{E} \;\; (i = 1,2,3)$$

$$D_{ij}(E,L) = \frac{D_i(E,L) + D_j(E,L)}{2}$$



MB, C.A. Ternes, 2606.13362

Wave packets

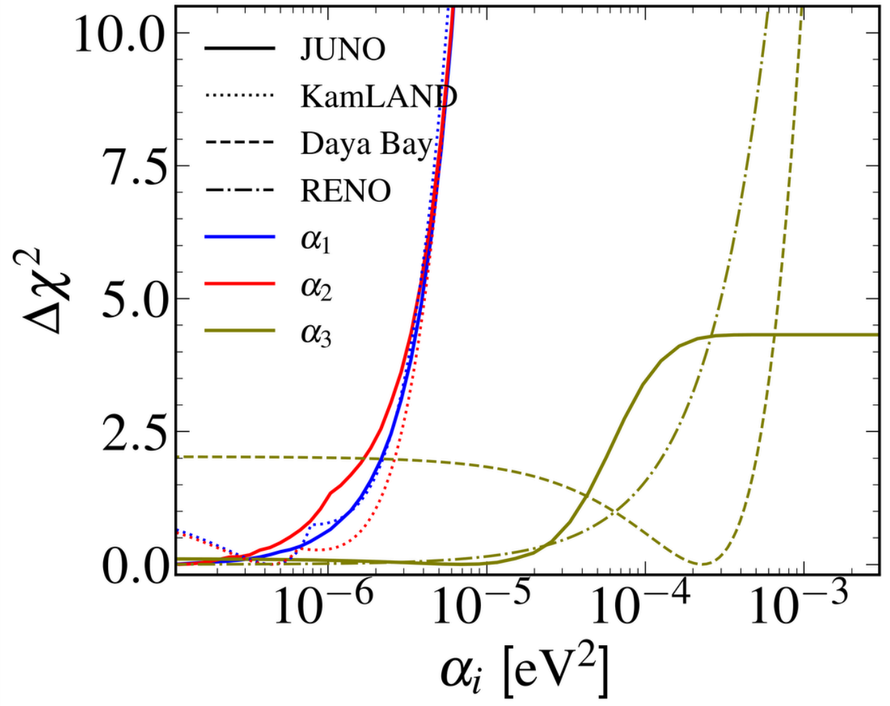
Environmental decoherence

Invisible decay

$$P_{ee}^{\text{damp}} = |U_{e1}|^4 \, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)}$$
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$$+ 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32} \, e^{-D_{32}(E,L)}$$

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Bounds on invisible decay



MB, C.A. Ternes, 2606.13362

Minimization over the standard oscillation parameters with **priors** from

- Daya Bay prior on θ_{13} for $\alpha_1,\ \alpha_2$

$$@\ 90\%\text{C.L.}: \quad \alpha_1 < 2.66 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_2 < 2.27 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_3 < 7.32 \times 10^{-5}\ \text{eV}^2$$

- For $\alpha_1,\ \alpha_2$ results **comparable with the full KamLAND dataset**
- Limited sensitivity to fast oscillations leads to **limited sensitivity on** α_3

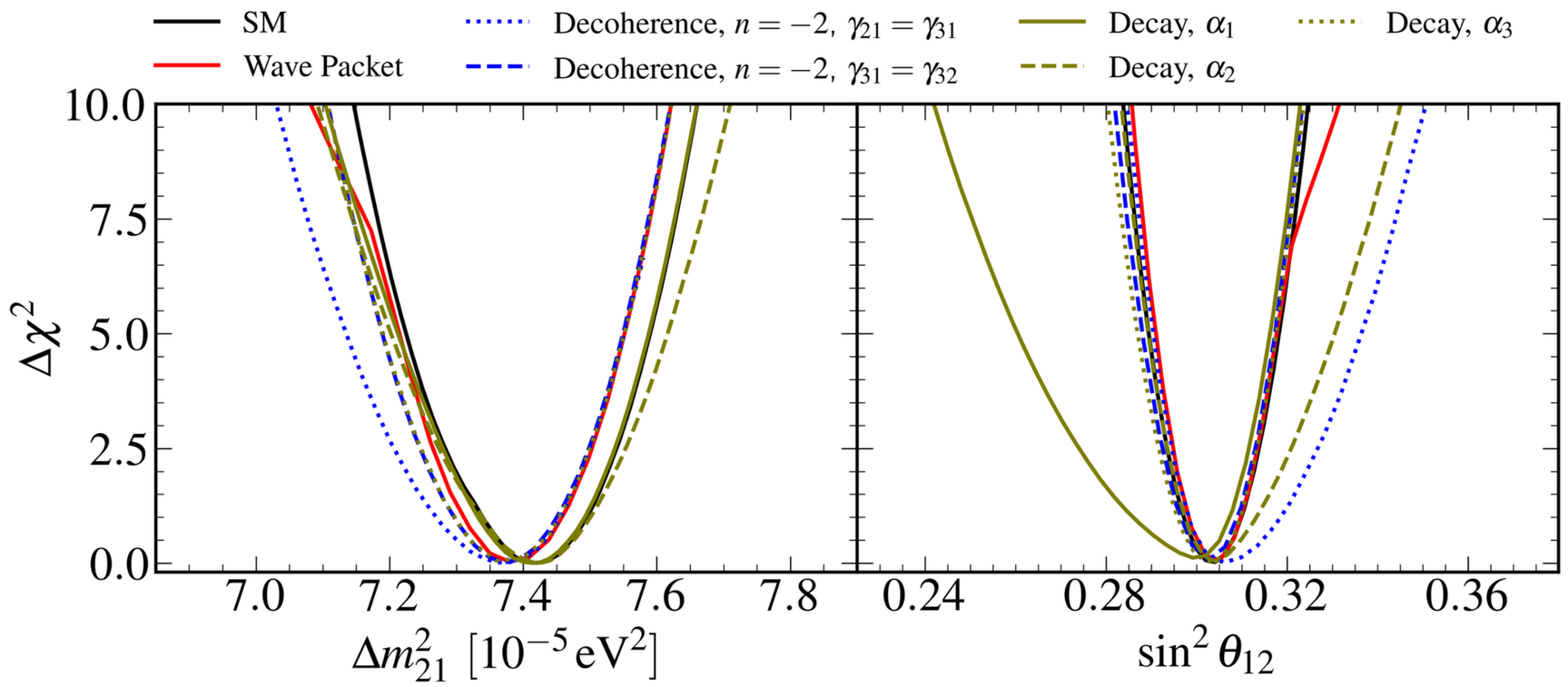
(M. C. Gonzalez-Garcia and M. Maltoni,0802.3699
C. A. Ternes and G. Pagliaroli, 2401.14316)

Limits from solar neutrino data

$$\begin{cases} \alpha_1 \leq 1.6 \times 10^{-13}\ \text{eV}^2 \\ \alpha_2 \leq 3.4 \times 10^{-13}\ \text{eV}^2 \end{cases}$$

(J. M. Berryman et al.,1411.0308
SNO Collaboration, 1812.01088)

χ^2 profiles



MB, C.A. Ternes, 2606.13362

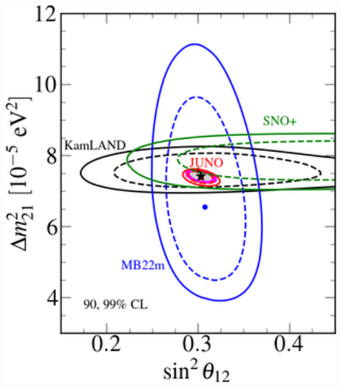
The **determination of the standard solar oscillation parameters remains robust** but non neglible effects might be present for the invisible decay scenario

As JUNO accumulates more statistics **its sensitivity to damping signatures is expected to improve significantly**, especially for scenarios related to fast oscillations

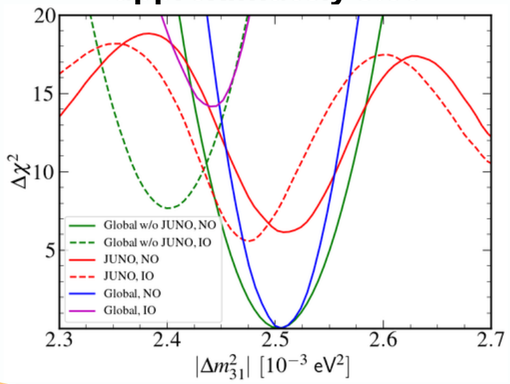
Conclusions

JUNO contribution to the Neutrino Global Fit

Percent-level uncertainty on the **solar parameters**



Preference for **normal ordering at approximately 3.8σ**



Damping effects in JUNO (90% CL limits)

Wave packet size

$$\sigma > 6.4 \times 10^{-4}\ \text{nm}$$

Stronger than DayaBay +RENO+KamLAND

Invisible decay

$$\alpha_1 < 2.6 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_2 < 2.6 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_3 < 7.5 \times 10^{-5}\ \text{eV}^2$$

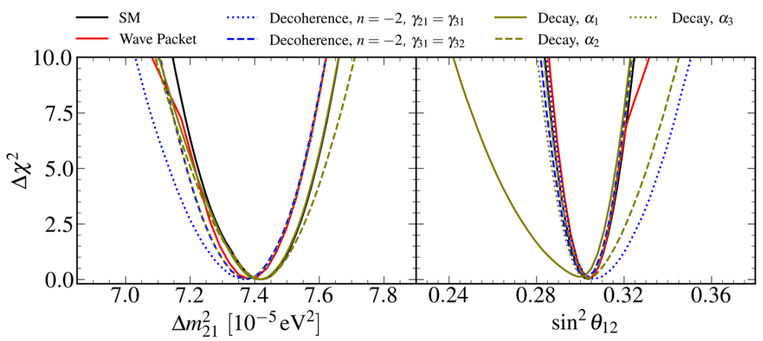
Limited by *L*

Environmental decoherence

	$\gamma_{21} = \gamma_{31}$ [GeV]	$\gamma_{31} = \gamma_{32}$ [GeV]
$n = 0$	2.87×10^{-22}	6.73×10^{-21}
$n = -1$	1.10×10^{-24}	3.77×10^{-23}
$n = -2$	3.75×10^{-27}	2.07×10^{-25}

Stronger than KamLAND

Still limited at higher CL



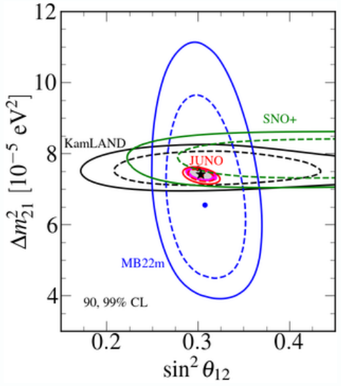
Conclusions

Thanks for the attention!

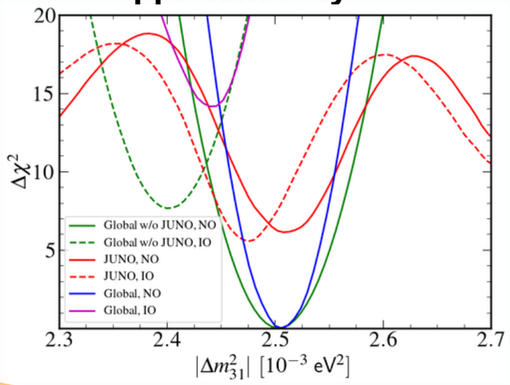
Martina Beccaria
martina.beccaria@gssi.it

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$$\alpha_2 < 2.6 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_3 < 7.5 \times 10^{-5}\ \text{eV}^2$$

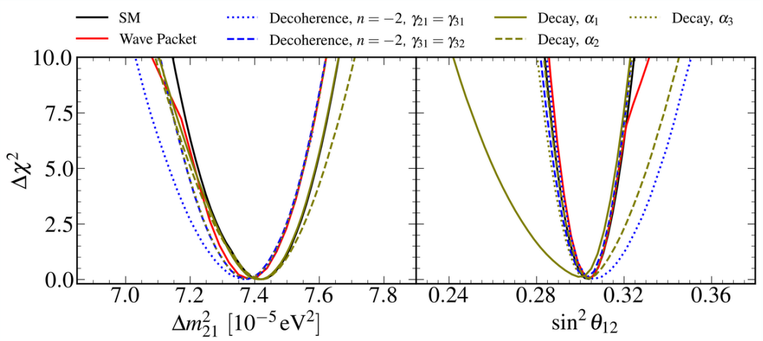
Limited by *L*

Environmental decoherence

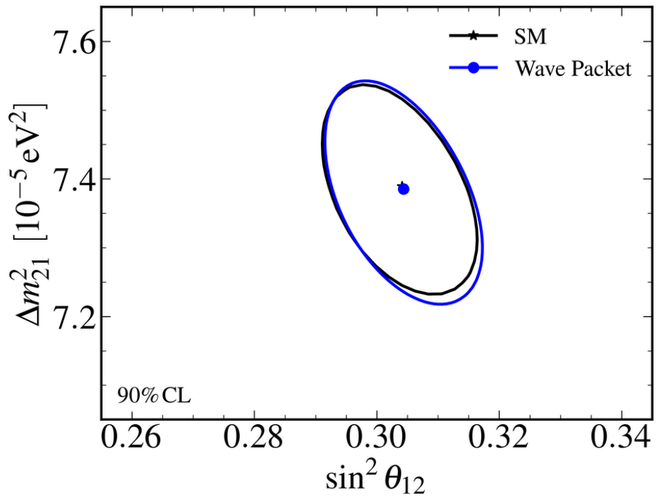
	$\gamma_{21} = \gamma_{31}$ [GeV]	$\gamma_{31} = \gamma_{32}$ [GeV]
$n = 0$	2.87×10^{-22}	6.73×10^{-21}
$n = -1$	1.10×10^{-24}	3.77×10^{-23}
$n = -2$	3.75×10^{-27}	2.07×10^{-25}

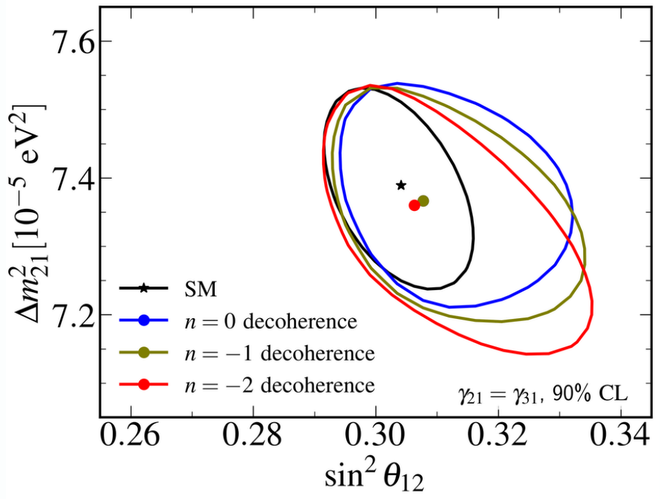
Stronger than KamLAND

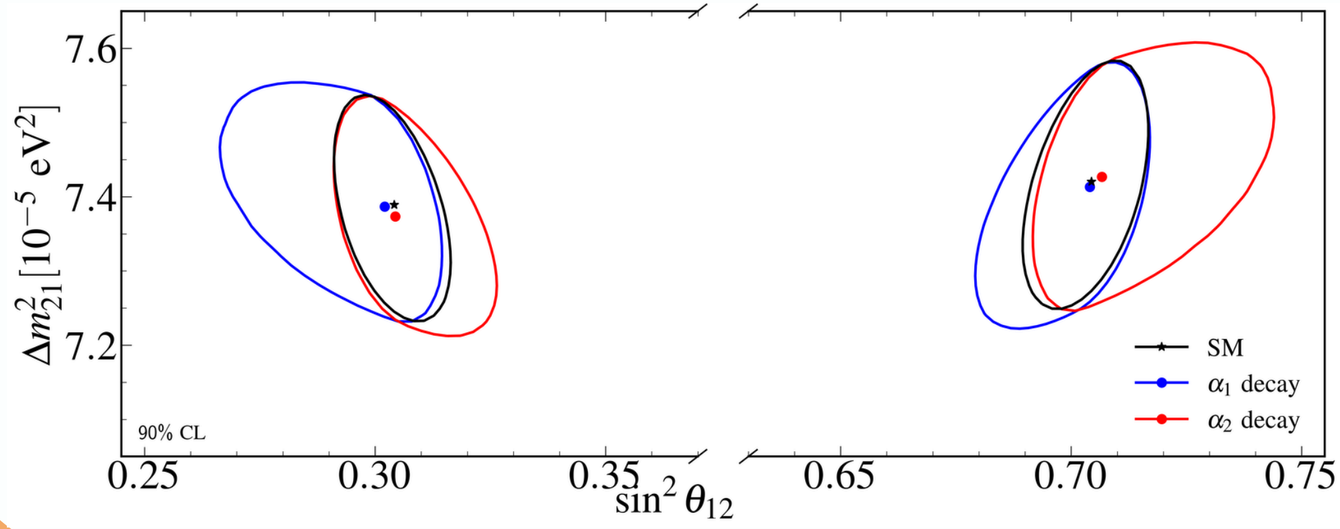
Still limited at higher CL

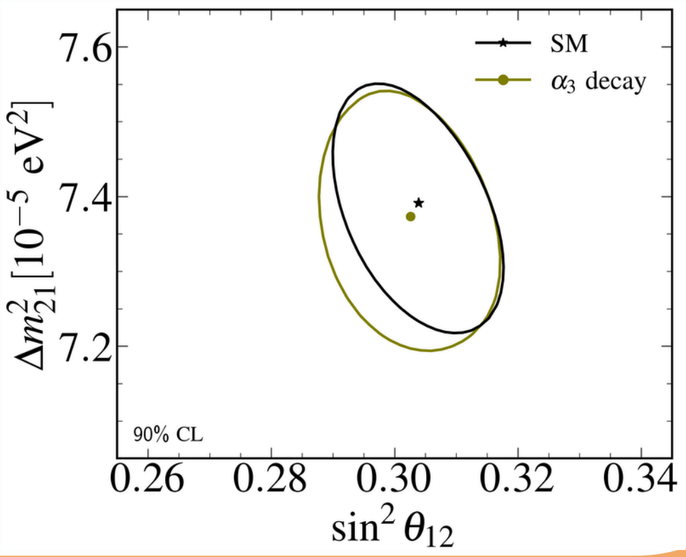


Damping effects: solar parameter plane



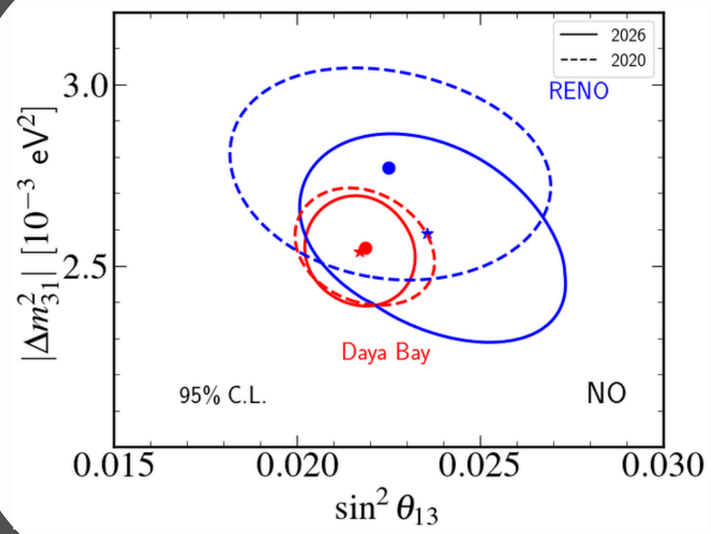


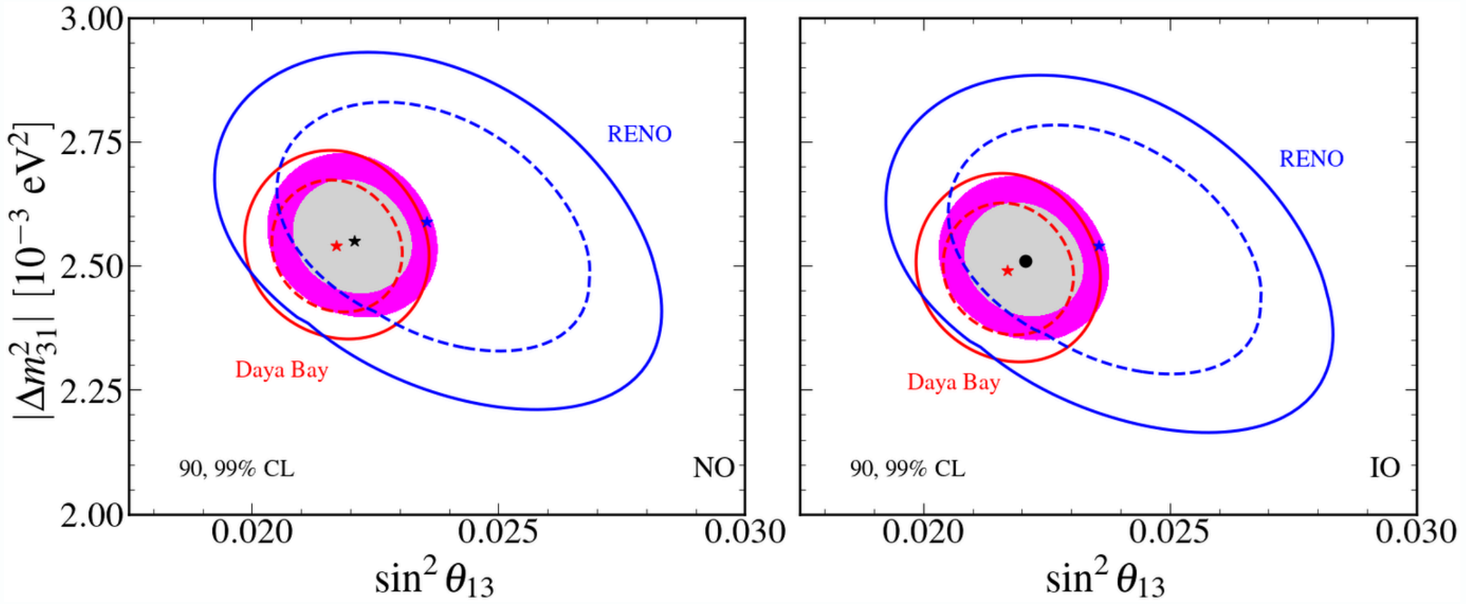




Reactor angle: θ_{13}

- Best determination thanks to short baseline reactors: **Daya Bay and RENO**
- Agreement improved with their final data releases

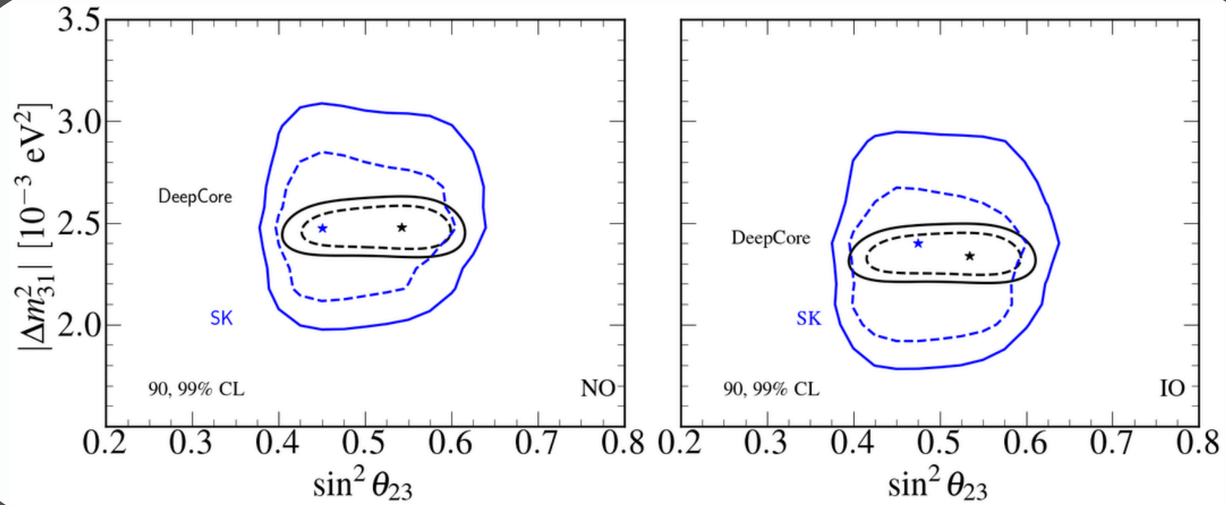


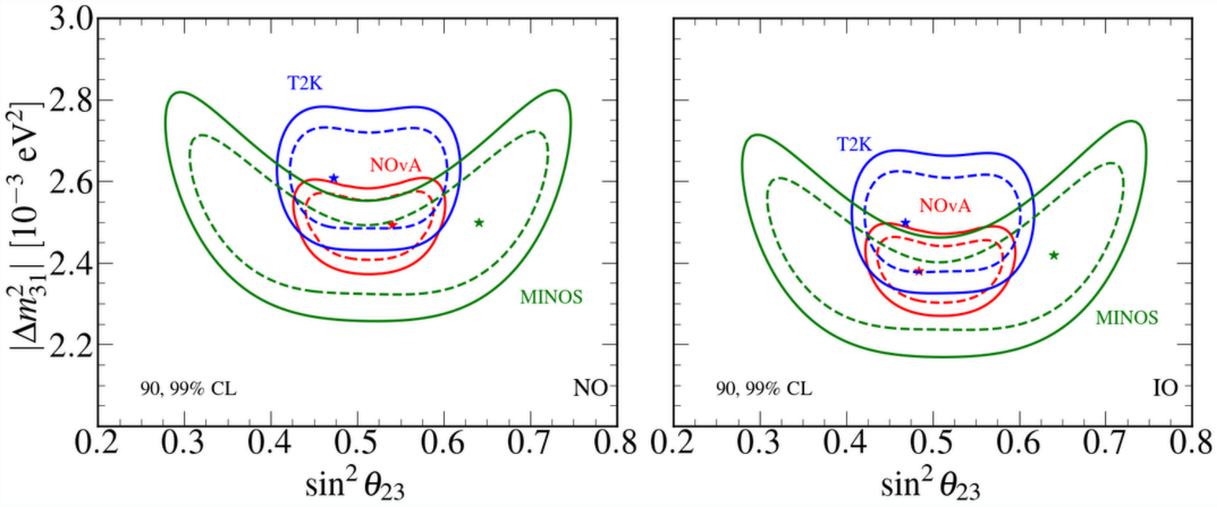


$$\sin^2\theta_{13} = (2.212^{+0.054}_{-0.055}) \cdot 10^{-2} \text{ (NO)}$$
$$\sin^2\theta_{13} = (2.231^{+0.048}_{-0.060}) \cdot 10^{-2} \text{ (IO)}$$

Atmospheric sector: $|\Delta m^2_{31}|, \theta_{23}$

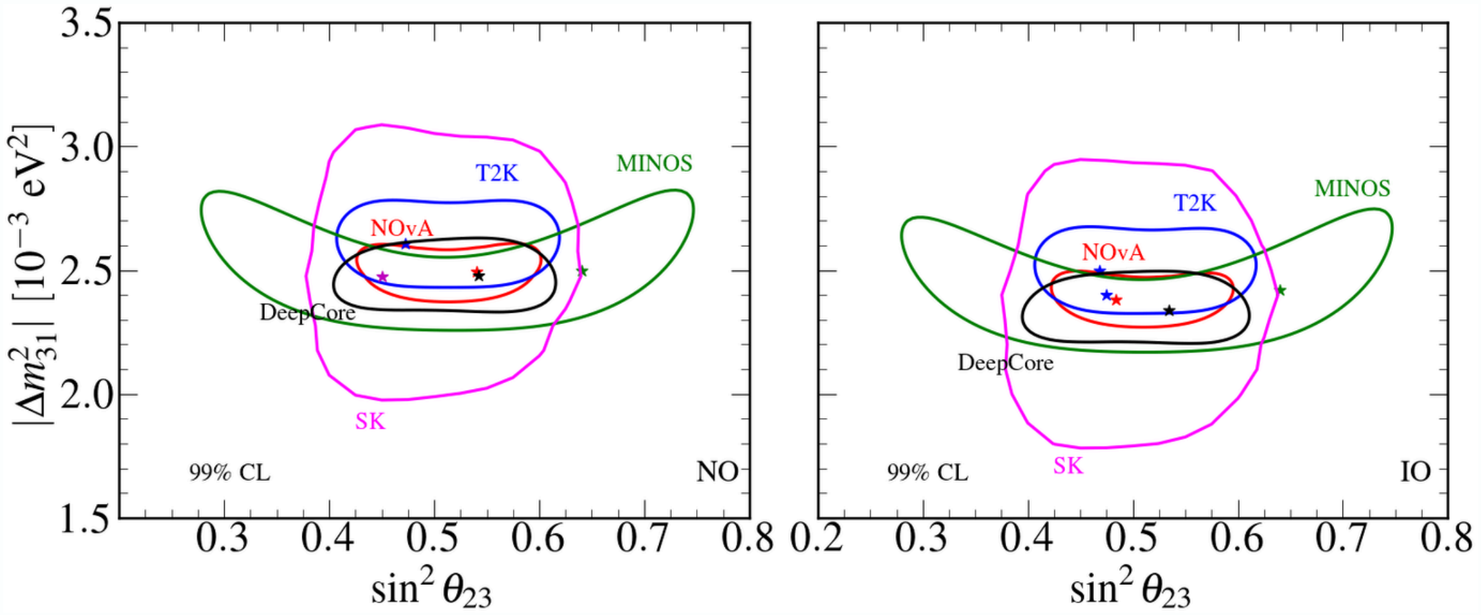
Current atmospheric neutrino experiments: **Super-Kamiokande** and **IceCube DeepCore**





Long baseline accelerators: **NOvA**, **T2K** and **MINOS**

Atmospheric sector: $|\Delta m^2_{31}|, \theta_{23}$



$$|\Delta m^2_{31}| = (2.506^{+0.016}_{-0.014}) \cdot 10^{-3}\text{eV}^2 \ \text{(NO)}$$
$$|\Delta m^2_{31}| = (2.440^{+0.017}_{-0.016}) \cdot 10^{-3}\text{eV}^2 \ \text{(IO)}$$

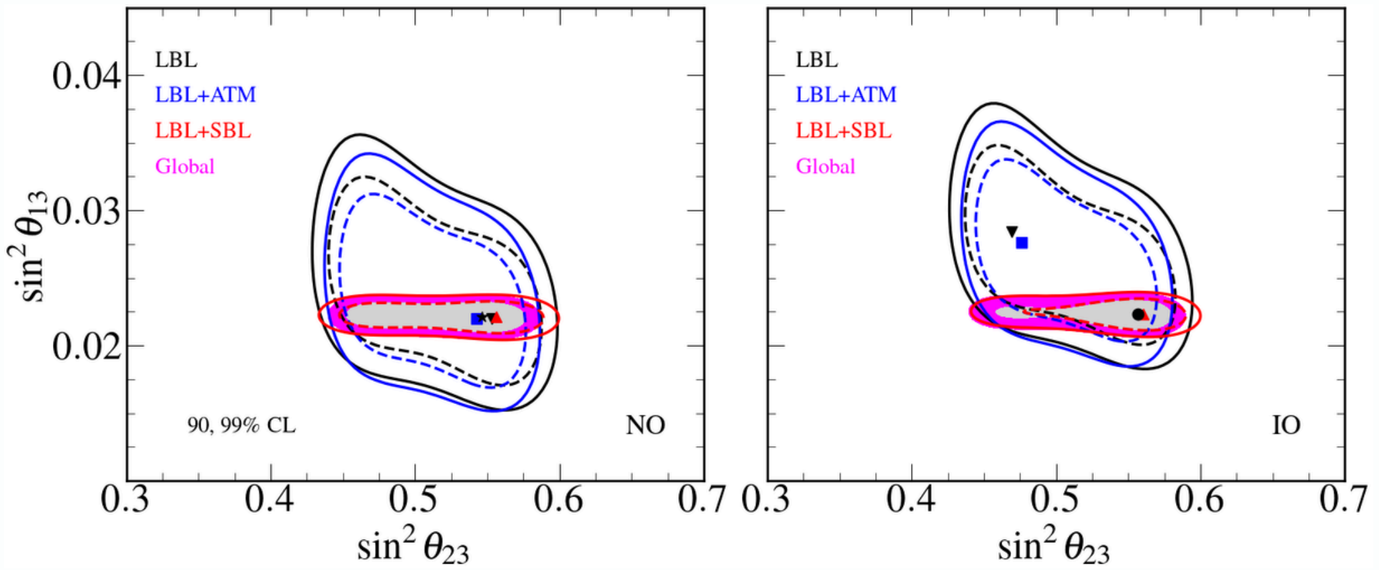
Global Fit value including JUNO 2nd data

Not possible to resolve the octant of the angle:

$\sin^2\theta_{23} > 0.5$ or $\sin^2\theta_{23} < 0.5$?

Mainly sensitive to $\sin^2 2\theta_{23}$

θ_{23} degeneracy



$$\sin^2\theta_{23} = (5.46^{+0.17}_{-0.24}) \cdot 10^{-1} \text{ (NO)}$$

$$\sin^2\theta_{23} = (5.57^{+0.12}_{-0.17}) \cdot 10^{-1} \text{ (IO)}$$

Small preference for $\sin^2\theta_{23} > 0.5$

Reactors help to **break degeneracy**

+

Not possible to resolve the octant of the angle:

$\sin^2\theta_{23} > 0.5$ or $\sin^2\theta_{23} < 0.5$?

Mainly sensitive to $\sin^2 2\theta_{23}$

CP phase δ

Lepton mixing matrix

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

If there is **CP invariance**:

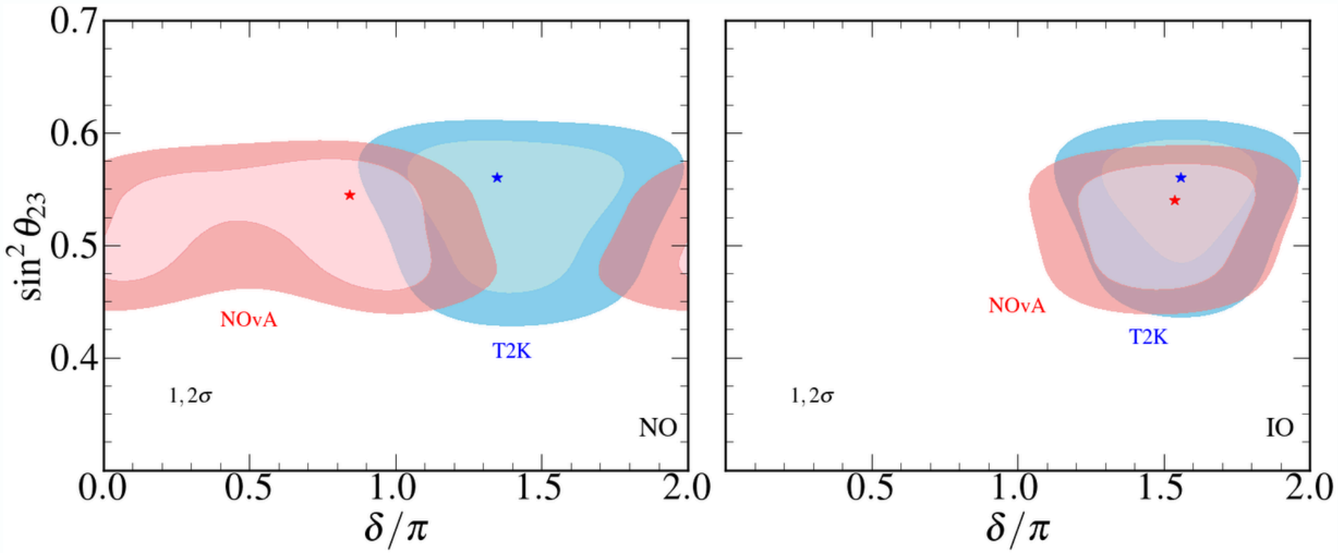
$$P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$\Updownarrow$$

$$U = U^*$$

- $\delta = 0, \pi$ → CP invariance
- $\delta \neq 0, \pi$ → CP violation

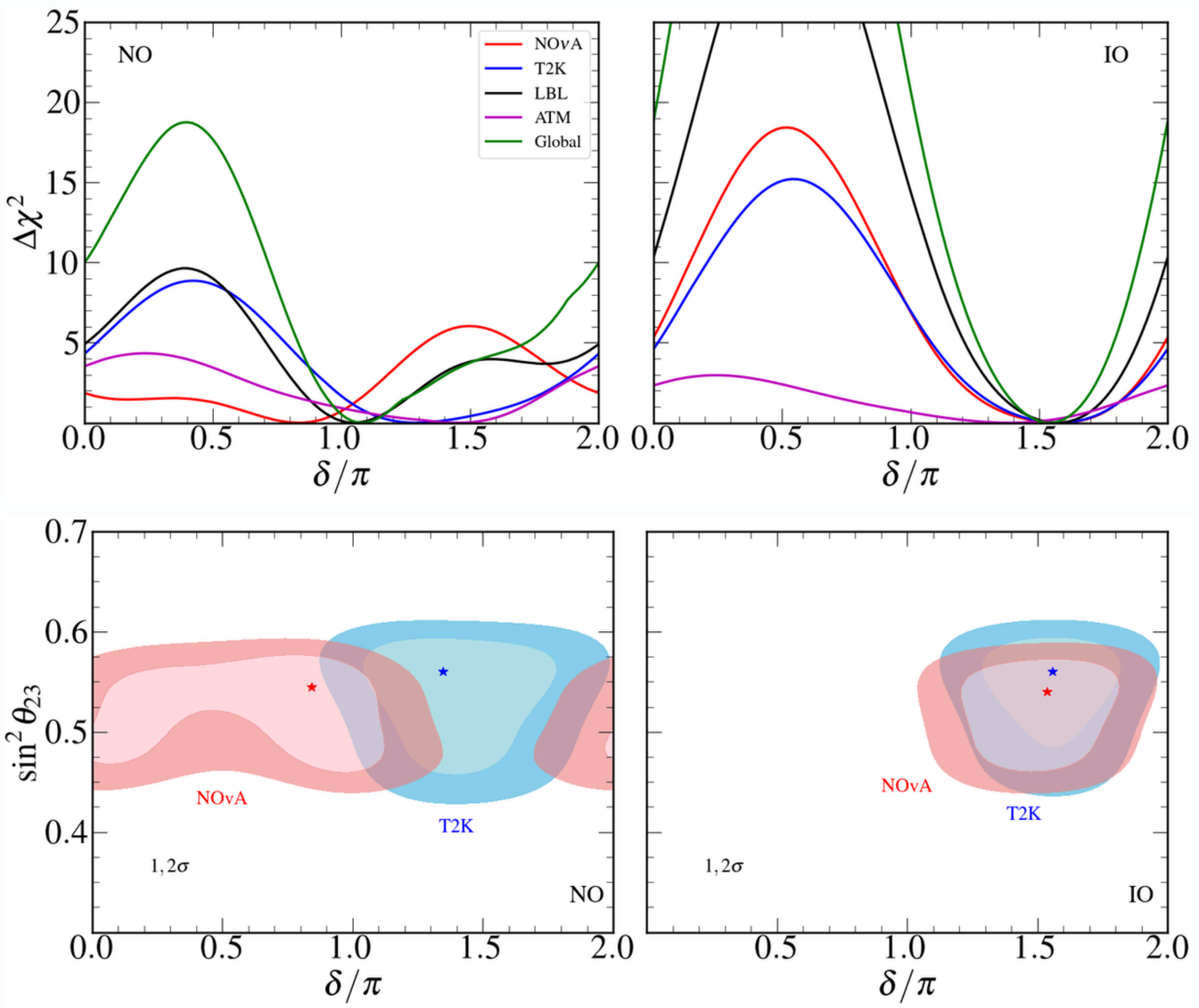
Disagreement in the measurement of the CP phase for the NO



Agreement in the measurement of the CP phase for the IO

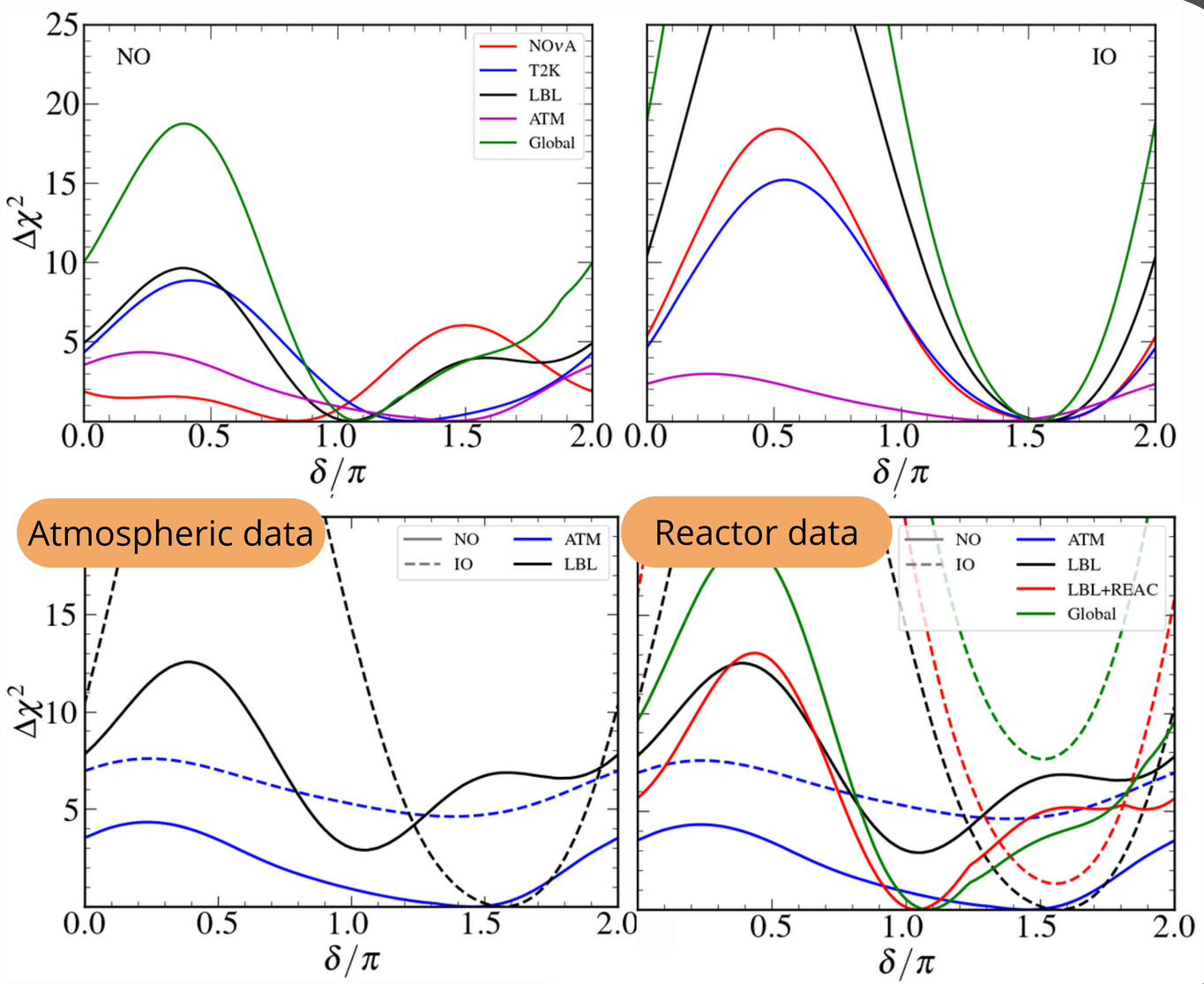
CP phase δ and mass ordering

Disagreement in the measurement of the CP phase for the NO



Agreement in the measurement of the CP phase for the IO

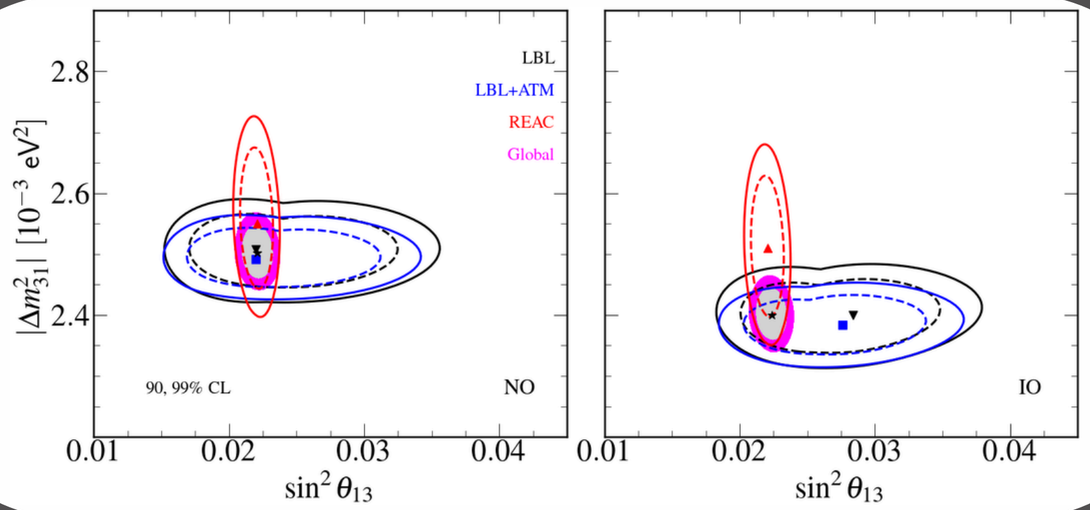
CP phase δ and mass ordering



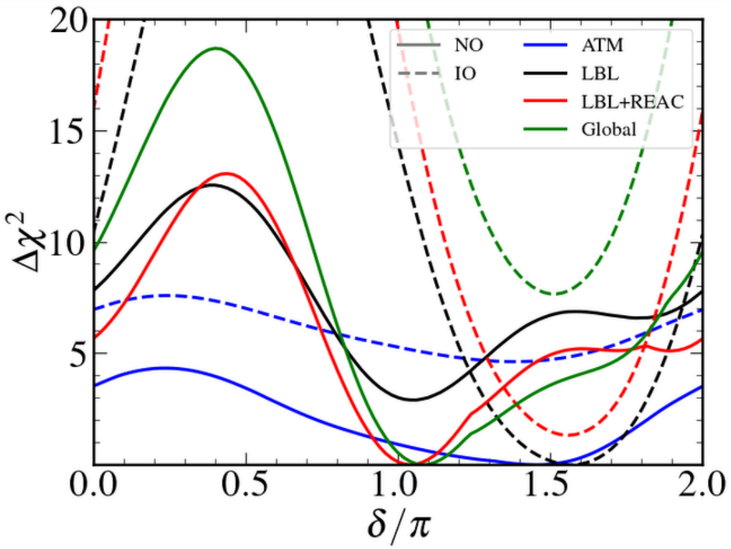
Preference for NO

Preference for NO

CP phase δ and mass ordering

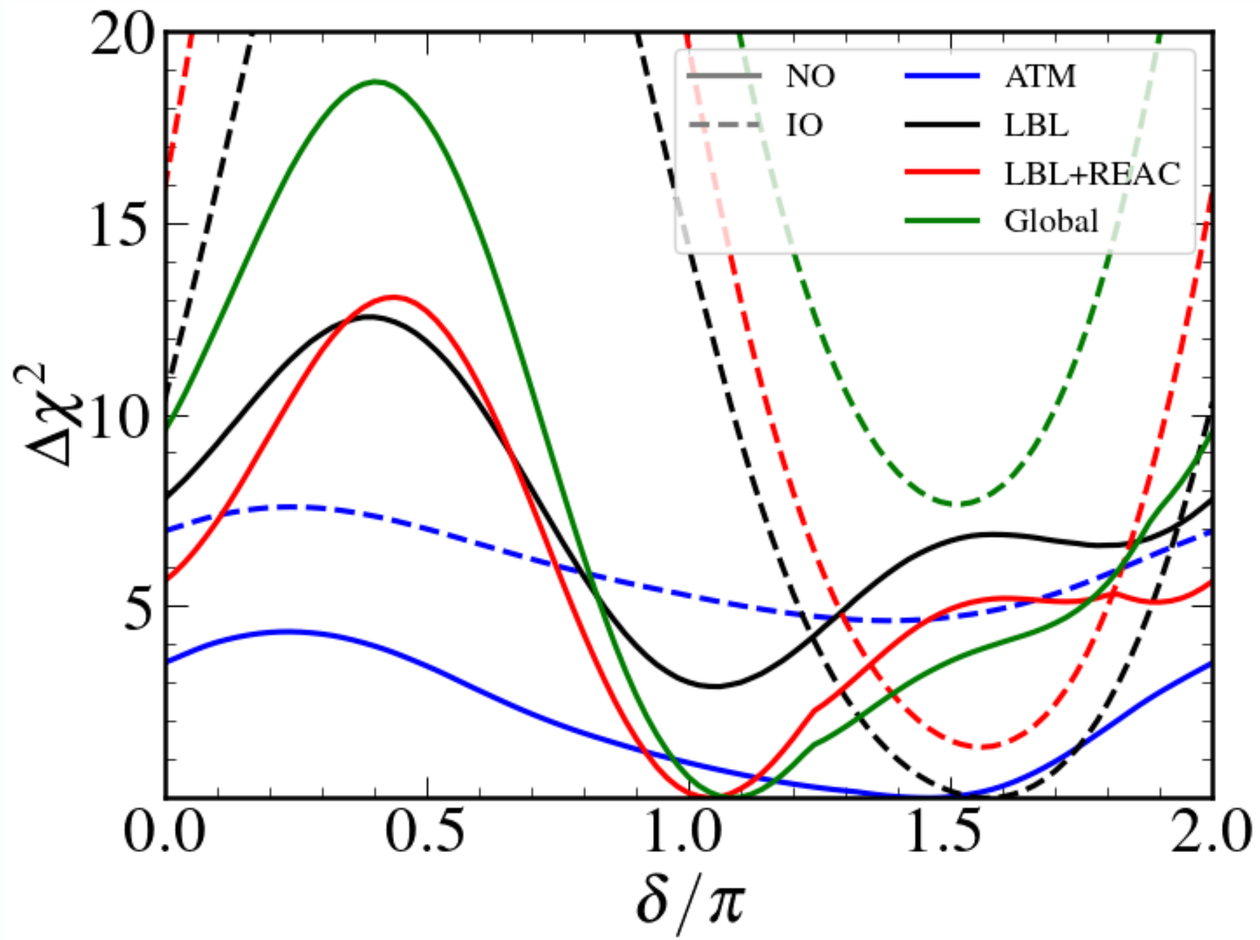


Better agreement between
LBL accelerators+atmospheric data
and reactor data
for the normal ordering



Preference
for NO

CP phase δ and mass ordering



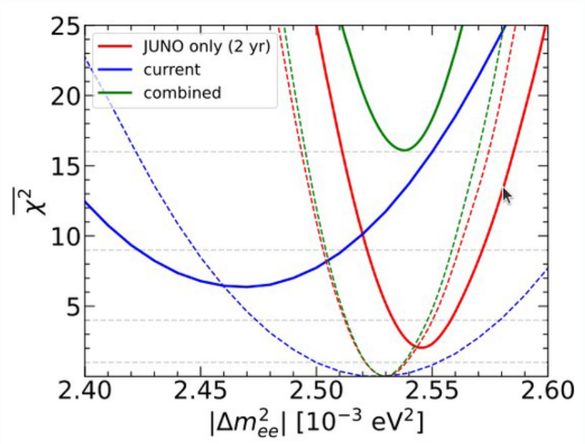
$$\delta = (1.08^{+0.13}_{-0.11}) \cdot \pi \ (\mathrm{NO})$$

$$\delta = (1.52^{+0.12}_{-0.13}) \cdot \pi \ (\mathrm{IO})$$

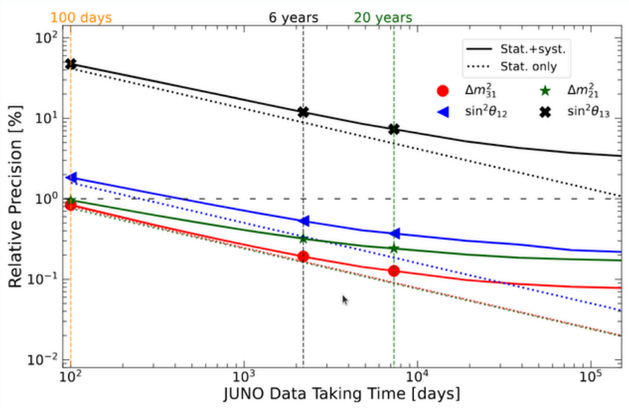
Future Prospects for the Global Fit

JUNO prospects

Mass Ordering determination
(see: Phys. Rev. D 104, 113004)

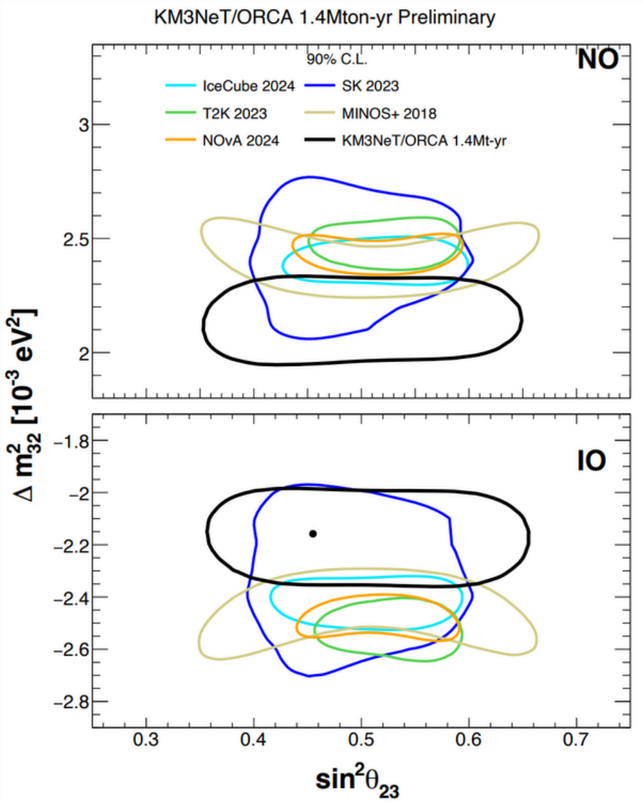


Precision measurement
(see: arXiv:2204.13249 [hep-ex])



Atmospheric sector

- Addition of KM3Net/ORCA



Credit: Paul De Jong, NEUTRINO2026