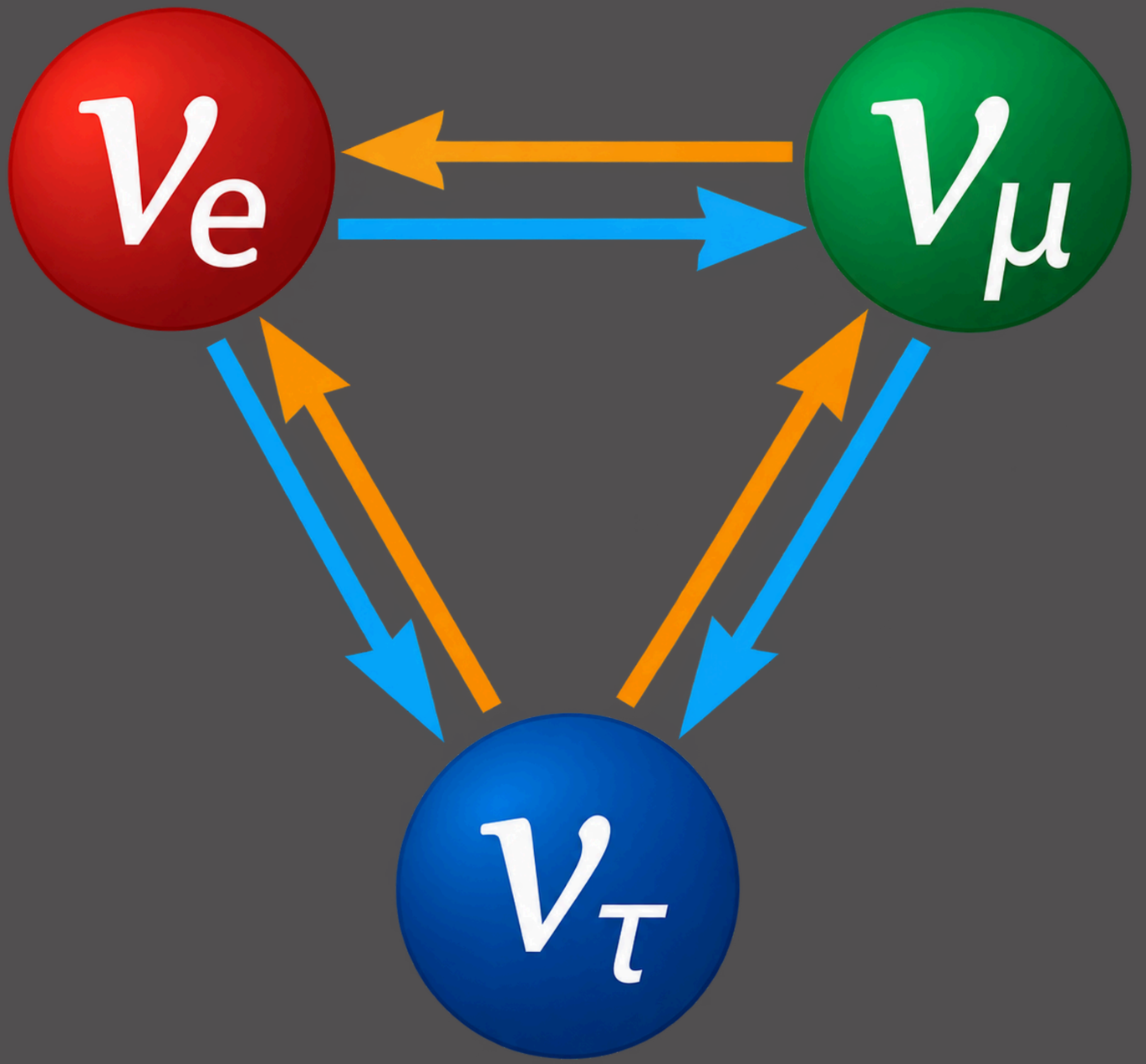
Neutrino phenomenology: from the standard 3-neutrino framework to BSM searches

MARTINA BECCARIA

SUPERVISOR: CHRISTOPH A. TERNES



Astroparticle PhD passage of the year 2026
22/10/2026

Neutrino Global Fit: JUNO contribution

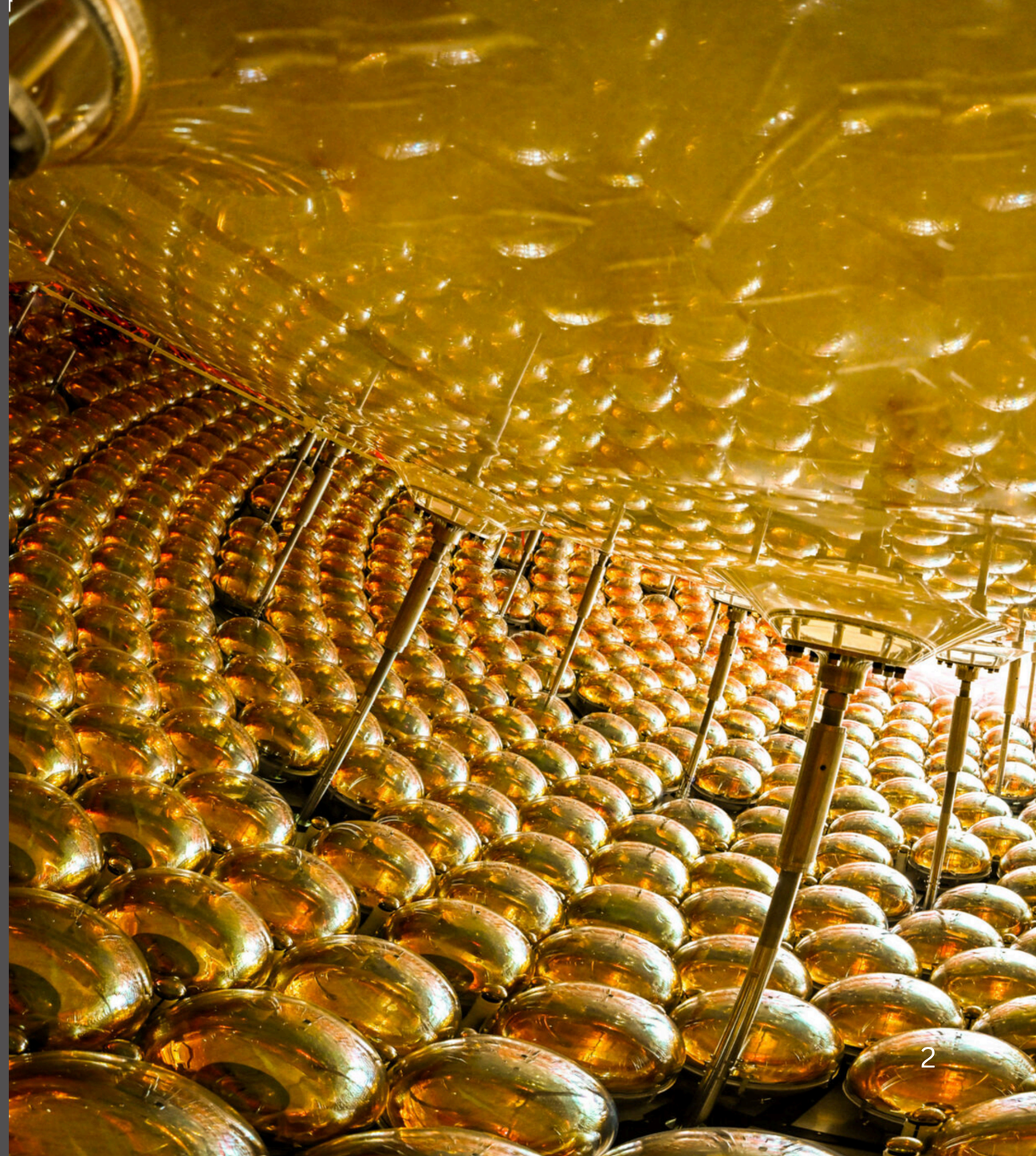
Based on
updated version (in preparation) of JHEP 02 (2021) 071

Damping effects on neutrino oscillations with JUNO

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

Invisible neutrino decay of solar neutrinos at DM experiments

Based on Martina Beccaria et al JCAP10(2026)025



Neutrino Global Fit: JUNO contribution

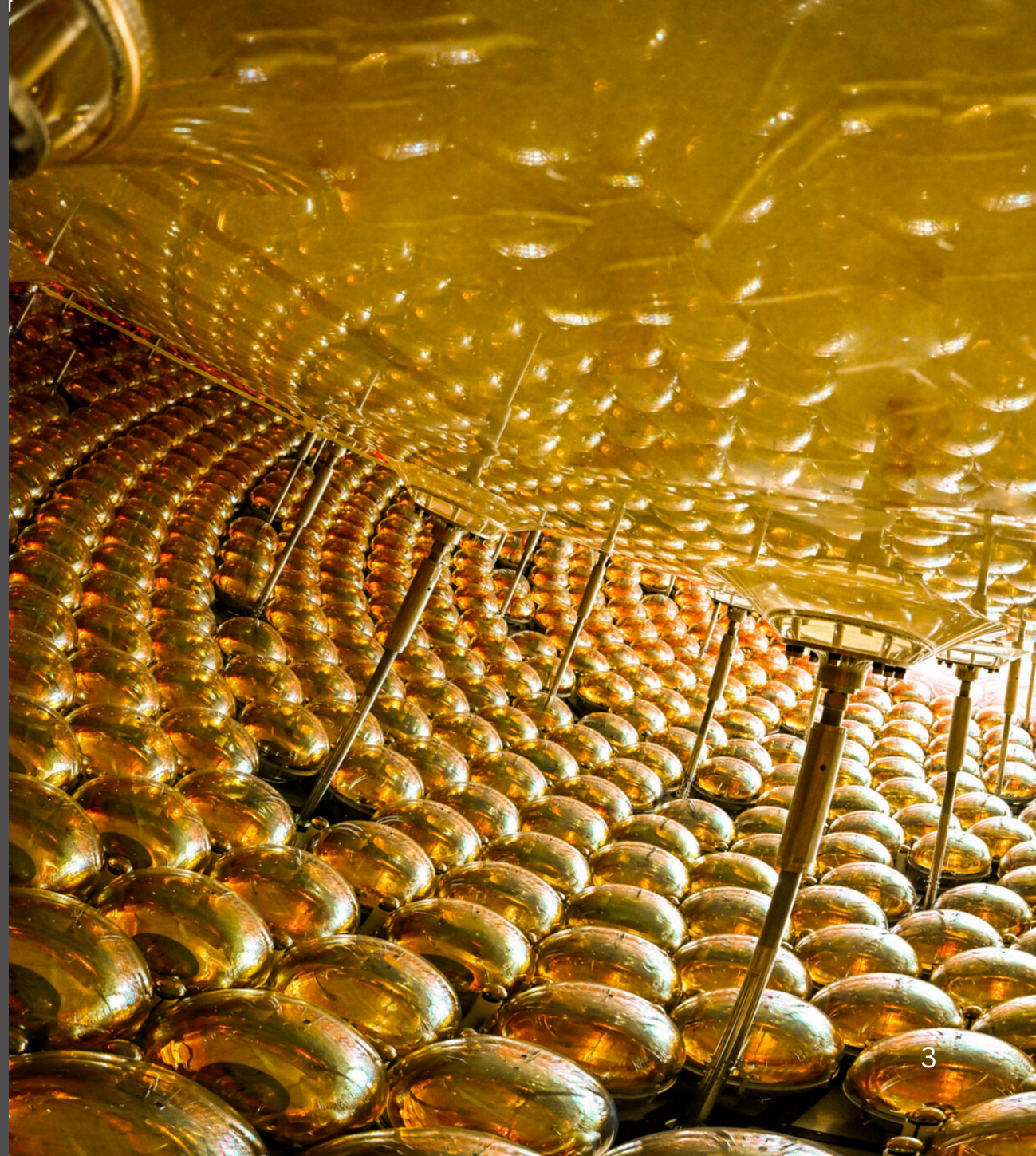
Based on
updated version (in preparation) of JHEP 02 (2021) 071

Damping effects on neutrino oscillations with JUNO

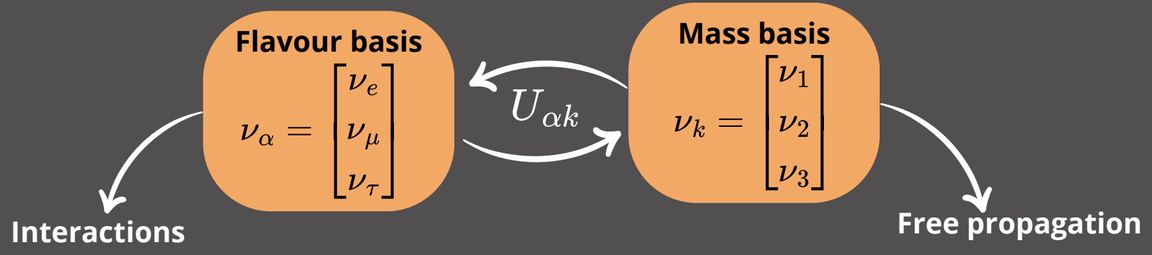
Based on
arXiv:2606.13362 [hep-ph]-M.Beccaria, C.A. Ternes

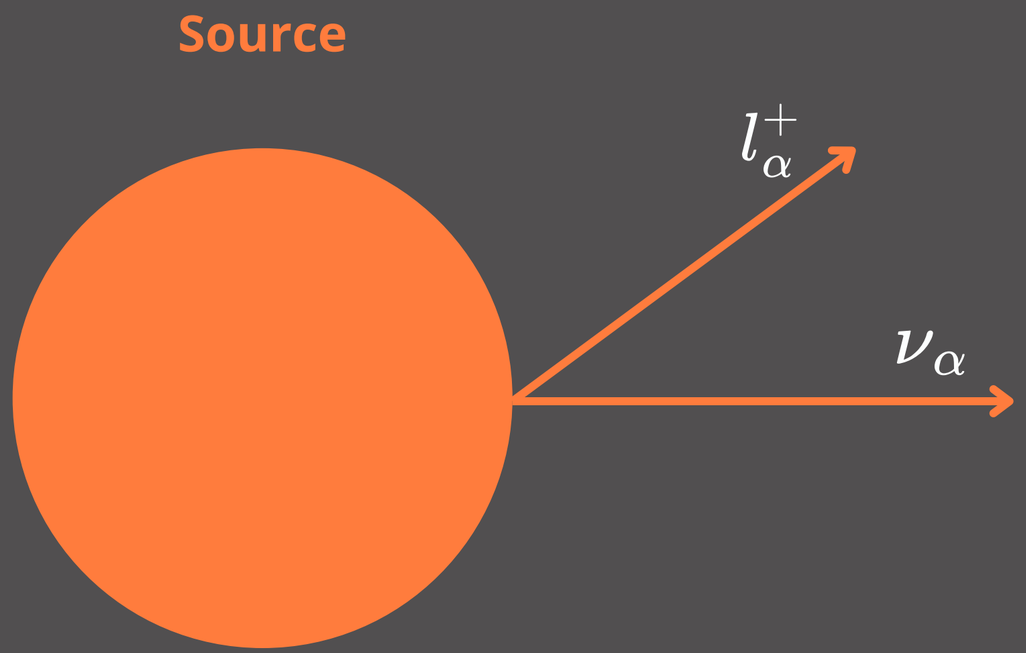
Invisible neutrino decay of solar neutrinos at DM experiments

Based on Martina Beccaria et al JCAP10(2026)025

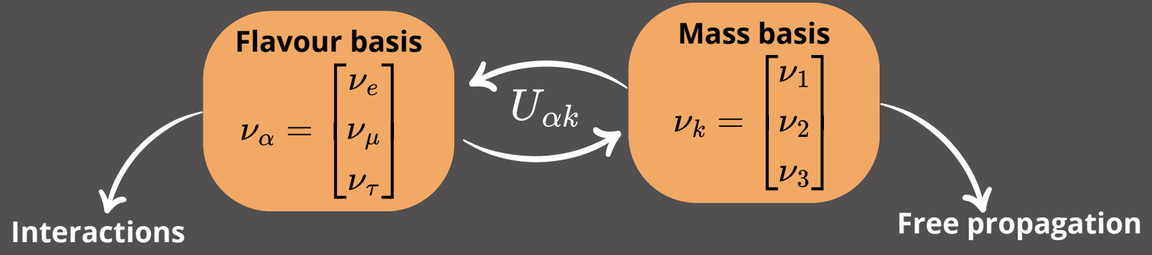


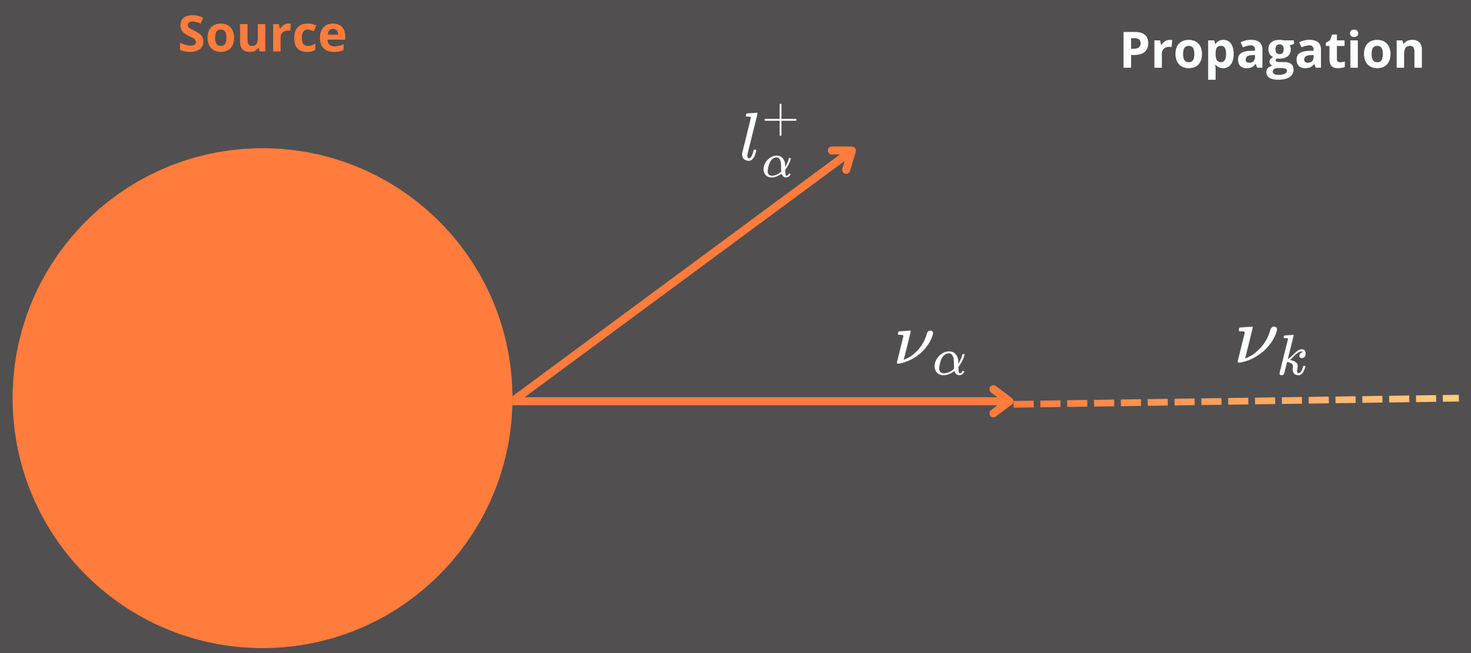
Neutrino Oscillations



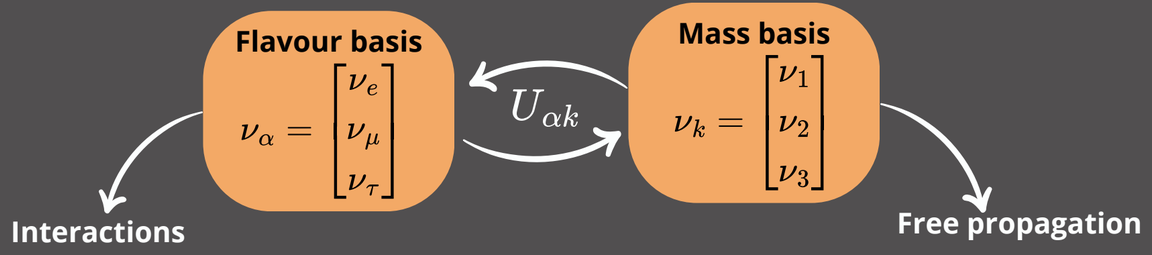


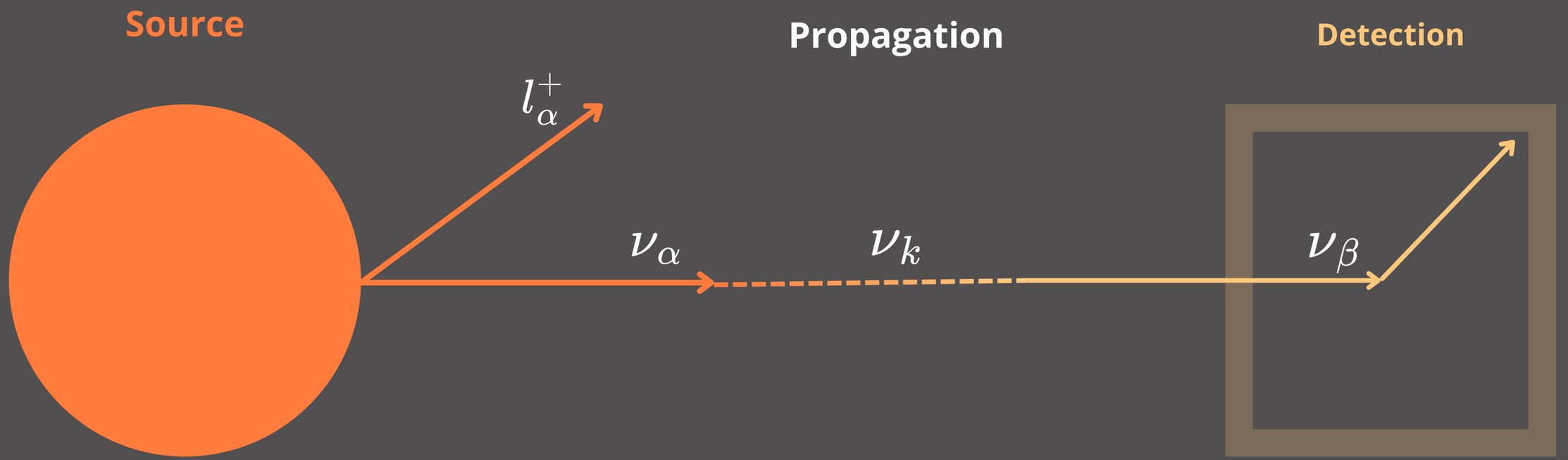
Neutrino Oscillations





Neutrino Oscillations

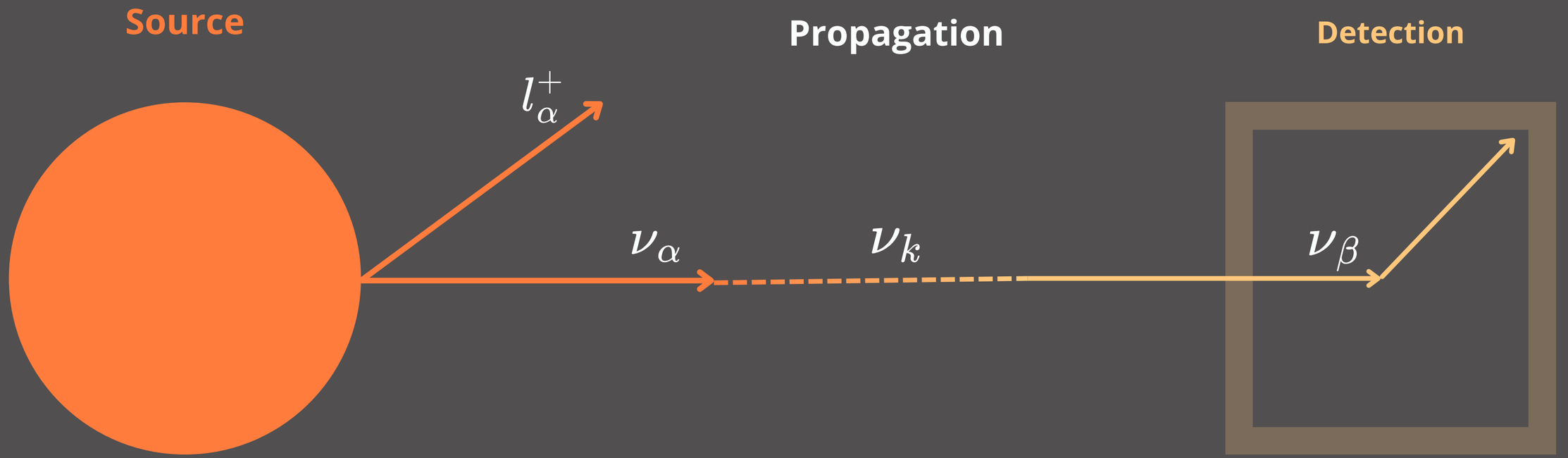




Neutrino Oscillations

Probability

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



Neutrino Oscillations

Probability

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

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

Neutrino Oscillations

Probability

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

Lepton mixing matrix

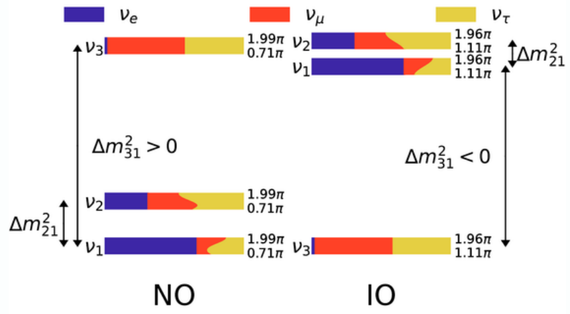
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix}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

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

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**

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

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

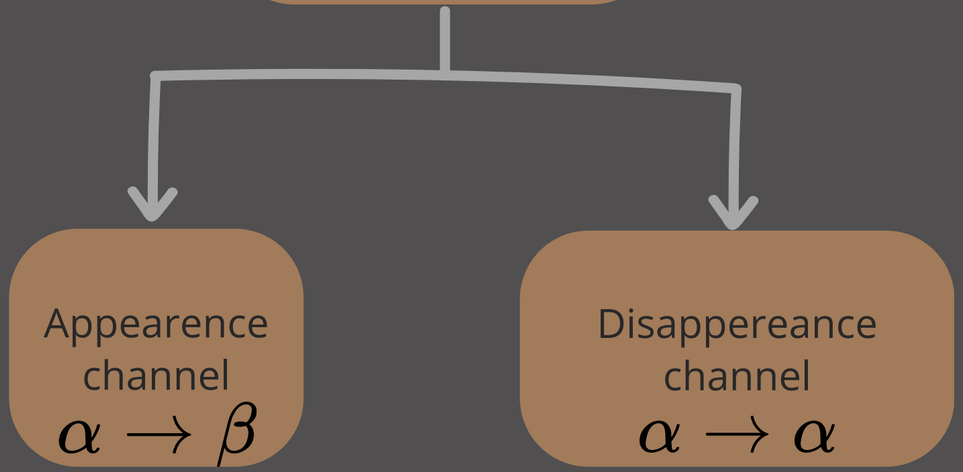
Appearence channel
$\alpha \rightarrow \beta$

Disappereance channel
$\alpha \rightarrow \alpha$

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

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

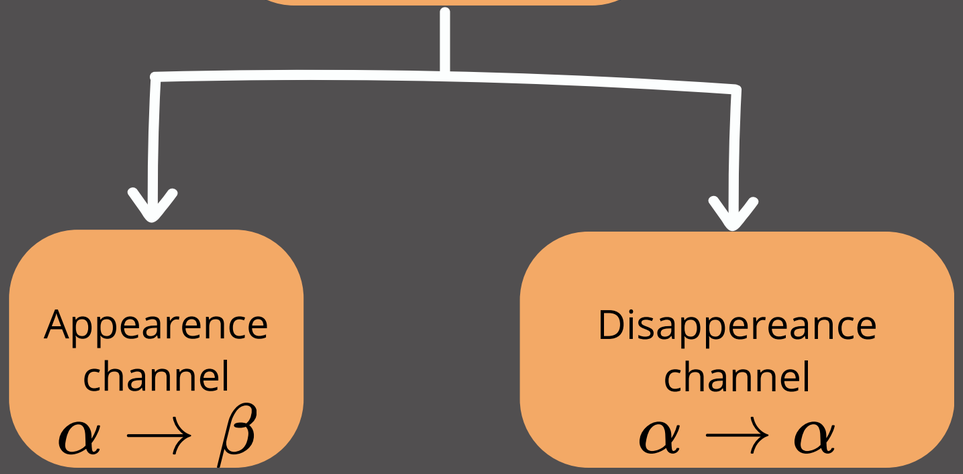
Combination of datasets from different experiments **enhances sensitivity**



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

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

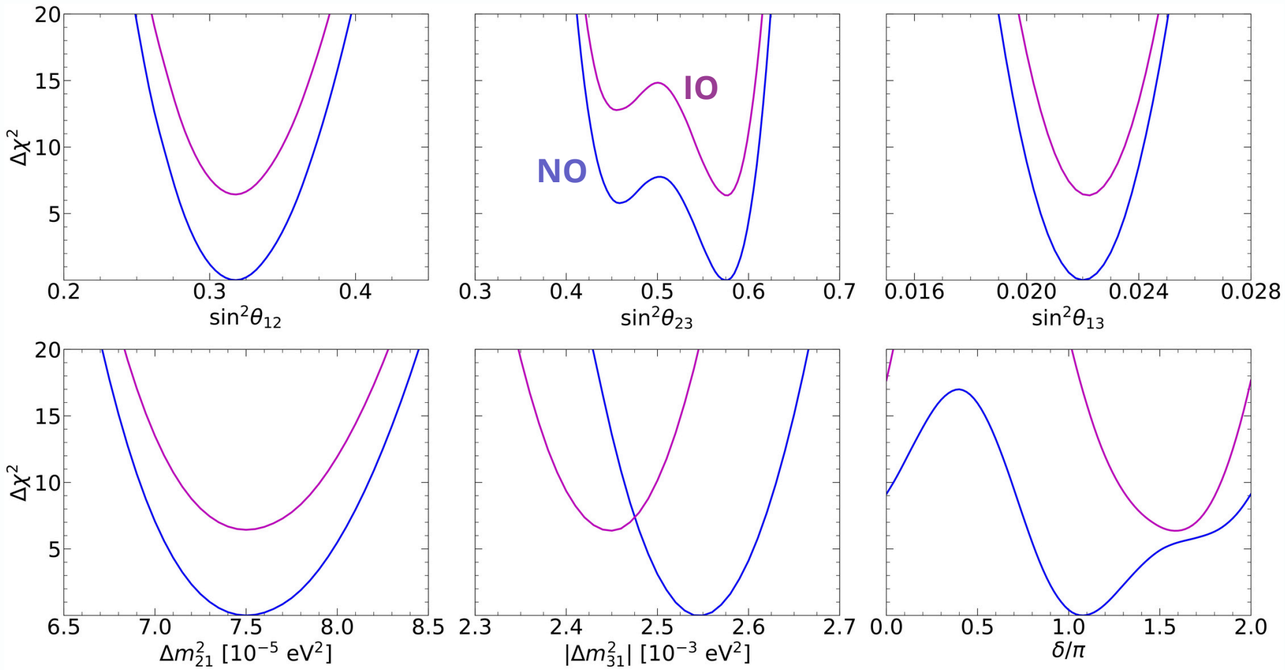
Combination of datasets from different experiments **enhances sensitivity**



Neutrino Global Fit

Valencia - Global Fit (2020)

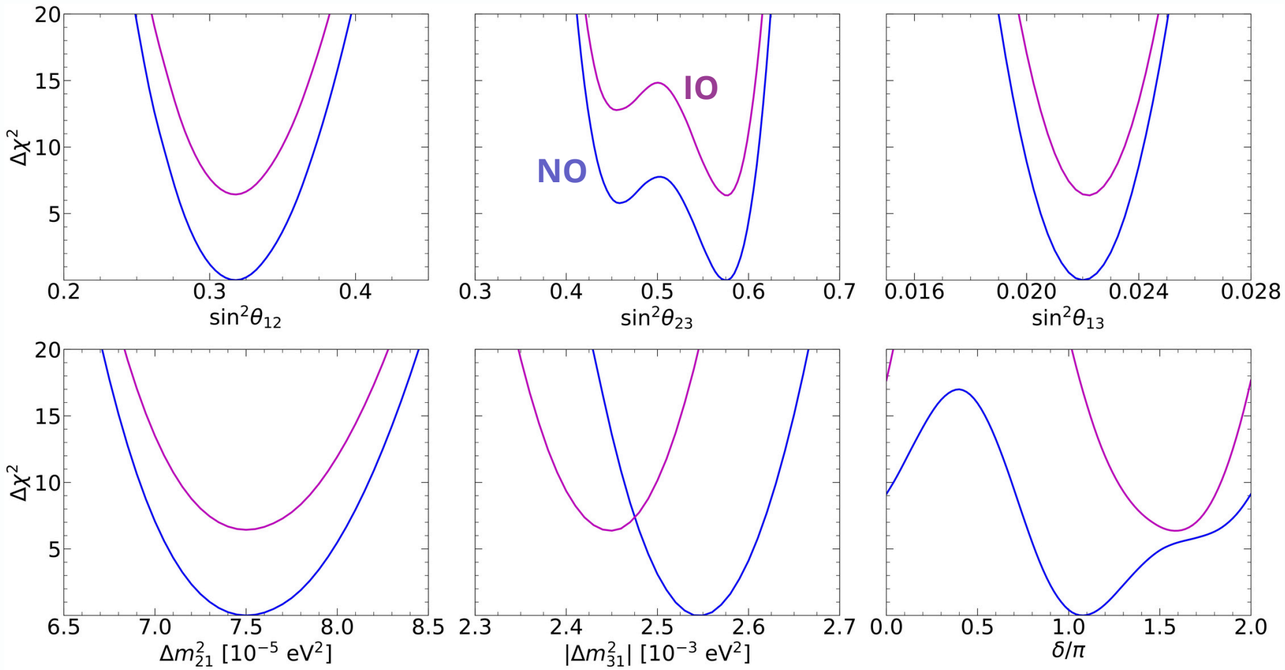
JHEP 02 (2021) 071



Neutrino Global Fit

Valencia - Global Fit (2020)

JHEP 02 (2021) 071



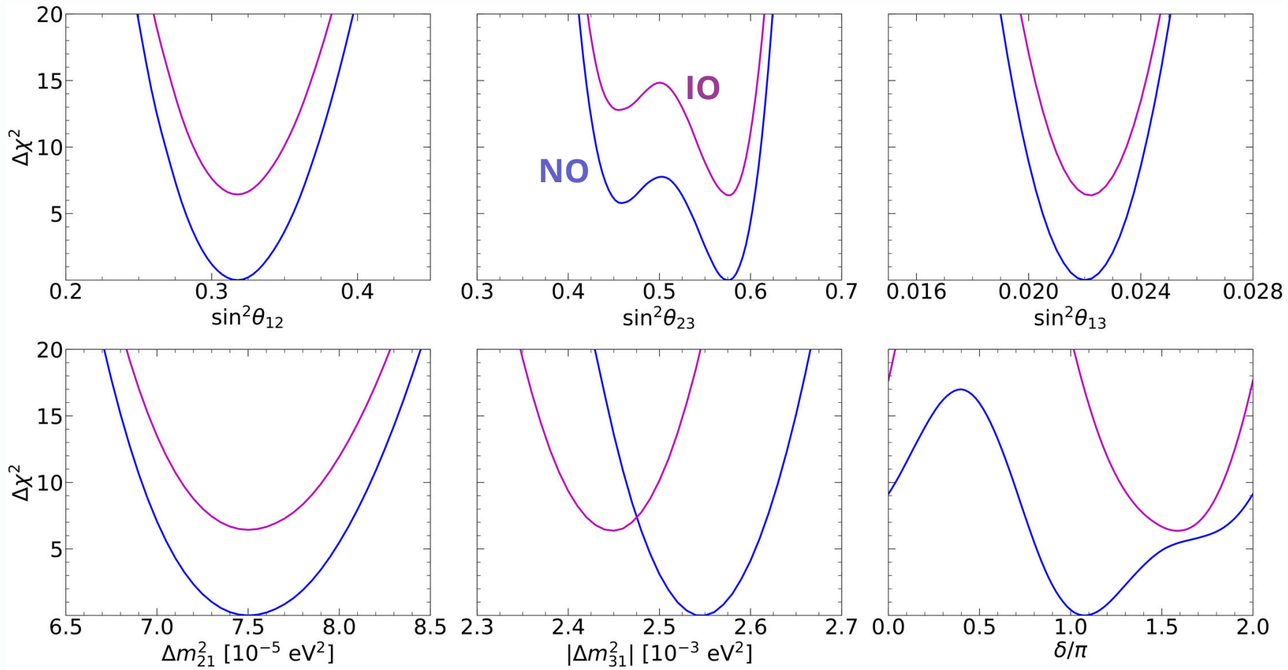
+

Results updated in **2026**

Neutrino Global Fit

Valencia - Global Fit (2020)

JHEP 02 (2021) 071



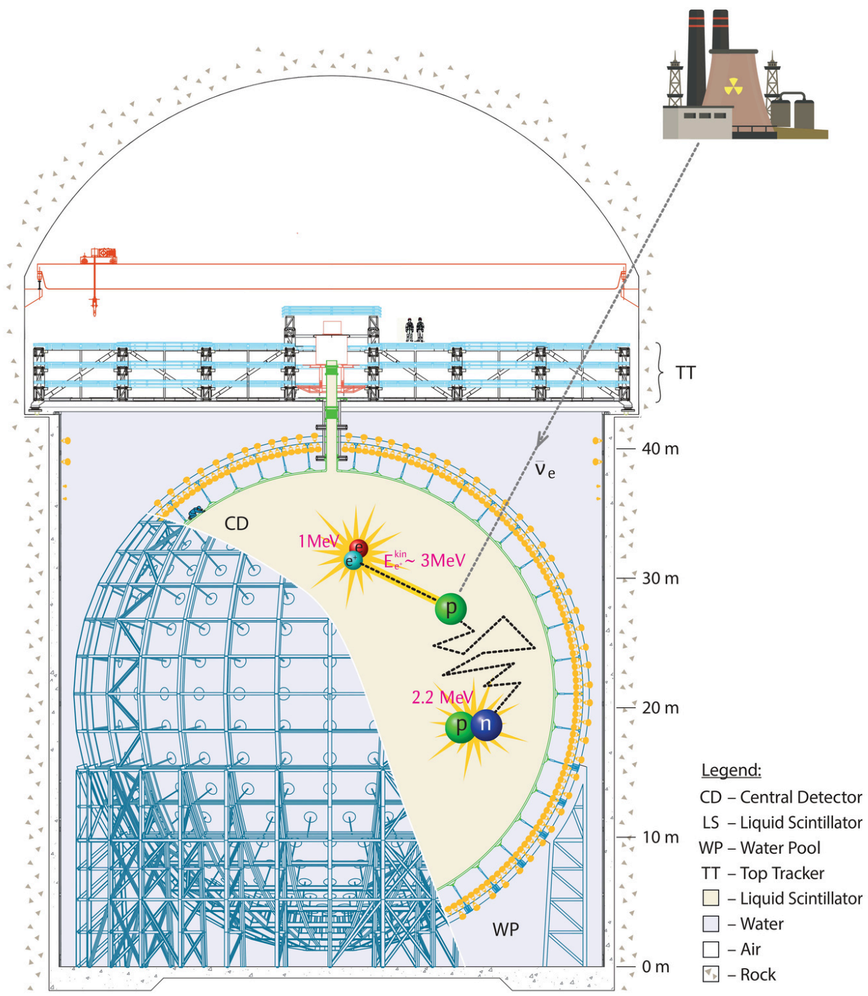
+

Results updated in **2026**

Main focus of (part of) my last year work:
JUNO contribution
to the Neutrino Global Fit

Neutrino Global Fit

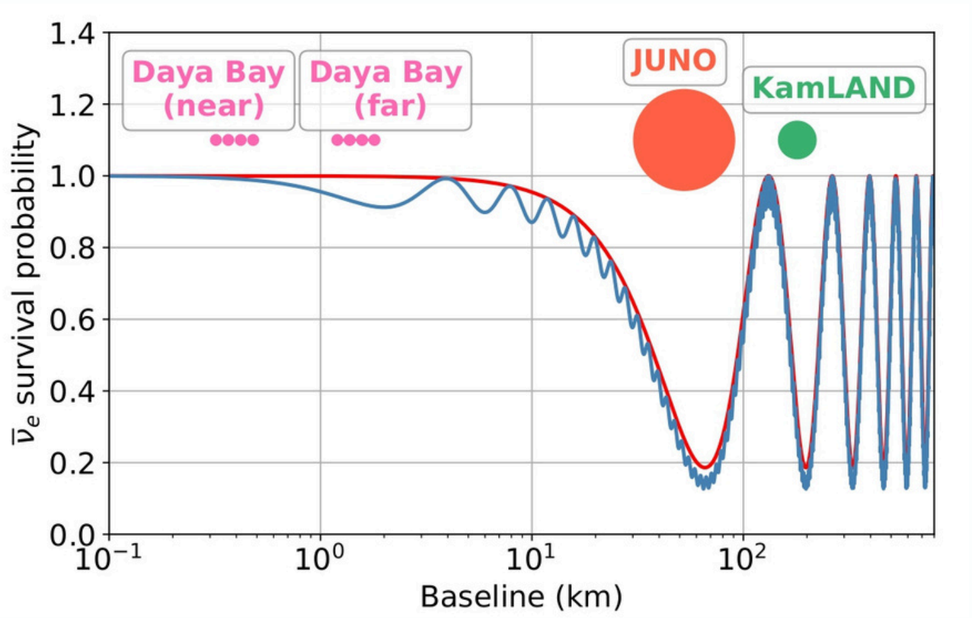
JUNO



Credit: arXiv:2104.02565

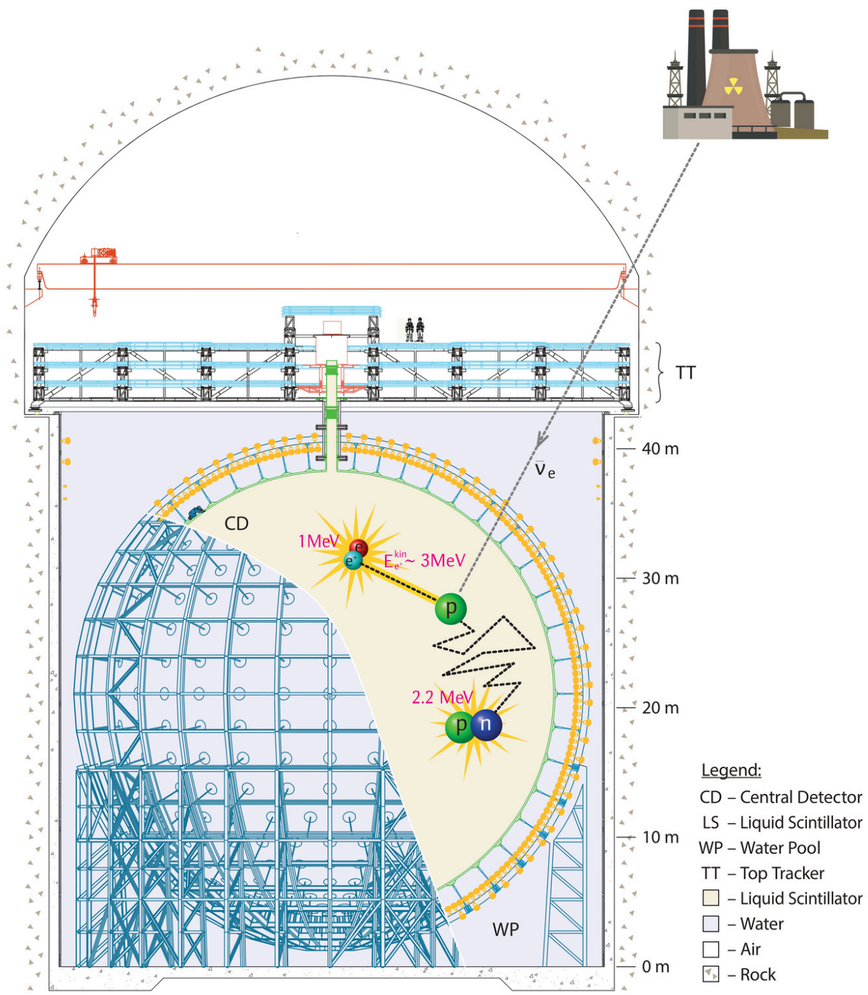
JUNO

Position



Excellent Energy Resolution

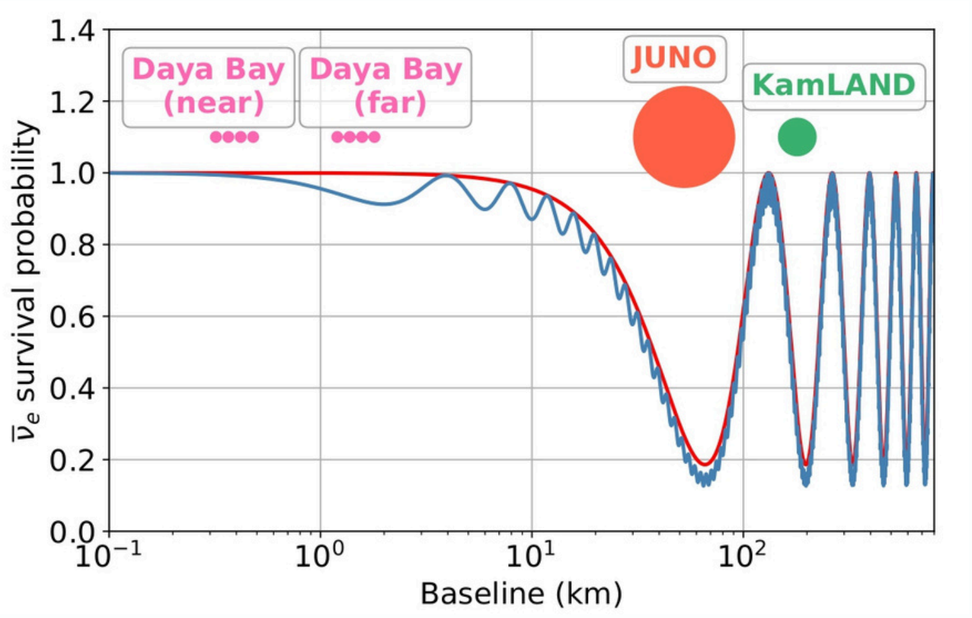
Dimensions



Credit: arXiv:2104.02565

JUNO

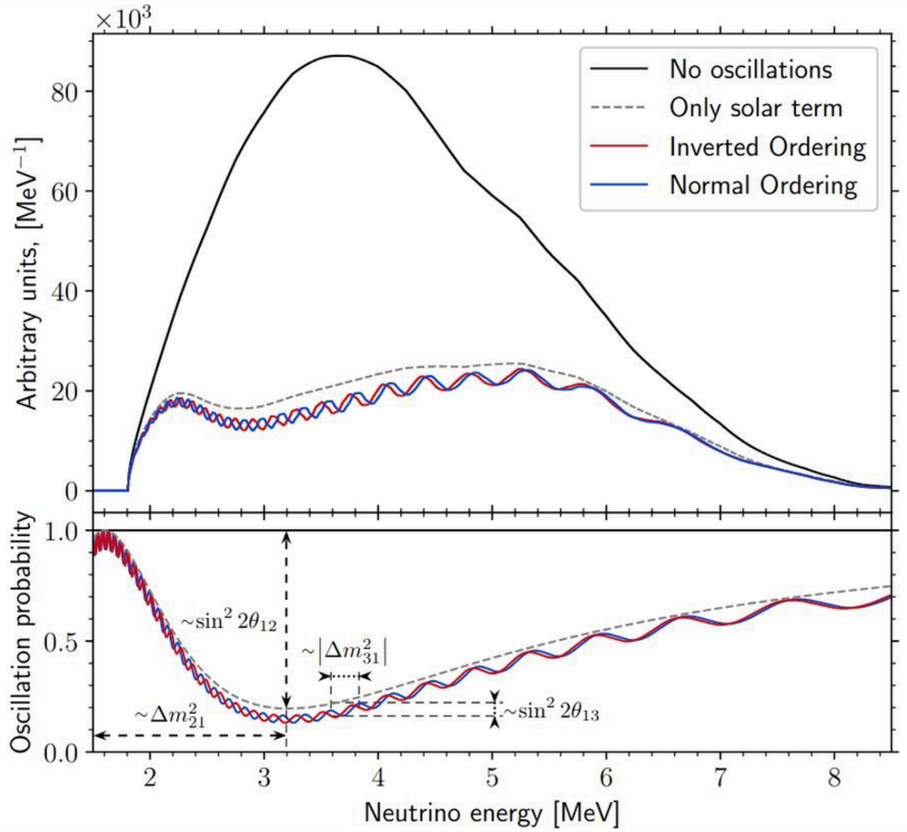
Position



Excellent Energy Resolution

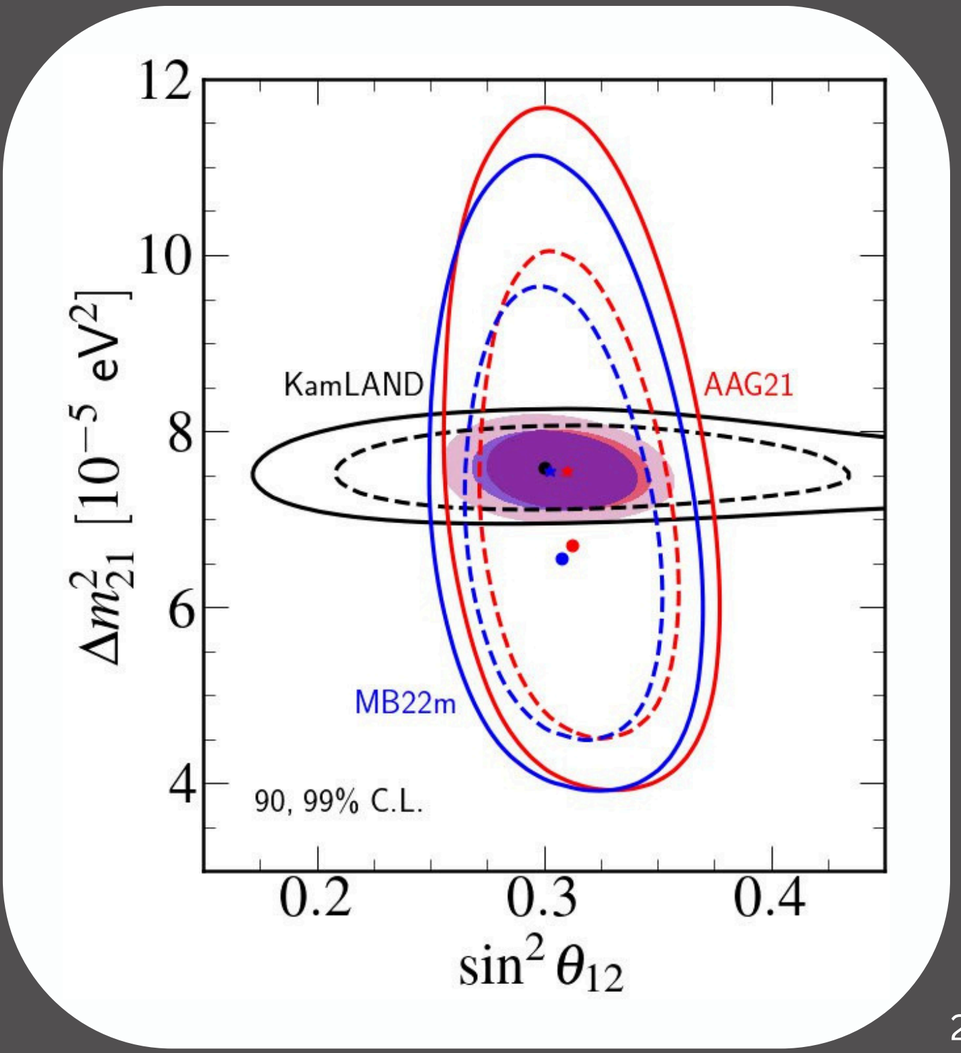
Dimensions

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



Credit: D. Basilico, LNGS Seminar

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

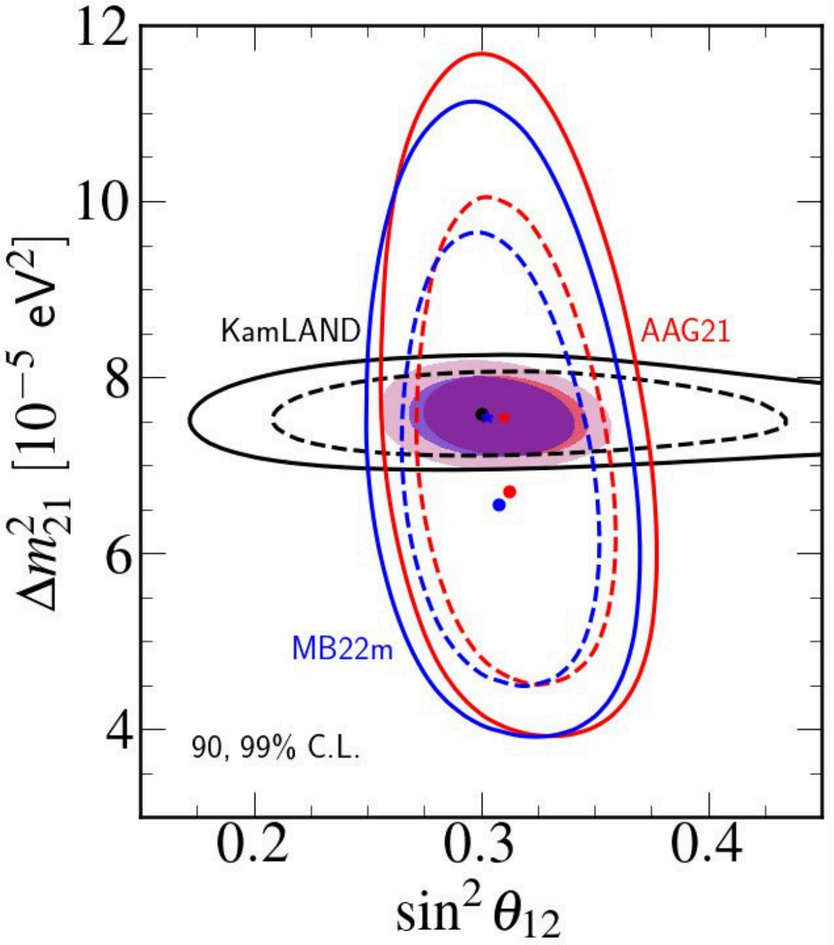


Solar sector: $\Delta m^2_{21}, \theta_{12}$ before 2025

high metallicity **MB22m**

low metallicity **AAG21**

Solar experiments



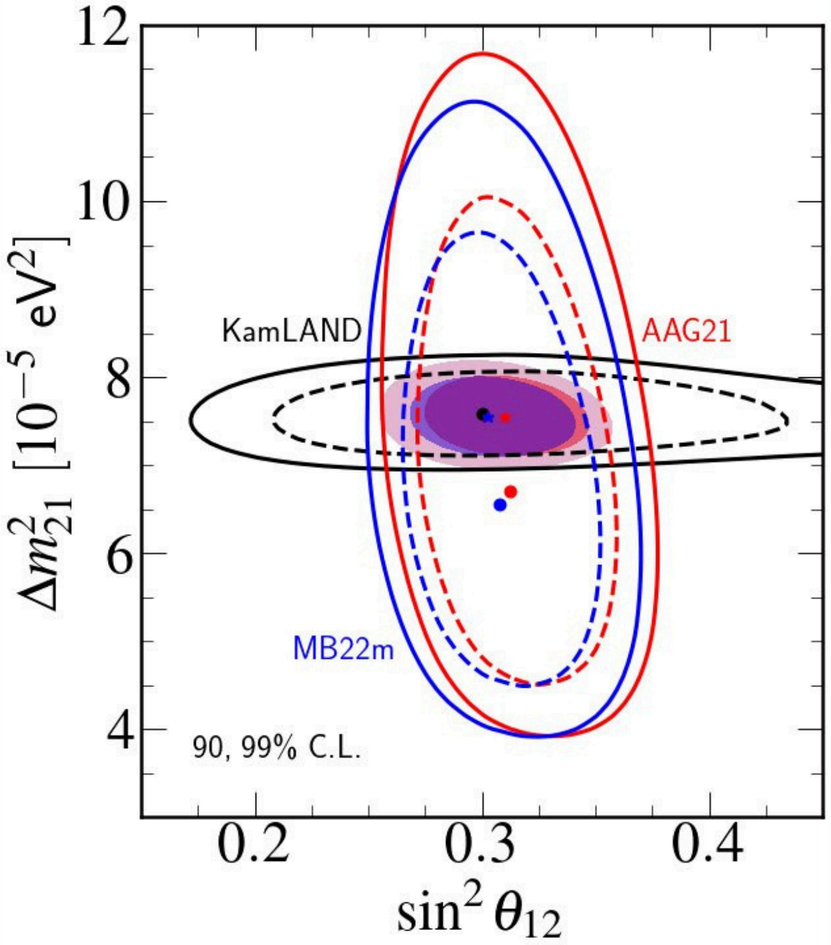
Solar sector: $\Delta m^2_{21}, \theta_{12}$ before 2025

high metallicity **MB22m**

low metallicity **AAG21**

Solar experiments

Long baseline reactor **KamLAND**



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

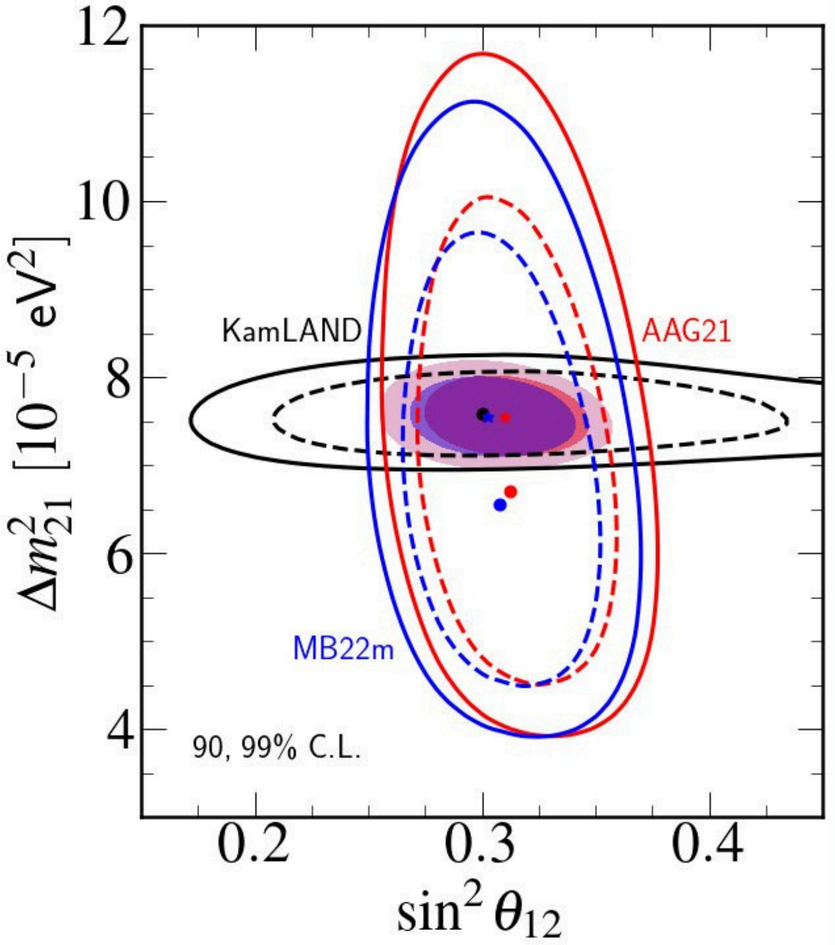
high metallicity **MB22m**

low metallicity **AAG21**

Solar experiments

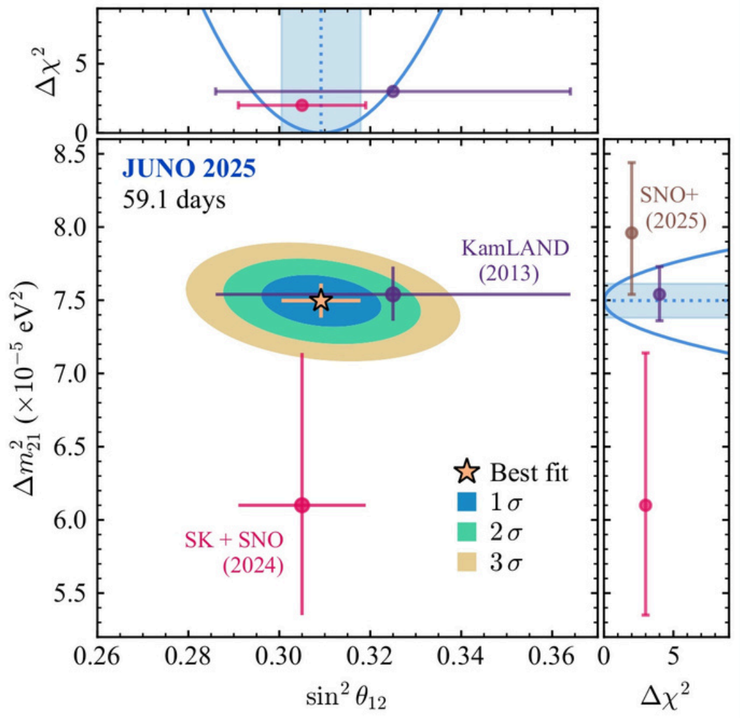
Long baseline reactor **KamLAND**

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

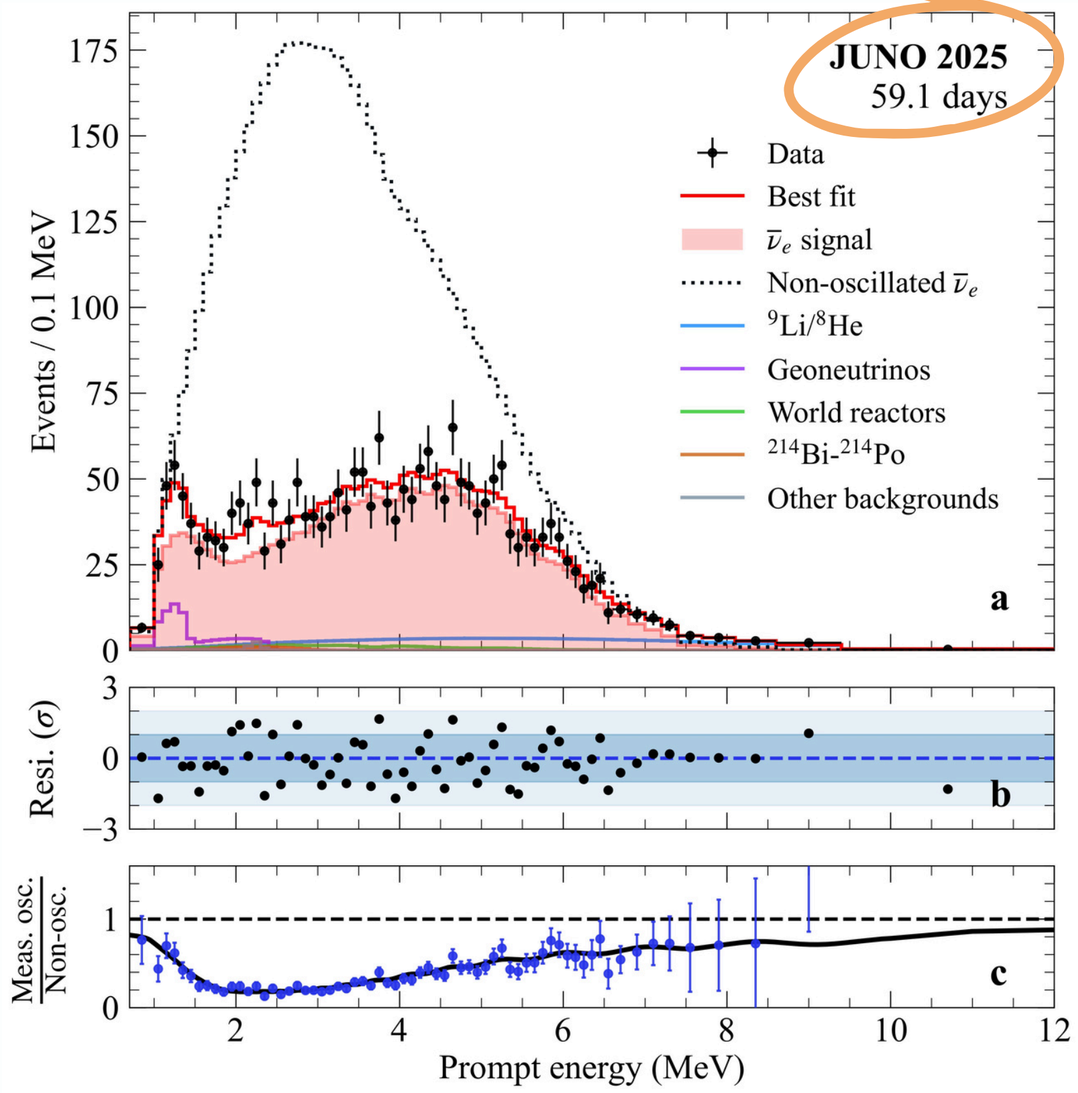


JUNO first results

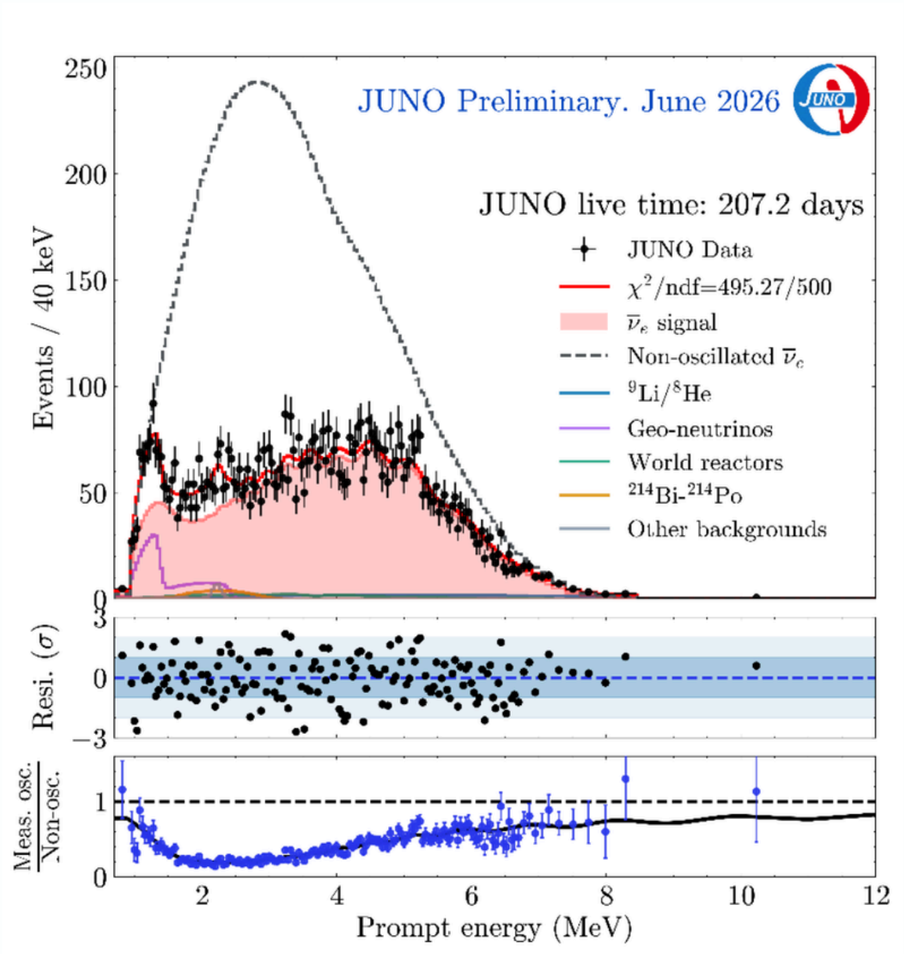
Nature 654 (2026) 8118, 343-348



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

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

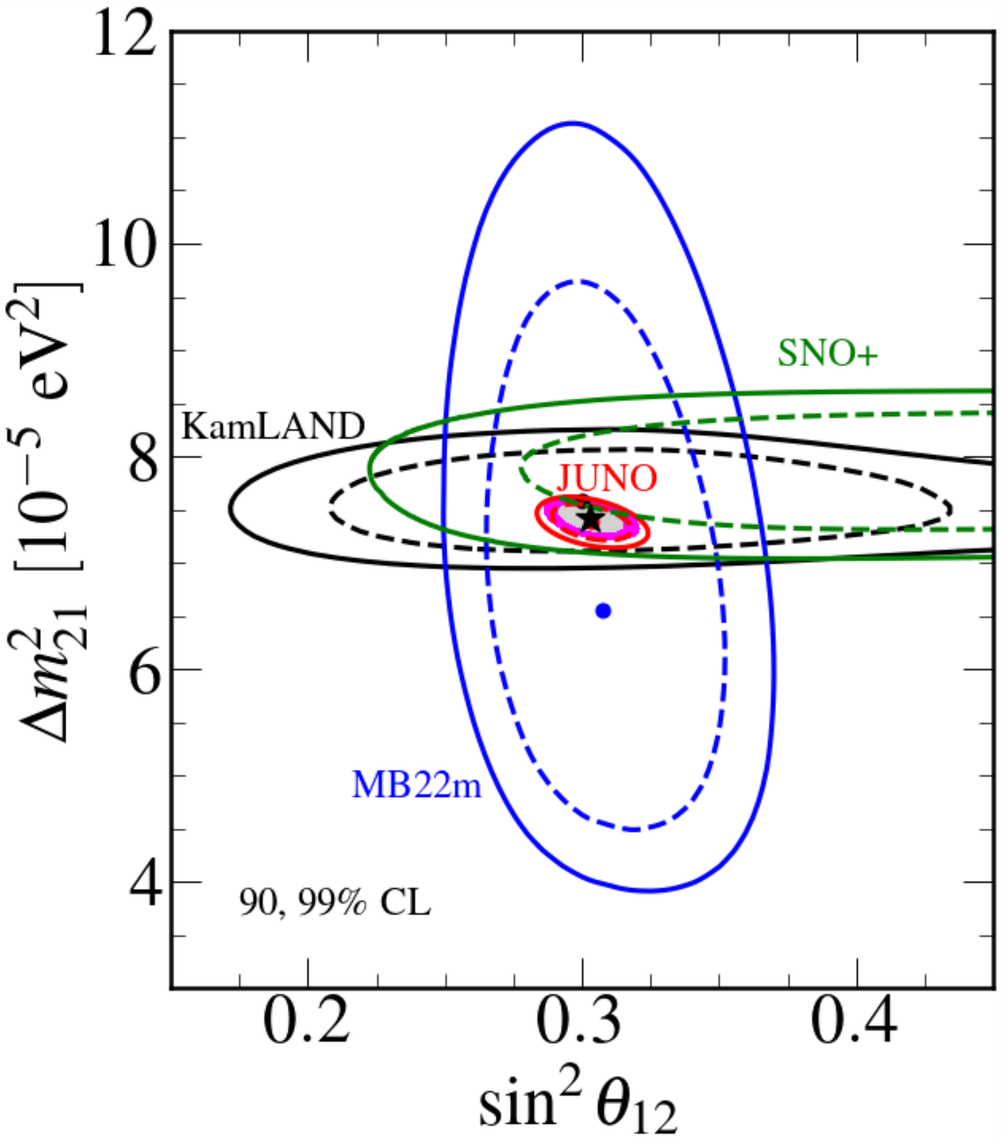
Updated solar sector

SNO+ first results

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

Data acquisition period
May 2022 -July 2025

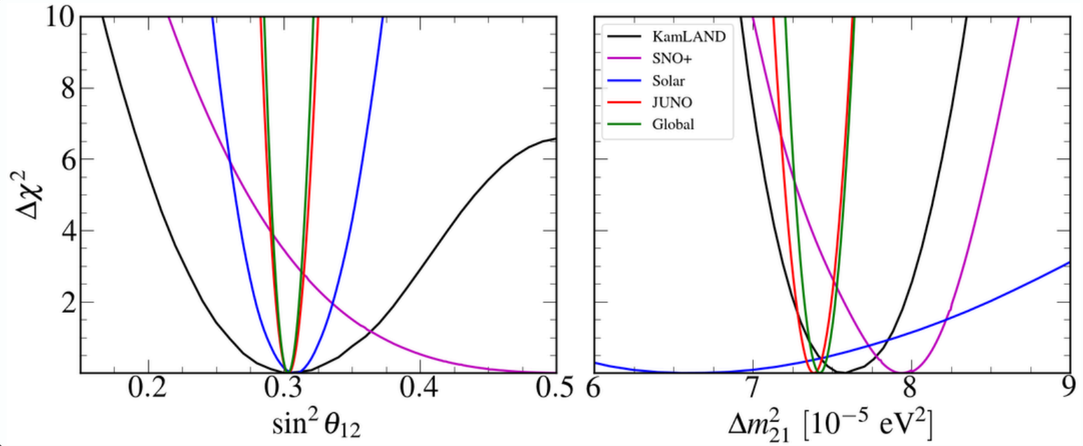
Phys.Rev.Lett. 135 (2025) 12, 121801
arXiv:2511.11856v2 [hep-ex]

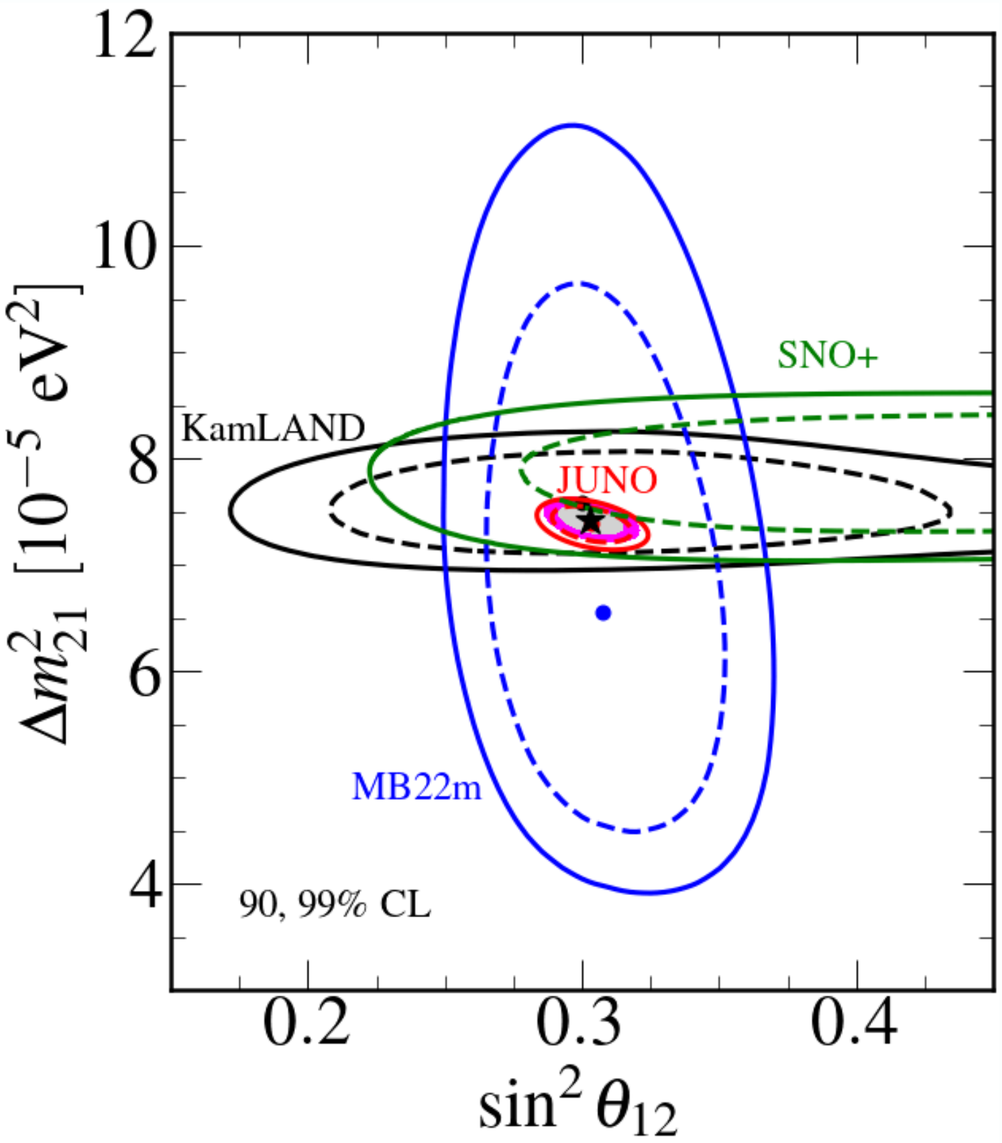


Updated solar sector

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

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

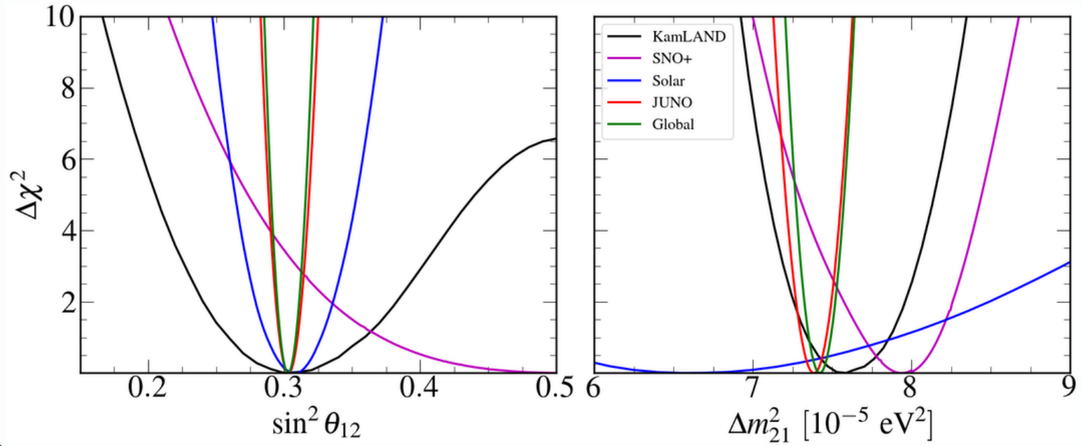




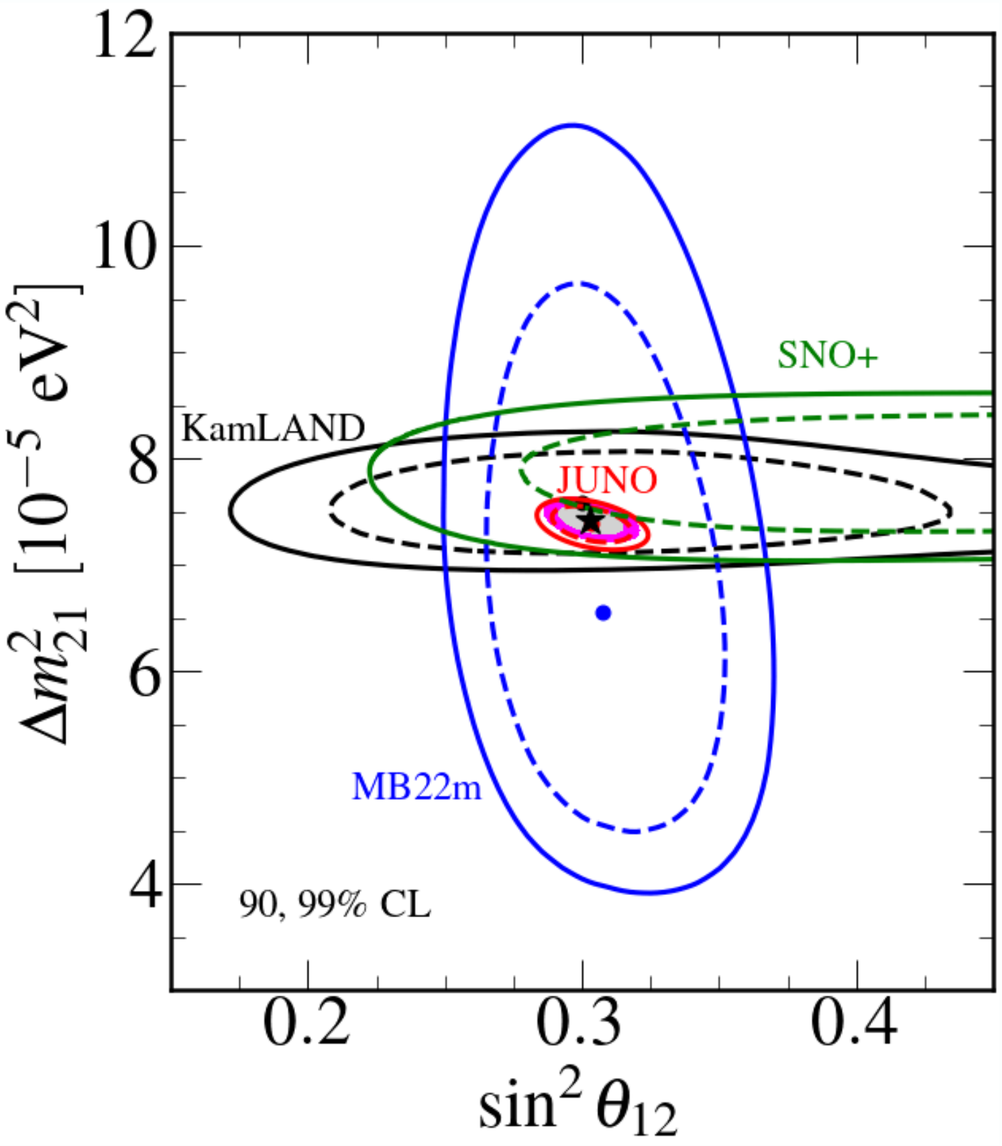
Updated solar sector

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

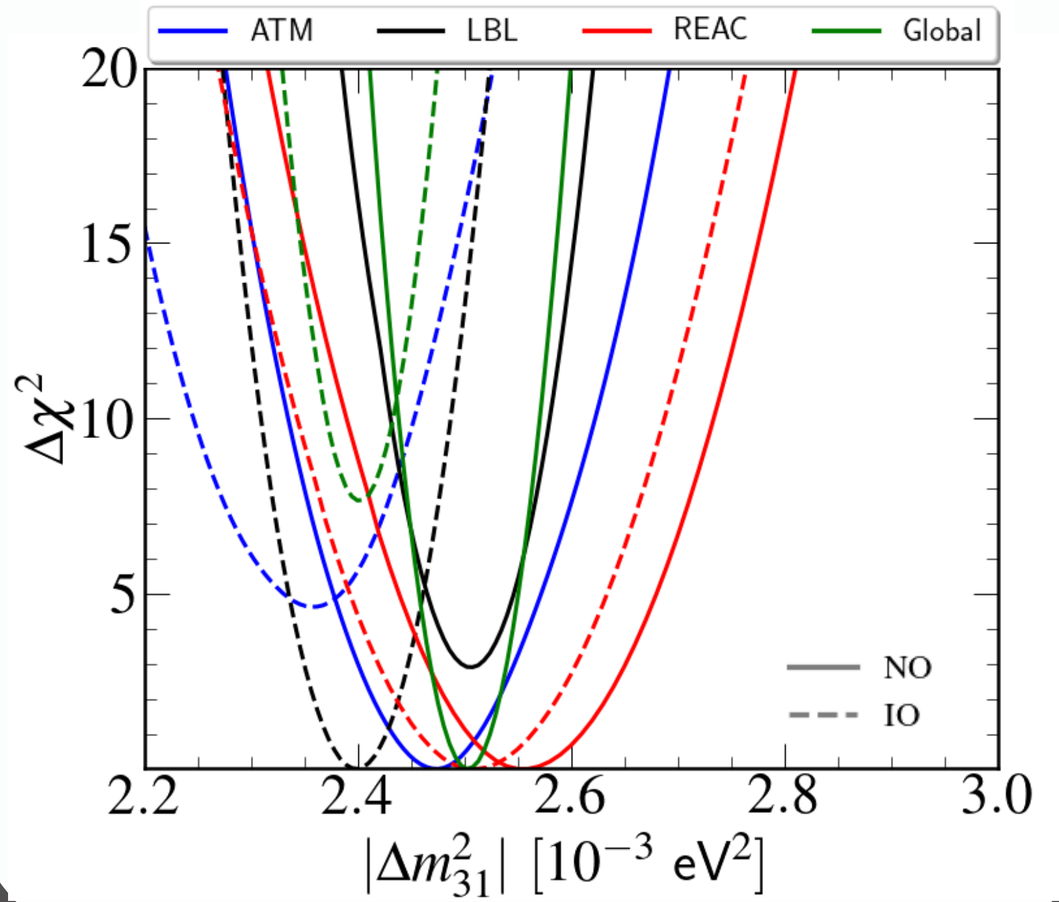
$$\frac{\sigma_{\Delta m^2_{21}}}{\Delta m^2_{21}} = 1.1\% \qquad \frac{\sigma_{\sin^2\theta_{12}}}{\sin^2\theta_{12}} = 2.1\%$$



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



Neutrino Mass ordering before 2026



Long baseline accelerators
NOvA, T2K

Inverted Ordering

Atmospheric data
IceCube-DC, SK

Normal Ordering

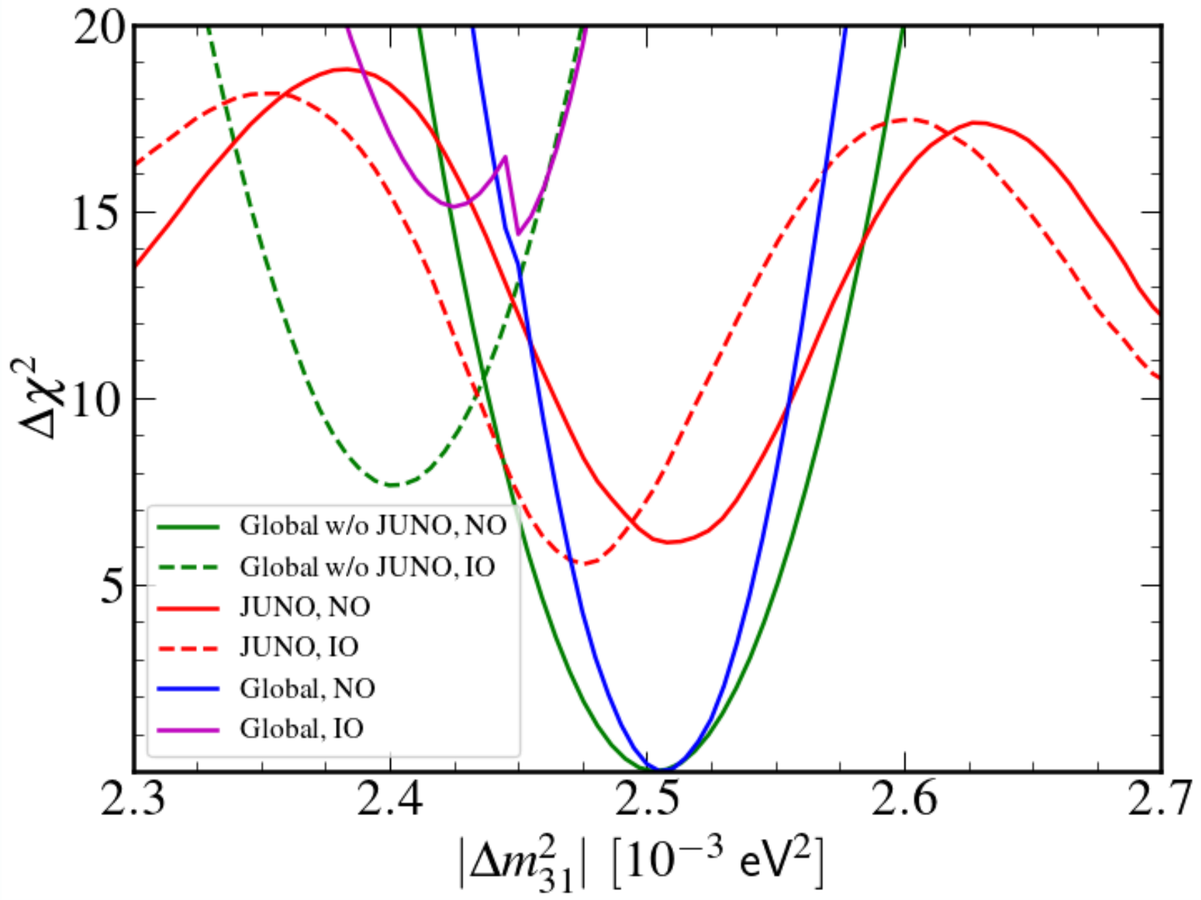
+Reactor data
Daya Bay, RENO

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



Preference for
normal ordering
at approximately
4σ

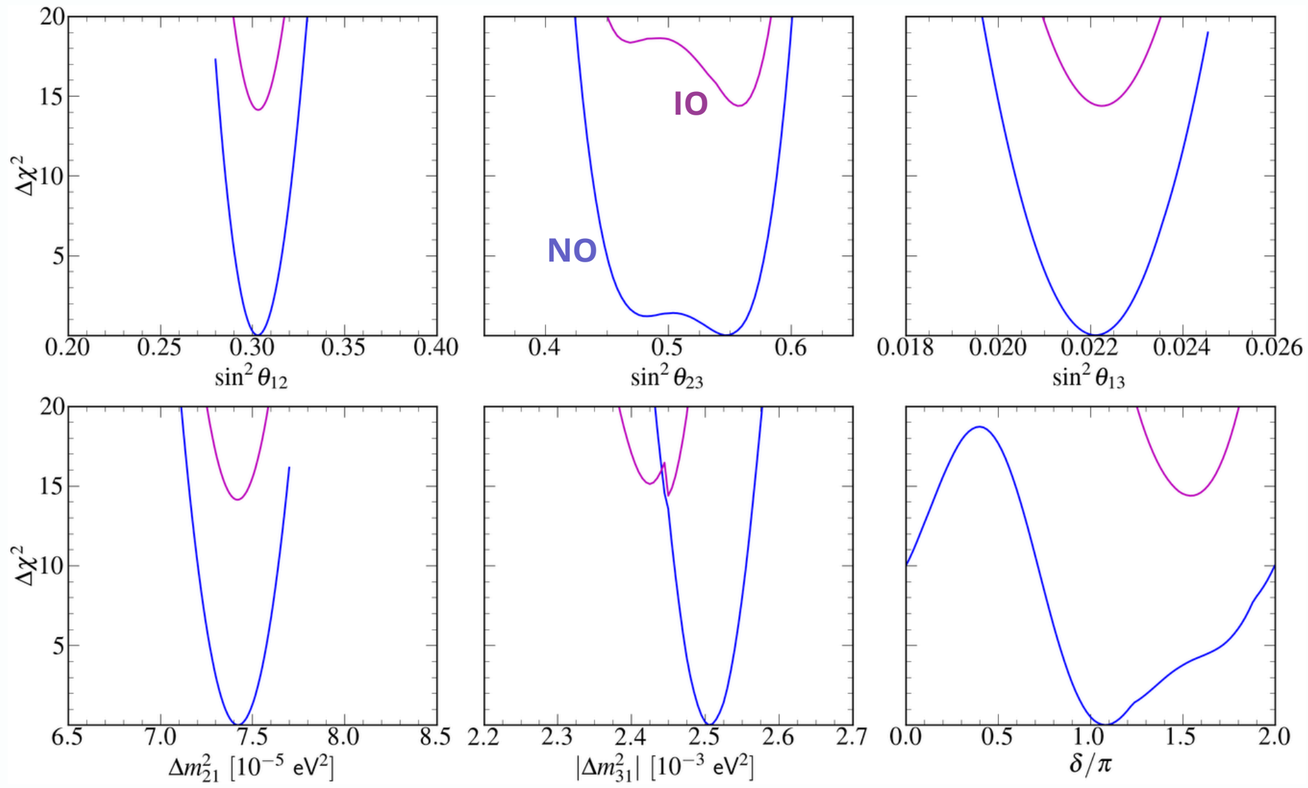
Interpolation issues present
when combining
different datasets:
we are working on it

Valencia Global Fit-Updated

See also other groups' works:
NuFit-JHEP 12 (2024) 216
Bari-PhysRevD.111.093006

Parameter	Best fit $\pm 1\sigma$
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.42^{+0.07}_{-0.04}$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.505^{+0.013}_{-0.017}$
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.450^{+0.033}_{-0.008}$
$\sin^2\theta_{12}/10^{-1}$	3.030 ± 0.057
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.46^{+0.17}_{-0.24}$
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.57^{+0.13}_{-0.14}$
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.210^{+0.053}_{-0.056}$
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.224^{+0.053}_{-0.055}$
δ/π (NO)	$1.08^{+0.11}_{-0.13}$
δ/π (IO)	1.54 ± 0.12

2026 values, preliminary



2026, preliminary

Neutrino Global Fit: JUNO contribution

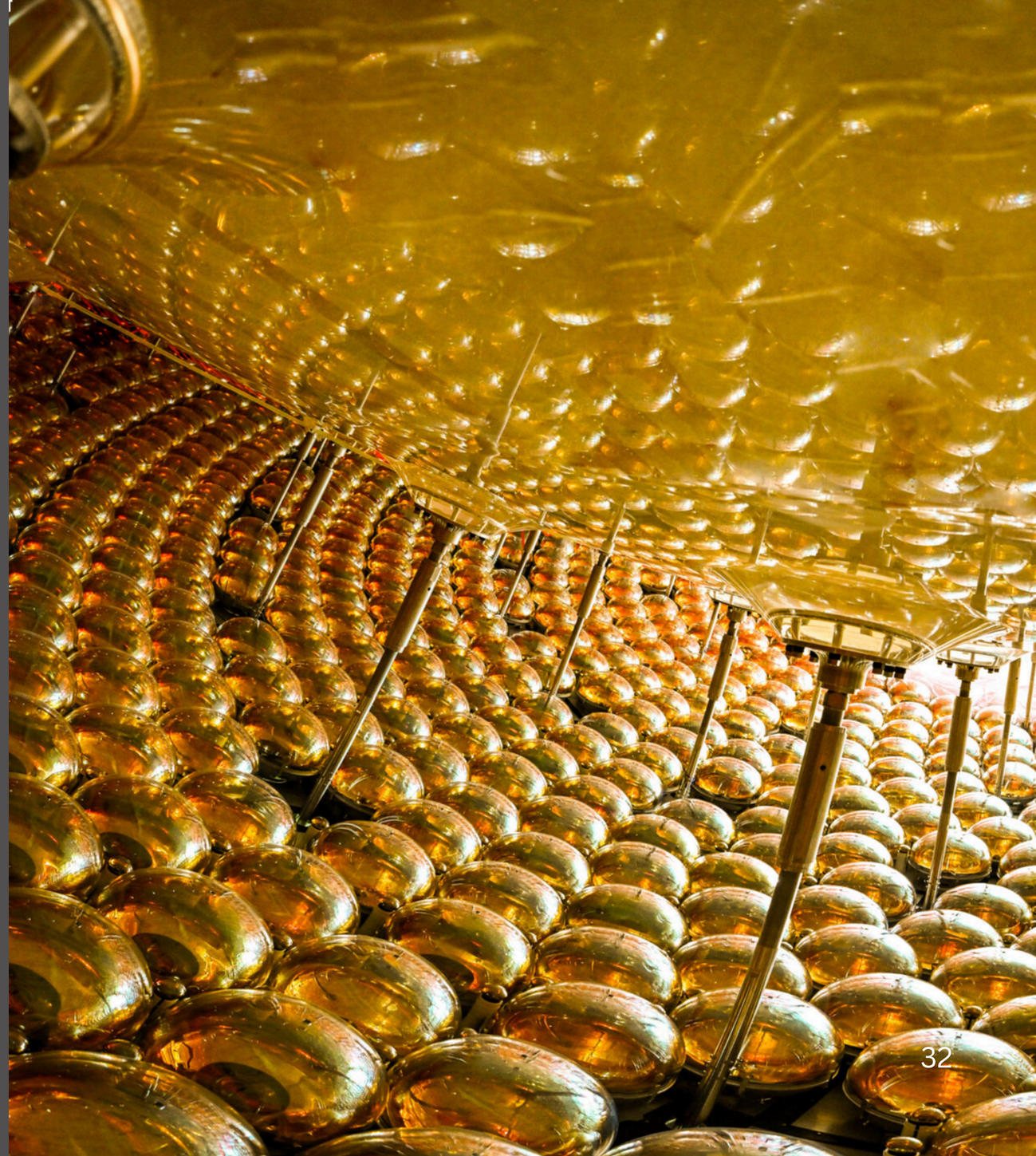
Based on
updated version (in preparation) of JHEP 02 (2021) 071

Damping effects on neutrino oscillations with JUNO

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

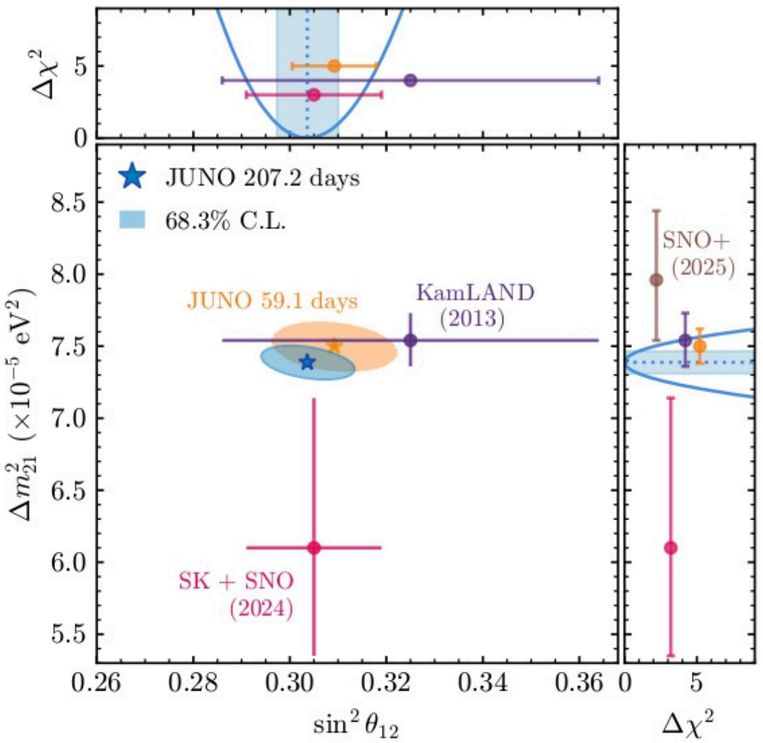
Invisible neutrino decay of solar neutrinos at DM experiments

Based on Martina Beccaria et al JCAP10(2026)025



JUNO results

arxiv:2609.37895



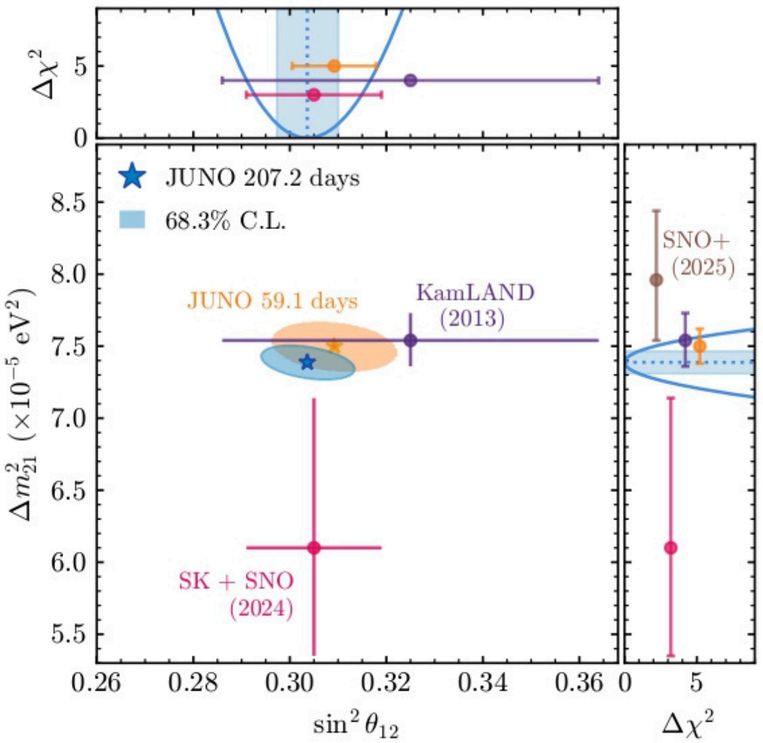
JUNO collaboration (207.2 days):

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

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

JUNO results

arxiv:2609.37895



JUNO collaboration (207.2 days):

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

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

DAMPING

How are these parameters affected?

Which constrains 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

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

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

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

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

STANDARD

Oscillation probability and damping effects

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

with

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

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

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

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

with

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

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

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

Wave packets

Environmental decoherence

Invisible decay

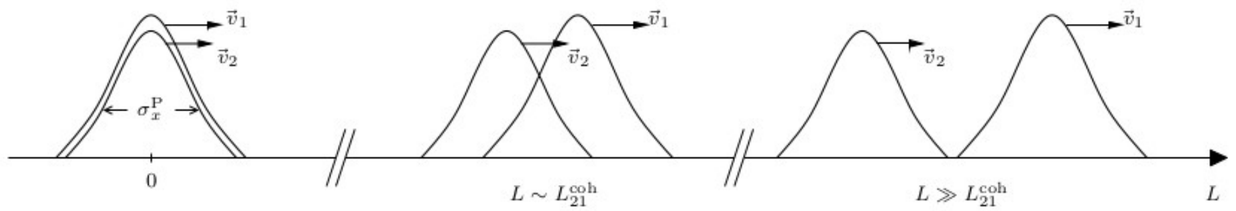
$$P_{ee}^{\text{damp}} = |U_{e1}|^4\, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} + 2|U_{e1}|^2|U_{e2}|^2 \cos 2\Delta_{21}\, e^{-D_{21}(E,L)} + 2|U_{e1}|^2|U_{e3}|^2 \cos 2\Delta_{31}\, e^{-D_{31}(E,L)} + 2|U_{e2}|^2|U_{e3}|^2 \cos 2\Delta_{32}\, e^{-D_{32}(E,L)}$$

DAMPING

Theoretical motivations

- 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

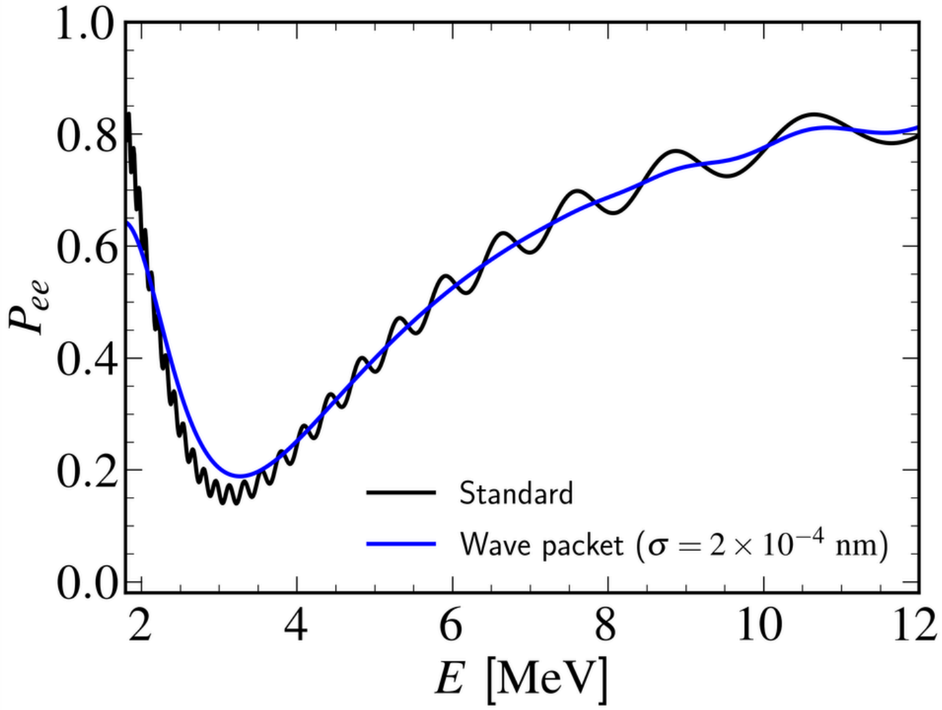
Invisible decay

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

DAMPING

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

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



Wave packets

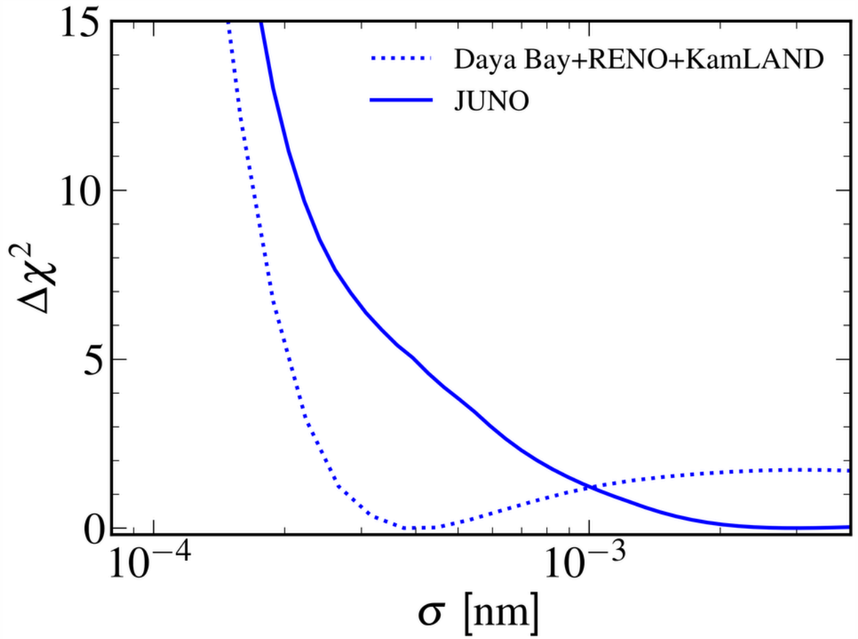
Environmental decoherence

Invisible decay

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

DAMPING

Bounds on neutrino wave packets width



- 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}

$$\sigma > 6.4 \times 10^{-4}\ \text{nm}\ @90\%\ \text{C.L.}$$

Stronger bound than DayaBay+RENO+KamLAND

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

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

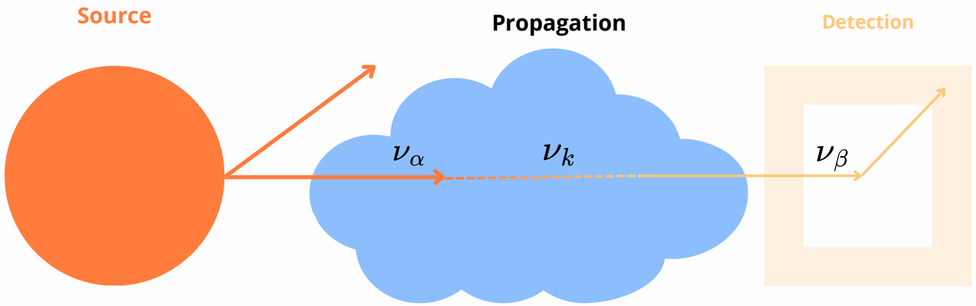
Theoretical motivations (1)

- 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

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

DAMPING

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

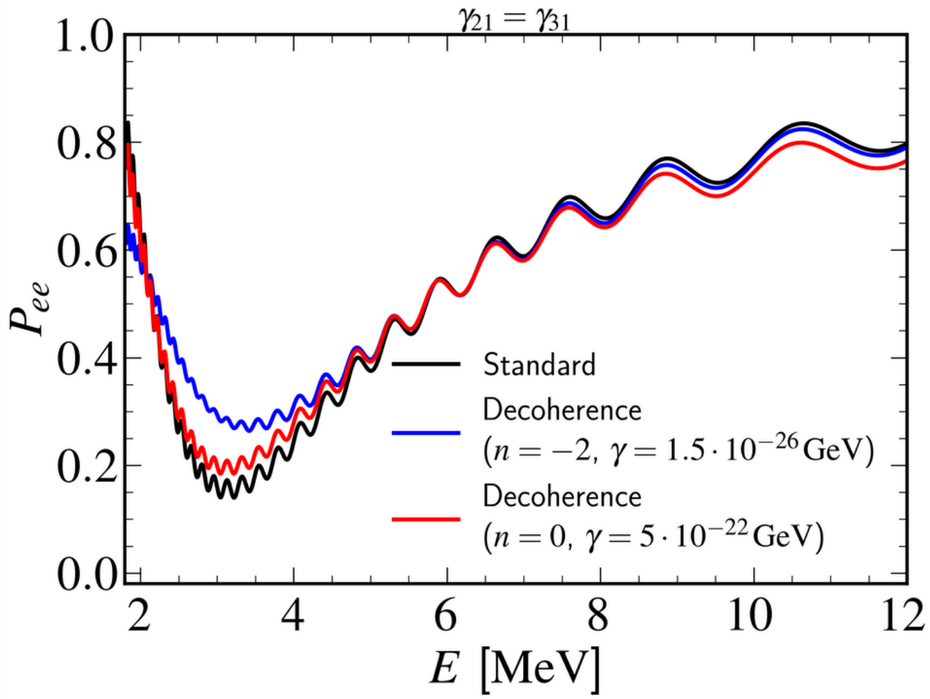
$$\begin{aligned} P_{ee}^{\text{damp}} = {} & |U_{e1}|^4 \, e^{-D_1(E,L)} + |U_{e2}|^4 e^{-D_2(E,L)} + |U_{e3}|^4 e^{-D_3(E,L)} \\ & + 2|U_{e1}|^2 |U_{e2}|^2 \cos 2\Delta_{21} \, e^{-D_{21}(E,L)} \\ & + 2|U_{e1}|^2 |U_{e3}|^2 \cos 2\Delta_{31} \, e^{-D_{31}(E,L)} \\ & + 2|U_{e2}|^2 |U_{e3}|^2 \cos 2\Delta_{32}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

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, $n = -2, -1, 0$



Wave packets

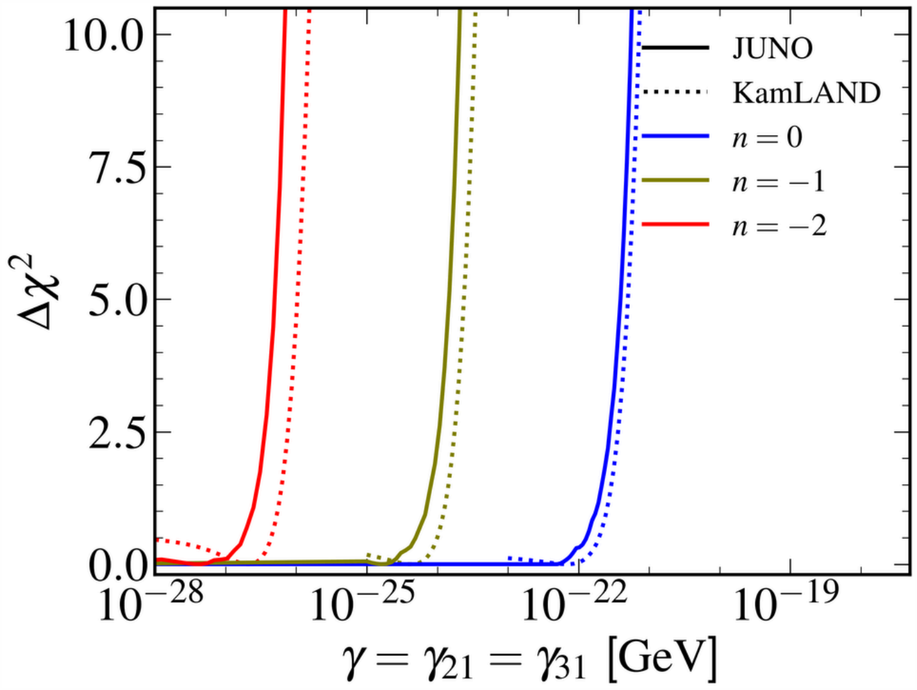
Environmental decoherence

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



- 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:

$$\gamma < 2.9 \times 10^{-22}\ \text{GeV}\quad (n = 0)$$

$$\gamma < 1.1 \times 10^{-24}\ \text{GeV}\ (n = -1)$$

$$\gamma < 3.8 \times 10^{-27}\ \text{GeV}\ (n = -2)$$

Stronger than the full KamLAND dataset

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

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

- 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

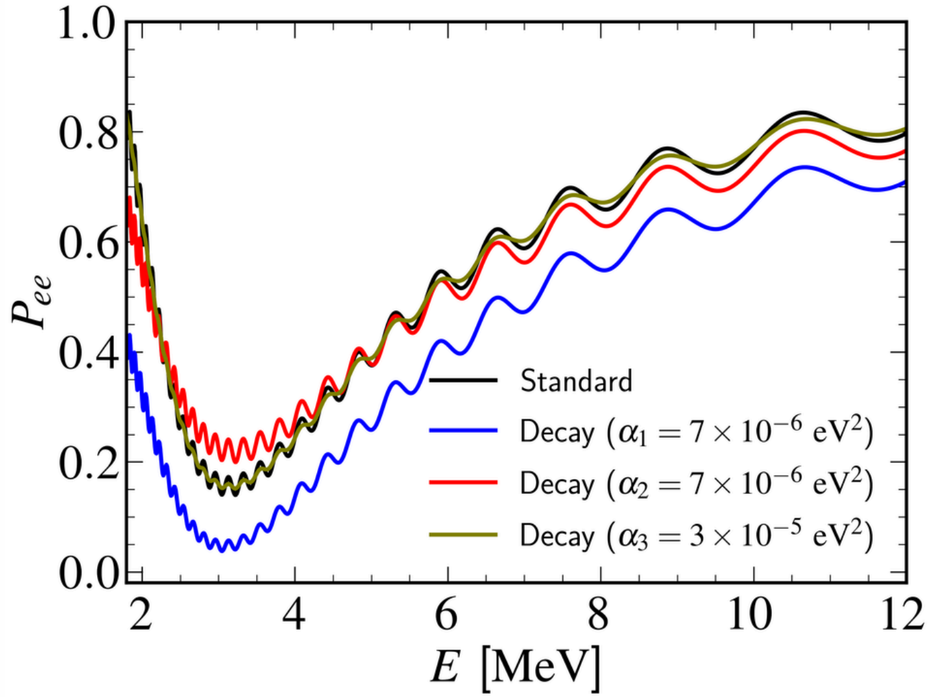
Invisible decay

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

DAMPING

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

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



Wave packets

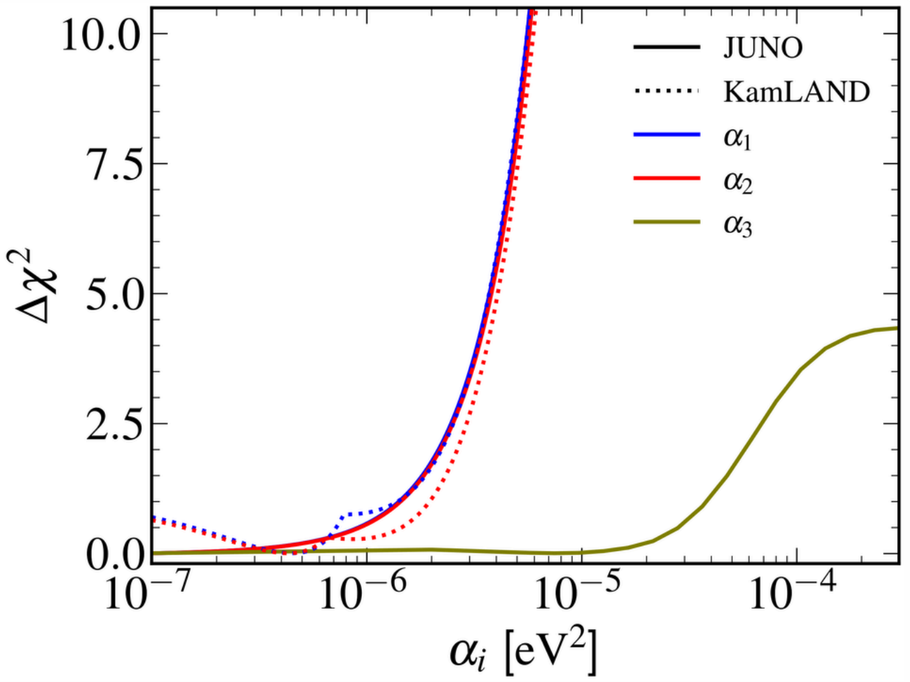
Environmental decoherence

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 invisible decay



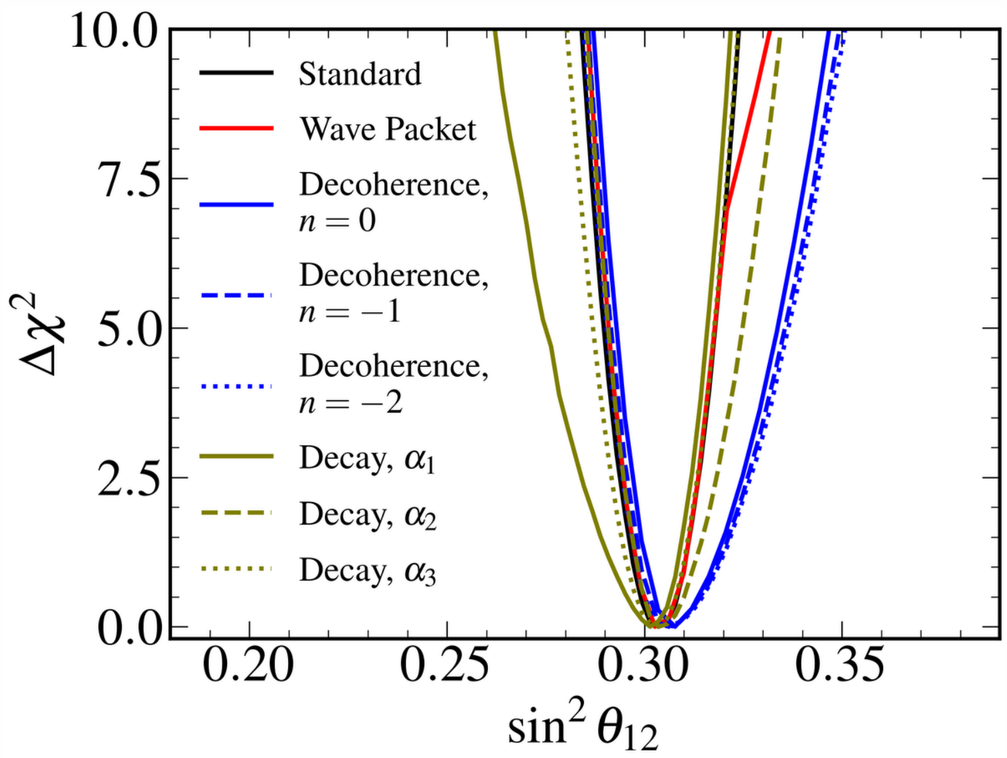
- Minimization over the standard oscillation parameters with **priors** from
  - Daya Bay prior on θ_{13} for $\alpha_1,\ \alpha_2$
  - solar data on $\Delta m^2_{21},\ \theta_{12}$ for α_3

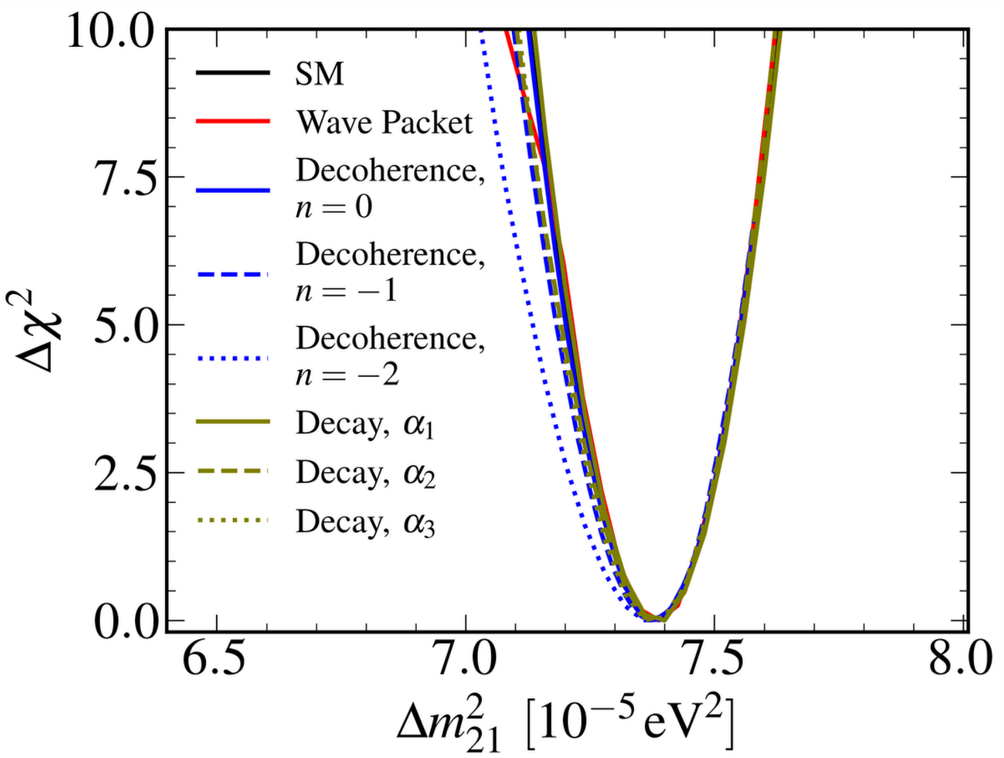
$$@\ 90\%\text{C.L.}: \quad \alpha_1 < 2.6 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_2 < 2.6 \times 10^{-6}\ \text{eV}^2$$
$$\alpha_3 < 7.5 \times 10^{-5}\ \text{eV}^2$$

- For α_1 and α_2 **results comparable with the full KamLAND dataset ,** bounds from solar experiments are much stronger
- Limited sensitivity to α_3

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

χ^2 profiles





The **determination of the standard solar oscillation parameters remains robust** under all damping scenarios considered

As JUNO accumulates more statistics and after it begins to resolve the fast oscillations pattern **its sensitivity to damping signatures is expected to improve significantly**

Neutrino Global Fit: JUNO contribution

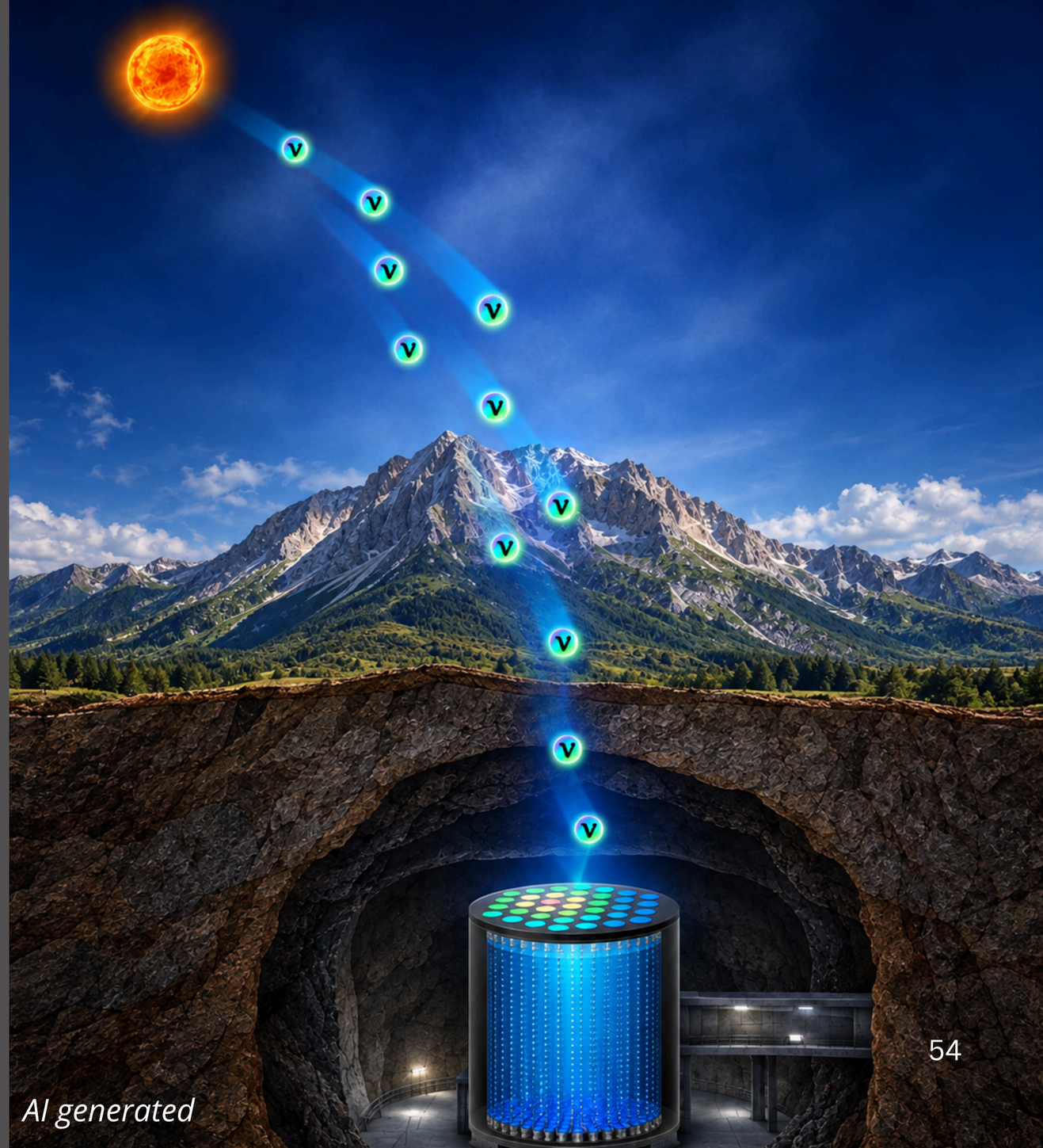
Based on
updated version (in preparation) of JHEP 02 (2021) 071

Damping effects on neutrino oscillations with JUNO

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

Invisible neutrino decay of solar neutrinos at DM experiments

Based on M. Beccaria et al JCAP10(2026)025

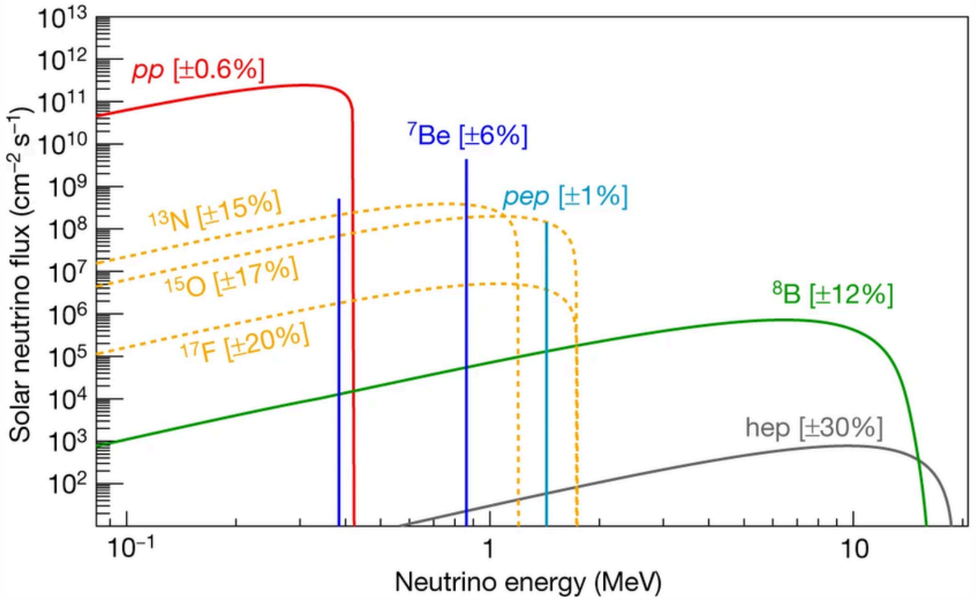


AI generated

Why solar neutrinos?

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

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

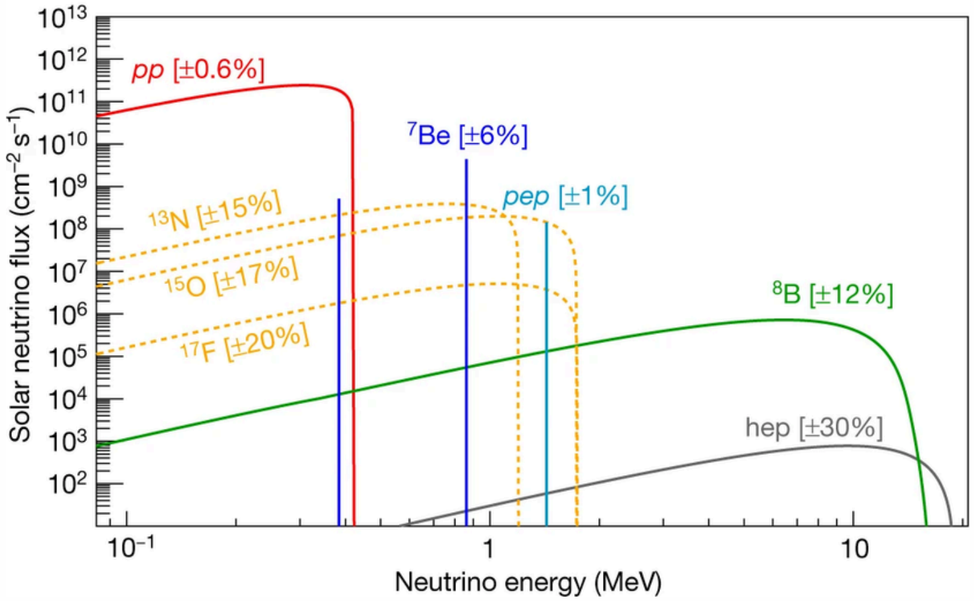


Credit: The Borexino Collaboration. Nature 562, 505–510 (2018).

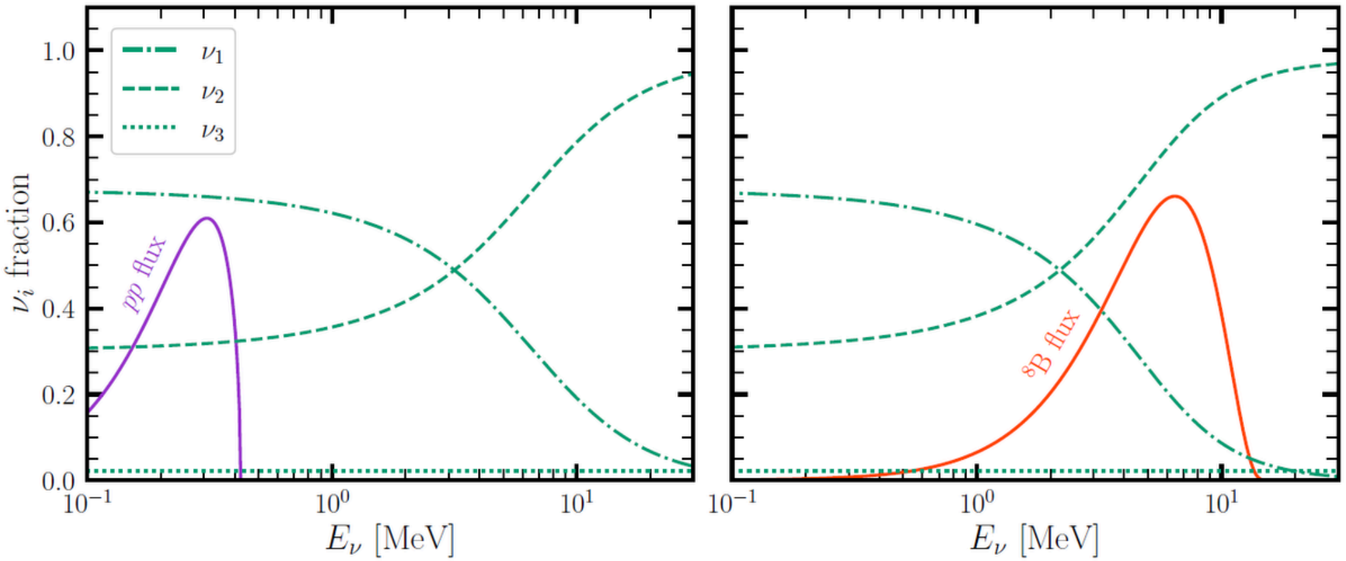
Why solar neutrinos?

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

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



Credit: The Borexino Collaboration. Nature 562, 505–510 (2018).



Mass states composition of the electron neutrino (fluxes in arbitrary units)

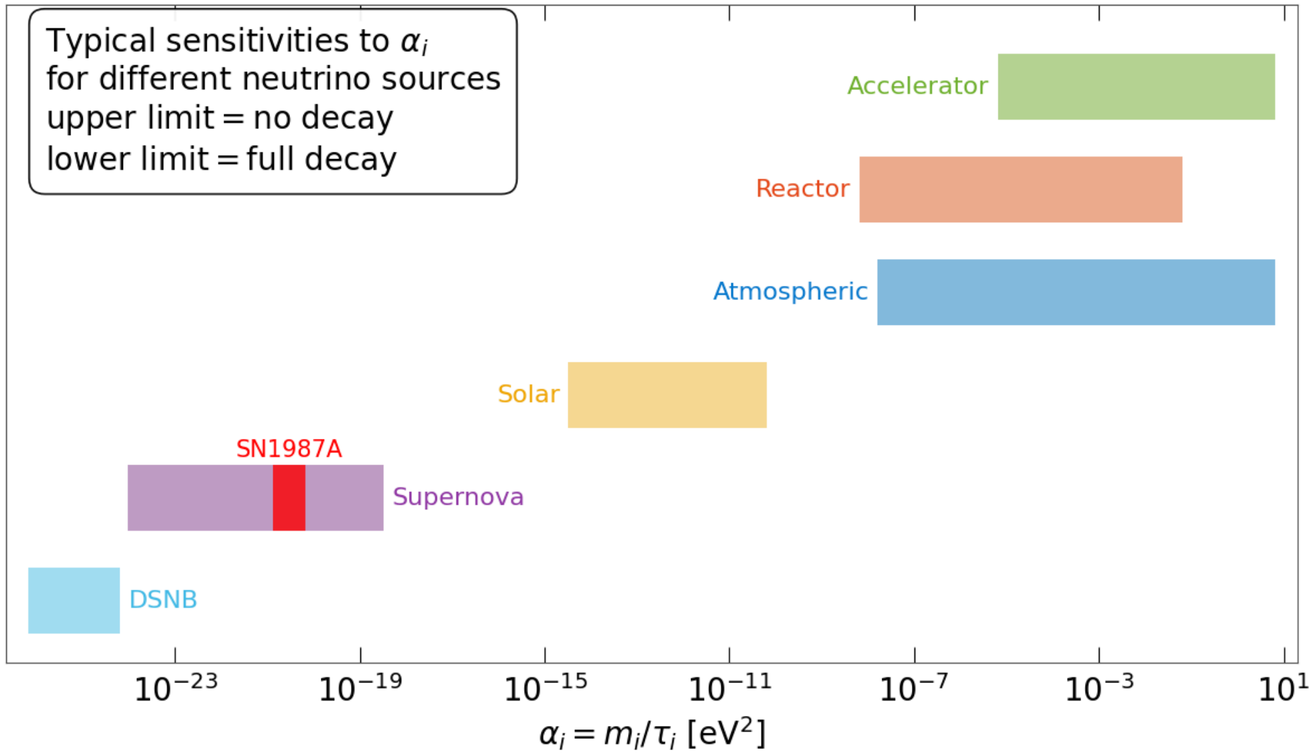
Sensitivity to α_1 and α_2

Why solar neutrinos for invisible decay?

Limits from solar neutrino data:

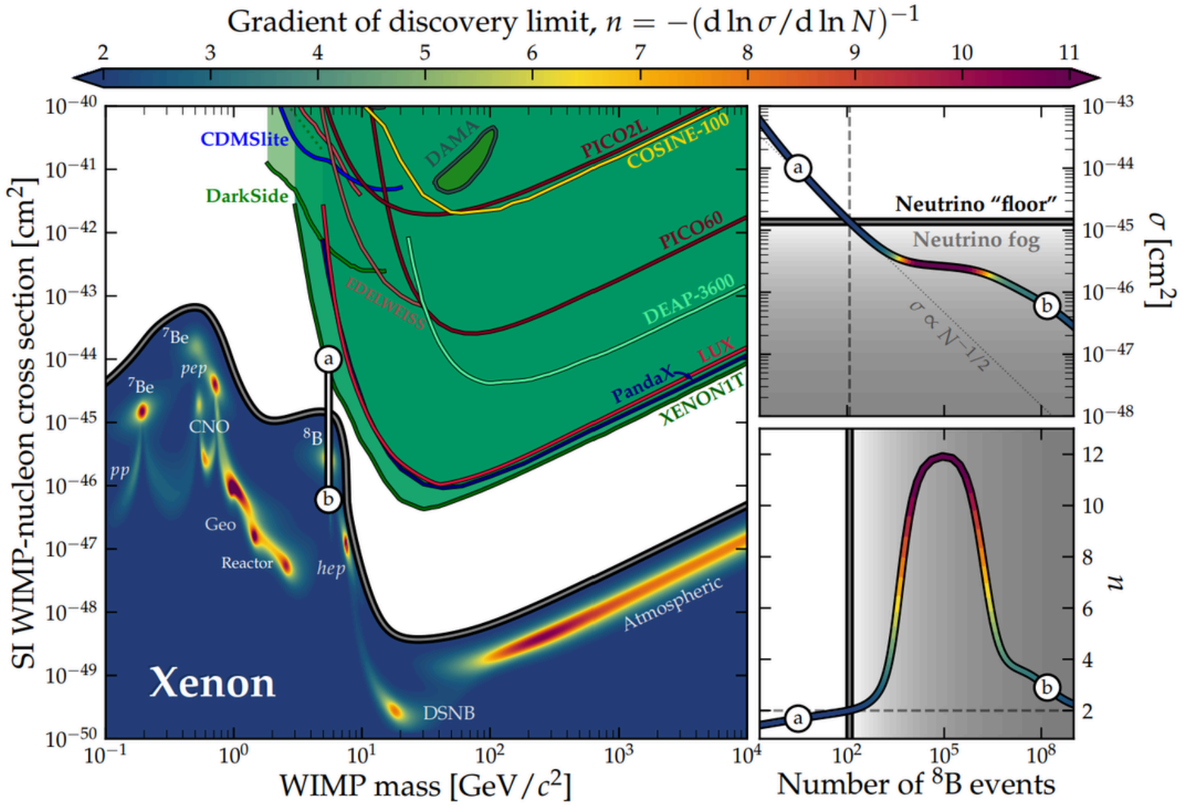
$$\alpha_1 \leq 1.6 \times 10^{-13}\ \mathrm{eV}^2$$

$$\alpha_2 \leq 3.4 \times 10^{-13}\ \mathrm{eV}^2$$



Adapted from arxiv:2307.03549

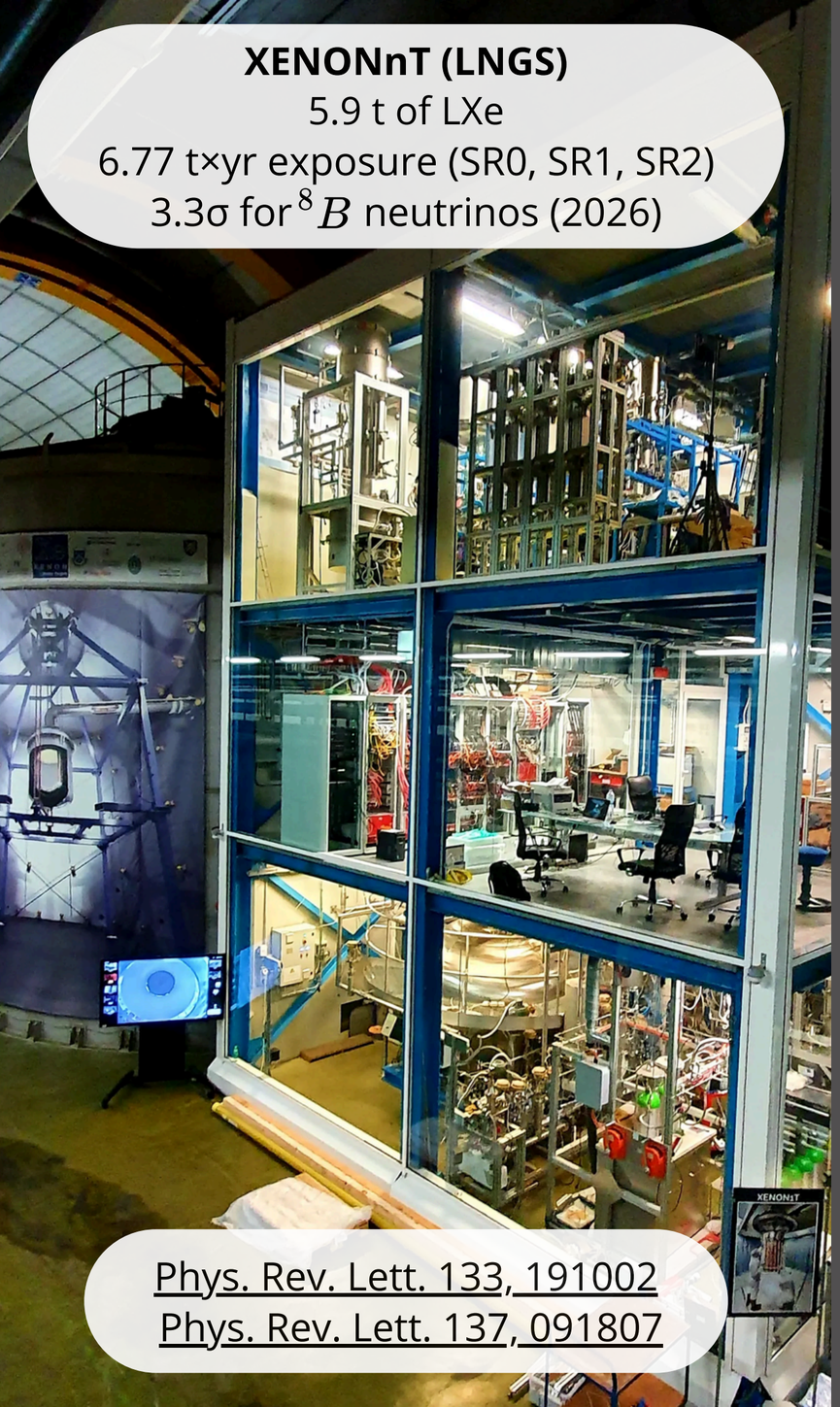
Direct Detection Dark Matter Experiments



Credit: C. A. J. O'Hare, Phys. Rev. Lett. 127, 251802

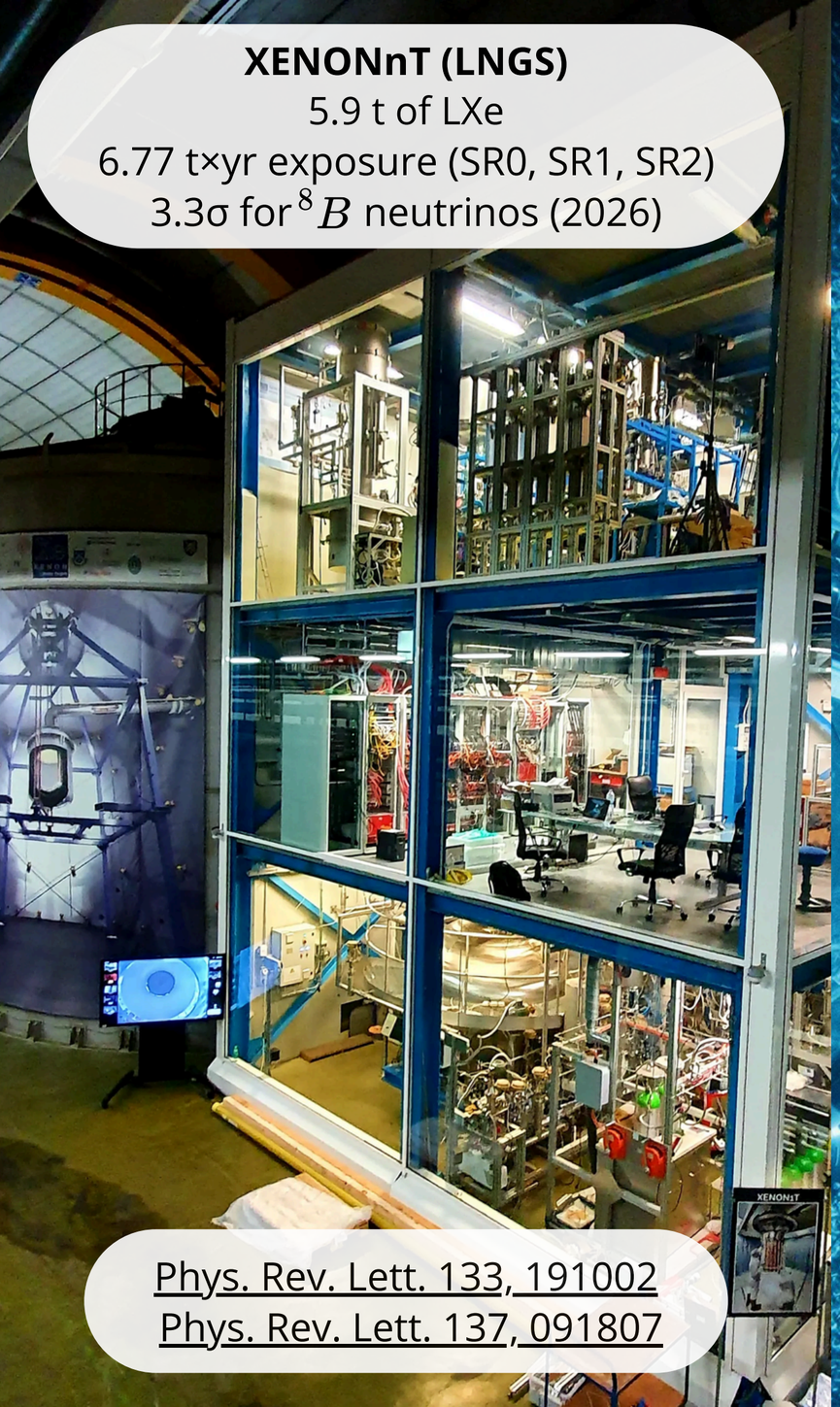
WIMPs searches

First evidences of CEνNS induced ^{8}B solar neutrinos in dual phase TPC LXe experiments!



XENONnT (LNGS)
5.9 t of LXe
6.77 t×yr exposure (SR0, SR1, SR2)
3.3σ for ^{8}B neutrinos (2026)

Phys. Rev. Lett. 133, 191002
Phys. Rev. Lett. 137, 091807



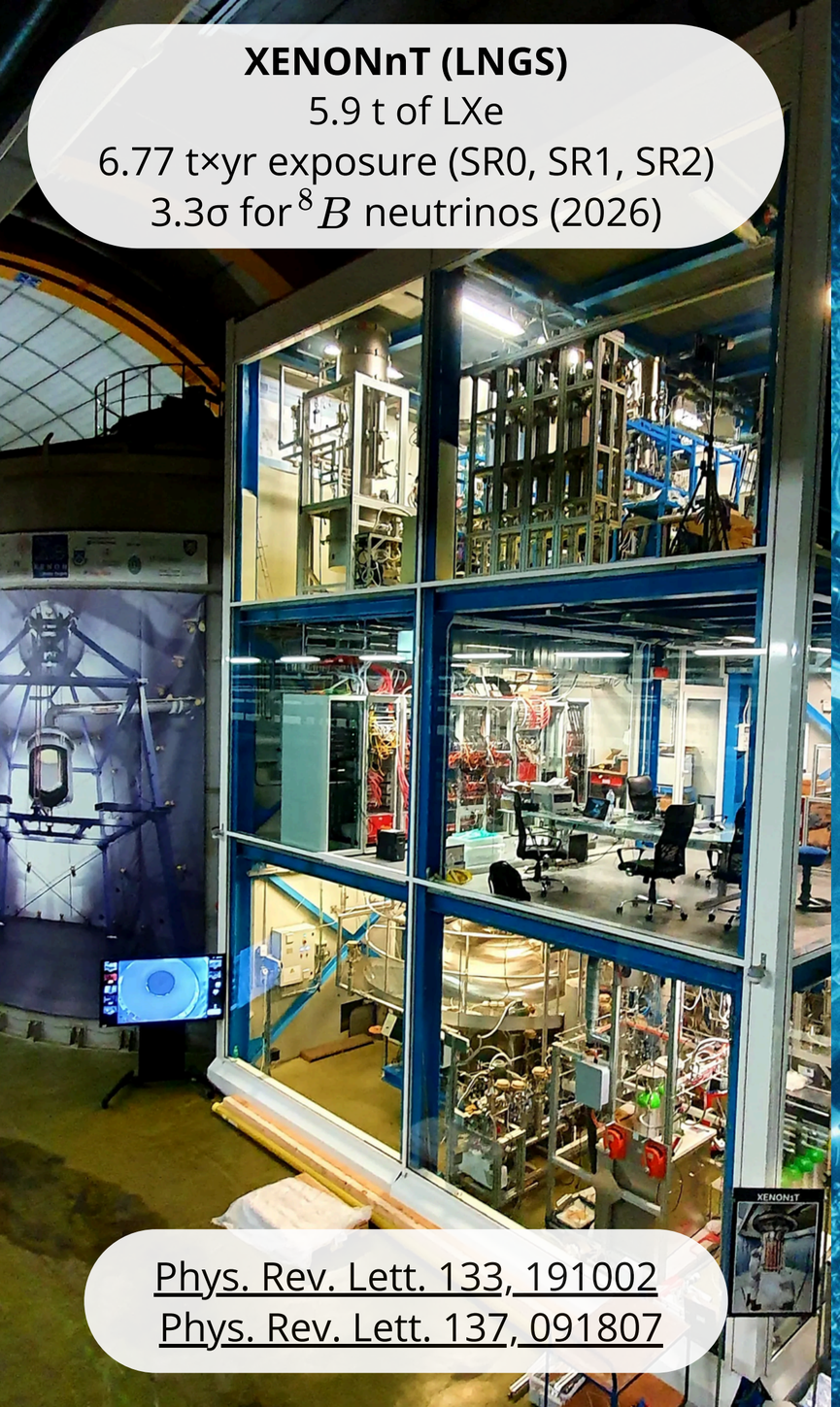
XENONnT (LNGS)
5.9 t of LXe
6.77 t×yr exposure (SR0, SR1, SR2)
3.3σ for ^{8}B neutrinos (2026)

Phys. Rev. Lett. 133, 191002
Phys. Rev. Lett. 137, 091807



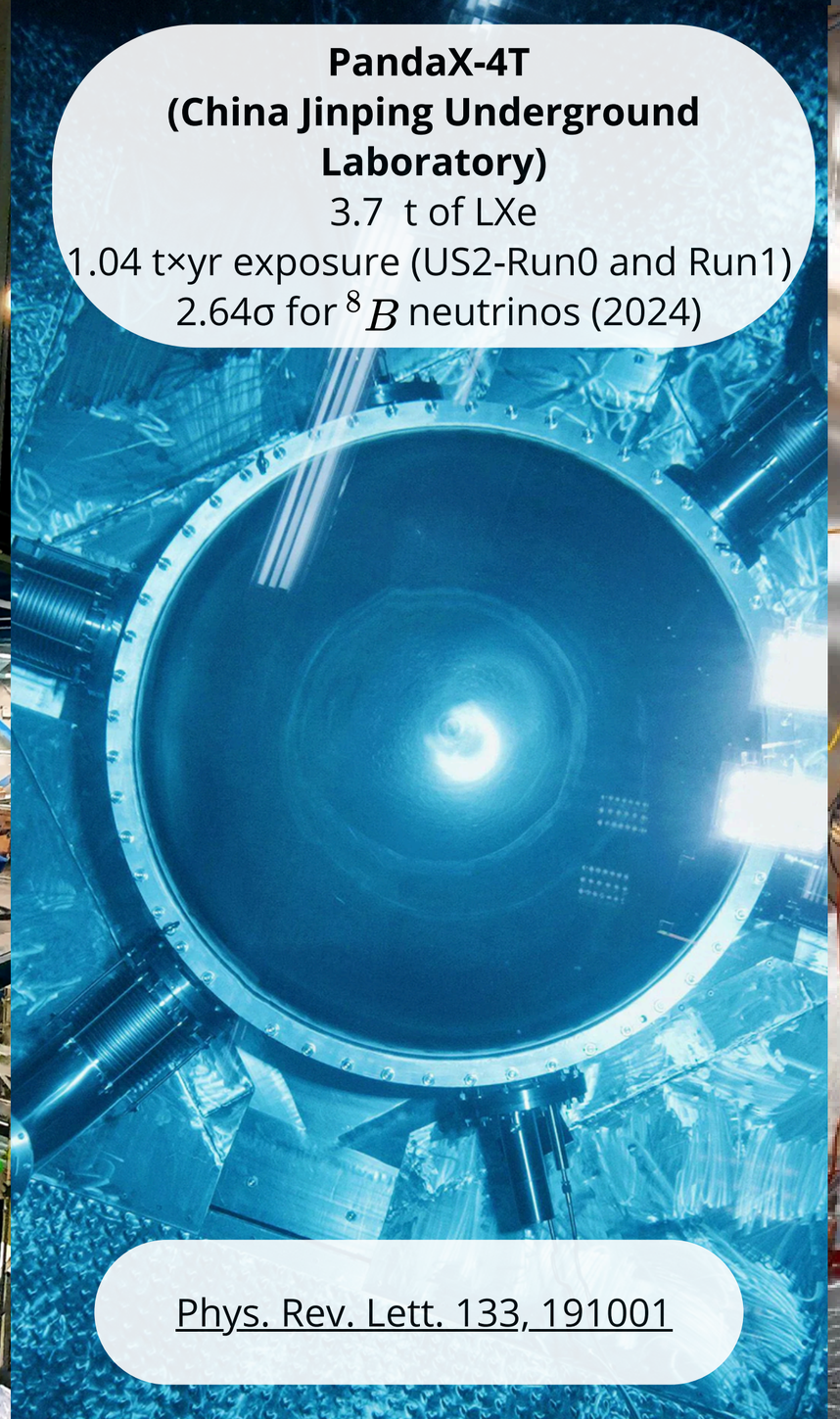
PandaX-4T
(China Jinping Underground Laboratory)
3.7 t of LXe
1.04 t×yr exposure (US2-Run0 and Run1)
2.64σ for ^{8}B neutrinos (2024)

Phys. Rev. Lett. 133, 191001



XENONnT (LNGS)
5.9 t of LXe
6.77 t×yr exposure (SR0, SR1, SR2)
3.3σ for ^{8}B neutrinos (2026)

Phys. Rev. Lett. 133, 191002
Phys. Rev. Lett. 137, 091807



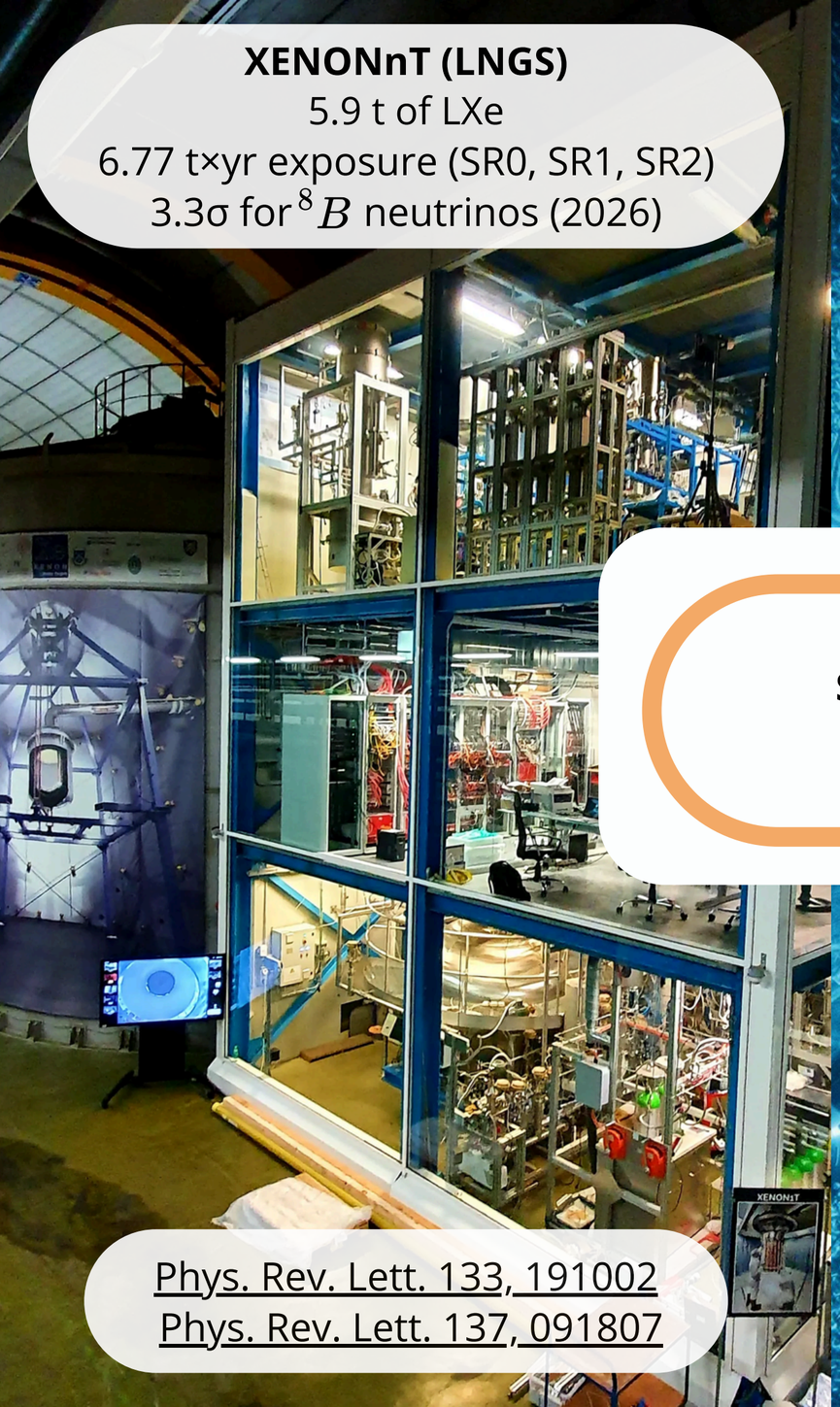
PandaX-4T
(China Jinping Underground Laboratory)
3.7 t of LXe
1.04 t×yr exposure (US2-Run0 and Run1)
2.64σ for ^{8}B neutrinos (2024)

Phys. Rev. Lett. 133, 191001



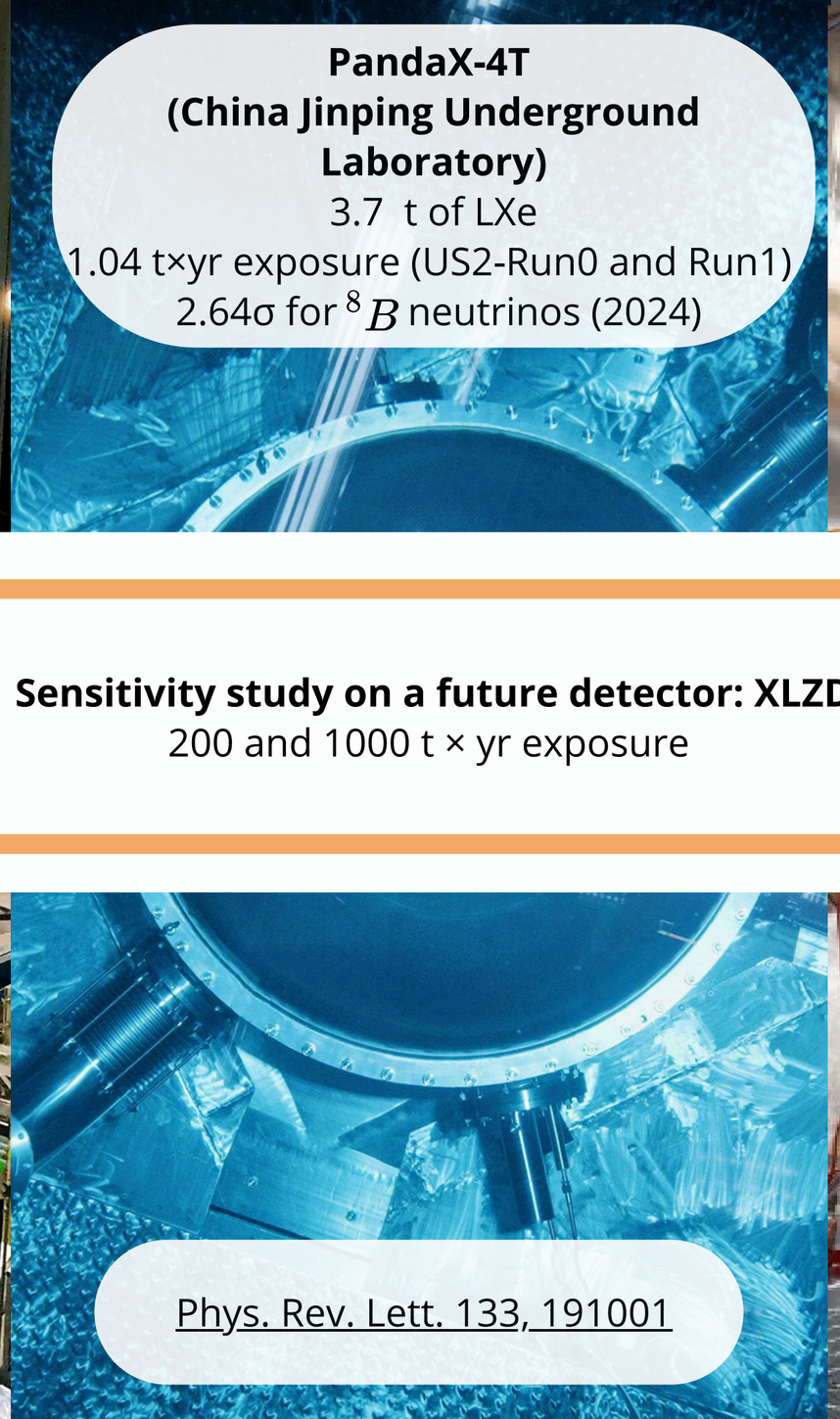
LUX-ZEPLIN (LZ)
(Sanford Underground Research Facility (SURF), USA)
7 t of LXe
5.7 t×yr exposure ((WS2025)
4.5σ for ^{8}B neutrinos (2025)

Phys. Rev. Lett. 137, 091806



XENONnT (LNGS)
5.9 t of LXe
6.77 t×yr exposure (SR0, SR1, SR2)
3.3σ for ^{8}B neutrinos (2026)

Phys. Rev. Lett. 133, 191002
Phys. Rev. Lett. 137, 091807



PandaX-4T
(China Jinping Underground Laboratory)
3.7 t of LXe
1.04 t×yr exposure (US2-Run0 and Run1)
2.64σ for ^{8}B neutrinos (2024)

Phys. Rev. Lett. 133, 191001



LUX-ZEPLIN (LZ)
(Sanford Underground Research Facility (SURF), USA)
7 t of LXe
5.7 t×yr exposure ((WS2025)
4.5σ for ^{8}B neutrinos (2025)

Phys. Rev. Lett. 137, 091806

Sensitivity study on a future detector: XLZD
200 and 1000 t × yr exposure

Events rate

$$\frac{dR^d}{dT} = \varepsilon^d \mathcal{F}^d(T) \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \sum_{l=e,\mu,\tau} \frac{d\phi_l}{dE_\nu} \frac{d\sigma_{\nu_l}}{dT}$$

exposure ε^d
and **energy-dependent efficiency** $\mathcal{F}^d(T)$
of the detector *d*

oscillated neutrino flux

$$\frac{d\phi_l}{dE_\nu} = \frac{d\phi_e^0}{dE_\nu} P_{el}$$

- unoscillated electron-neutrino flux
  $\frac{d\phi_e^0}{dE_\nu}$
  It depends on the solar model and its uncertainties

- oscillation probability considering **invisible neutrino decay**
  P_{el}

differential cross section
of Standard Model processes

Events rate

$$\frac{dR^d}{dT} = \varepsilon^d \mathcal{F}^d(T) \int_{E_\nu^{min}}^{E_\nu^{max}} dE_\nu \sum_{l=e,\mu,\tau} \frac{d\phi_l}{dE_\nu} \frac{d\sigma_{\nu_l}}{dT}$$

Coherent Elastic Neutrino-Nucleus Scattering

$\mathrm{CE}\nu\mathrm{NS}$

- **nuclear** recoil energy: $T = T_N$
- Only the **high-energy tail of the solar neutrinos** can be detected

Elastic scattering on electrons

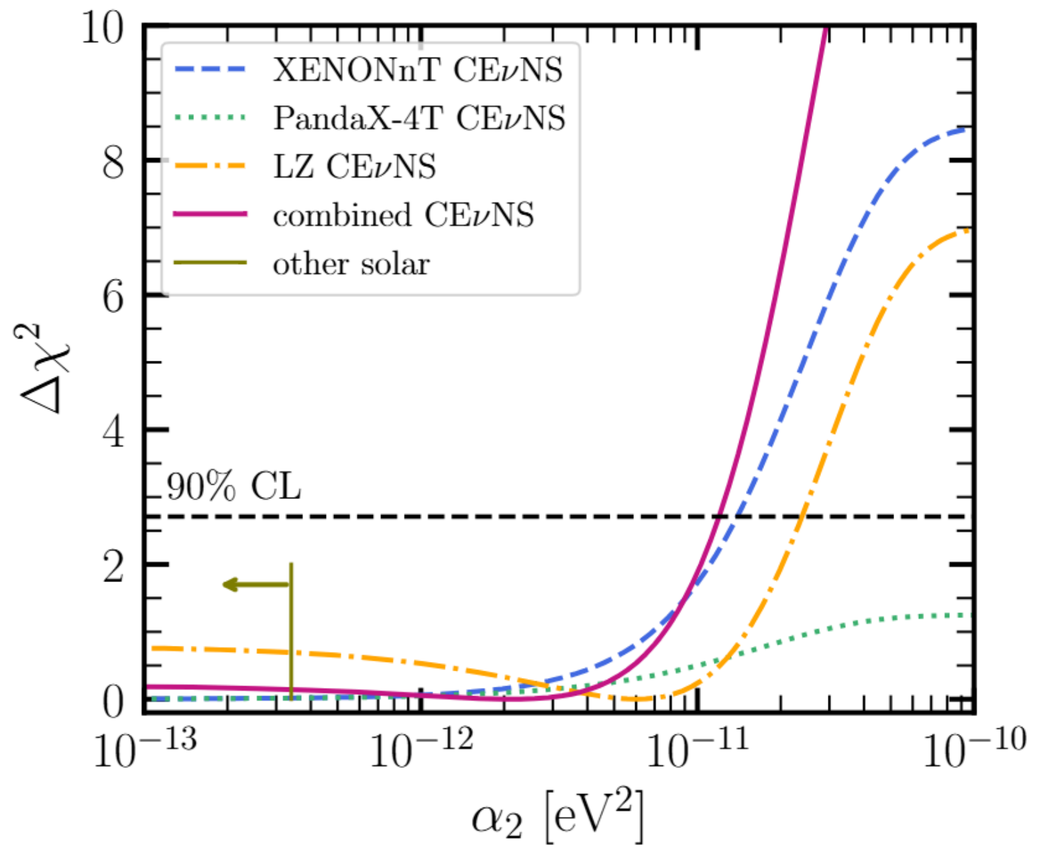
$\mathrm{E}\nu\mathrm{ES}$

- **electron** recoil energy: $T = T_e$
- Difficult to disentangle from **background**

differential cross section of Standard Model processes

Different processes, different backgrounds

Results: current experiments



$\alpha_2 < 1.2 \times 10^{-11}$ eV^2 @90% CL

Independent channel already comparable with **single** solar neutrino experiments (SNO: Phys. Rev. D 99, 032013)

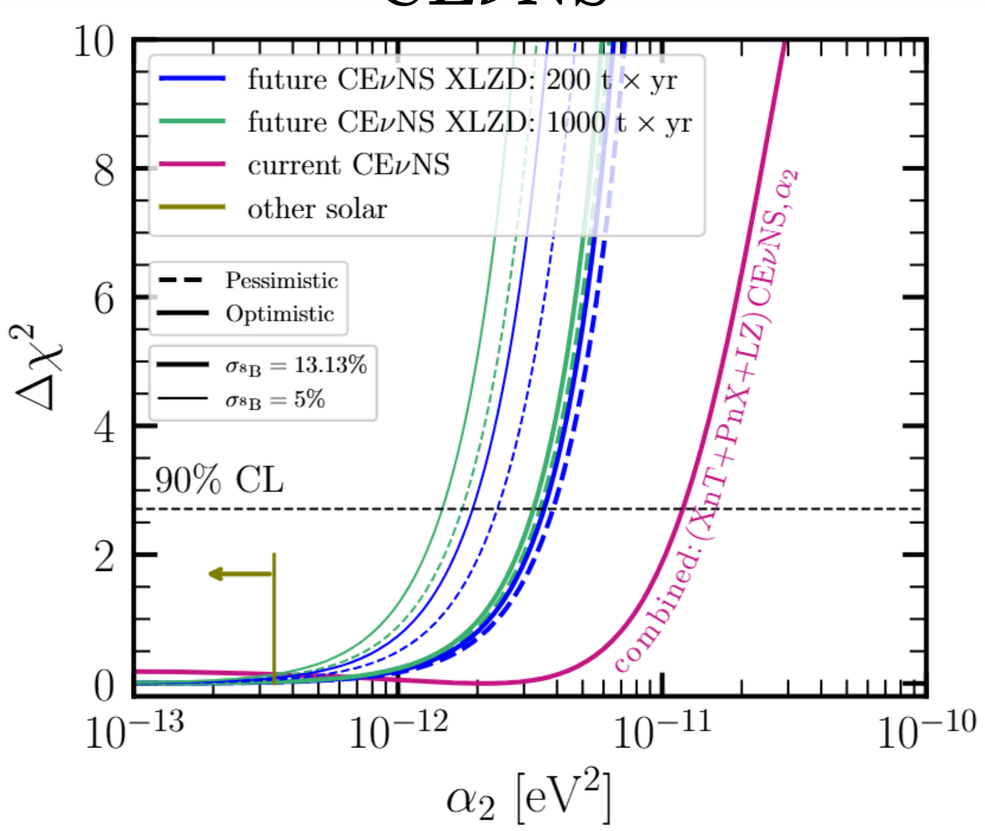
Results: sensitivity study

Background

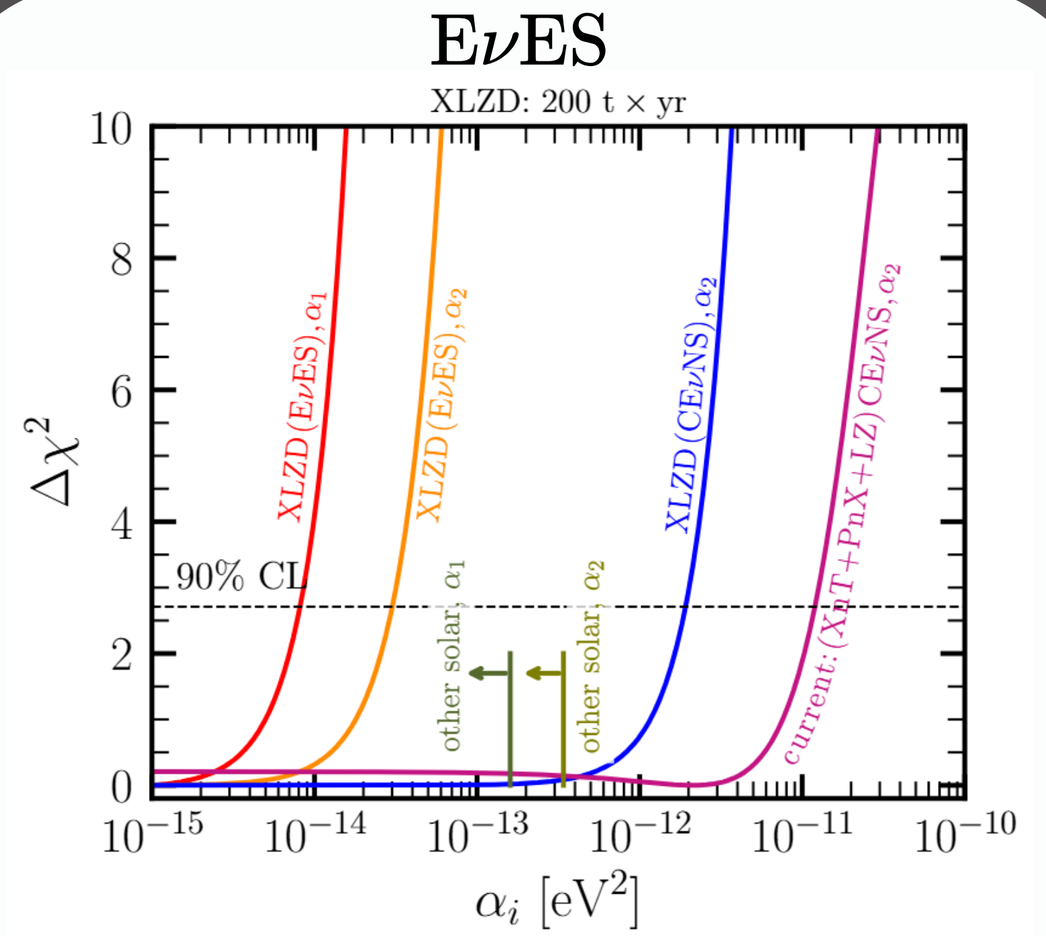
- **optimistic** scenario: x0.5 compared to LZ
- **pessimistic** scenario: x2 compared to LZ

Main issue related to
^{8}B uncertainty

$\alpha_2 < \mathbf{O(10^{-12})\ eV^2\ @90\%\ CL}$
under the most
optimistic assumptions



Results: sensitivity study



Background

- Obtained from sensitivity studies (DARWIN)

$$\alpha_1 < 7.9 \times 10^{-15}\ \text{eV}^2$$

$$\alpha_2 < 3.0 \times 10^{-14}\ \text{eV}^2$$

@90% CL

considerably stronger than CEνNS and future dedicated solar neutrino experiments

Conclusions

JUNO results

Contribution to the Neutrino Global Fit

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

Preference for **normal ordering at approximately 4σ**

Damping effects contraints

Wave packet size

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

Stronger than DayaBay +RENO+KamLAND

Env. decoherence

$$\gamma < 2.9 \times 10^{-22}\ \mathrm{GeV}\quad (n = 0)$$
$$\gamma < 1.1 \times 10^{-24}\ \mathrm{GeV}\ (n = -1)$$
$$\gamma < 3.8 \times 10^{-27}\ \mathrm{GeV}\ (n = -2)$$

Stronger than KamLAND

Invisible decay

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

Limited by *L*

Invisible neutrino decay of solar neutrinos at Dark Matter experiments

Bound from CEvNS data

$$\alpha_2 < 1.2 \times 10^{-11}\ \mathrm{eV}^2$$

Sensitivity study for CEvNS

$$\alpha_2 < O(10^{-12})\ \mathrm{eV}^2$$

Sensitivity study for EvES

$$\alpha_1 < 7.9 \times 10^{-15}\ \mathrm{eV}^2$$
$$\alpha_2 < 3.0 \times 10^{-14}\ \mathrm{eV}^2$$

Scientific publications

- M. Beccaria, V. Beligotti, V. De Romeri, G. Pagliaroli, D. K. Papoulias, F. Pompa and C. A. Ternes. *Invisible decay of solar neutrinos at dark matter experiments*, 2026. JCAP10(2026)025
- M. Beccaria and C. A. Ternes, *Probing damping effects in neutrino oscillations with the first JUNO data*, 2026. arXiv:2606.13362 [hep-ph]
- M. Beccaria, *Neutrino Oscillations: Global Fit and implications on Dark Matter searches (PoS)*, 2026. 10.22323/1.507.0050.

Workshops and conferences

- Bridging low energy high precision experiments with theory: a roadmap towards measurable signatures of quantum gravity. 16-18 September 2026, Assergi-Italy.
- Neutrino Oscillation Workshop (NOW). 31 Aug-6 Sept 2026, Otranto-Italy.
  Talk: Global Fit to Neutrino Oscillation data.
- @FlipPhysics workshop. 26-29 May 2026, Valencia-Spain.
  Talk: Global Fit to Neutrino Oscillation data.
- Les Rencontres de Physique de la Vallée d'Aoste. 1-7 March 2026, La Thuile- Italy.
  Talk: Global Fit to Neutrino Oscillation data.
- Neutrinos from Home 2025. 2-5 December 2025, Online.
- Dark Tools Workshop. 16-19 June 2025, Turin-Italy

PhD/young researchers schools

- ISAPP Summer School 2026 "The Low Energy Frontier: Dark Matter and Neutrinos in Theory and Experiments". 20-31 July 2026, Garching-Germany.
- 4th Training School COST Action COSMIC WISPers. 17-20 June 2026, Corfù-Greece.
  Talk: Neutrino Oscillations and Ultra Light Dark Matter.
- Scientific Communication in Astronomy School – 3rd edition. 13-17 October 2025, Bertinoro-Italy.
  Talk: Neutrino Oscillations: Global Fit and implications on DM searches.
- 3rd Training School COST Action COSMIC WISPers. 16-19 September 2025, Annecy- France.
  Short Talk: *Neutrino Oscillations: Global Fit and implications on DM searches*.

Grants

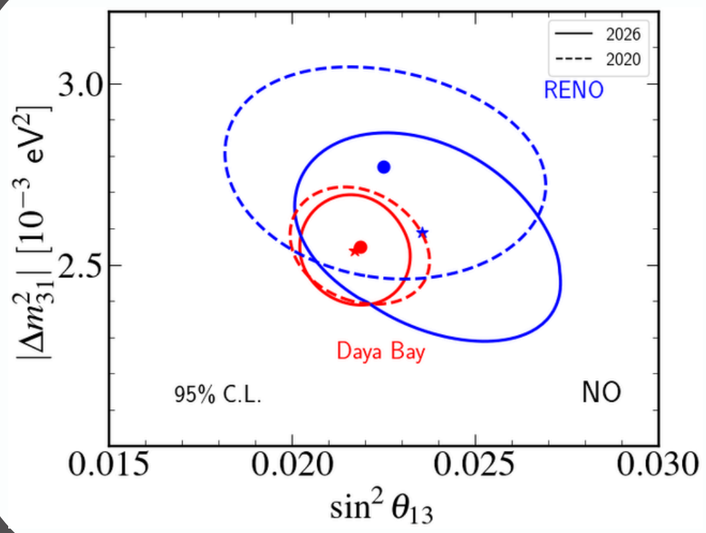
- Young Research Grant @LaThuille conference
- STSM grant with COST action COSMIC WISPers: visiting in Valencia, Spain

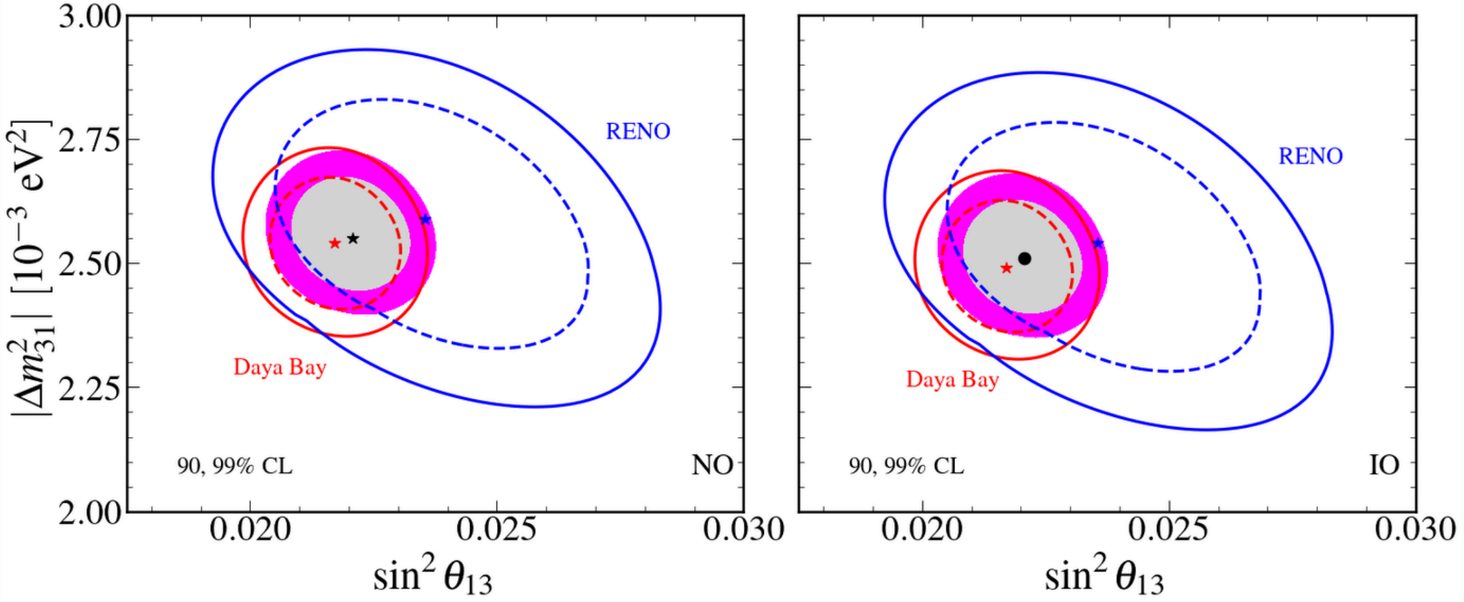
Outreach

- GSSI visitor center guide
- "Stelle e Spazio" program

Reactor angle: θ_{13}

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

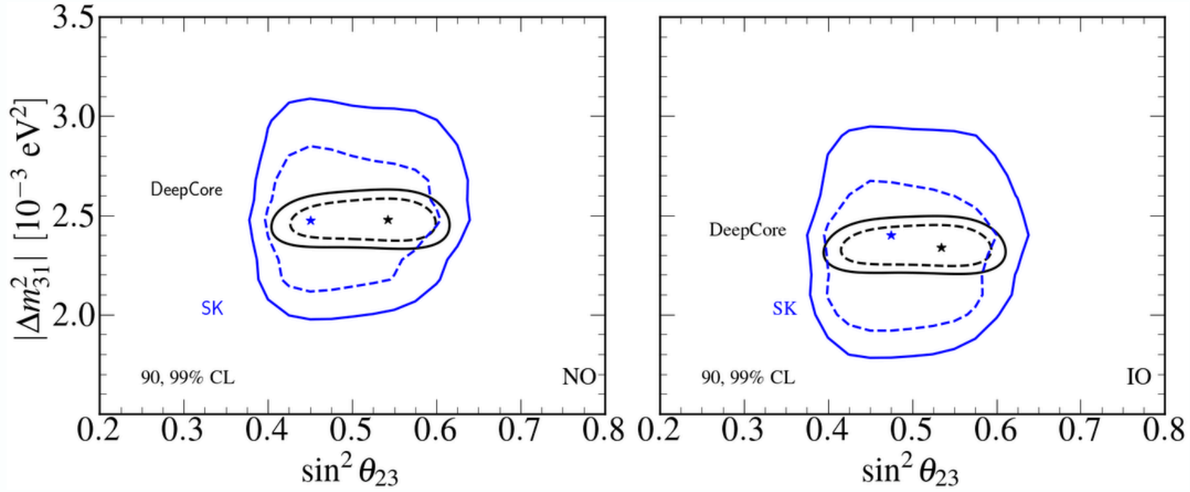


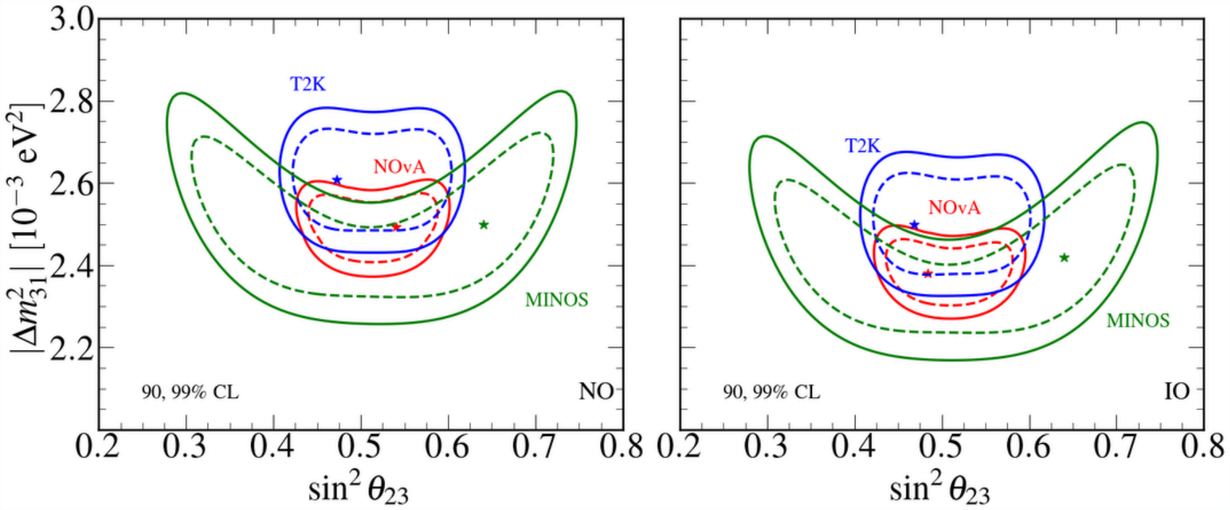


$$\sin^2\theta_{13} = (2.210^{+0.055}_{-0.054}) \cdot 10^{-2} \text{ (NO)}$$
$$\sin^2\theta_{13} = (2.238^{+0.052}_{-0.058}) \cdot 10^{-2} \text{ (IO)}$$

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

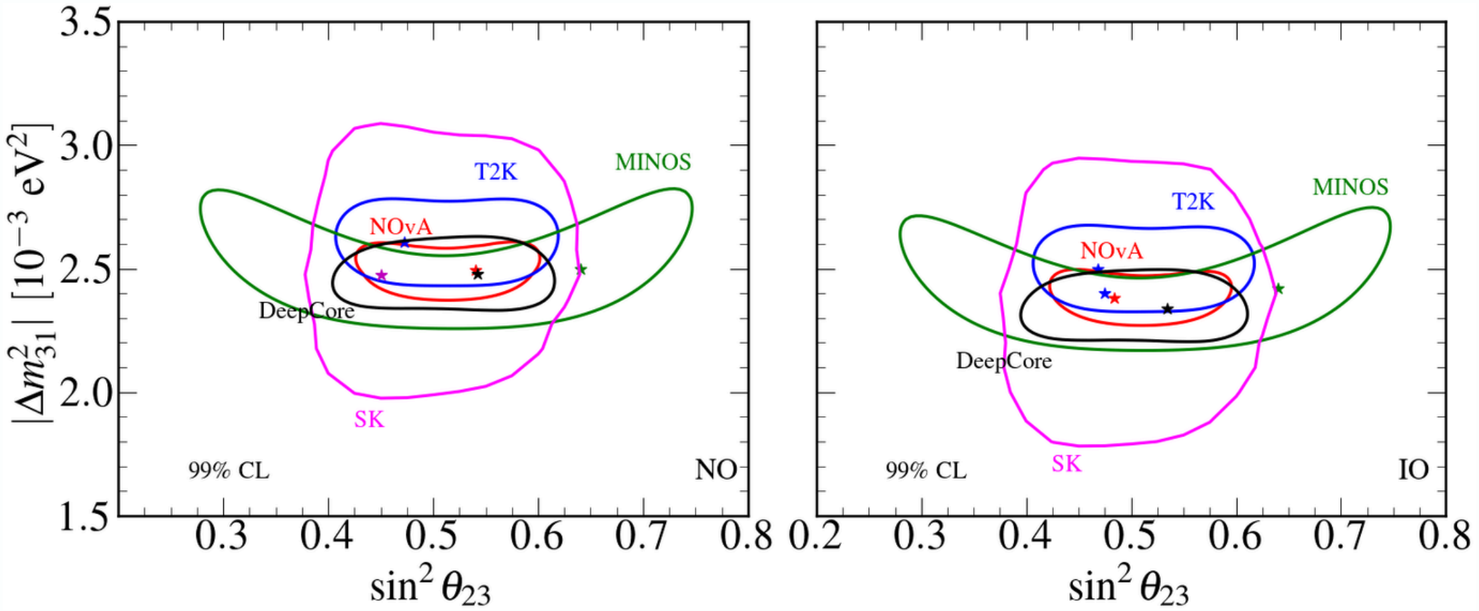
Current atmospheric neutrino experiments: **Super-Kamiokande** and **IceCube DeepCore**





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

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



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

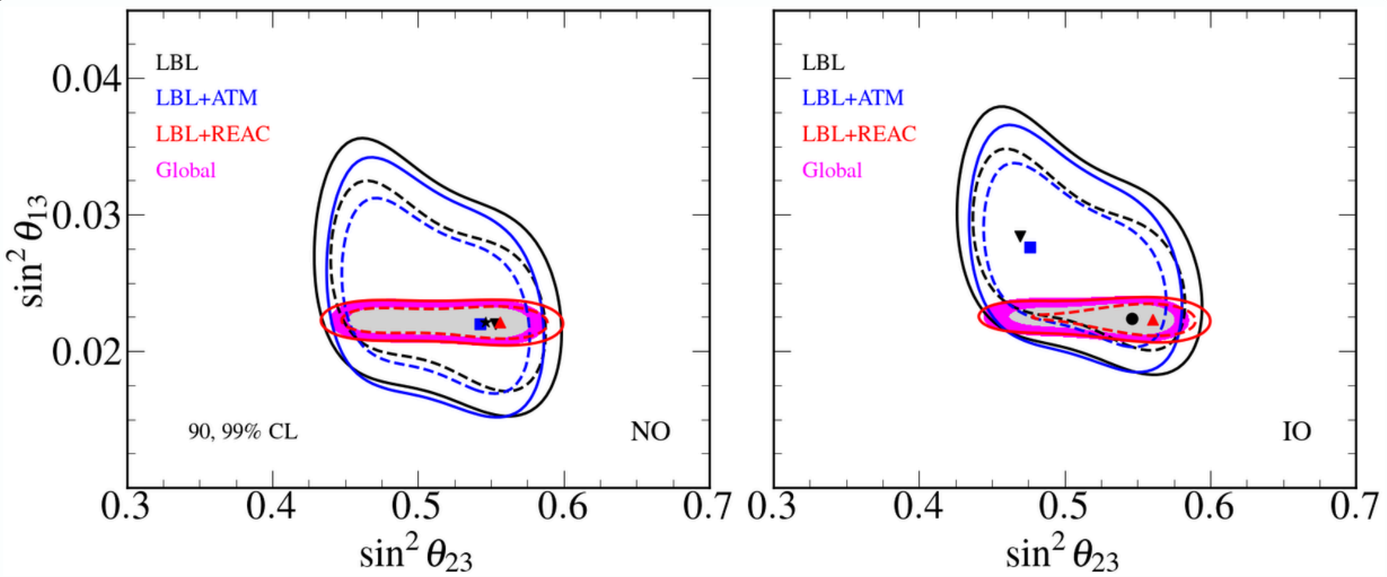
Not possible to resolve the octant of the angle:

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

Mainly sensitive to

$\sin^2 2\theta_{23}$

θ_{23} degeneracy



$$\sin^2\theta_{23} = (5.46^{+0.17}_{-0.28}) \cdot 10^{-1} \text{ (NO)}$$

$$\sin^2\theta_{23} = (5.46^{+0.16}_{-0.19}) \cdot 10^{-1} \text{ (IO)}$$

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**:

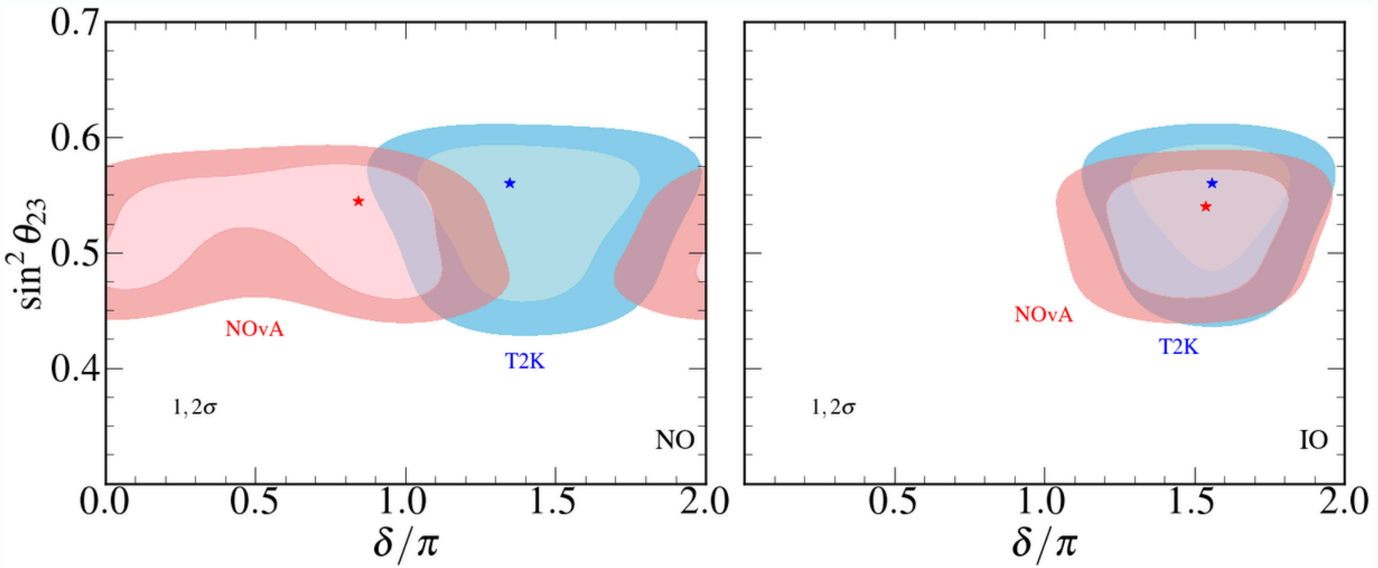
$$P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$$

$$\Updownarrow$$

$$U = U^*$$

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

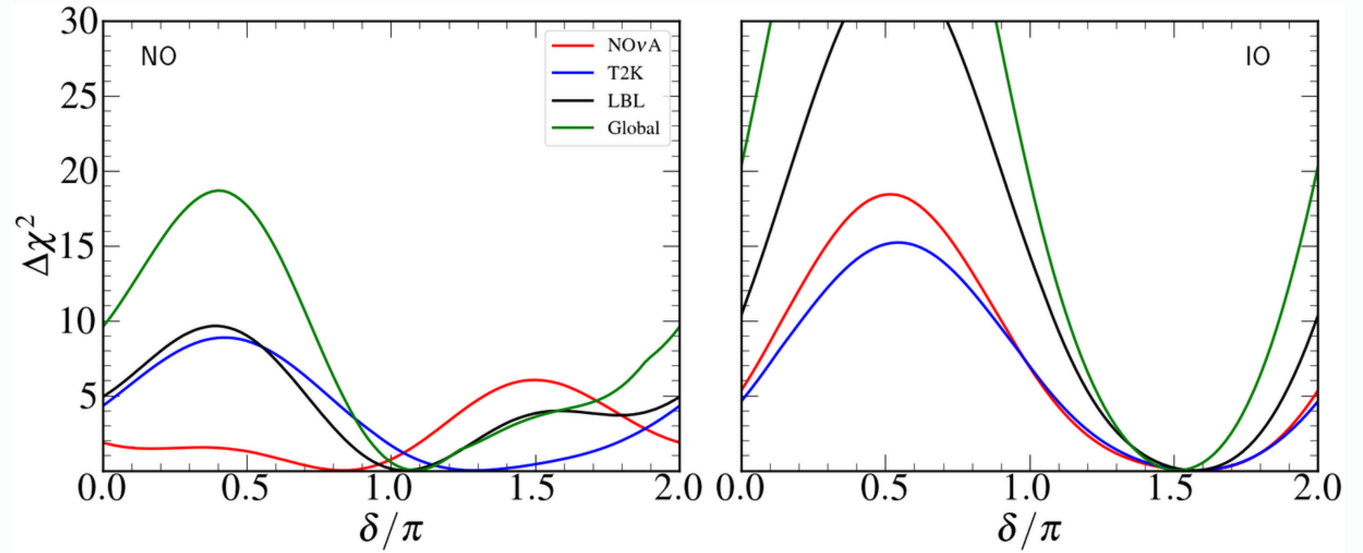
Disagreement in the measurement of the CP phase for the NO

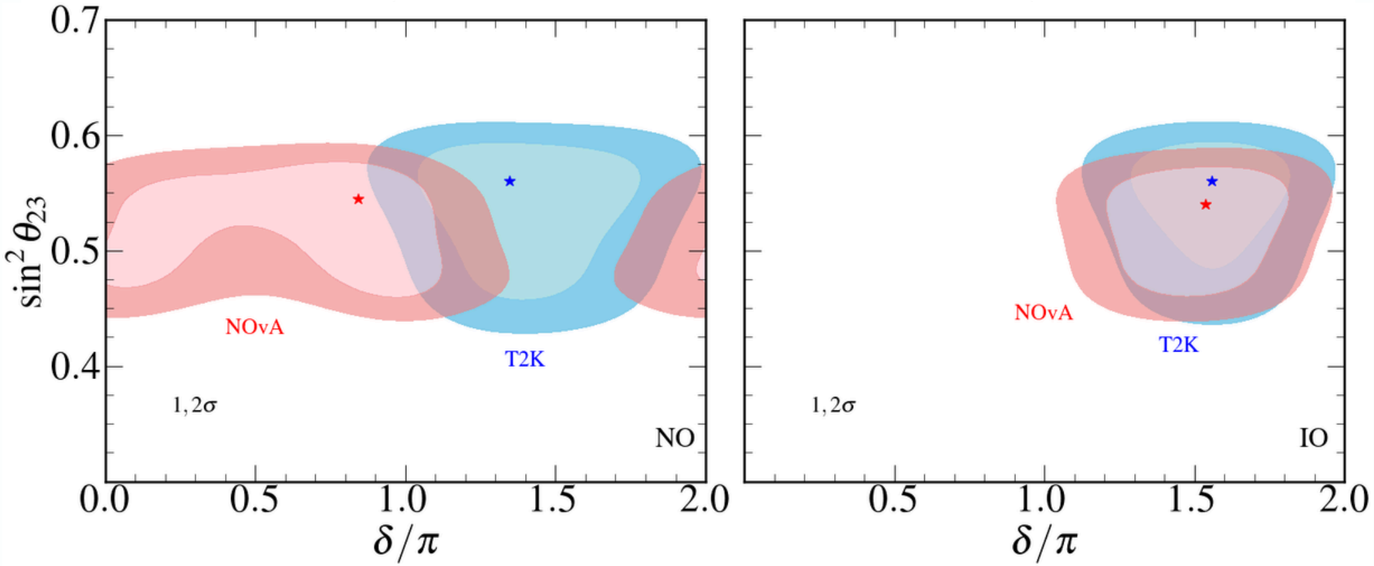


Agreement in the measurement of the CP phase for the IO

CP phase δ and mass ordering

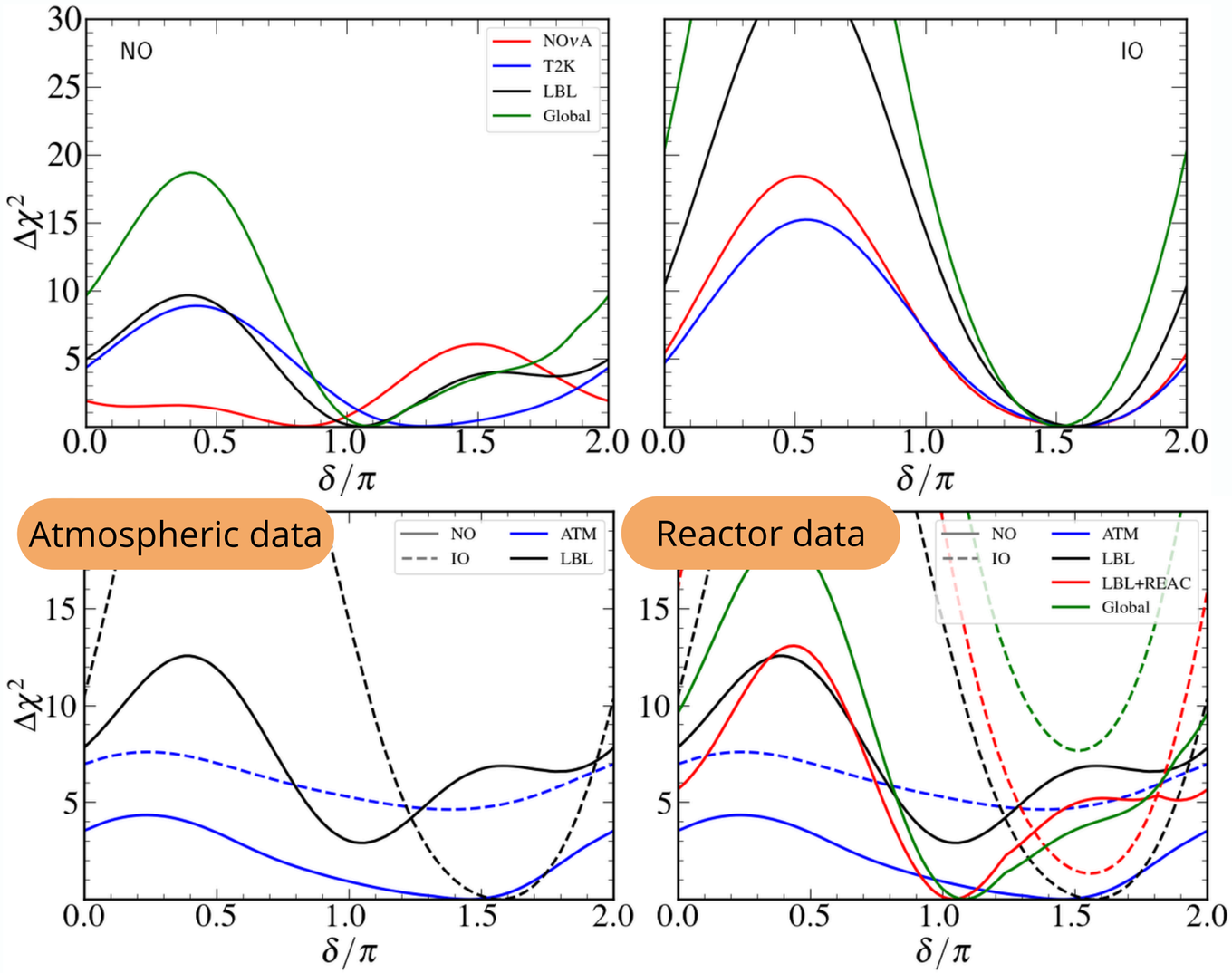
Disagreement in the measurement of the CP phase for the NO





Agreement in the measurement of the CP phase for the IO

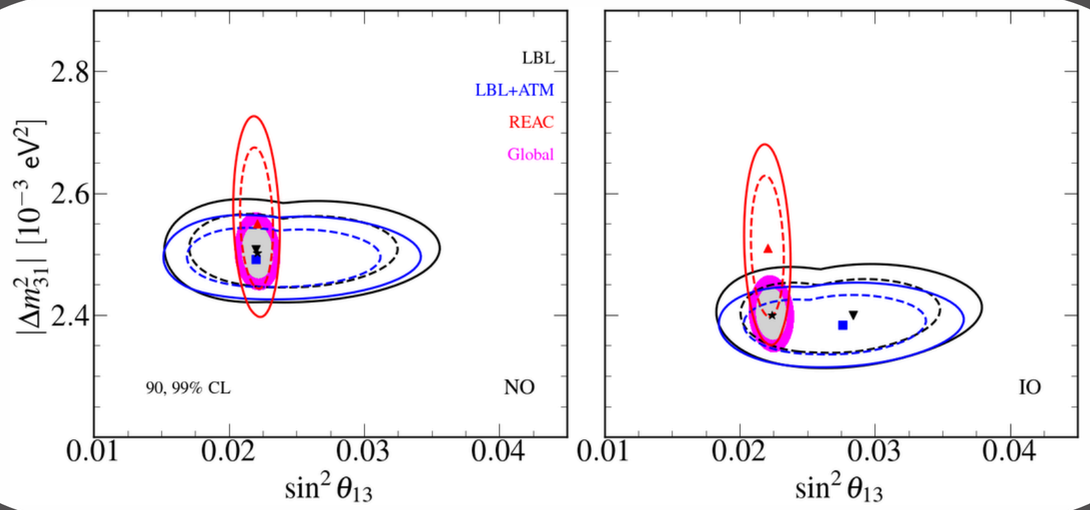
CP phase δ and mass ordering



Preference for NO

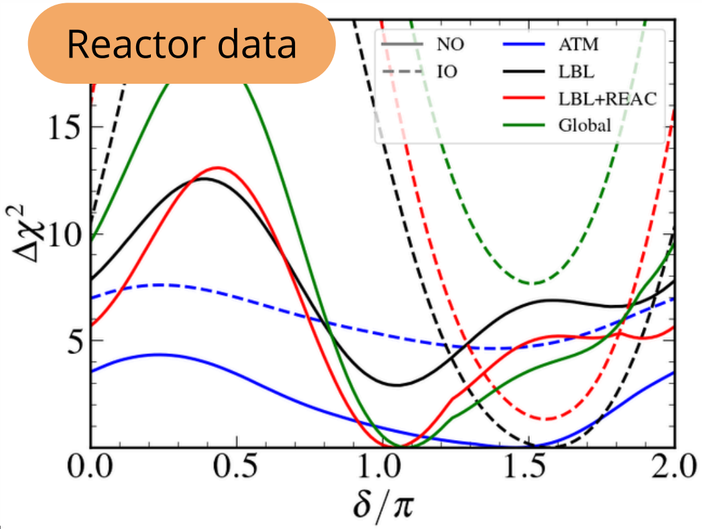
Preference for NO

CP phase δ and mass ordering



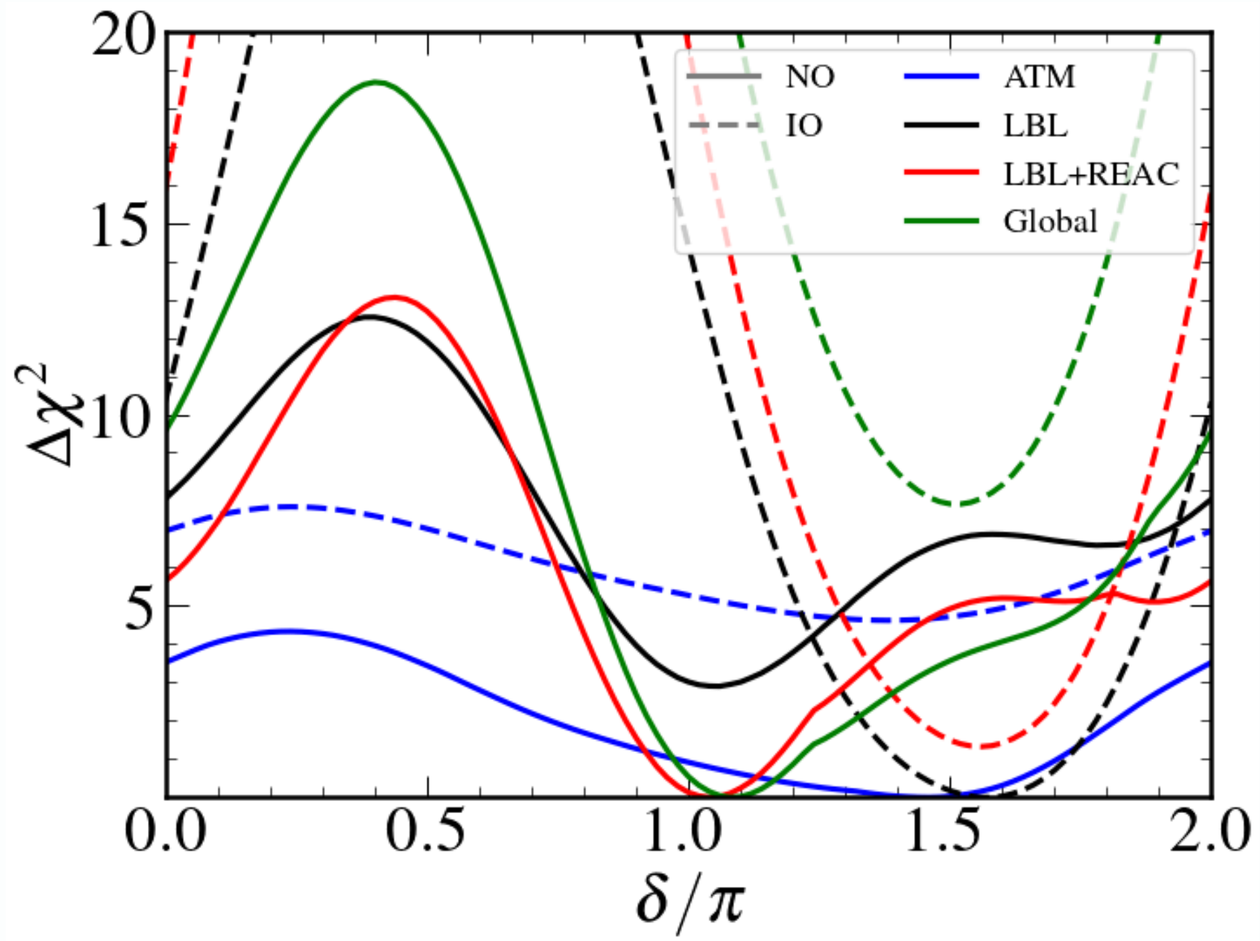
Better agreement between
LBL accelerators+atmospheric data
and reactor data
for the normal ordering

Reactor data



Preference
for NO

CP phase δ and mass ordering



Preference for **normal ordering** at 2.7σ

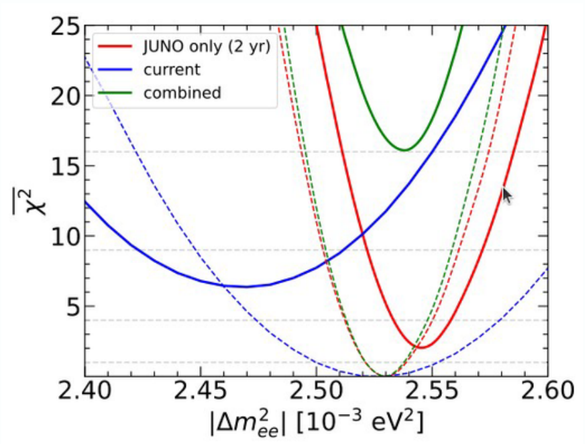
$$\delta = (1.08^{+0.13}_{-0.11}) \cdot \pi \ (\mathrm{NO})$$

$$\delta = (1.52^{+0.11}_{-0.13}) \cdot \pi \ (\mathrm{IO})$$

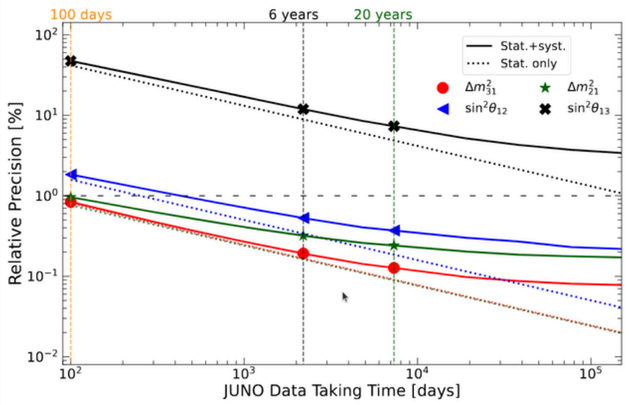
Future Prospects for the Global Fit

JUNO prospects

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

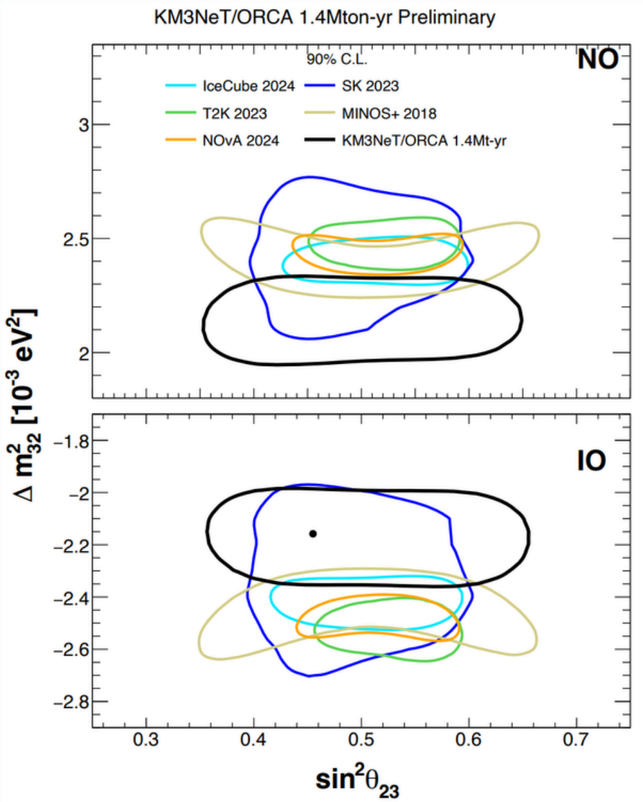


Precision measurement
(see: arXiv:2204.13249 [hep-ex])



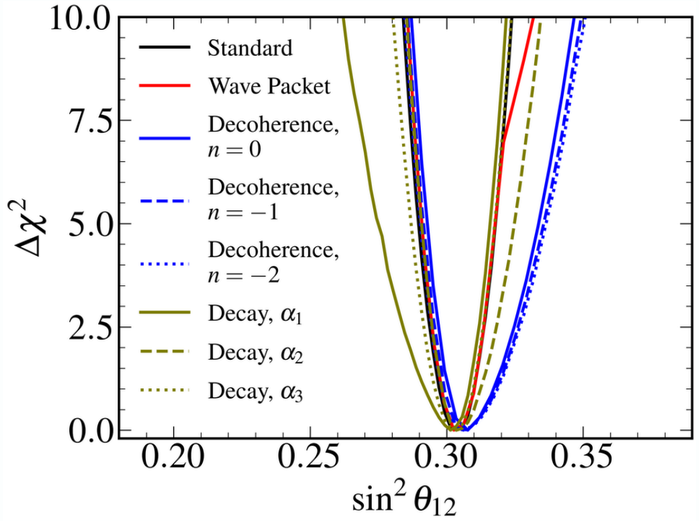
Atmospheric sector

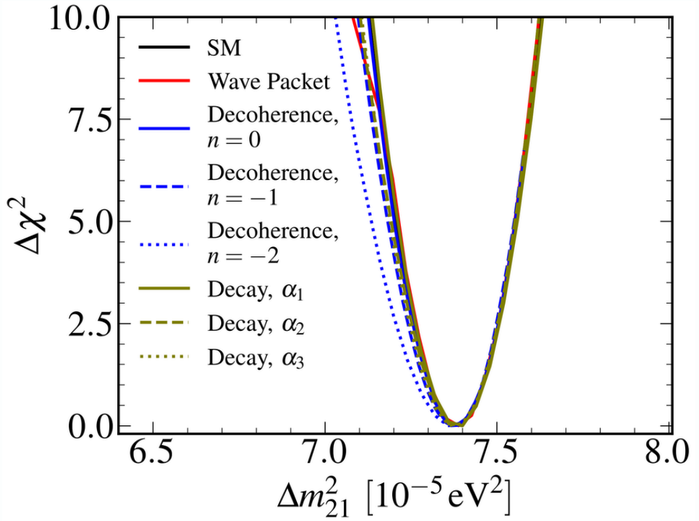
- Addition of KM3Net/ORCA

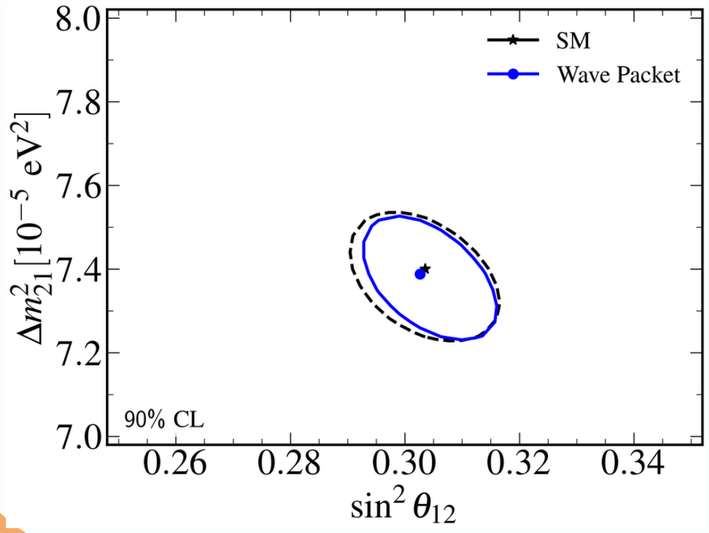


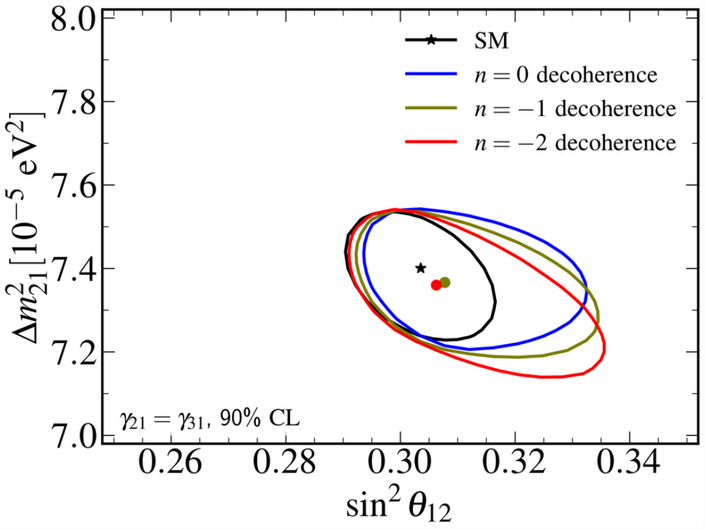
Credit: Paul De Jong, NEUTRINO2026

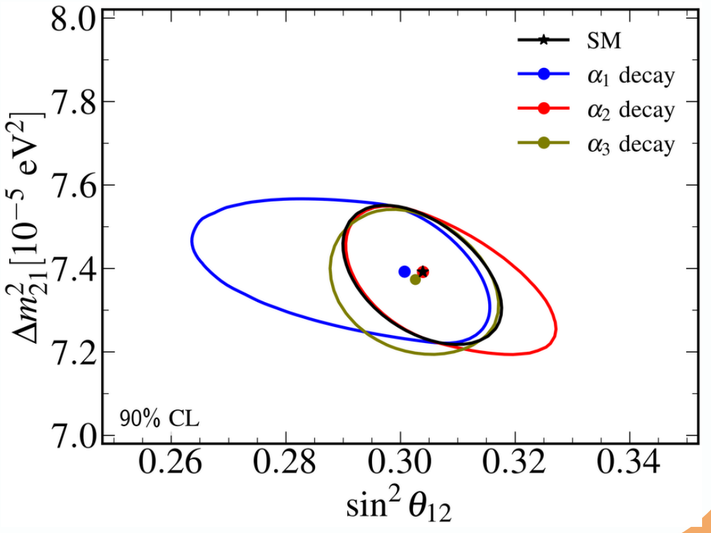
Solar parameters with damping effects











Direct Detection DM experiments: analysis

$$N_i = R_i(1+\gamma) + \sum_k B_{i,k}(1+\beta_k), \tag{3.16}$$

where R_i are either the CEνNS or the EνES rates and the spectra of the background components $B_{i,k}$ are provided by each Collaboration [57–59, 75]. We compare our predictions with the measured data D_i (in the case of XLZD we generate a fake data set without neutrino decay) using

$$\chi^2 = \min_{\gamma,\beta_k} \left\{ 2\left[\sum_i N_i - D_i + D_i \ln\left(\frac{D_i}{N_i}\right)\right] + \left(\frac{\gamma}{\sigma_\gamma}\right)^2 + \sum_k \left(\frac{\beta_k}{\sigma_{\beta_k}}\right)^2 \right\}. \tag{3.17}$$

Here, γ and β_k are the nuisance parameters accounting for the neutrino flux predictions (with uncertainties [94, 95] $\sigma_{\rm B} = 13.13\%$ and $\sigma_{pp} = 0.59\%$ for ^{8}B and pp neutrinos, respectively) and for the normalization of each background component (with associated uncertainties σ_{β_k}).

XENONnT: EvES background

