Three-neutrino phenomenology and global analyses

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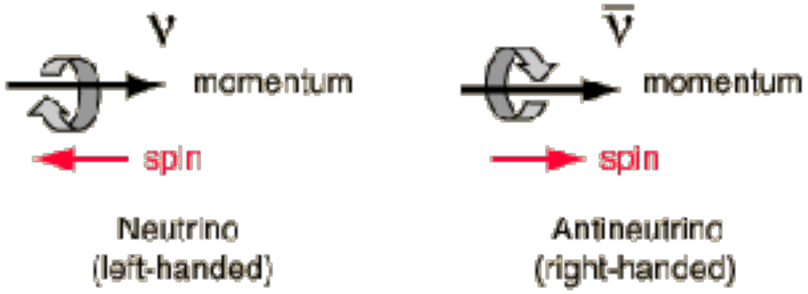
Conselleria d'Educació, Universitats i Ocupació

Neutrinos in the Standard Model

- There are three light neutrinos associated to the charged leptons.

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$$

- The SM only contains LH neutrinos (and RH antineutrinos): no $SU(2)_L$ RH neutrinos



- Only neutral fermion: Dirac or Majorana nature?

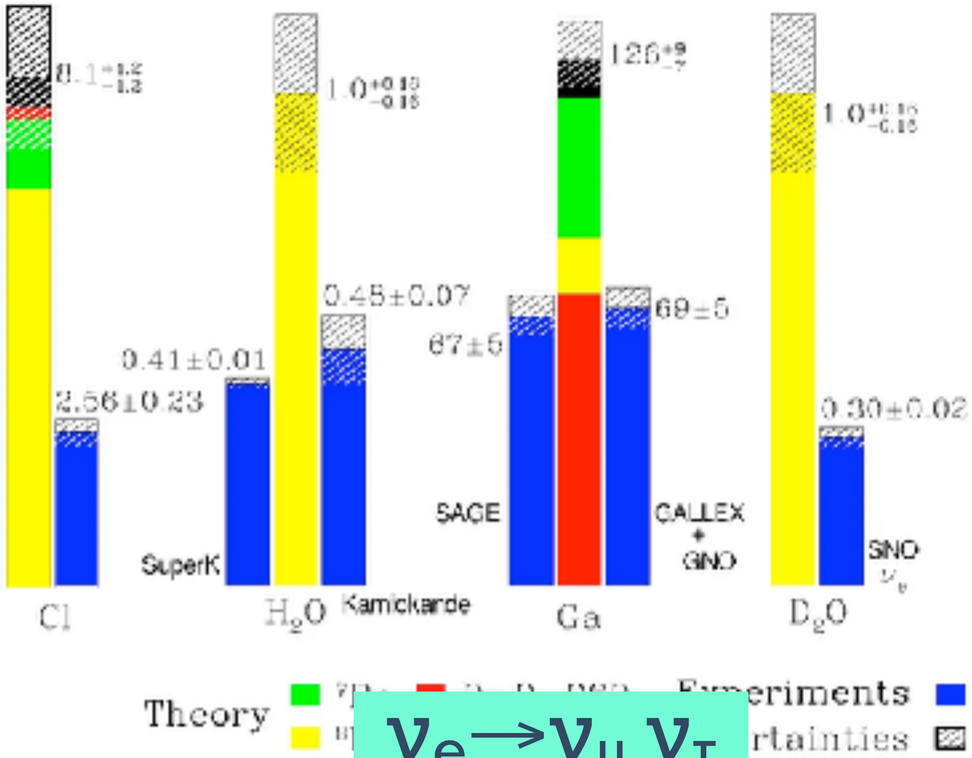
- No mass term for neutrinos can be built with the content of the SM:

Dirac mass term	Majorana mass term	Lowest dim mass term
$m\overline{\nu}_R \nu_L$	$\frac{1}{2} m \nu_L^T \mathcal{C}^\dagger \nu_L$	$\frac{g}{\Lambda}(L_L^T \sigma_2 \phi)\mathcal{C}^\dagger(\phi^T \sigma_2 L_L)$
✗	✗	✗

Neutrinos are strictly massless in the Standard Model!

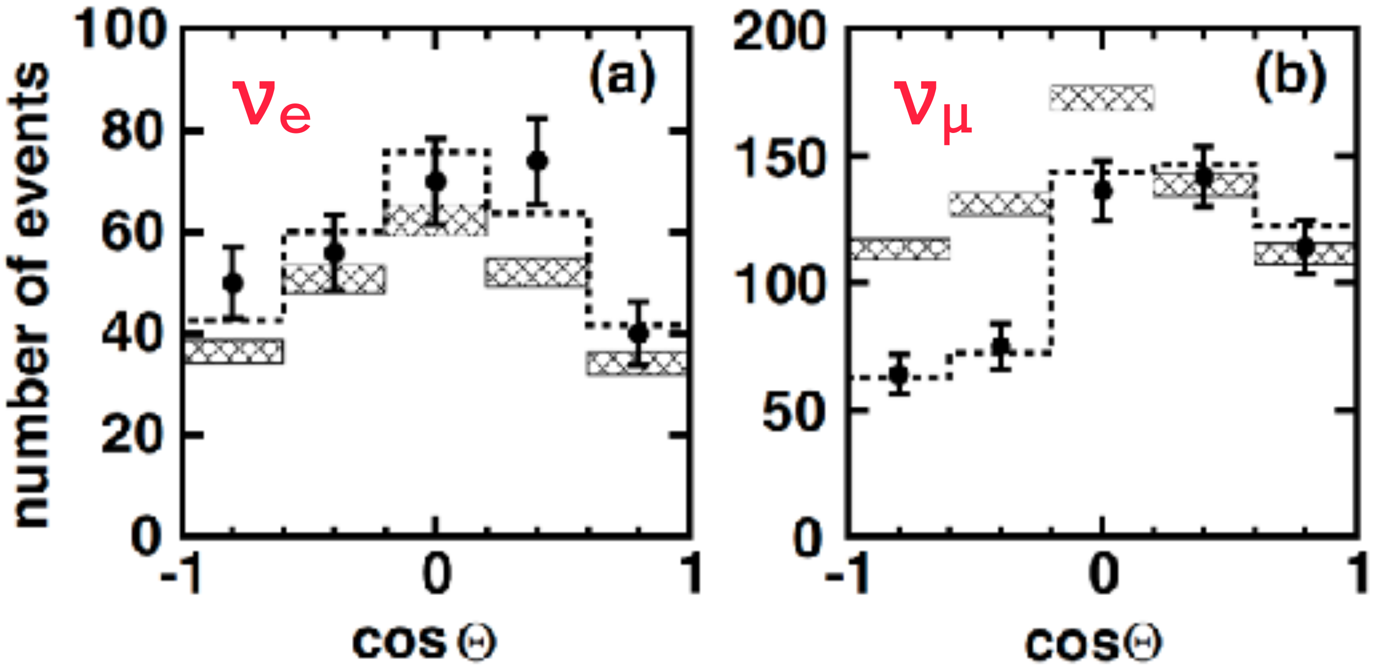
Neutrino anomalies

Solar neutrino problem (60's)



$\nu_e \rightarrow \nu_\mu, \nu_\tau$

Atmospheric neutrino anomaly (80's)



$\nu_\mu \rightarrow \nu_\tau$

- 1998-2002: anomalies explained via flavour oscillations due to neutrino mixing

$$\nu_\alpha = \sum_k U_{\alpha k} \nu_k$$

neutrino mass eigenstates

Neutrinos are massive!!

2015: Nobel Prize

The three-flavour ν picture

neutrino mixing

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

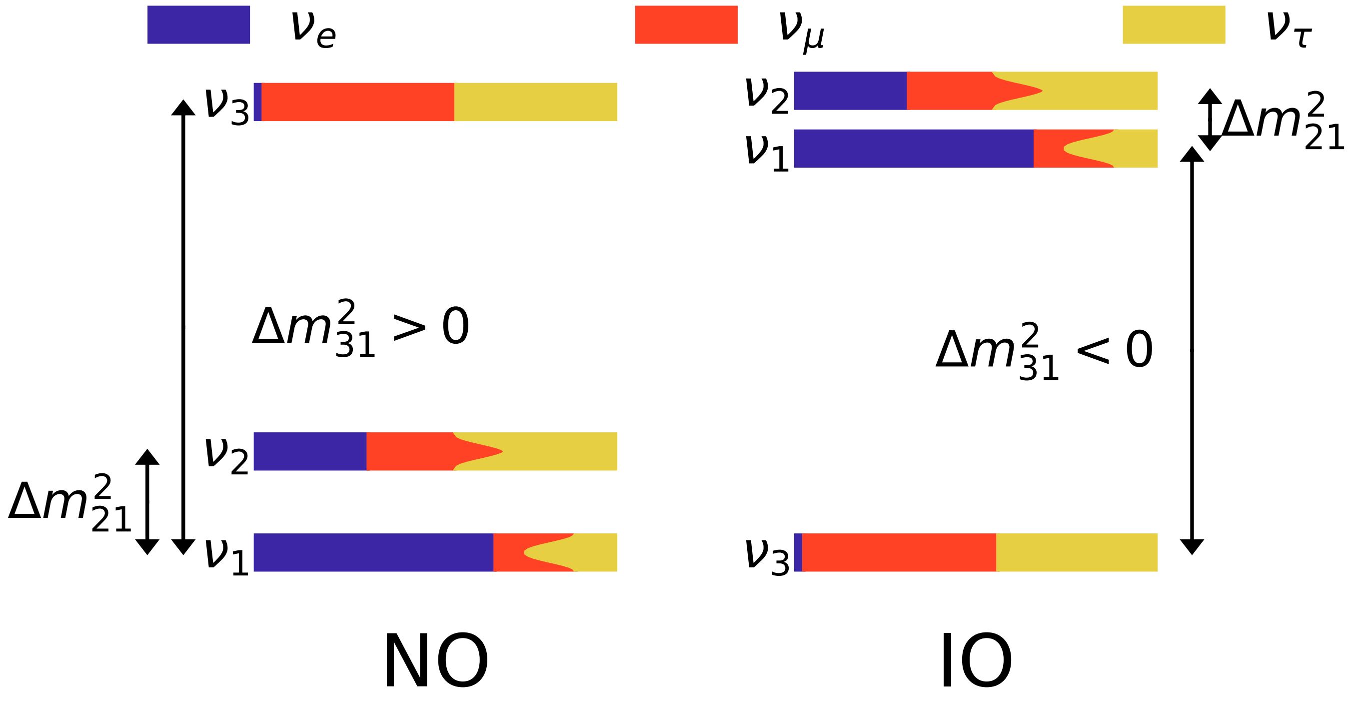
neutrino mass spectrum

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

⇒ absolute neutrino mass: m_0

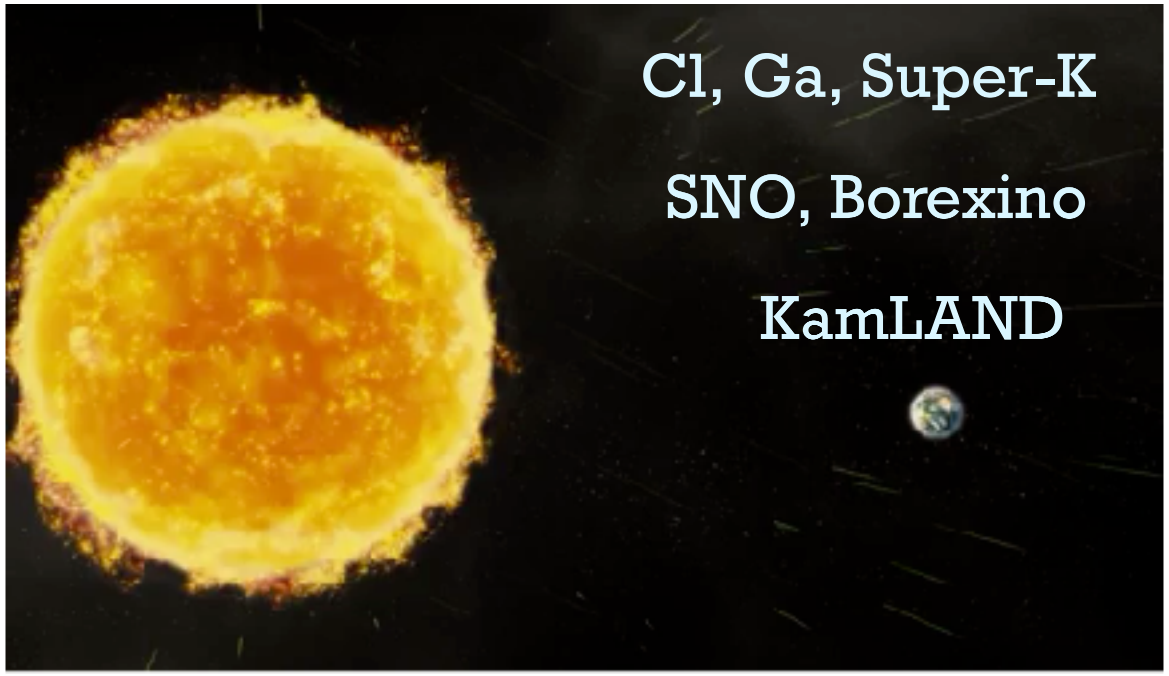
⇒ two mass splittings:

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



Neutrino oscillations

Solar sector

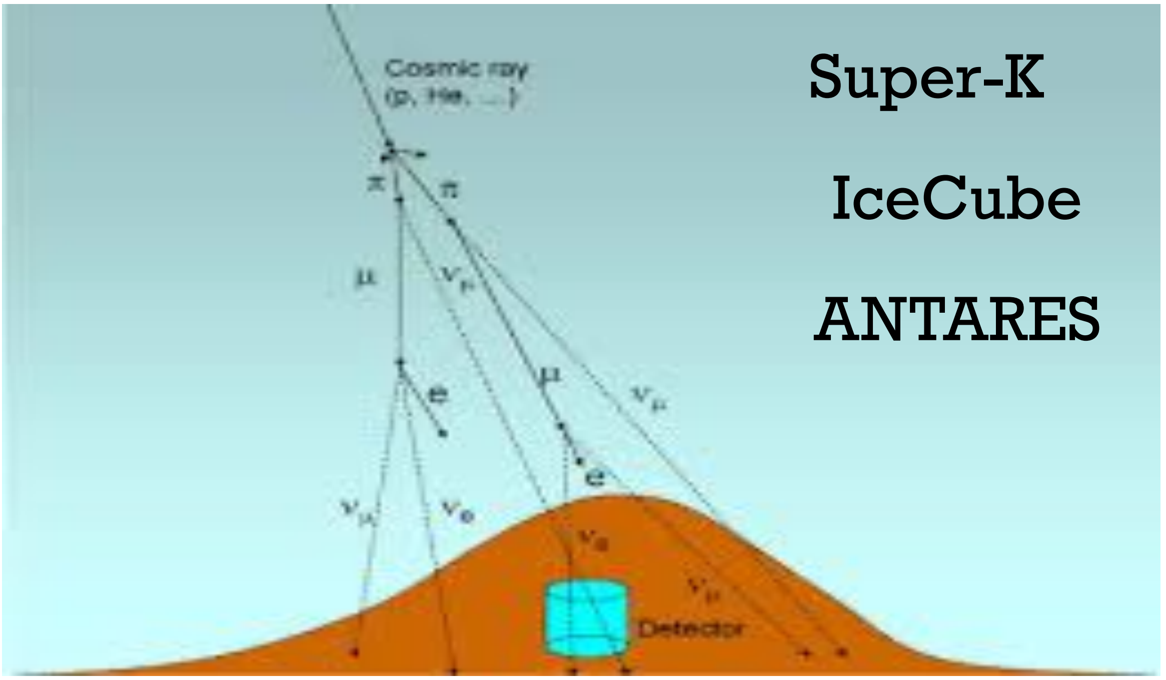


Cl, Ga, Super-K

SNO, Borexino

KamLAND

Atmospheric sector



Super-K

IceCube

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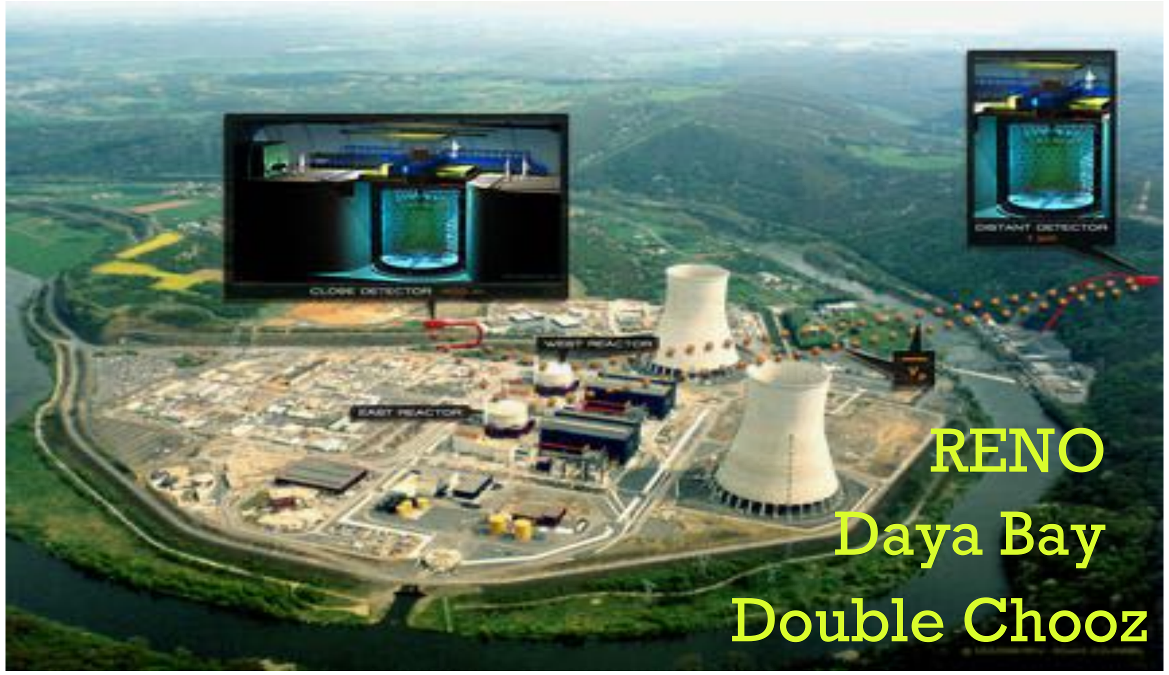
Reactor sector

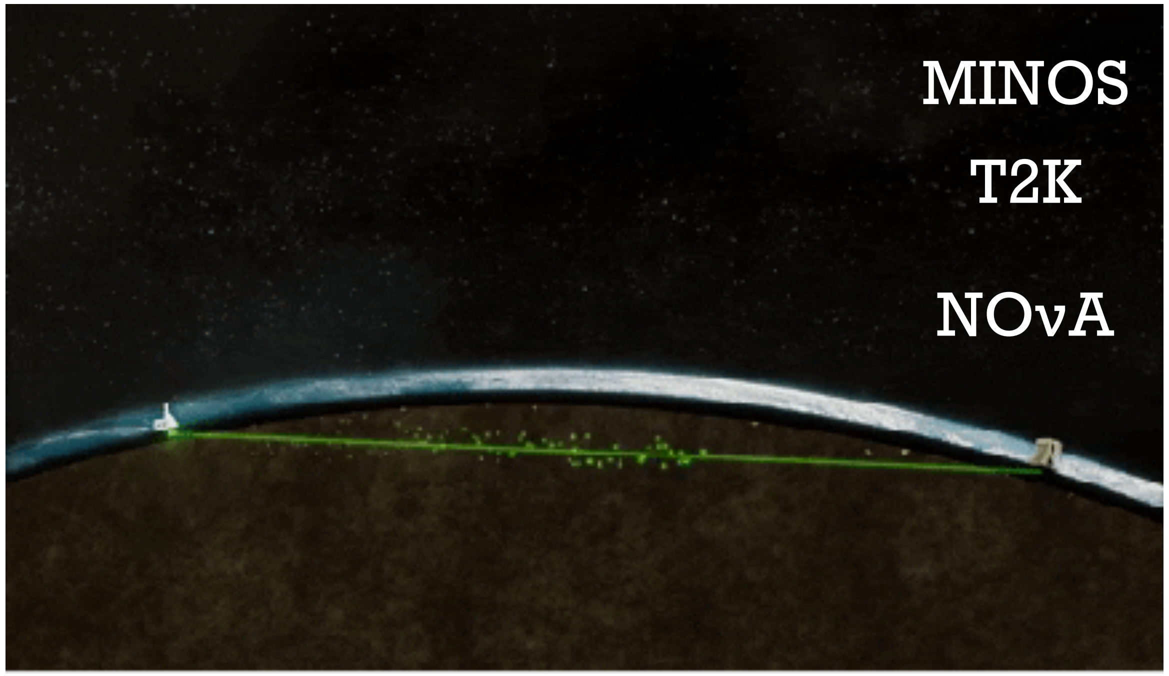


RENO

Daya Bay

Double Chooz

Accelerator sector



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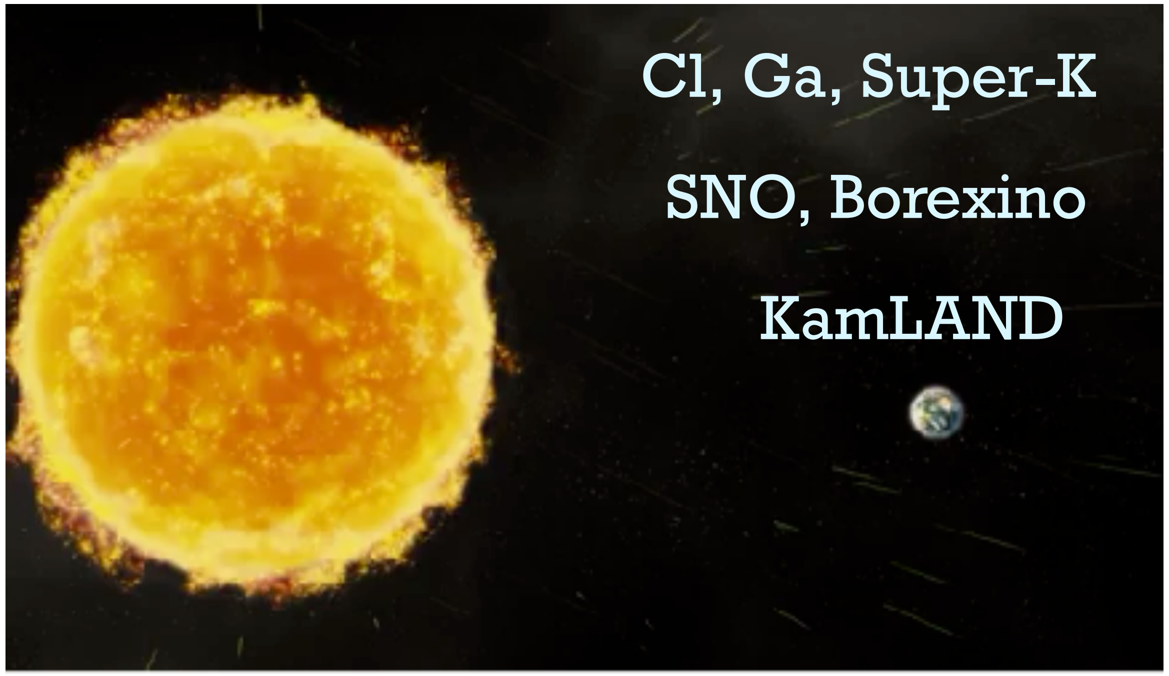
T2K

NOvA

Neutrino oscillations

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

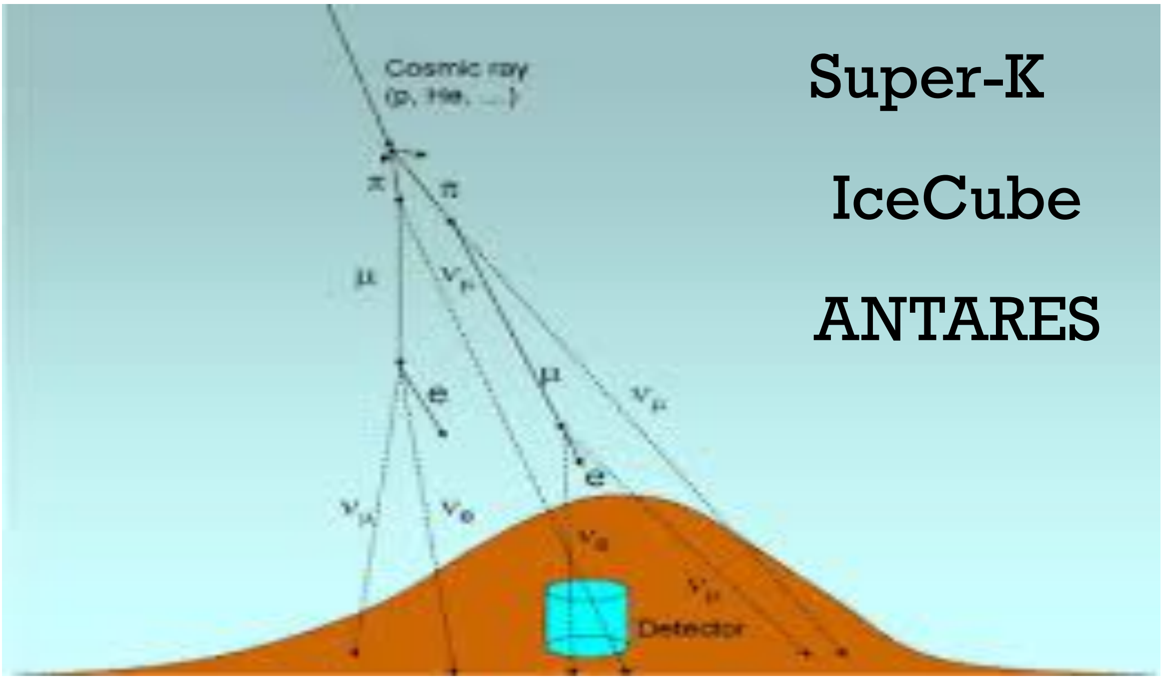


Cl, Ga, Super-K

SNO, Borexino

KamLAND

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

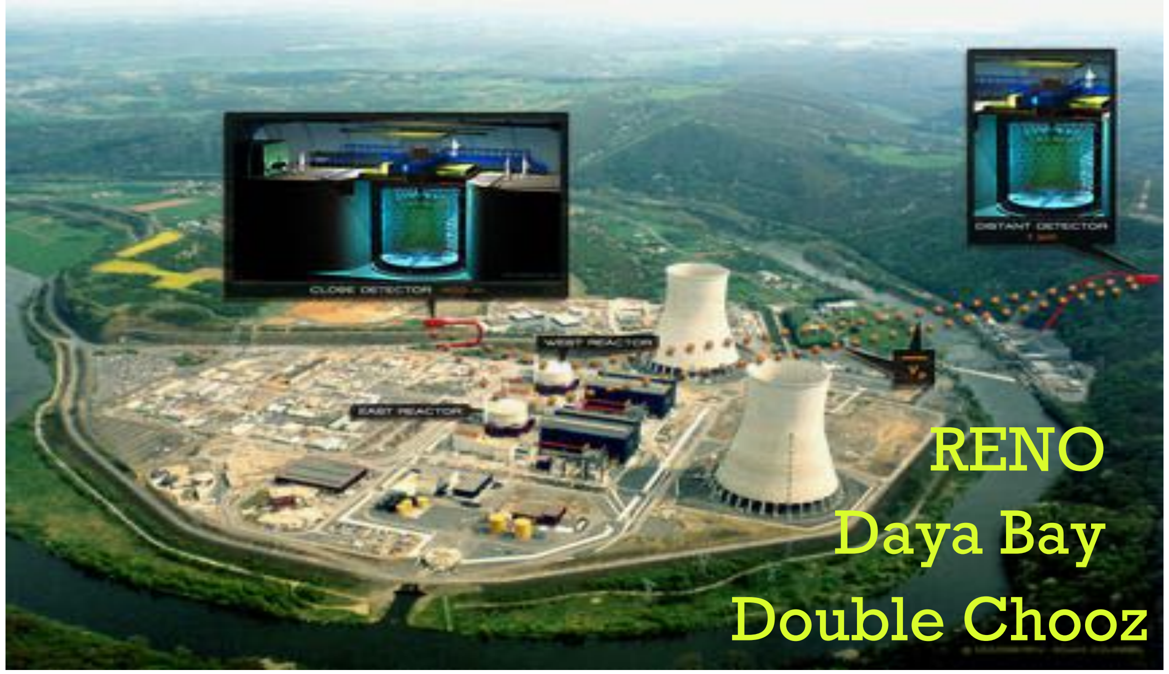


Super-K

IceCube

ANTARES

Reactor sector: θ_{13}, Δm^2_{31}

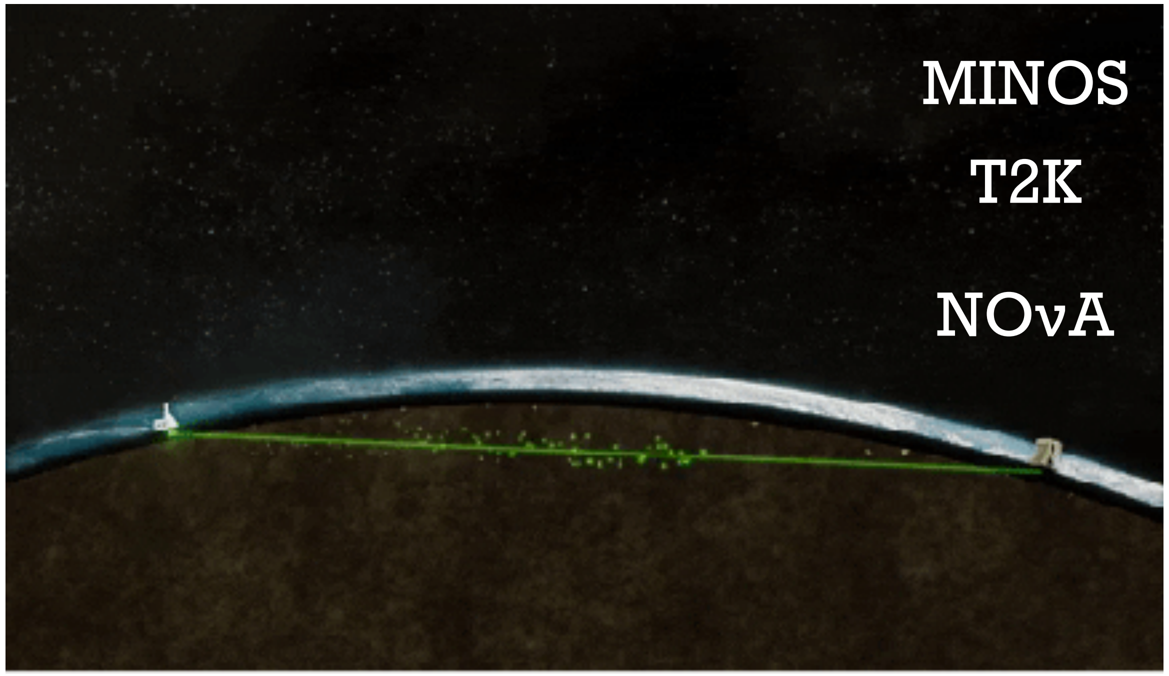


RENO

Daya Bay

Double Chooz

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

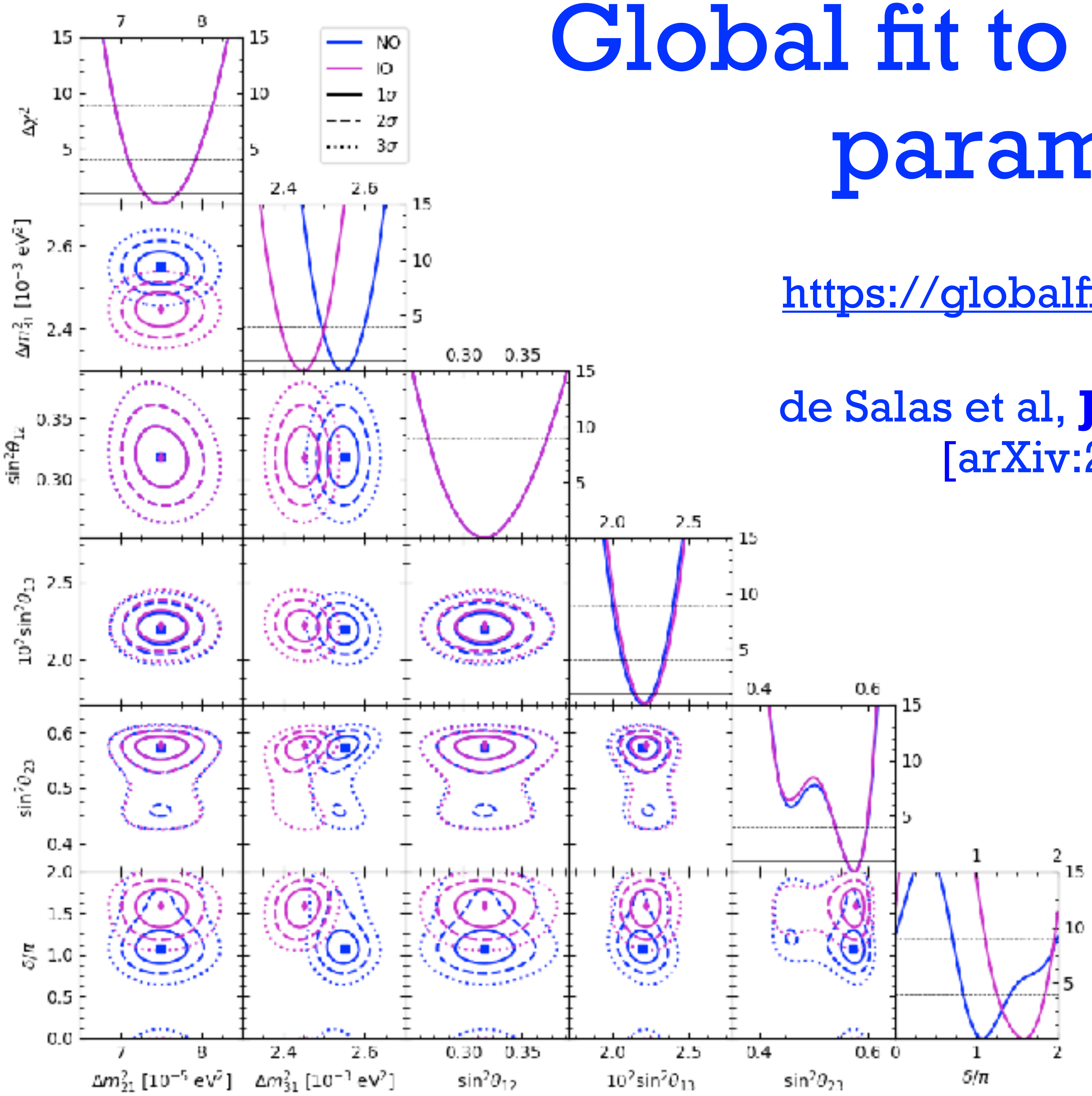


MINOS

T2K

NOνA

Global fit to ν oscillation parameters



https://globalfit.astroparticles.es/

de Salas et al, **JHEP 02 (2021) 071**
[arXiv:2006.11237]

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]

See also NuFIT and Bari group analyses

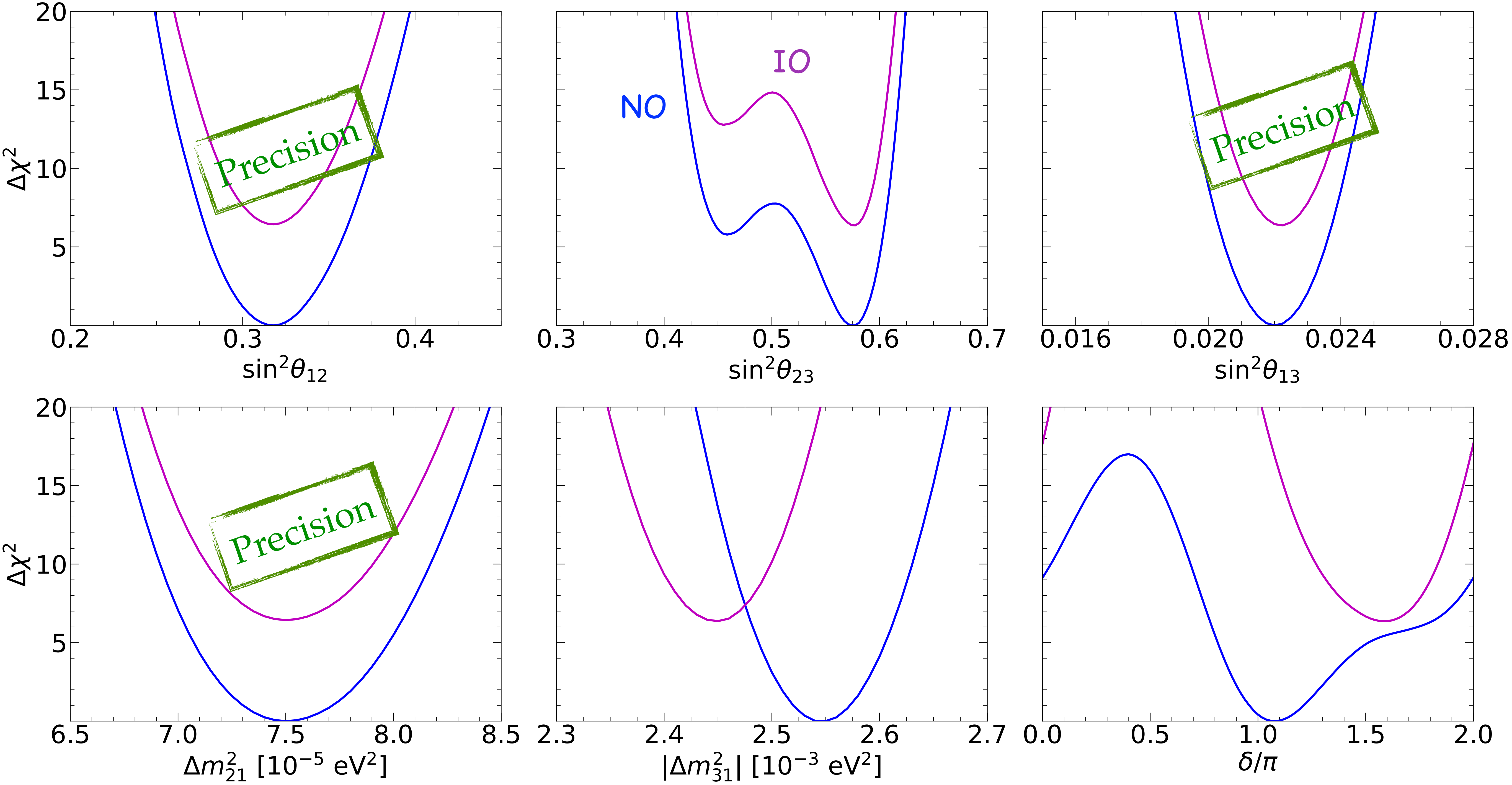
https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1.1%
$\|\Delta m^2_{31}\|$ $[10^{-3}\mathrm{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.37–2.53	
$\sin^2\theta_{12}$ $/10^{-1}$	3.18 ± 0.16	2.71 3.69	5.2%
$\sin^2\theta_{23}$ $/10^{-1}$ (NO)	5.74 ± 0.14	4.34–6.10	5.1%
$\sin^2\theta_{23}$ $/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	4.33 6.08	
$\sin^2\theta_{13}$ $/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.000 2.405	3.0%
$\sin^2\theta_{13}$ $/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.018–2.424	
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.71–1.99	20%
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.11–1.96	9.0%

relative 1σ uncertainty

Global fit to ν oscillation parameters

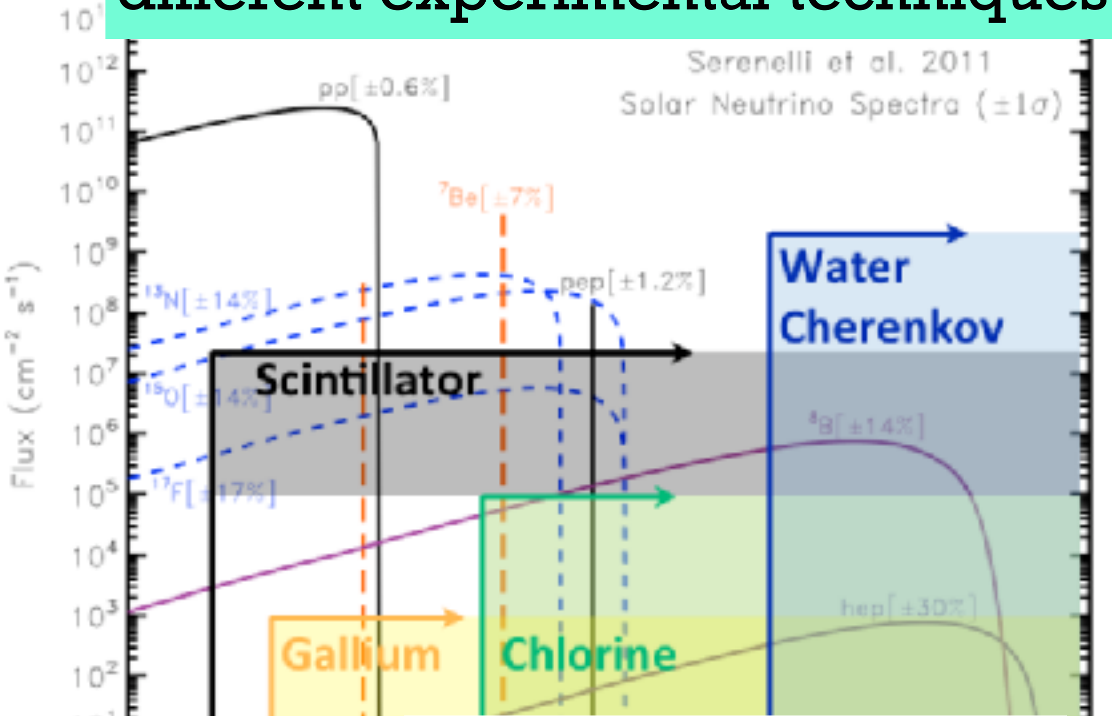
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



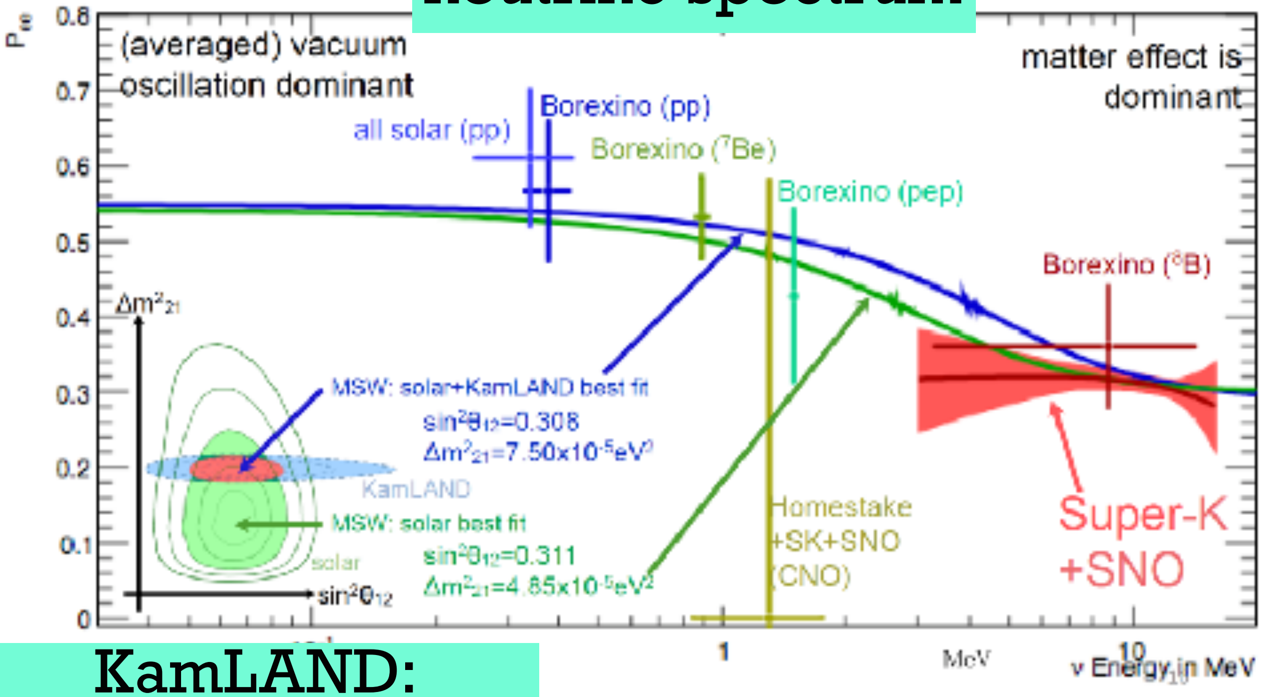
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

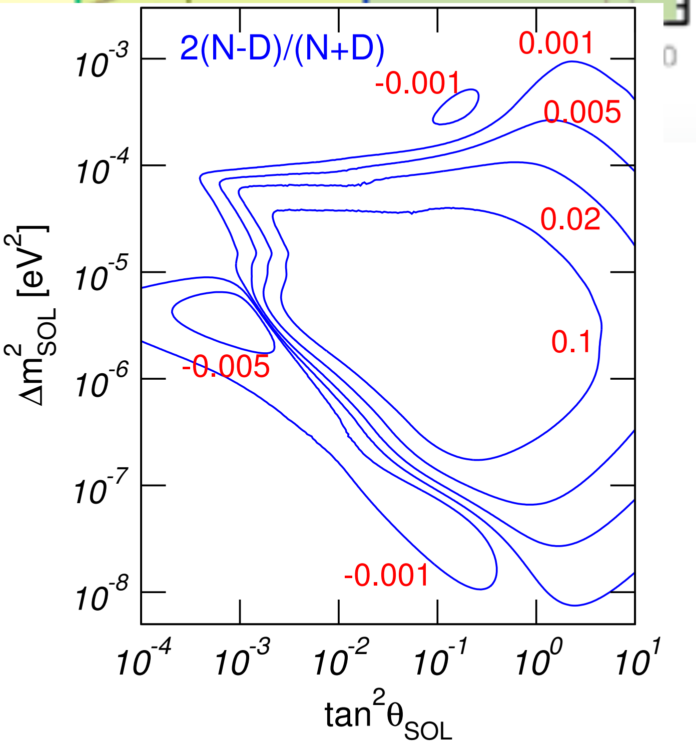
different experimental techniques



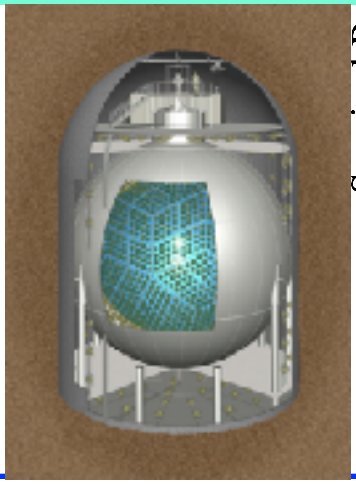
neutrino spectrum

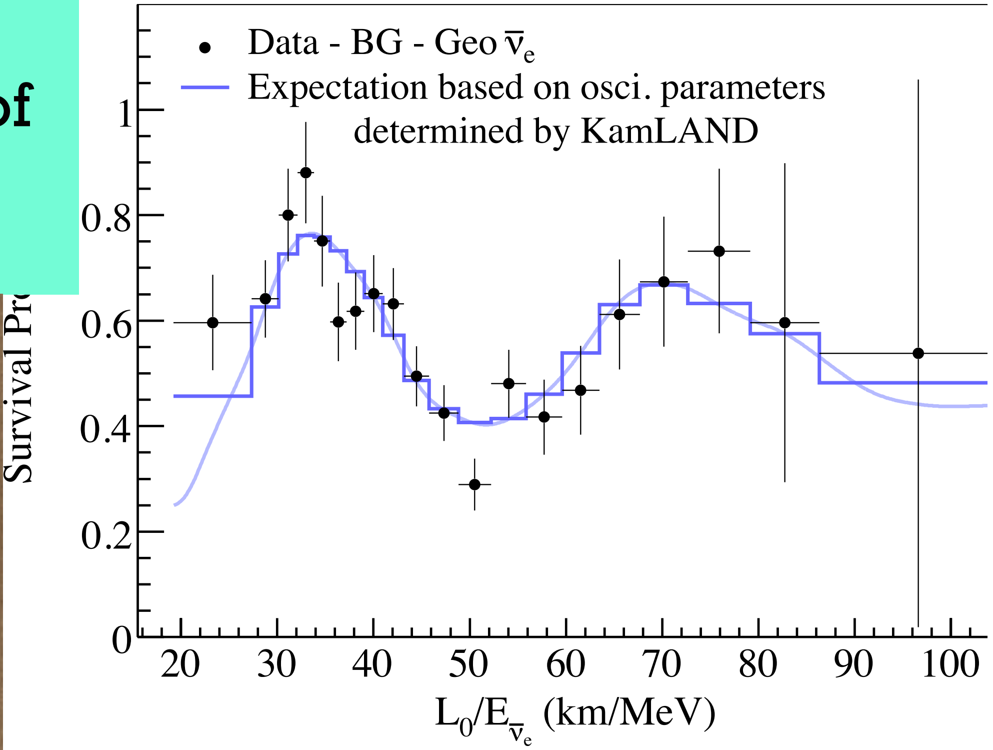


day/night asymmetry

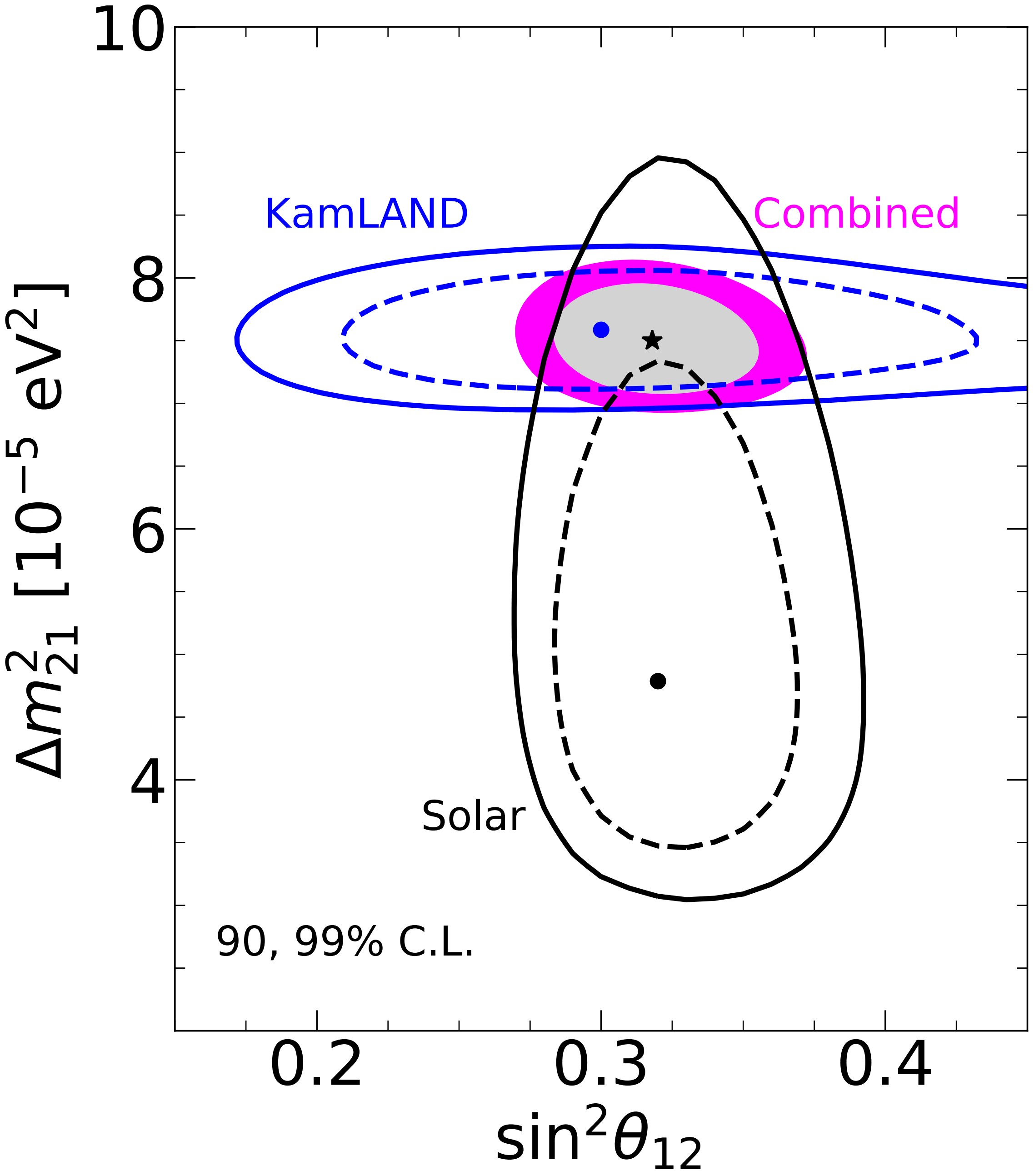


KamLAND: precise measurement of oscillation frequency



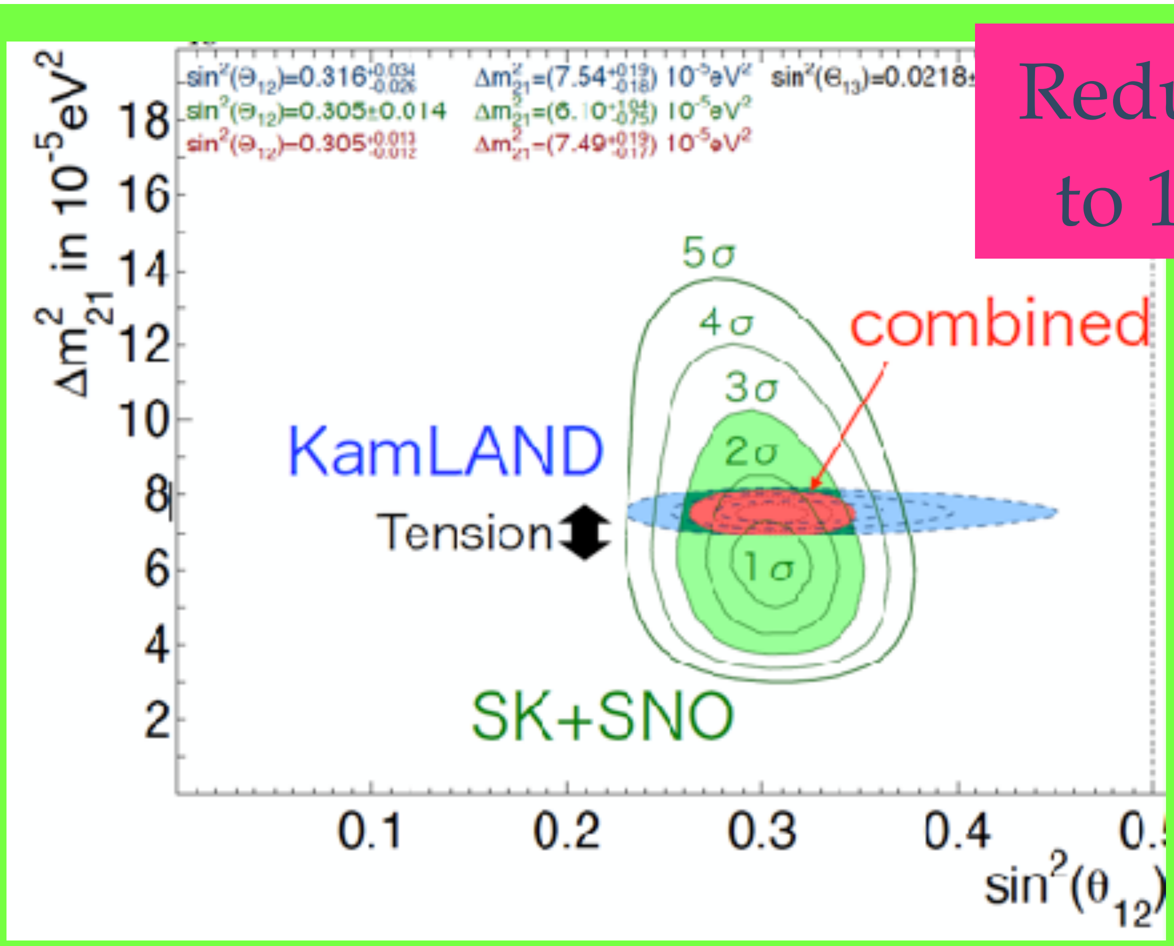


The solar sector



de Salas et al, **JHEP 02 (2021) 071**
[arXiv:2006.11237]

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

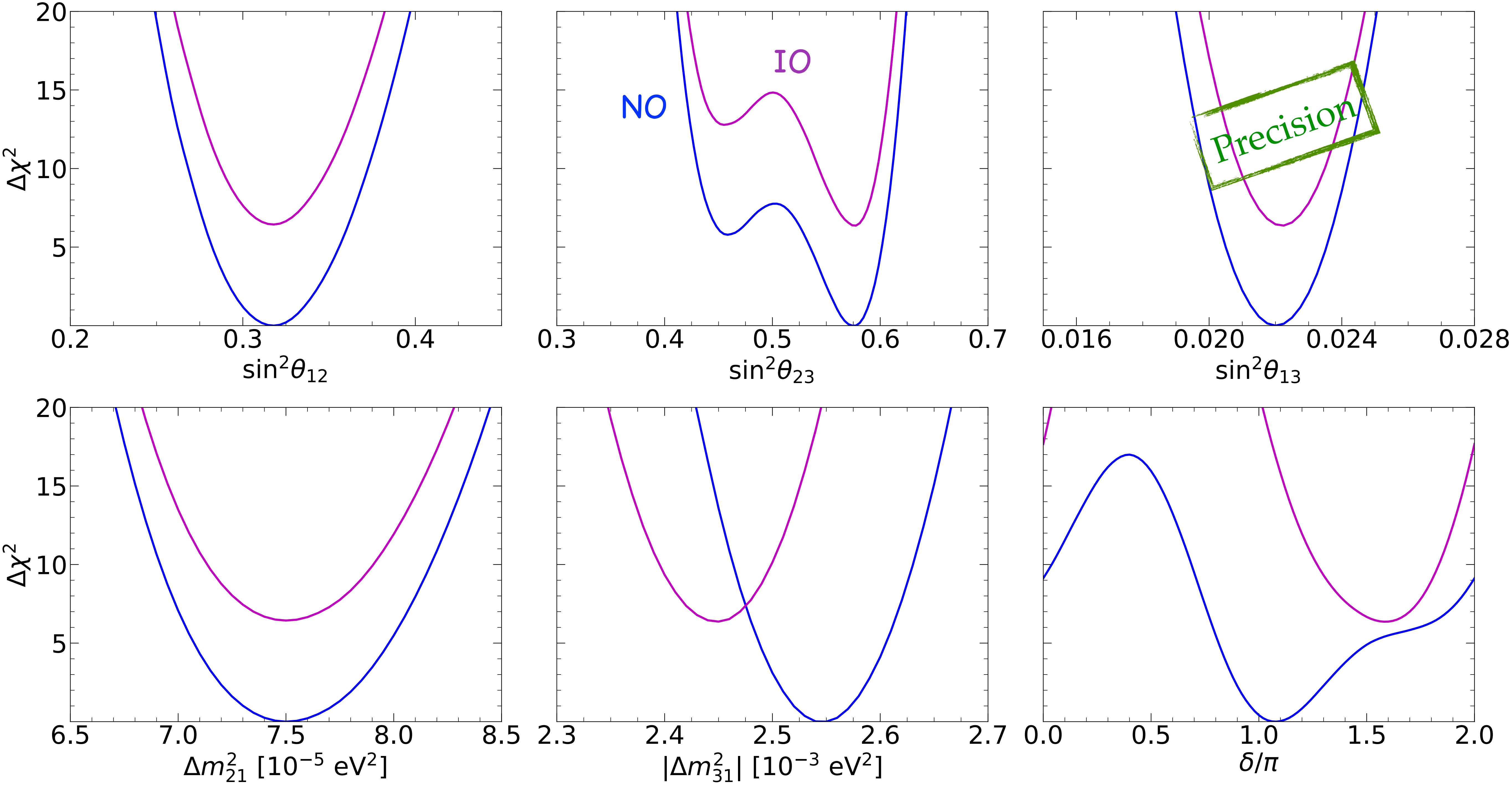


Reduced to 1.5σ

Y. Koshio, Neutrino-2022

Global fit to ν oscillation parameters

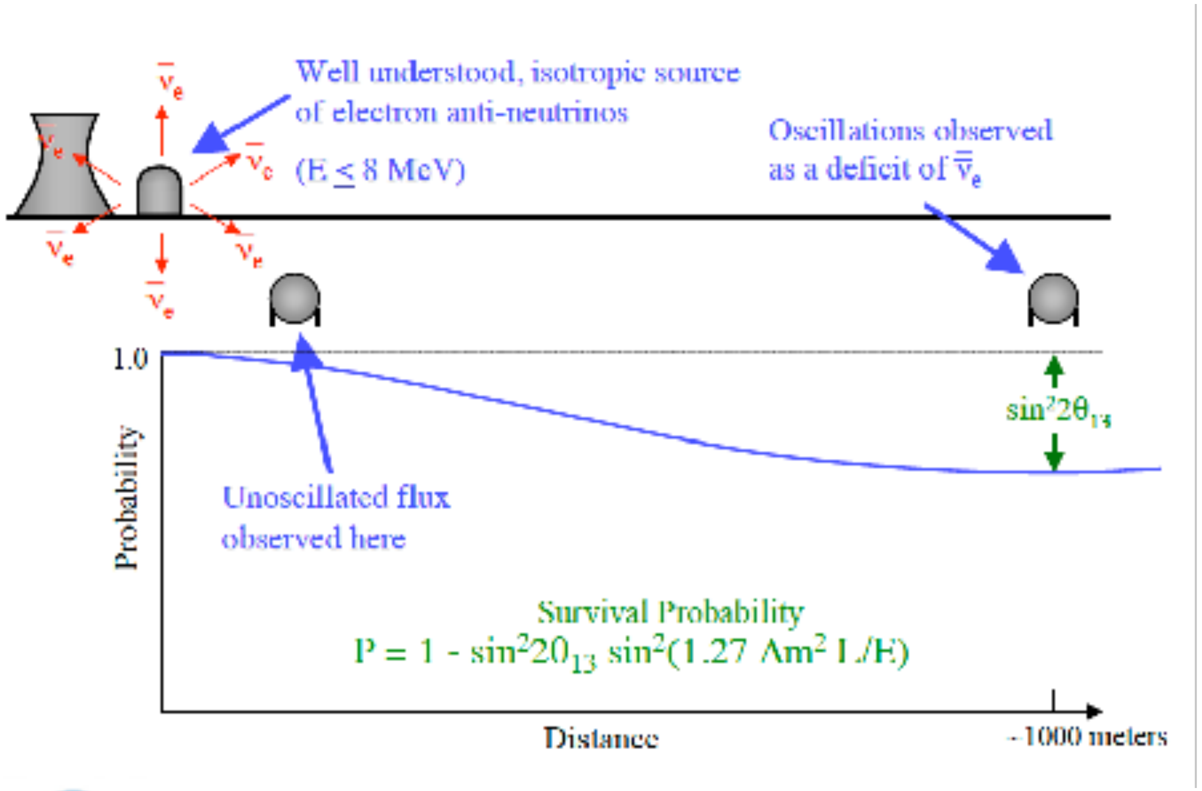
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The reactor sector

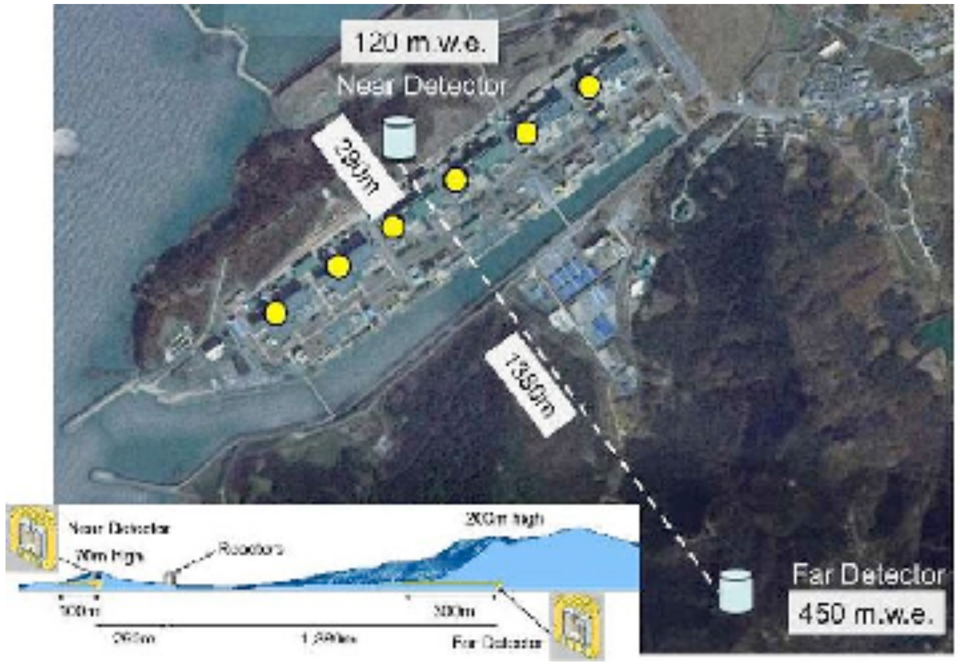
New generation of experiments

- ✦ more powerful reactors
- ✦ larger detector volume
- ✦ 2-8 detectors at 100 m – 1 km



2 cores + 1 ND + 1 FD

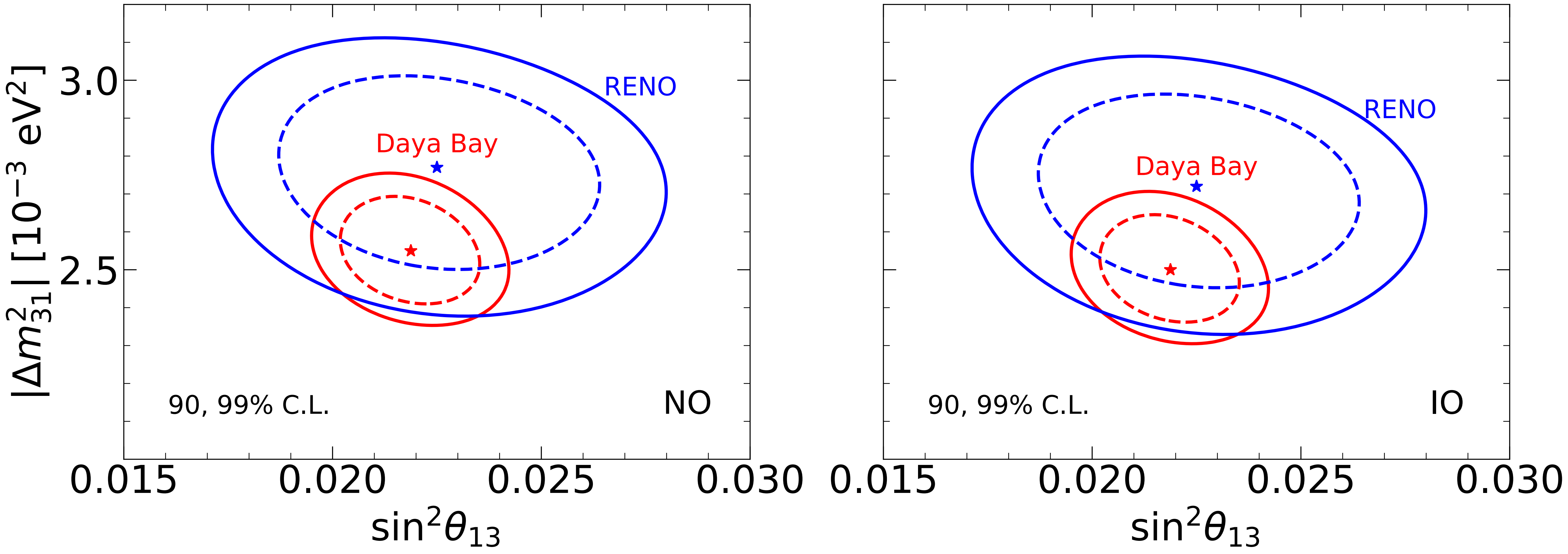
6 cores + 4 ND + 4FD



6 cores + 1 ND + 1 FD

The reactor sector

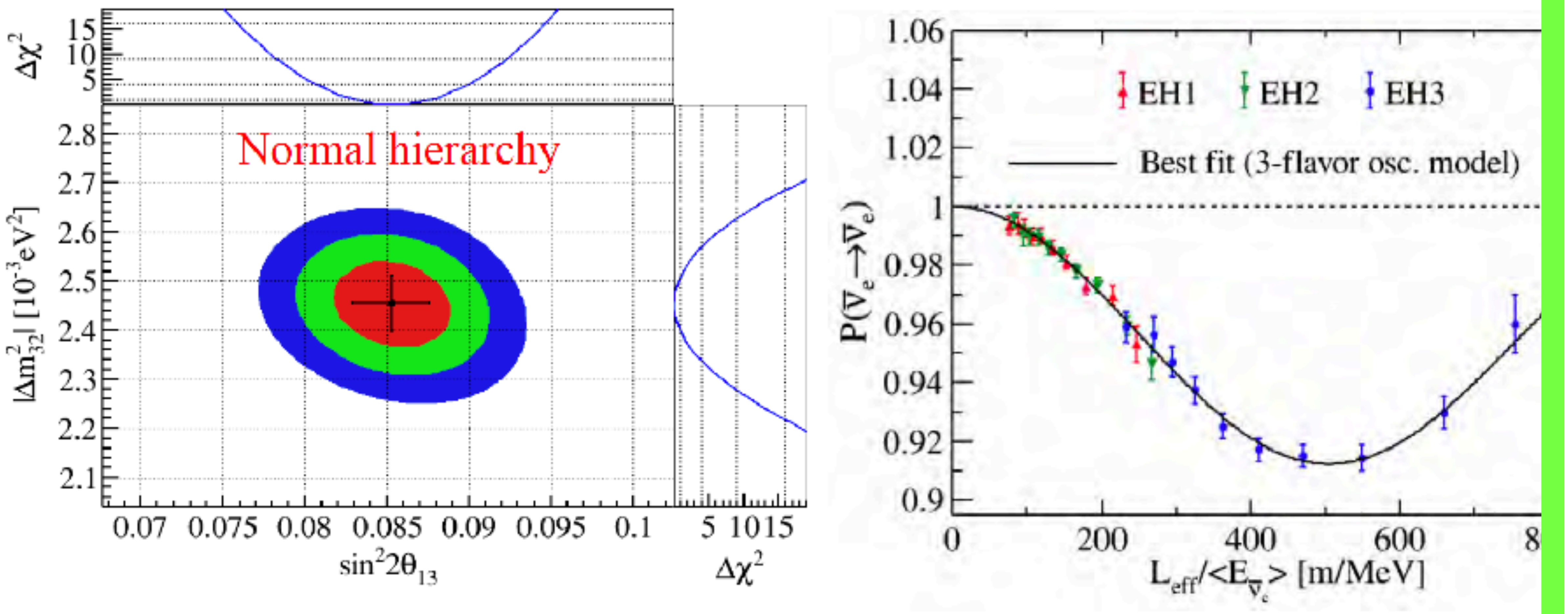
de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]



- Daya Bay: 1958-day data: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (3.4%)
- RENO: 2900-day data: $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ (7%)

Precision dominated by Daya Bay

The reactor sector



Best-fit results: $\chi^2/\mathrm{ndf} = 559/518$

$$\sin^2 2\theta_{13} = 0.0853^{+0.0024}_{-0.0024}$$ (2.8% precision)

Daya Bay: 3158-day data

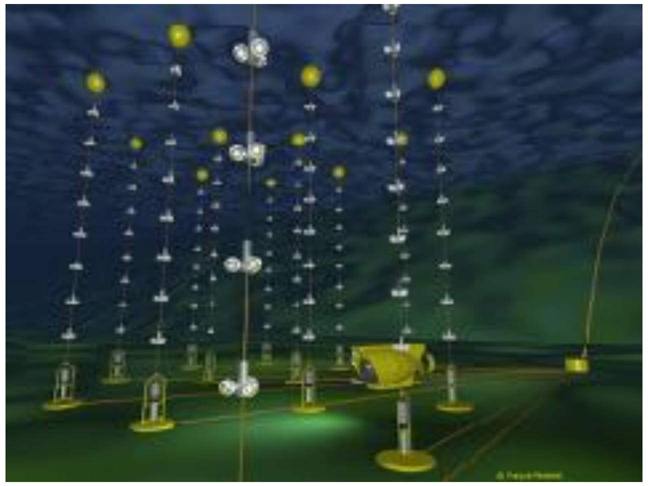
K. Luk, Neutrino-2022

The atmospheric sector

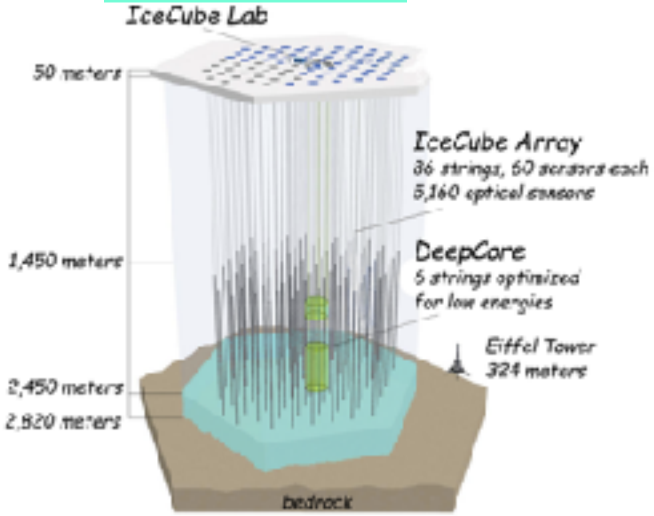
Atmospheric experiments

Super-Kamiokande

ANTARES

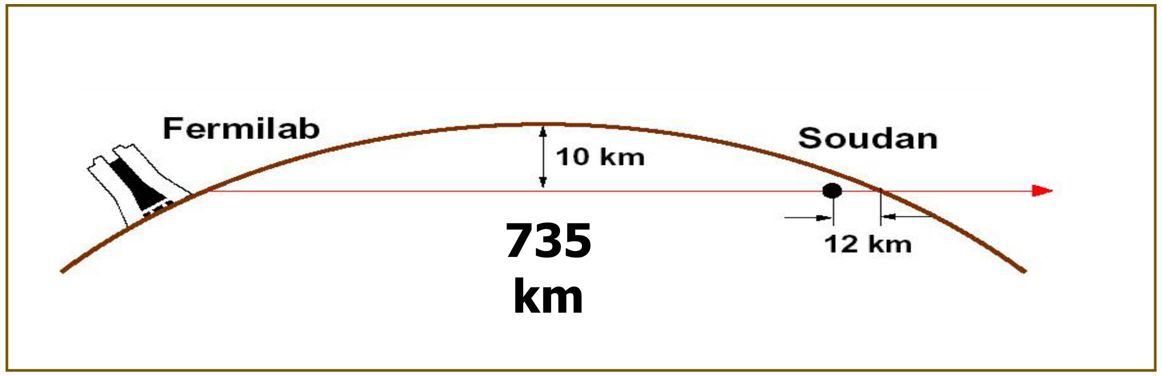


IceCube

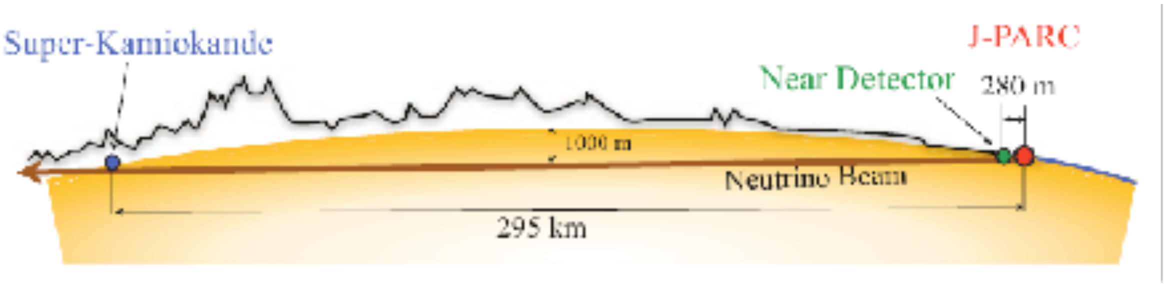


Accelerator long-baseline experiments

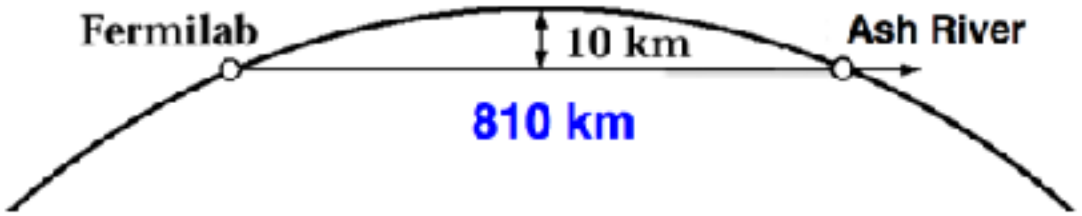
MINOS



T2K



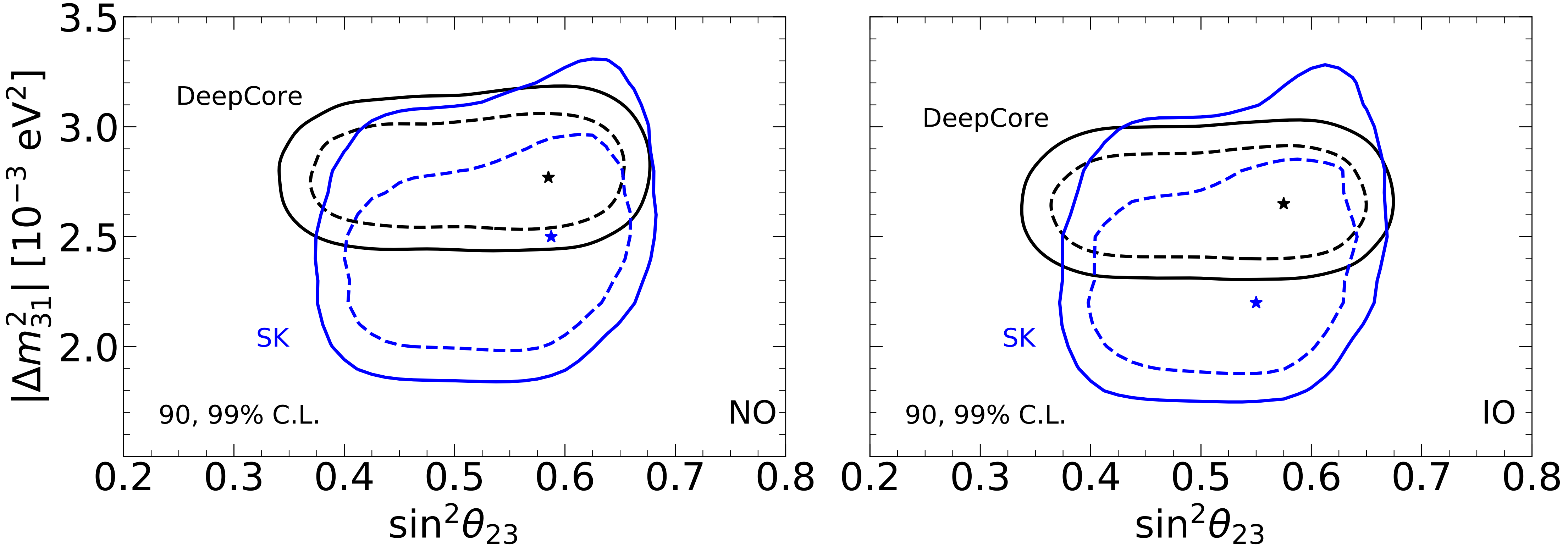
NOvA

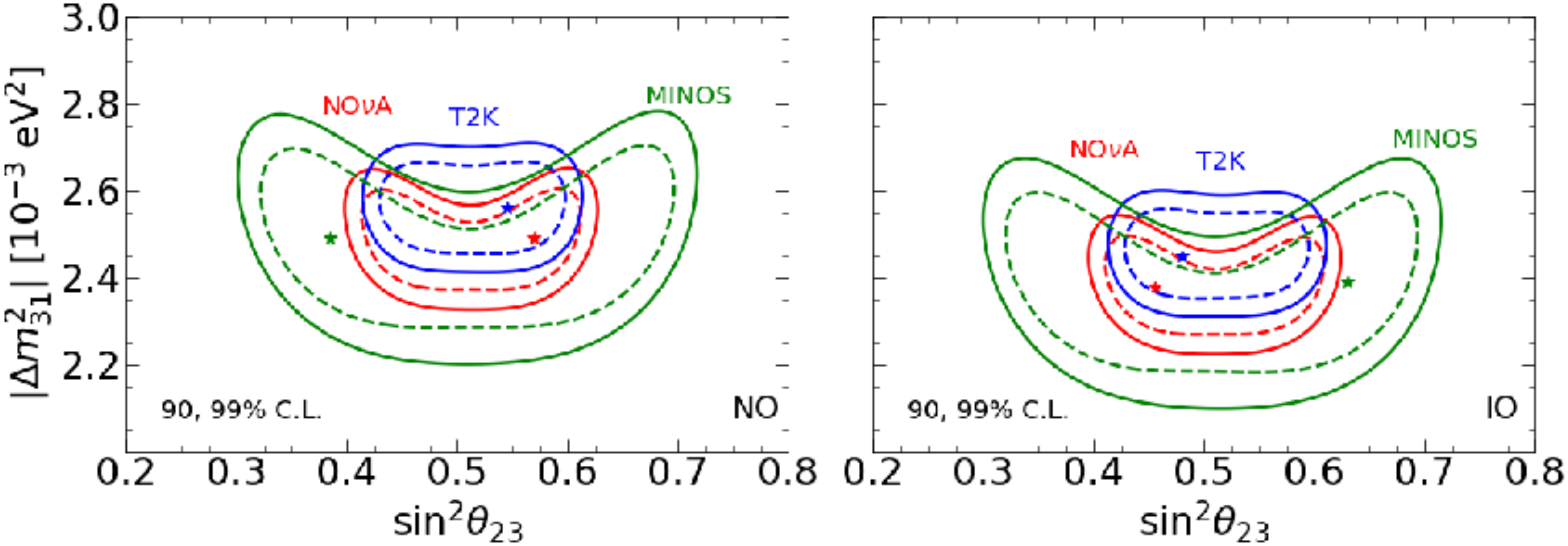


→ consistent with atmospheric data

→ atm ν oscillations confirmed by lab exps

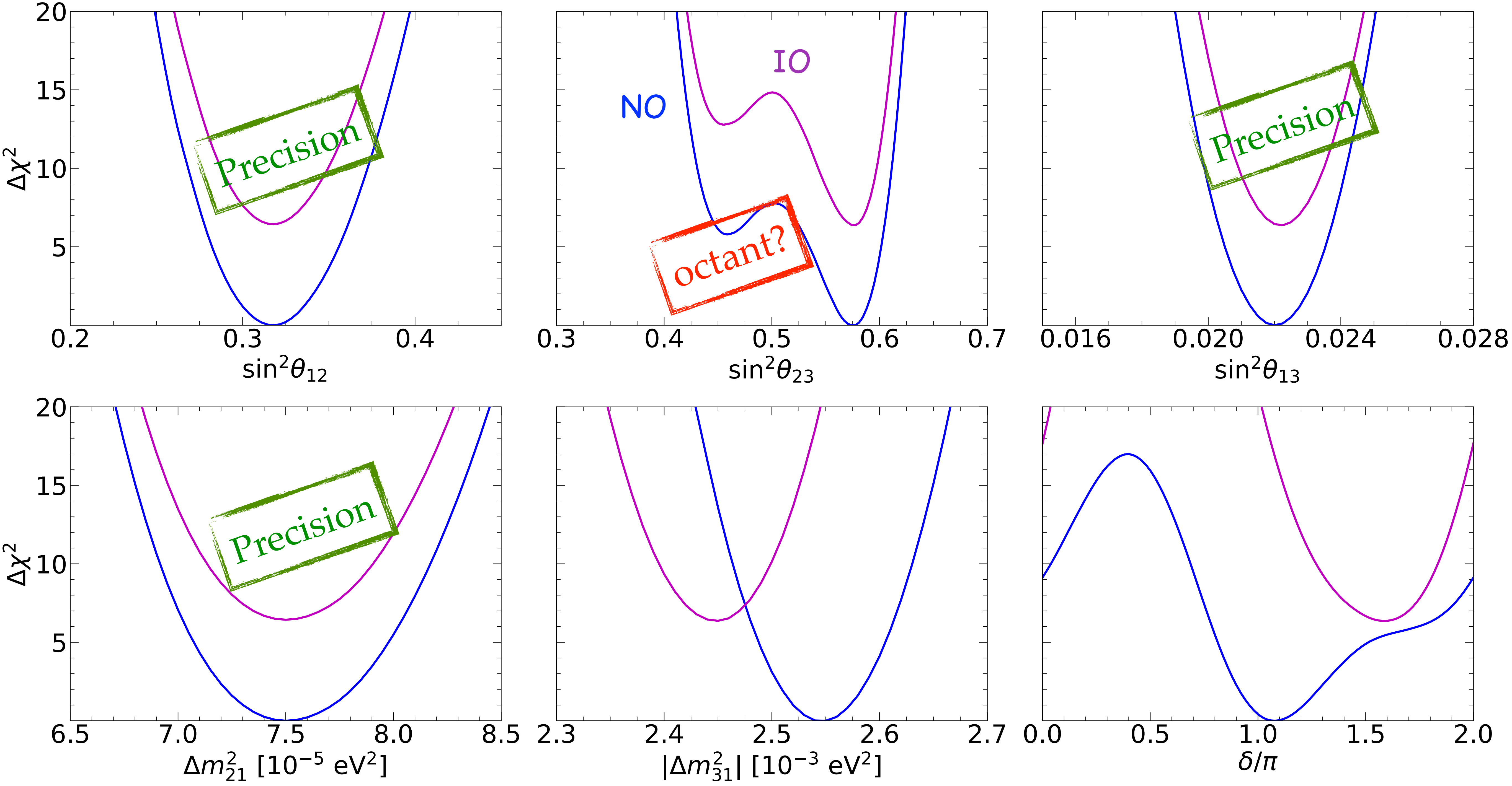
The atmospheric sector





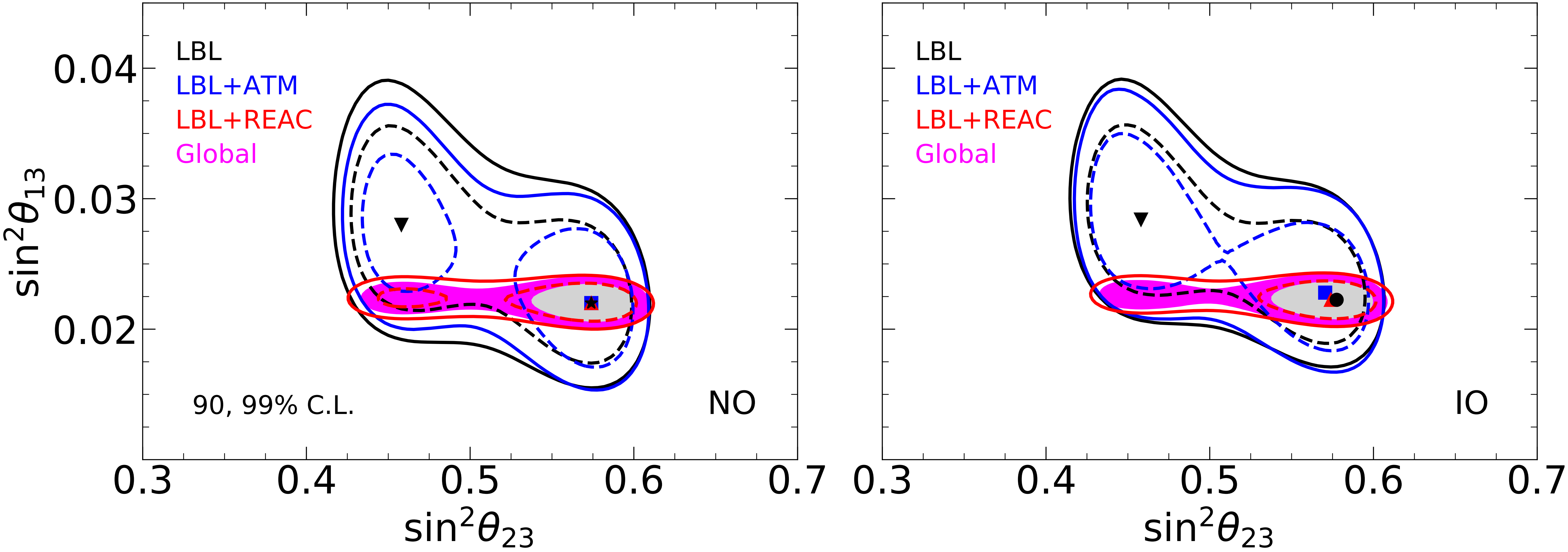
Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The octant of θ_{23}

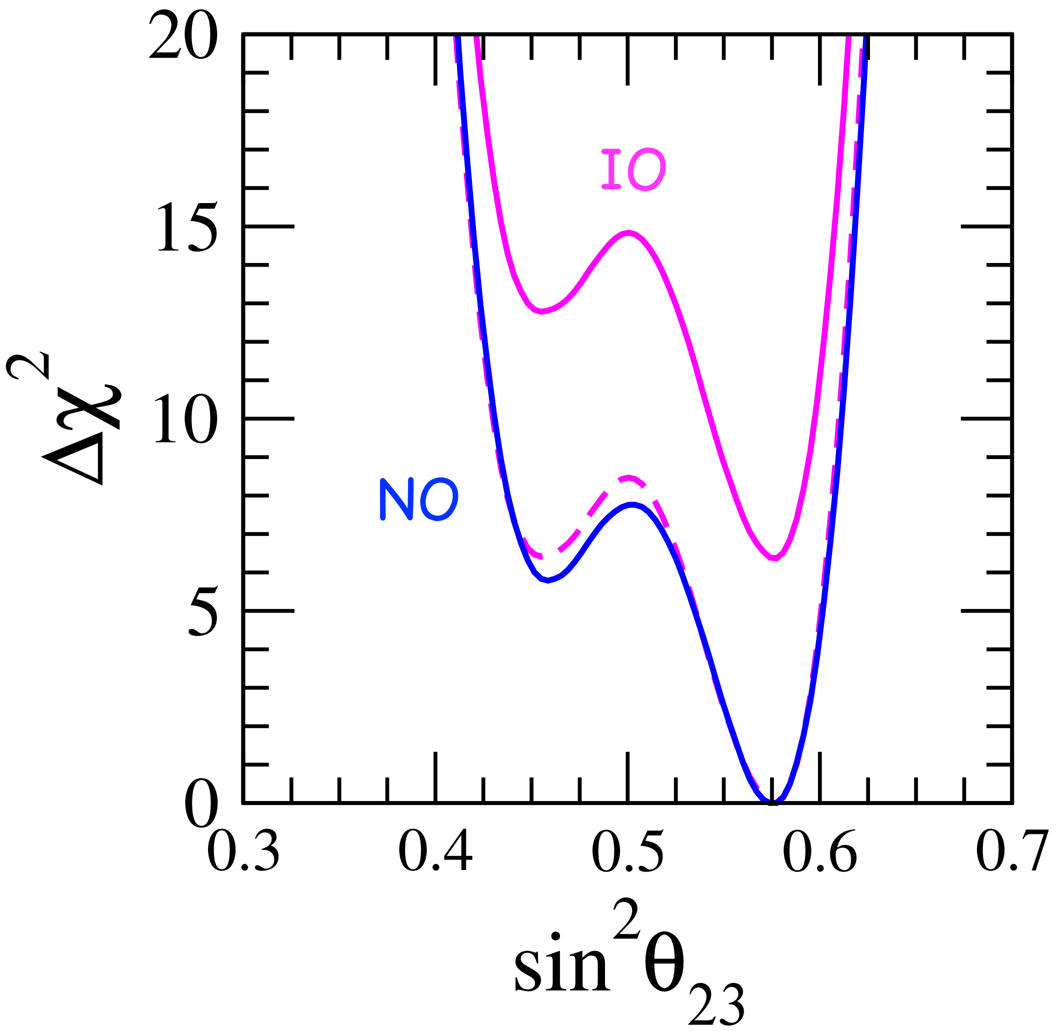
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



- ✦ The combination of LBL experiments slightly prefers $\theta_{23} < 45°$ for both orderings
- ✦ The combination with atmospheric data shifts the preferred θ_{23} to the second octant
- ✦ The combination with SBL reactors also breaks the degeneracy in favor of 2nd octant

The octant of θ_{23}

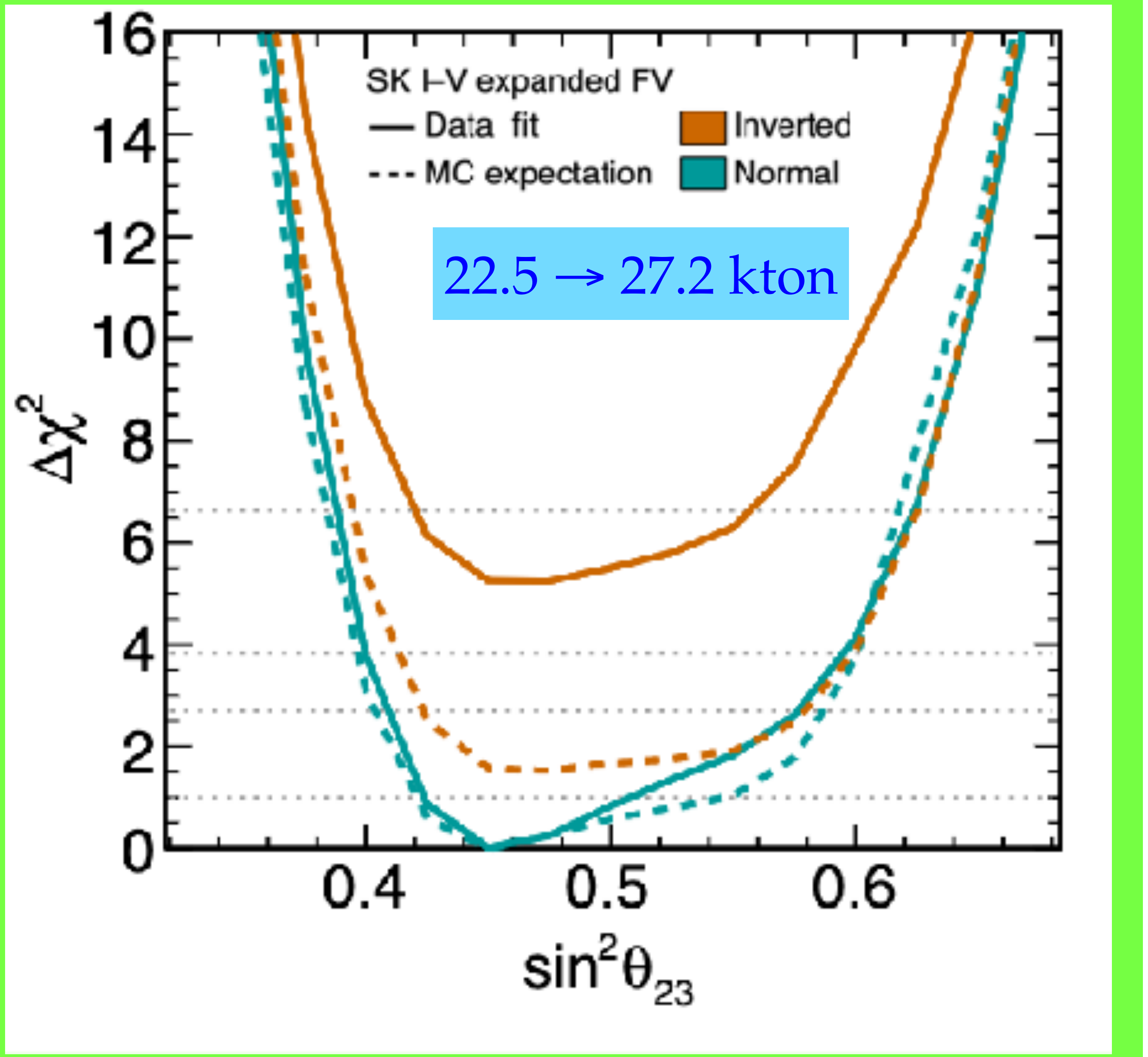
de Salas et al, JHEP 02 (2021) 071



1st octant disfavored with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)

$\Delta\chi^2$ (45°) = 7.8 (8.5) for NO (IO)

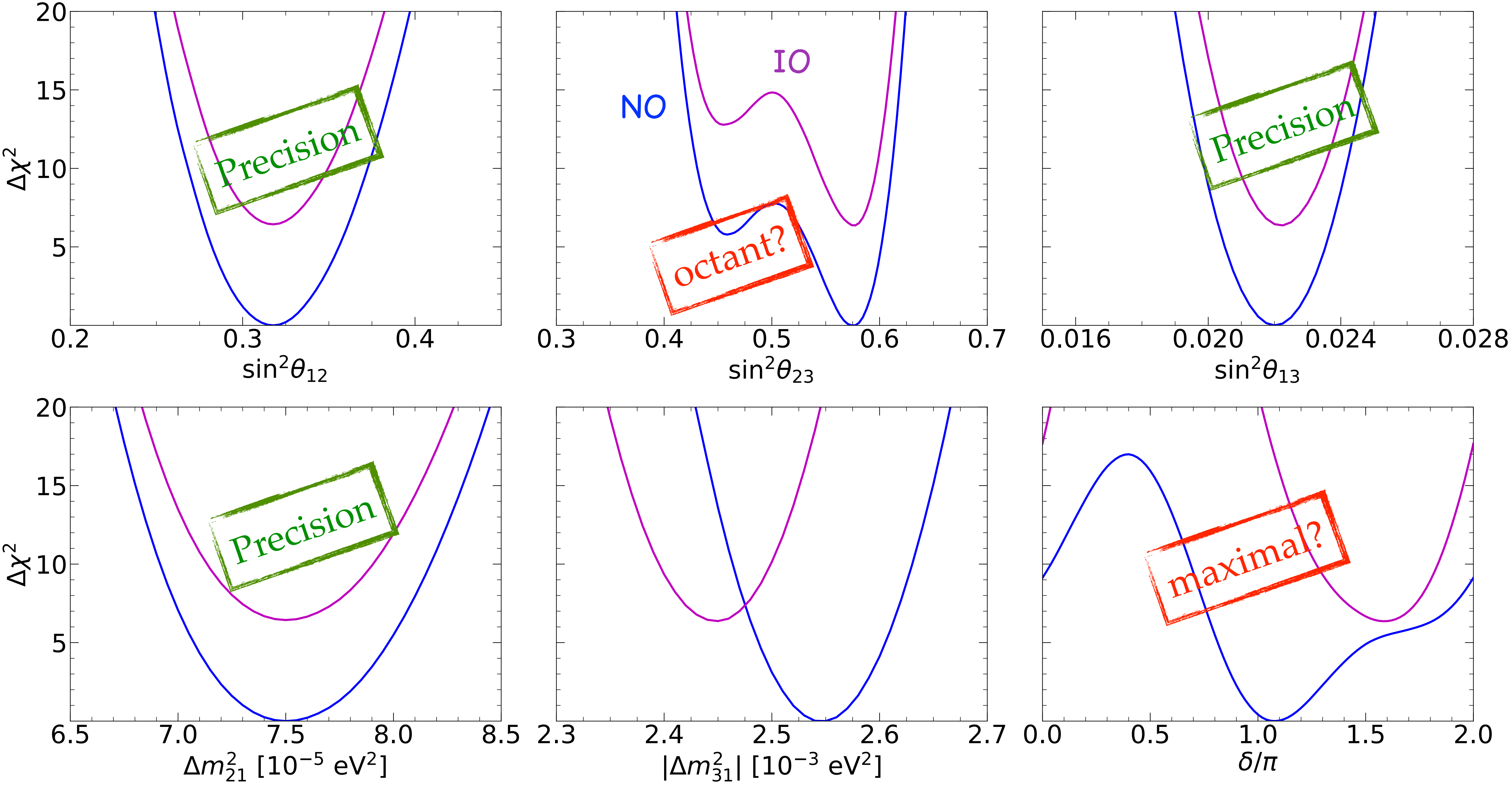
Super-K Coll. arXiv:2311.05105



Best fit at $\sin^2\theta_{23} = 0.45$, with UO allowed at 1σ

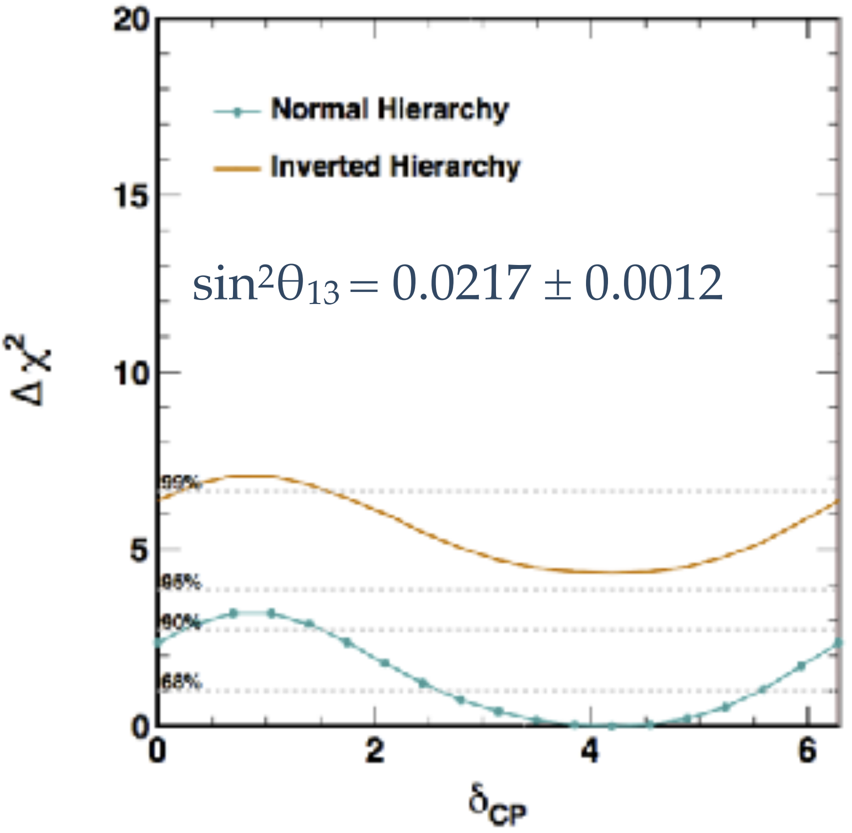
Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The CP phase

Super-Kamiokande (atm)



$\sin^2\theta_{13} = 0.0217 \pm 0.0012$

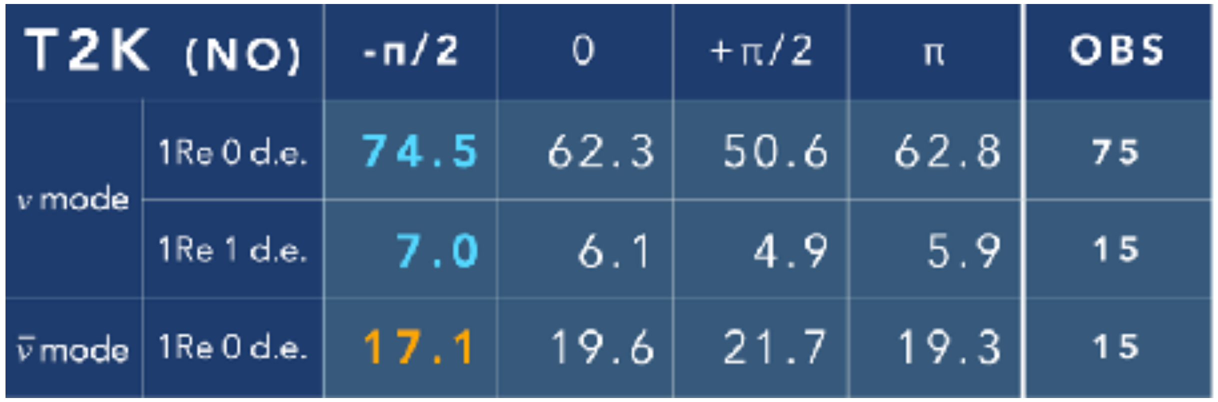
- ✦ δ_{BF} = 1.5π (1.2π) for NO (IO)
- ✦ preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

T2K

H. Tanaka, TAUP 2019

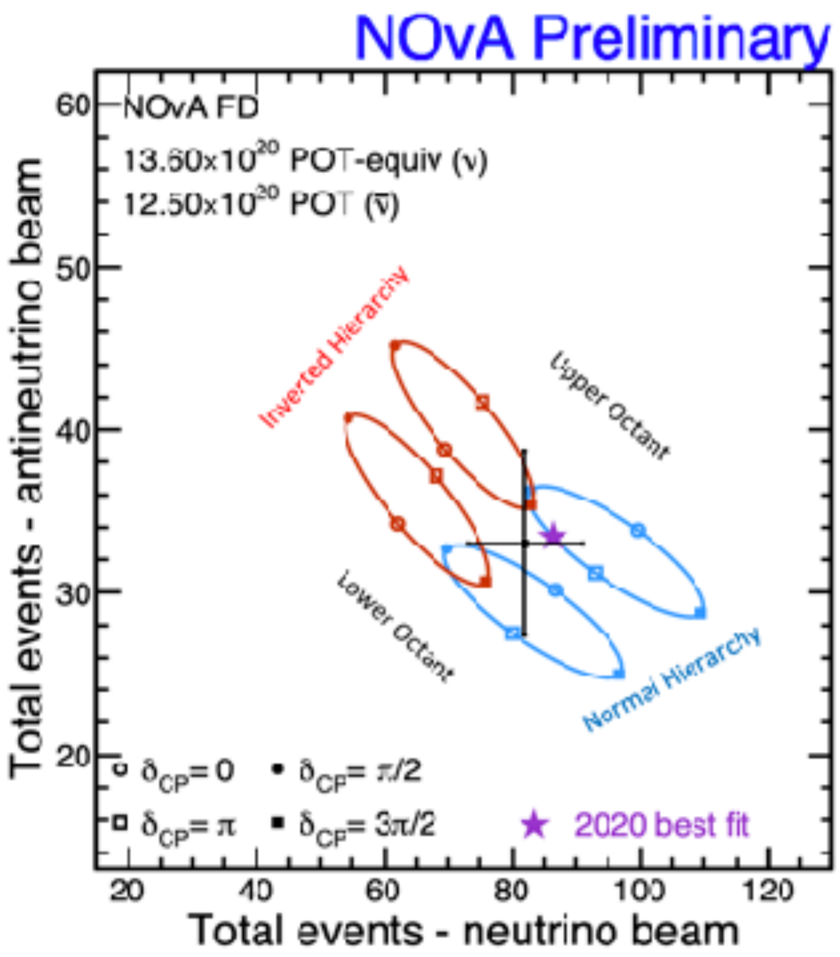
$\delta_{BF} \simeq 3\pi/2$ due to better agreement with observed ν_e and $\bar{\nu}_e$ events



T2K (NO)		-π/2	0	+π/2	π	OBS
ν mode	1Re 0 d.e.	74.5	62.3	50.6	62.8	75
	1Re 1 d.e.	7.0	6.1	4.9	5.9	15
$\bar{\nu}$ mode	1Re 0 d.e.	17.1	19.6	21.7	19.3	15

NOvA

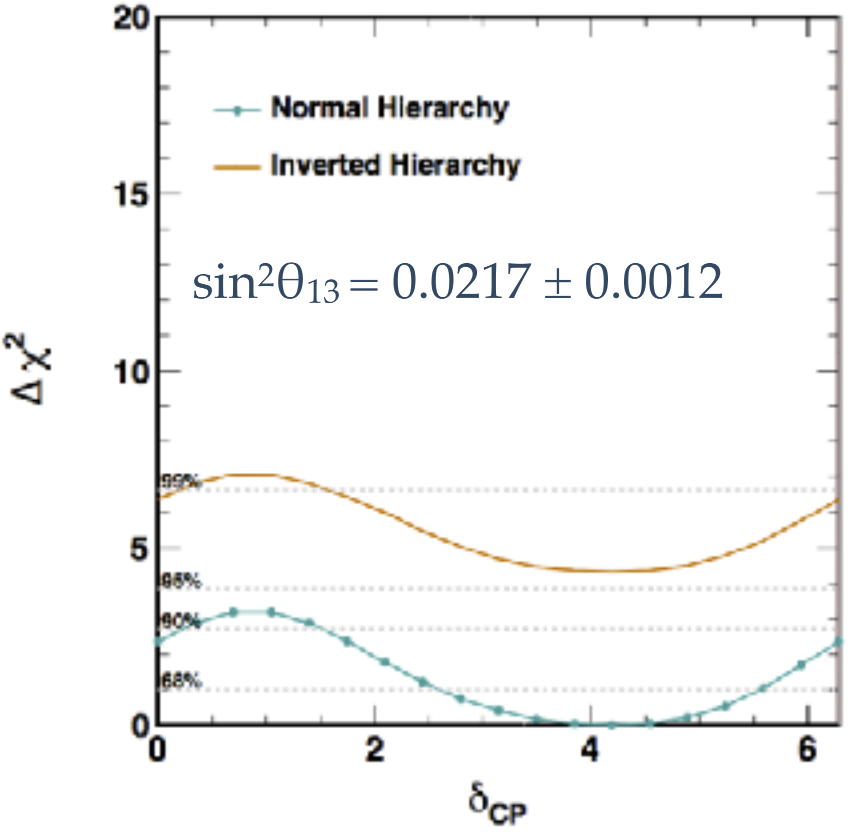
No strong asymmetry in the ν_e / $\bar{\nu}_e$ app rates



P Vahle, TAUP 2021

The CP phase

Super-Kamiokande (atm)

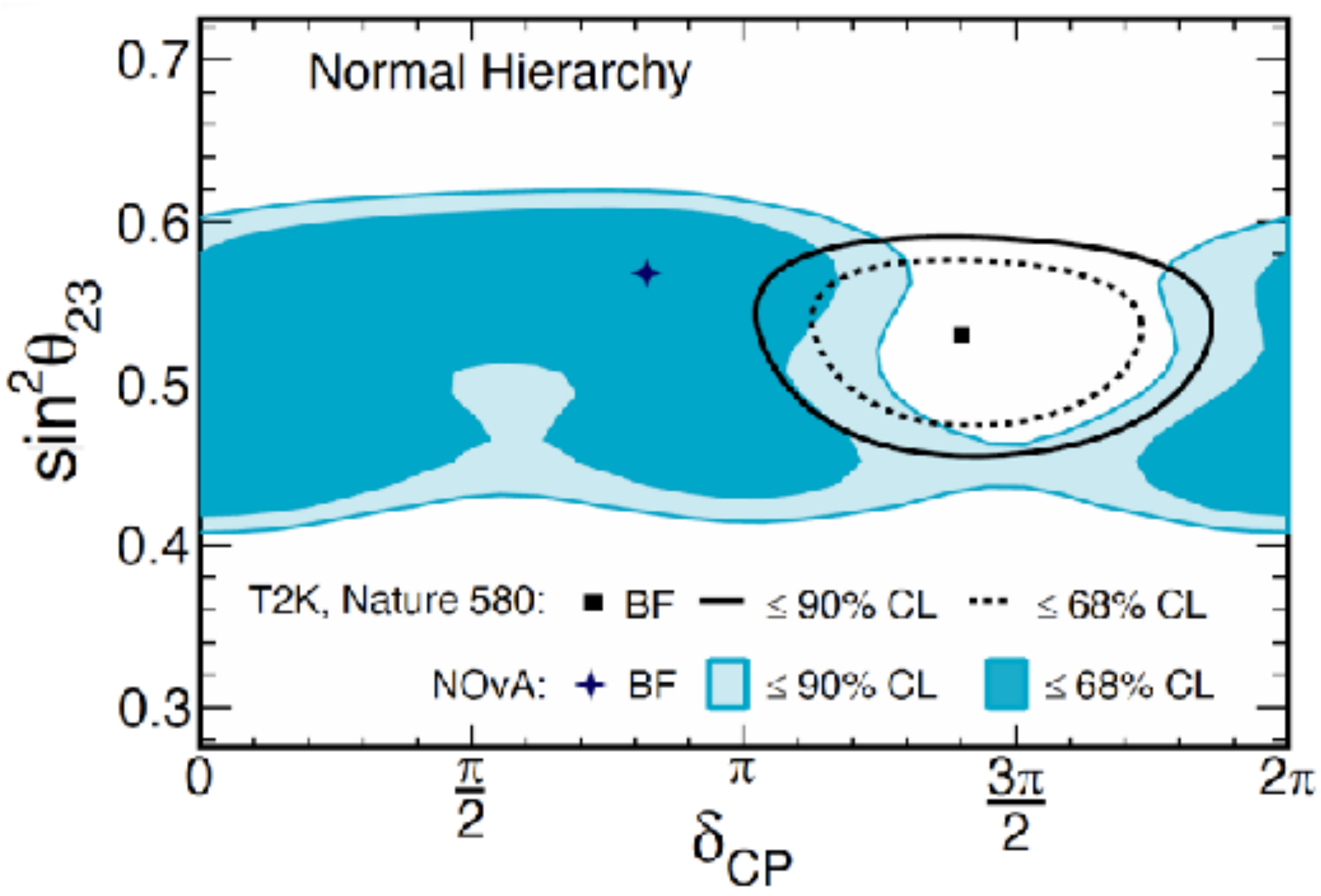


$\sin^2\theta_{13} = 0.0217 \pm 0.0012$

- δ_{BF} = 1.5π (1.2π) for NO (IO)
- preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

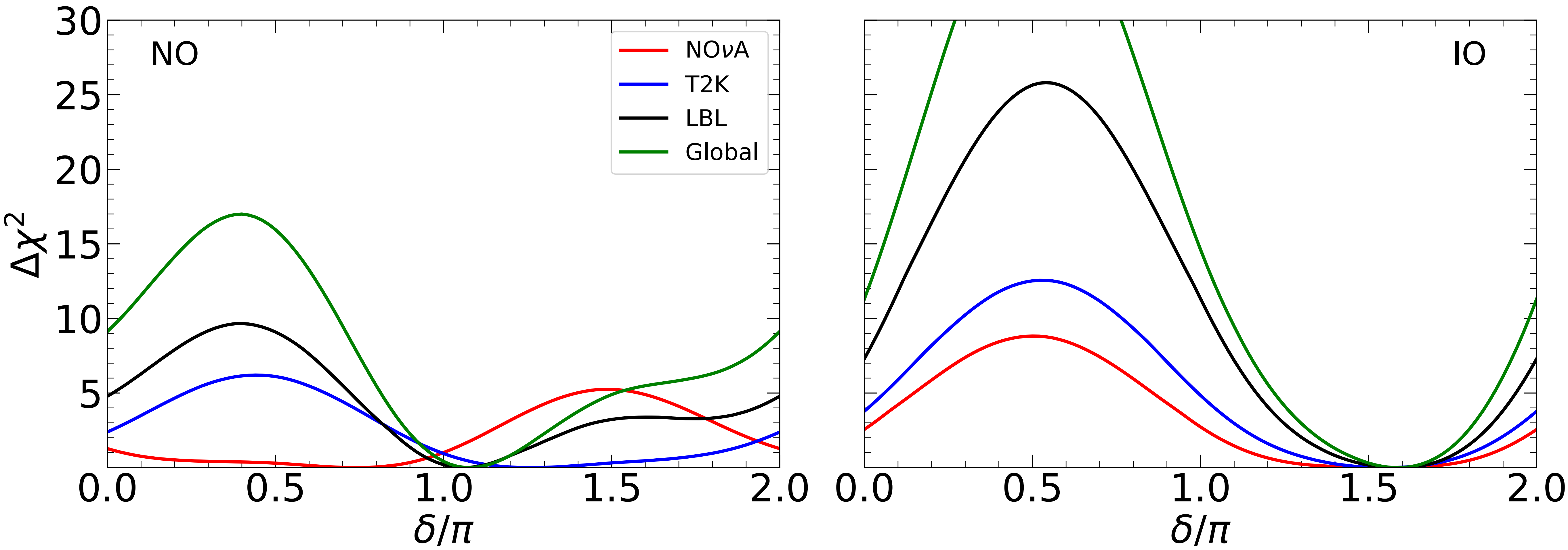
Slight tension between T2K and NOvA results for NO



A. Himmel, Neutrino 2020

The CP phase

de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]



- NO: there is a mismatch between NOvA and T2K and SK atmospheric results

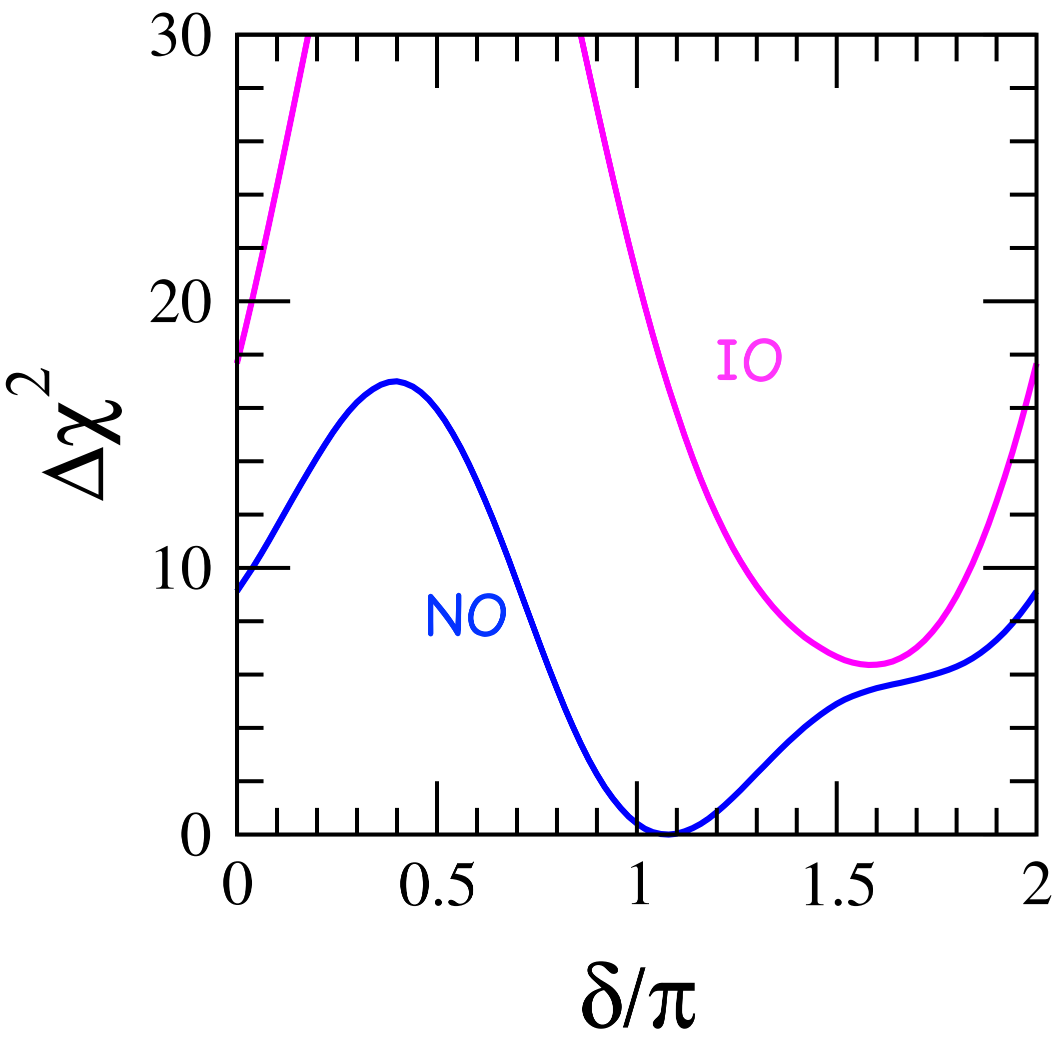
  $\delta_{BF} = 1.08\pi$; $\delta = \pi/2$ (0) disfavored at 4.0σ (3.0σ); $\delta = 3\pi/2$ with $\Delta\chi^2 = 4.9$

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

  $\delta_{BF} = 1.58\pi$; $\delta = \pi/2$ (π) disfavored at 6.2σ (3.8σ)

The CP phase

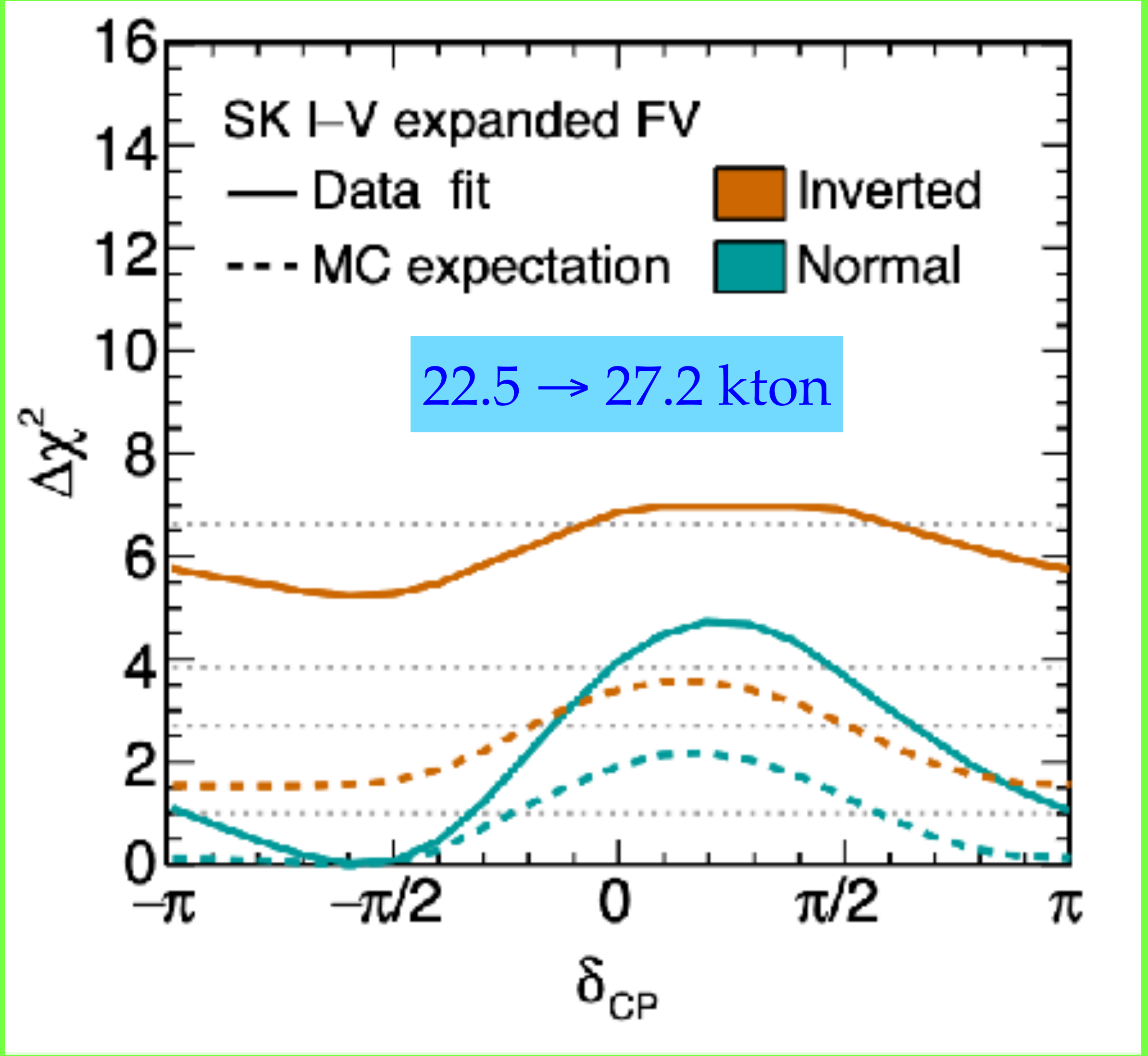
de Salas et al, JHEP 02 (2021) 071



NO: δ_{BF} = 1.08π (NOvA-T2K tension)
δ= π/2 (0) disfavored at 4.0σ (3.0σ)

IO: δ_{BF} = 1.58π ;
δ= π/2 (π) disfavored at 6.2σ (3.8σ)

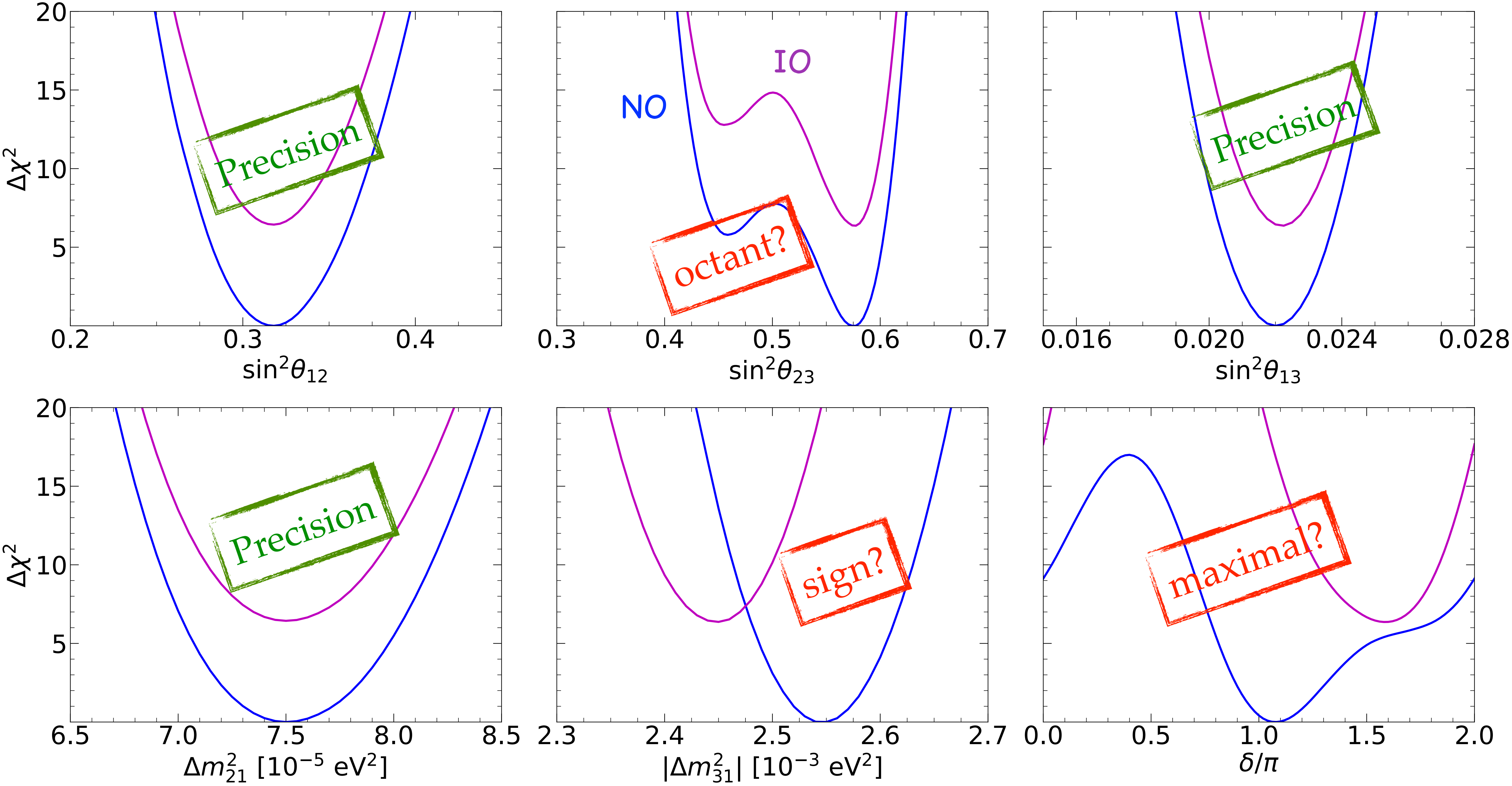
Super-K Coll. arXiv:2311.05105



Best fit at δ ≈ -0.6π for both orderings and increased sensitivity

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The mass ordering

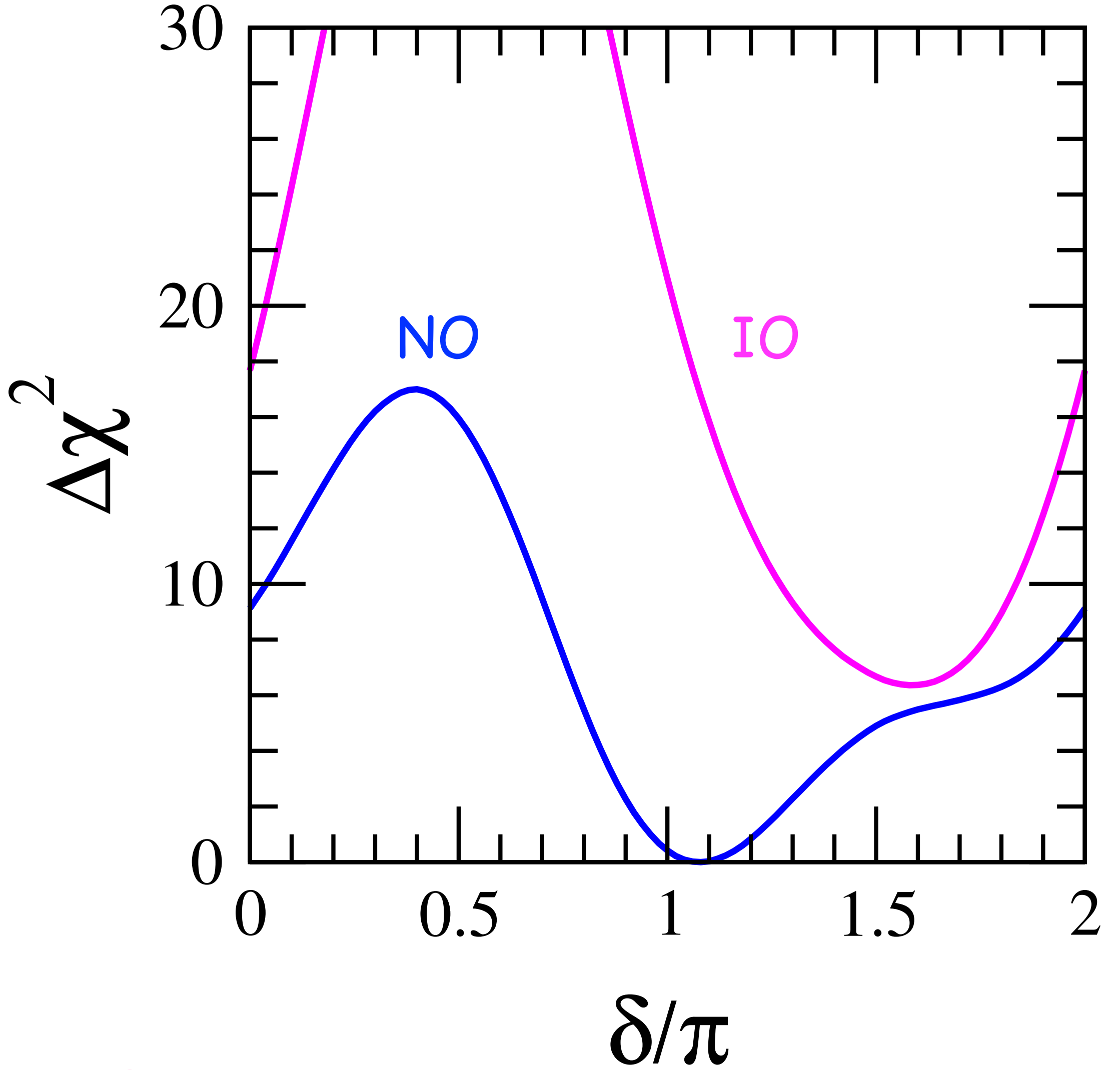
- T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.4$

- T2K + NOvA combined prefer IO with $\Delta\chi^2 \approx 2.4$ (tension in δ for NO)

- LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.4$ (tension in Δm^2_{31} measurement in IO)

- Atmos. sensitivity: Super-K ($\Delta\chi^2 \approx 3.5$) and DeepCore ($\Delta\chi^2 \approx 1.0$)

- Global fit: $\Delta\chi^2 = 6.4 \rightarrow$ 2.5σ preference for NO

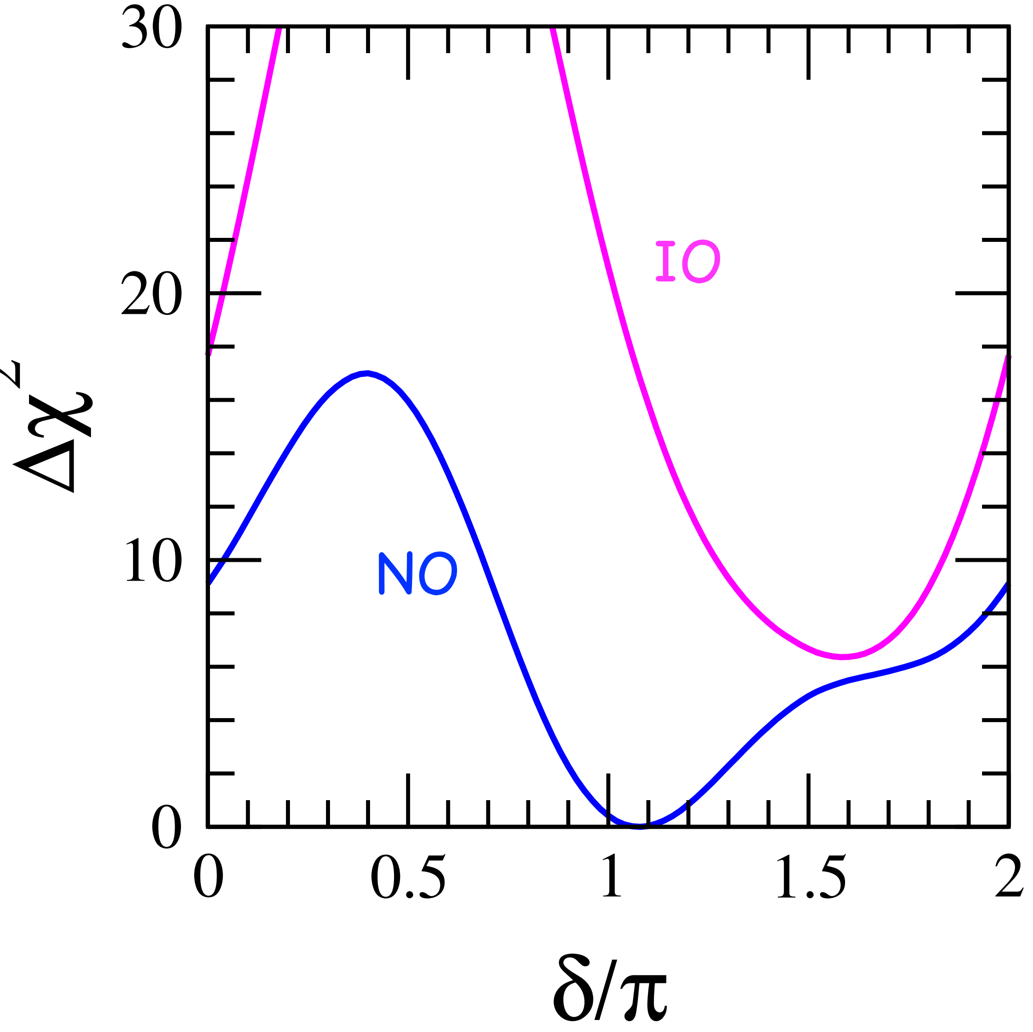


de Salas et al, JHEP 02 (2021) 071

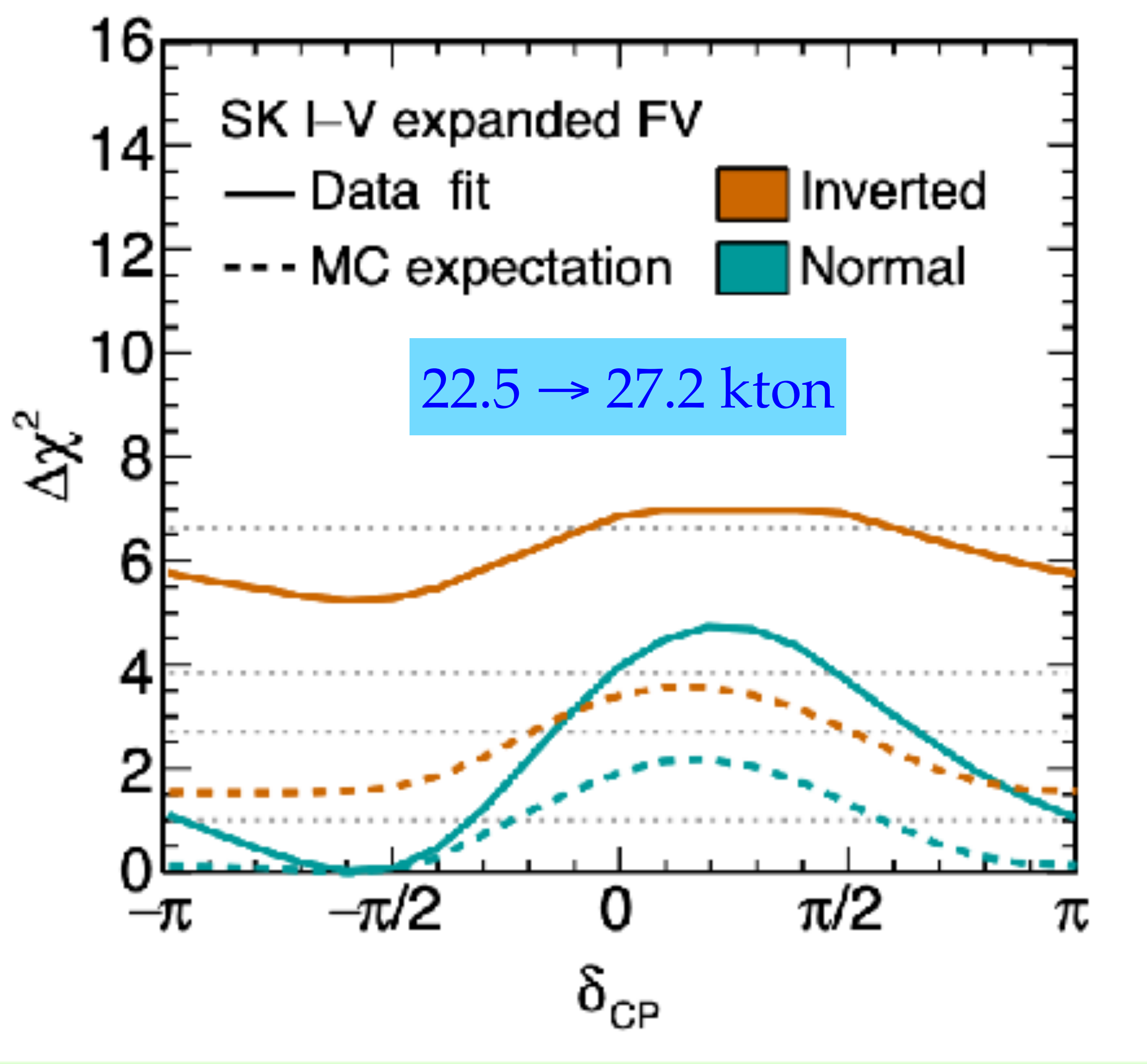
The mass ordering

Super-K Coll. arXiv:2311.05105

de Salas et al, JHEP 02 (2021) 071



2.5σ preference for NO



22.5 → 27.2 kton

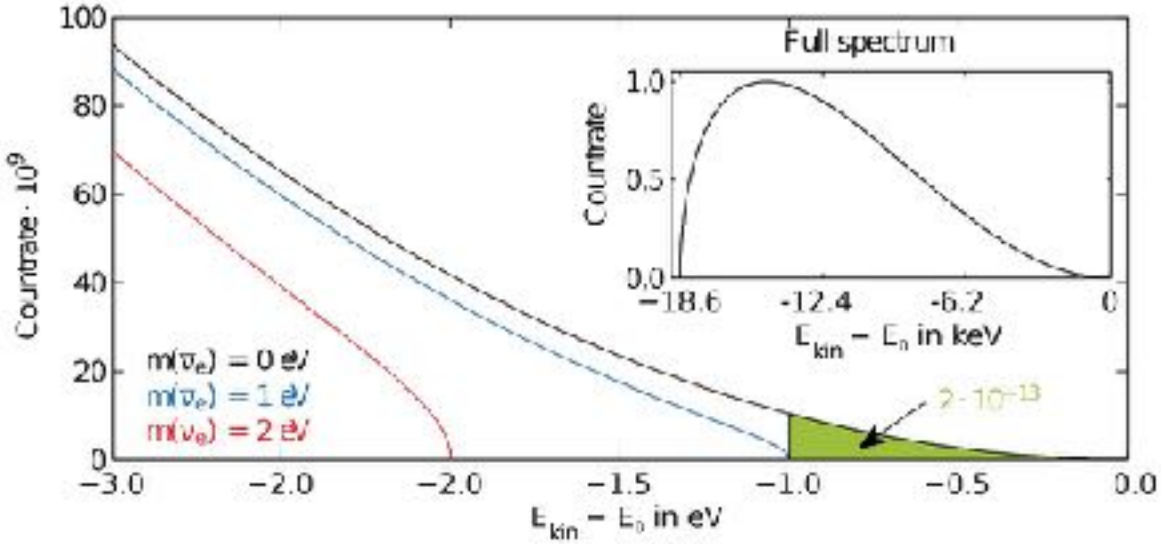
Slightly higher preference for NO:
$\Delta\chi^2 = 3.5 \rightarrow 5.2$

Bounds on neutrino mass

- β decay (KATRIN)

$$m_\beta = \sqrt{\sum |U_{ei}|^2 m_i^2} < 0.8\,\mathrm{eV}\ (90\%\ \mathrm{C.L.})$$

Nat. Phys. **18**, 160–166 (2022)



- 0νββ decay (if Majorana)

$$m_{\beta\beta} = \left|\sum U_{ei}^2 m_i\right| < 36 - 305\,\mathrm{meV}\ (90\%\ \mathrm{C.L.})$$

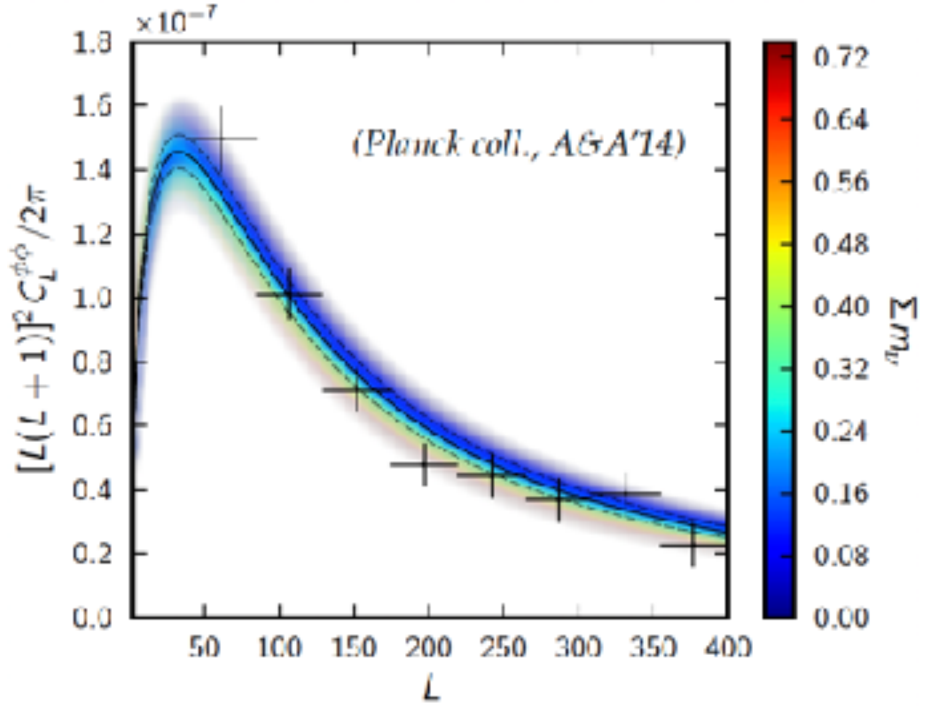
F. Simkovic, Neutrino 2022

- Cosmological measurements

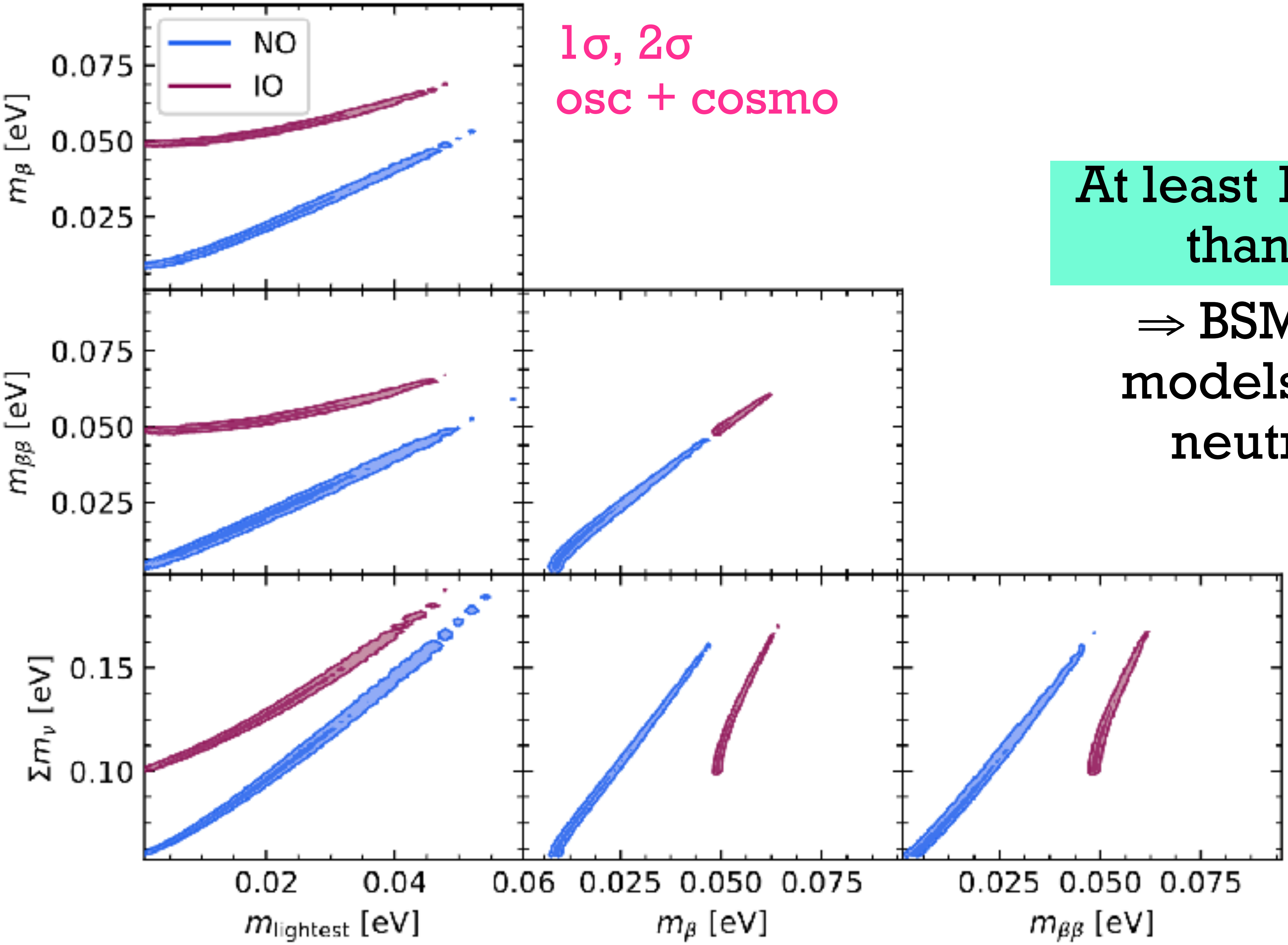
  (CMB anisotropies, lensing, LSS,…)

$$\sum m_i < 0.09 - 0.12\,\mathrm{eV}(95\%\ \mathrm{C.L.})$$

Planck Coll, 2018; DiValentino et al, PRD2021



Bounds on neutrino mass



1σ, 2σ
osc + cosmo

At least 10^7 times lighter than electrons!!

⇒ BSM neutrino mass models should explain neutrino lightness!

de Salas et al, JHEP 02 (2021) 071

The mass ordering

Experimental sensitivity to neutrino masses:

- ✦ ν-oscillations: Δm^2_{ij}
- ✦ β-decay: $m_\beta = f(m_i,\theta_{ij})$
- ✦ 0νββ: $m_{\beta\beta} = f(m_i,\theta_{ij},\phi_i)$
- ✦ Cosmology: Σm_i

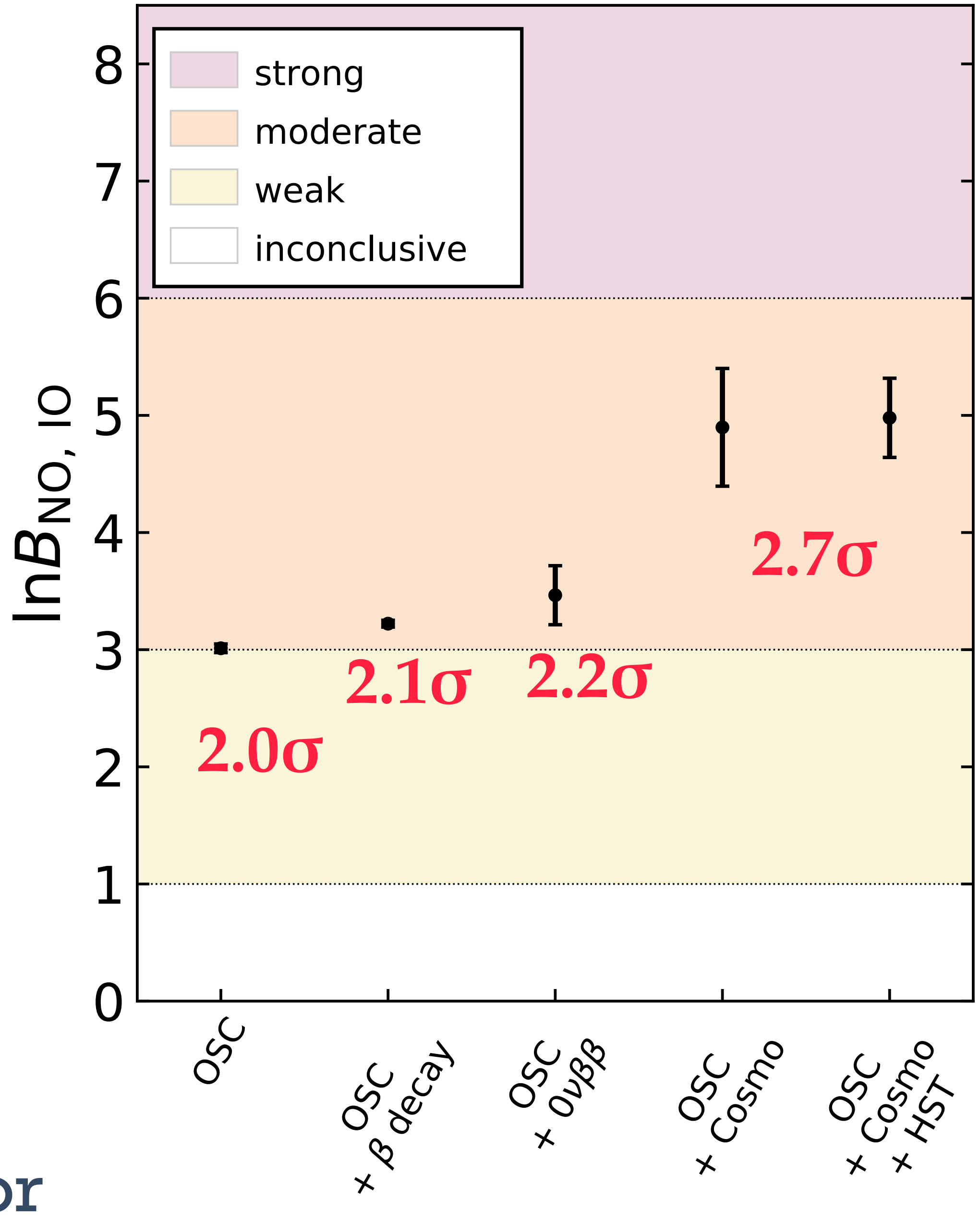
Results from the combined bayesian analysis:

⇒ weak/moderate preference for NO driven by oscillation data (2.0σ)

⇒ β-decay and 0νββ have little impact on MO.

⇒ cosmological data enhances the preference for NO from 2.0σ to 2.7σ

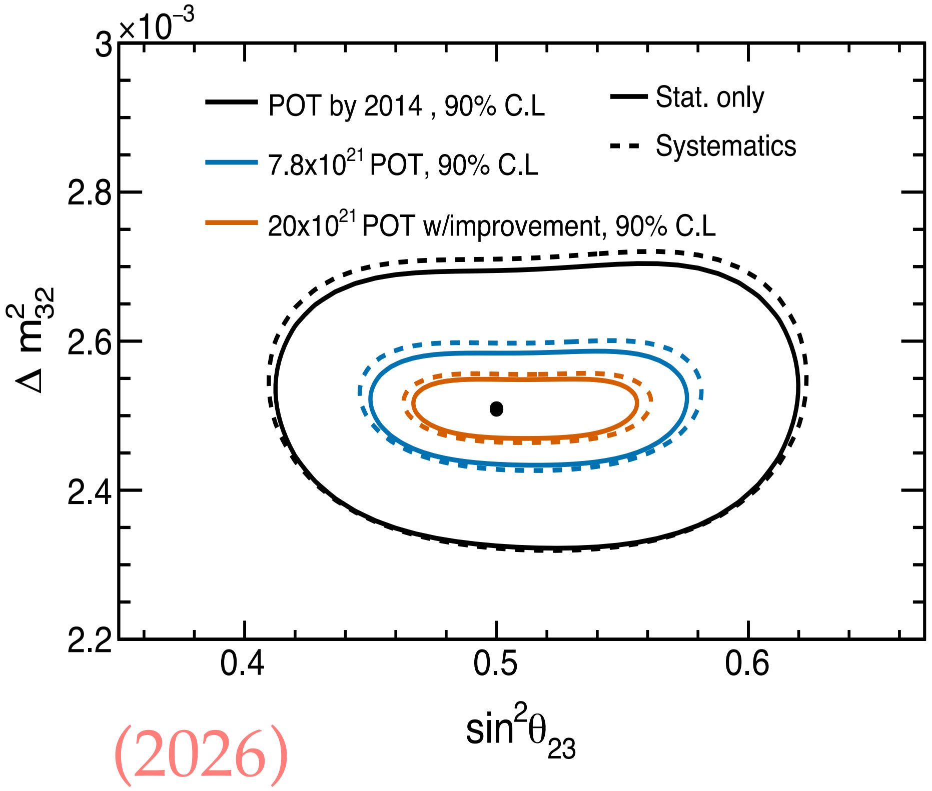
de Salas et al, JHEP 02 (2021) 071



Future prospects in neutrino oscillations

Prospects for precision

T2K **Abe et al, 1609.04111**



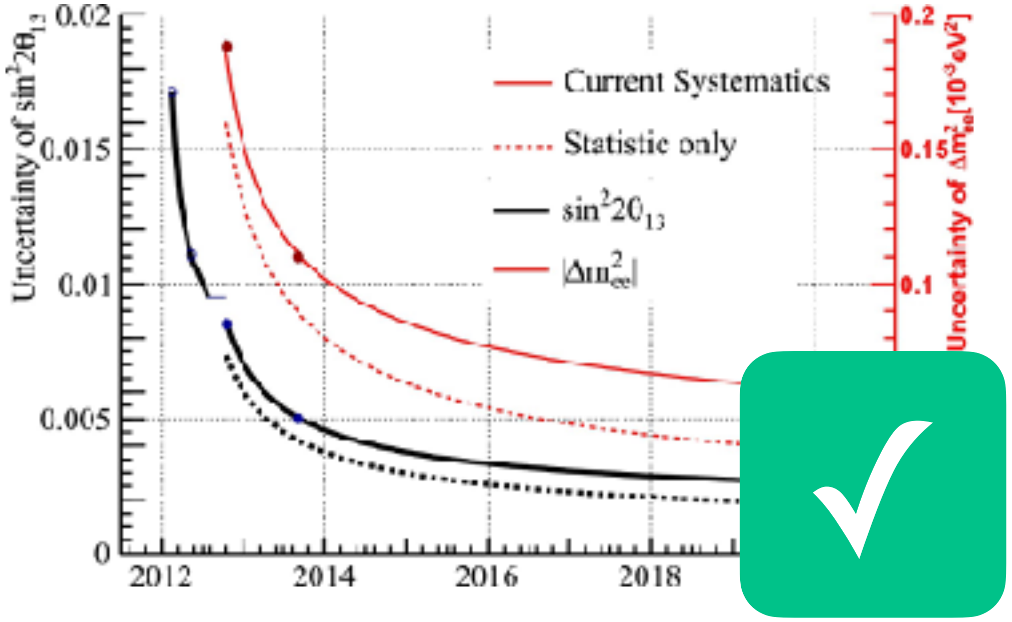
(2026)

~1% precision on Δm^2_{32}

~1-3% precision on $\sin^2\theta_{23}$

DayaBay

Cao and Luk, 1605.01502

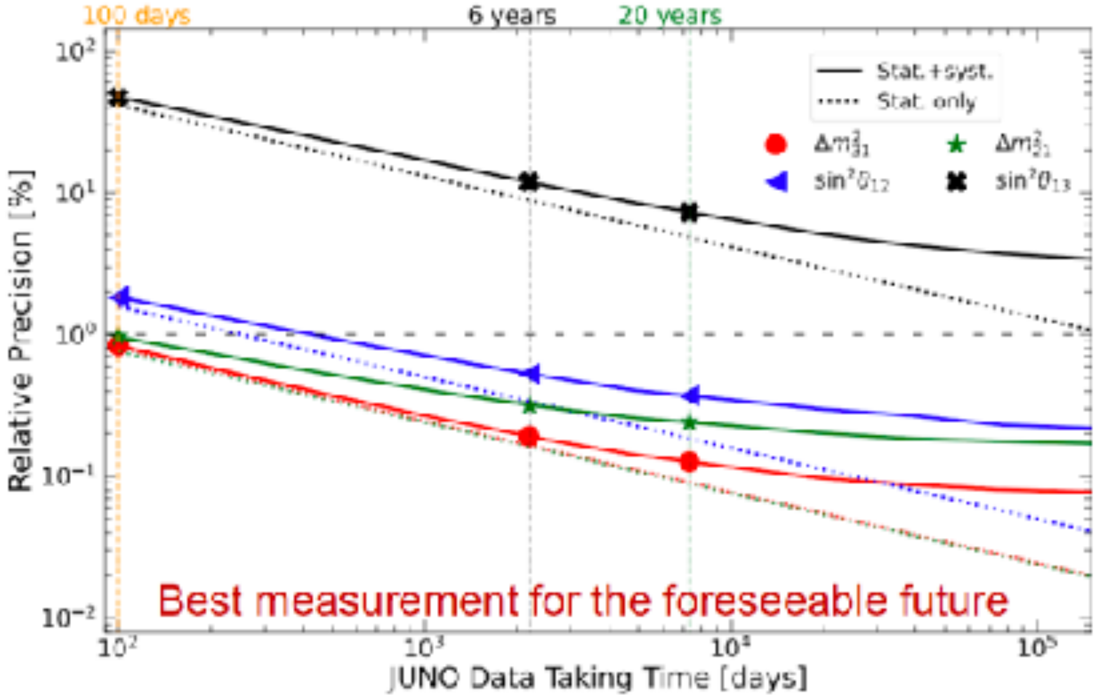


✓

< 3% precision in $\sin^2 2\theta_{13}$ and Δm^2_{ee}

2.7% in $\sin^2 2\theta_{13}$
[Z, Yu, TAUP'21]

JUNO (also SNO+)



6 years:

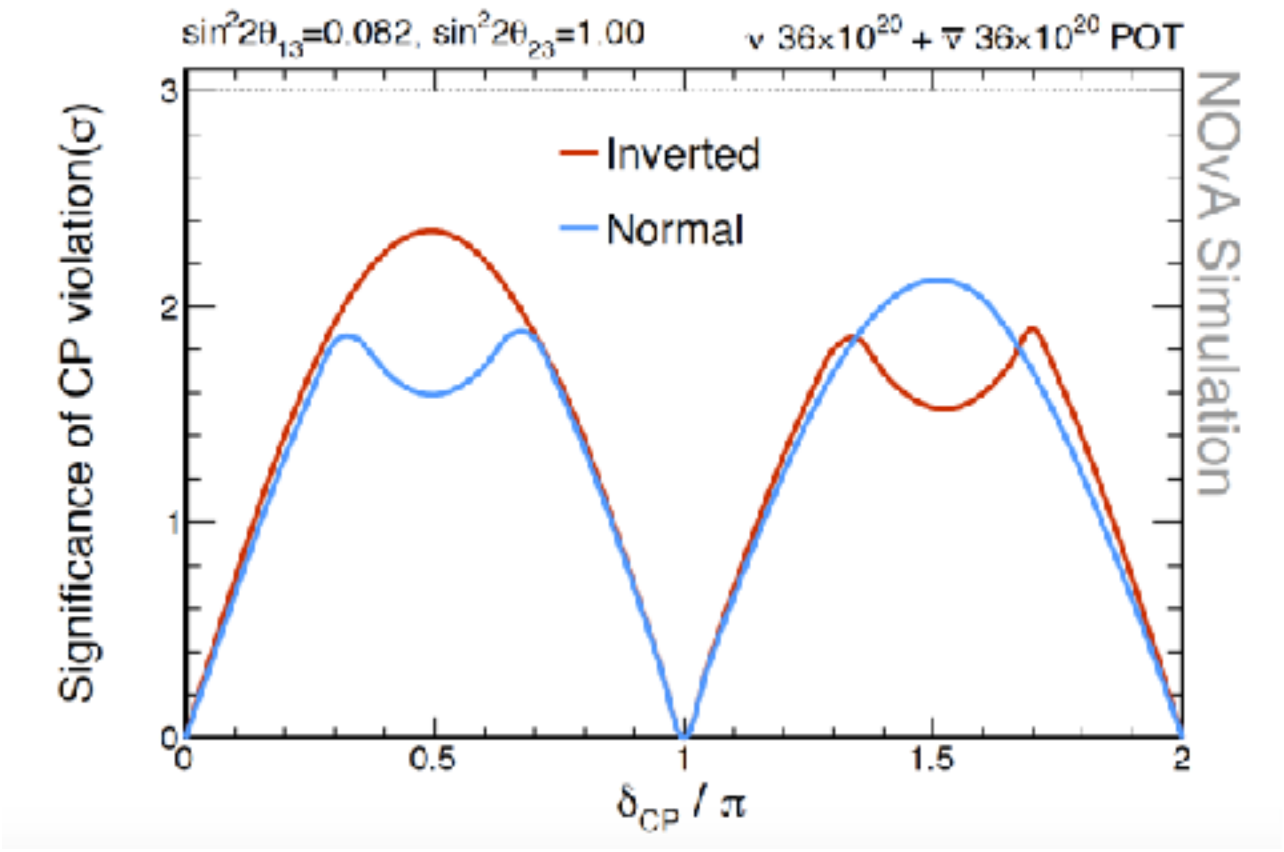
< 0.5% precision on $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

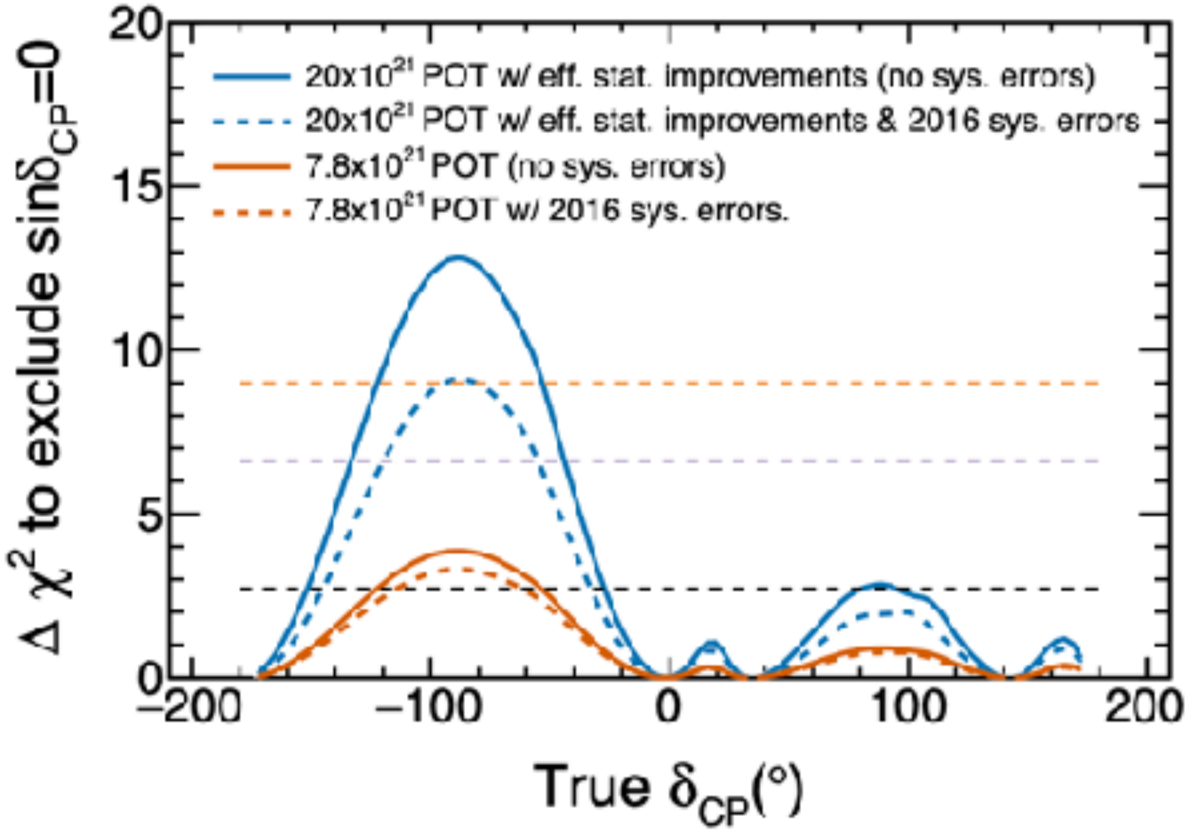
J. Zhao, Neutrino 2022

Prospects for CP violation

NOvA **M. Sánchez, Neutrino’18**
P. Vahle, TAUP’21

T2K **Abe et al, 1609.04111**



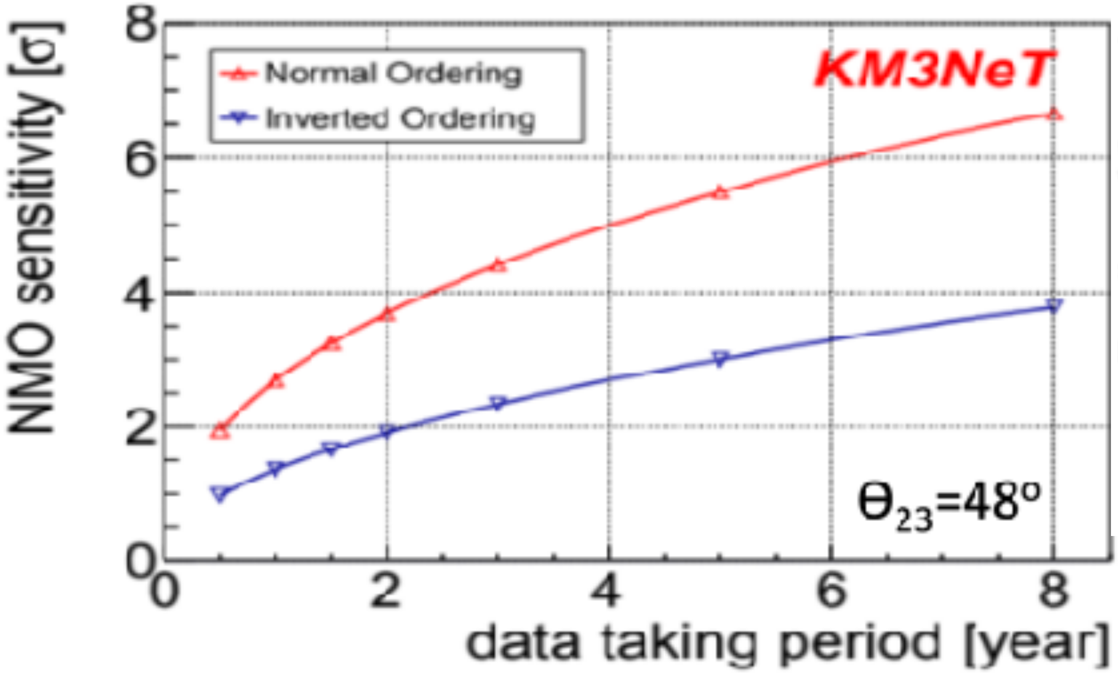


- ✦ by 2026 (60-70 x 10^{20} POT):
  ~ 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

- ✦ by 2026 (20×10^{21} POT):
  > 3σ sensitivity on CP violation for 3π/2

Prospects for mass ordering

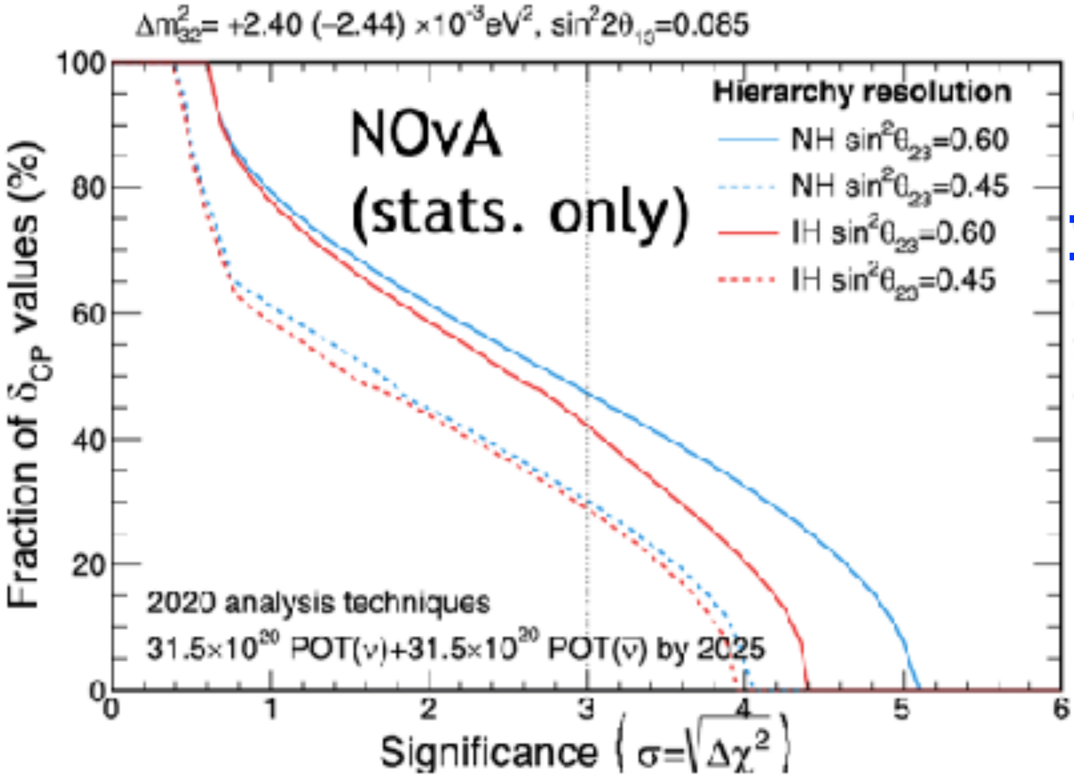
ORCA



- ✦ 3σ determination of MO in 4-5 yr

A. Heijboer, Neutrino 2022

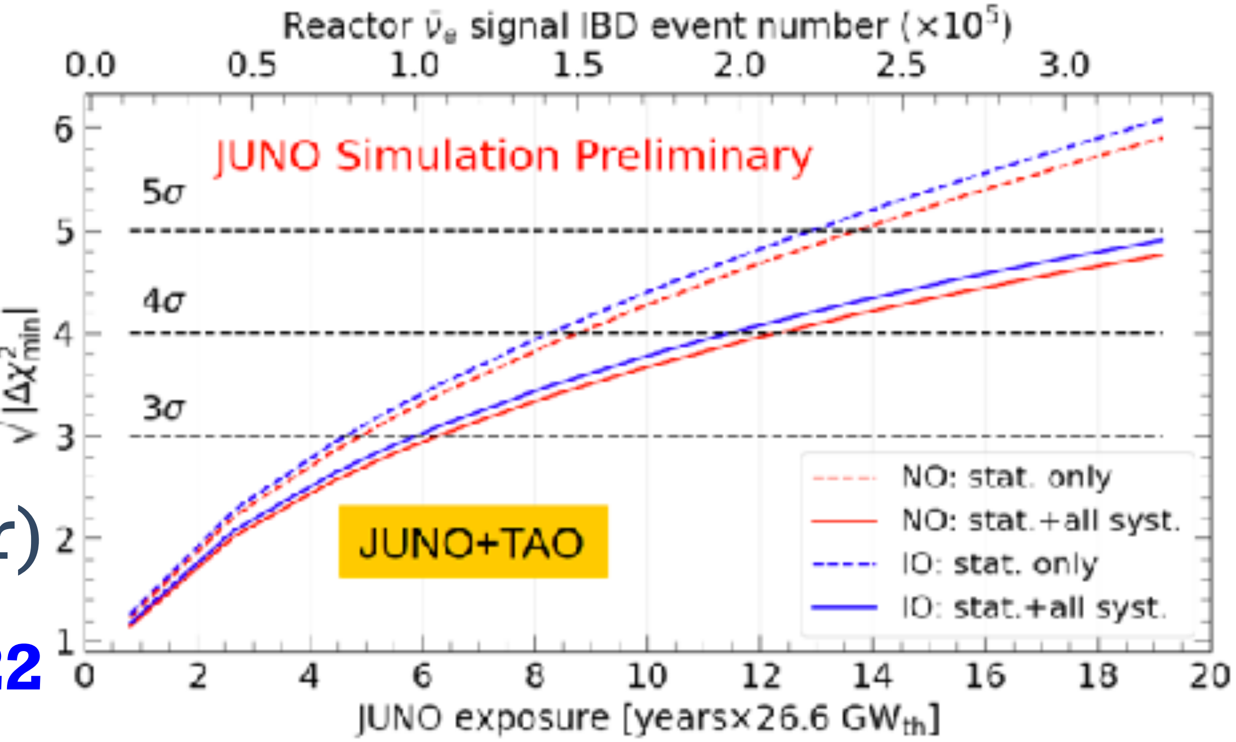
NOvA



P. Vahle, TAUP'21

- ✦ 2026: 3σ sensitivity for 30-50% of δ

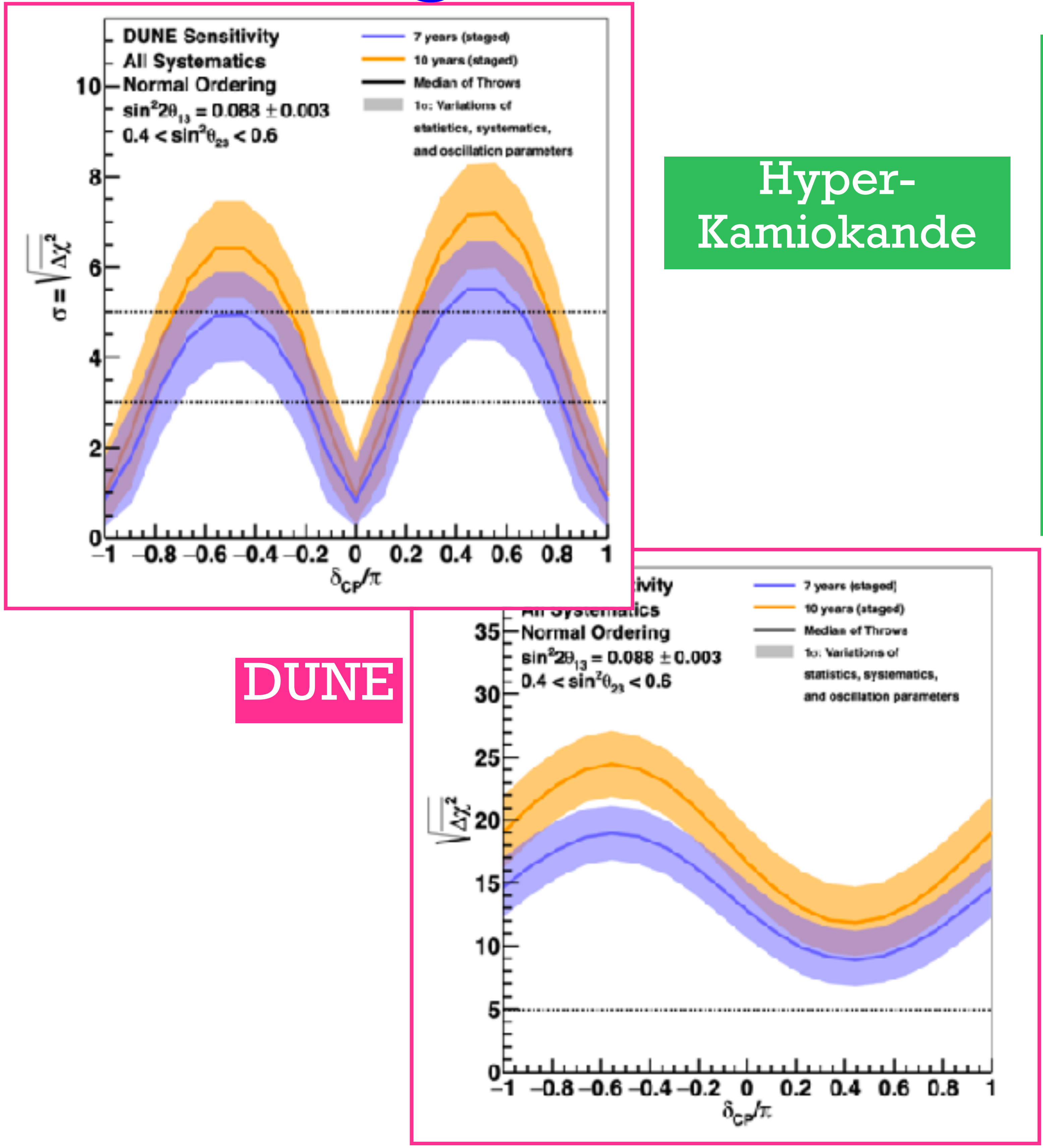
JUNO



- ✦ 3σ sensitivity (6 yr)

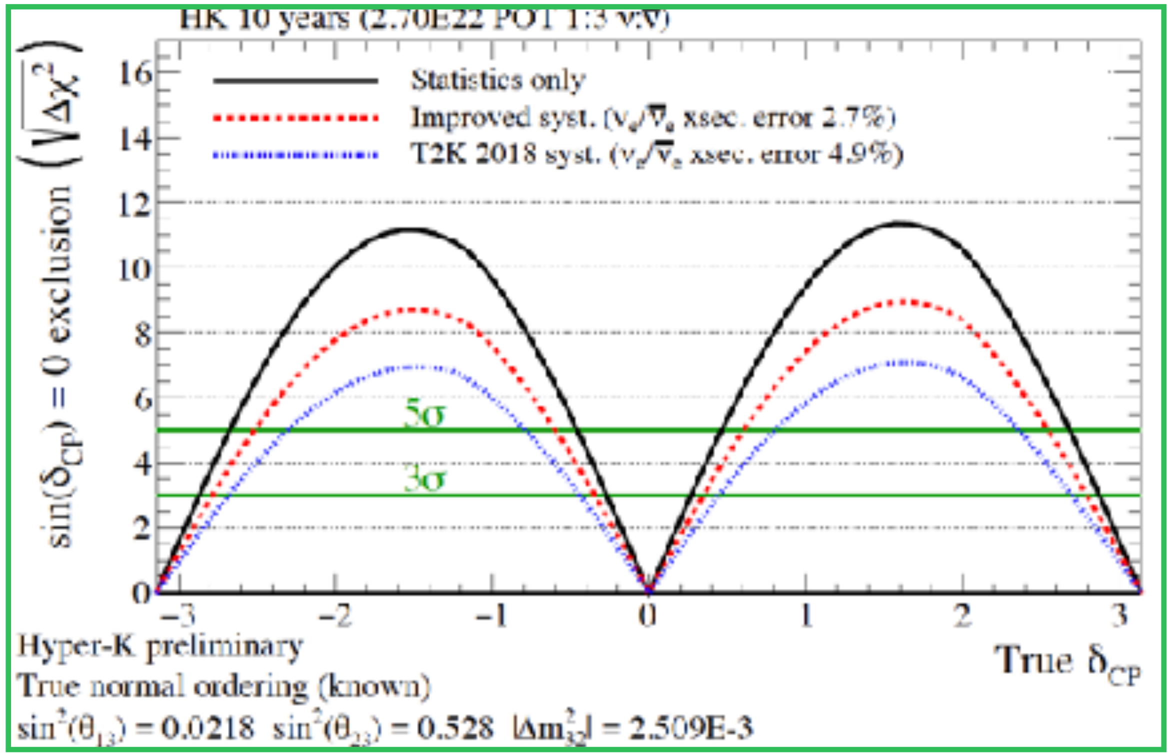
J. Zhao, Neutrino 2022

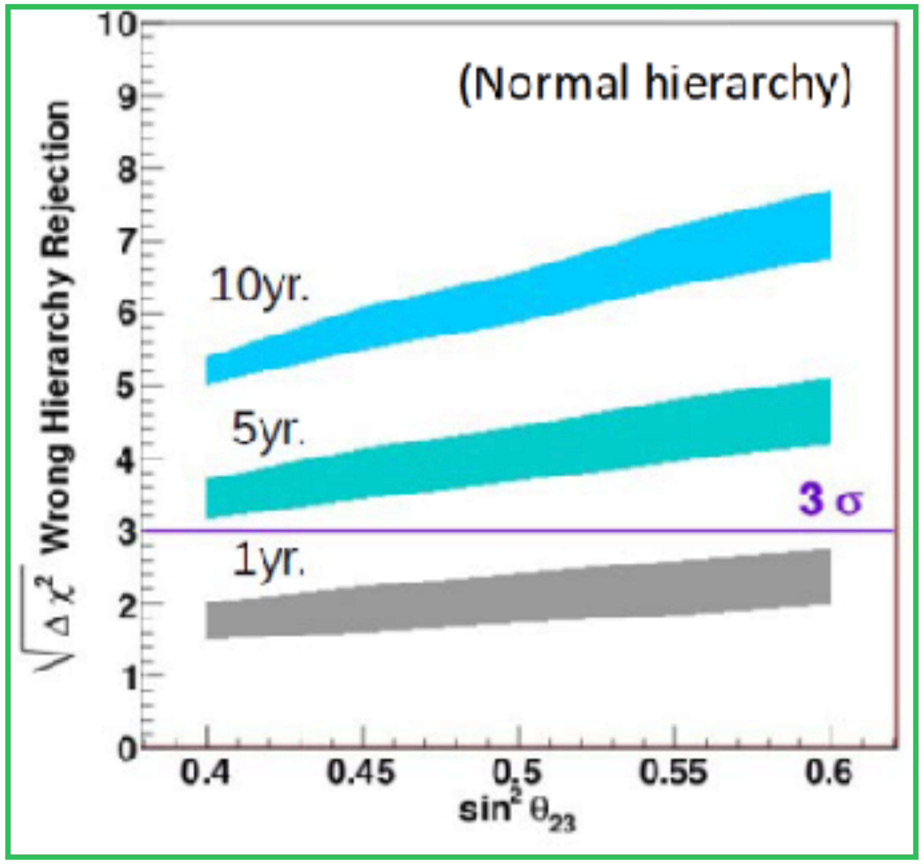
Next generation experiments



DUNE

Hyper-Kamiokande





Beyond the standard three-neutrino scenario

Beyond the standard scenario

- ✦ Neutrino results suggest the presence of **physics BSM** to explain:
  - ✓ light neutrino masses (mass generation mechanism)
  - ✓ large neutrino mixing compared to quark sector (flavour problem)
  - ✓ short-distance anomalies (LSND, ~~reactor~~ and Ga anomalies)

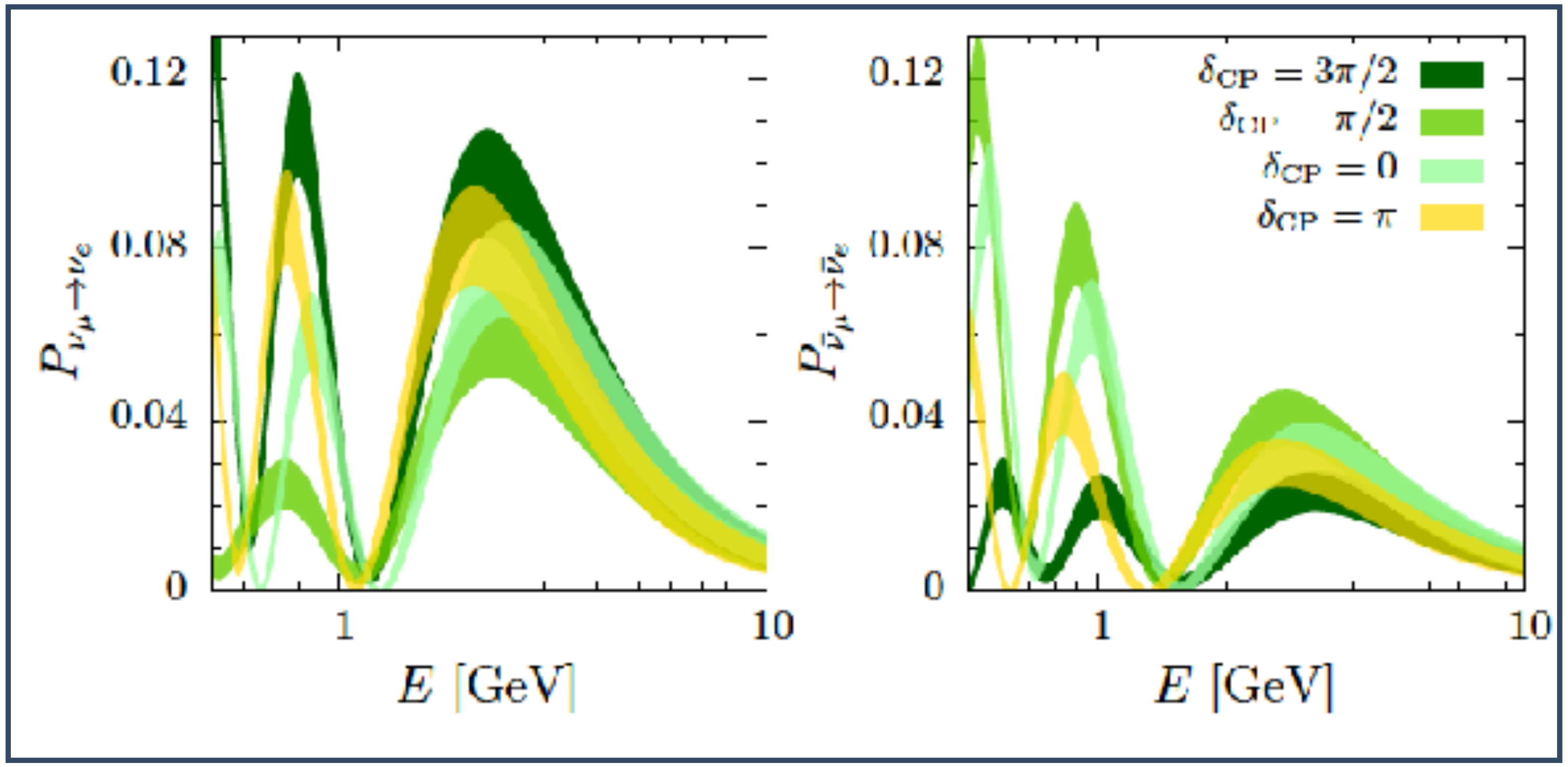
- ✦ Many different **BSM scenarios** analyzed in the literature:
  - ✓ neutrino non-standard interactions (NSI) with matter
  - ✓ exotic neutrino electromagnetic properties
  - ✓ presence of light sterile neutrinos
  - ✓ mixing with heavy sterile neutrinos: non-unitary neutrino mixing (NU)

⇒ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

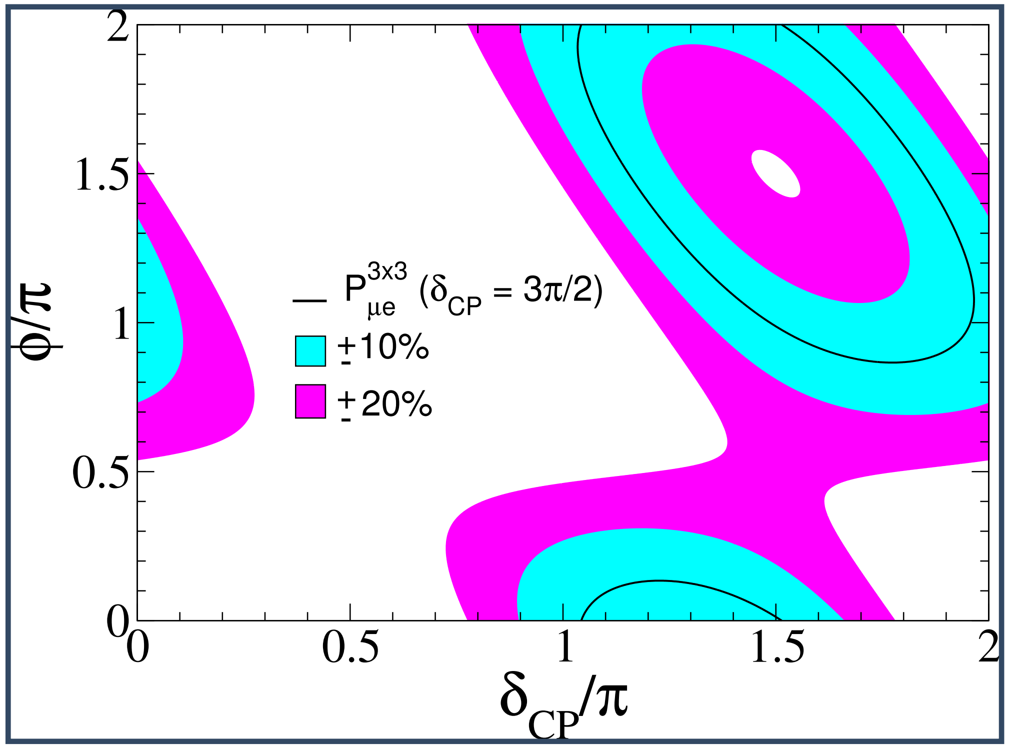
Non-unitary neutrino mixing

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P_{\mu e}^{3\times 3} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P_{\mu e}^{I} + \alpha_{11}^2|\alpha_{21}|^2$$ **with** $P_{\mu e}^{I}(\phi)$

The new phases (ϕ) will modify the standard oscillation picture in LBL experiments, such as DUNE



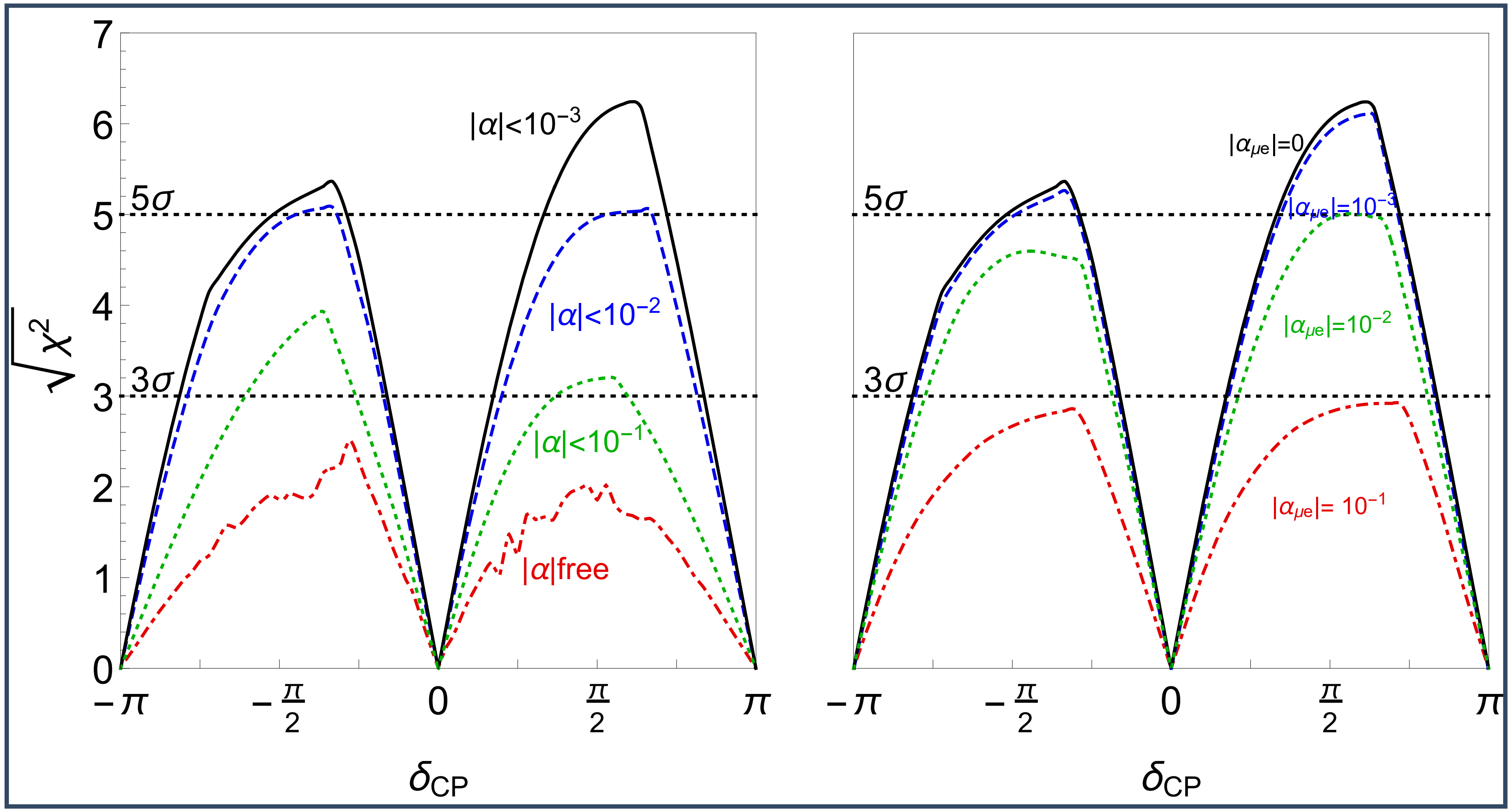
Escrihuela et al, NJP 2017



Miranda, MT, Valle, PRL 117 (2016)

→ (δ, ϕ) degeneracies in $P_{\mu e}$ for E≳ 3 GeV spoil sensitivity to δ

DUNE CP sensitivity with NU



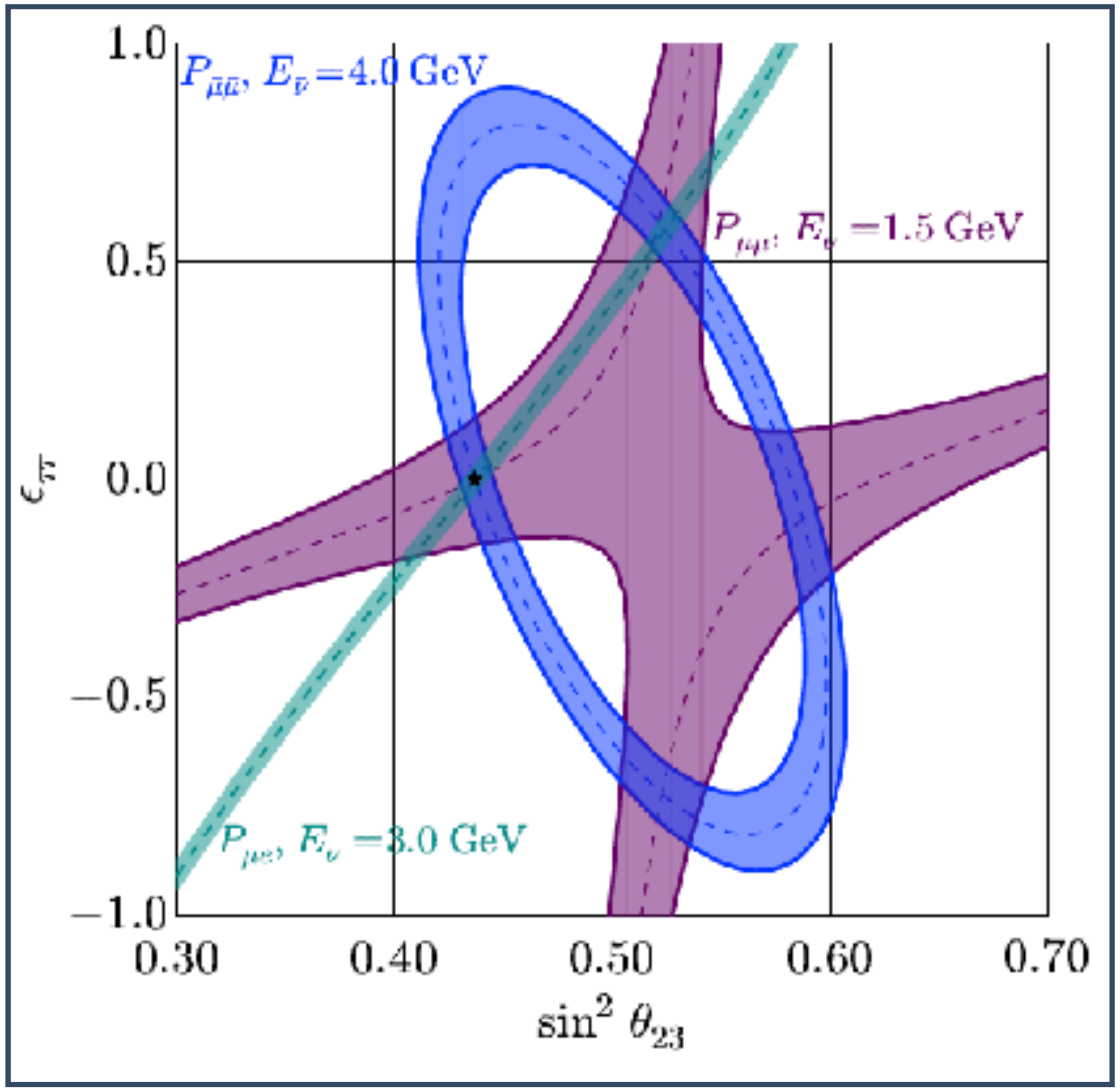
Fernández-Martínez et al (DUNE-BSM Working Group)

→ The sensitivity to CP violation might be spoiled in the absence of priors on NU

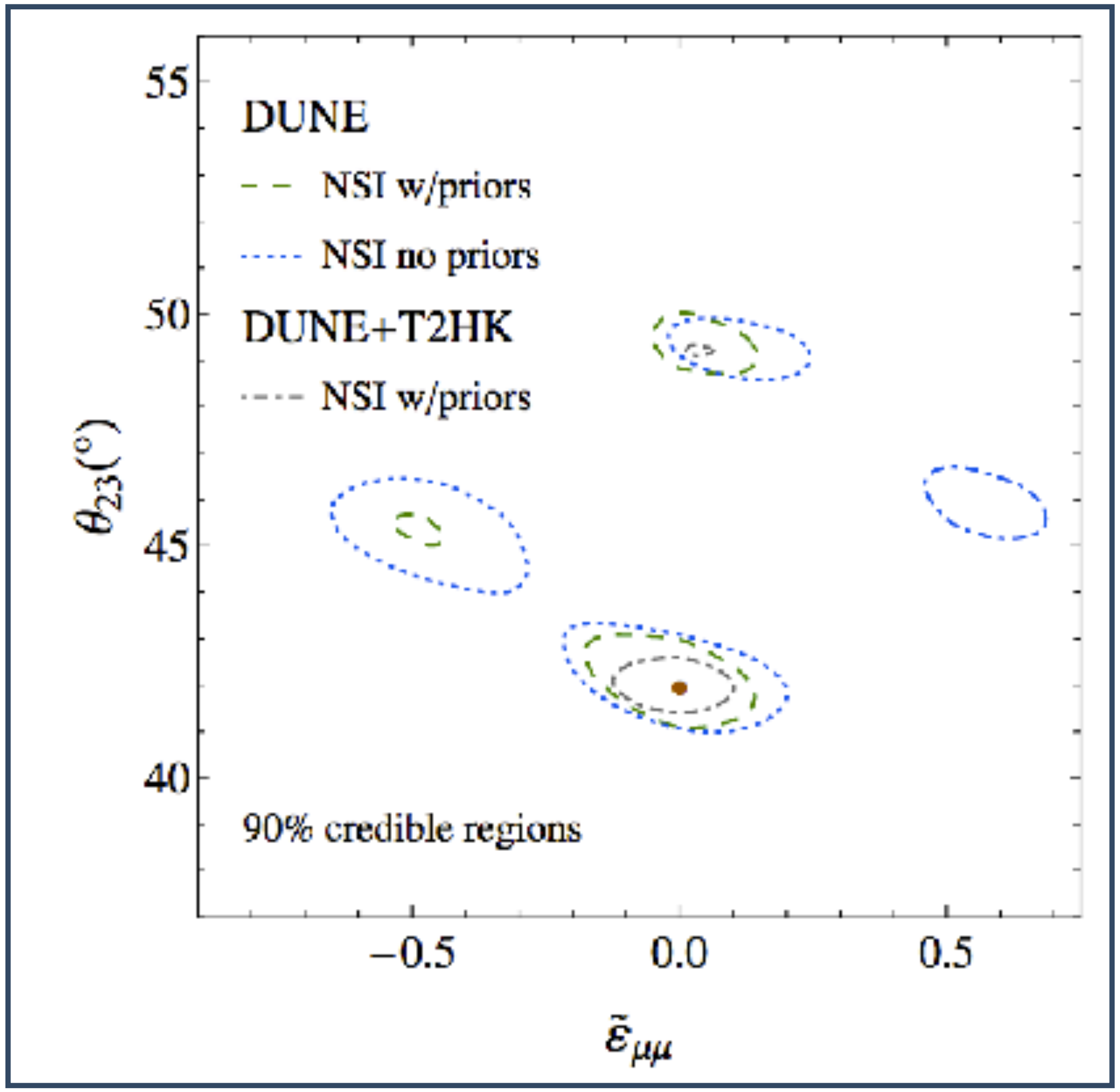
→ With priors based on current bounds (10^{-2}), the effect is less dramatic

NSI at future LBL experiments

(θ_{23}-$\epsilon_{\tau\tau}$) degeneracy in DUNE



Gouvea and Kelly, NPB 2016

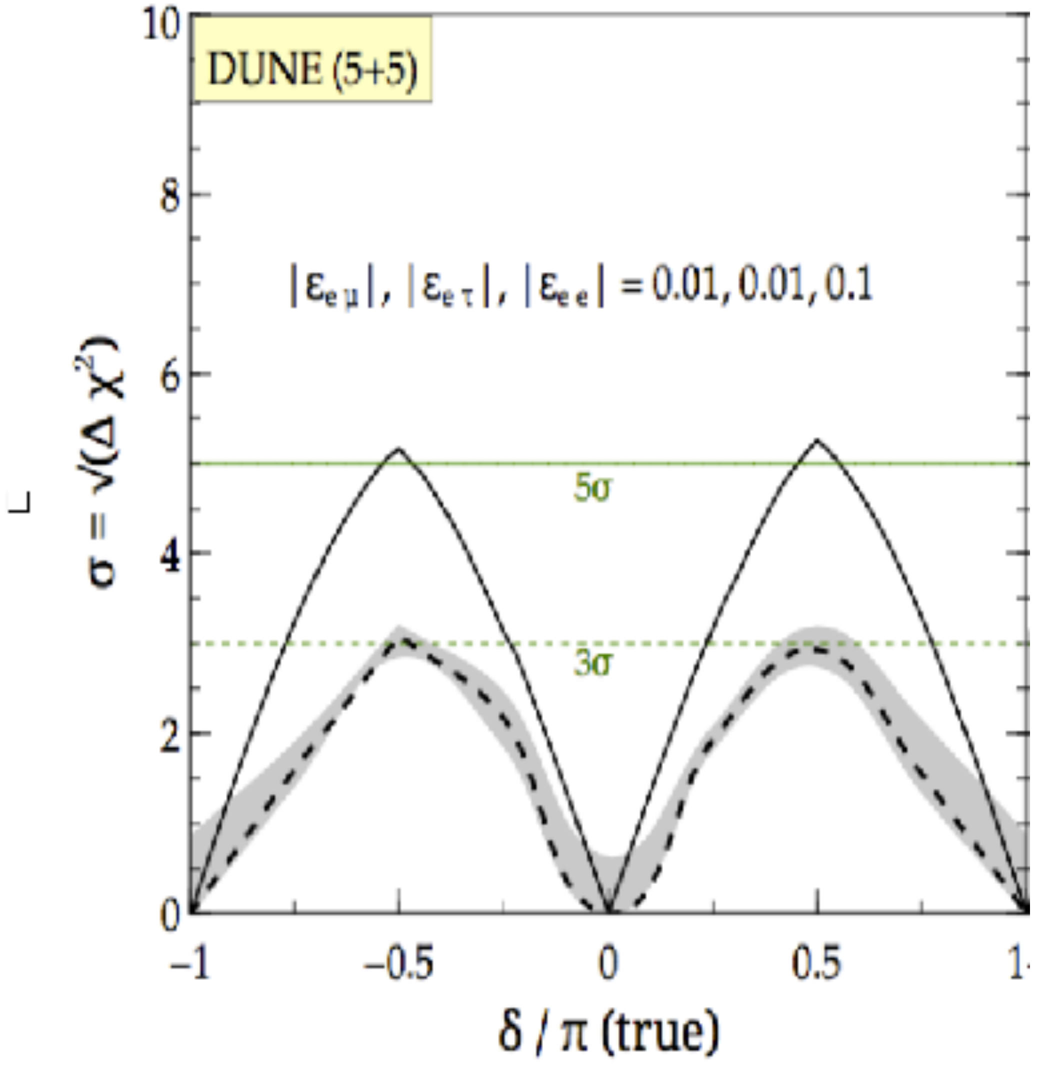


Coloma, JHEP 2016

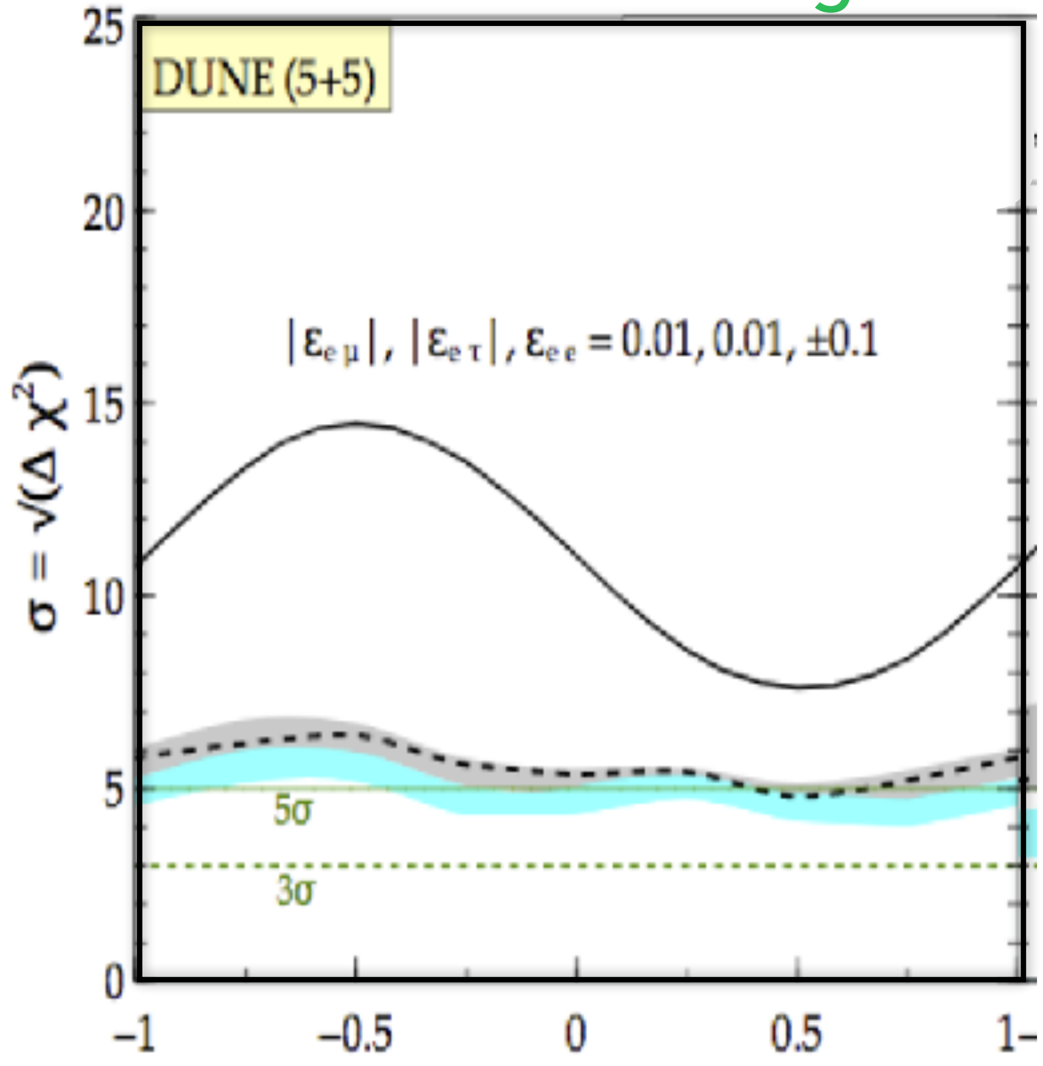
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation



mass ordering



Masud and Mehta, PRD 2016

Beyond the 3-neutrino scenario

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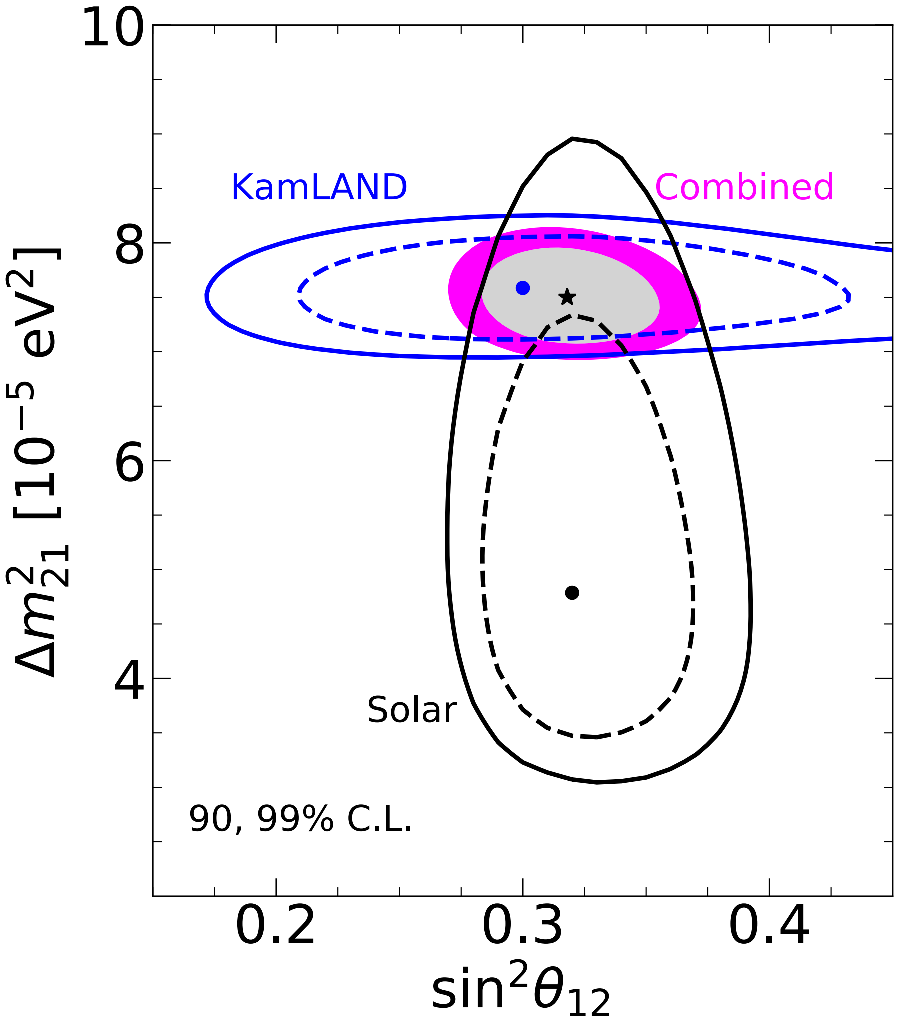
⇒ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

Can they also help reducing the current tensions?

The solar-KamLAND Δm^2_{21} tension



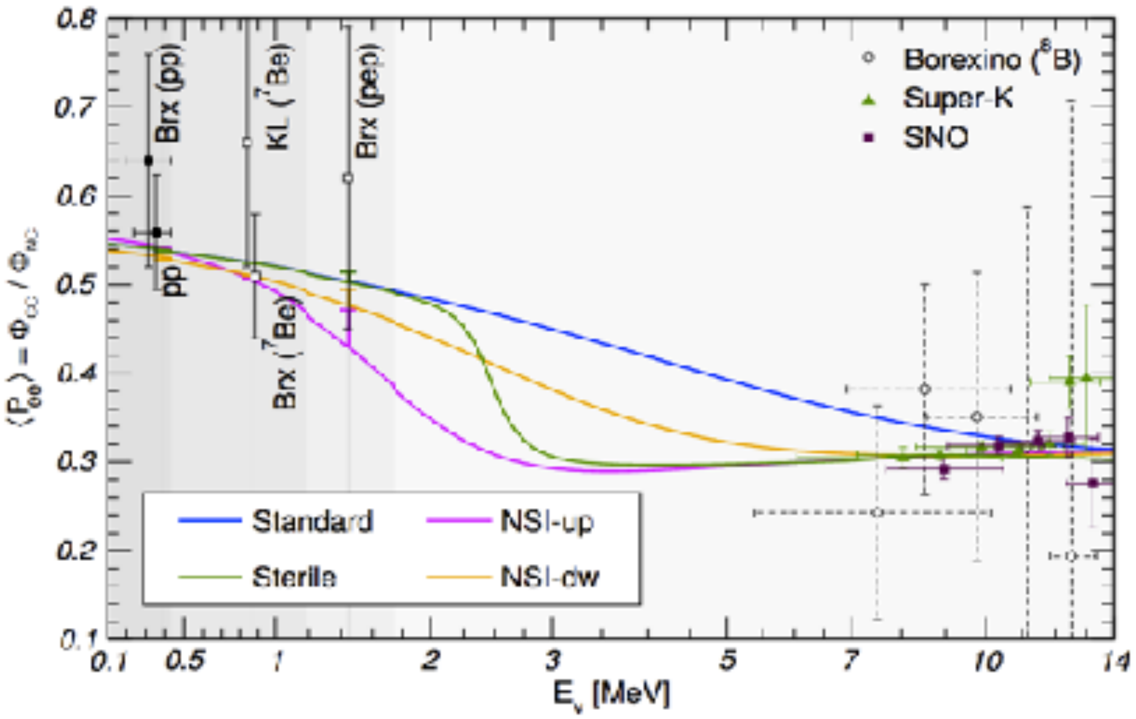
⇒ 2σ (1.5σ) tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ Δm^2_{21} preferred by KamLAND predicts steep upturn and smaller D/N asymmetry

✦ **NSI** (ε ~0.3) can reconcile both results:

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected

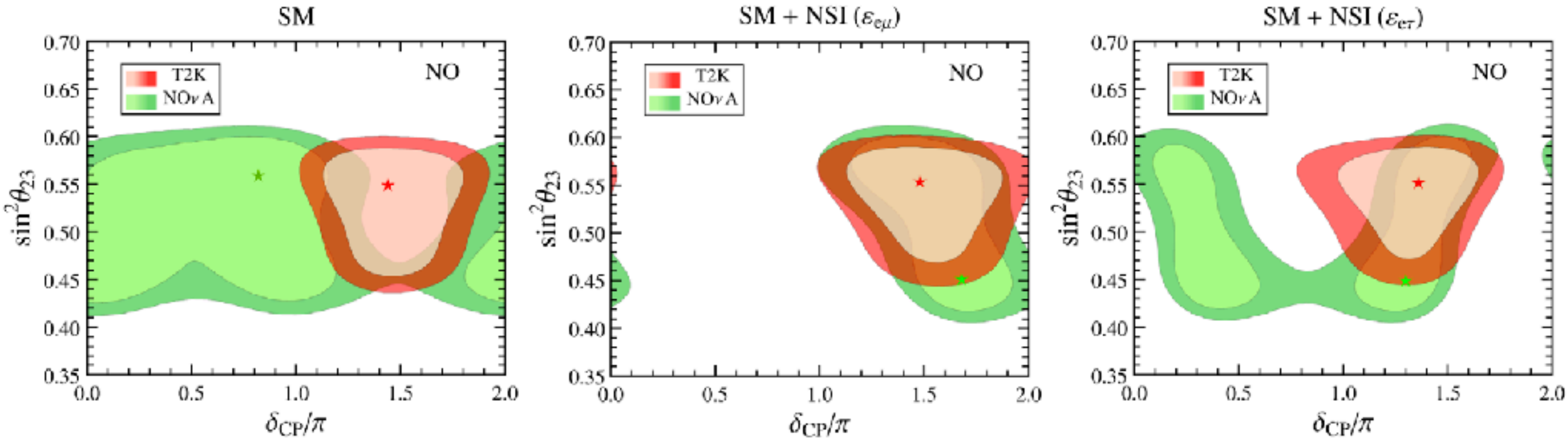


Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

The T2K-NOvA δ_{CP} tension

✦ NSI may include new sources of CP violation besides δ_{CP}: $\varepsilon_{\alpha\beta} = |\varepsilon_{\alpha\beta}| \exp(i\phi_{\alpha\beta})$

✦ CP-violating NSI with a new complex phase $\phi_{e\mu}$ or $\phi_{e\tau}$ close to maximal with NSI couplings $\varepsilon_{e\mu}$ or $\varepsilon_{e\tau}$ of the order of 0.2 may reconcile T2K and NOvA results.



Chatterjee and Palazzo, PRL 2021

Denton et al, PRL 2021

Summary

- ✦ From global fits to neutrino oscillation data:
  - ✓ precise determinations for most parameters (1.3-10%)
  - ✓ preference for $\theta_{23} > 45°$, 1st octant value disfavoured with $\Delta\chi^2 \geq 5.8$ (6.4)
  - ✓ 2.5σ hint for normal ordering (driven by oscillation data)

    ⇒ Recent atmospheric Super-Kamiokande data!
  - ✓ $\delta_{BF} = 1.08\pi$ (1.58π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.0σ (6.2σ)

    ⇒ New data from T2K and NOvA?
- ✦ In the near future (2026-2030):
  - ✓ oscillation parameters will be measured with 0.6-3% precision
  - ✓ θ_{23} octant can be resolved at more than 3σ (for some values)
  - ✓ 2-3σ sensitivity to CP violation at NOvA and T2K
  - ✓ 3σ sensitivity to MO from reactor, accelerator and nu-telescopes

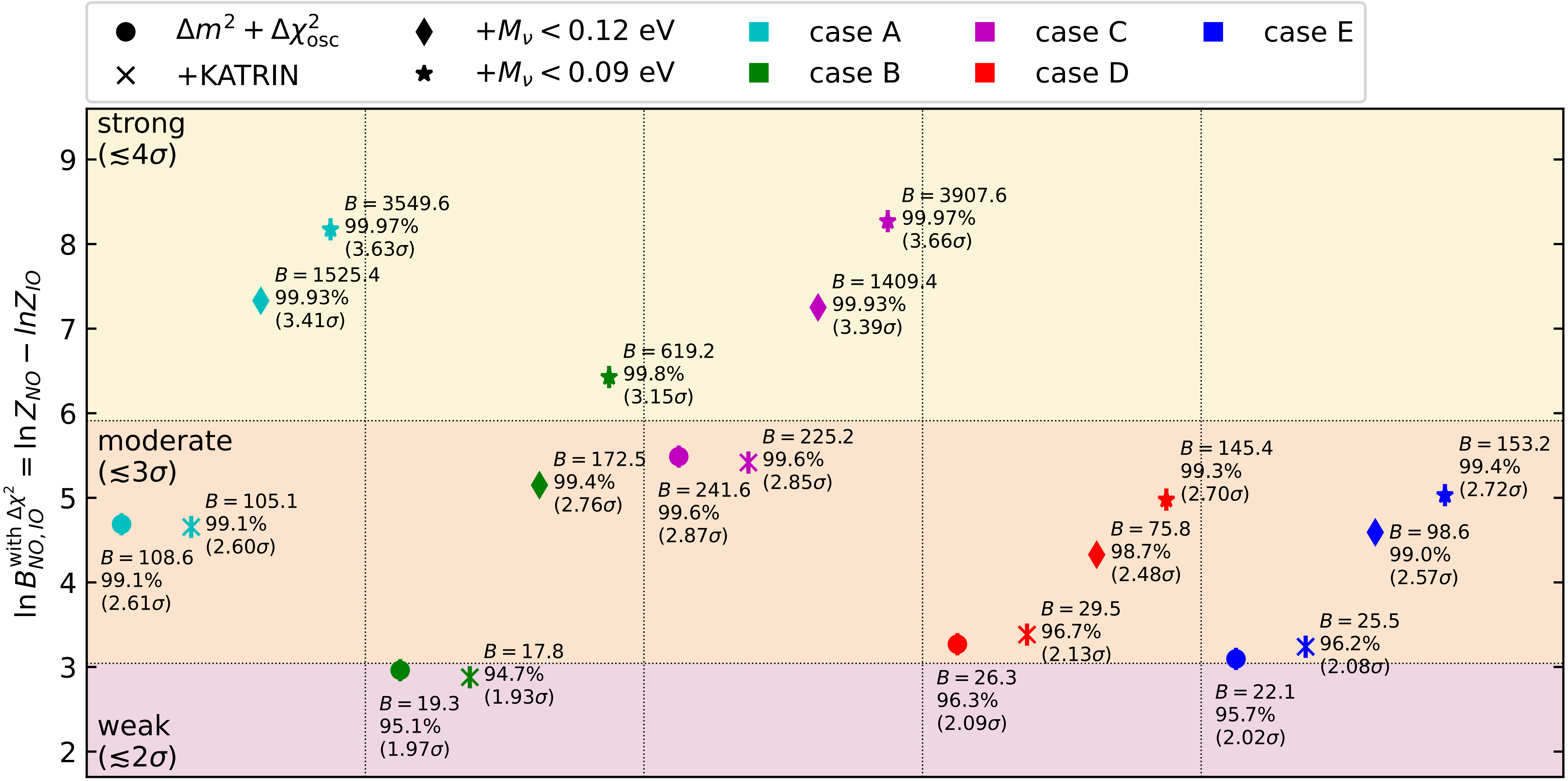
  ⇒ Sensitivities above 3σ from one experiment: DUNE, Hyper-Kamiokande

✦ New physics BSM may affect the current description of neutrino oscillations relaxing tensions or worsening the precision of measurements.

Backup

Preference for NO (with OSC)

Gariazzo et al, JCAP 10 (2022) 010



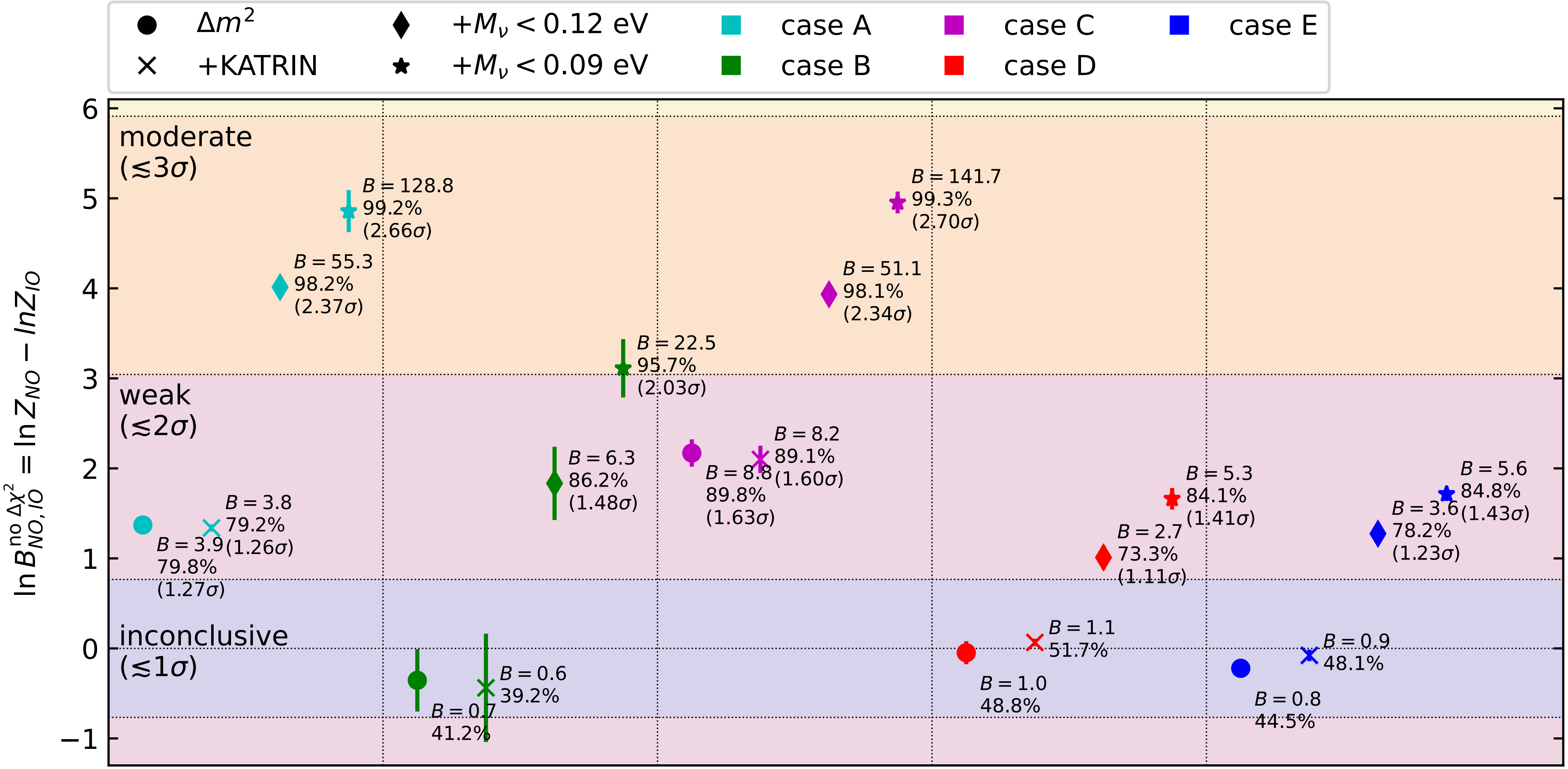
log m_i (gauss) m_i log m_i log m_0 (m_0) Σm

independent prior on the 3 masses

+ priors on Δm^2_{ij}

Preference for NO (without OSC)

Gariazzo et al, JCAP 10 (2022) 010



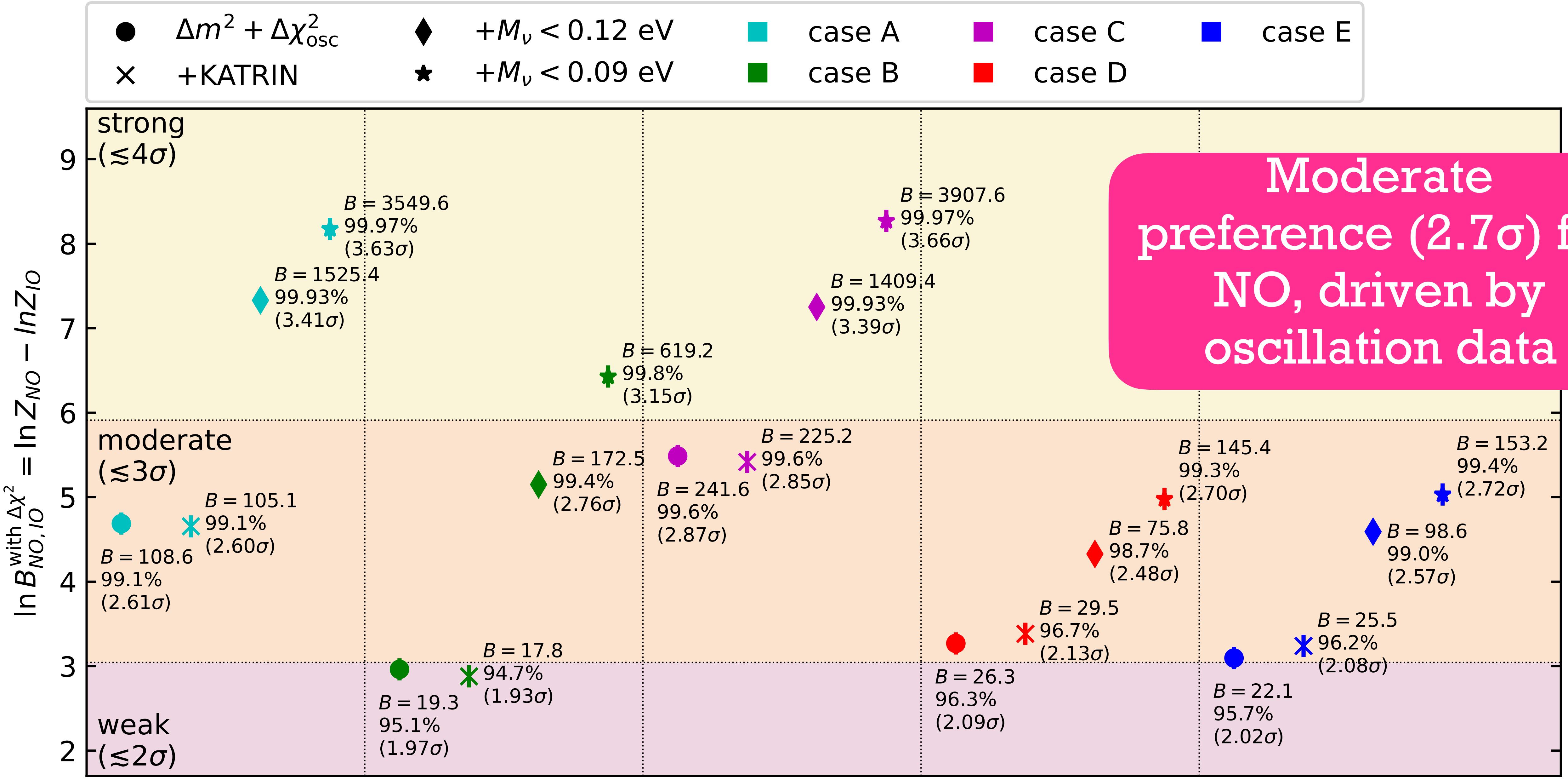
log m_i (gauss) m_i log m_i log m_0 (m_0) Σm

independent prior on the 3 masses

+ priors on Δm^2_{ij}

Preference for NO (with OSC)

Gariazzo et al, JCAP 10 (2022) 010



Moderate preference (2.7σ) for NO, driven by oscillation data

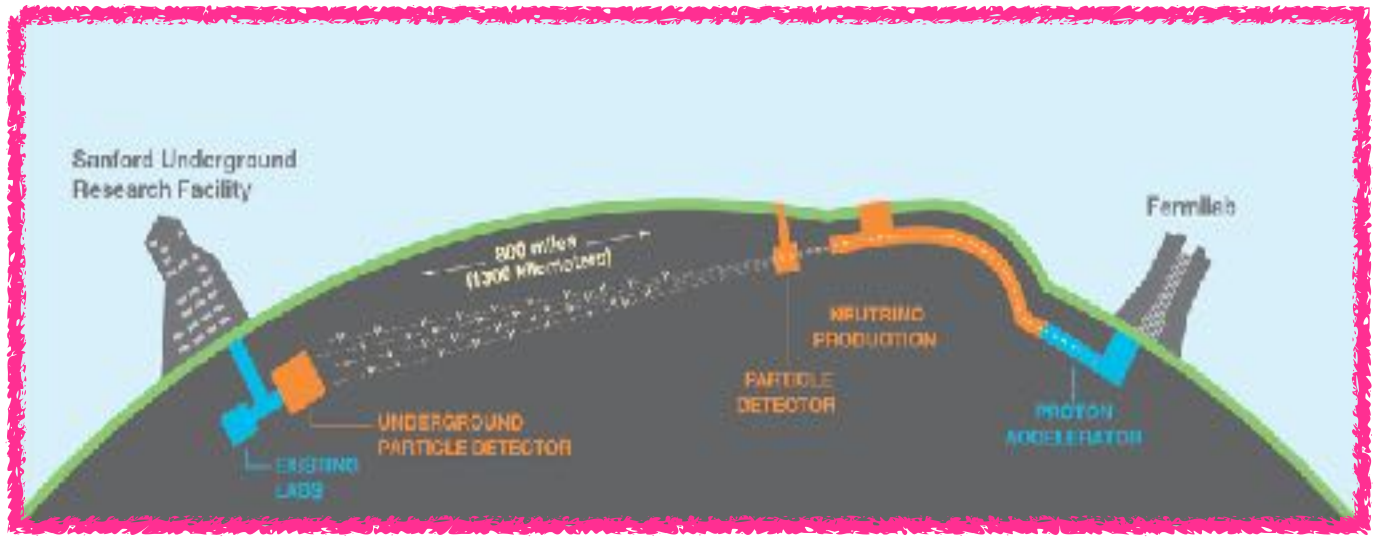
log m_i (gauss) m_i log m_i log m_0 (m_0) Σm

independent prior on the 3 masses

+ priors on Δm^2_{ij}

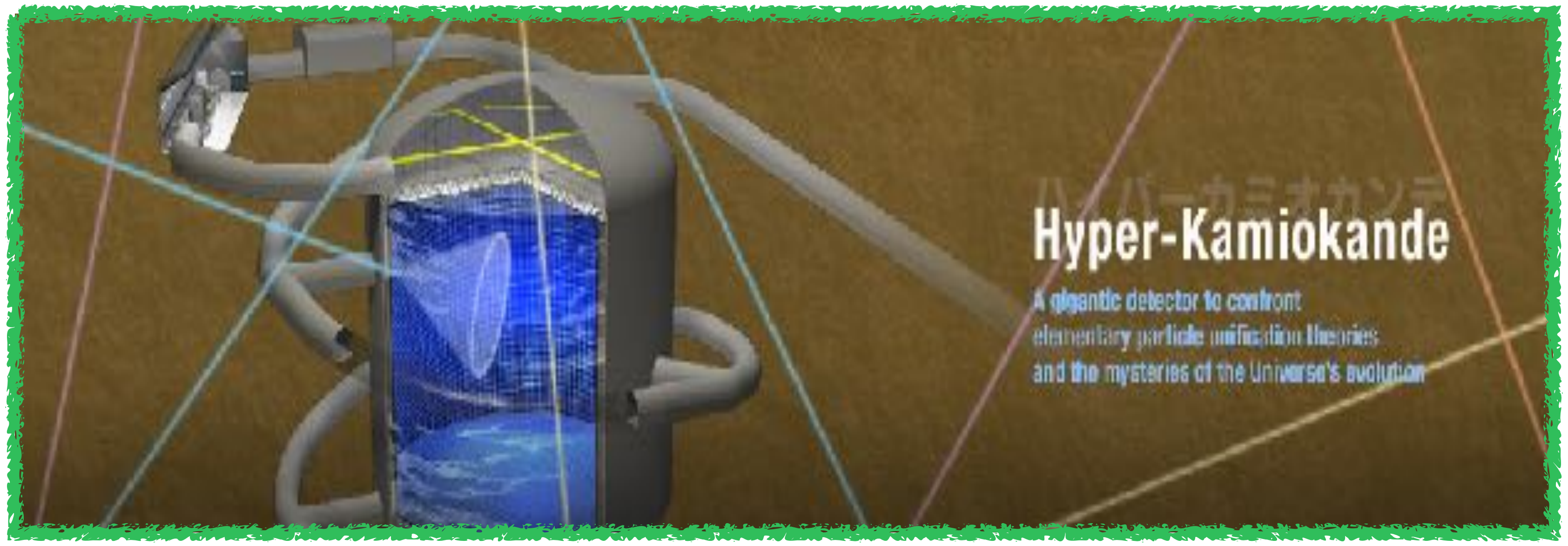
Next generation experiments

DUNE



- 1.2 MW → 2.4 MW wide-band beam
- Baseline: 1300km
- 4x10 kt Liquid Argon TPCs
- capability to probe 2nd oscillation max
- great sensitivity to mass ordering

Hyper-Kamiokande



- 188 kton water Cherenkov
- Baseline: 295 km
- T2HK: great sensitivity to δ_{CP}

Non-unitary light neutrino mixing

- Most models of neutrino masses include **new extra heavy states**

Ex: type I seesaw,
inverse seesaw

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix} \qquad \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

→ (3x3) light neutrino mixing matrix U is **non-unitary** in general

- NxN **non-unitary mixing matrix** described with $2N^2-(2N-1)$ parameters

→ 13 parameters are needed to describe a non-unitary (3x3) matrix

→ besides the 4 standard ones (θ_{ij} and δ_{CP}), 9 more parameters are needed

- General parameterization for non-unitary NxN mixing matrix

$$U^{n\times n} = \begin{pmatrix} N & W \\ V & T \end{pmatrix} \quad \text{with} \quad N = N^{NP} U^{3\times 3} = \begin{pmatrix} \alpha_{11} & 0 & 0 \\ \alpha_{21} & \alpha_{22} & 0 \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} U^{3\times 3}$$

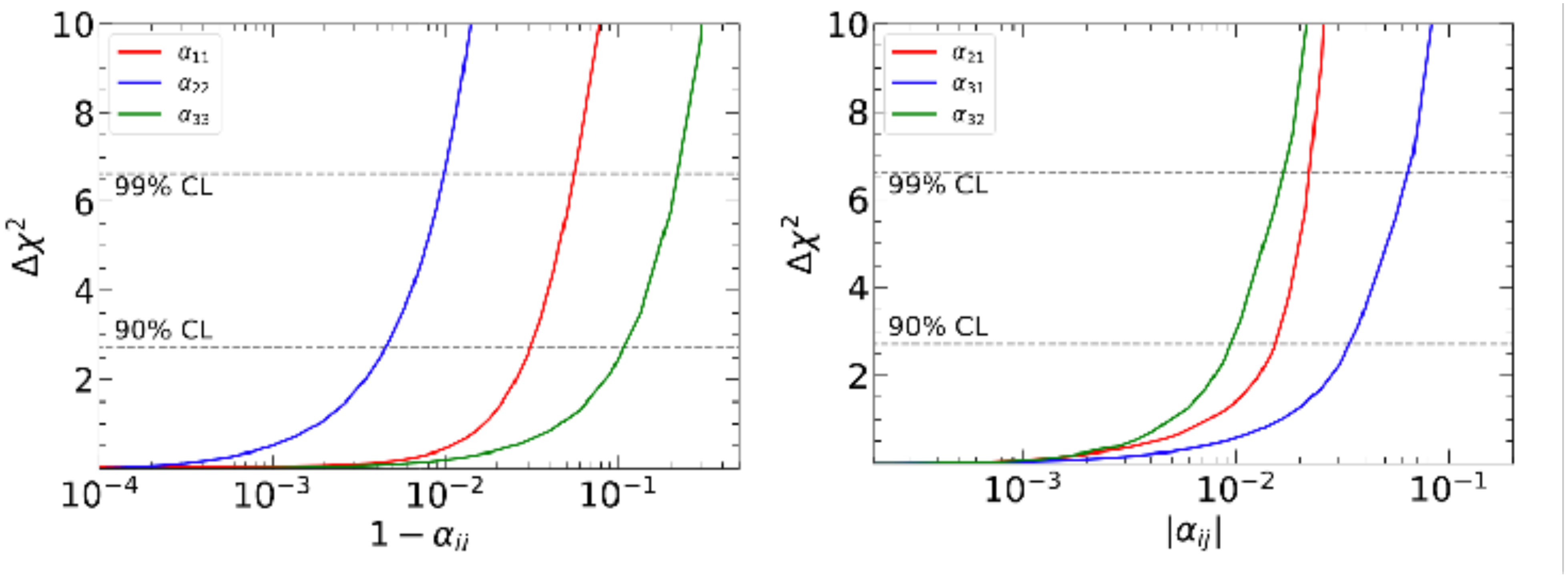
Escrihuela et al, PRD92 (2015)

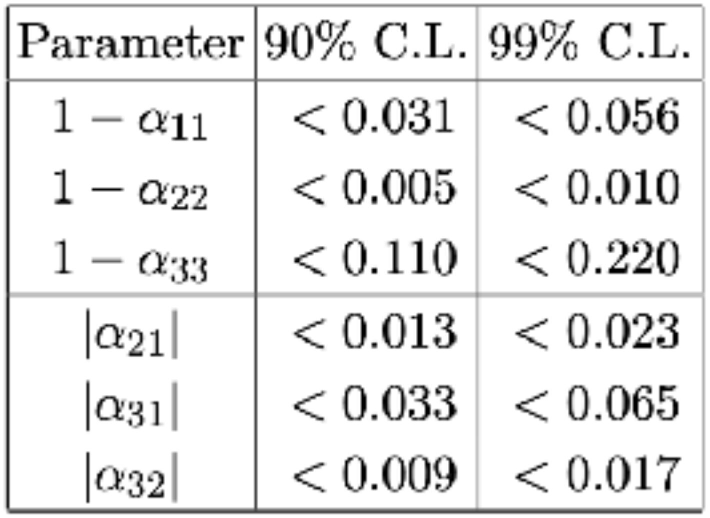
See also Xing, PRD2012 for n=6

→ α_{ii} real, α_{ij} complex: 9 new parameters

Bounds on neutrino NU mixing

✦ Analysis of **short-baseline** and **long-baseline** neutrino experiments: NOMAD and NuTeV and MINOS, NOvA and T2K.



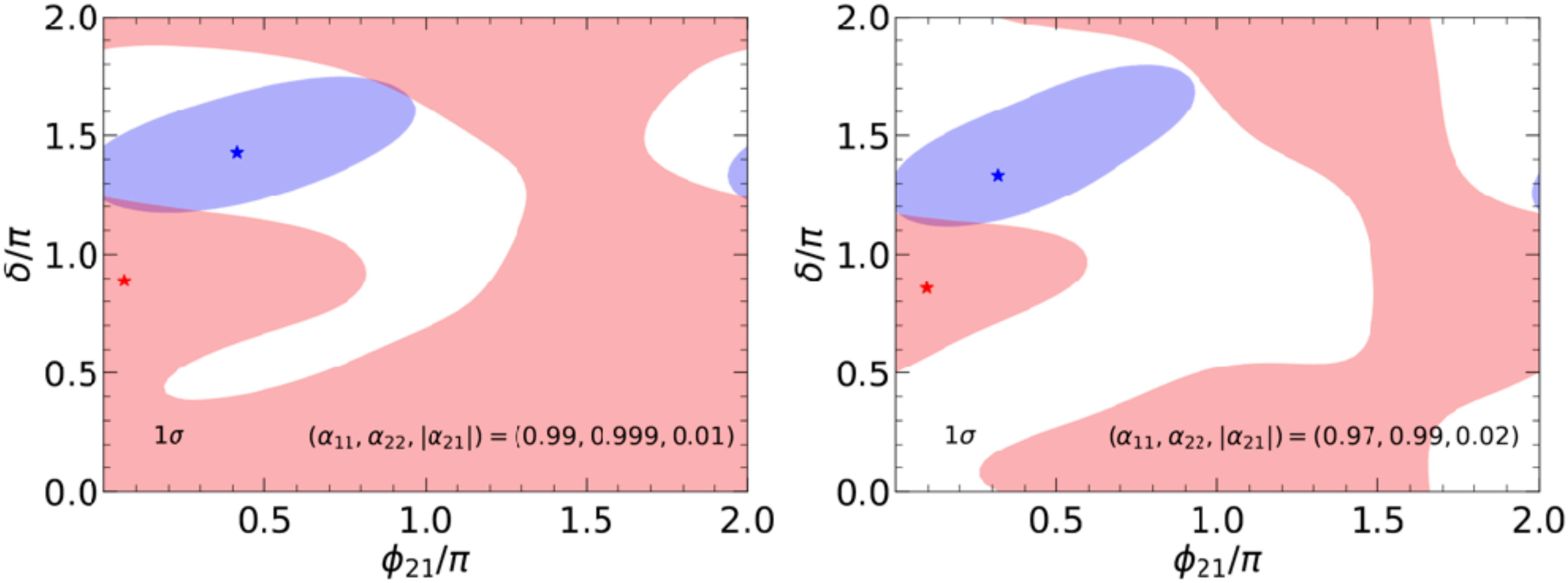


Parameter	90% C.L.	99% C.L.
$1-\alpha_{11}$	< 0.031	< 0.056
$1-\alpha_{22}$	< 0.005	< 0.010
$1-\alpha_{33}$	< 0.110	< 0.220
$\|\alpha_{21}\|$	< 0.013	< 0.023
$\|\alpha_{31}\|$	< 0.033	< 0.065
$\|\alpha_{32}\|$	< 0.009	< 0.017

Forero, Giunti, Ternes, MT, PRD 2022

The T2K-NOvA δ_{CP} tension

Non-unitary mixing analysis of T2K and NOvA (normal ordering)

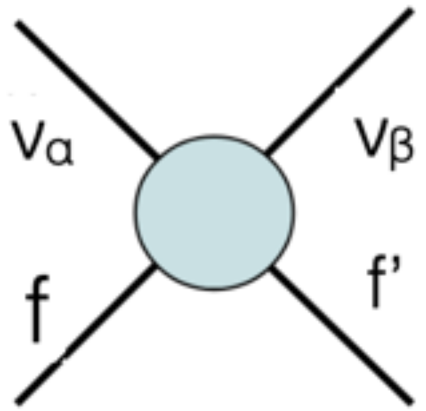


Forero et al, PRD 2022

- NU includes additional sources of CP violation.
- In this case, the tension is not alleviated in the context of NU neutrino mixing, since the new phase has the same effect on T2K and NOvA

Neutrino NSI with matter

✦ New 4-fermion interactions involving neutrinos



CC-NSI: $\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{f f' X}\,(\bar{\nu}_\alpha\gamma^\mu P_L \ell_\beta)\,(\bar{f}'\gamma_\mu P_X f)$

$\Rightarrow$ effect on neutrino production and detection

(source) (detector)

NC-NSI: $\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{f X}\,(\bar{\nu}_\alpha\gamma^\mu P_L \nu_\beta)\,(\bar{f}\gamma_\mu P_X f)$

$\epsilon_{\alpha\beta} \neq 0$ → NSI violate lepton flavor (FC-NSI)

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0$ → NSI violate lepton universality (NU-NSI)

$\Rightarrow$ mainly affecting neutrino propagation in matter:

(but also detection, e.g., Super-K and Borexino)

✦ NSI may affect the 3-neutrino oscillation picture:

$\Rightarrow$ precision measurements at current experiments

$\Rightarrow$ sensitivity reach of upcoming experiments (degeneracies)