Neutrino masses and mixings

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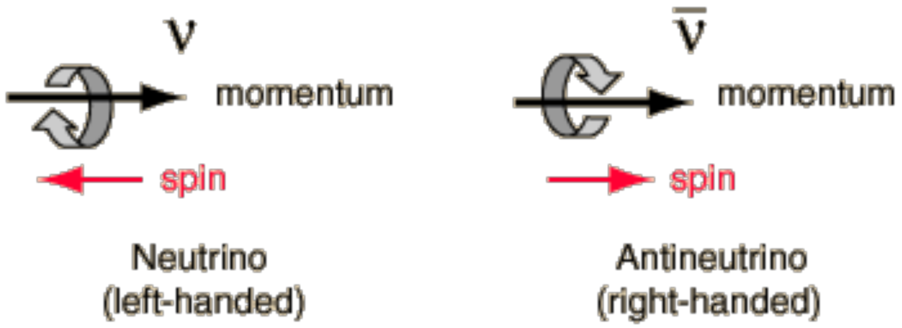
Neutrinos in the Standard Model

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



- Only neutral fermion: Dirac or Majorana nature?

$$\psi_R \equiv \psi_L^C = \hat{C}\overline{\psi}^T$$

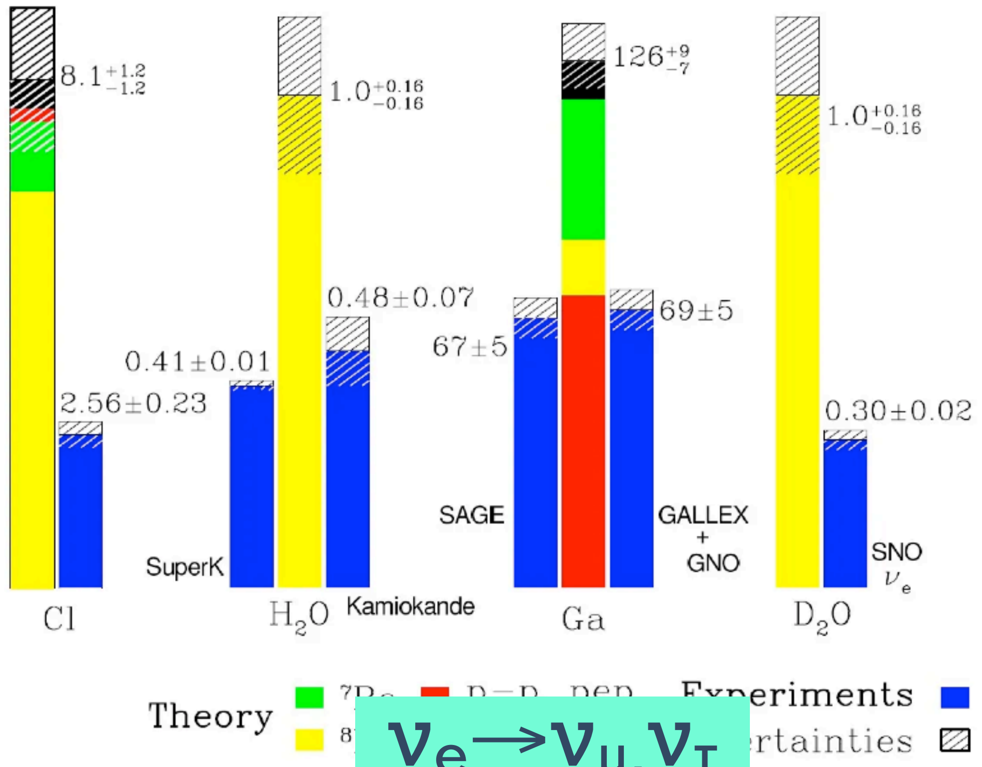
- No mass term for neutrinos can be built with the content of the SM:

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

Neutrinos are strictly massless in the Standard Model!

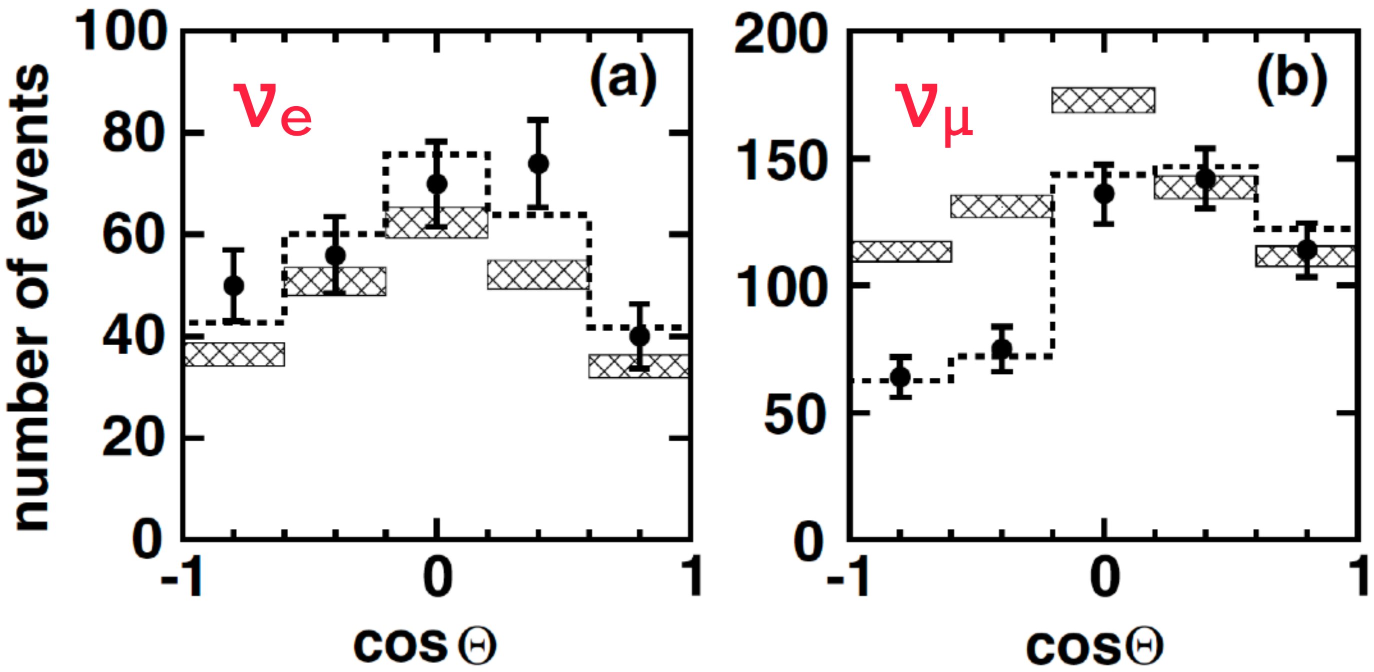
Neutrino anomalies

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

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

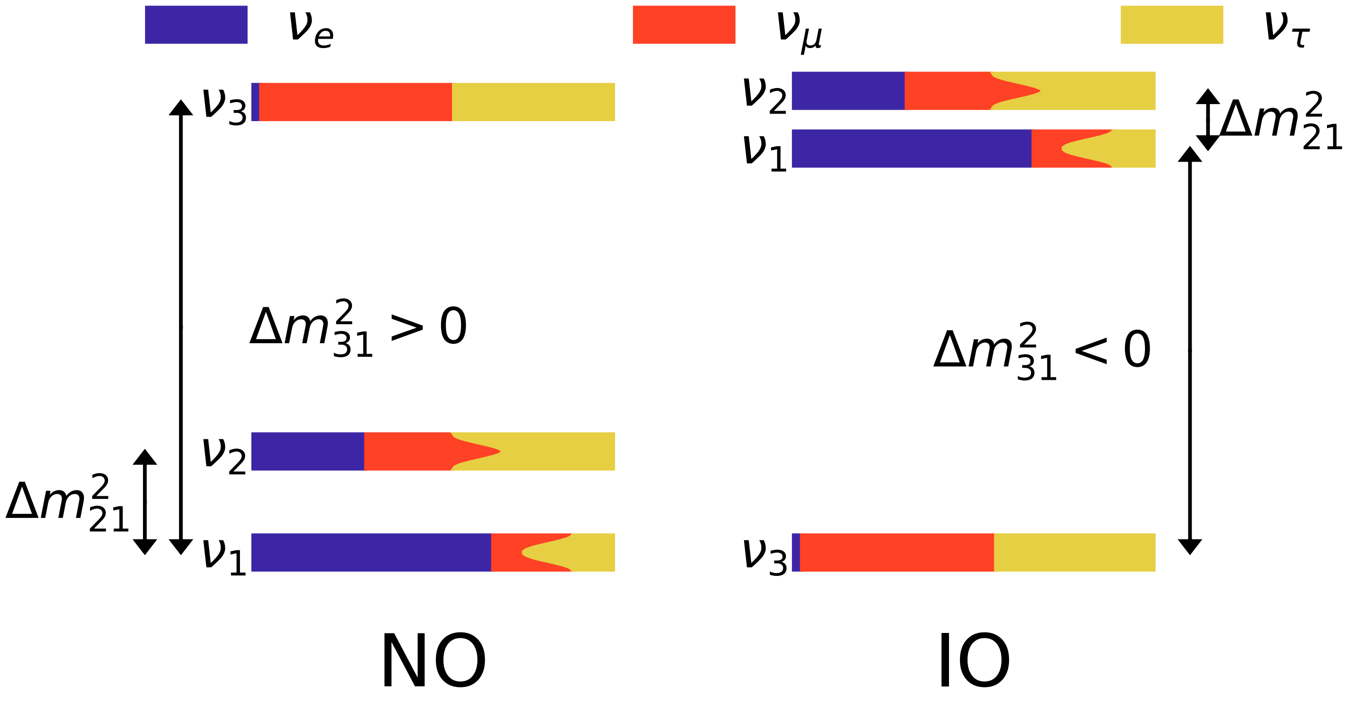
neutrino mass spectrum

- ✓ 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

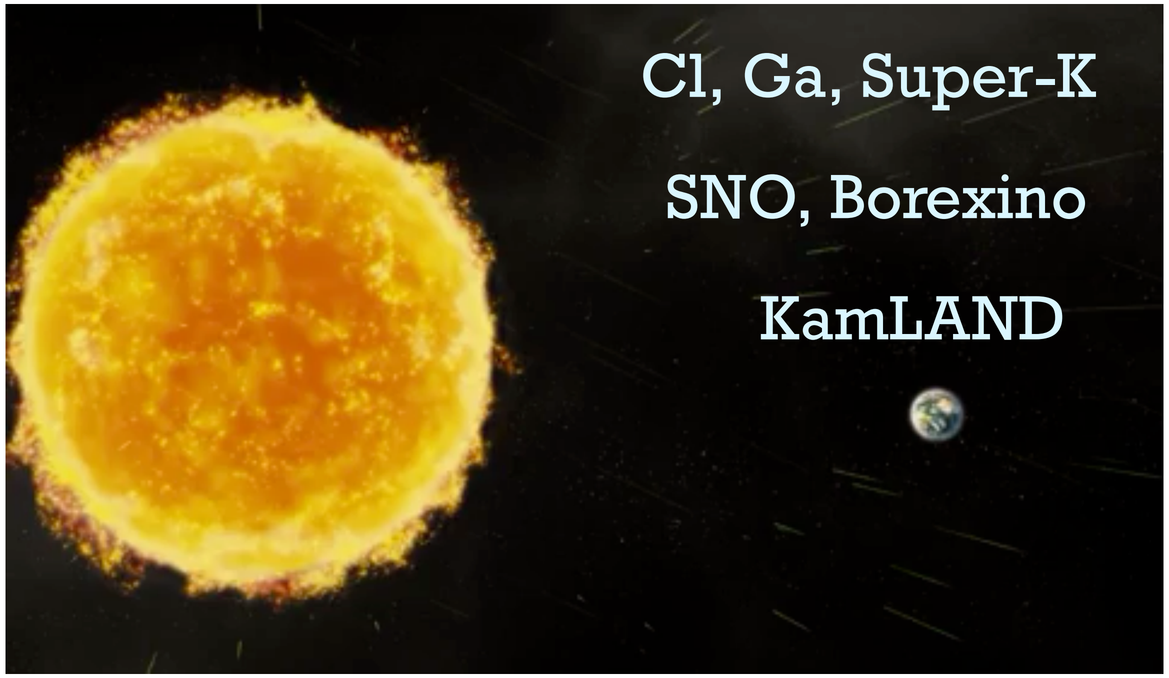
⇒ two mass splittings:

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



Neutrino oscillations

Solar sector

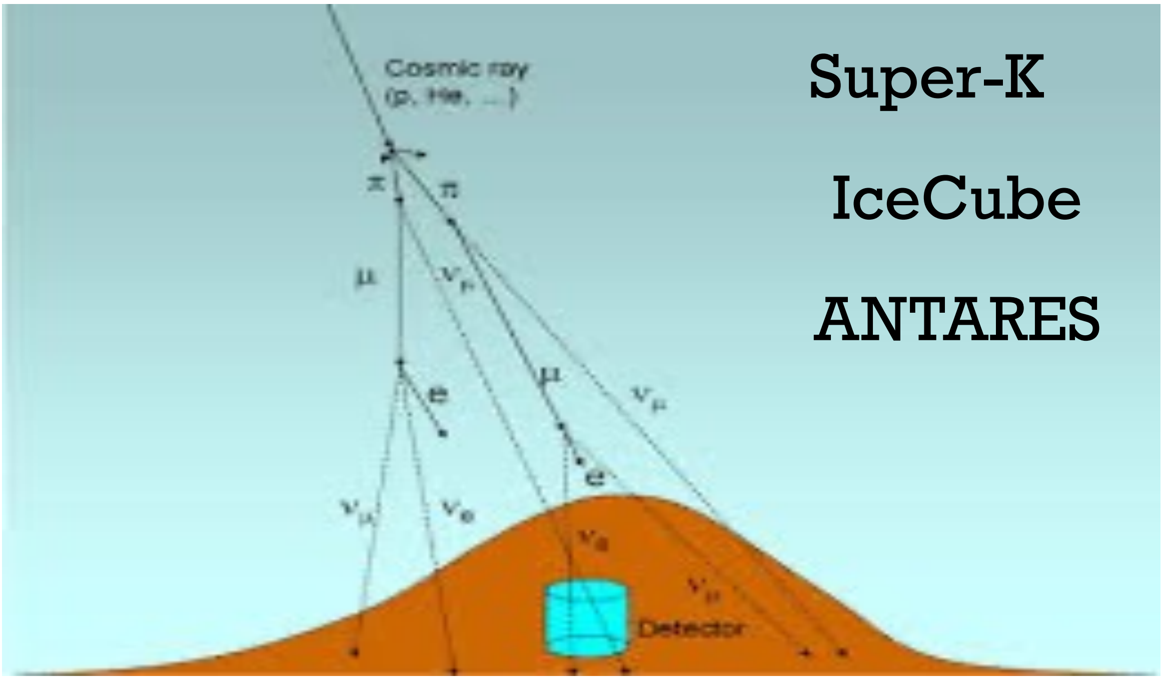


Cl, Ga, Super-K

SNO, Borexino

KamLAND

Atmospheric sector



Super-K

IceCube

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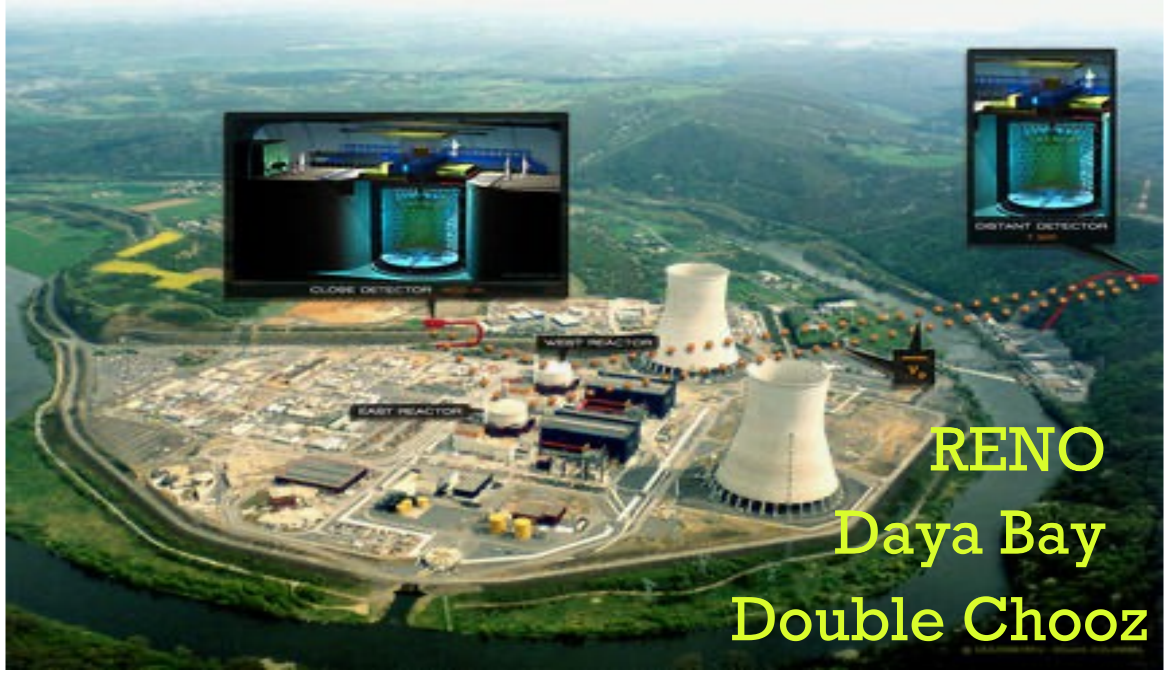
Reactor sector

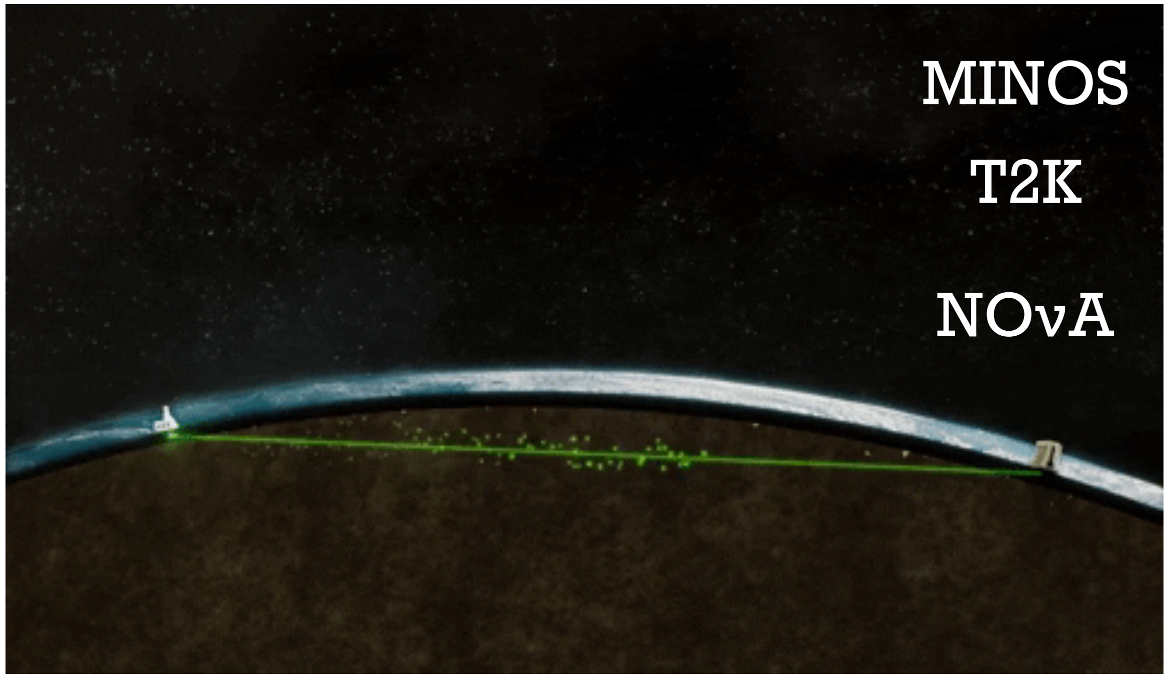


RENO

Daya Bay

Double Chooz

Accelerator sector



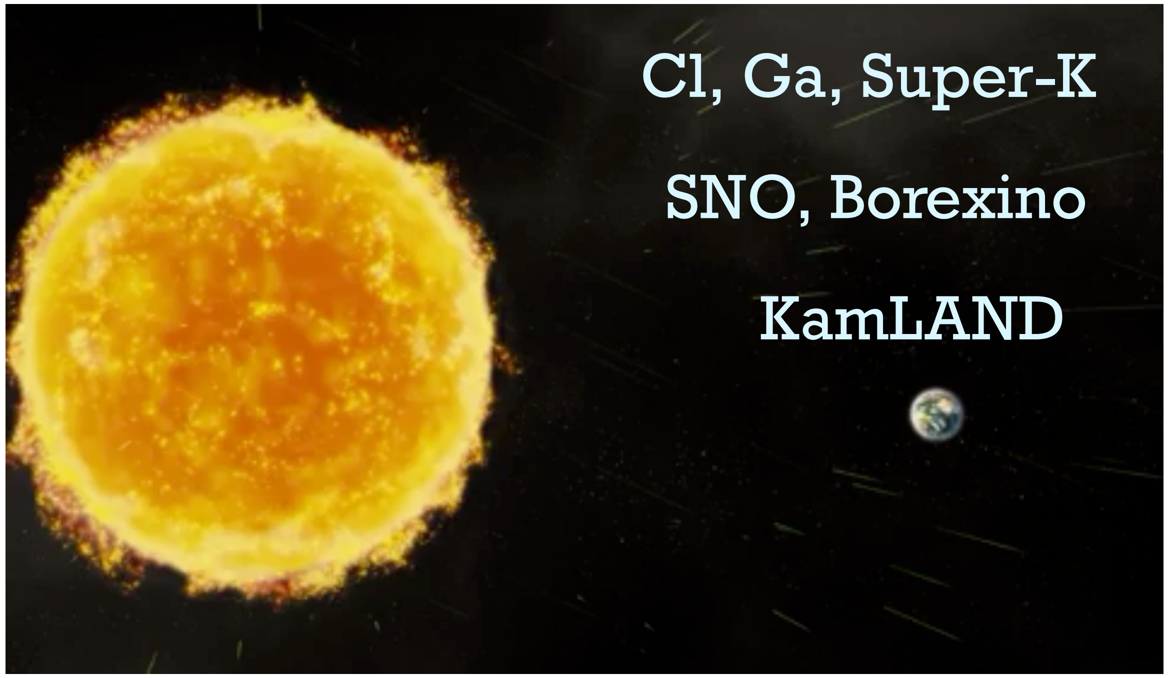
MINOS

T2K

NOνA

Neutrino oscillations

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

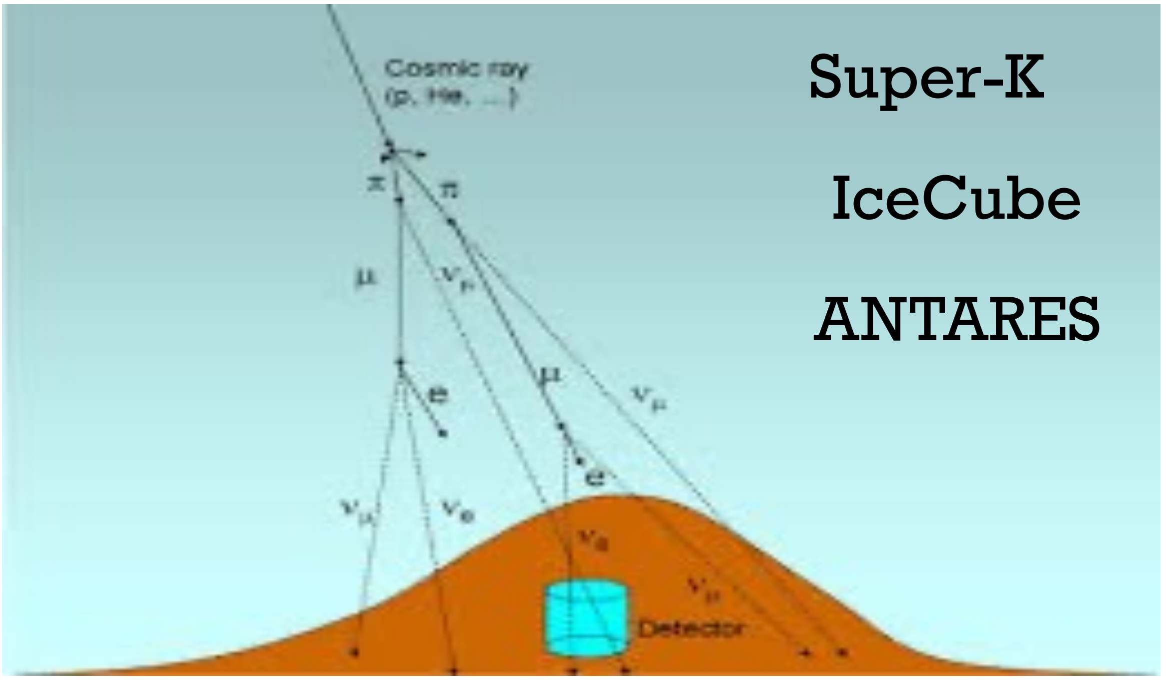


Cl, Ga, Super-K

SNO, Borexino

KamLAND

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



Super-K

IceCube

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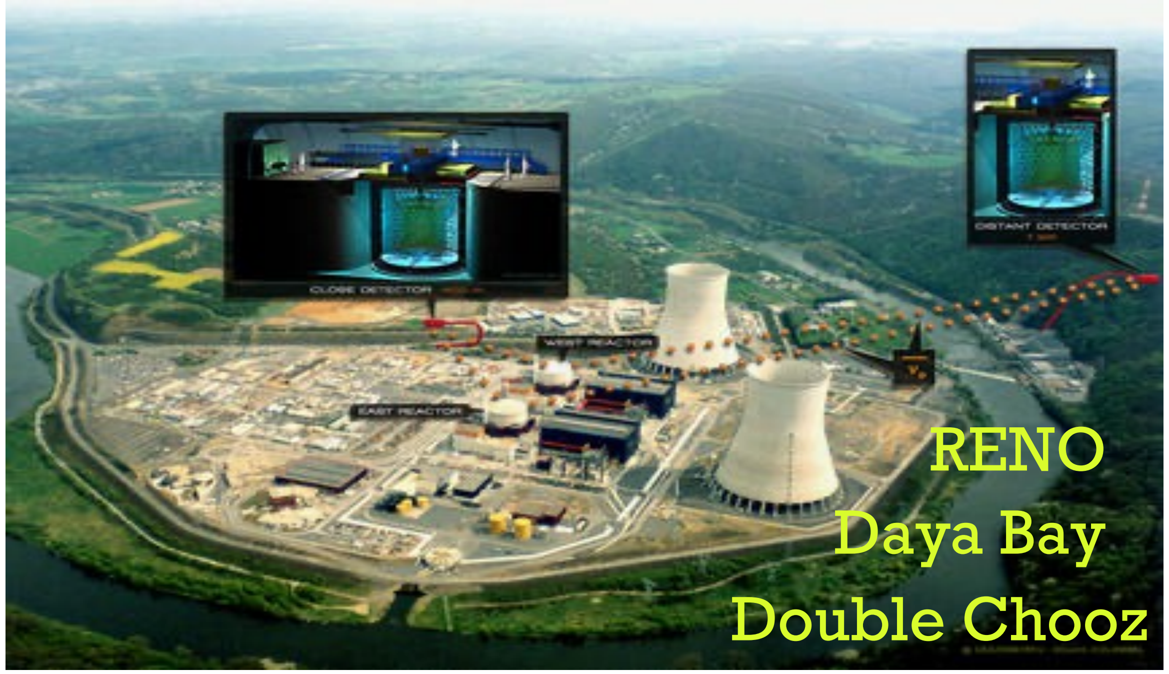
Reactor sector: θ_{13}, Δm^2_{31}



RENO

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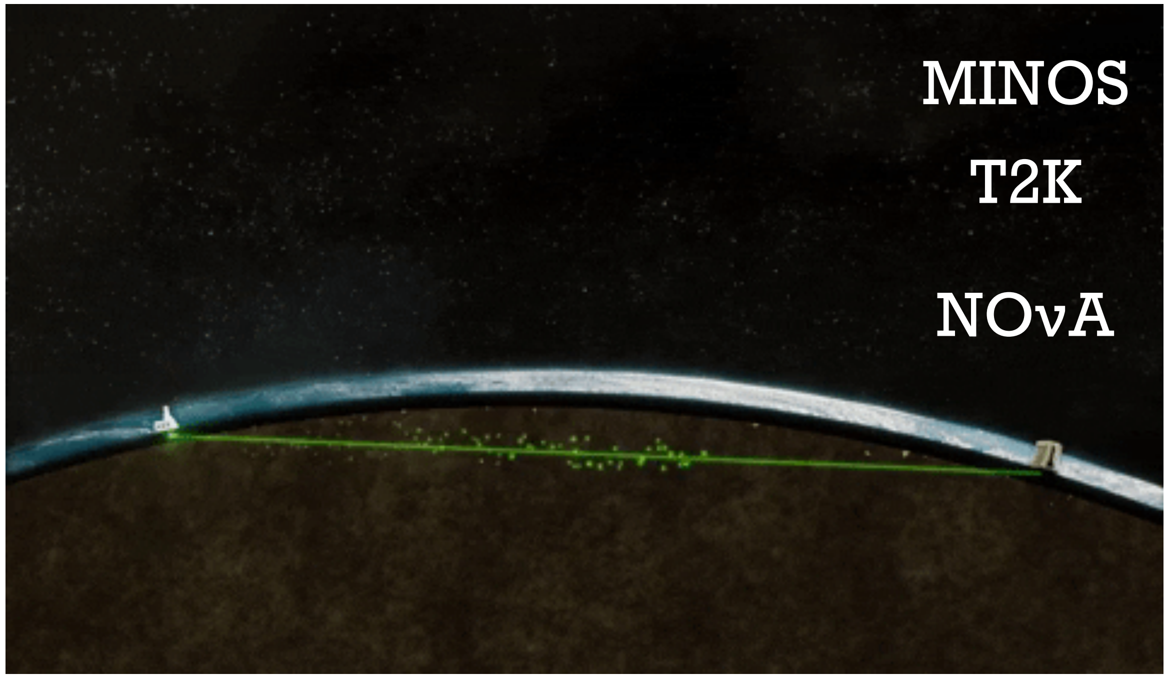
Accelerator sector: θ_{23}, θ_{13}, Δm^2_{31}, δ

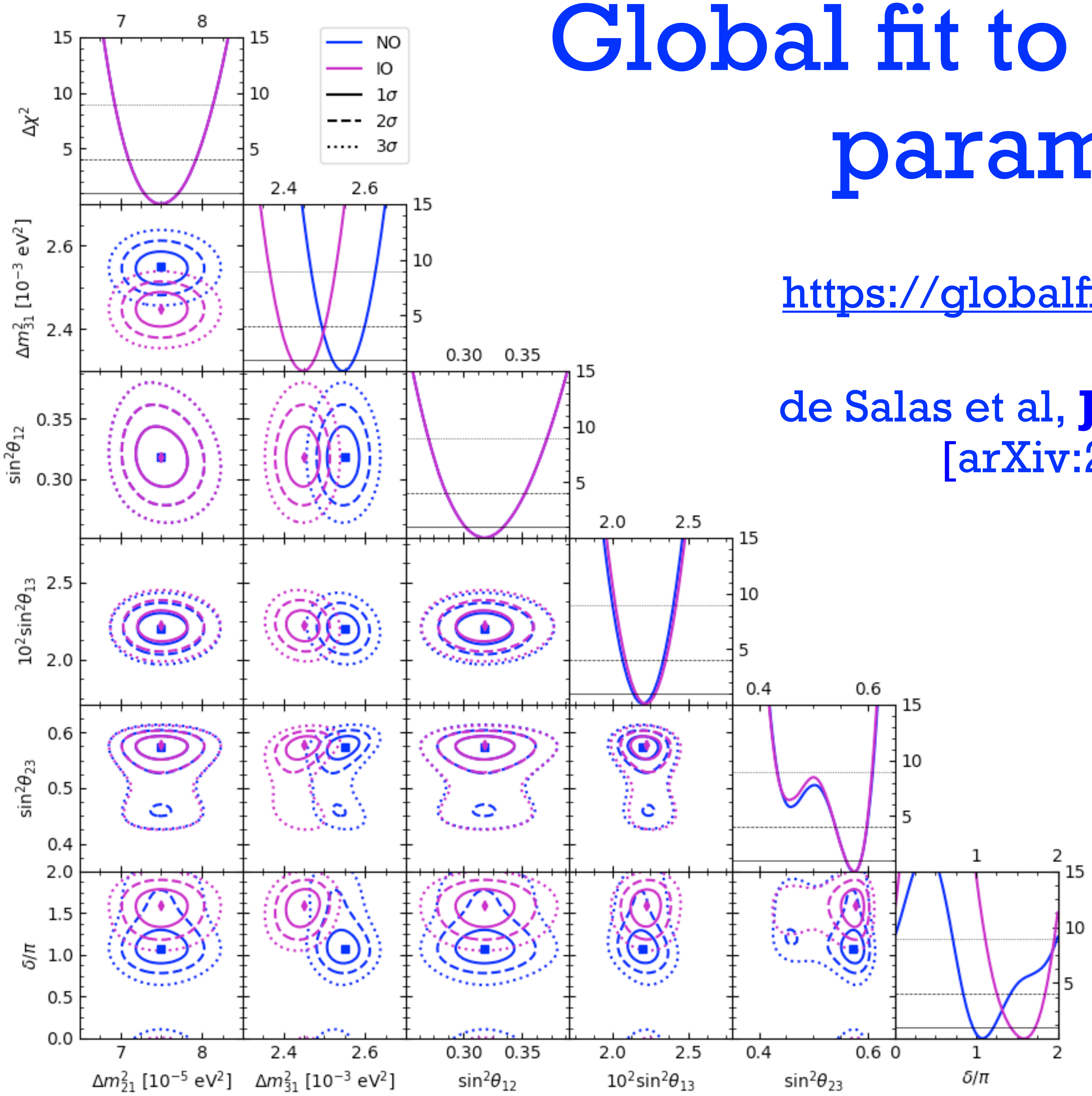


MINOS

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]

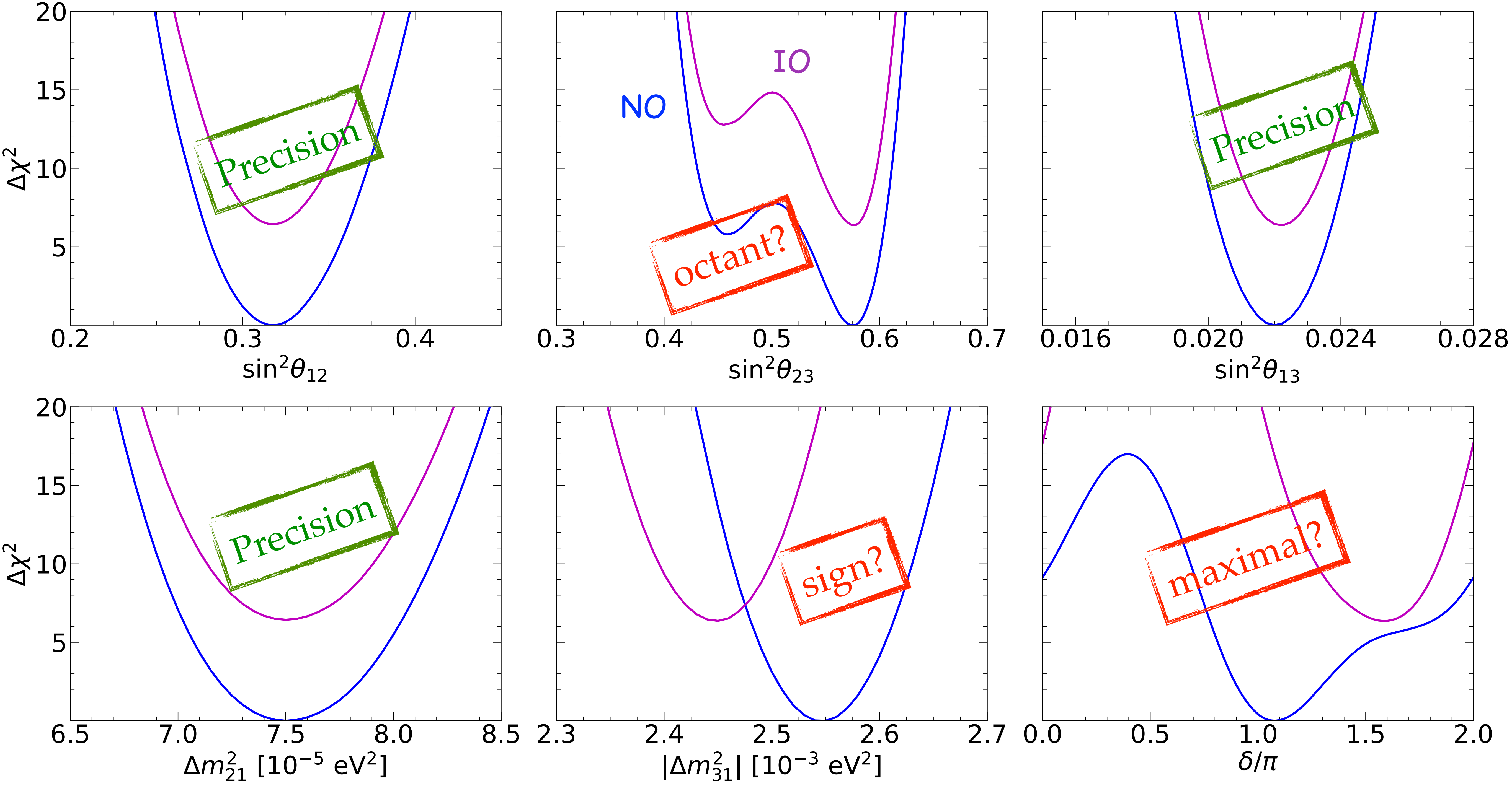
See also NuFIT and Bari group analyses

https://globalfit.astroparticles.es/

parameter	best fit ± 1σ	3σ range	relative 1σ uncertainty
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.50^{+0.22}_{-0.20}$	6.94–8.14	2.7%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.47–2.63	1.1%
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (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%

Global fit to ν oscillation parameters

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



Precision

octant?

Precision

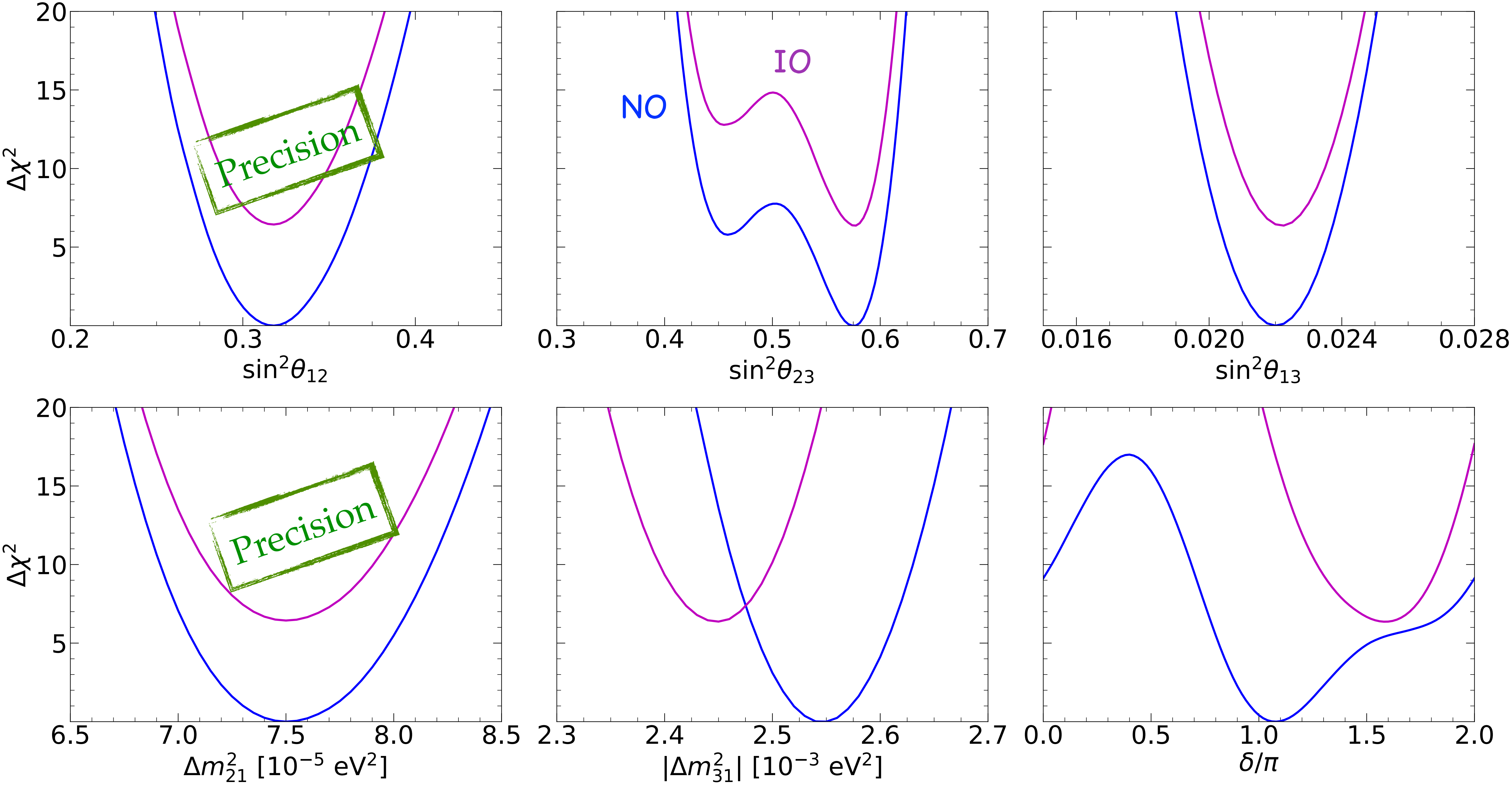
Precision

sign?

maximal?

Global fit to ν oscillation parameters

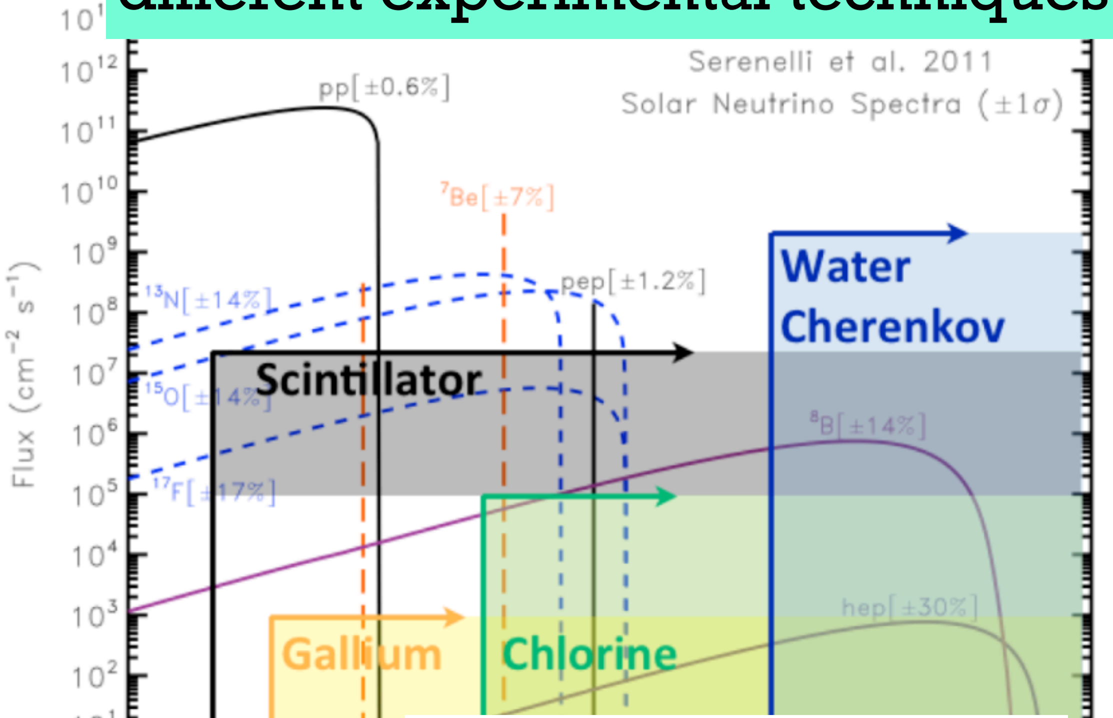
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



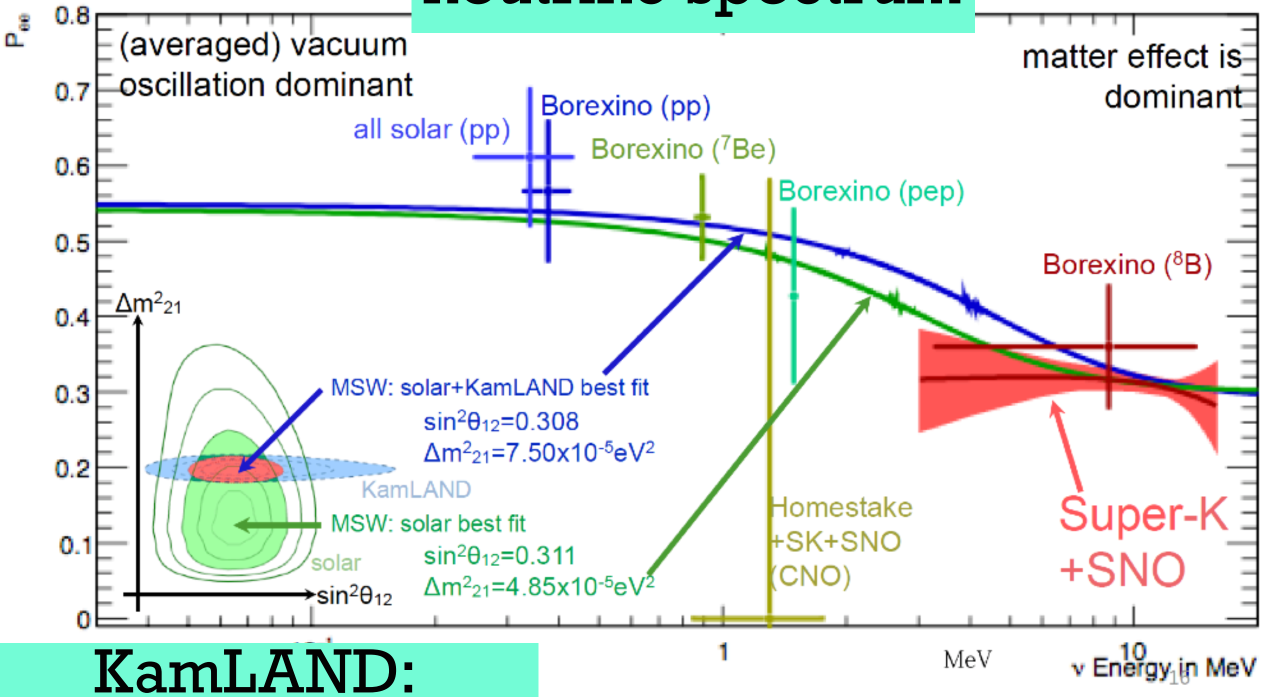
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

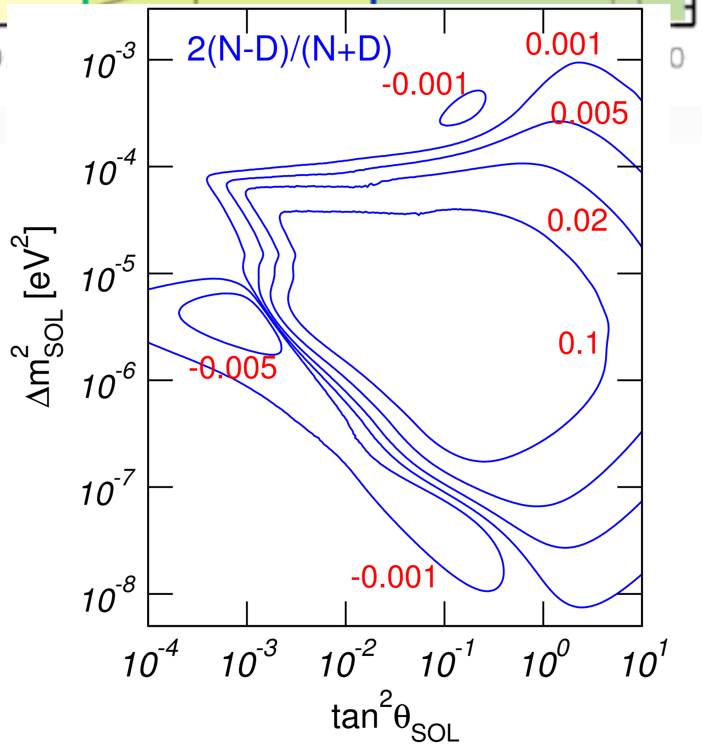
different experimental techniques



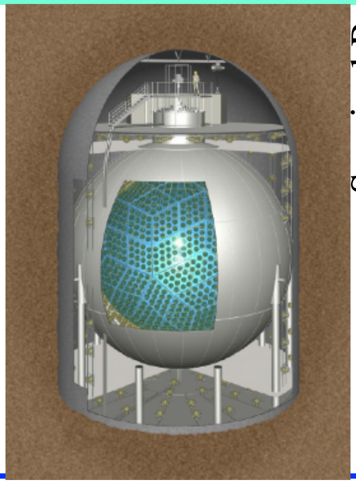
neutrino spectrum

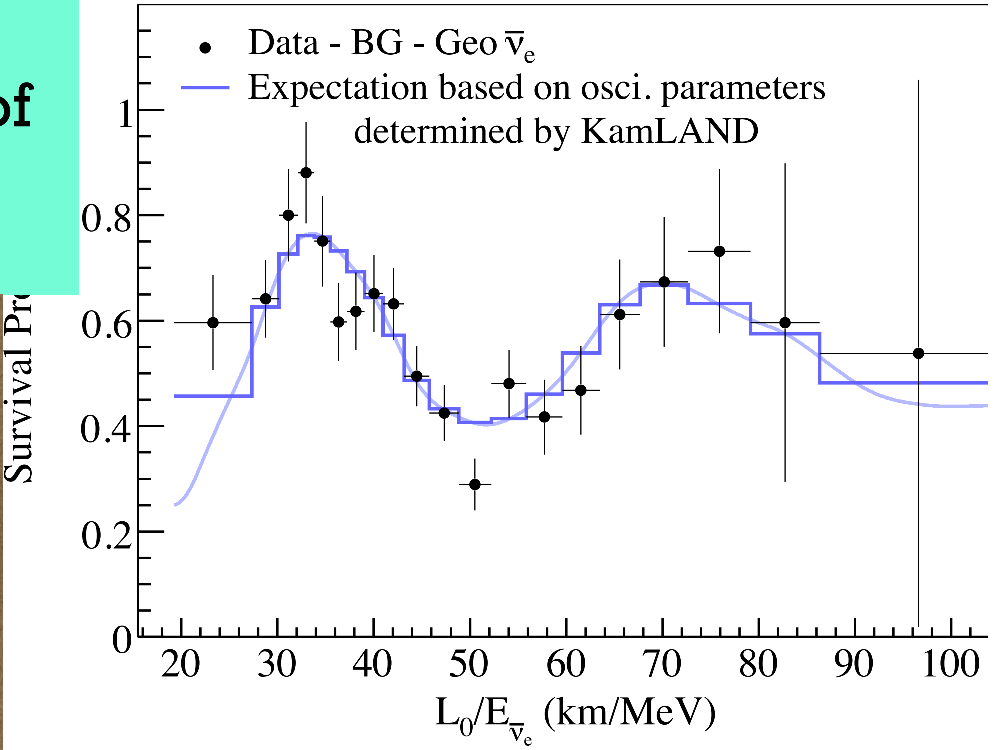


day/night asymmetry

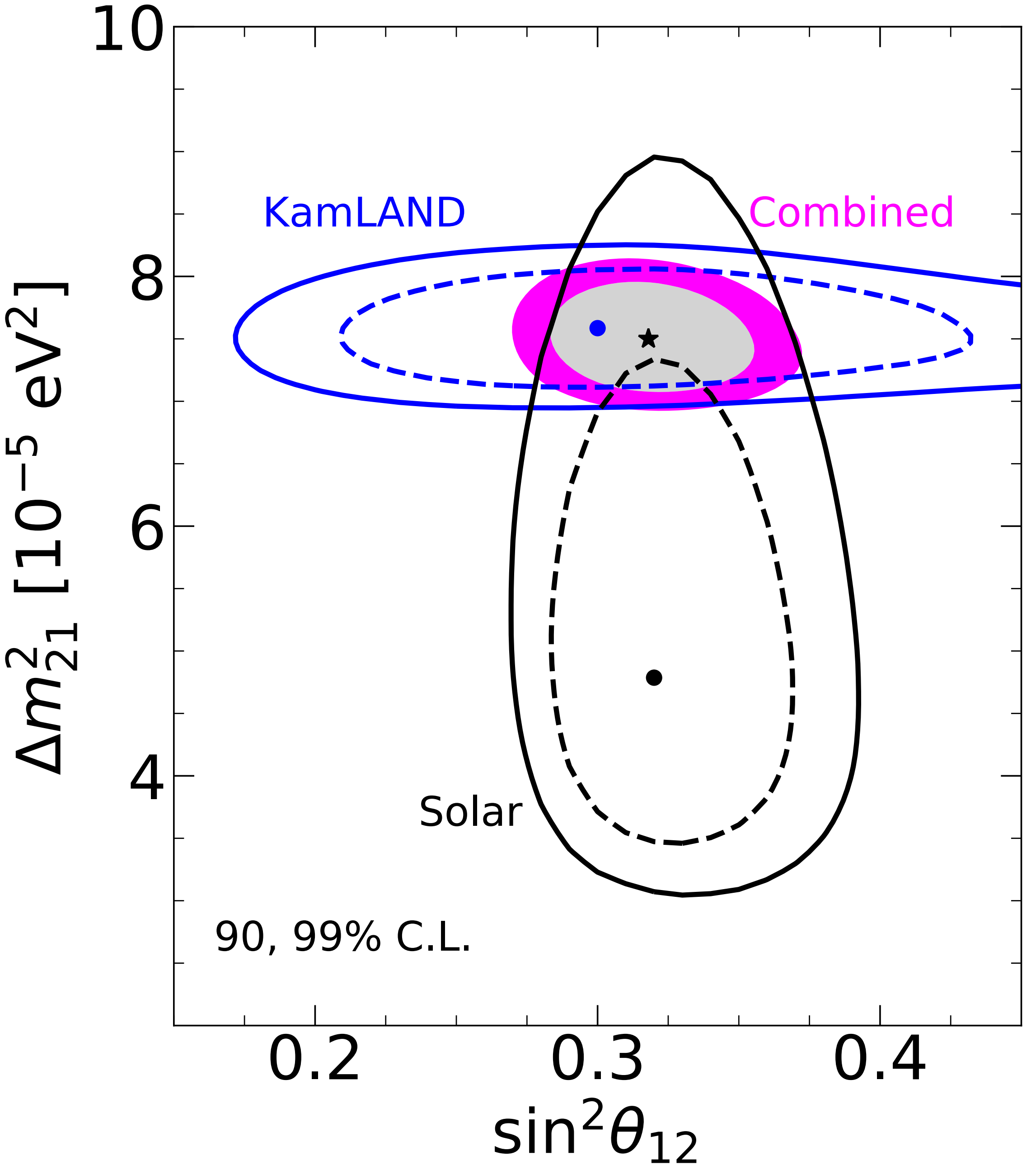


KamLAND: precise measurement of oscillation frequency



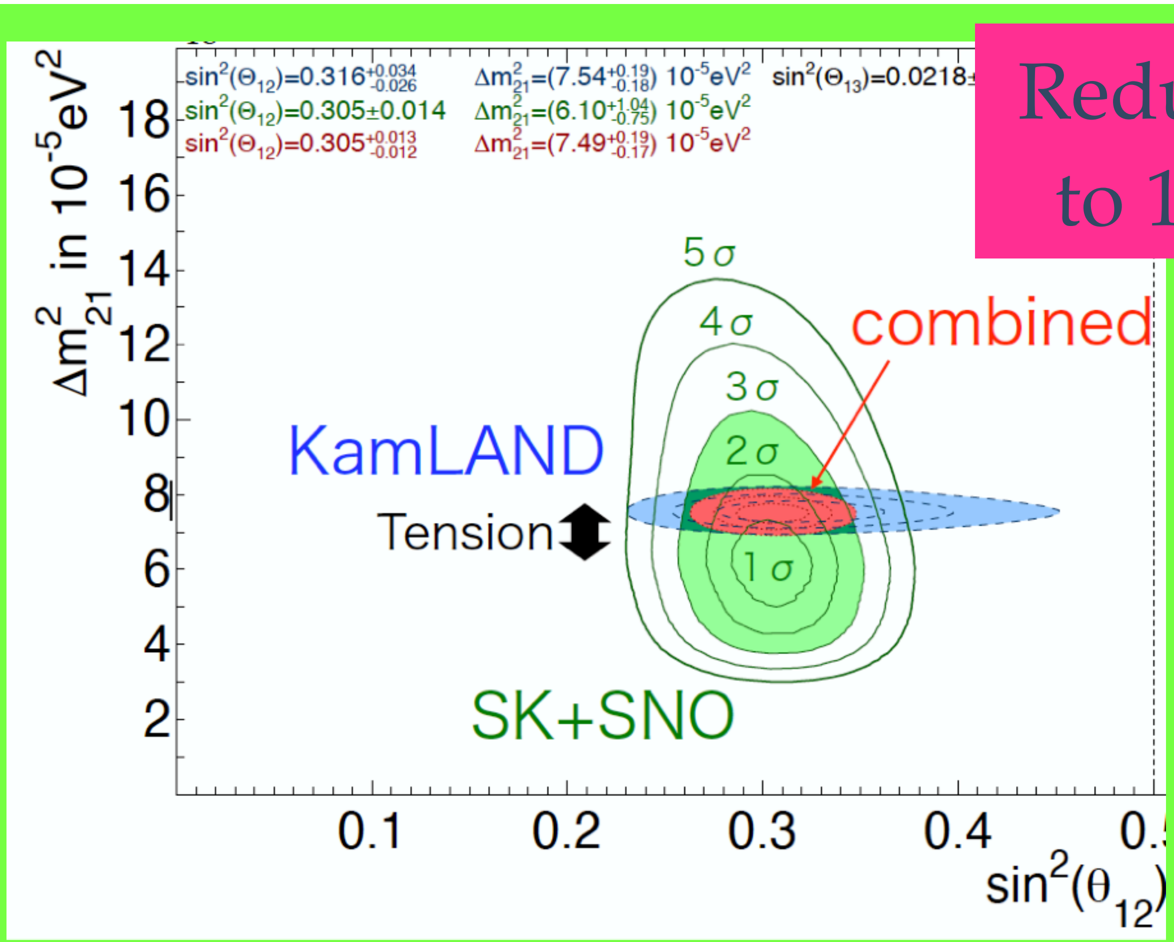


The solar sector



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


$\sin^2(\Theta_{12})=0.316^{+0.034}_{-0.026}$ $\Delta m^2_{21}=(7.54^{+0.19}_{-0.18})\ 10^{-5}\text{eV}^2$ $\sin^2(\Theta_{13})=0.0218\pm$

$\sin^2(\Theta_{12})=0.305\pm0.014$ $\Delta m^2_{21}=(6.10^{+1.04}_{-0.75})\ 10^{-5}\text{eV}^2$

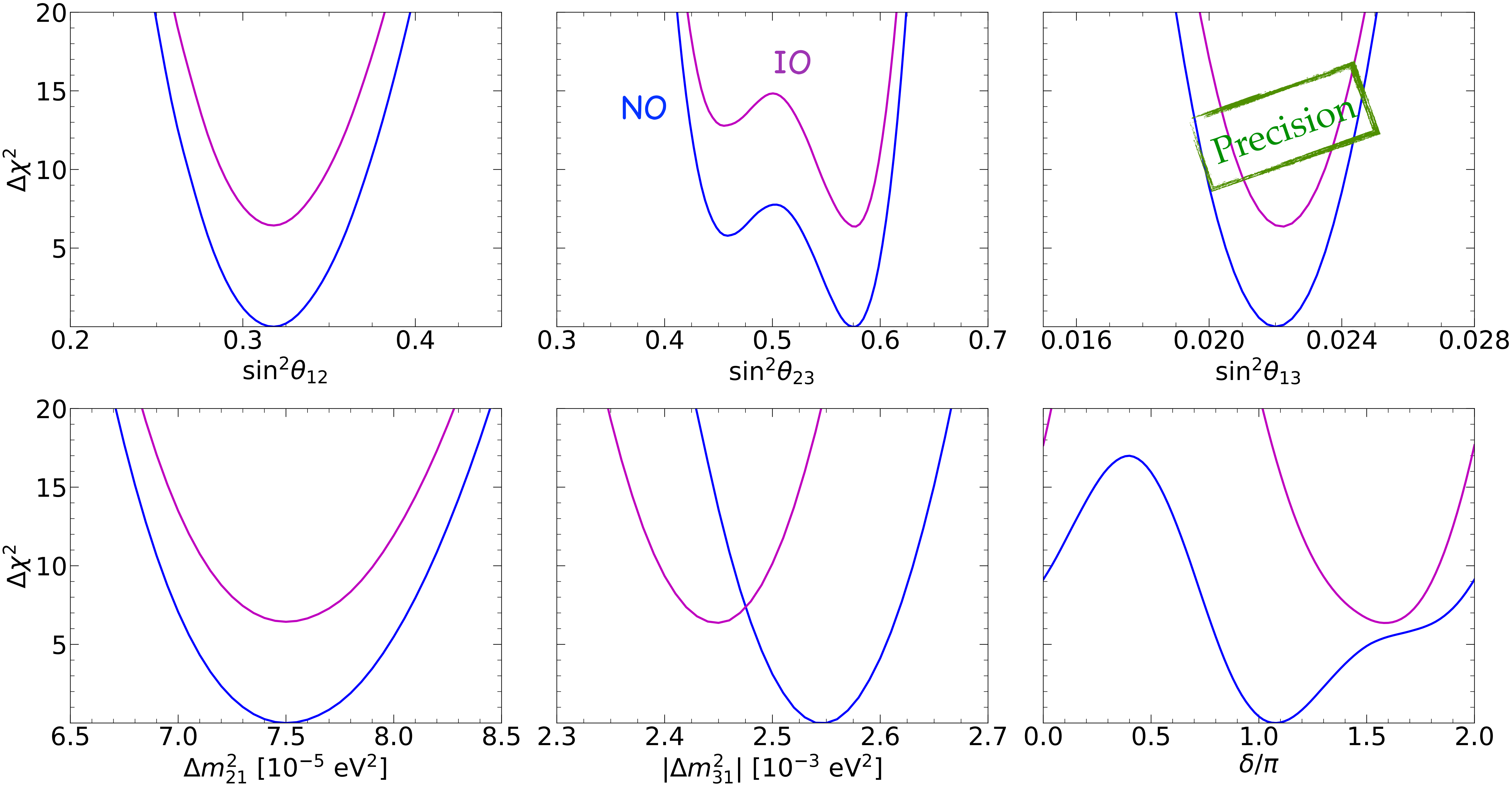
$\sin^2(\Theta_{12})=0.305^{+0.013}_{-0.012}$ $\Delta m^2_{21}=(7.49^{+0.19}_{-0.17})\ 10^{-5}\text{eV}^2$

Reduced to 1.5σ

Y. Koshio, Neutrino-2022

Global fit to ν oscillation parameters

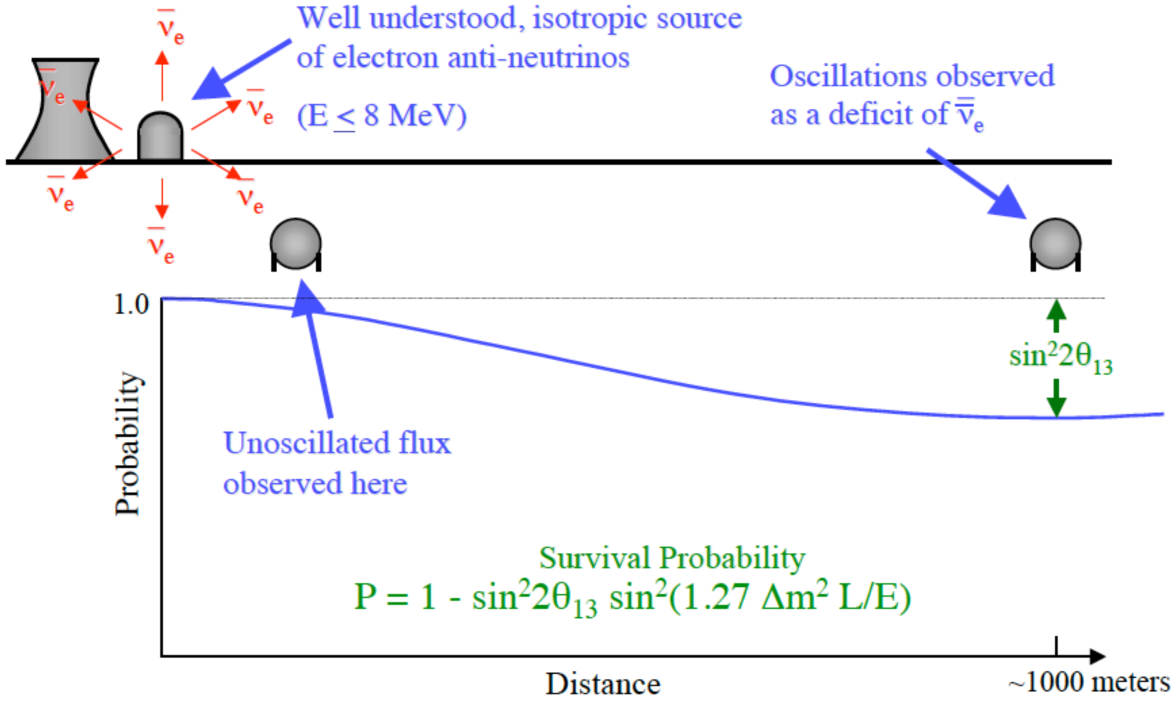
de Salas et al, **JHEP 02 (2021) 071** [arXiv:2006.11237]



The reactor sector

New generation of experiments

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



Well understood, isotropic source of electron anti-neutrinos ($E \leq 8$ MeV)

Oscillations observed as a deficit of $\bar{\nu}_e$

Unoscillated flux observed here

Survival Probability

$P = 1 - \sin^2 2\theta_{13} \sin^2(1.27\,\Delta m^2\, L/E)$

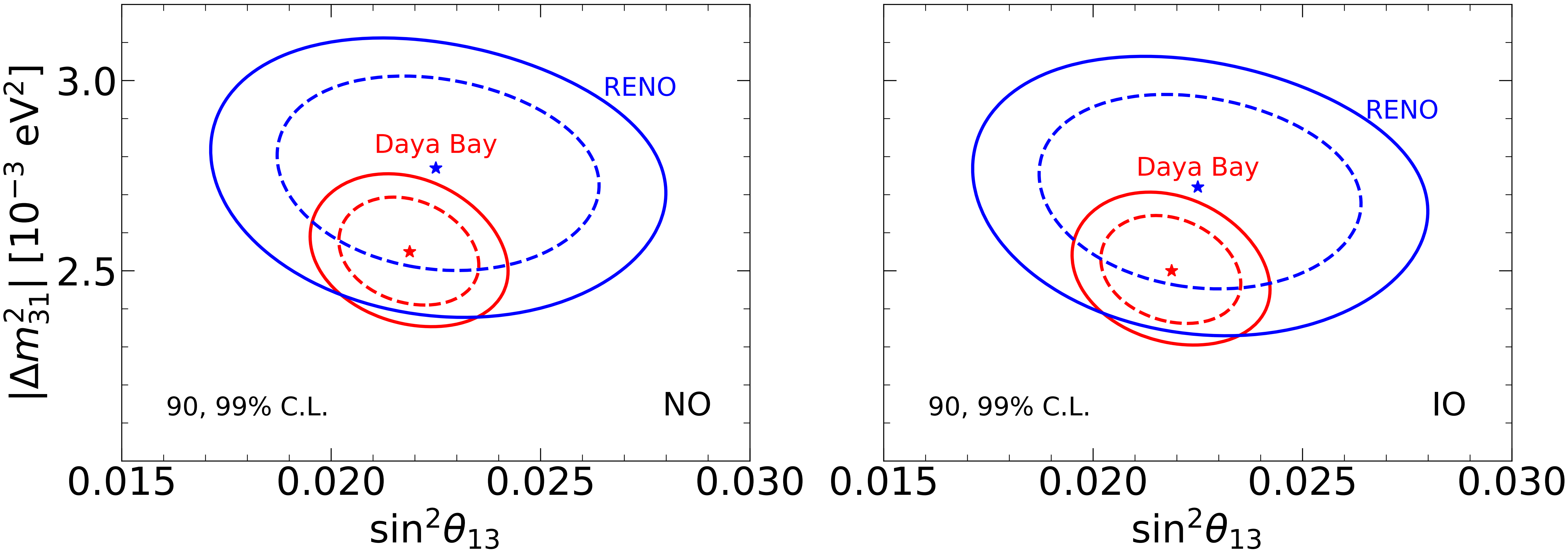
6 cores + 4 ND + 4FD

2 cores + 1 ND + 1 FD

6 cores + 1 ND + 1 FD

The reactor sector

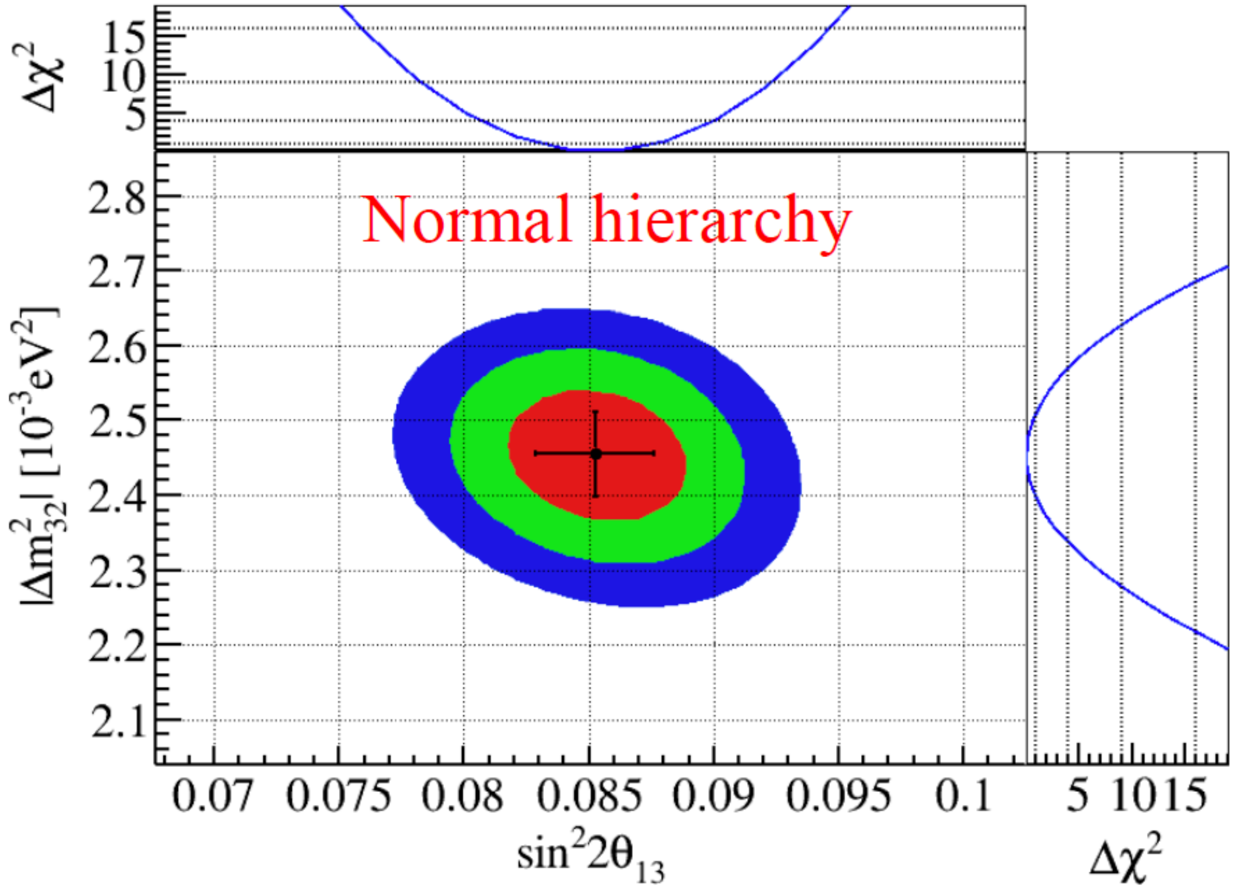
de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]

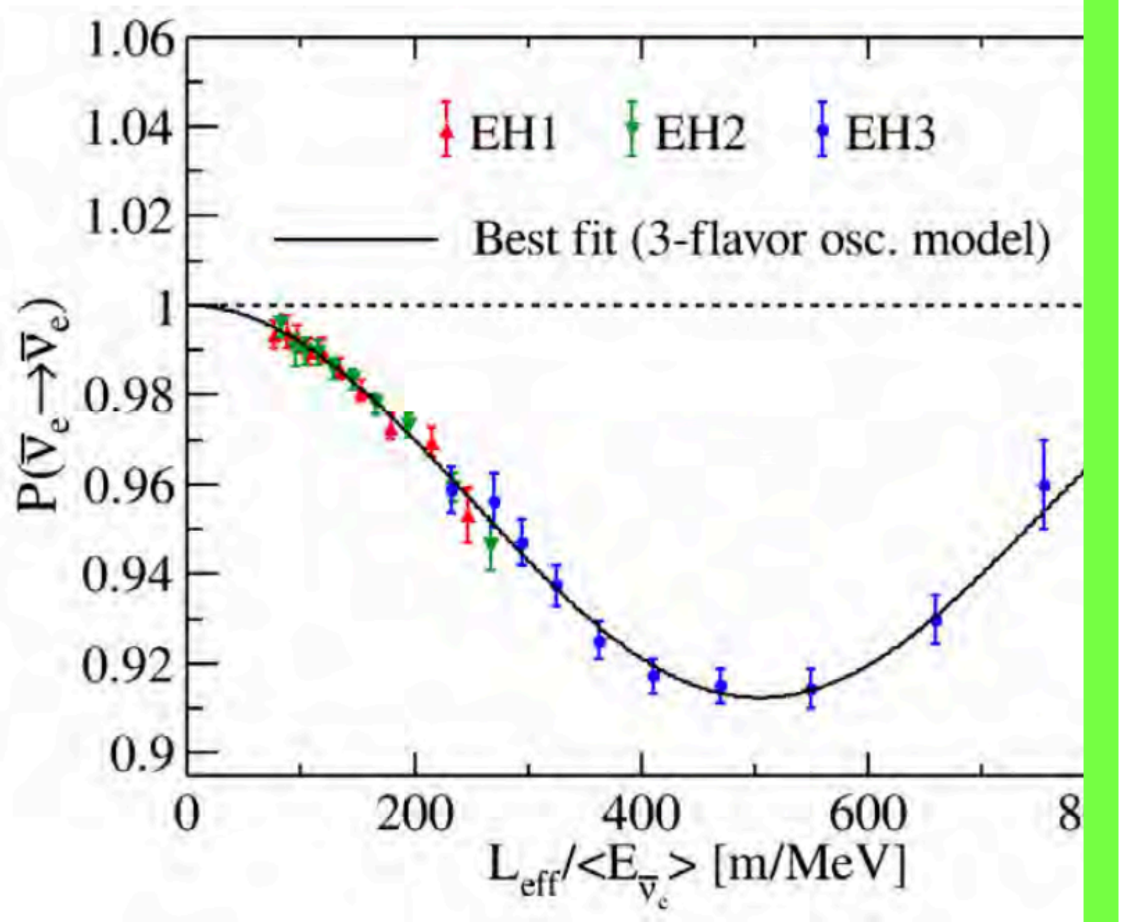


- Daya Bay: 1958-day data: $\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$ (3.4%)
- RENO: 2900-day data: $\sin^2 2\theta_{13} = 0.0892 \pm 0.0063$ (7%)

Precision dominated by Daya Bay

The reactor sector





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

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

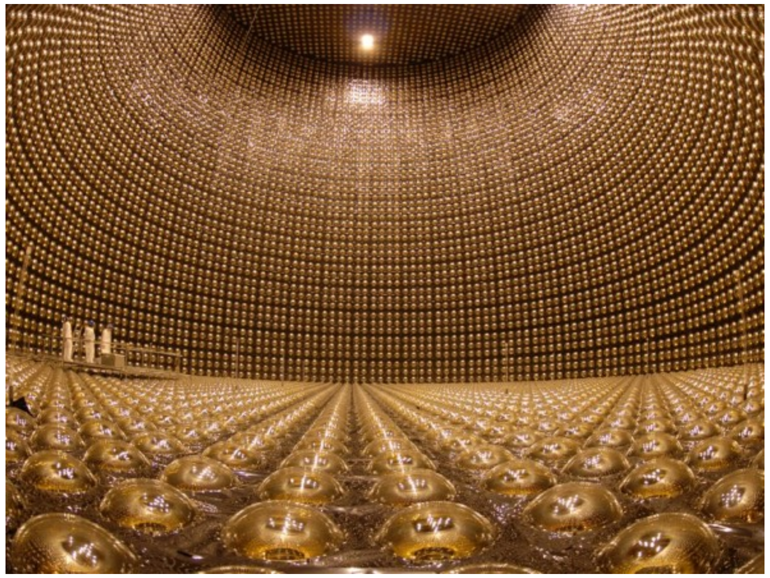
Daya Bay: 3158-day data

K. Luk, Neutrino-2022

The atmospheric sector

Atmospheric experiments

Super-Kamiokande



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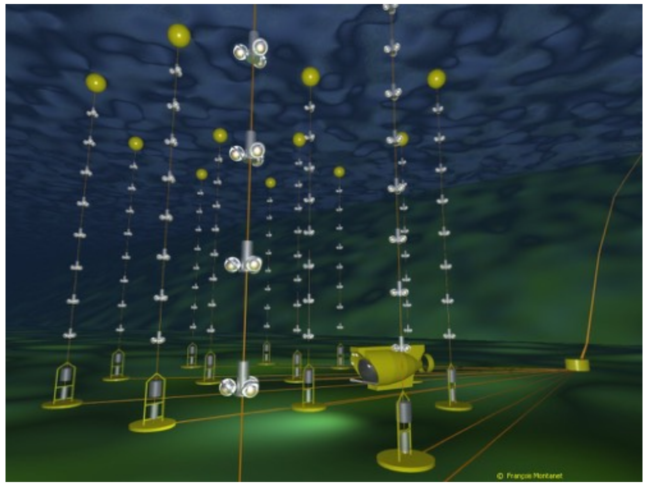
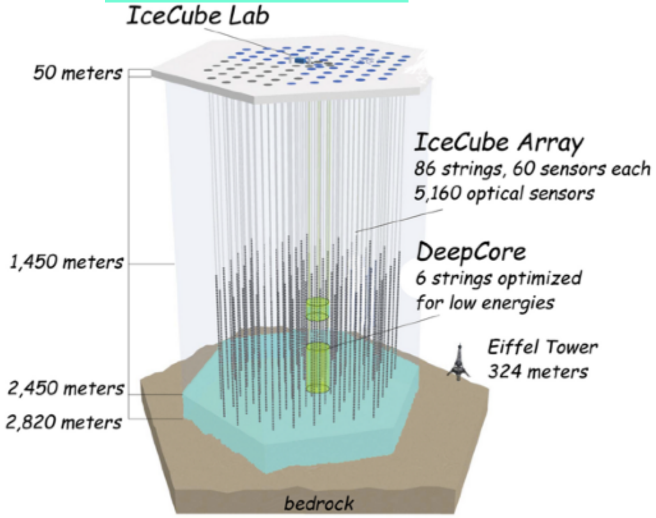
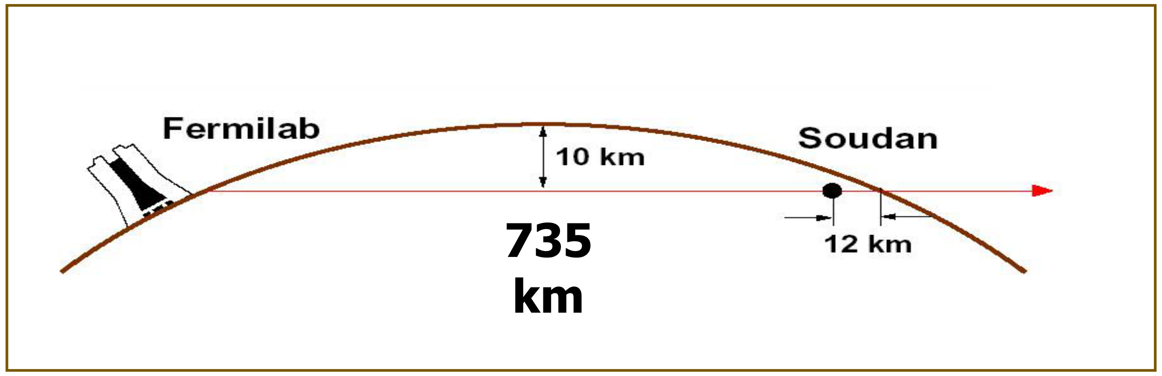


IceCube

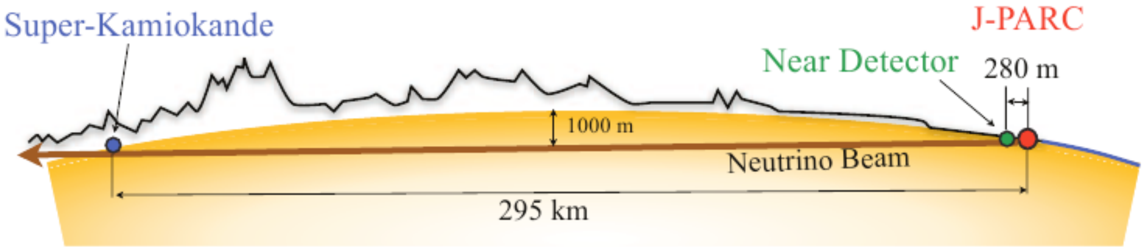


Accelerator long-baseline experiments

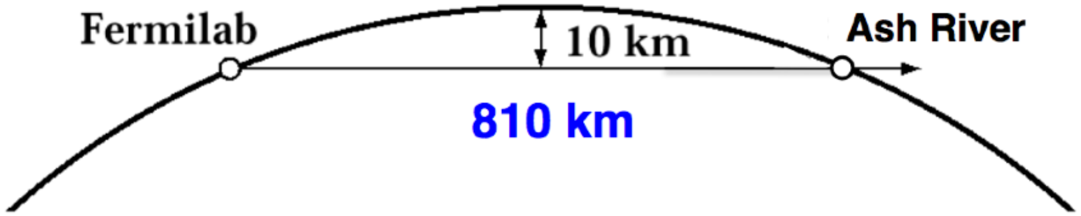
MINOS



T2K



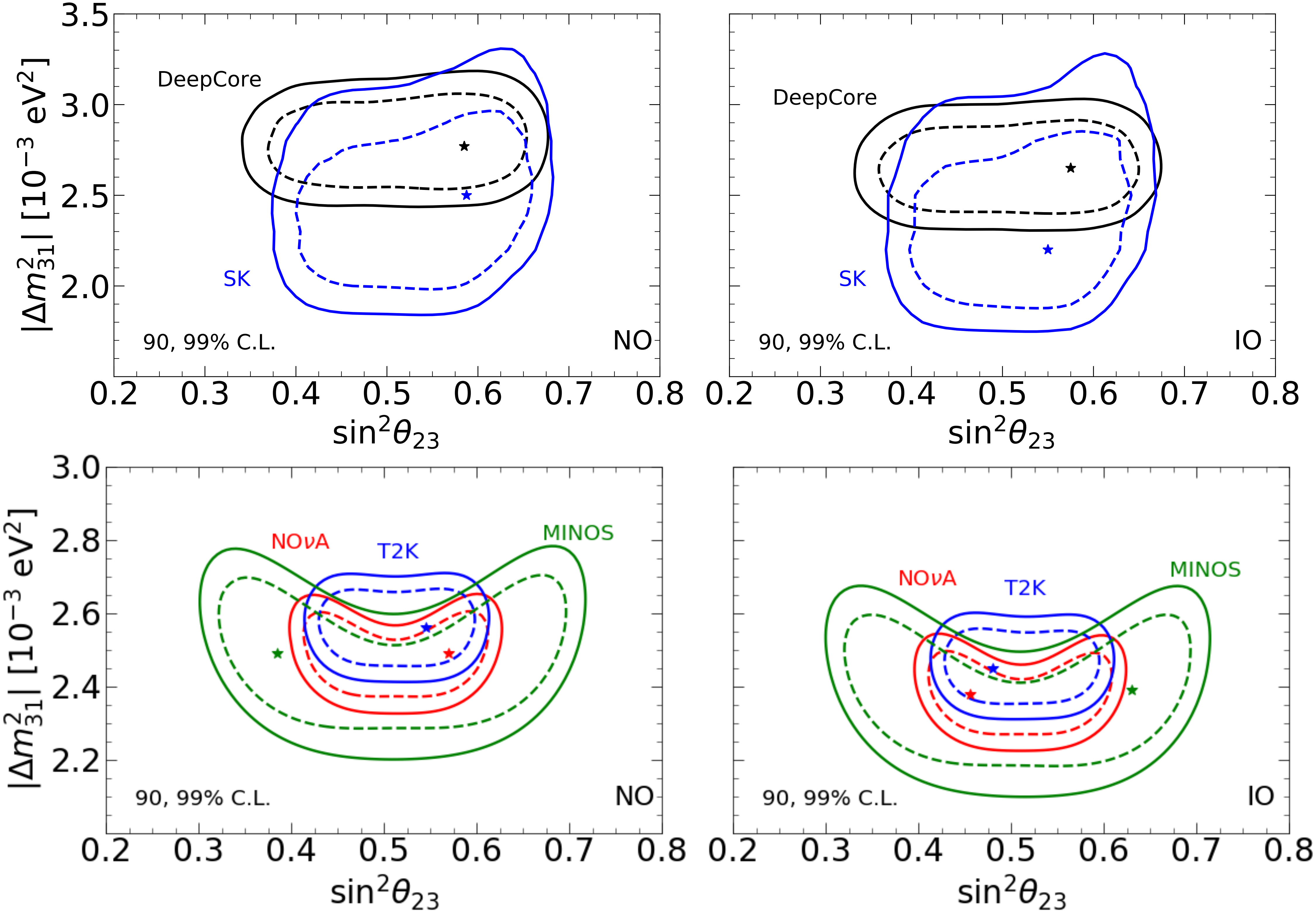
NOvA



→ consistent with atmospheric data

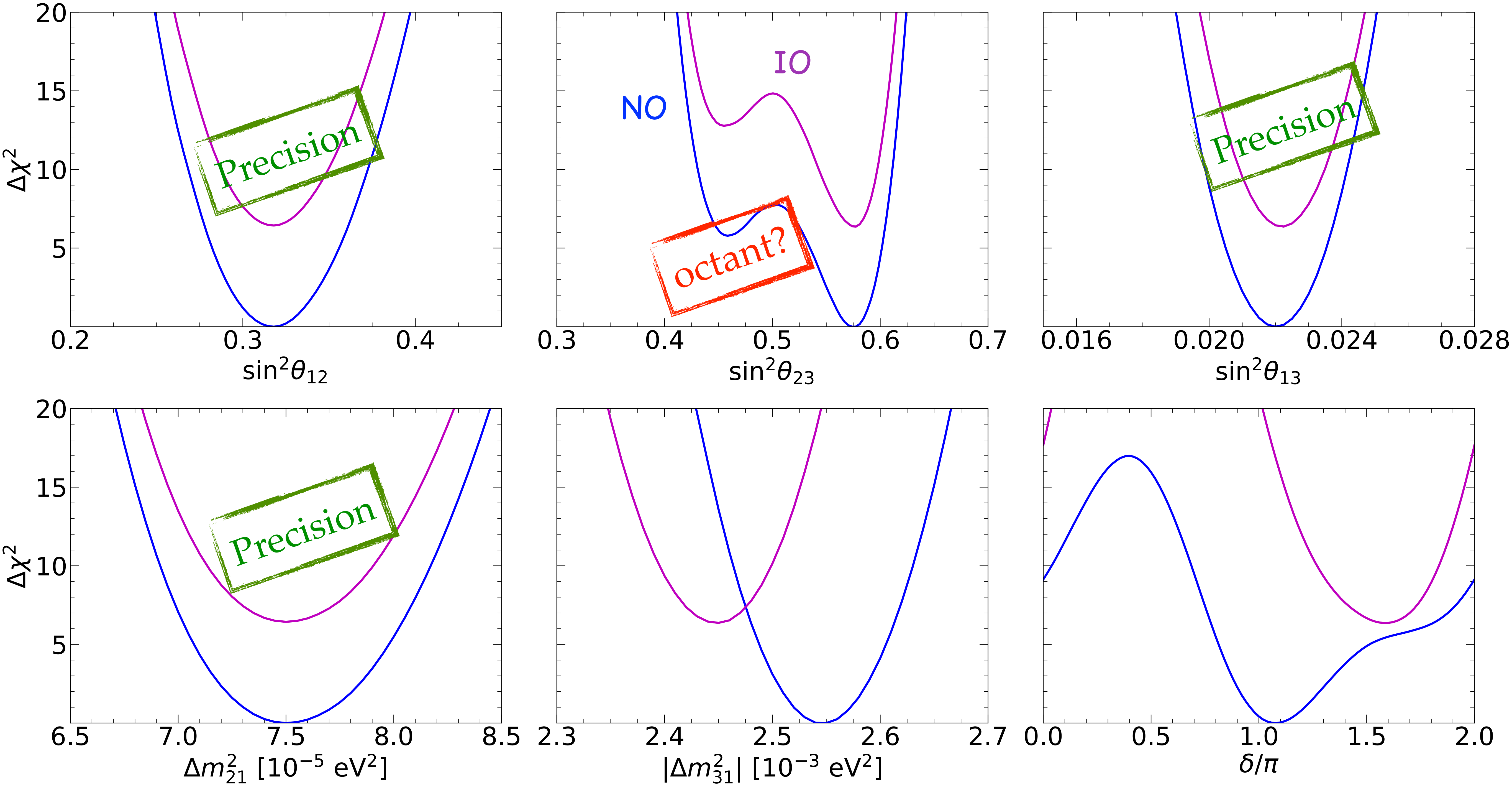
→ atm ν oscillations confirmed by lab exps

The atmospheric sector



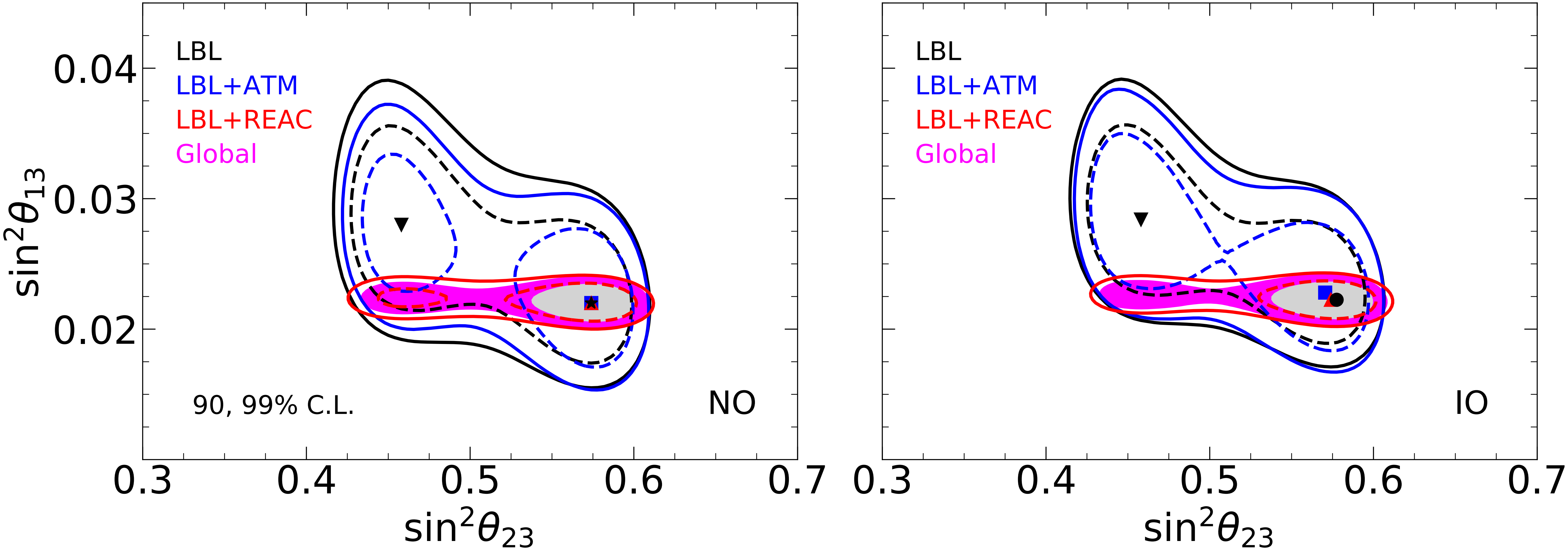
Global fit to ν oscillation parameters

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



The octant of θ_{23}

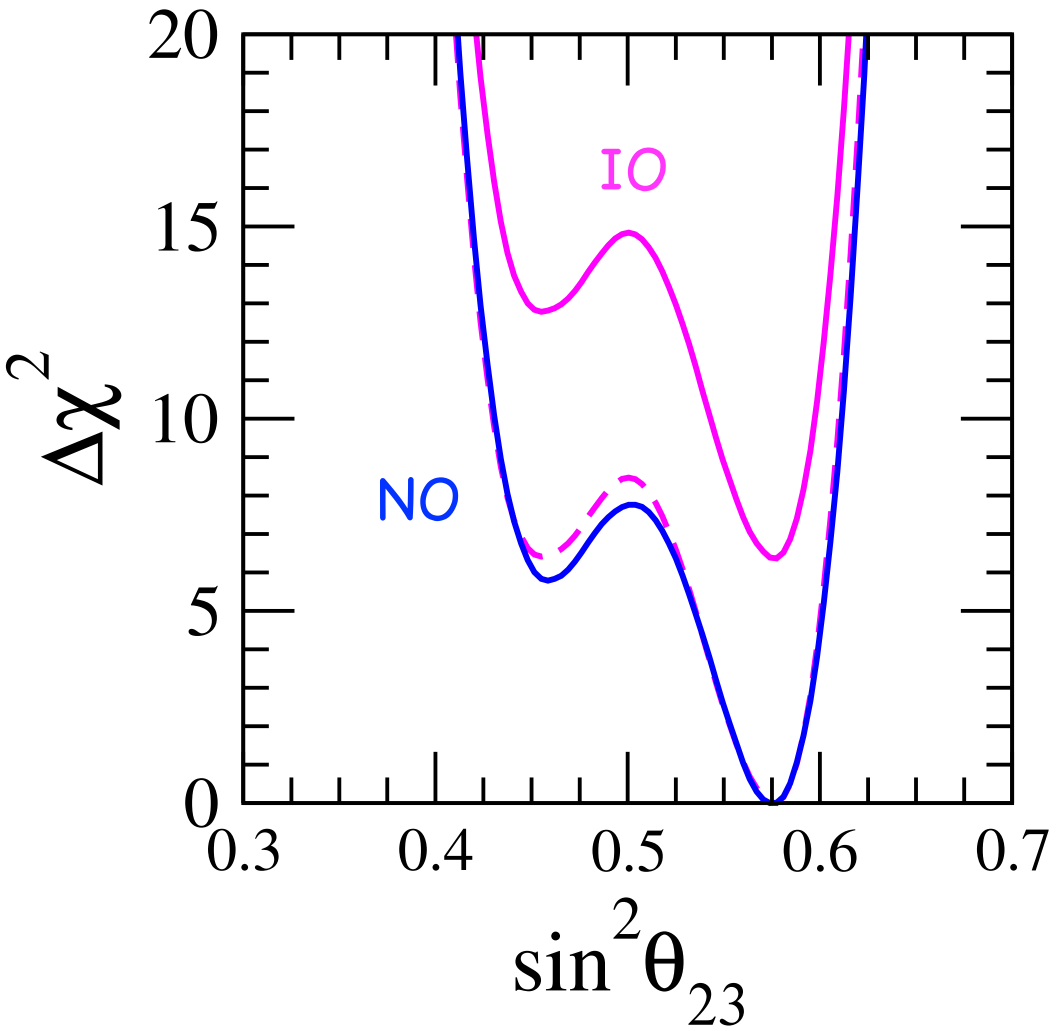
de Salas et al, **JHEP 02 (2021) 071**[arXiv:2006.11237]



- 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

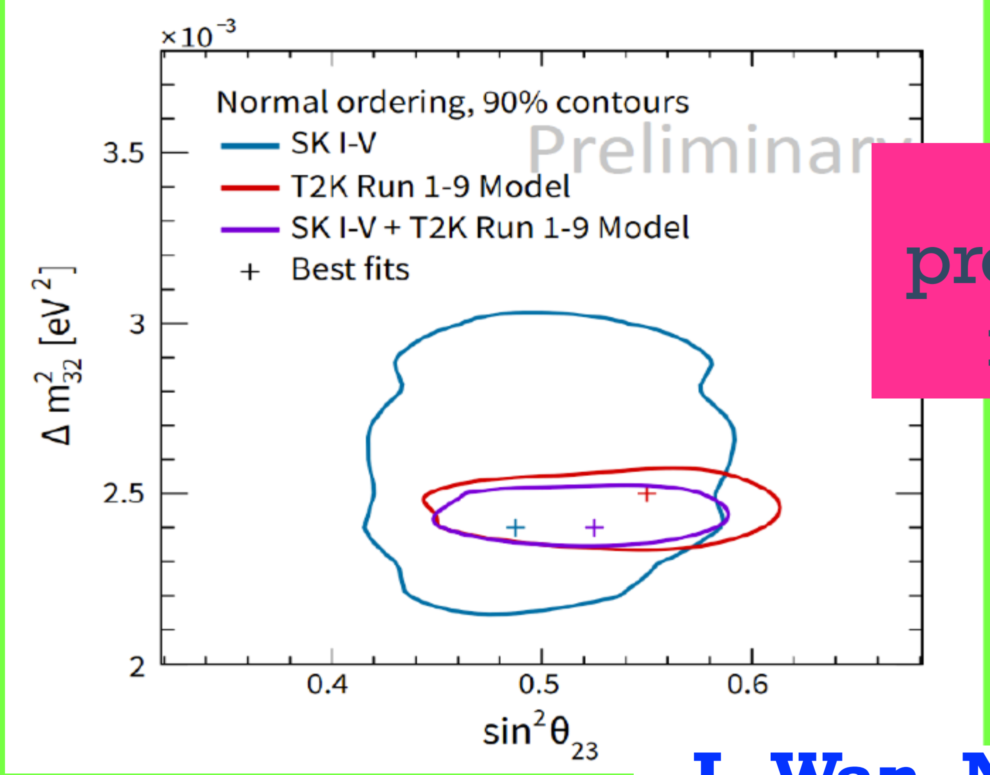
The octant of θ_{23}

de Salas et al, JHEP 02 (2021) 071



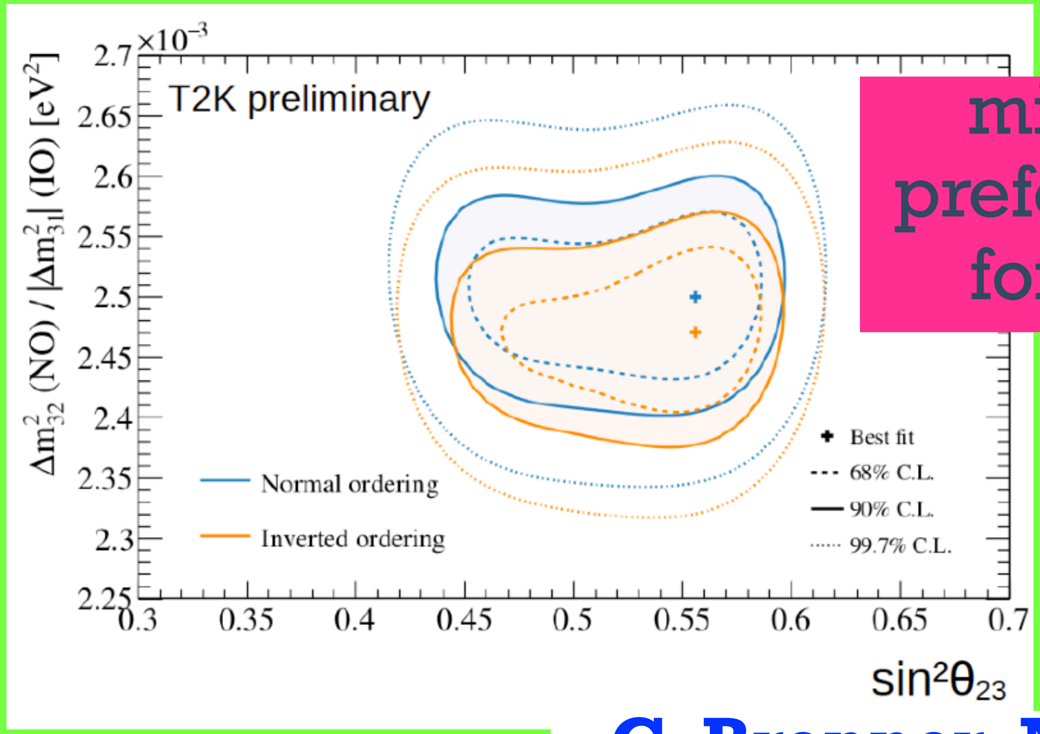
1st octant disfavored with $\Delta\chi^2 \geq 5.8$ (6.4) for NO (IO)

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



slight preference for LO

L. Wan, Nu 2022

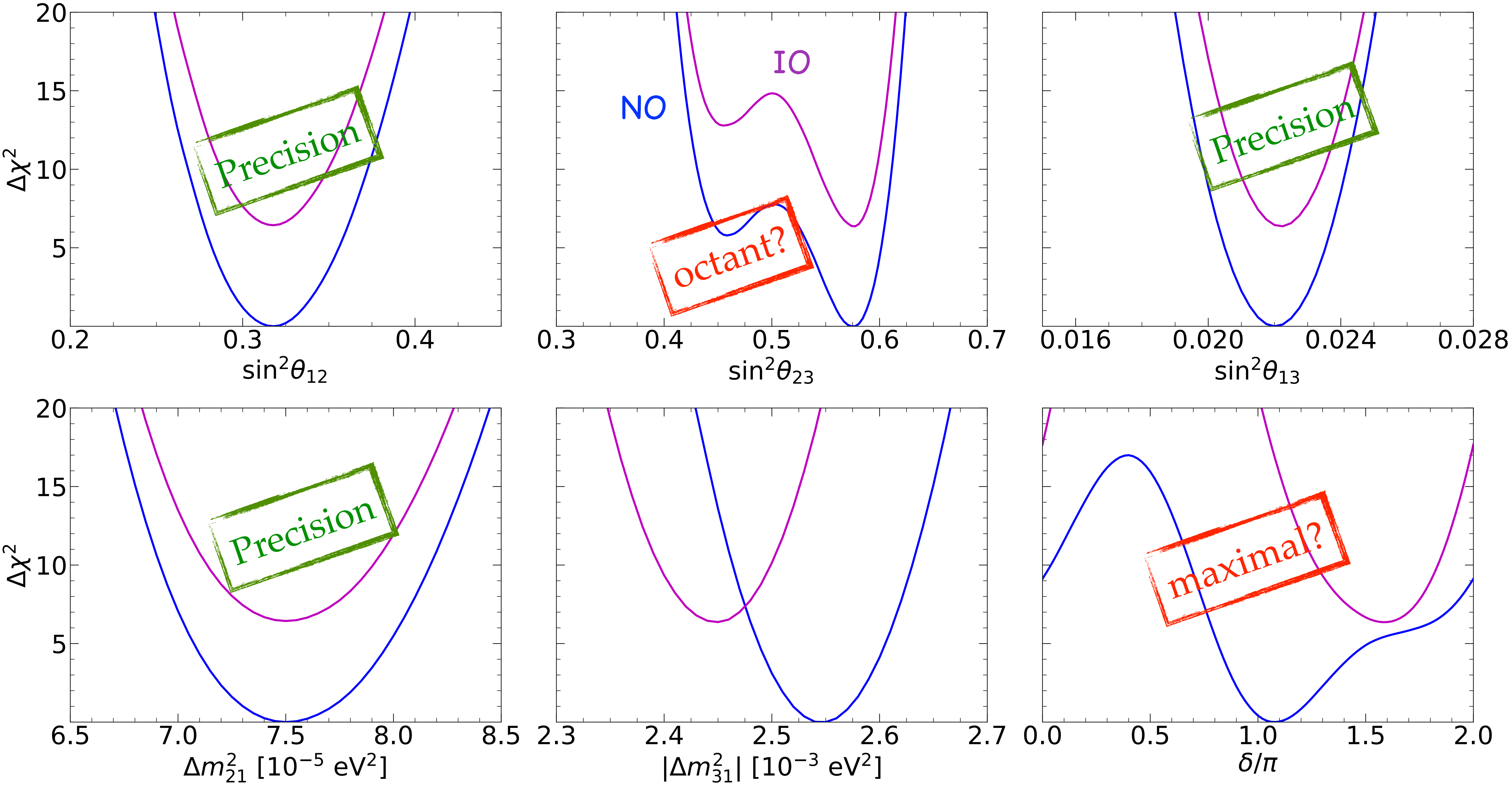


milder preference for UO

C. Bronner, Nu 2022

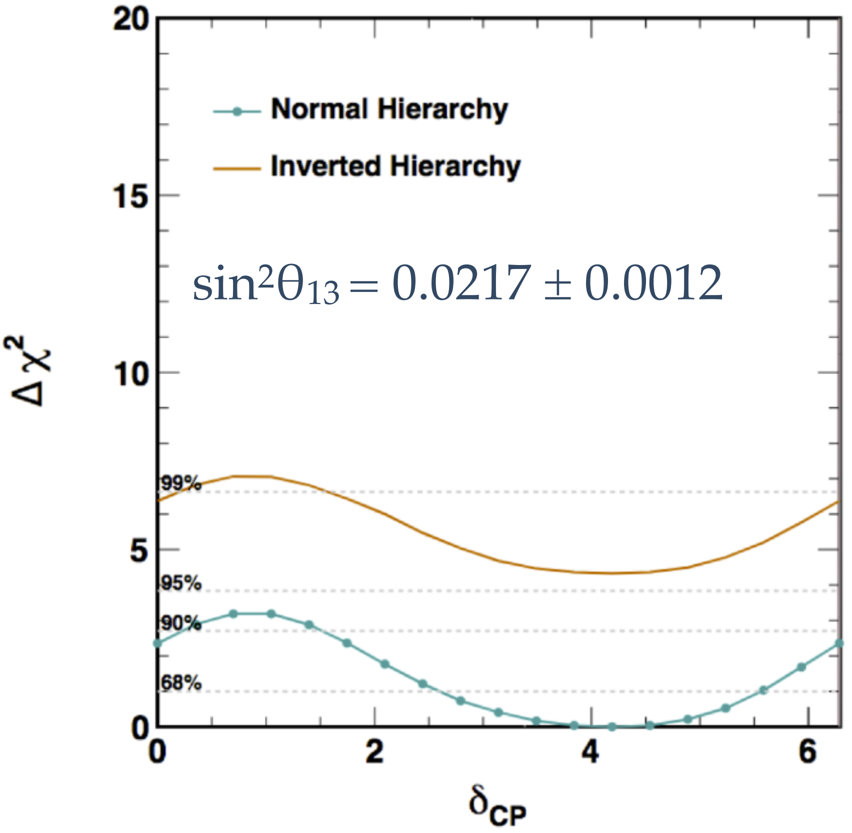
Global fit to ν oscillation parameters

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

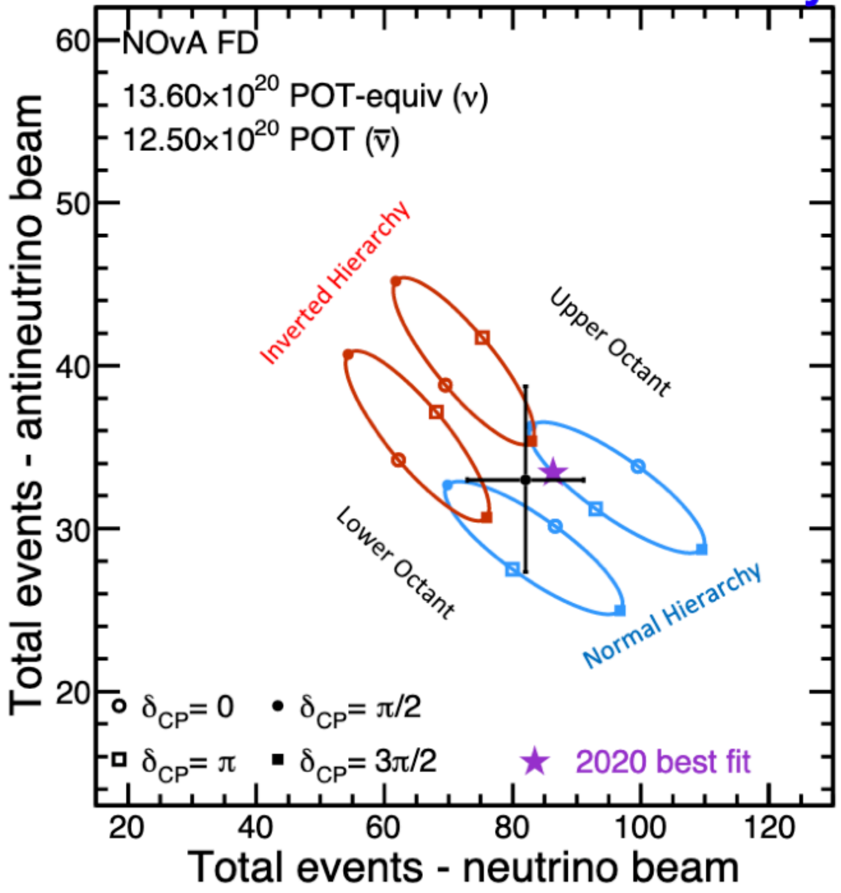
T2K (NO)		-π/2	0	+π/2	π	OBS
ν mode	1Re 0 d.e.	74.5	62.3	50.6	62.8	75
	1Re 1 d.e.	7.0	6.1	4.9	5.9	15
ν̄ mode	1Re 0 d.e.	17.1	19.6	21.7	19.3	15

NOvA

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

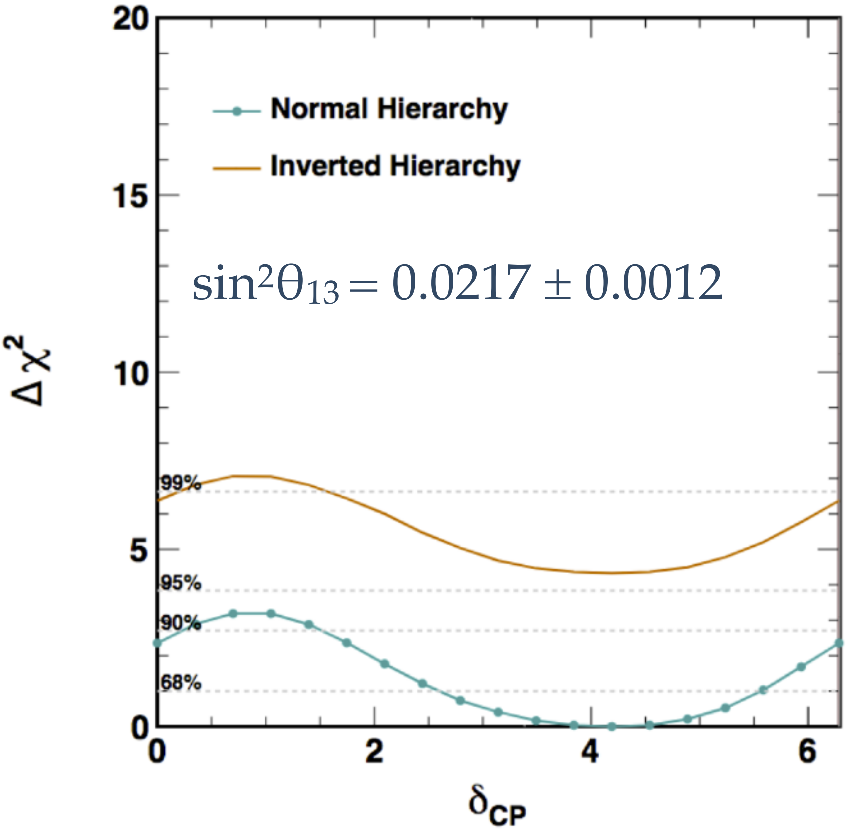
P Vahle, TAUP 2021

NOvA Preliminary



The CP phase

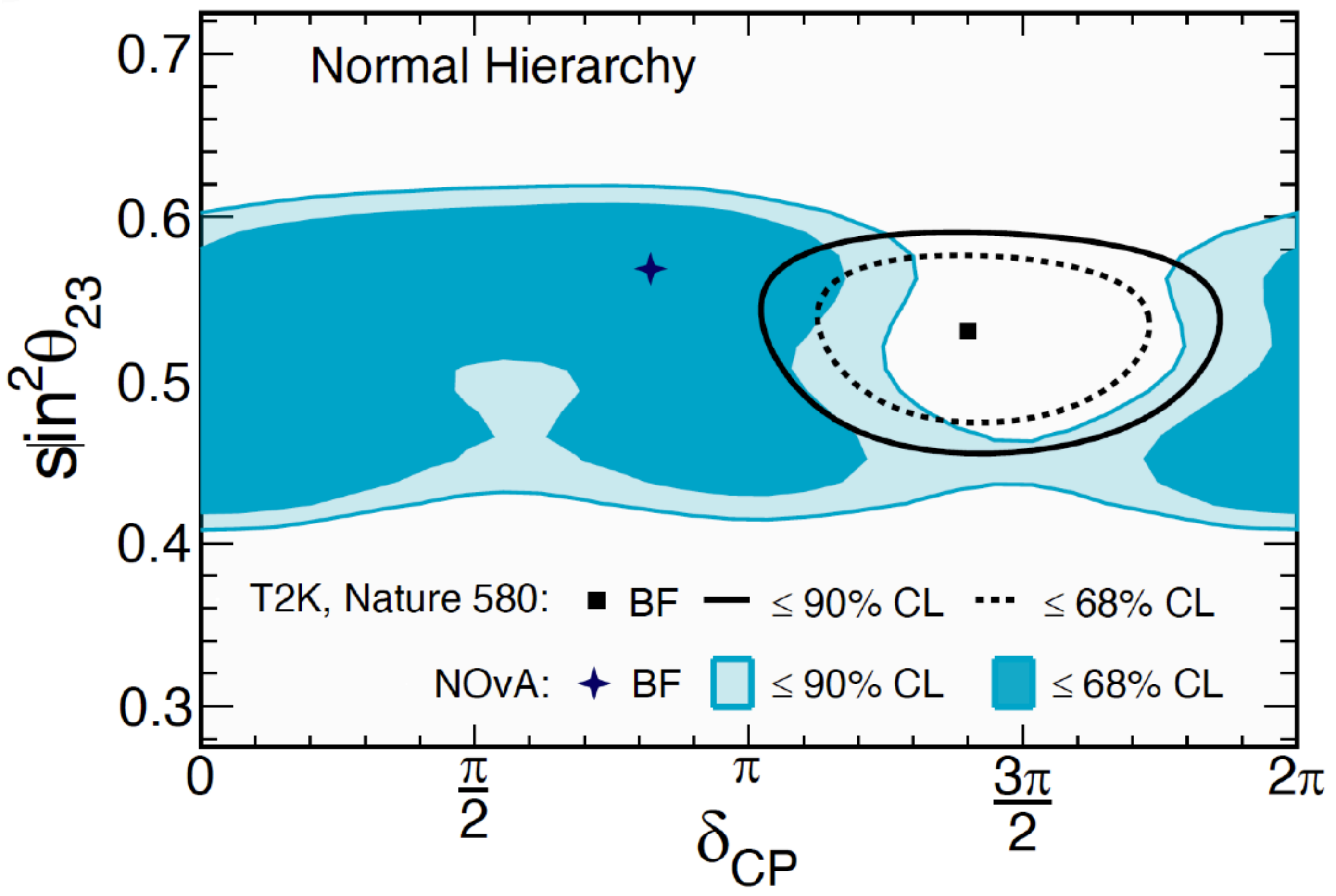
Super-Kamiokande (atm)



- $\delta_{BF} = 1.5\pi\ (1.2\pi)$ for NO (IO)
- preference driven by sub-GeV e-like samples

SK Collab. PRD97 (2018)

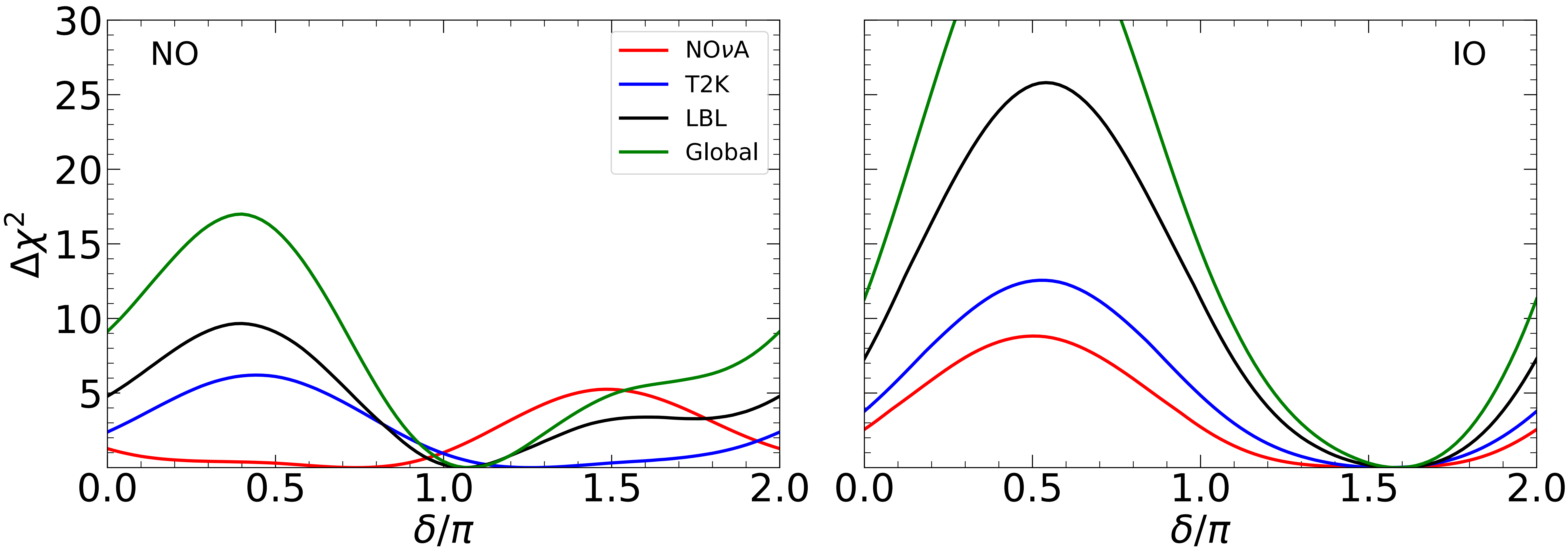
Slight tension between T2K and NOvA results for NO



A. Himmel, Neutrino 2020

The CP phase

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



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

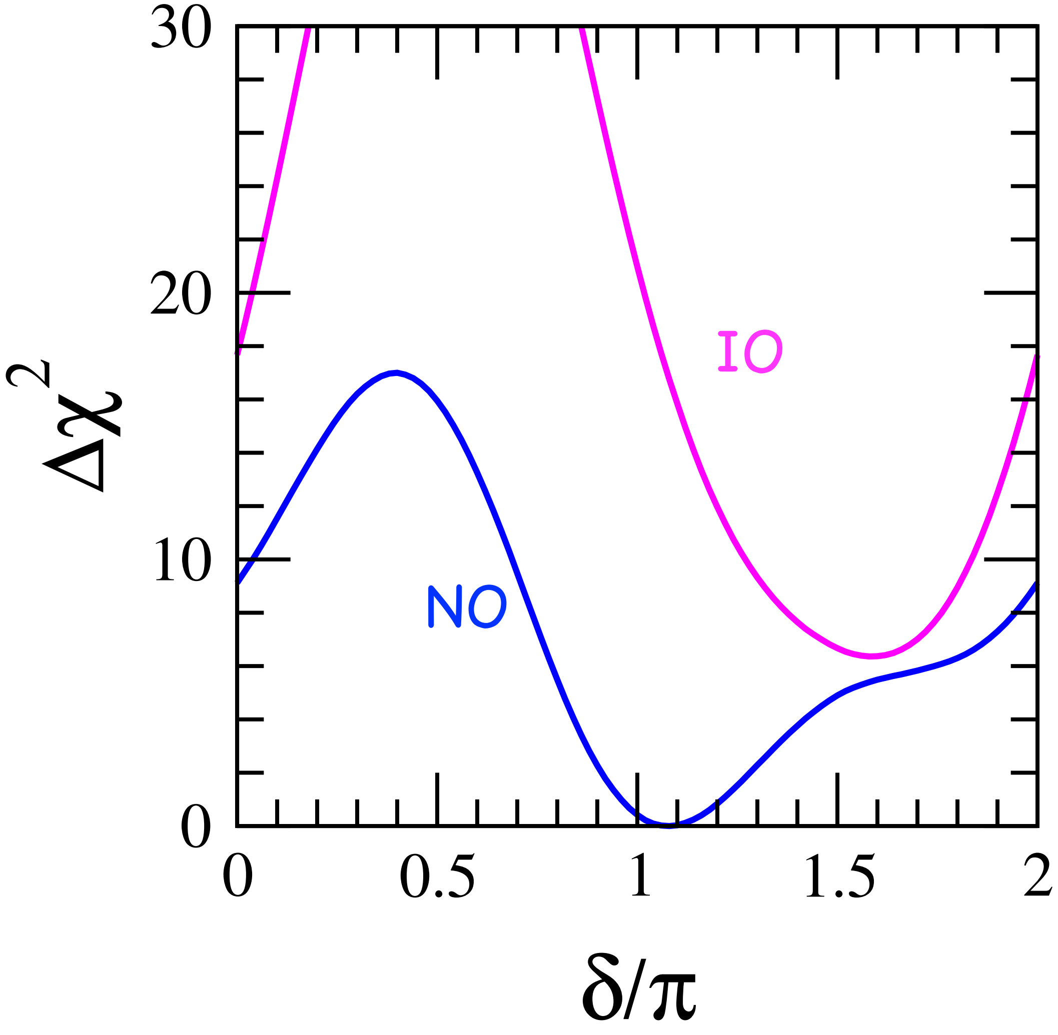
  $\delta_{BF} = 1.08\pi$; $\delta = \pi/2$ (0) disfavored at 4.0σ (3.0σ); $\delta = 3\pi/2$ with $\Delta\chi^2 = 4.9$

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

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

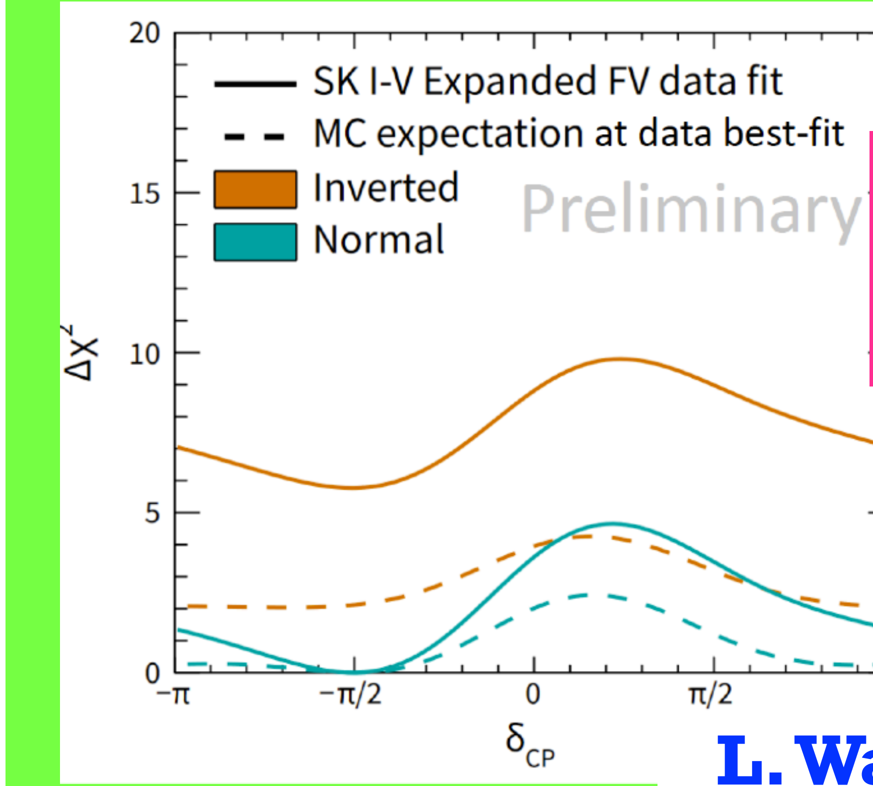
The CP phase

de Salas et al, JHEP 02 (2021) 071



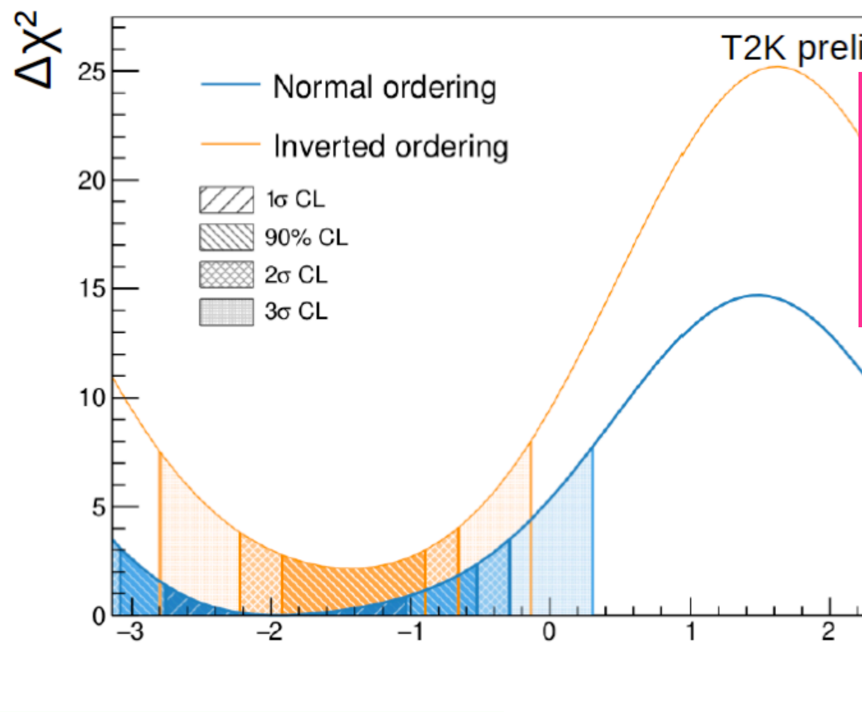
NO: $\delta_{BF} = 1.08\pi$ (NOvA-T2K tension)
$\delta = \pi/2$ (0) disfavored at 4.0σ (3.0σ)

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



improved sensitivity to δ_{CP}

L. Wan, Nu 2022

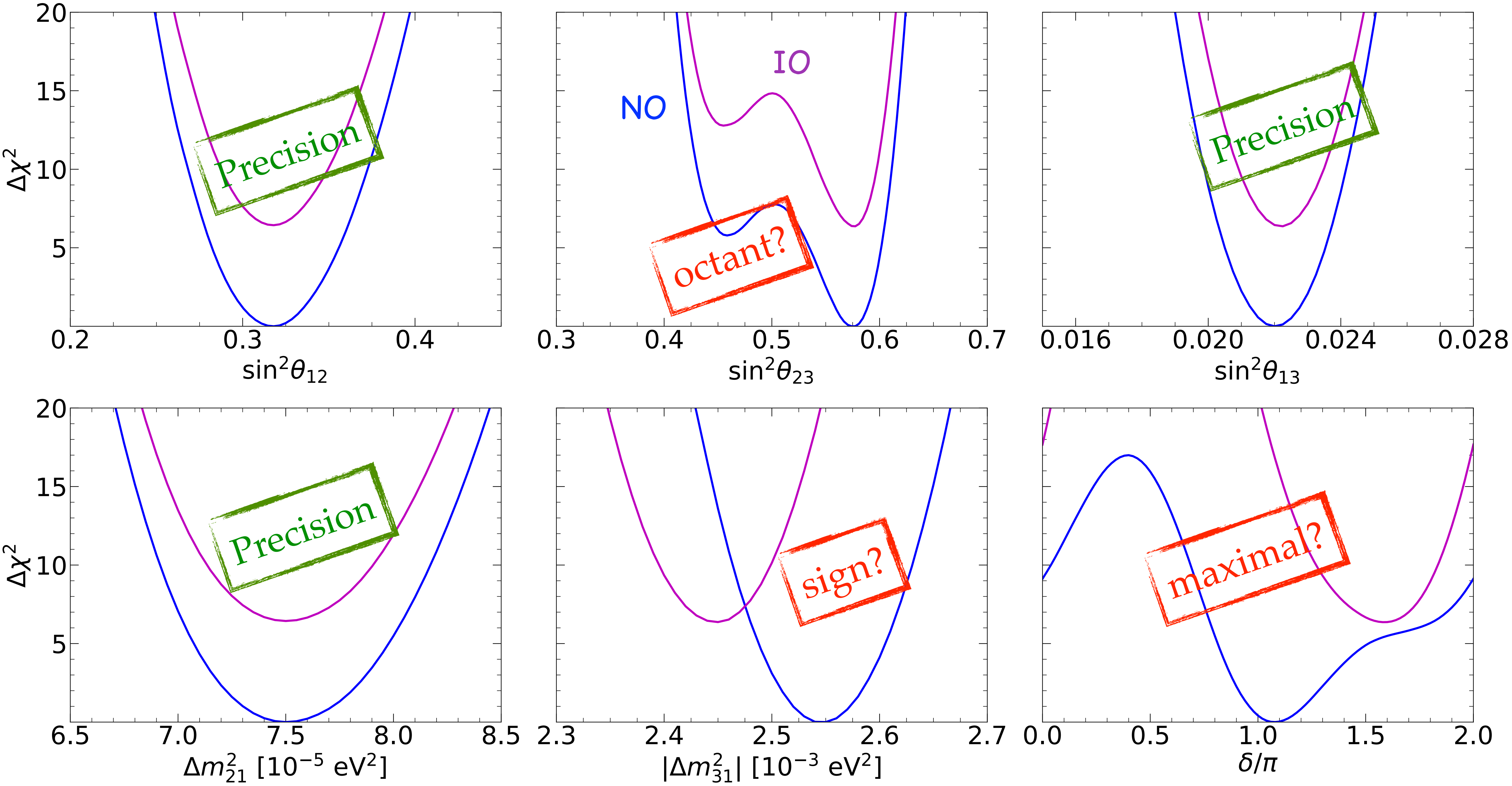


same sensitivity to δ_{CP}

C. Bronner, Nu 2022

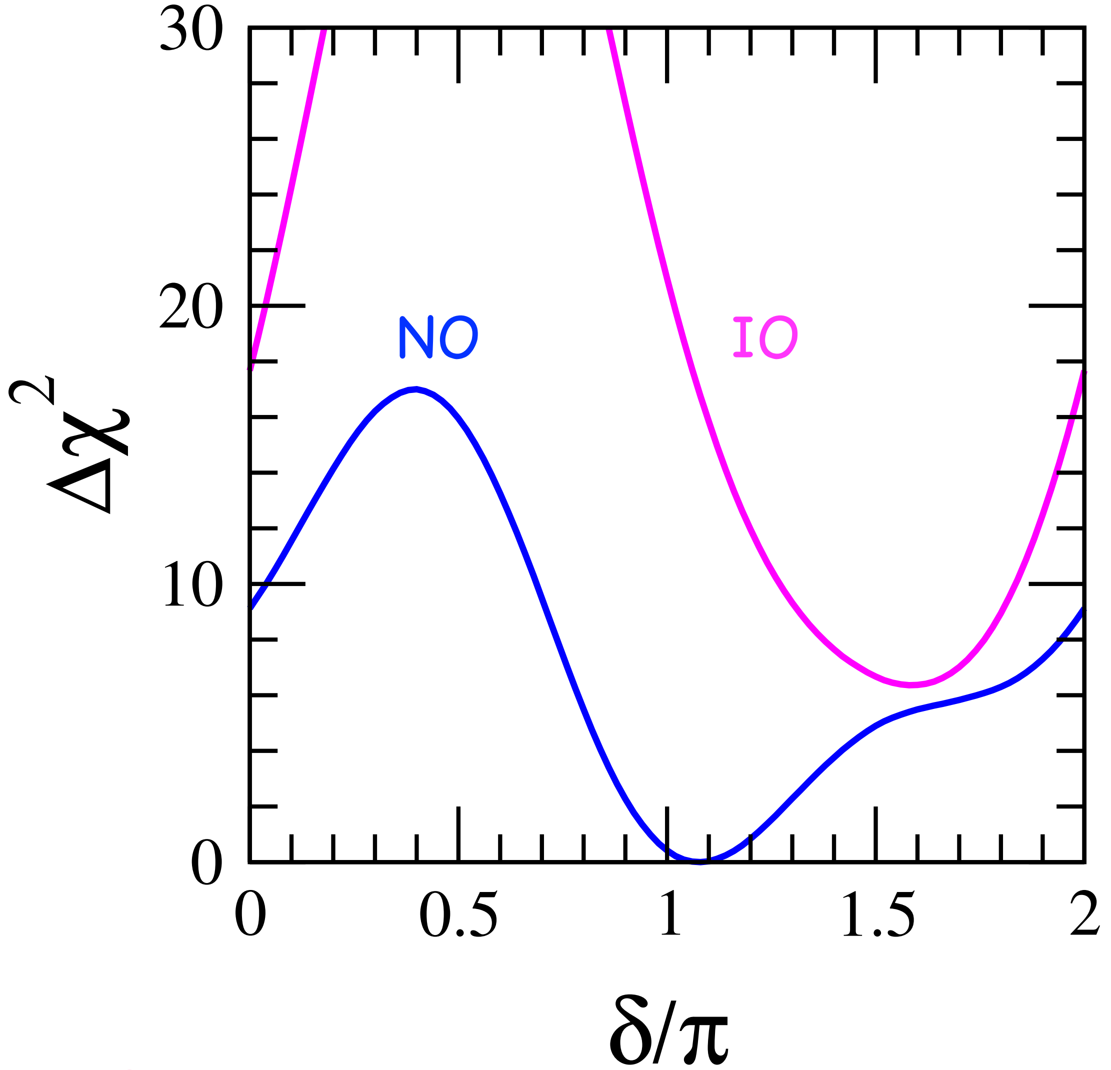
Global fit to ν oscillation parameters

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



The mass ordering

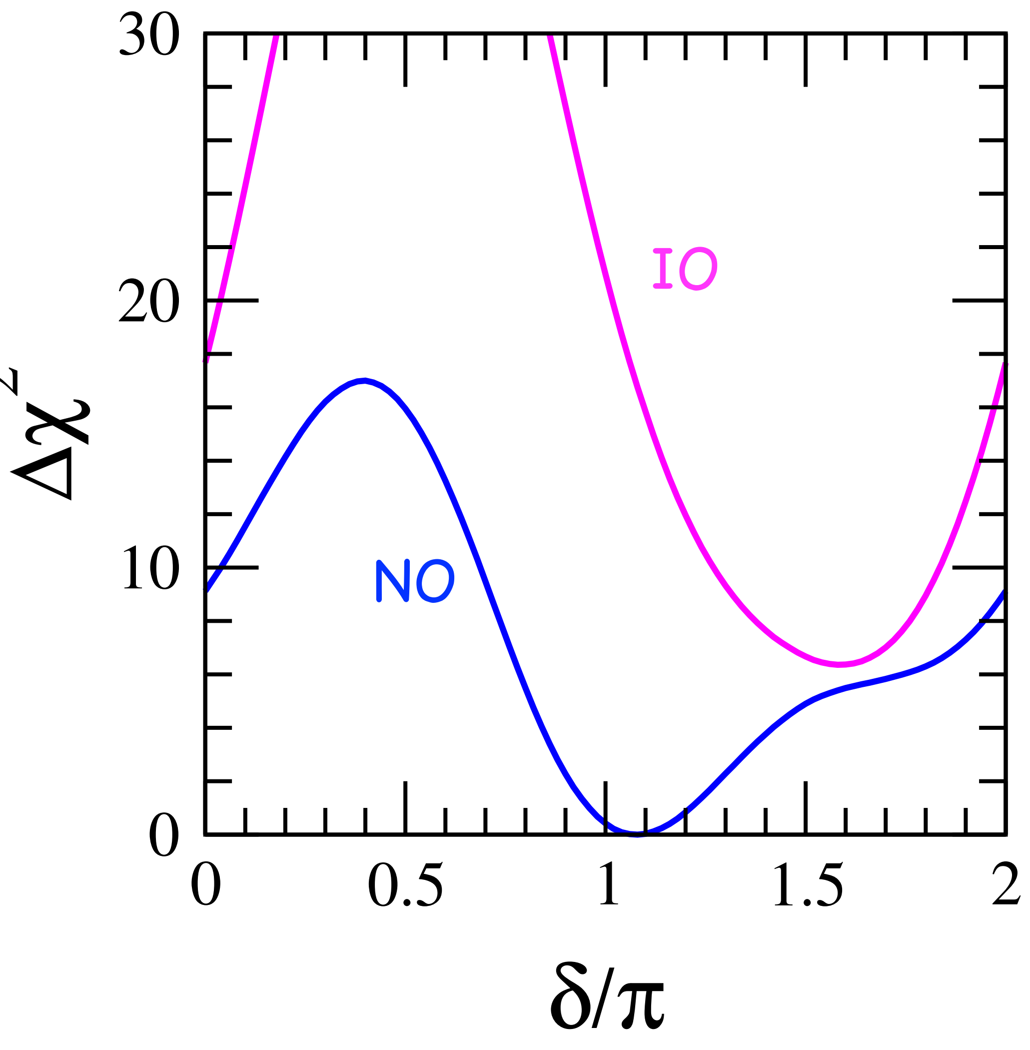
- ✦ T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.4$
- ✦ T2K + NOvA combined prefer IO with $\Delta\chi^2 \approx 2.4$ (tension in δ for NO)
- ✦ LBL + REAC prefer NO with $\Delta\chi^2 \approx 1.4$ (tension in Δm^2_{31} measurement in IO)
- ✦ Atmos. sensitivity: Super-K ($\Delta\chi^2 \approx 3.5$) and DeepCore ($\Delta\chi^2 \approx 1.0$)
- ✦ Global fit: $\Delta\chi^2 = 6.4$ → 2.5σ preference for NO



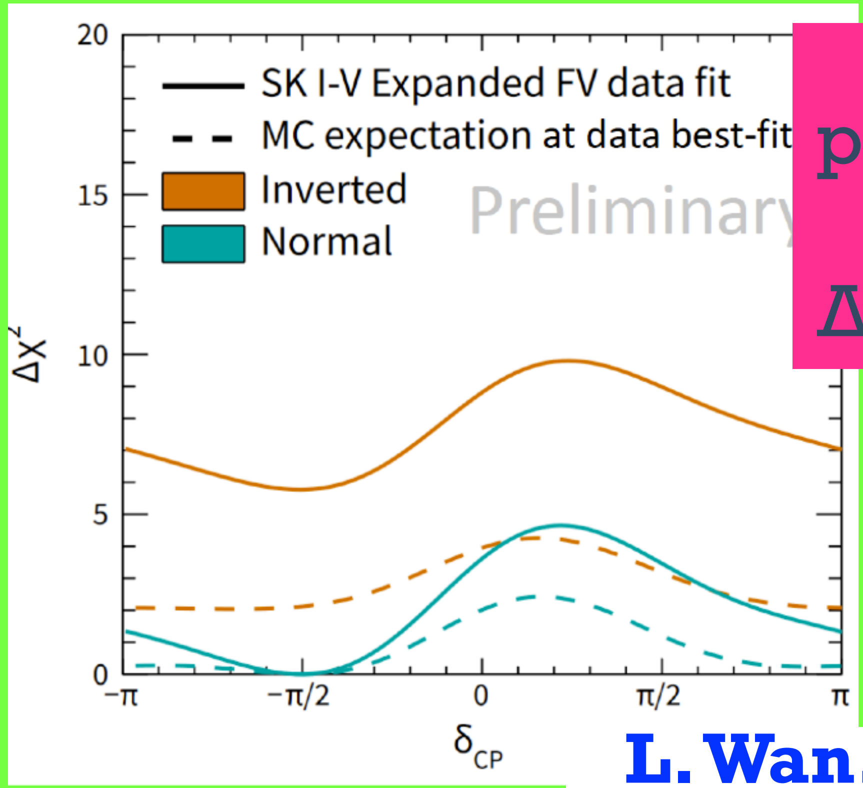
de Salas et al, JHEP 02 (2021) 071

The mass ordering

de Salas et al, JHEP 02 (2021) 071

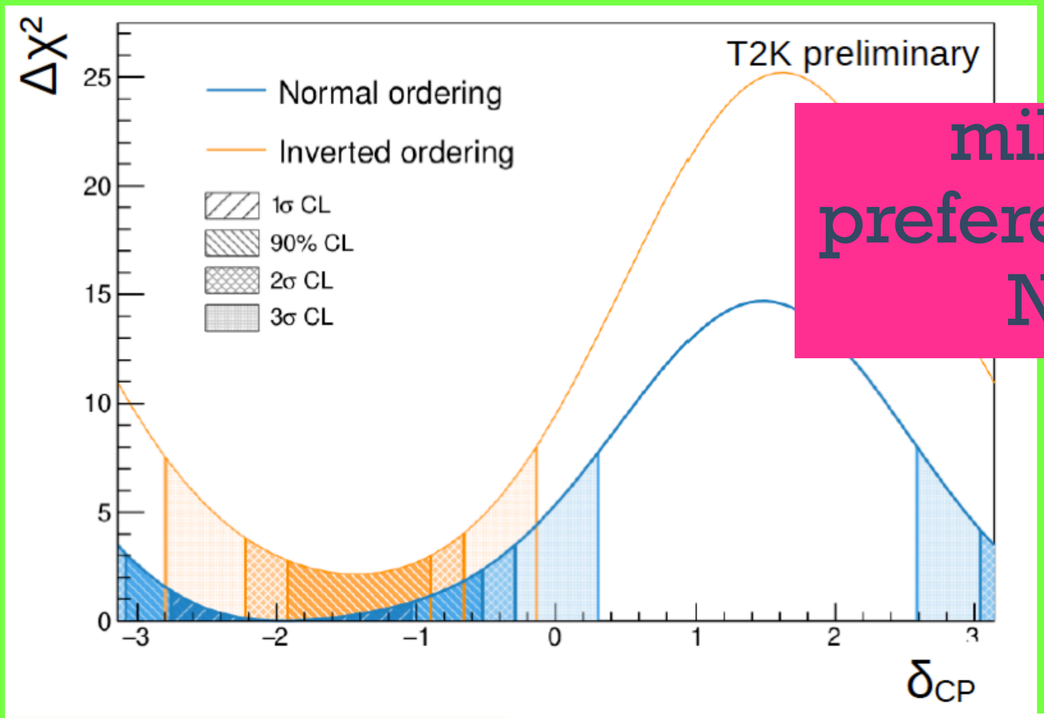


2.5σ preference for NO



higher preference for NO:
$\Delta\chi^2 = 3.5 \rightarrow 5.8$

L. Wan, Nu 2022

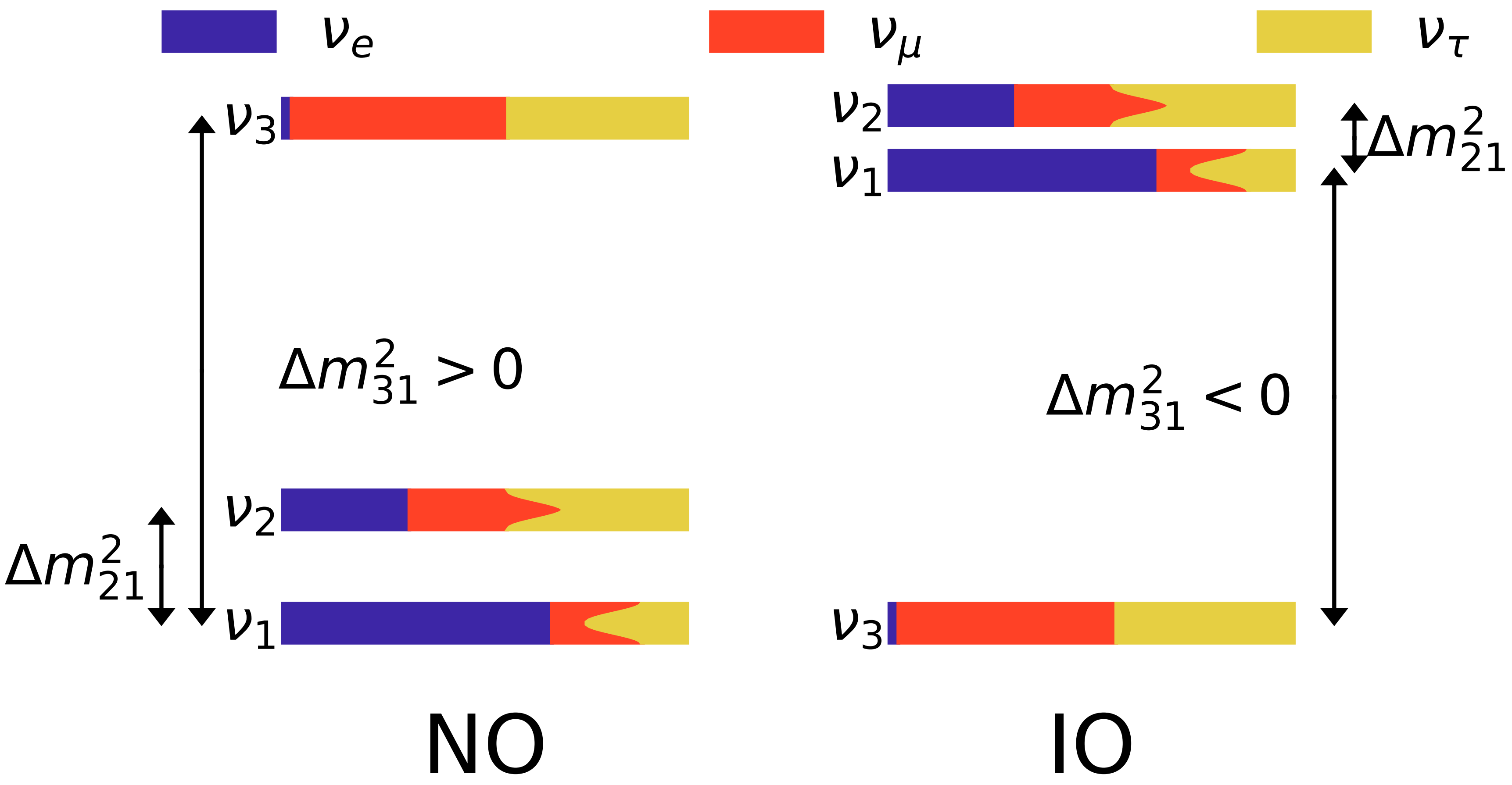


milder preference for NO

C. Bronner, Nu 2022

Neutrino masses

- From oscillations we know that (at least 2) neutrinos do have mass!!



- What about the absolute mass scale? Do we have information?

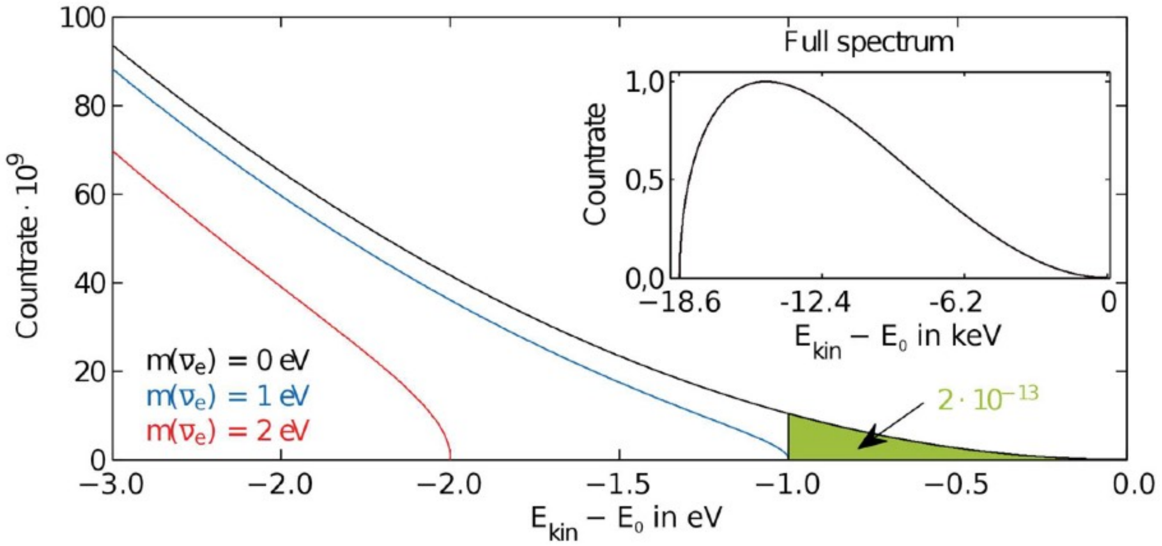
From oscillations: $\boxed{m_\nu \geq \sqrt{\Delta m^2_{31}(\mathrm{NO})} \gtrsim 0.05\,\mathrm{eV}}$

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)

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

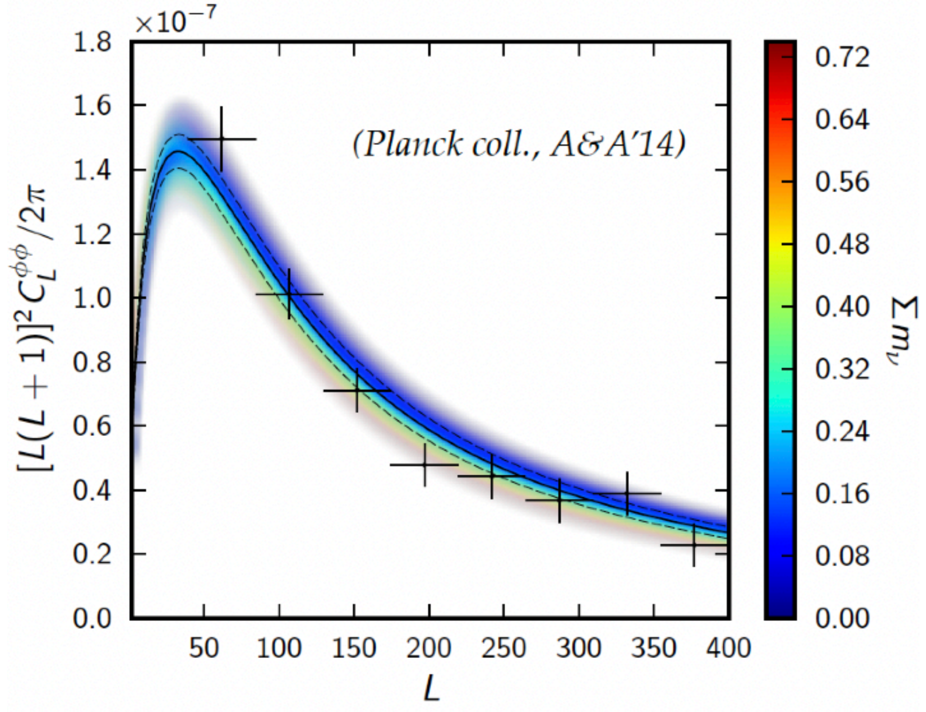
F. Simkovic, Neutrino 2022

- Cosmological measurements

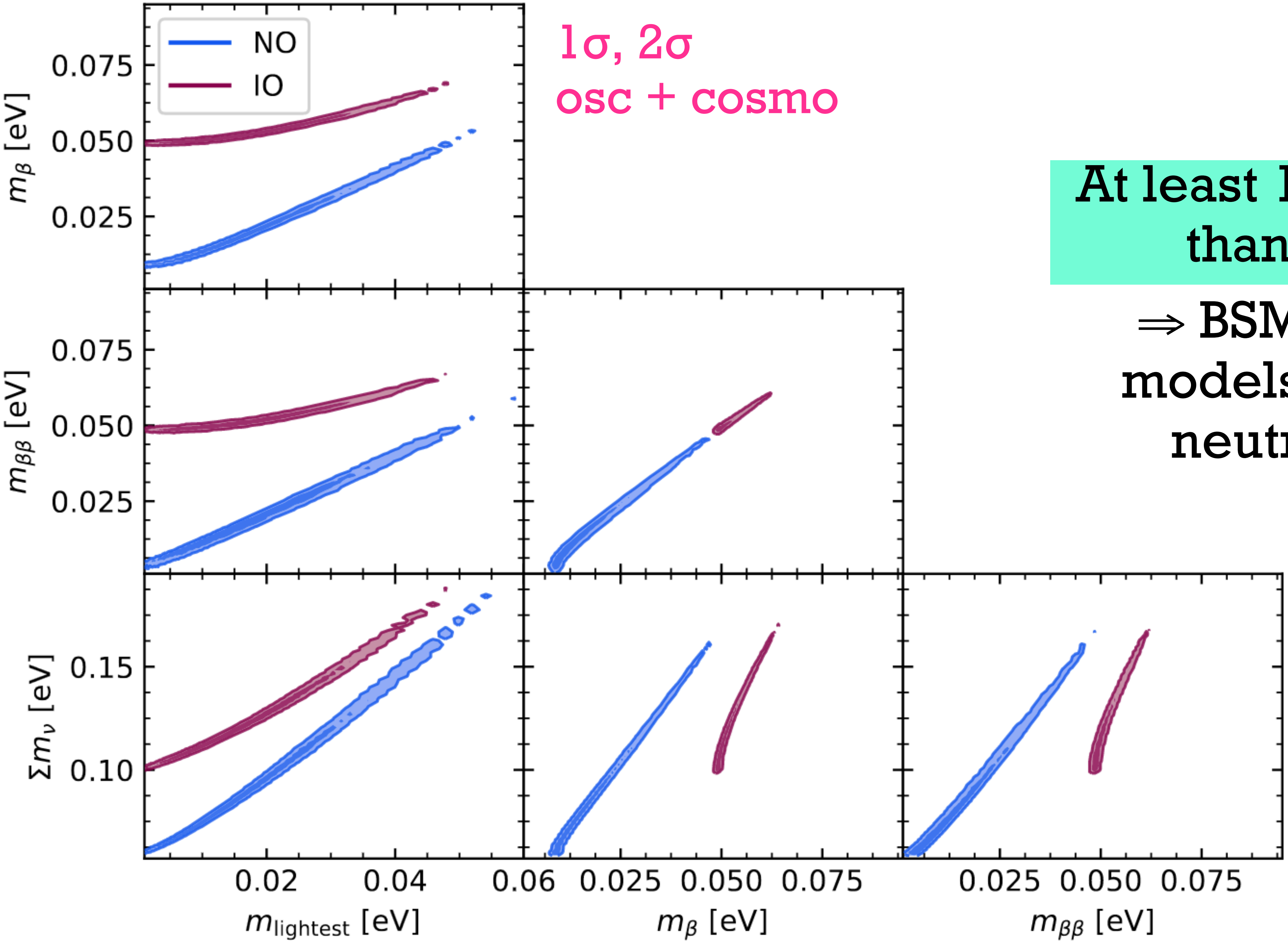
(CMB anisotropies, lensing, LSS,…)

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

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

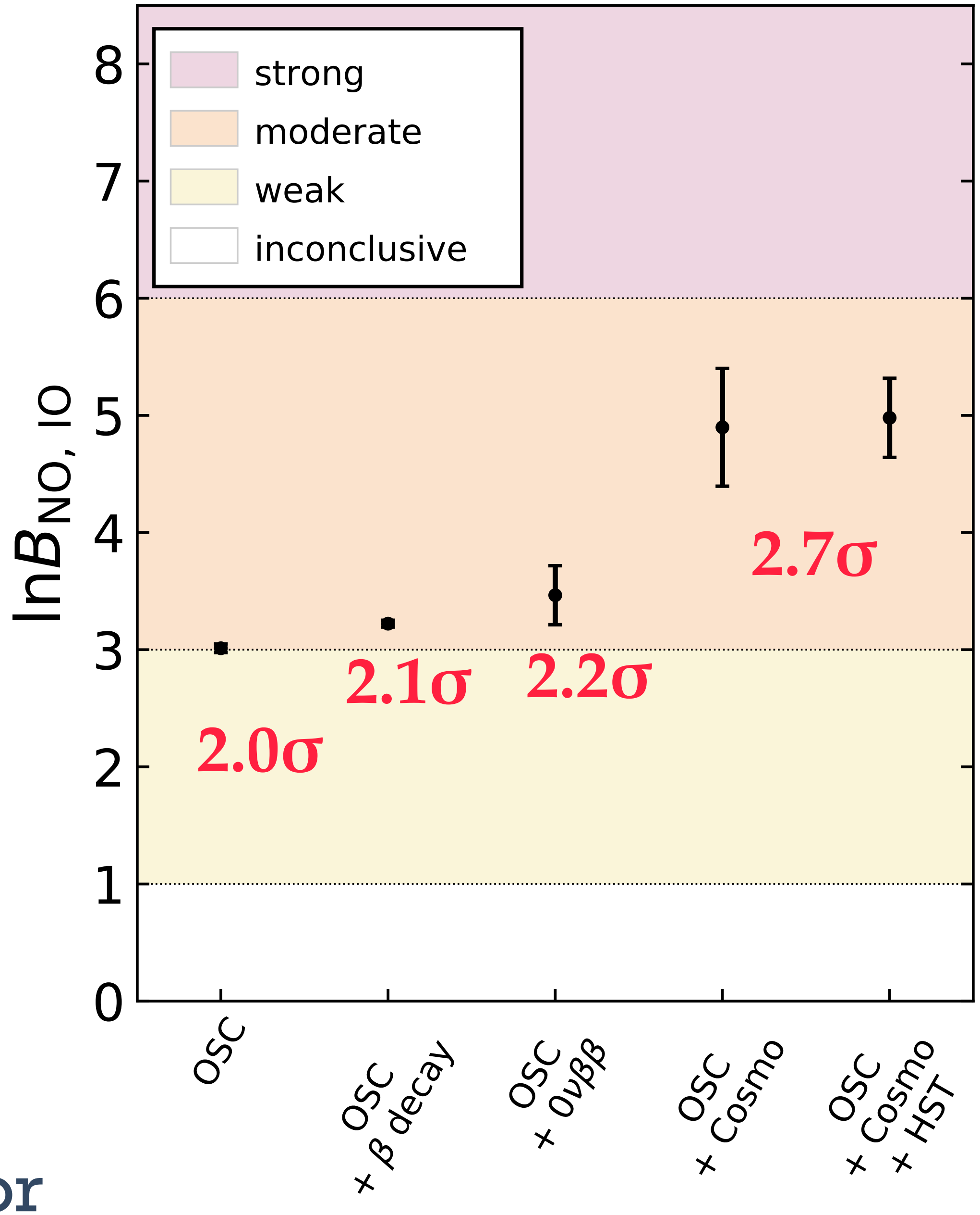
Results from the combined bayesian analysis:

⇒ 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

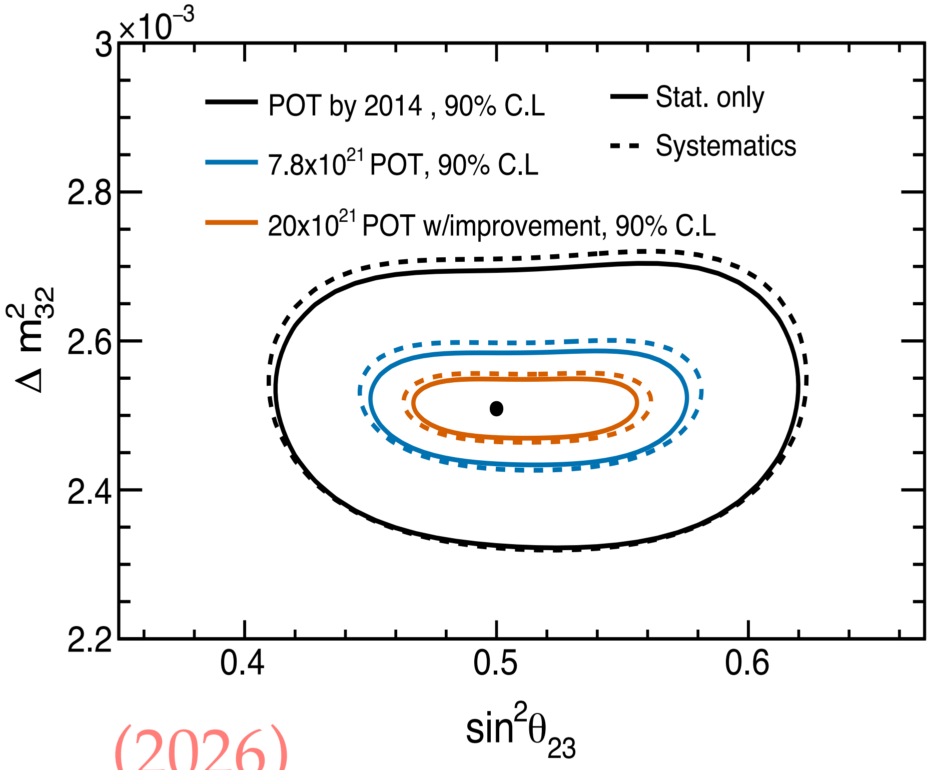
de Salas et al, JHEP 02 (2021) 071



Future prospects in neutrino oscillations

Prospects for precision

T2K **Abe et al, 1609.04111**



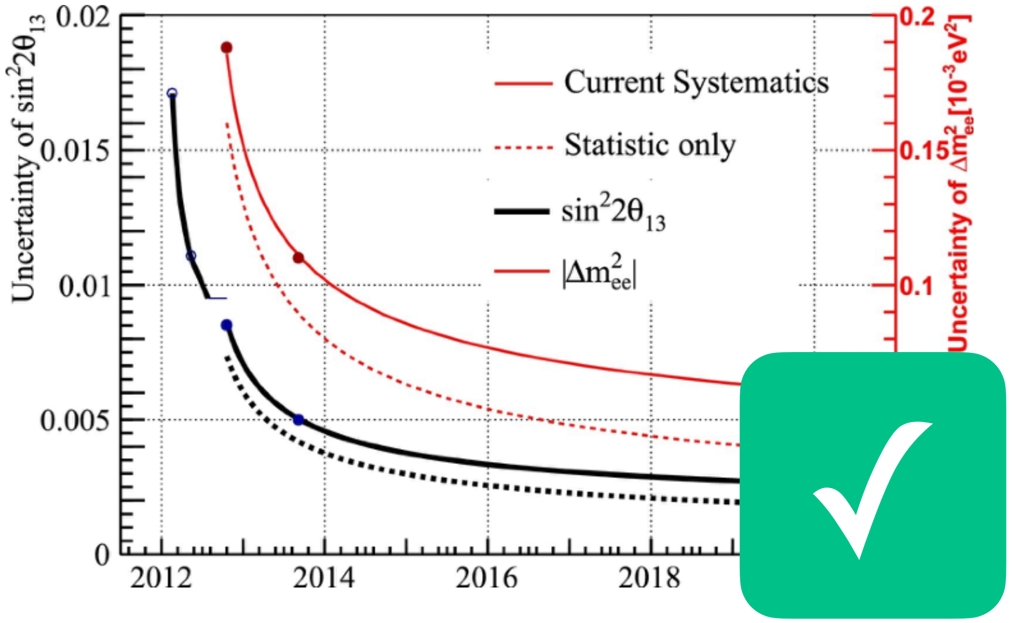
(2026)

~1% precision on Δm^2_{32}

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

DayaBay

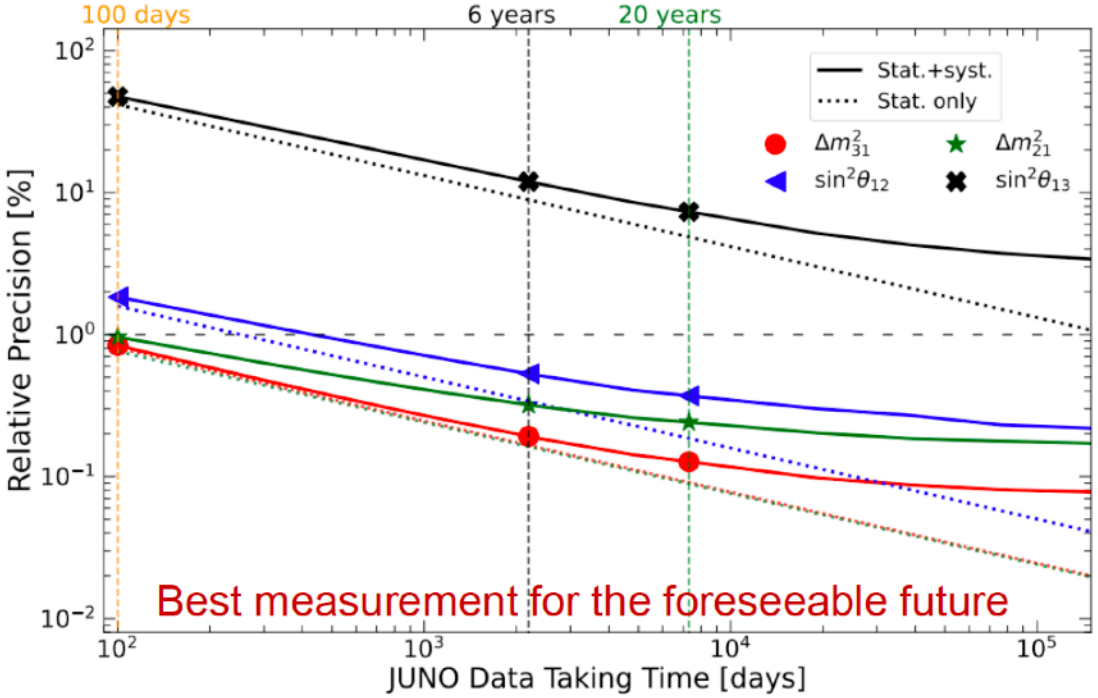
Cao and Luk, 1605.01502



< 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+)



J. Zhao, Neutrino 2022

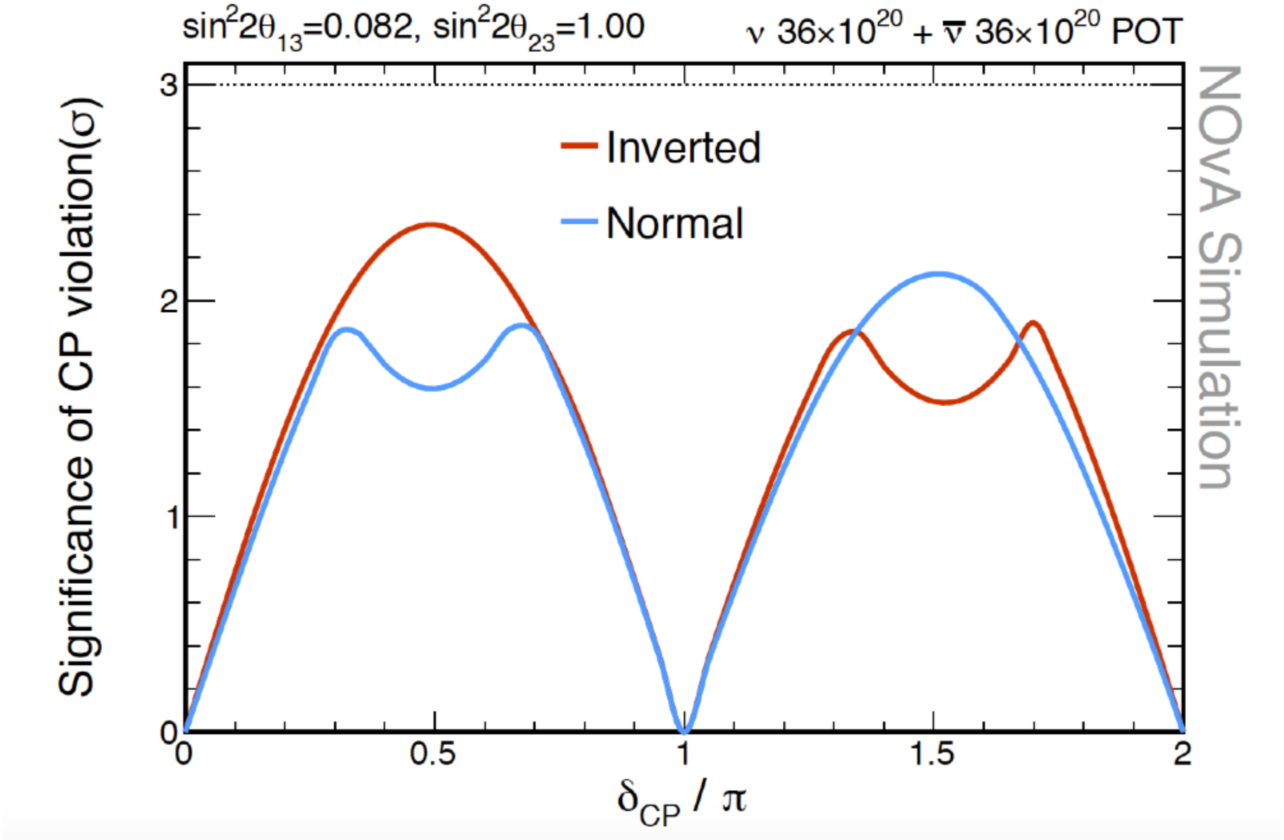
6 years:

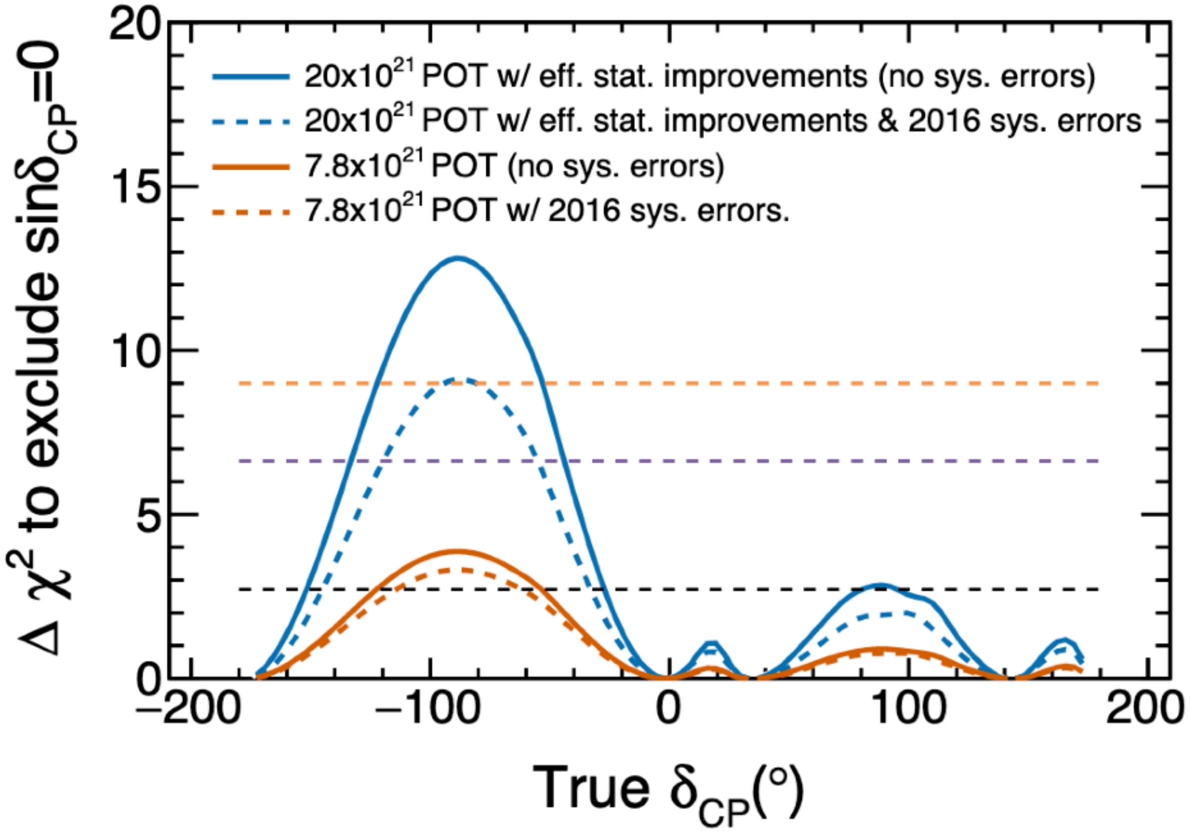
< 0.5% precision on $\sin^2 2\theta_{12}$, Δm^2_{21}, $|\Delta m^2_{31}|$

Prospects for CP violation

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

T2K **Abe et al, 1609.04111**



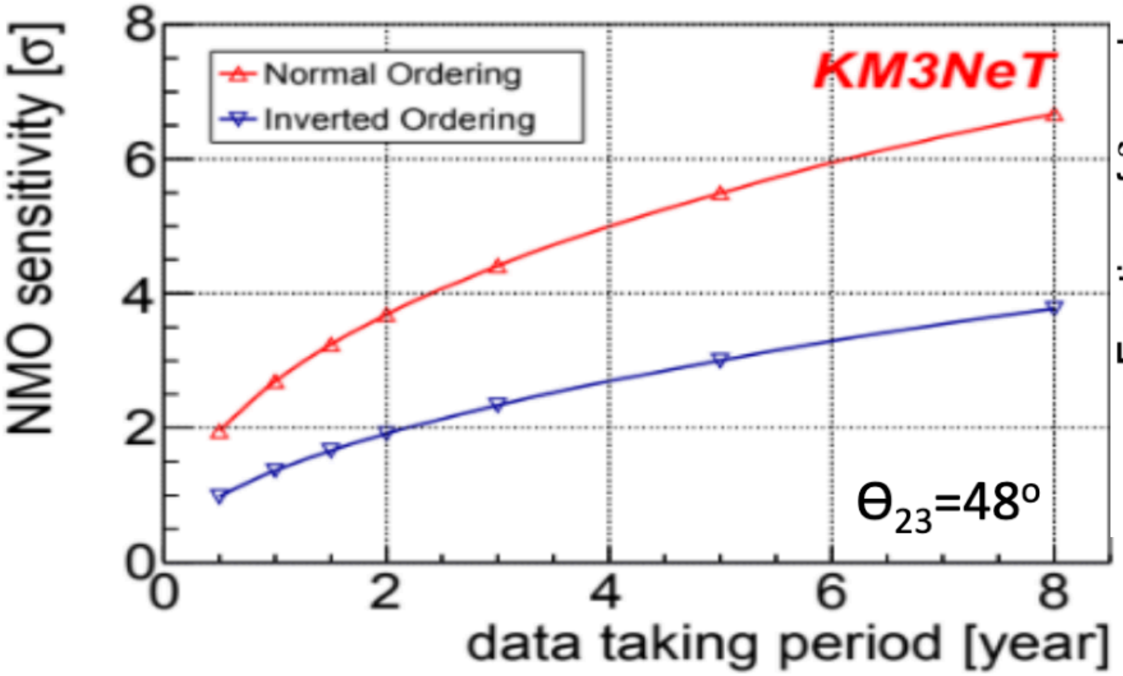


✦by 2026 (60-70 x 10^{20} POT):
~ 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

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

Prospects for mass ordering

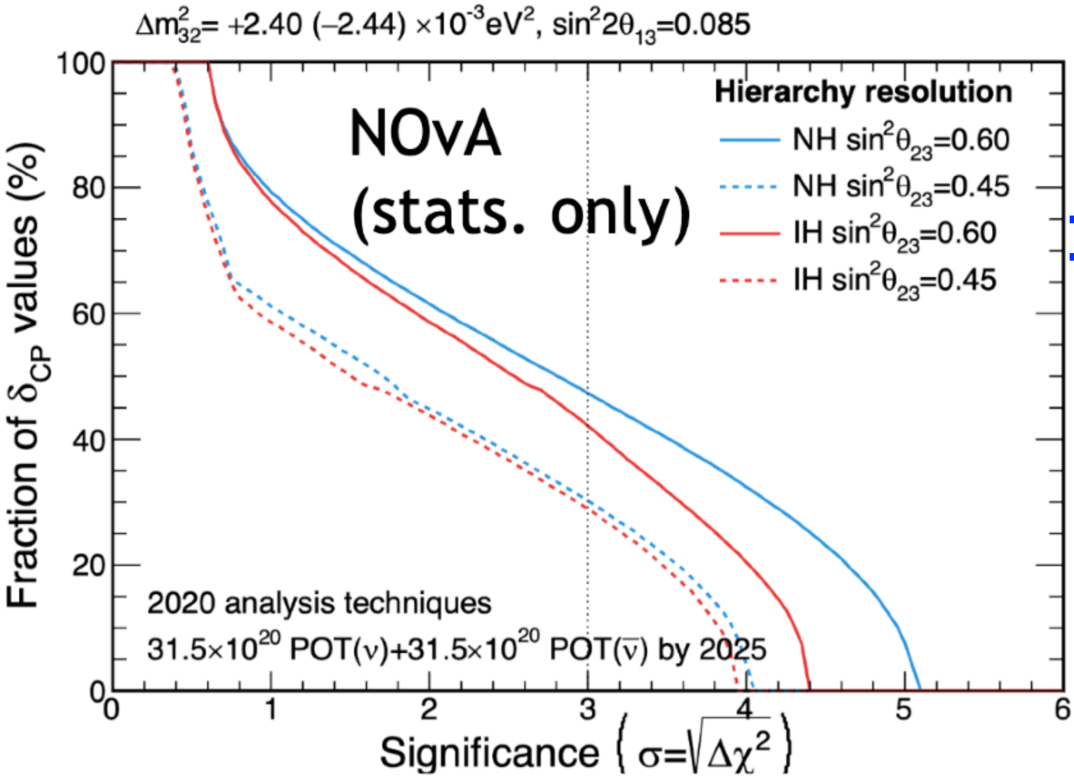
ORCA



- 3σ determination of MO in 4-5 yr

A. Heijboer, Neutrino 2022

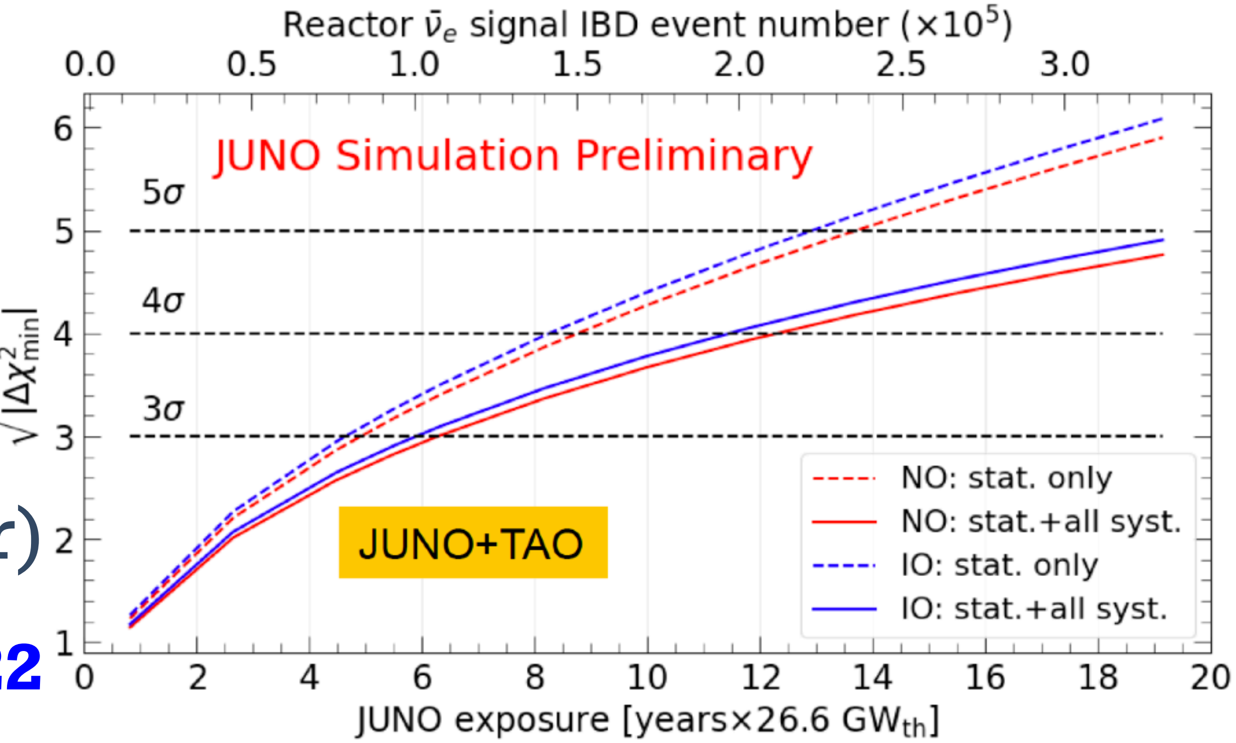
NOvA



P. Vahle, TAUP'21

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

JUNO

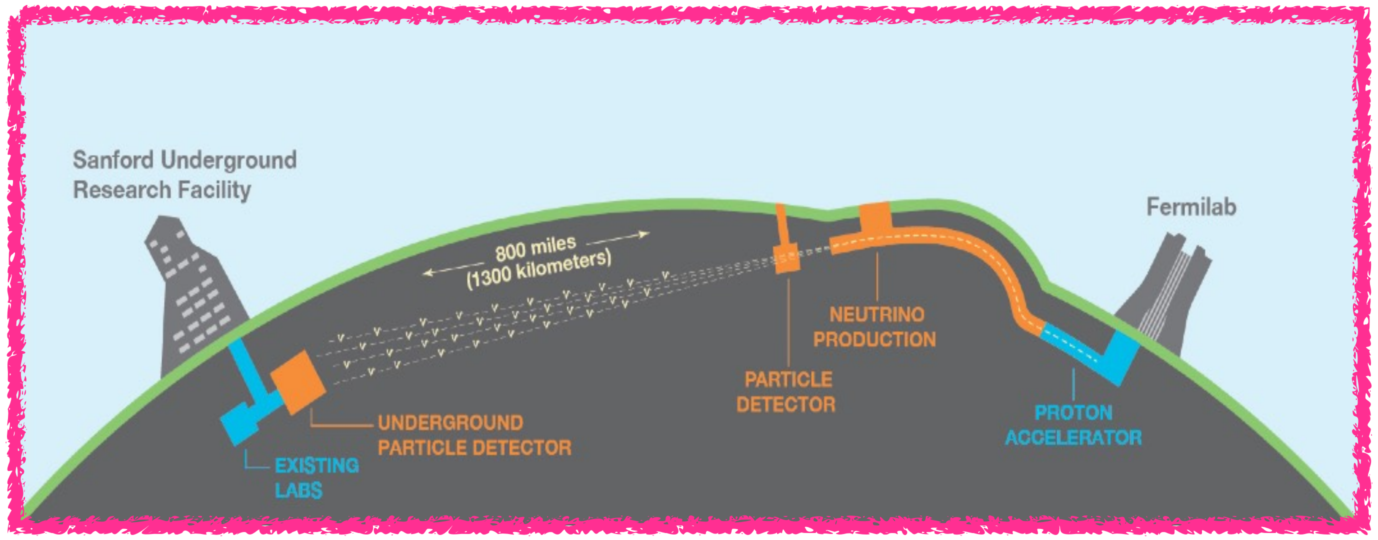


- 3σ sensitivity (6 yr)

J. Zhao, Neutrino 2022

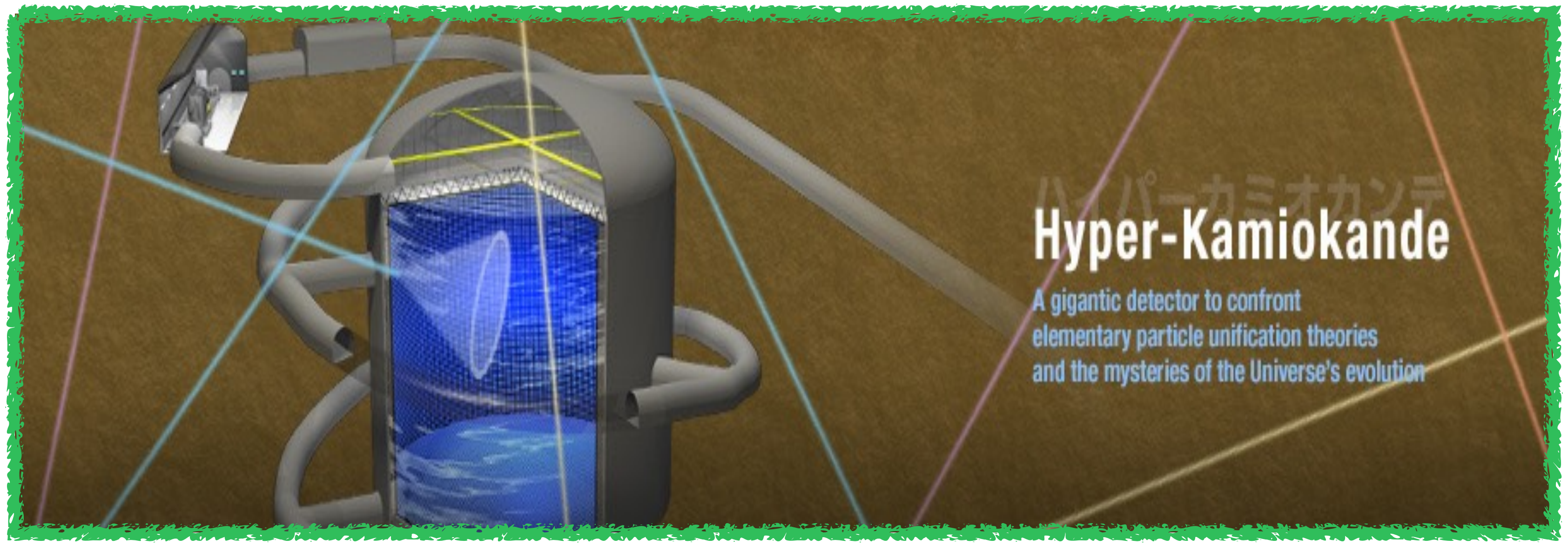
Next generation experiments

DUNE



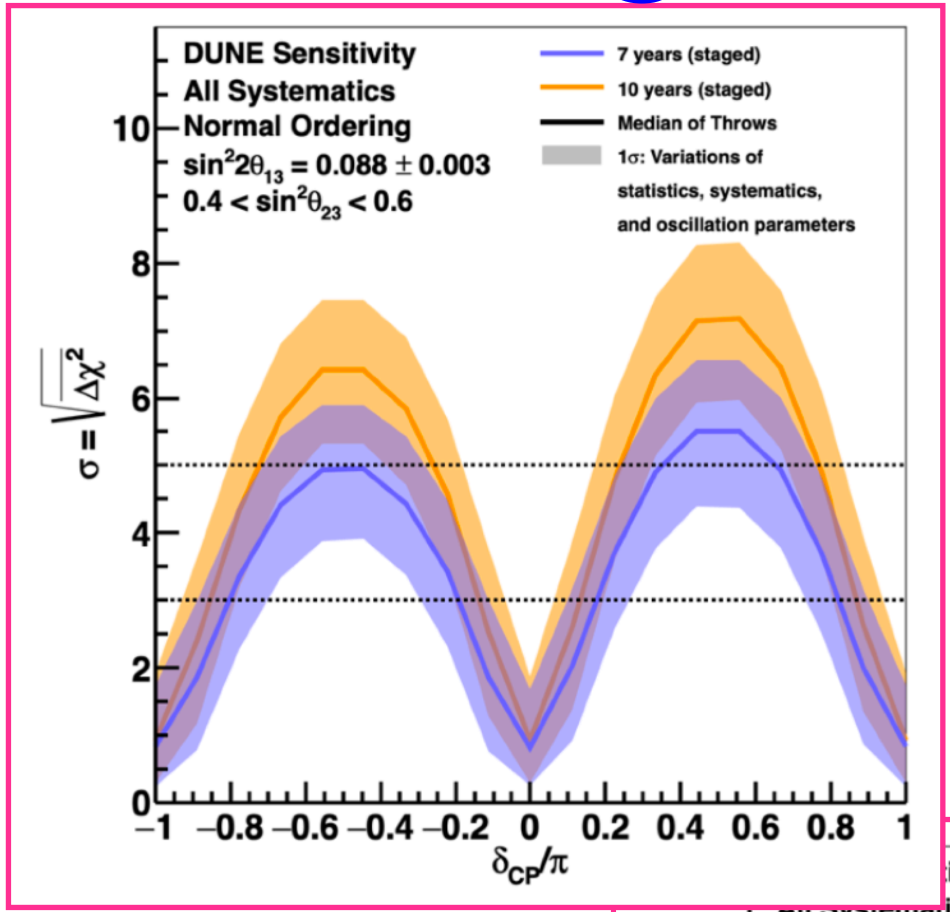
- 1.2 MW → 2.4 MW wide-band beam
- Baseline: 1300km
- 4x10 kt Liquid Argon TPCs
- capability to probe 2nd oscillation max
- great sensitivity to mass ordering

Hyper-Kamiokande

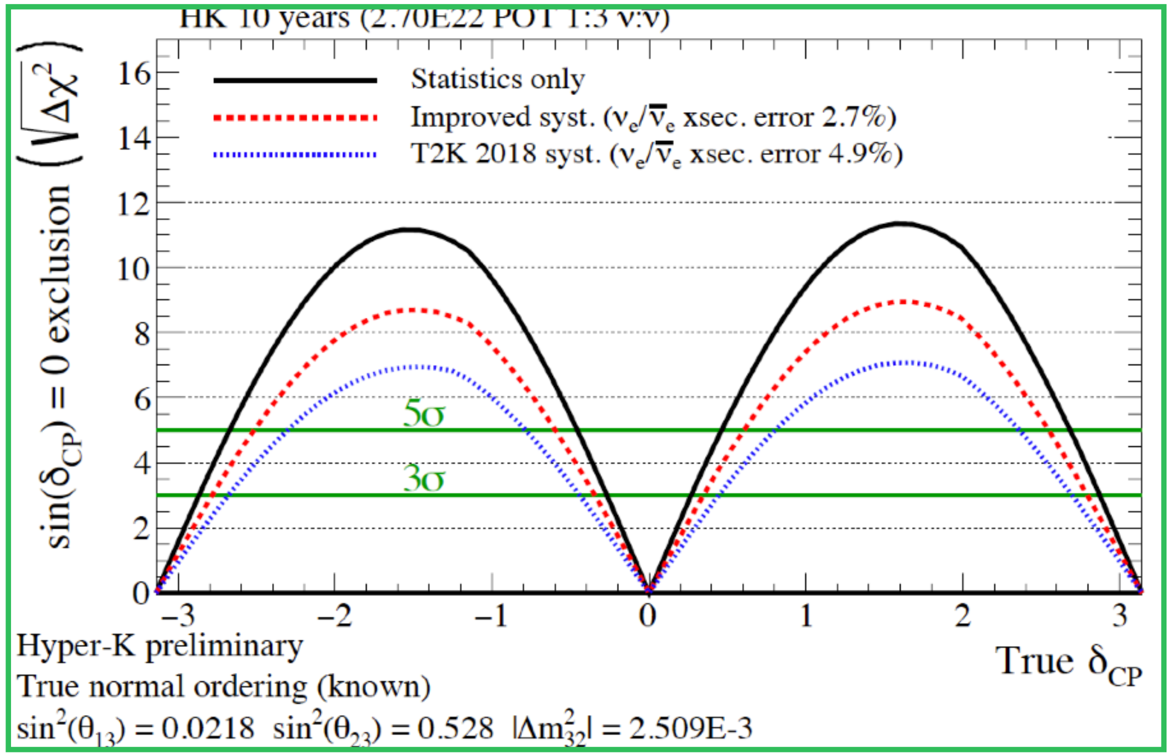


- 188 kton water Cherenkov
- Baseline: 295 km
- T2HK: great sensitivity to δ_{CP}
- T2HKK (1100km) will have similar sensitivities as DUNE

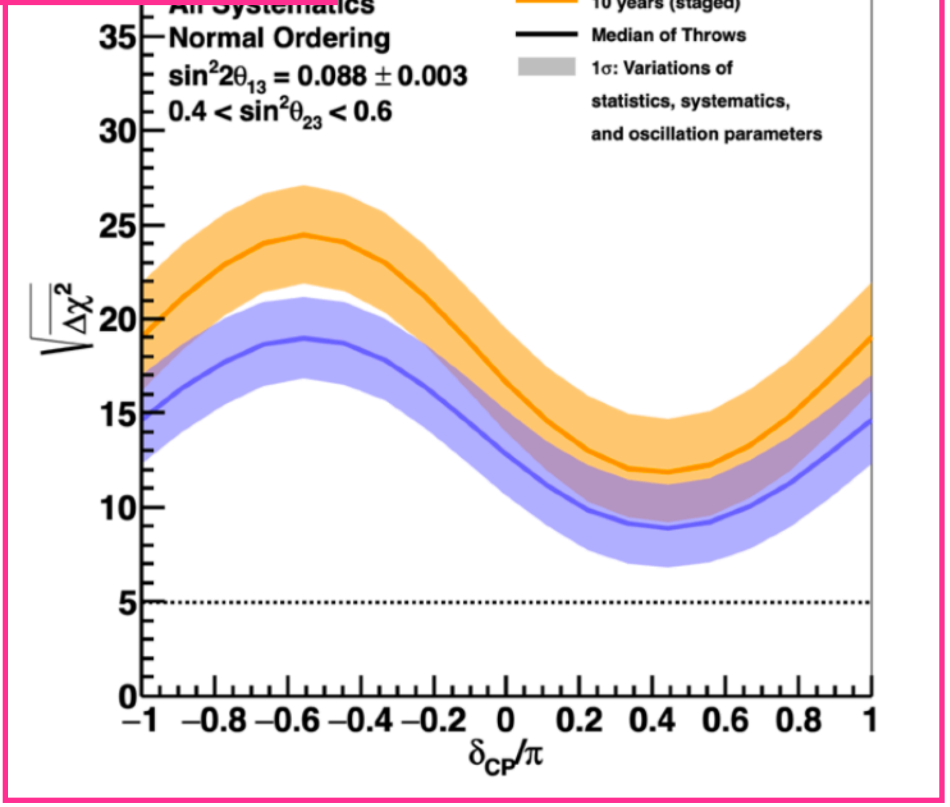
Next generation experiments

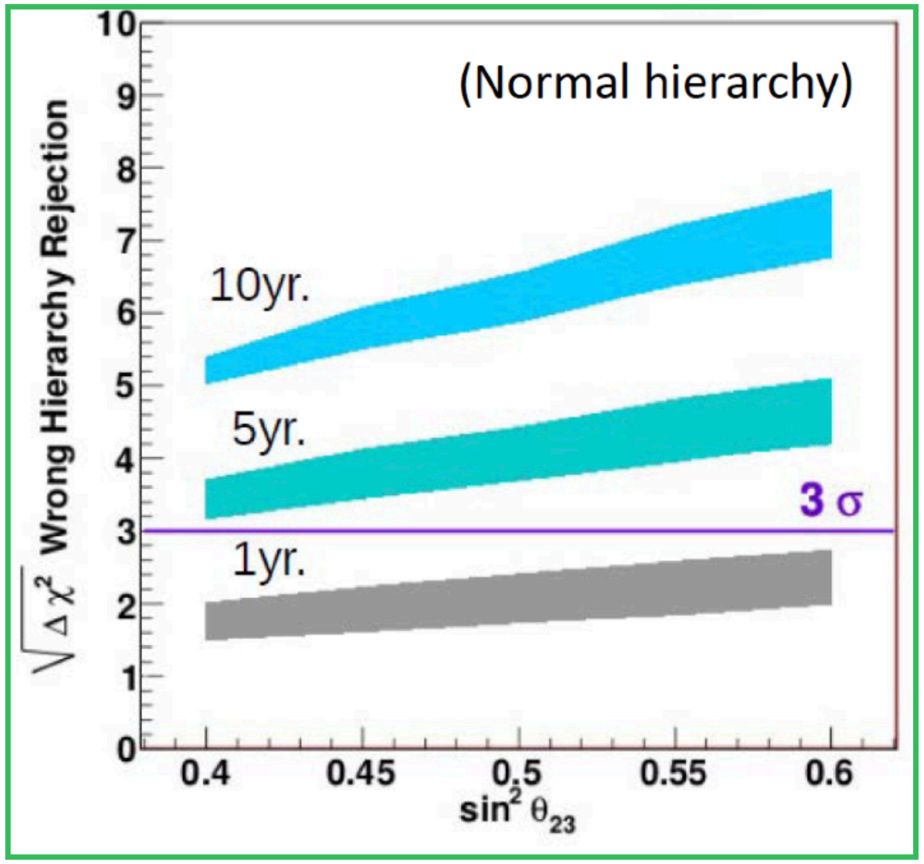


Hyper-Kamiokande



DUNE





Beyond the standard three-neutrino scenario

Beyond the 3-neutrino 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)

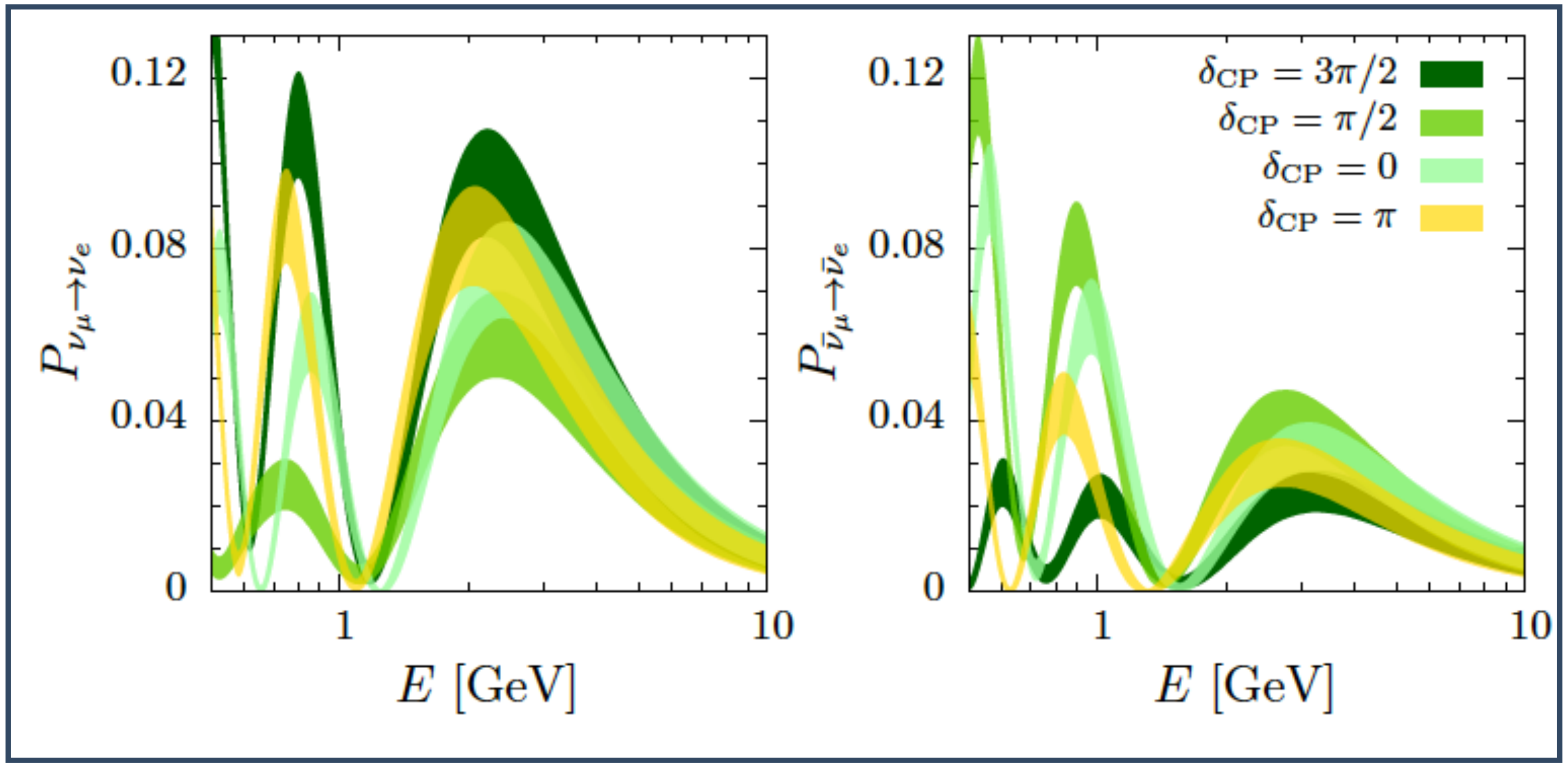
⇒ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

Non-unitary neutrino mixing

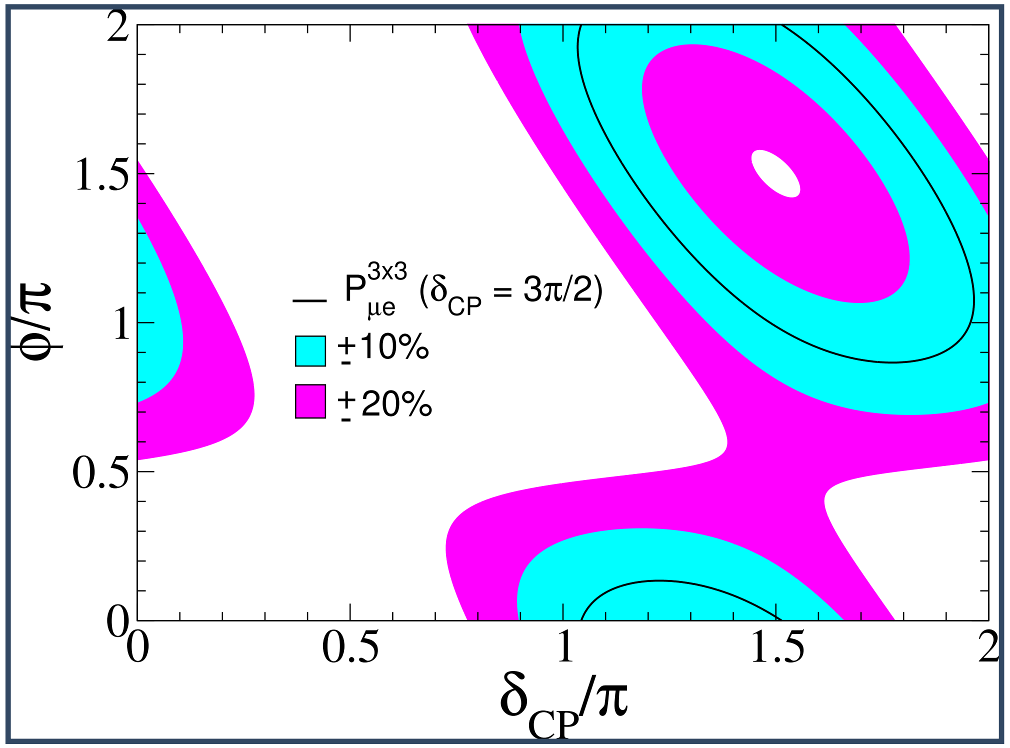
$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times 3}_{\mu e} + \alpha_{11}^2\alpha_{22}|\alpha_{21}|P^{I}_{\mu e} + \alpha_{11}^2|\alpha_{21}|^2$$

with $P^{I}_{\mu e}(\phi)$

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



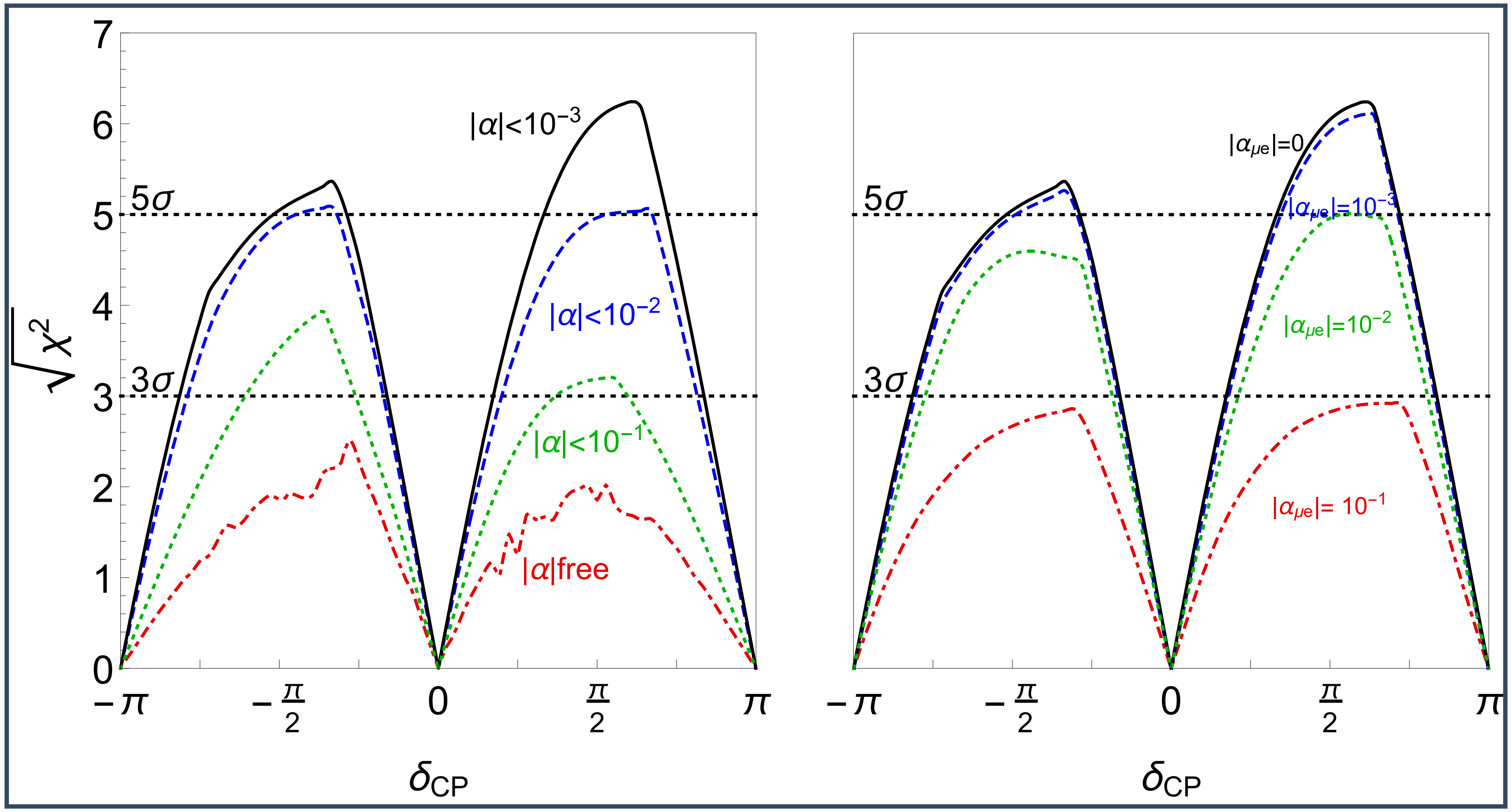
Escrihuela et al, NJP 2017



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



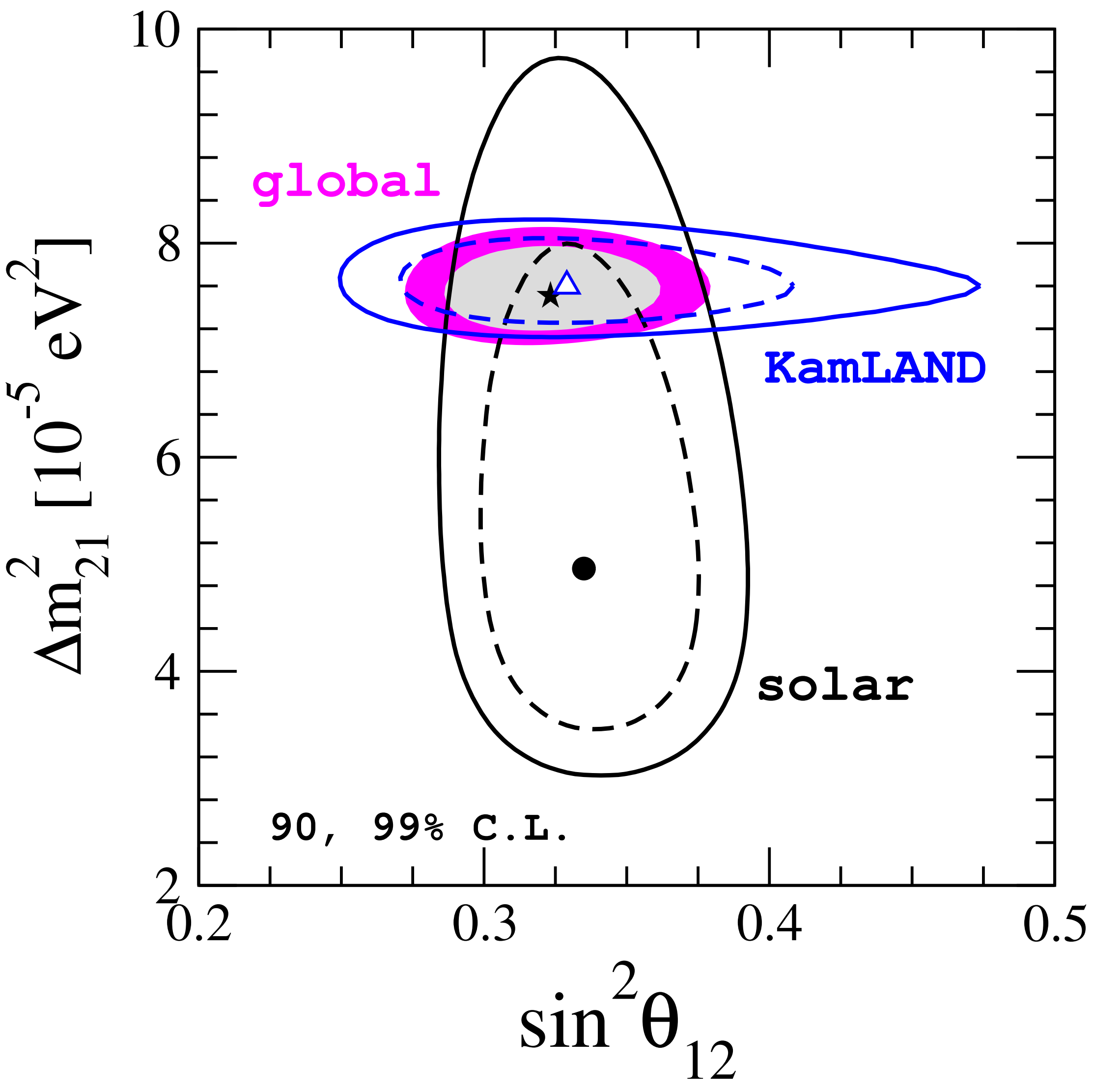
Fernández-Martínez et al (DUNE-BSM Working Group)

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

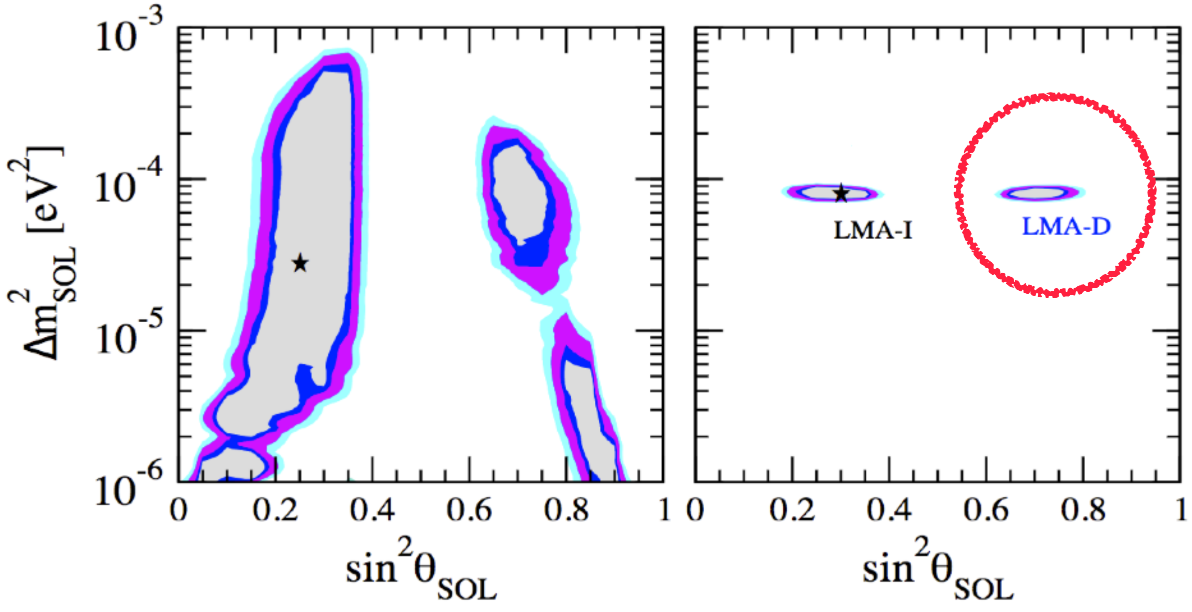
→ With priors based on current bounds (10^{-3}-10^{-2}), the effect is less dramatic

NSI in the solar neutrino sector

Standard 3ν oscillations

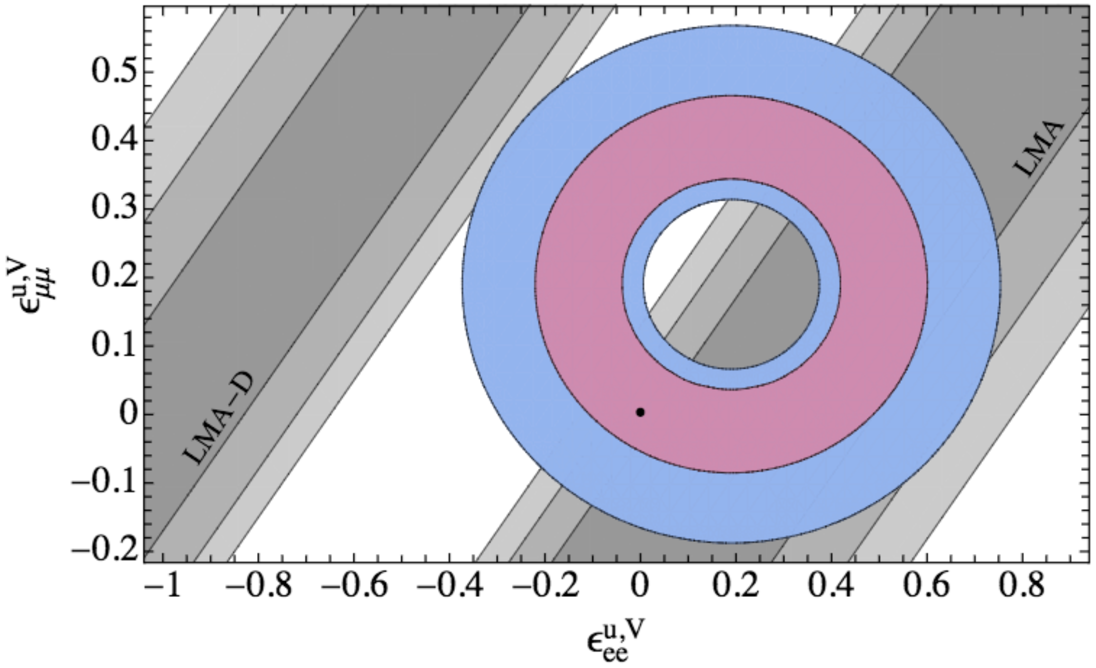


de Salas et al, PLB782 (2018) 633



Miranda et al, JHEP 2006

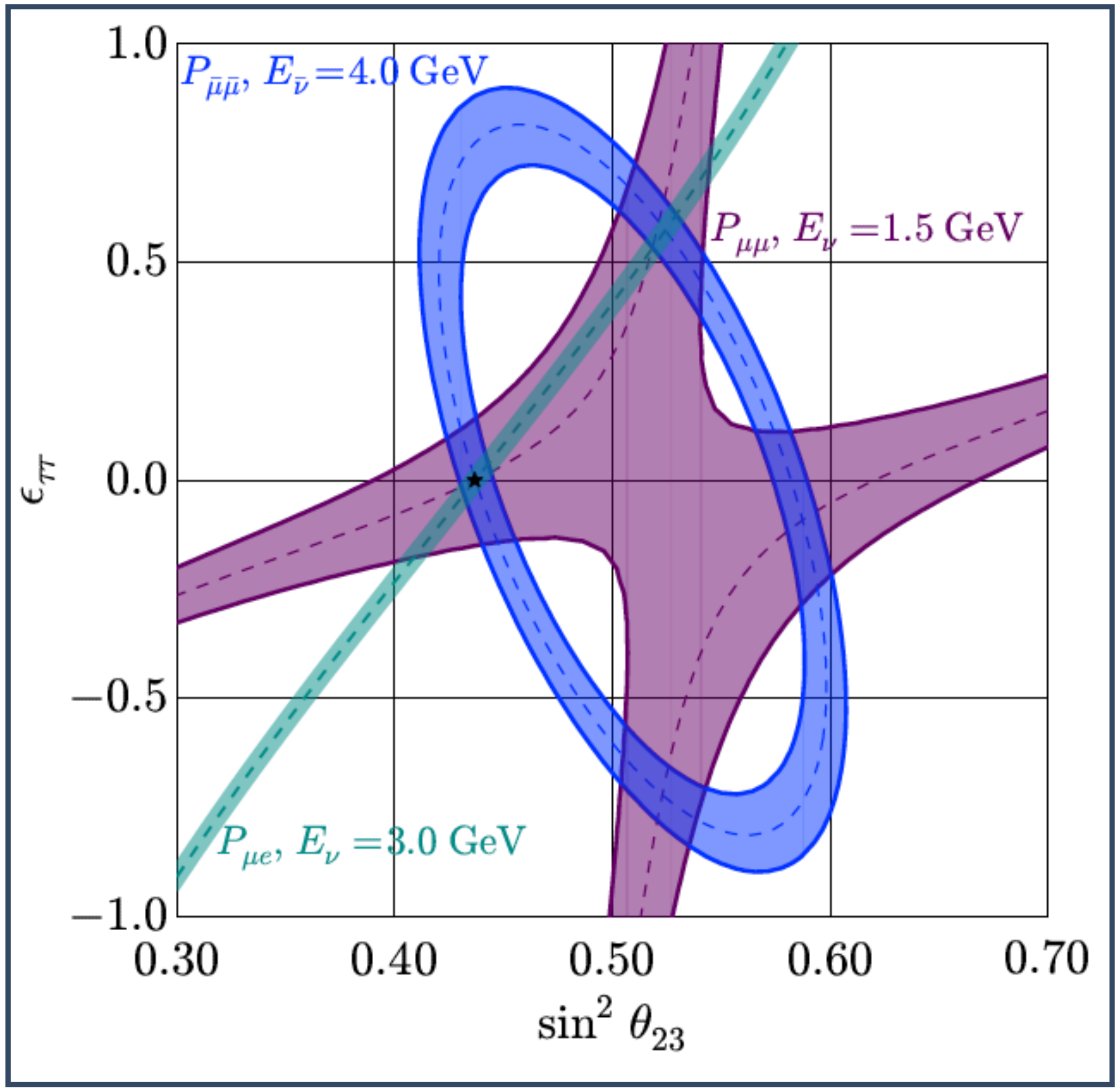
Solar + CEνNS



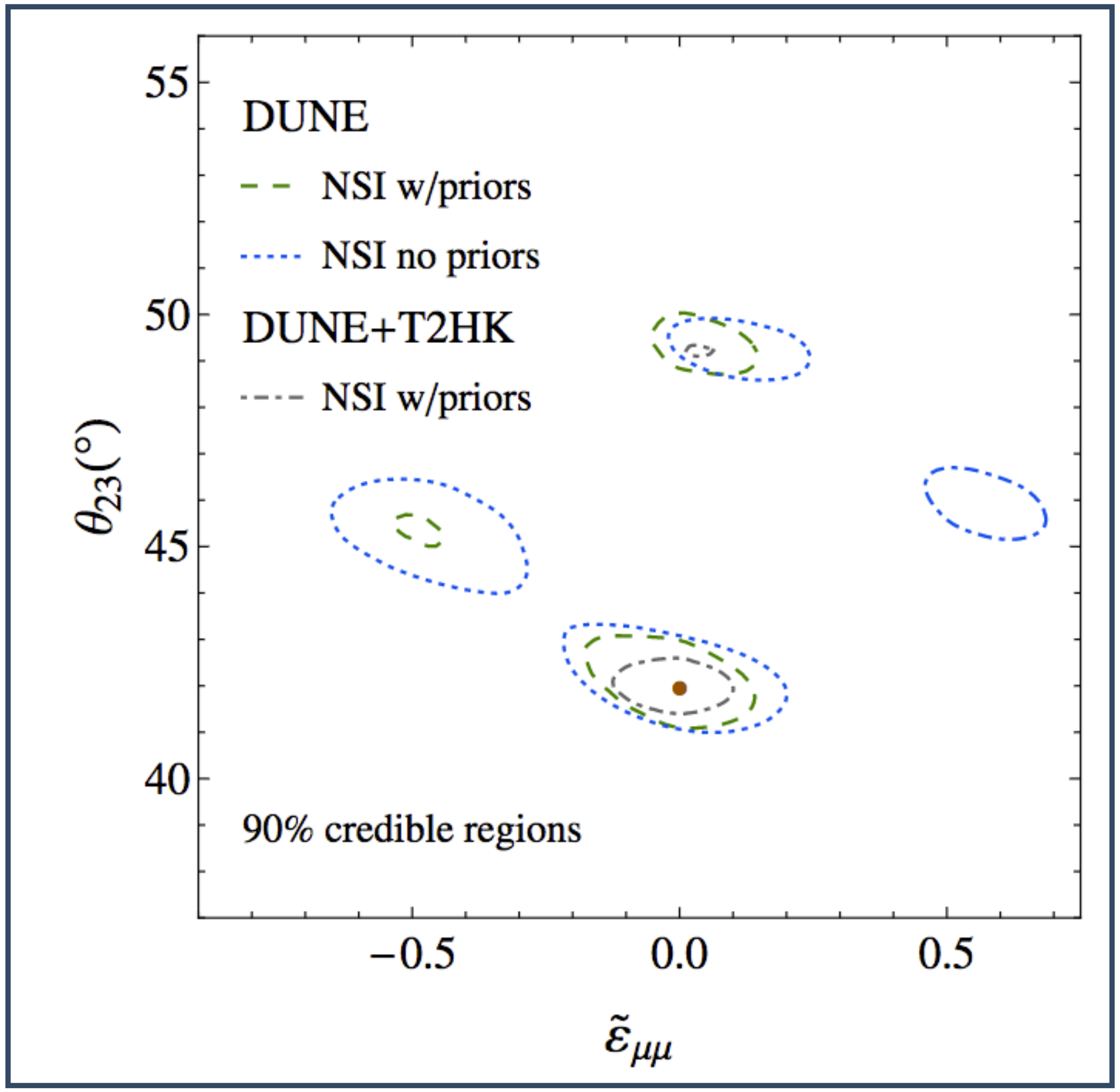
Coloma et al, PRD 2017

NSI at future LBL experiments

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



Gouvea and Kelly, NPB 2016



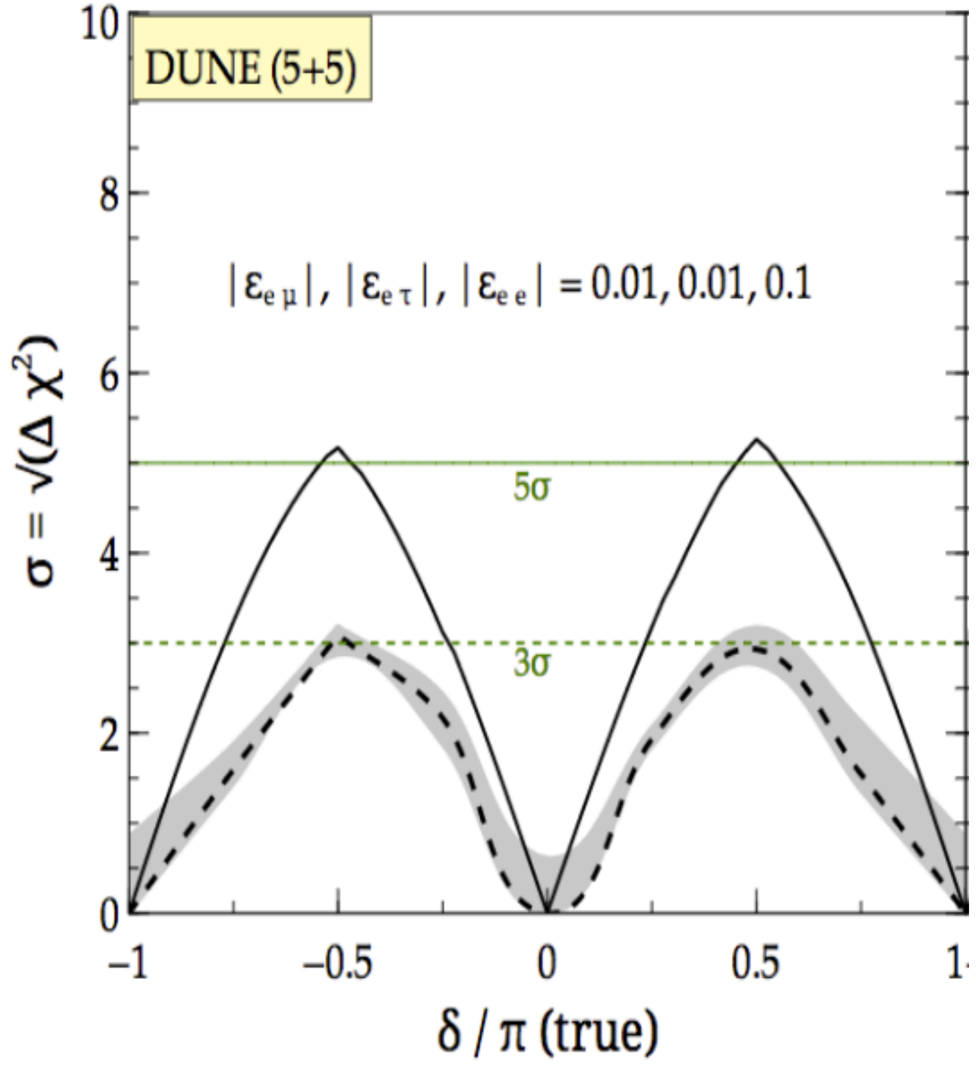
Coloma, JHEP 2016

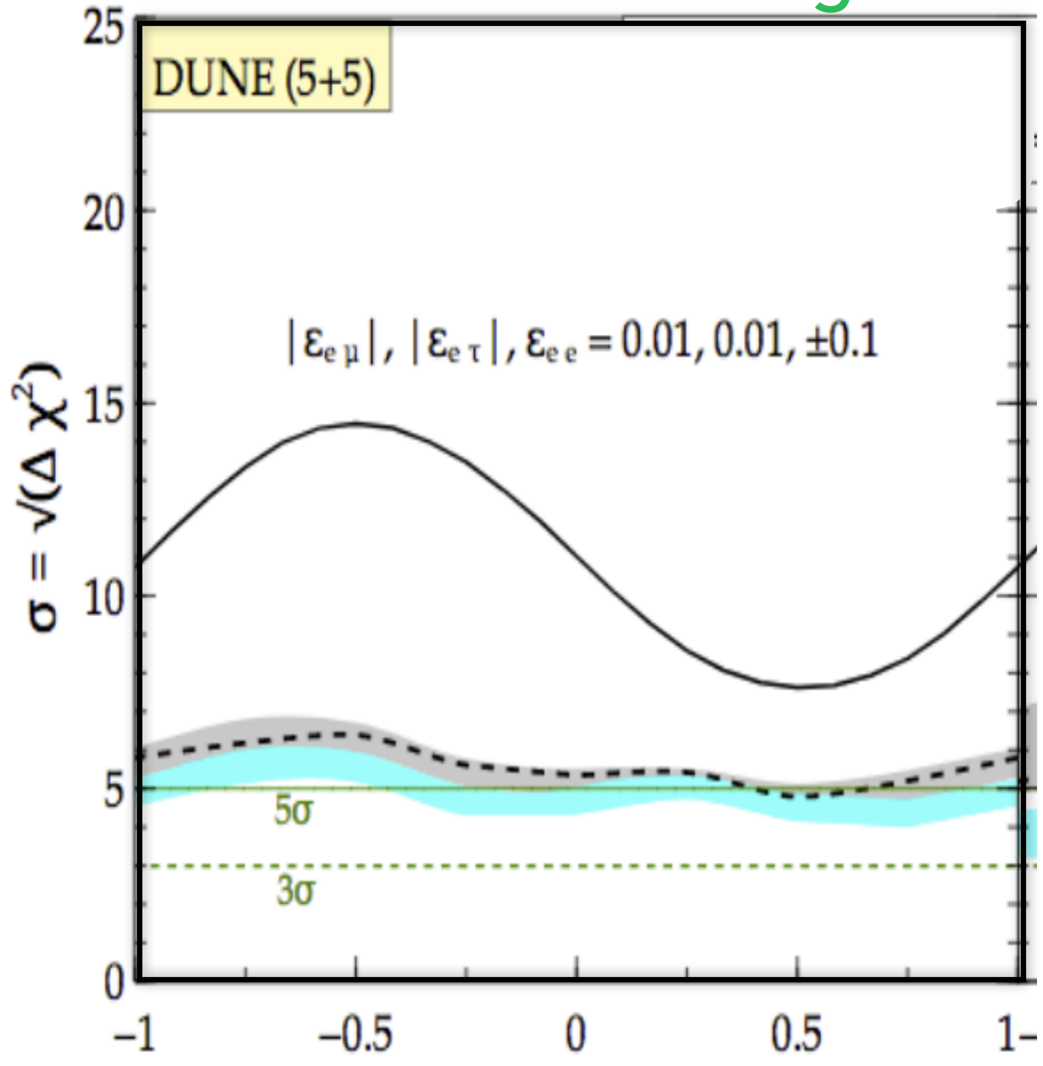
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation

mass ordering





Masud and Mehta, PRD 2016

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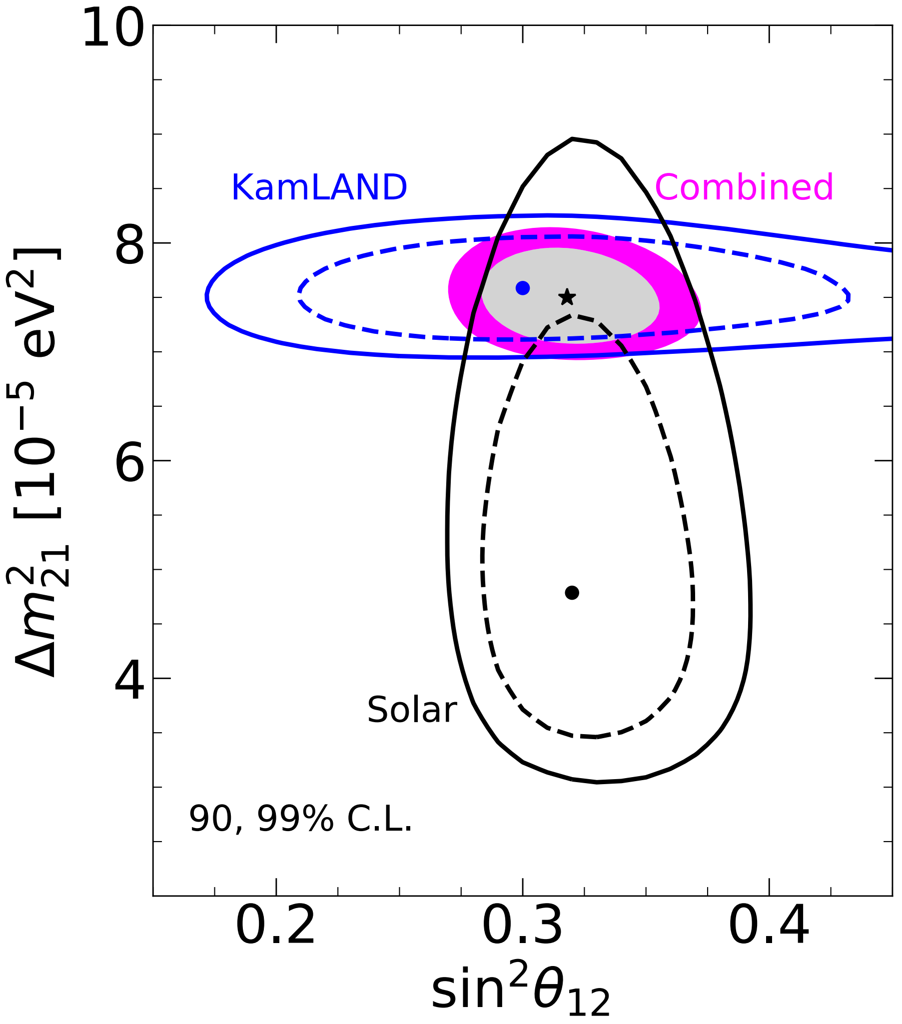
⇒ the presence of new physics may affect our current description of 3-nu oscillations as well as the future measurements

Can they also help reducing the current tensions?

The solar-KamLAND Δm^2_{21} tension



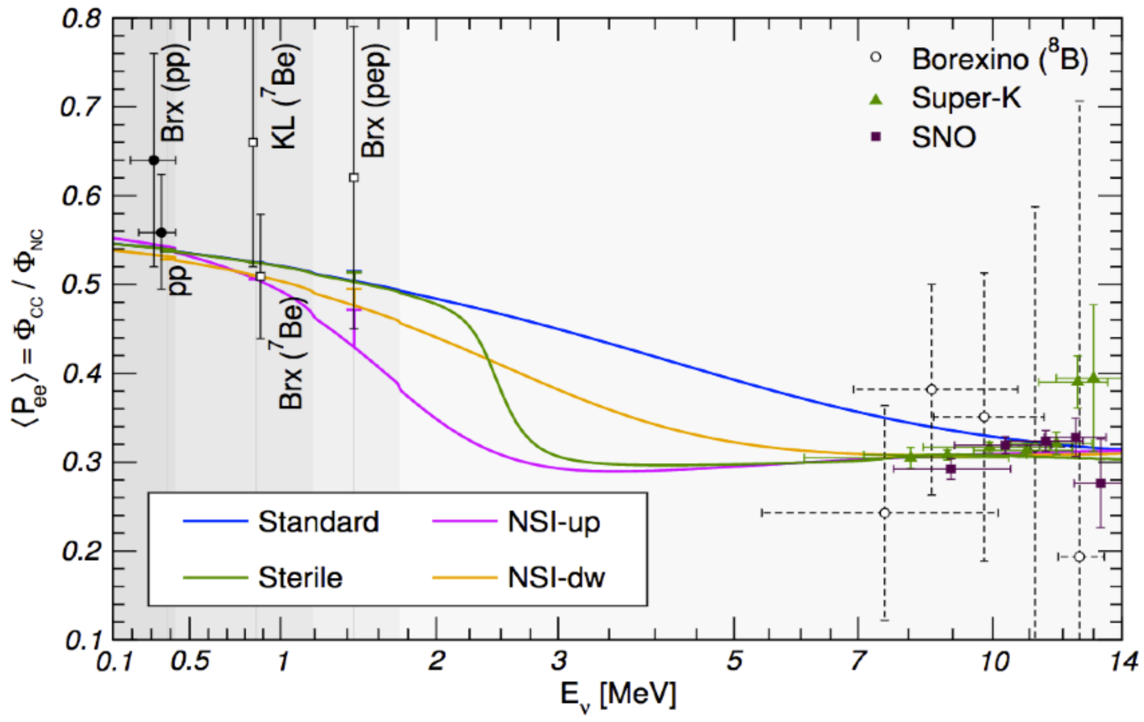
⇒ 2σ (1.5σ) tension between preferred value of Δm^2_{21} from KamLAND and solar data

⇒ 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

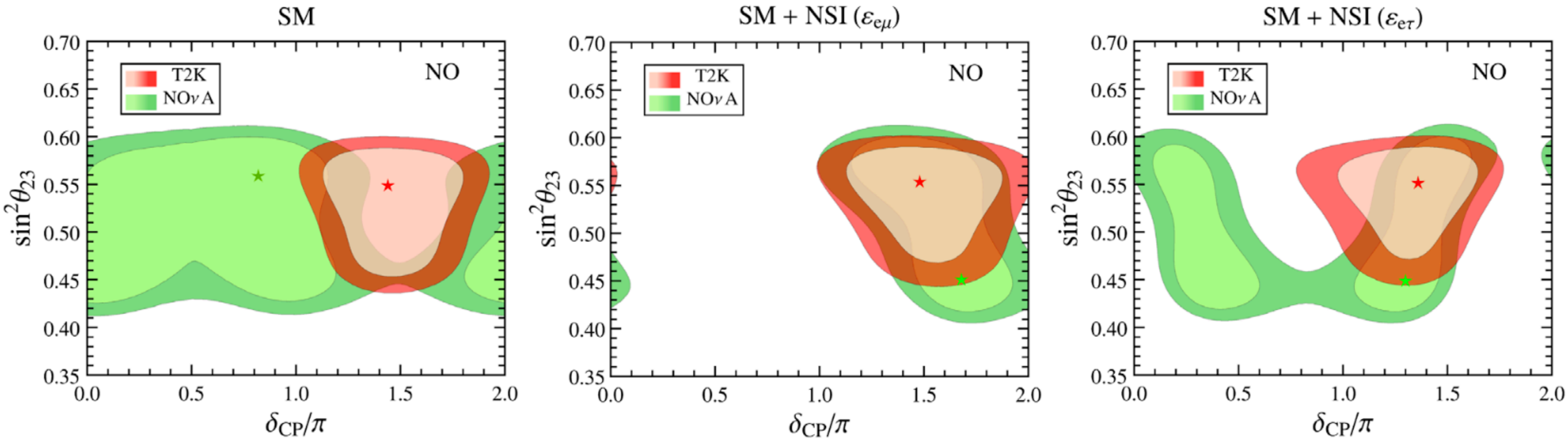


Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

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

✦ Current status of three-neutrino oscillation parameters:

- ✓ very precise and robust determinations for most of them (1.3-10%)
- ✓ preference for $\theta_{23} > 45°$, 1st octant value disfavoured with $\Delta\chi^2 \geq 5.8$ (6.4)
- ✓ $\delta_{BF} = 1.08\pi$ (1.58π) for NO (IO) ; $\delta = \pi/2$ disfavored at 4.0σ (6.2σ)
- ✓ 2.5σ hint for normal ordering from atmospheric, LBL and reactor data
- ✓ sensitivity on mass ordering driven by oscillation data so far.

✦ By 2025/2026:

- ✓ 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 a single experiment: DUNE, Hyper-Kamiokande

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