

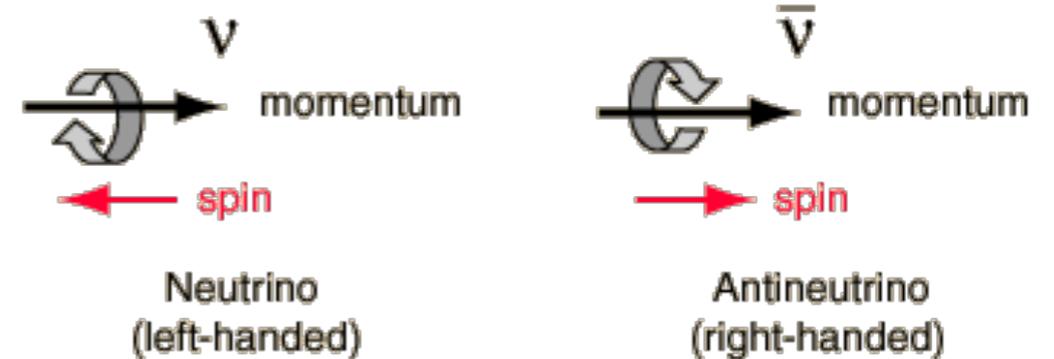
Neutrino oscillations and beyond: precision era meets new physics

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IFIC, CSIC/Universitat de València

GSSI Astroparticle Colloquia - 25 February 2026

Neutrinos in the Standard Model

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



- ◆ Only neutral fundamental fermion: **Dirac** or **Majorana** nature?
- ◆ No mass term for neutrinos can be built with the content of the SM:

Dirac mass term

$$m \bar{\nu}_R \nu_L$$



Majorana mass term

$$\frac{1}{2} m \nu_L^T C^\dagger \nu_L$$



Lowest dim mass term

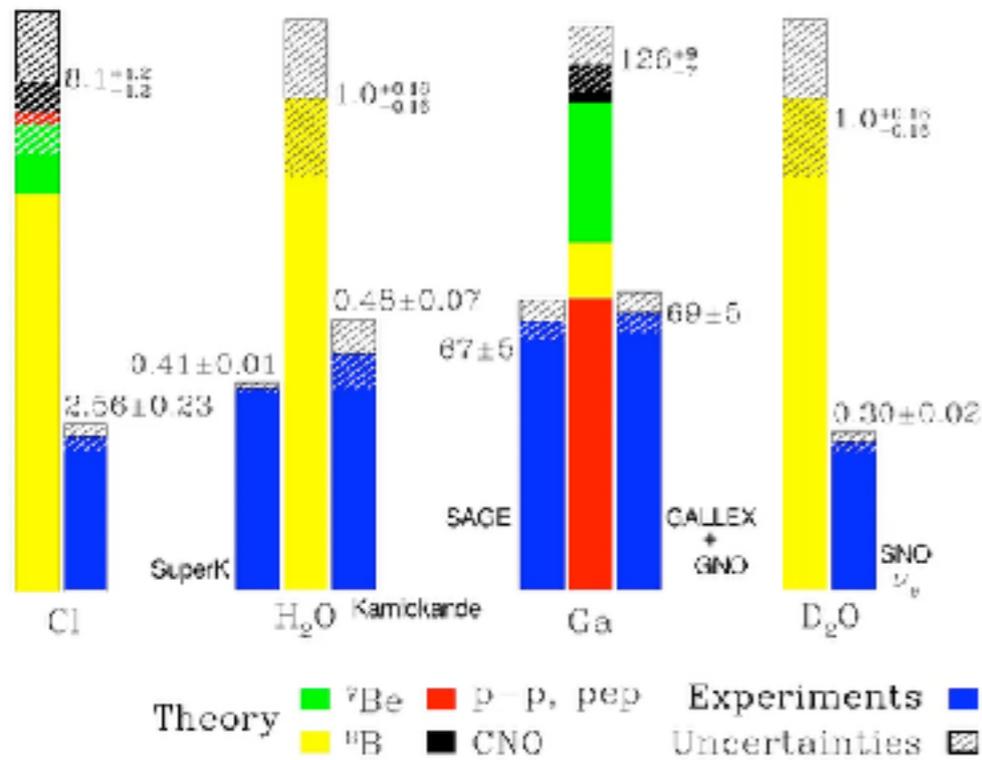
$$\frac{g}{\Lambda} (L_L^T \sigma_2 \phi) C^\dagger (\phi^T \sigma_2 L_L)$$



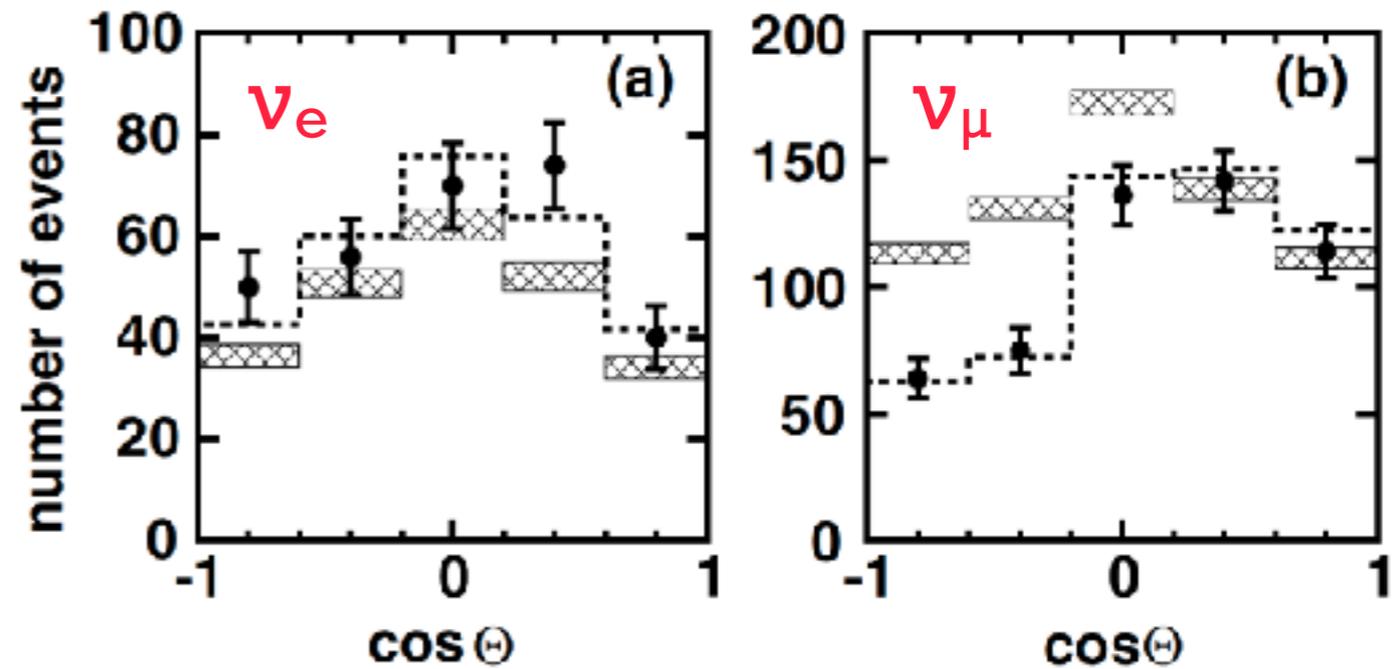
Neutrinos are strictly massless in the Standard Model!

Neutrino anomalies

Solar neutrino problem (60's)



Atmospheric neutrino anomaly (80's)



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

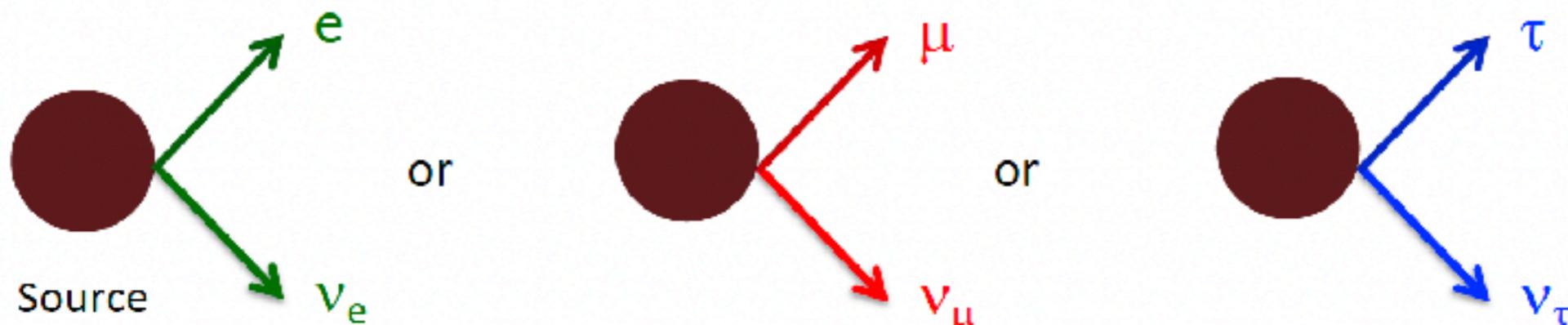


$$\nu_\mu \rightarrow \nu_\tau$$

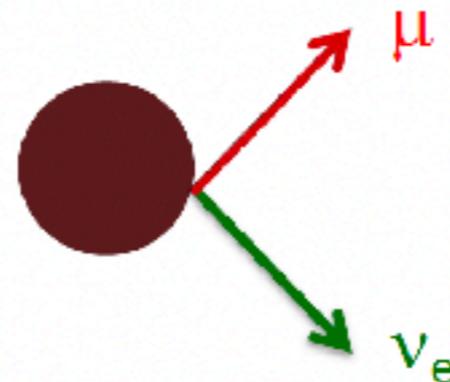
2015: Nobel Prize

Neutrino production in the SM

Weak interactions conserve flavour: neutrinos are always produced together with their associated charged lepton (e , μ , τ)

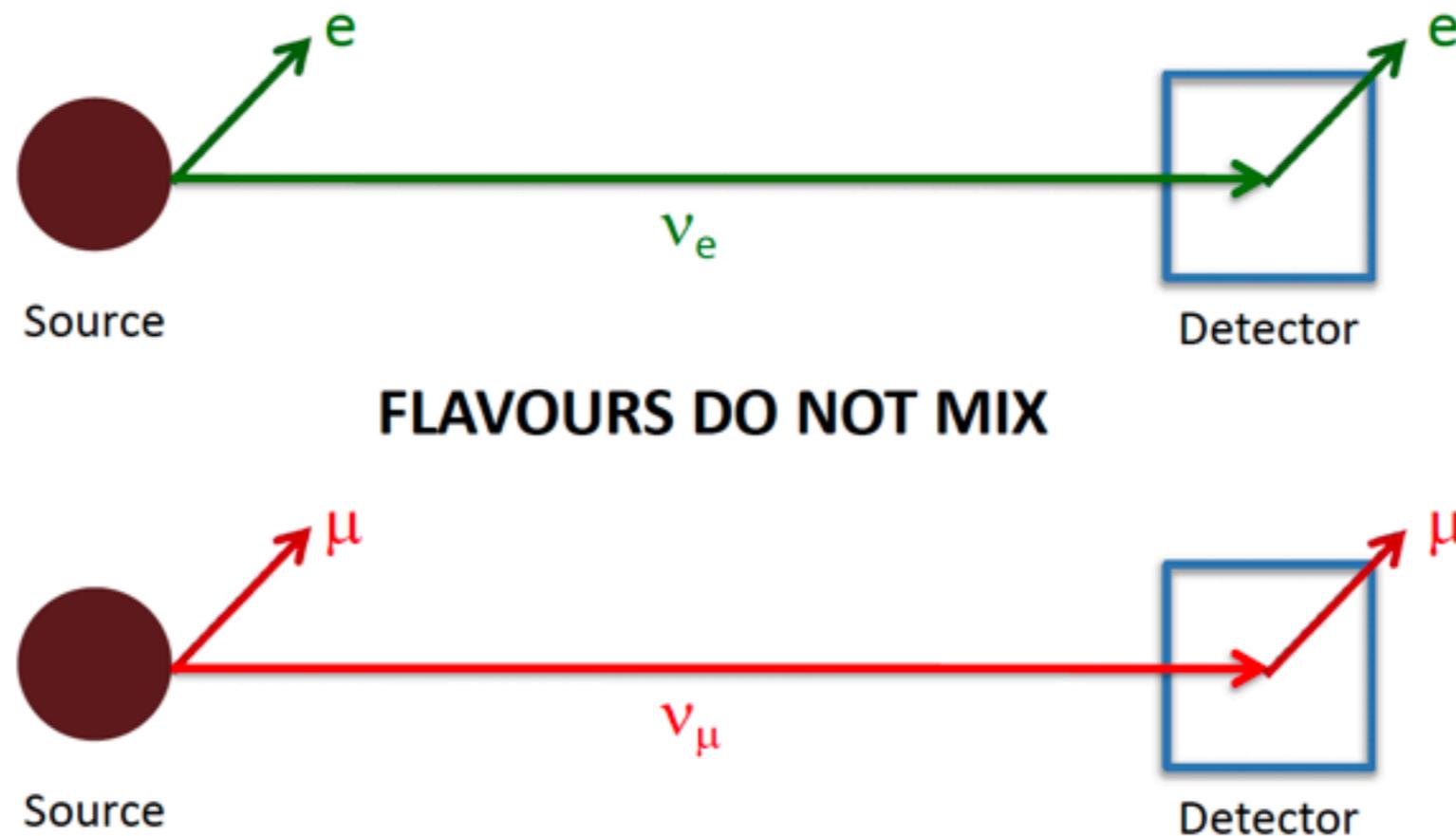


NEVER

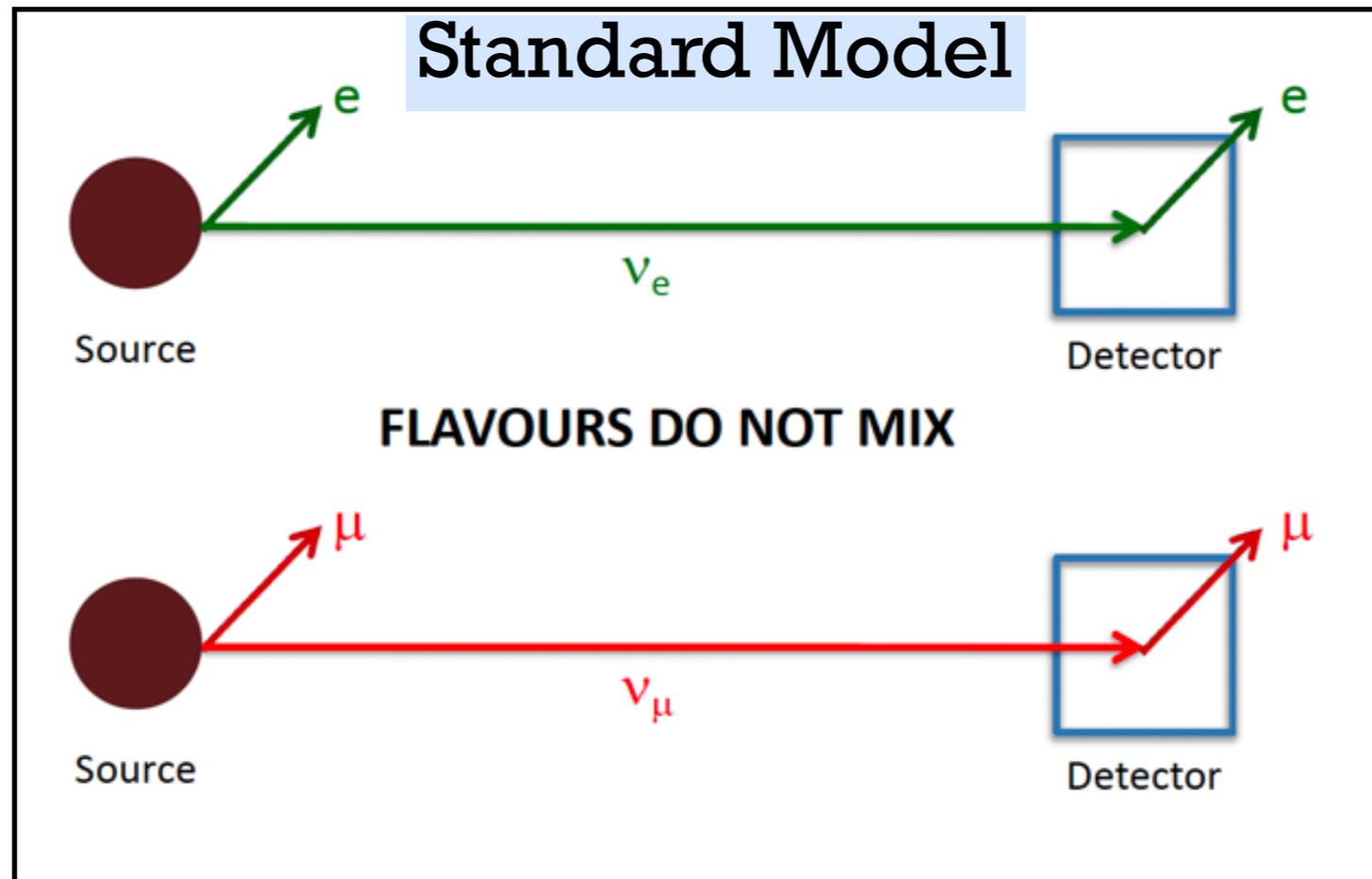


Neutrino detection

Neutrinos are indirectly detected through the observation of their associated charged lepton



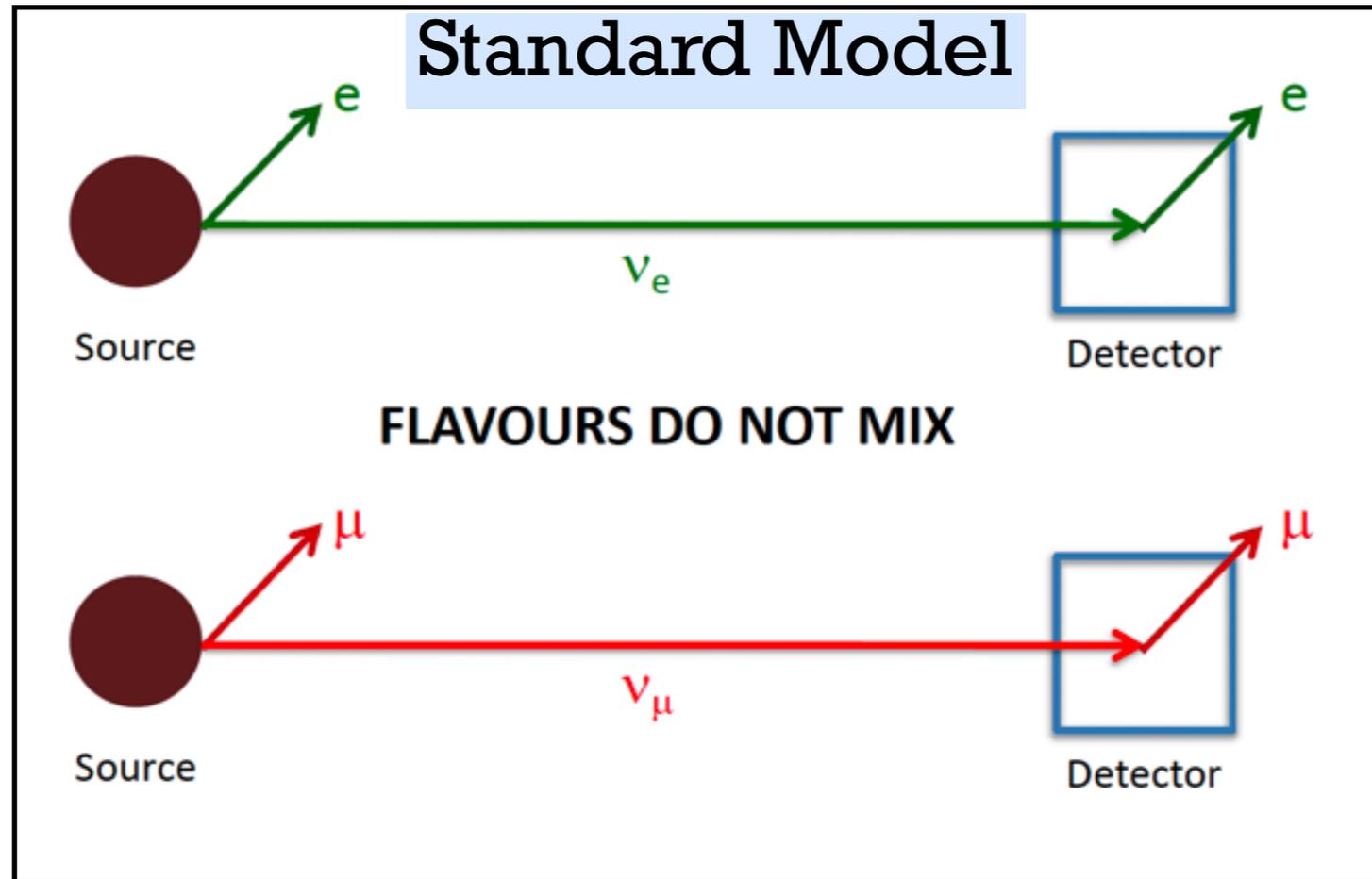
Neutrino oscillations



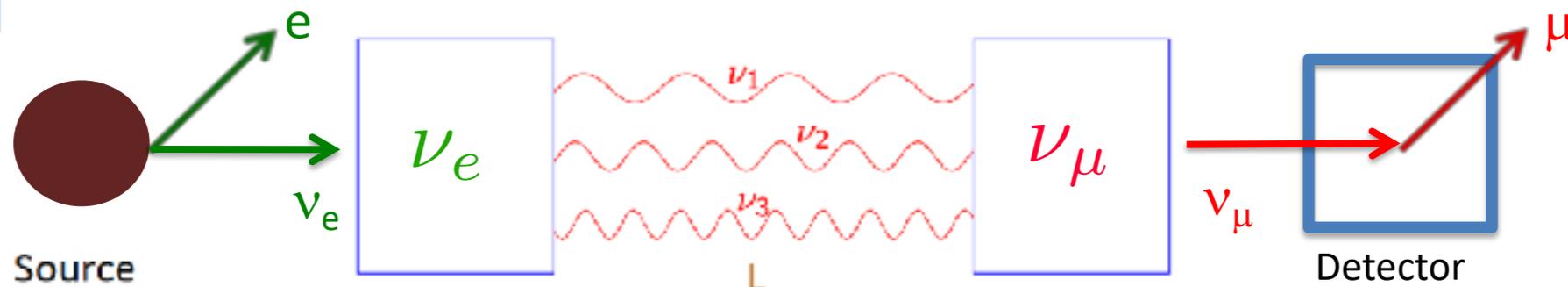
However



Neutrino oscillations



However



$$\nu_{\alpha L} = \sum_k U_{\alpha k} \nu_{k L} \quad \text{neutrino mass eigenstates}$$

Neutrinos oscillate



© Johan Jarnestad/The Royal Swedish Academy of Sciences

Neutrinos are massive!!

The three-flavour ν picture

neutrino mixing

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

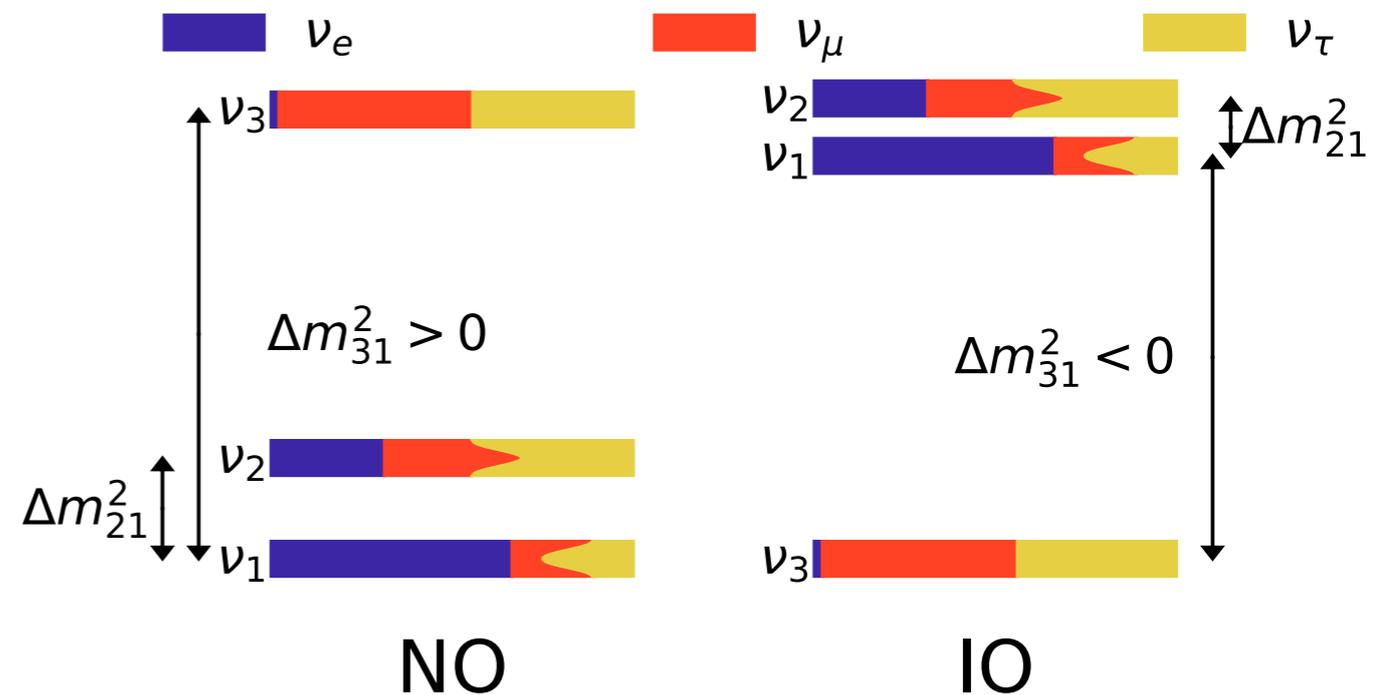
neutrino mass spectrum

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

⇒ absolute neutrino mass: m_0

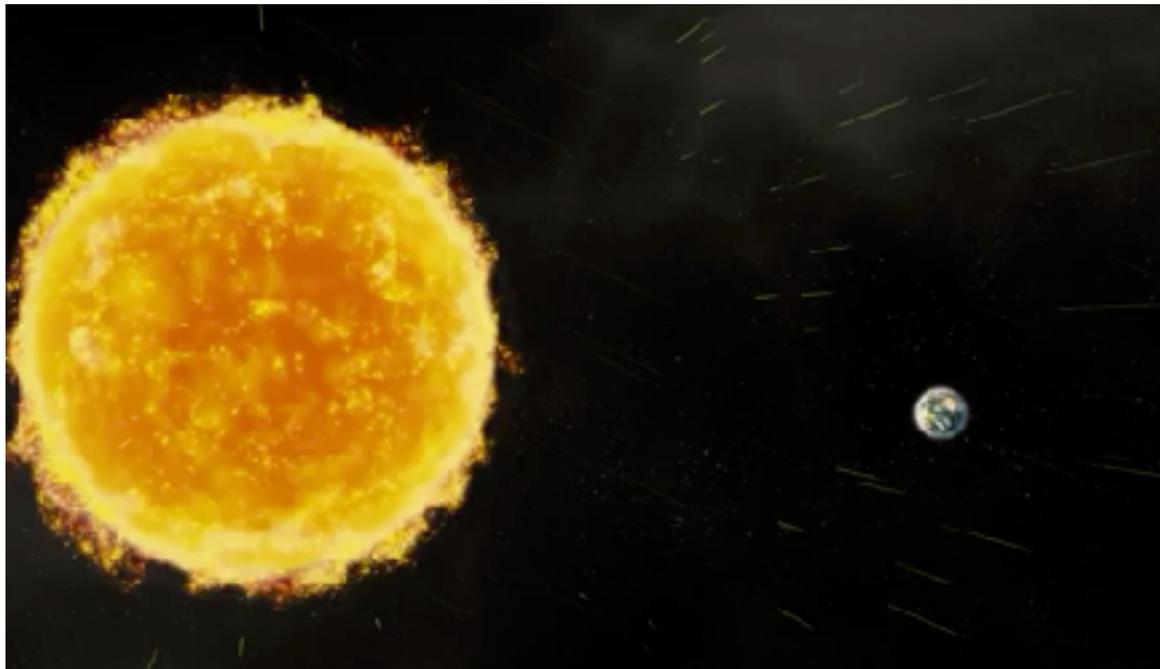
⇒ two mass splittings:

$$\Delta m_{21}^2, \Delta m_{31}^2$$

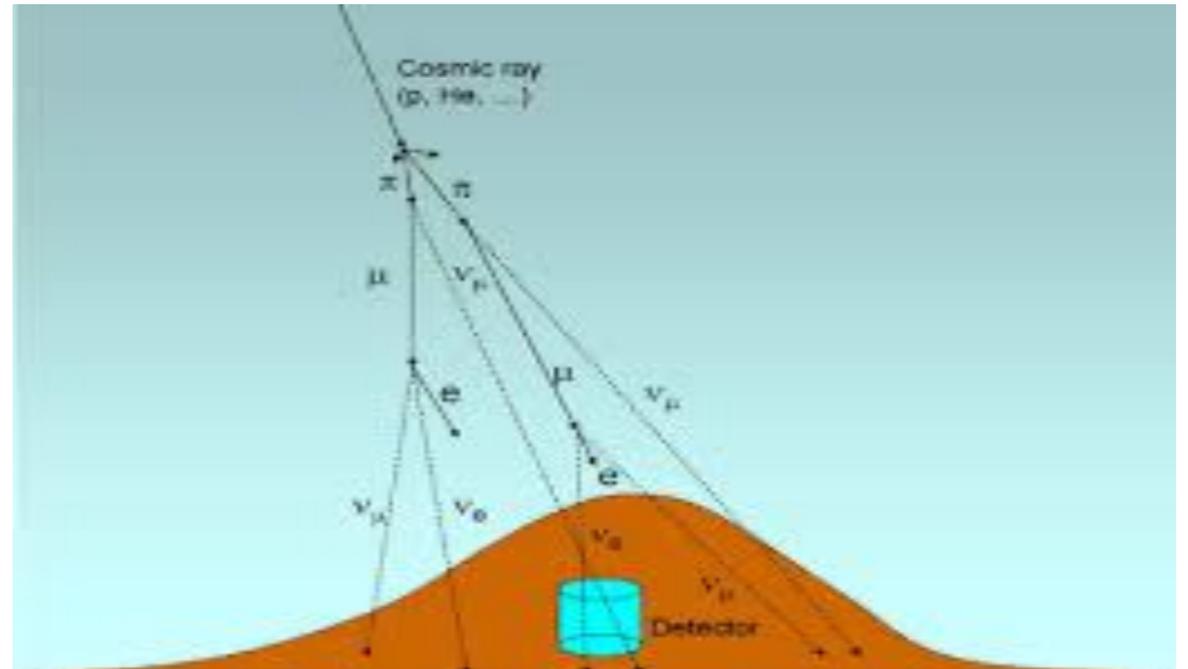


Neutrino oscillations

Solar neutrinos



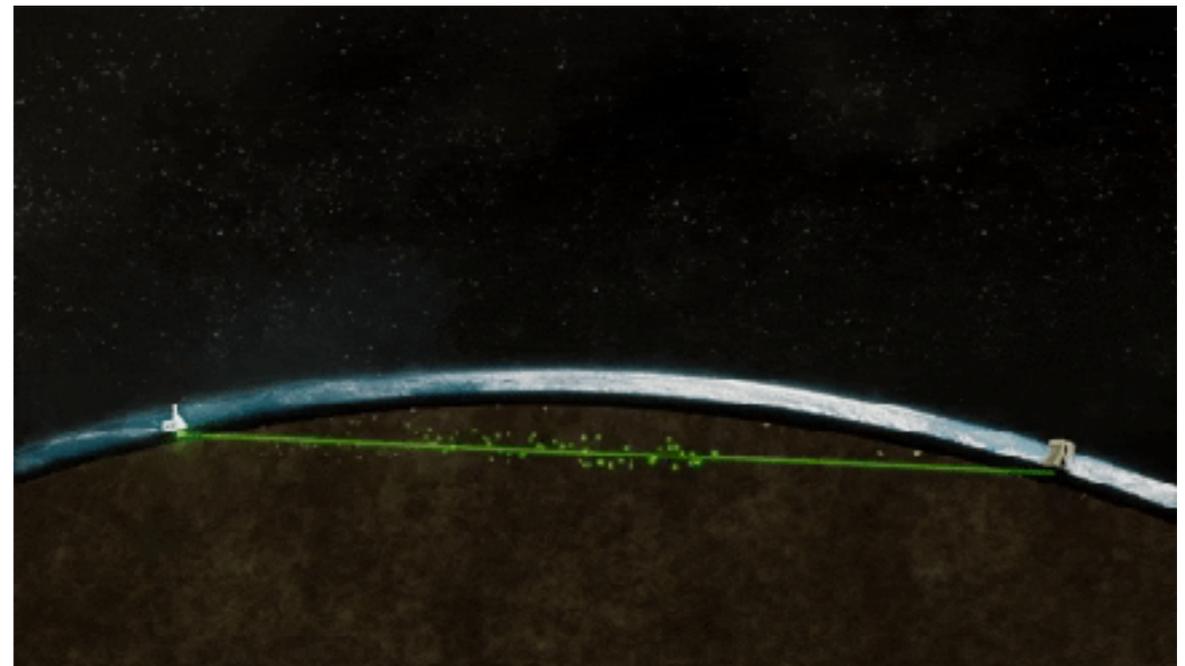
Atmospheric neutrinos



Reactor neutrinos

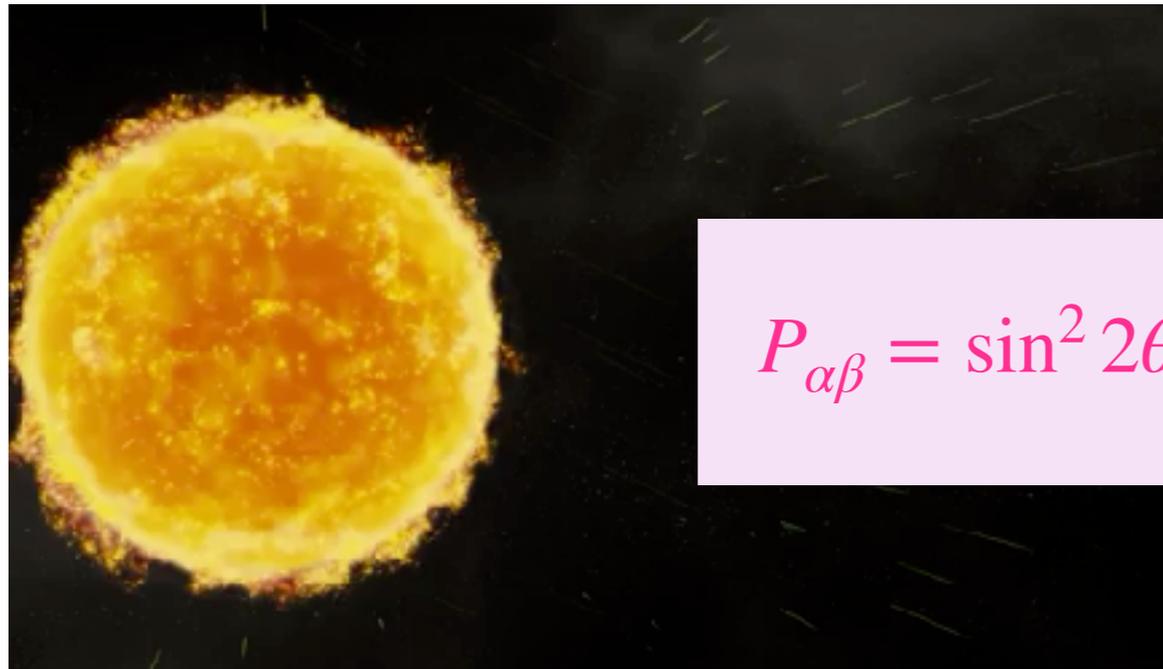


Accelerator neutrinos



Neutrino oscillations

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



$$P_{\alpha\beta} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

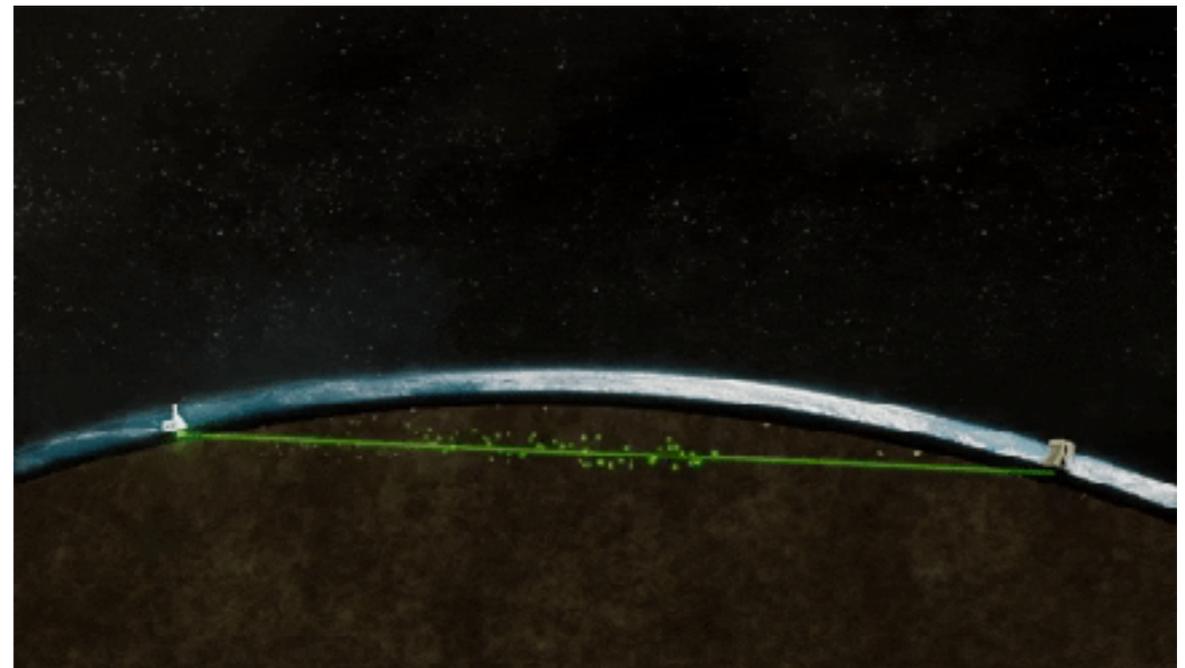
Atmospheric sector: $\theta_{23}, \Delta m^2_{31}$



Reactor sector (SBL): $\theta_{13}, \Delta m^2_{31}$



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

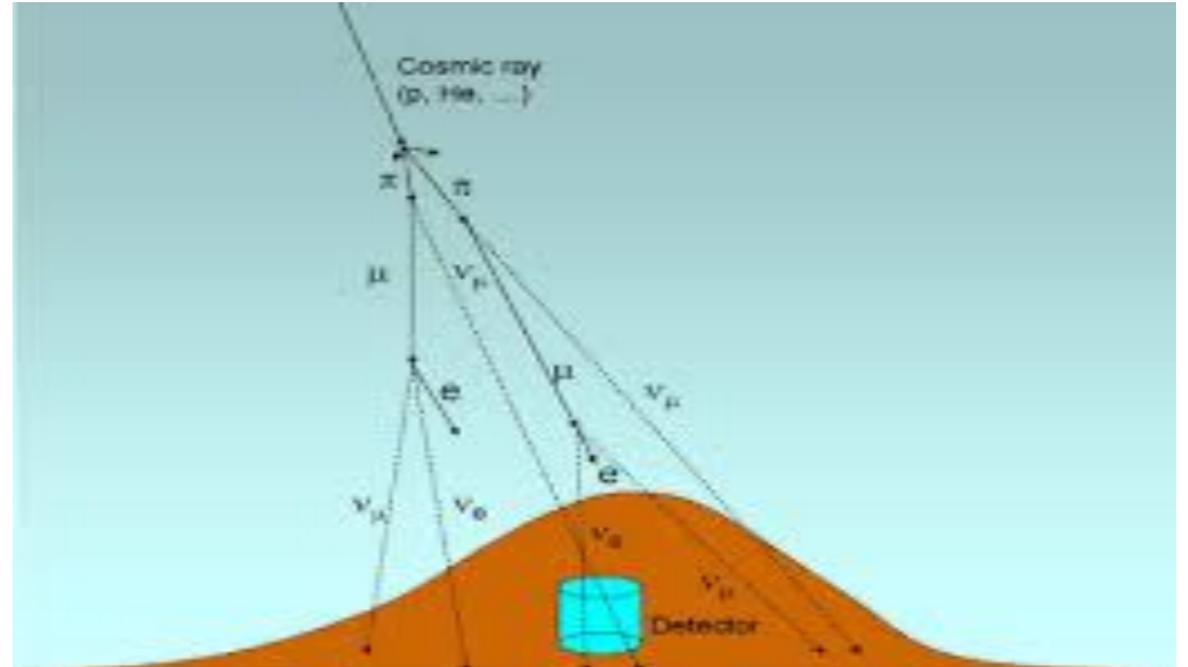


Neutrino oscillations

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



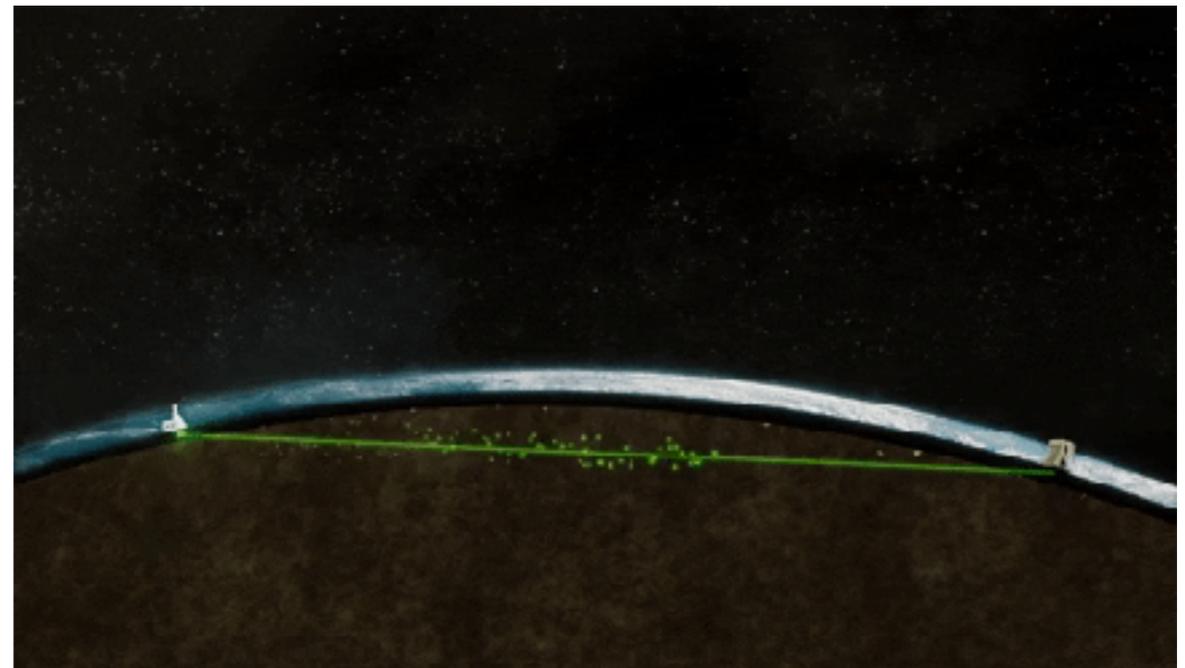
Atmospheric sector: θ_{23} , θ_{13} , Δm^2_{31} , δ



Reactor sector (SBL): θ_{13} , Δm^2_{31}



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



Global analysis to ν oscillations

1

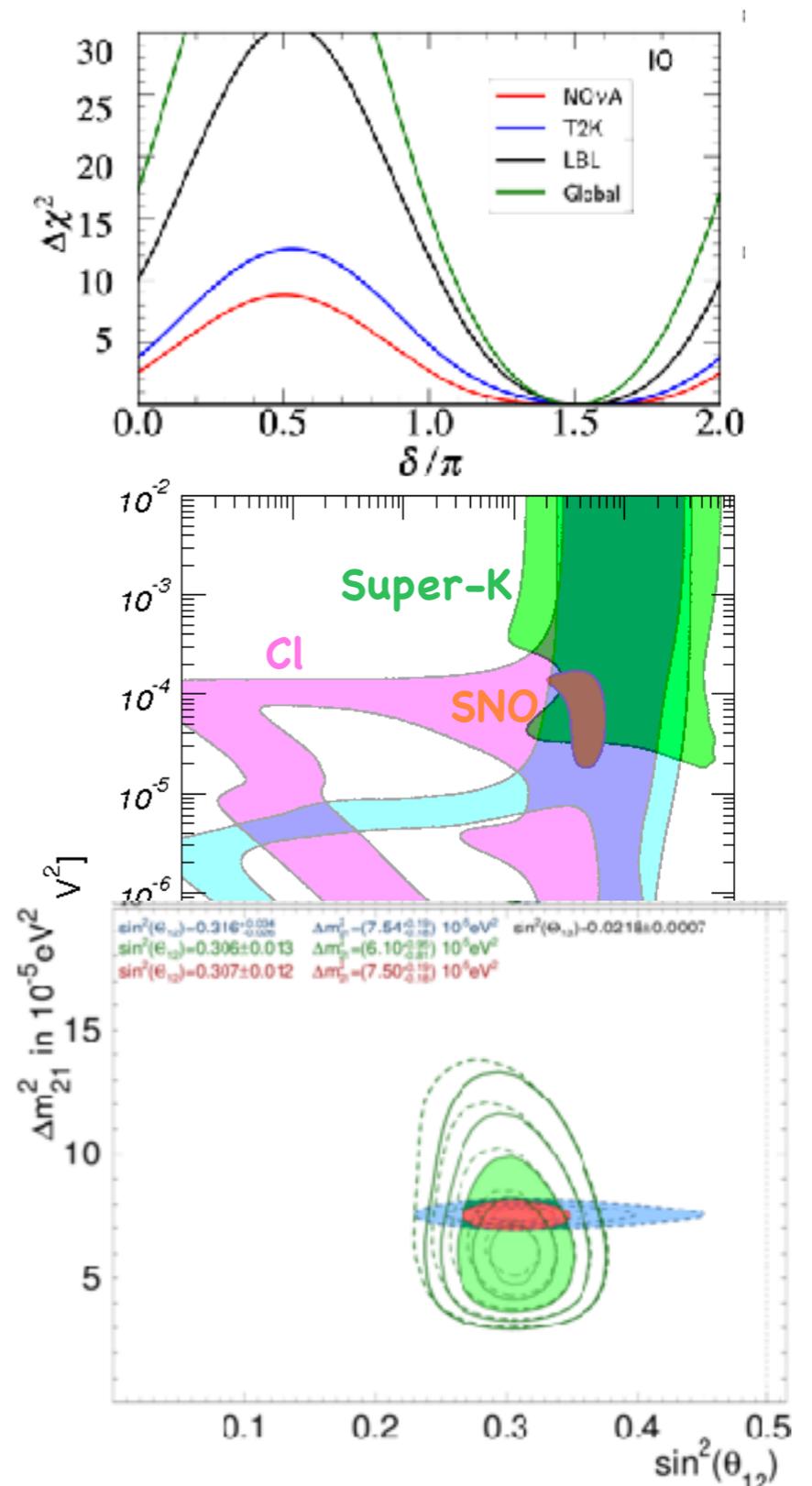
Compensate low statistics in subleading oscillation effects searches

2

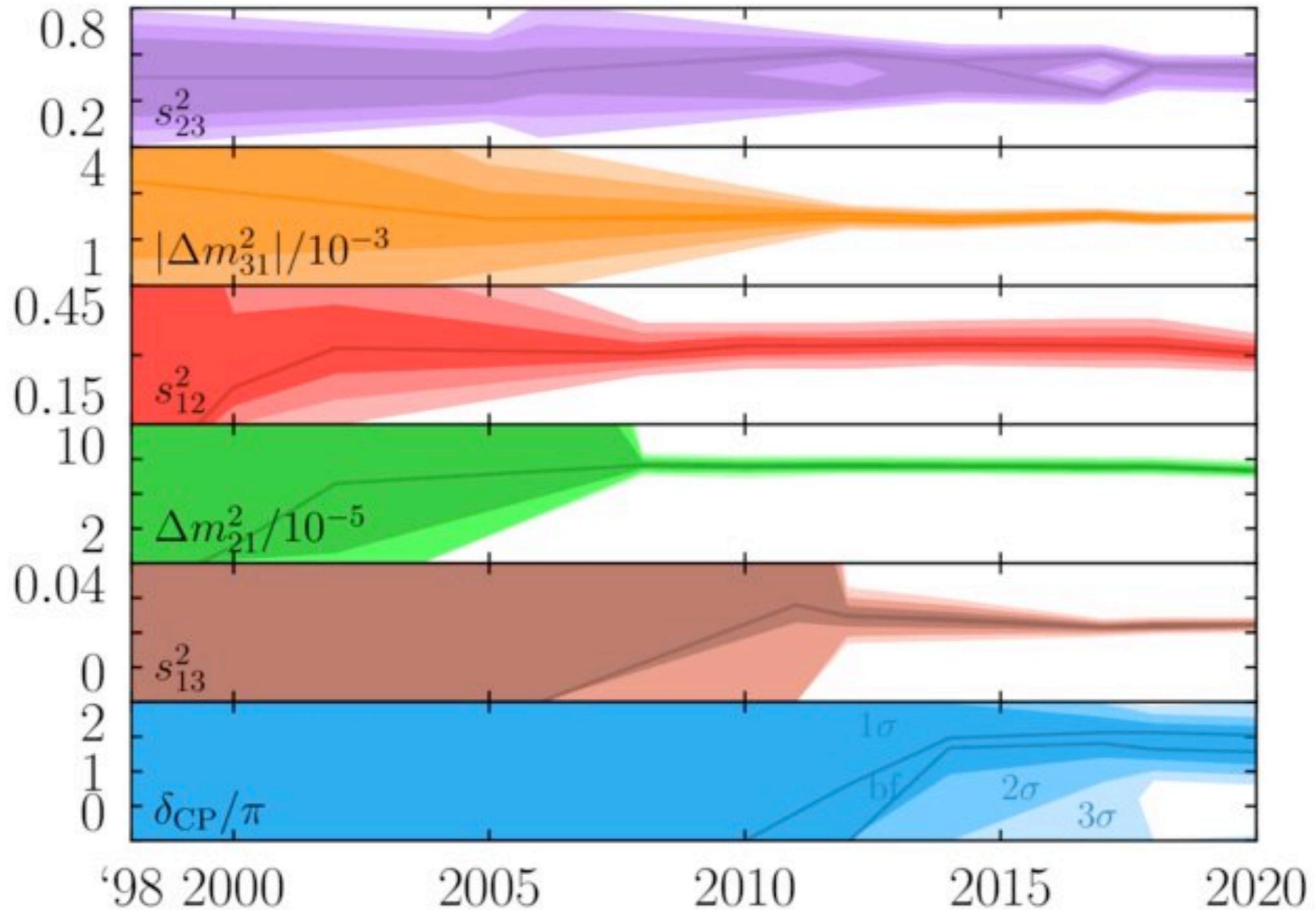
Exploit synergies among experiments

3

Reveal tensions among data



Three-neutrino oscillation parameters



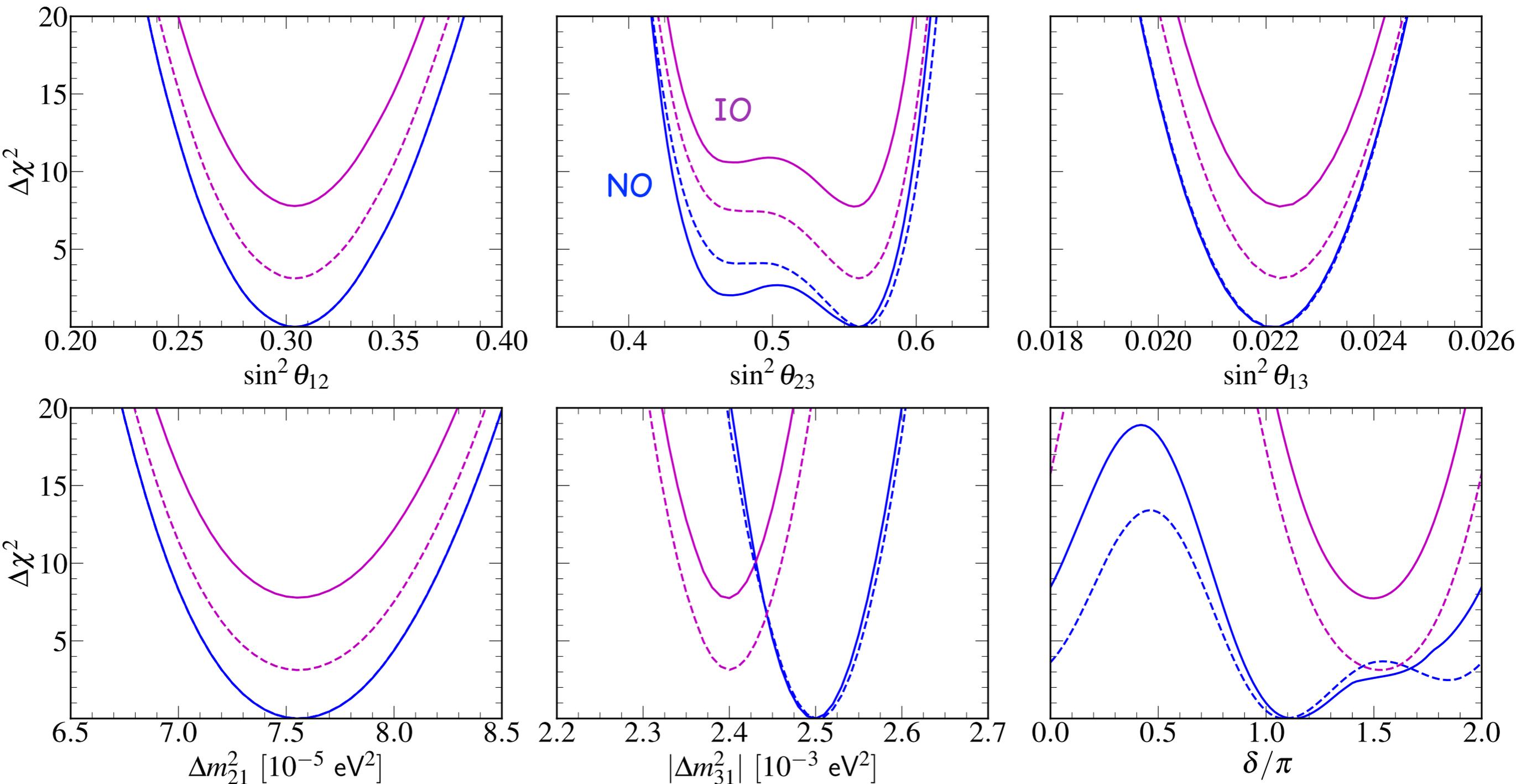
Denton et al, Snowmass Neutrino Frontier: NF01 Report [arXiv:2212.00809]

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071**

<https://globalfit.astroparticles.es/>

UPDATED!



See also NuFIT and Bari Group

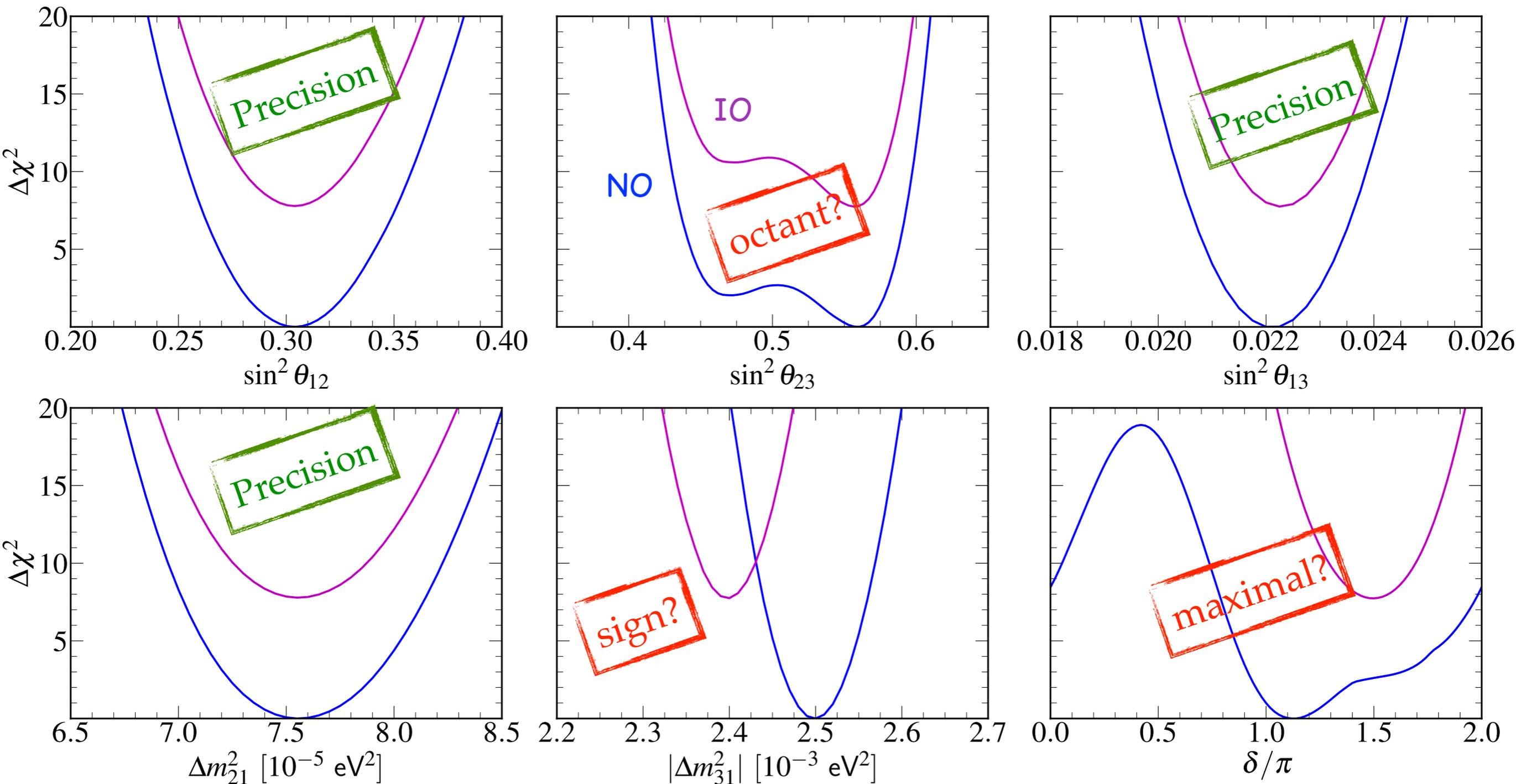
— w SK-atm --- w/o SK.atm

Global fit to ν oscillation parameters

de Salas et al, **JHEP 02 (2021) 071**

<https://globalfit.astroparticles.es/>

UPDATED!



with SK atmospheric

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

Global fit to ν oscillation parameters

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncert	
Δm_{21}^2 [10^{-5}eV^2]	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7%	
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	2.50 ± 0.02	2.43–2.57	0.9%	mass ordering?
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (IO)	2.40 ± 0.02	2.33–2.46		
$\sin^2 \theta_{12} / 10^{-1}$	3.04 ± 0.16	2.57–3.55	5.4%	
$\sin^2 \theta_{23} / 10^{-1}$ (NO)	$5.60^{+0.13}_{-0.22}$	4.32–5.96	4.8%	octant?
$\sin^2 \theta_{23} / 10^{-1}$ (IO)	$5.57^{+0.14}_{-0.20}$	4.34–5.93		
$\sin^2 \theta_{13} / 10^{-2}$ (NO)	$2.20^{+0.07}_{-0.04}$	2.05–2.38	2.5%	
$\sin^2 \theta_{13} / 10^{-2}$ (IO)	$2.23^{+0.05}_{-0.06}$	2.06–2.39		
δ / π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	10-18%	maximal CP violation??
δ / π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87		

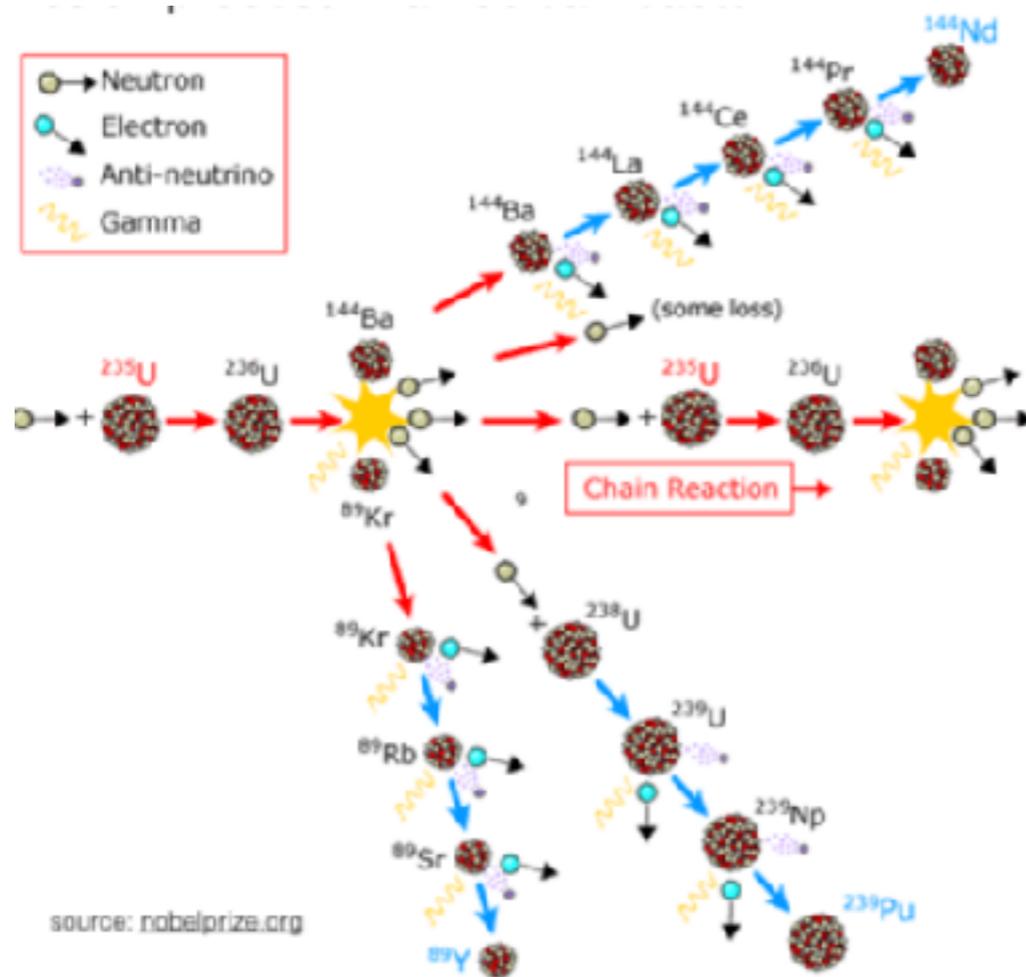
Neutrino oscillations

Reactor sector: θ_{13} , Δm^2_{31}

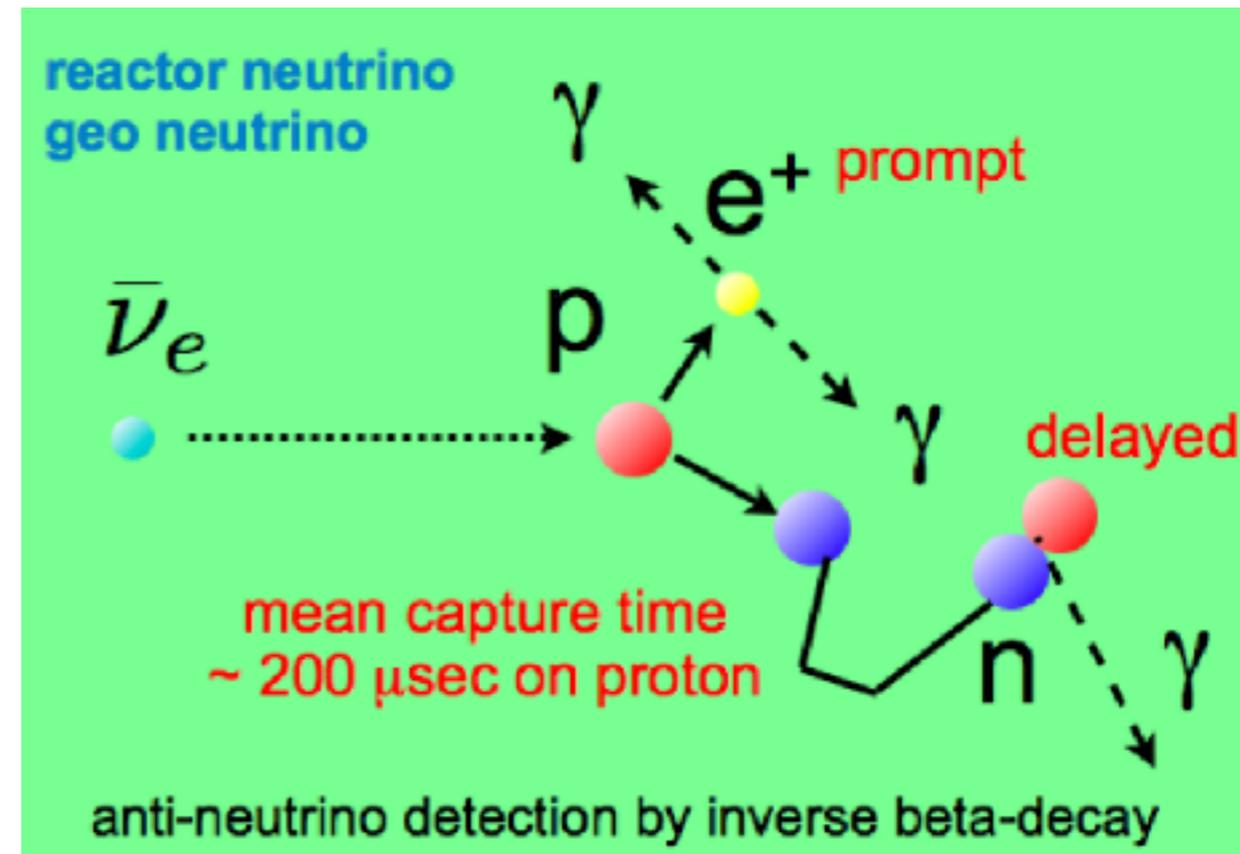


Reactor neutrinos

Production: fission processes in nuclear reactors

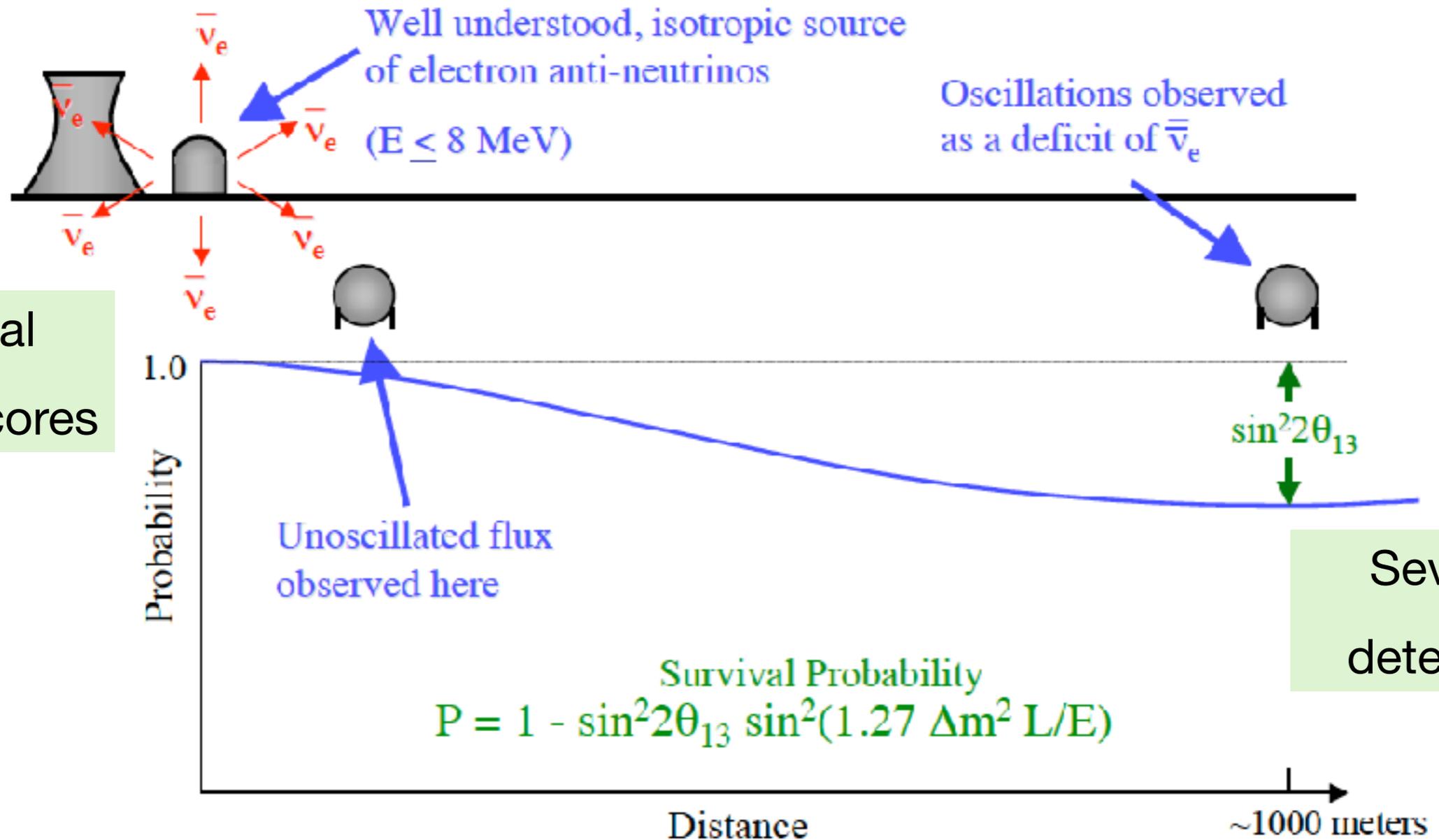


Detection: inverse beta decay



1 GW reactor: more than 10^{20} antineutrinos/s

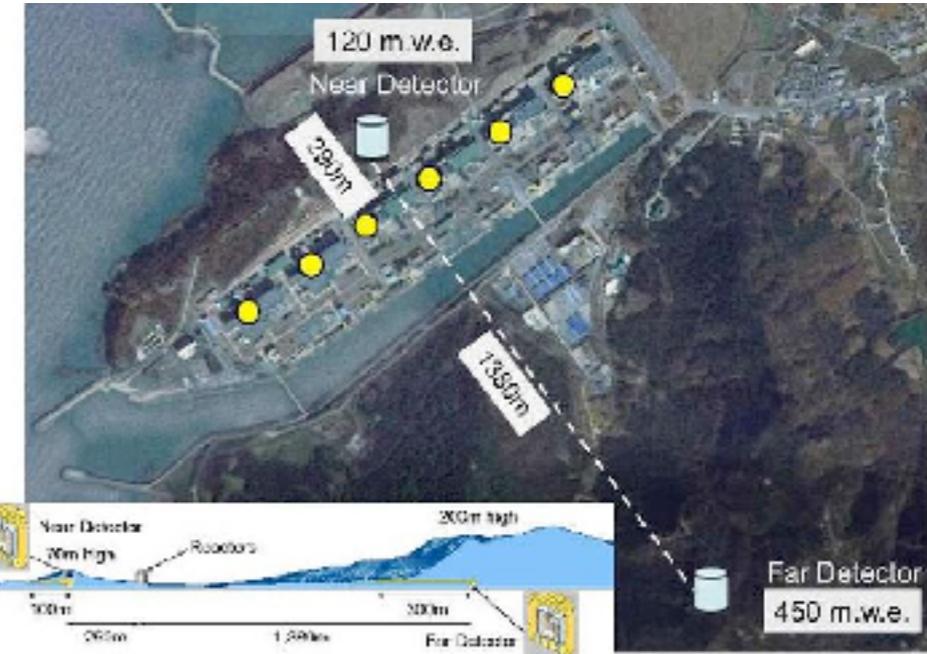
SBL reactor experiments



$L \sim 1$ km: $\theta_{13}, |\Delta m^2_{31}| \sim \text{few } 10^{-3} \text{ eV}^2$

oscillations in vacuum

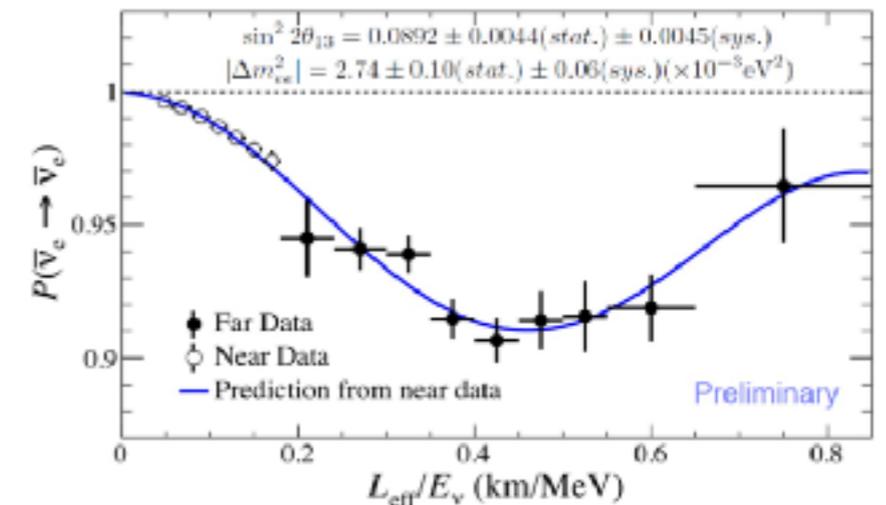
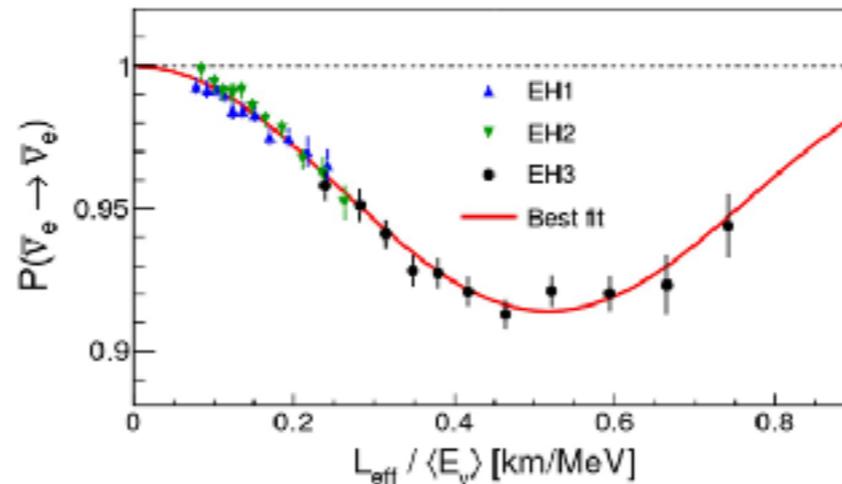
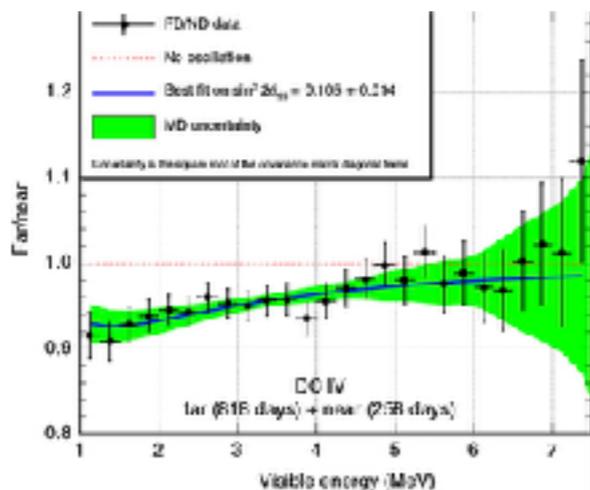
SBL reactor experiments



2 reactors + 1 ND + 1 FD (10 ton)

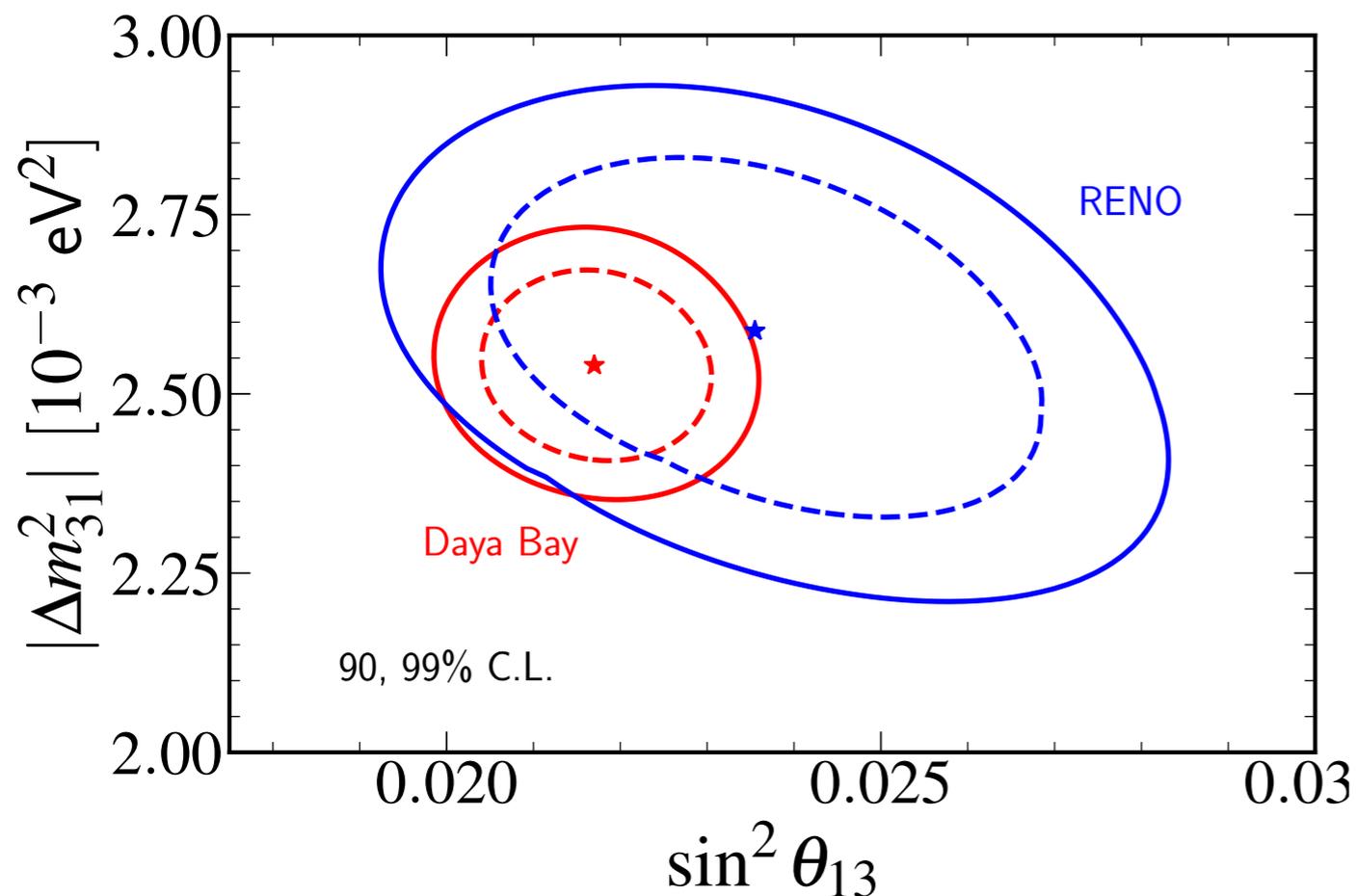
6 reactors + 4 ND + 4FD (20 ton)

6 reactors + 1 ND + 1 FD (16 ton)



The reactor sector

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



◆ **Double Chooz** first measured θ_{13} but now its precision is not comparable.

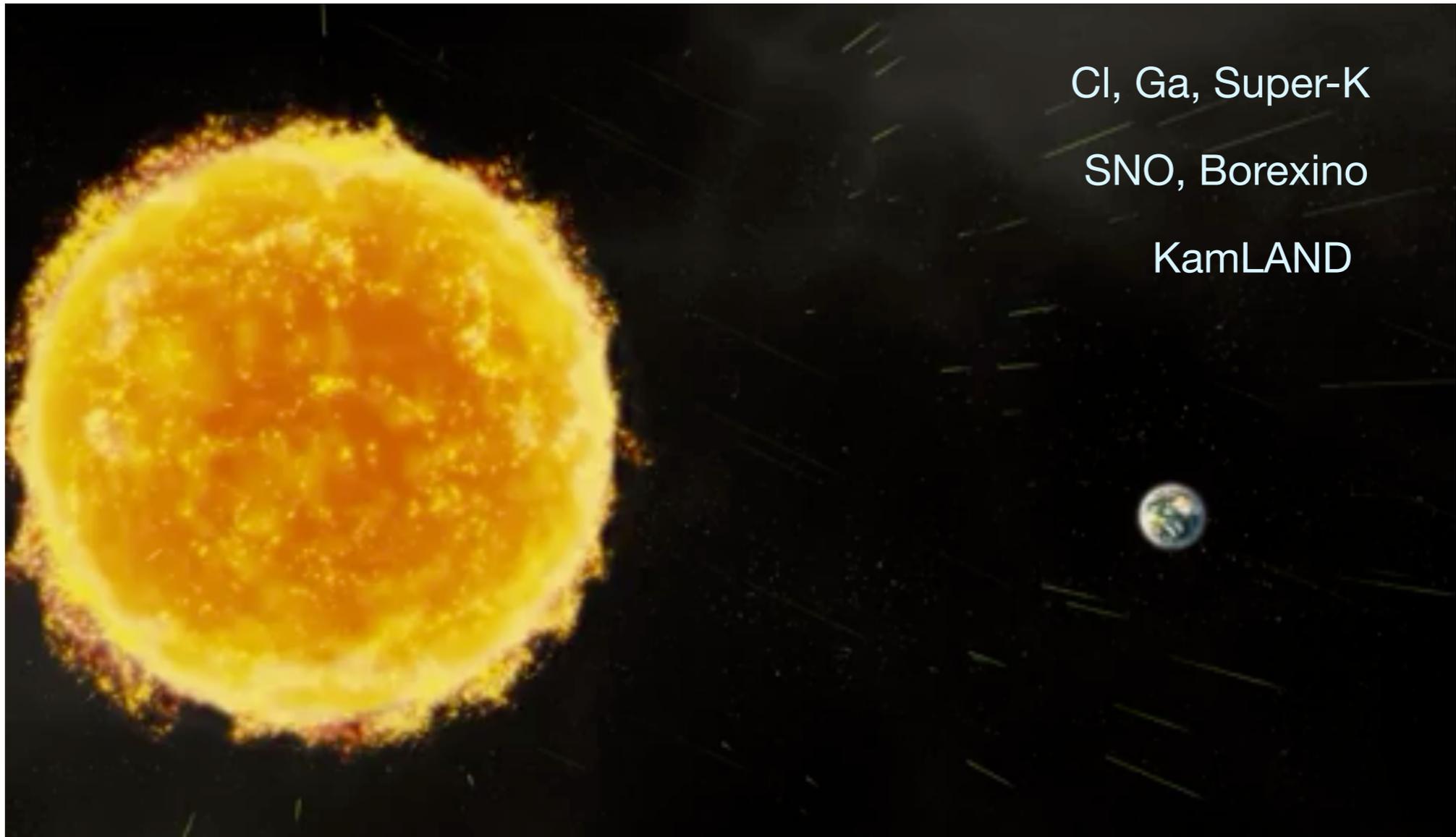
◆ Precision dominated by **RENO** and **Daya Bay**.

$$\sin^2 \theta_{13} = 0.0221 \pm 0.0006$$

$$|\Delta m_{31}^2| = (2.56 \pm 0.05) \times 10^{-3} \text{ eV}^2$$

Neutrino oscillations

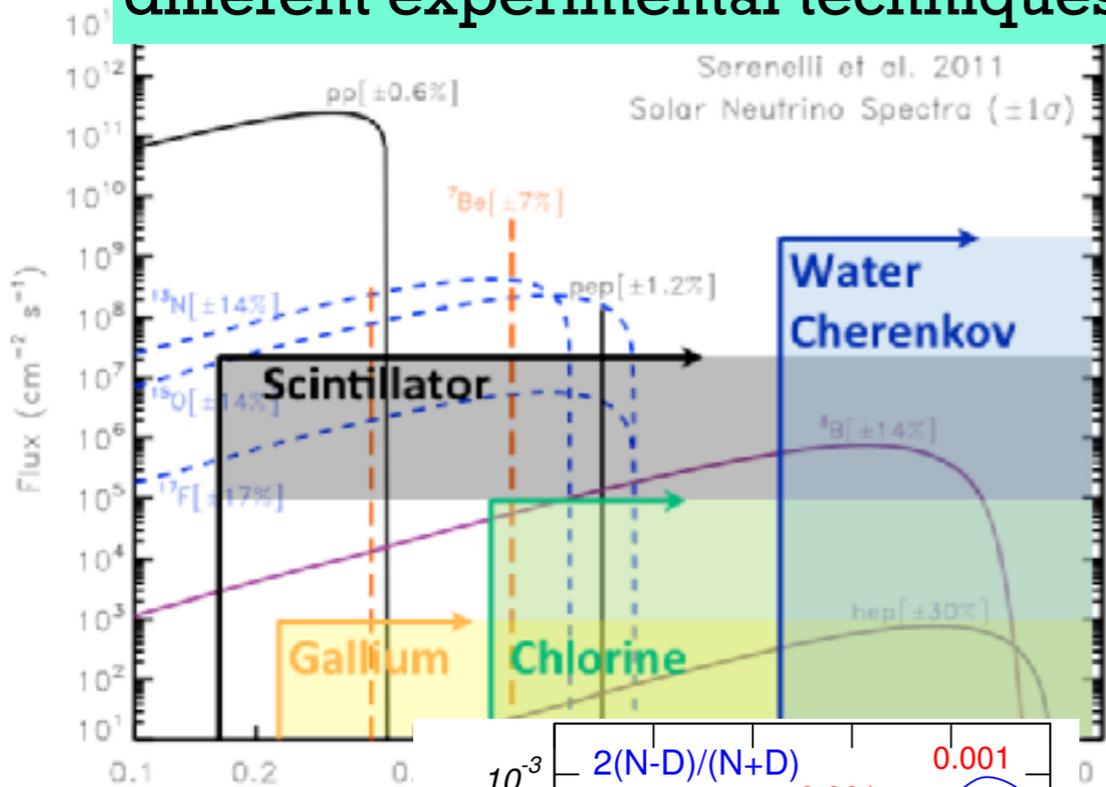
Solar sector: θ_{12} , θ_{13} , Δm^2_{21}



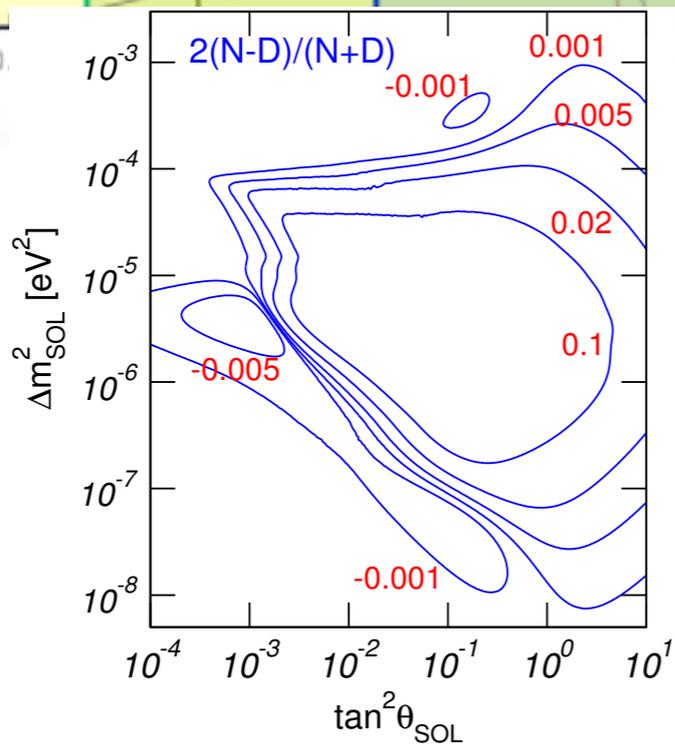
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

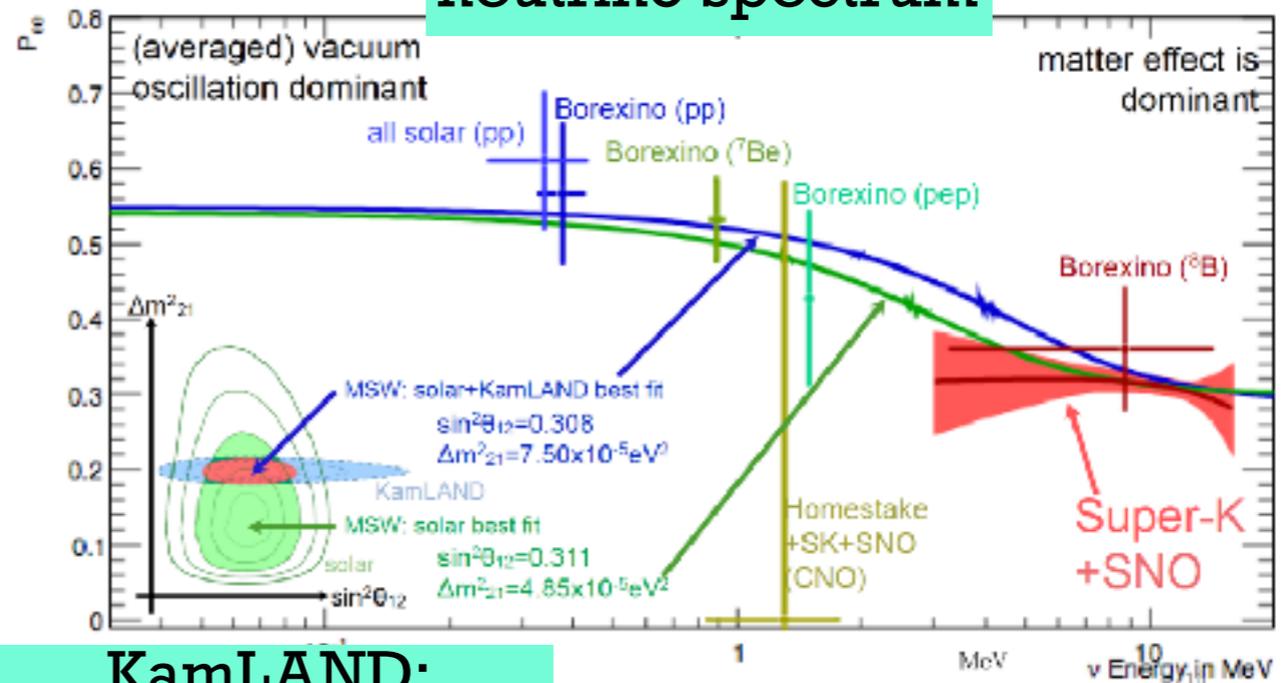
different experimental techniques



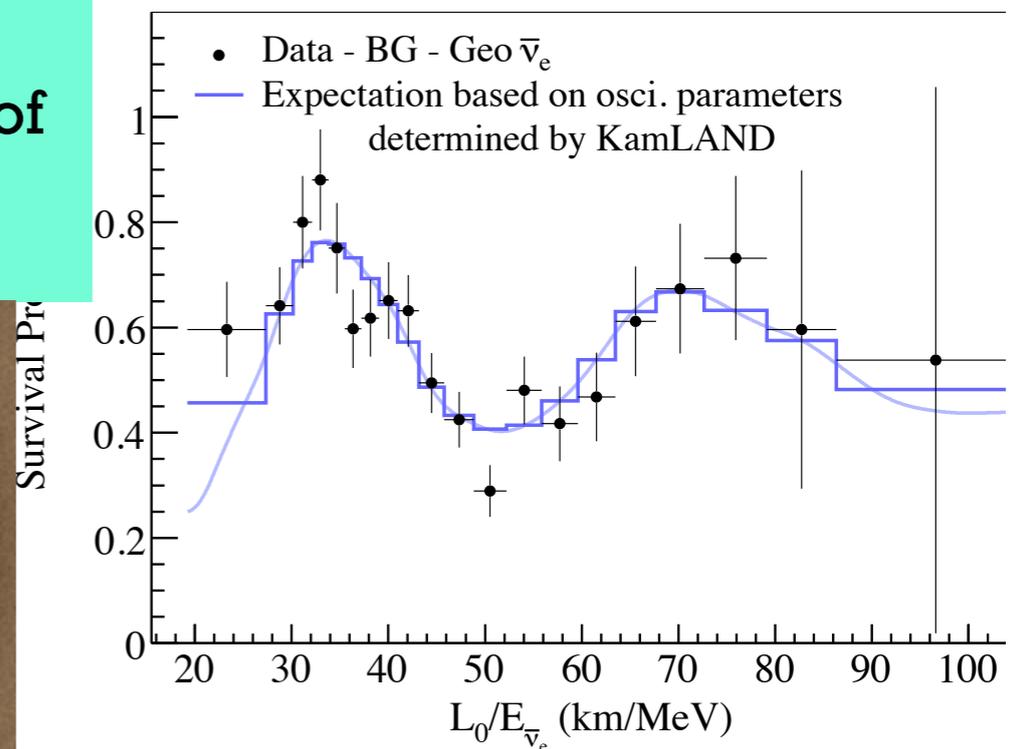
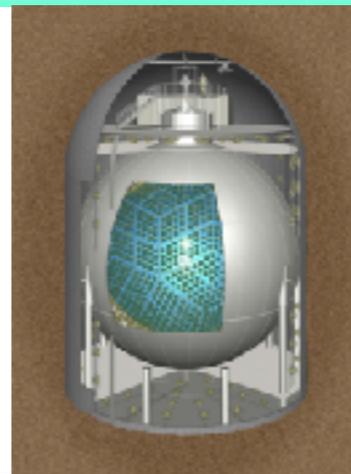
day/night asymmetry



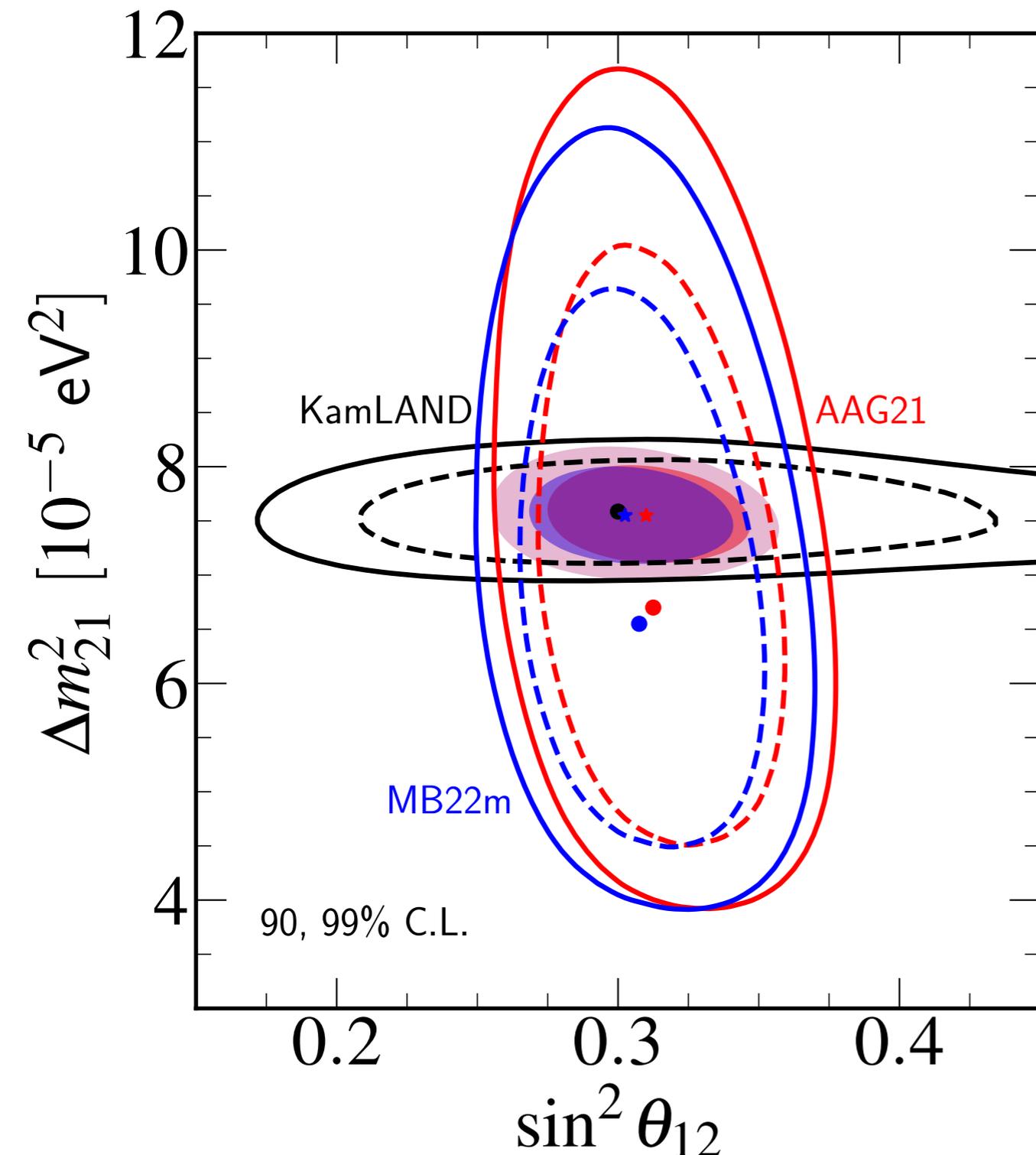
neutrino spectrum



KamLAND:
precise measurement of oscillation frequency



The solar sector



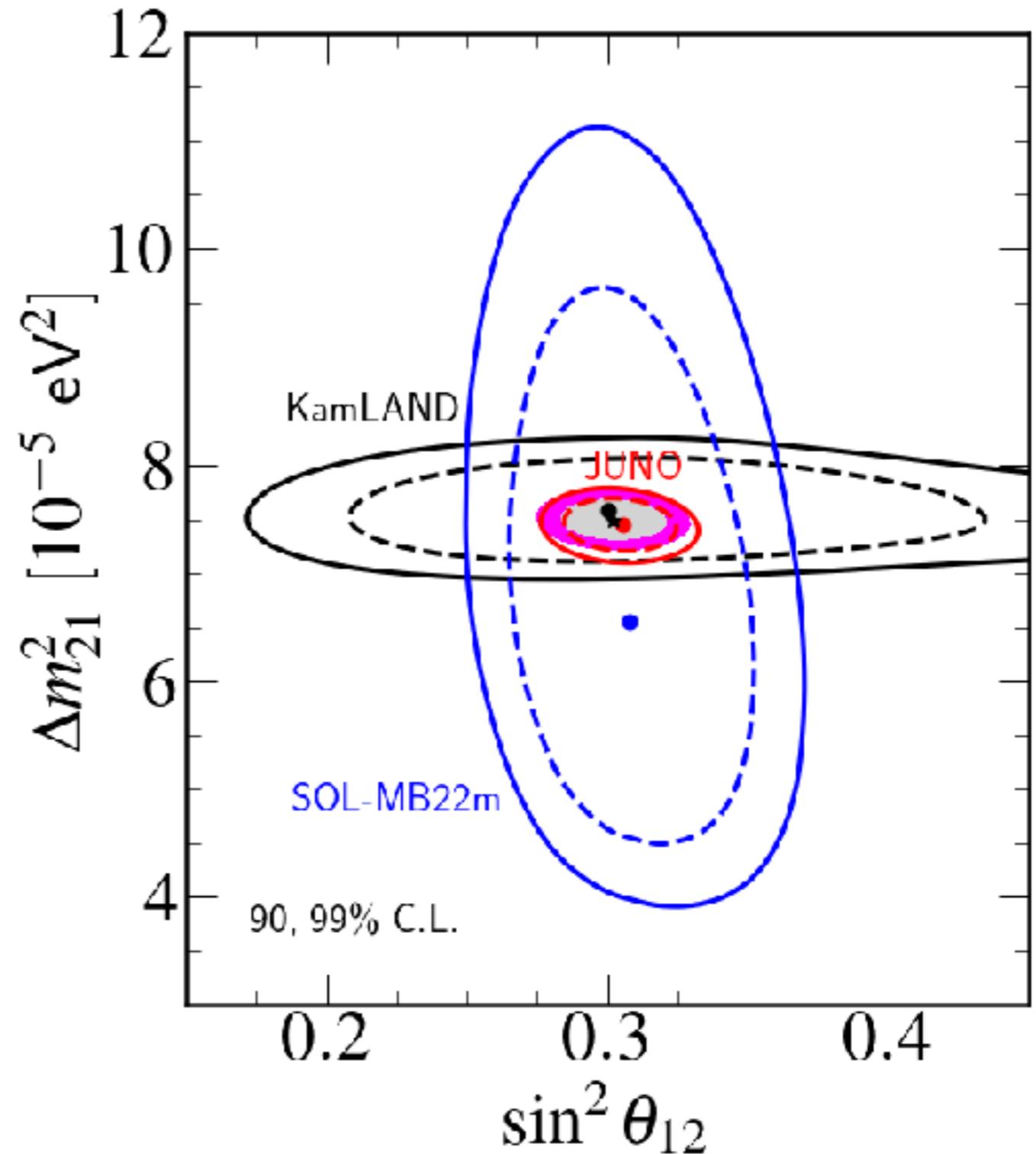
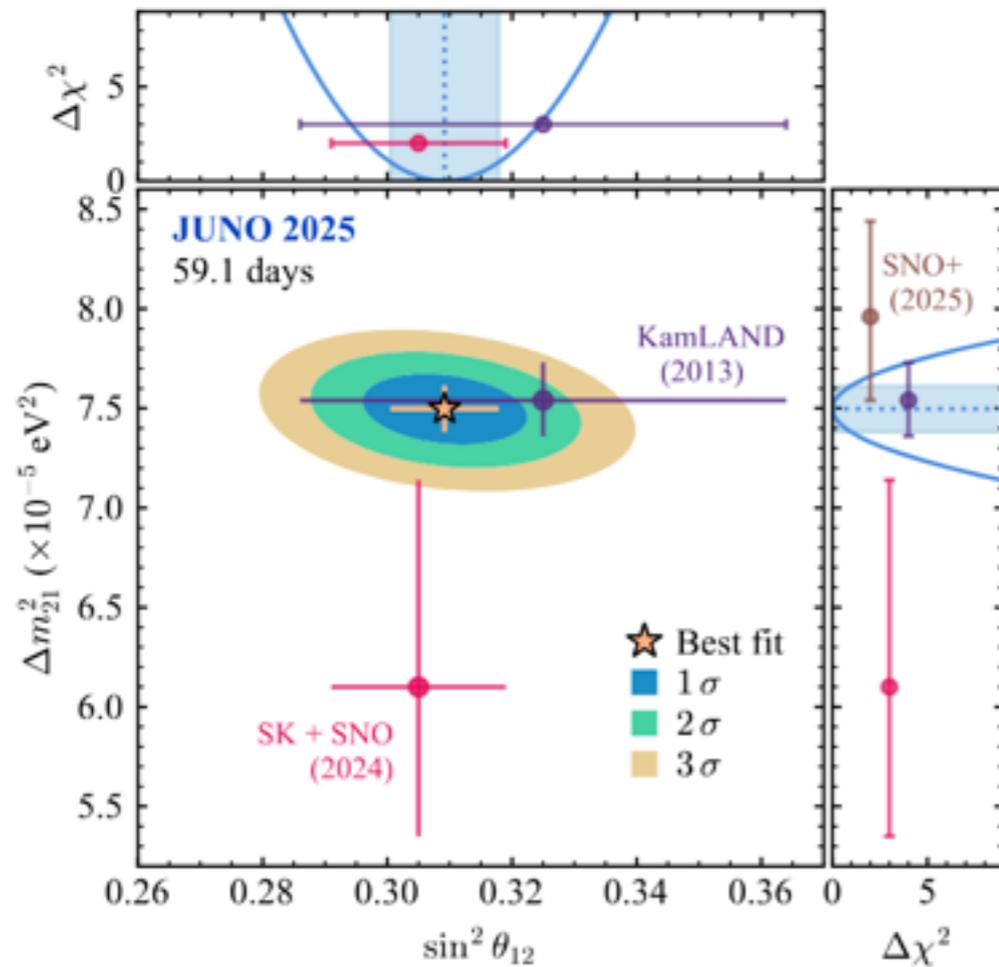
- ◆ θ_{12} measurement dominated by solar neutrino data
- ◆ Δm^2_{21} is better measured by KamLAND.
- ◆ **1.5 σ mismatch** between the values of Δm^2_{21} measured by solar and KamLAND

$$\sin^2 \theta_{12} = 0.304 \pm 0.016$$

$$\Delta m^2_{21} = (7.55 \pm 0.21) \times 10^{-5} \text{ eV}^2$$

The solar sector after JUNO

[arXiv:2511.14593]



- ◆ 59.1 days of exposure
- ◆ world-leading precision in Δm^2_{21} and θ_{12}

M. Beccaria, C. A. Ternes

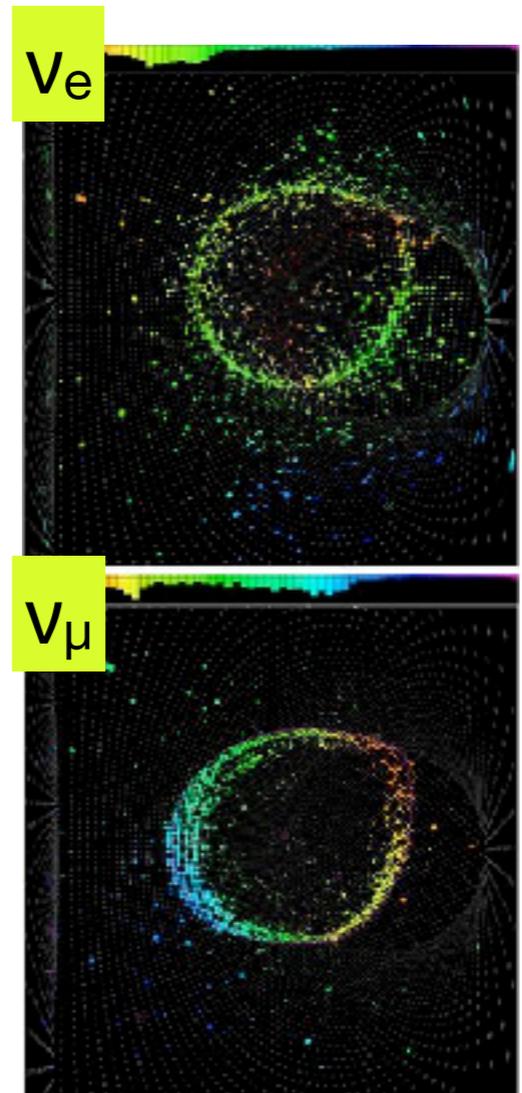
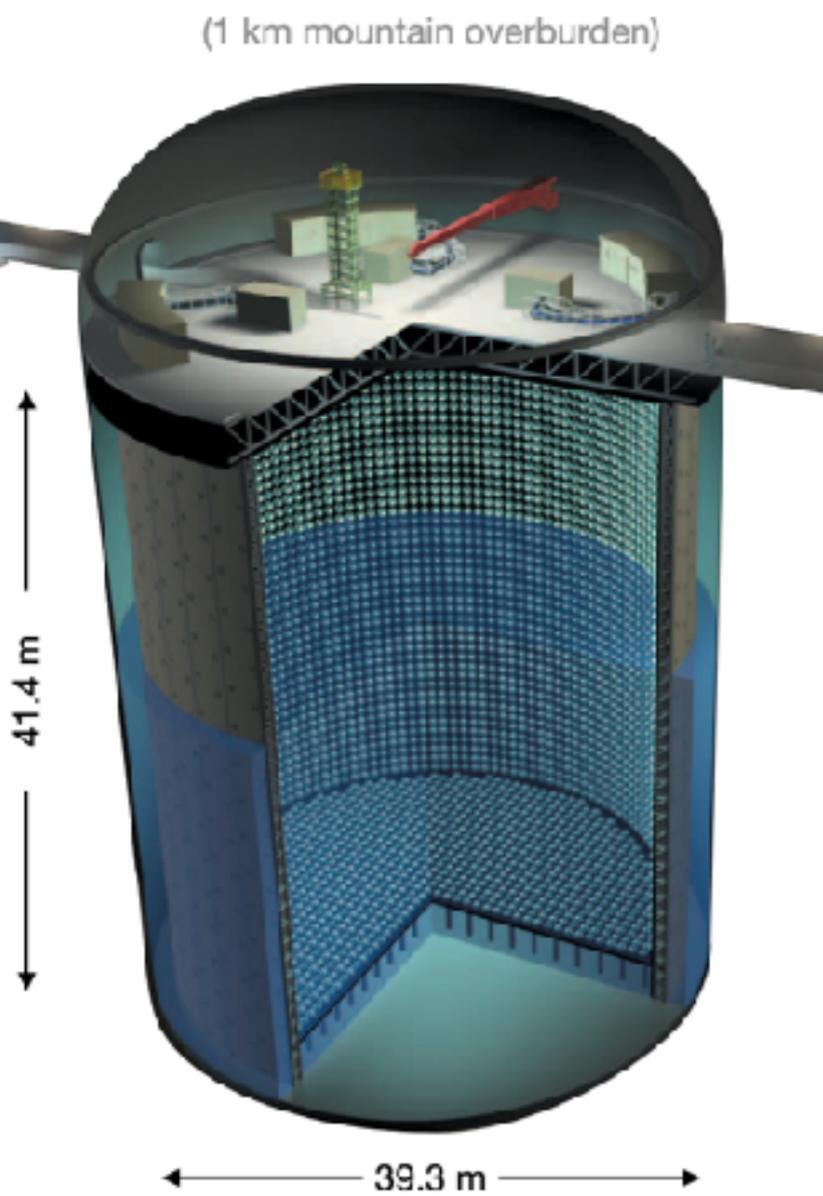
Neutrino oscillations

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



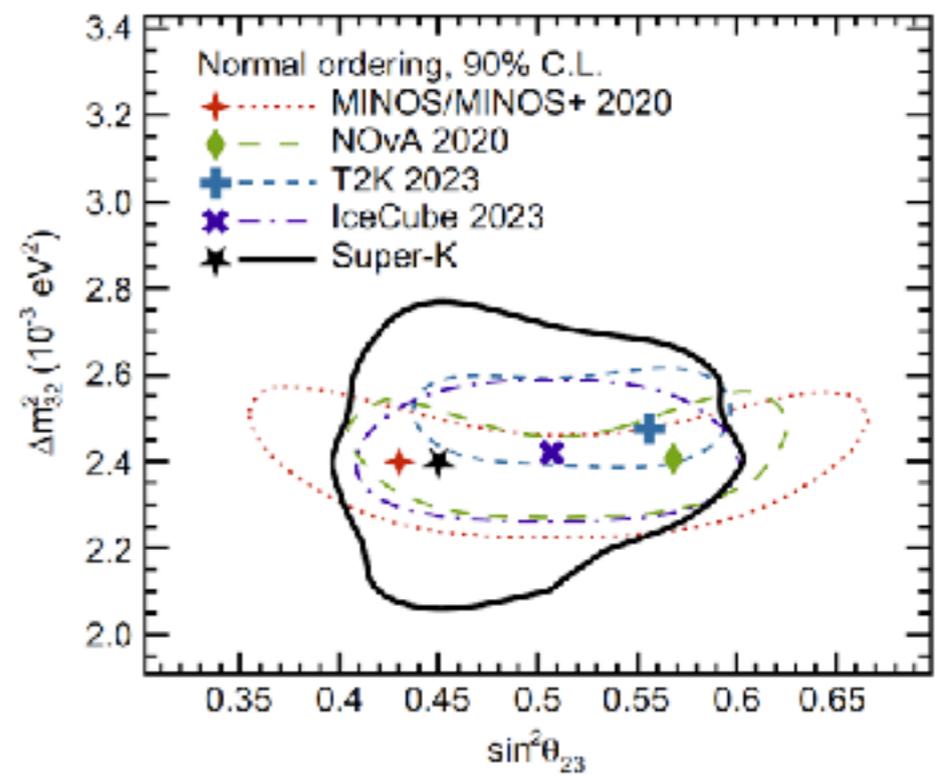
The atmospheric sector

Super-Kamiokande detects atmospheric neutrinos since 1996.
Neutrino oscillations discovery in 1998



$$P_{\nu_{\mu} \rightarrow \nu_{\mu}} \simeq 1 - \sin^2 2\theta_{23} \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E} \right)$$

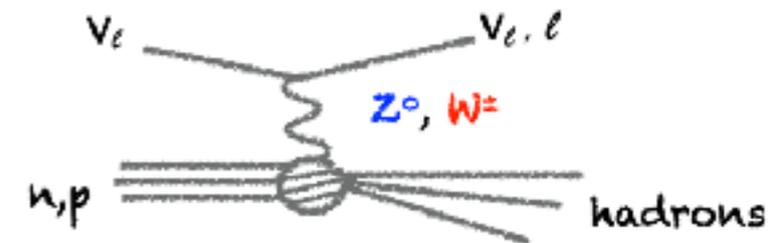
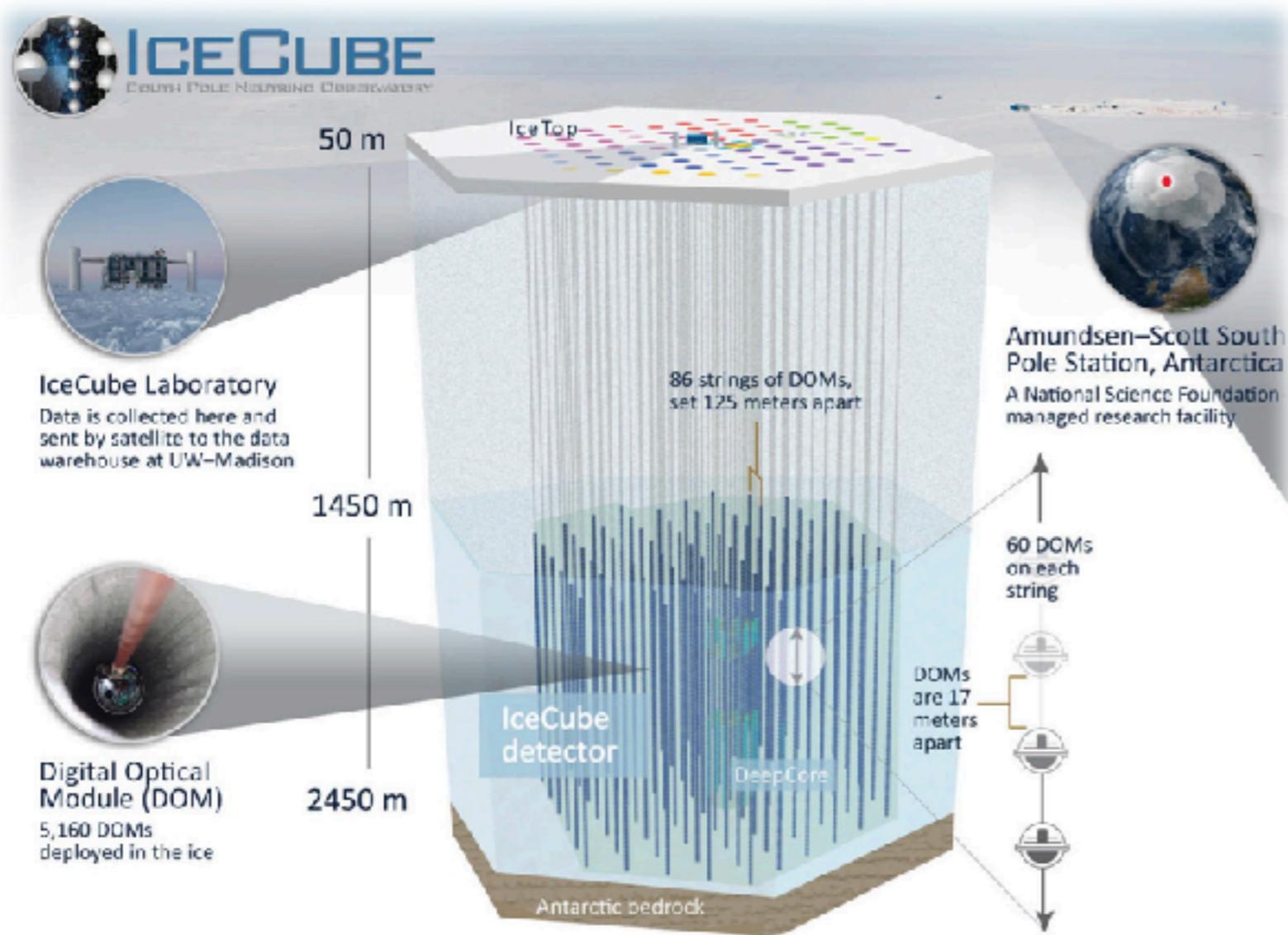
SK Collab, PRD 109 (2024) 072014



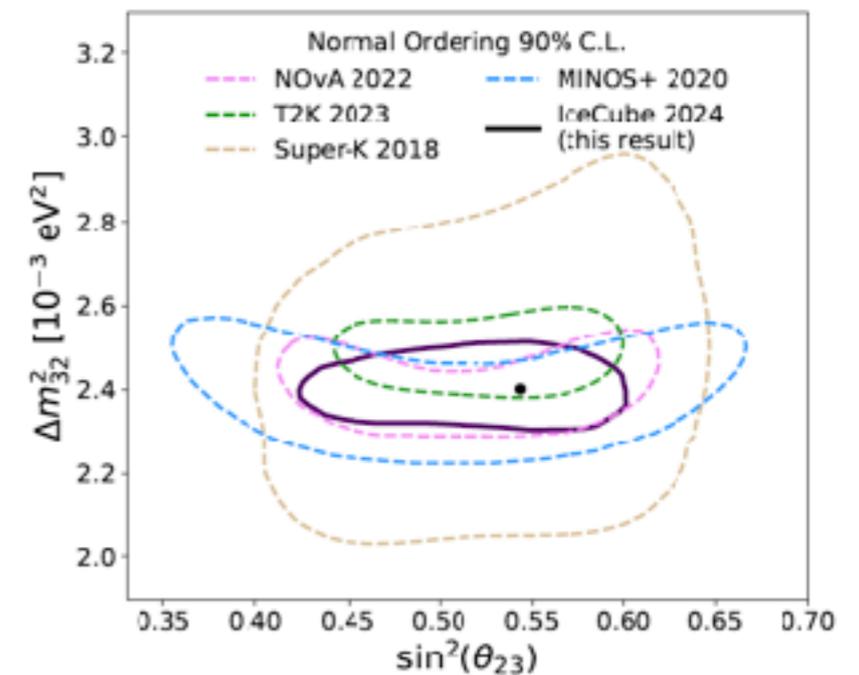
→ very good sensitivity to θ_{23} and Δm_{32}^2

The atmospheric sector

IceCube detects atmospheric neutrinos using 1 km³ of ice as detector at the South Pole



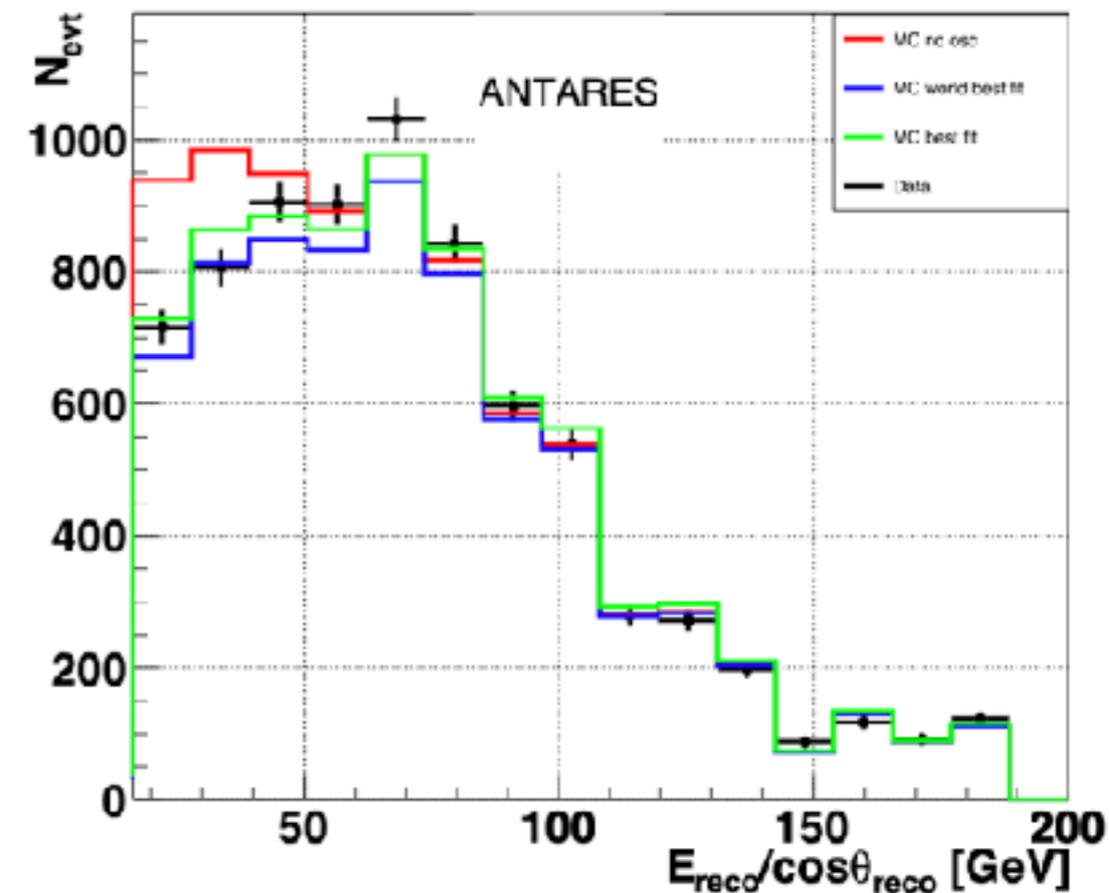
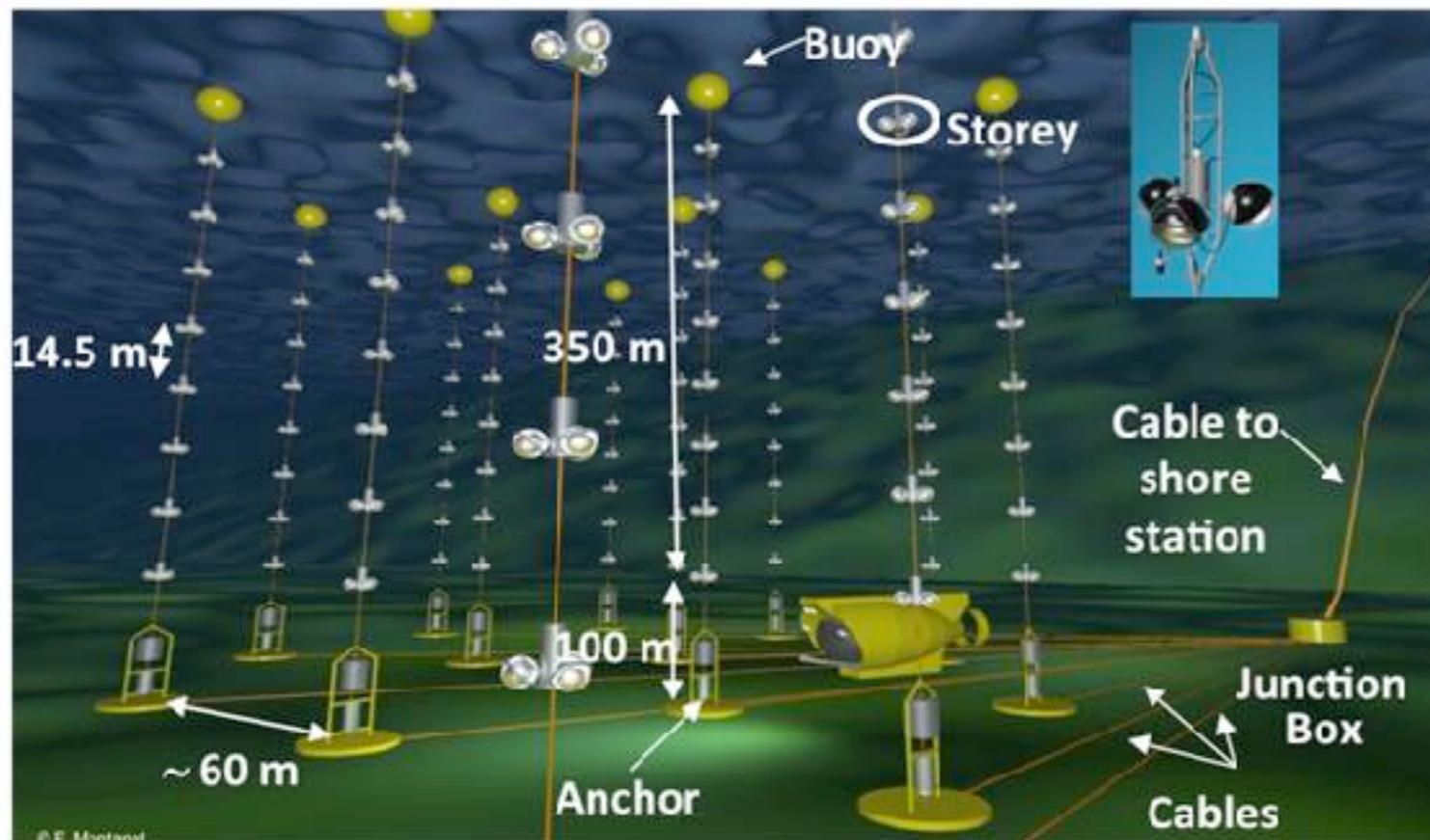
IceCube Collab, arXiv:2405.02163



→ higher precision than Super-Kamiokande

The atmospheric sector

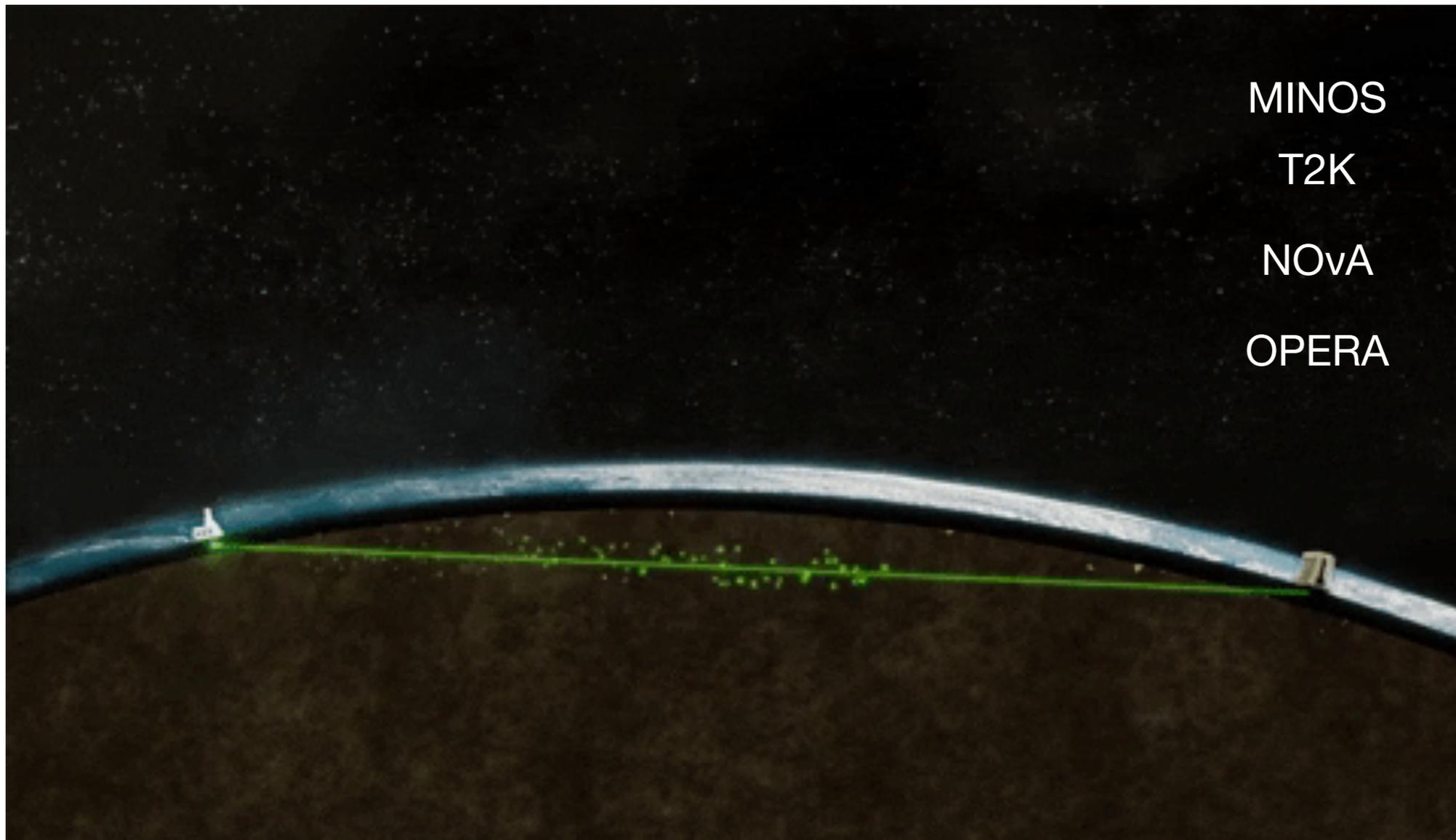
ANTARES observed atmospheric neutrinos at the Mediterranean Sea



→ results in agreement with oscillations in the channel $\nu_{\mu} \rightarrow \nu_{\tau}$

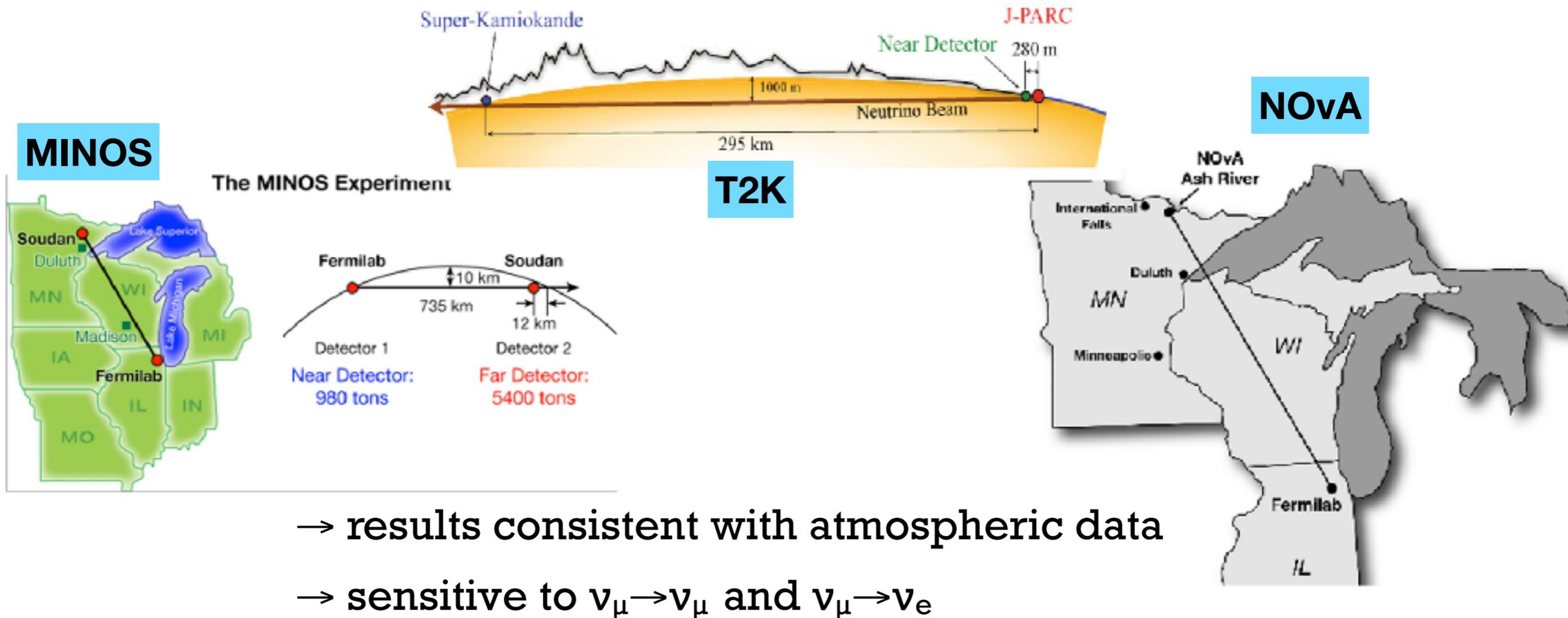
Neutrino oscillations

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



The accelerator sector

- ◆ Designed to check the atmospheric neutrino oscillation channel
- ◆ $L/E \sim 500 \text{ km/GeV}$ to be sensitive to $\Delta m^2_{31} \sim \text{few } 10^{-3} \text{ eV}^2$
- ◆ Combine near detector + far detector



The accelerator sector

ν_μ and $\bar{\nu}_\mu$ disappearance

$$P(\nu_\mu \rightarrow \nu_\mu) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) = 1 - \sin^2(2\theta_{23}) \sin^2 \left(1.27 \frac{\Delta m_{32}^2 L}{E} \right)$$

→ only sensitive to $\sin^2 2\theta_{23}$ and $|\Delta m_{32}^2|$

ν_e and $\bar{\nu}_e$ appearance (in matter)

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \simeq \sin^2 \theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}]$$

$$(\mp) \alpha \frac{J_0 \sin \delta_{CP}}{A(1-A)} \sin \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}]$$

$$+ \alpha \frac{J_0 \cos \delta_{CP}}{A(1-A)} \cos \Delta_{31} \sin(A\Delta_{31}) \sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

$$\alpha = \Delta m_{21}^2 / \Delta m_{31}^2 \sim 1/30$$

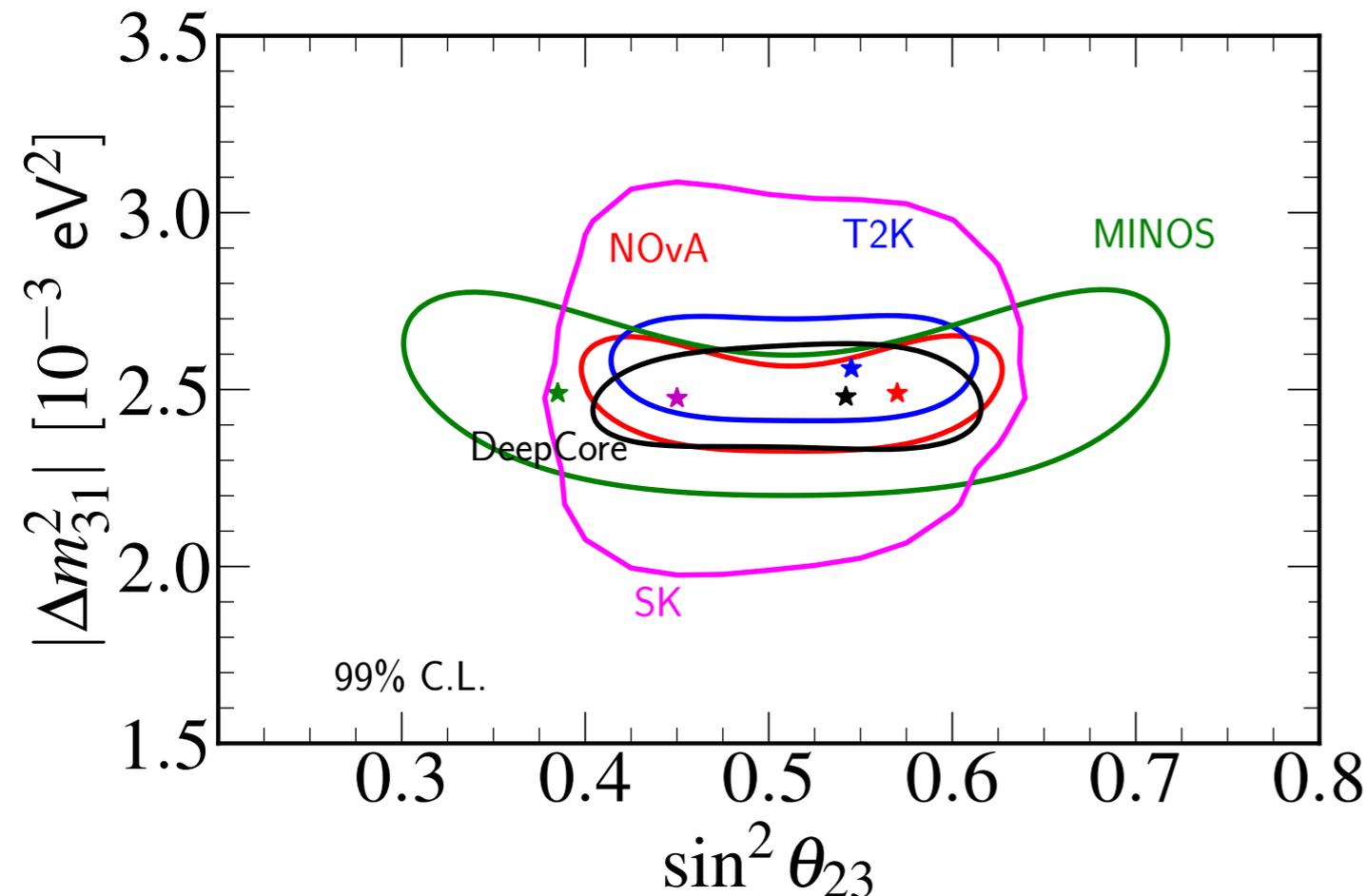
$$J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos \theta_{13}$$

$$A = (\mp) 2\sqrt{2} G_F n_e E / \Delta m_{31}^2$$

→ Sensitivity to δ_{CP} , the mass ordering (sign A) and the octant of θ_{23}

Atmospheric & accelerator sector

($\sin^2\theta_{23} - \Delta m^2_{31}$) regions from individual experiments

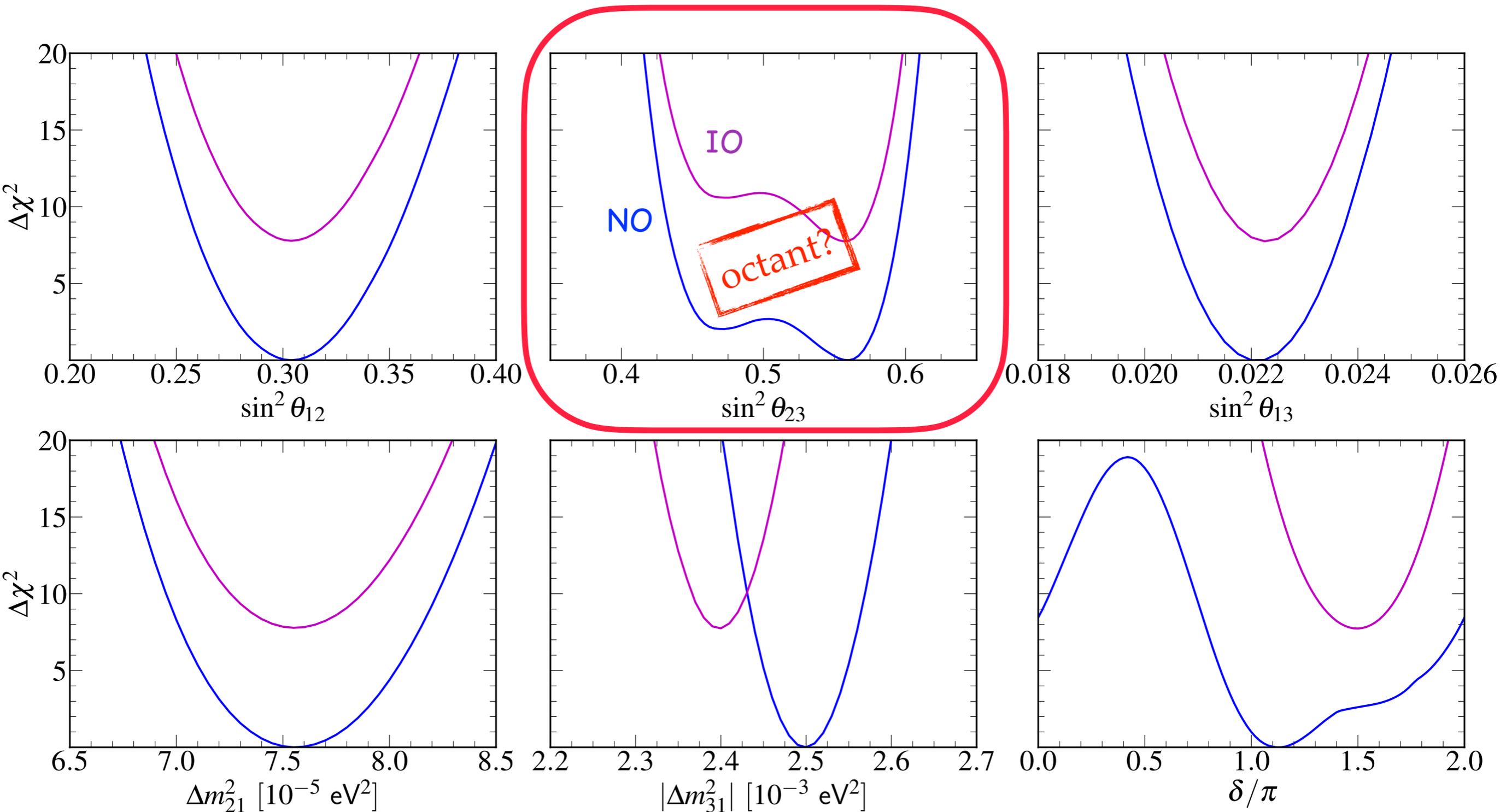


$$\sin^2\theta_{23} = 0.574 \pm 0.014$$

$$\Delta m^2_{31} = (2.55 \pm 0.03) \times 10^{-3} \text{ eV}^2$$

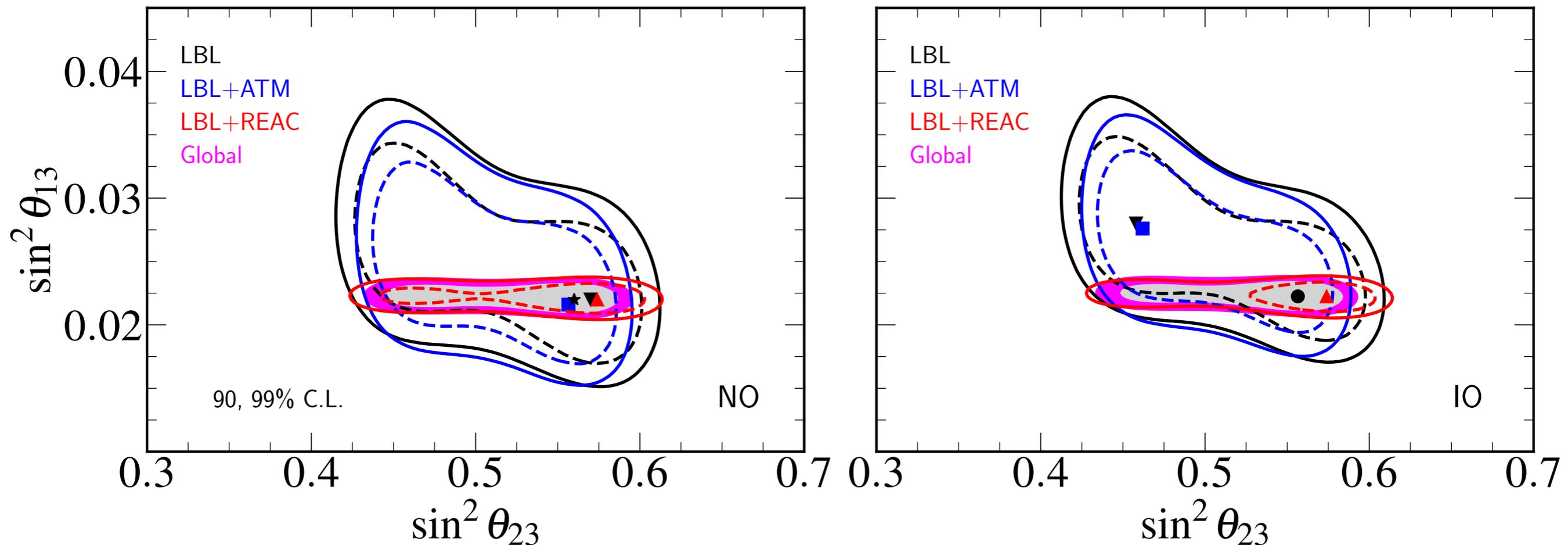
- ◆ Great agreement among all the experiments
- ◆ Best sensitivity obtained at T2K (closely followed by NOvA and DeepCore)
- ◆ IC-DeepCore starts being competitive with LBL accelerator experiments

Global fit to ν oscillation parameters



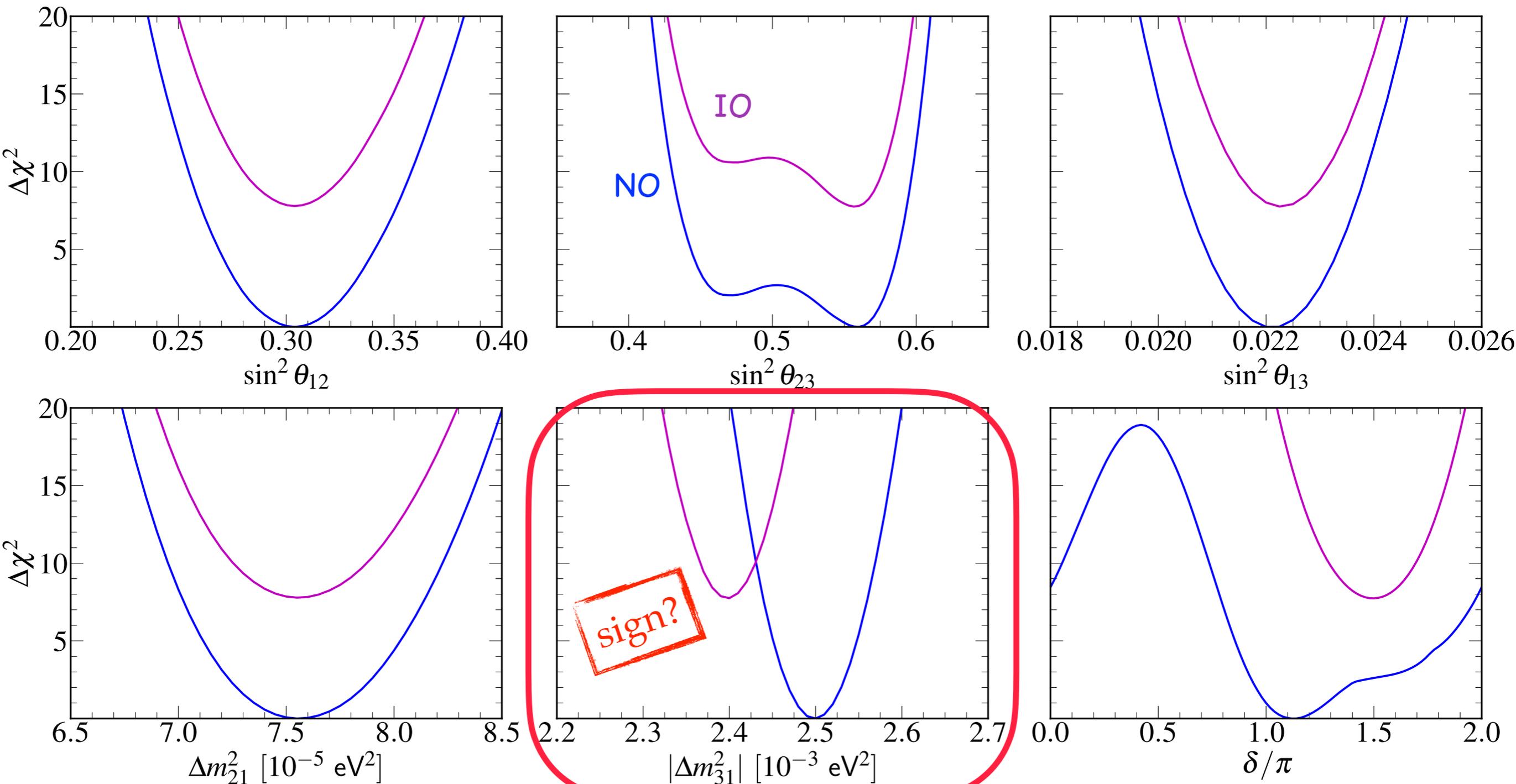
with SK atmospheric

The octant of θ_{23}



- ◆ **LBL** combination slightly prefer UO (NO) and LO(IO) with $\Delta\chi^2 = 0.3-0.4$
- ◆ **LBL + ATM** prefers UO (NO) and LO(IO) with $\Delta\chi^2 \sim 0.3-1$
- ◆ **REAC** breaks the degeneracy in favor of UO (NO and IO) with $\Delta\chi^2 \sim 3.5-5.2$ over LO
- ◆ **Global** analysis show a milder preference for UO with $\Delta\chi^2 \sim 2.0$ (2.9) for NO (IO)

Global fit to ν oscillation parameters



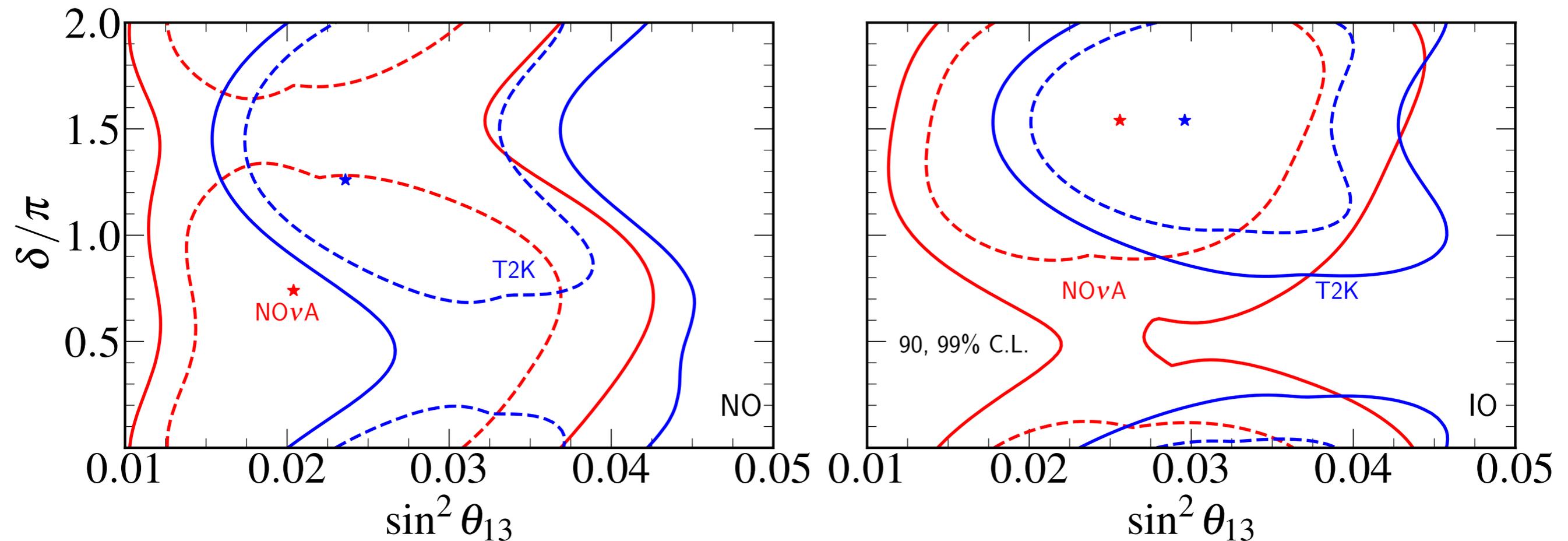
with SK atmospheric

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

The mass ordering

- ◆ T2K and NOvA separate analyses prefer **NO** with $\Delta\chi^2 \approx 0.2-0.4$

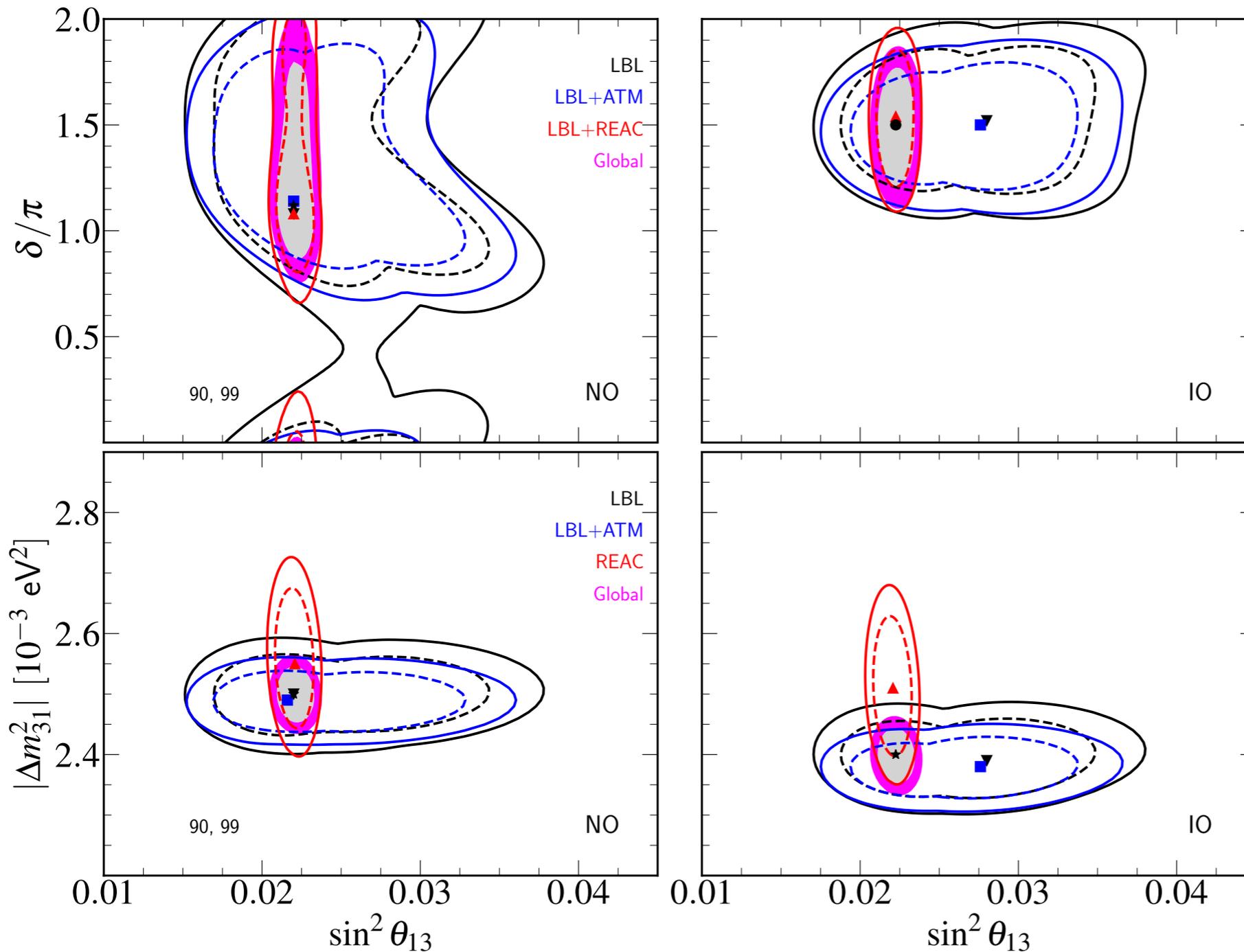
Tension between T2K and NOvA δ preference in NO



- ➔ The LBL combination (T2K + NOvA + MINOS) prefer **IO** with $\Delta\chi^2 \approx 2.6$

The mass ordering

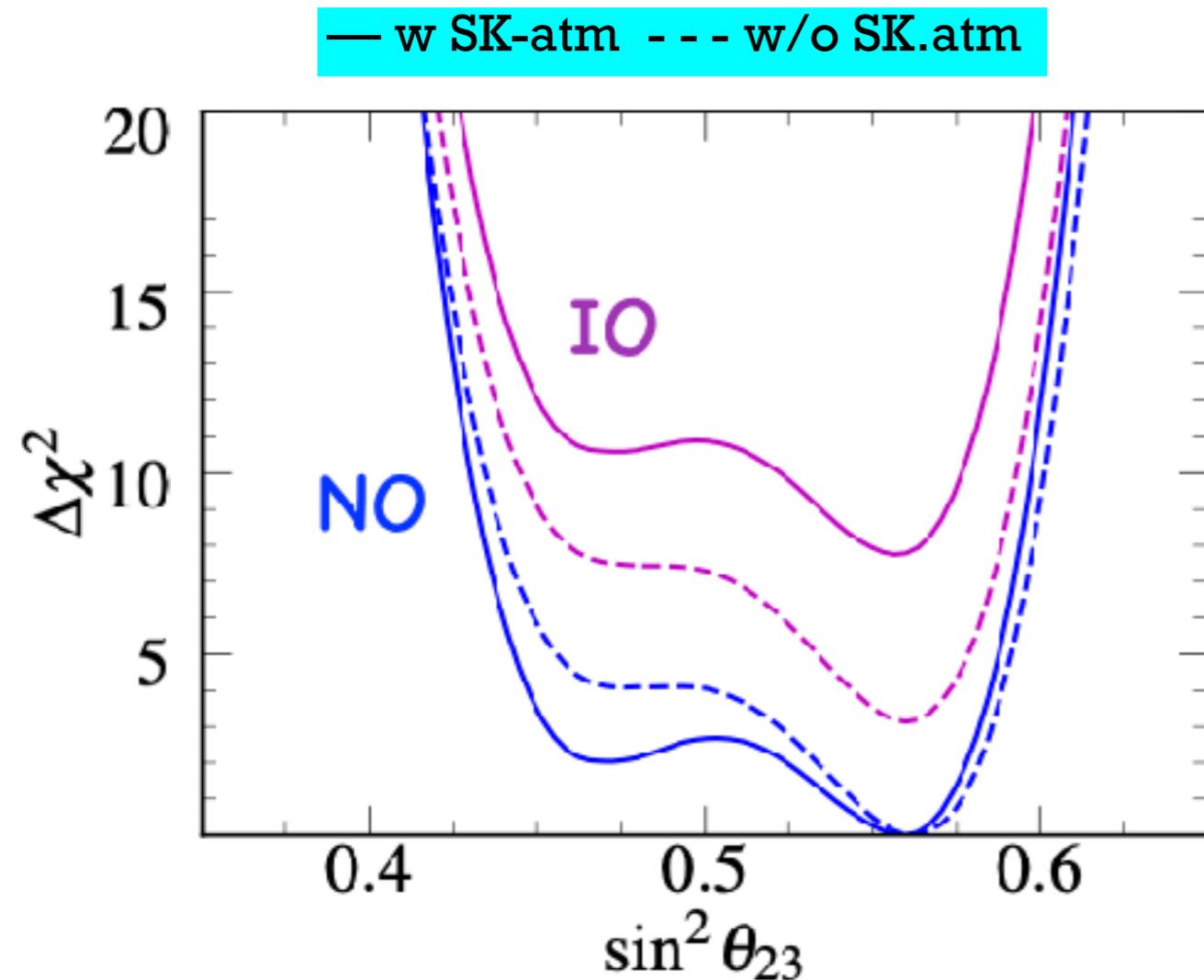
Tension between LBL and REAC Δm^2_{31} preference in IO



◆ LBL and REAC data show better agreement in NO

➔ LBL + REAC prefer **NO** with $\Delta\chi^2 \approx 0.7$

The mass ordering



- ◆ T2K and NOvA separate analyses prefer NO with $\Delta\chi^2 \approx 0.2-0.4$
- ◆ LBL prefer IO with $\Delta\chi^2 \approx 2.6$ (tension NO)
- ◆ **LBL + REAC** prefer NO with $\Delta\chi^2 \approx 0.7$ (tension in Δm^2_{31} measurement in IO)

◆ **SK-atm** prefers NO with $\Delta\chi^2 = 5.69$ (5.23) for θ_{13} constrained (free)

◆ From the **global fit**: $\Delta\chi^2$ (IO-NO) = 7.7 (3.1) w SK-atm (w/o SK-atm)

assuming Wilk's theorem: 2.8σ (1.8σ) **preference for NO** w SK-atm (w/o SK-atm)

The mass ordering

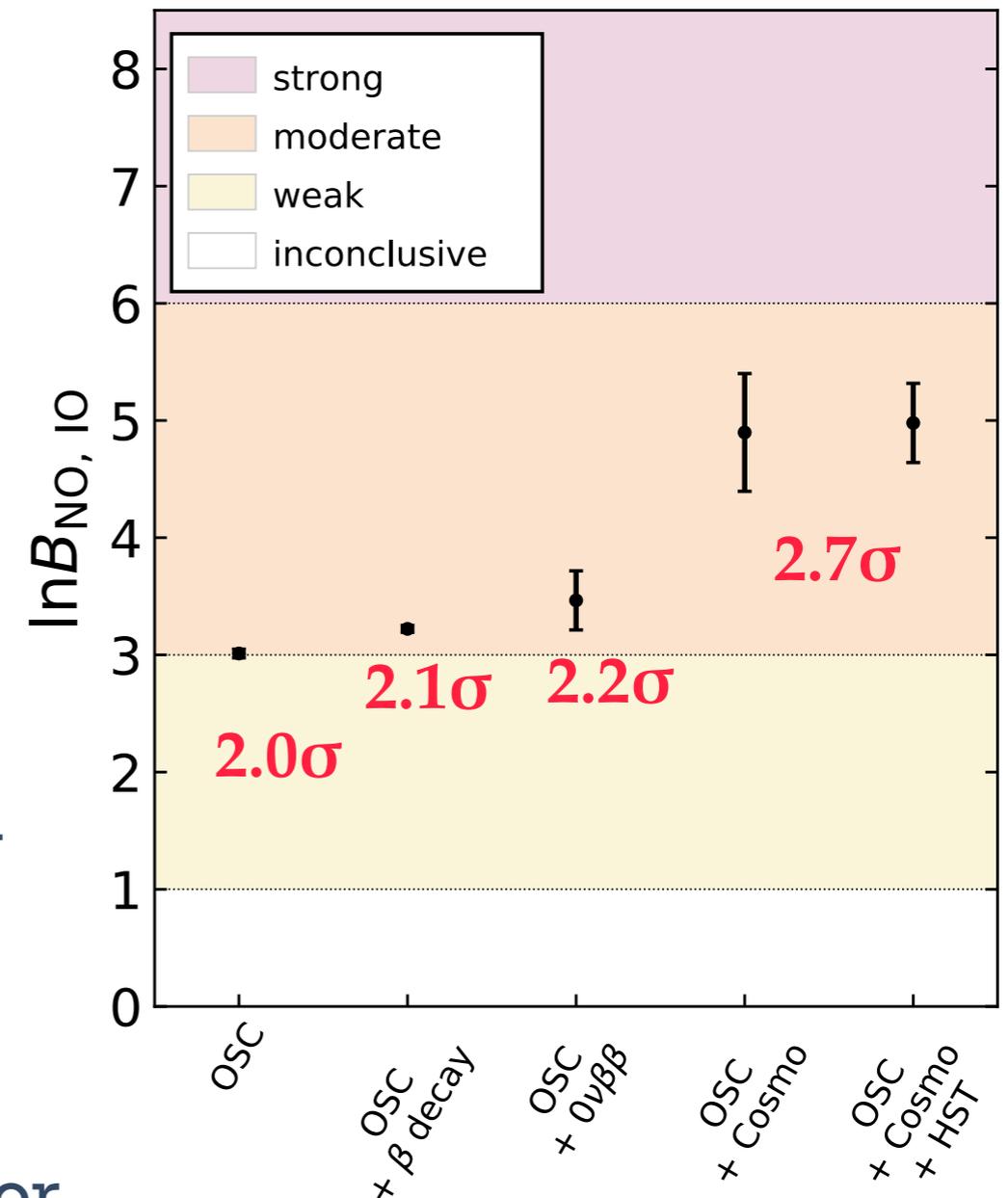
Experimental sensitivity to neutrino masses:

- ◆ ν -oscillations: Δm^2_{ij}
- ◆ β -decay: $m_\beta = f(m_i, \theta_{ij})$ $m_\beta < 1.1 \text{ eV}$ (90% CL)
- ◆ $0\nu\beta\beta$: $m_{\beta\beta} = f(m_i, \theta_{ij}, \phi_i)$
- ◆ Cosmology: Σm_i $\Sigma m_\nu < 0.12$ (0.15) eV NO (IO) (95%CL)

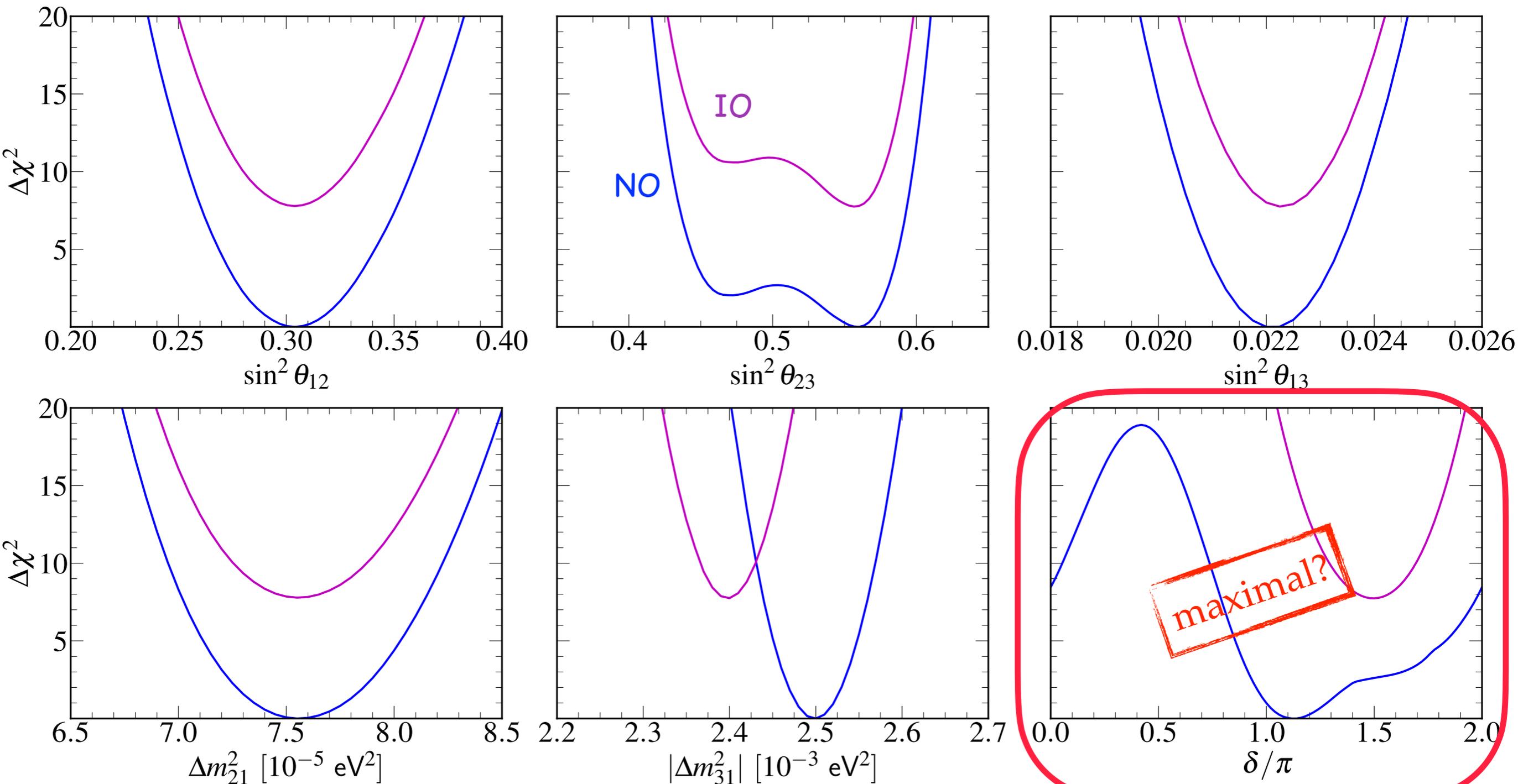
Results from the combined bayesian analysis:

- ⇒ weak/moderate preference for NO driven by oscillation data (2.0σ)
- ⇒ β -decay and $0\nu\beta\beta$ 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



Global fit to ν oscillation parameters

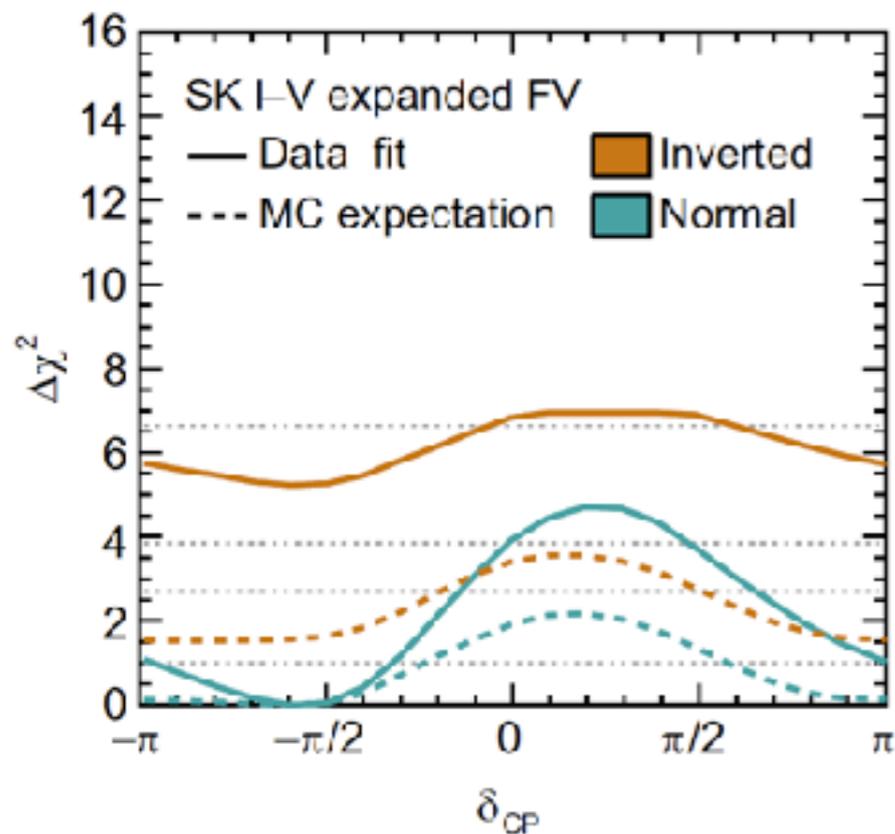


with SK atmospheric

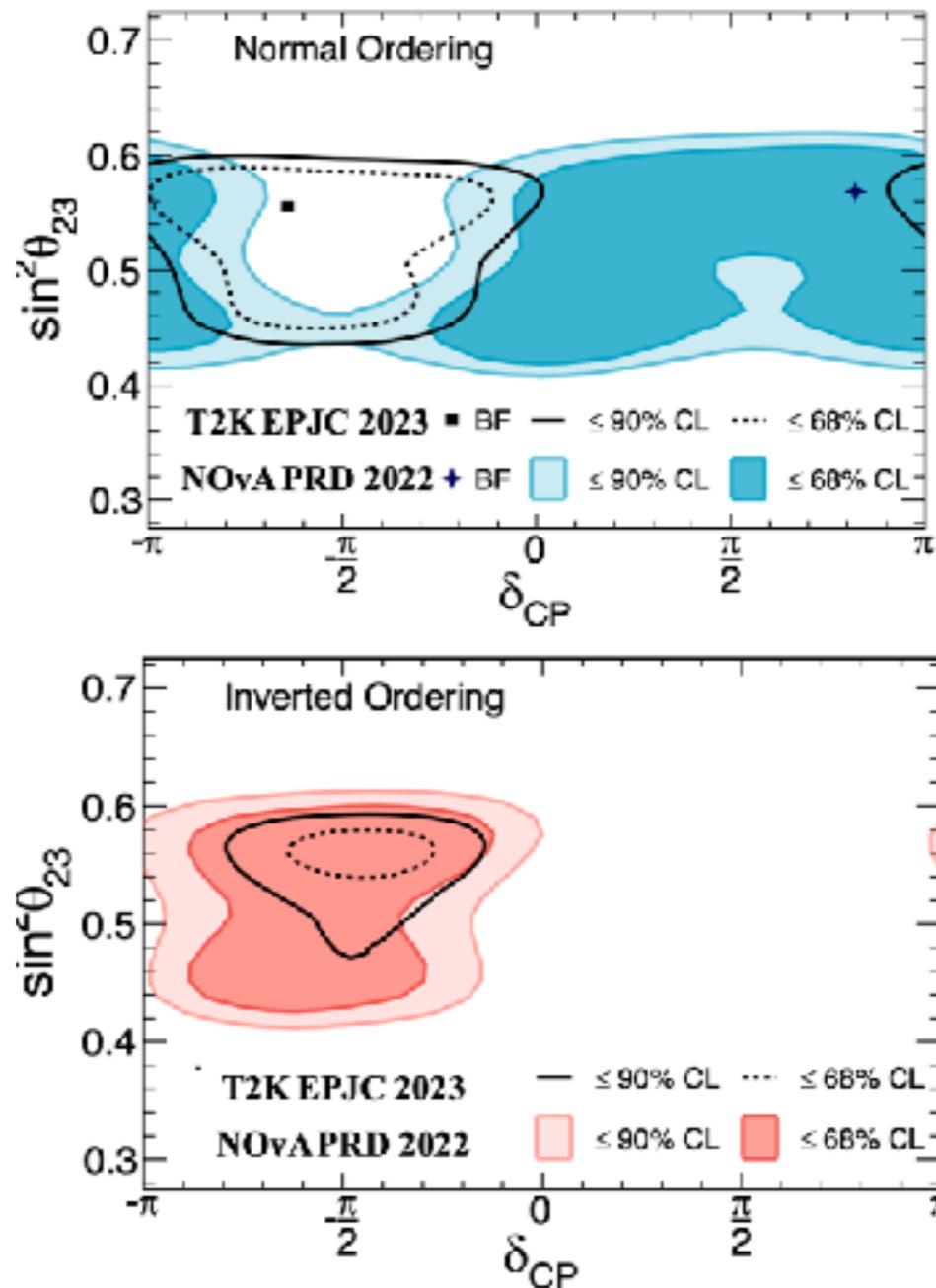
The CP phase

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

SK Collab, PRD 109 (2024) 072014



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

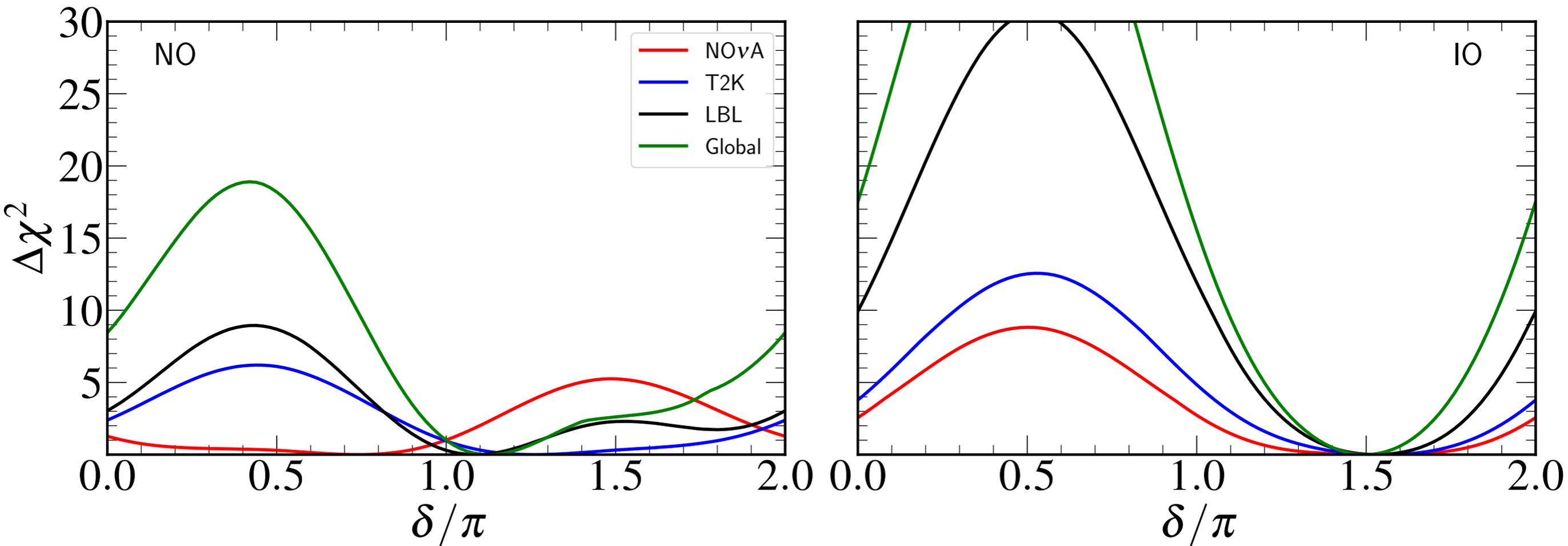


A. Booth, 2024

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

NOvA results depend on mass ordering

The CP phase



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

$$\delta_{\text{BF}} = 1.12\pi ; \delta = \pi/2 \text{ (0) disfavored at } 4.3\sigma \text{ (} 2.9\sigma\text{)}$$

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

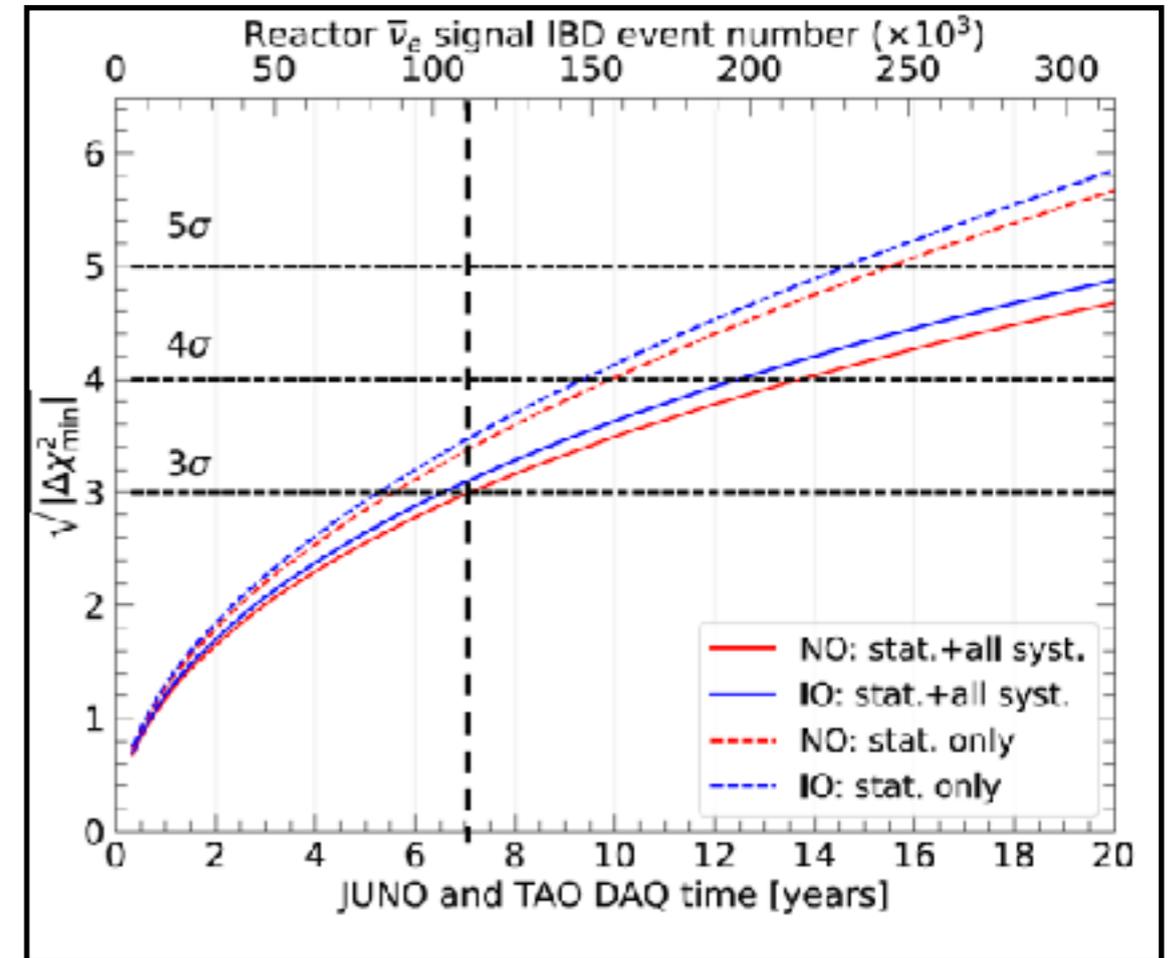
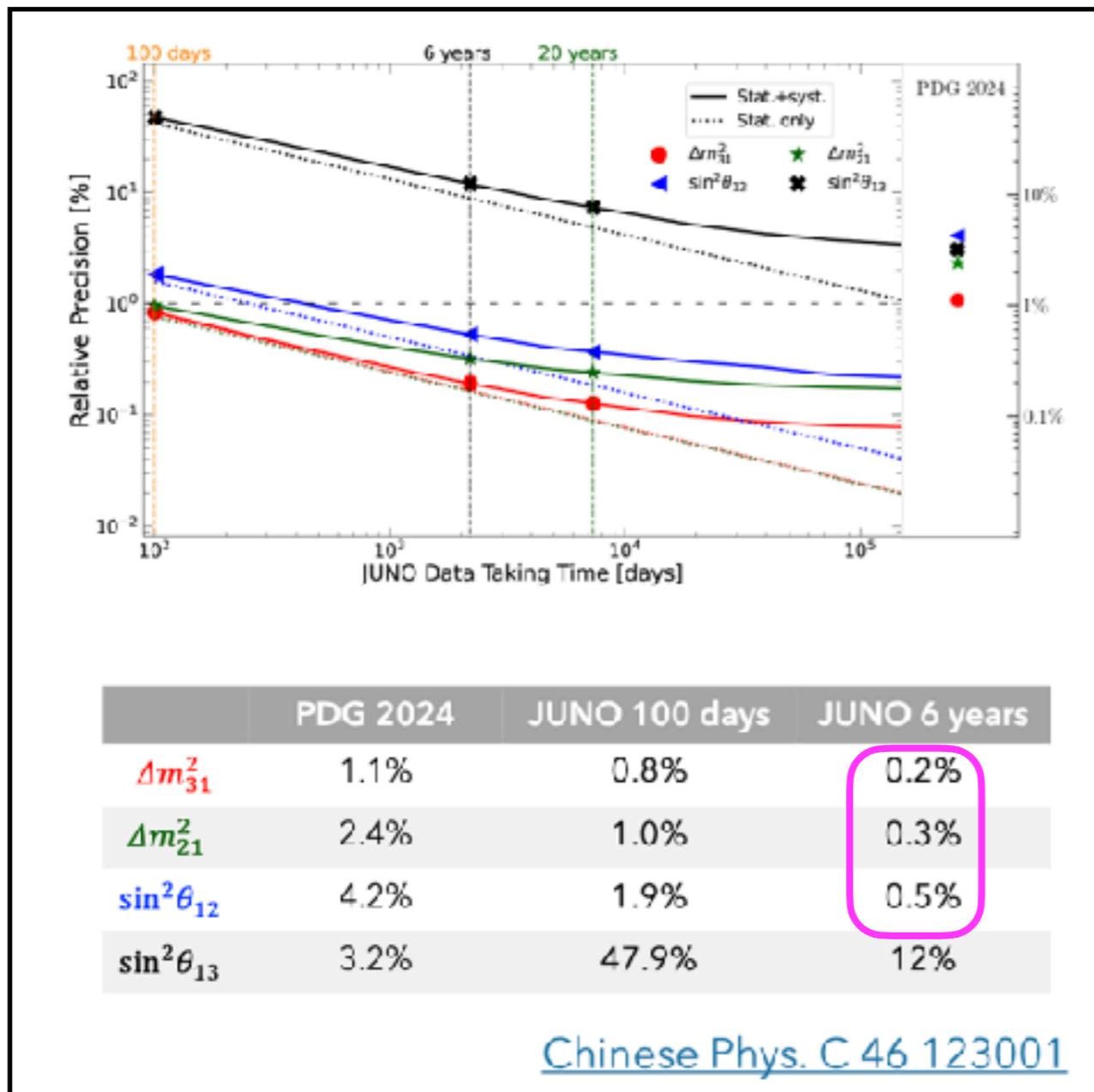
$$\delta_{\text{BF}} = 1.5\pi ; \delta = \pi/2 \text{ (}\pi\text{) disfavored at } 6.8\sigma \text{ (} 3.9\sigma\text{)}$$

Neutrino oscillations in the short/medium term

JUNO reactor experiment

► precision and mass ordering

V. Cerrone @ NOW 2024

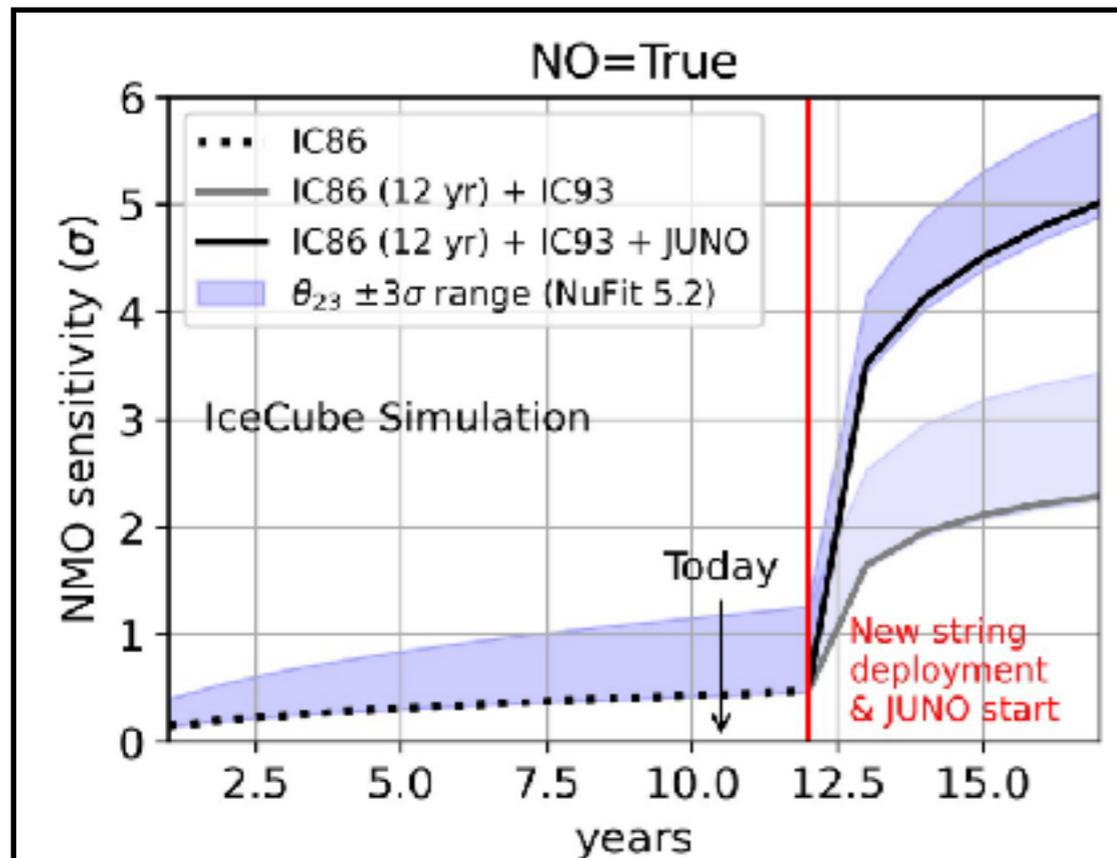


- ◆ 3σ sensitivity in ~ 7 years of data
- ◆ Combined analysis with atmospheric experiments will enhance the sensitivity

JUNO + atmospheric experiments

IceCube Upgrade + JUNO

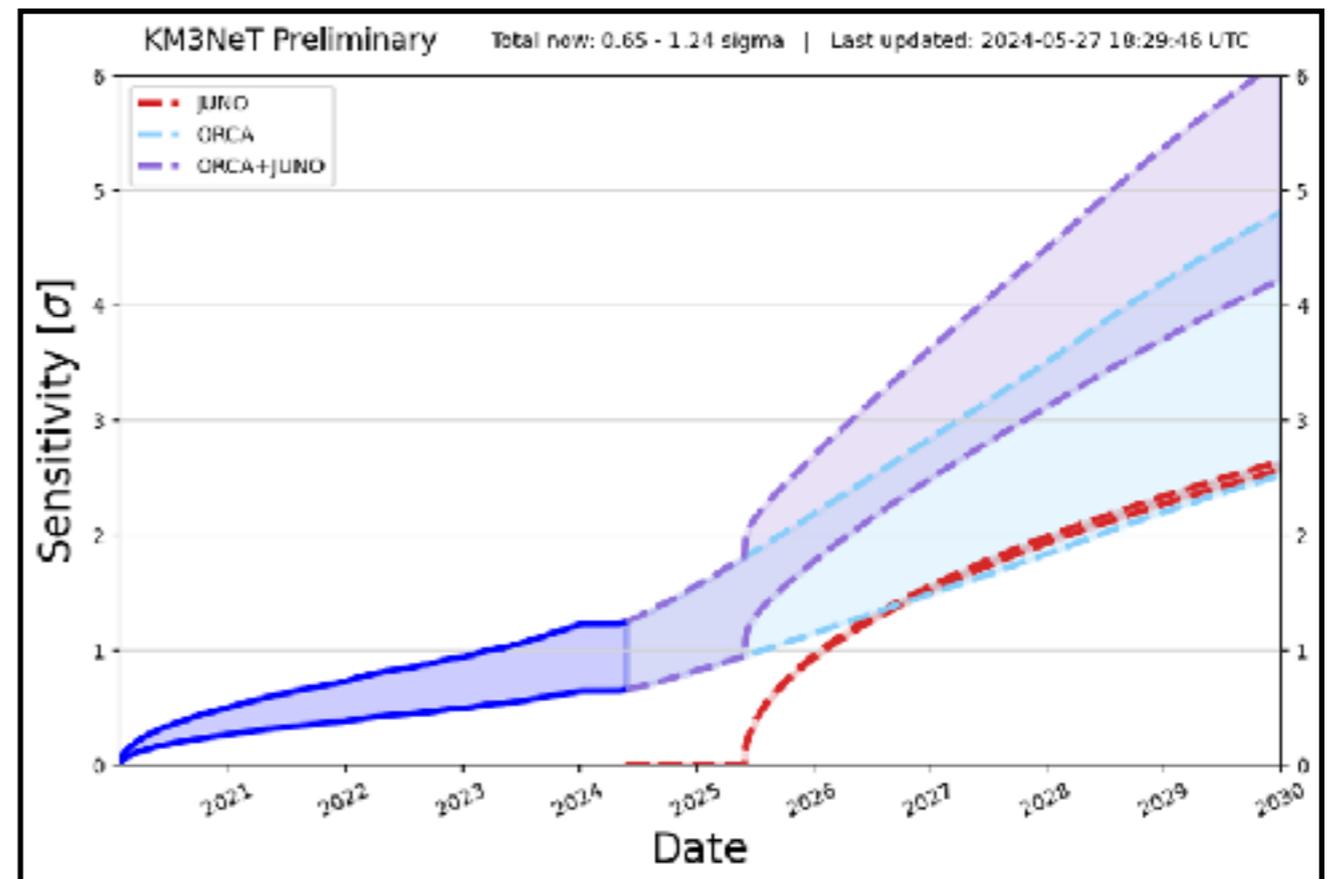
A. Terliuk @ NOW 2024



- ◆ Up to 3σ sensitivity to neutrino mass ordering (5σ with JUNO)

ORCA + JUNO

P. Migliozzi @ NOW 2024



- ◆ 4- 6σ sensitivity to neutrino MO by 2030 (below 3σ with JUNO only)

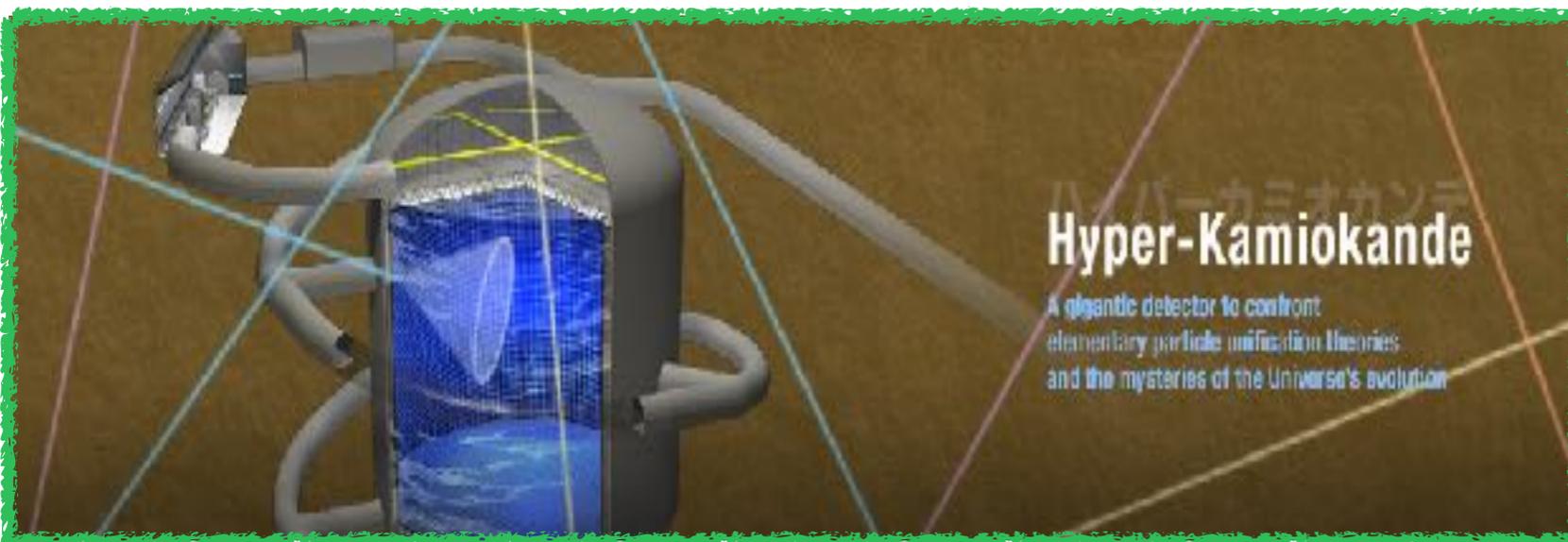
Next generation of ν experiments

DUNE



- ◆ 1.2 MW wide-band beam from FNAL to SURF (1300km)
- ◆ 4x10 kt Liquid Argon TPCs
- ◆ capability to probe 2nd oscillation max
- ◆ great sensitivity to mass ordering

Hyper-Kamiokande

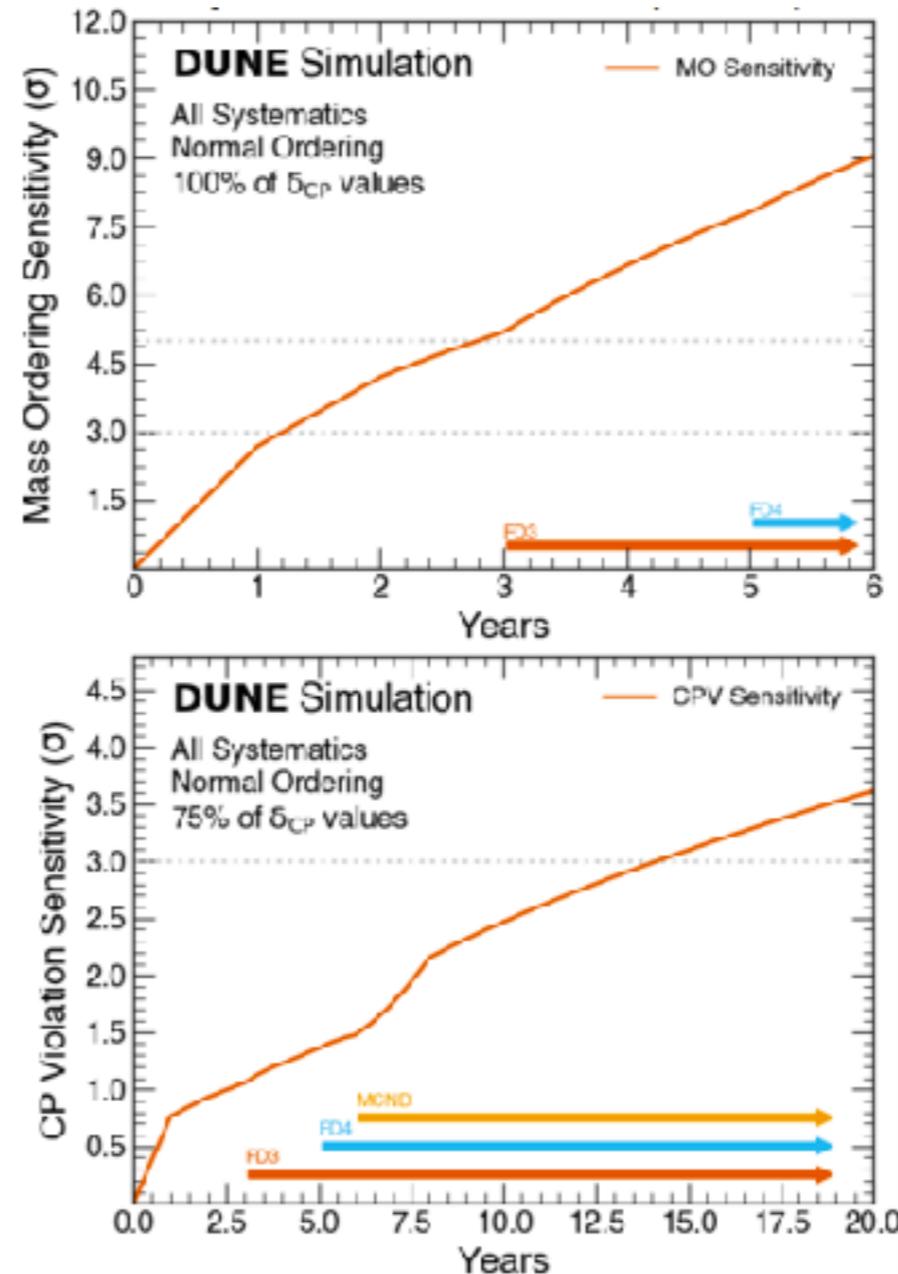
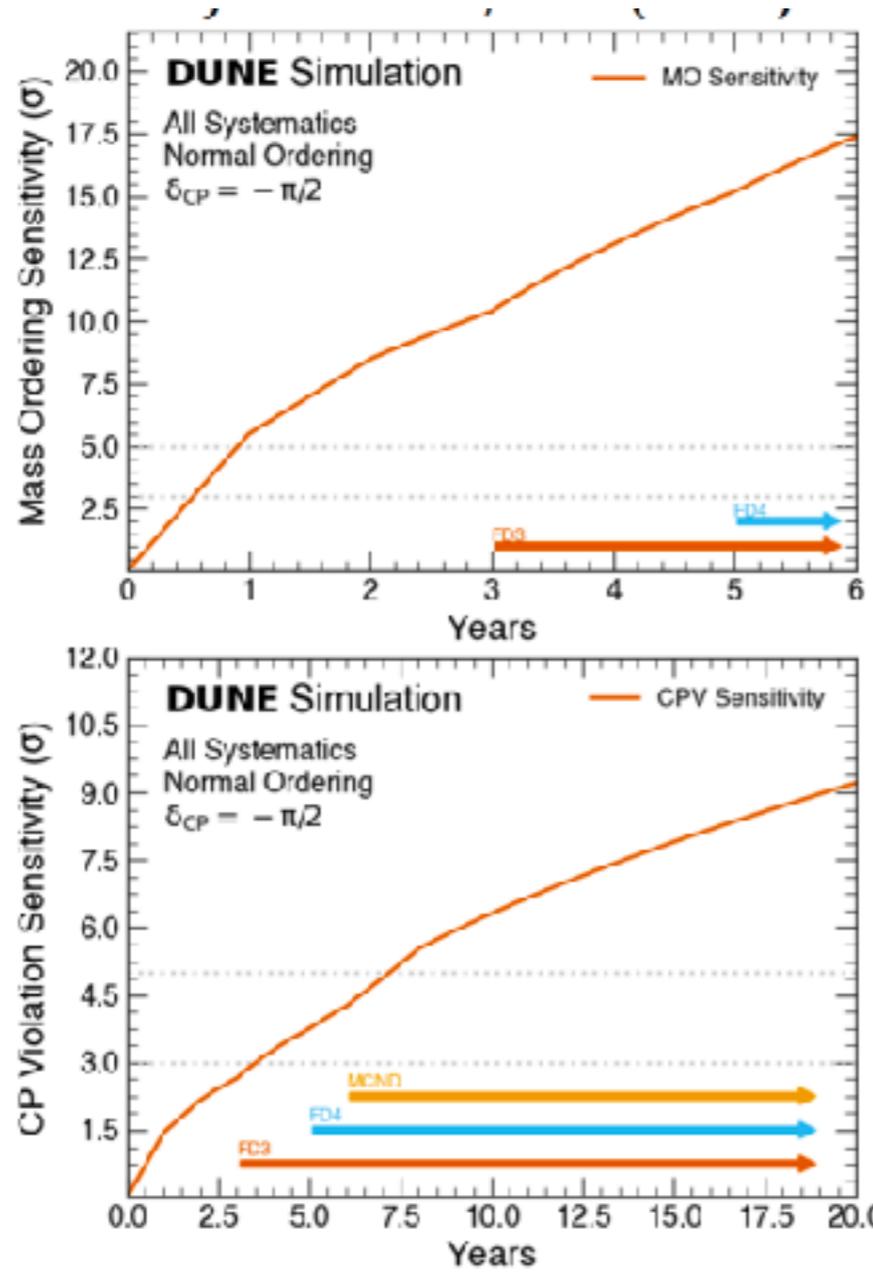


- ◆ 188 kton water Cerenkov
- ◆ T2HK: great sensitivity to δ_{CP}
- ◆ T2HKK (1100km) will have similar sensitivities as DUNE

Next generation of ν experiments

DUNE

C. Marshall@Neutrino'24



Ultimate precision in δ_{CP} : 6-16°

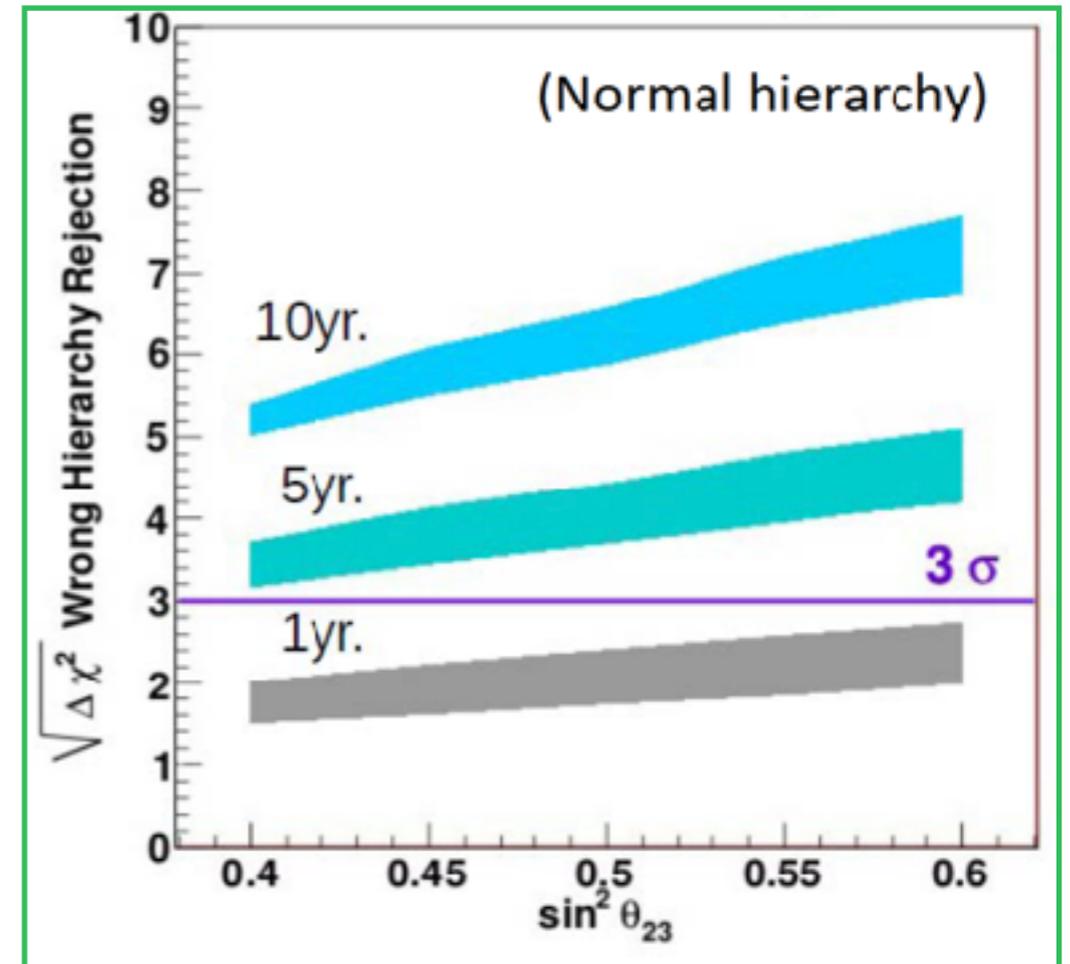
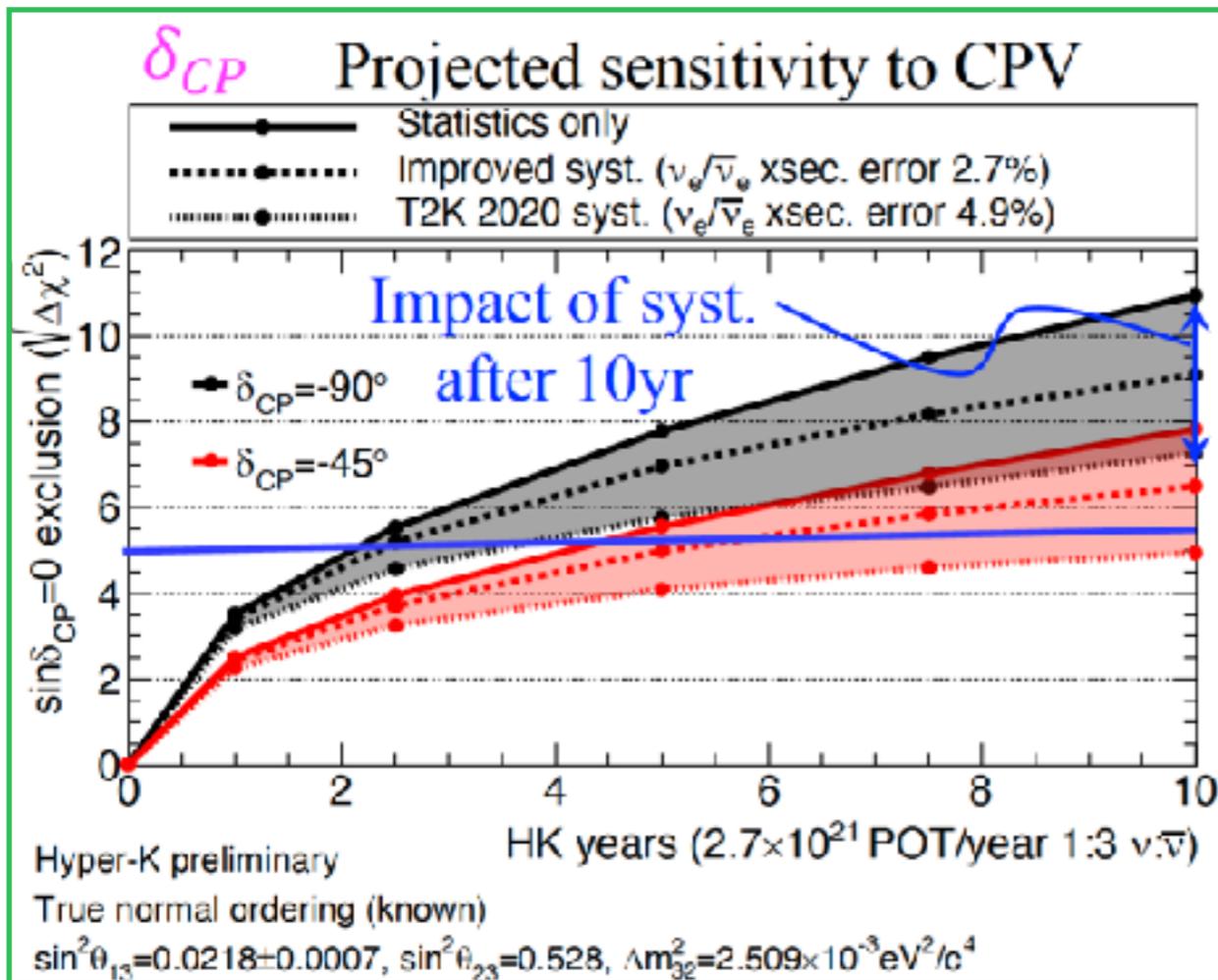
- ◆ Best-case oscillation scenarios:
 - >5 σ mass ordering sensitivity in 1 year
 - >3 σ CPV sensitivity in 3.5 years

- ◆ Worst-case oscillation scenarios:
 - >5 σ mass ordering sensitivity in 3 years
 - +10yr: CPV over 75% of δ_{CP} values at >3 σ

Next generation of ν experiments

Hyper-Kamiokande

S. Moriyama @ Neutrino'24



- ◆ $>5\sigma$ CPV discovery for $>60\%$ of δ_{CP}
- ◆ 1σ resolution of δ_{CP} in 10 yrs:
 $\sim 20^\circ$ ($\sim 6^\circ$) for $\delta_{CP} = -90^\circ$ (0°)

- ◆ $>5\sigma$ sensitivity to mass ordering for all values of θ_{23} for NO

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:
 - ✓ presence of light sterile neutrinos
 - ✓ mixing with heavy sterile neutrinos: non-unitary neutrino mixing
 - ✓ neutrino non-standard interactions (NSI) with matter
 - ✓ exotic neutrino electromagnetic properties

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

Global fit to ν oscillation parameters

parameter	best fit $\pm 1\sigma$	3σ range	relative 1σ uncert	
Δm_{21}^2 [10^{-5}eV^2]	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7%	
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (NO)	2.50 ± 0.02	2.57	0.9%	mass ordering?
$ \Delta m_{31}^2 $ [10^{-3}eV^2] (IO)	2.40 ± 0.02	2.46	0.9%	mass ordering?
$\sin^2 \theta_{12} / 10^{-1}$	3.04 ± 0.04	3.04–3.55	5.4%	
$\sin^2 \theta_{23} / 10^{-1}$ (NO)	4.32 ± 0.04	4.32–5.96	4.8%	
$\sin^2 \theta_{23} / 10^{-1}$ (IO)	4.34 ± 0.04	4.34–5.93	4.8%	octant?
$\sin^2 \theta_{13} / 10^{-2}$ (NO)	$2.23^{+0.07}_{-0.04}$	2.05–2.38	2.5%	
$\sin^2 \theta_{13} / 10^{-2}$ (IO)	$2.23^{+0.05}_{-0.06}$	2.06–2.39	2.5%	
δ / π (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	10-18%	maximal CP violation??
δ / π (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87	10-18%	maximal CP violation??

Not valid in presence of BSM!

Sterile neutrinos

◆ **sterile neutrino** = singlet fermion of the Standard Model

→ it has no interactions (exceptions: Higgs, mixing and physics BSM)

Motivations: sterile neutrinos can explain...

◆ neutrino oscillation anomalies ($m \sim eV$)

◆ small neutrino masses (seesaw mechanism, $m > TeV - M_{Planck}$)

◆ baryon asymmetry of the universe (leptogenesis, $m \gg 1 GeV$)

◆ (part of) the dark matter of the universe.

Light sterile neutrinos

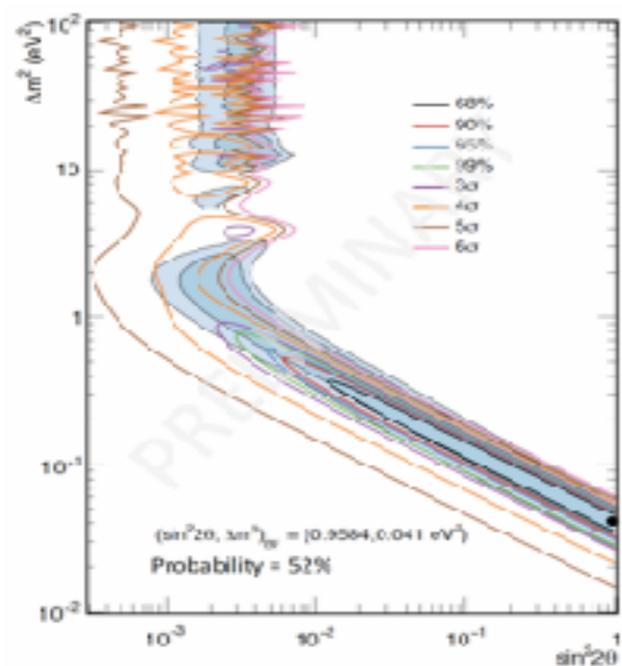
◆ LEP measurement of invisible Z decay width:

$$N_\nu = 2.984 \pm 0.008 \quad (\text{light, active neutrinos})$$

Hints for a fourth (sterile) neutrino ($\Delta m^2 \sim 1\text{-}10 \text{ eV}^2$)

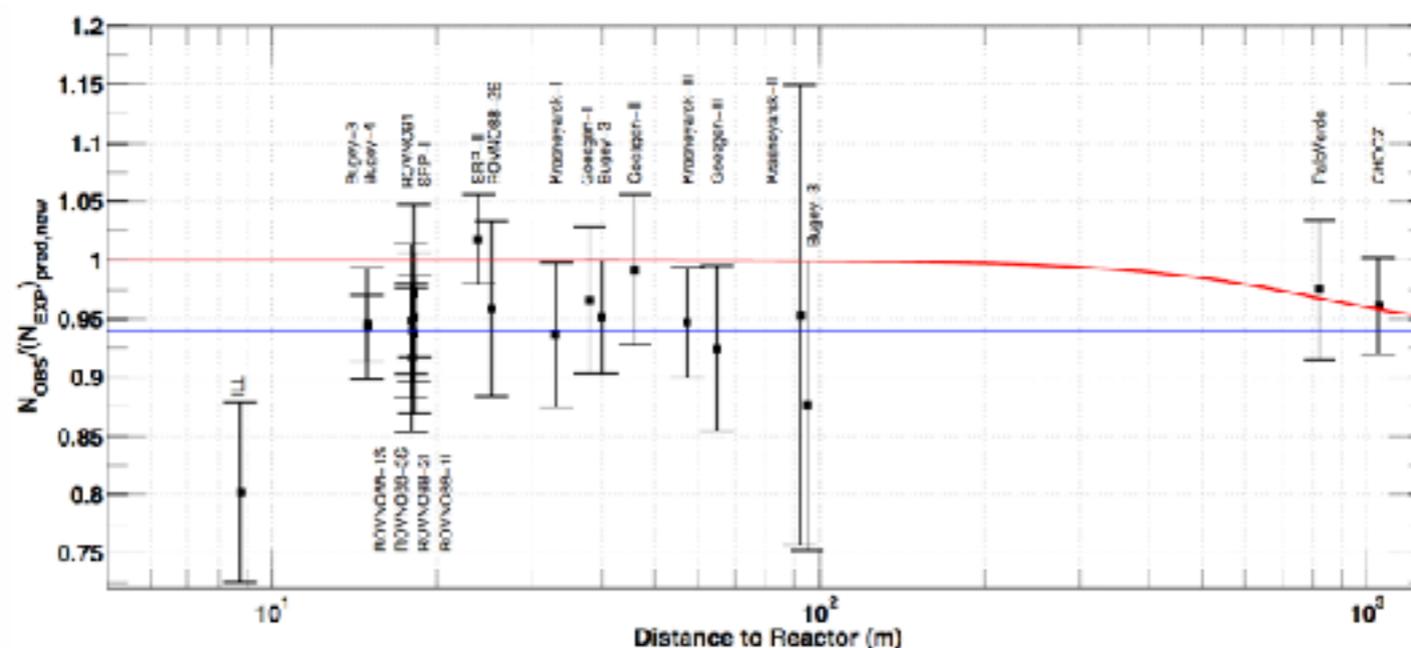
LSND & MiniBooNE

$$\nu_\mu \rightarrow \nu_e$$



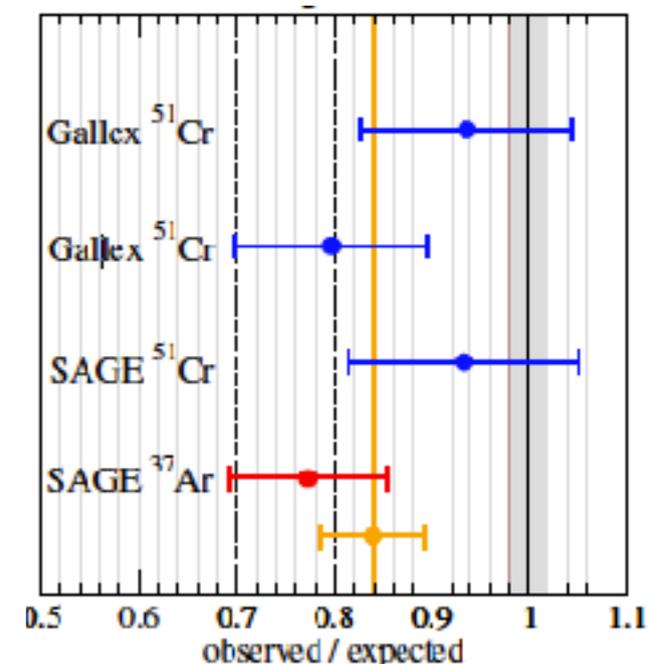
Reactor anomaly

$$\bar{\nu}_e \rightarrow \bar{\nu}_e$$



Gallium anomaly

$$\nu_e \rightarrow \nu_e$$



Light sterile neutrinos

◆ LEP measurement of invisible Z decay width:

$$N_\nu = 2.984 \pm 0.008$$

(light, active neutrinos)

Hints for a fourth (sterile) neutrino ($\Delta m^2 \sim 1-10 \text{ eV}^2$)

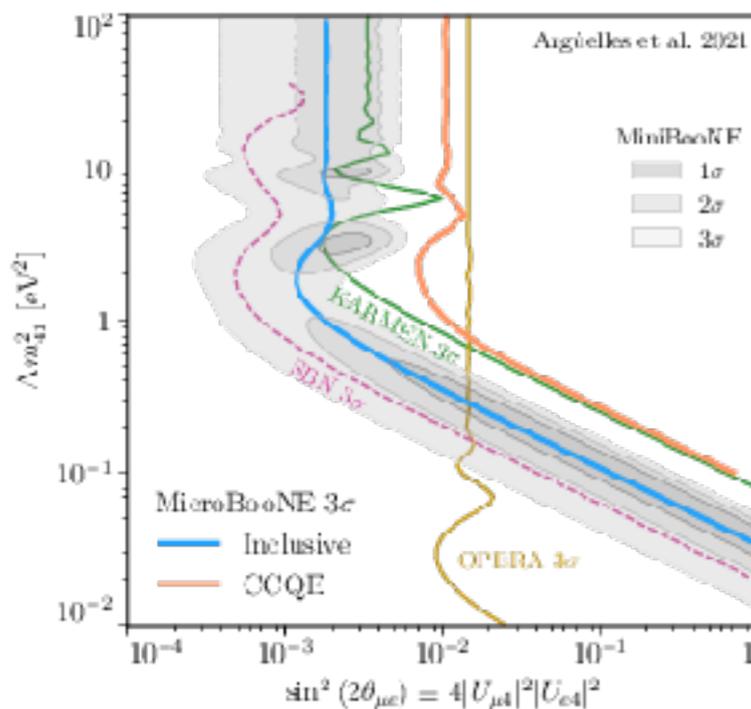
LSND & MiniBooNE



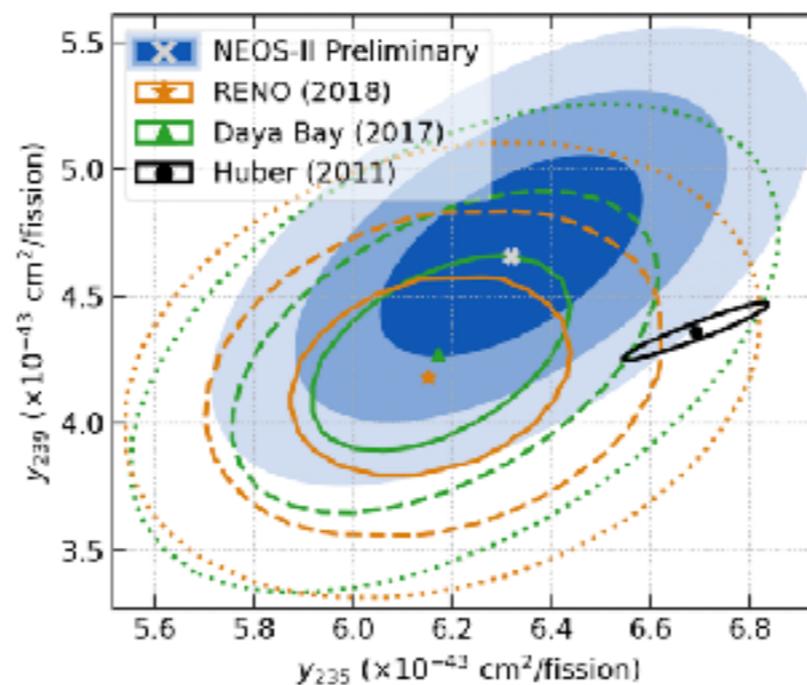
Reactor anomaly



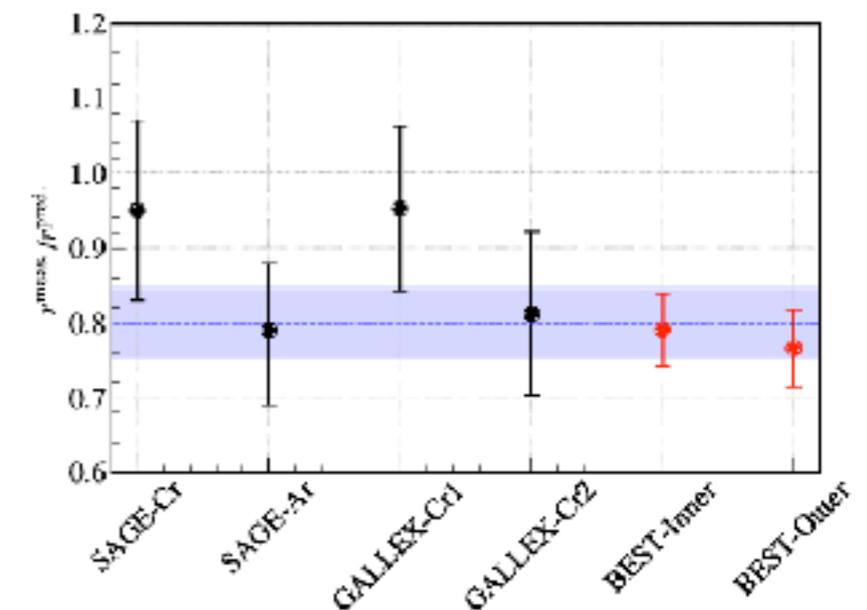
Gallium anomaly



Being tested by MicroBooNE



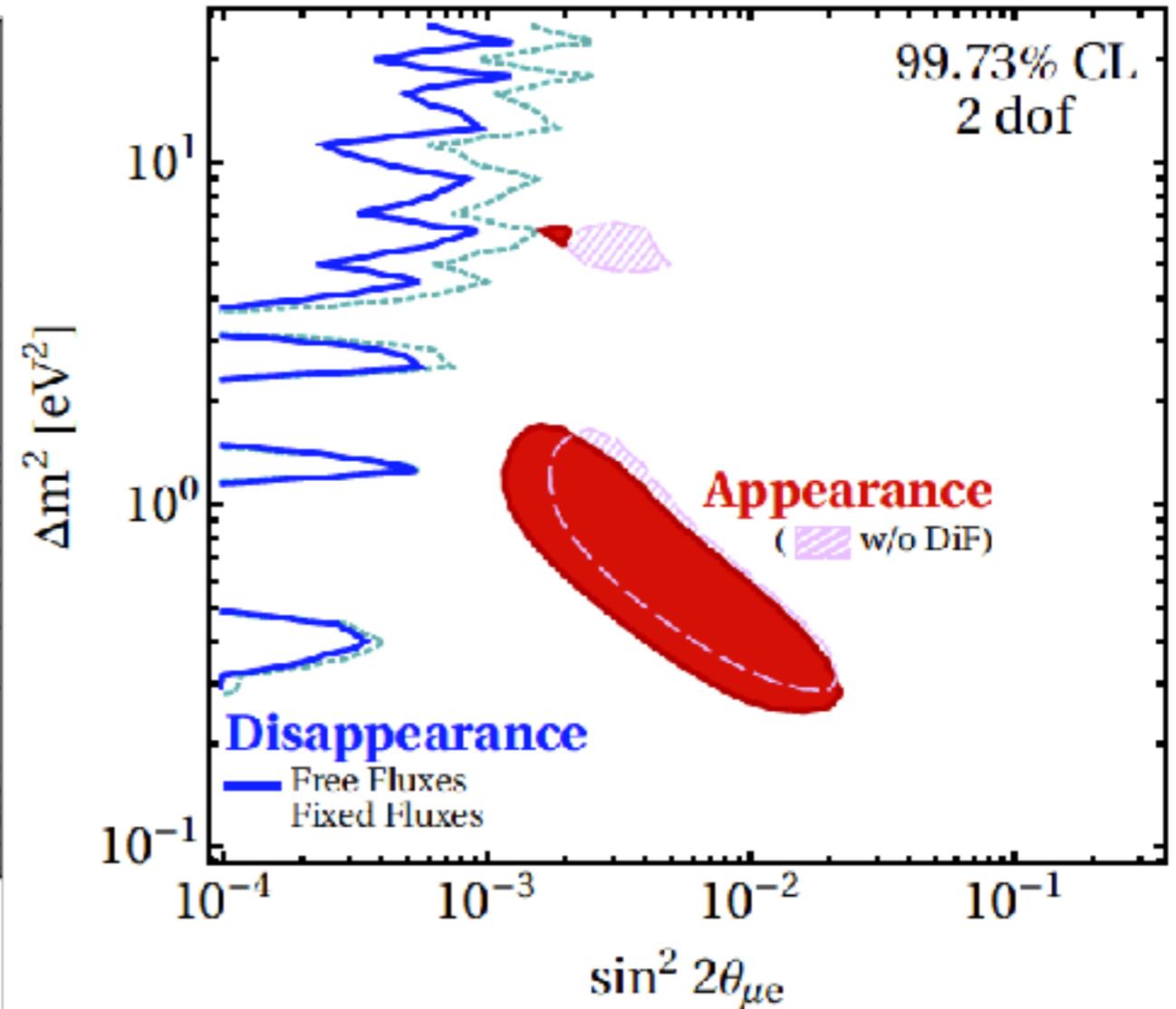
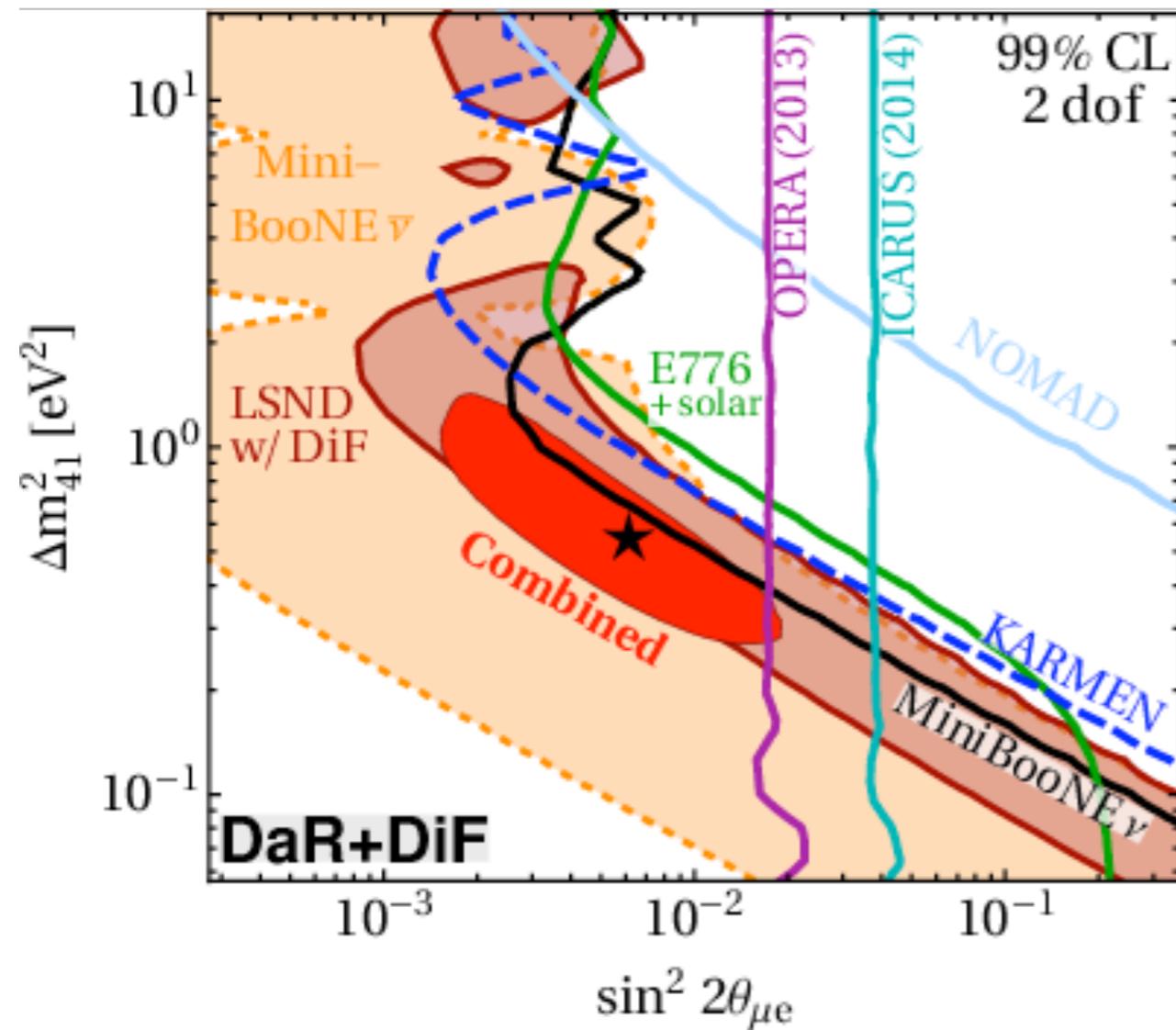
5-10% ^{235}U flux reduction



4 σ confirmation

Global fit in 3+1 neutrino scheme

Dentler et al, JHEP 2018 [See also Giunti et al]



⇒ Constraints on short-baseline $\nu_{\mu} \rightarrow \nu_e$ oscillations

⇒ strong tension between appearance (LSND/MiniBooNE) and disappearance experiments: SK, IceCube, MINOS/+,...

eV-sterile neutrino in Cosmology

- ◆ In Cosmology, sterile neutrinos with eV masses contribute to:

Σm_ν = sum of neutrino masses N_{eff} = relativistic degrees of freedom

- ◆ Considering the presence 4th light sterile neutrino:

$$\rightarrow \Sigma m_\nu \gtrsim 0.05 \text{ eV} + \sqrt{\Delta m_{41}^2} > 1 \text{ eV}$$

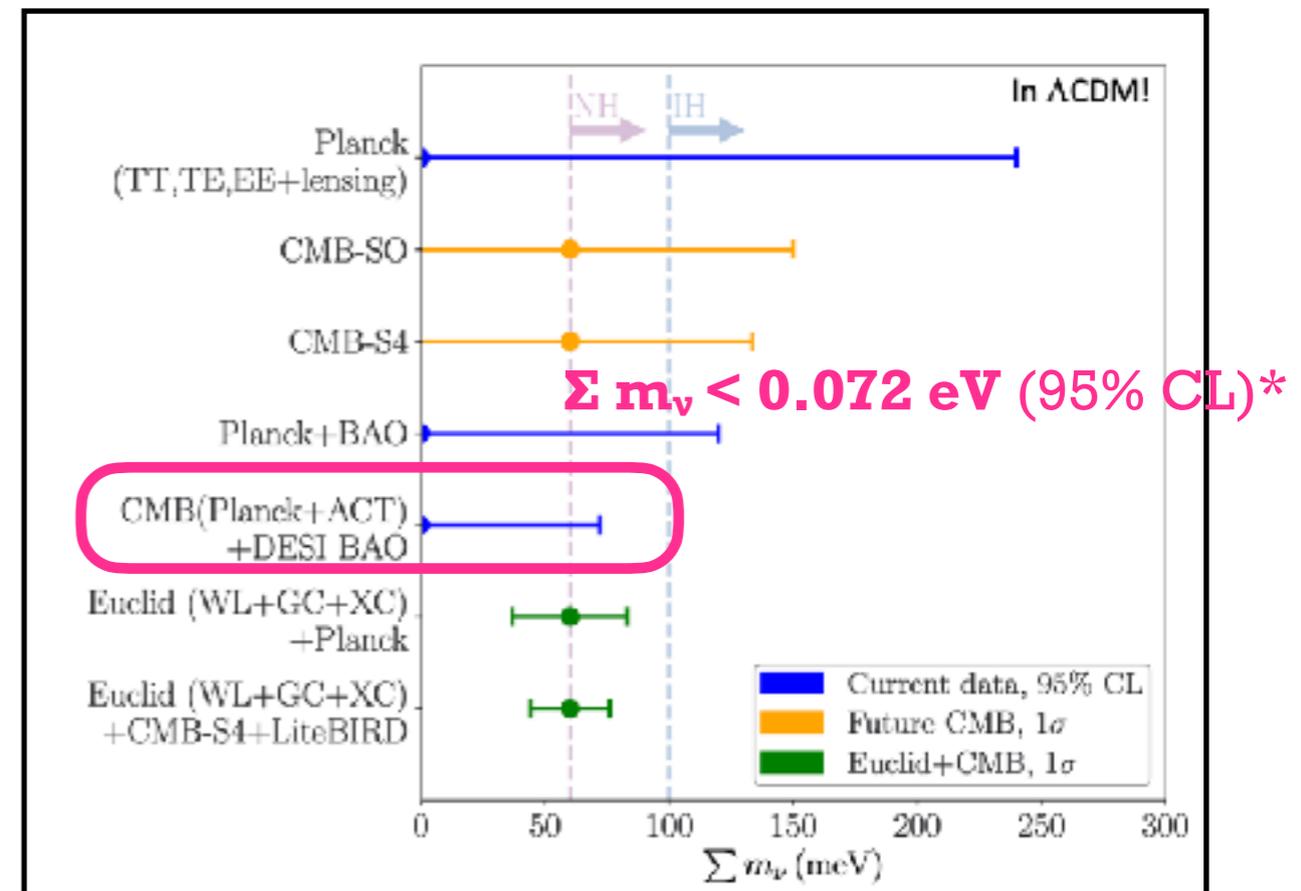
$$\rightarrow N_{\text{eff}} \approx 4$$

- ◆ Cosmological constraints:

$$N_{\text{eff}} = 2.96^{+0.34}_{-0.33}$$

Strong tension between the eV sterile neutrino hypothesis and cosmology

M. Archidiacono @ Neutrino 2024



Non-unitary light neutrino mixing

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

Ex: type I seesaw, inverse seesaw

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

→ (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

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

Escrivuela et al, PRD92 (2015)

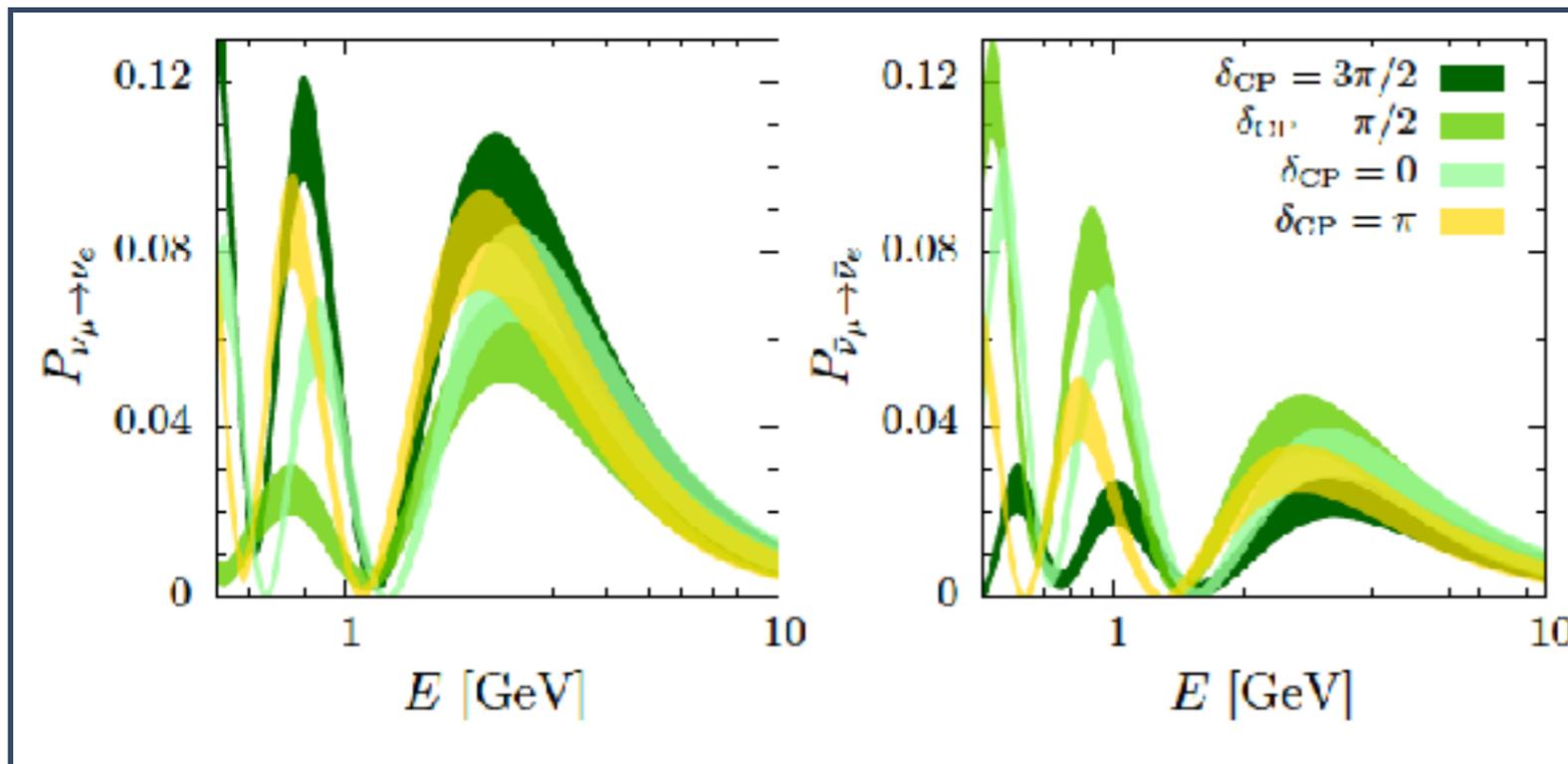
See also Xing, PRD2012 for n=6

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

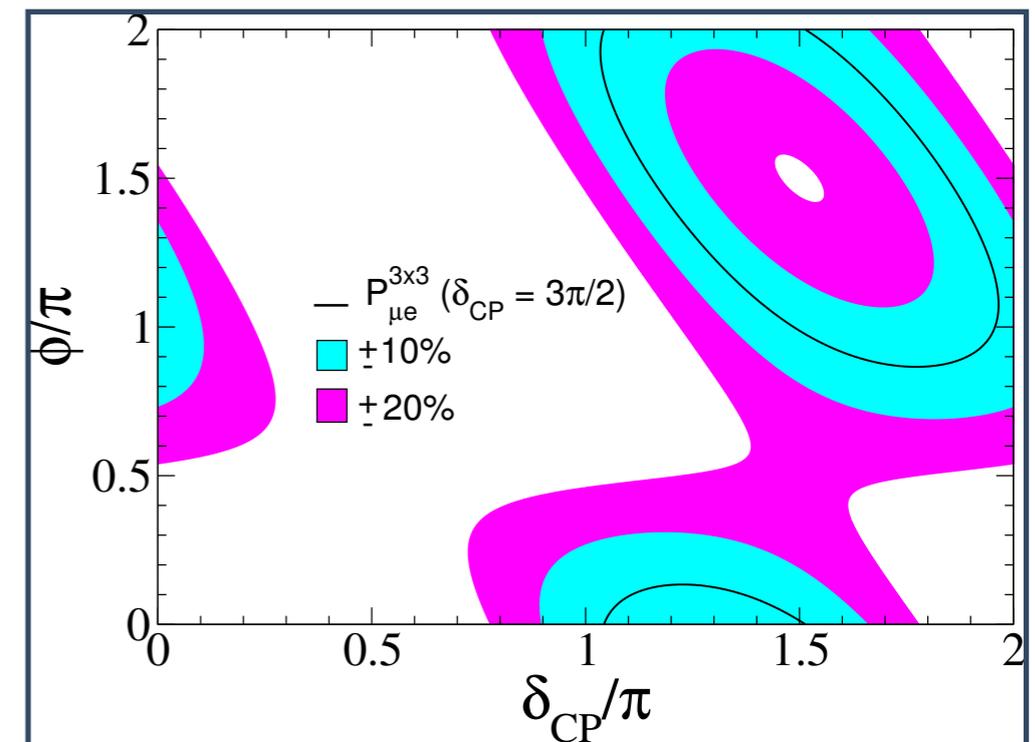
NU neutrino oscillations in DUNE

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

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



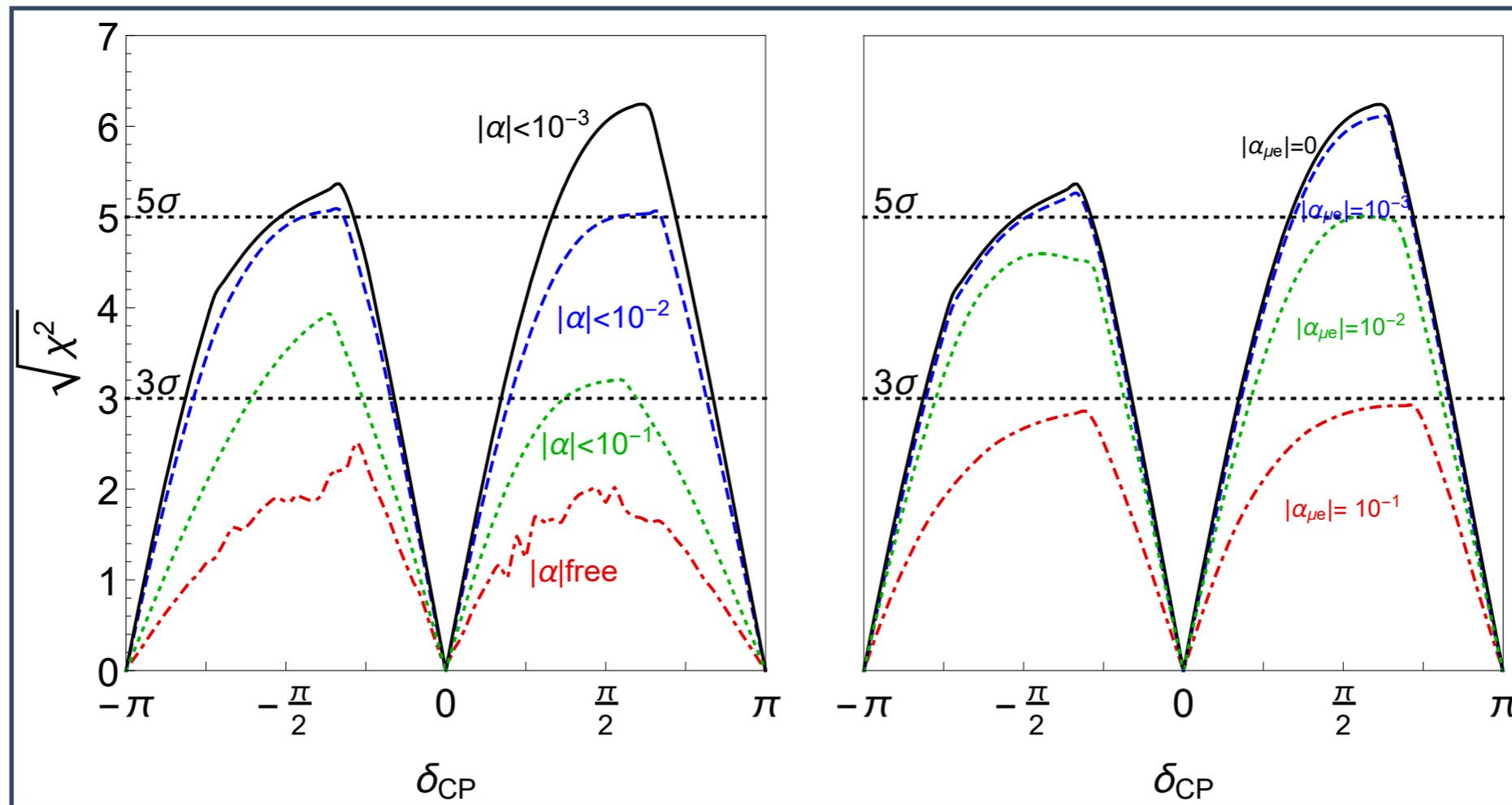
Escrivuela et al, NJP 2017



Miranda, MT, Valle, PRL 117 (2016)

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

DUNE CP sensitivity with NU



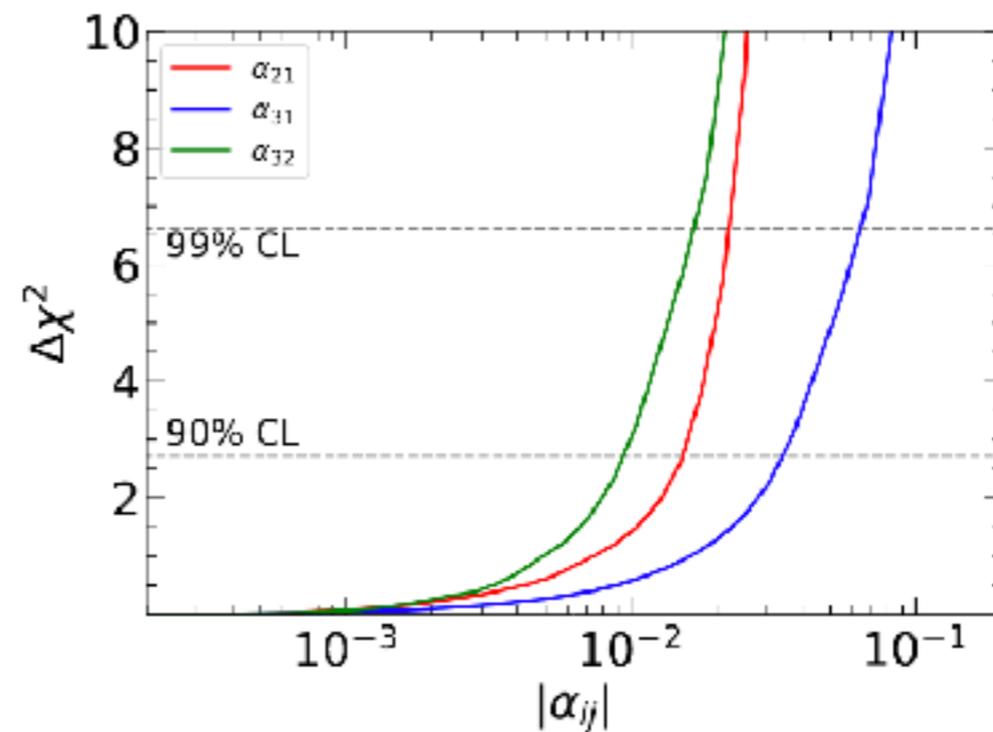
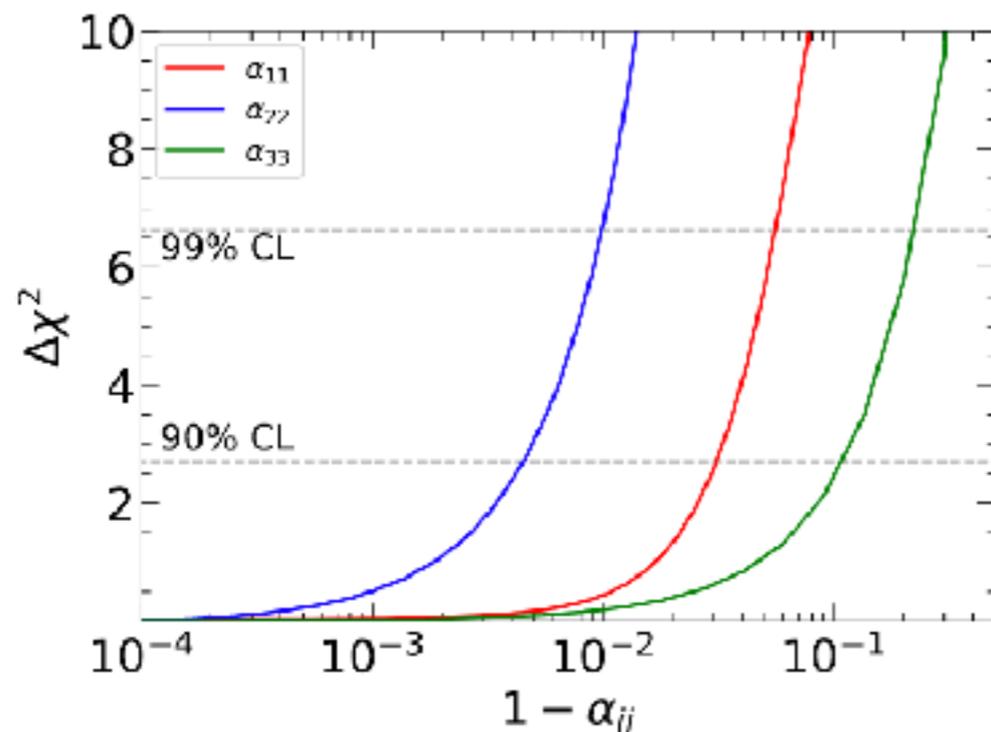
Fernández-Martínez et al (DUNE-BSM Working Group)

→ 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

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, Tórtola, PRD 2022

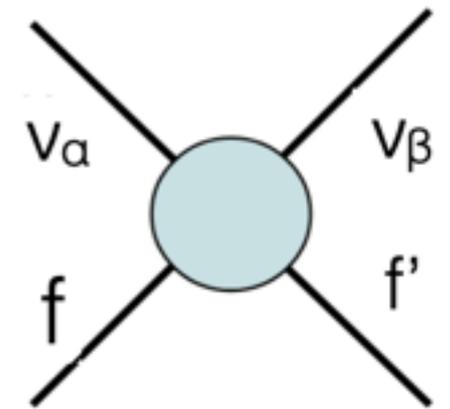
Non-standard neutrino interactions

- ◆ New 4-fermion interactions involving neutrinos

CC-NSI:

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

⇒ effect on neutrino **production** and **detection**



NC-NSI:

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

(X= L,R)

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

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

⇒ mainly affecting neutrino **propagation** in matter:

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

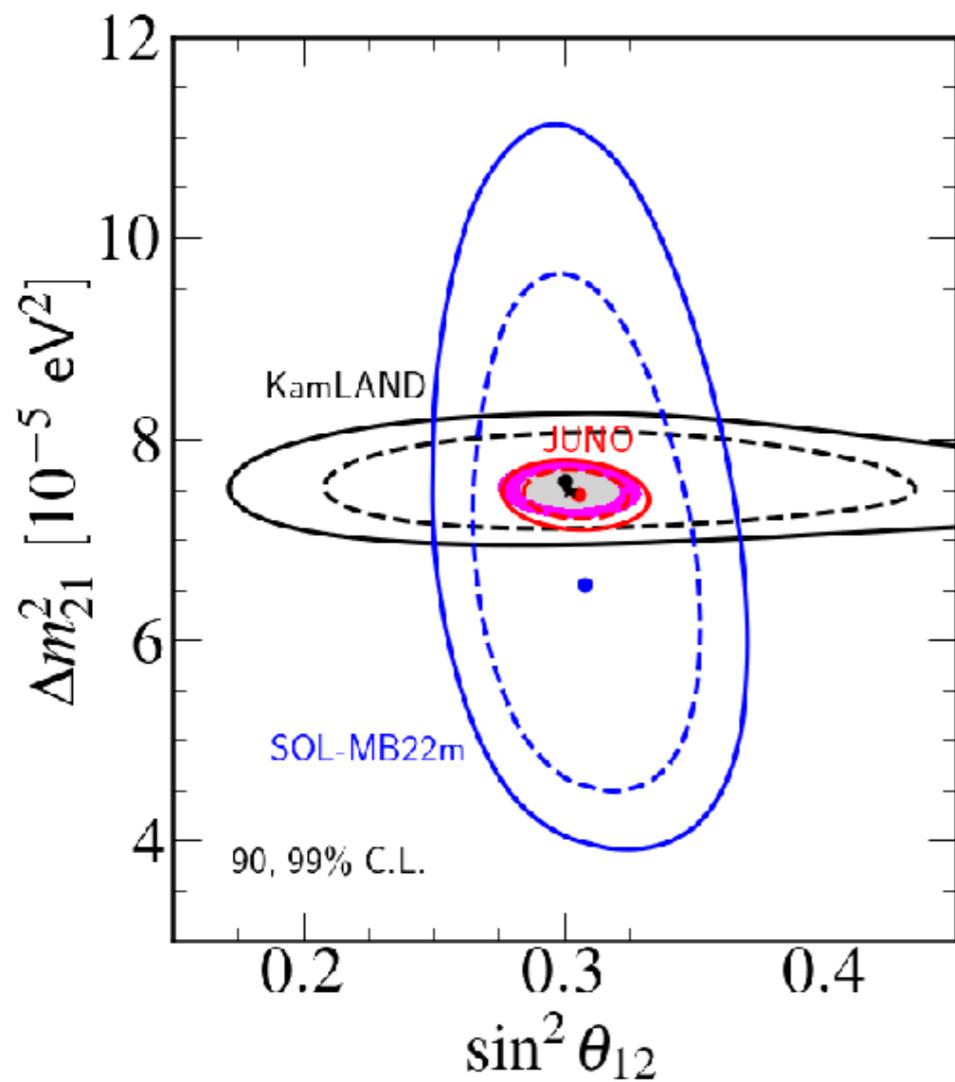
- ◆ NSI may affect the **3-neutrino oscillation picture**:

⇒ precision measurements at current experiments

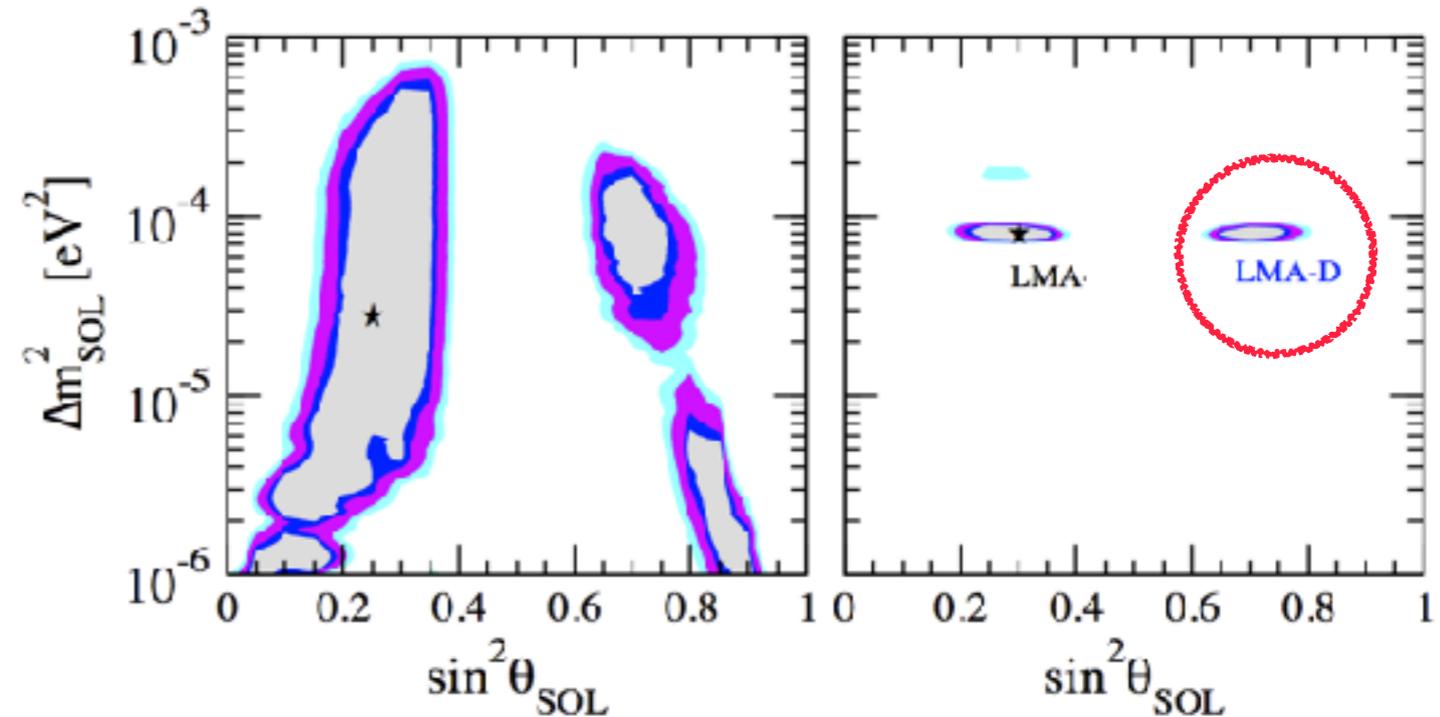
⇒ sensitivity reach of upcoming experiments (degeneracies)

NSI in the solar neutrino sector

Standard 3ν oscillations

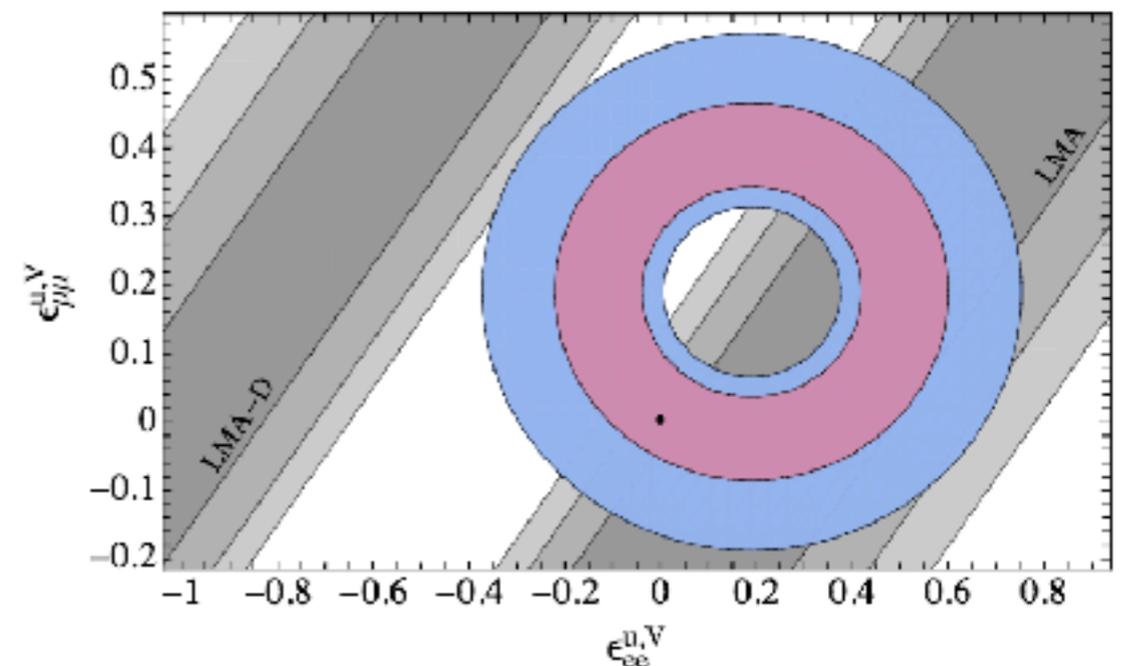


de Salas et al, PLB782 (2018) 633



Miranda et al, JHEP 2006

Solar + CEvNS

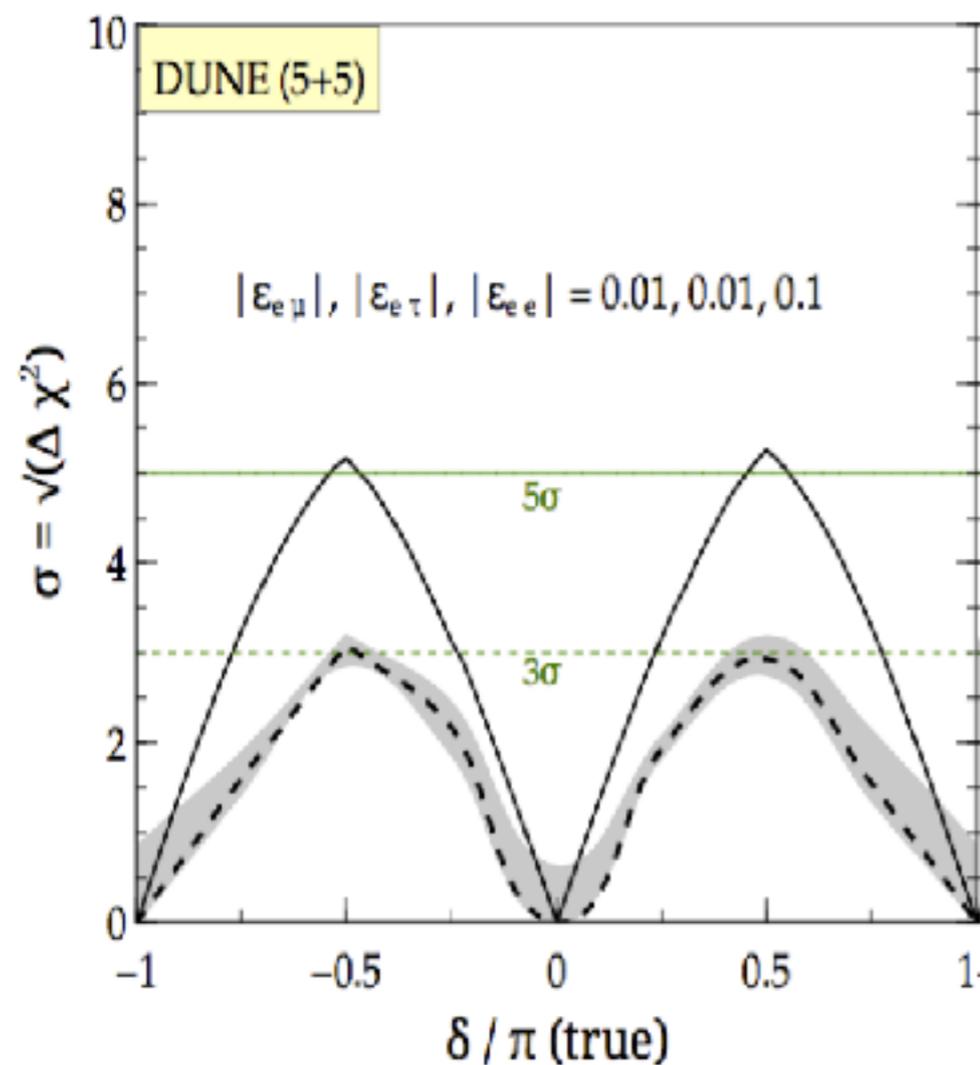


Coloma et al, PRD 2017

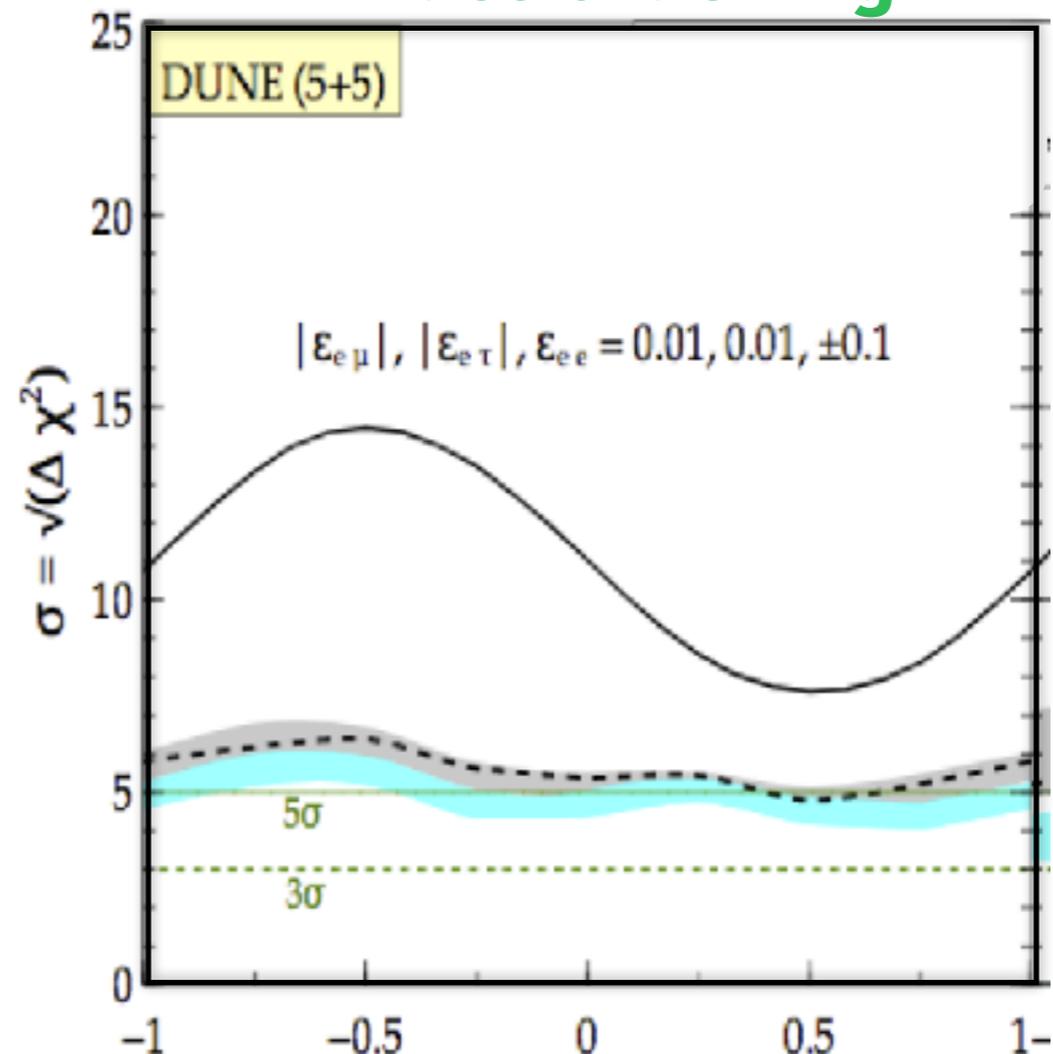
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation

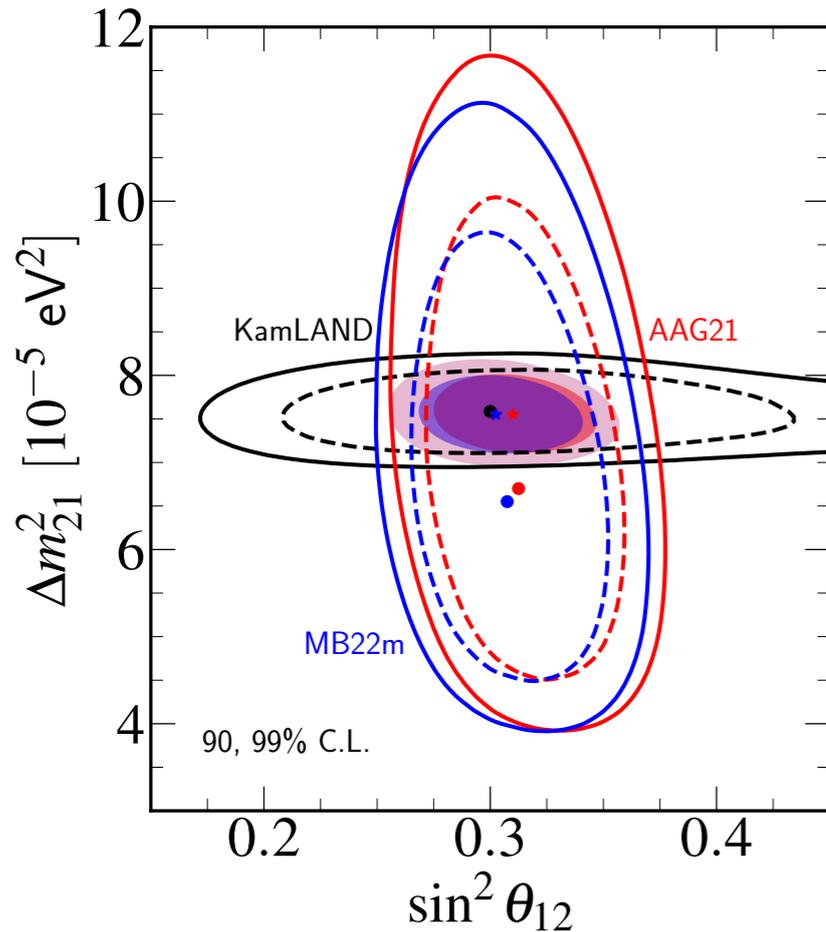


mass ordering



Masud and Mehta, PRD 2016

NSI in the solar sector



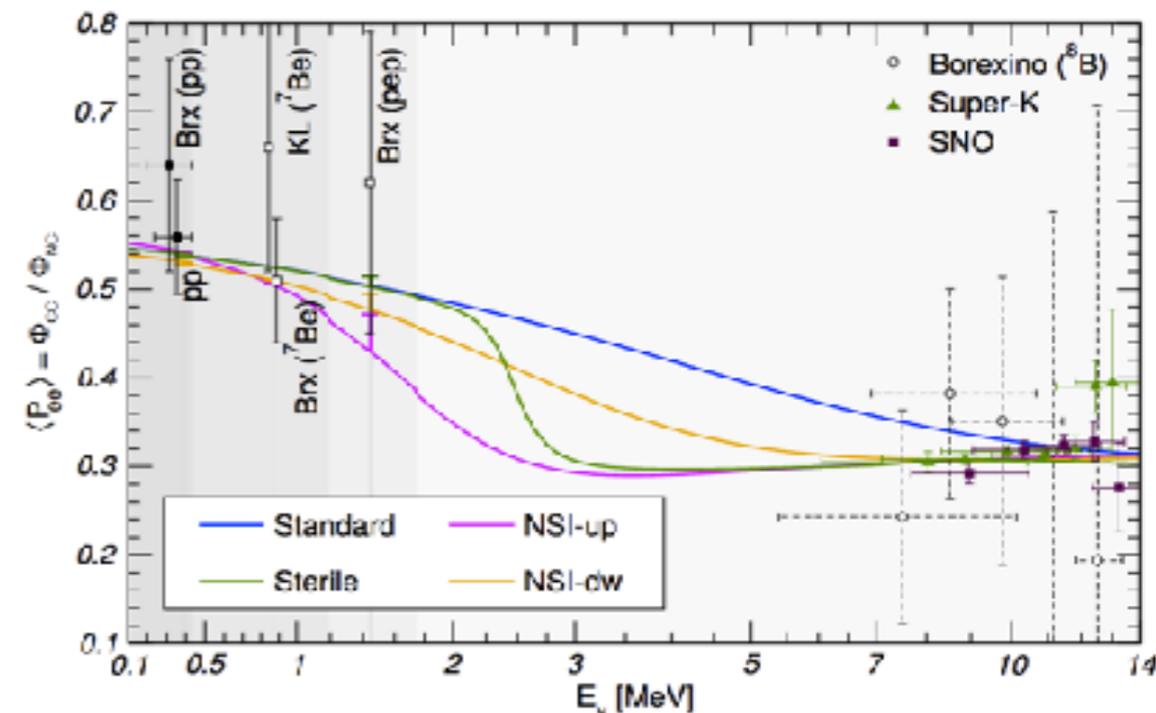
⇒ tension between preferred value of Δm^2_{21} from KamLAND and solar data

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

◆ **NSI** ($\epsilon \sim 0.3$) can reconcile both results:

⇒ flatter spectrum at intermediate E-region

⇒ larger D/N asymmetries can be expected



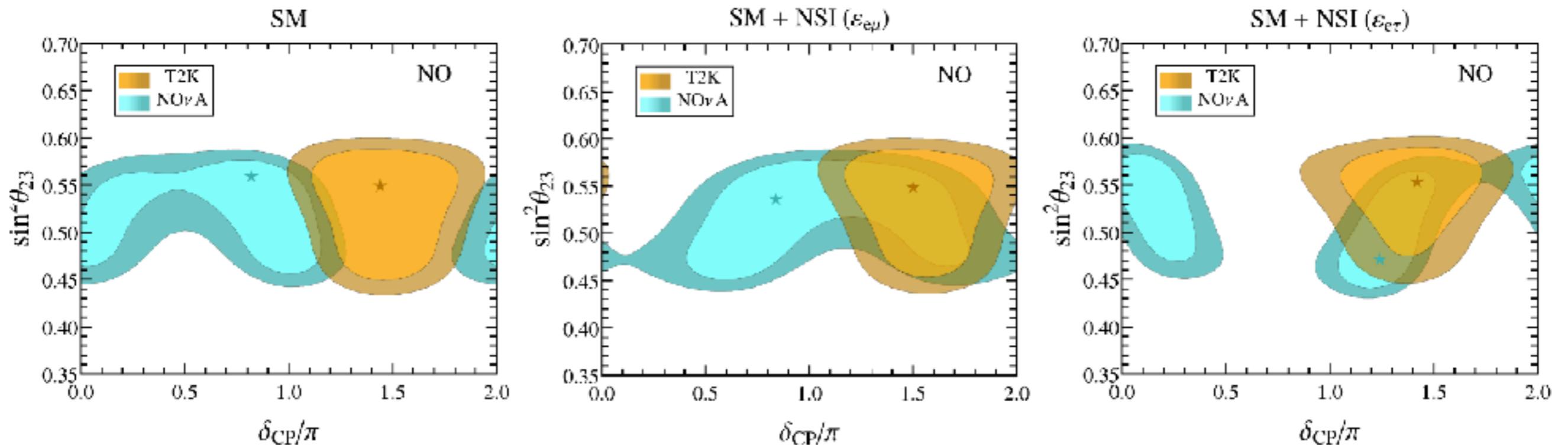
Escrivuela et al, PRD80 (2009); Coloma et al, PRD96 (2017)

Maltoni & Smirnov, EPJ 2015

NSI & the T2K-NO ν A δ_{CP} tension

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

◆ Maximal CP-violating NSI couplings $\varepsilon_{e\mu}$ and $\varepsilon_{e\tau}$ of order ~ 0.1 - 0.2 may reconcile T2K and NO ν A results.



Chatterjee and Palazzo, arXiv:2409.10599

Chatterjee and Palazzo, PRL 2021

Denton et al, PRL 2021

$$|\varepsilon_{e\mu}| = 0.125$$

$$\varphi_{e\mu} = 1.35\pi$$

$$|\varepsilon_{e\tau}| = 0.22$$

$$\varphi_{e\tau} = 1.70\pi$$

Summary

- ◆ **Global fits to neutrino oscillations** exploit complementarities of data sets to enhance the sensitivity of individual experiments.
- ◆ From the **updated three-neutrino global fit**:
 - ✓ precise determinations for most parameters ($\sim 1 - 5\%$)
 - ✓ slight preference for $\theta_{23} > 45^\circ$ - LO disfavoured by $\Delta\chi^2 \geq 2.0$ (2.9) for NO (IO)
 - ✓ **normal ordering** preferred over IO with $\Delta\chi^2 = 7.7$ (3.1) w SK (w/o SK)
 - ✓ $\delta_{\text{BF}} = 1.12\pi$ (1.5π) for NO (IO) ; $\delta = \pi/2$ **disfavored** at 4.3σ (6.8σ) for NO (IO)
- ◆ First **JUNO** data established leading precision in solar parameters
- ◆ In **the near future**, global fits (JUNO+) will be useful to enhance sensitivities.
- ◆ **Next generation experiments** (DUNE, HyperK) will provide sensitivities above 3σ for CPV and mass ordering
- ◆ **New physics BSM** may affect the current description of neutrino oscillations relaxing tensions or worsening the precision of measurements.

Thank you!

Grazie!