Neutrino Theory & Phenomenology (III)

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Three-Neutrino phenomenology

The three-flavour ν picture

neutrino mixing

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

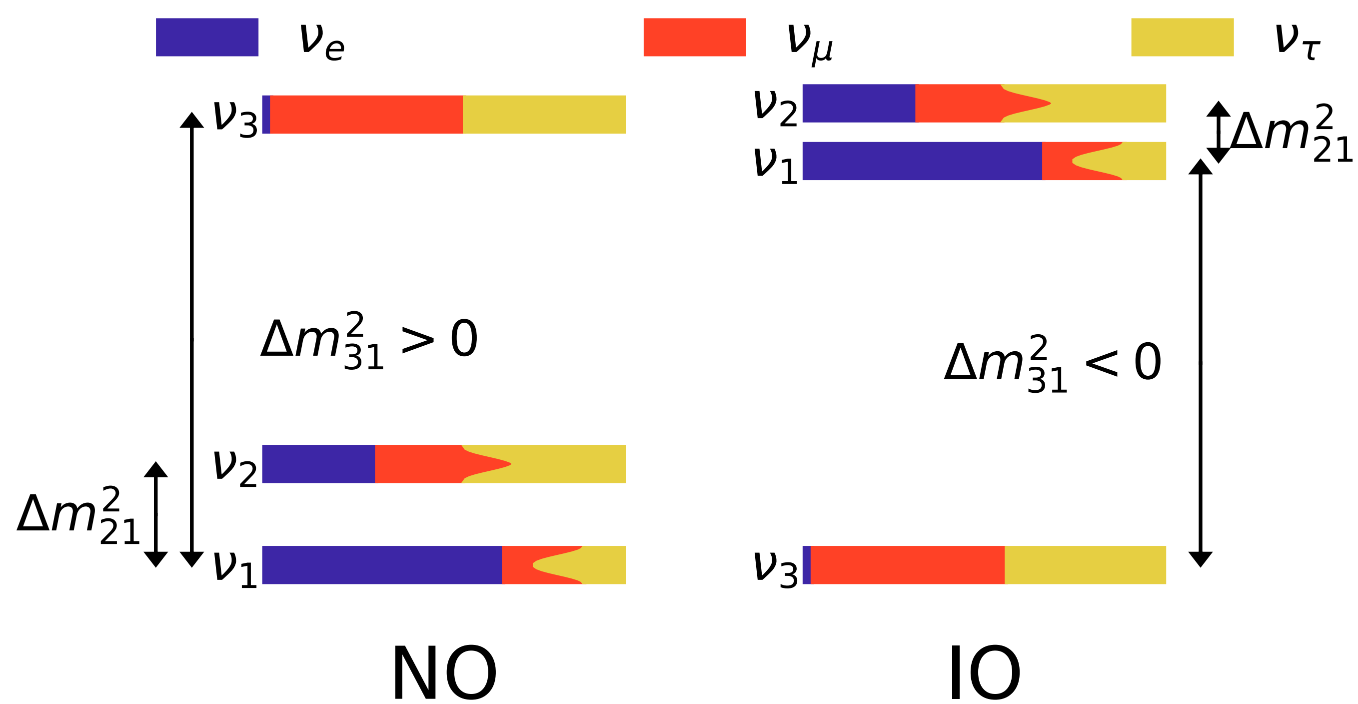
- ✓ 3 mixing angles: θ_{12}, θ_{23}, θ_{13}
- ✓ 3 CP phases: 1 Dirac + 2 Majorana
- ✓ 3 masses: m_1, m_2, m_3

⇒ absolute neutrino mass: m_0

⇒ two mass splittings:

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

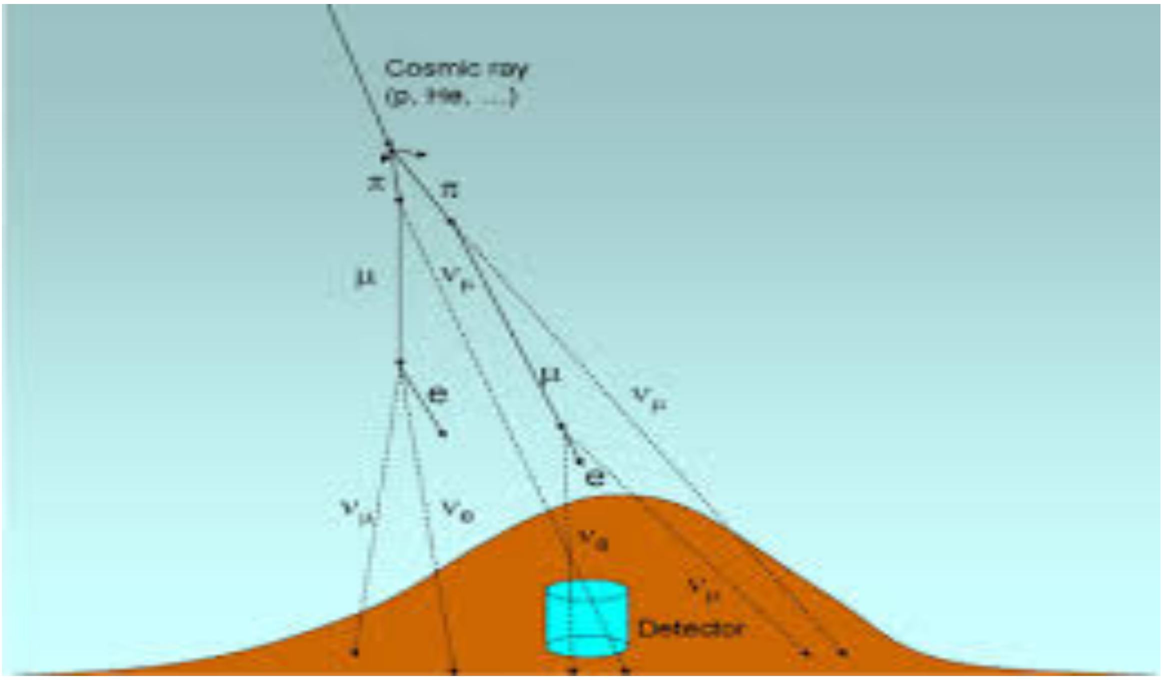
neutrino mass spectrum



Neutrino oscillations

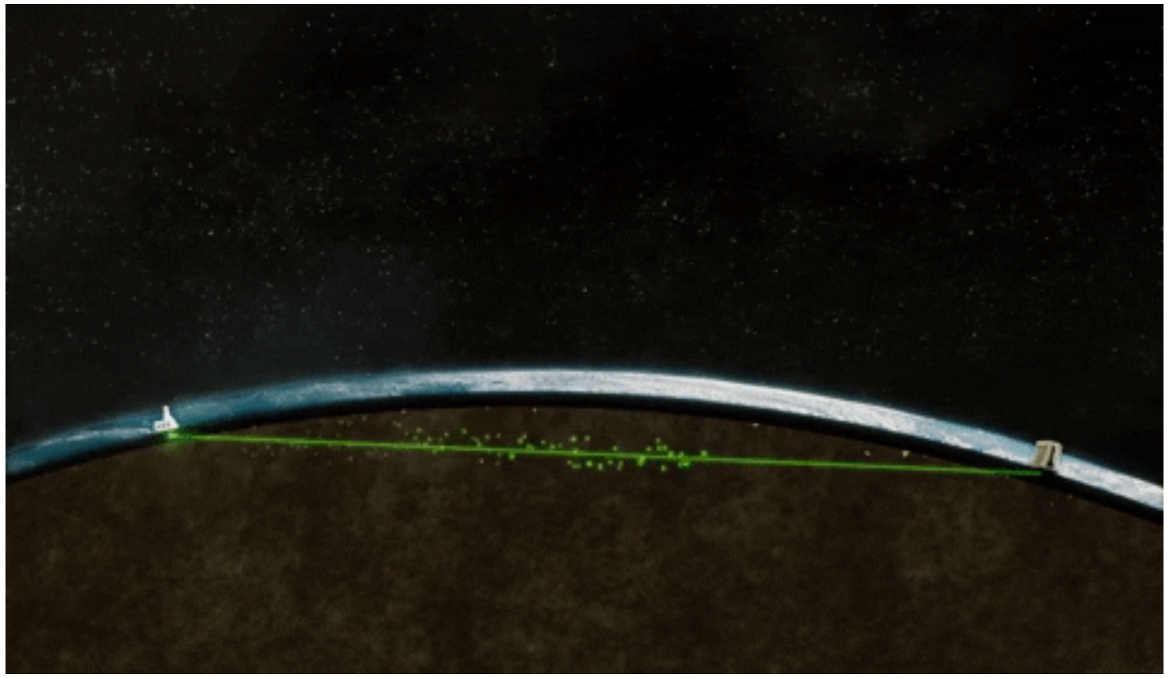
Solar neutrinos

Atmospheric neutrinos



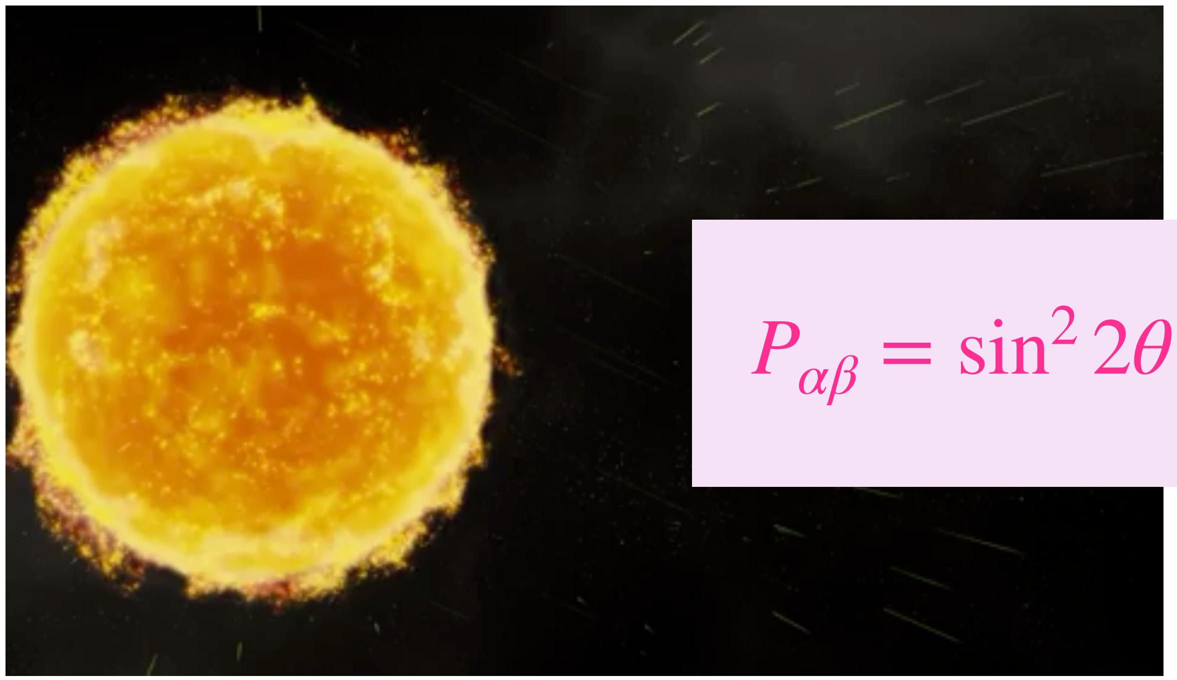
Reactor neutrinos

Accelerator neutrinos

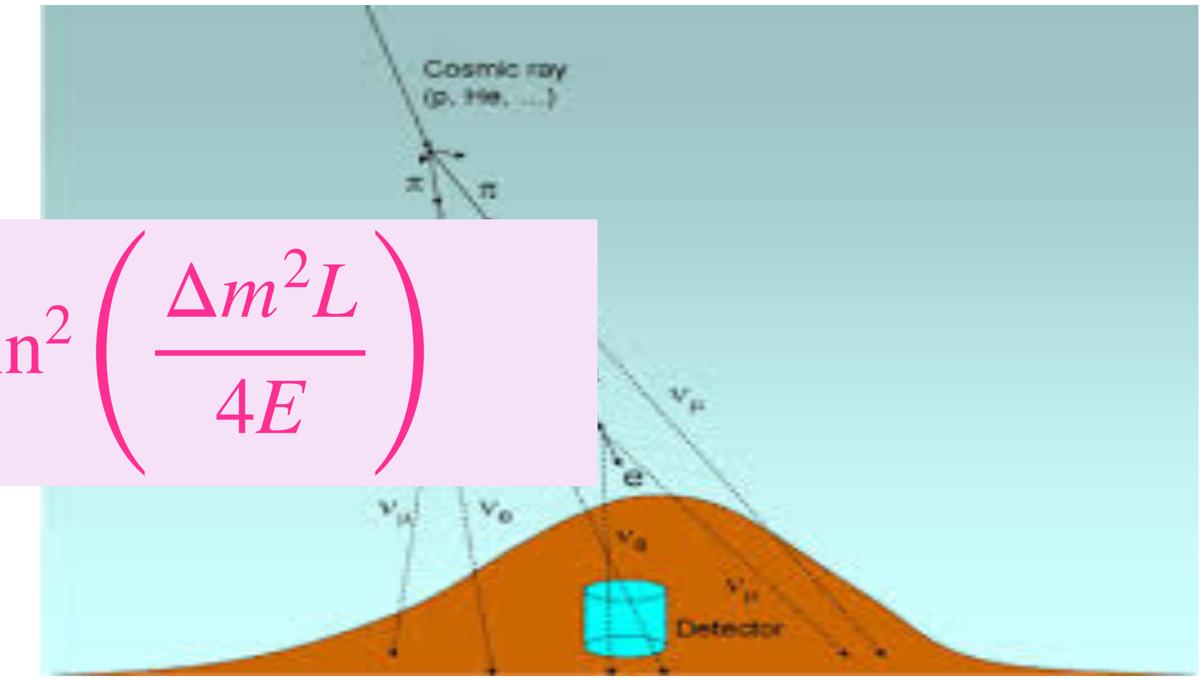


Neutrino oscillations

Solar sector: θ_{12}, Δm^2_{21}



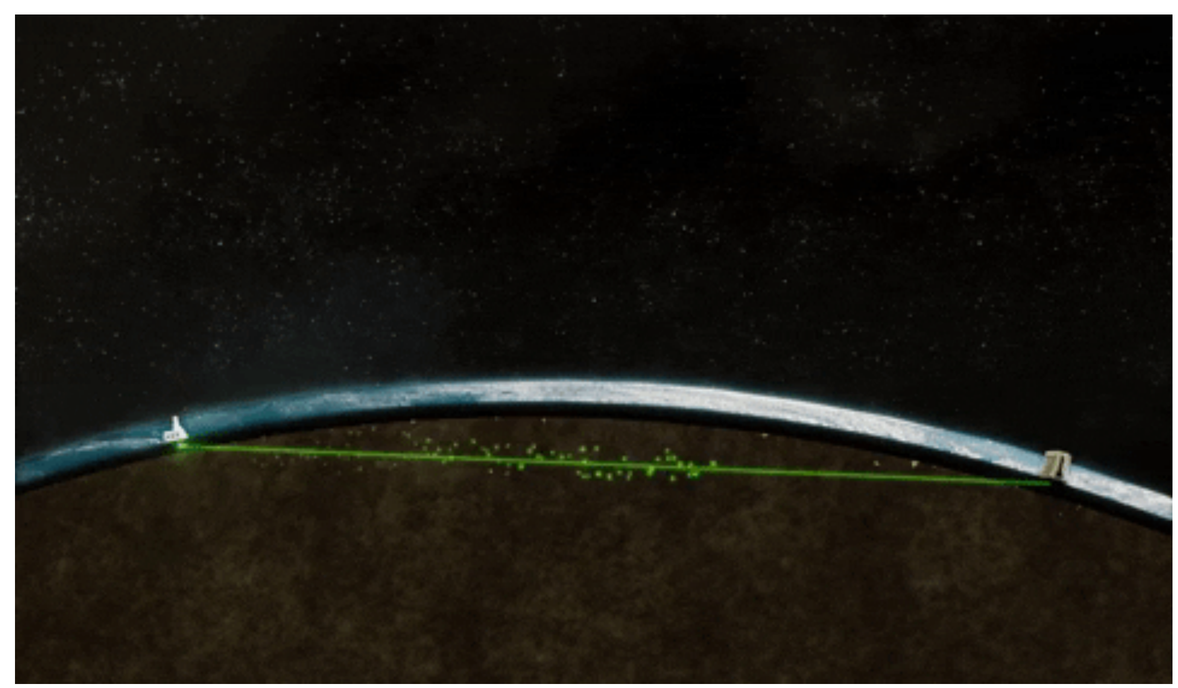
Atmospheric sector: θ_{23}, Δm^2_{31}



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

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

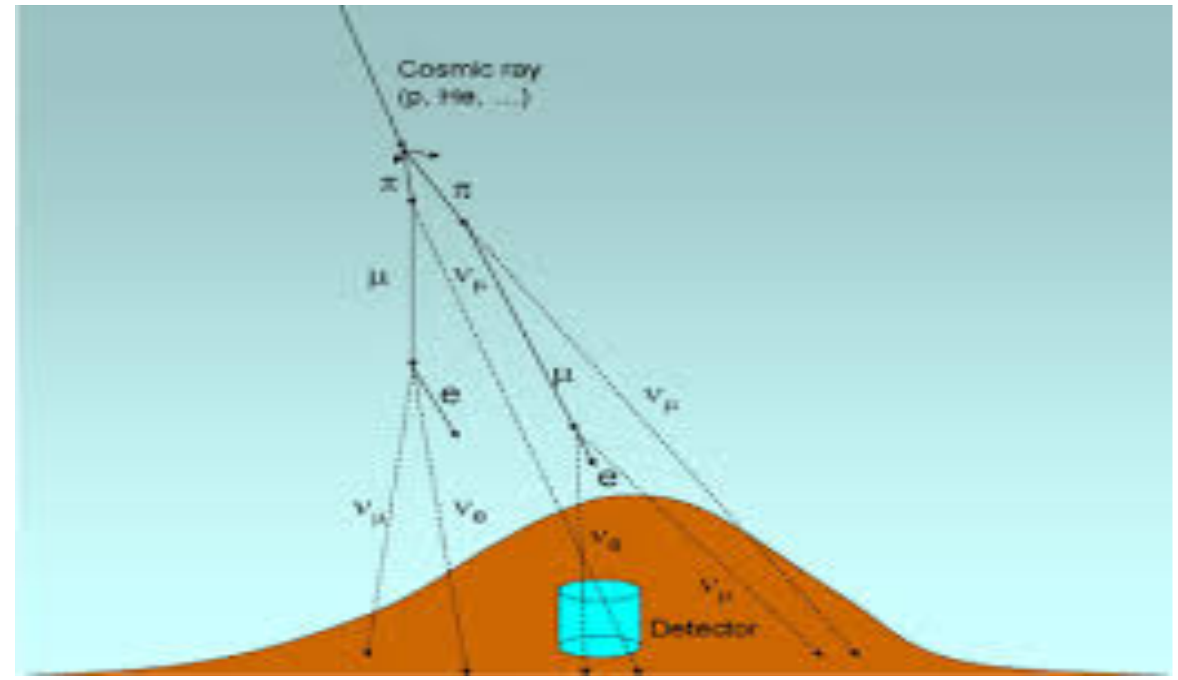
Accelerator sector: θ_{23}, Δm^2_{31}



Neutrino oscillations

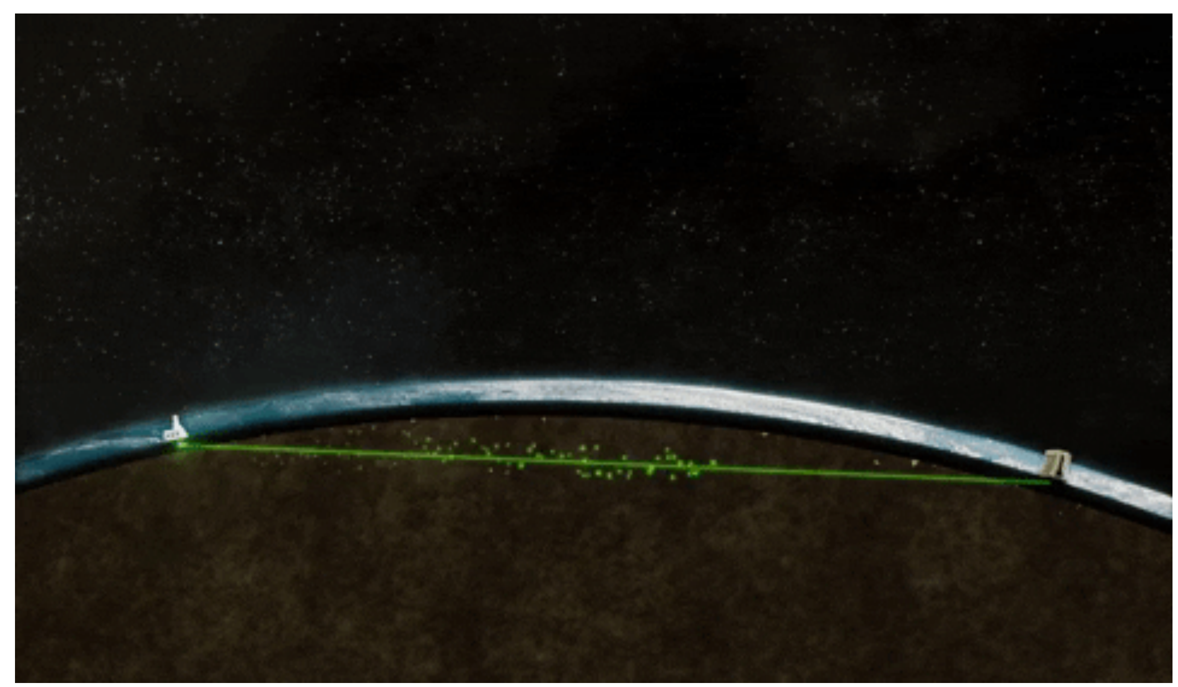
Solar sector: θ_{12}, θ_{13}, Δm^2_{21}

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



Three-neutrino oscillations

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} Re(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j})\sin^2\left(\frac{\Delta m^2_{ij}L}{4E}\right) + 2\sum_{i>j} Im(U^*_{\alpha i}U_{\alpha j}U_{\beta i}U^*_{\beta j})\sin\left(\frac{\Delta m^2_{ij}L}{2E}\right)$$

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

atmos + accel

$(\nu_\mu \to \nu_\tau)$

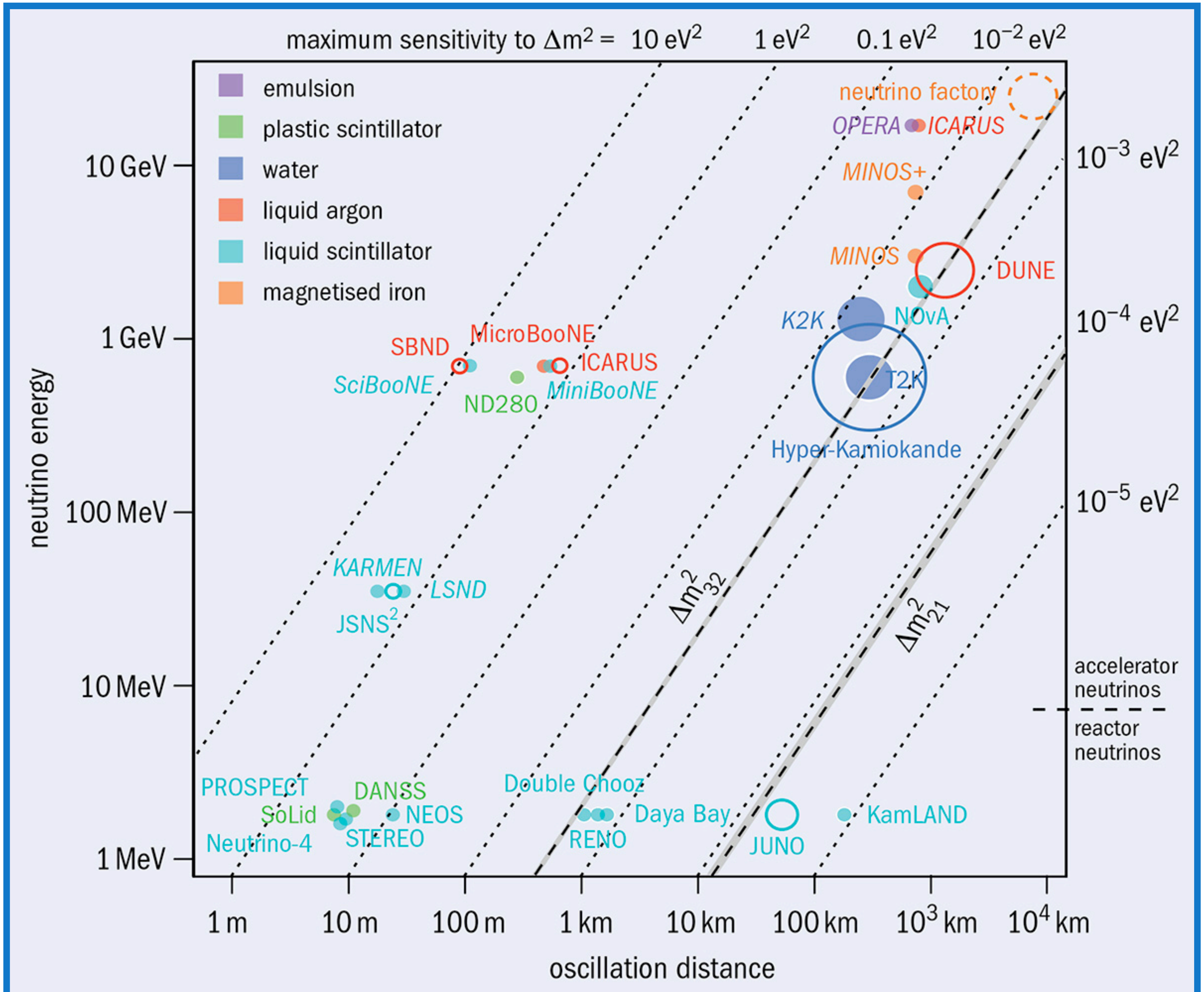
SBL reac + accel

$(\nu_e \to \nu_x$ and $\nu_\mu \to \nu_e)$

solar + LBL reac

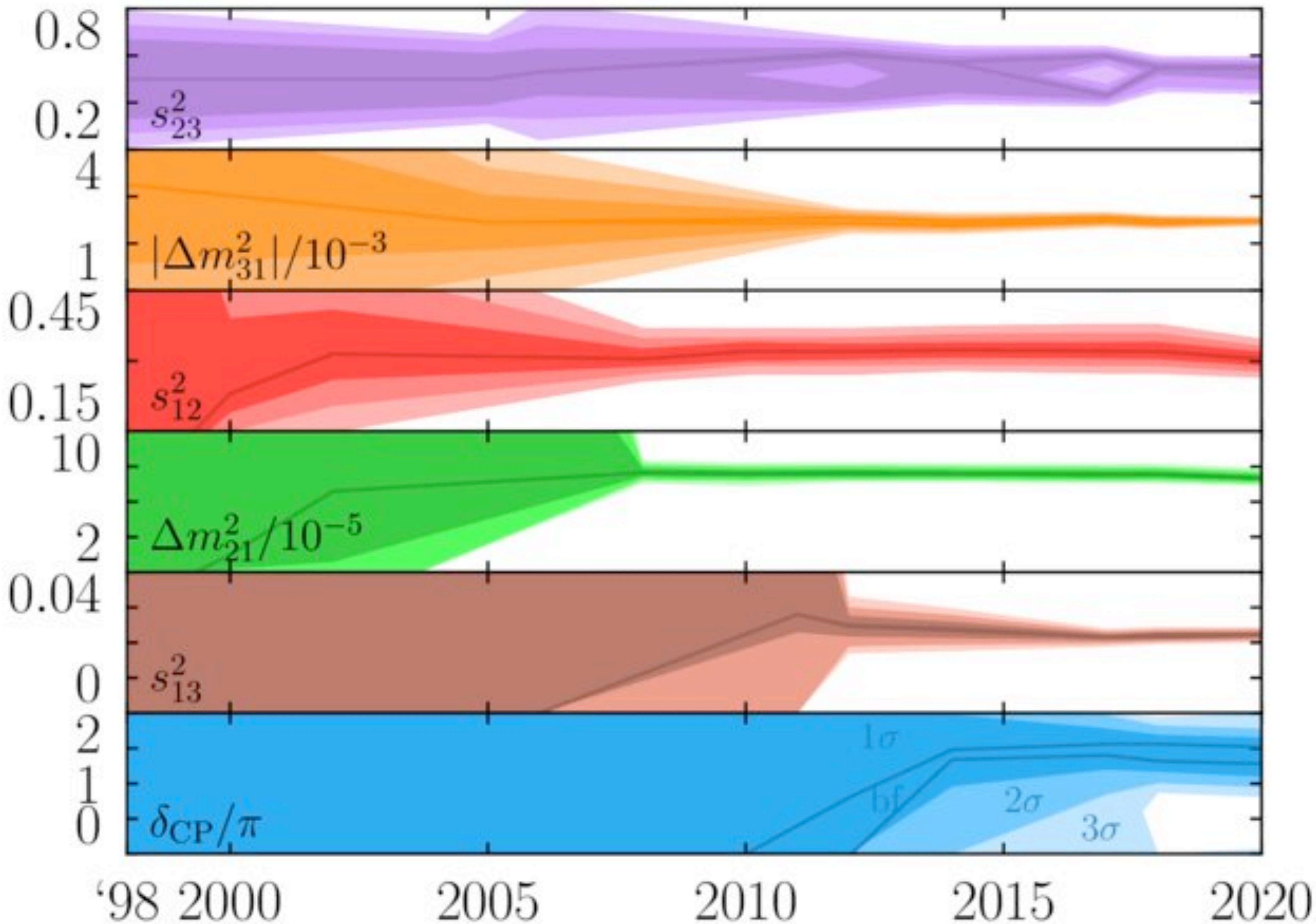
$(\nu_e \to \nu_x)$

Maximal sensitivity at
$$\frac{\Delta m^2_{ij}L}{4E} \sim \frac{\pi}{2} = 1.27\frac{\Delta m^2_{ij}[eV^2]\,L[km]}{E[GeV]}$$



M Rayner, CERN Courier, 2020

Three-neutrino oscillation parameters

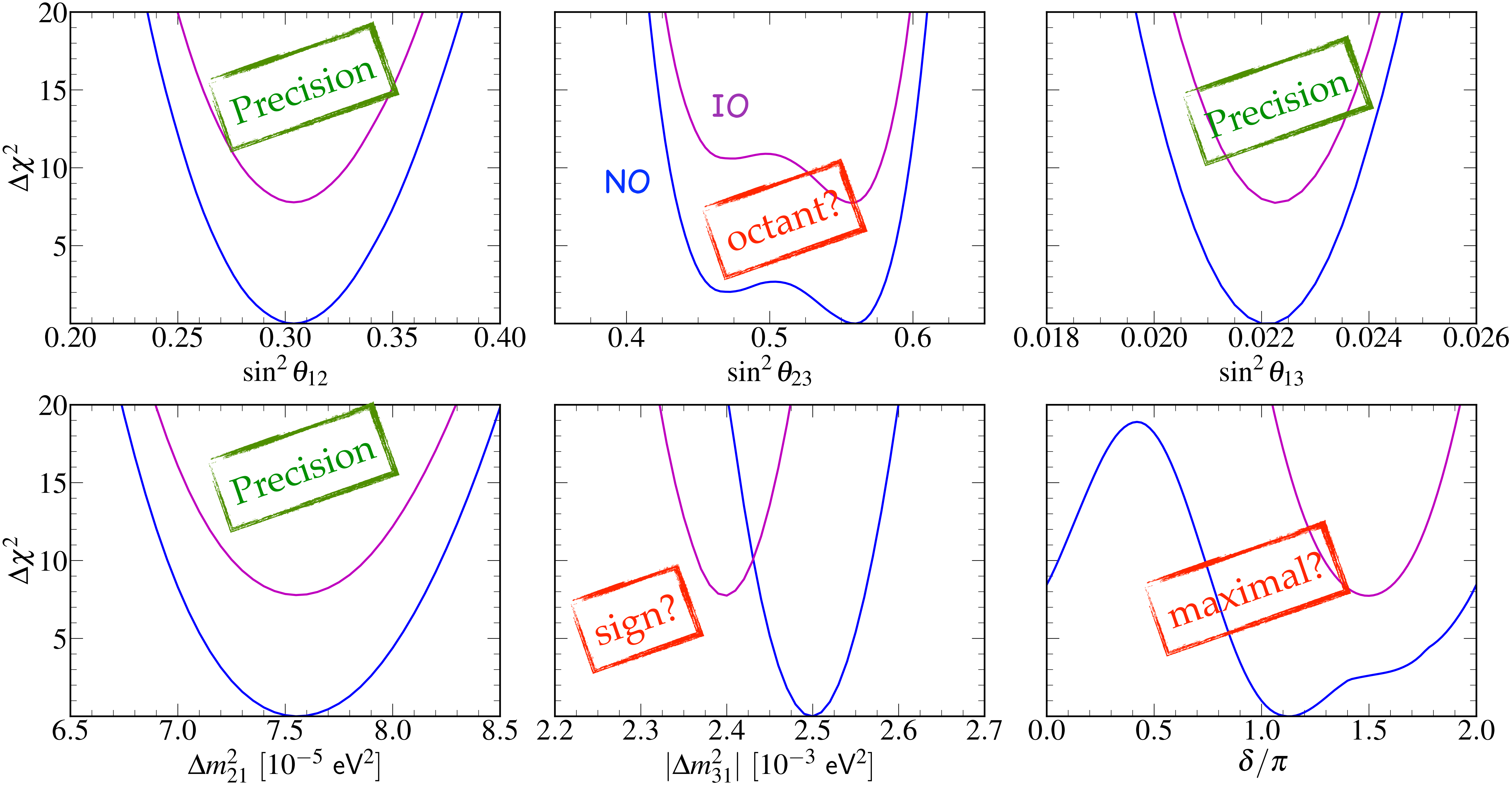


measured parameters:
θ_{12}, θ_{23}, θ_{13}, Δm^2_{21}, $|\Delta m^2_{31}|$

unknown quantities:
sign(Δm^2_{31}), θ_{23}-octant, δ_{CP}

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

Global fit to ν oscillation parameters



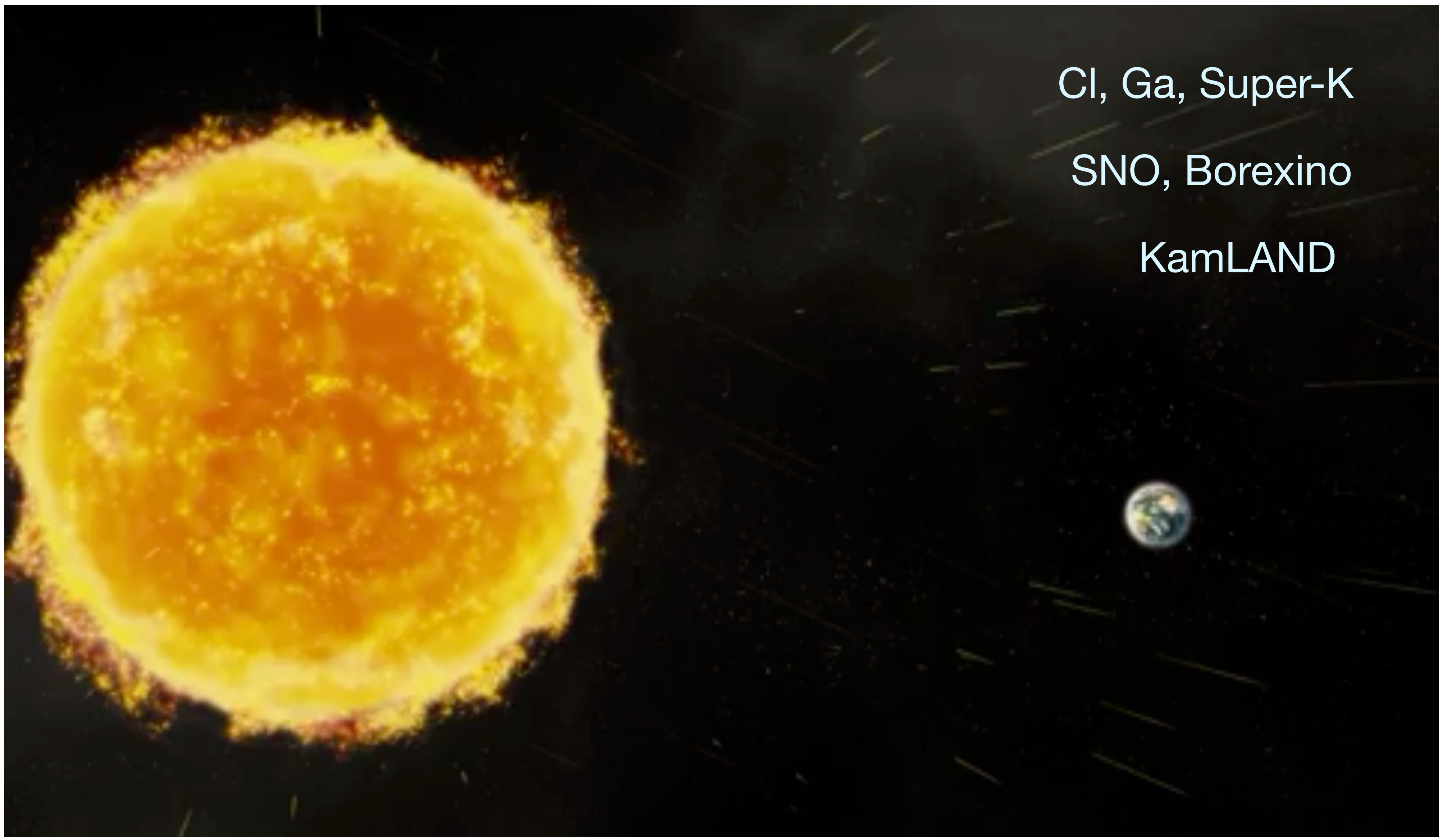
$\Delta\chi^2$(IO-NO) = 7.7

Global fit to ν oscillation parameters

parameter	best fit ± 1σ	3σ range	relative 1σ uncert	
$\Delta m^2_{21}\ [10^{-5}\mathrm{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7 %	
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ (NO)	2.50 ± 0.02	2.43–2.57	0.9 %	mass ordering?
$\lvert\Delta m^2_{31}\rvert\ [10^{-3}\mathrm{eV}^2]$ (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

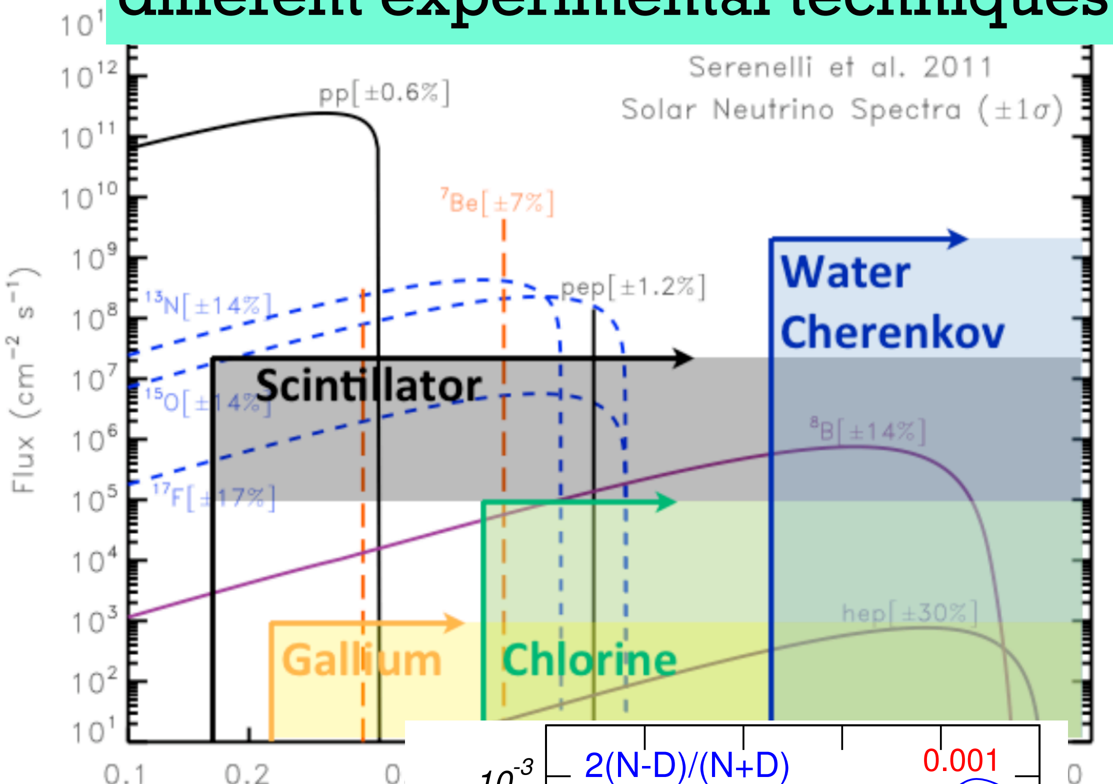
Solar sector: θ_{12}, θ_{13}, Δm^2_{21}



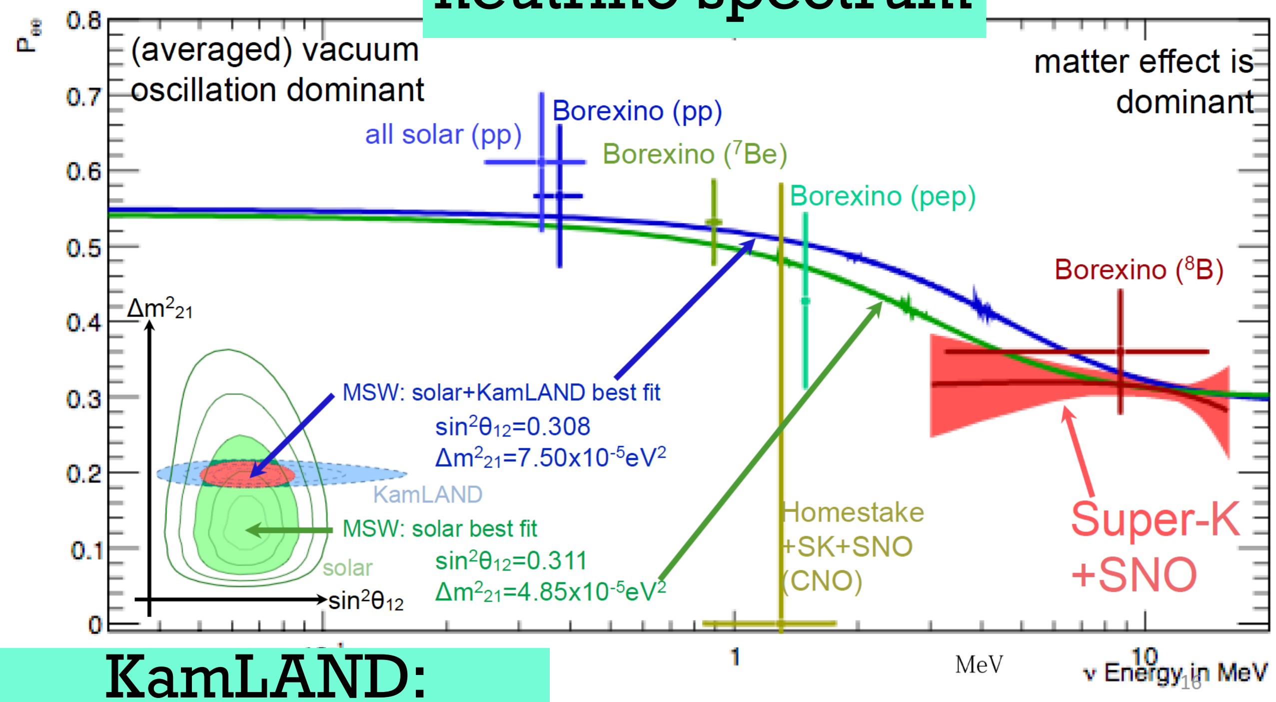
The solar sector

Solar experiments have measured neutrino disappearance for ~ 50 years

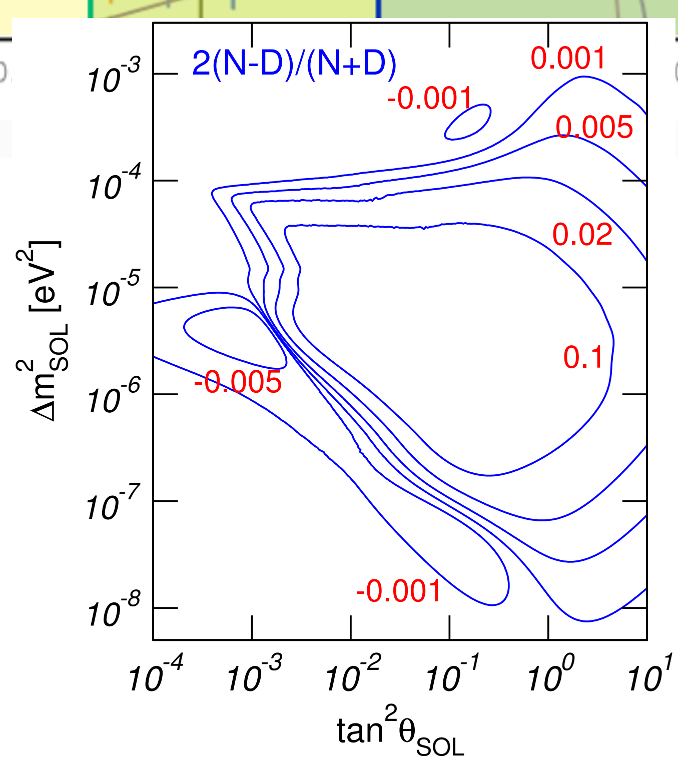
different experimental techniques



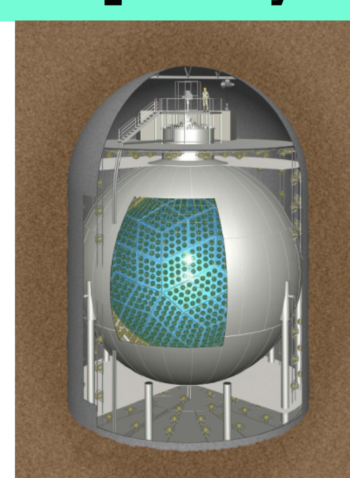
neutrino spectrum

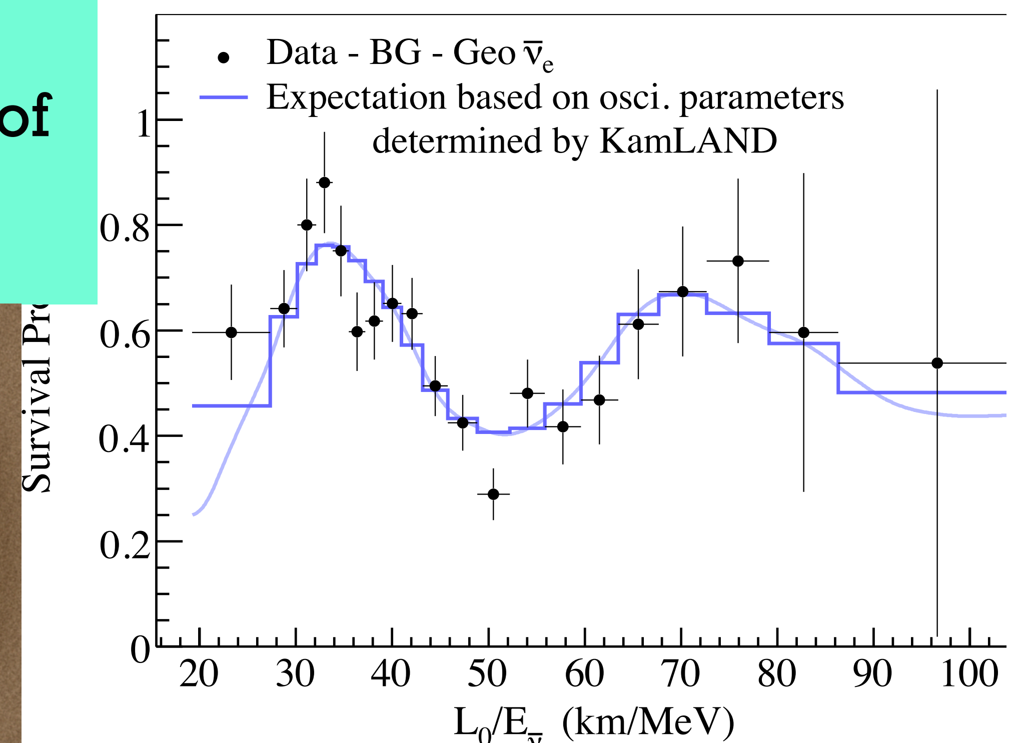


day/night asymmetry

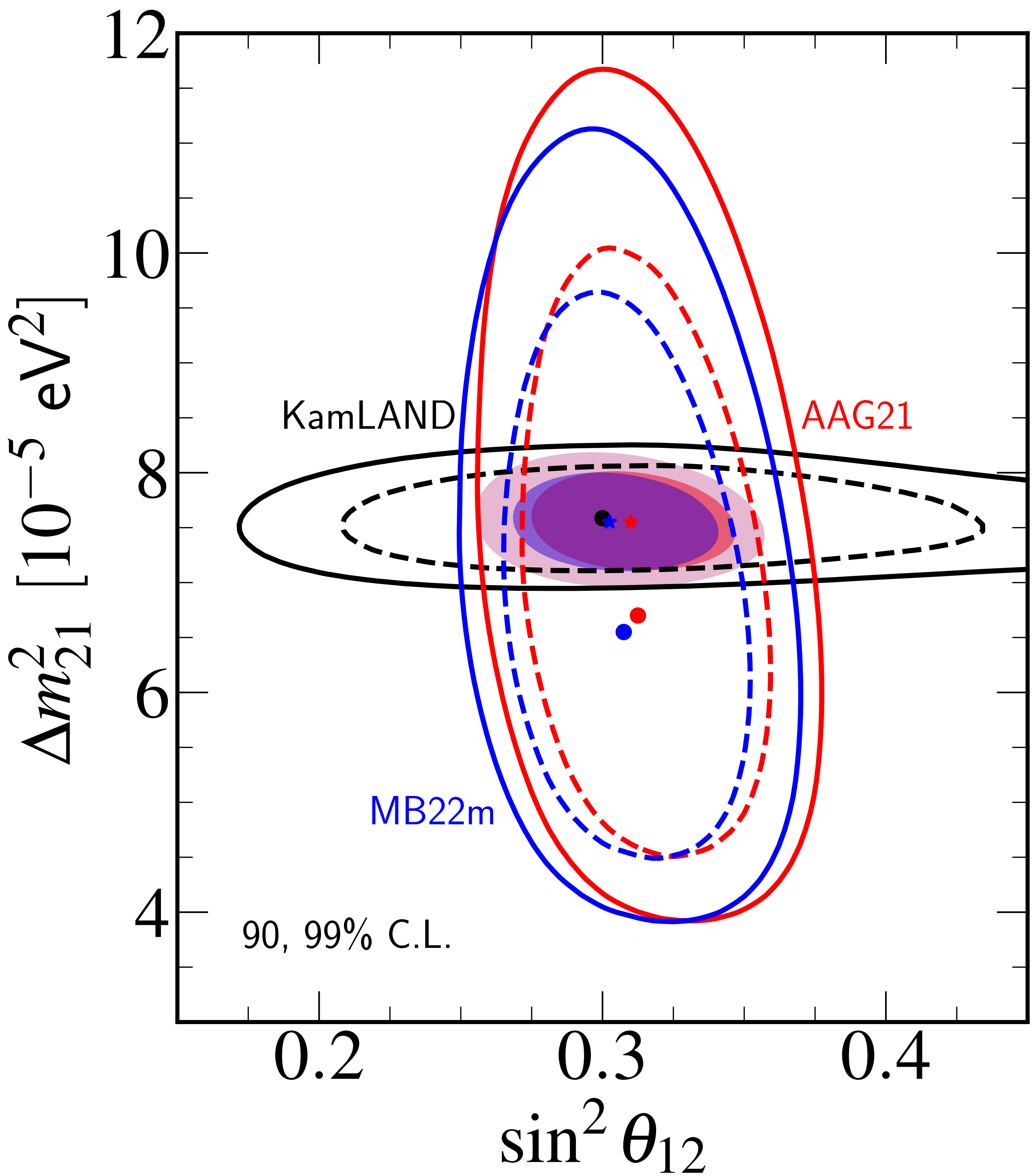


KamLAND: precise measurement of oscillation frequency





The solar sector



- ✦ θ_{12} measurement 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

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

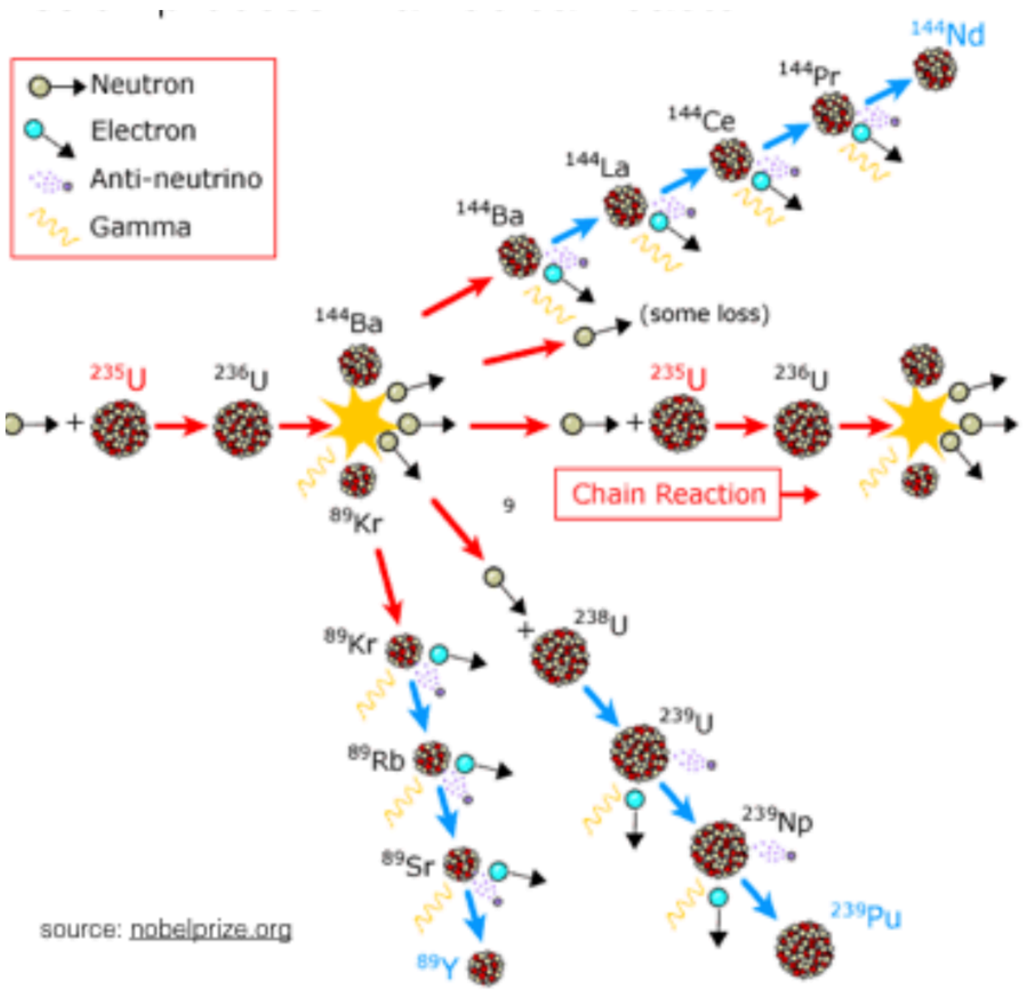
$$\Delta m^2_{21} = (7.55 \pm 0.21) \times 10^{-5}\ \mathrm{eV}^2$$

Neutrino oscillations

Reactor sector: θ_{13}, Δm^2_{31}

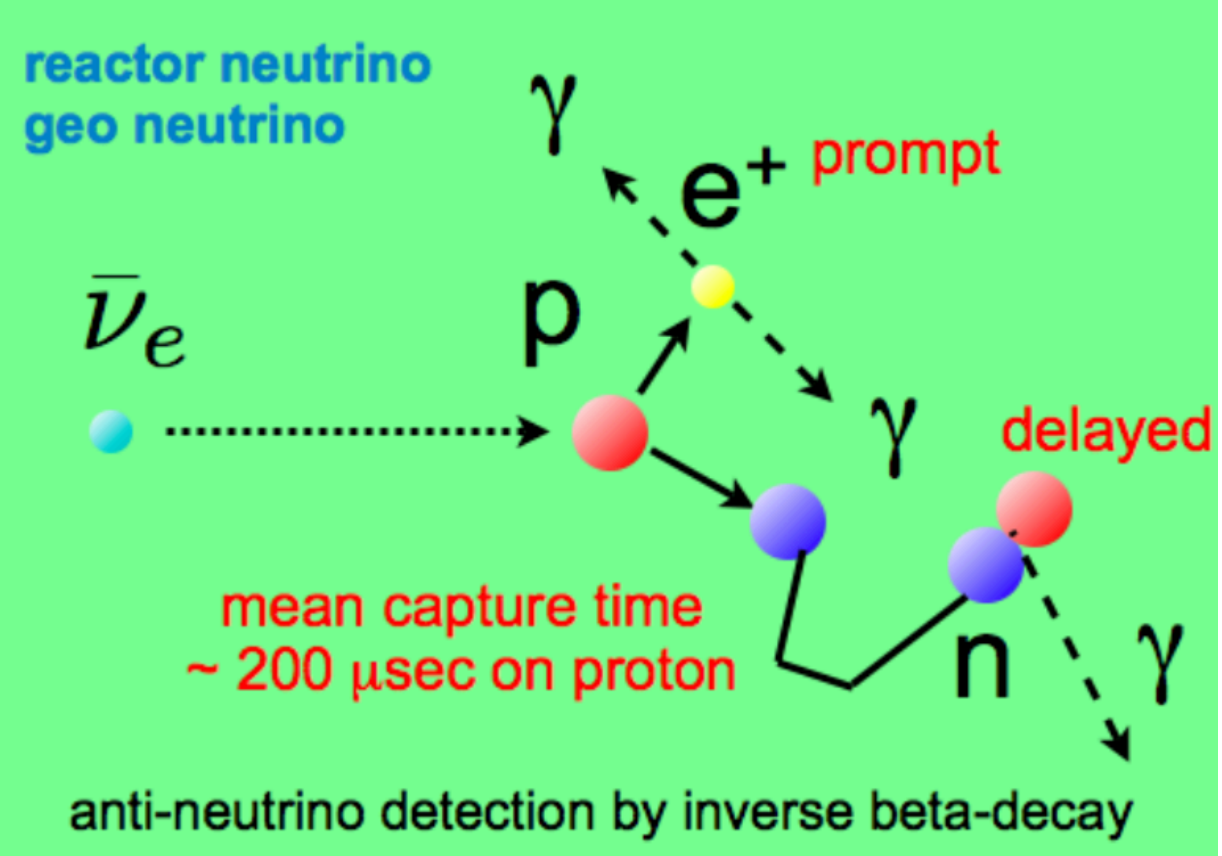
Reactor neutrinos

Production: fission processes in nuclear reactors

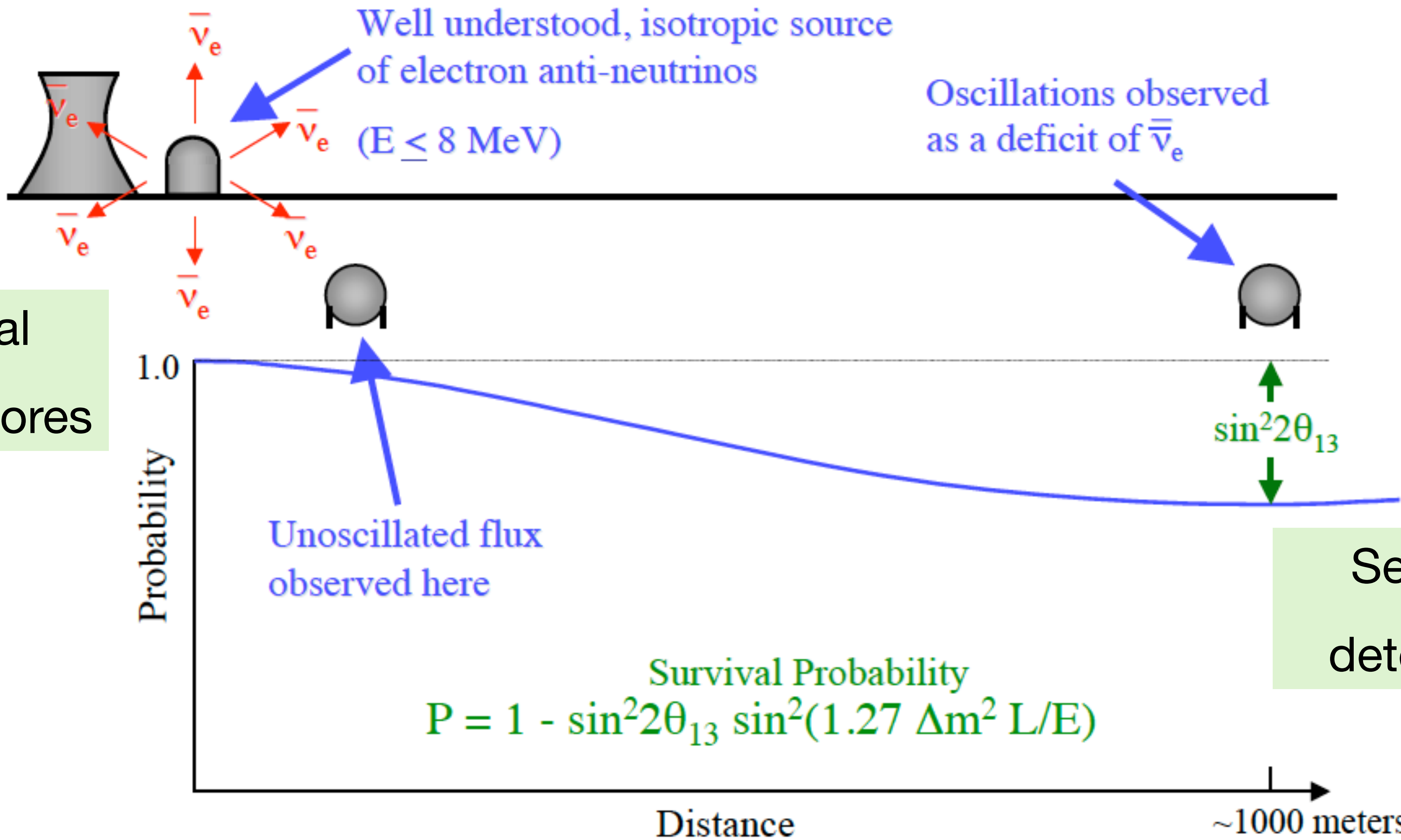


1 GW reactor: more than 10^{20} antineutrinos/s

Detection: inverse beta decay



SBL reactor experiments



Several reactor cores

Several detectors

L ~1 km: θ_{13}, Δm^2_{31}

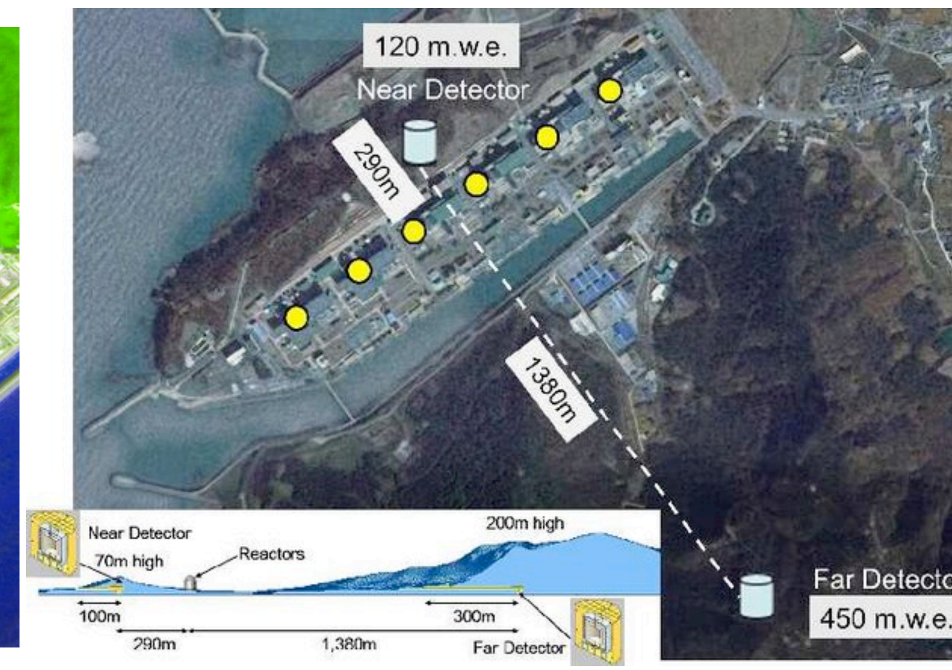
→ sensitive to $|\Delta m^2_{31}|$ ~ few 10^{-3} eV^2

oscillations in vacuum

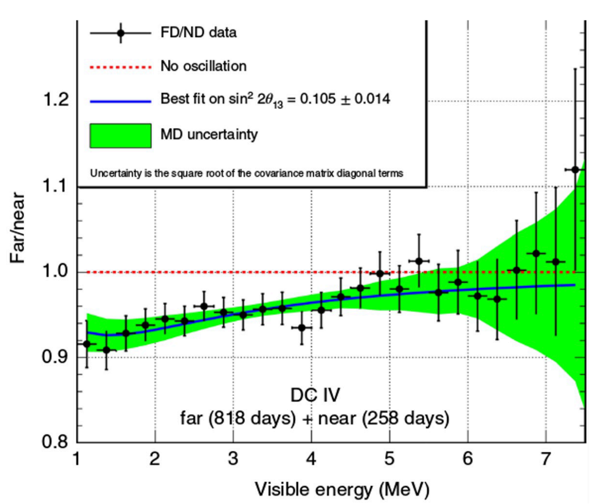
SBL reactor experiments

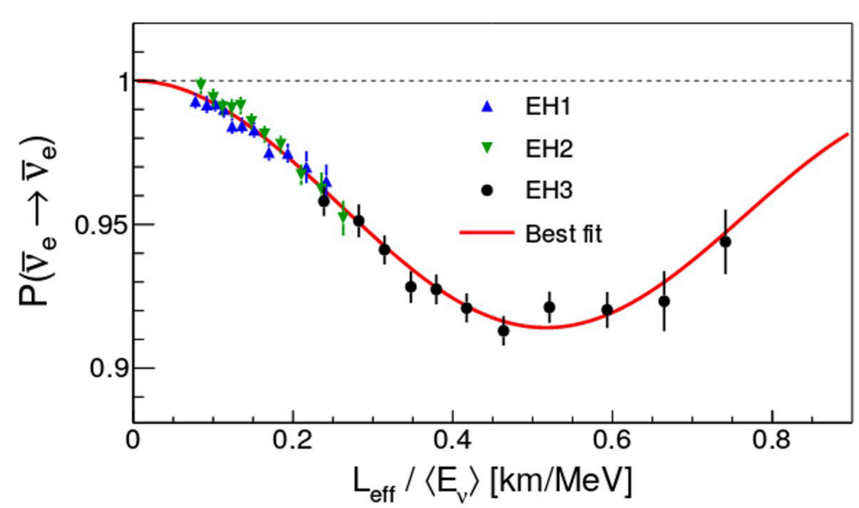
2 reactors + 1 ND + 1 FD (10 ton)

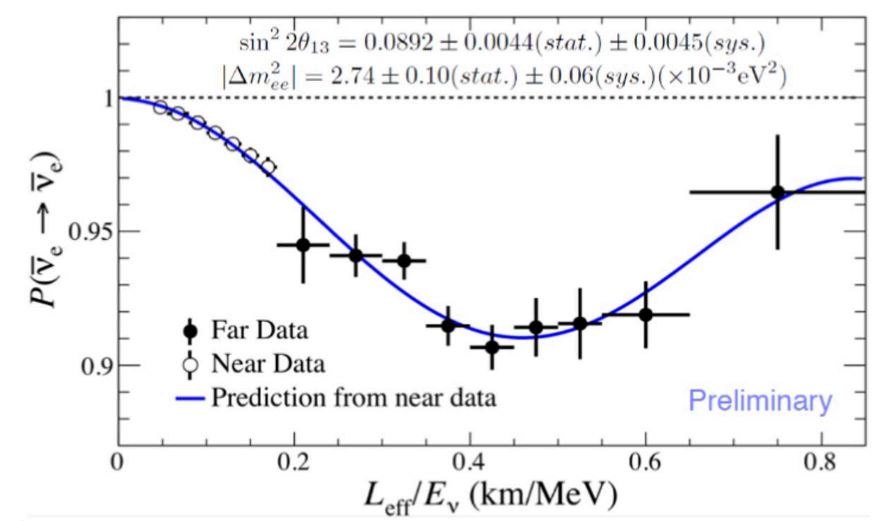
6 reactors + 4 ND + 4FD (20 ton)



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

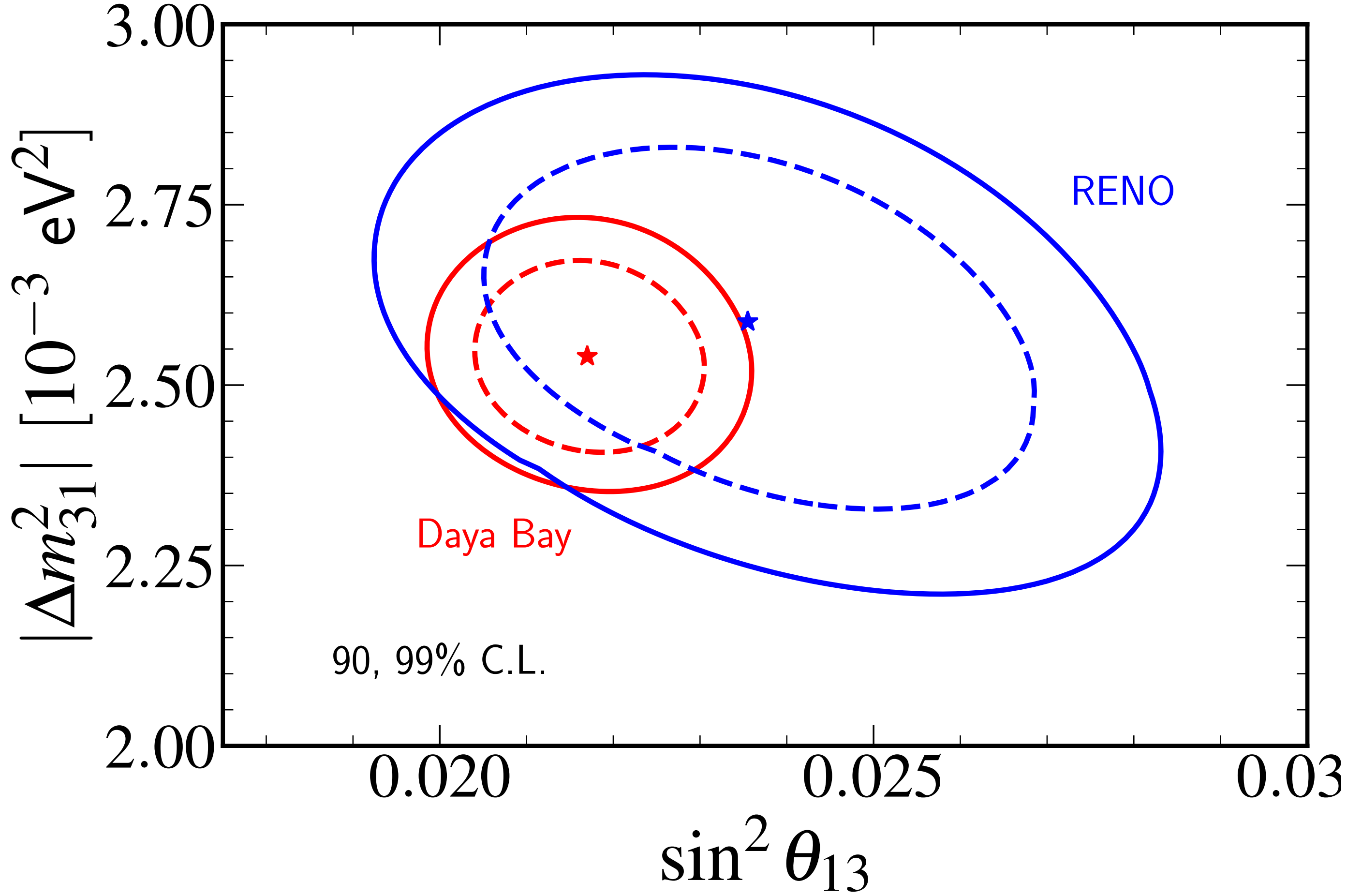






The reactor sector

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



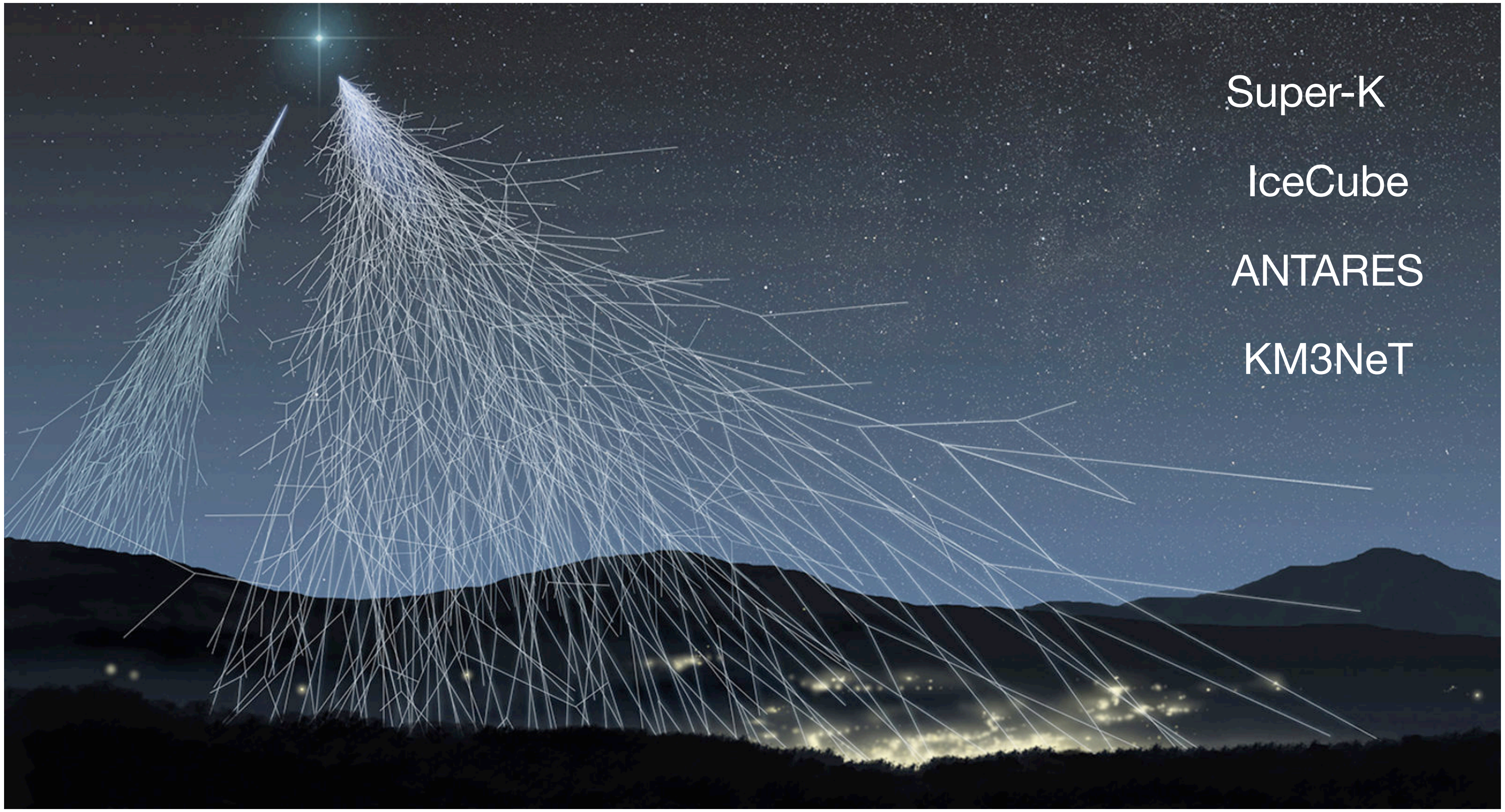
- **Double Chooz** first measured θ_{13} but now its precision is not comparable.
- Precision dominated by **RENO** and **Daya Bay**.

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

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

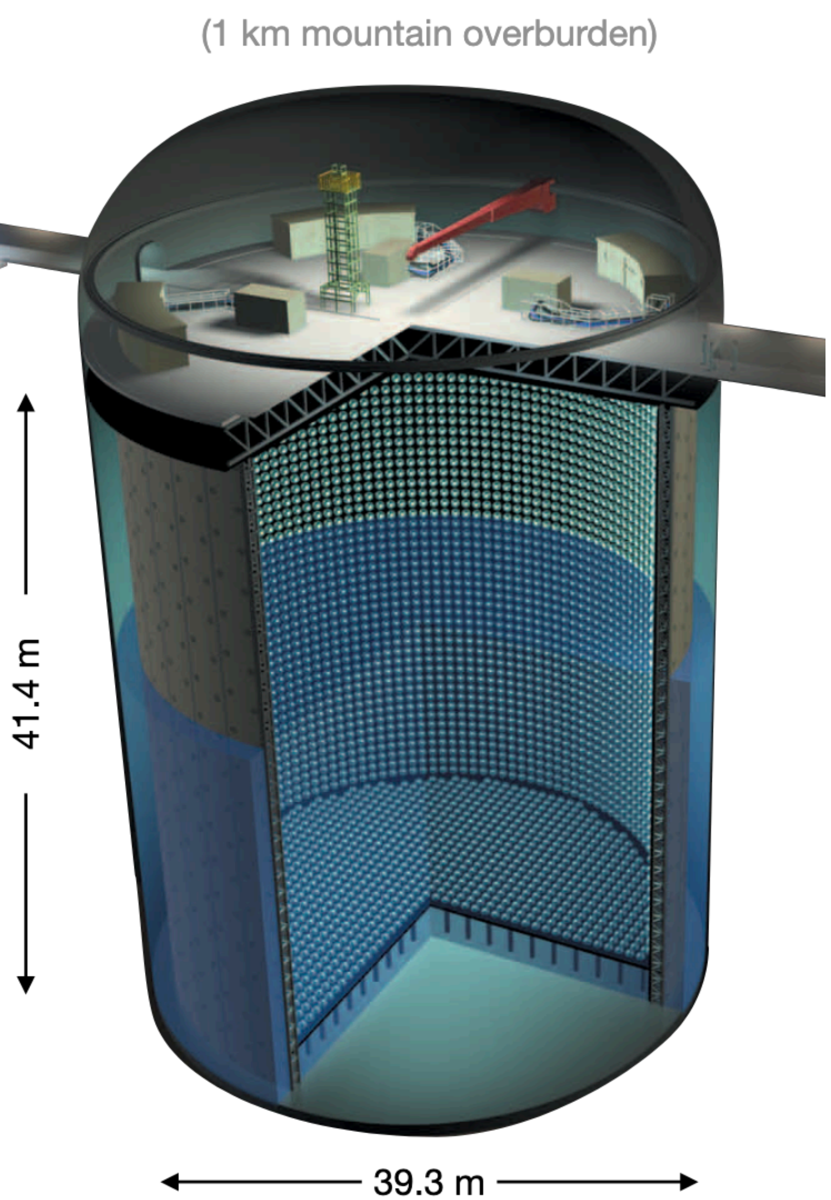
Neutrino oscillations

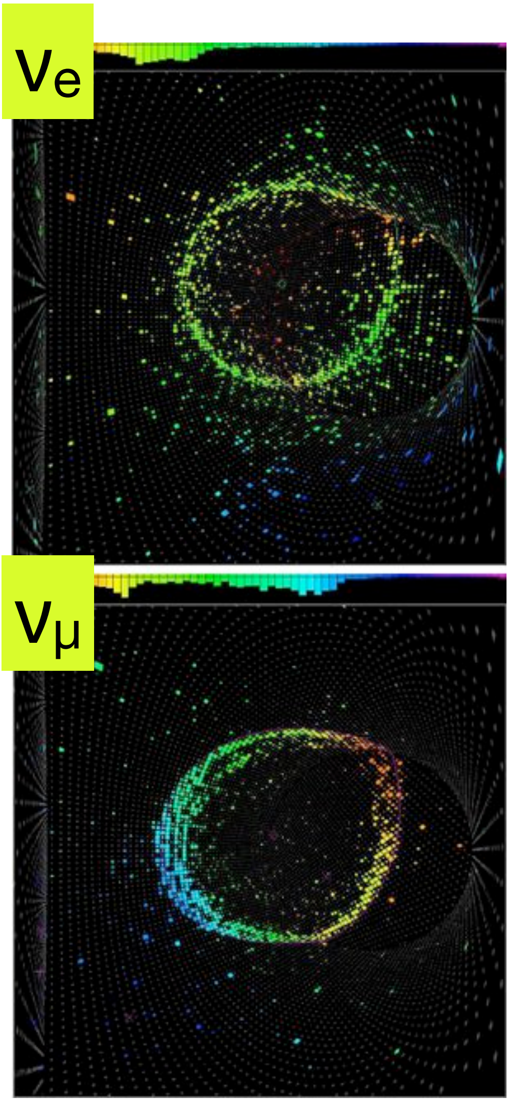
Atmospheric sector: θ_{23}, θ_{13}, Δm^2_{31}, δ



The atmospheric sector

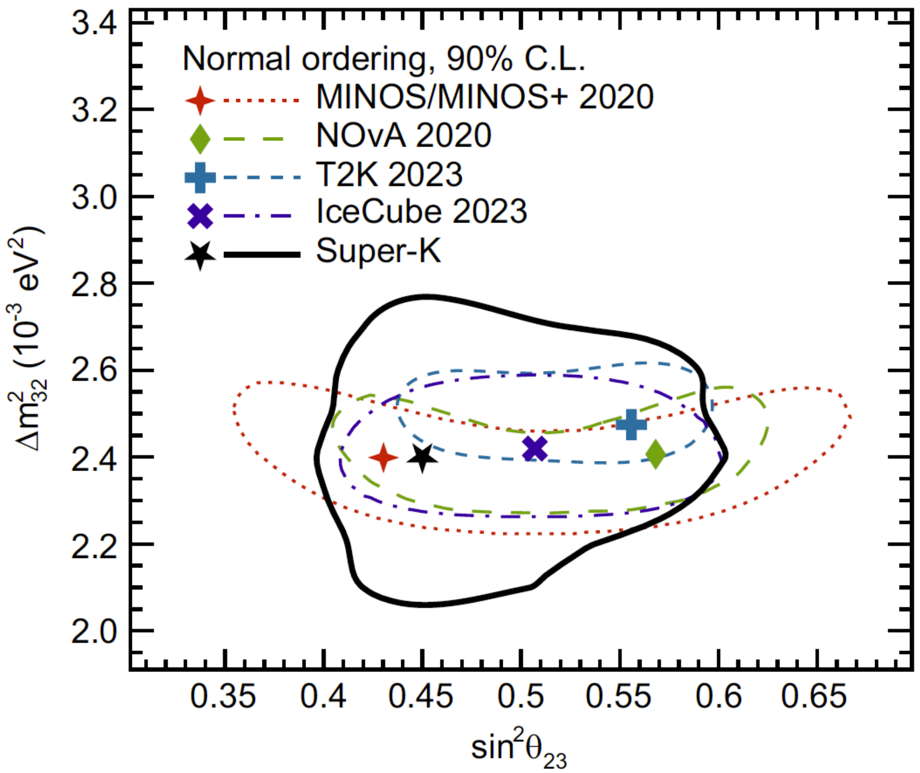
Super-Kamiokande detects atmospheric neutrinos since 1996.
Neutrino oscillations discovery in 1998





$$P\nu_\mu \to \nu_\mu \simeq 1 - \sin^2 2\theta_{23}\ \sin^2\left(\frac{\Delta m^2_{32}}{4E} L\right)$$

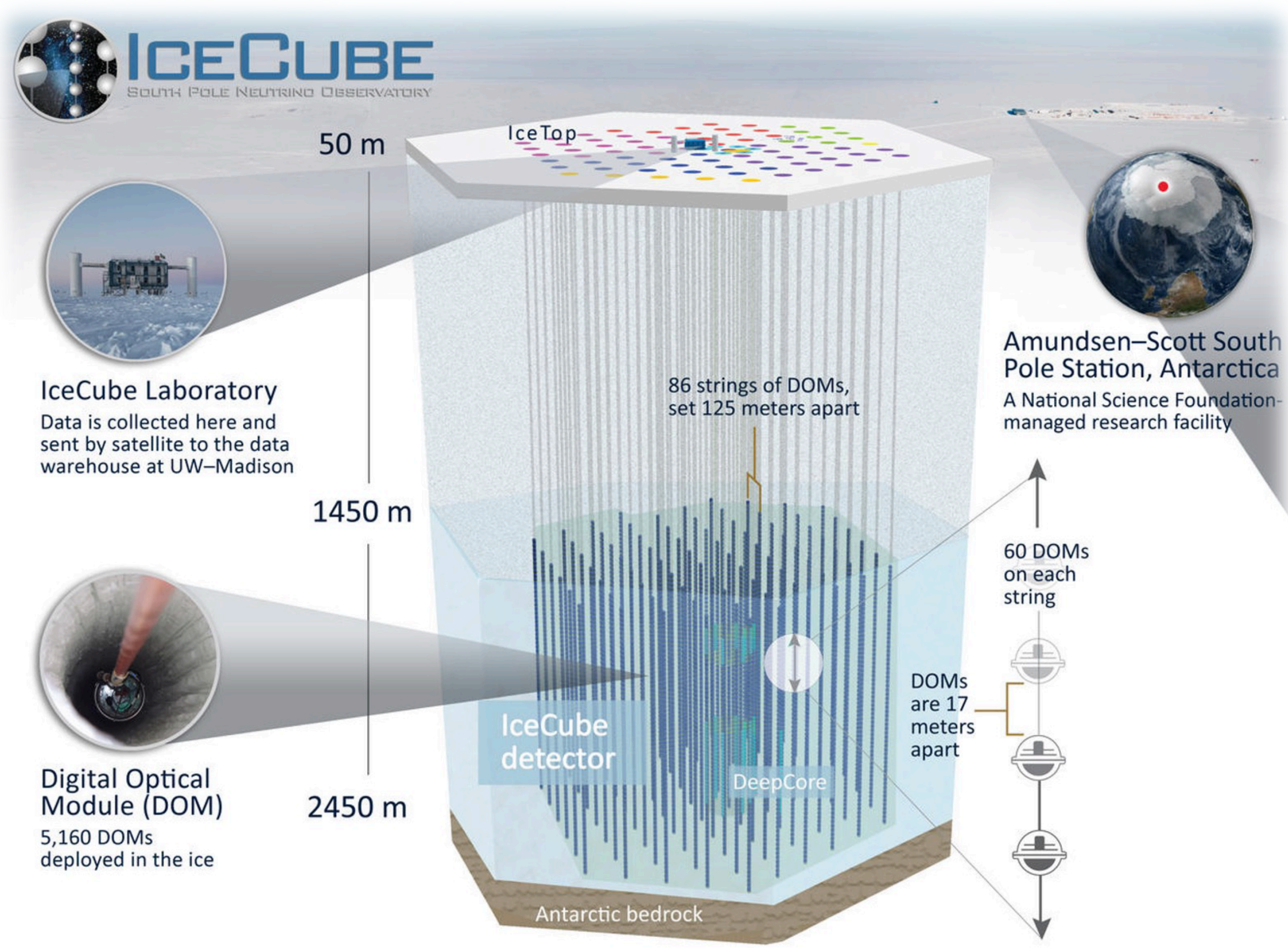
SK Collab, PRD 109 (2024) 072014

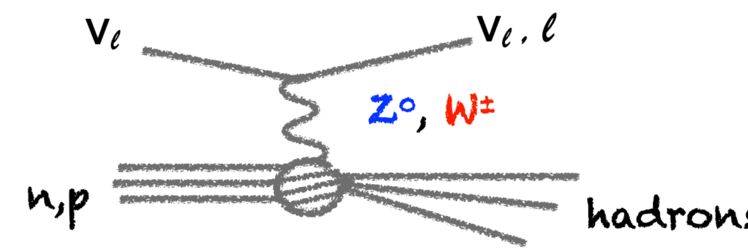


→ very good sensitivity to θ_{23} and Δm^2_{32}

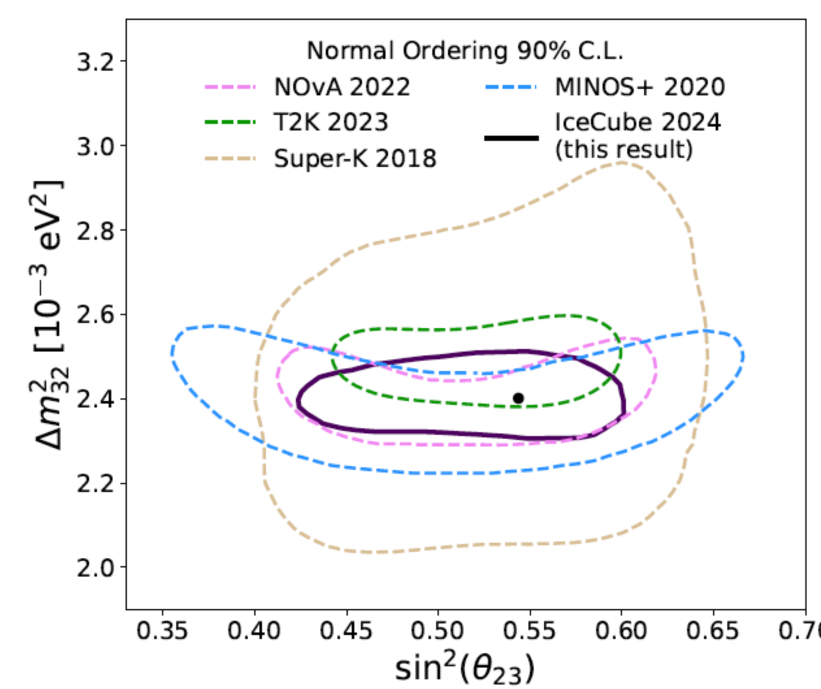
The atmospheric sector

IceCube detects atmospheric neutrinos using 1 km^3 of ice as detector at the South Pole





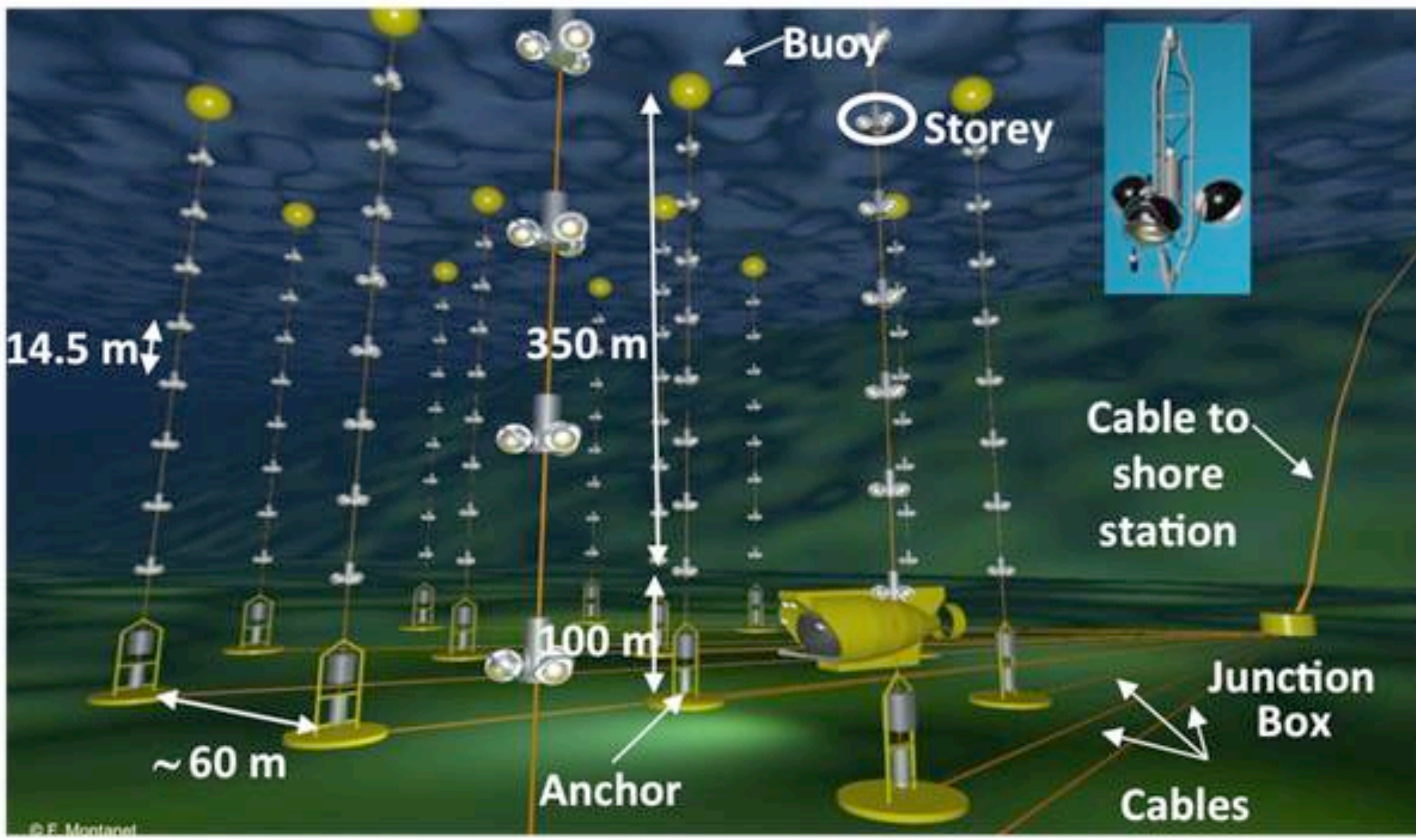
IceCube Collab, arXiv:2405.02163

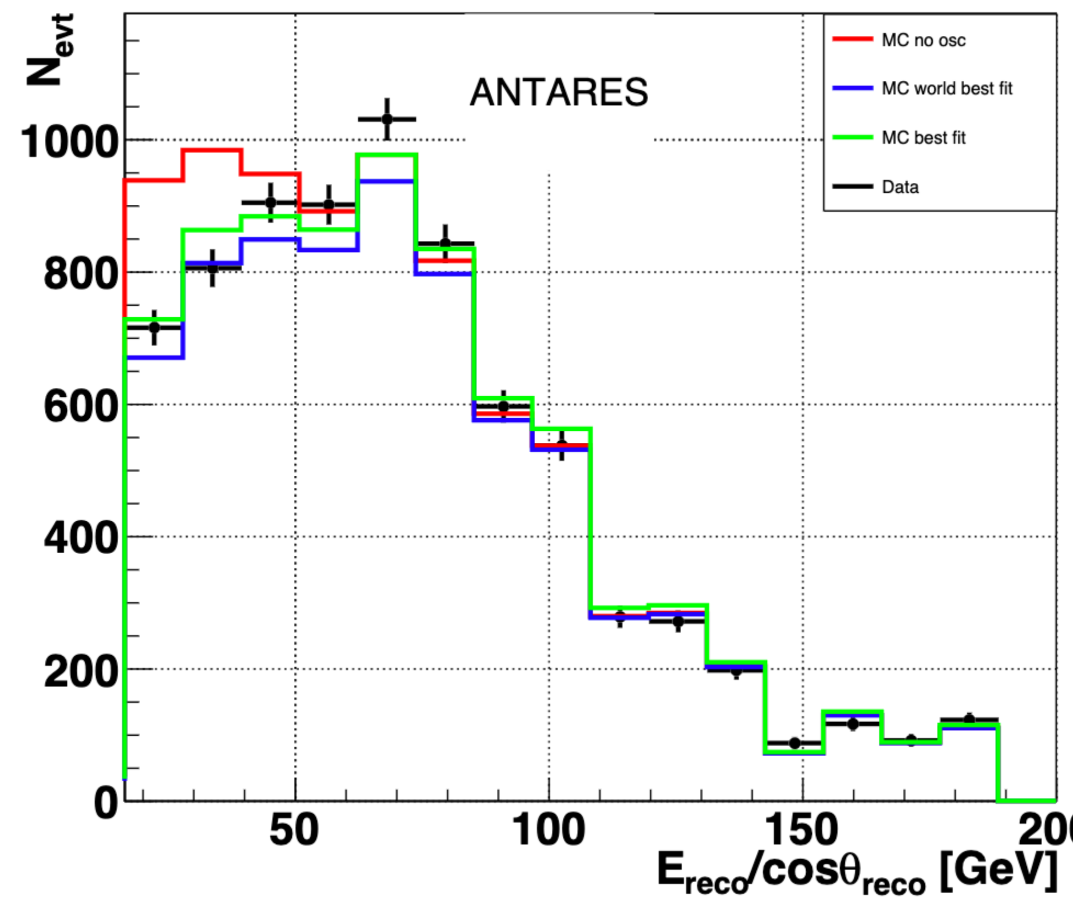


→ more precise than Super-Kamiokande

The atmospheric sector

ANTARES observed atmospheric neutrinos at the Mediterranean Sea

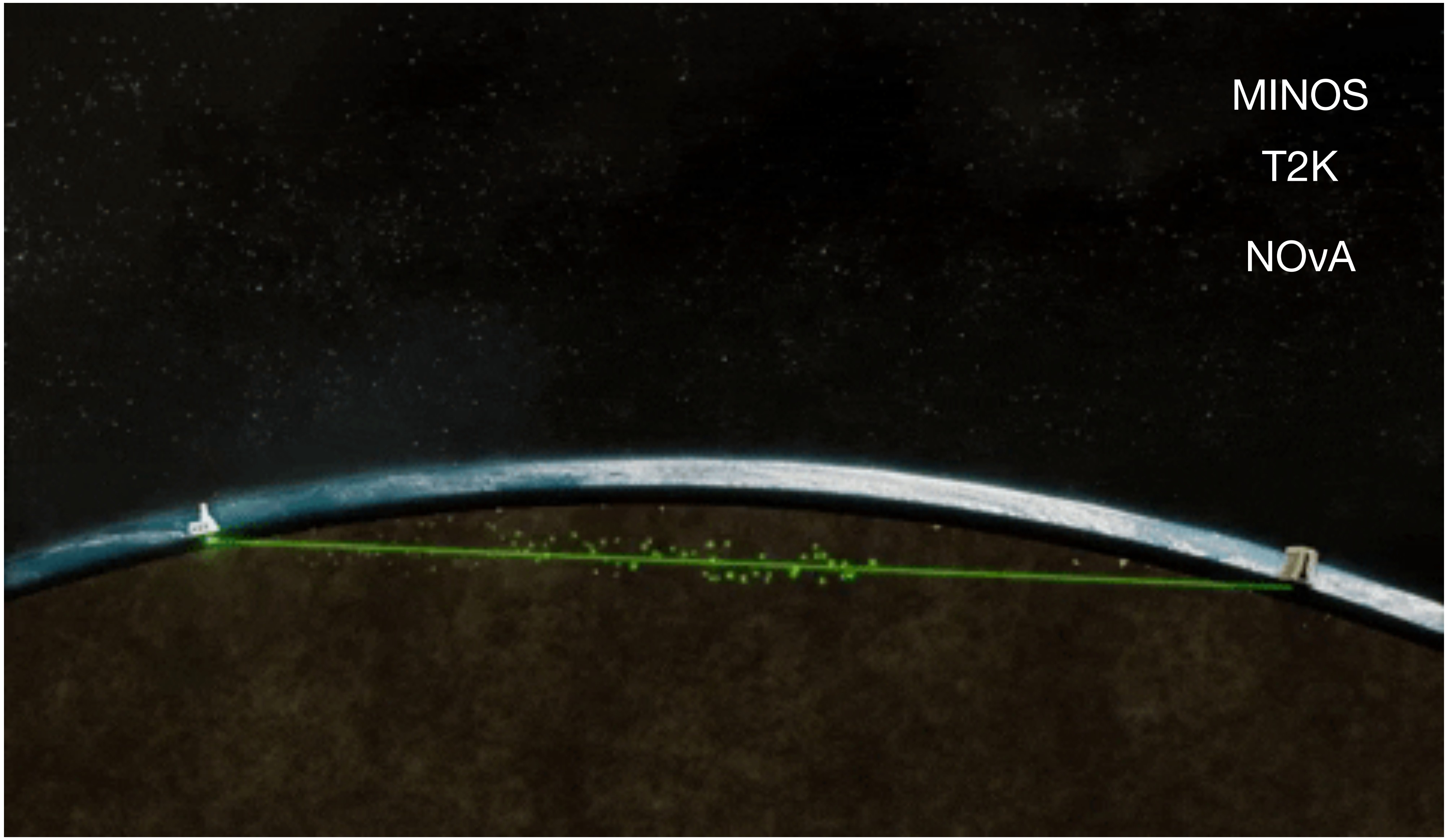




→ results in agreement with oscillations in the channel $\nu_\mu \rightarrow \nu_\tau$

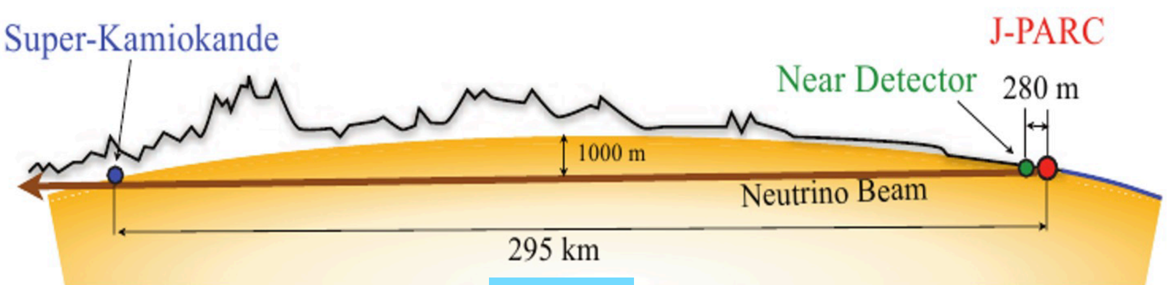
Neutrino oscillations

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



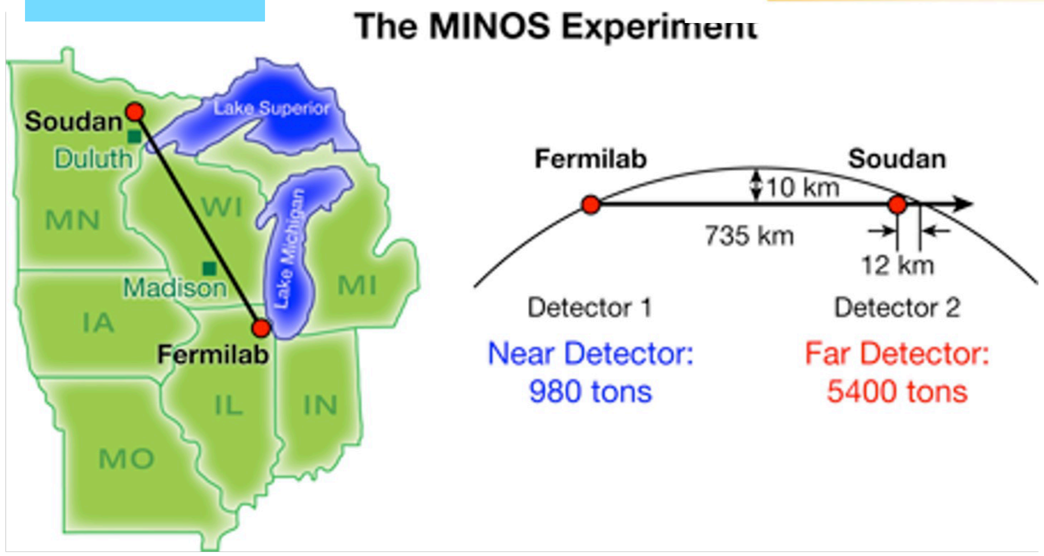
The accelerator sector

- Designed to check the atmospheric neutrino oscillation channel
- L/E ~500 km/GeV to be sensitive to Δm^2_{31} ~ few 10^{-3} eV^2
- Combine near detector + far detector

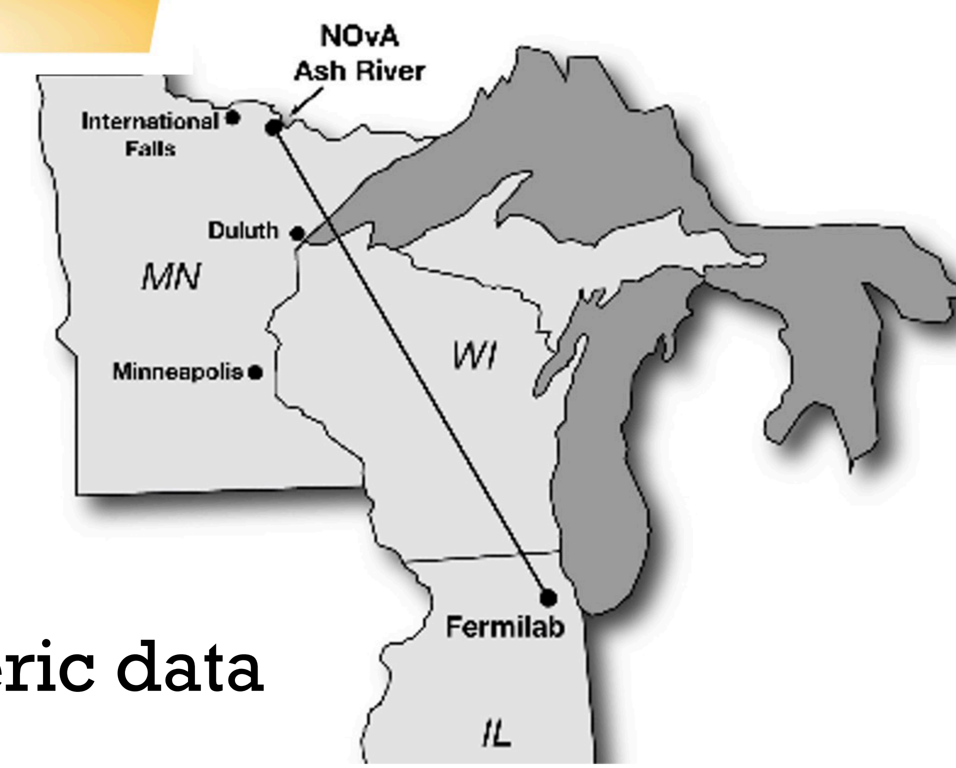


T2K

MINOS



NOvA



→ results consistent with atmospheric data

→ sensitive to $\nu_\mu \to \nu_\mu$ and $\nu_\mu \to \nu_e$

The accelerator sector

ν_μ and $\bar{\nu}_\mu$ disappearance

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

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

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

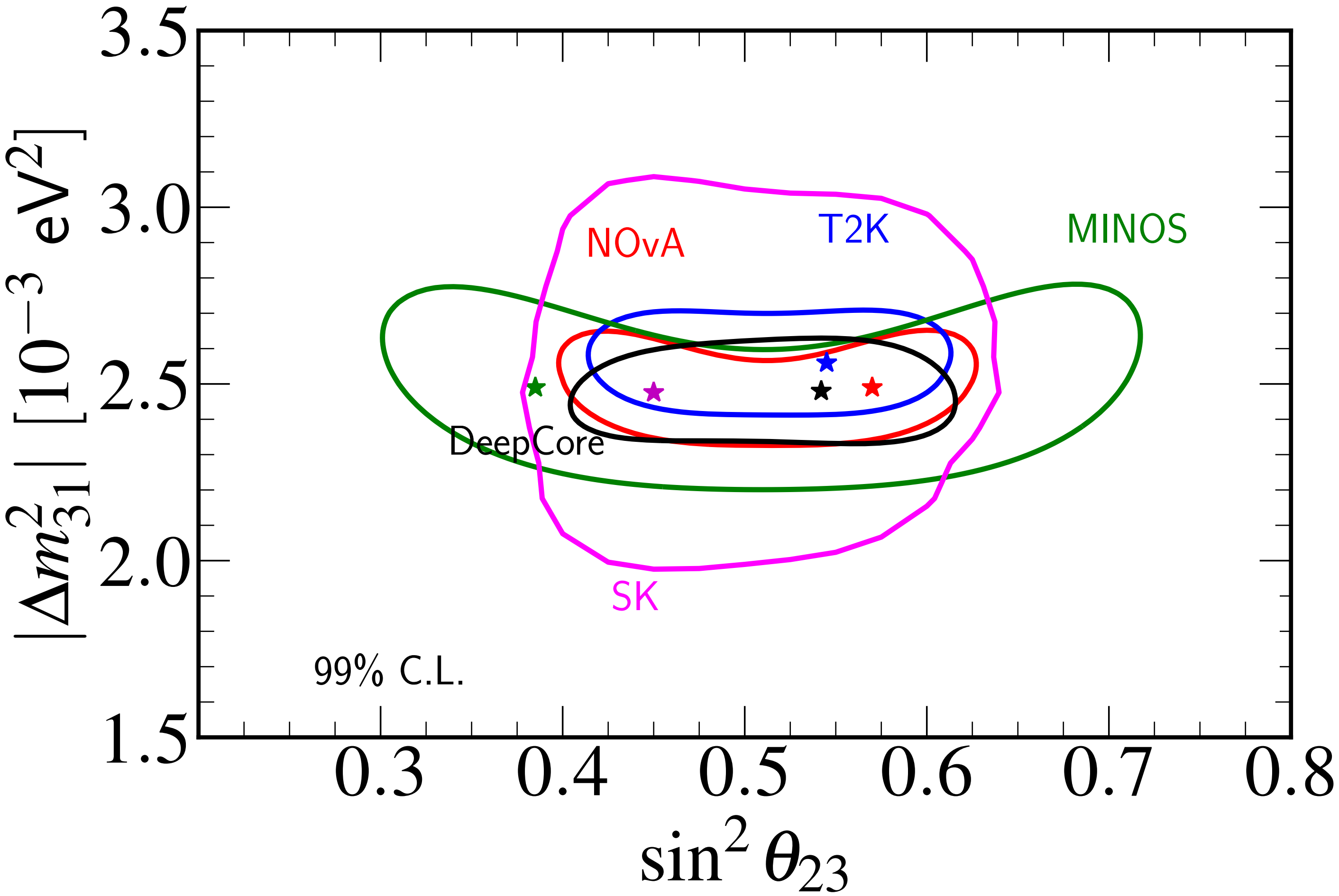
$$P(\overline{\nu}_\mu \to \overline{\nu}_e) \simeq sin^2\theta_{23} \frac{\sin^2 2\theta_{13}}{(A-1)^2} \sin^2[(A-1)\Delta_{31}$$
$$(\mp)\alpha \frac{J_0 \sin\delta_{CP}}{A(1-A)} \sin\Delta_{31} \sin(A\Delta_{31}) sin[(1-A)\Delta_{31}]$$
$$+\alpha \frac{J_0 \cos\delta_{CP}}{A(1-A)} \cos\Delta_{31} \sin(A\Delta_{31}) sin[(1-A)\Delta_{31}] + O(\alpha^2)$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31} \sim 1/30$$
$$J_0 = \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \cos\theta_{13}$$
$$A = (\mp) 2\sqrt{2} G_F n_e E/\Delta m^2_{31}$$

→ 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

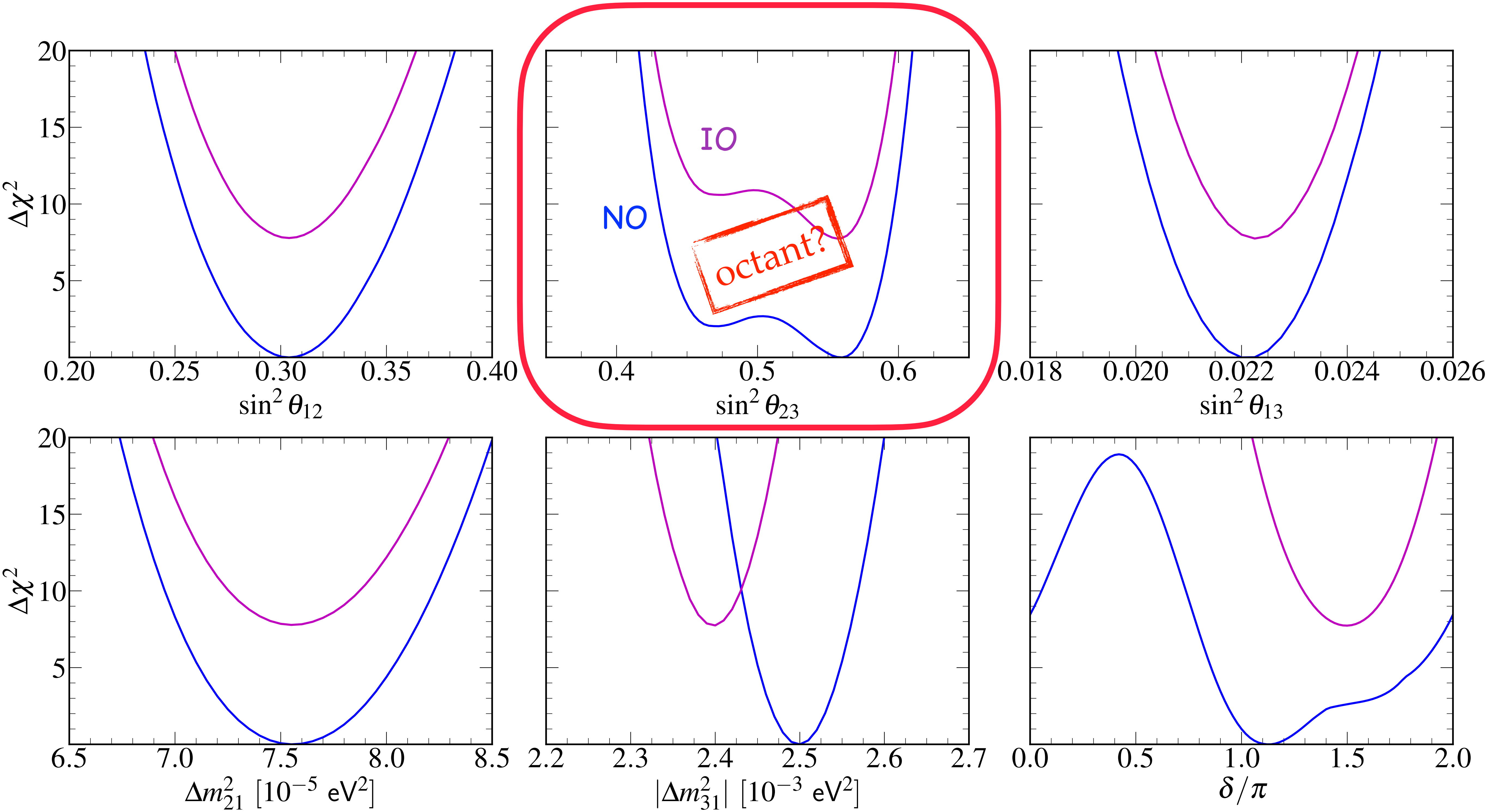


$\sin^2\theta_{23} = 0.574 \pm 0.014$

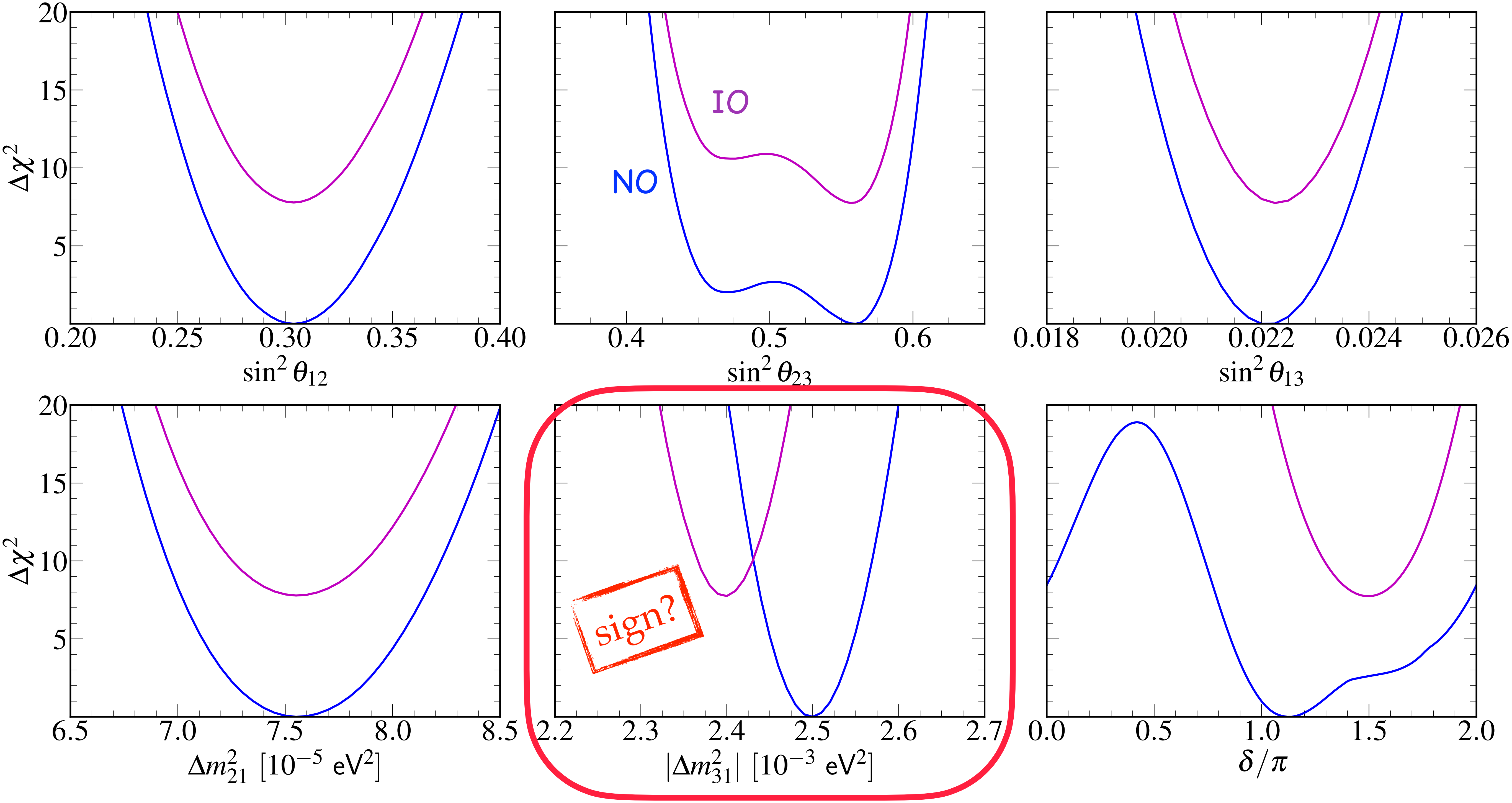
$\Delta m^2_{31} = (2.55 \pm 0.03) \times 10^{-3}$ eV^2

- 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

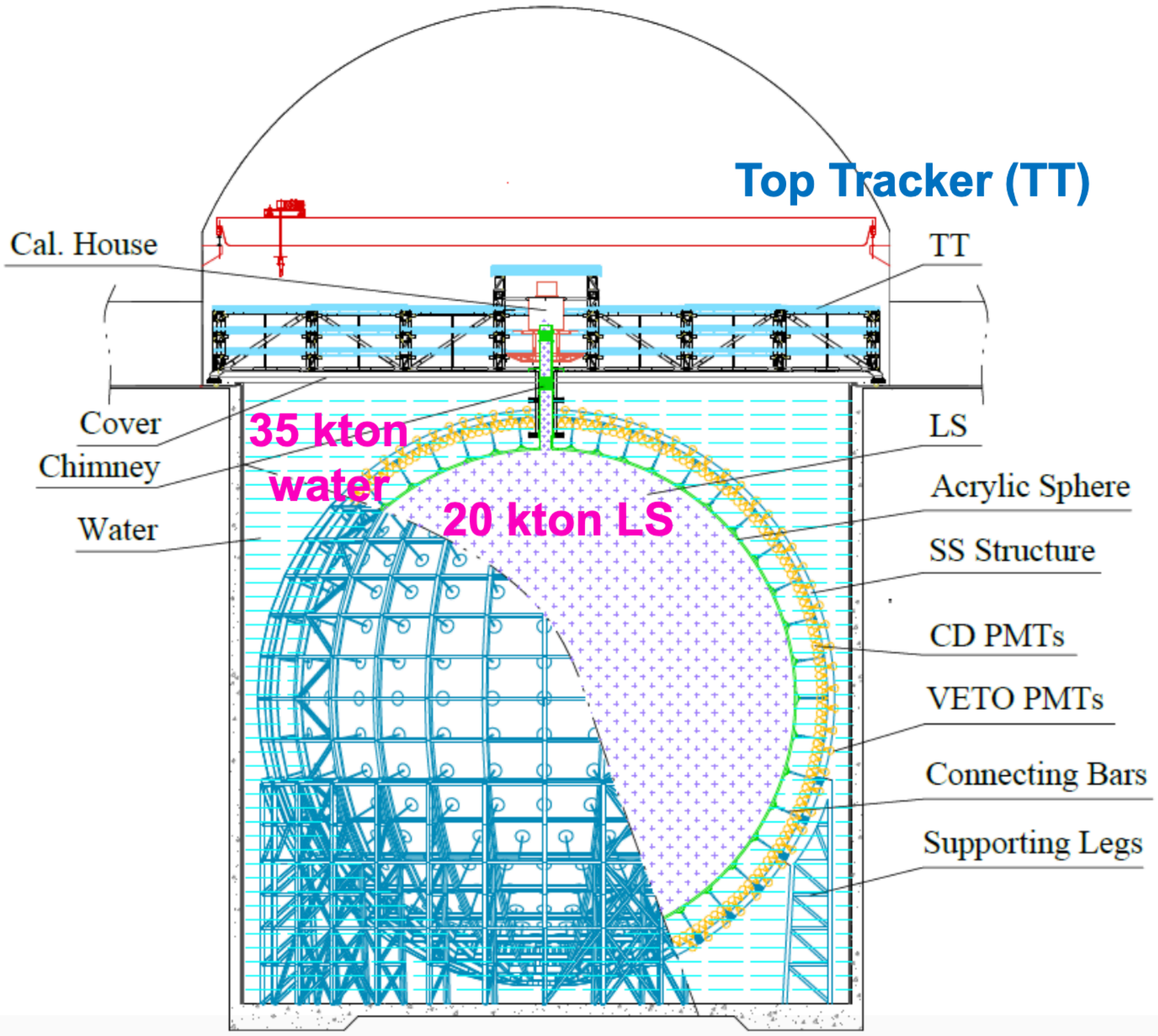


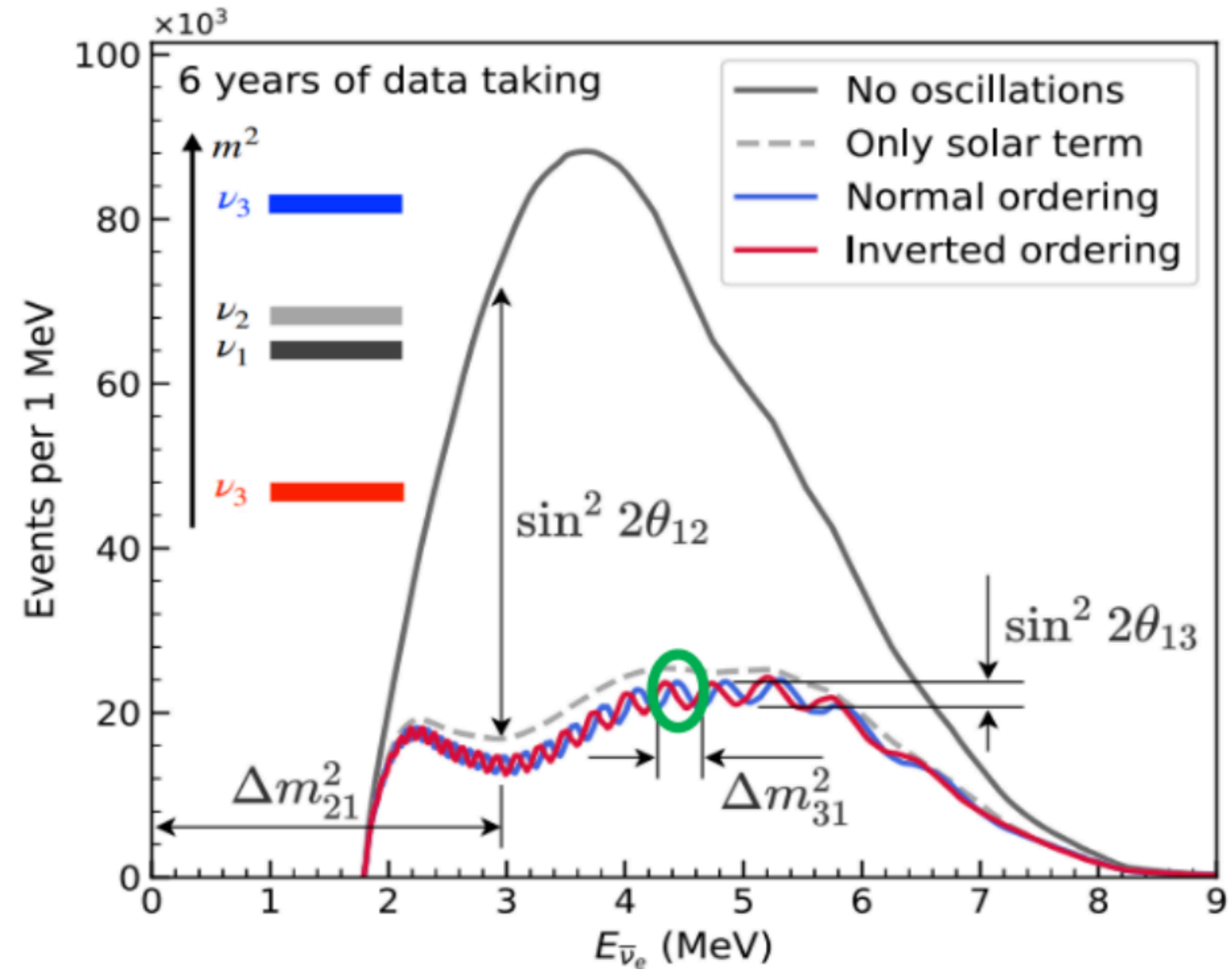
Global fit to ν oscillation parameters



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

JUNO reactor experiment





$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \boxed{\cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)}$$

slow "solar" component

$$- \boxed{\sin^2 2\theta_{13} \left[\cos^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right) + \sin^2\theta_{12} \sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right)\right]}$$

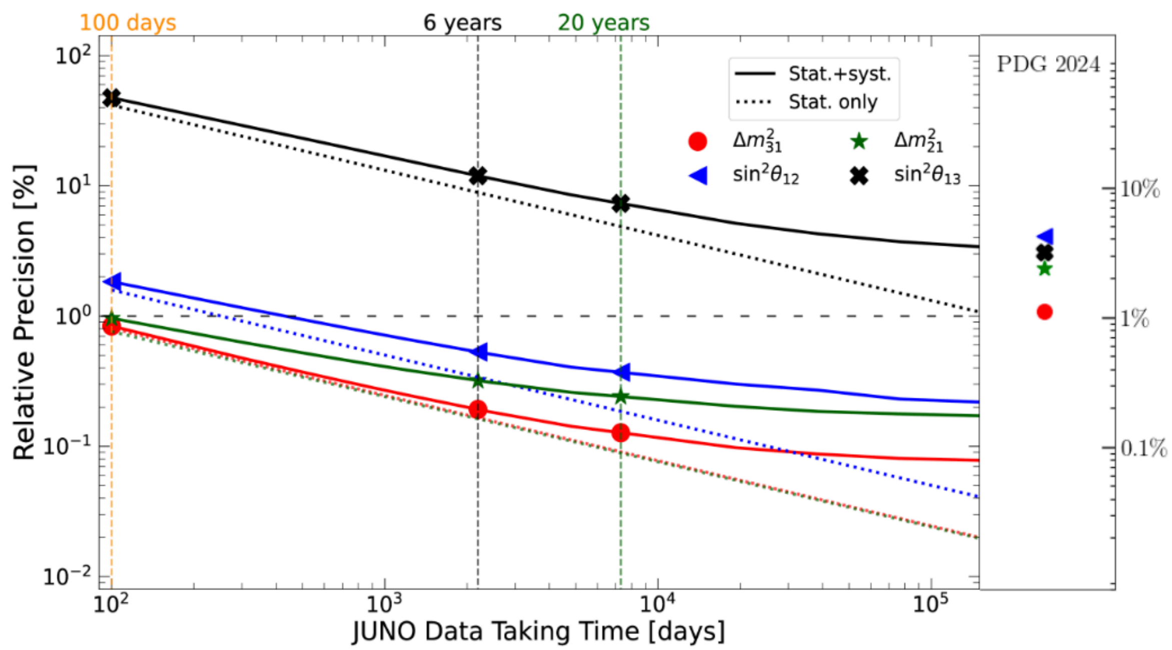
fast "atmospheric" component

L ~50 km:
θ_{12}, Δm^2_{21}, θ_{13}, Δm^2_{31}

JUNO reactor experiment

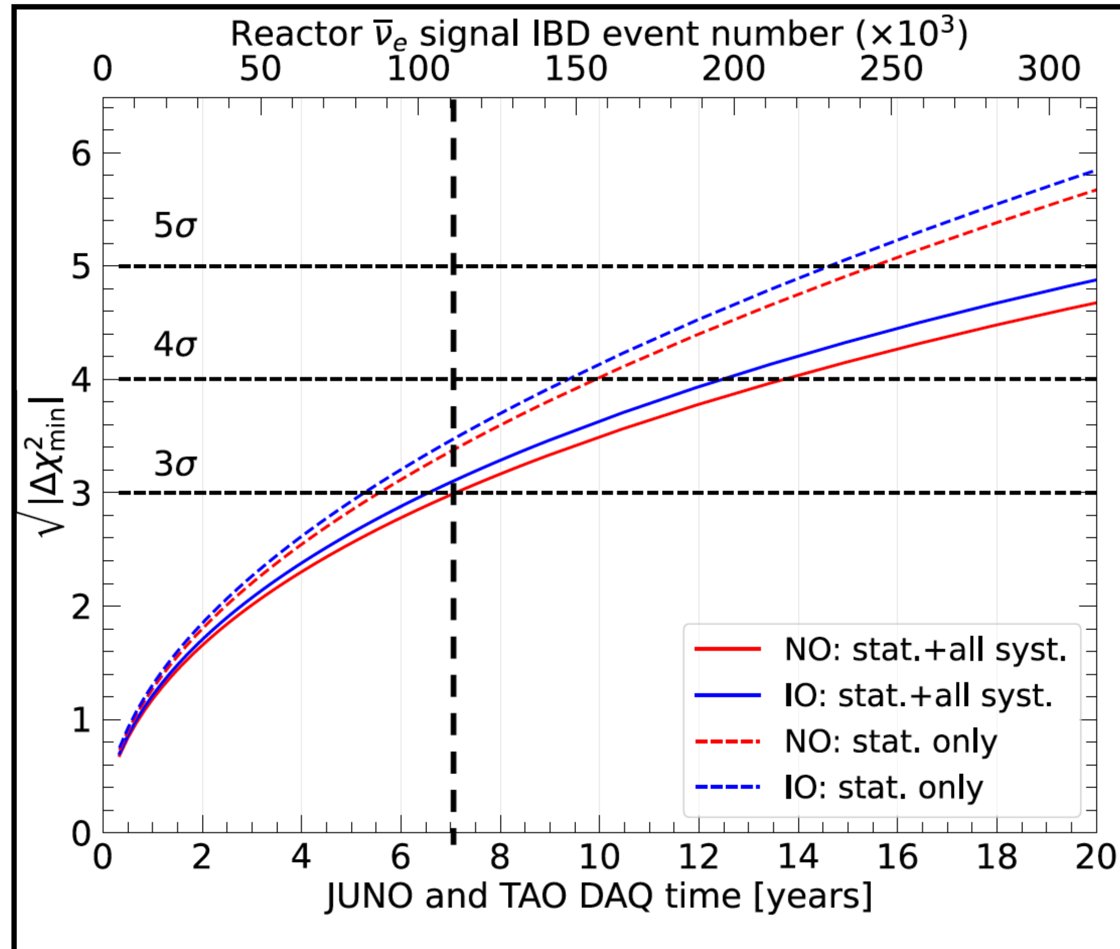
➤ precision and mass ordering

V. Cerrone @ NOW 2024



	PDG 2024	JUNO 100 days	JUNO 6 years
Δm^2_{31}	1.1%	0.8%	0.2%
Δm^2_{21}	2.4%	1.0%	0.3%
$\sin^2\theta_{12}$	4.2%	1.9%	0.5%
$\sin^2\theta_{13}$	3.2%	47.9%	12%

Chinese Phys. C 46 123001



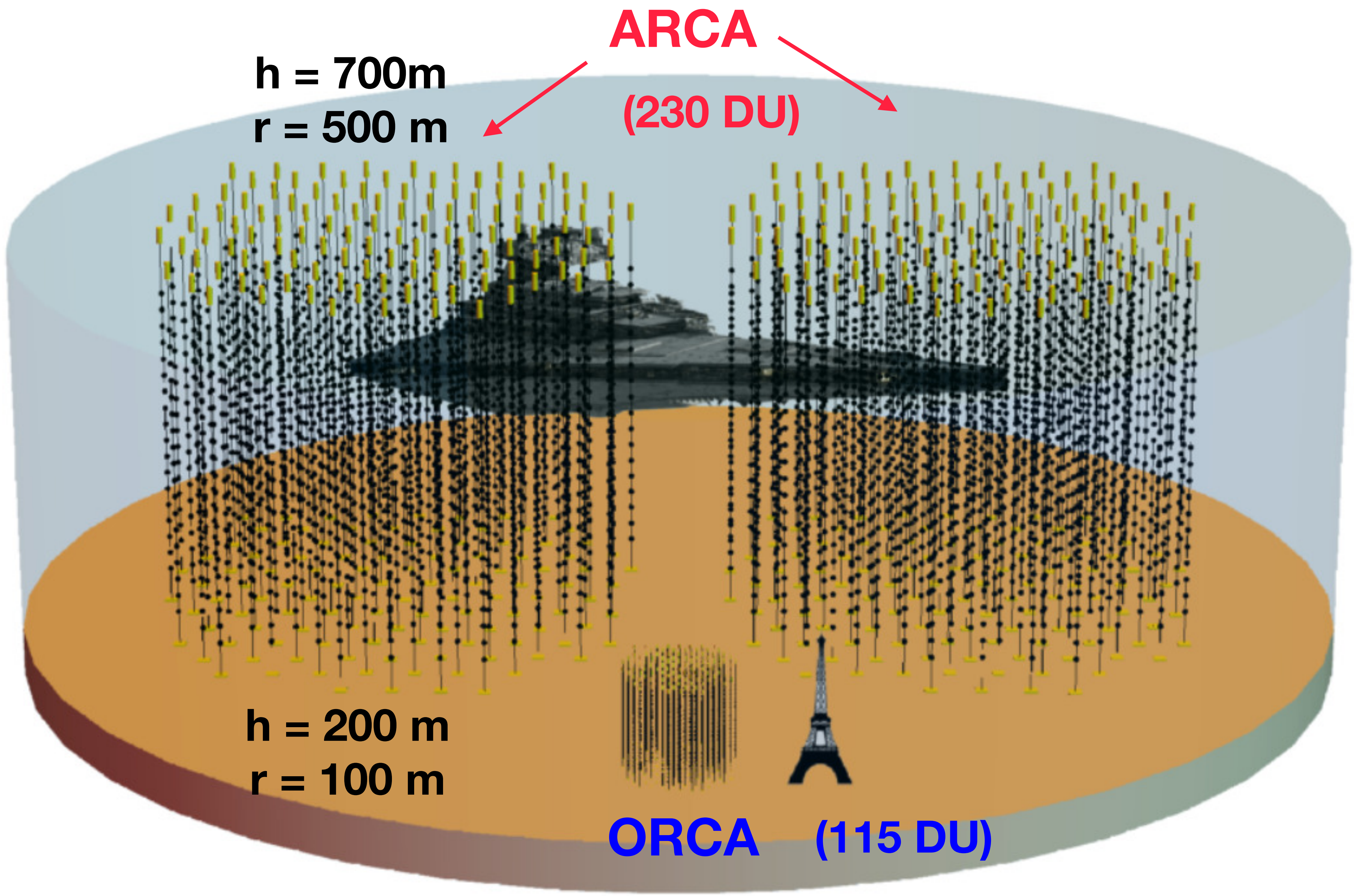
✦ 3σ sensitivity in ~7 years of data

KM3NeT-ORCA

KM3NeT: two underwater neutrino telescopes at the Mediterranean, ARCA (astrophysical neutrinos) and ORCA (atmosp. neutrinos)

Digital Optical Module 31×3” PMTs

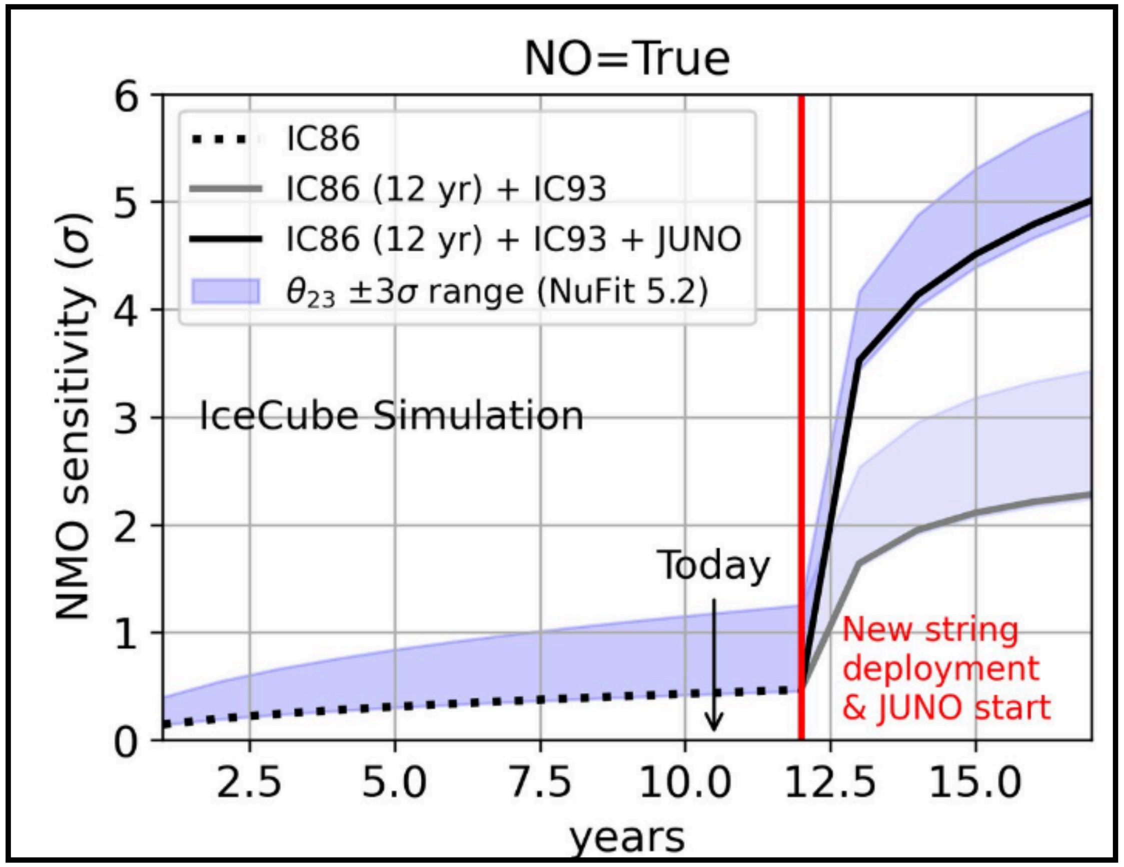
18 DOM per DU



JUNO + atmospheric experiments

IceCube Upgrade + JUNO

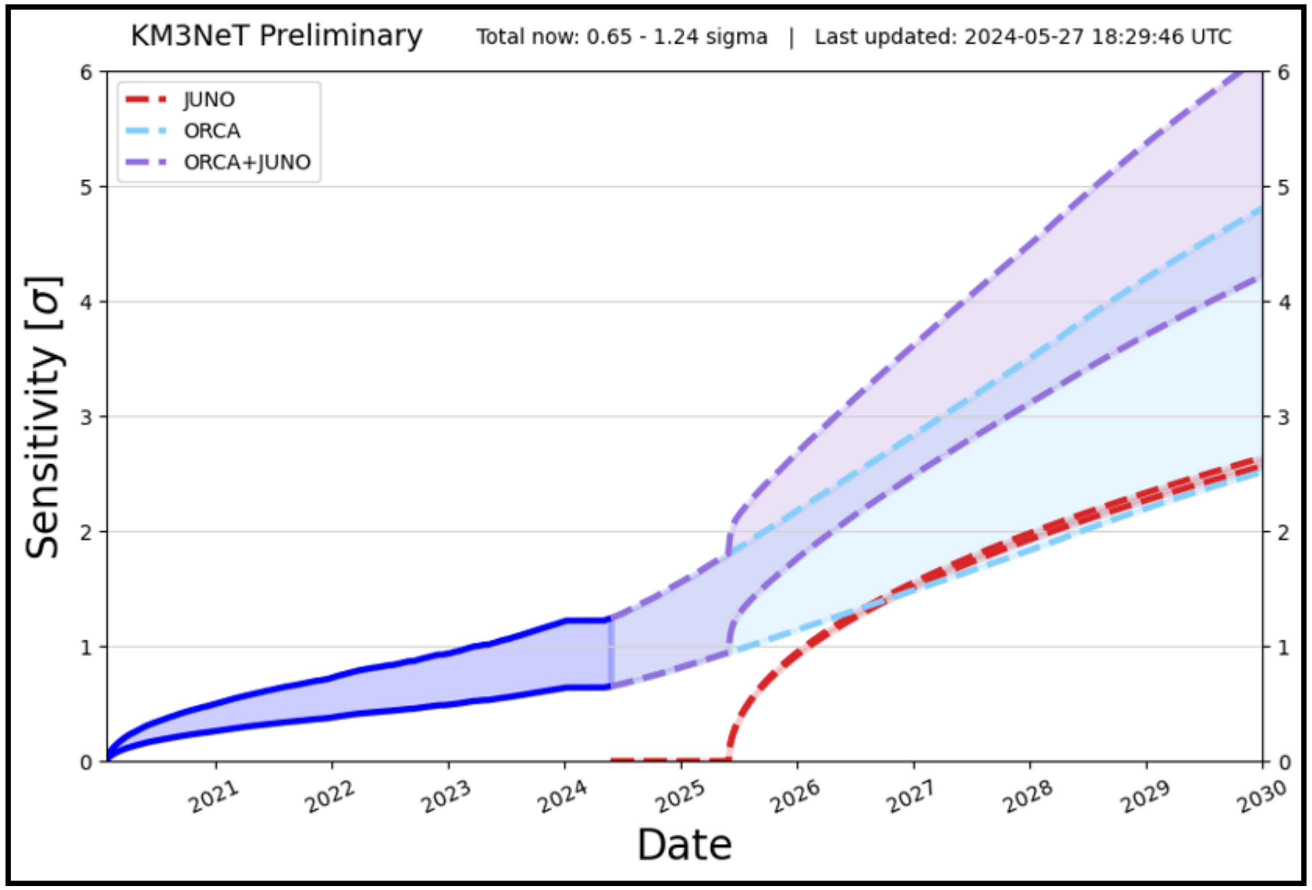
A. Terliuk @ NOW 2024



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

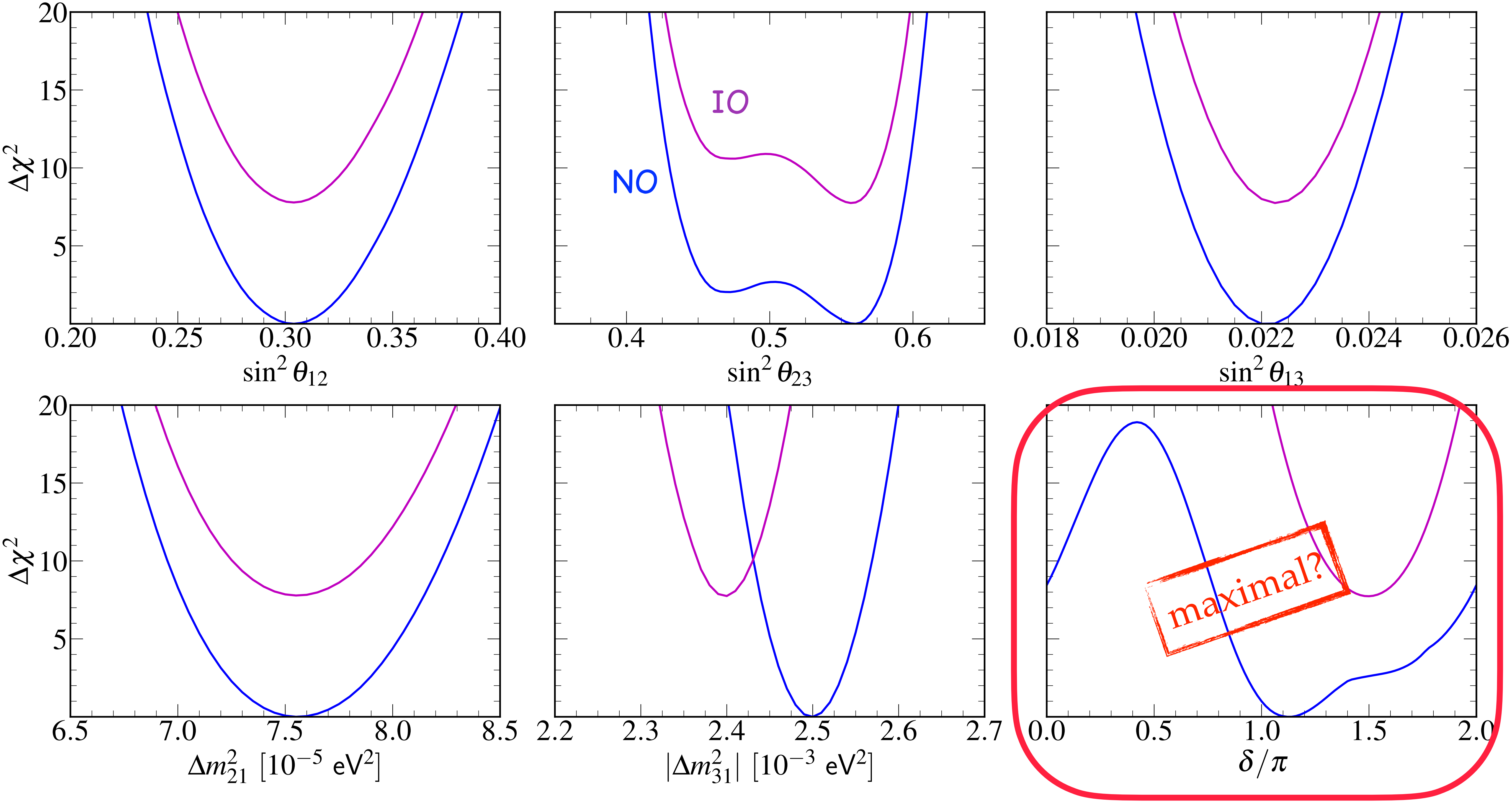
ORCA + JUNO

P. Migliozzi @ NOW 2024



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

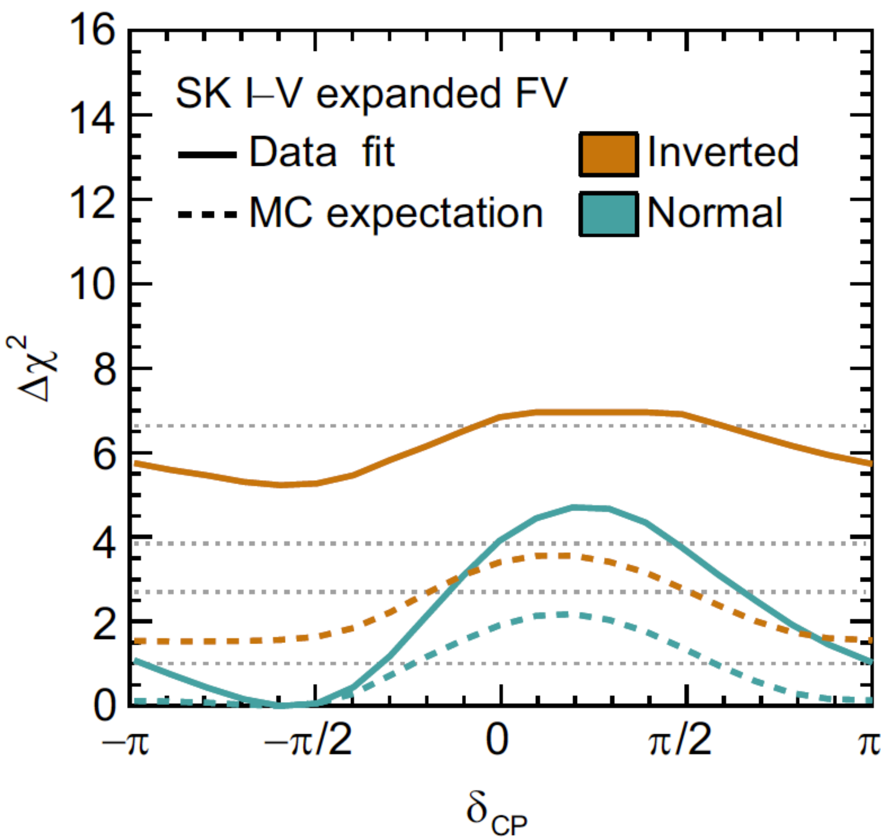
Global fit to ν oscillation parameters



The CP phase

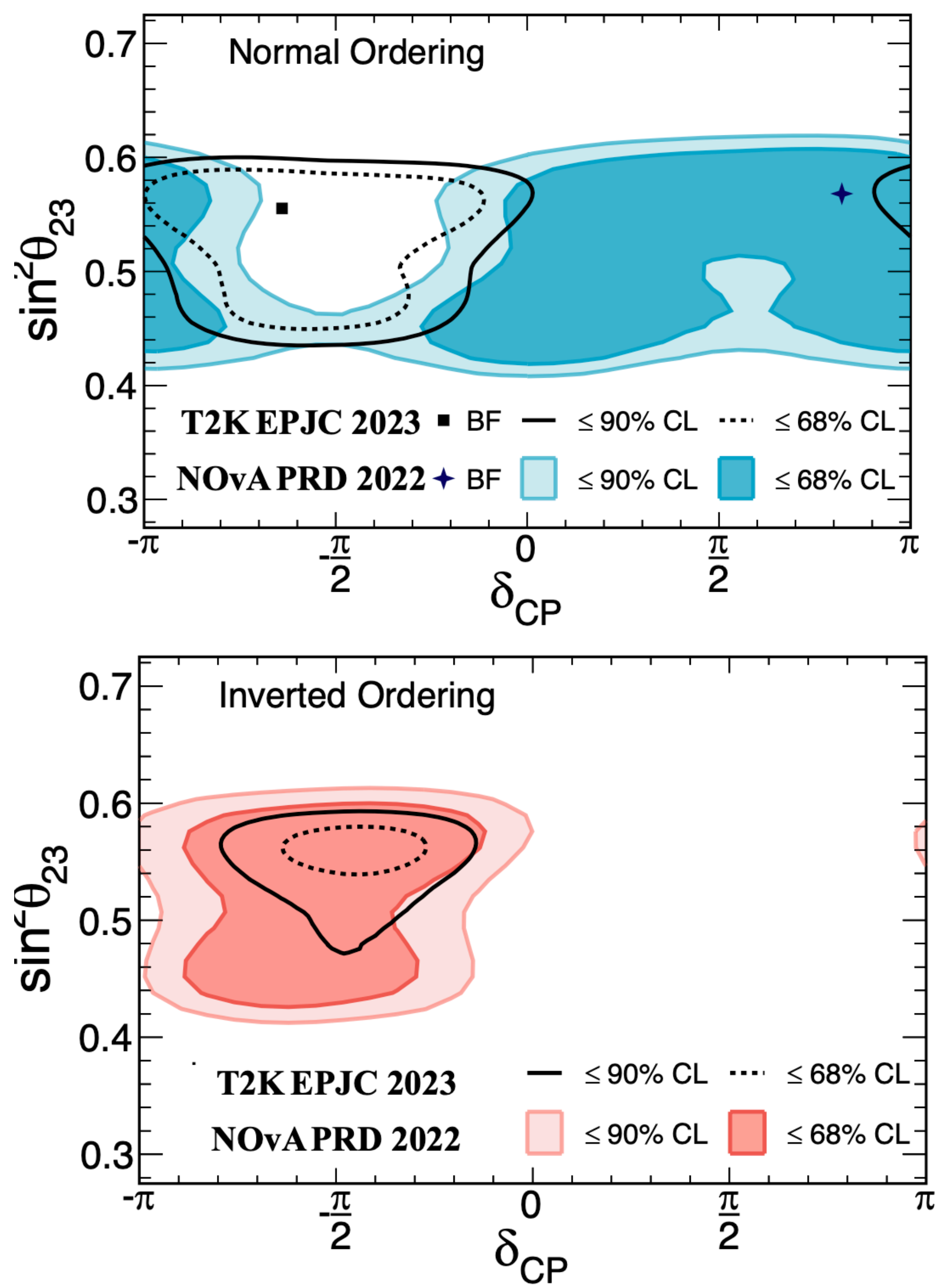
Observation of the appearance channels $\nu_\mu \to \nu_e$ in atmospheric and accelerator experiments and allows to measure the δ_{CP}

SK Collab, PRD 109 (2024) 072014



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

A. Booth, 2024



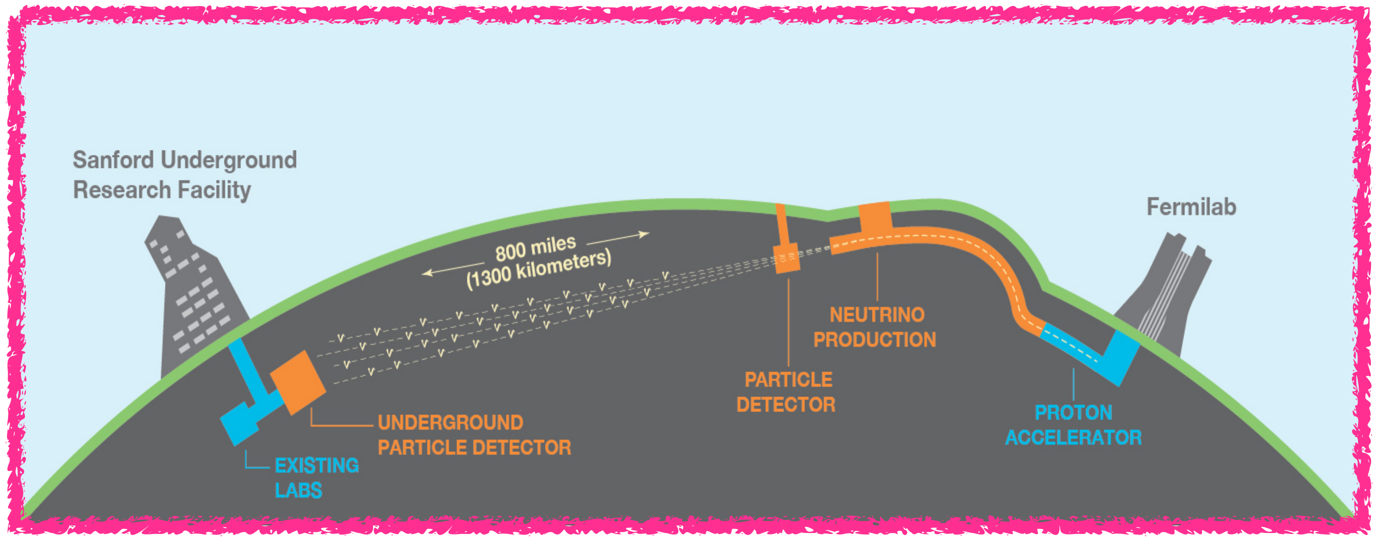
T2K prefers also $\delta_{CP} \sim 3\pi/2$

NOvA results depend on mass ordering

Next generation experiments: DUNE, Hyper-K

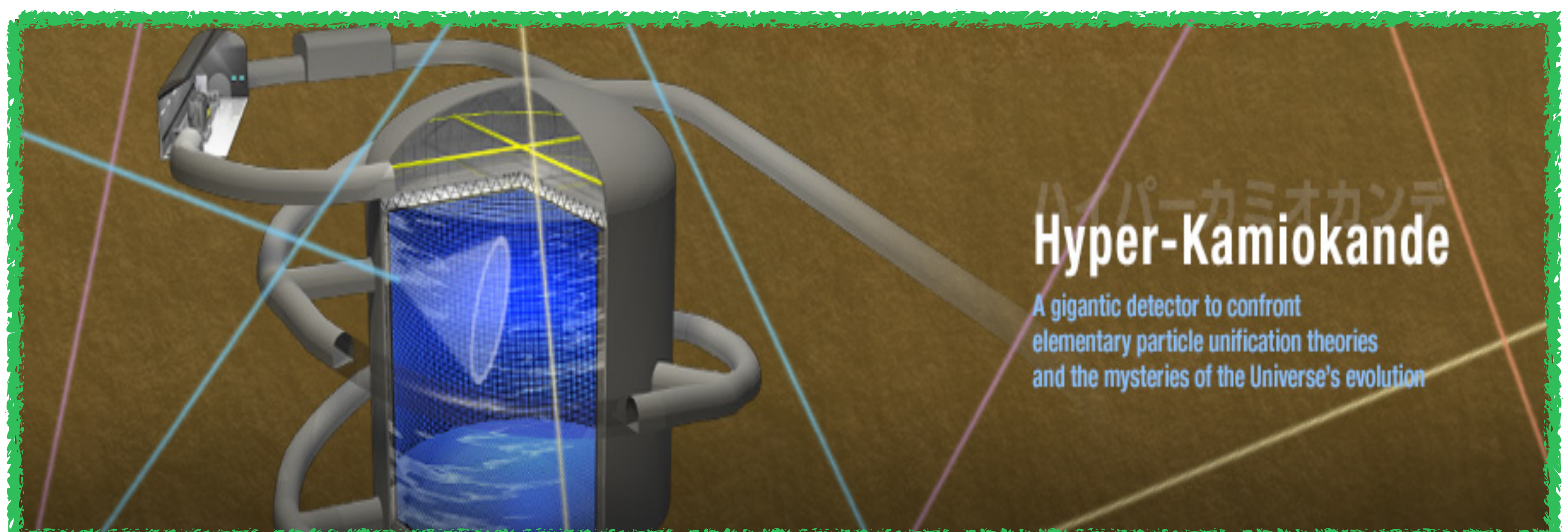
Next generation of ν experiments

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

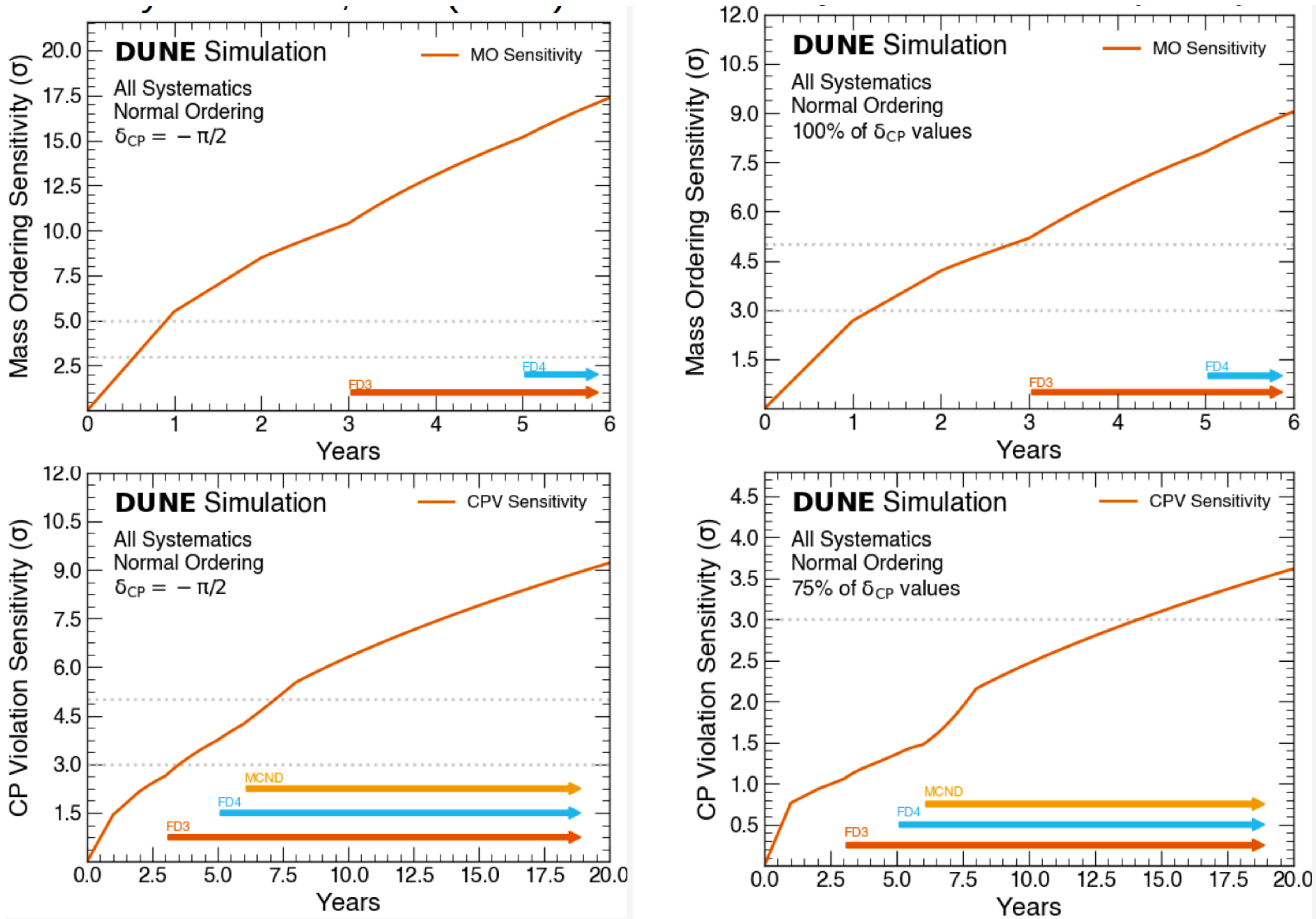


- 188 kton water Cerenkov
- T2HK: great sensitivity to δ_{CP}
- T2HKK (1100km) will have similar sensitivities as DUNE

Next generation of ν experiments

DUNE

C. Marshall@ Neutrino'24



Ultimate precision in δ_{CP}: 6-16°

✦ Best-case oscillation scenarios:

>5σ mass ordering sensitivity in 1 year

>3σ CPV sensitivity in 3.5 years

✦ Worst-case oscillation scenarios:

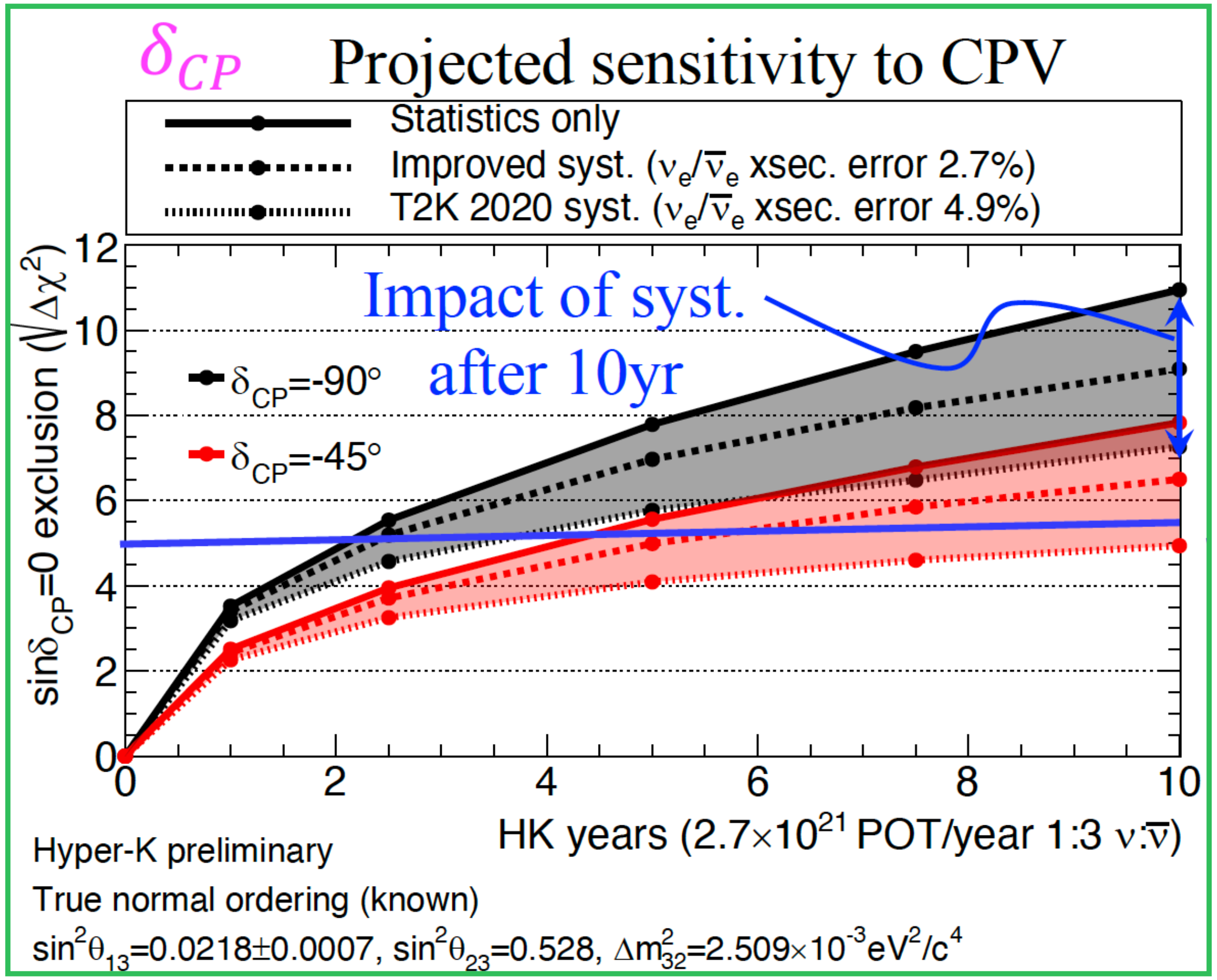
>5σ mass ordering sensitivity in 3 years

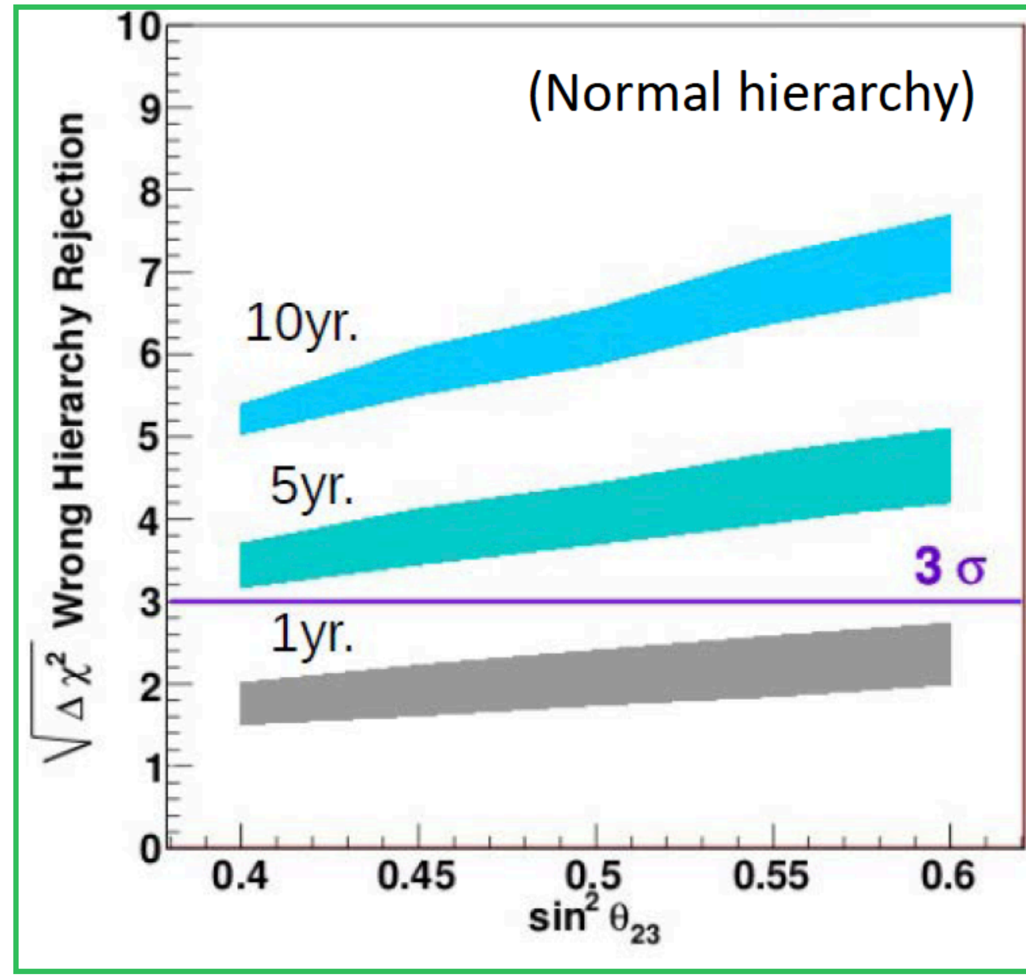
+10yr: CPV over 75%of δ_{CP} values at >3σ

Next generation of ν experiments

Hyper-Kamiokande

S. Moriyama @ Neutrino'24



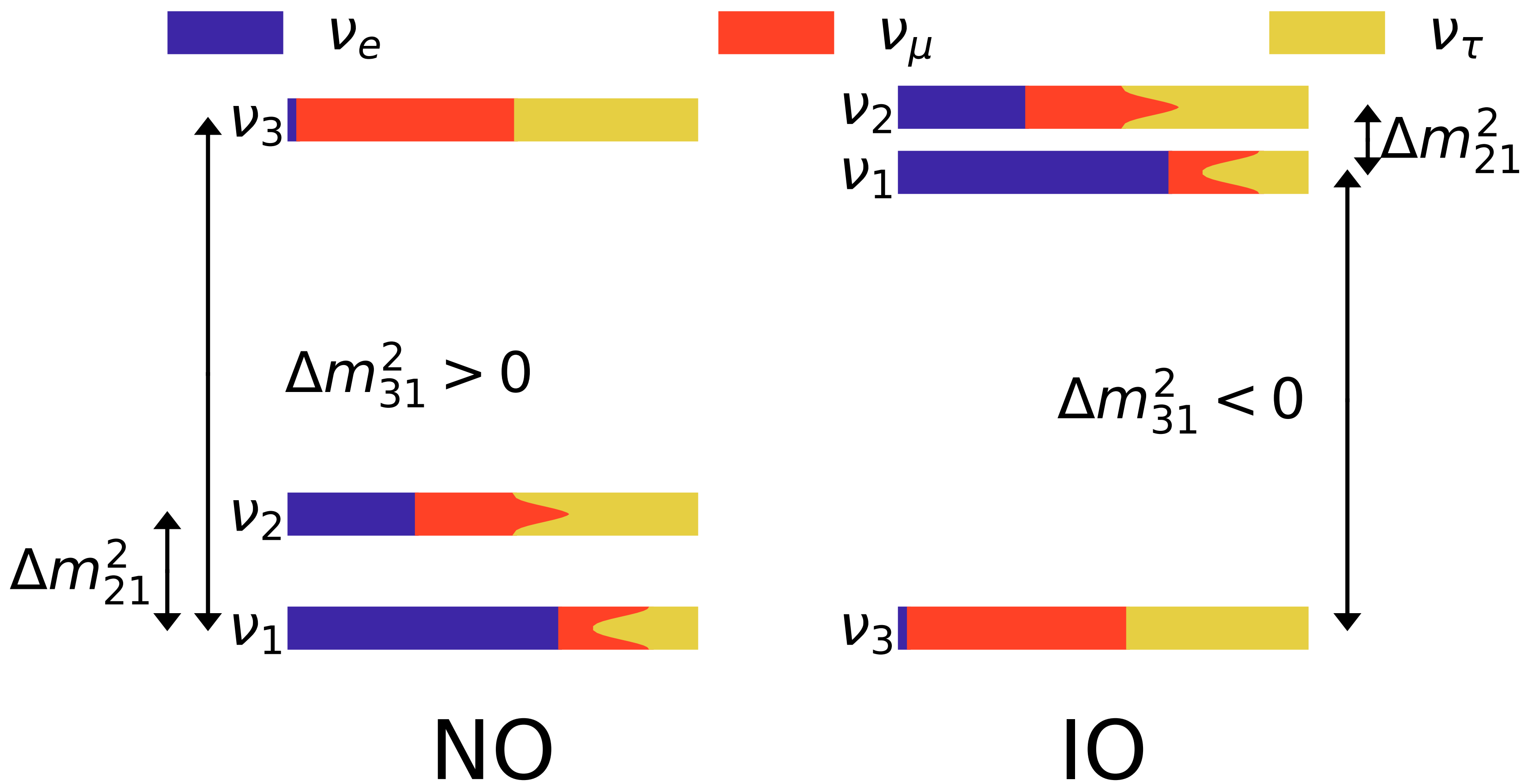


- >5σ CPV discovery for >60% of δ_{CP}
- 1σ resolution of δ_{CP} in 10 yrs: ~20° (~6°) for $\delta_{CP} = -90°$ (0°)

- >5σ sensitivity to mass ordering for all values of θ_{23} for NO

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

Neutrino mass scale

Neutrino oscillations

$$\sum m_\nu|_{\rm NO} \gtrsim 0.06\,{\rm eV}$$

$$\sum m_\nu|_{\rm IO} \gtrsim 0.1\,{\rm eV}$$

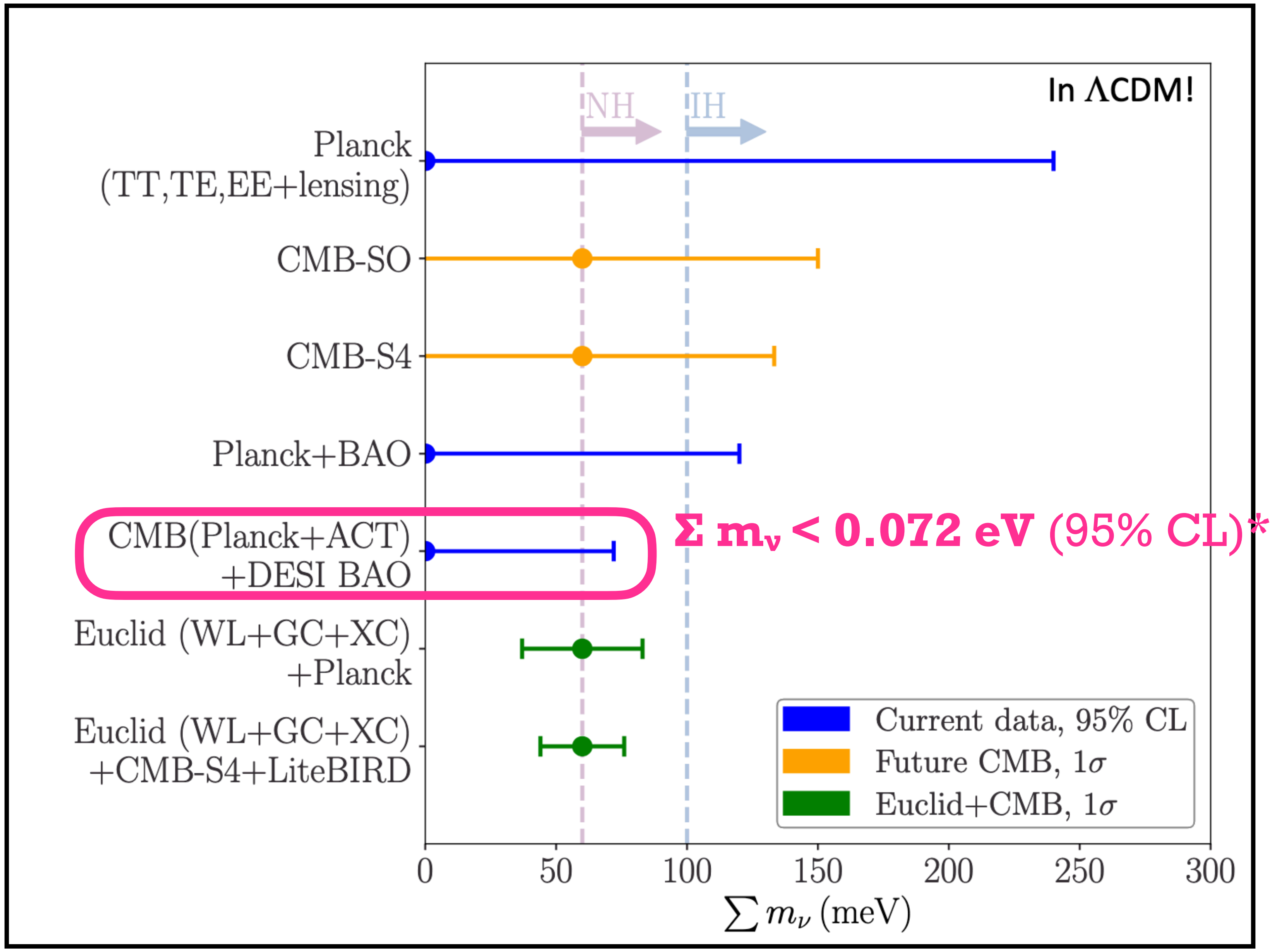
Direct constraints

✦ new world-best direct neutrino mass constraint from KATRIN:

m_β < 0.45 eV (90% CL)

C. Wiesinger @ ICHEP 2024

Cosmological constraints



Σ m_ν < 0.072 eV (95% CL)*

M. Archidiacono @ Neutrino 2024

* Relaxed to **Σ m_ν < 0.11 eV** (Naredo-Tuero, arXiv:2407.13831)

Neutrino physics beyond the Standard Model

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

$\Rightarrow$ 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 ± 1σ	3σ range	relative 1σ uncert	
Δm^2_{21} $[10^{-5}\mathrm{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	**2.7 %**	
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (NO)	2.50±0.02	[illegible]2.57	**0.9 %**	mass ordering?
$\lvert\Delta m^2_{31}\rvert$ $[10^{-3}\mathrm{eV}^2]$ (IO)	2.40±0.0[illegible]	[illegible]6		
$\sin^2\theta_{12}/10^{-1}$	3.04[illegible]	[illegible]–3.55	**5.4%**	
$\sin^2\theta_{23}/10^{-1}$ (NO)	[illegible]	4.32–5.96	**4.8%**	octant?
$\sin^2\theta_{23}/10^{-1}$ (IO)	[illegible]	4.34–5.93		
$\sin^2\theta_{13}/10^{-2}$ (N[illegible]	[illegible]$^{+0.07}_{-0.04}$	2.05–2.38	**2.5%**	
$\sin^2\theta_{13}/10^{-2}$ [illegible]	$2.23^{+0.05}_{-0.06}$	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		

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 ~ eV)

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

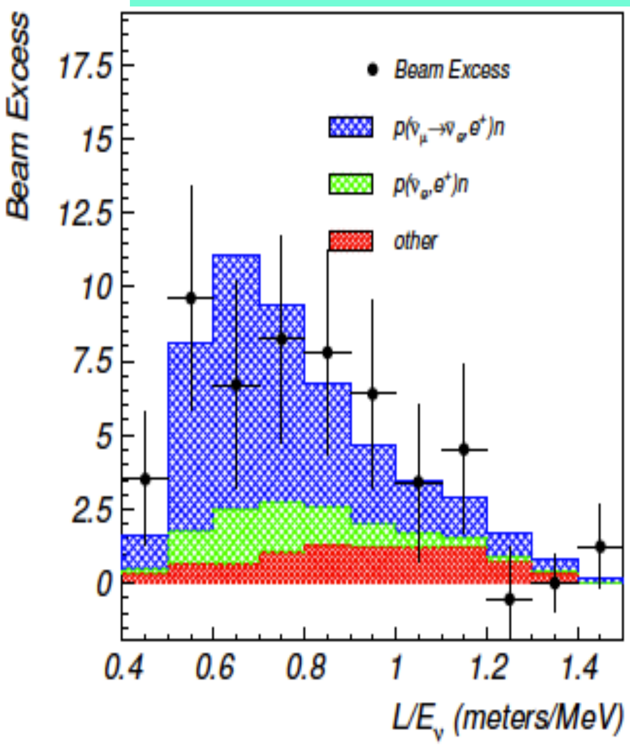
✦ baryon asymmetry of the universe (leptogenesis, m>> 1 GeV)

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

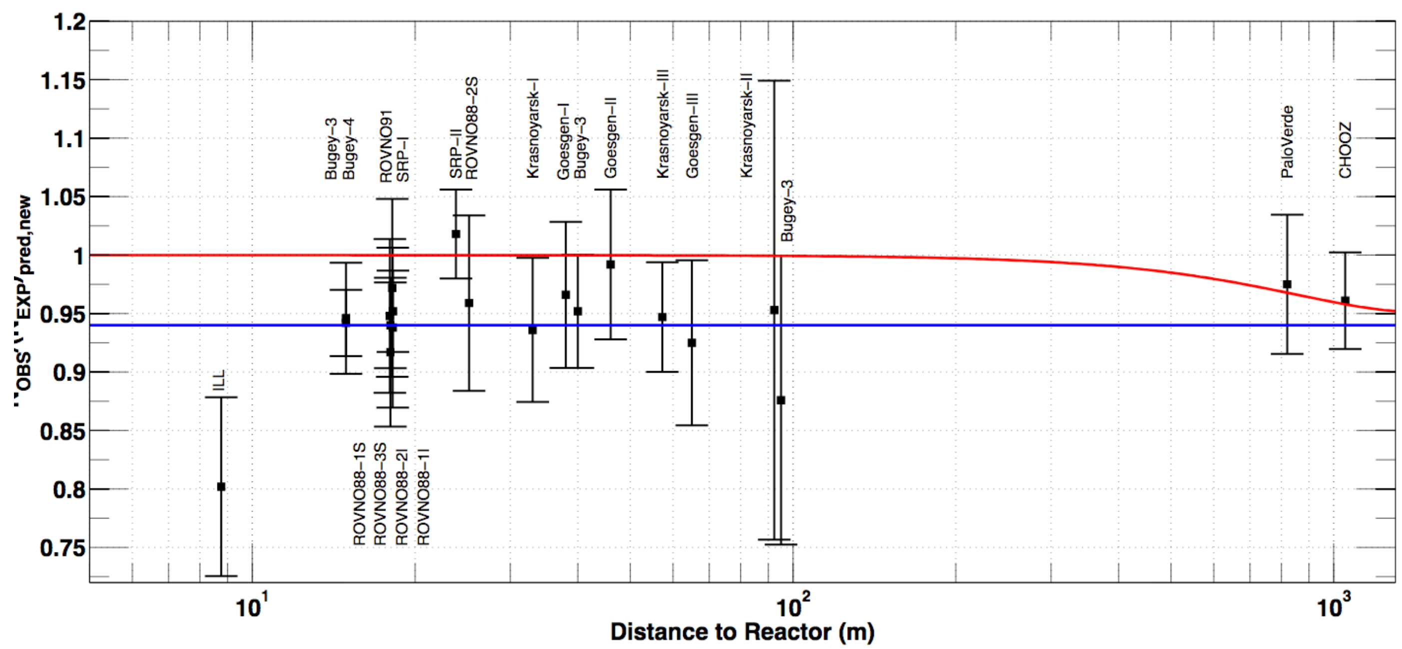
Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

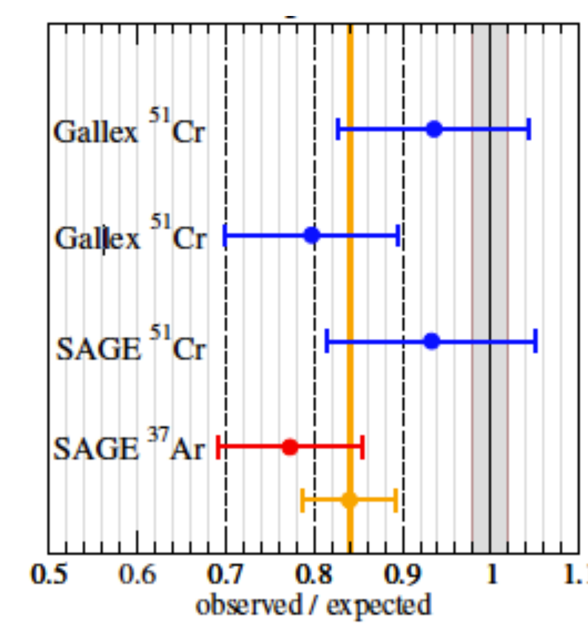
LSND & MiniBooNE



Reactor anomaly



Gallium anomaly



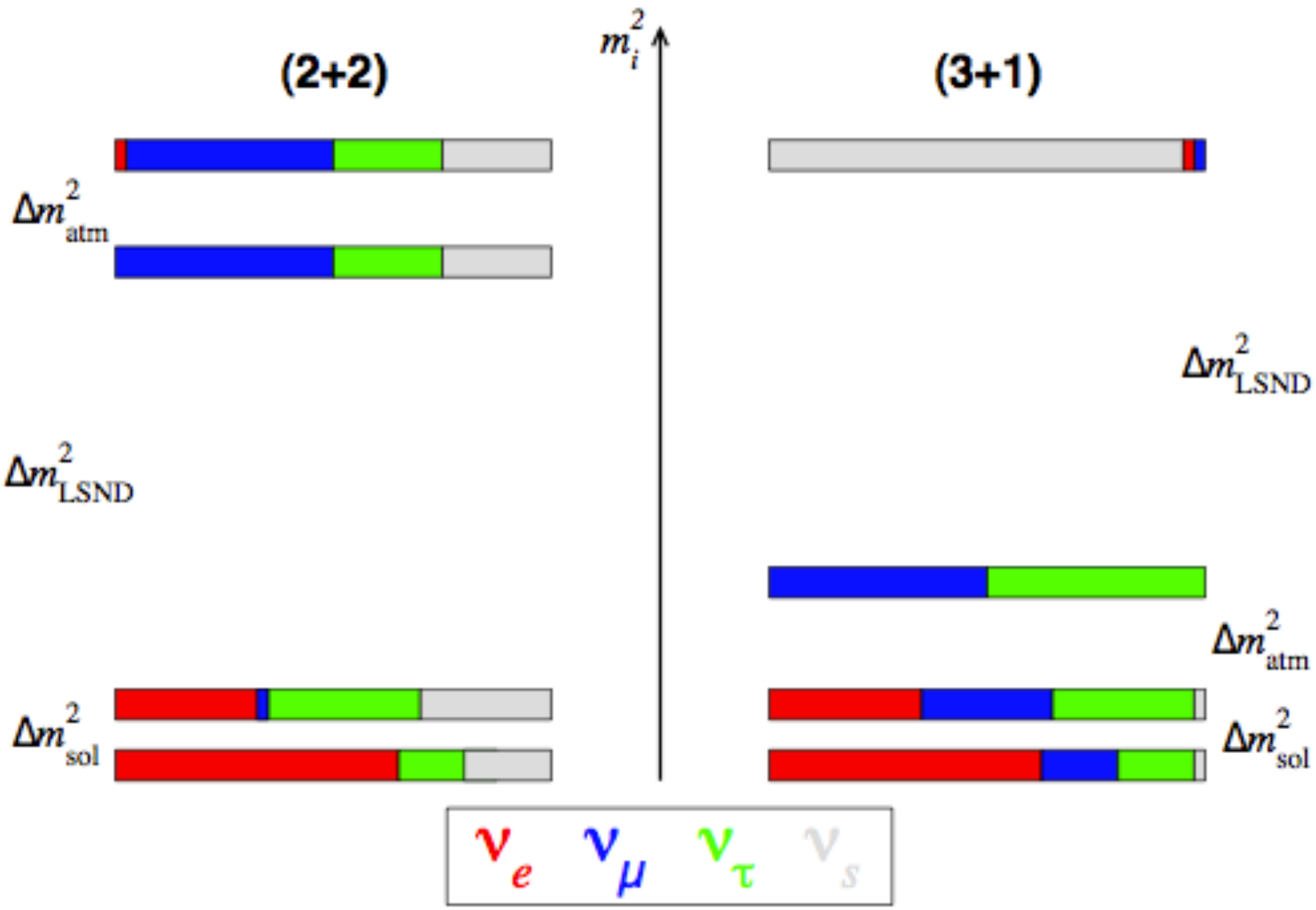
Explained with neutrino oscillations with Δm²~1 eV² in the channels:

$\overline{\nu}_\mu \to \overline{\nu}_e$ $\qquad$ $\overline{\nu}_e \to \overline{\nu}_x$ $\qquad$ $\nu_e \to \nu_x$

Interpretation of the anomalies

$\Delta m^2_{sol} \sim 8\mathrm{x}10^{-5}\ \mathrm{eV}^2$ $\Delta m^2_{atm} \sim 2\mathrm{x}10^{-3}\ \mathrm{eV}^2$ $\Delta m^2_{LSND} \sim 1\ \mathrm{eV}^2$

⇒ Can only be accommodated considering four neutrino states



The new neutrino could not be produced at Z decay

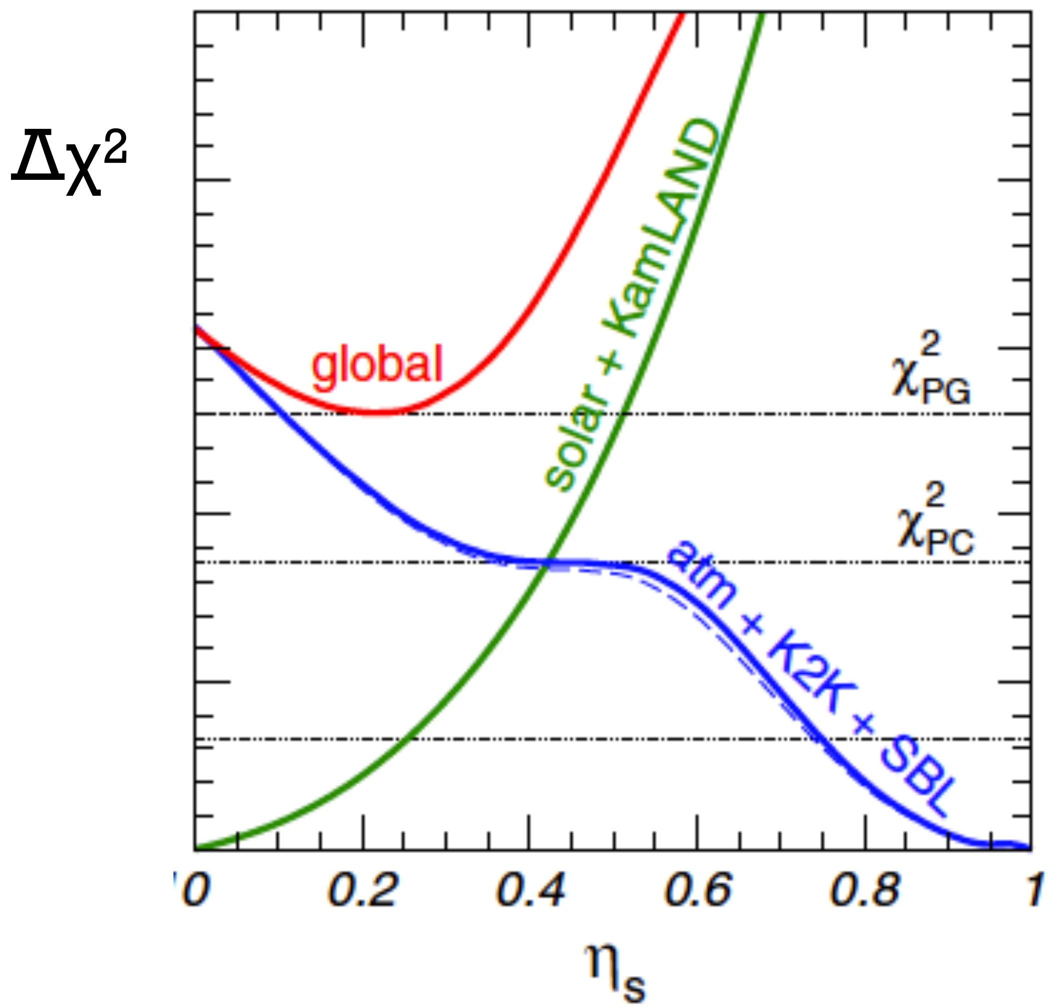
$N_\nu = 2.984 \pm 0.008$ (LEP)

→ Sterile neutirno

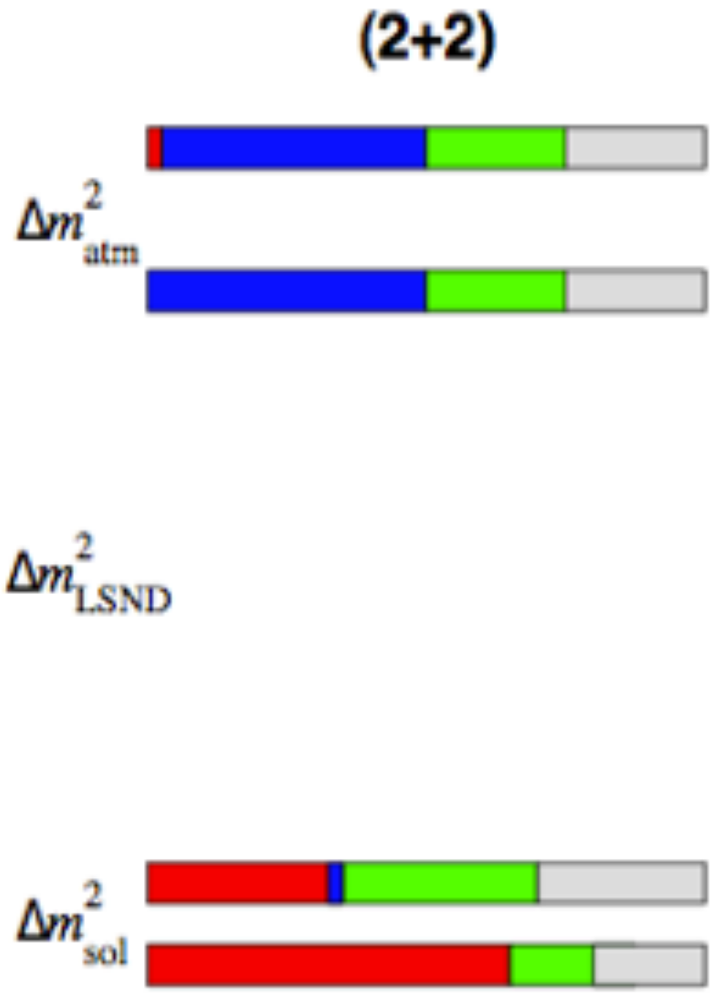
2+2 neutrino scheme

✦This scheme requires the presence of sterile neutrinos either in solar or atmospheric neutrinos

✦However, solar and atmospheric data show a strong preference for active oscillations



excluded by solar and atmospheric data

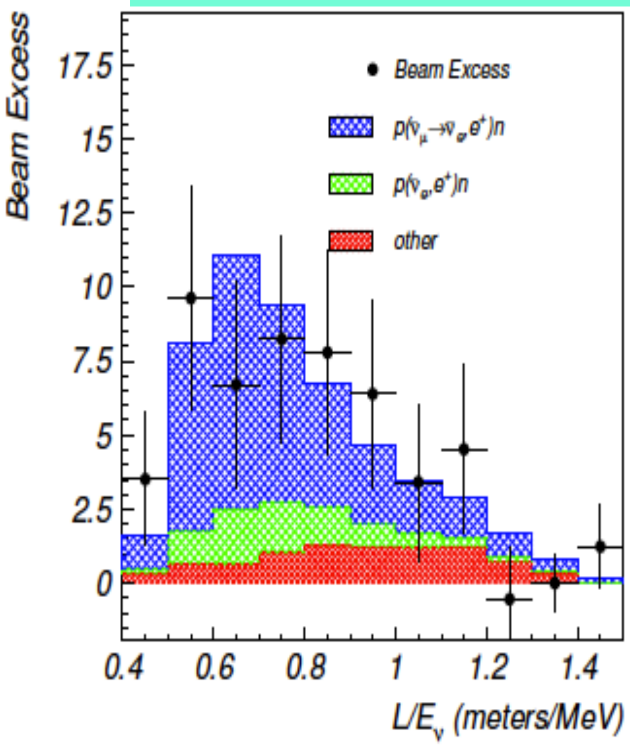


Maltoni et al, NPB643 (2003), NJP06 (2004)

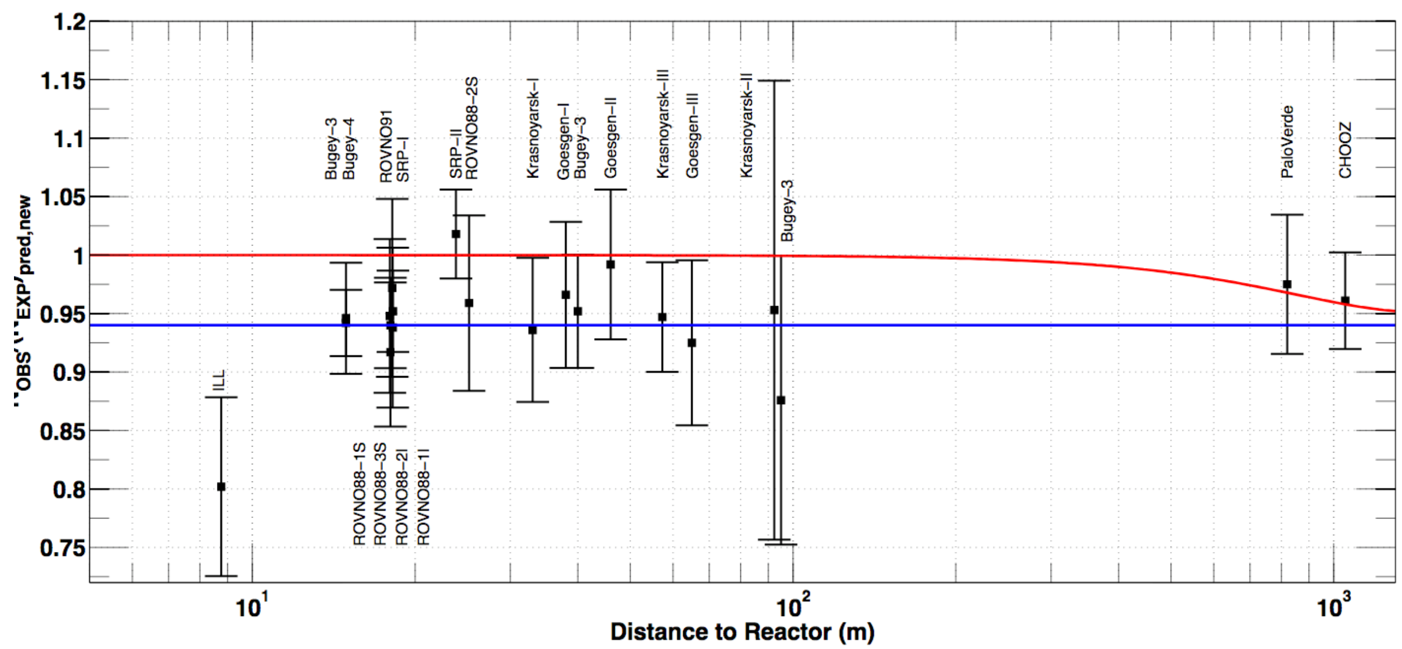
Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

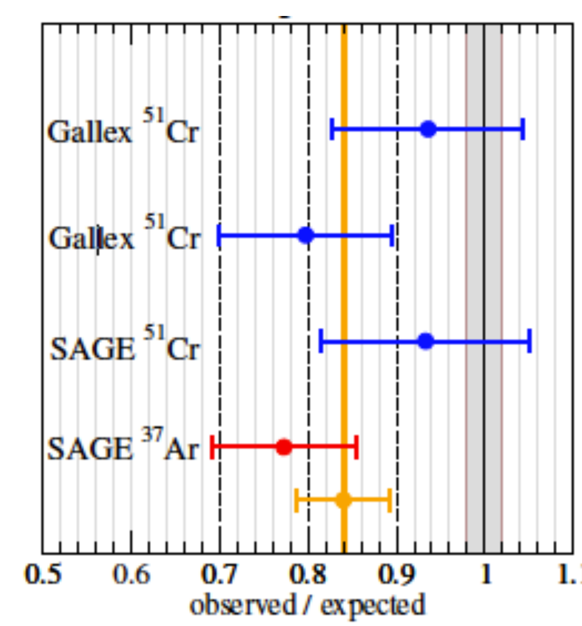
LSND & MiniBooNE



Reactor anomaly



Gallium anomaly

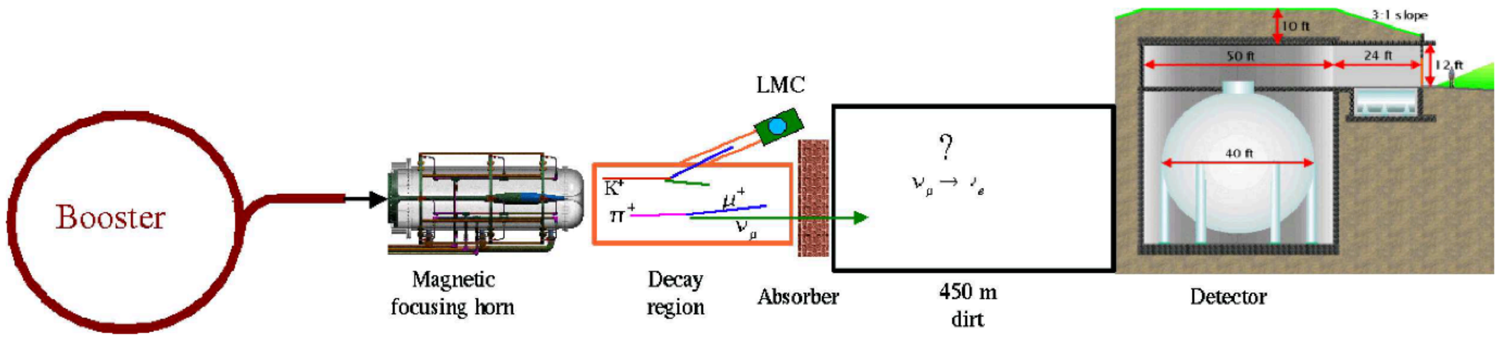


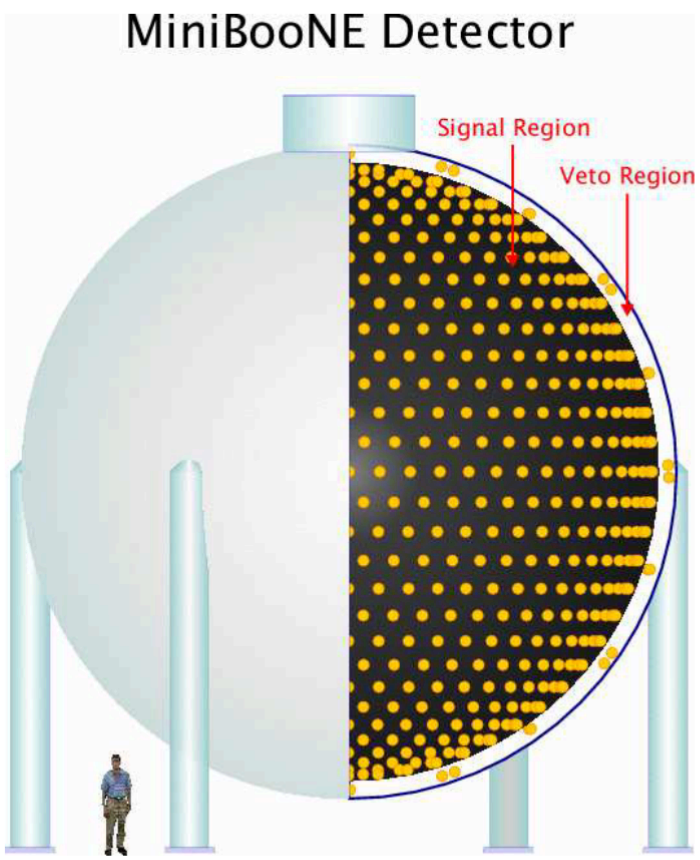
Explained with neutrino oscillations with $\Delta m^2 \sim 1$ eV^2 in the channels:

$\overline{\nu}_\mu \to \overline{\nu}_e$ $\quad$ $\overline{\nu}_e \to \overline{\nu}_x$ $\quad$ $\nu_e \to \nu_x$

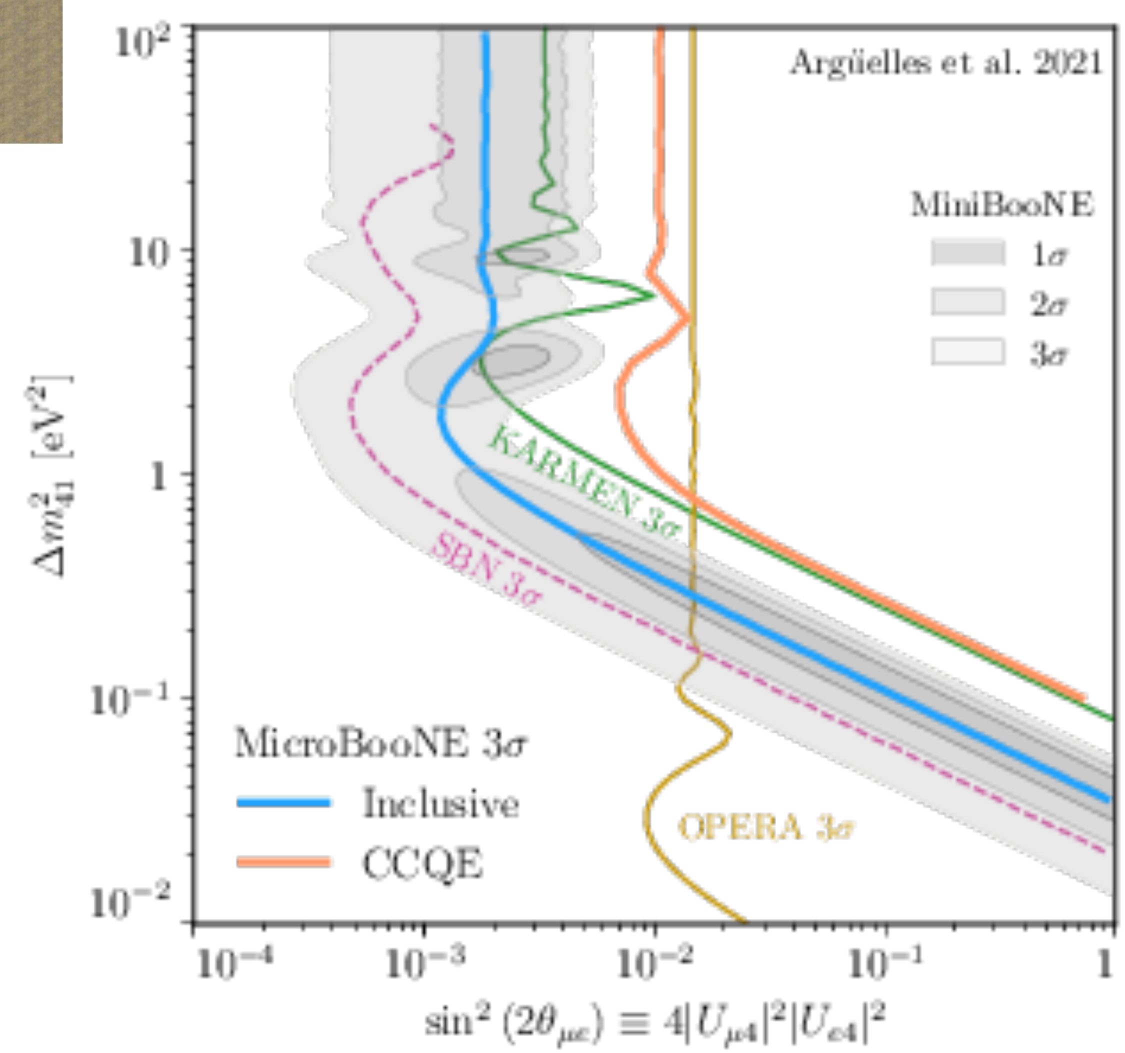
Testing the LSND anomaly

Experiments designed to check LSND signal: **MiniBooNE** & **MicroBooNE**





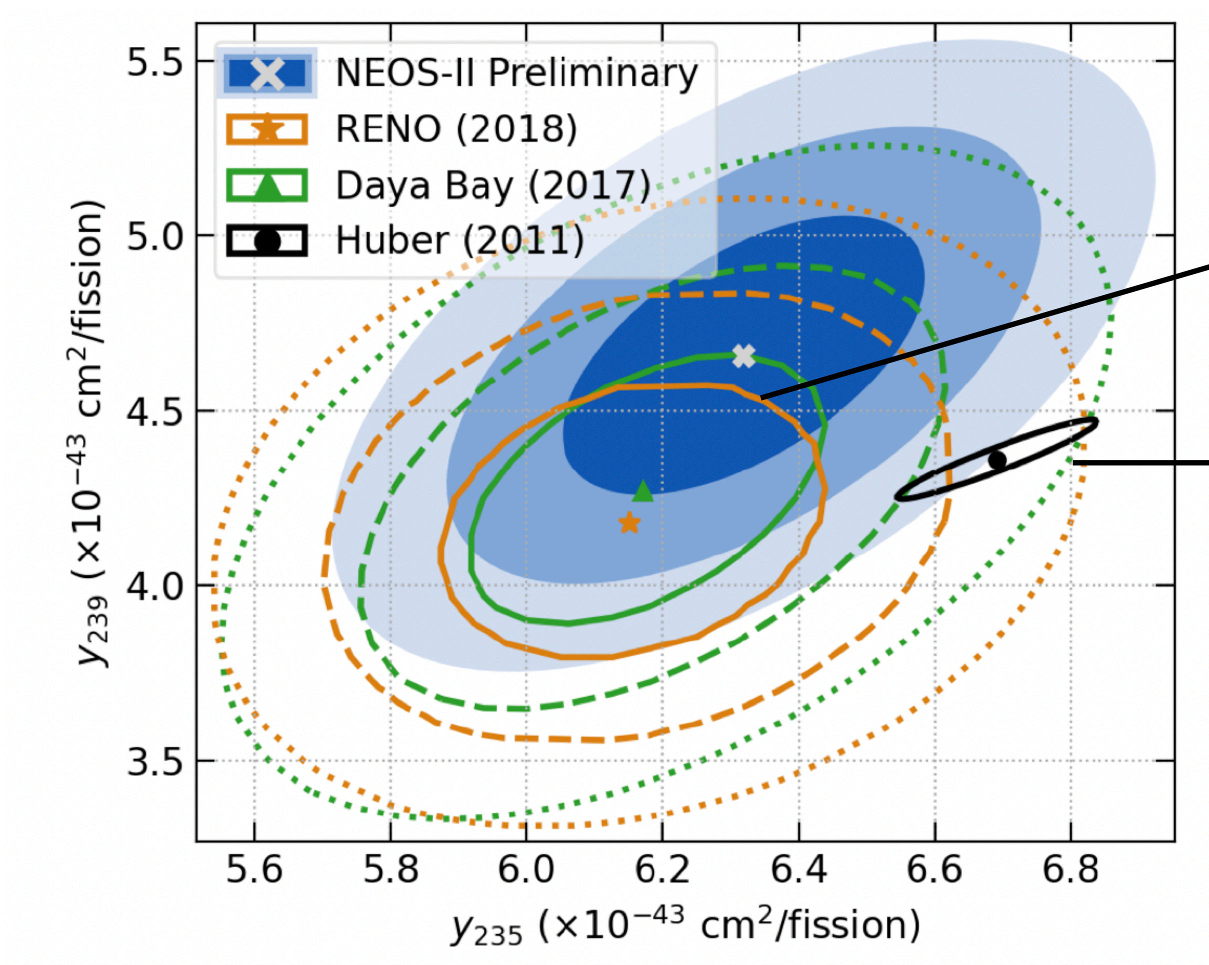
Argüelles et al, 2021



→ Not enough evidences to confirm or rule out the anomaly

The reactor anomaly

New theoretical models and reactor results indicate that the neutrino flux for ^{235}U should be reduced by 5-10 % with respect to previous estimations



Measurements at reactor experiments NEOS, RENO and DayaBay

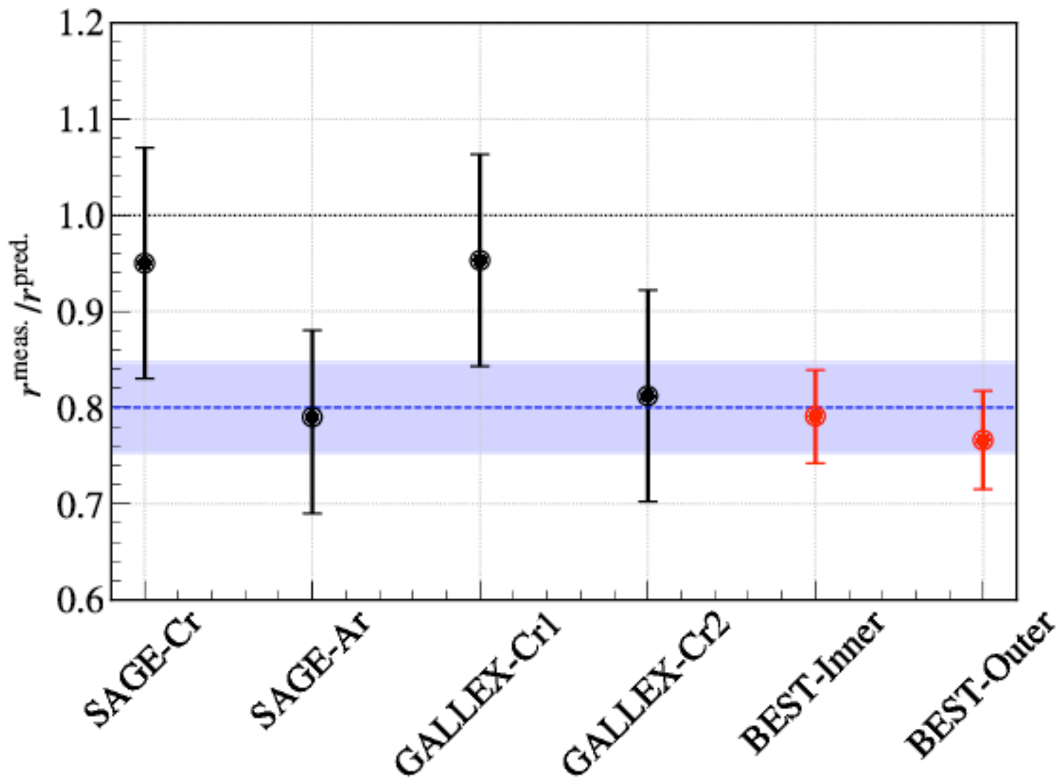
Previous theoretical predictions

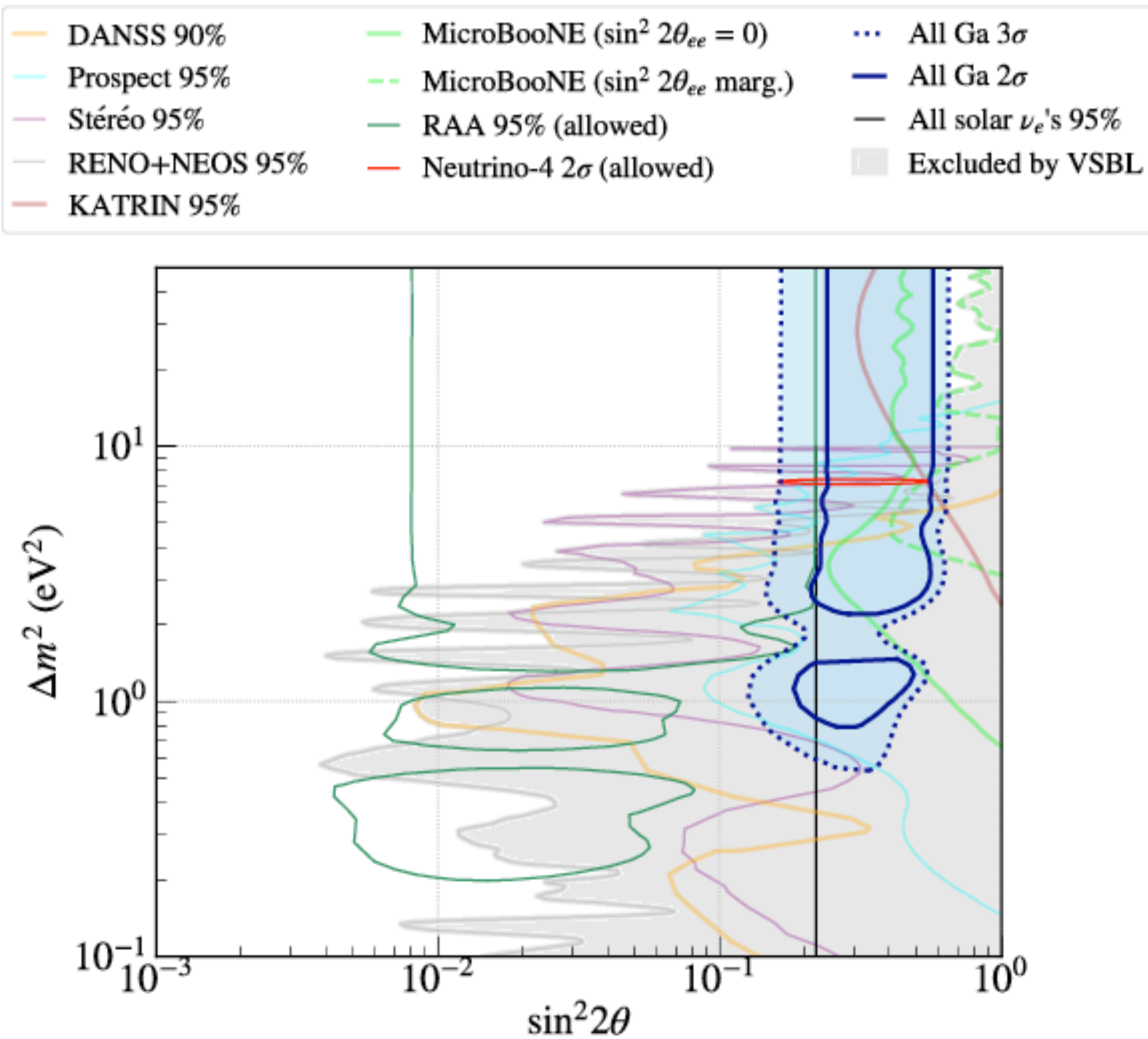
→ this result reconciles experimental data with theoretical predictions, solving the reactor neutrino flux anomaly

P. Vogel, Neutrino 2022

Current status of the Ga anomaly

✦ Recently confirmed by BEST (Baksan Experiment on Sterile Transitions) at 4σ



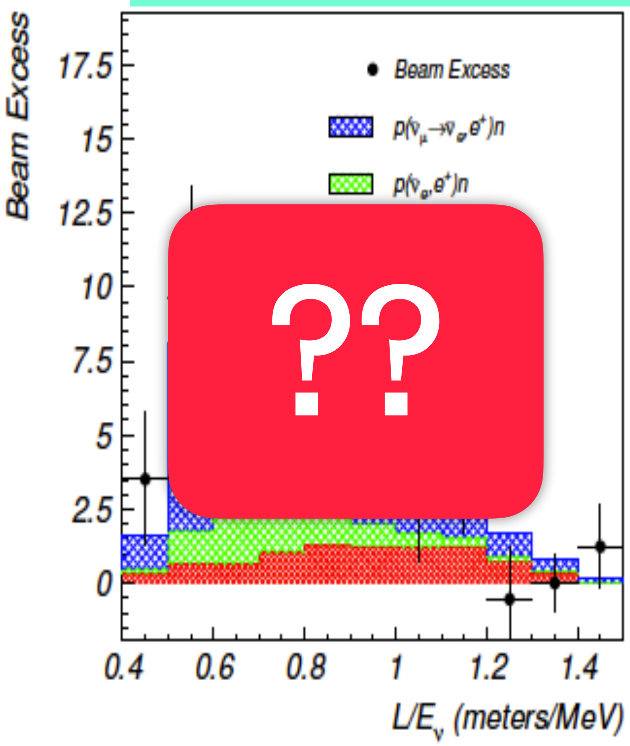


Barinov et al, PRC 2022

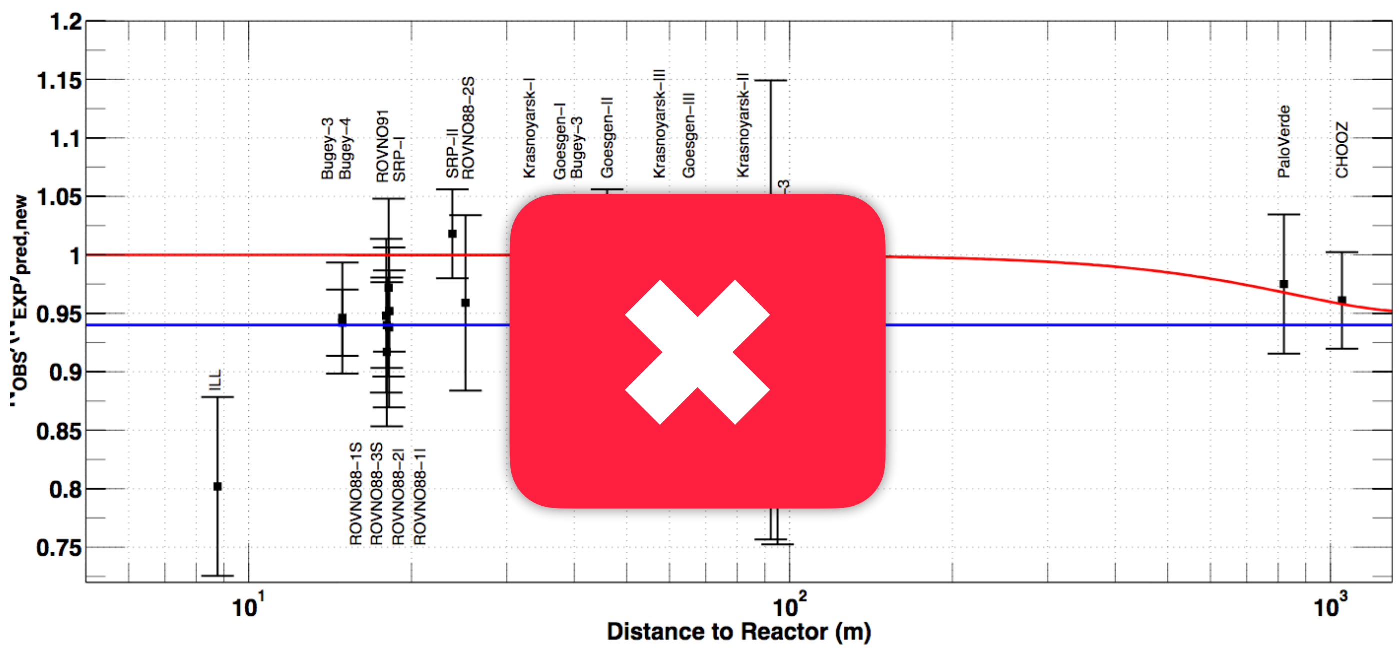
Hints for a light sterile neutrino

Anomalies in neutrino experiments with very short baselines source-detector (10-100 m)

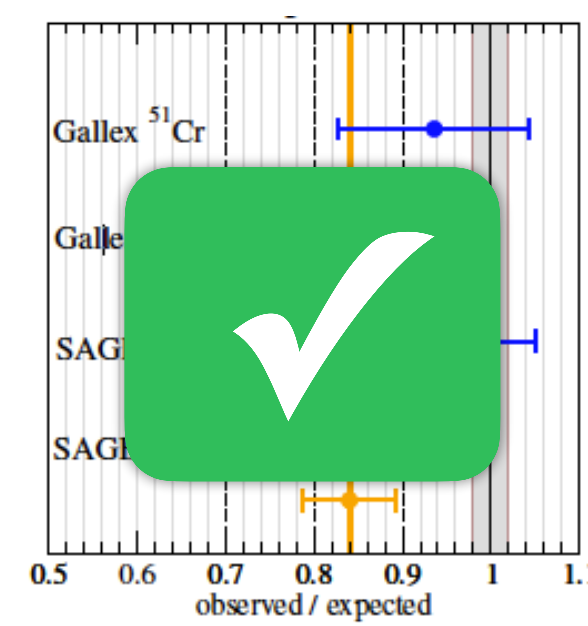
LSND & MiniBooNE



Reactor anomaly



Gallium anomaly

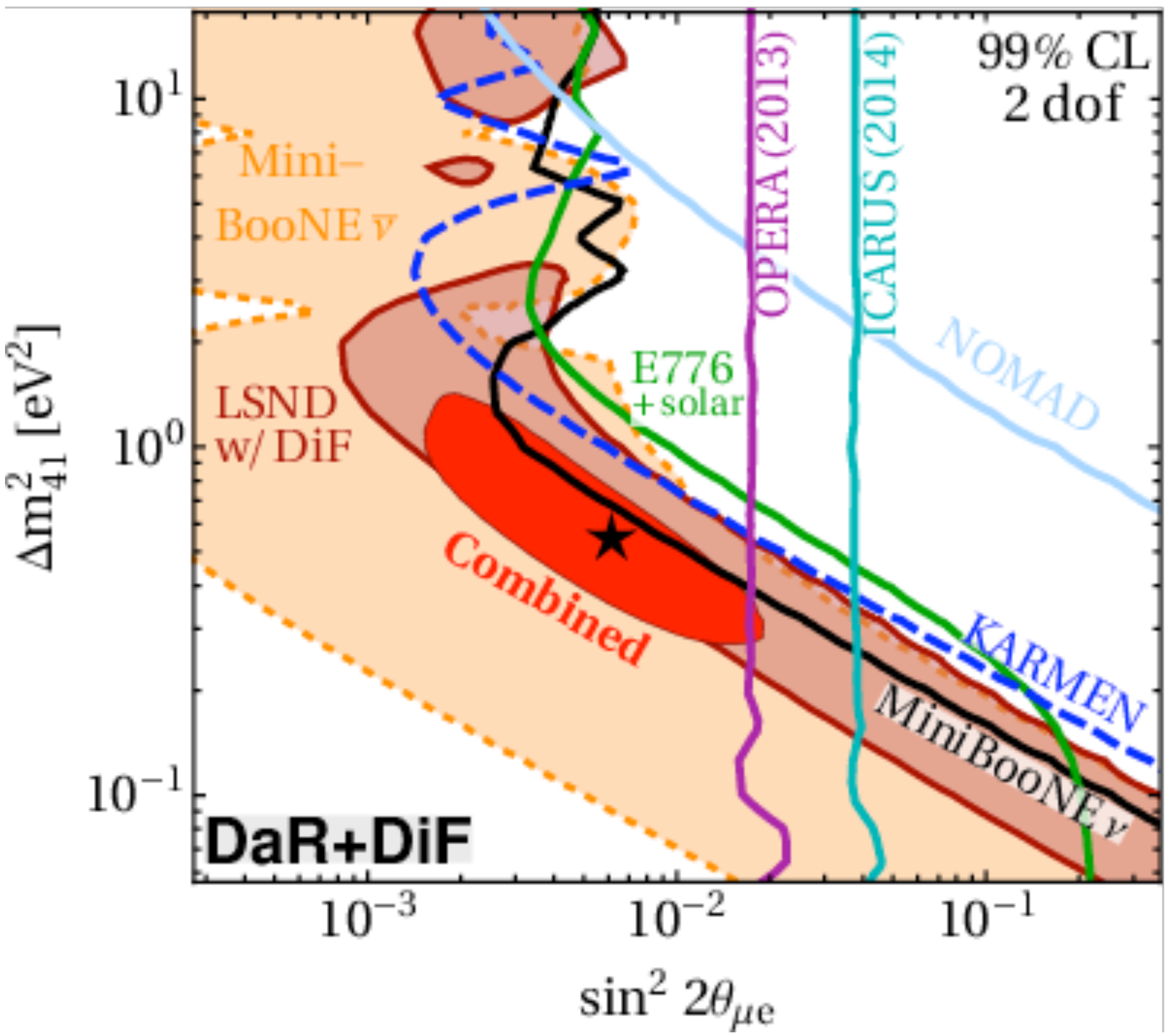


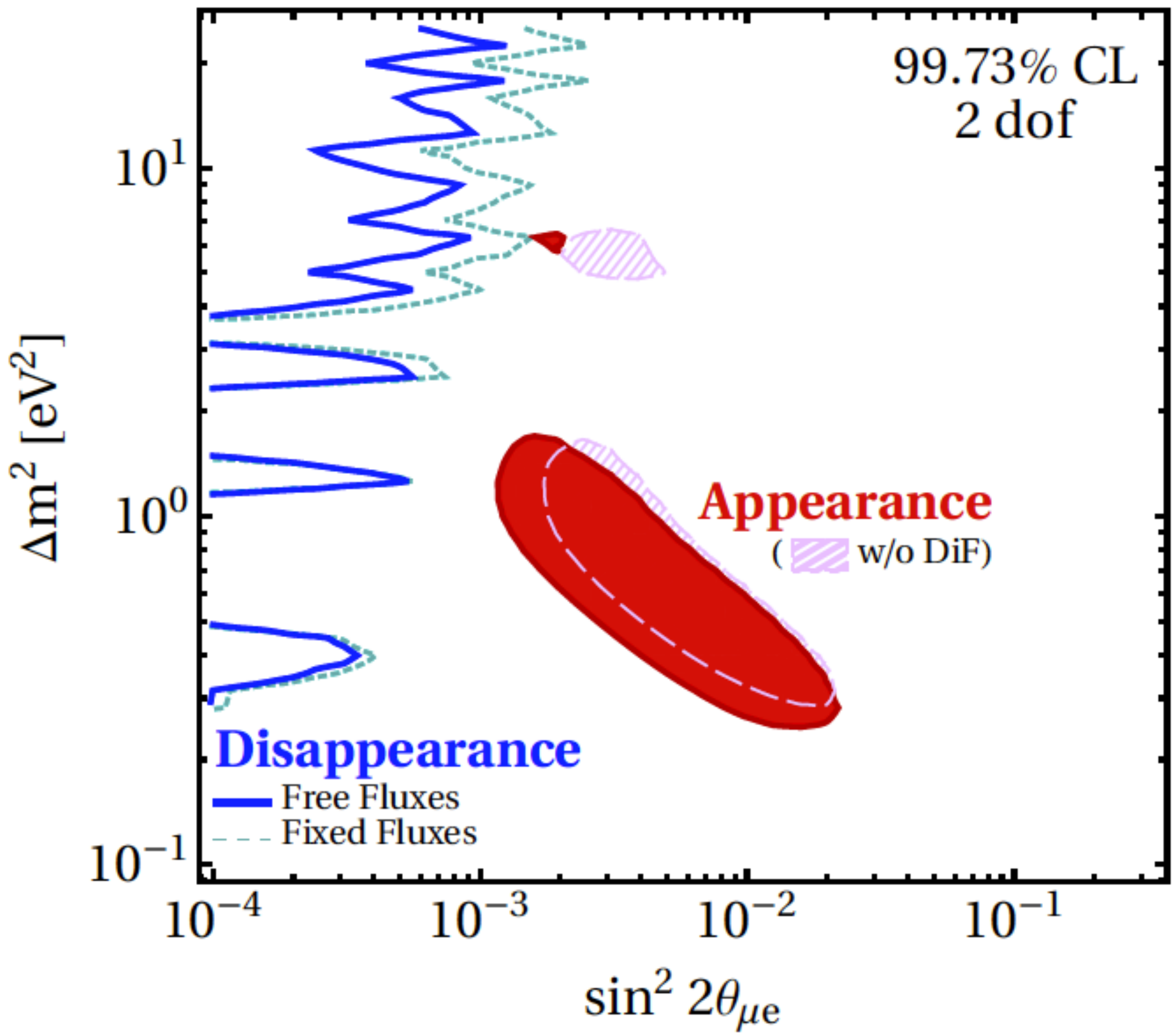
Explained with neutrino oscillations with $\Delta m^2 \sim 1$ eV^2 in the channels:

$\overline{\nu}_\mu \to \overline{\nu}_e$ $\qquad$ $\overline{\nu}_e \to \overline{\nu}_x$ $\qquad$ $\nu_e \to \nu_x$

Global fit in 3+1 neutrino scheme

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





⇒ Constraints on short-baseline $\nu_\mu \to \nu_e$ 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:

$\Sigma\, m_\nu$ = sum of neutrino masses N_{eff} = relativistic degrees of freedom

✦ Considering the presence 4th light sterile neutrino:

$$\rightarrow \sum m_\nu \gtrsim 0.05\,\text{eV} + \sqrt{\Delta m^2_{41}} > 1\,\text{eV}$$

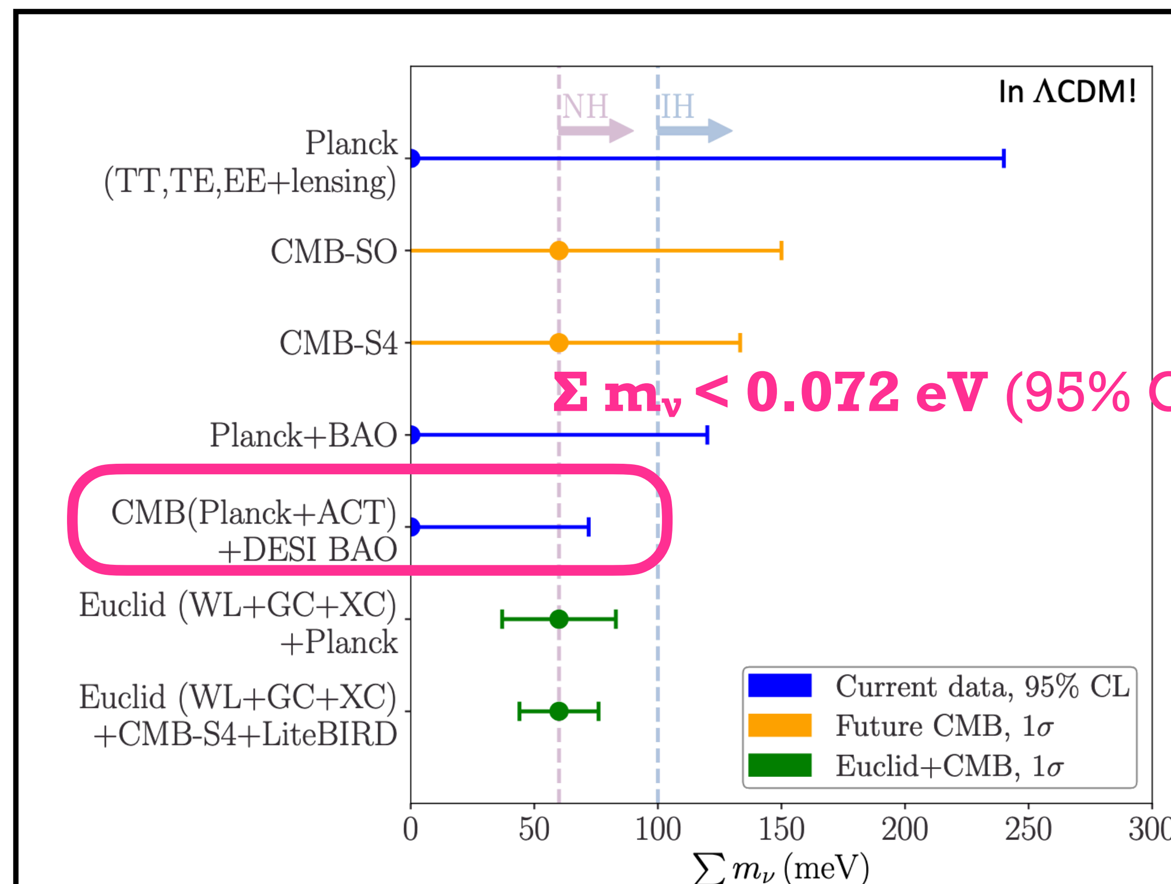
$\rightarrow$ $N_{eff} \approx 4$

✦ 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



$\Sigma\, m_\nu < 0.072$ eV (95% CL)*

Non-unitary light neutrino mixing

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

Ex: type I seesaw, inverse seesaw $\begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$ $\begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$

→ (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)

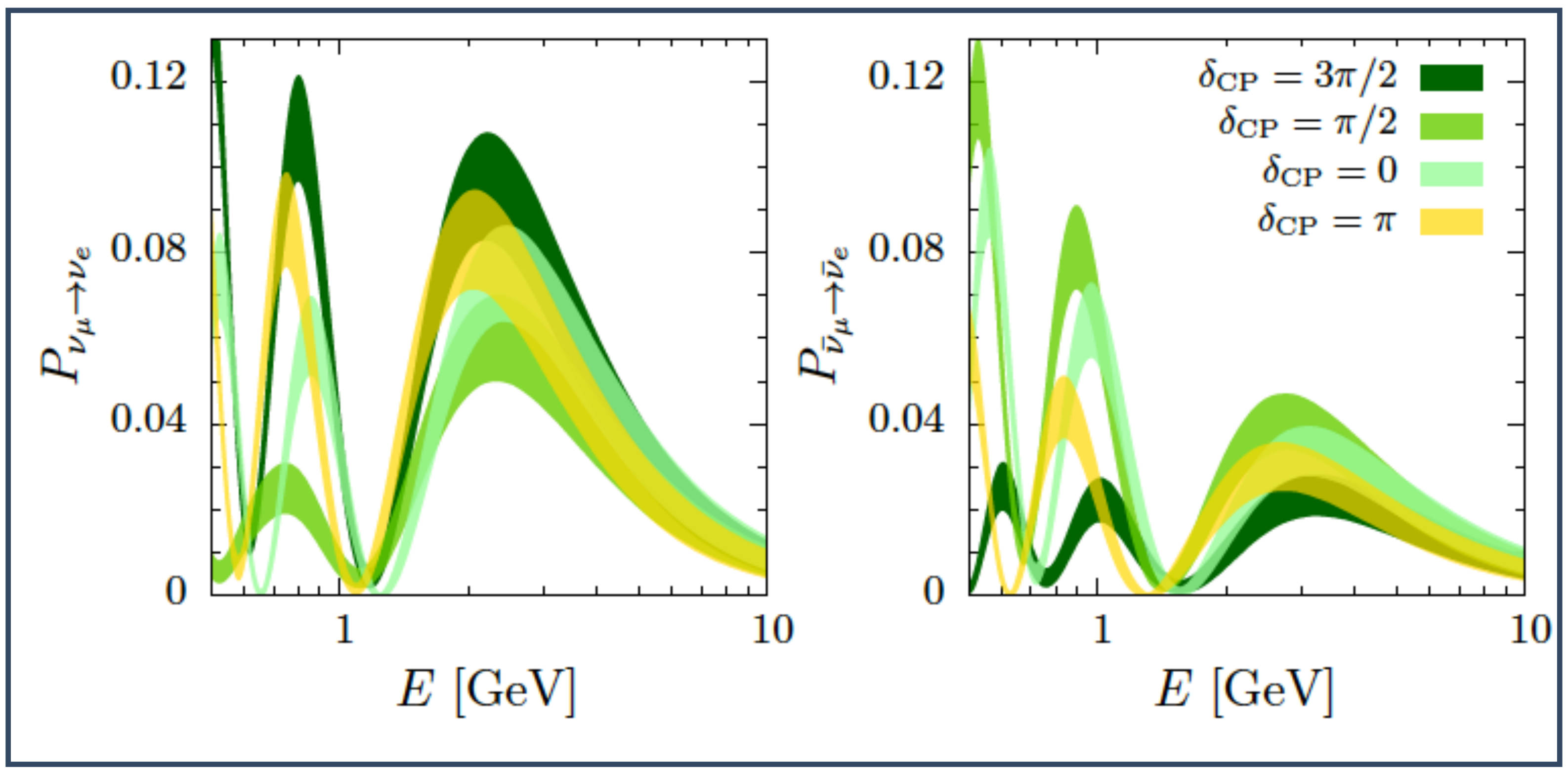
See also Xing, PRD2012 for n=6

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

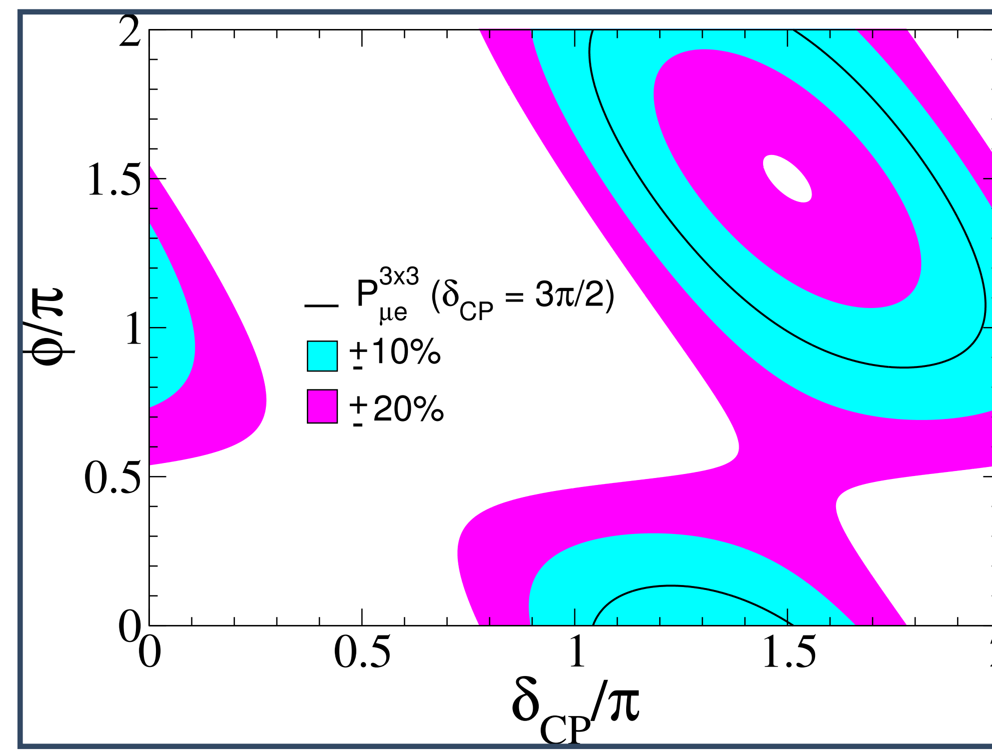
NU neutrino oscillations in DUNE

$$P_{\mu e} = (\alpha_{11}\alpha_{22})^2 P^{3\times3}_{\mu e} + \alpha^2_{11}\alpha_{22}|\alpha_{21}|P^I_{\mu e} + \alpha^2_{11}|\alpha_{21}|^2$$ **with** $P^I_{\mu e}(\phi)$

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



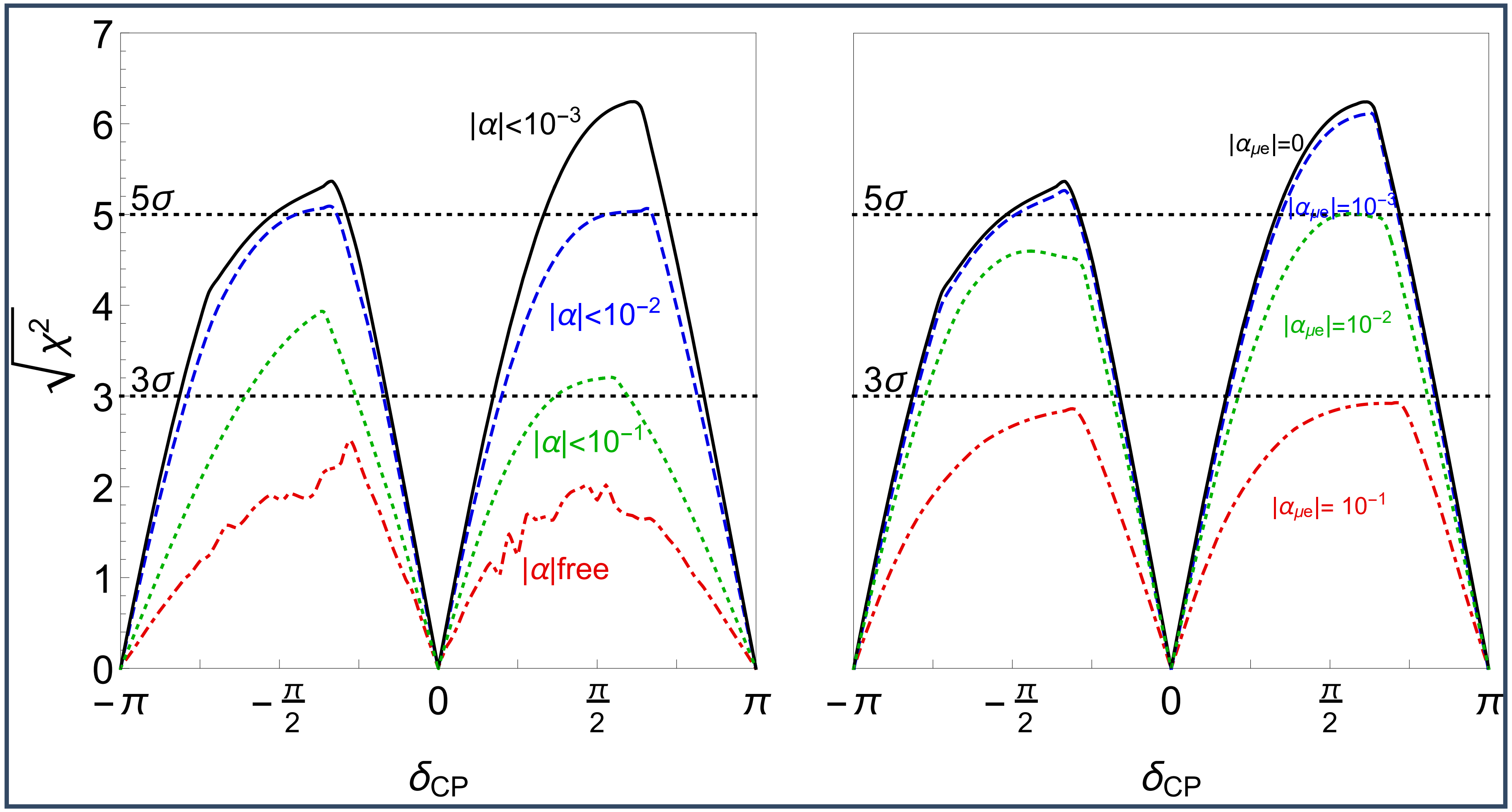
Escrihuela et al, NJP 2017



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



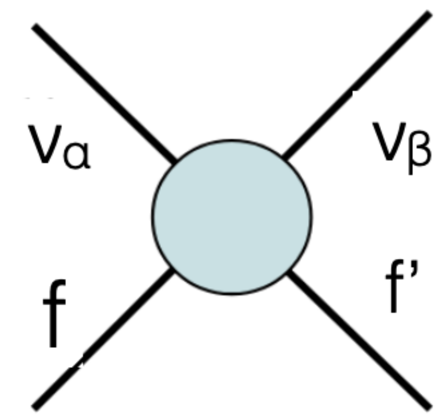
Fernández-Martínez et al (DUNE-BSM Working Group)

→ 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

Non-standard neutrino interactions

- New 4-fermion interactions involving neutrinos



(X= L,R)

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

$\Rightarrow$ effect on neutrino production and detection

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

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

$\epsilon_{\alpha\alpha} - \epsilon_{\beta\beta} \neq 0$ $\rightarrow$ 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)

Models leading to sizeable NSI

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

$$\epsilon \sim \left(\frac{g_X^2}{m_X^2}\right)G_F^{-1}$$

- models with heavy mediator: m_X >> 100 GeV ⇒ ϵ << 1
- models with light mediator: $m_X \sim$ 10 MeV, $\epsilon \sim 1$ with $g_X \sim 10^{-4}$-10^{-5}

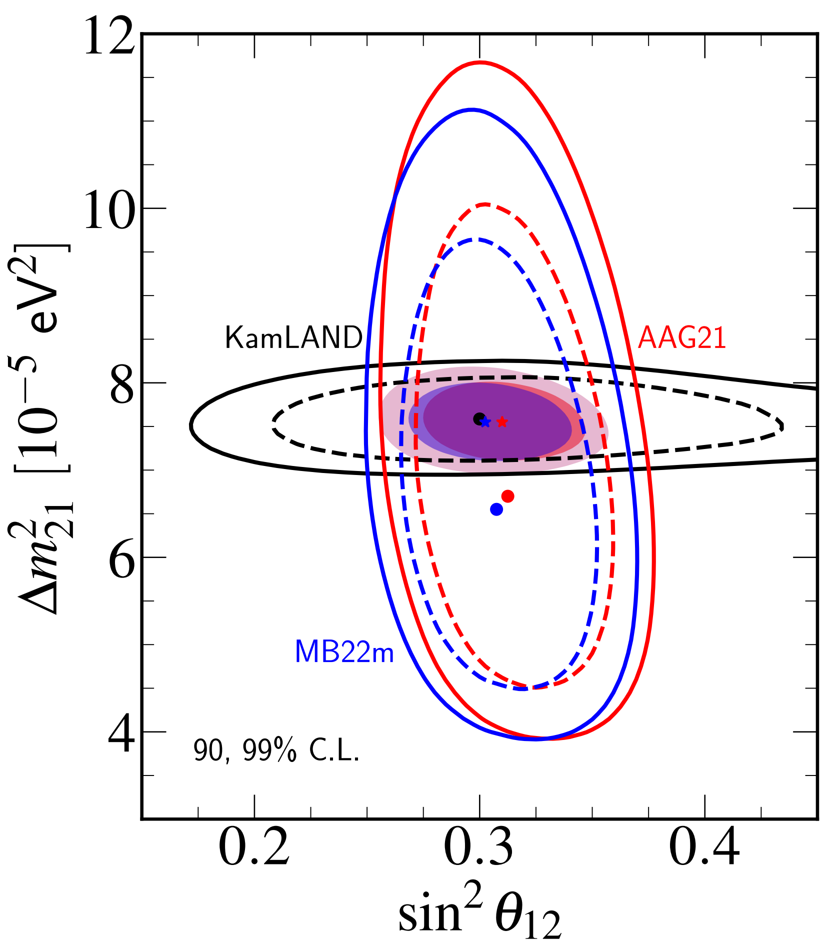
⇒ bounds on production avoided due to small coupling

⇒ NSI effect suppressed in scattering exp. with $q^2 \gg M_X^2$ (NuTeV, CHARM, q ~ GeV)

⇒ BBN bounds can be avoided with $m_X \gtrsim$ 10 MeV

10 MeV < m_X < 1 GeV

NSI in the solar sector



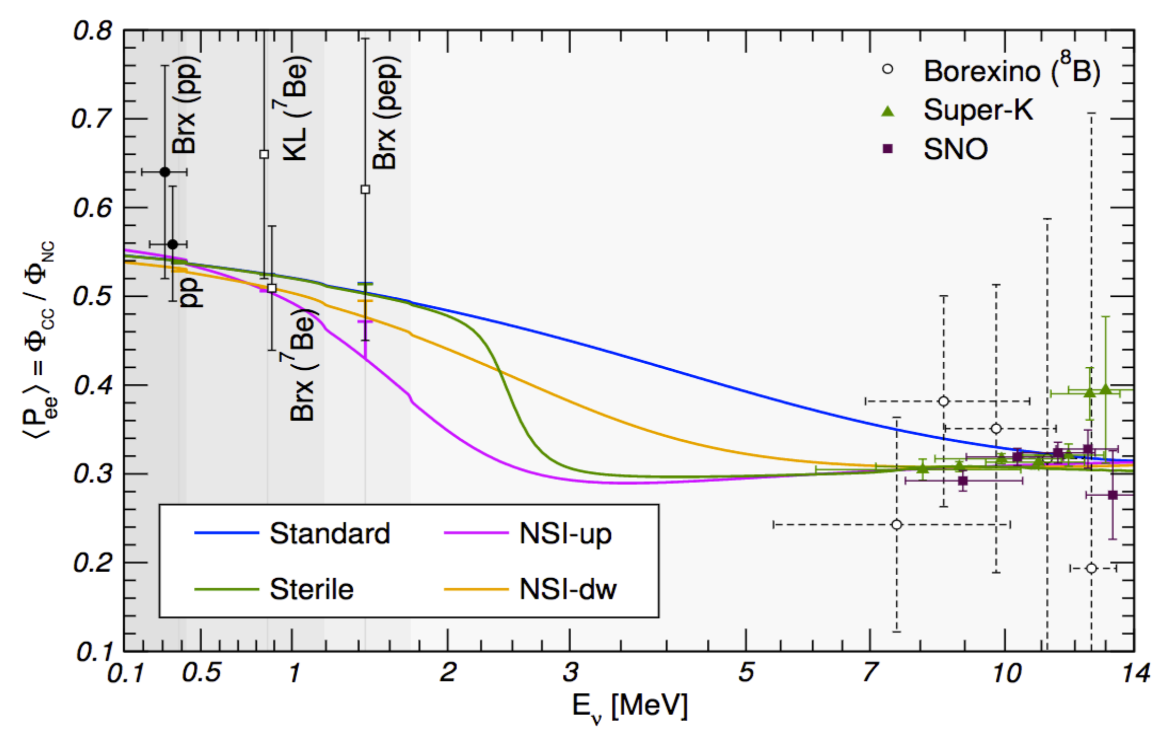
⇒ tension between preferred value of Δm^2_{21} from KamLAND and solar data

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

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

⇒ flatter spectrum at intermediate E-region

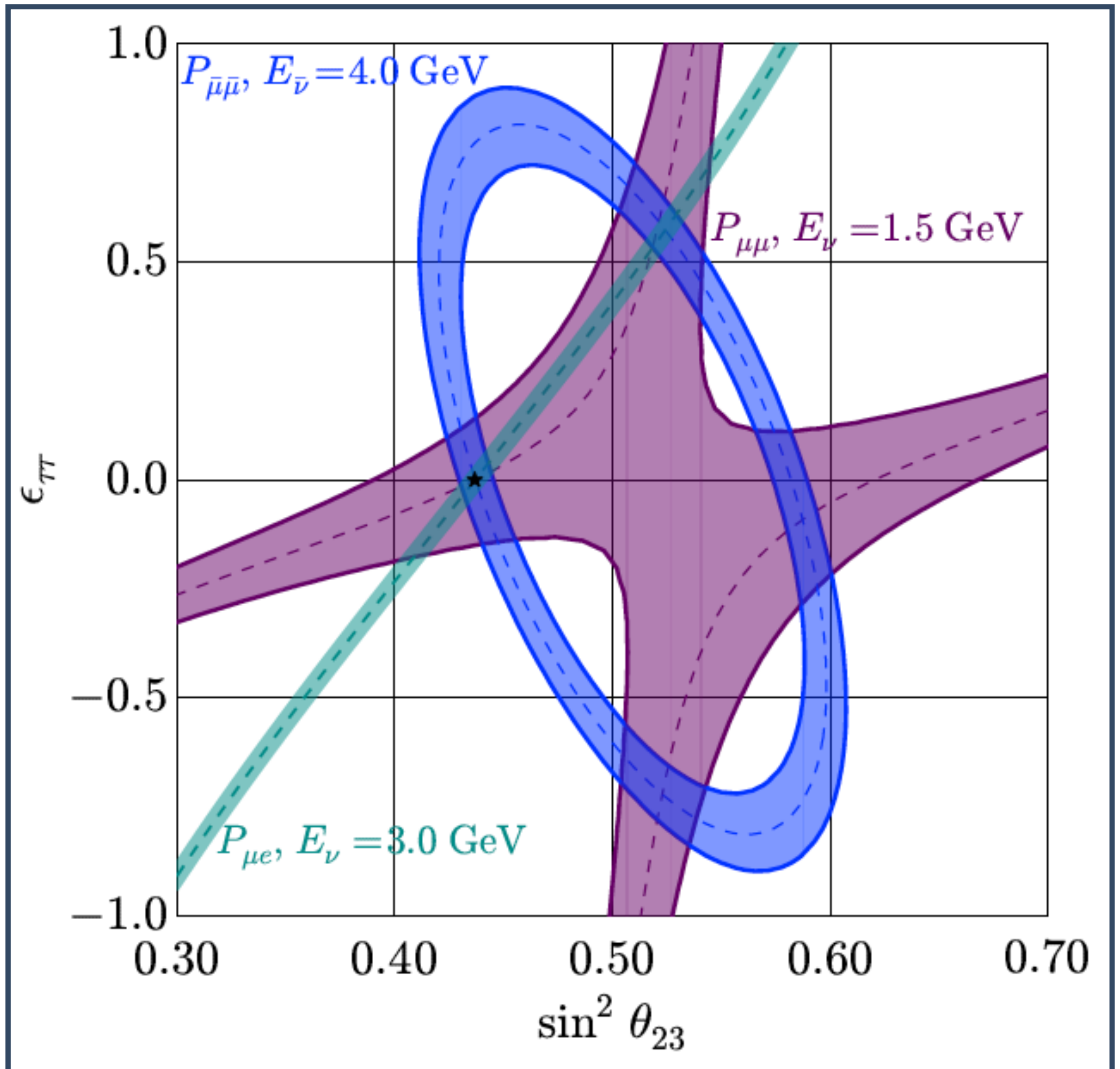
⇒ larger D/N asymmetries can be expected



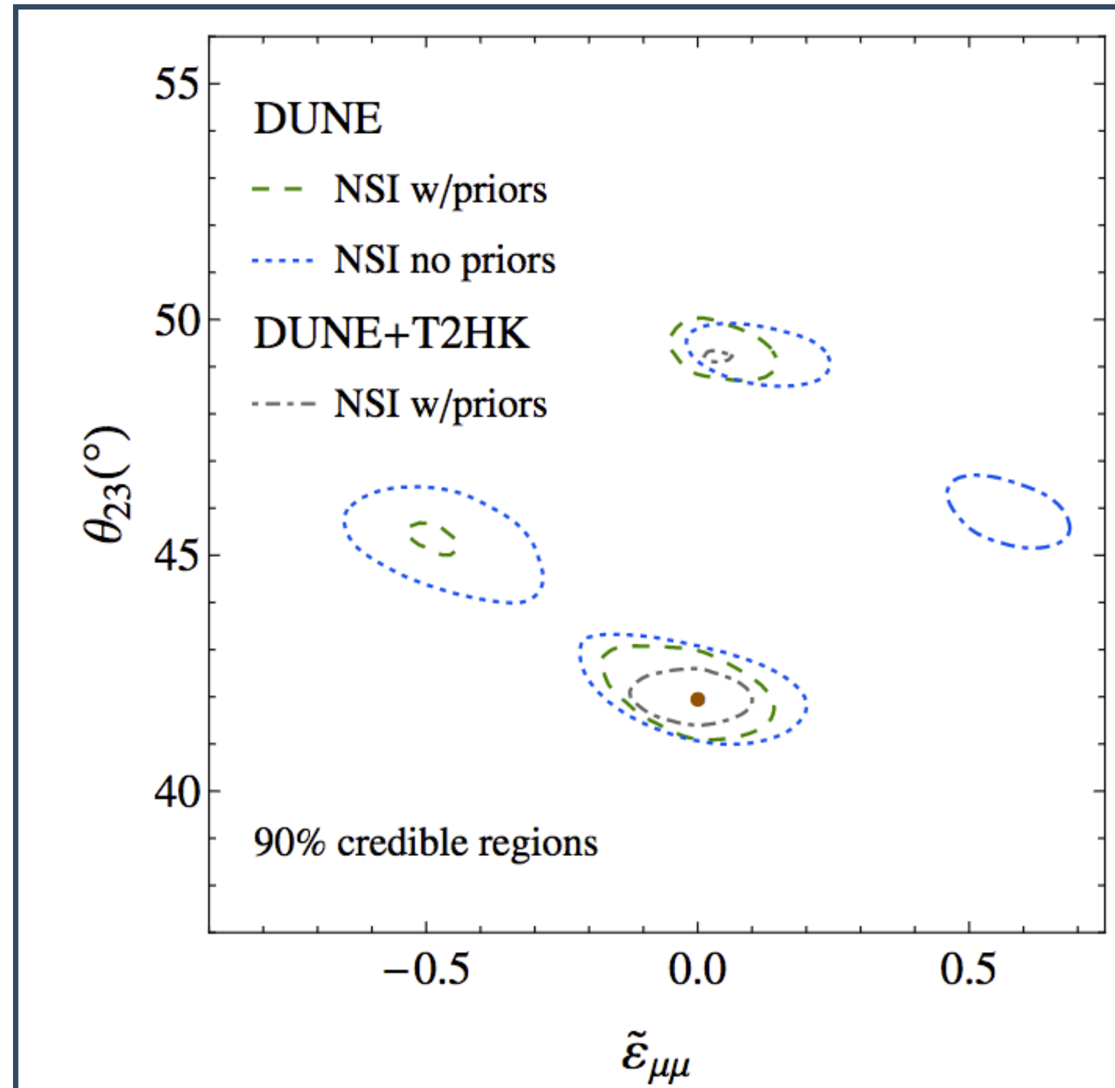
Escrihuela et al, PRD80 (2009); Coloma et al, PRD96 (2017) Maltoni & Smirnov, EPJ 2015

NSI at future LBL experiments

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



Gouvea and Kelly, NPB 2016

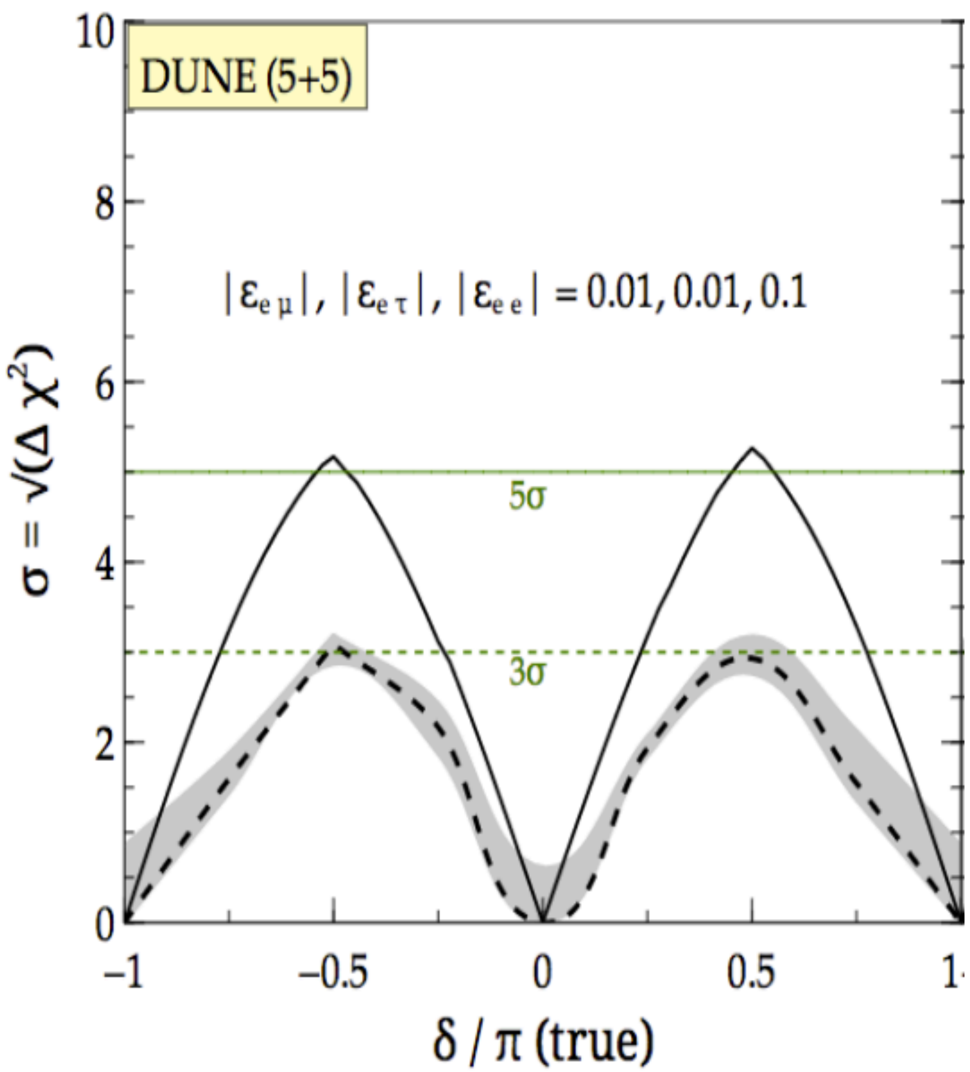


Coloma, JHEP 2016

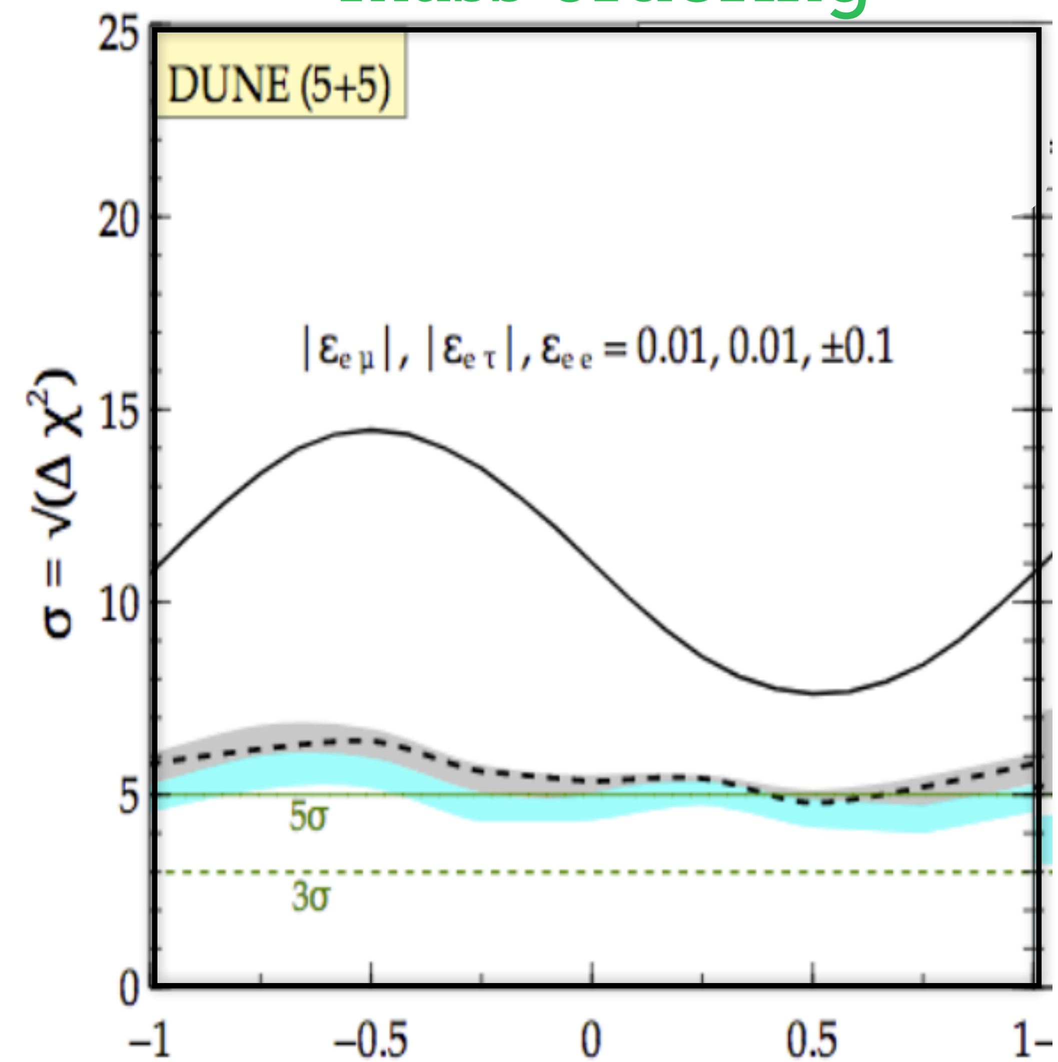
NSI at future LBL experiments

NSI can significantly spoil DUNE's sensitivity to:

CP violation



mass ordering

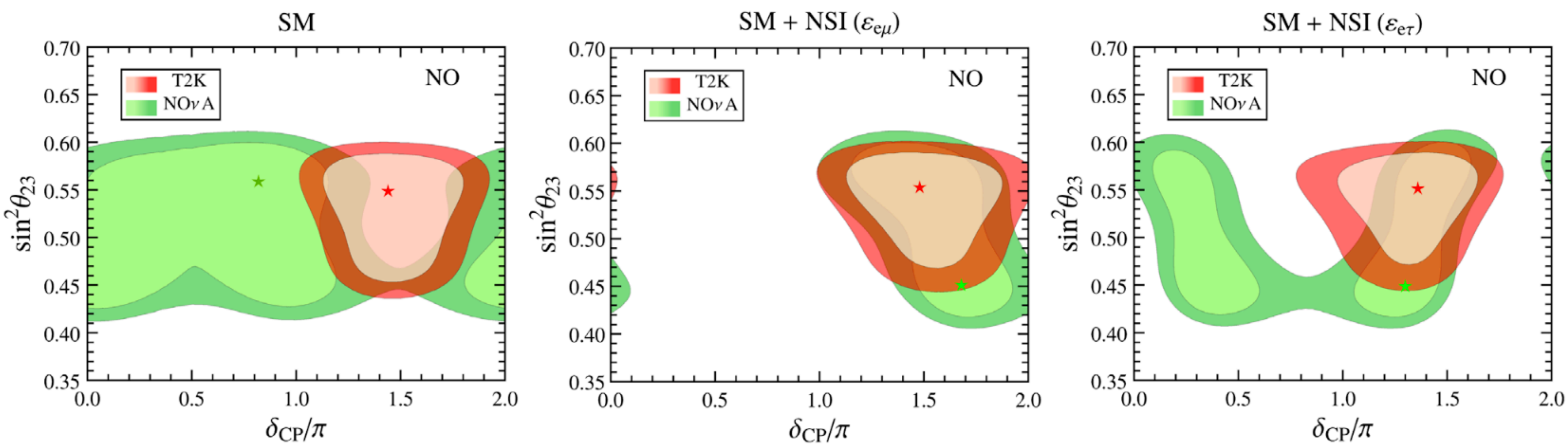


Masud and Mehta, PRD 2016

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**

BSM searches with CEvNS experiments

Physics potential of CEvNS

Freedman, PRD 1974

Barranco et al, JHEP 2005

Nuclear form factor

$$\frac{d\sigma}{dT} = \frac{G_F^2 M}{4\pi}\left(1 - \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right)\boxed{Q_{\mathrm{w}}^2}\boxed{[F_{\mathrm{w}}(q^2)]^2} + \boxed{\frac{G_F^2 M}{4\pi}\left(1 + \frac{MT}{2E_\nu^2} - \frac{T}{E_\nu}\right)F_A(q^2)}$$

Weak nuclear charge

Axial contribution: small for most nuclei, it cancels out for nuclei with even number of p and n

$$Q_W = [Z(1 - 4\sin^2\theta_W) - N]$$

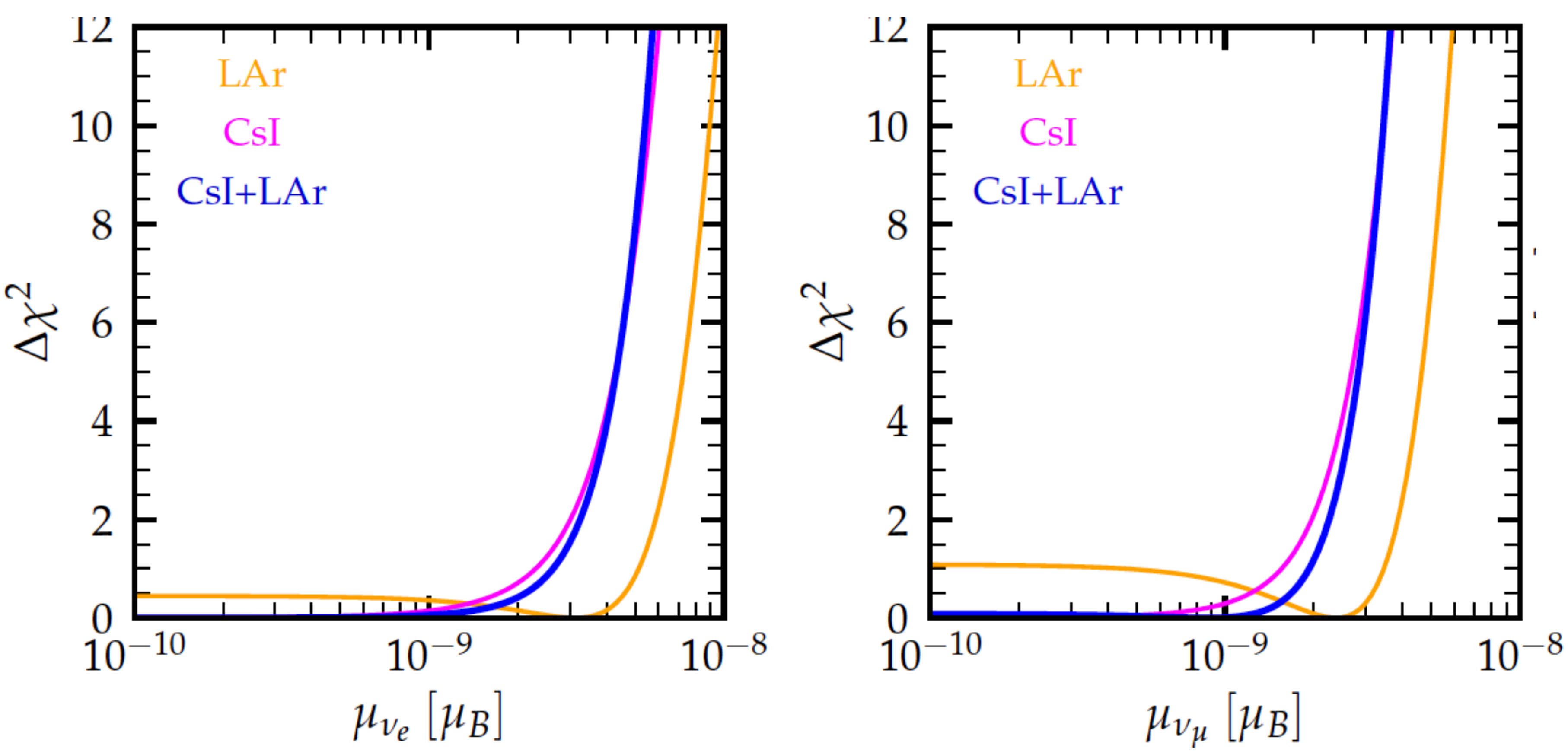
$\sin^2\theta_W \sim 0.23$ → neutron contribution dominates

- ✦ **Standard Model tests:** nuclear physics, EW measurements (θ_W)
- ✦ **BSM searches:** neutrino electromagnetic properties, NSI, couplings with new mediator particles,…

Neutrino magnetic moment

- Minimal SM extension (with m_ν) predicts $\mu_\nu \simeq 3\times10^{-19}\left(\frac{m_\nu}{\mathrm{eV}}\right)\mu_B$ ➡ larger in BSM
- The (effective) neutrino magnetic moment gives extra contribution to CEvNS cross section:

$$\frac{d\sigma_{\nu_\ell\mathcal{N}}}{dE_{\rm nr}}\bigg|^{\rm MM}_{\rm CE\nu NS} = \frac{\pi\alpha^2_{\rm EM}}{m_e^2}\left(\frac{1}{E_{\rm nr}}-\frac{1}{E_\nu}\right)Z^2F^2_W(|\vec{q}|^2)\left|\frac{\mu_{\nu_\ell}}{\mu_{\rm B}}\right|^2$$

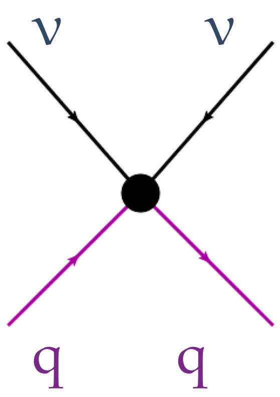


90% C.L. limits

$$\mu_{\nu_e} < 3.6\ (3.8)\times10^{-9}\ \mu_B$$
$$\mu_{\nu_\mu} < 2.4\ (2.6)\times10^{-9}\ \mu_B$$

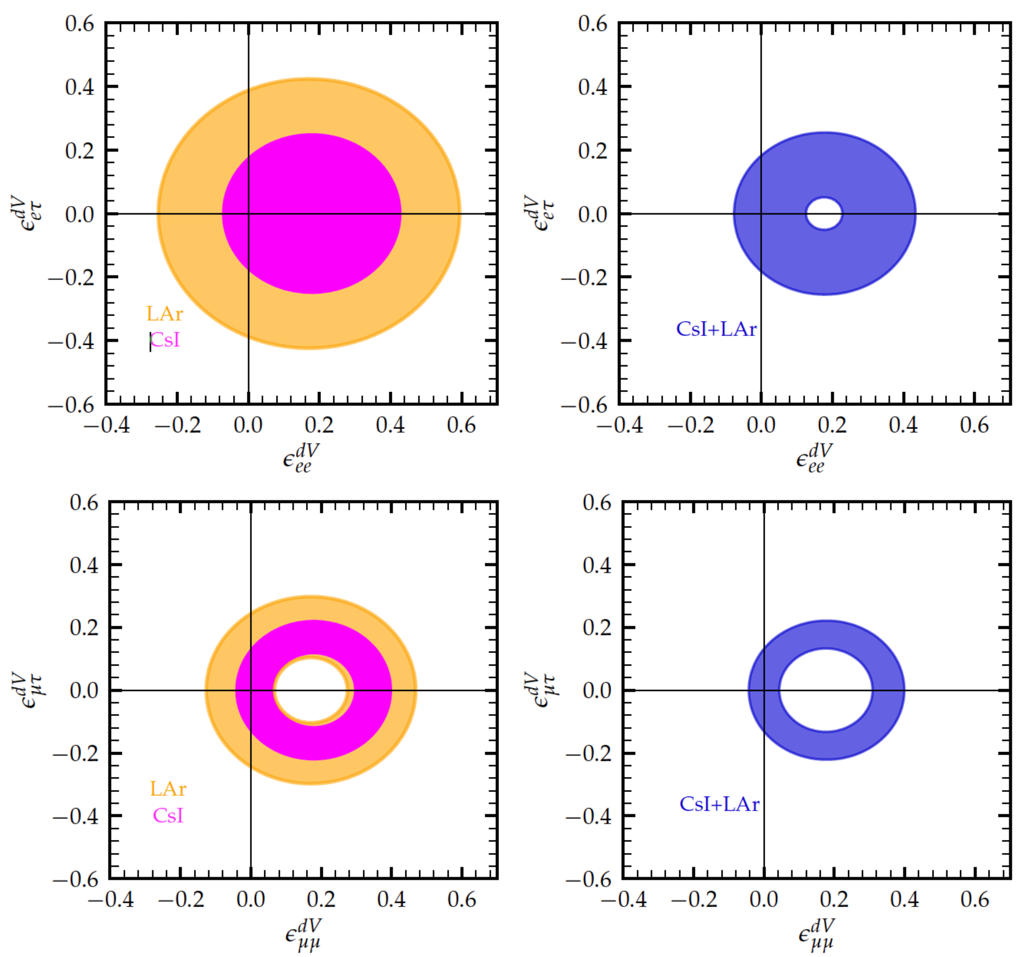
Data from COHERENT Experiment

Non-standard interactions



$$Q_V^{\mathrm{NSI}} = \left[\left(g_V^p + 2\varepsilon_{\ell\ell}^{uV} + \varepsilon_{\ell\ell}^{dV}\right) Z + \left(g_V^n + \varepsilon_{\ell\ell}^{uV} + 2\varepsilon_{\ell\ell}^{dV}\right) N\right] + \sum_{\ell,\ell'} \left[\left(2\varepsilon_{\ell\ell'}^{uV} + \varepsilon_{\ell\ell'}^{dV}\right) Z + \left(\varepsilon_{\ell\ell'}^{uV} + 2\varepsilon_{\ell\ell'}^{dV}\right) N\right].$$

Flavour-changing NSI



Non-Universal NSI