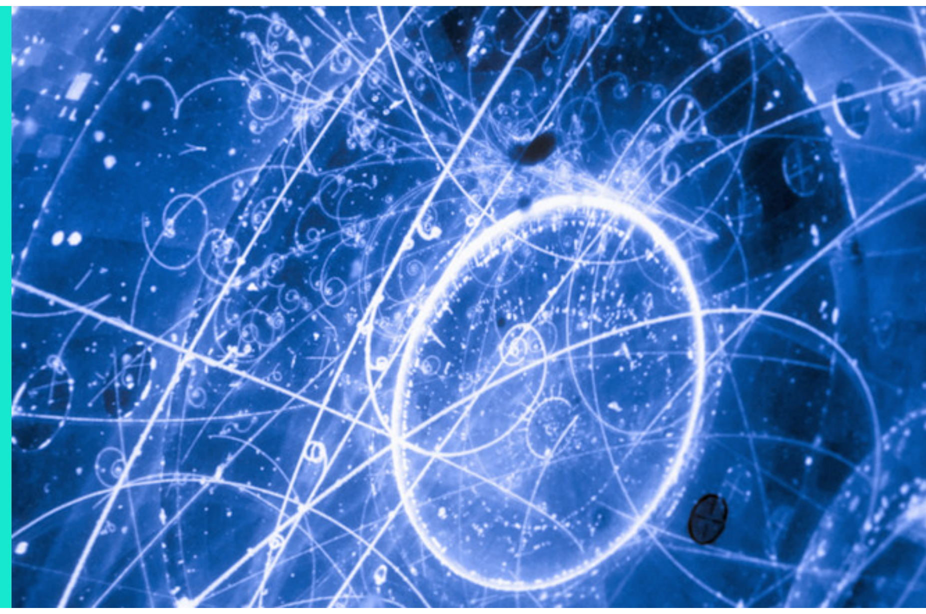
Status of the Three Neutrino Framework



Iván Martínez Soler

RADPyC26

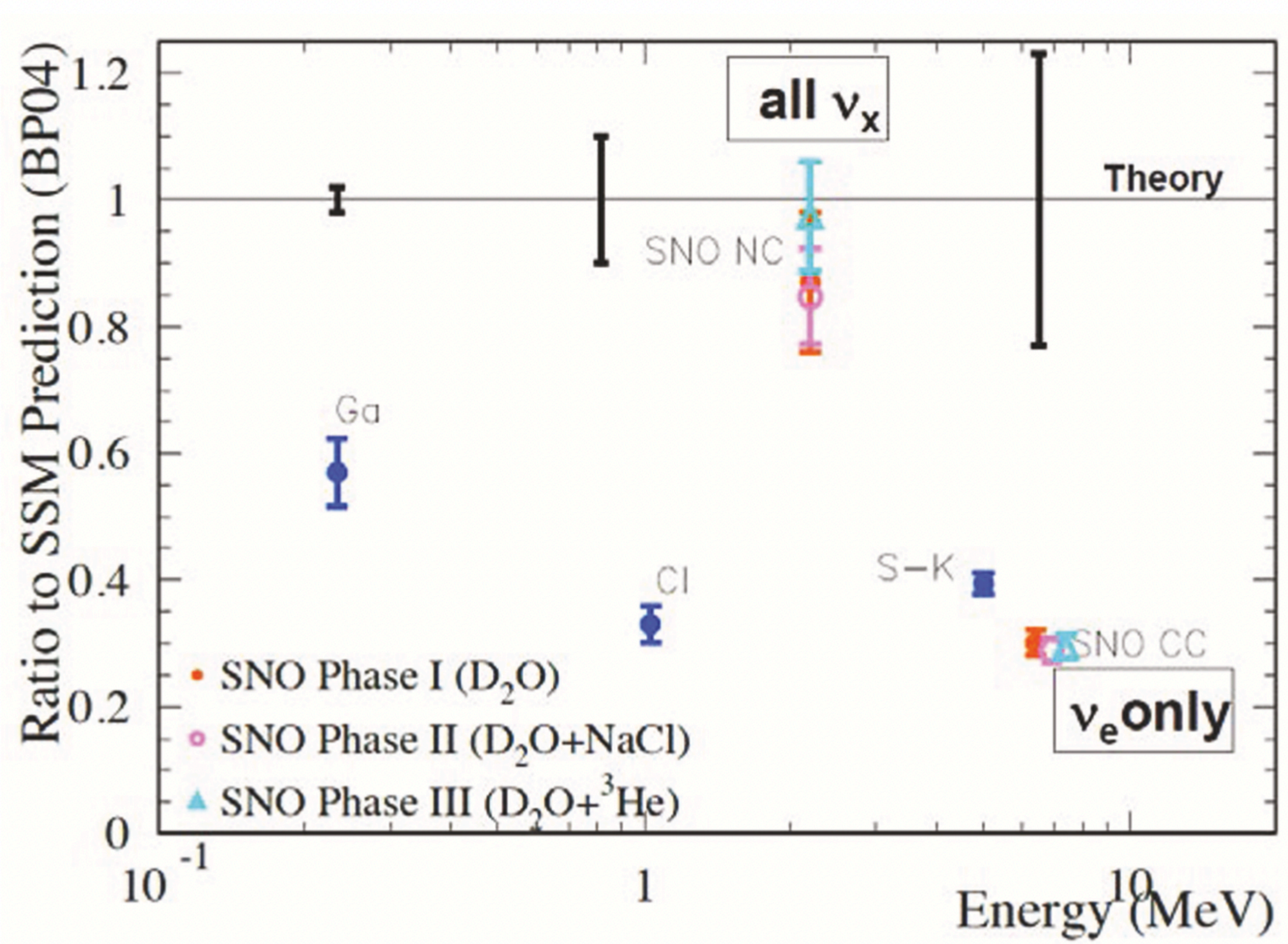
June 19, 2026

Durham University

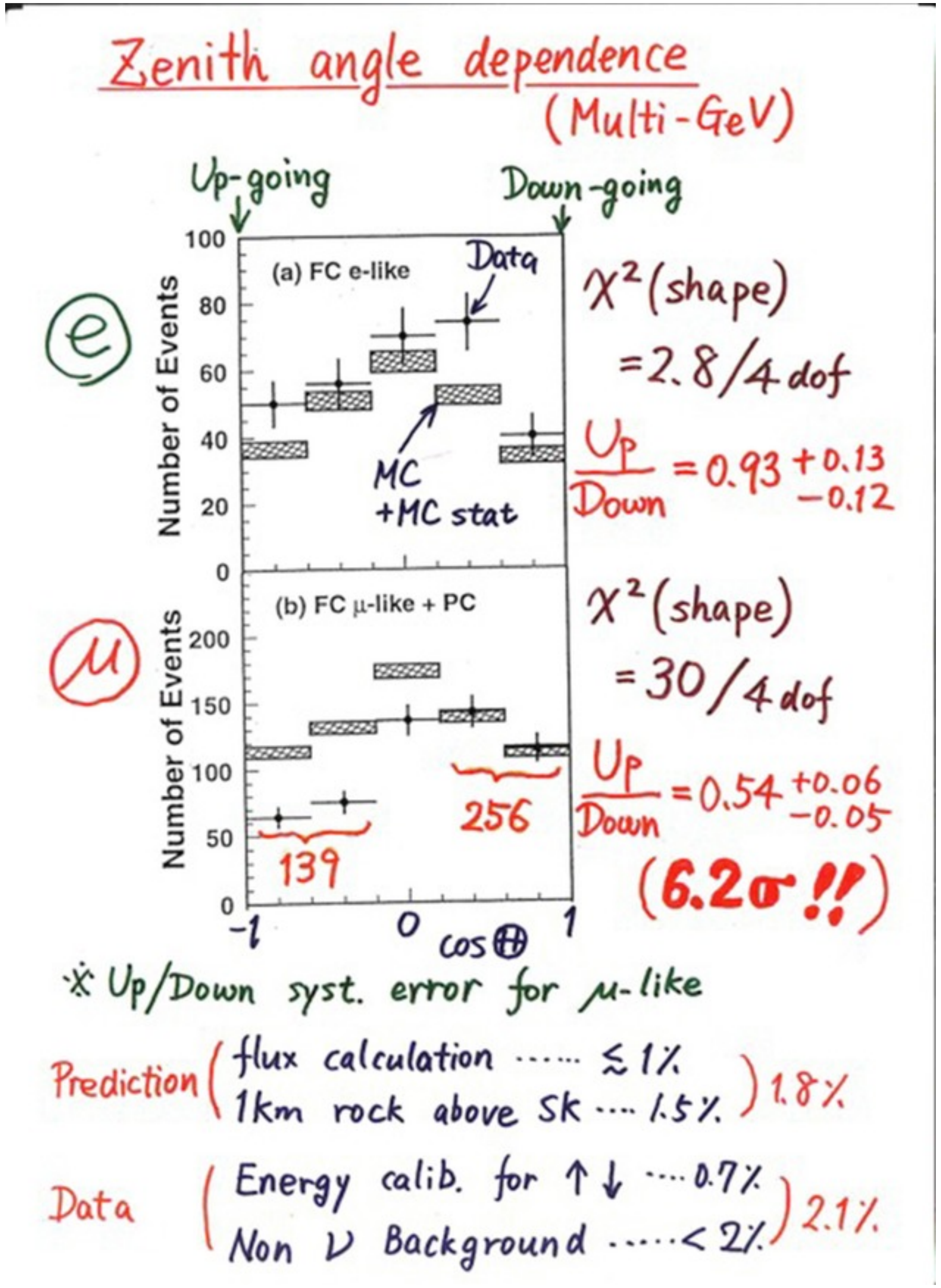
IP3

Evidence for Flavor Oscillation

Flavor oscillations are the only evidence that **neutrinos are massive particles**



Arthur MacDonald. Nobel lecture



Takaaki Kajita (Super-kamiokande) Neutrino 98

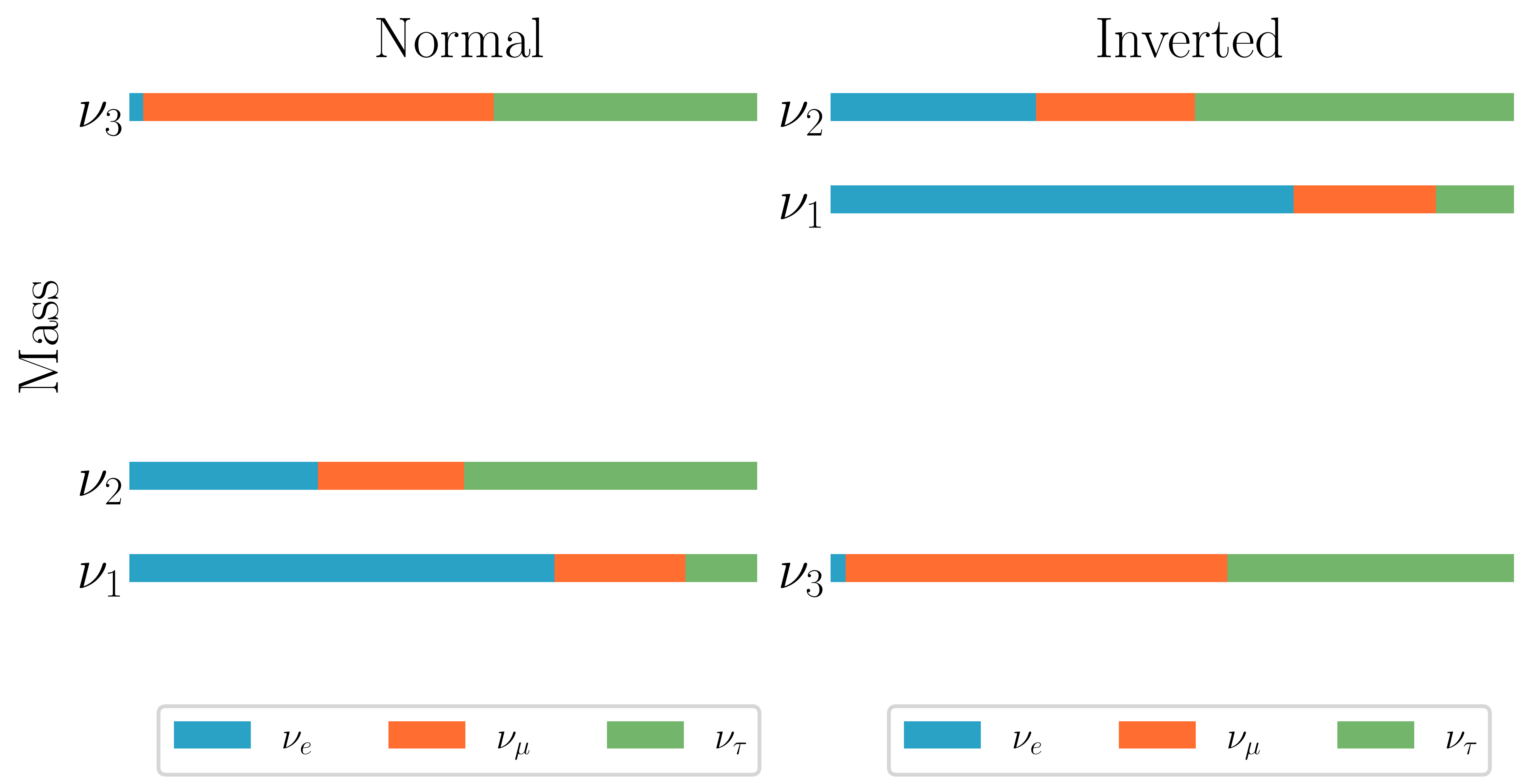
3ν mixing

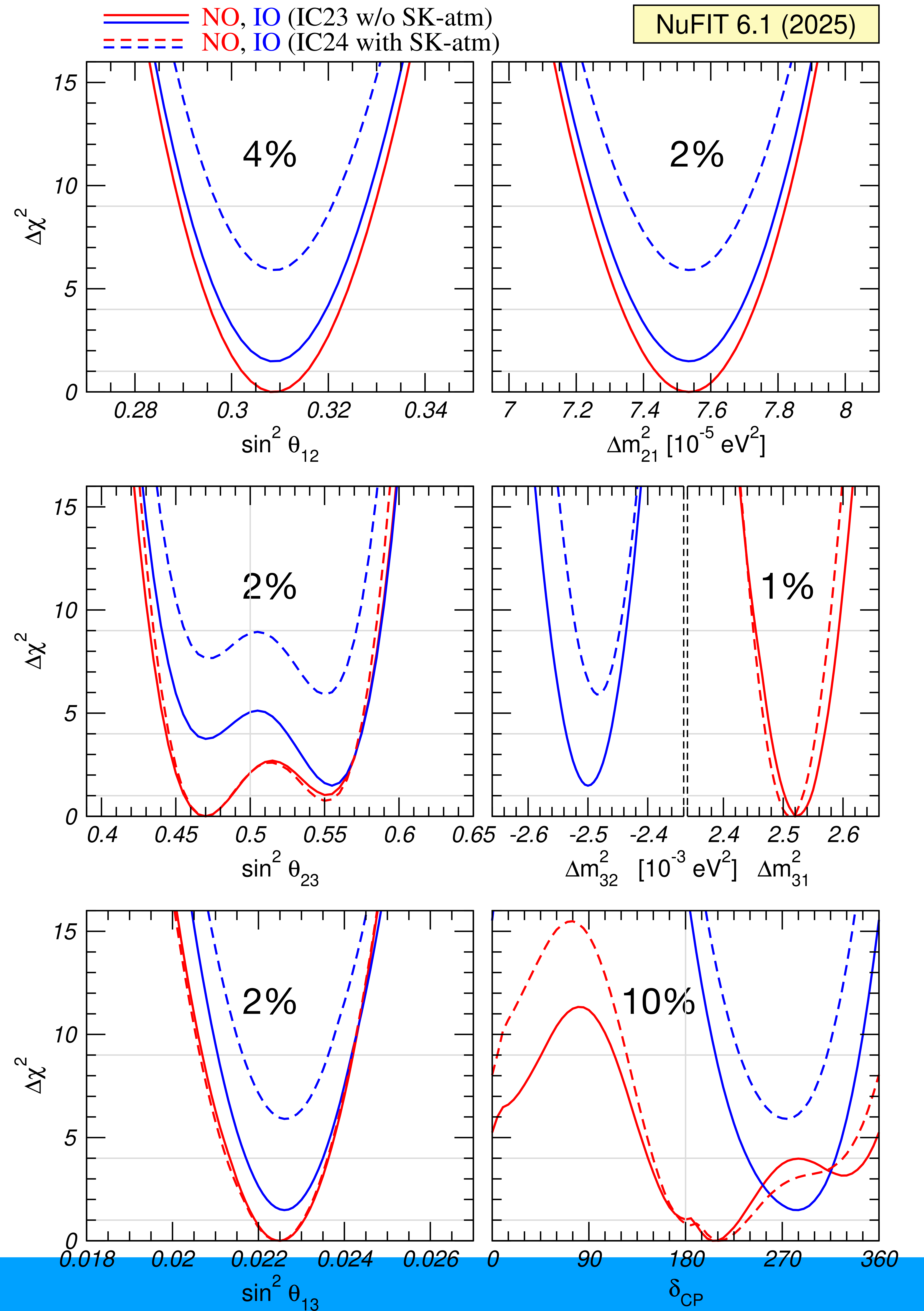
In the 3ν **scenario**, neutrino evolution is described by six parameters

$$i\frac{d\nu}{dE} = \frac{1}{2E}\left(U^{\dagger}\text{diag}(0,\Delta m^2_{21},\Delta m^2_{31})U\right)\nu$$

$$\nu_\alpha = \sum U_{\alpha i}\nu_i \qquad\qquad U = U(\theta_{23})U(\theta_{13},\delta_{cp})U(\theta_{12})$$

Mass ordering





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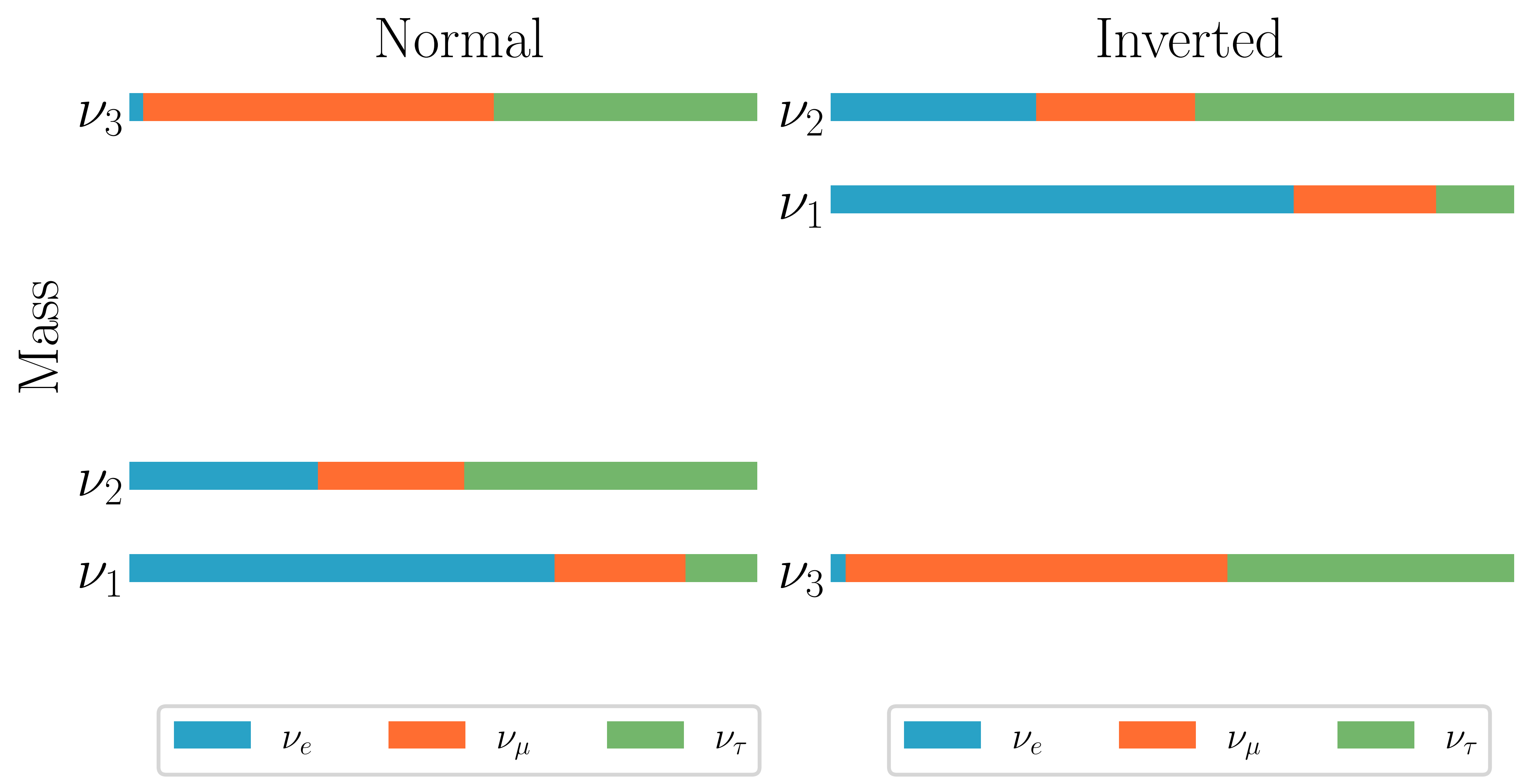

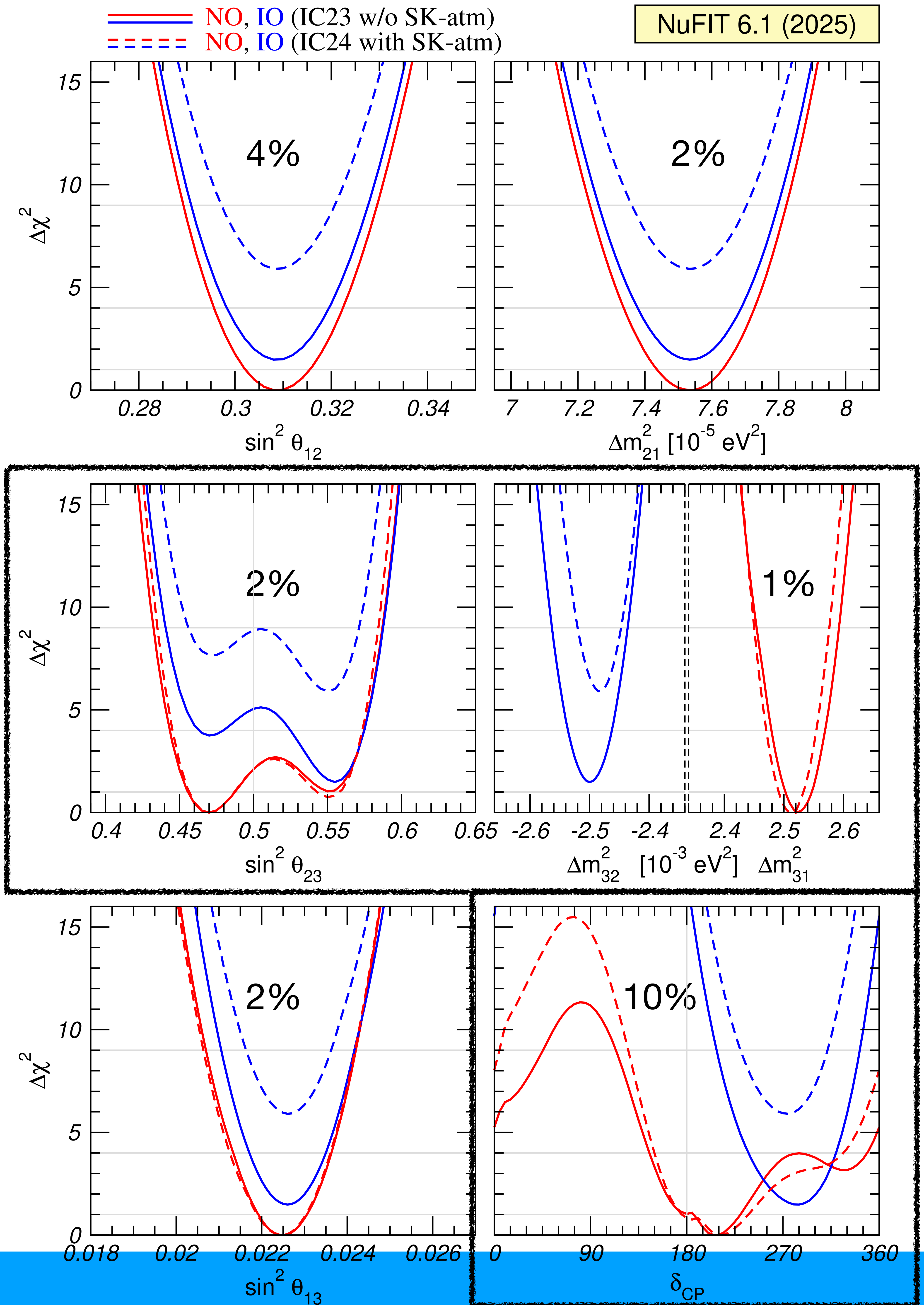

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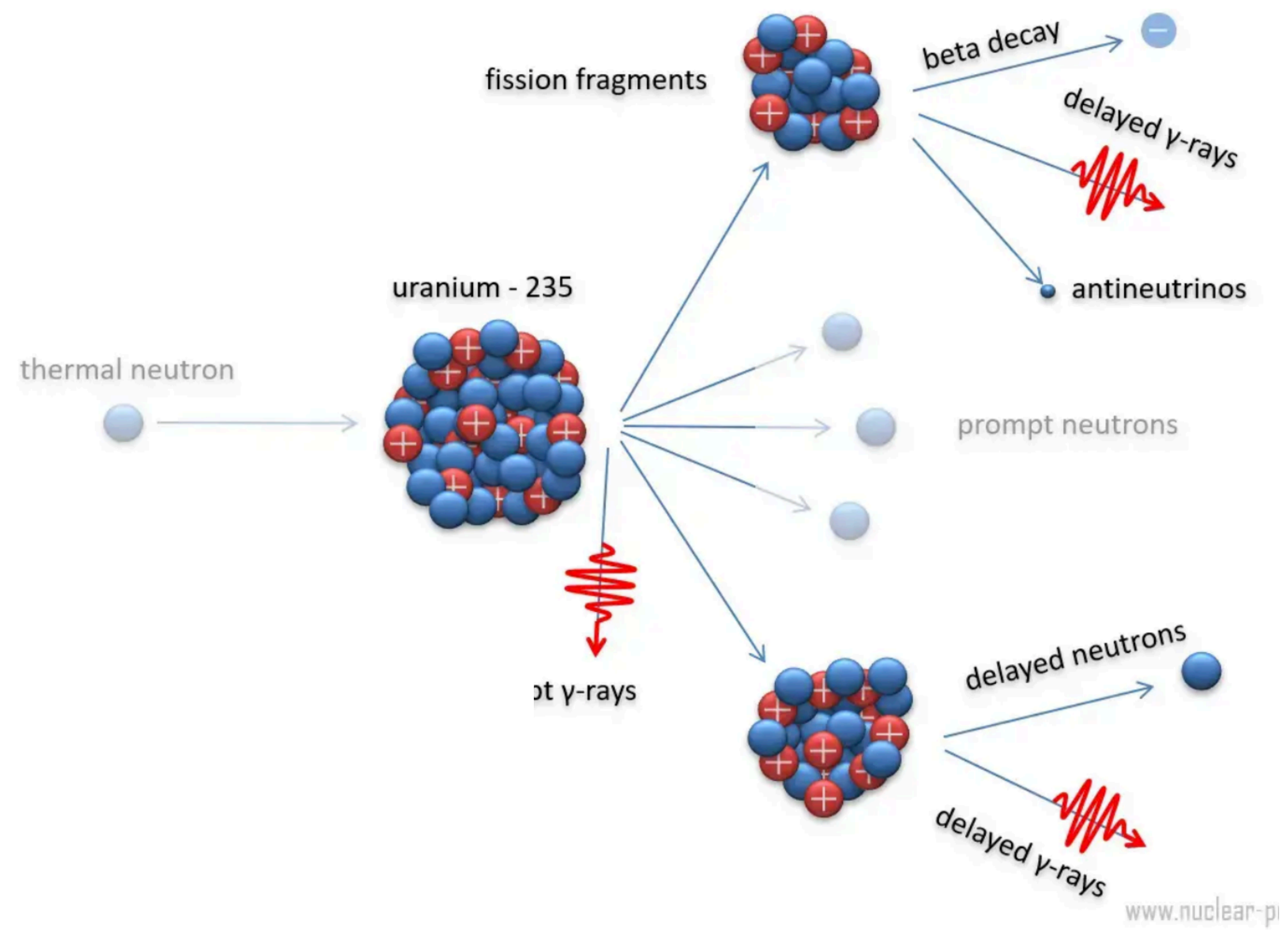
Experiment	Dominant	Important
Solar	$\sin^2\theta_{12}$	Δm^2_{21}
Reactor LBL	Δm^2_{21}	$\sin^2\theta_{12}$
Reactor MBL	$\sin^2\theta_{13}$	$\|\Delta m^2_{31}\|$
Atmospheric	$\|\Delta m^2_{31}\|$ $\sin^2\theta_{23}$	$\sin^2\theta_{13}$ δ_{cp}
Accelerator Disapp	$\|\Delta m^2_{31}\|$ $\sin^2\theta_{23}$	
Accelerator App	δ_{cp}	$sign(\Delta m^2_{31})$ $\sin^2\theta_{23}$ $\sin^2\theta_{13}$

Ivan Martinez-Soler (IPPP)

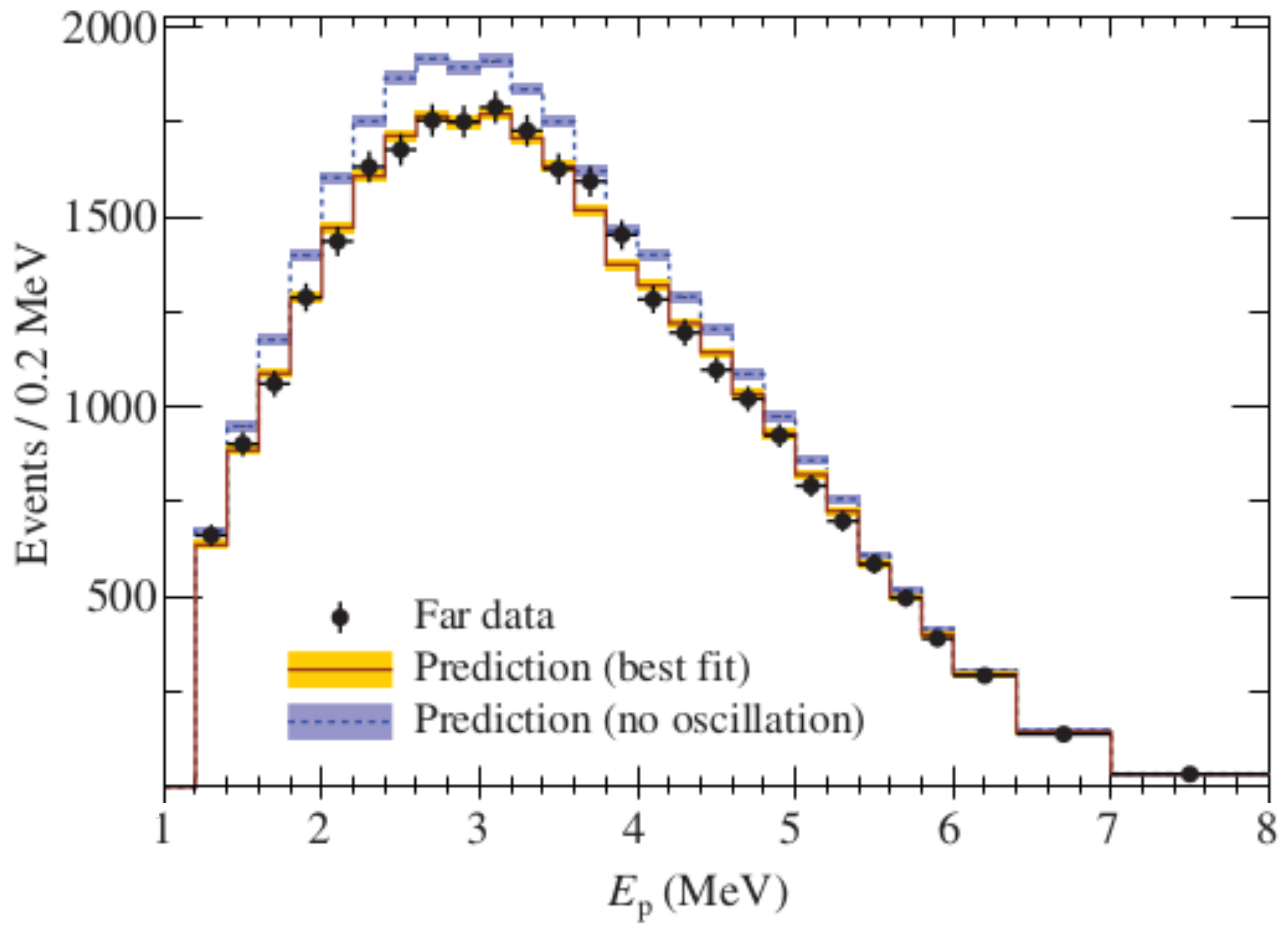
Reactor Neutrinos



In reactor experiments, a **flux of $\bar{\nu}_e$** is created with energies around the ~ MeV

The neutrino flux is created due to the **fission** of four different isotopes:

$$^{235}\mathrm{U}(\sim 56\%),^{238}\mathrm{U}(\sim 8\%),^{238}\mathrm{Pu}(\sim 30\%),^{241}\mathrm{Pu}(\sim 6\%)$$



Double-Chooz, RENO, and Daya Bay established that $\theta_{13} \neq 0$

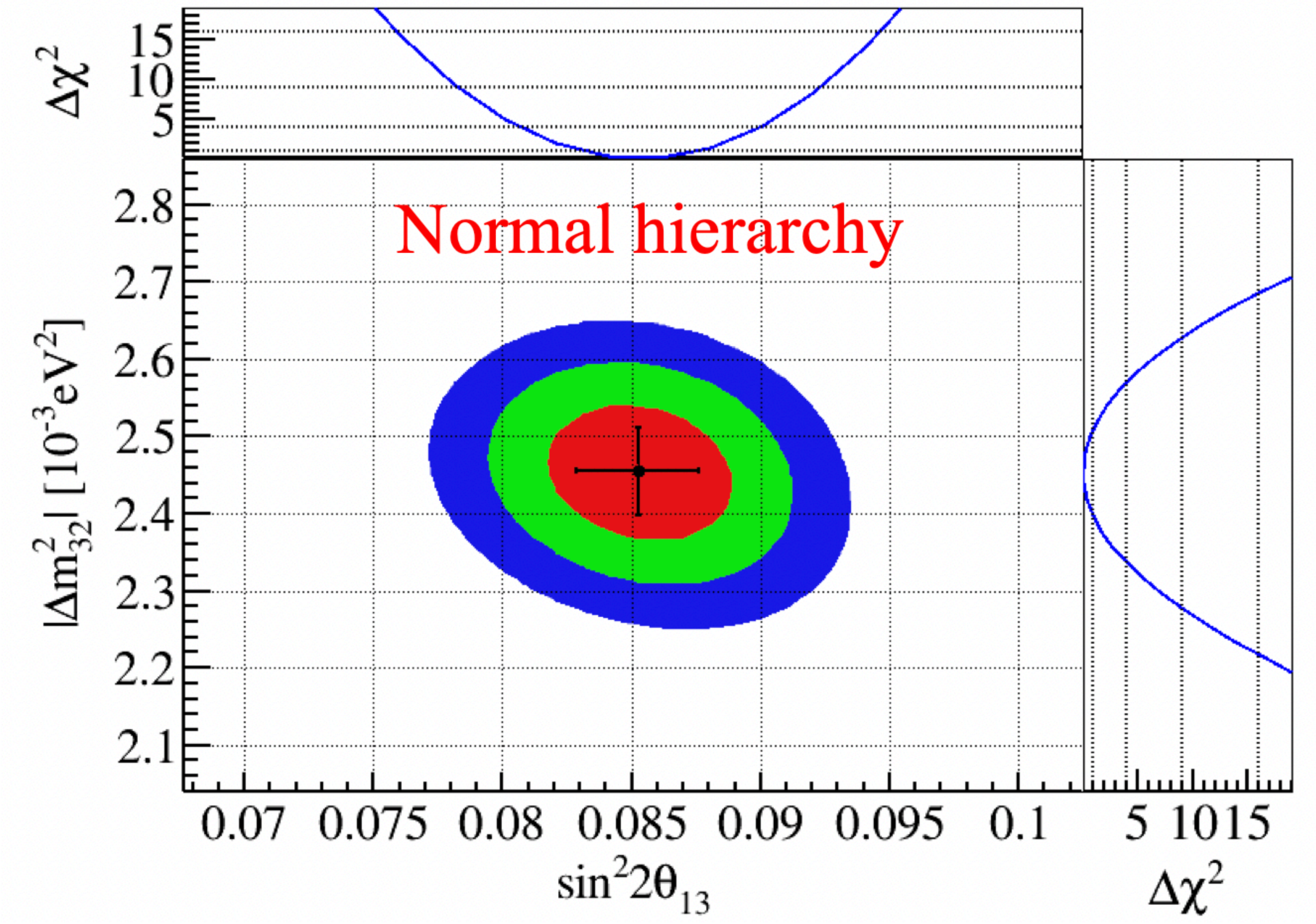
S.H. Seo et al. (RENO) PRD 98 (2018) arXiv:1610.04326

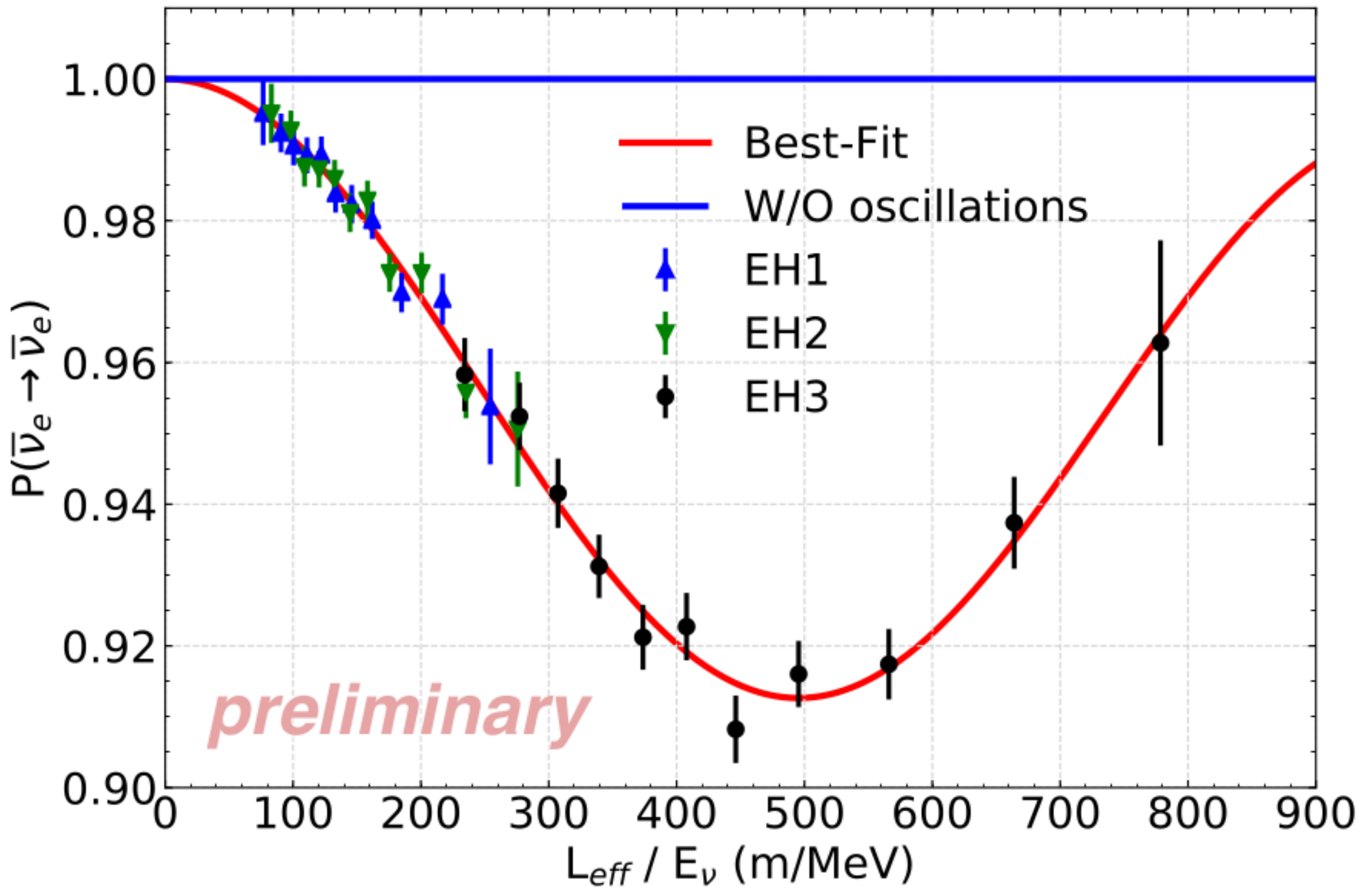
Reactor neutrinos: θ_{13} and Δm^2_{ee}

The **spectral information** from reactor experiments determines θ_{13} and Δm^2_{31}

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee}$$

$$\Delta m^2_{ee} = \cos^2\theta_{12}\Delta m^2_{31} + \sin^2\theta_{12}\Delta m^2_{32}$$

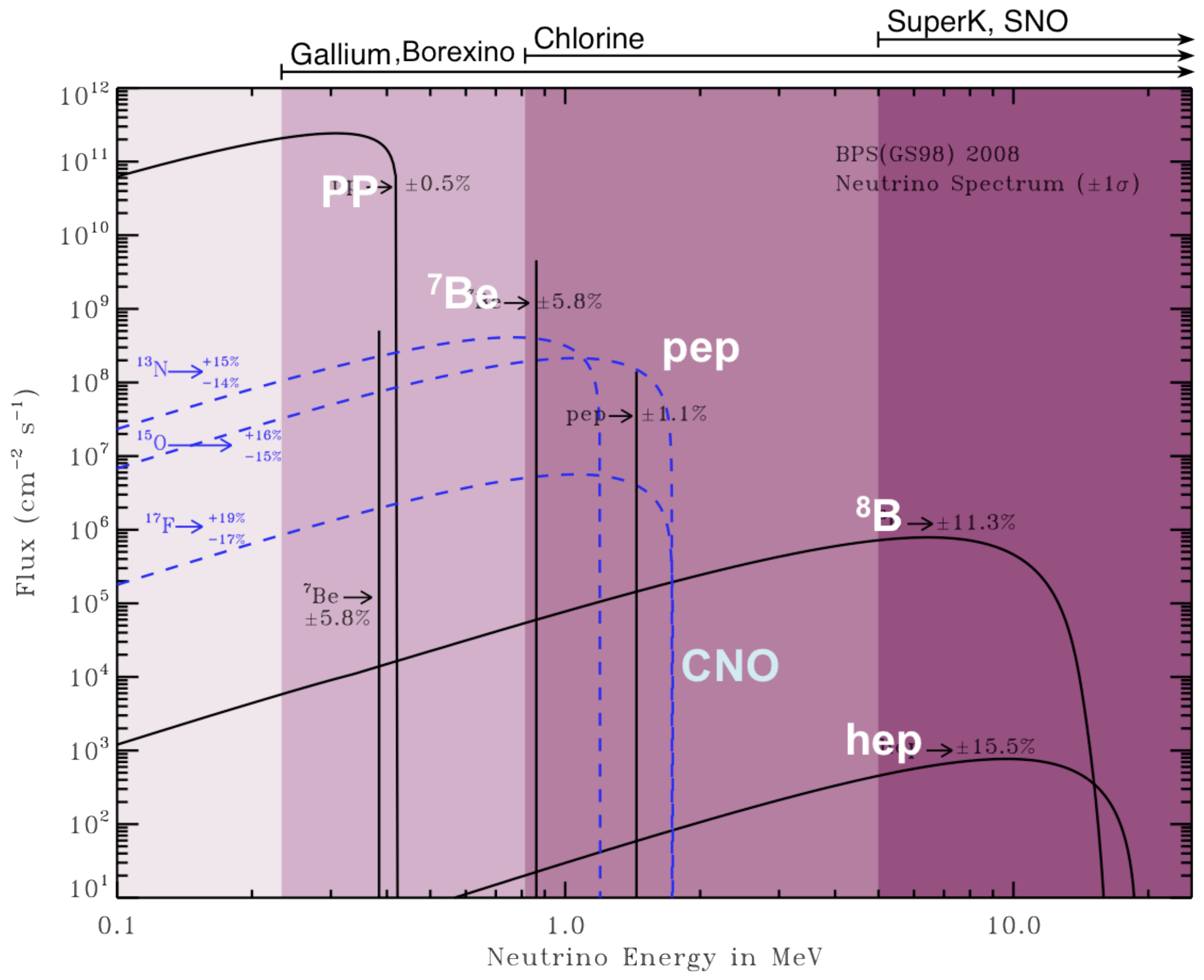




K. Luk (DayaBay) Neutrino 2022

- Near detector imposes an upper bound over Δm^2_{31}
- The oscillation measured at the far detector imposes a lower bound on θ_{13} and Δm^2_{31}

Solar Sector: θ_{12} and Δm^2_{21}

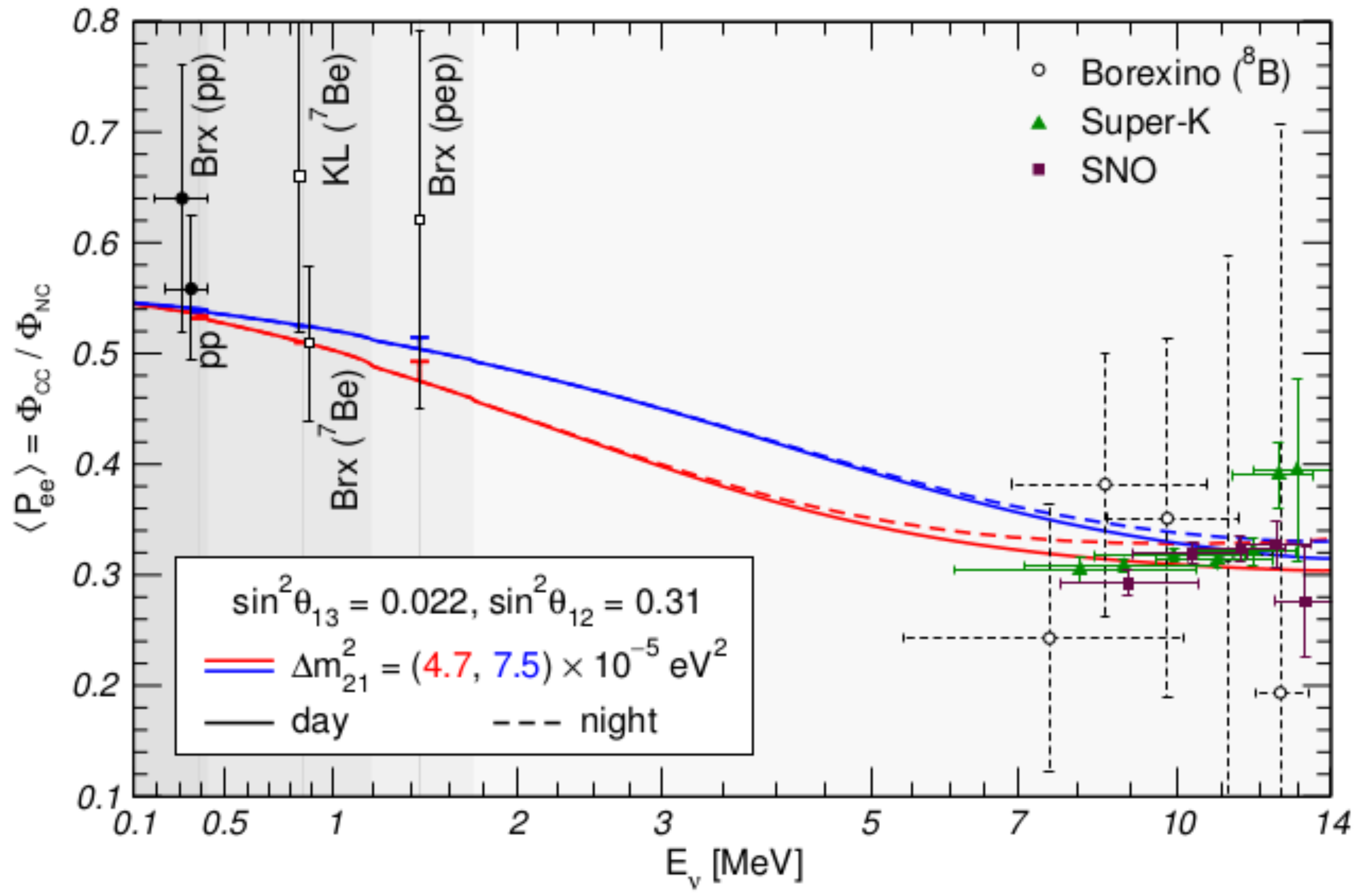


Solar neutrinos are produced by **nuclear fusions** reactions

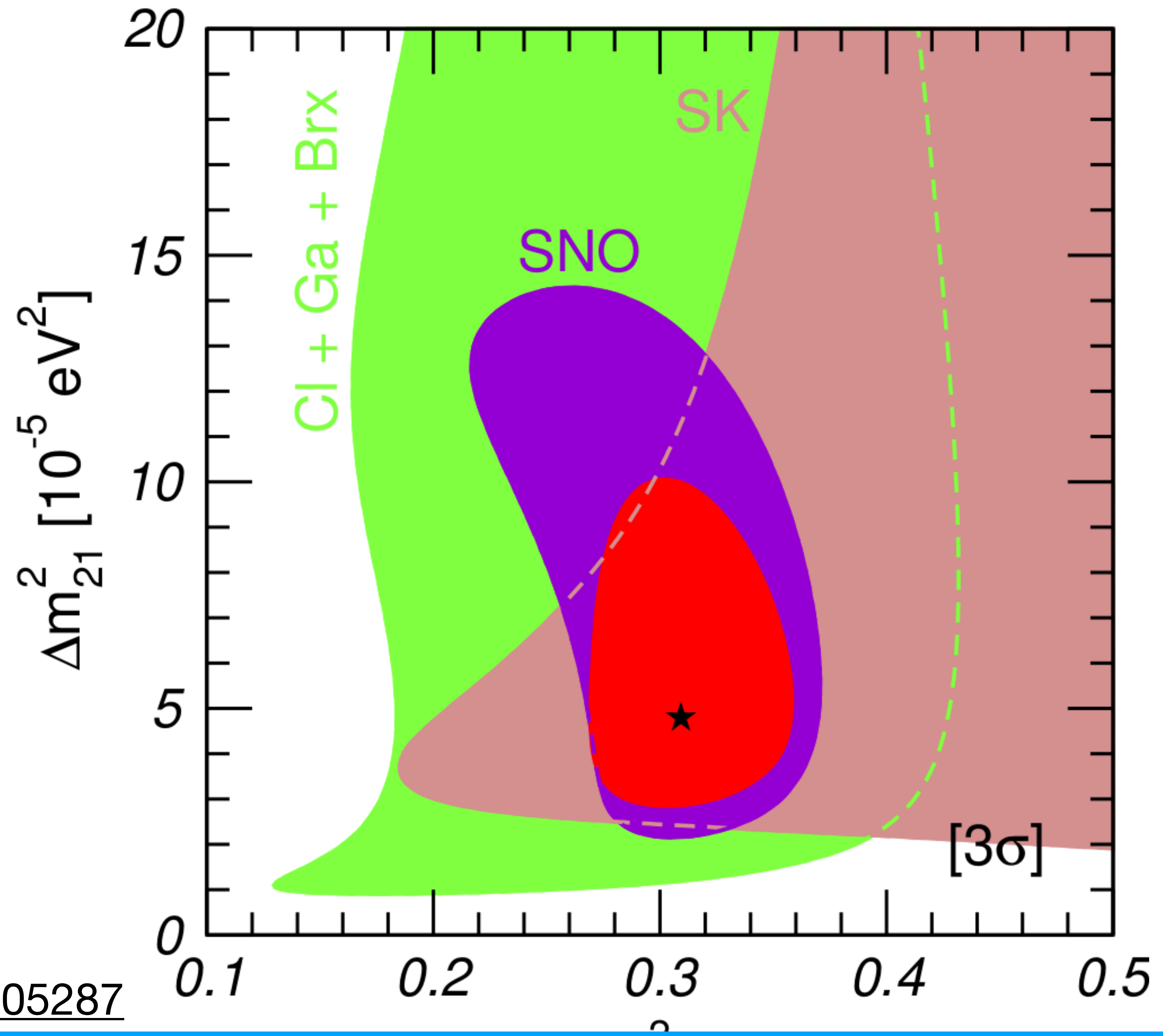
Survival probability for neutrinos from dense solar regions

$$P^{2\nu}_{eff}(\Delta m^2_{21}, \theta_{12}) = \frac{1}{2}(1 + \cos\theta^m_{12}\cos\theta_{12})$$

Sensitivity to θ_{12} is dominant, while Δm^2_{21} is probe throught matter effects



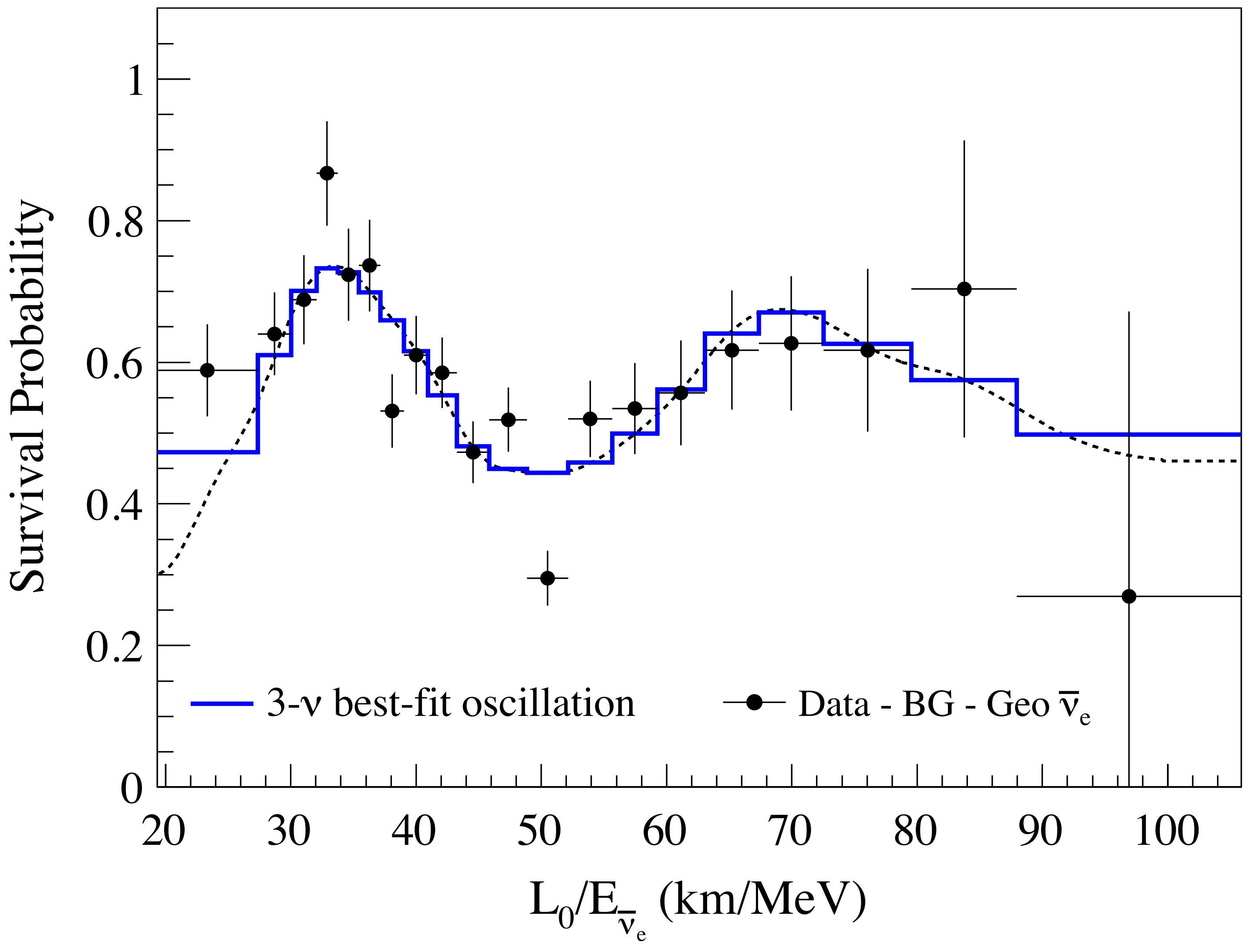
The constraint over θ_{12} are mainly driven by **SK+SNO**



Maltoni and Smirnov, EPJA 52 (2016) arXiv:1507.05287

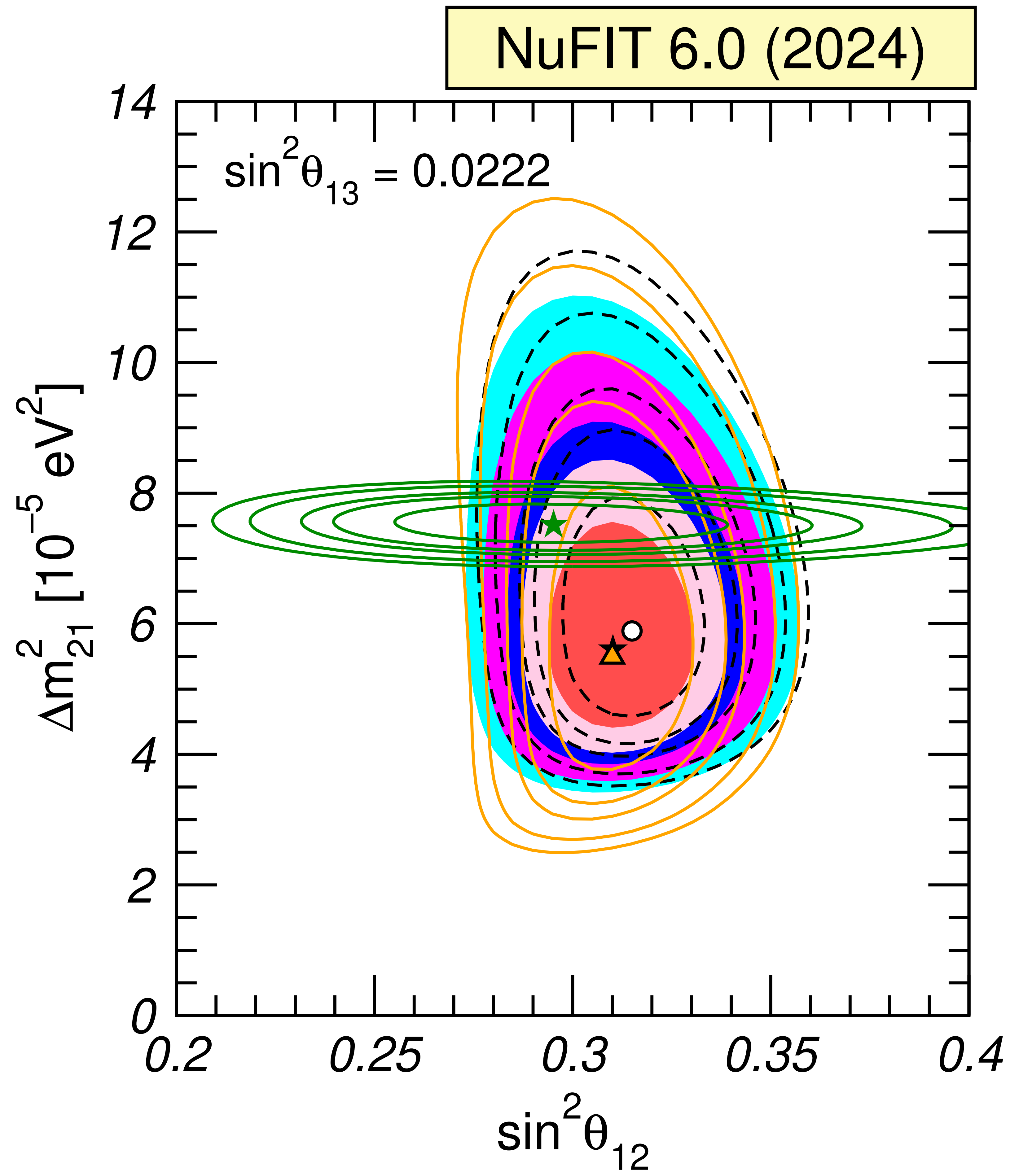
Solar Sector: θ_{12} and Δm^2_{21}

Δm^2_{21} is determined by **long-baseline reactor** experiments



A. Gando et al. (KamLAND) PRD 88 (2013)

Tension in the determination of Δm^2_{21} between reactor and solar experiments

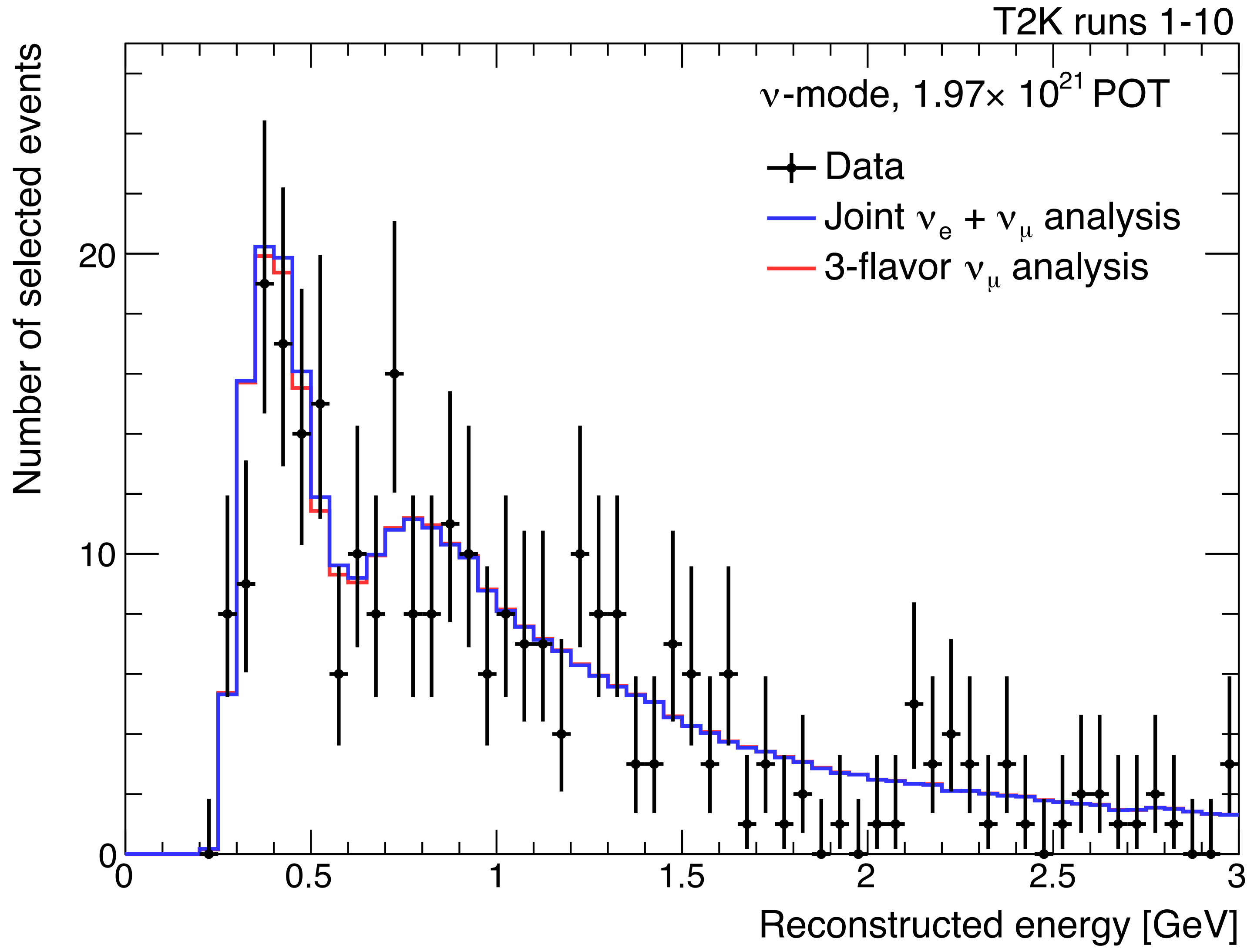


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

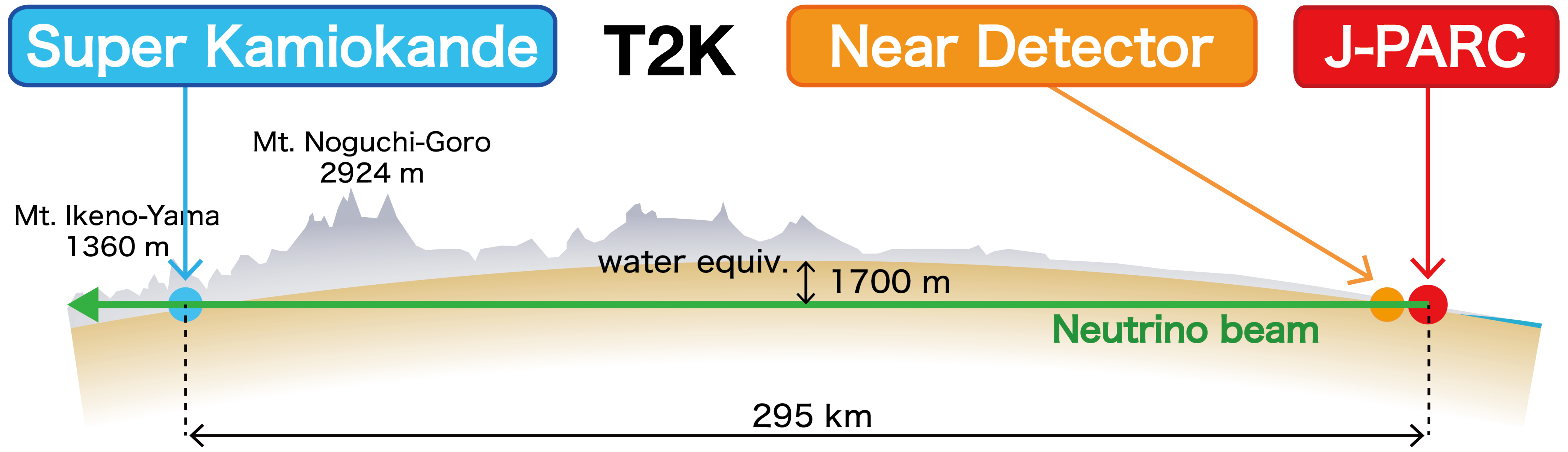
Long-Baseline Accelerators

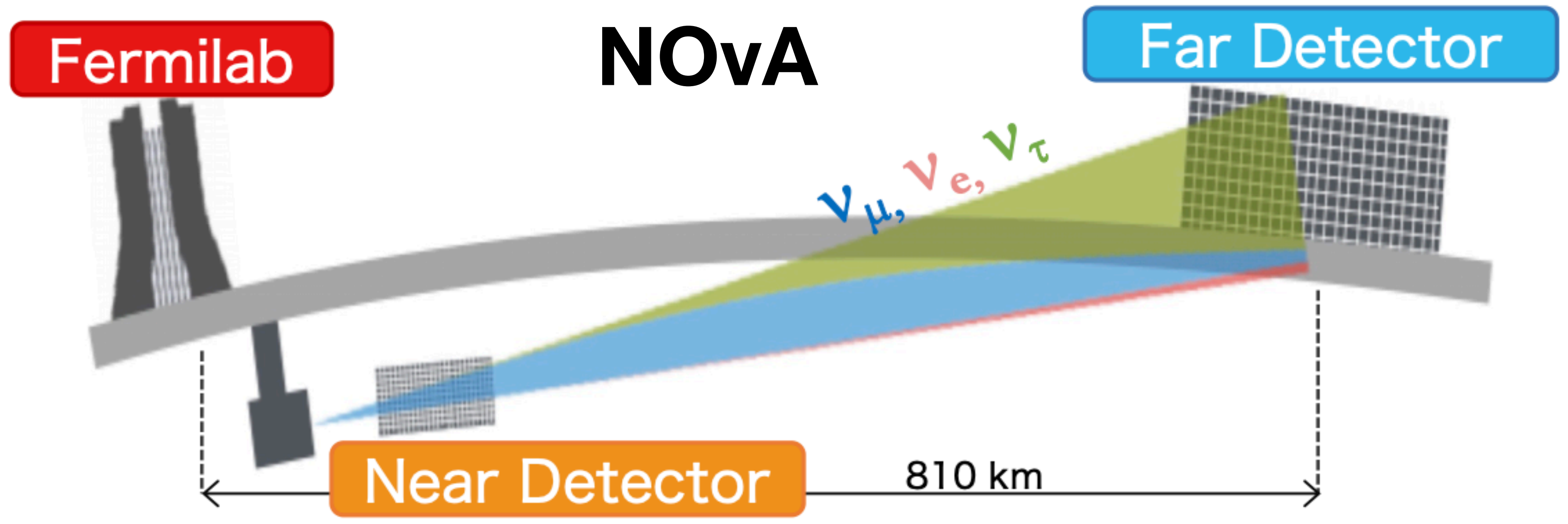
Neutrinos are generated from **pion/kaon decays** caused by an accelerated proton beam hitting a target.

Neutrinos travel ~ 100 Km and have energies $E \sim 1$ GeV, making these experiments **sensitive to** $\Delta m^2_{31}, \sin\theta_{23}, \delta_{CP}$



Abe et al., (T2K) PRD 108 (2023) arXiv:2305.09916





LBL: Δm^2_{31} and $\sin 2\theta_{23}$

Accelerator experiments are sensitive to Δm^2_{31} and $\sin^2 2\theta_{23}$, searching for ν_μ**-disappearance**

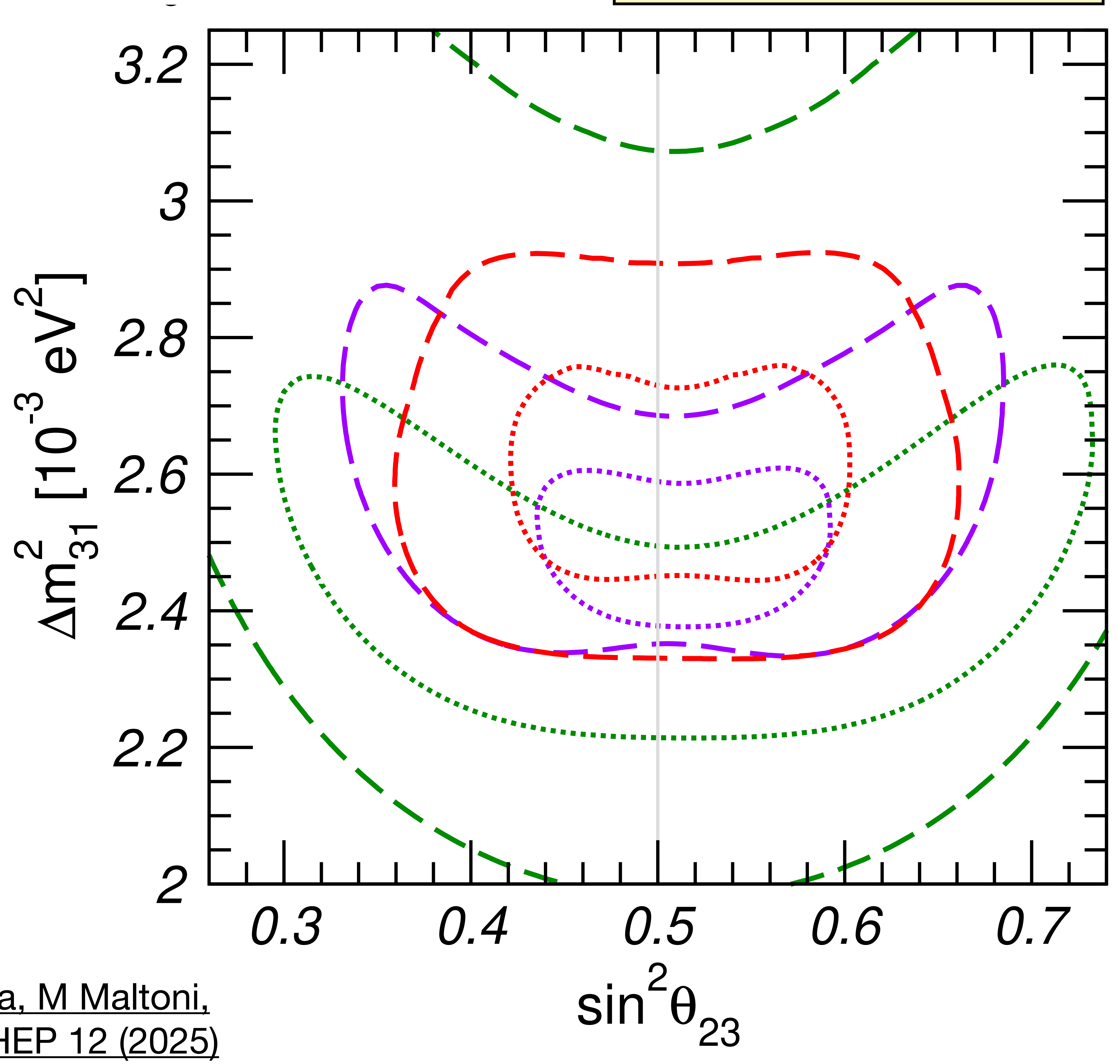
$$P_{\mu\mu} \simeq 1 - \sin^2 2\theta_{\mu\mu} \sin^2 \frac{\Delta m^2_{\mu\mu} L}{4E}$$

$$\Delta m^2_{\mu\mu} = \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32} + \cos\delta_{cp}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}$$

$$\sin^2\theta_{\mu\mu} = \cos^2\theta_{13}\sin^2\theta_{23}$$

It can discriminate whether θ_{23} is maximal or not

NuFIT 6.0 (2024)



I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

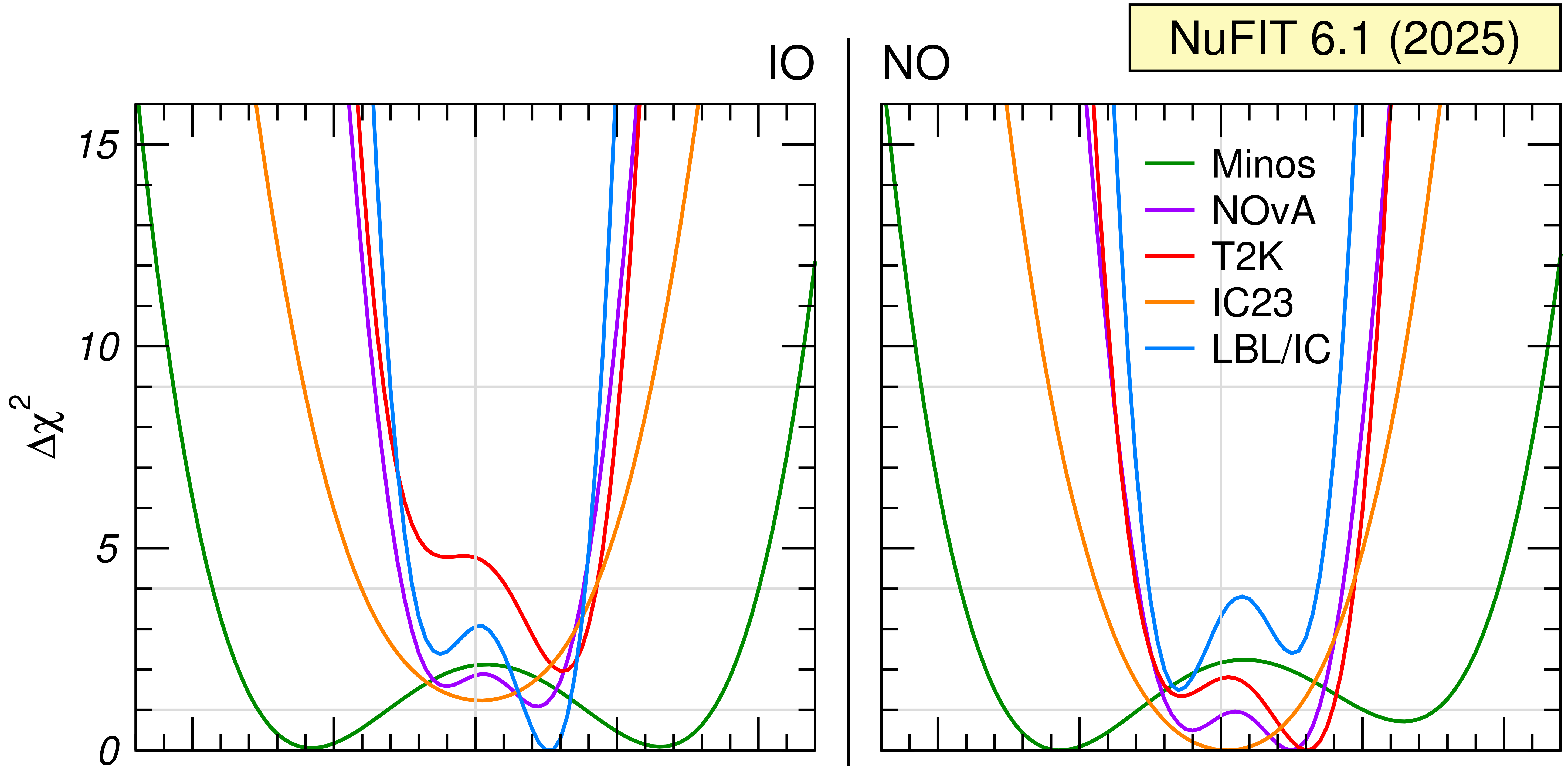
LBL: δ_{CP} , $\sin\theta_{23}$ and Ordering

Accelerator experiments can search for ν_e-**appearance**

$$P_{\nu_\mu \to \nu_e} \approx 4\sin^2\theta_{13}\sin^2\theta_{23}(1+2oA) - C\sin\delta_{cp}(1+oA)$$

Octant θ_{23} **Ordering** **CP-violation**

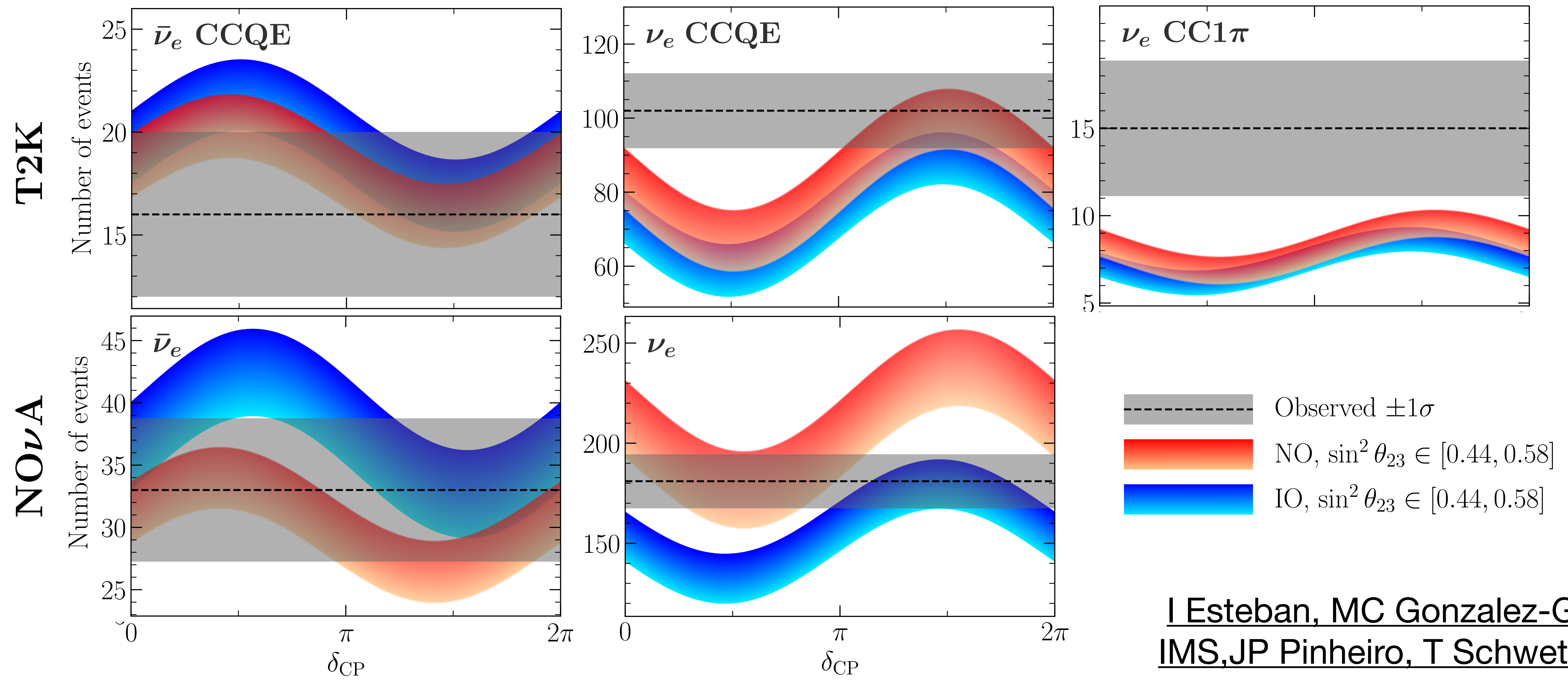
Preference for the **higher-octant and IO**

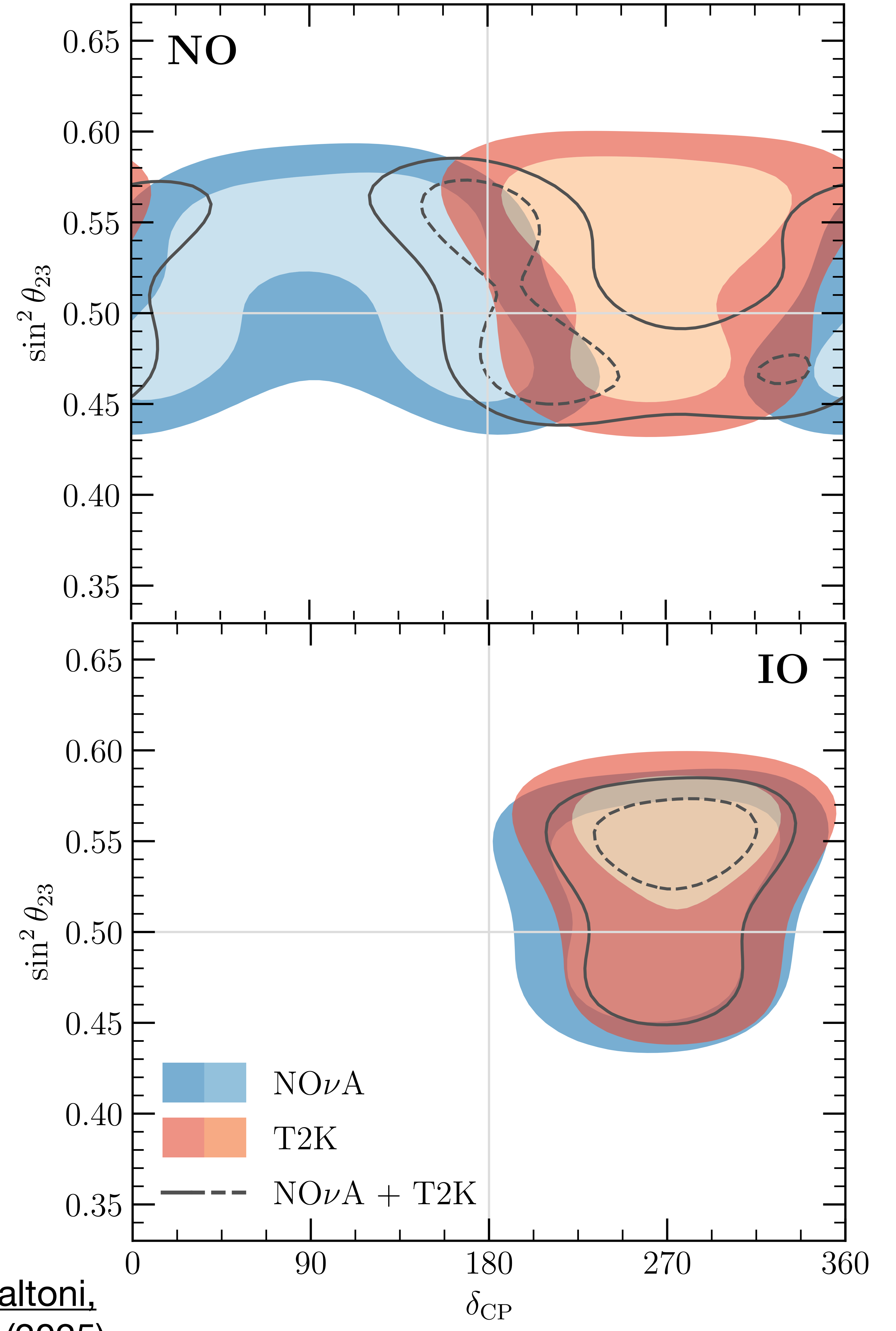


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

Long-Baseline Accelerators

The **tension** between **T2K** and **NOvA** over δ_{CP} and NO shifts the LBL preference toward **IO**

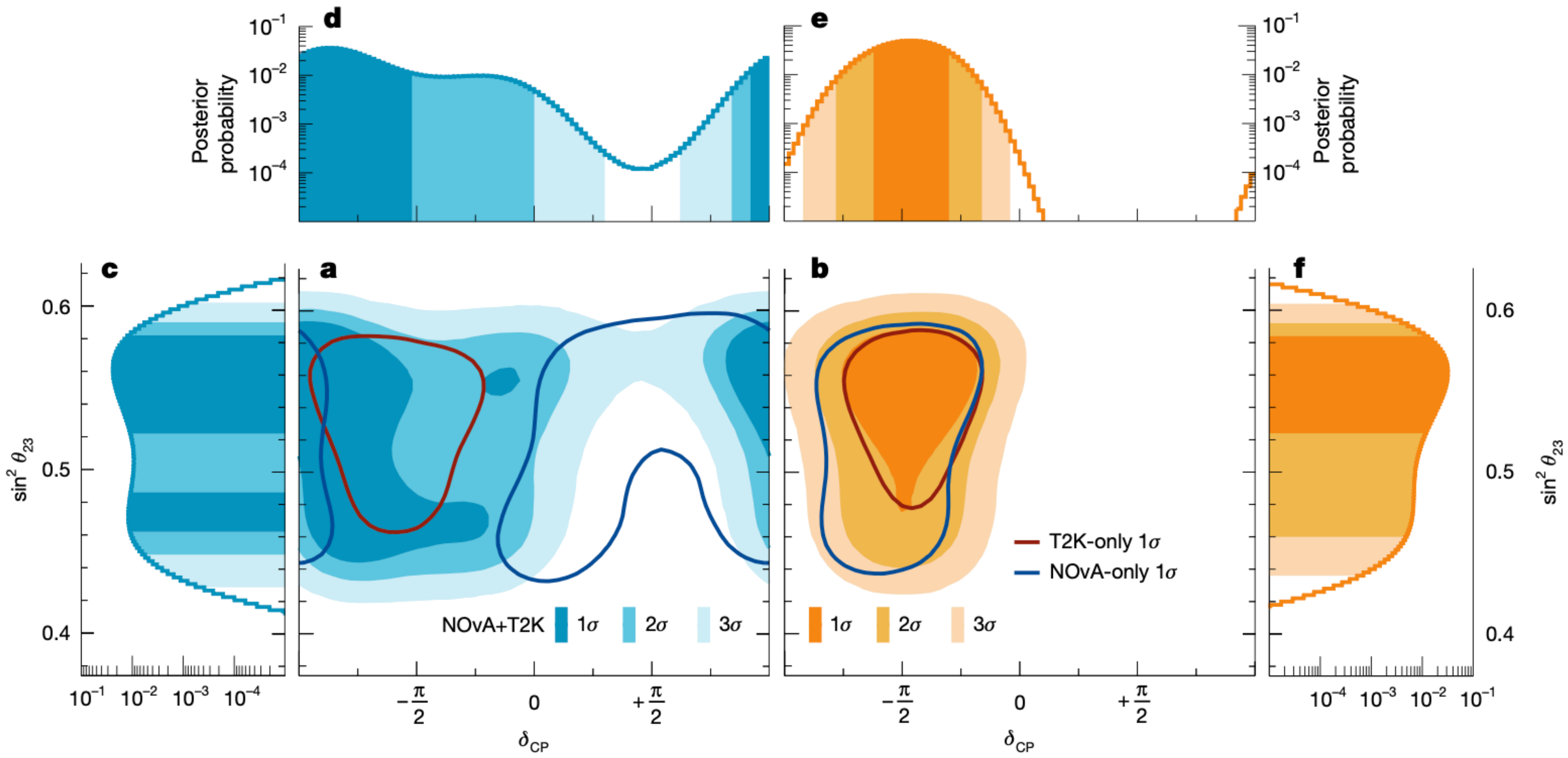




I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

NOvA-T2K joint fit

NOvA and T2K have performed a joint fit, showing **good agreement with global analysis**



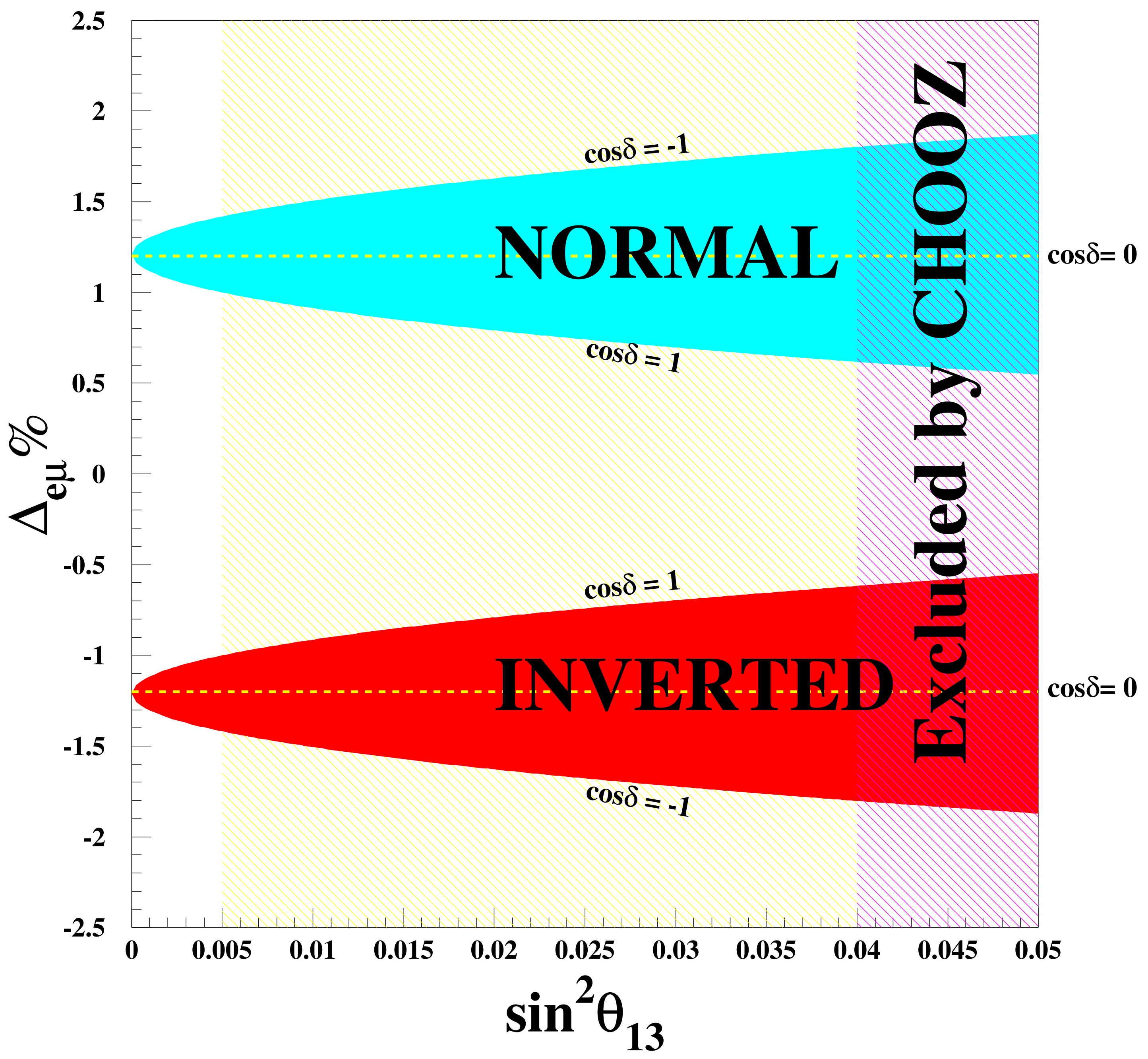
No correlation between the flux, detector and cross-section

S. Abubakar, et al. (T2K and NOvA), Nature 646 (2025) 8086

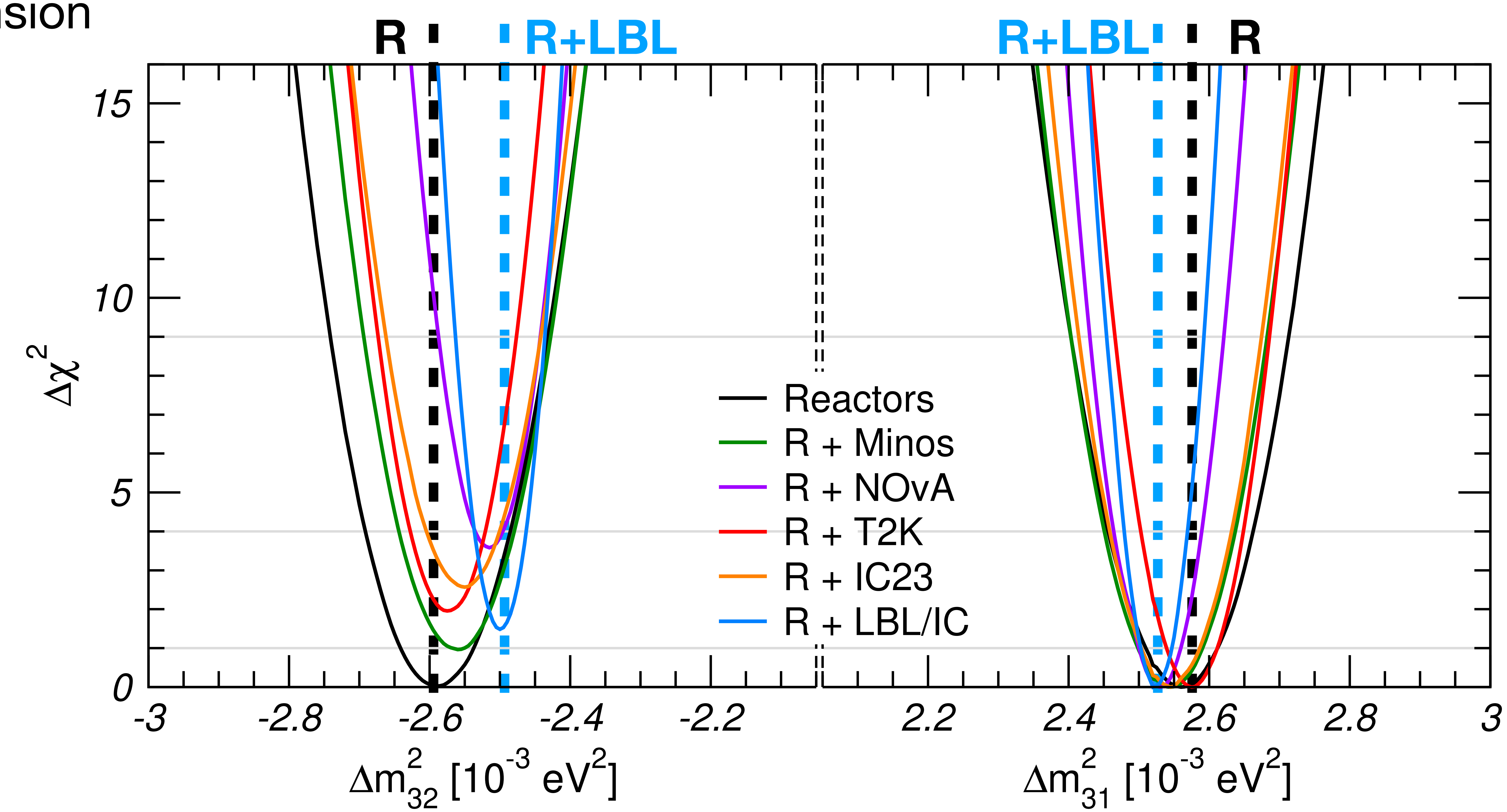
LBL+Reactors

Full LBL-reactor combo eases T2K-NOvA tension

- Combining LBL($\Delta m^2_{\mu\mu}$) and reactors (Δm^2_{ee}) **strengthens NO preference**



Nunokawa, Parke, Funchal, PRD 72(2005) arXiv: hep-ph/0503283



NuFIT 6.1 (2025)

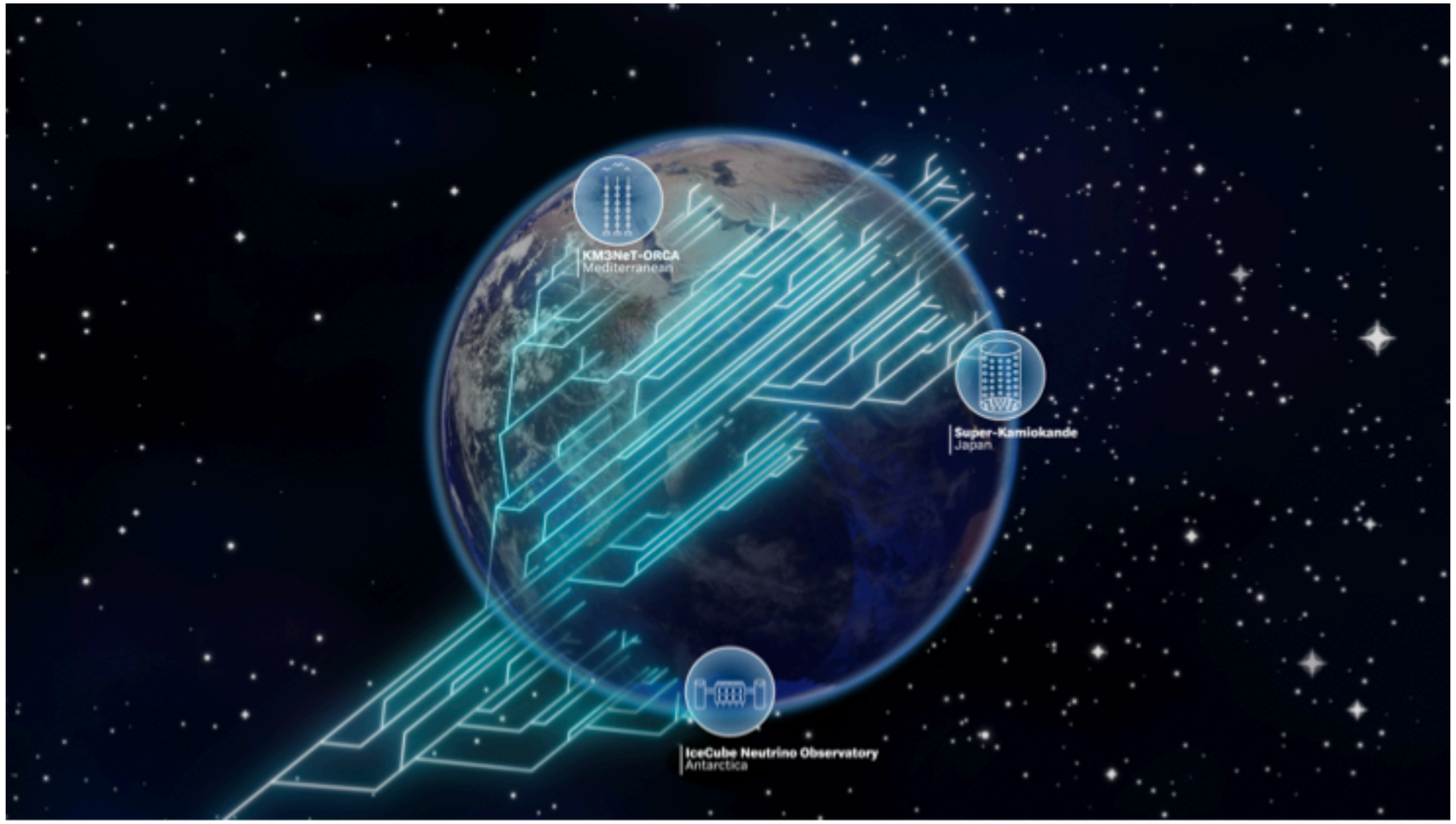
$$\Delta_{e\mu} = (\Delta m^2_{ee} - \Delta m^2_{\mu\mu})/\Delta m^2$$

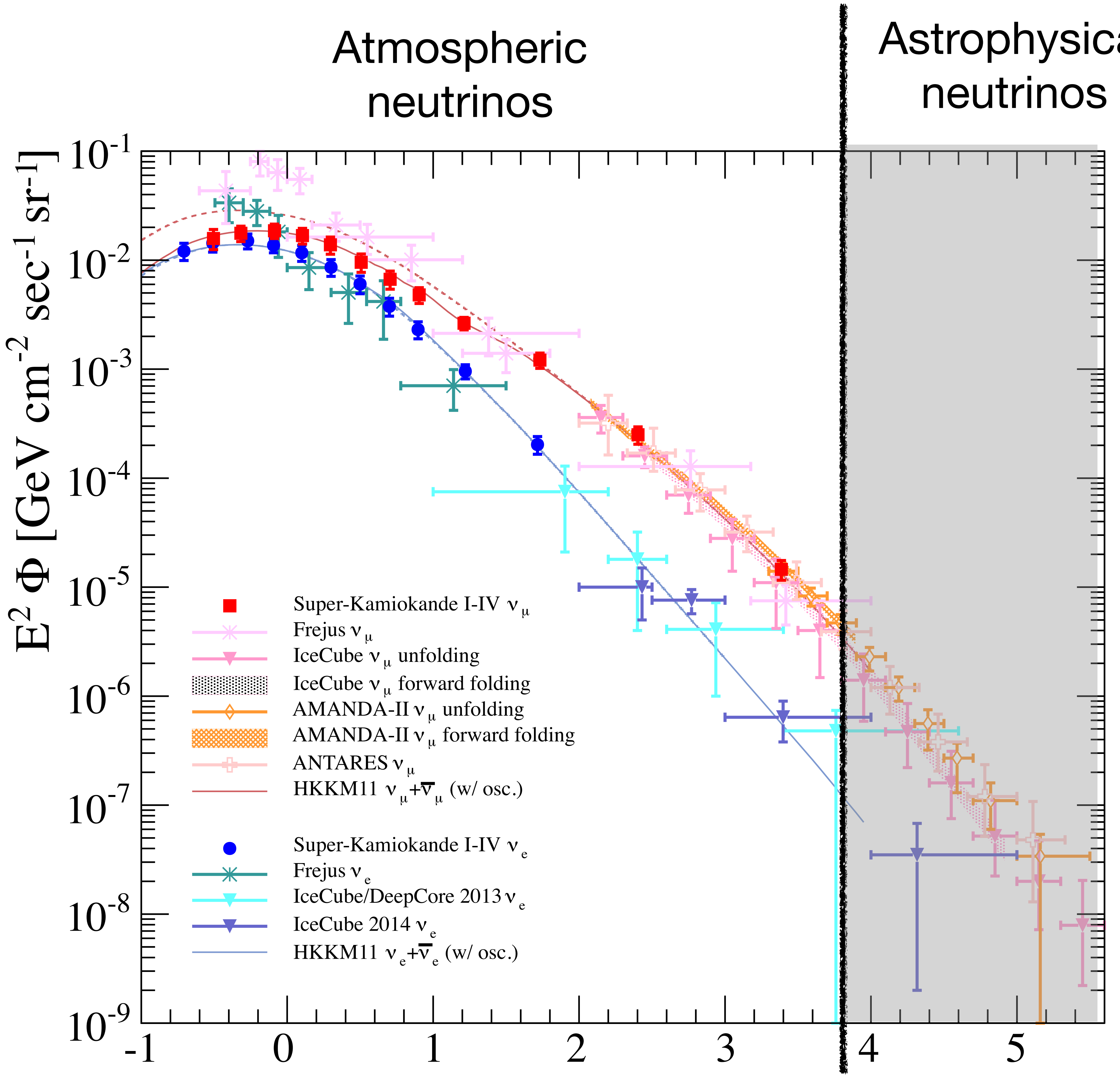
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

How can atmospheric neutrinos contribute?

Atmospheric Neutrinos

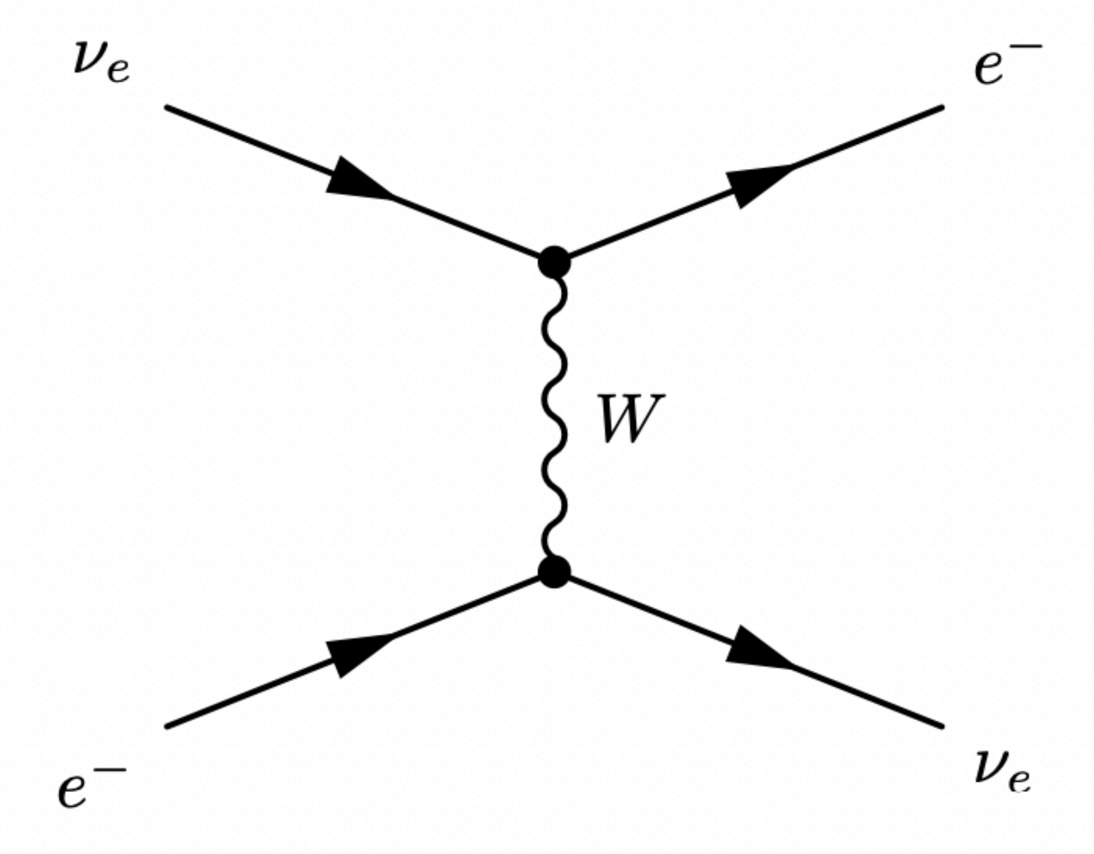
Atmospheric neutrinos are created in the **collision of cosmic rays** with the atmospheric nuclei





E. Richard et al. (SK), Phys.Rev.D 94 (2016) 5, 052001

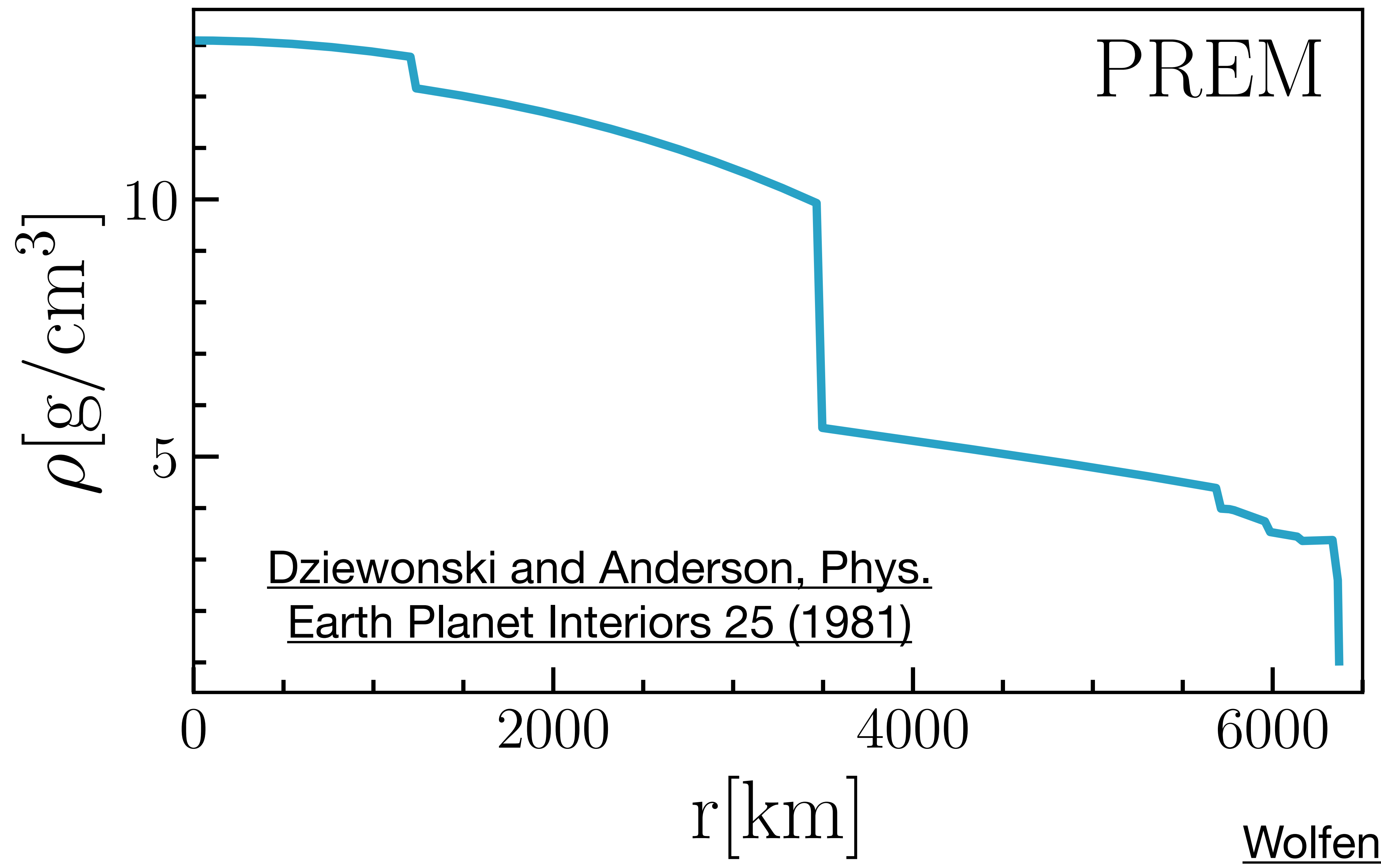
Neutrino Evolution in Matter

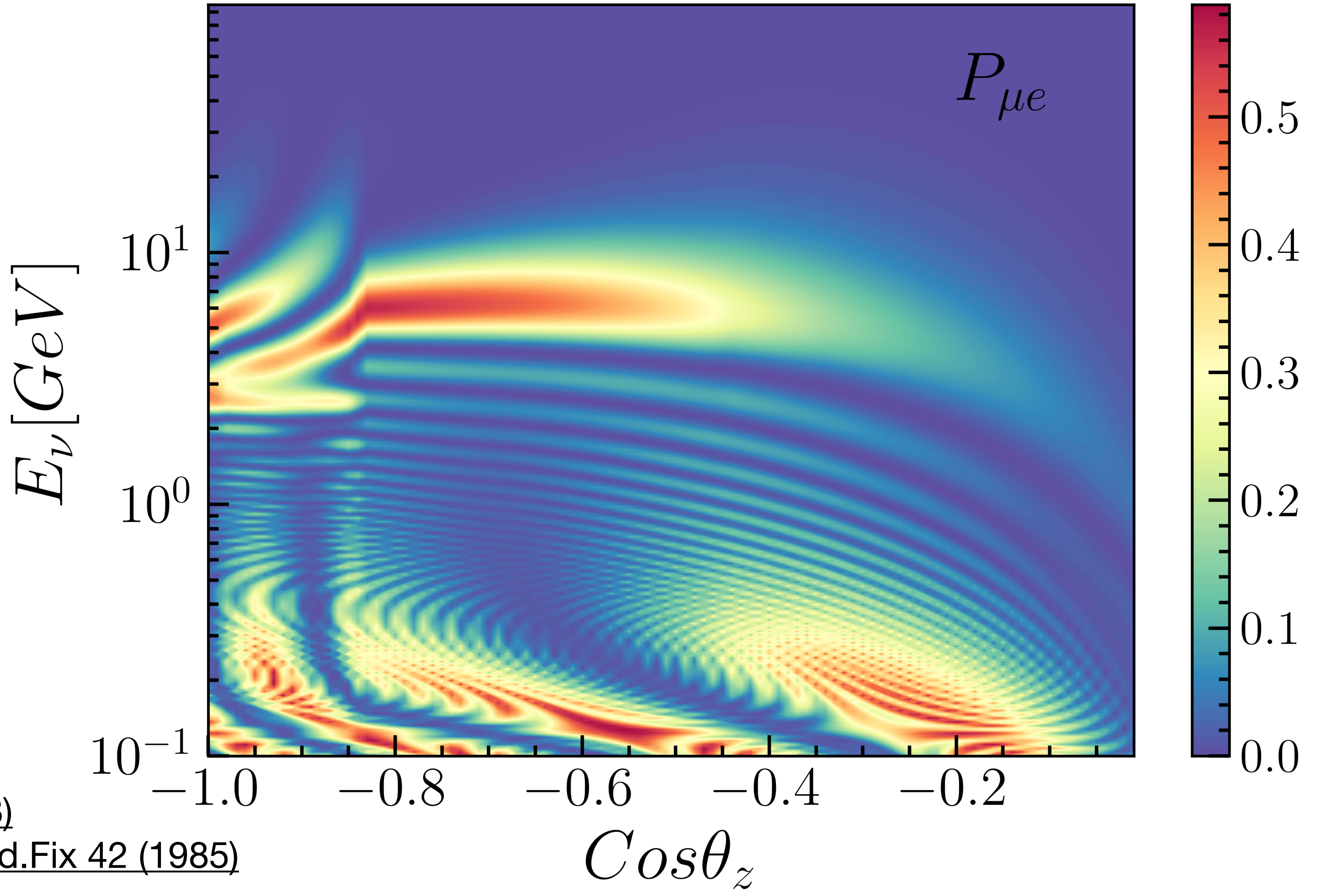


Matter effects play a crucial role in the evolution of atmospheric neutrinos

$$i\frac{d\nu}{dE} = \frac{1}{2E_\nu}\left(U^\dagger \mathrm{diag}(0, \Delta m^2_{21}, \Delta m^2_{31})U \pm V_{mat}\right)\nu$$

$$V_{mat} = 2\sqrt{2}G_F N_e E_\nu \mathrm{diag}(1,0,0)$$





Wolfenstein, PRD 17 (1978)
Mikheyev and Smirnov, Yad.Fix 42 (1985)

Sub-GeV

For atmospheric neutrinos, both fluxes are sensitive to δ_{CP}

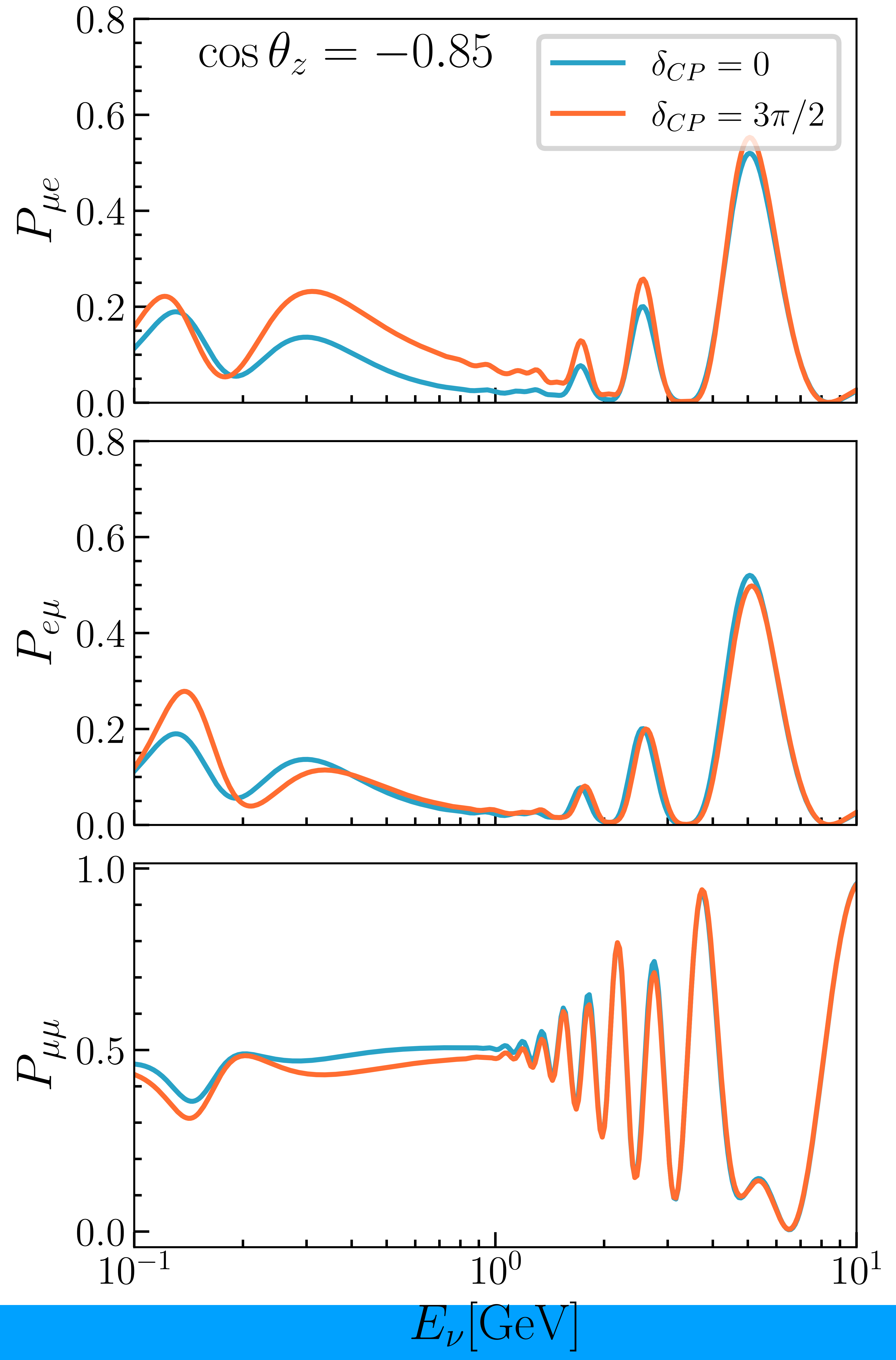
- In the case of $\delta_{cp} \neq 0$, **the CPT conservation** implies

$$P(\nu_\mu \to \nu_e) \neq P(\nu_e \to \nu_\mu)$$

- The impact of δ_{cp} depends mainly on the neutrino direction

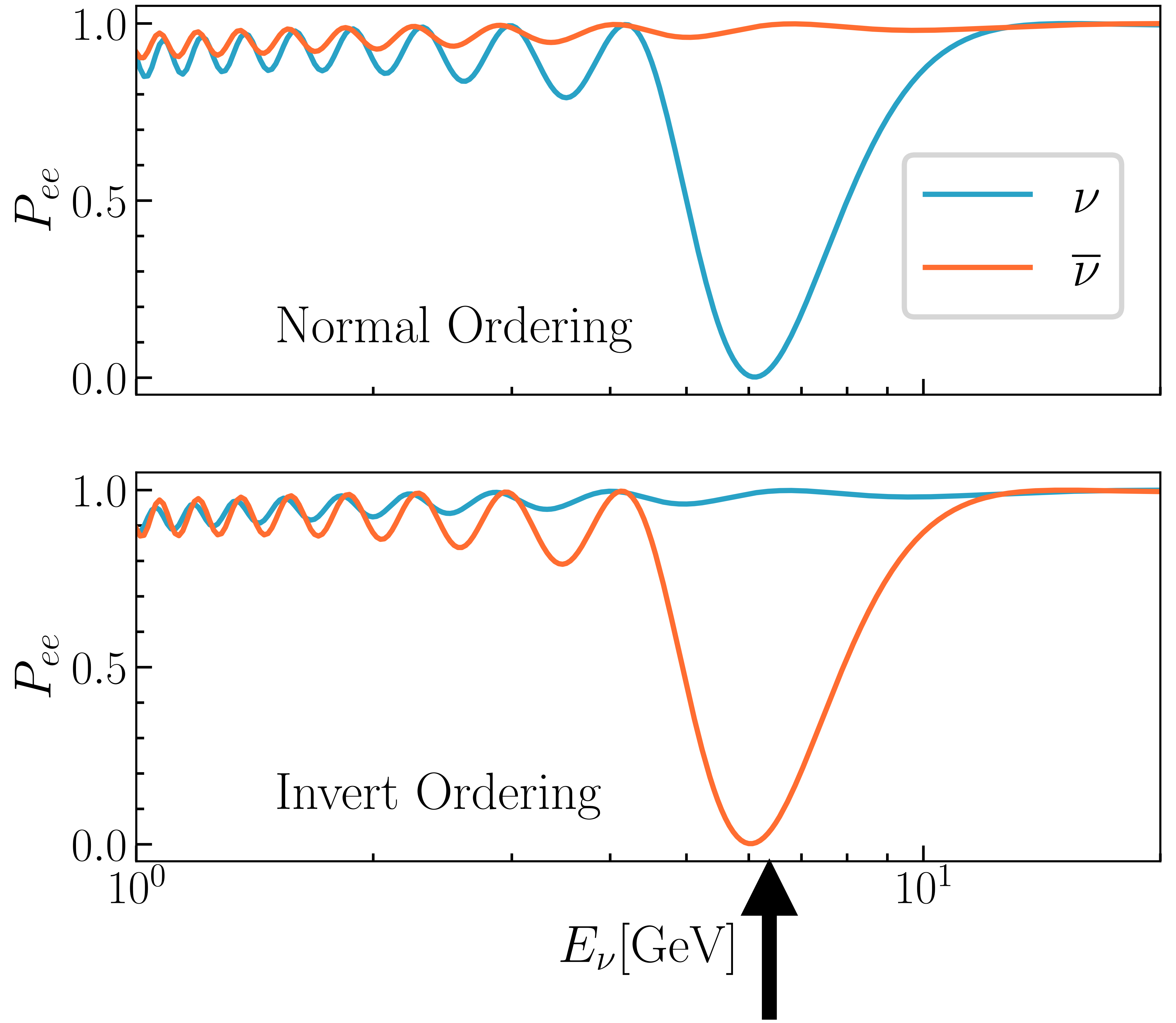
- $P_{\mu\mu}$ contribute to measuring the phase via $\cos\delta_{CP}$

Minakata, Nunokawa, Parke, PLB 537 (2002) Minakata, Nunokawa, Parke, PRD 66 (2002)
Denton and Parke, PRD 109 (2024)

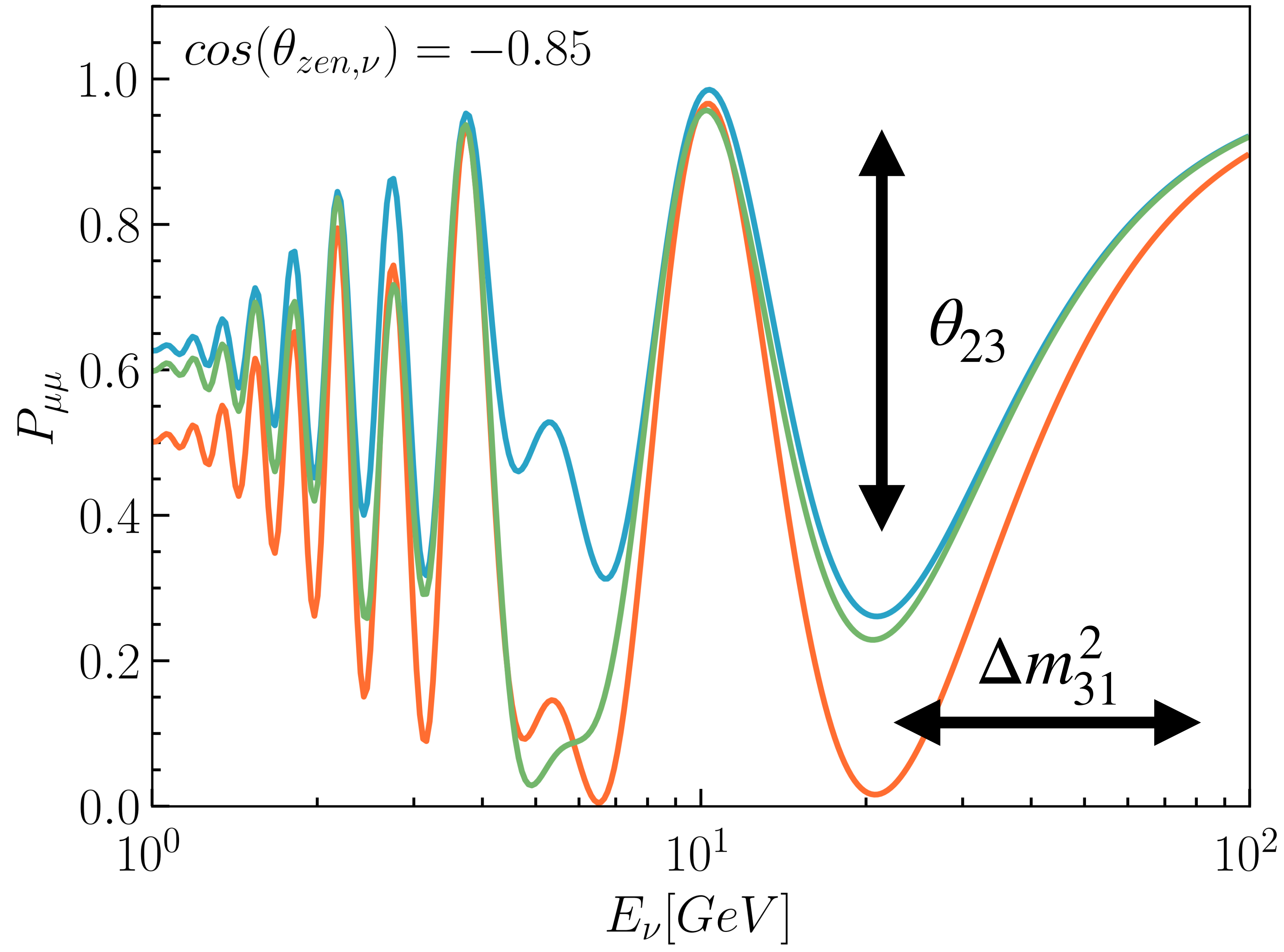


Multi-GeV

At the **GeV scale**, trajectories crossing the mantle experience a resonance, making neutrinos sensitive to the **mass ordering**:



In the multi-GeV region, neutrino evolution is dominated by Δm^2_{31} and $\sin^2\theta_{23}$



The enhancement of θ_{13}^{eff} lead to a deep in P_{ee} for ν ($\overline{\nu}$) for NO (IO)

Palomares-Ruiz and Petcov, NPB 712 (2005)

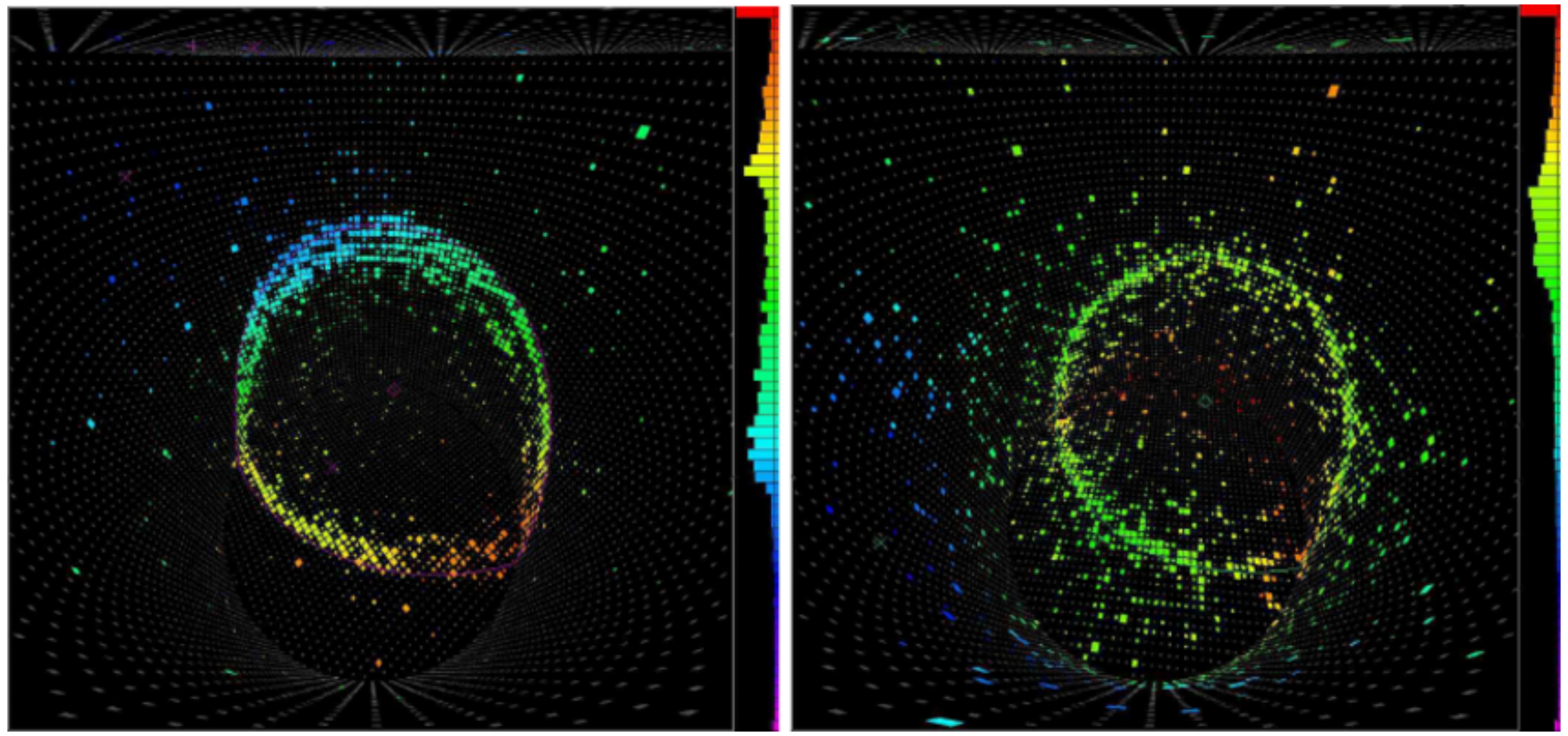
Akhmedov, Maltoni and Smirnov, JHEP 05 (2007)

Super-Kamiokande

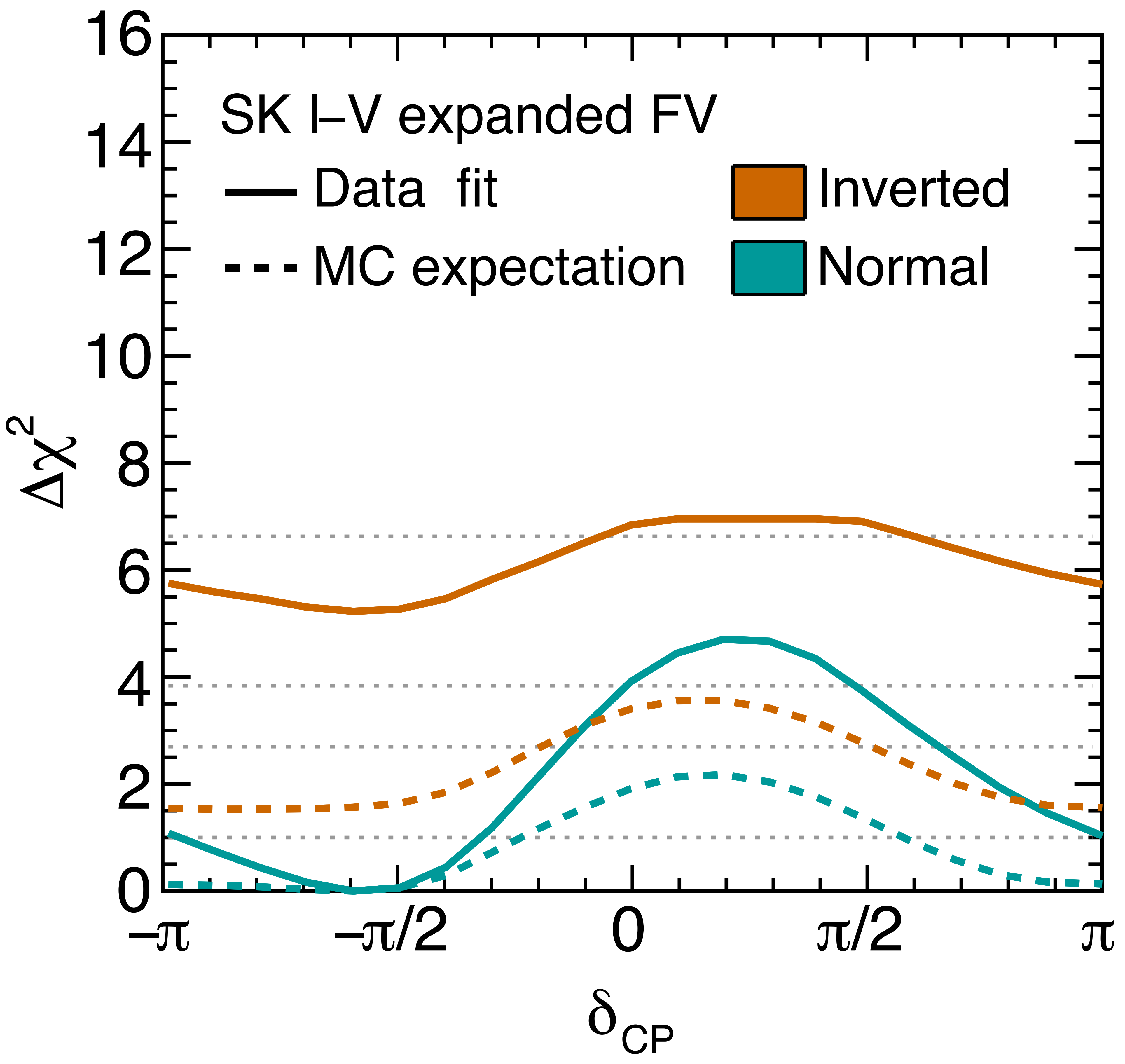
Several experiments have measured the atmospheric neutrino flux, with **SK** starting from the **sub-GeV scale**.

Super-Kamiokande (SK)

- 22.5 kton water Cherenkov
- Small sample at multi-GeV due to the volume
- The event sample is divided in FC, PC and Up-μ



Abe et al. (Super-Kamiokande), PRD 97 (2018)

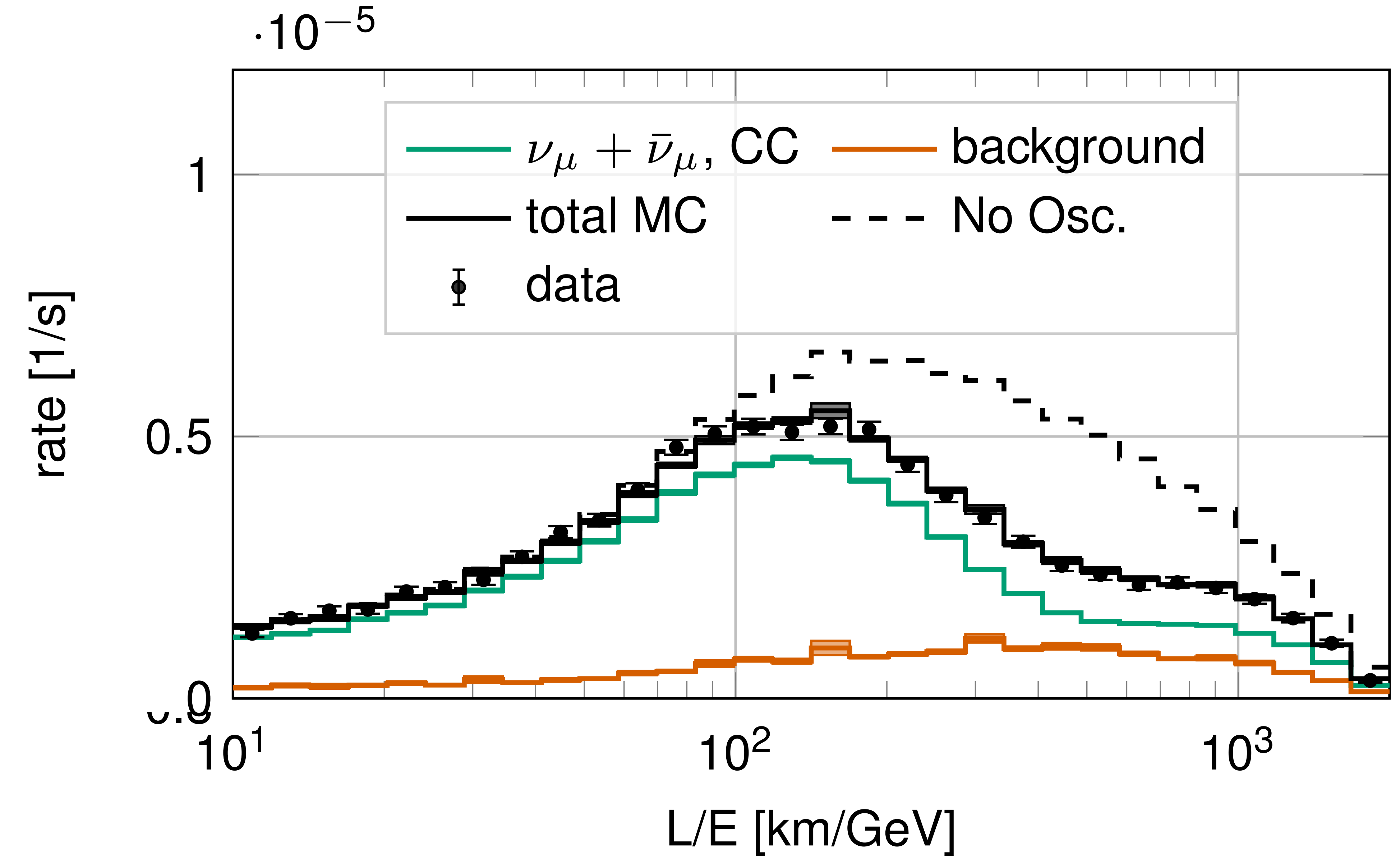


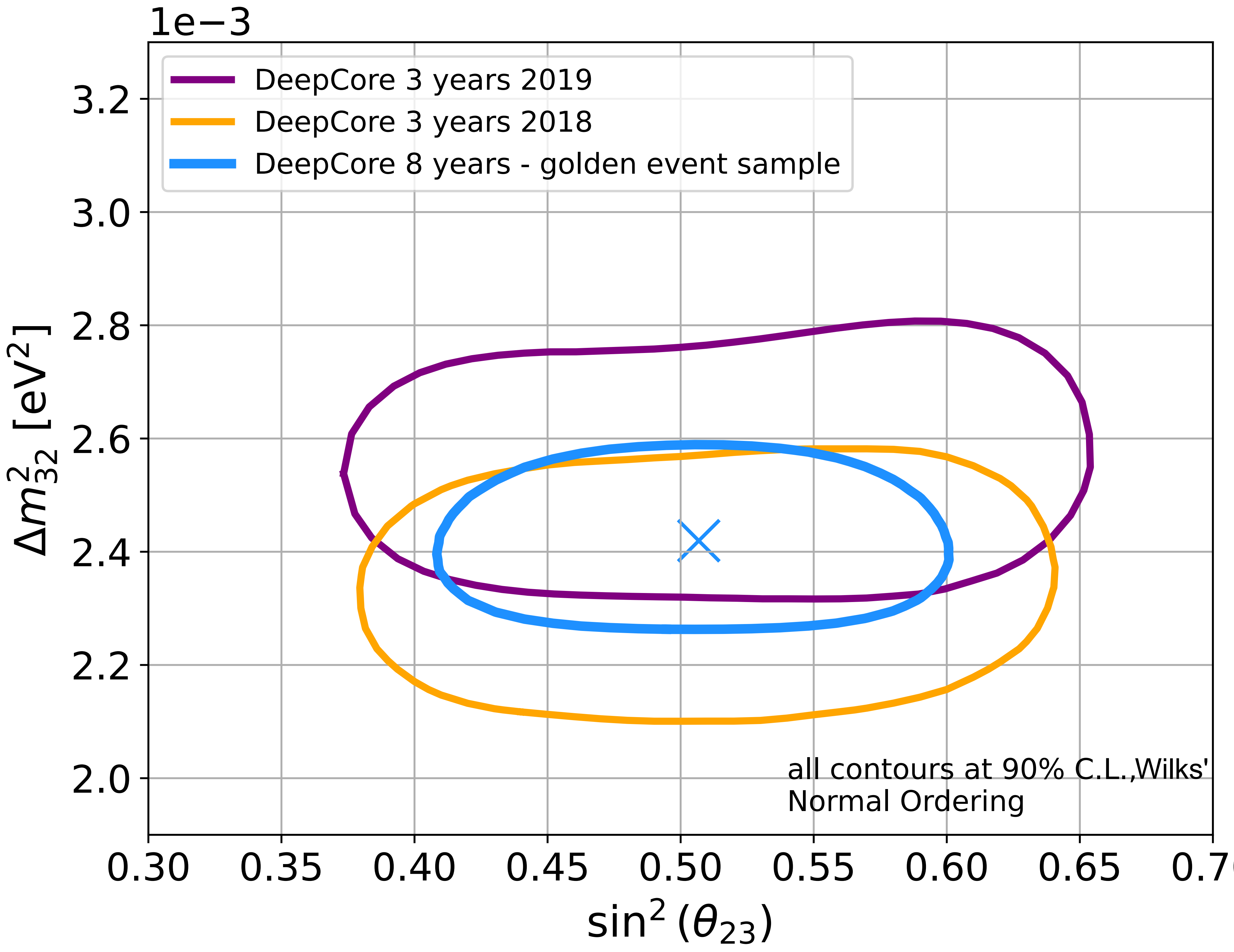
Wester et al. (Super-Kamiokande), arXiv: 2311.05105

IceCube

The **neutrino telescopes** measure the atmospheric neutrino flux from the **multi-GeV** scale

- $\sim 1\text{km}^3$ ice Cherenkov
- The sample is divided into tracks and cascades



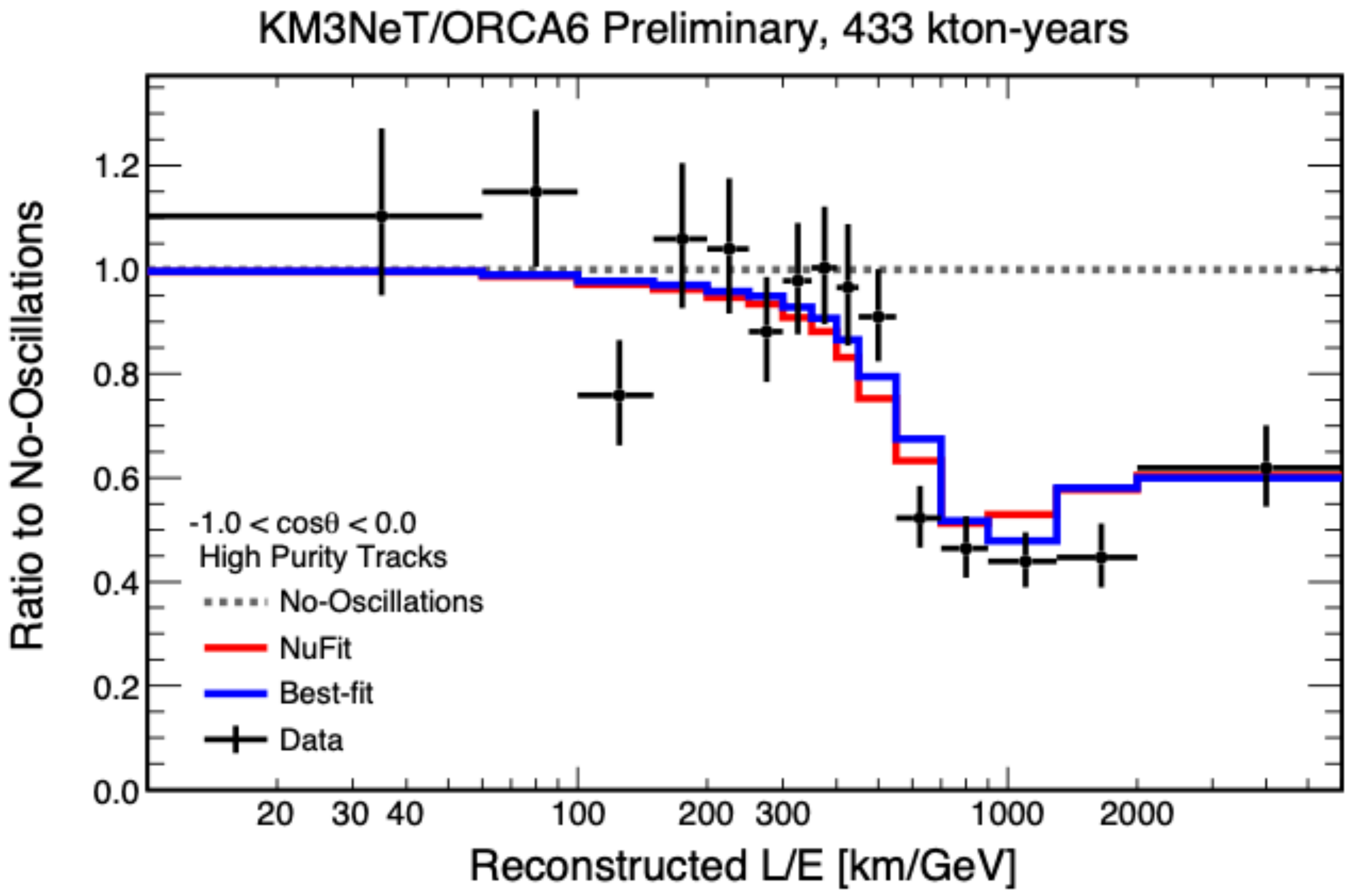


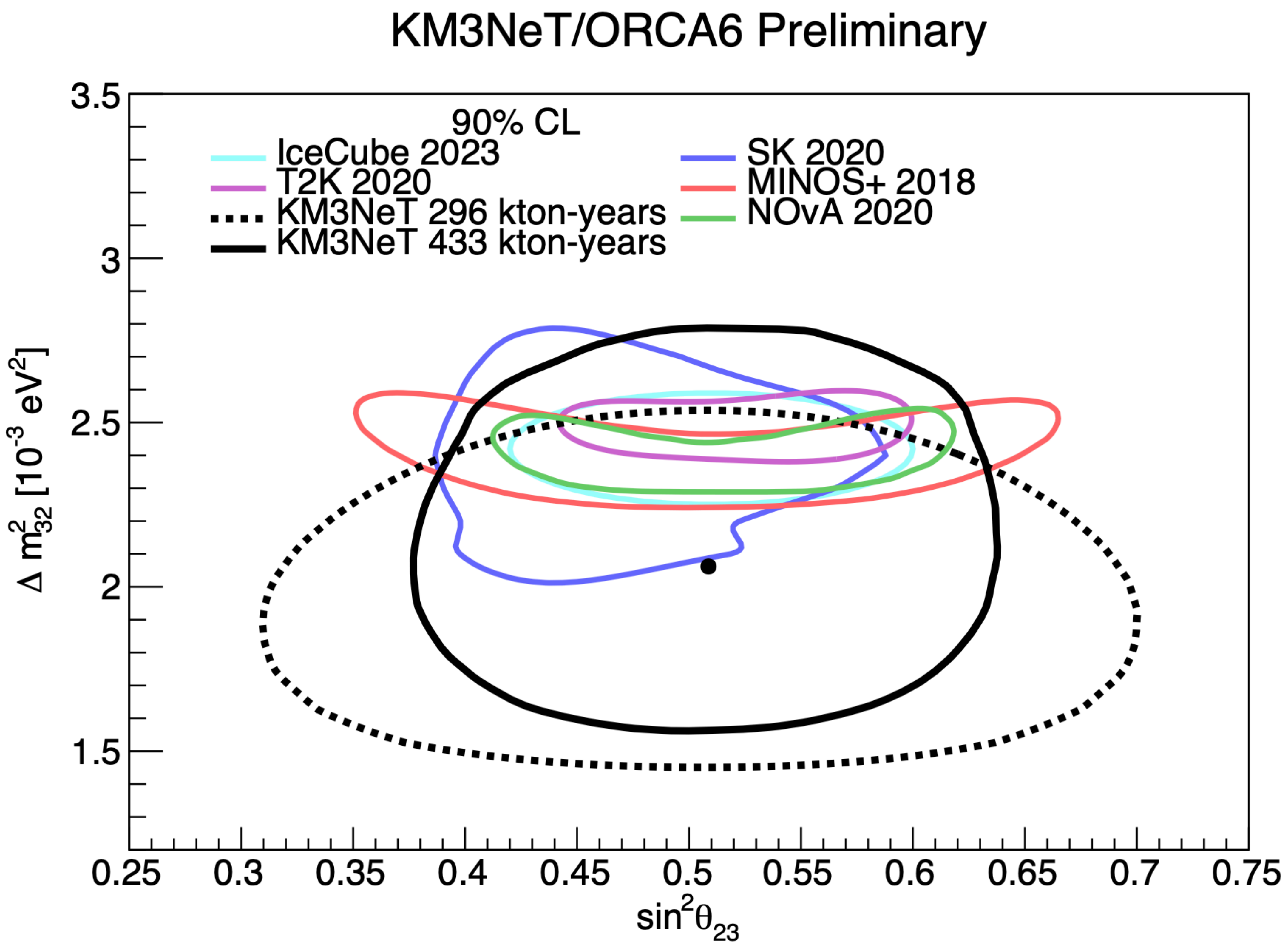
Abbasi et al. (IceCube), PRD 108 (2023)
Abbasi et al. (IceCube), arXiv: 2405.02163

ORCA

ORCA measures the multi-GeV component of the atmospheric neutrino flux from **~2GeV**

The total expected volume is 7 Mt, with events classified into high-purity tracks, low-purity tracks, and showers



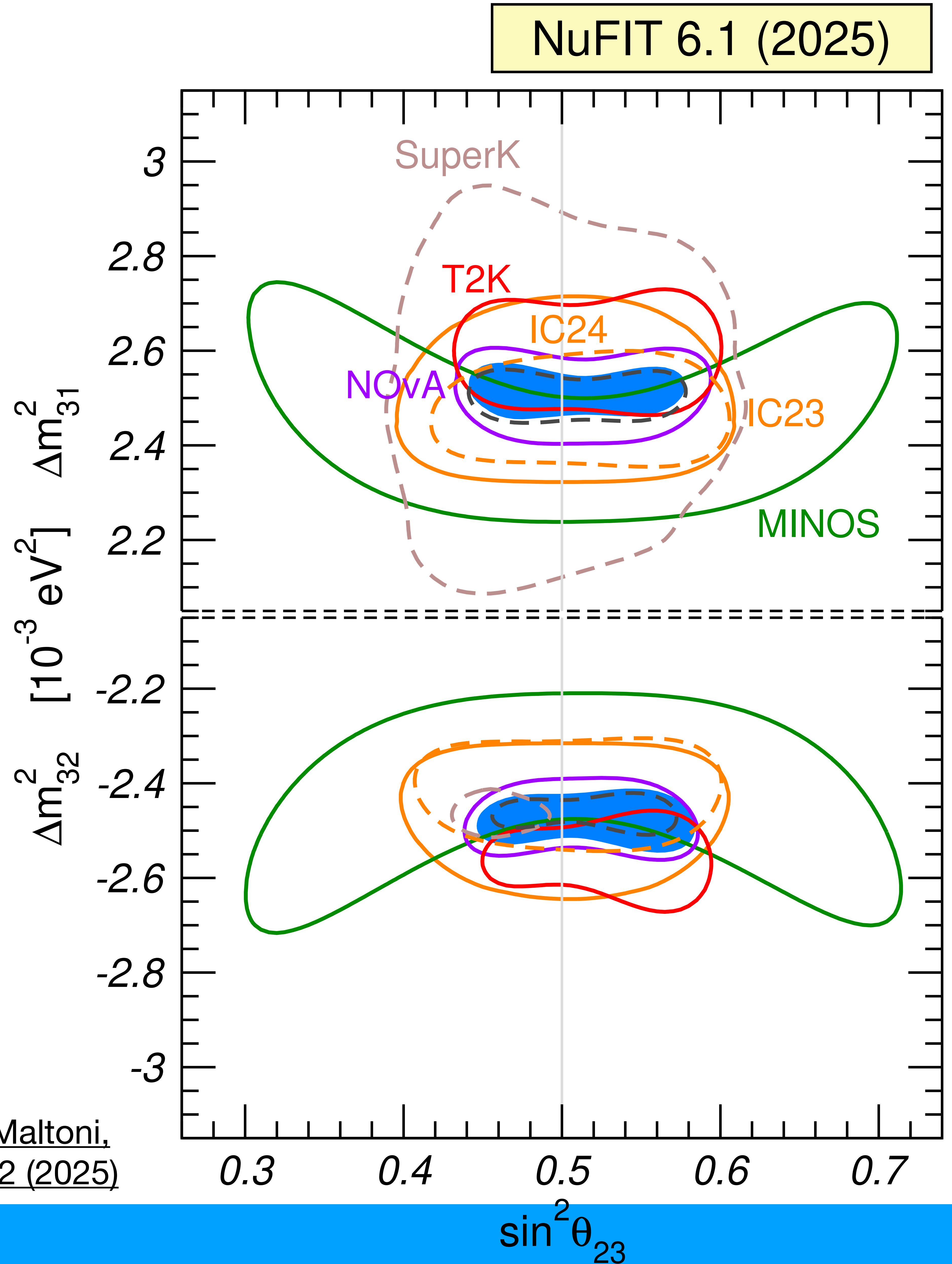


Carretero et al. (KM3NeT), PoS ICRC2023
Aiello (KM3NeT), EPJC 82, 26 (2022)

Atmospheric Mass-Squared Splitting

Combining different datasets results in significant **synergy**, as the global **regions are smaller** than the individual ones.

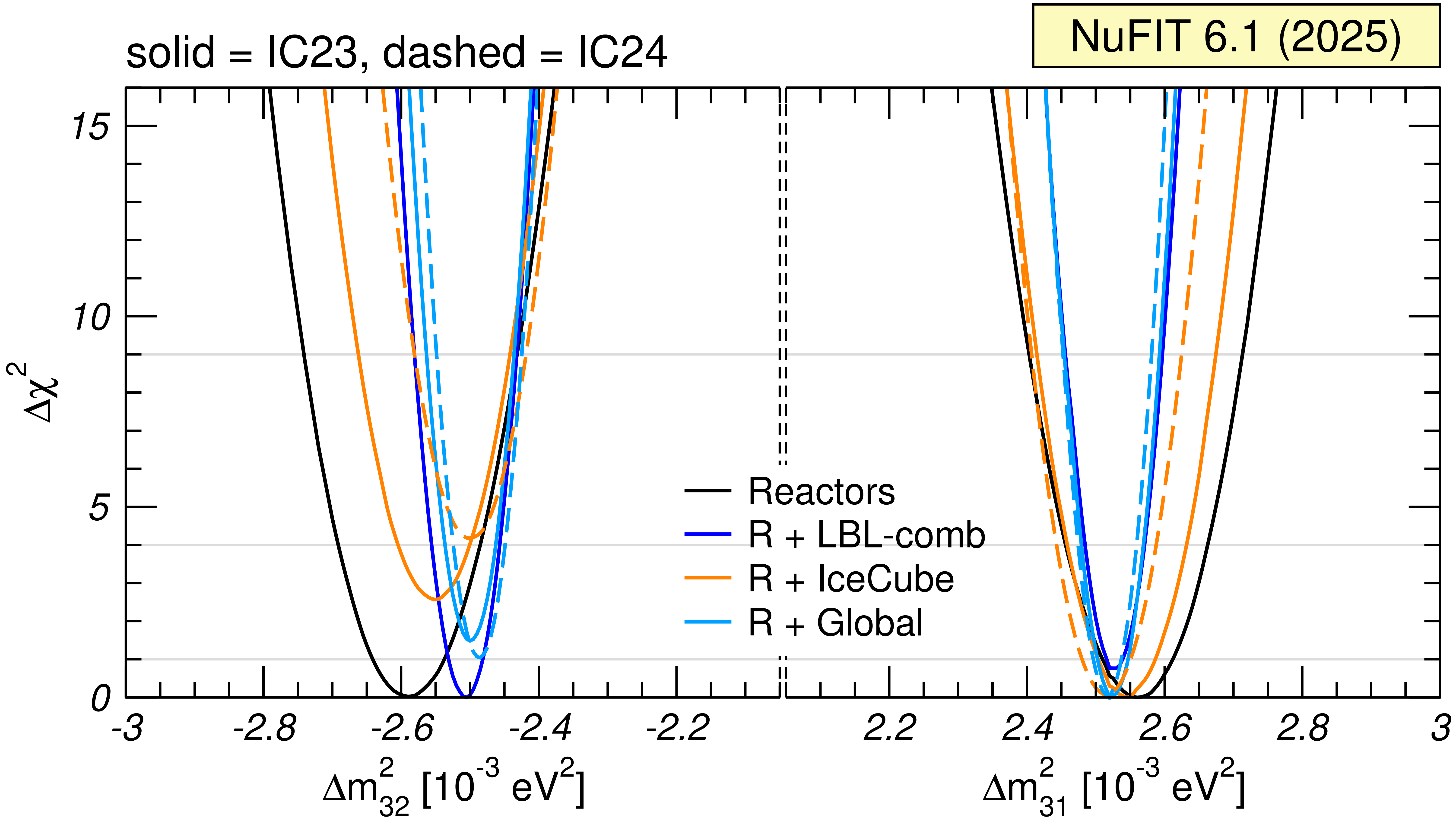
- Colored regions: LBL+IC23
- Black-dashed: LBL+IC24+SK
- Good agreement with **reactor** experiments
- Preference for the higher octant ($\sin^2\theta_{23} = 0.561$)



I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

Mass Ordering

- Combining **IC24+Reactors**, we get a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Super-Kamiokande** alone shows a preference for NO of $\Delta\chi^2 \sim 4.5$
- **Combining IC+SK+global fit** results in a preference for NO of $\Delta\chi^2 \sim 6.1$



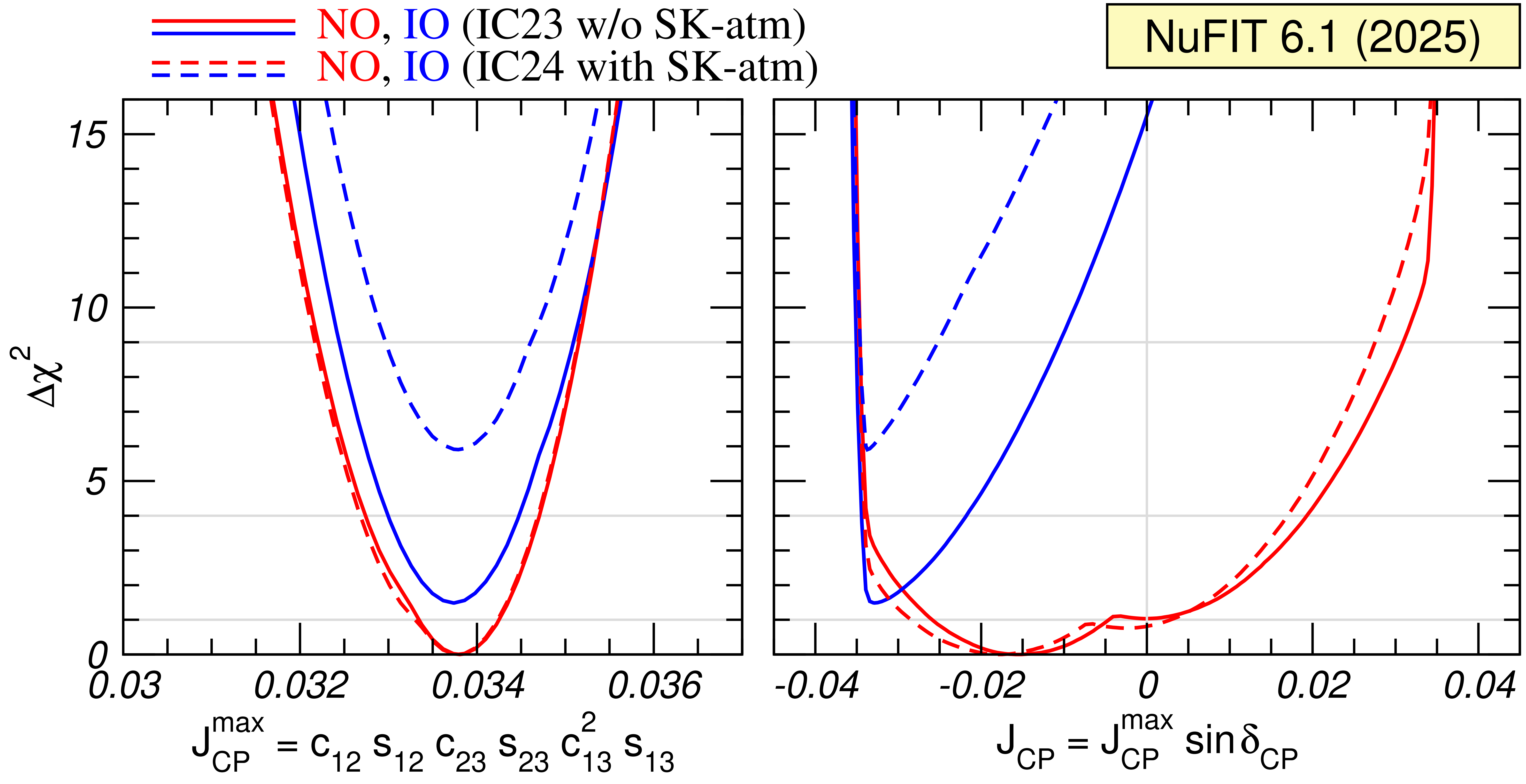
I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

CP-violation

The Jarlskog Invariant provides a convention-independent measurement of the violation of the CP symmetry

CP-conservation is margnizaly disfavored

$$J_{CP} = \mathrm{Im}[U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}]$$
$$= J^{\max}_{CP} \sin \delta_{CP}$$

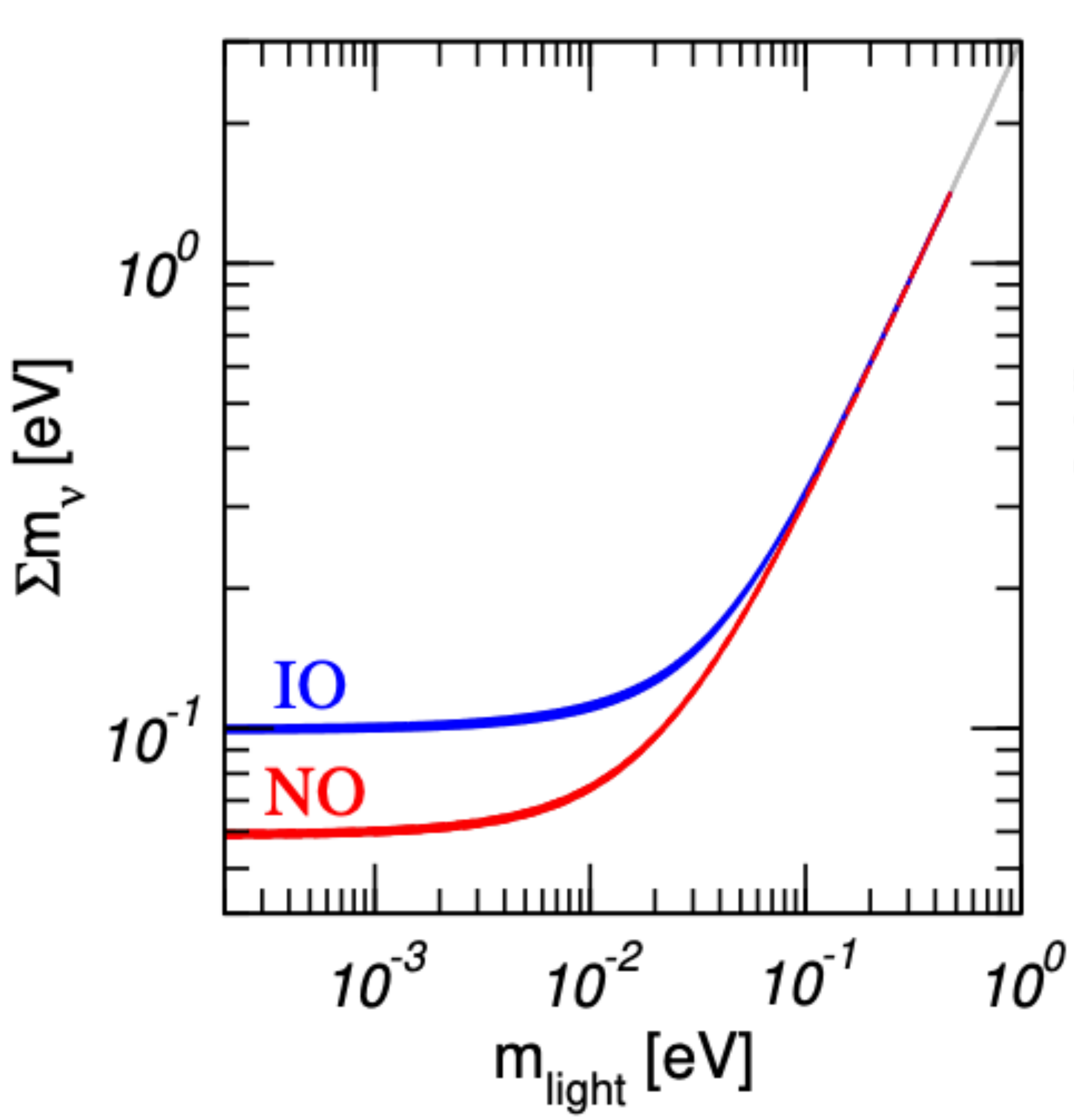


I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

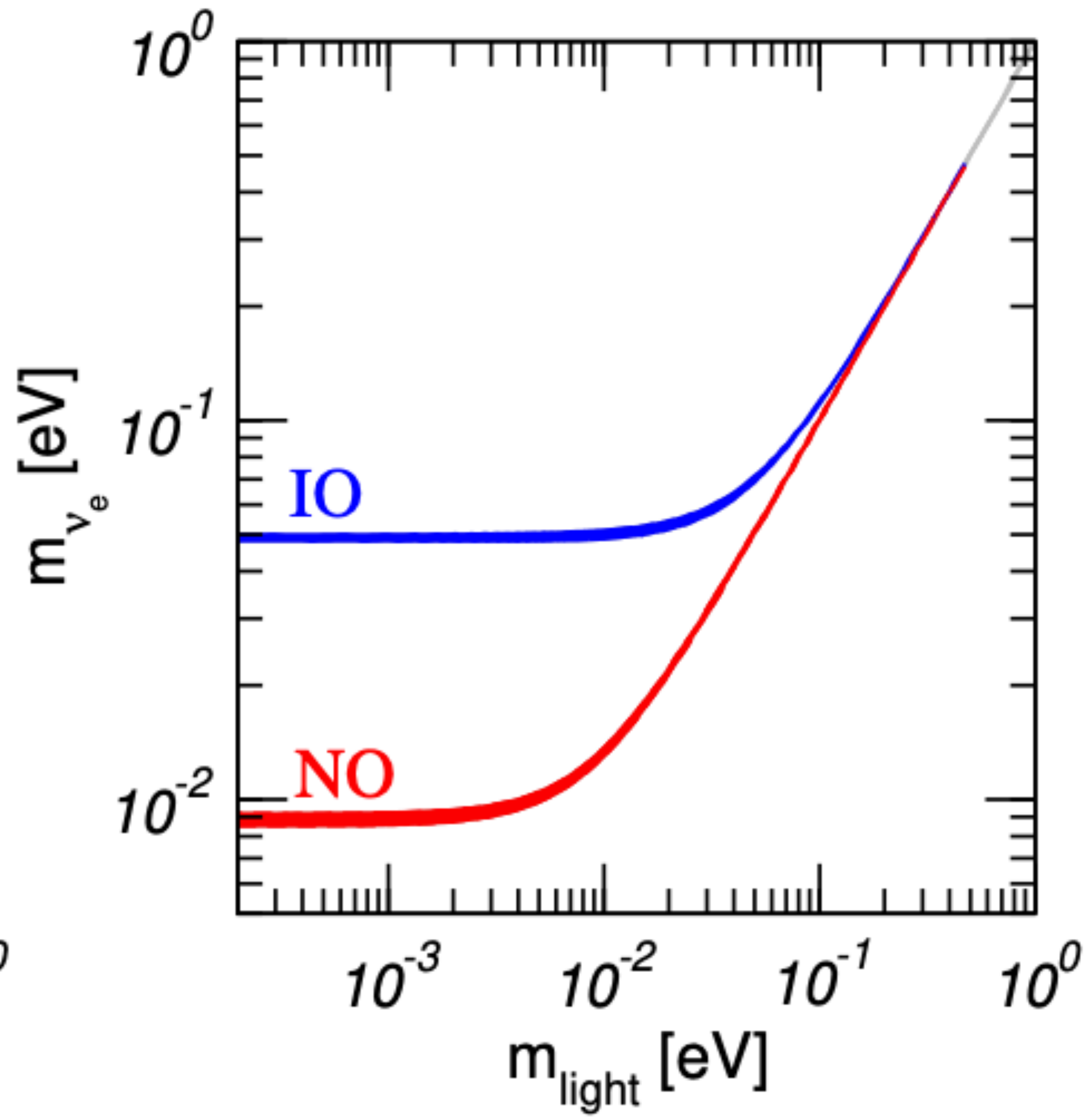
Neutrino Mass Scale

Additional information is needed to measure the absolute neutrino mass scale

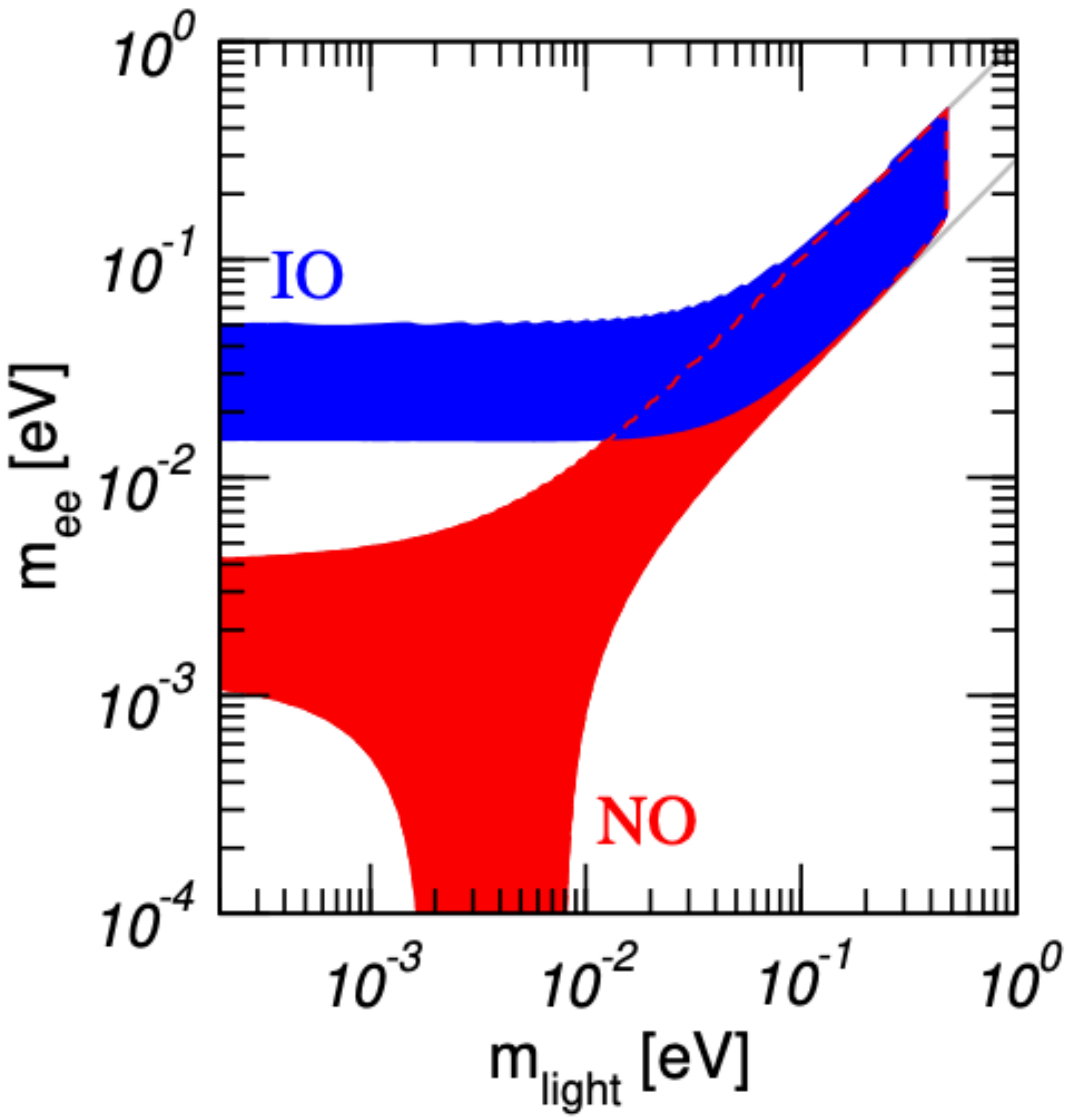
Cosmology



Beta decay (KATRIN)



$0\nu\beta\beta$



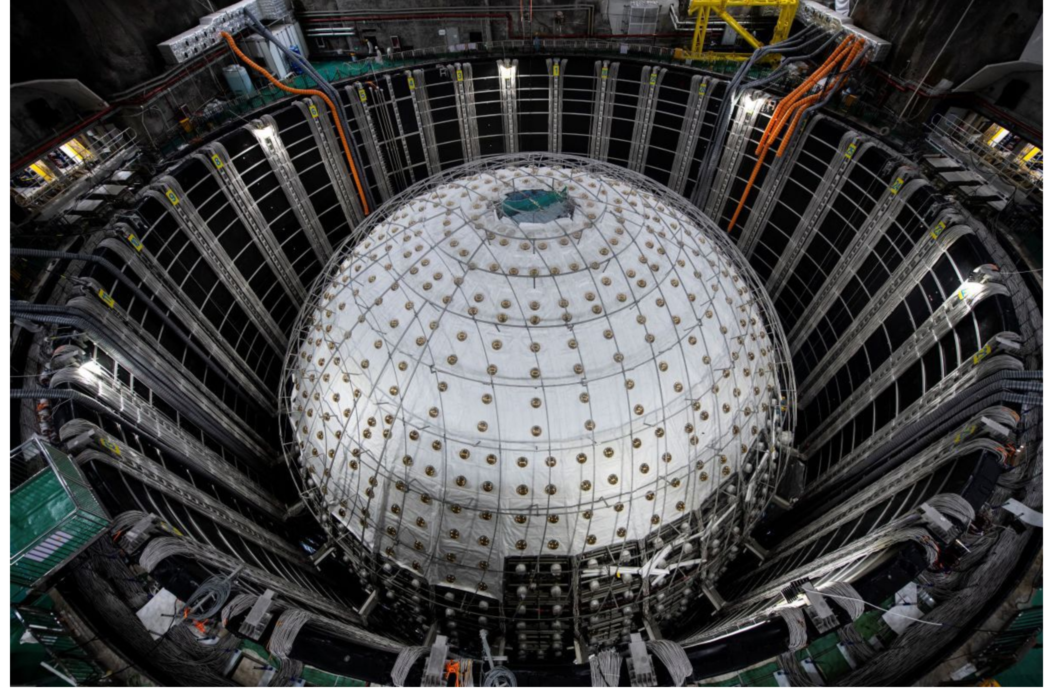
NuFIT 6.0 (2024)

I Esteban, MC Gonzalez-Garcia, M Maltoni, IMS,JP Pinheiro, T Schwetz, JHEP 12 (2025)

This picture might change soon…

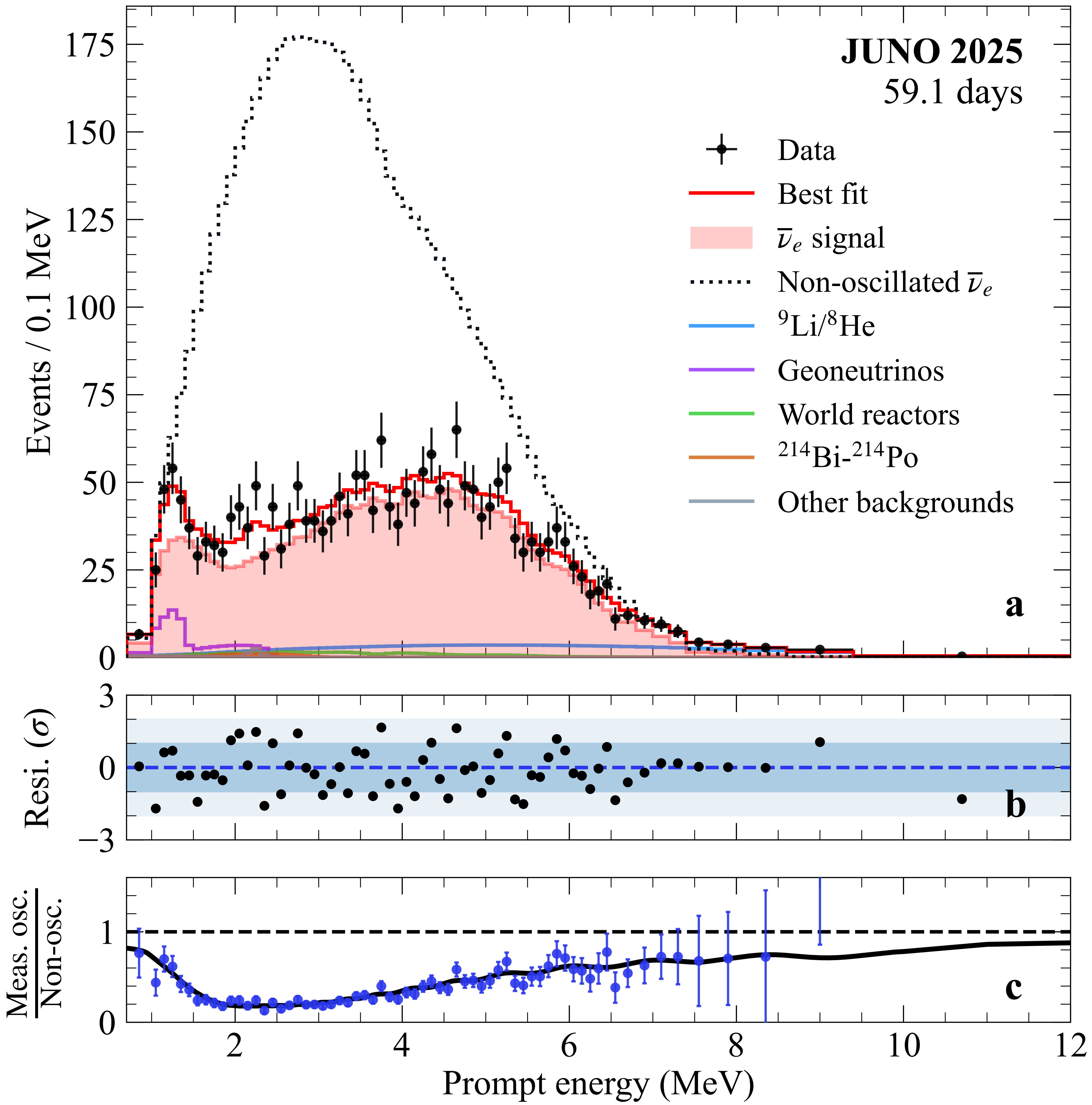
JUNO

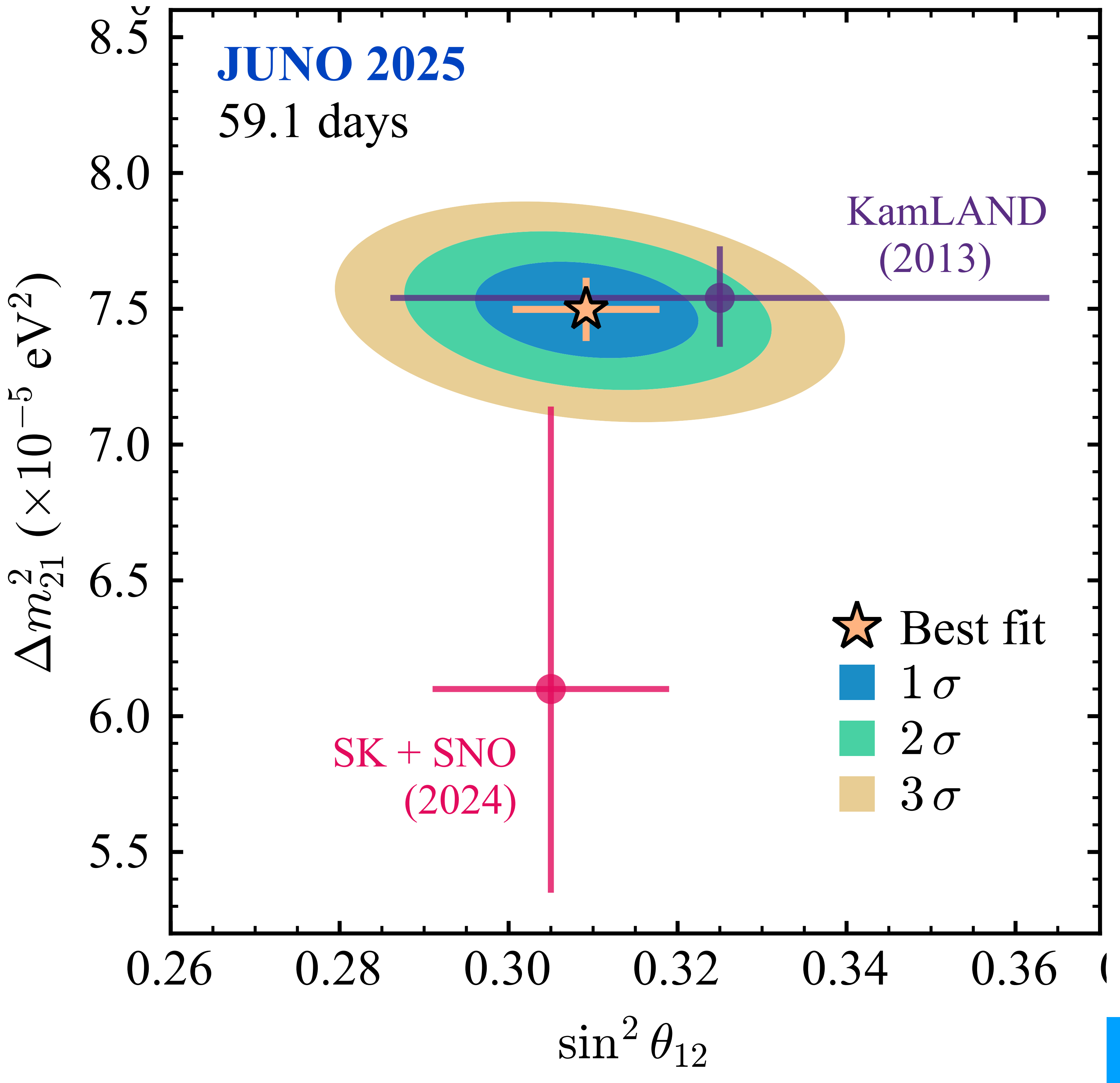
JUNO has performed the most precise measurement of Δm^2_{12} and $\sin^2\theta_{12}$



$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$
$$-\frac{1}{2}\sin^2 2\theta_{13}\left(1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\,\sin^2\left(2|\Delta_{ee}| \pm \phi\right)\right)$$

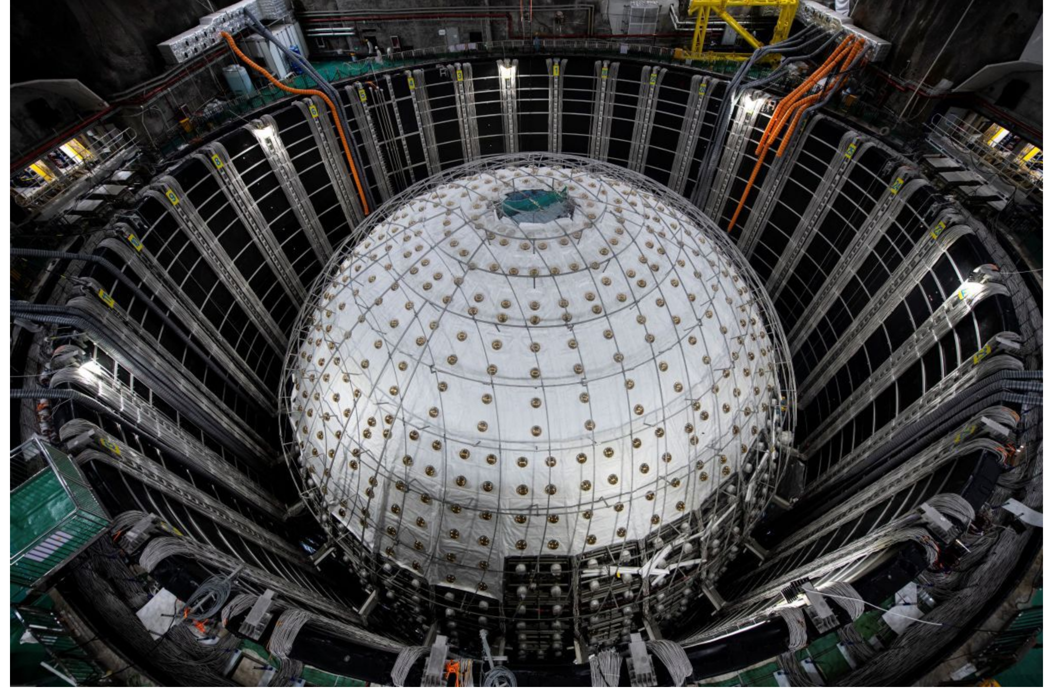
S. Parke, PRD 93 (2016)





A. Abusleme et al. (JUNO), arXiv:2511.14593

JUNO

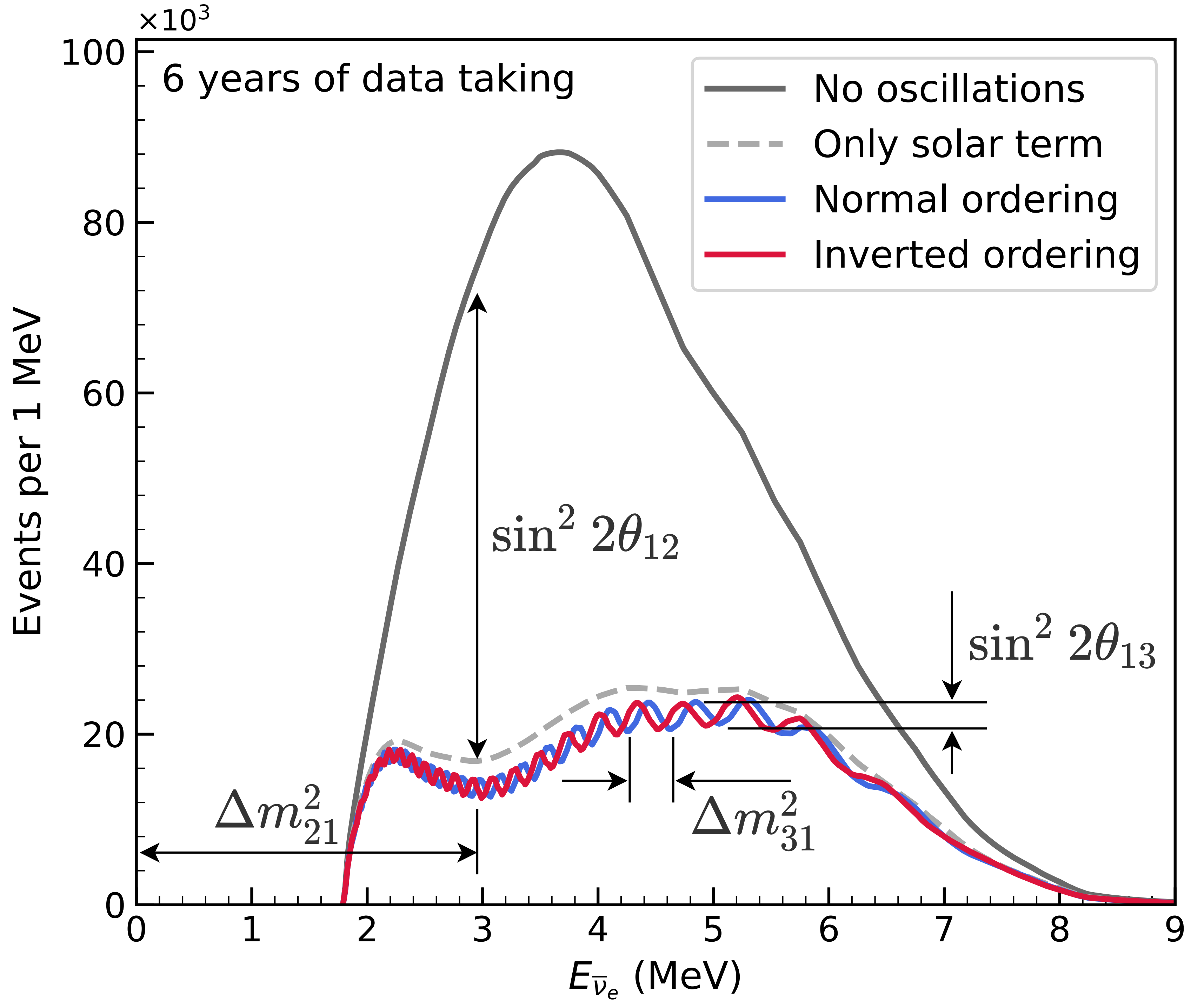


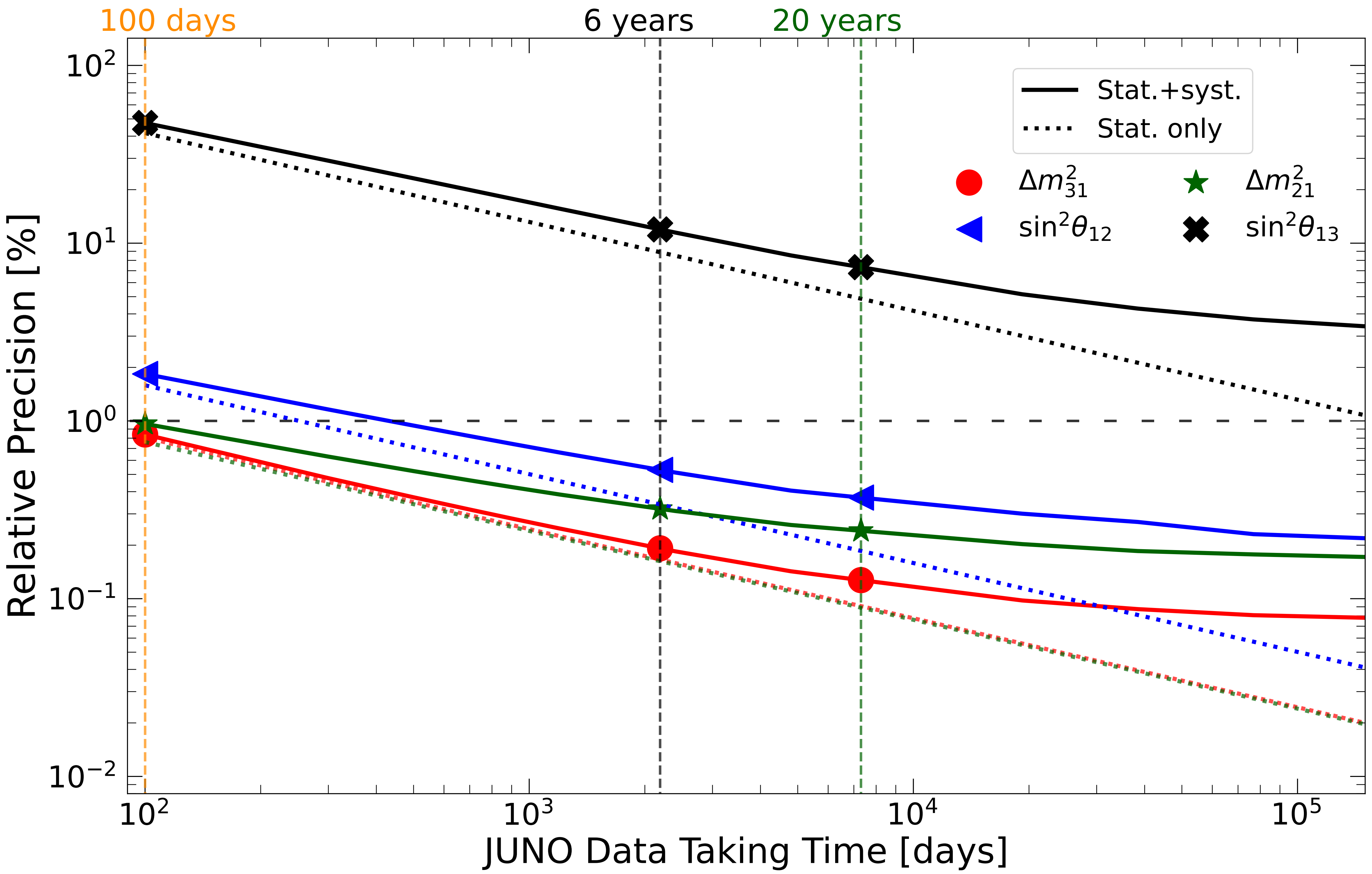
The goal of JUNO is to determine the neutrino mass ordering

$$P_{ee} = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} - \frac{1}{2}\sin^2 2\theta_{13}(1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\,\sin^2\left(2|\Delta_{ee}| \pm \phi\right))$$

S. Parke, PRD 93 (2016)

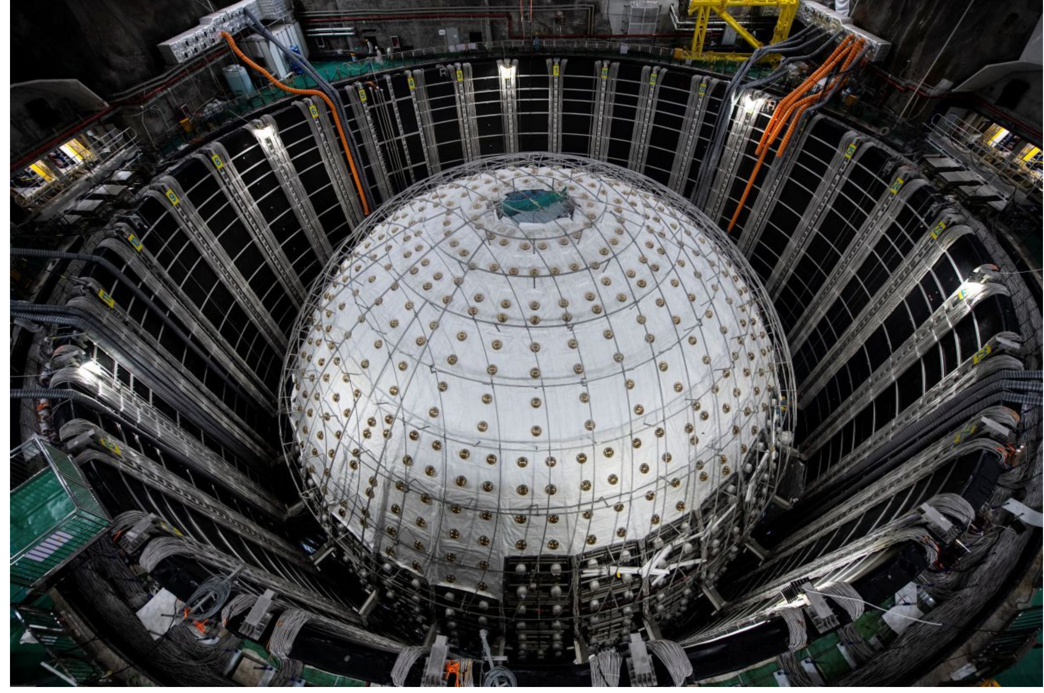
$$\phi = \arctan(\cos 2\theta_{12}\tan\Delta_{21}) \qquad \Delta m^2_{ee} = \Delta m^2_{31} - \sin^2\theta_{12}\Delta m^2_{21}$$





A. Abusleme et al. (JUNO) Chin.Phys.C 46 (2022)

JUNO



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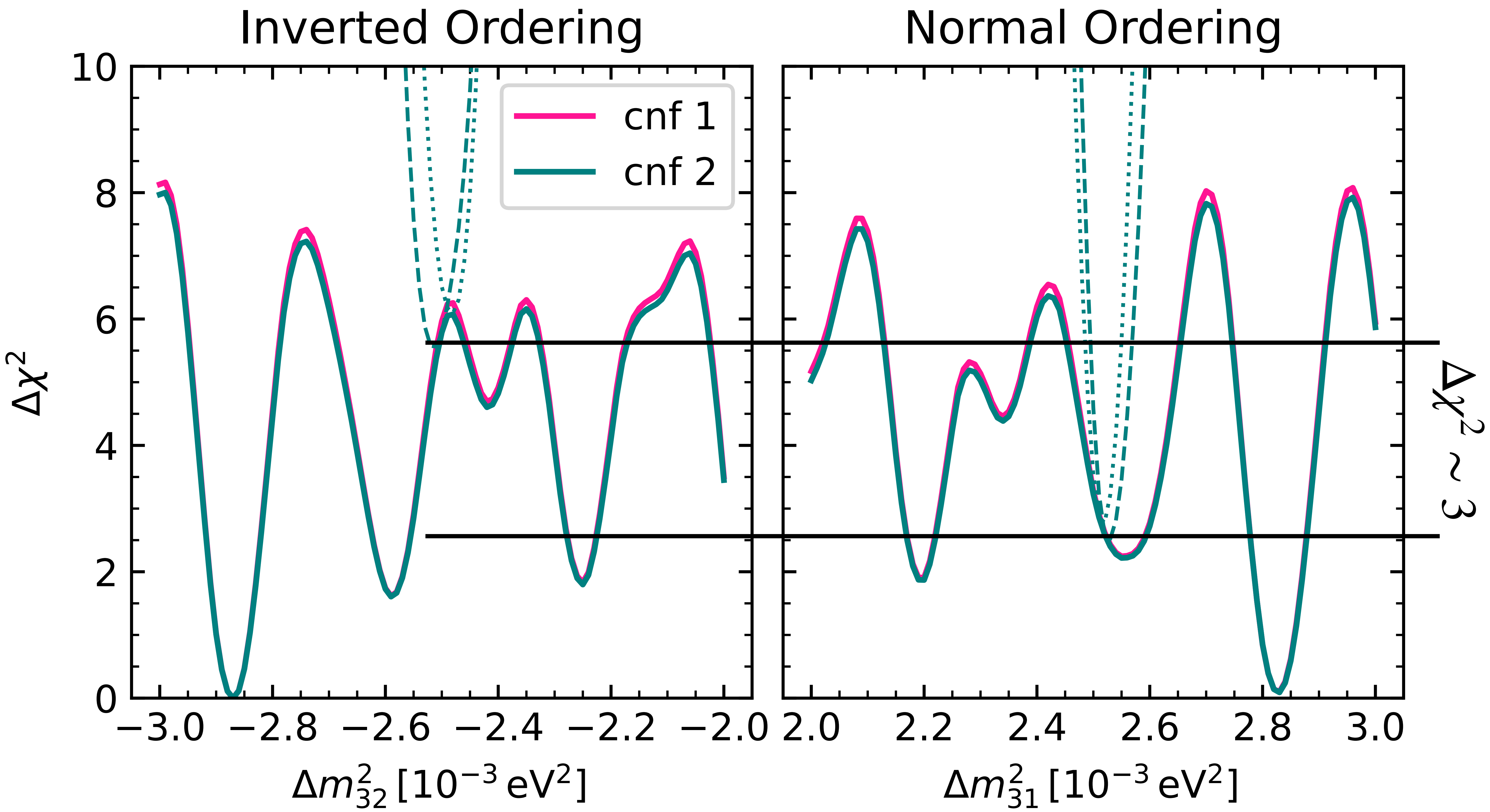
S. Parke, PRD 93 (2016)

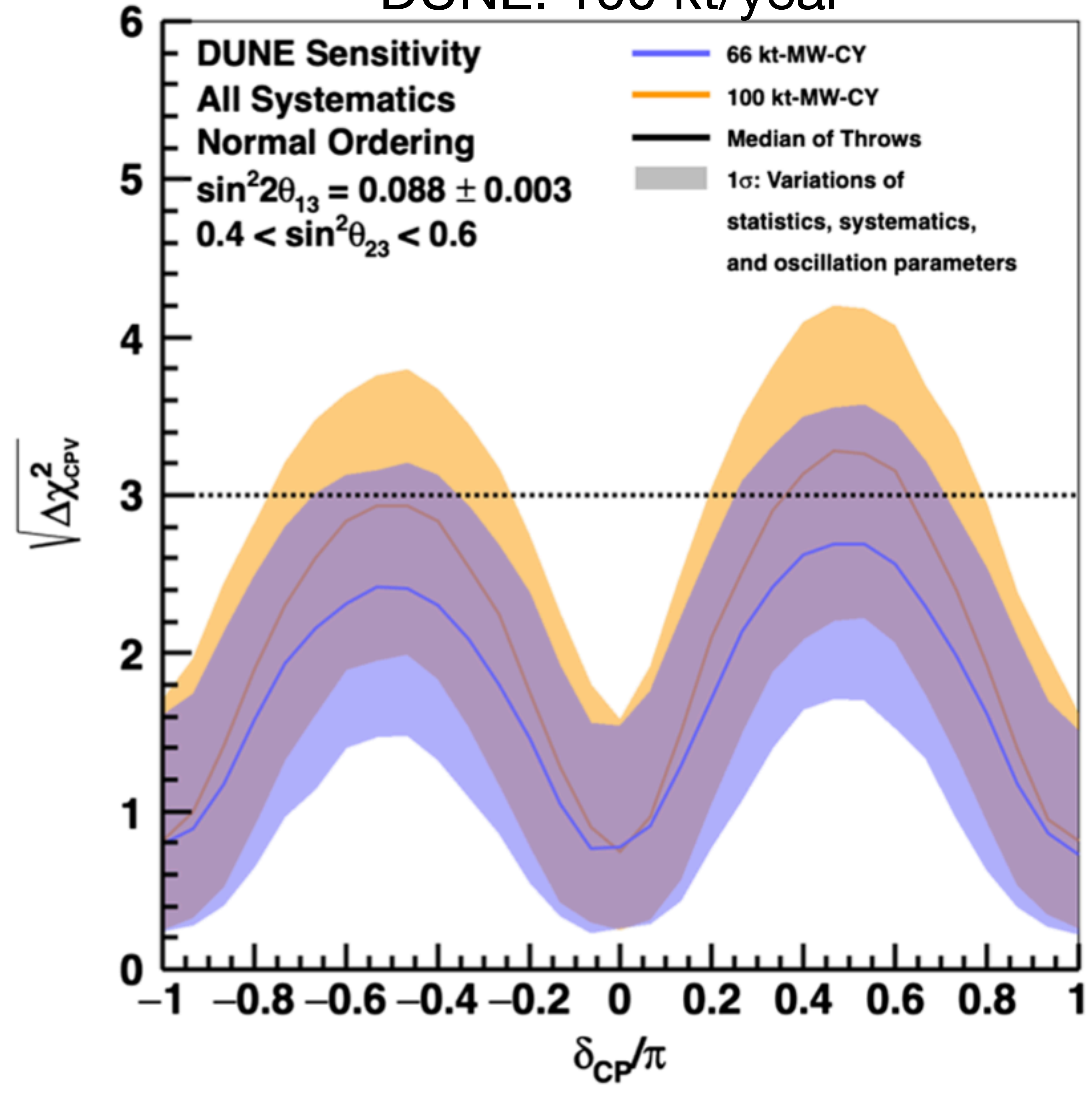


- JUNO alone currently lacks sensitivity to the mass ordering
- When combined with NuFit 6.1, preference for NO $\Delta\chi^2 \sim 3$
- This picture is affected by systematic uncertainties: backgrounds, energy scale, and resolution…

I. Esteban, M.C. Gonzalez-Garcia, M. Maltoni, IMS, J. P. Pinheiro, T. Schwetz JHEP 04 (2026) 089

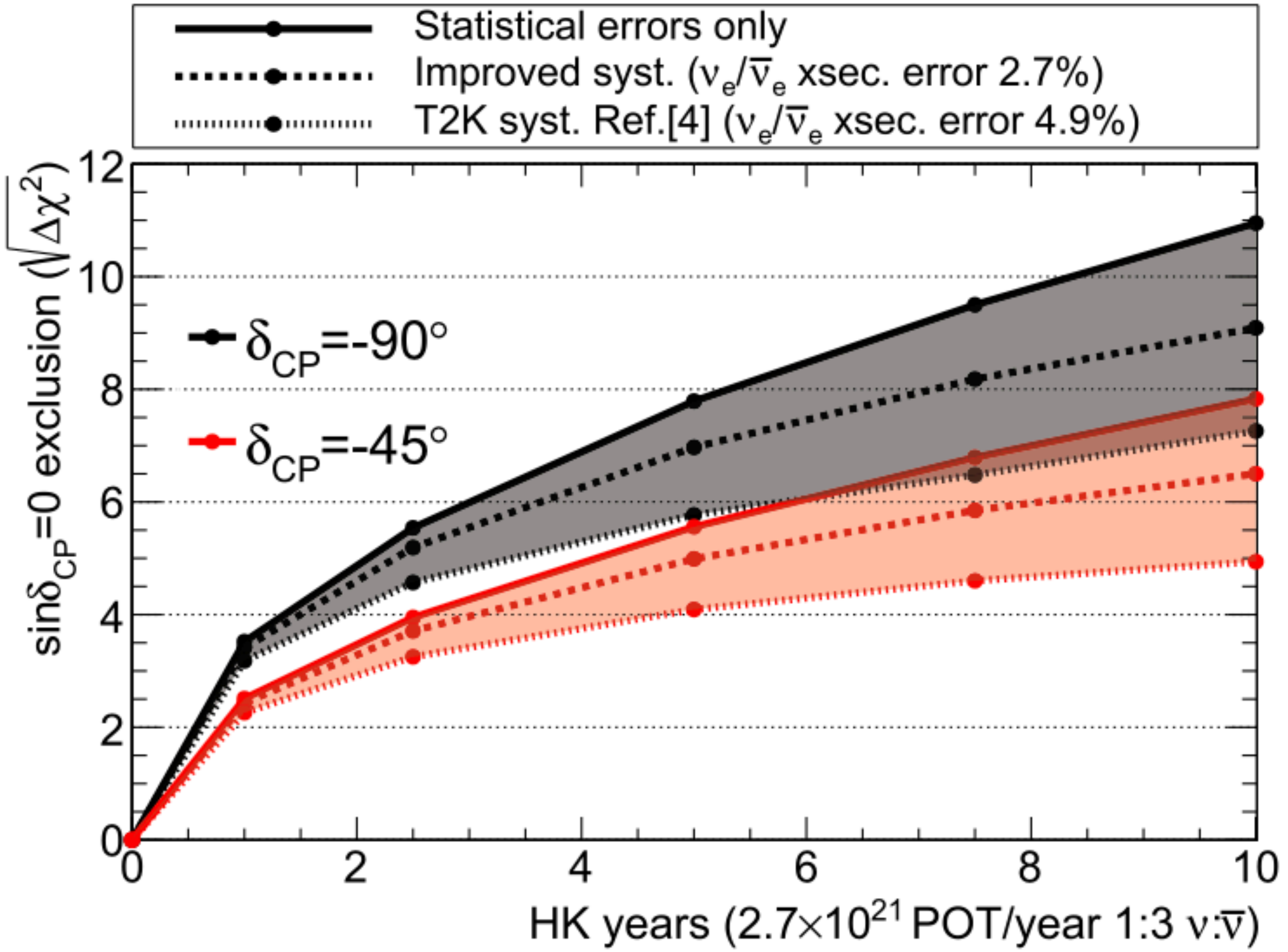
DUNE and HK

DUNE: 100 kt/year



A. Abed Abud et al. (DUNE), PRD 105

HK



K. Abe et al. (HK), EPJC 2026

Beyond 3ν mixing…

Pseudo-Dirac neutrinos

One fundamental question is the **origin of the neutrino masses.** To explain that, we can consider the SM as an effective field theory

$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{\mathscr{L}_{d=5}}{\Lambda} + \cdots$$

Ivan Martinez-Soler (IPPP)

Pseudo-Dirac neutrinos

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$$\mathscr{L}_{eff} = \mathscr{L}_{SM} + \frac{\mathscr{L}_{d=5}}{\Lambda} + \cdots$$

- At d=5, we have the Weinberg operator

$$\mathscr{L}^{\nu}_{mass} \supset Y_\nu \bar{L}_L \tilde{\phi} N_R + \frac{1}{2} M_R \bar{N}^c_R N_R + h.c.$$

Type-I seesaw:

- Introduce right-handed neutrinos
- Allow L number violation

- For $M_R >> \text{v}$

$$m_\nu \sim \frac{Y^\dagger_\nu Y_\nu \text{v}^2}{M_R}$$

- eV neutrino masses can be explained with $Y_\nu \sim 1$
- Heavy neutrinos can hardly be tested

$$m_N \approx M_R + \mathcal{O}\left(m_\nu\right)$$

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- There are other scenarios where the Majorana mass can take smaller values $(M_R << M_D)$

Wolfenstein, Nucl. Phys. B 186, 147 (1981)
Petcov, PLB 110, 245 (1982)
Valle and Singer, PRD 28, 540 (1983)

Ivan Martinez-Soler (IPPP)

Pseudo-Dirac neutrinos

Considering three right-handed neutrinos

$$M = \begin{pmatrix} 0_3 & M_D \\ M_D & M_R \end{pmatrix}$$

We can obtain the neutrino evolution by diagonalizing $M^\dagger M$

The unitary matrix

$$V = \frac{1}{\sqrt{2}} \begin{pmatrix} U & 0 \\ 0 & U_R \end{pmatrix} \cdot \begin{pmatrix} 1_3 & i \cdot 1_3 \\ \varphi & -i\varphi \end{pmatrix}$$

- U :PMNS matrix
- U_R: mixing of the sterile sector
- $\varphi = \mathrm{diag}(e^{-i\phi_1}, e^{-i\phi_2}, e^{-i\phi_3})$

Pseudo-Dirac neutrinos

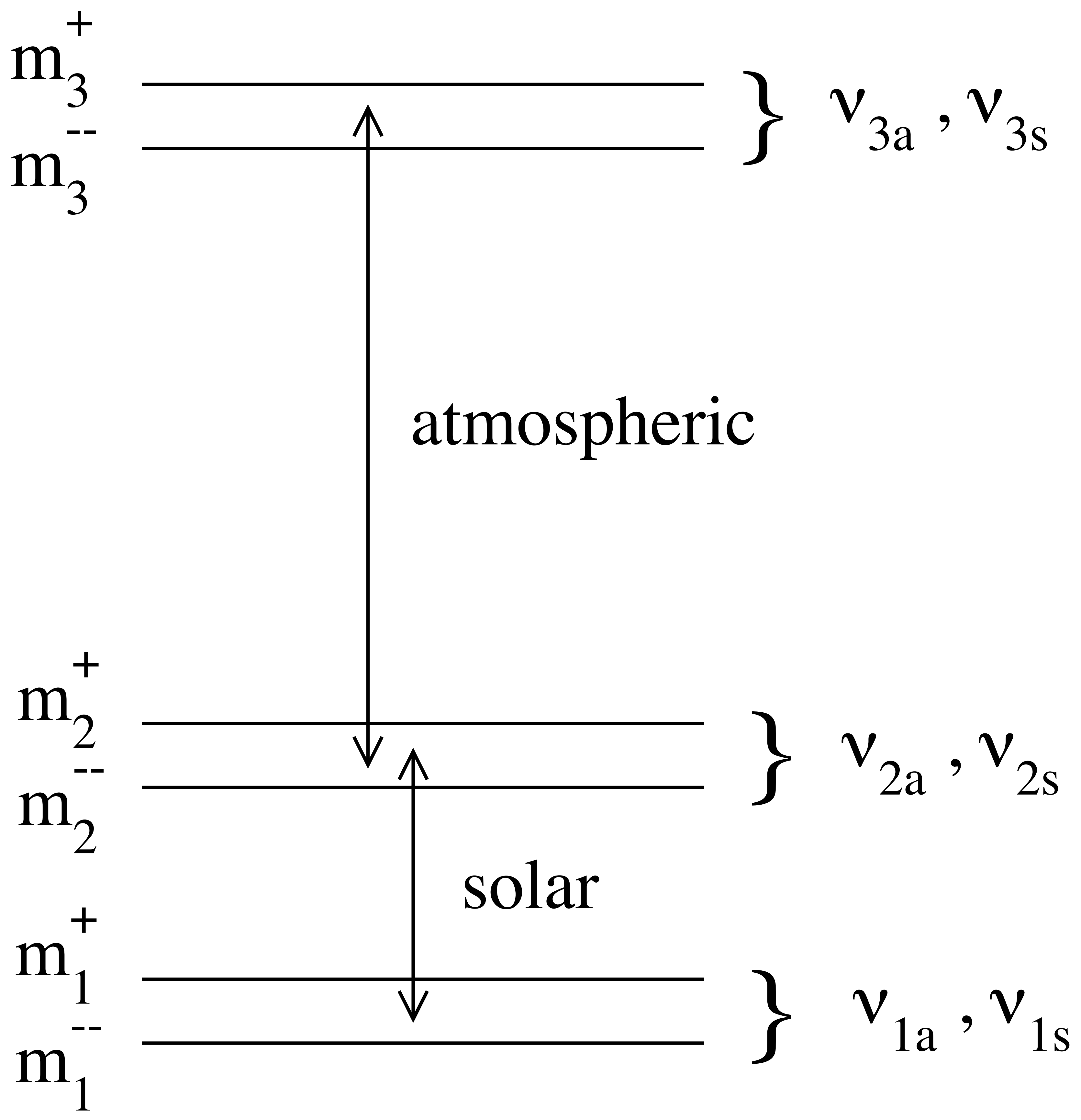
Active neutrinos can be written as a superposition of two mass eigenstates

$$\nu_{\alpha L} = \frac{1}{\sqrt{2}} U_{\alpha j}(\nu_{js} + i\,\nu_{ja})$$

$$m_{js}^2 = m_j^2 + \frac{1}{2}\delta m_j^2 \qquad m_{ja}^2 = m_j^2 - \frac{1}{2}\delta m_j^2$$

The mass difference is proportional to the Majorana mass

$$\delta m^2 \sim M_D M_R$$



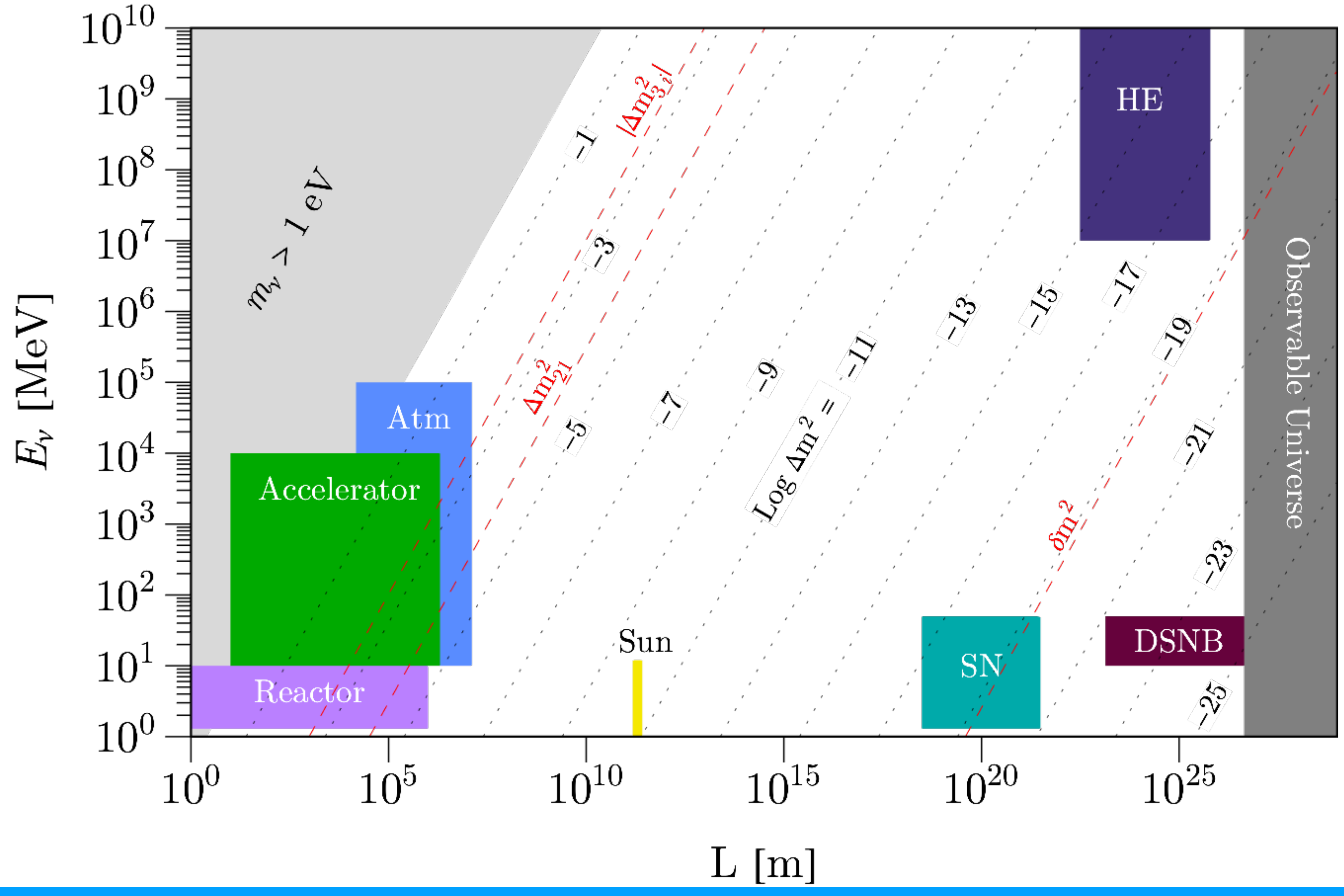
Ivan Martinez-Soler (IPPP)

Pseudo-Dirac neutrinos

Active neutrinos can be written as a superposition of two mass eigenstates

The mass splitting between active and sterile neutrinos induces oscillations on astrophysical scales

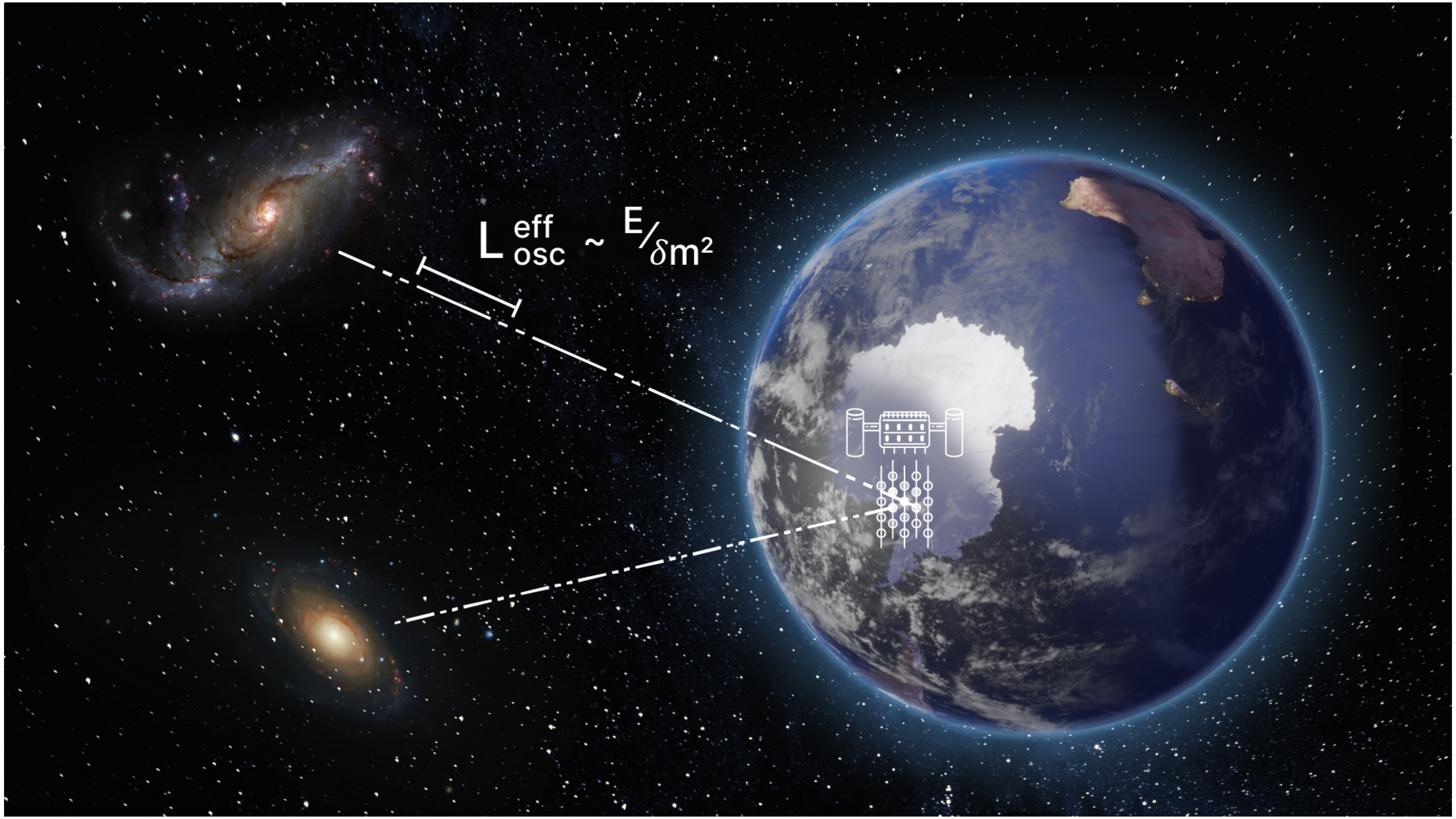
$$P_{\alpha\beta} = \frac{|U_{\alpha k}|^2 |U_{\beta k}|^2}{2}\left(1 + \cos\left(\frac{\delta m_k^2 L}{2E}\right)\right)$$



Ivan Martinez-Soler (IPPP)

New Astrophysical Sources

The long distance travelled by astrophysical neutrinos and its energies has open the possibility to explore other BSM scenarios

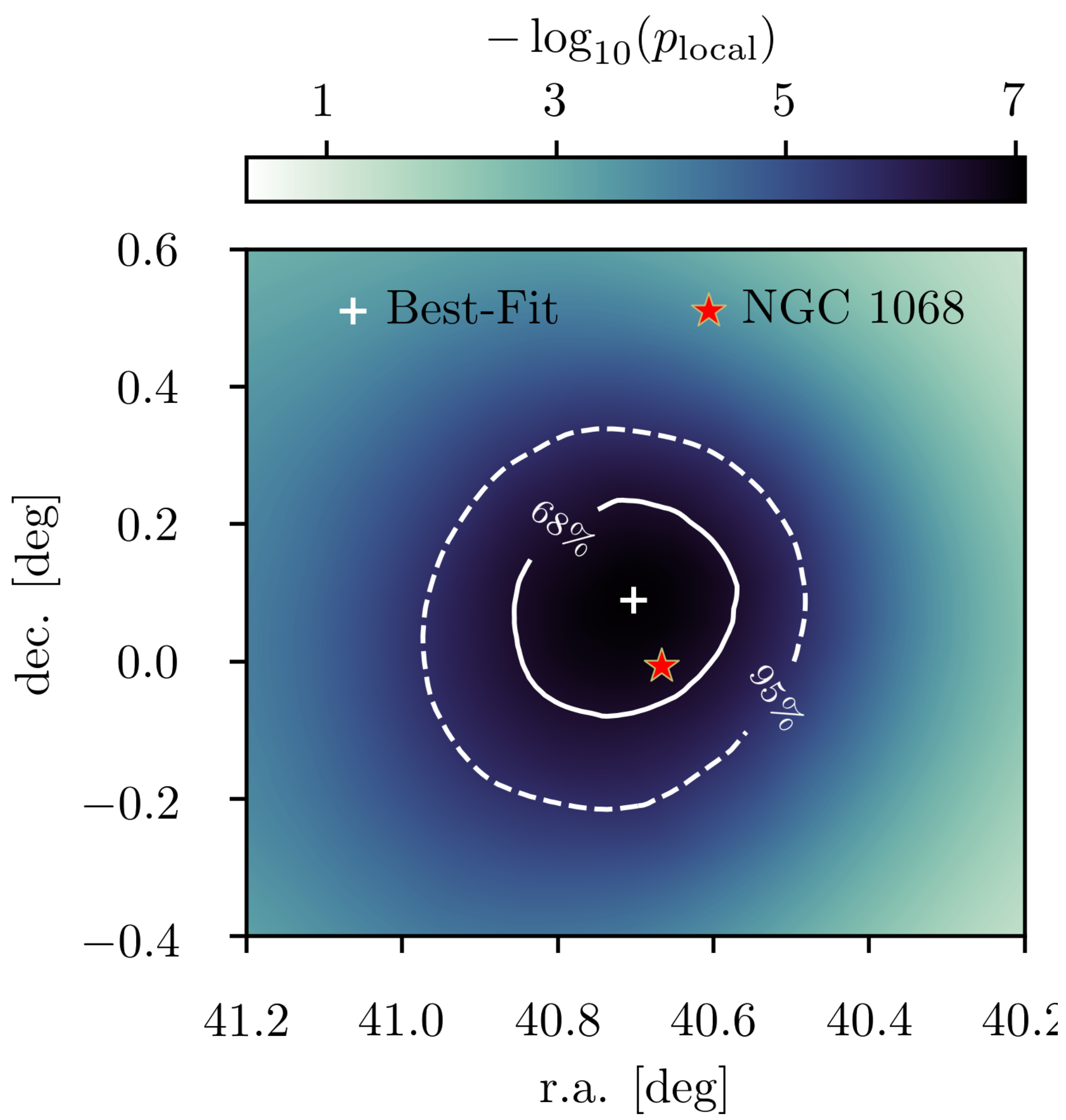


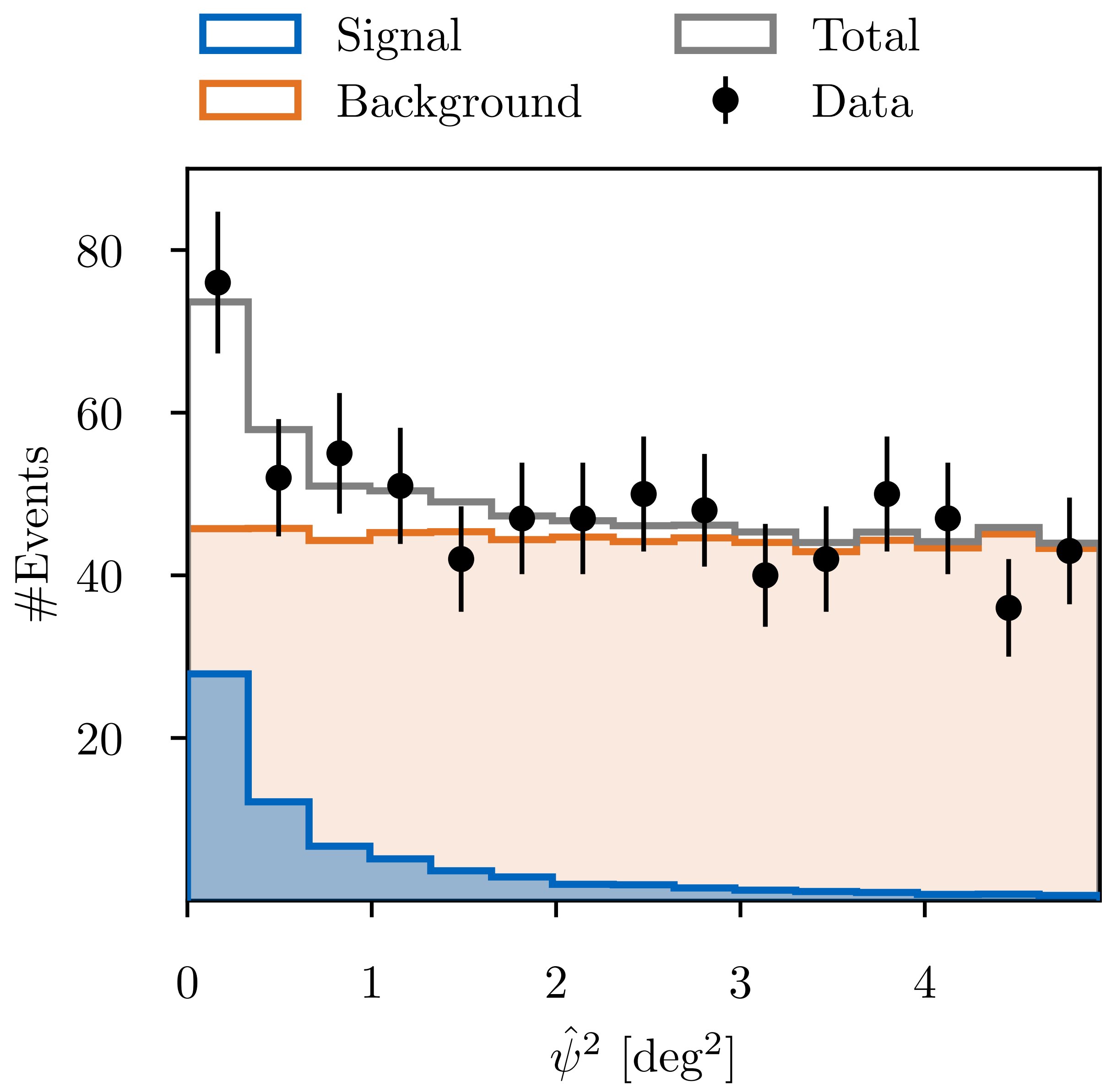
Ivan Martinez-Soler (IPPP)

Point Sources

The most significant source observed by IceCube is **NGC 1068** with a significance of 4.2σ

- The analysis is optimized for searching tracks from the Northern Hemisphere
- The analysis assumes a single power law finding a preference for $\gamma = 3.2 \pm 0.2$ and an excess of 79^{+22}_{-20} events
- Most of the events have energies between 1.5TeV and 15TeV





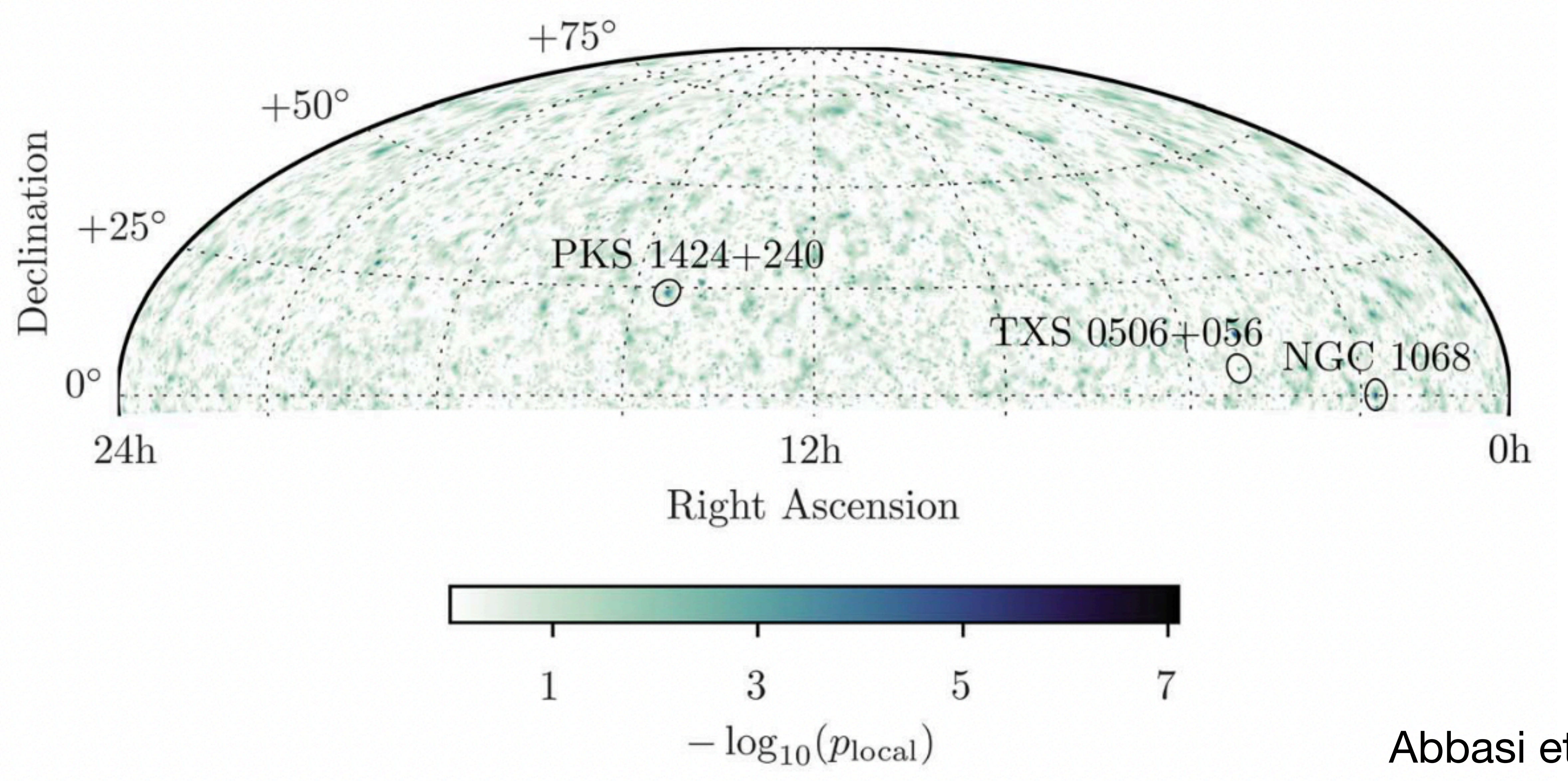
Abbasi et al. (IceCube) Science 378, 538 (2022)

Point Sources

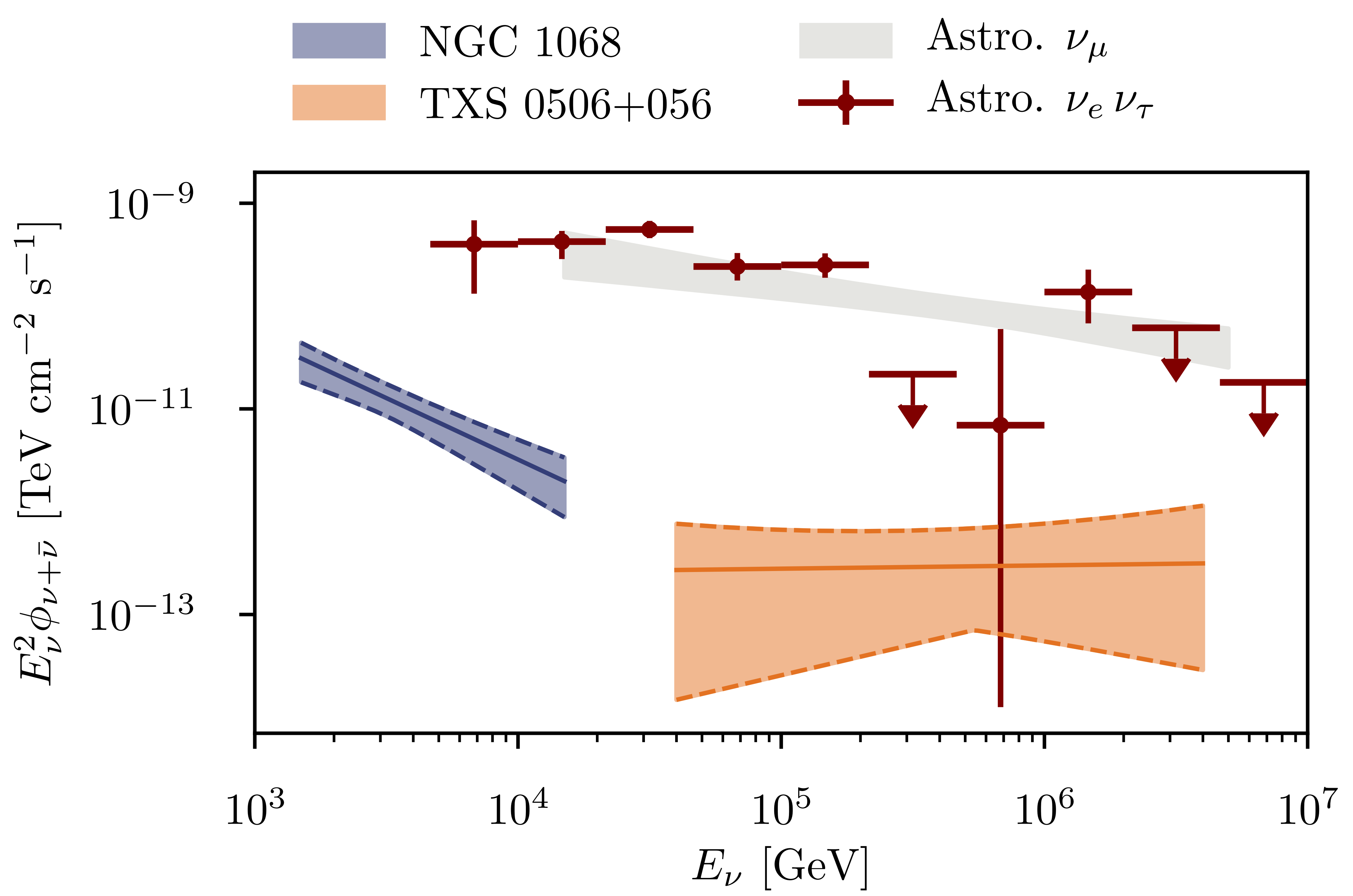
Beyond NGC 1068, IceCube has identified more candidate sources

The most significant point sources

Source	$-\log_{10} p$	$\hat{\gamma}$	z
NGC 1068	7.0	3.2	0.0038
PKS 1424+240	4.0	3.5	0.6047
TXS 0506+056	3.6	2.0	0.3365



These sources contribute no more than $\sim 1\,\%$ to the total diffuse flux measured.

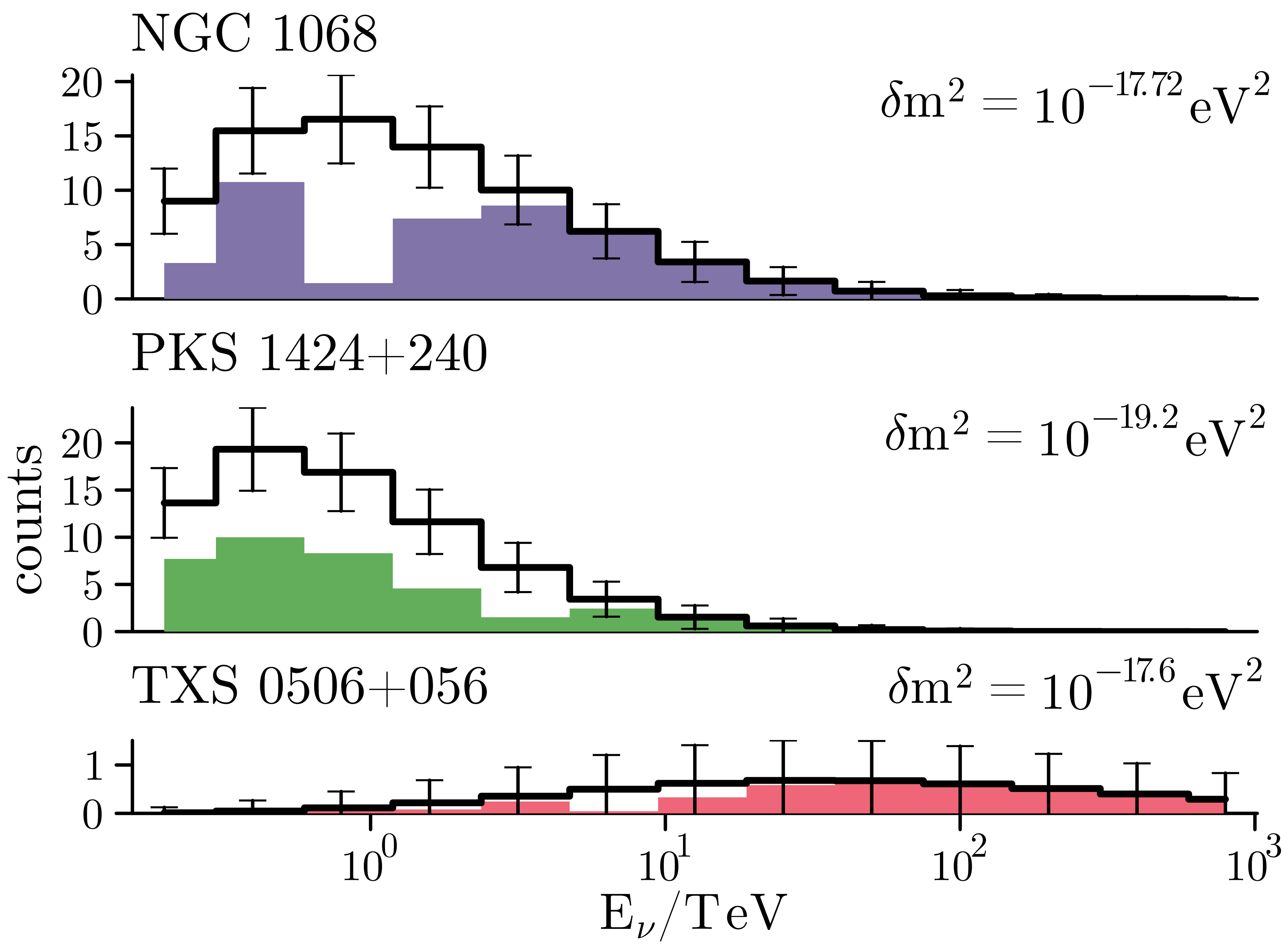


Abbasi et al. (IceCube) Science 378, 538 (2022)

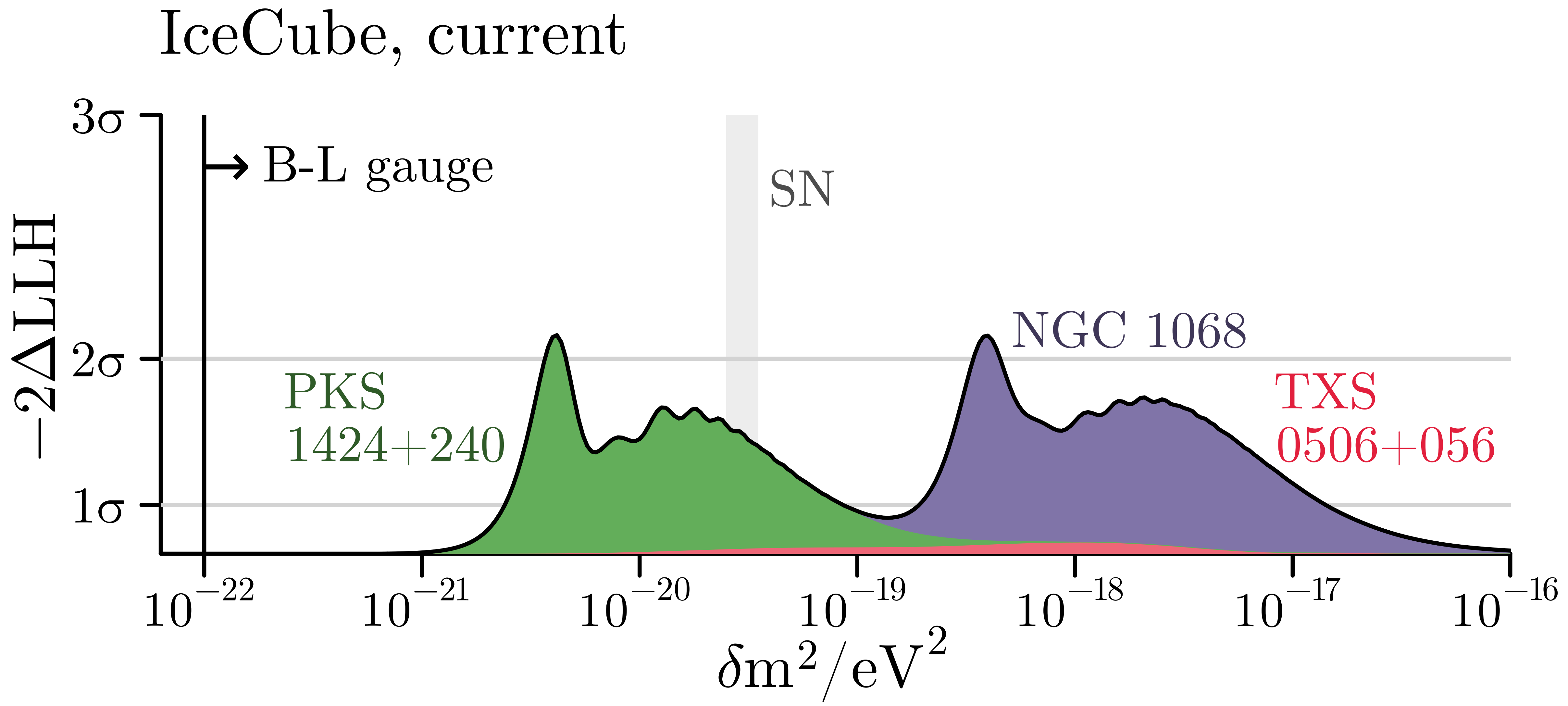
Point Sources

In this analysis, we consider the most significant candidate sources observed by IceCube

A dip in the neutrino spectra of several sources will robustly indicate this scenario.



The pseudo-Dirac scenario can be explored with a high significance by combining several sources.



Carloni, IMS, Arguelles, Babu, Bhupal, PRD 109 (2024) L051702

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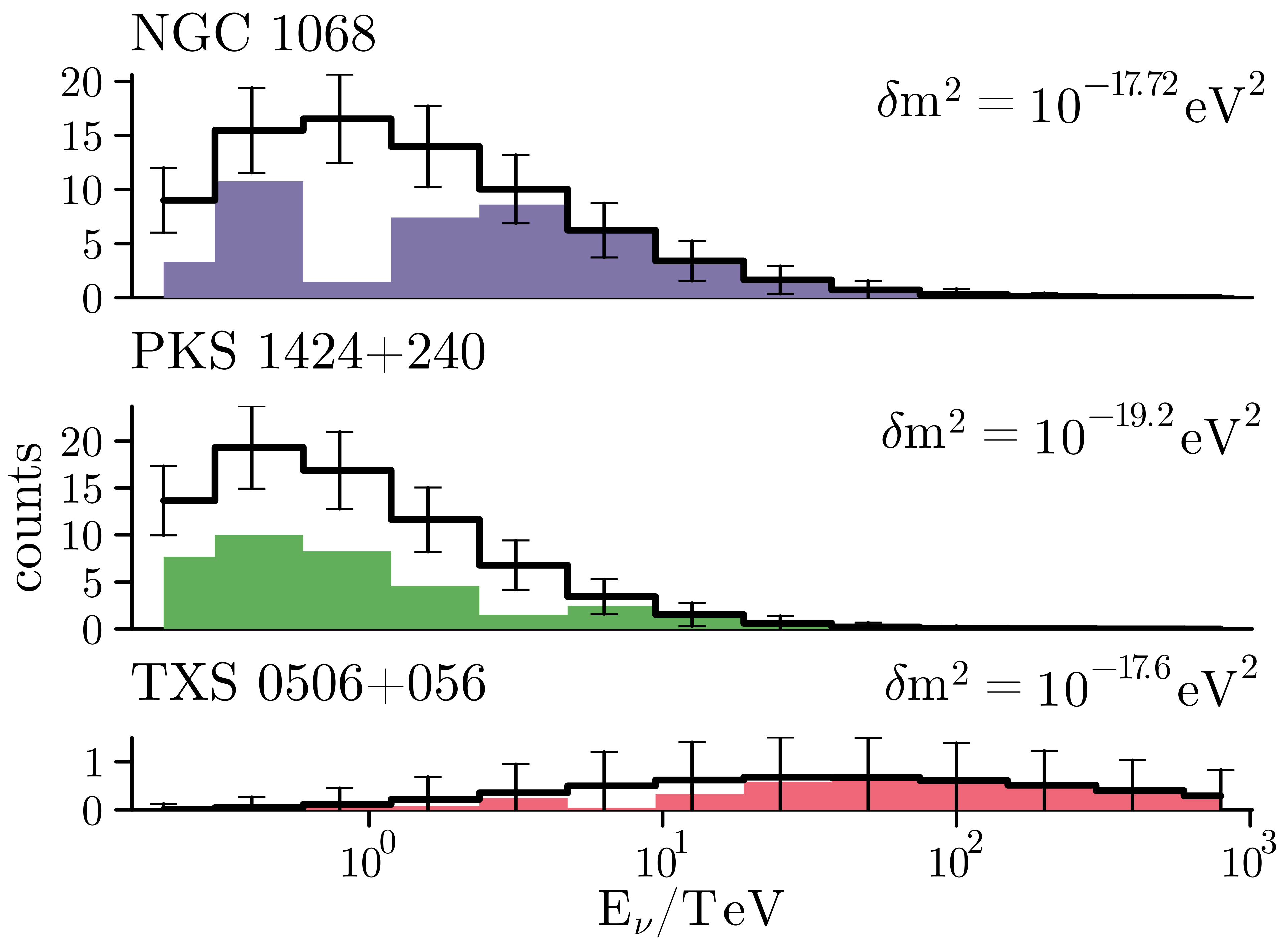

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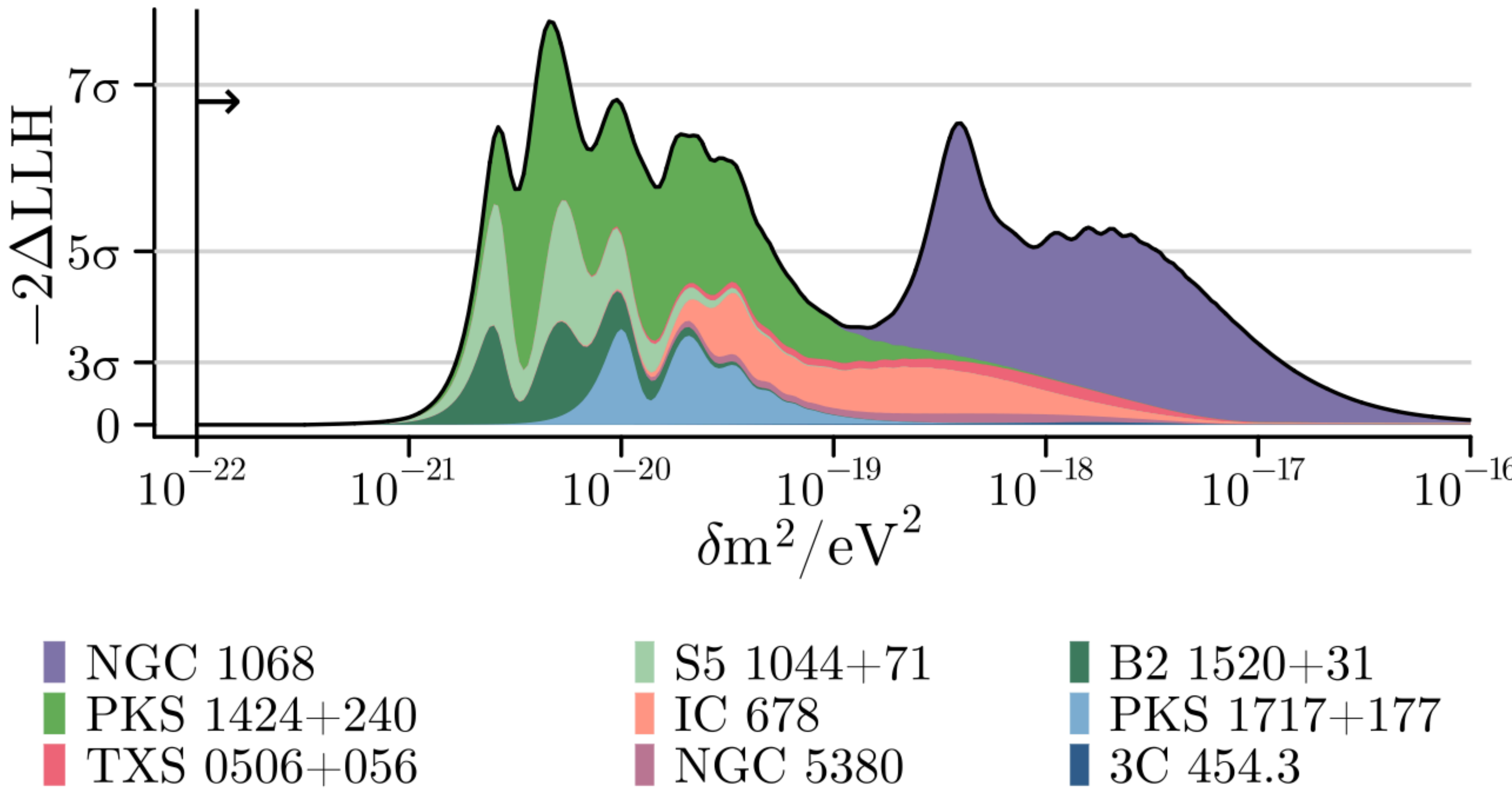


Carloni, IMS, Arguelles, Babu, Bhupal, PRD 109 (2024) L051702

Conclusions

The 3ν mixing provide a consistent description of the results

- For θ_{23}, the precision is $20\,\%$ at 3σ with a small preference for **lower octant** (higher octant) combining IC24+SK+global fit (global)

- For δ_{cp}, almost the **entire region is allowed** to 3σ, with a preference close to CP-conservation for NO and maximal CP-violation for IO.

- For the **mass ordering**, there is almost no preference for ordering until the combination with IC24 and SK, which shows a preference for NO.

- **No indication** of the neutrio mass scale

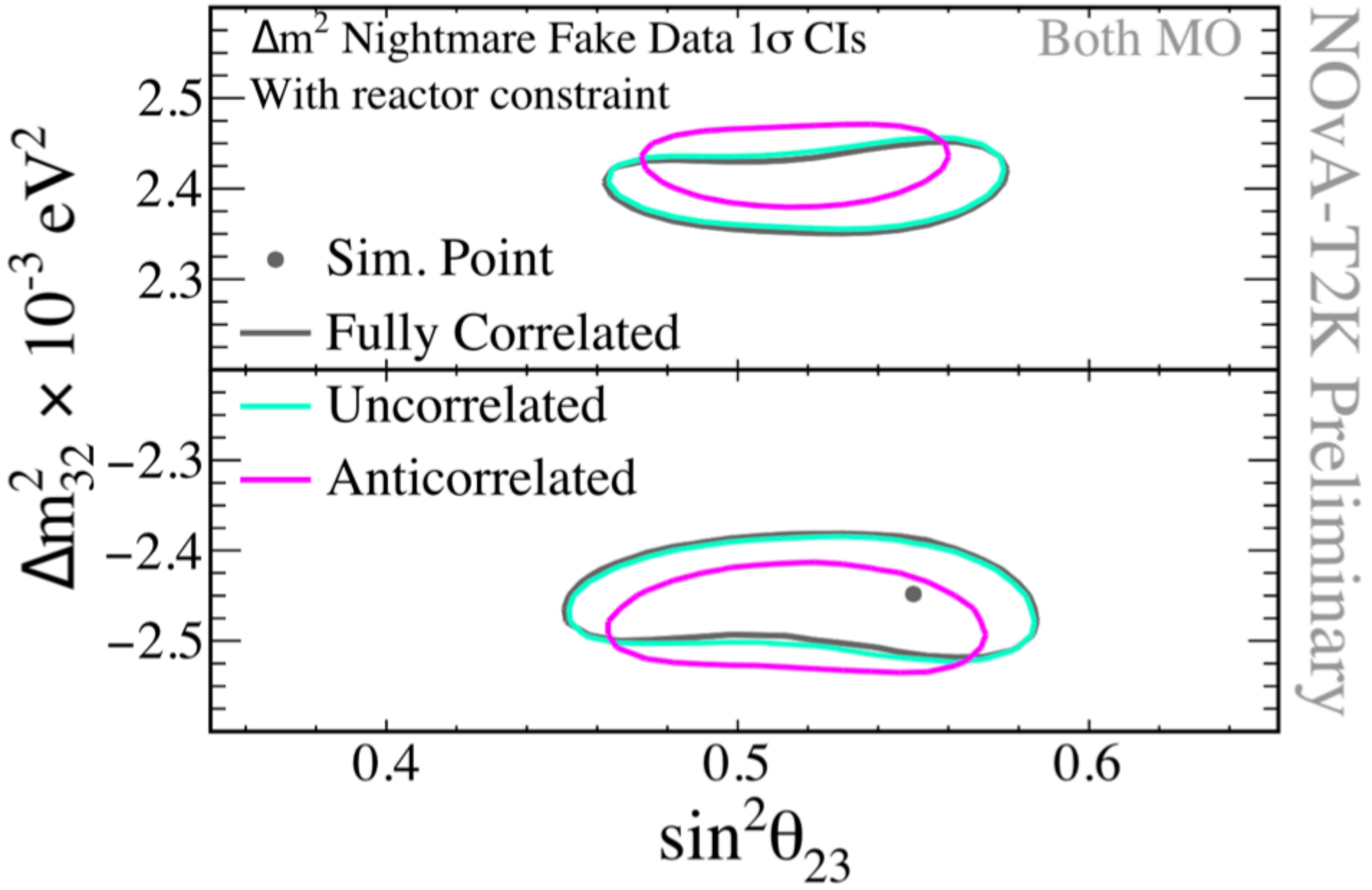
Even after achieving precise measurements of the neutrino oscillation parameters, **fundamental questions** will remain, such as the origin of the neutrino masses

- In this context, the study of neutrinos from **astrophysical sources** may provide important insights into the underlying mechanism.

Gracias!

NOvA-T2K joint fit

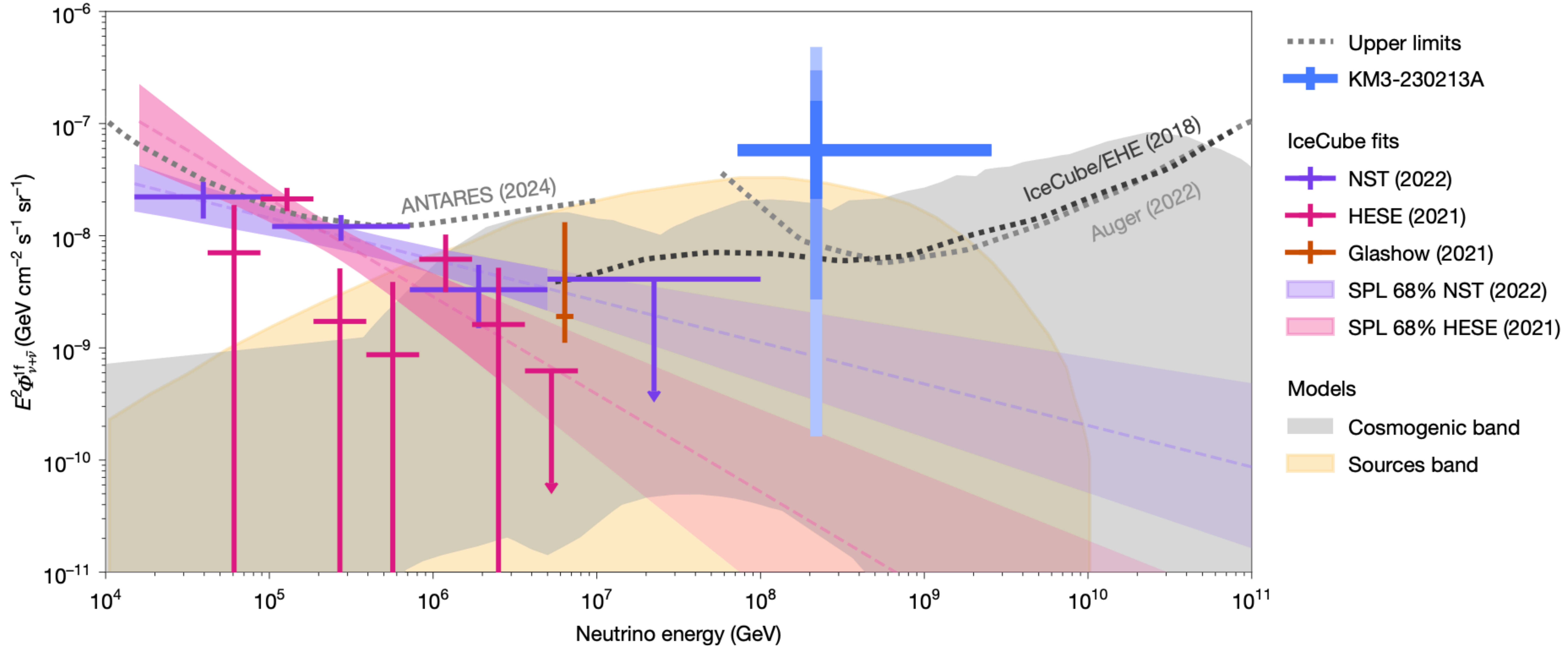
- **Several cross-section models** were explored, along with their impact on **potential correlations**
- The **uncorrelated and correlated** models **agree** with negligible differences.



Zoya Vallari (Joint Experimental-Theoretical Physics Seminar, Fermilab, 2024)

New Astrophysical Sources

At high energies, neutrino telescopes have revealed new neutrino sources



KM3NeT, Nature 638 (2025)