Fermilab

October 14th, 2026

Recent News on Neutrino Oscillations

Pedro Machado

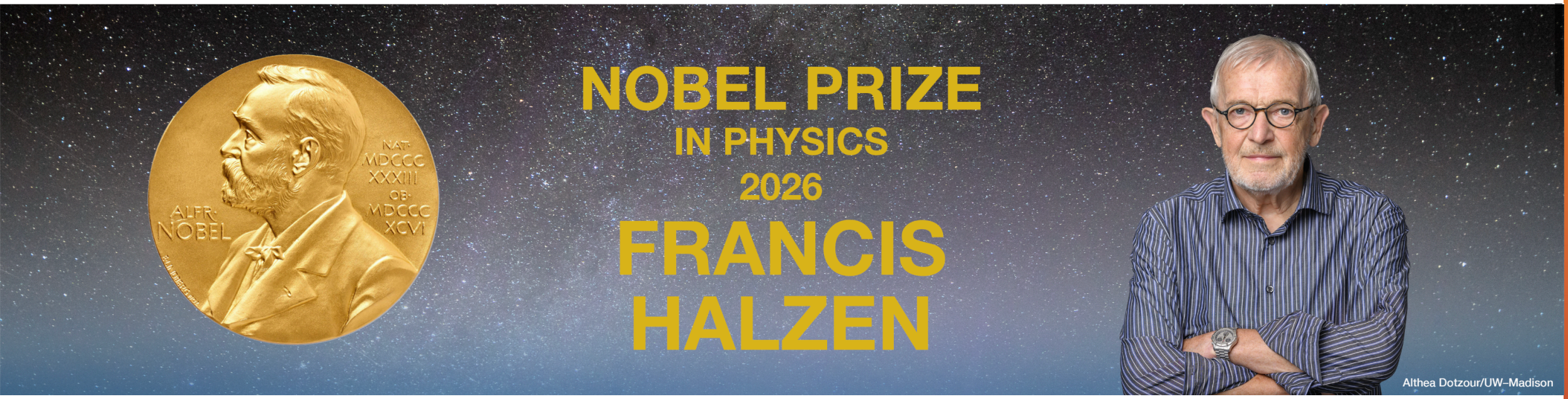
U.S. DEPARTMENT of ENERGY

Fermi National Accelerator Laboratory is managed by FermiForward for the U.S. Department of Energy Office of Science

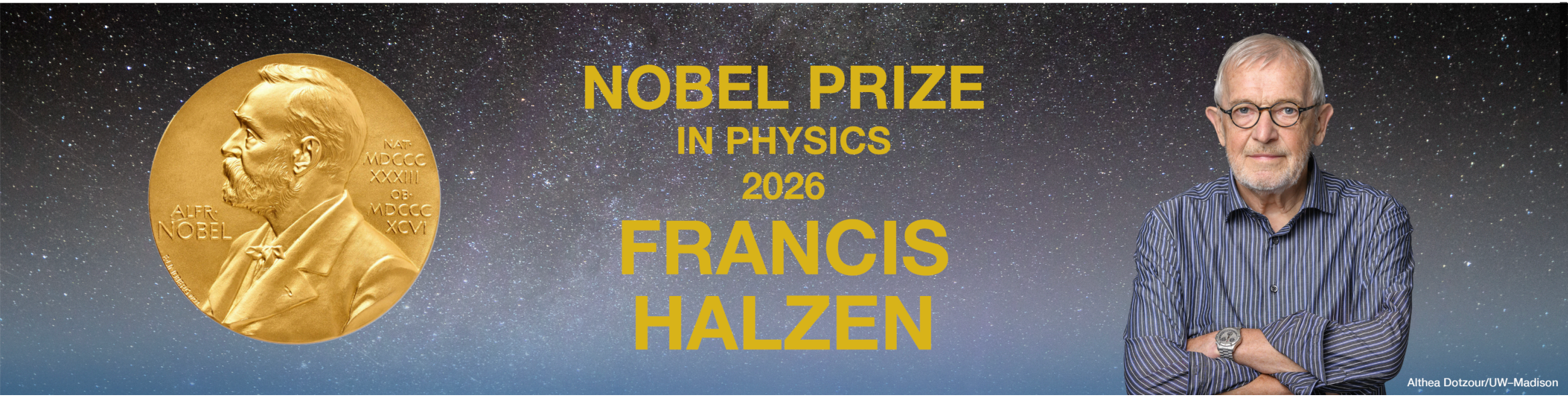
FERMI NATIONAL ACCELERATOR LABORATORY

Why neutrinos?

Why neutrinos?



Why neutrinos?





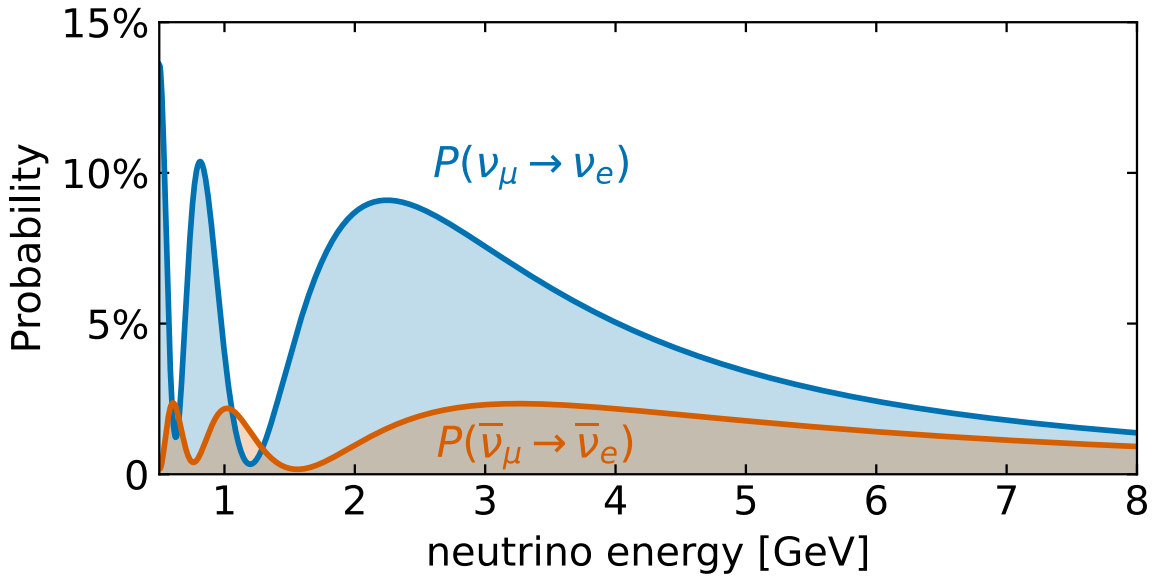


We should start a petition with the City of Madison to fix this misspelling!

Why neutrinos?

- The universe is made of matter, not antimatter
- Generating this asymmetry in the early universe requires matter and antimatter to behave differently
- This is called **Charge Parity** violation
- **CP** violation in the neutrino sector can be 1000 times larger than CP violation in the quark sector





*This does not mean we will be able to answer *"Where did everything come from?"*
This is a much *much* ***much*** harder question!

Why neutrinos?

Higgs mechanism: unique prediction for charged fermions, confirmed by data for *b*, *t*, *τ*, maybe *μ*

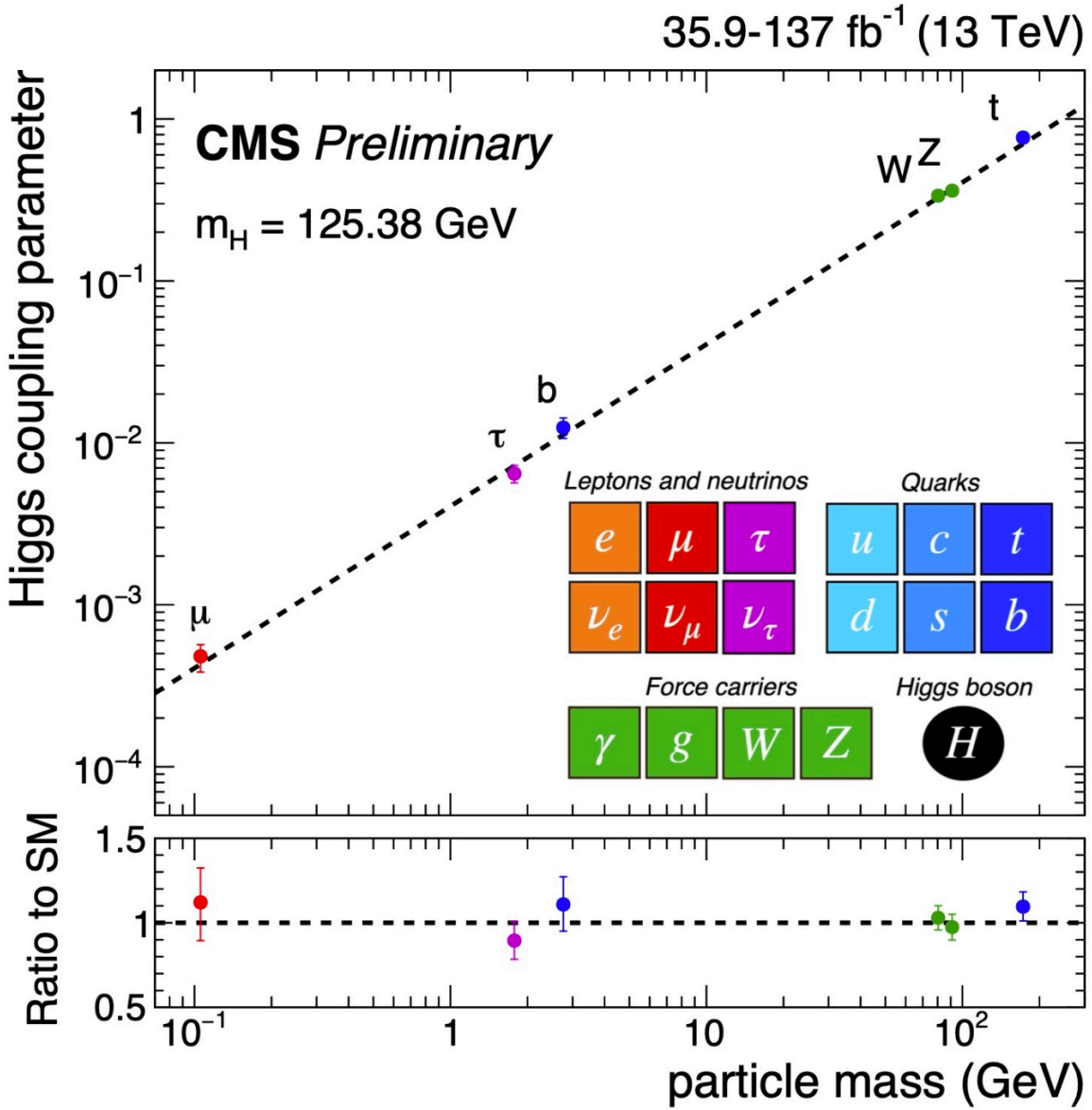
But for neutrinos, **it breaks**

1) New **unobserved** particles required

2) Additional freedom

Neutrinos are the only particle in the standard model that do not follow the vanilla Higgs mechanism

m_ν: only lab-based evidence of BSM

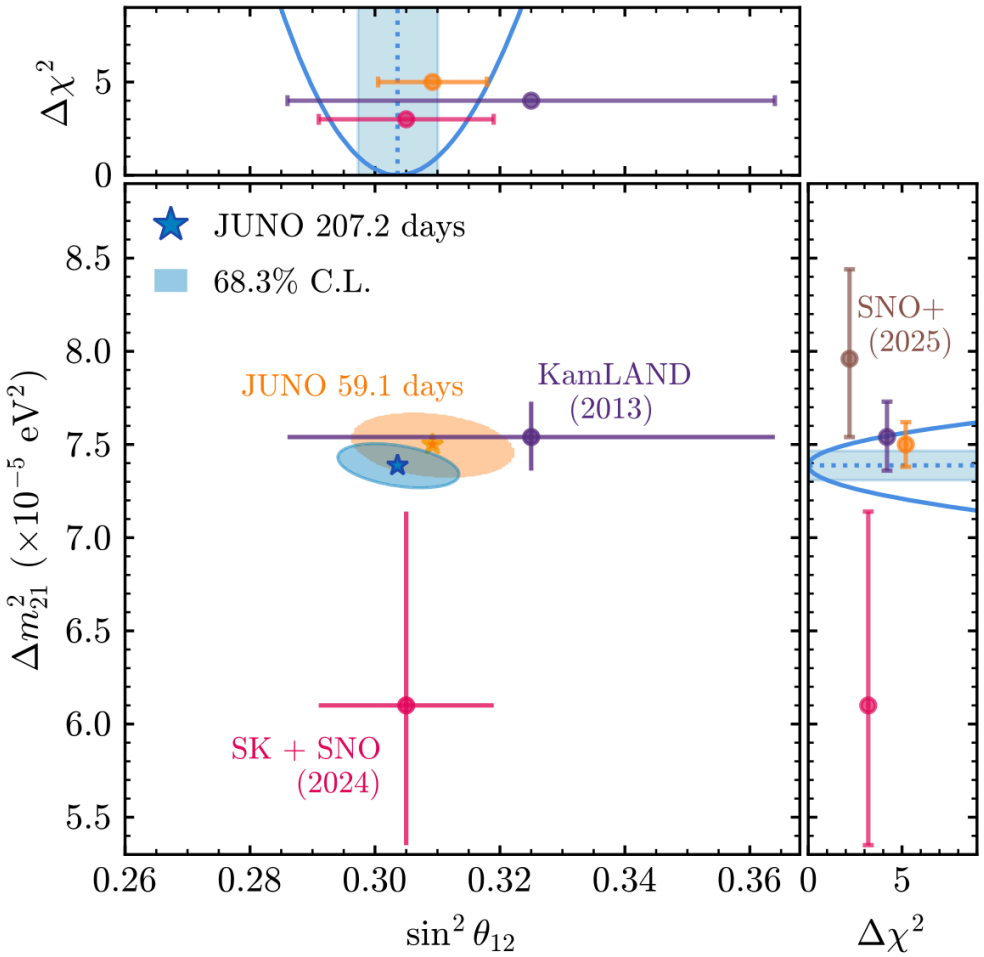


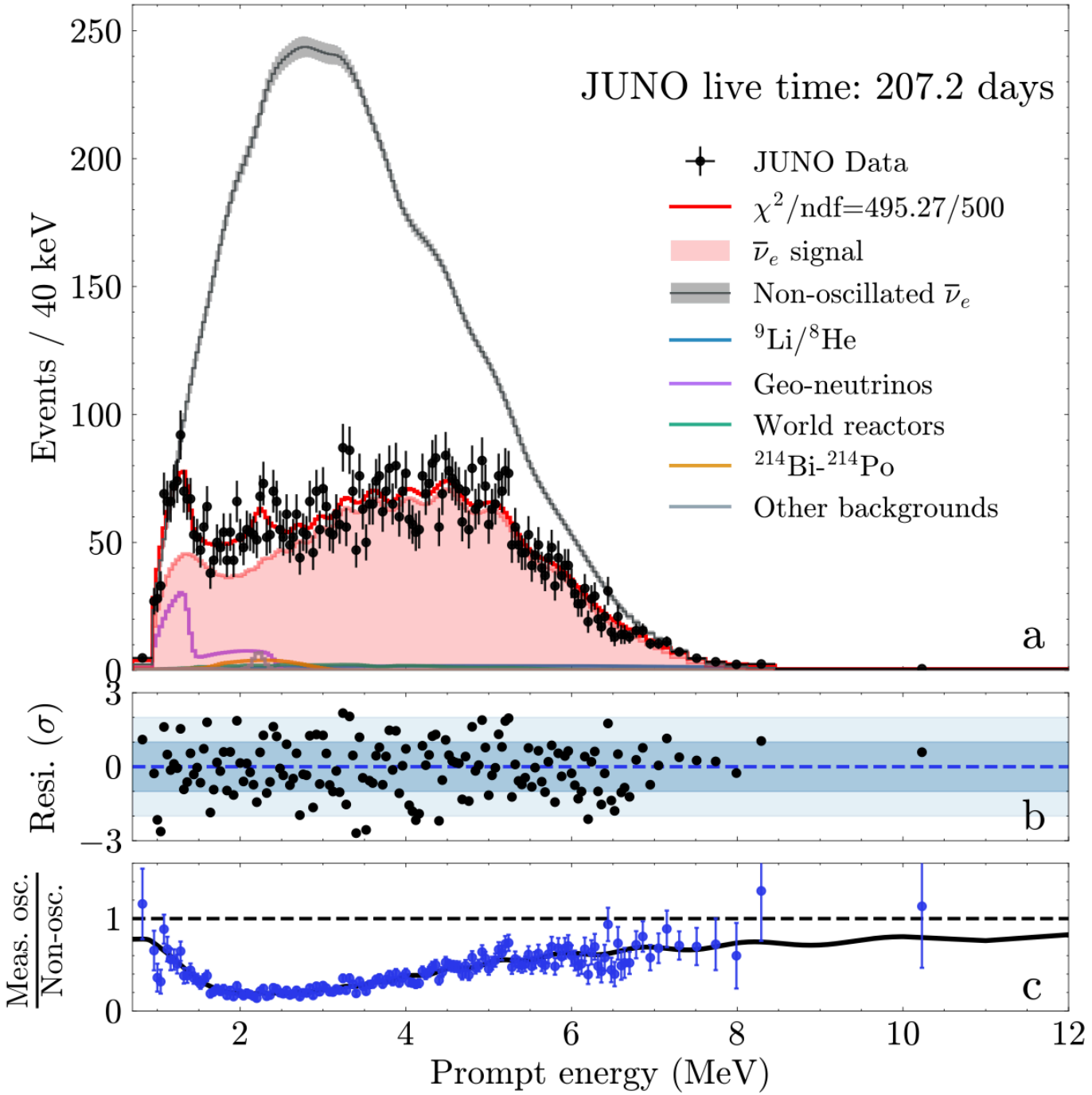
Precision on neutrino oscillation parameters

JUNO

20 kton, 207 days

Detection via IBD





JUNO 2609.37895

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JUNO

20 kton, 207 days

Detection via IBD

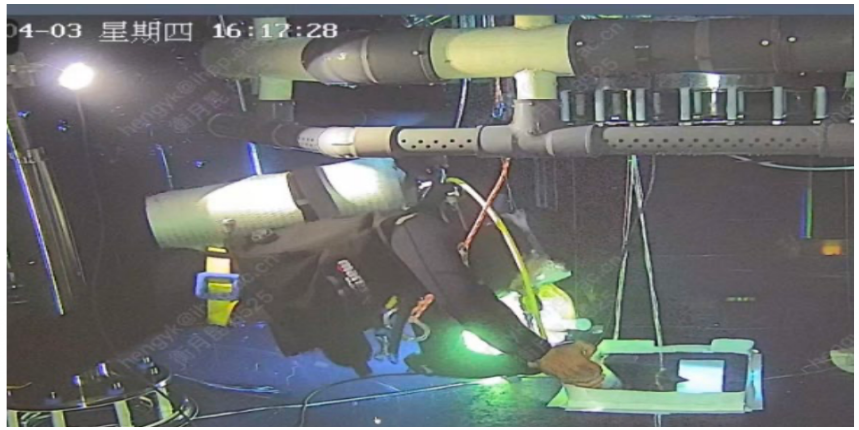
Energy resolution for ^{68}Ge is ~3.5% @ 2× 0.511 MeV at the center, slightly worse than the expected 3.1%

Fitting constrained by the near detector spectra from TAO (talk by Yichen) **and Daya Bay** (PRL 130 16, 161802)

The energy resolution is critical for the determination of the mass ordering

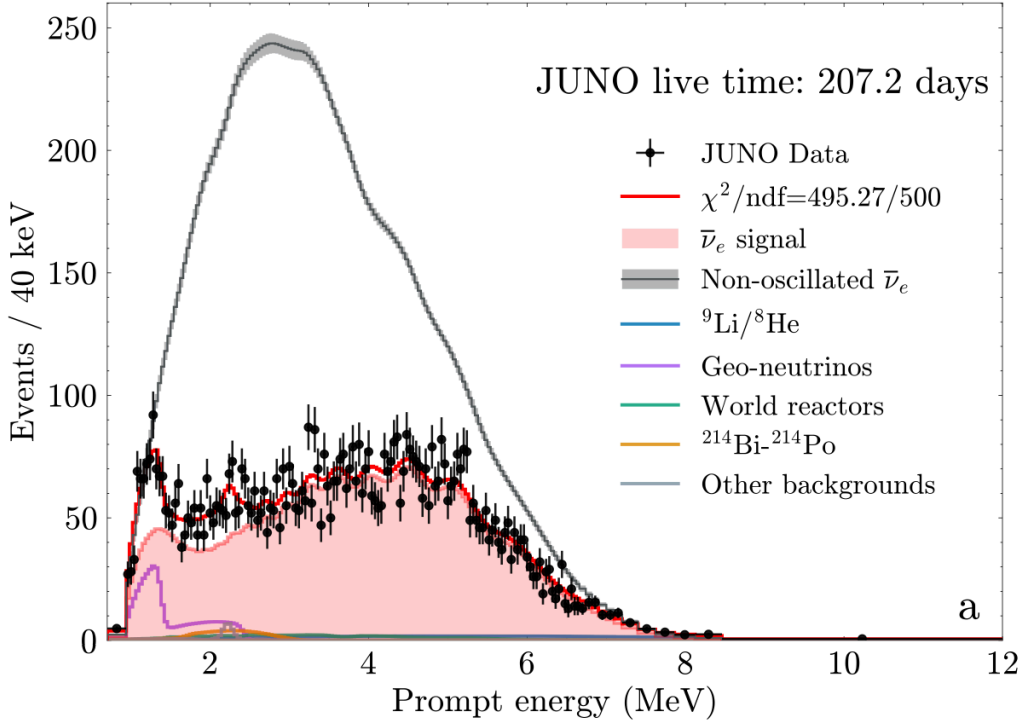
And some cracks here and there… all fixed!







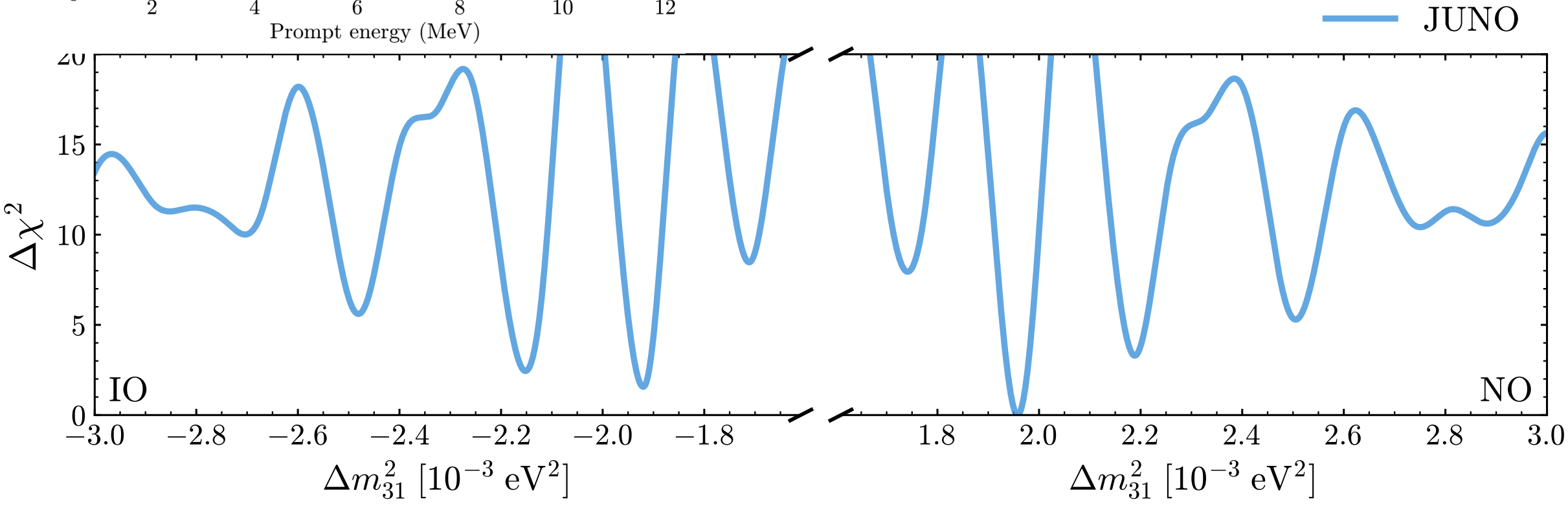
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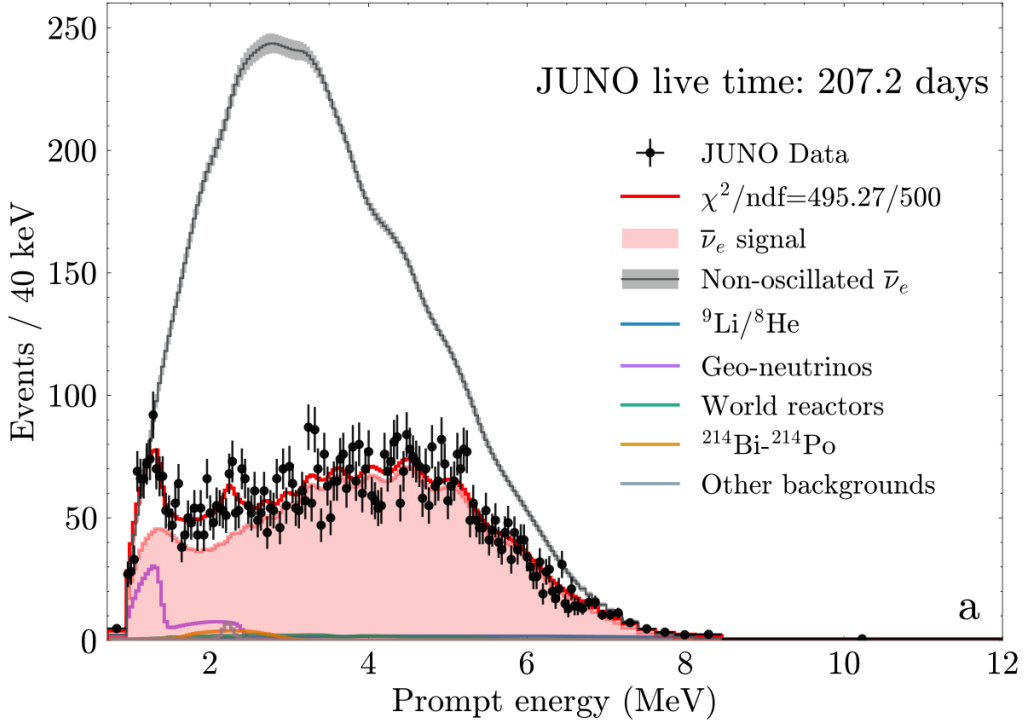


There is a lot of degeneracy on the JUNO measurement of the atmospheric mass splitting

Is the first observed atmospheric wiggle the 10th? The 12th?

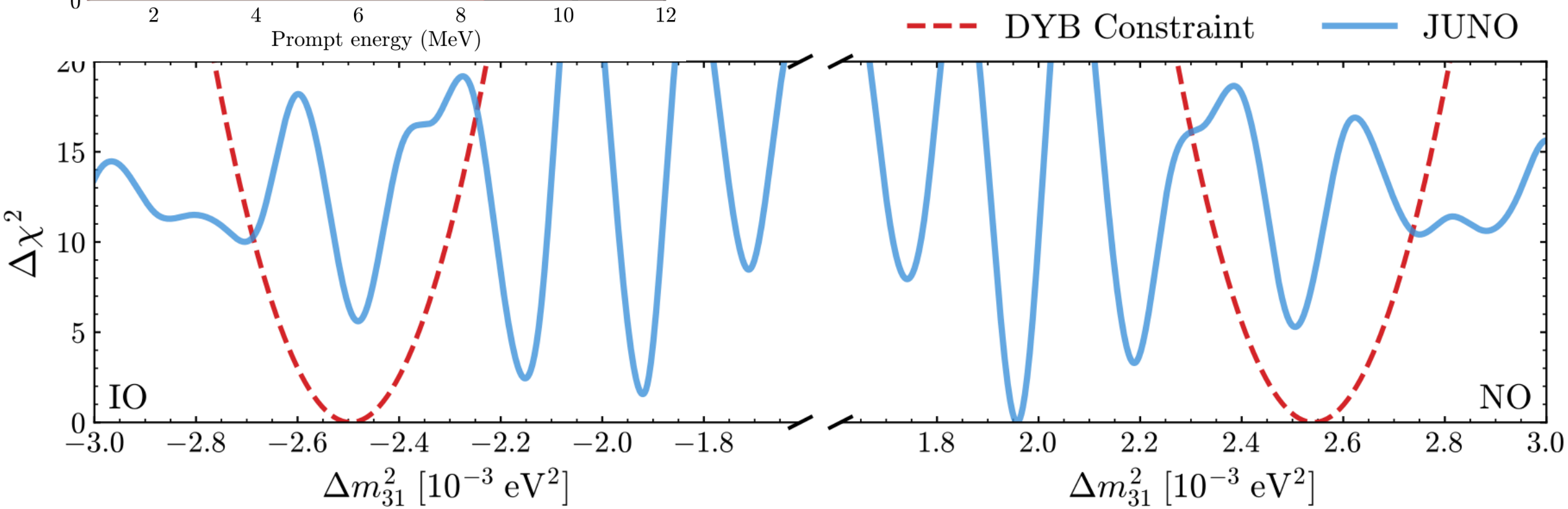
adapted from JUNO 2609.37895



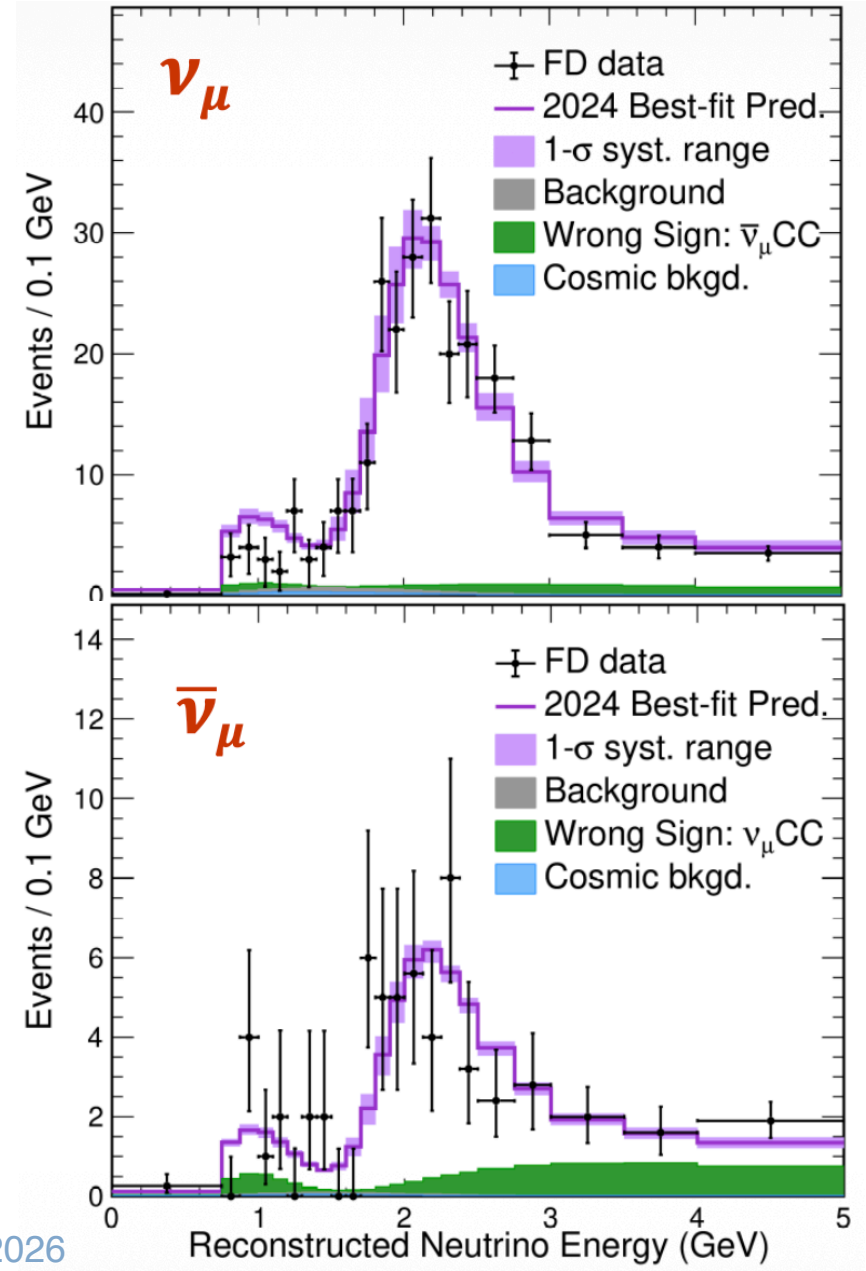


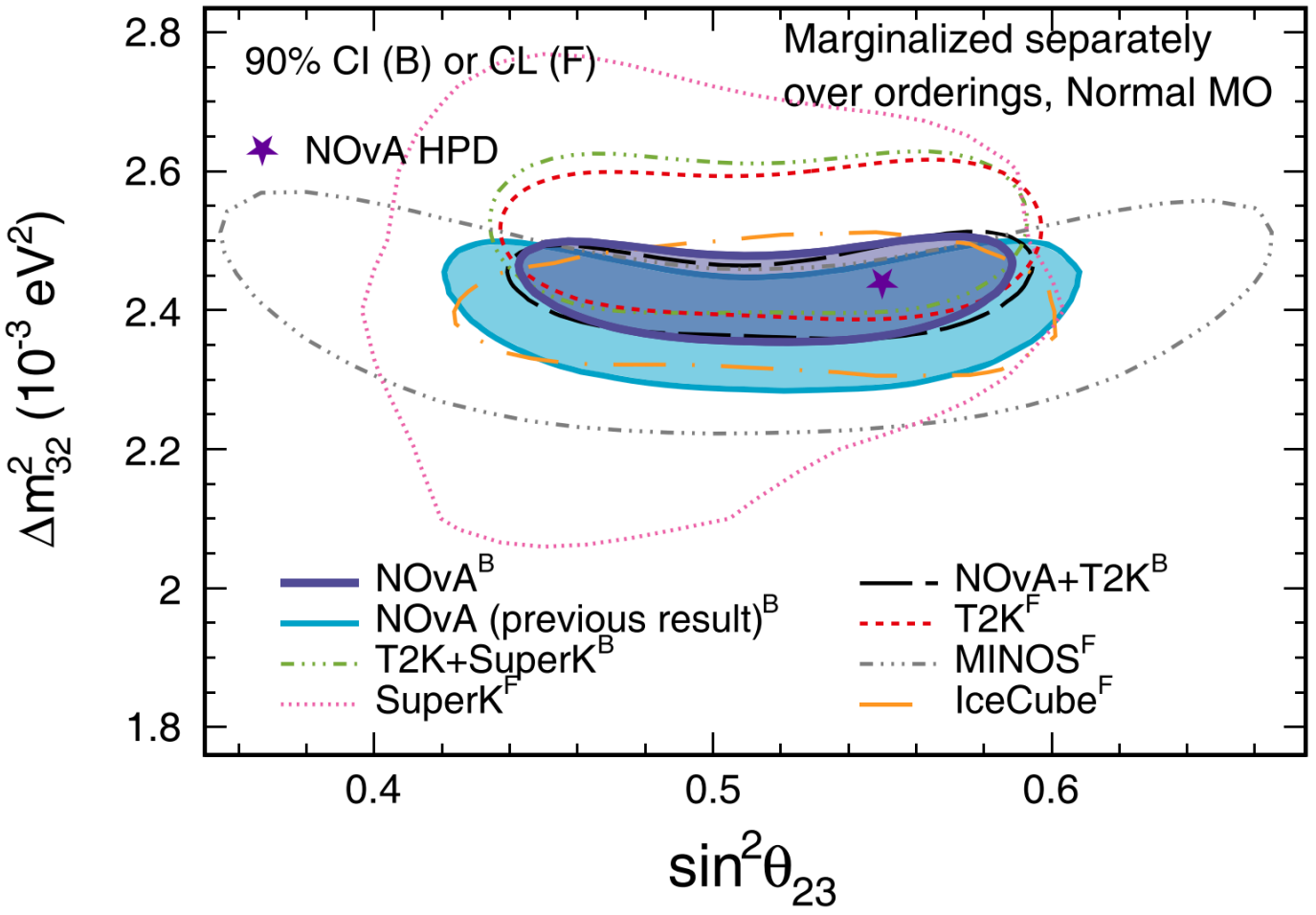
$$\Delta m^2_{31} = -2.482^{+0.025}_{-0.026} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO}),$$
$$\Delta m^2_{31} = +2.509^{+0.027}_{-0.025} \times 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}).$$

JUNO 2609.37895



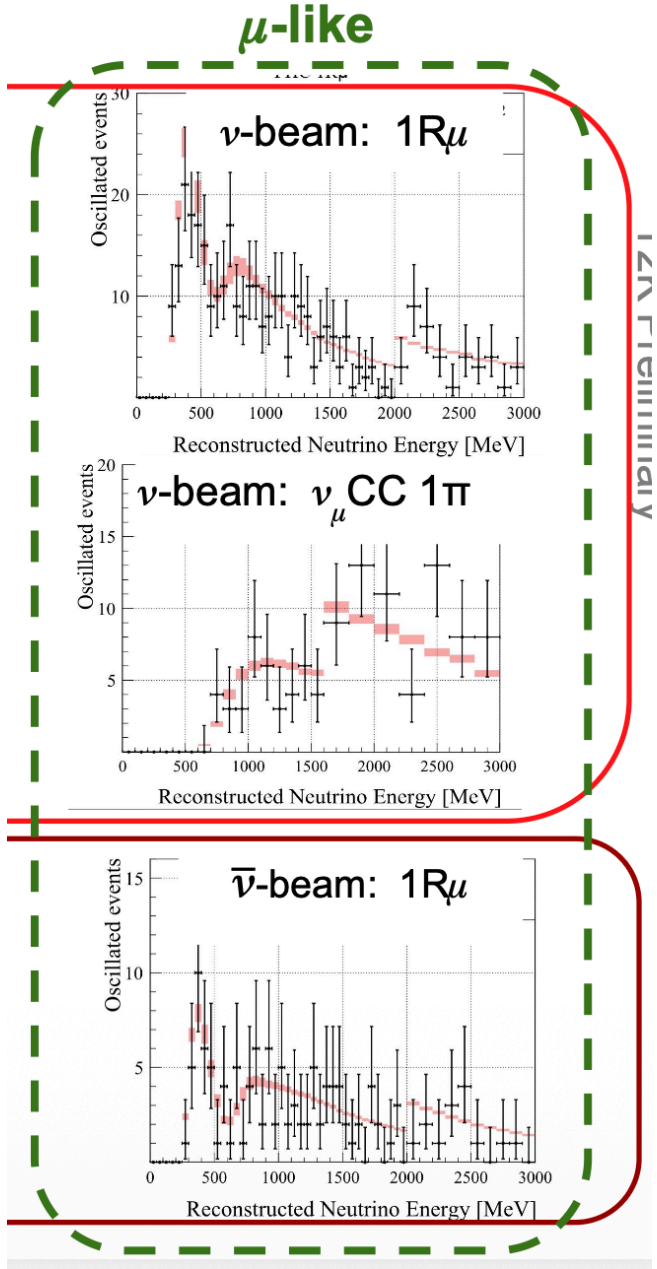
NOvA disappearance: Δm^2_{32} and θ_{23}

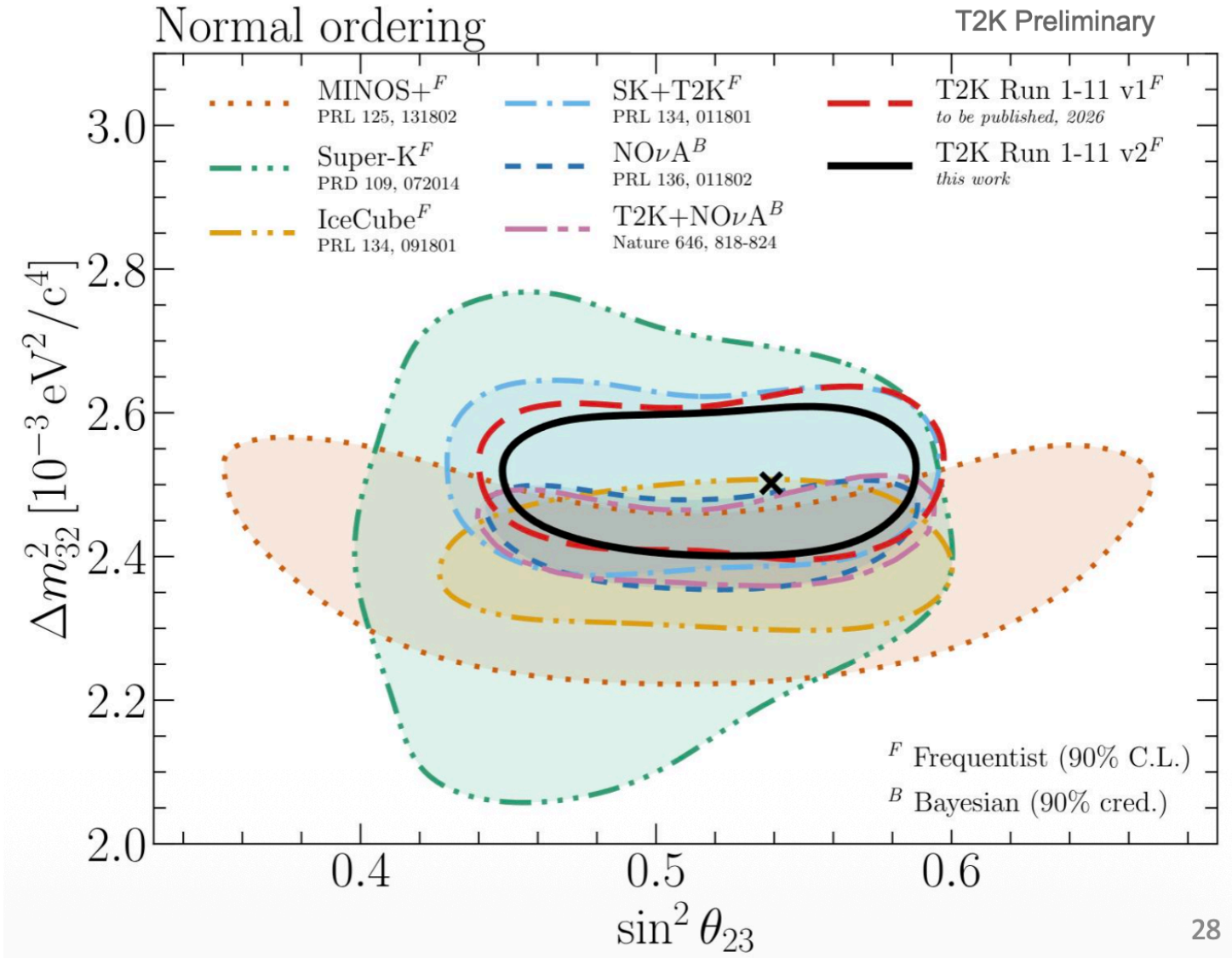




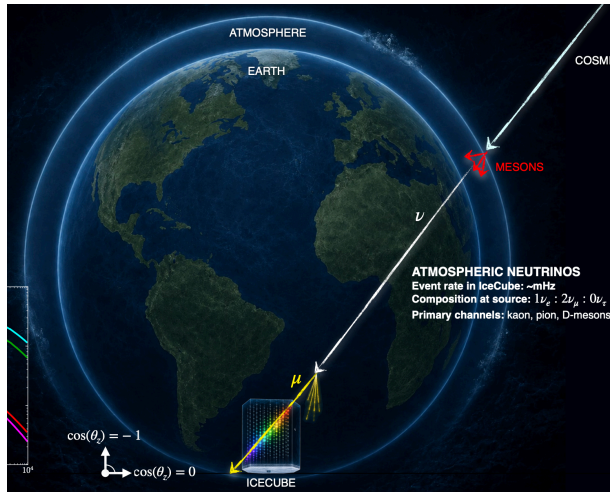
NOvA PRL 2026

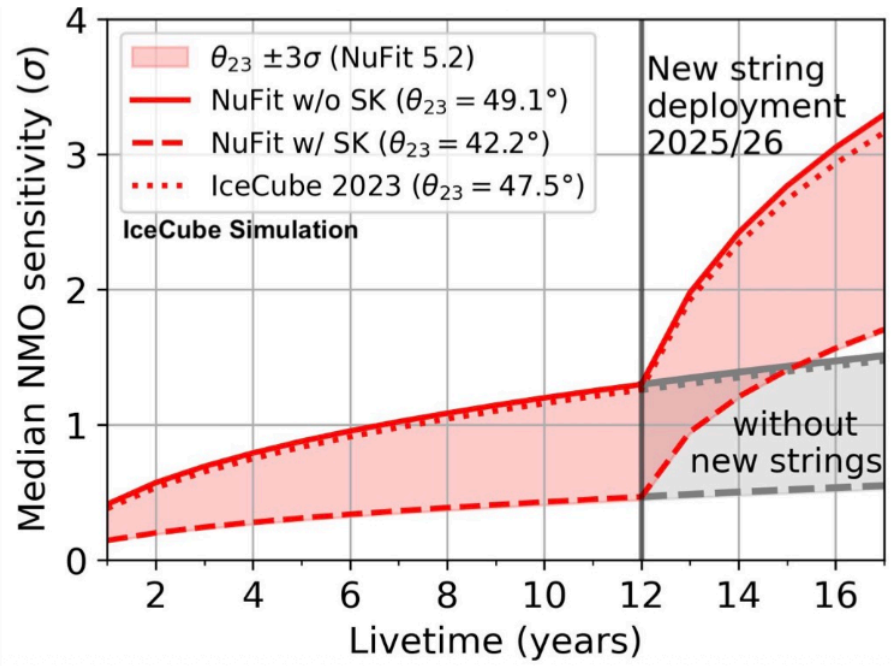
T2K disappearance: Δm^2_{32} and θ_{23}



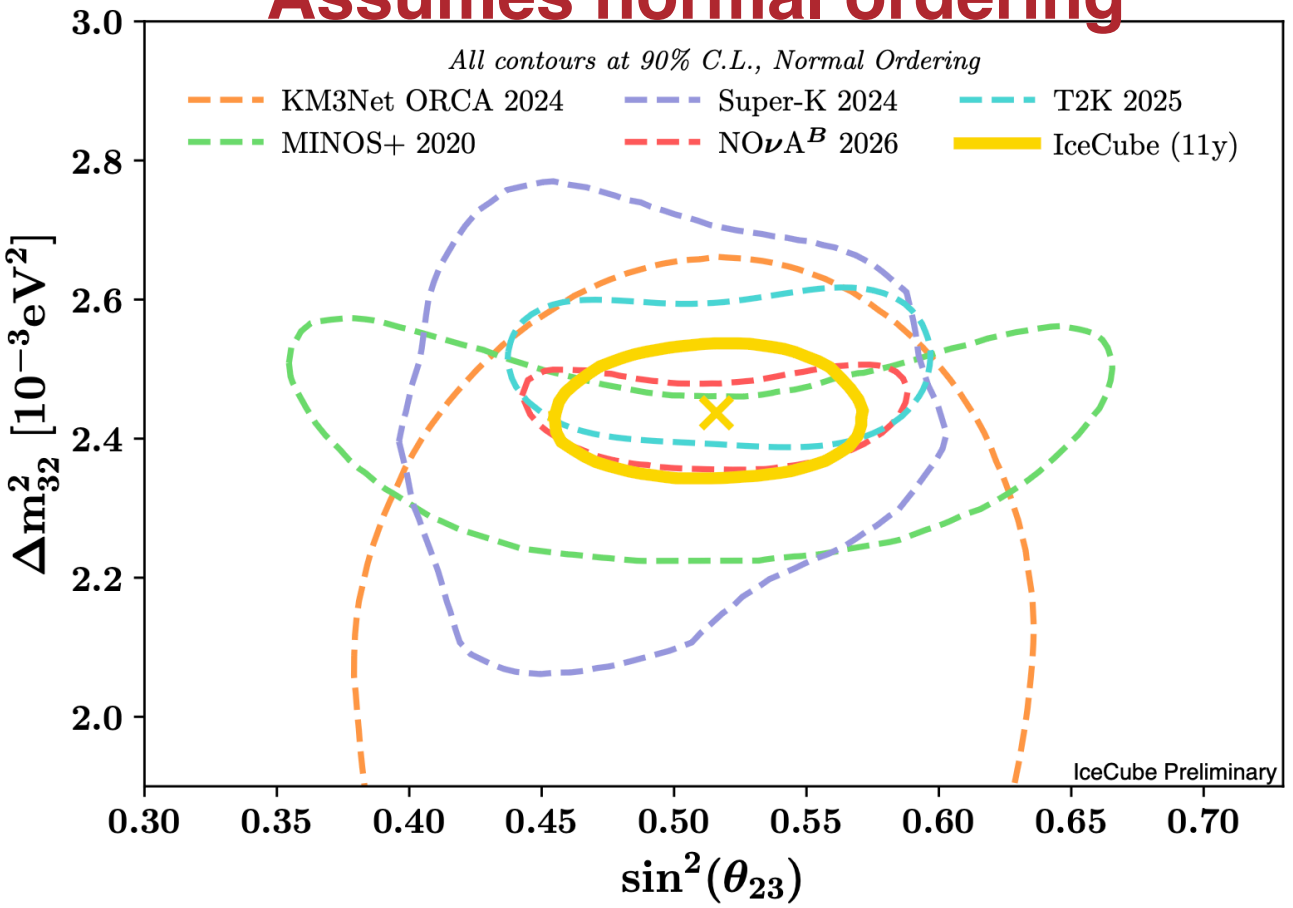


IceCube - DeepCore





***Assumes normal ordering**



Best Fit:

$$\Delta m^2_{32} = 2.437^{+0.043}_{-0.048} \times 10^{-3}\,\text{eV}^2$$
$$\sin^2(\theta_{23}) = 0.516^{+0.024}_{-0.035}$$

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Mass ordering

Mass ordering

There are 3 (or 4) main ways to measure the mass ordering

The JUNO way

Measure precisely the phase on the oscillation frequency after several oscillations (NO and IO lead to distinguishable shifts)

The matter effect way

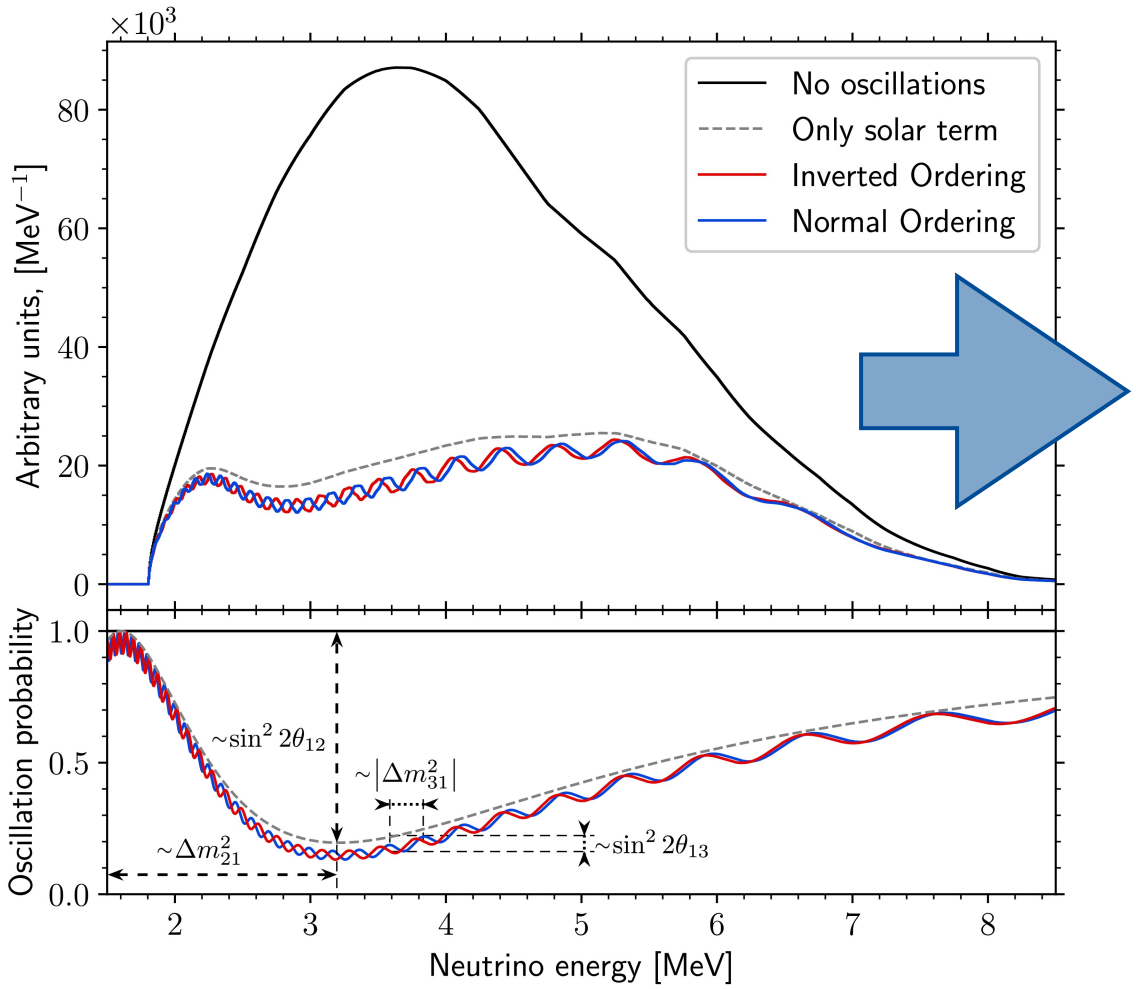
Compare $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ after long propagations

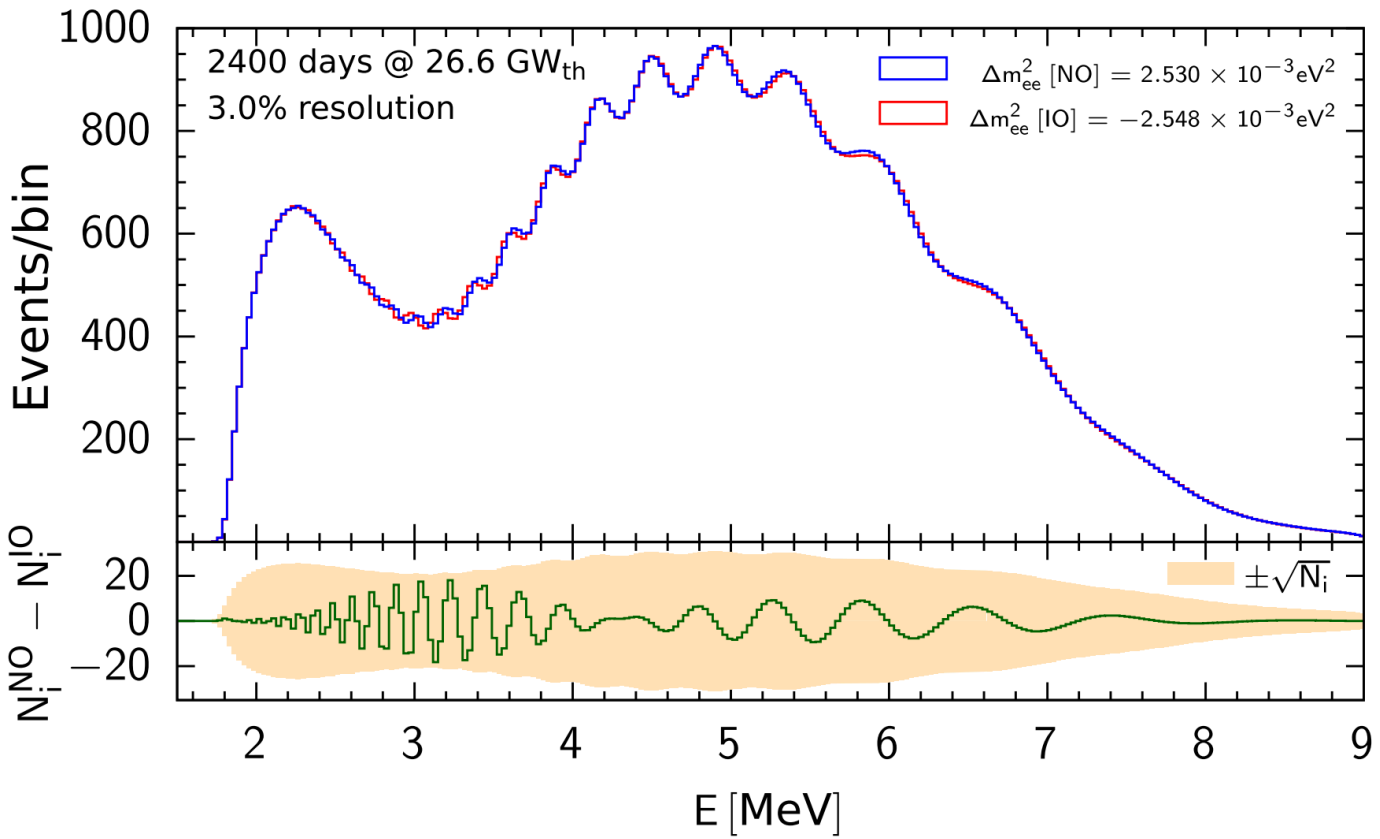
(IceCube, KM3NeT, SuperK, HK; DUNE, NOvA)

The reactor+accelerator way

Compare the mass splitting measured with reactor neutrinos versus accelerator neutrinos (JUNO+Daya Bay+T2K+NOvA)

Mass ordering





Forero et al. 2021

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Mass ordering

Reactor and accelerator neutrinos combined can get the mass ordering

Measure the frequency at reactors

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

Measure the frequency at accelerator

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

Compare them to get the mass ordering

$$|\Delta m^2_{ee}| = |\Delta m^2_{\mu\mu}| \pm \cos 2\theta_{12}\Delta m^2_{21}$$

Nunokawa Parke Zukanovich-Funchal 2005, Parke Zukanovich-Funchal 2024

Mass ordering

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Measure the frequency at reactors

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Daya Bay, JUNO

Measure the frequency at accelerator

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

T2K, NOvA

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Nunokawa Parke Zukanovich-Funchal 2005, Parke Zukanovich-Funchal 2024

Mass ordering

Current measurements of the atmospheric mass splitting:

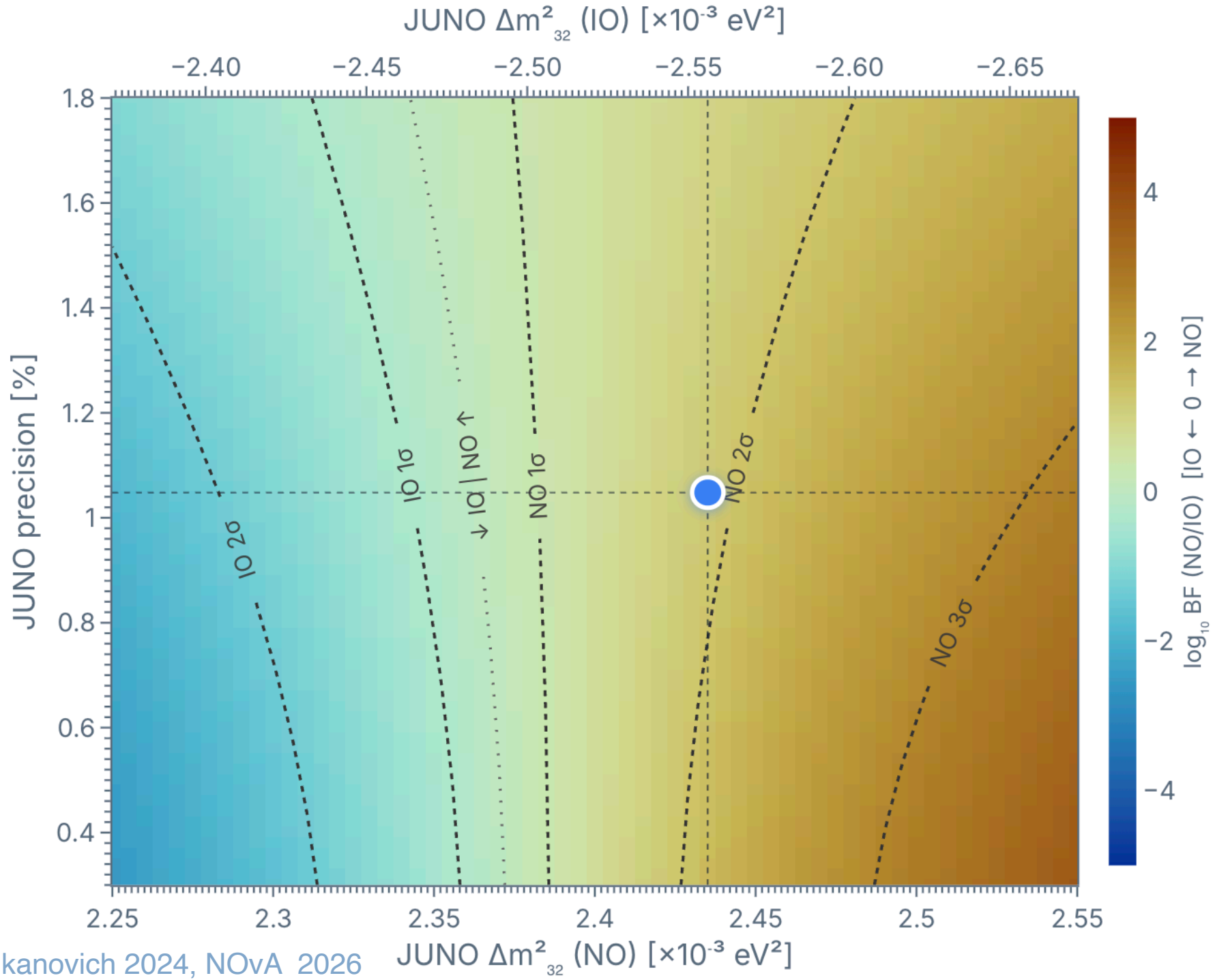
R Reactors	JUNO 2609.37895	$\Delta m^2_{31} = 2.509^{+0.027}_{-0.025}$ eV^2	$\Delta m^2_{31} = -2.482^{+0.025}_{-0.026}$ eV^2
	Daya Bay 2211.14988	$\Delta m^2_{32} = 2.466^{+0.060}_{-0.060}$ eV^2	$\Delta m^2_{32} = -2.571^{+0.060}_{-0.060}$ eV^2
A Accelerators	NOvA 2606.14121	$\Delta m^2_{32} = 2.431^{+0.036}_{-0.034}$ eV^2	$\Delta m^2_{32} = -2.479^{+0.036}_{-0.036}$ eV^2
	T2K 2506.05889	$\Delta m^2_{32} = 2.506^{+0.039}_{-0.052}$ eV^2	not quoted

**of course, each experiment quotes a different convention…*

Mass ordering

NOvA recently evaluated that for NOvA+DB+JUNO

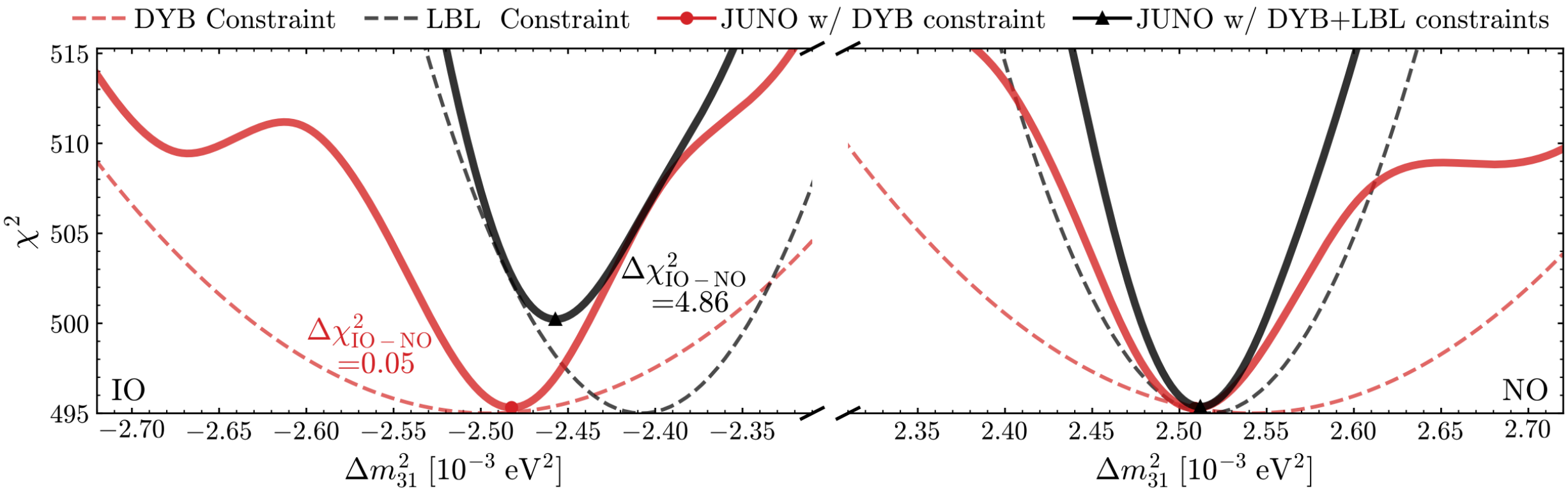
https://nova-nusoft.fnal.gov/



Parke Zukanovich 2024, NOvA 2026

Mass ordering

JUNO combined their measurement with Daya Bay and the (NuFit) global fit long baseline, obtaining 2.1σ preference for normal ordering



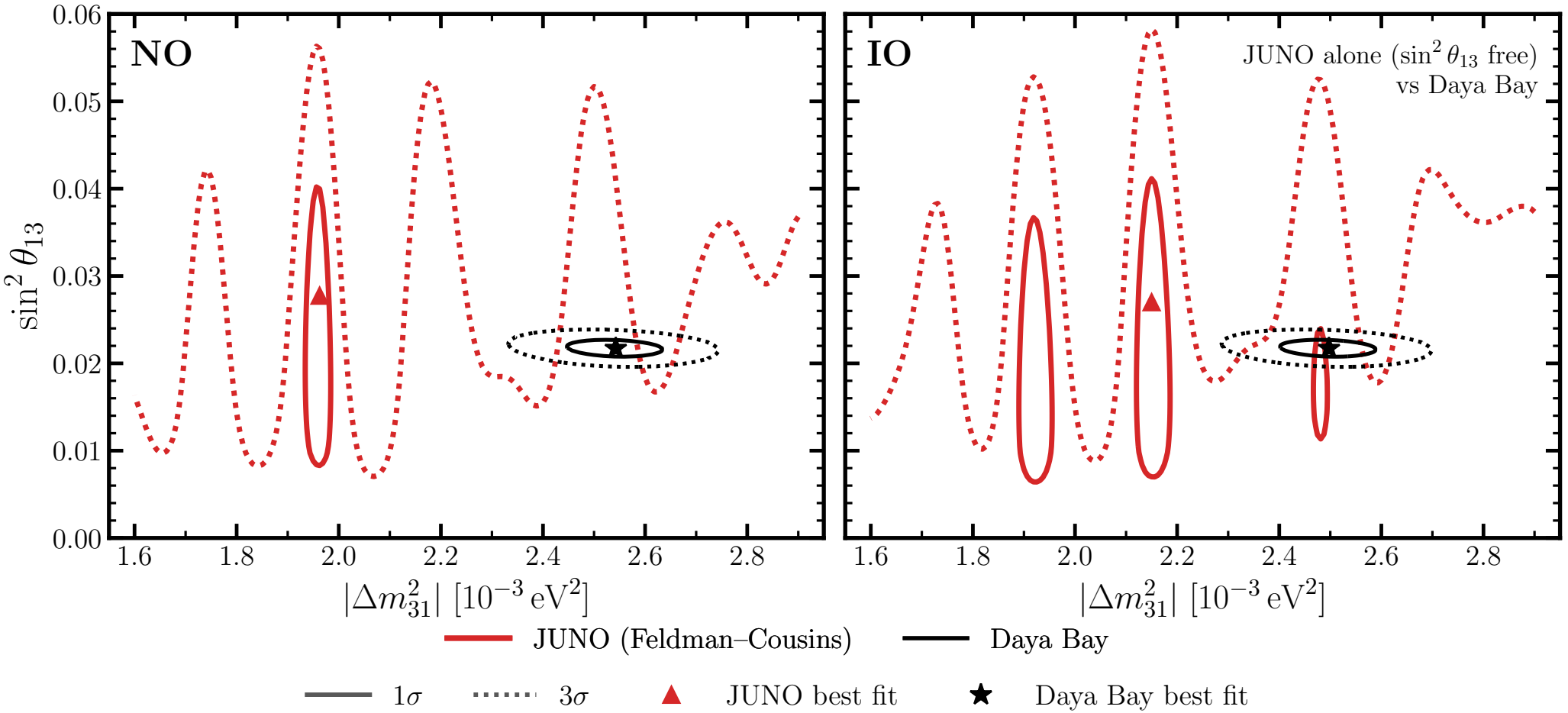
Mass ordering

Where does that 2.1σ come from exactly?

Work in progress with João P. Pinheiro

Mass ordering

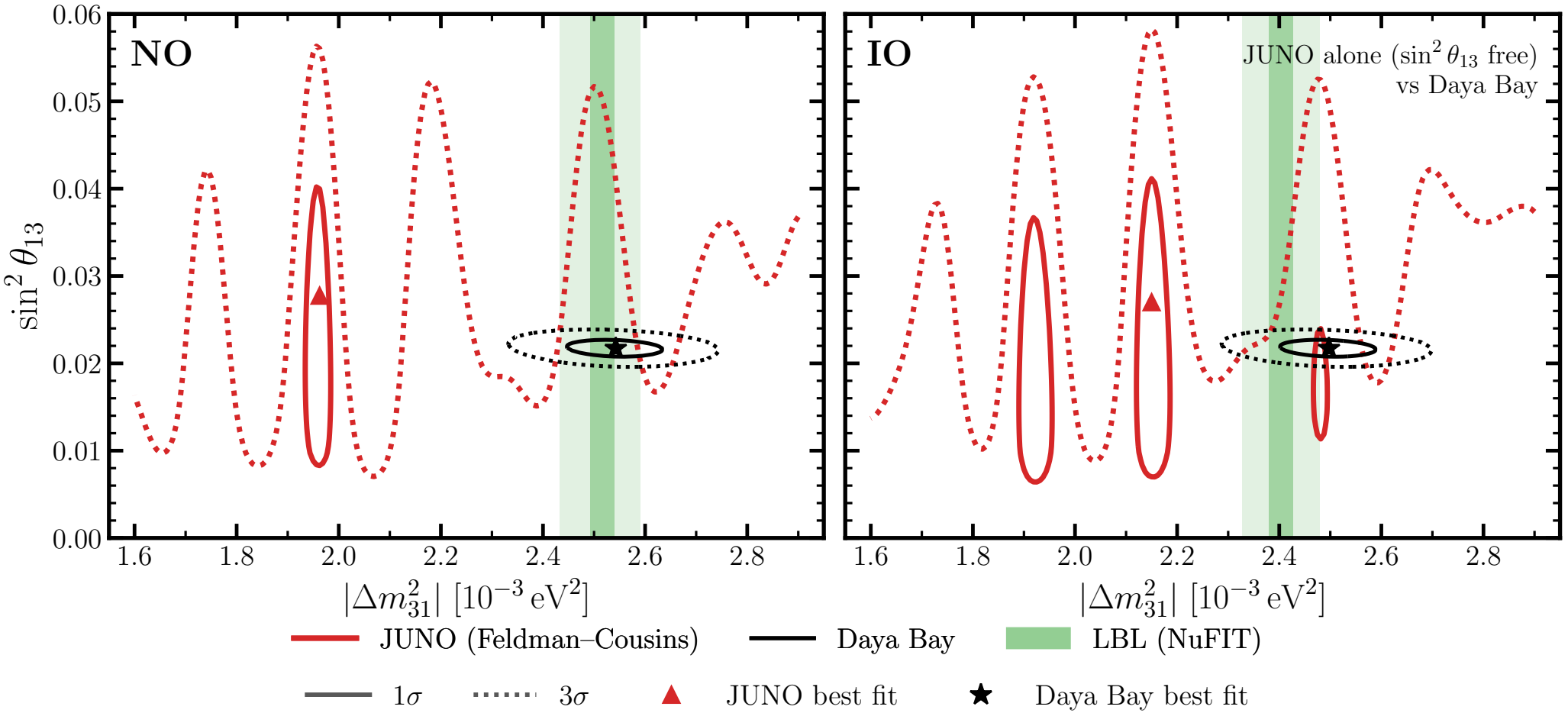
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Mass ordering

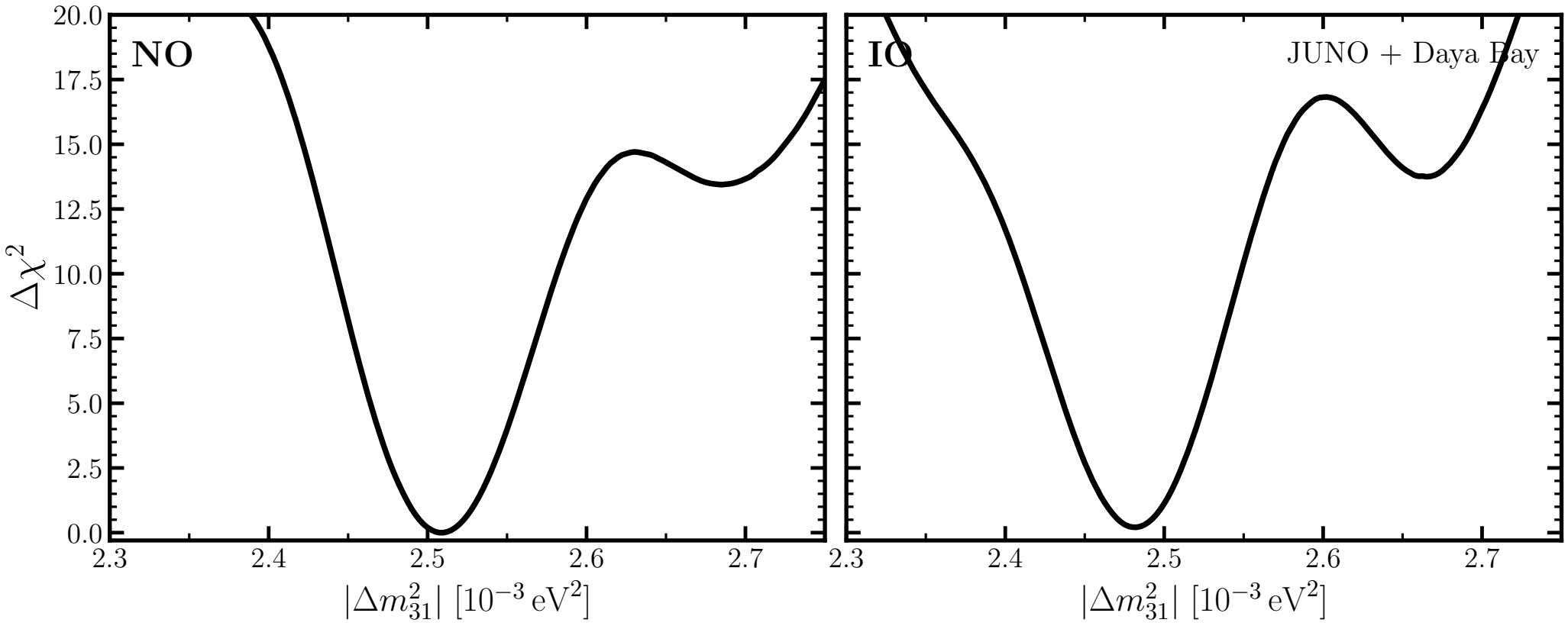
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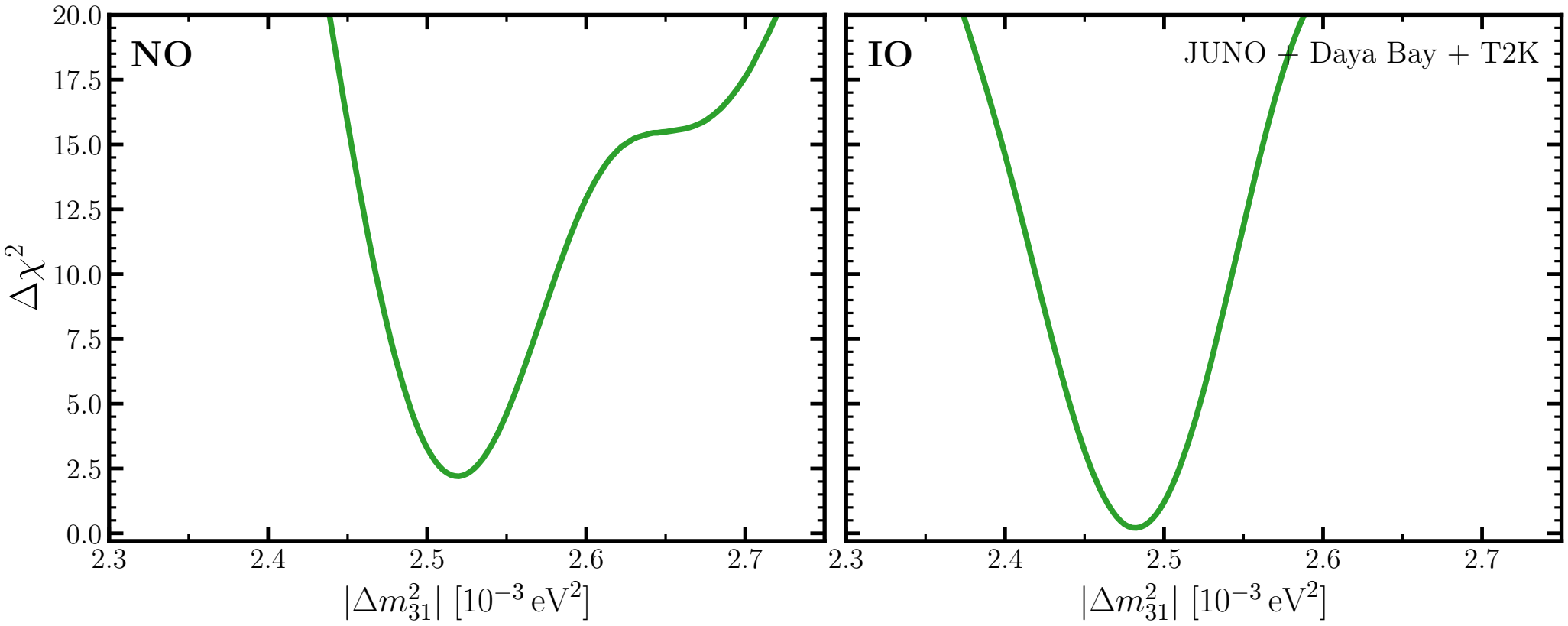


Work in progress with João P. Pinheiro

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Mass ordering

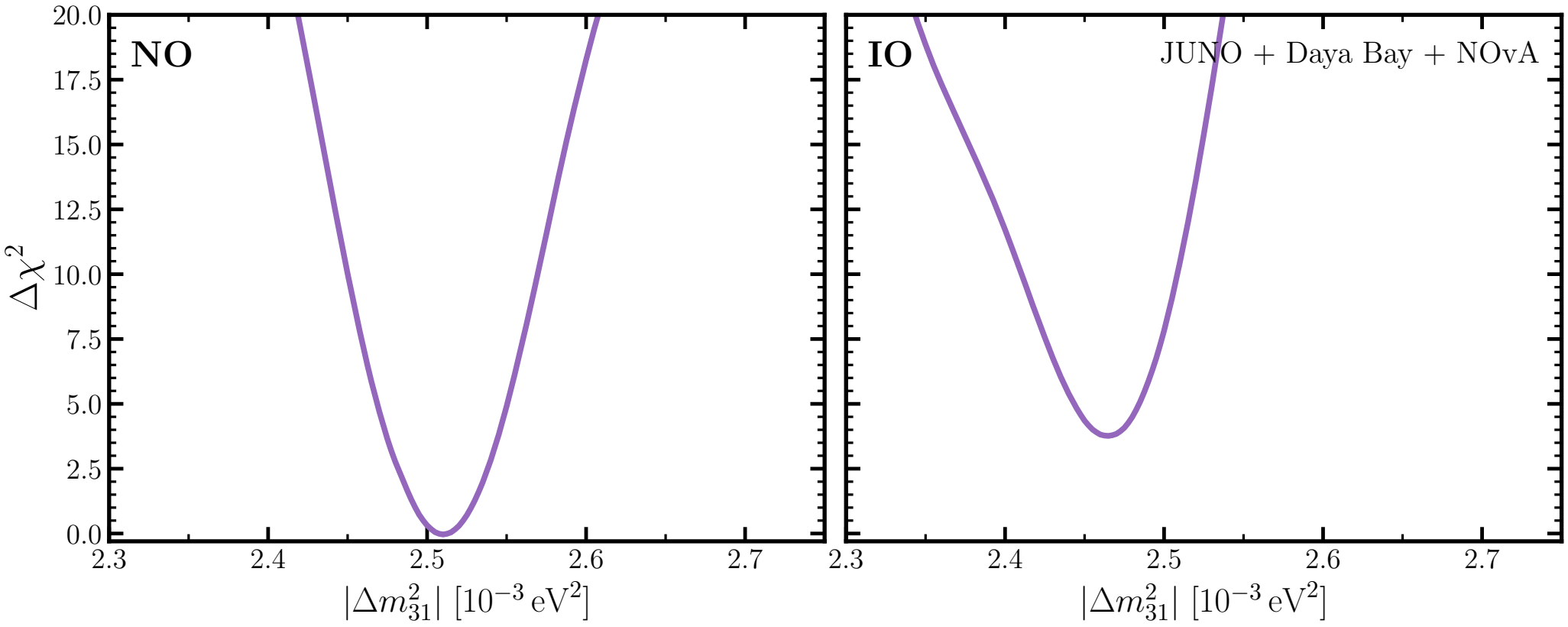
Where does that 2.1σ come from exactly?



Work in progress with João P. Pinheiro

Mass ordering

Where does that 2.1σ come from exactly?



Work in progress with João P. Pinheiro

Mass ordering

Where does that 2.1σ come from exactly?

Besides, NOvA or T2K alone prefer NO,
but their combination slightly favor IO
due to a tension on the CP phase

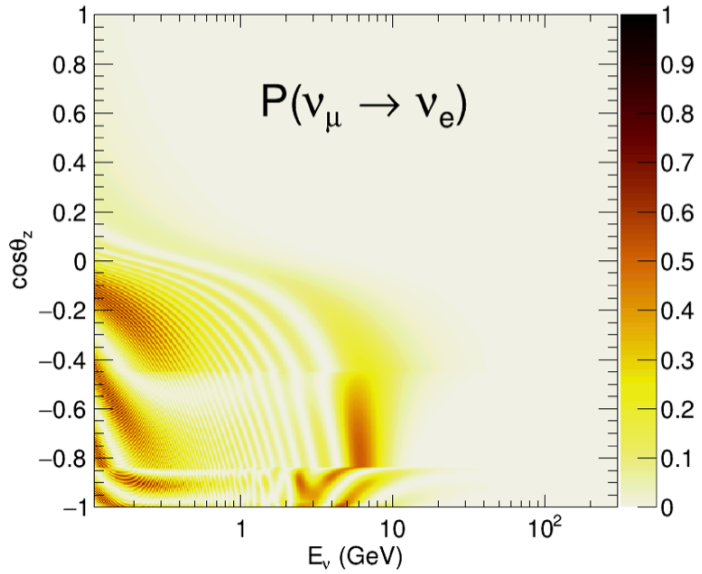
Several small effects here and there,
pulling on different directions,
lead to the 2.1σ preference

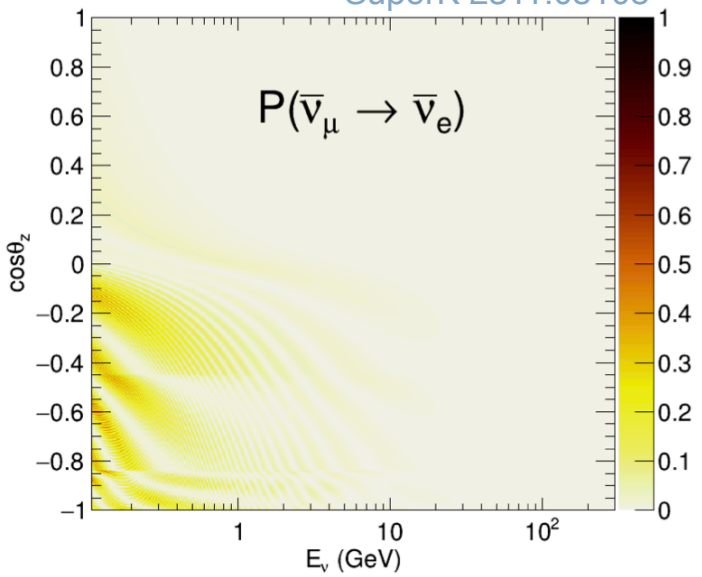
Work in progress with João P. Pinheiro

Mass ordering - atmospheric neutrinos

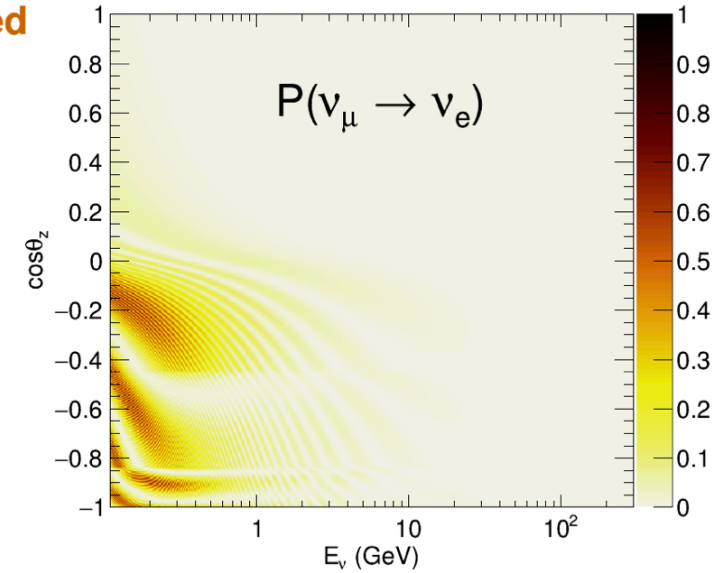
SuperK 2311.05105

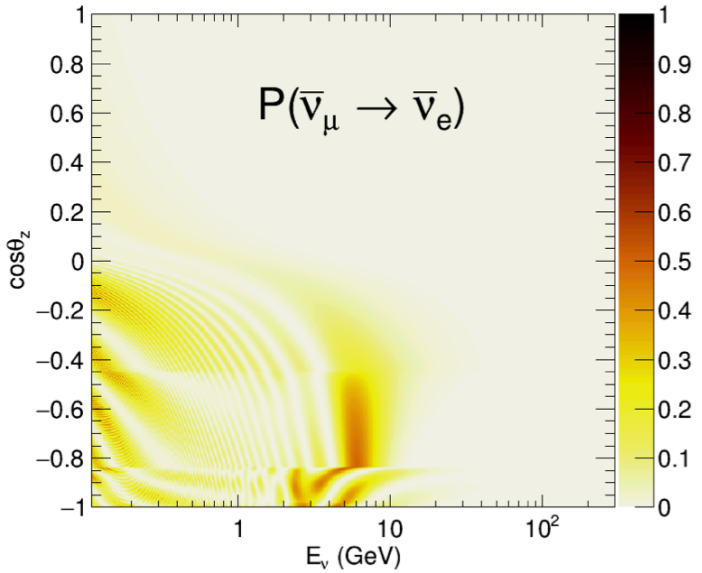
Normal



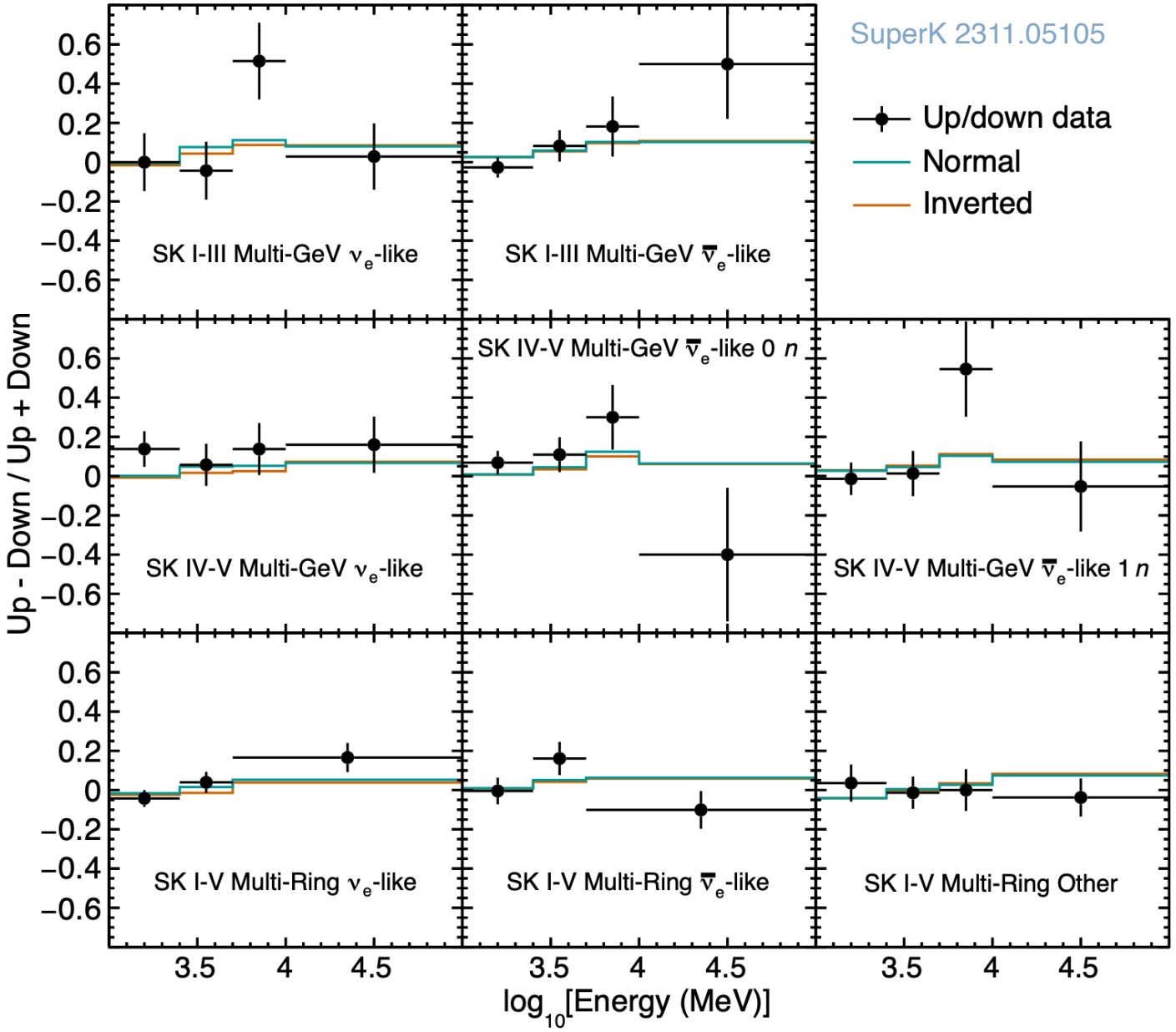


Inverted





Mass ordering - atmospheric neutrinos



92% preference for NO

Mass ordering - atmospheric neutrinos

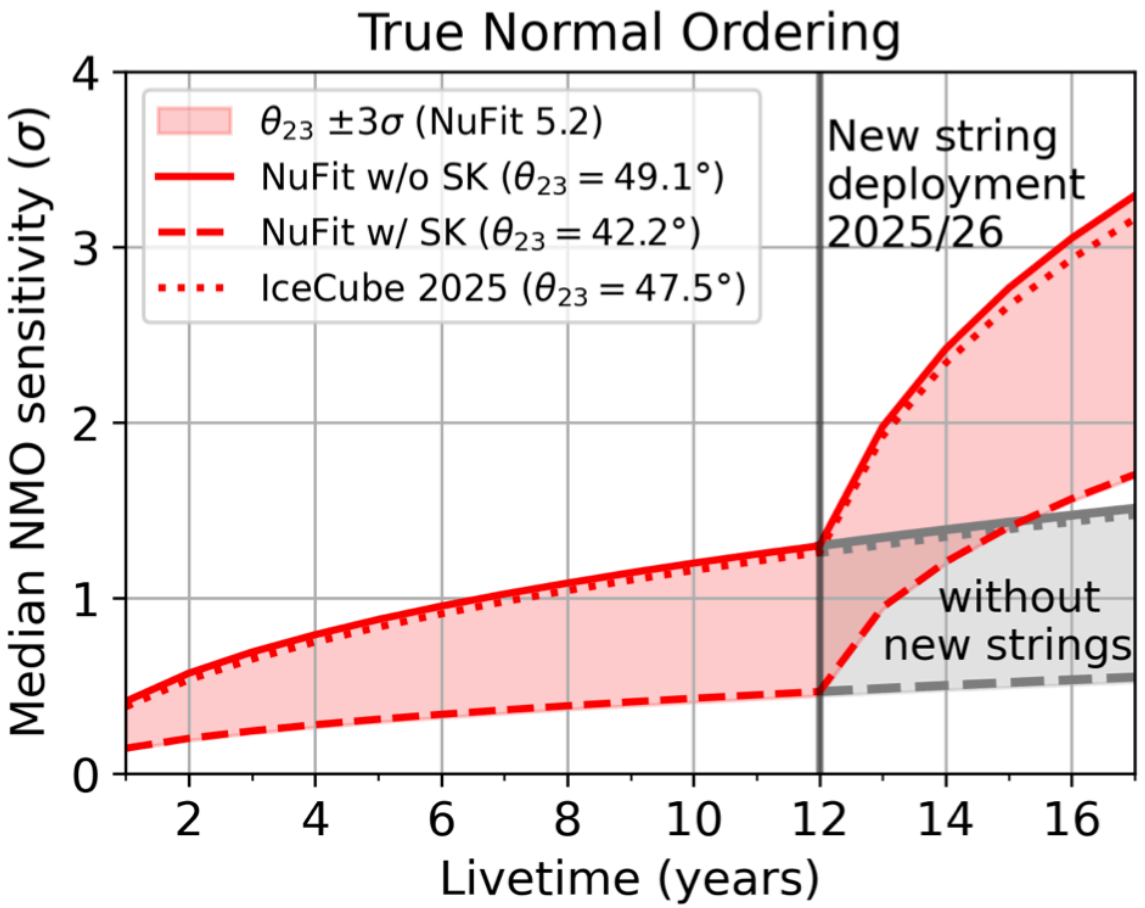
$$\Delta\chi^2_{\mathrm{IO-NO}} = 4.62 \qquad (\mathrm{JUNO\ \&\ NuFIT\text{-}6.1\ w/o\ SK\text{-}ATM}),$$
$$\Delta\chi^2_{\mathrm{IO-NO}} = 9.41 \qquad (\mathrm{JUNO\ \&\ NuFIT\text{-}6.1\ with\ SK\text{-}ATM}),$$

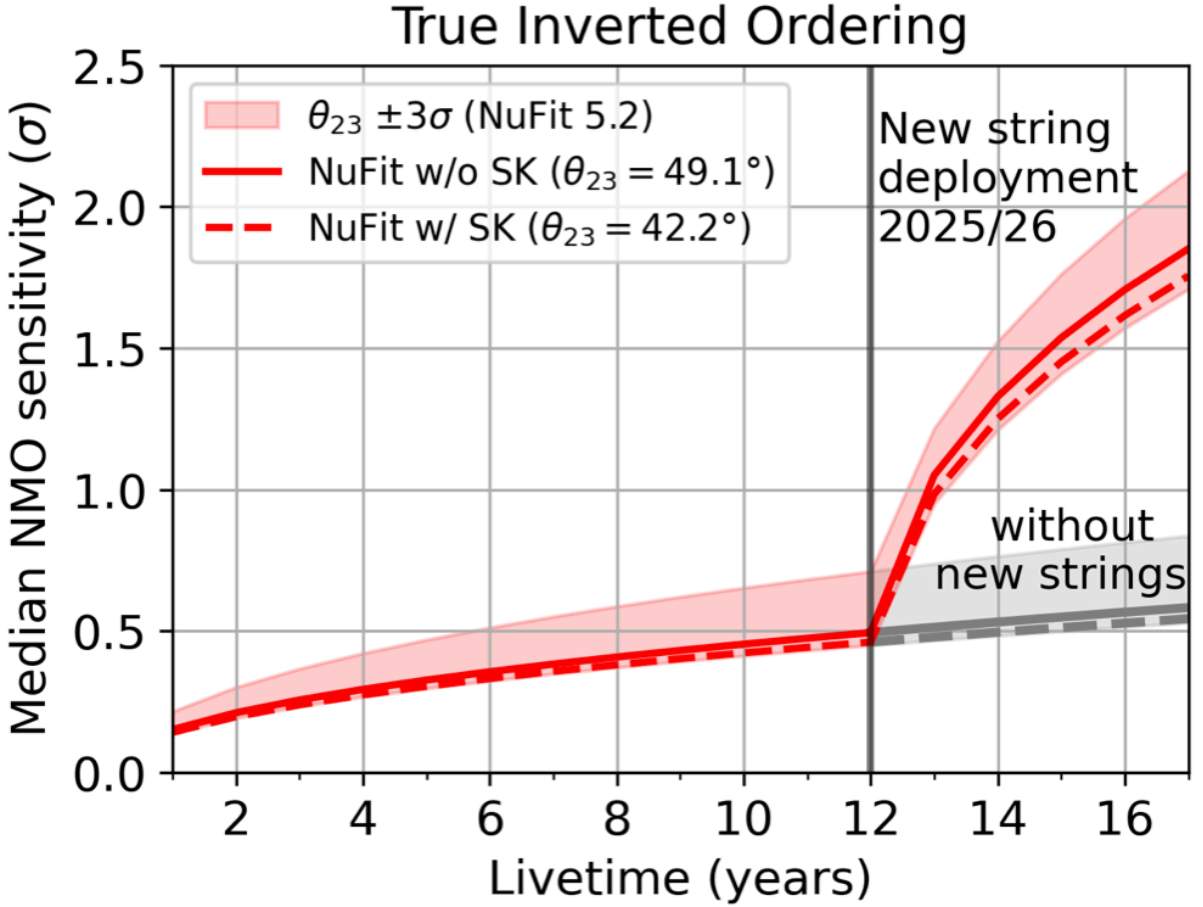
Esteban et al. 2601.09791

Fully correlating flux and cross section uncertainties,
using atmospheric neutrinos only (SK + DeepCore + ORCA),
leads to stronger preference of 3.3σ for NO

Jin et al. 2610.12208

Mass ordering - atmospheric neutrinos

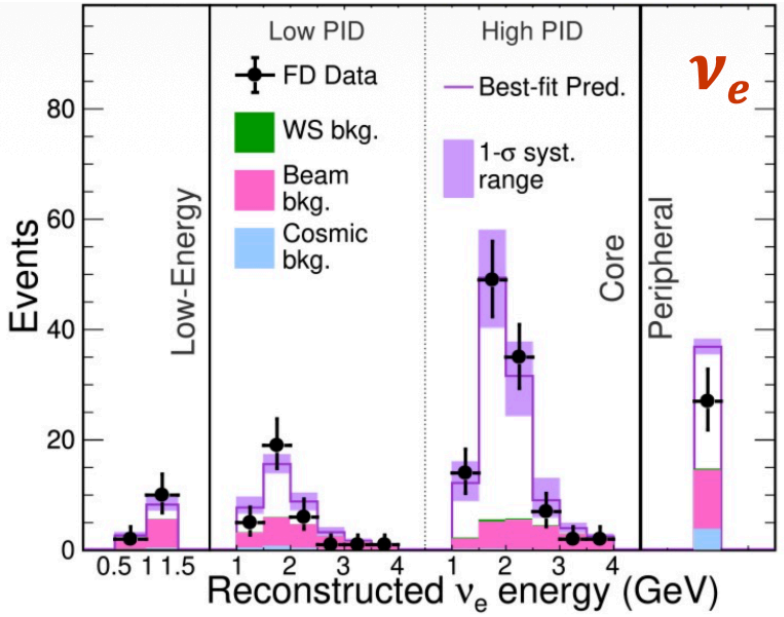




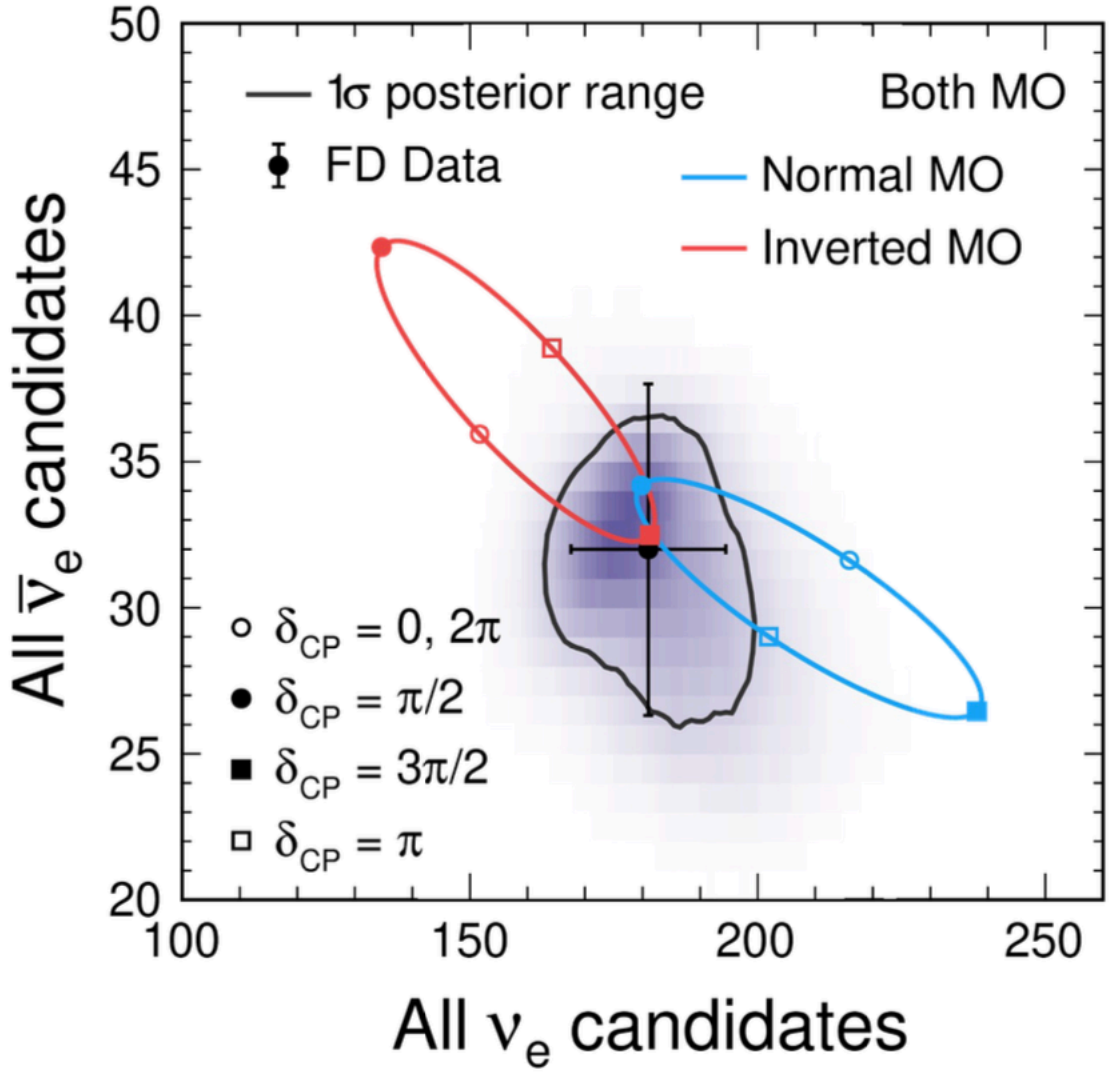
IceCube 2509.13066

CP violation

NOvA appearance: CP violation

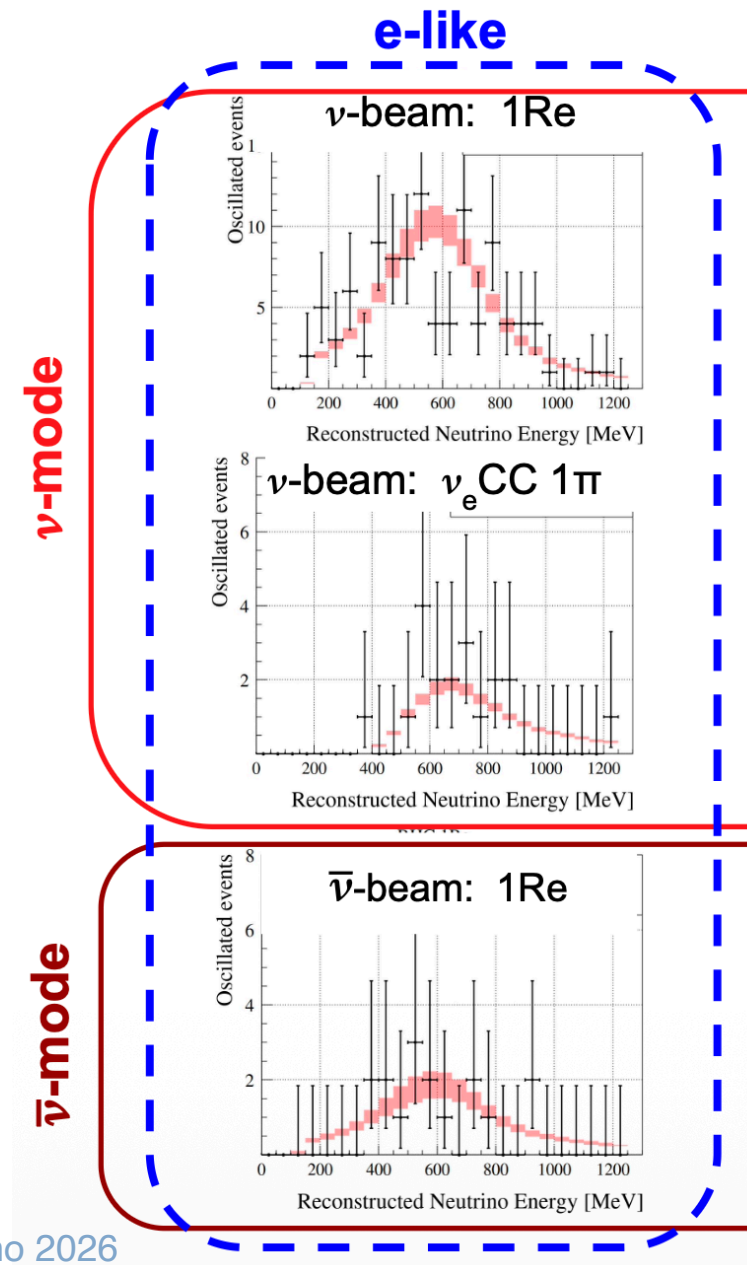


181 ν_e (63 bgs) 32 $\bar{\nu}_e$ (12 bgs)

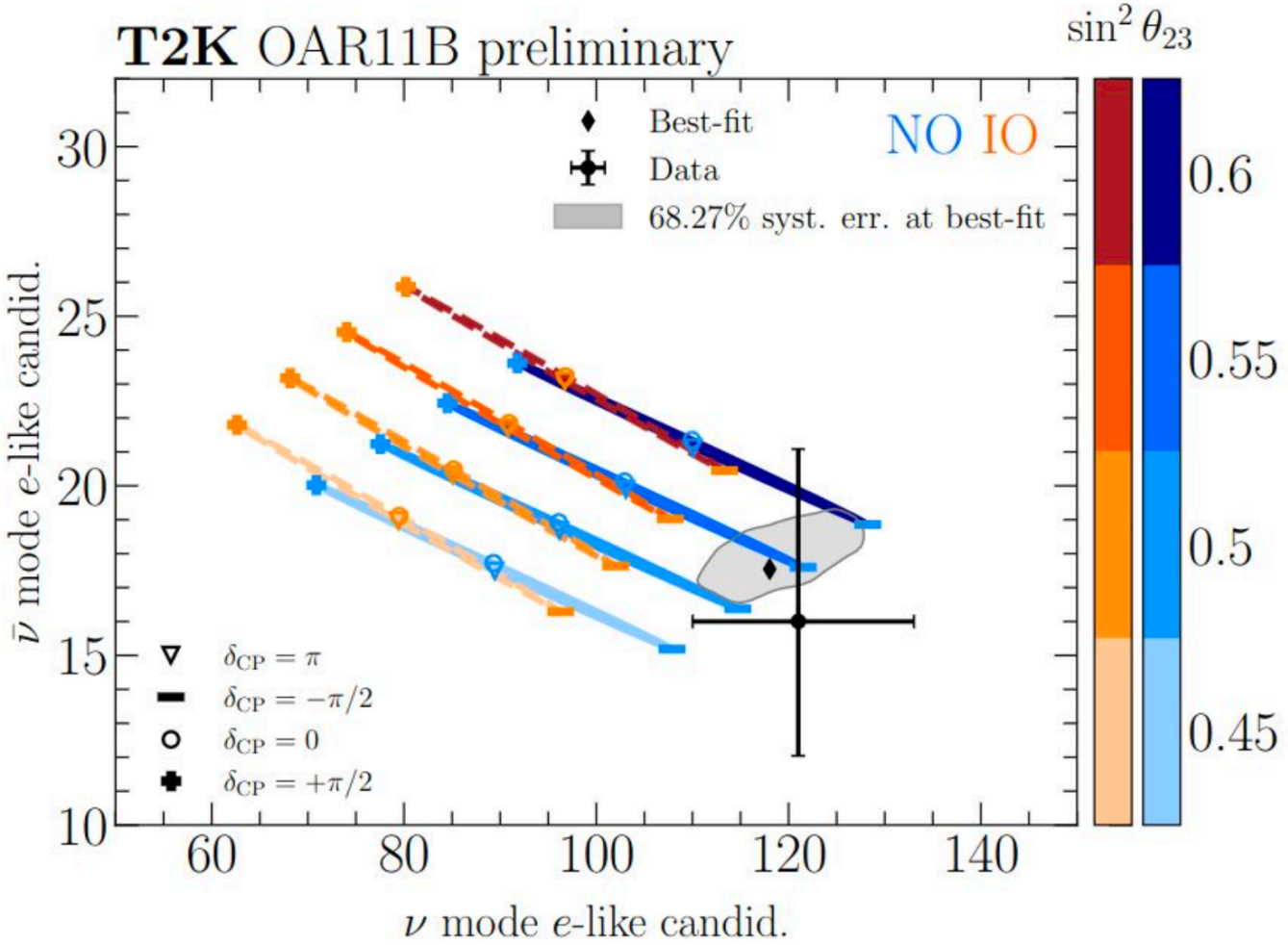


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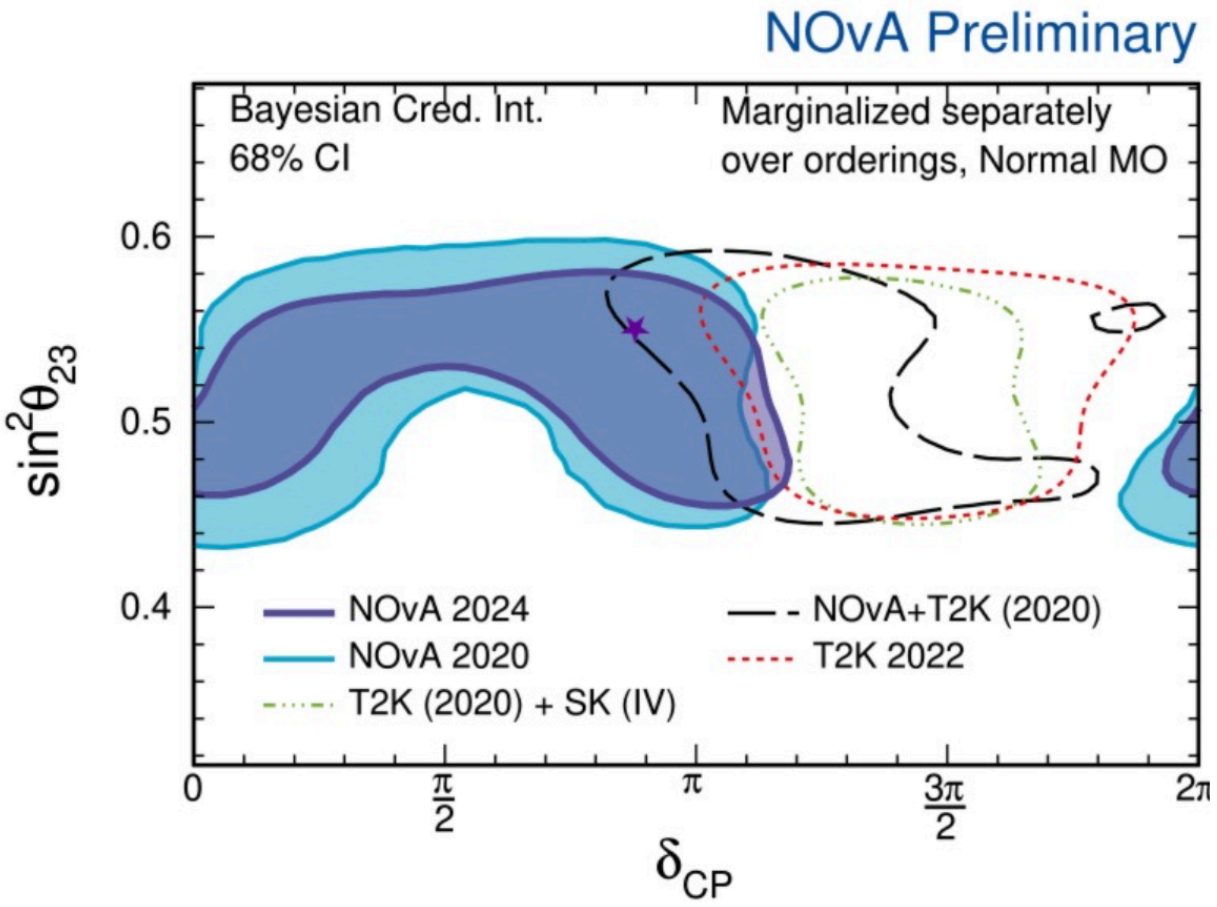
T2K appearance: CP violation

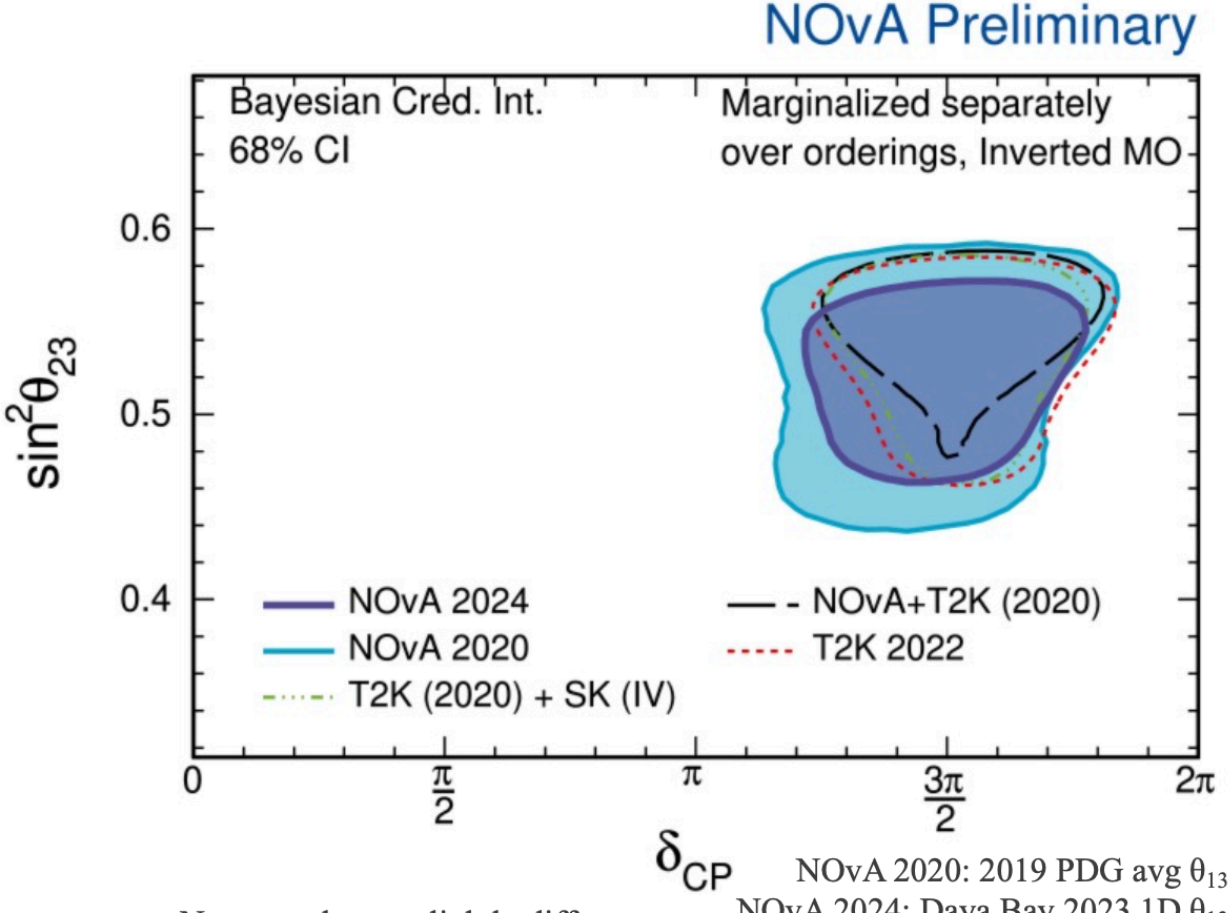


121 ν_e (~27 bgs) 16 $\bar{\nu}_e$ (~8.6 bgs)



NOvA + T2K appearance: CP violation

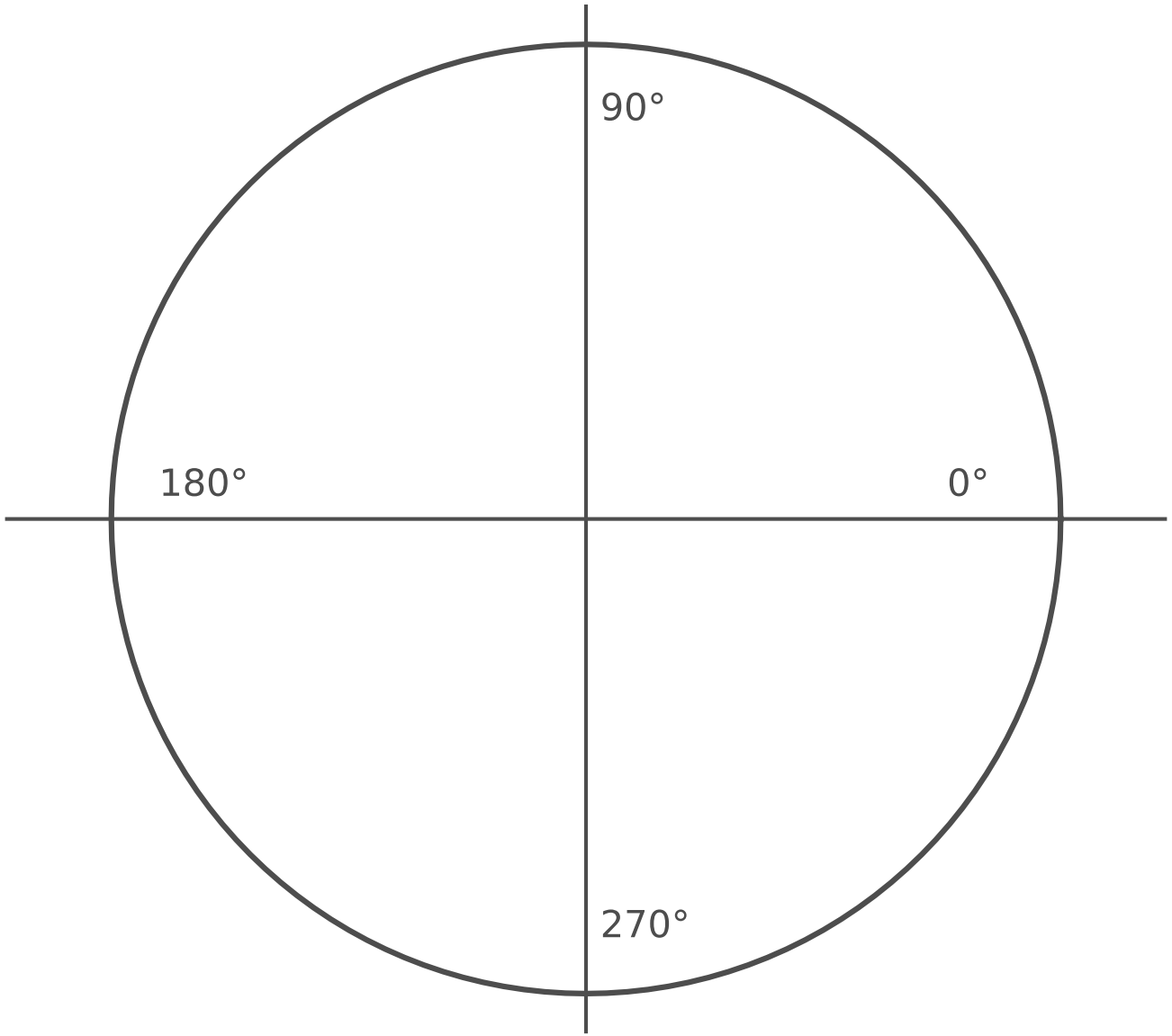




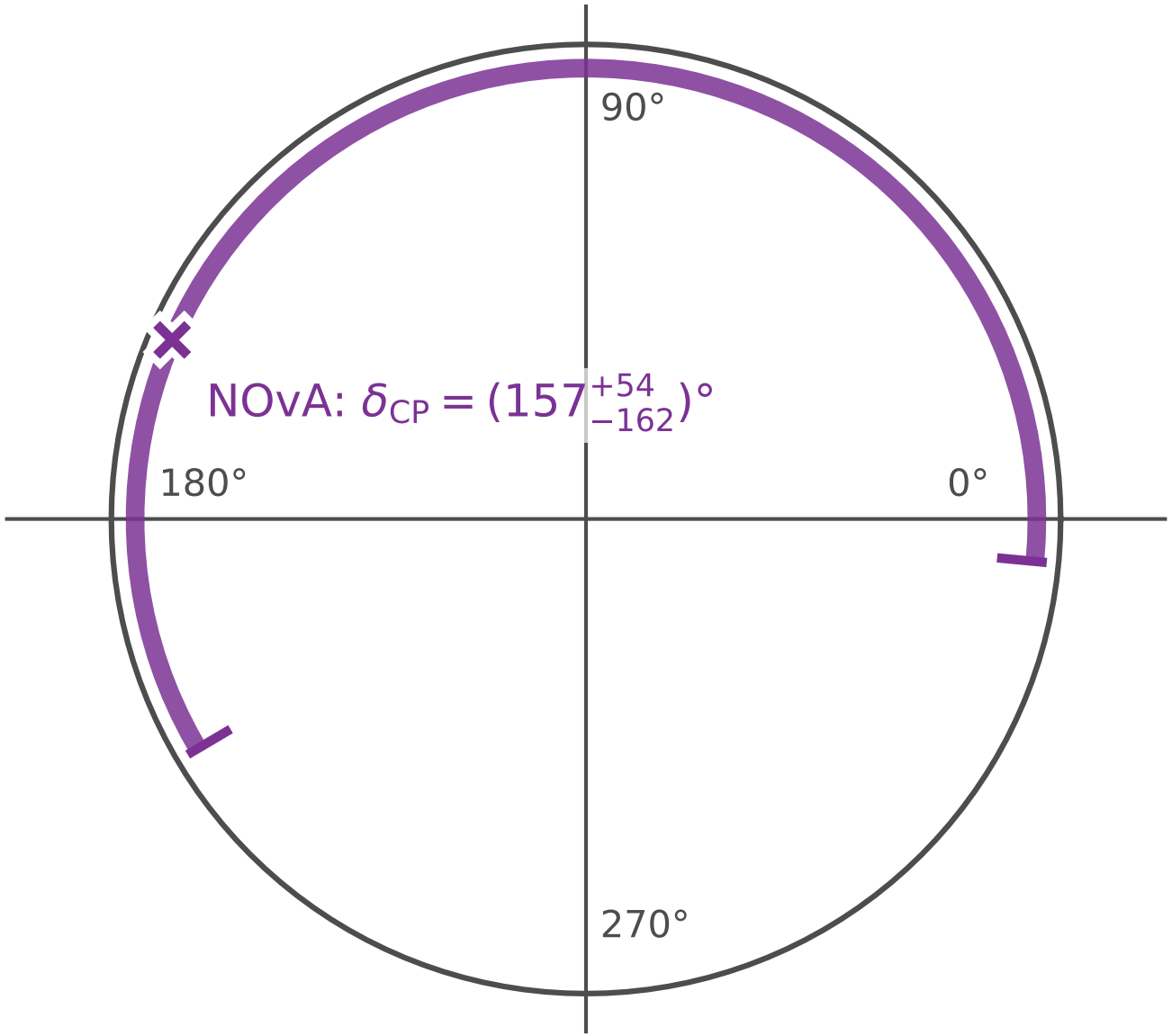
NOvA 2020: 2019 PDG avg θ_{13}

NOvA 2024: Daya Bay 2023 1D θ_{13}

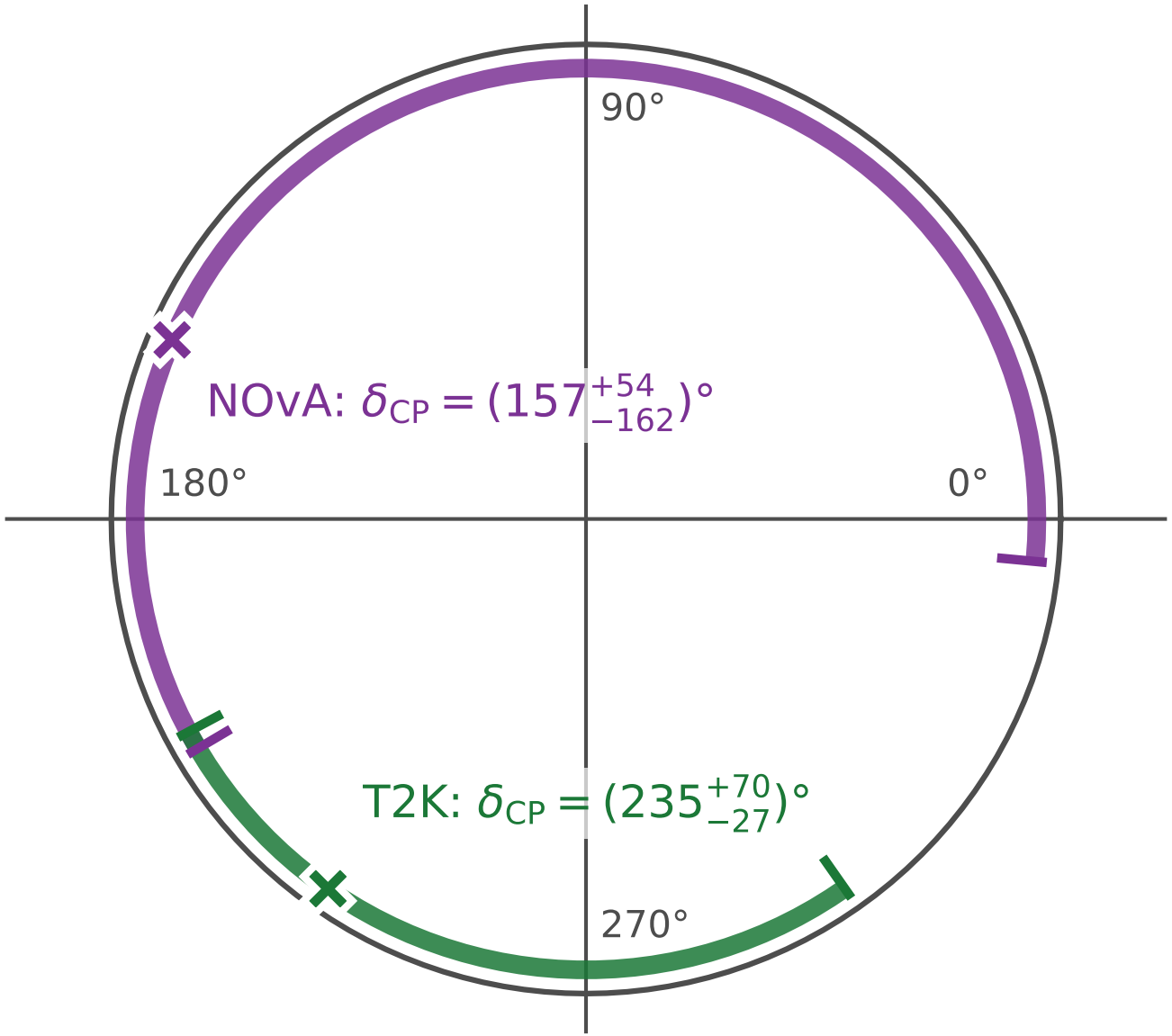
δ_{CP} for normal ordering



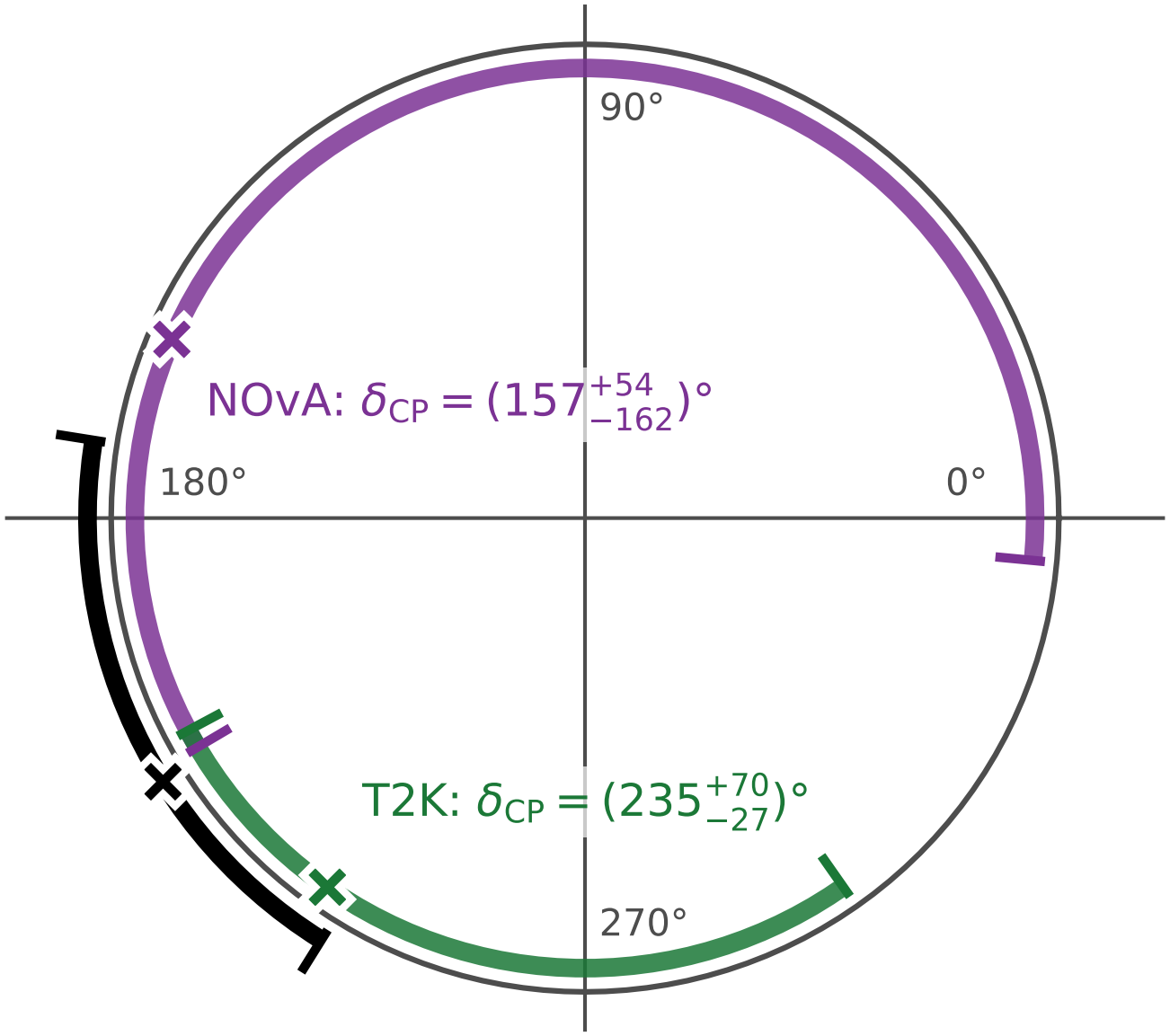
δ_{CP} for normal ordering



δ_{CP} for normal ordering



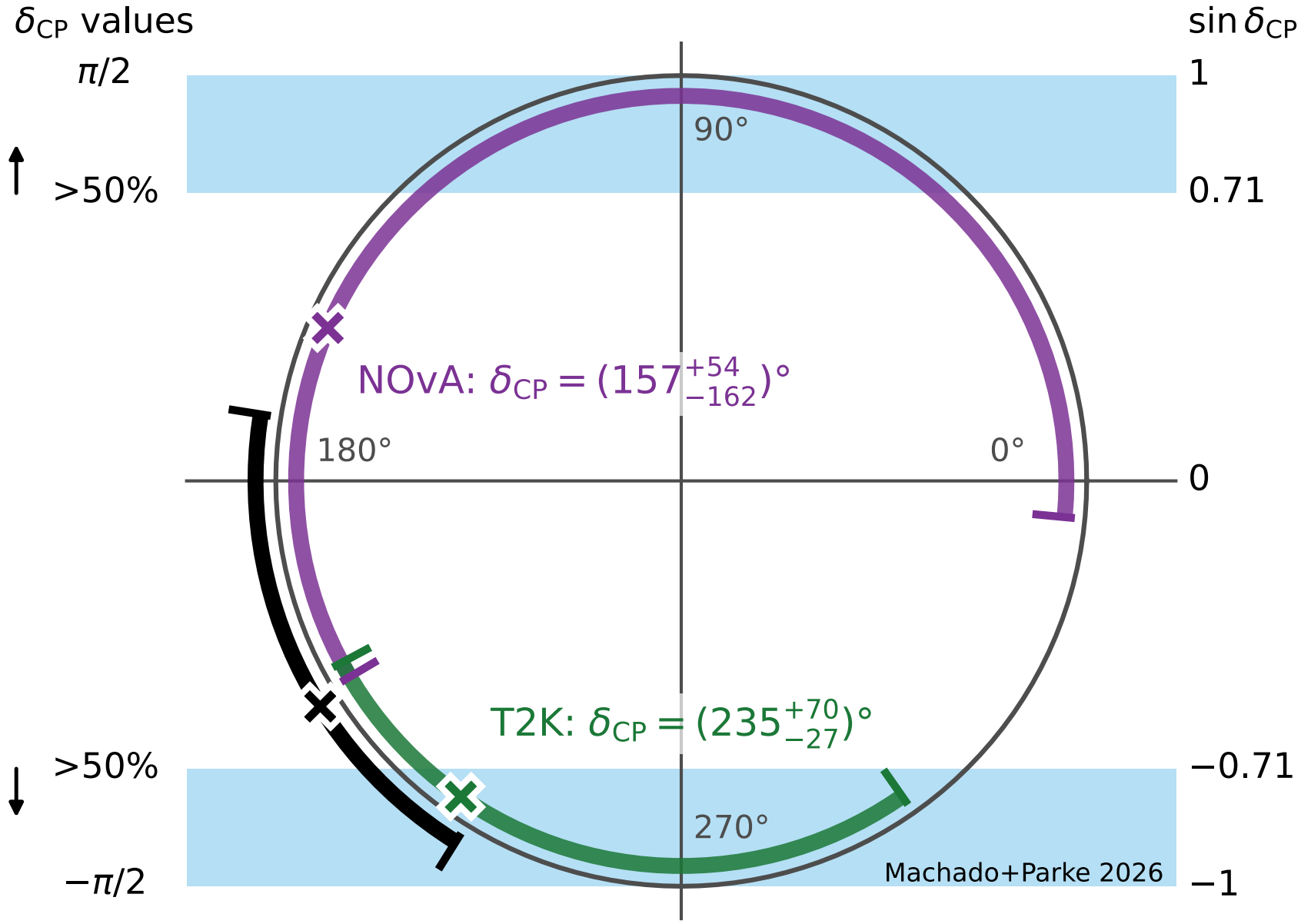
δ_{CP} for normal ordering



NuFit 6.0: $\delta_{CP} = (212^{+26}_{-41})°$

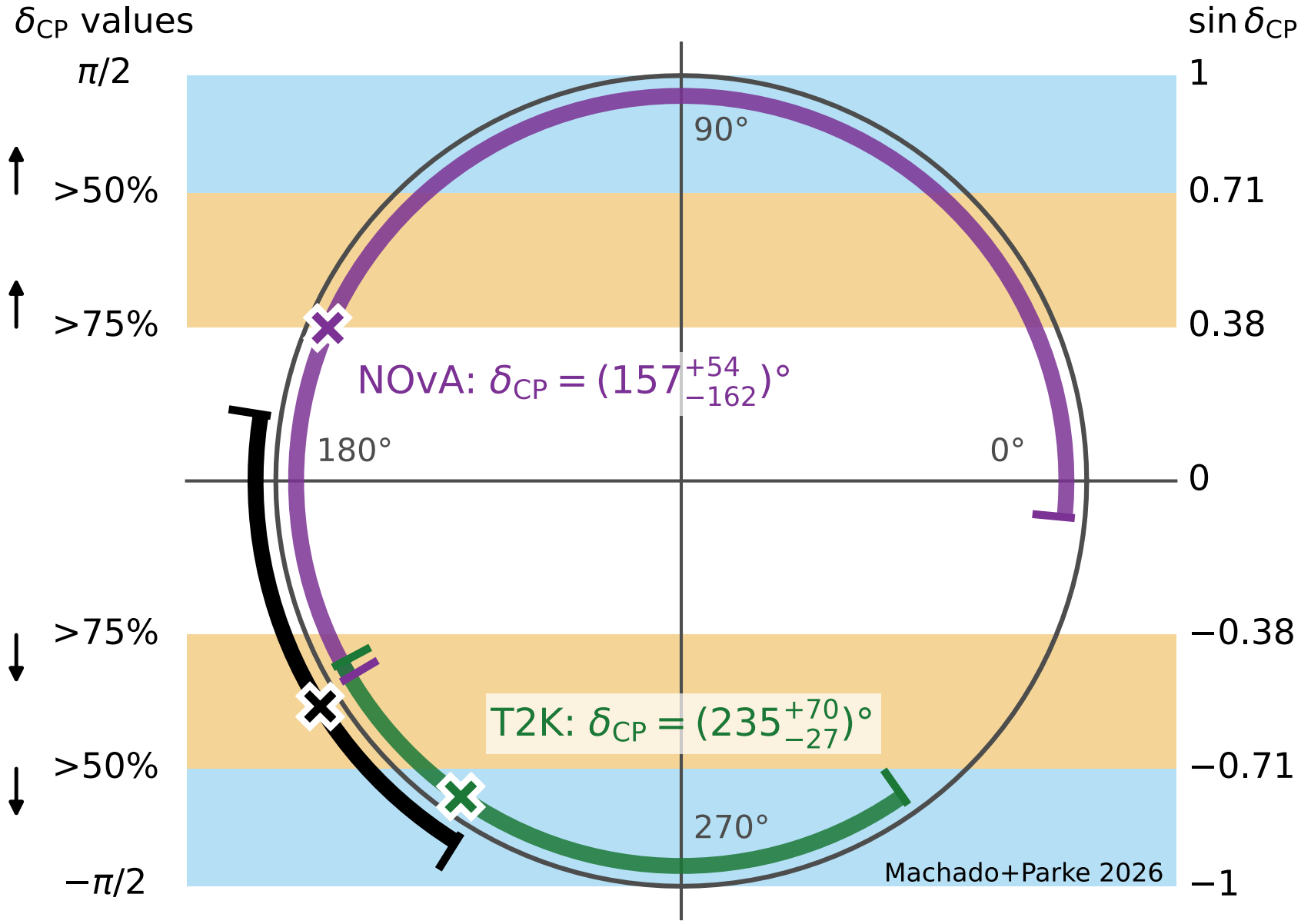
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δ_{CP} for normal ordering



NuFit 6.0: $\delta_{CP} = (212^{+26}_{-41})°$

δ_{CP} for normal ordering



NuFit 6.0: $\delta_{CP} = (212^{+26}_{-41})°$

Conclusions

Lots of things happening on the neutrino oscillation world!

Good hints for normal mass ordering, but still tensions around

CP violation still wide open

We are starting to scratch the surface
of the complete three-neutrino paradigm

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