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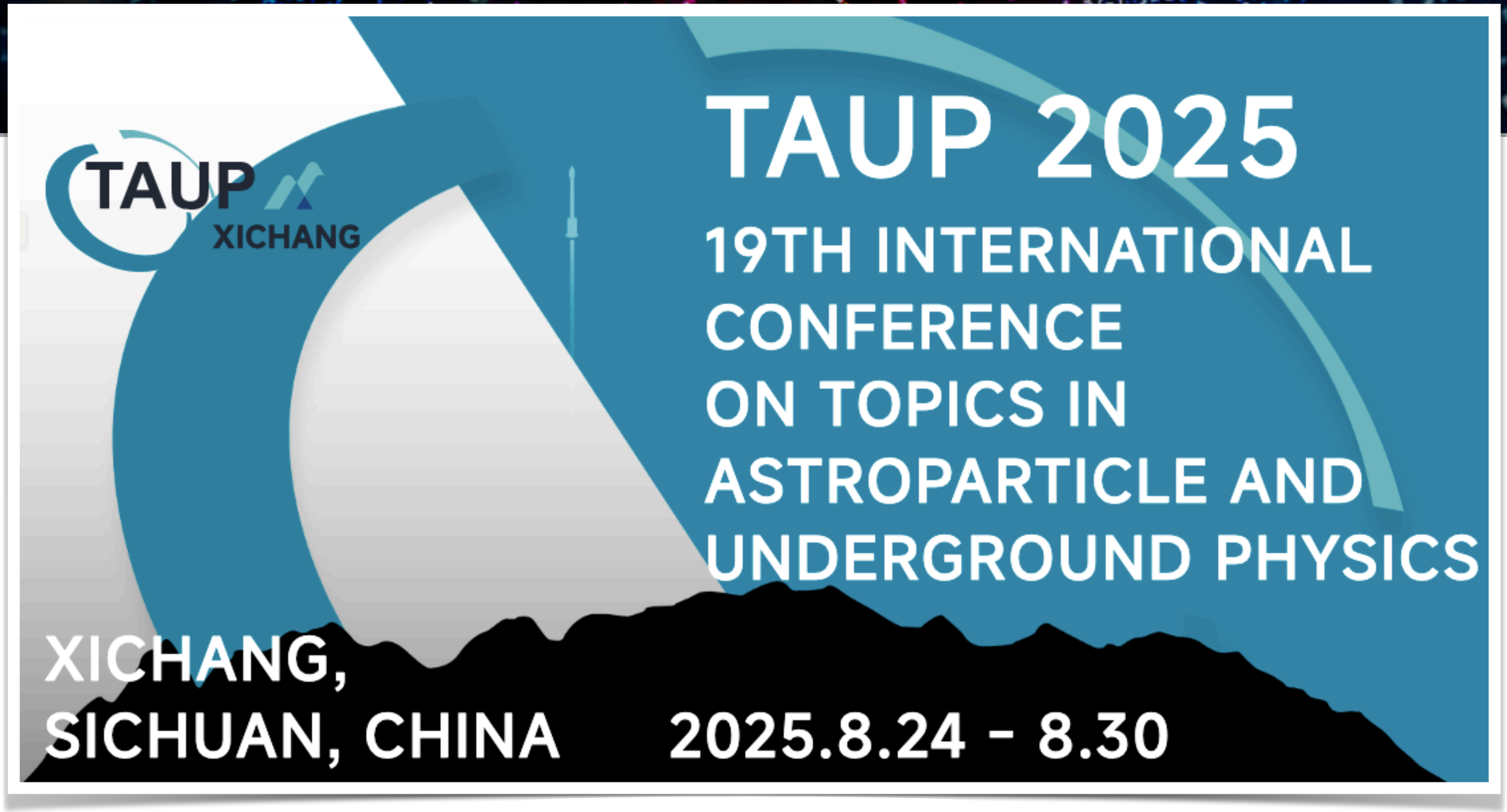
Neutrino theory (neutrino masses, mixing, and interactions)



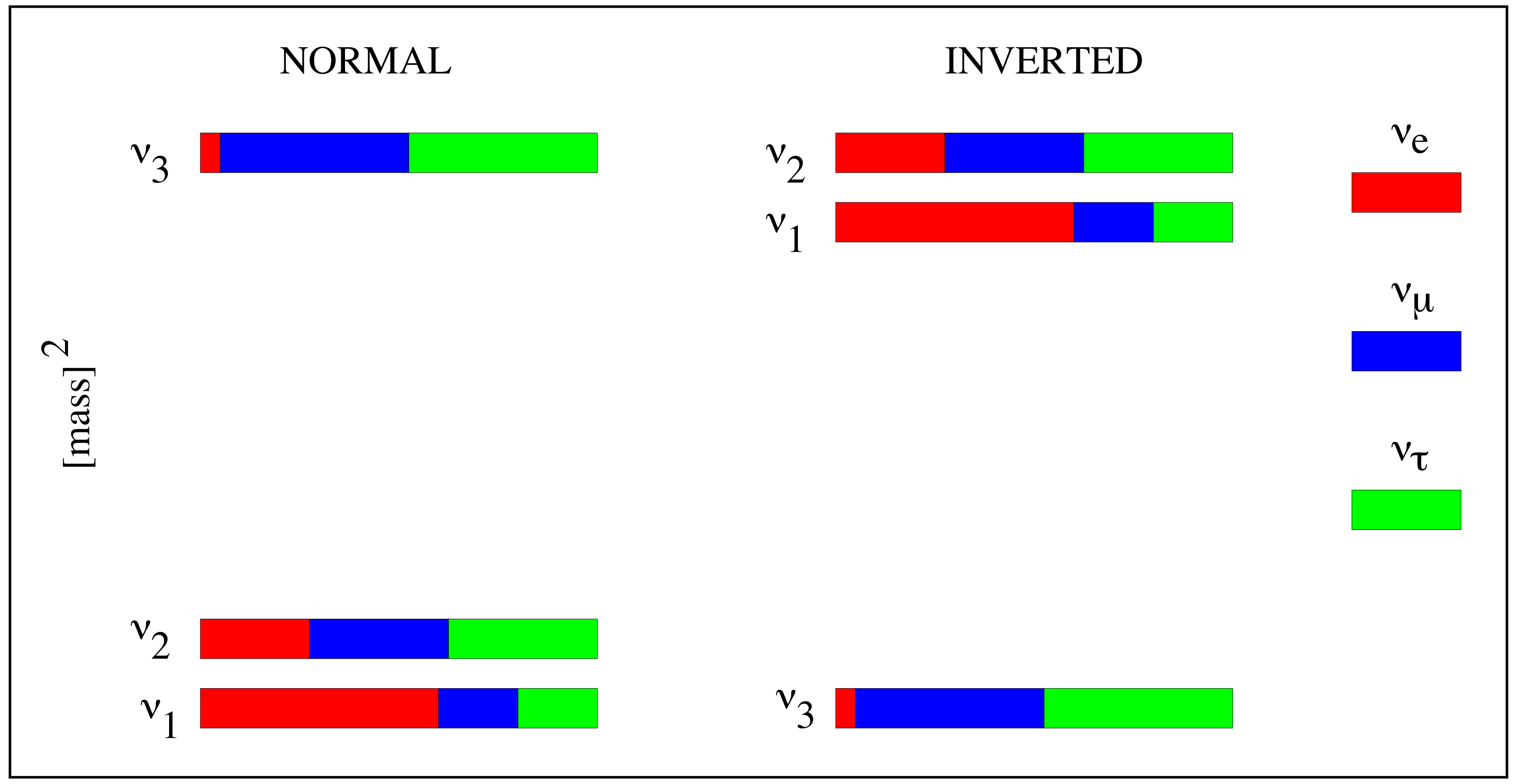
KIT
Karlsruher Institut für Technologie

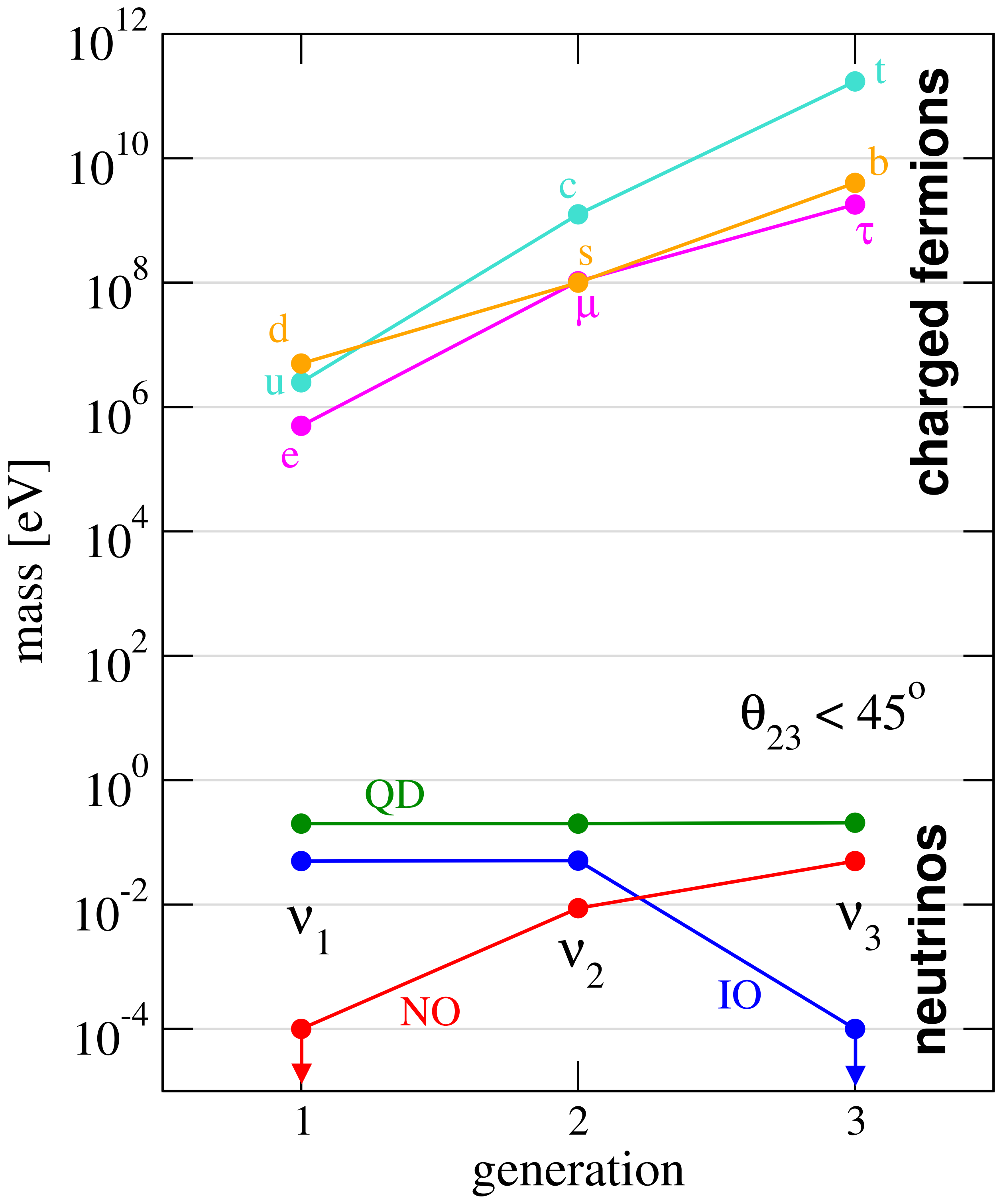
Outline

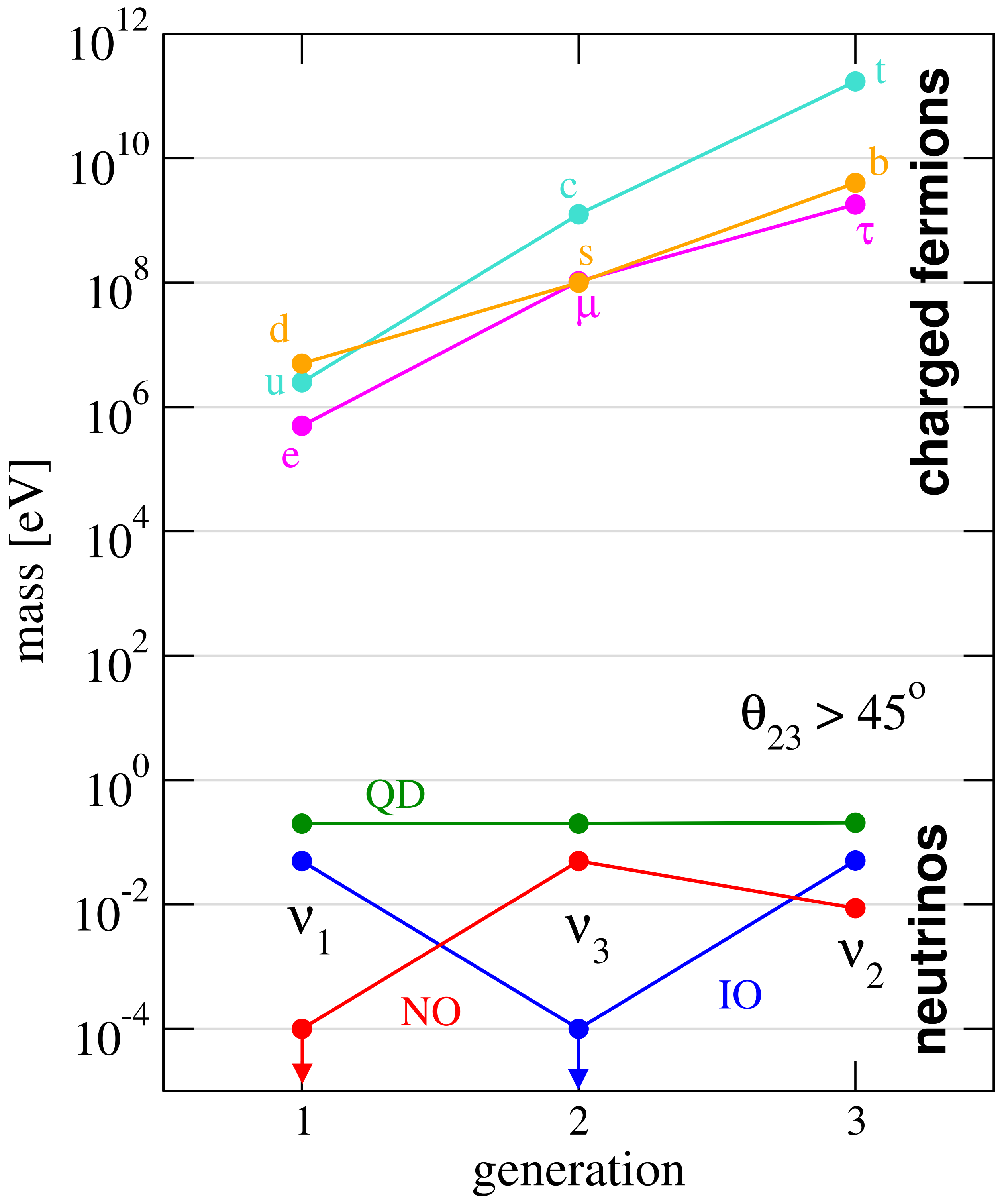
- The neutrino challenge for theory
- The success story of three-flavour oscillations
- Tensions in the standard three-flavour paradigm / signs of new physics?
    - short-baseline anomalies
    - the neutrino tension in cosmology

The neutrino challenge

- neutrino masses are tiny
- mixing of leptons is very different than for quarks







Leptons	Quarks
$\theta_{12} \approx 33^\circ$	$\theta_{12} \approx 13^\circ$
$\theta_{23} \approx 45^\circ$	$\theta_{23} \approx 2^\circ$
$\theta_{13} \approx 9^\circ$	$\theta_{13} \approx 0.2^\circ$

$$U_{PMNS} = \frac{1}{\sqrt{3}} \begin{pmatrix} \mathcal{O}(1) & \mathcal{O}(1) & \epsilon \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(1) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix} \qquad U_{CKM} = \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & \epsilon \\ \epsilon & \epsilon & 1 \end{pmatrix}$$

Standard Model EFT

- **Weinberg 1979:** $$\frac{Y^2_{ab}}{\Lambda}\overline{L^c_a}\tilde{\phi}^*\,\phi^\dagger L_b \quad\rightarrow\quad \frac{1}{2}\overline{\nu^c_{aL}}m_{ab}\nu_{bL}$$

- unique operator at dim-5 consistent with SM gauge symmetry, Majorana neutrino mass after EWSB

- **low-energy phenomenology** encoded in m_{ab}
  symmetric complex matrix → 6+3 real parameters (after removing unphys. phases):
  - 6 neutrino oscillation params: $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$
  - 1 absolute mass observable: lightest neutrino mass m_0

  } good prospects to determine experimentally
  - 2 Majorana phases α, β (neutrinoless double beta decay)

Standard Model EFT

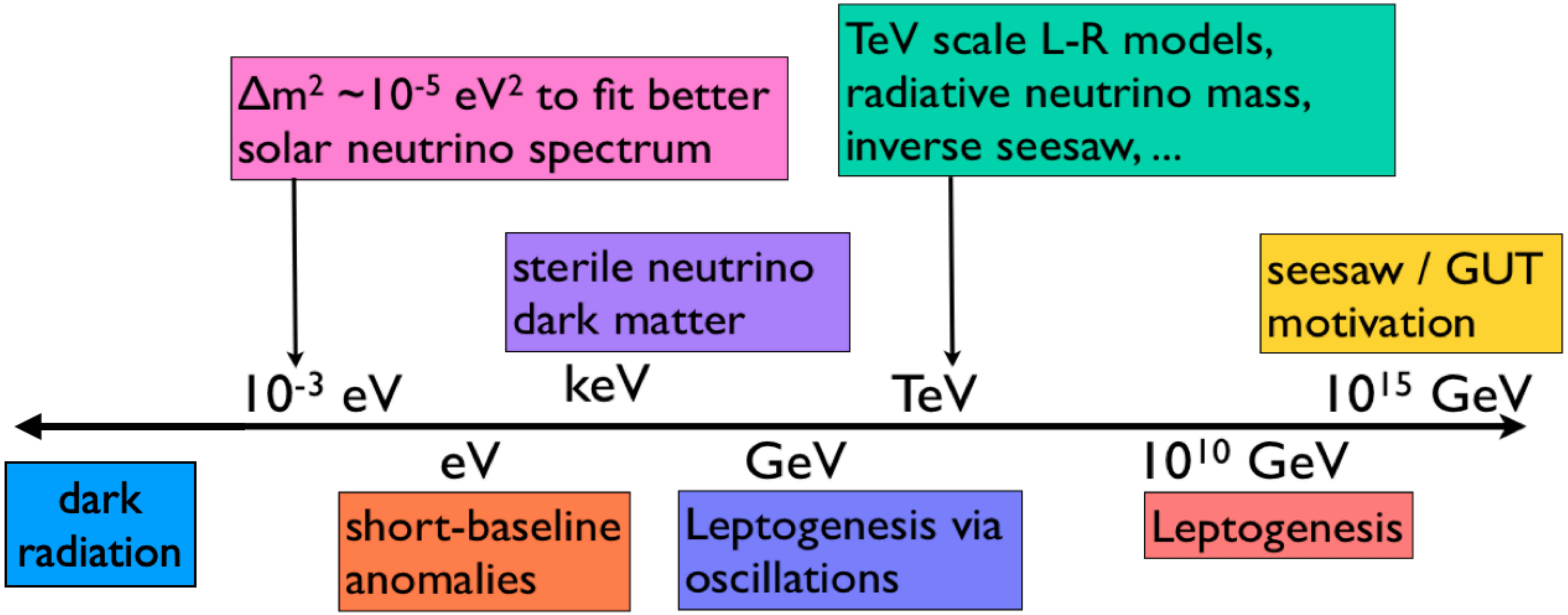
- **Weinberg 1979:** $$\frac{Y_{ab}^2}{\Lambda} \overline{L_a^c} \tilde{\phi}^* \phi^\dagger L_b \quad \to \quad \frac{1}{2} \overline{\nu_{aL}^c} m_{ab} \nu_{bL}$$

- unique operator at dim-5 consistent with SM gauge symmetry, Majorana neutrino mass after EWSB

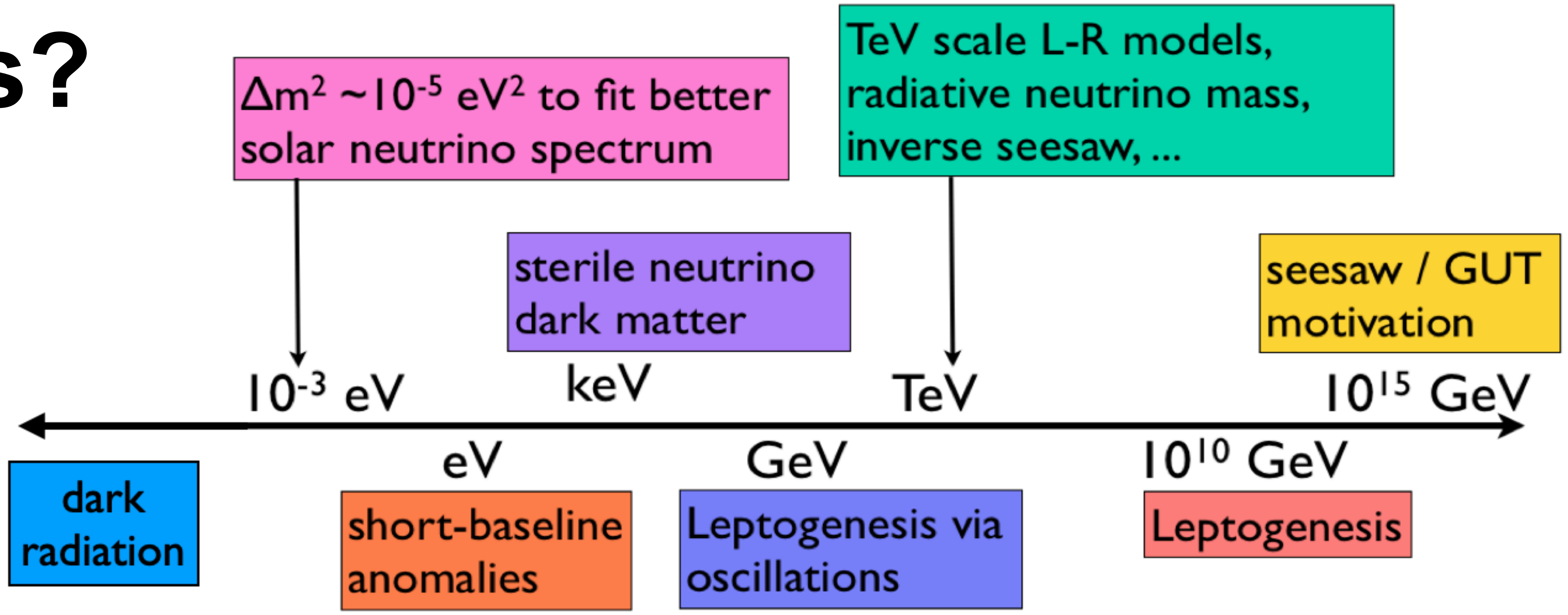
- No indication of scale of new physics!

$$m_\nu \approx 0.06\,\mathrm{eV} \left(\frac{Y}{1}\right)^2 \left(\frac{10^{15}\,\mathrm{GeV}}{\Lambda}\right) \approx 0.06\,\mathrm{eV} \left(\frac{Y}{10^{-6}}\right)^2 \left(\frac{1\,\mathrm{TeV}}{\Lambda}\right)$$

What is the scale of new physics?



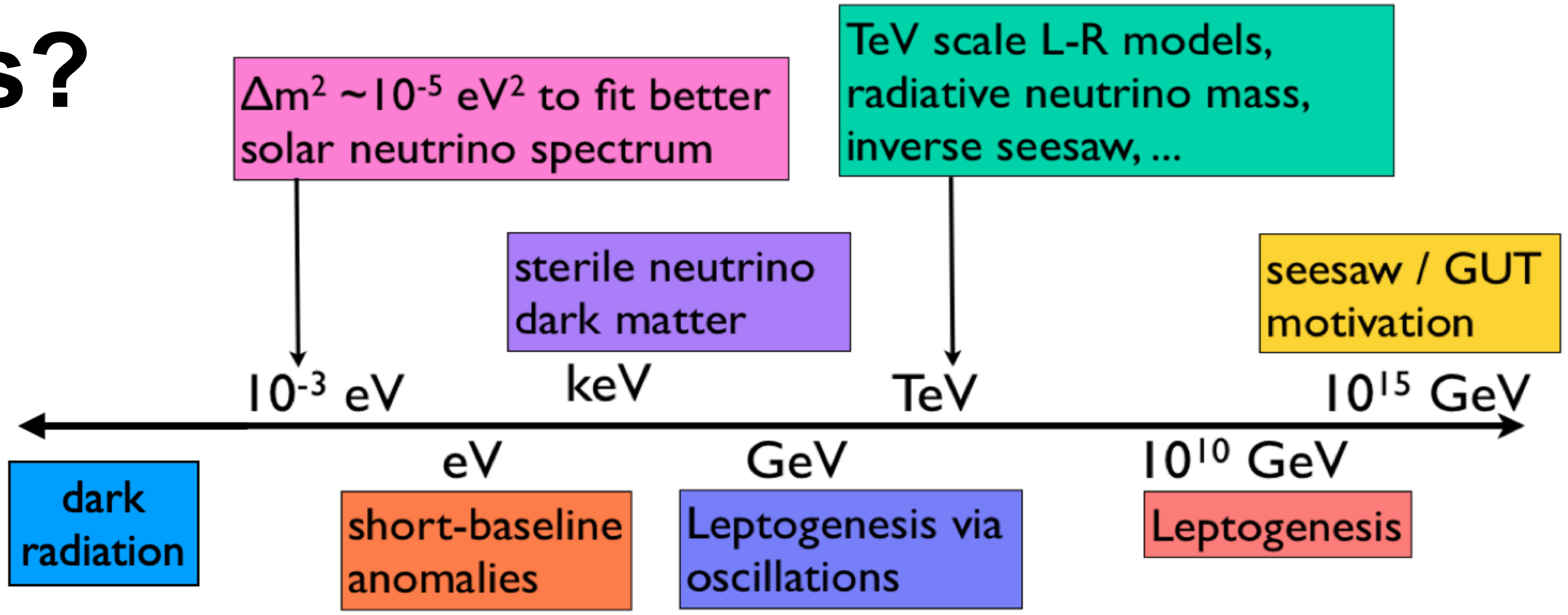
Where to look for new physics?



Phenomenological approach:

- test the three-flavour paradigm as accurately as possible,
- look for deviations:
  - non-unitarity (sterile neutrinos)
  - absolute mass observables — cosmology vs oscillations
  - non-standard neutrino interactions
  - complementary signatures: LHC, SHiP, cLFV, astrophysics,…

Where to look for new physics?



Phenomenological approach:

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  - non-unitarity (sterile neutrinos)
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this talk

Prediction of the EFT approach to neutrino mass:

Lepton number violation by $\Delta L = 2$

- unique opportunity for **neutrinoless double-beta decay** searches
- the importance of testing this prediction cannot be overstated
- key to make progress towards incorporating neutrino mass into the SM

Prediction of the EFT approach to neutrino mass:

Lepton number violation by $\Delta L = 2$

- observation of $0\nu\beta\beta$:
  ``prove´´ of Majorana nature of neutrinos (new type of fermion)
  confirm expectation of EFT paradigm and predicting power of gauge symmetry

- non-observation of $0\nu\beta\beta$:
  Dirac mass dominance and (very accurate) conservation of lepton number:
  - paradigm shift about global symmetries
  - intricate cancellation mechanism

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Status of three-flavour neutrino oscillations

- Determination of the 6 neutrino oscillation parameters:
  $\Delta m^2_{21}, \Delta m^2_{31}, \theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$

- most accurately determined from joint analysis of global data:
  - solar neutrinos θ_{12}, sgn(Δm^2_{21})
  - atmospheric neutrinos $\theta_{23}, \Delta m^2_{31}$
  - reactor neutrinos:
    long-baseline (180 km) $|\Delta m^2_{21}|, \theta_{12}$
    short-baseline (2.5 km) $\theta_{13}, |\Delta m^2_{31}|$
  - long-baseline accelerators $\theta_{23}, \Delta m^2_{31}, \delta_{CP}$

www.nu-fit.org

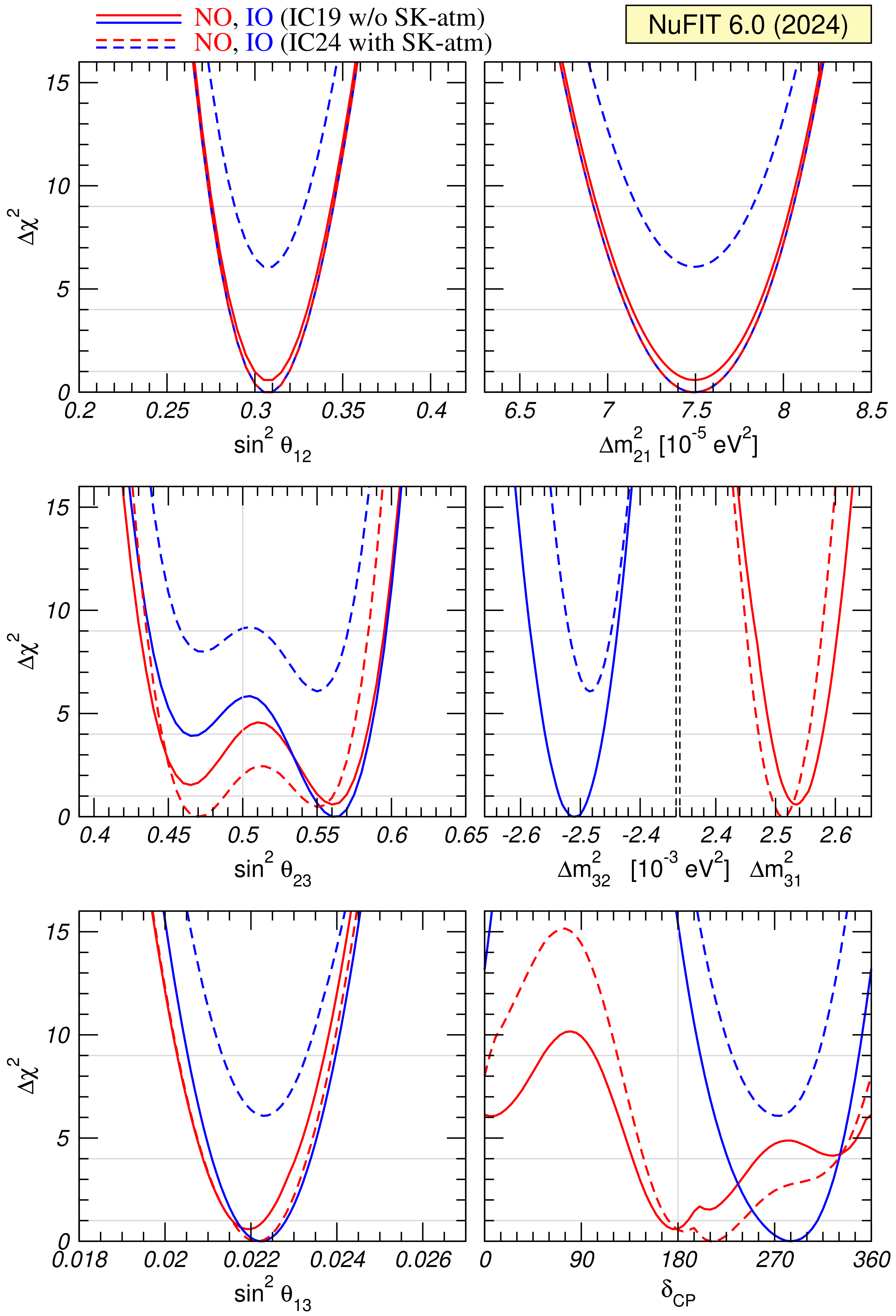
- NuFit-6.0
  Esteban, Gonzalez-G., Maltoni, Martinez-S., Pinheiro, TS, 2410.05380
  http://www.nu-fit.org/
- s. also
  Capozzi et al., 2503.07752
  talk by A. Marrone

3-flavour oscillation parameters

- robust determination of 5 parameters, relative precision at 3σ:

θ_{13}: 8%, θ_{12}: 13%, θ_{23}: 20%

$|\Delta m^2_{31}|$: 5.1%, Δm^2_{21}: 15%



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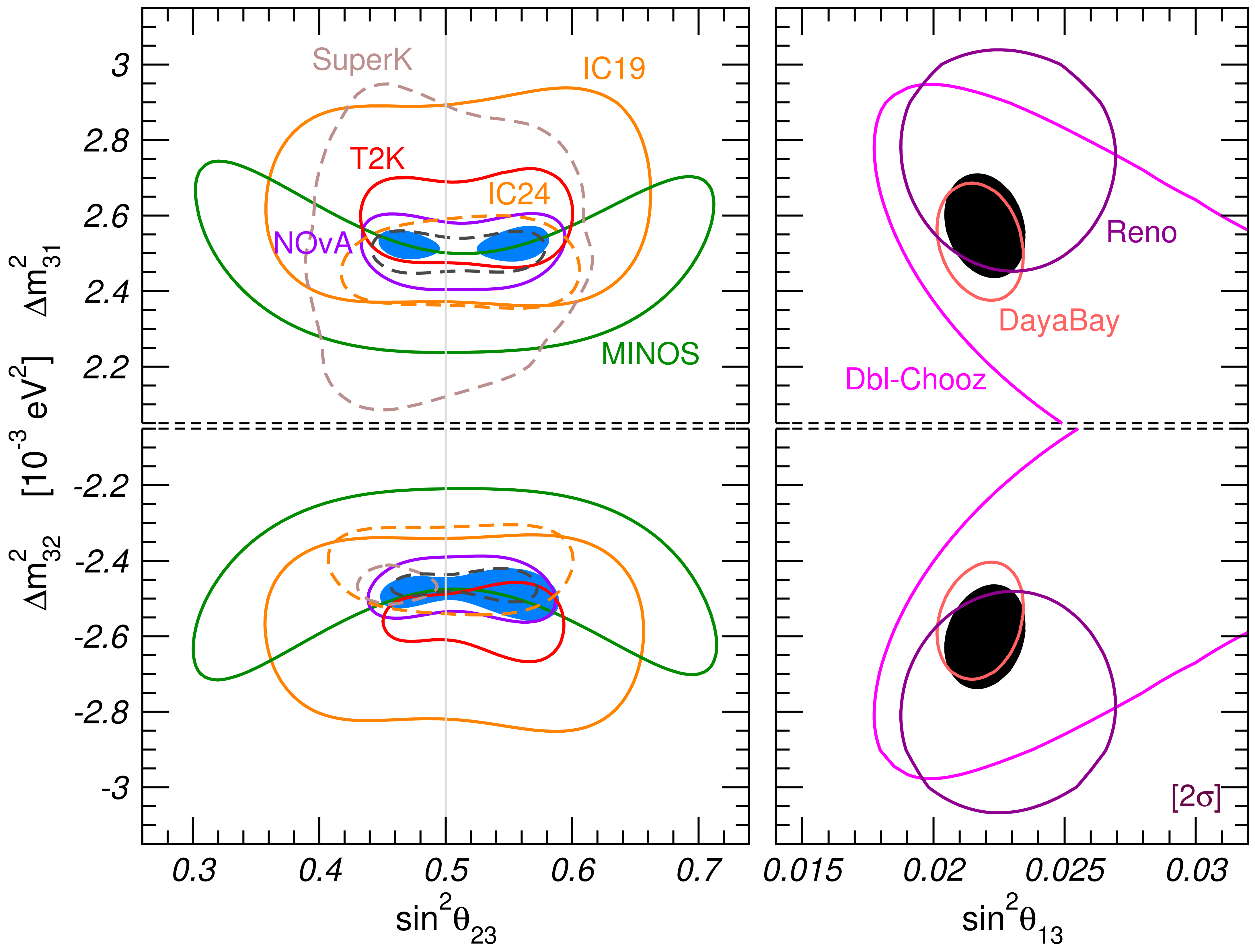
- robust determination of 5 parameters, relative precision at 3σ:

  θ_{13}: 8%, θ_{12}: 13%, θ_{23}: 20%

  $|\Delta m^2_{31}|$: 5.1%, Δm^2_{21}: 15%

- complementarity of various data sets
- non-trivial consistency checks of 3-flavour paradigm

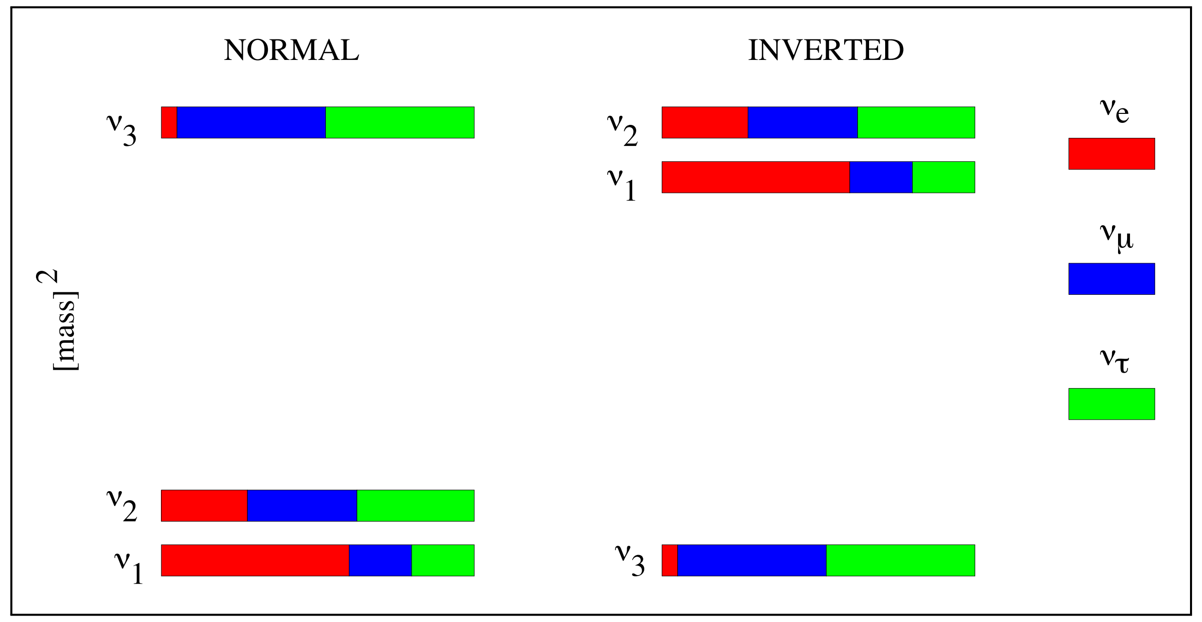
NuFIT 6.0 (2024)

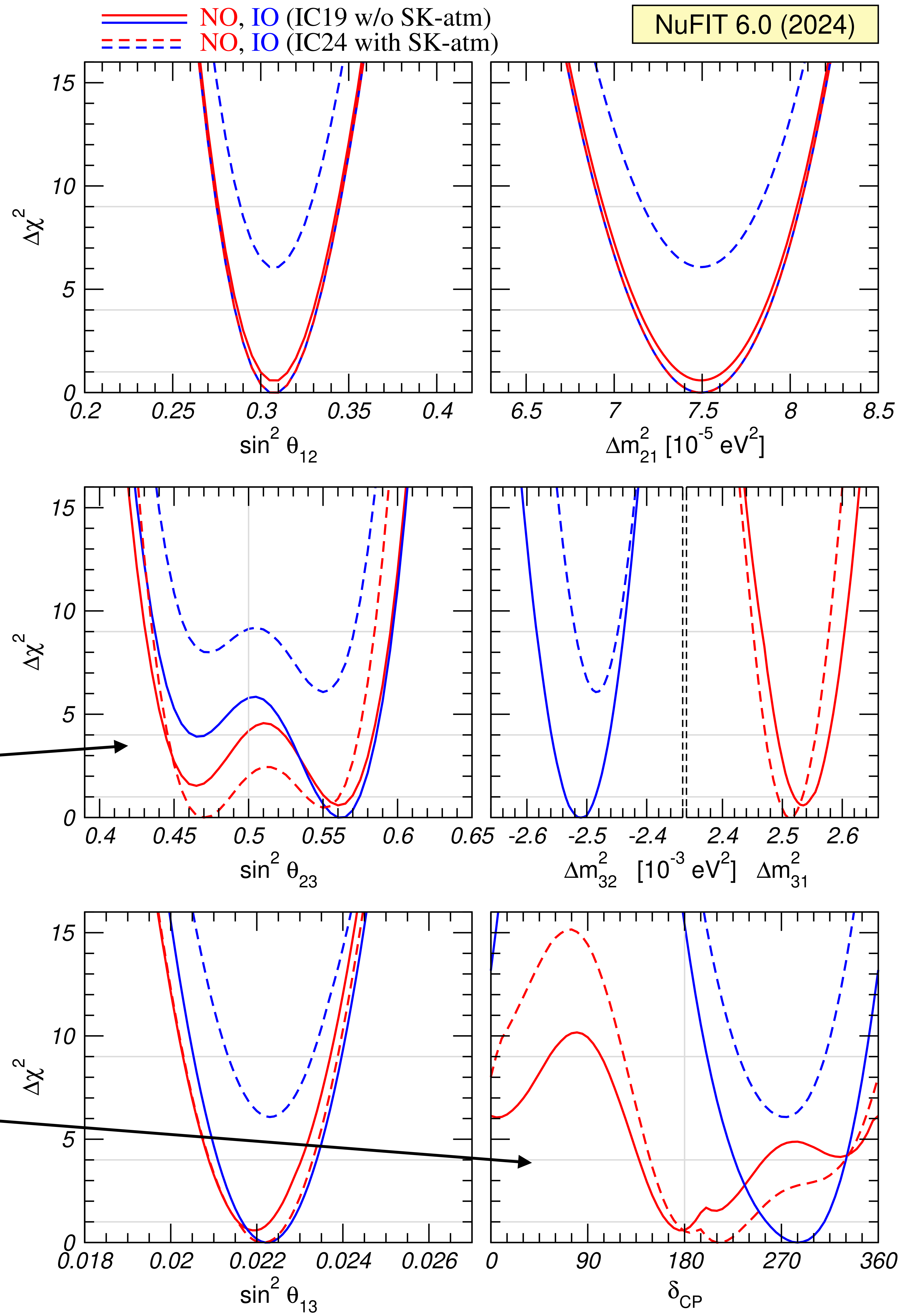


3-flavour oscillation parameters

the unknowns:

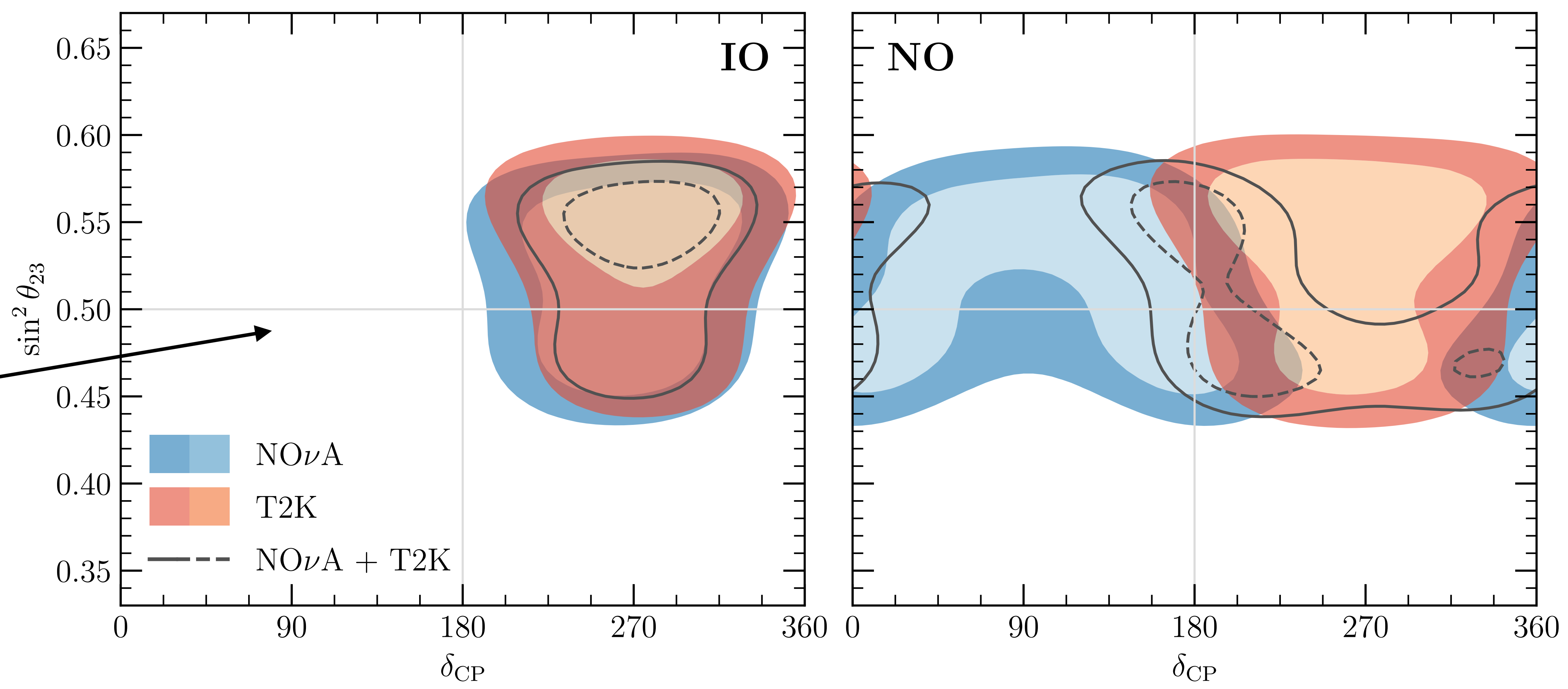
- neutrino mass ordering (red versus blue curves)
- octant ambiguity of θ_{23}
- complex phase δ_{CP} (leptonic CP violation)

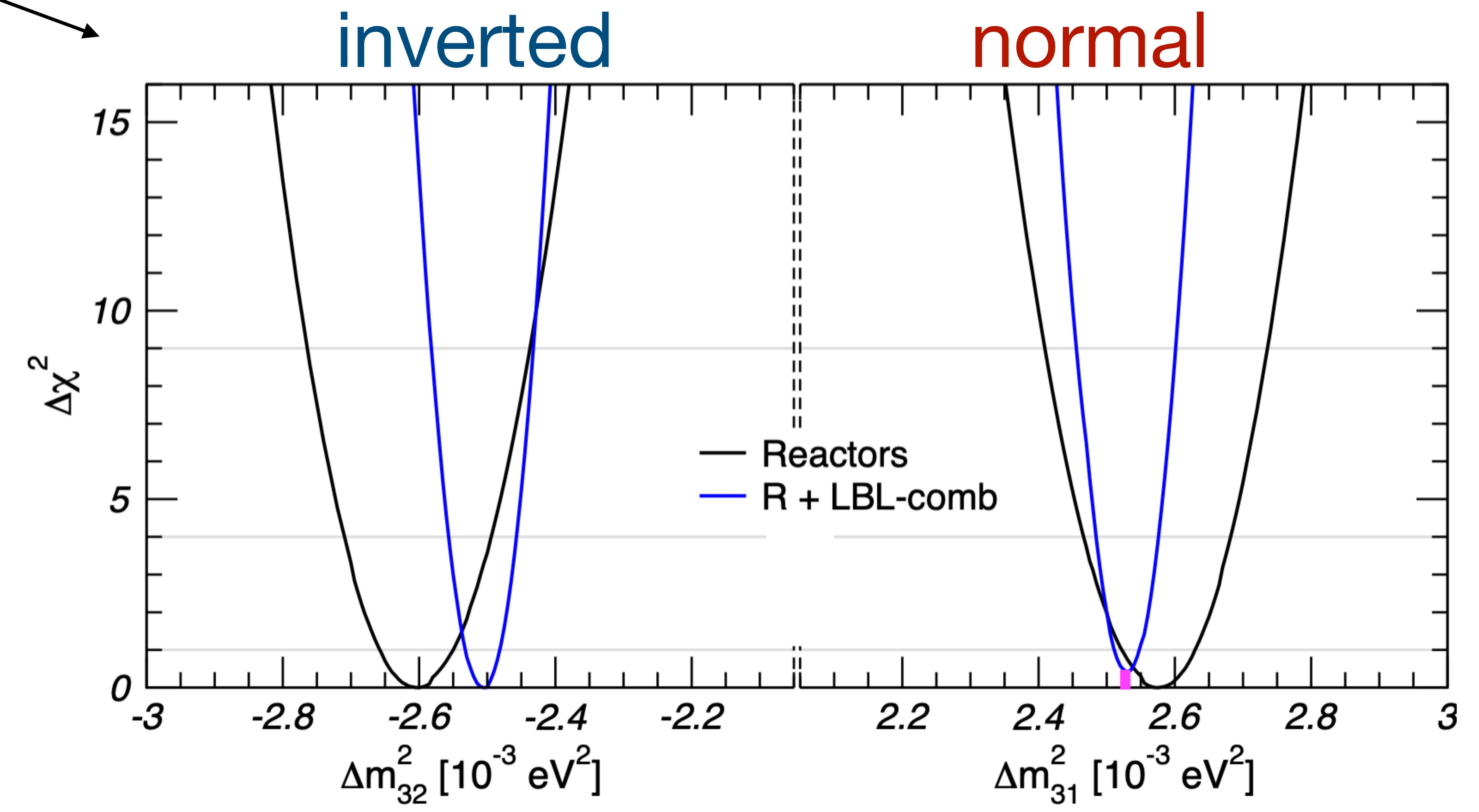




Neutrino mass ordering

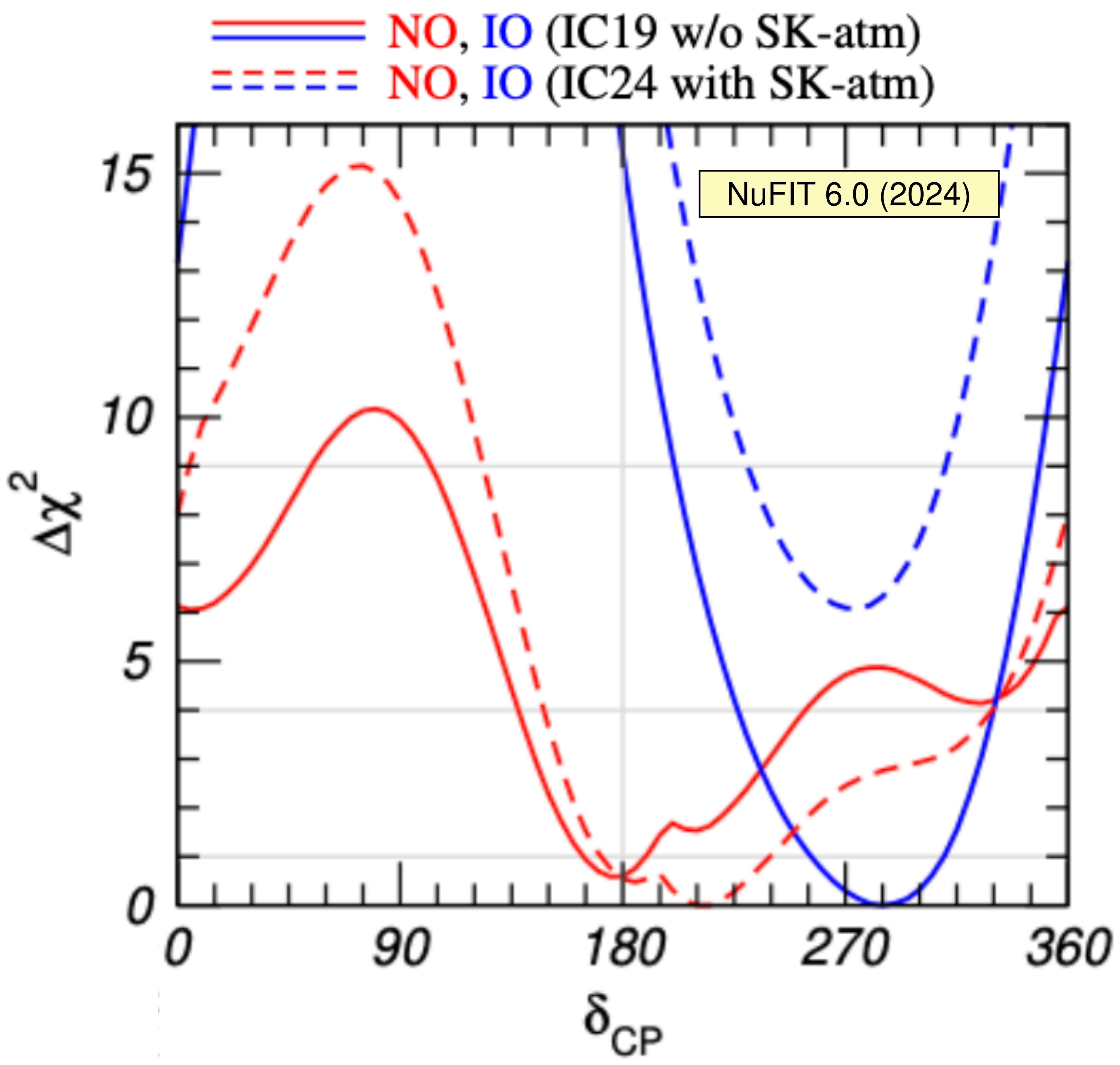
- different tendencies in global fit
  - T2K & NOvA (appearance) combination prefer inverted ordering
  - Reactor vs accelerator disappearance prefer normal ordering
  - SuperK and IC24 atmospheric prefer normal ordering

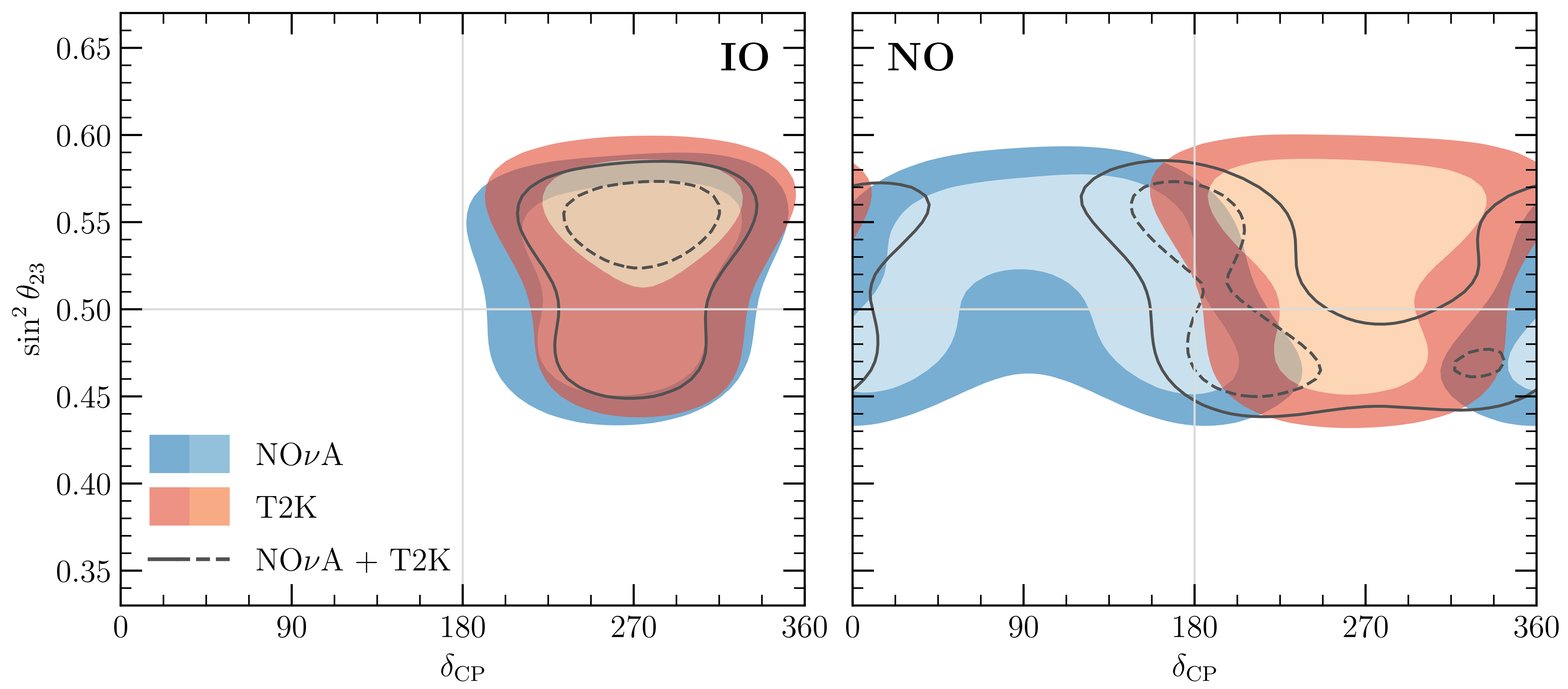




- final result in global fit: overall preference for normal ordering with $\Delta\chi^2_{\mathrm{IO-NO}} \approx 6.1$
  - sensitive to changes in the data

CP violation





- normal ordering:

  CP conservation ($\delta_{CP} \approx 180°$) at 1σ

- inverted ordering:

  preference for $\delta_{CP} \approx 270°$ (maximal CPV)

  CP conservation disfavoured at $> 3.6\sigma$

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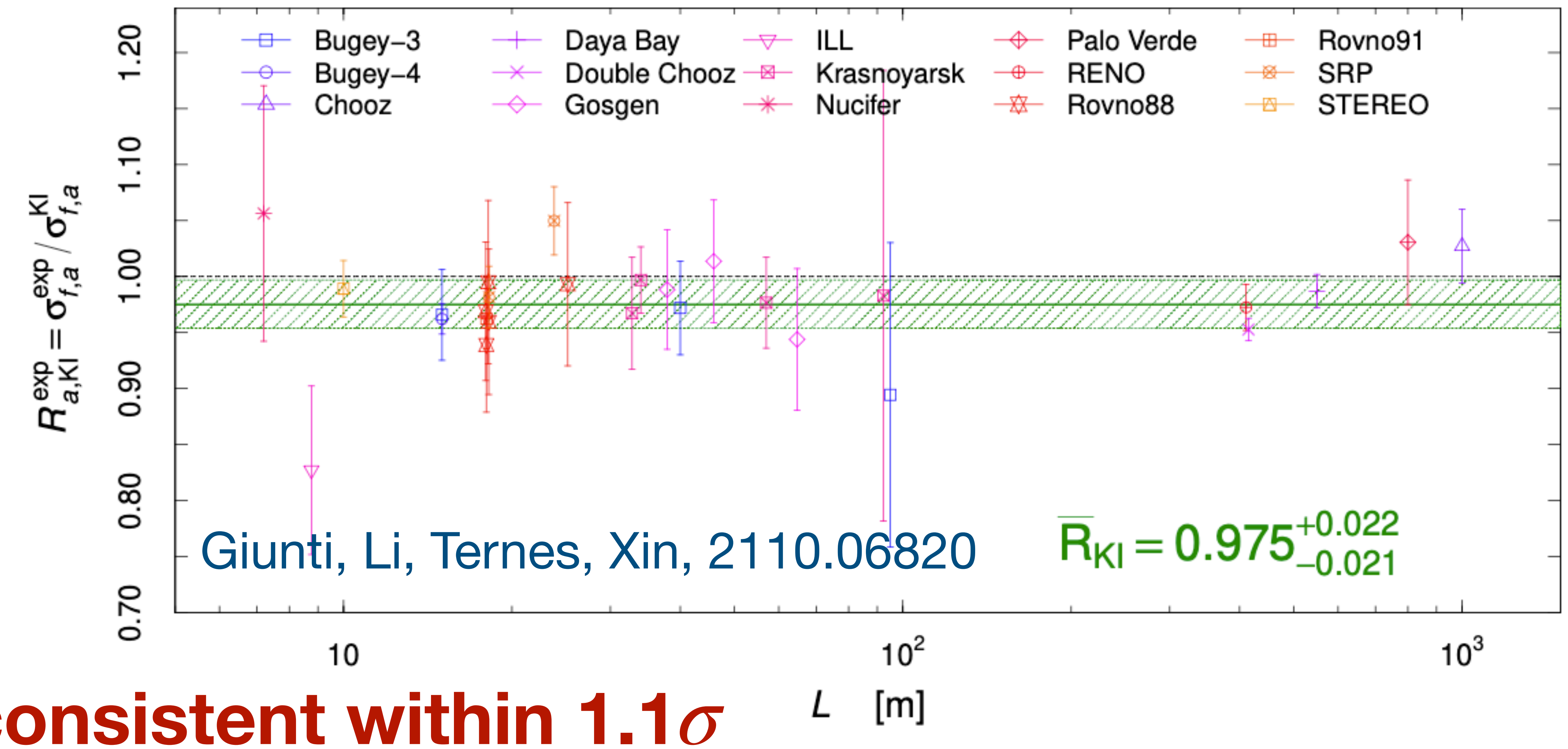
Short-baseline anomalies

Anomaly	Channel	Status	Explanation
Reactor rate and shape	$\nu_e \to \nu_e$	fading away (< 2σ) systematics dominated	systematics/nuclear physics
Gallium / BEST	$\nu_e \to \nu_e$	very significant (~5σ)	
LSND	$\nu_\mu \to \nu_e$	significant (3.8σ) ~25 yr anomaly	
MiniBooNE	$\nu_\mu \to \nu_e$	very significant (4.8σ) relies on background estimate	

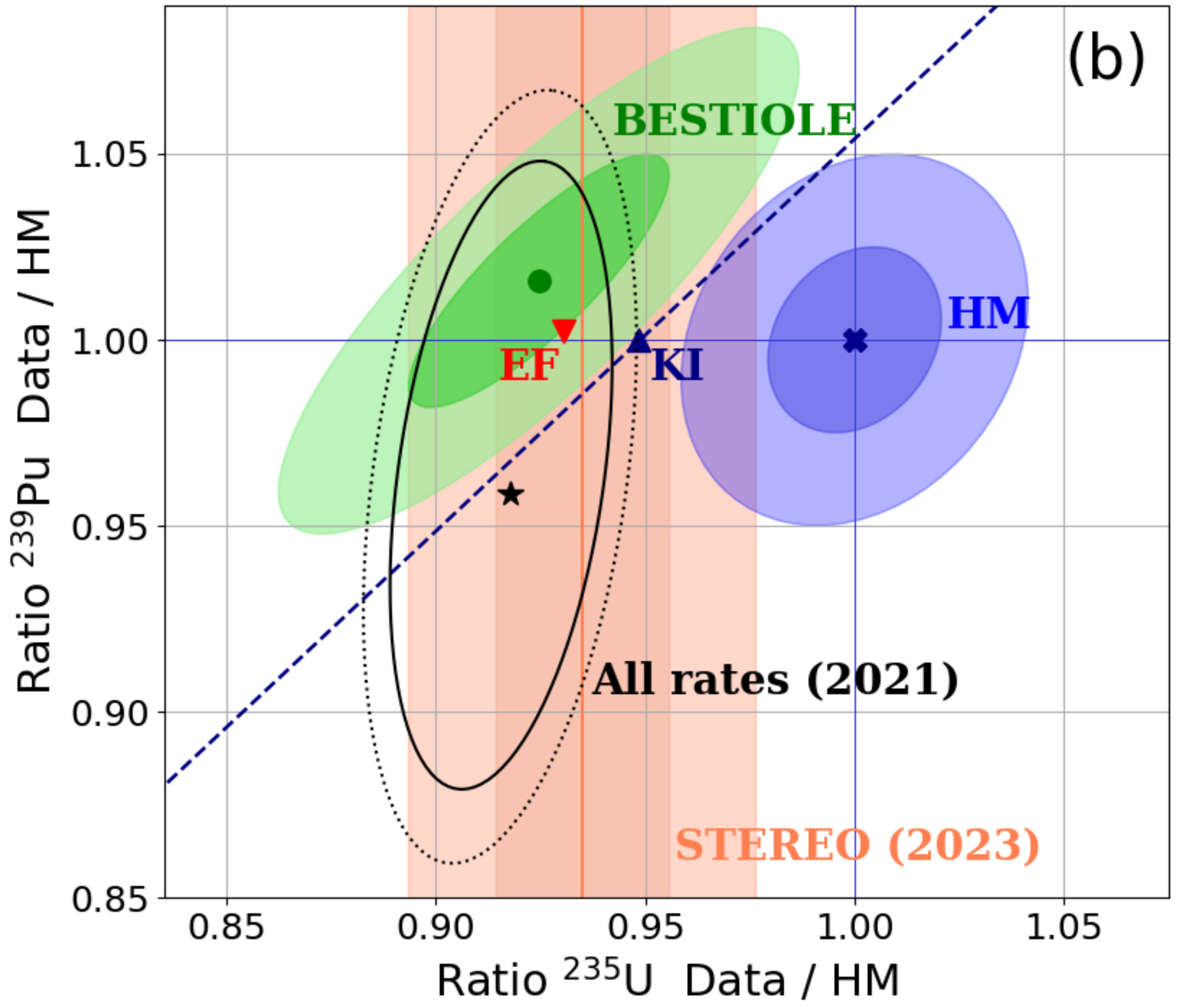
Reactor anomaly

- 2021: measurement of $^{235}U/^{239}Pu$ beta-sepctra @ Kurchatov Inst. (KI)
  Kopeikin, Skorokhvatov, Titov, 2103.01684
  5.4% smaller than ILL → suggests bias in ^{235}U ILL spectrum

- „ad-initio“ calculation of reactor neutrino spectrum Perissé et al. 2304.14992
  good agreement with measured neutrino rates



consistent within 1.1σ

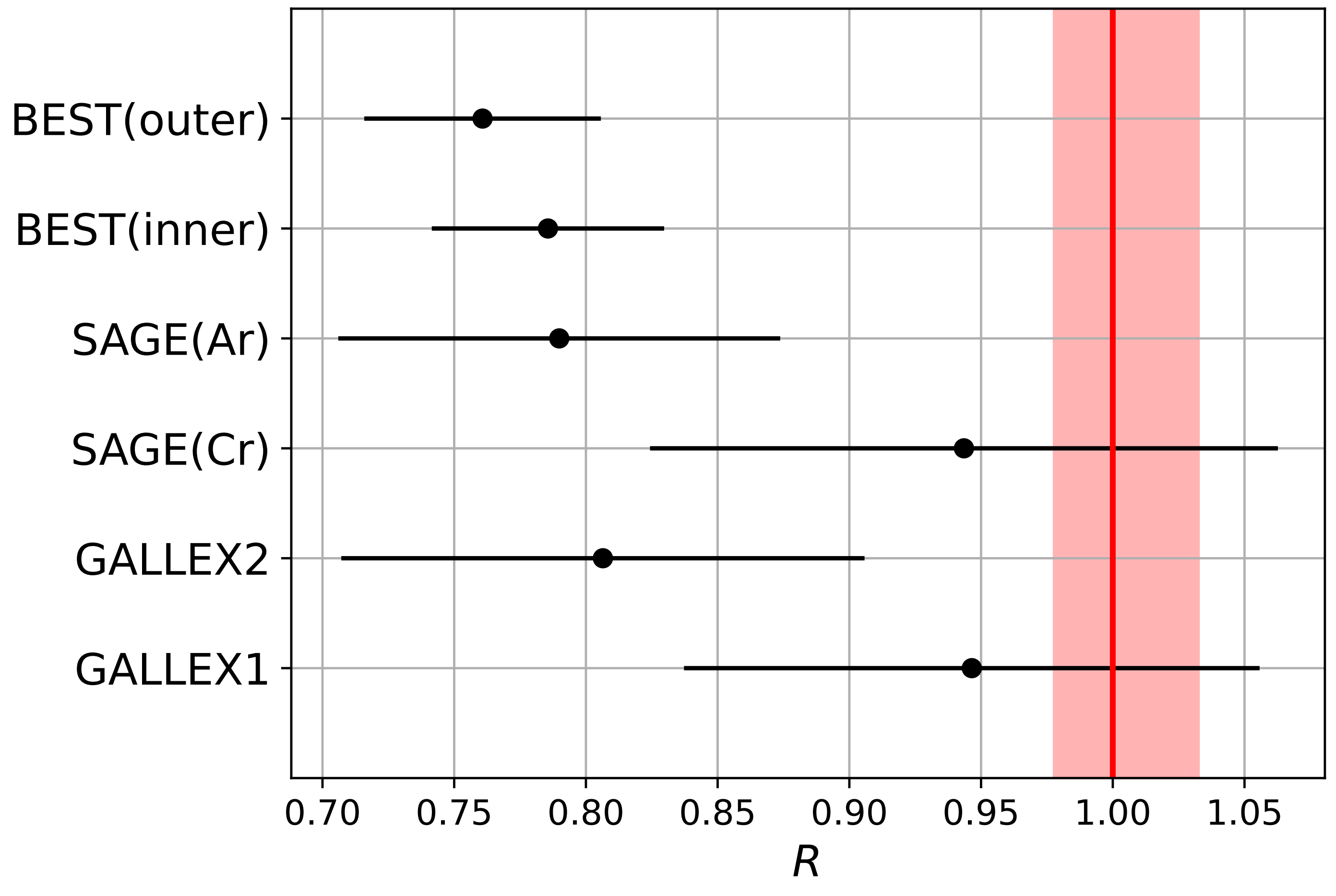


The gallium anomaly and BEST results

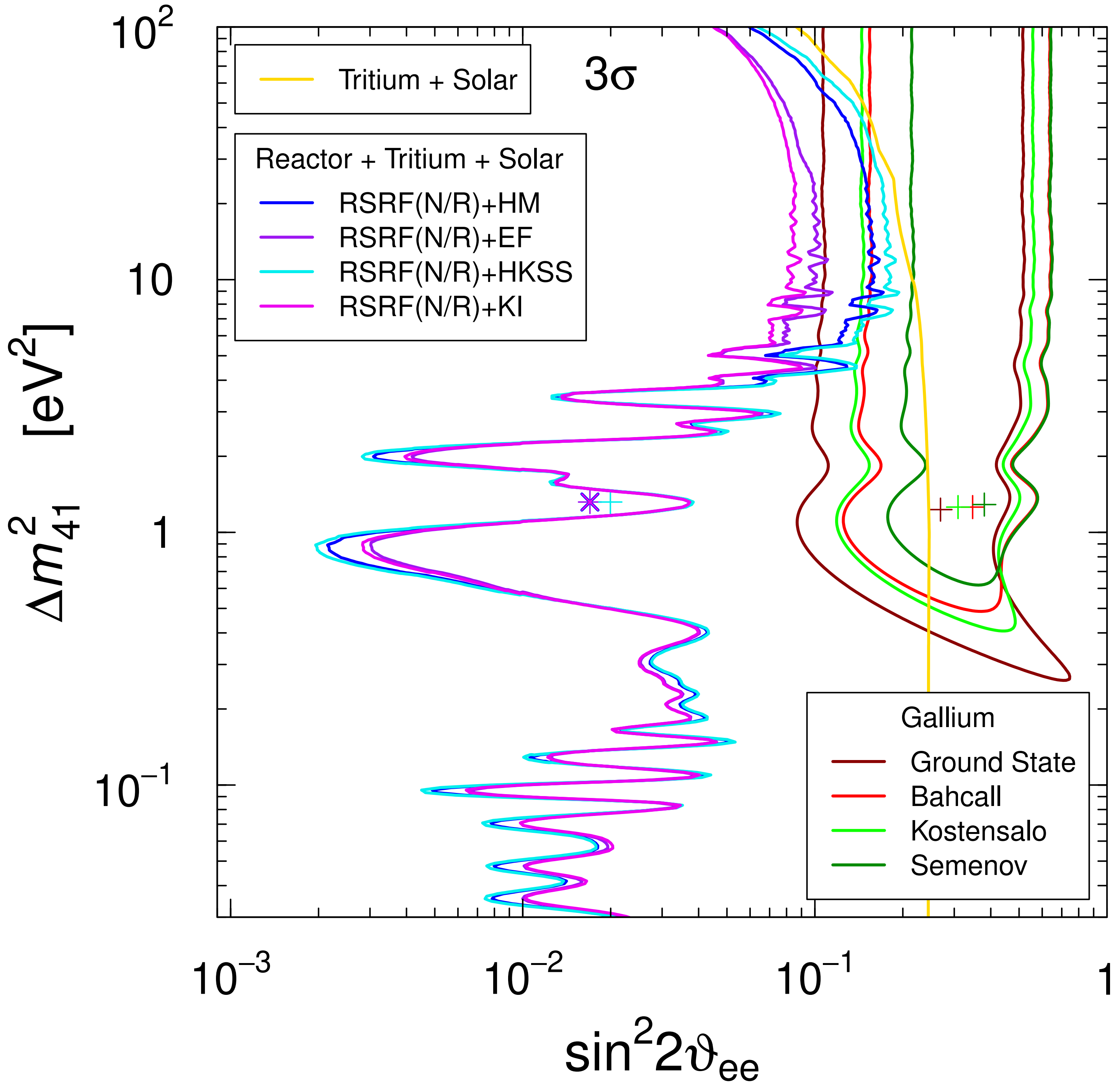
- Measurements of gallium experiments with radioactive ^{51}Cr or ^{37}Ar sources: rates lower than expected at high significance

	$\chi^2_{\rm null}/{\rm dof}$	p-value
CS1, BEST	32.1/2	1.1×10^{-7} (5.3σ)
CS1, all	36.3/6	2.4×10^{-6} (4.7σ)
CS2, BEST	34.7/2	2.9×10^{-8} (5.5σ)
CS2, all	38.4/6	9.4×10^{-7} (4.9σ)

Farzan, TS, 2306.09422
cross sections CS1, CS2
Haxton et al., 2303.13623
s. also Cadeddu et al, 2507.13103



- sterile neutrino oscillations in severe tension with solar and reactor neutrinos and cosmology
  Giunti, Li, Ternes, Tyagi, Xin, 2209.00916; Berryman, Coloma, Huber, TS, Zhou, 2111.12530; Goldhagen, Maltoni, Reichard, TS, 2109.14898



Giunti, Li, Ternes, Tyagi, Xin, 2209.00916

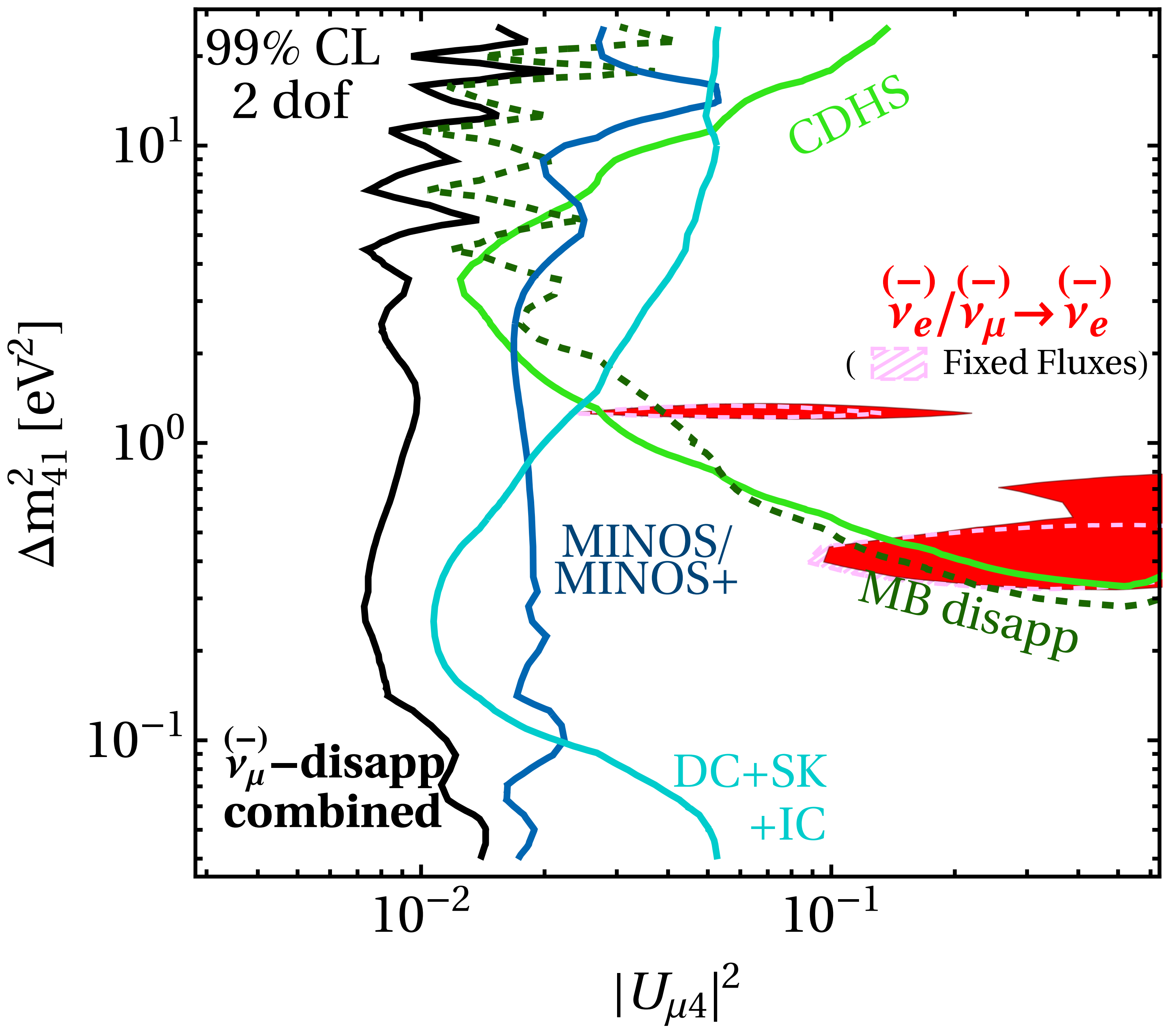
- **no convincing explanation is known** (BSM or conventional)
  Brdar, Gehrlein, Kopp, 2303.05528; Farzan, TS, 2306.09422

LSND, MiniBooNE

tension between appearance and disappearance data

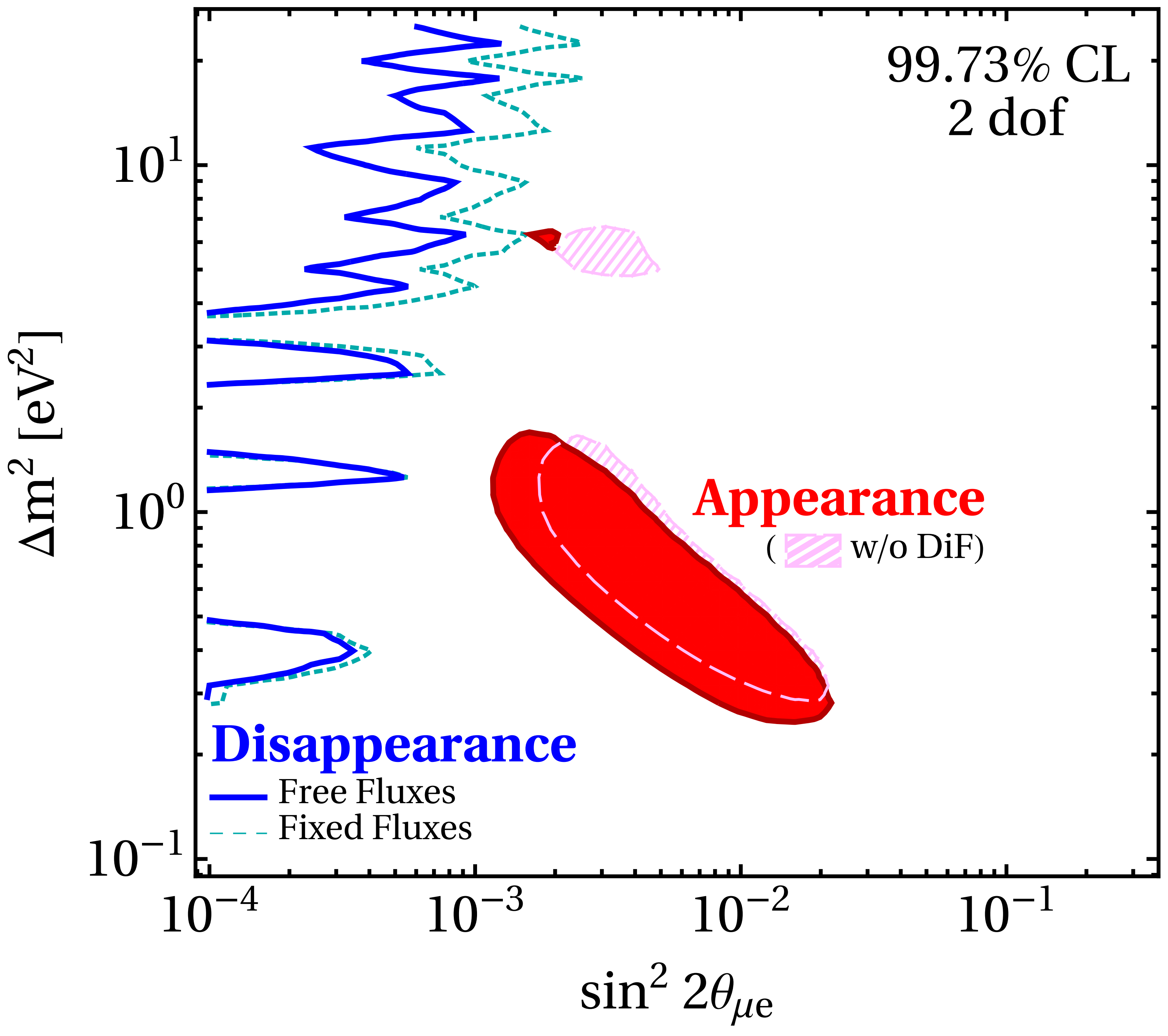
sterile oscillation explanation of LSND/MiniB robustly disfavoured

$$\sin^2 2\theta_{\mu e} \approx \frac{1}{4} \sin^2 2\theta_{ee} \sin^2 2\theta_{\mu\mu}$$



non-observation of oscillations in ν_μ disappearance (CDHS, MiniB, MINOS+, SK, IceCube)

Dentler et al, 1803.10661



consistency of appearance and disapp. data with a p-value $< 10^{-6}$

MiniBooNE and a decaying sterile neutrino

Palomares, Pascoli, TS, hep-ph/0505216; Gninenko, 0902.3802, 1009.5536; Bertuzzo, Jana, Machado, Zukanovich, 1807.09877; Ballett, Pascoli, Ross-Lonergan, 1808.2915; Arguelles, Hostert, Tsai, 1812.08768; Fischer, Hernandez, TS, 1909.09561; Dentler, Esteban, Kopp, Machado, 1911.01427; deGouvea, Peres, Prakash, Stenico, 1911.01447; Brdar, Fischer, Smirnov, 2007.14411; Abdallah, Gandhi, Roy, 2010.06159; Abdullahi, Hostert, Pascoli, 2007.11813; Abdullahi et al., 2308.02543; Hoster, Kelly, Zhou, 2406.04401; …

- sterile neutrino *N* with m_N ~ keV to ~500 MeV
- produce *N* either by mixing or by up-scattering
- decay:
  - $N \to \phi\, \nu_e$ with standard neutrino interaction in detector
  - electromagn. decay inside MB detector $N \to \nu\gamma \,/\, \nu e^{\pm} \,/\, \nu\pi^0 \,/\, \ldots$ (no LSND)
- exciting new physics / rich phenomenology / predict signatures in existing (near detectors) and/or upcoming experiments (e.g., Fermilab SBN, DUNE, HK, IceC)

Short-baseline anomalies

no convincing indication for eV-scale sterile neutrino oscillations

Anomaly	Channel	Status	Explanation
Reactor rate and shape	$\nu_e \to \nu_e$	fading away (< 2σ) systematics dominated	systematics/nuclear physics
Gallium / BEST	$\nu_e \to \nu_e$	very significant (~5σ)	**unknown**
LSND	$\nu_\mu \to \nu_e$	significant (3.8σ) ~25 yr anomaly	**unknown** HNL decay?
MiniBooNE	$\nu_\mu \to \nu_e$	very significant (4.8σ) relies on background estimate	

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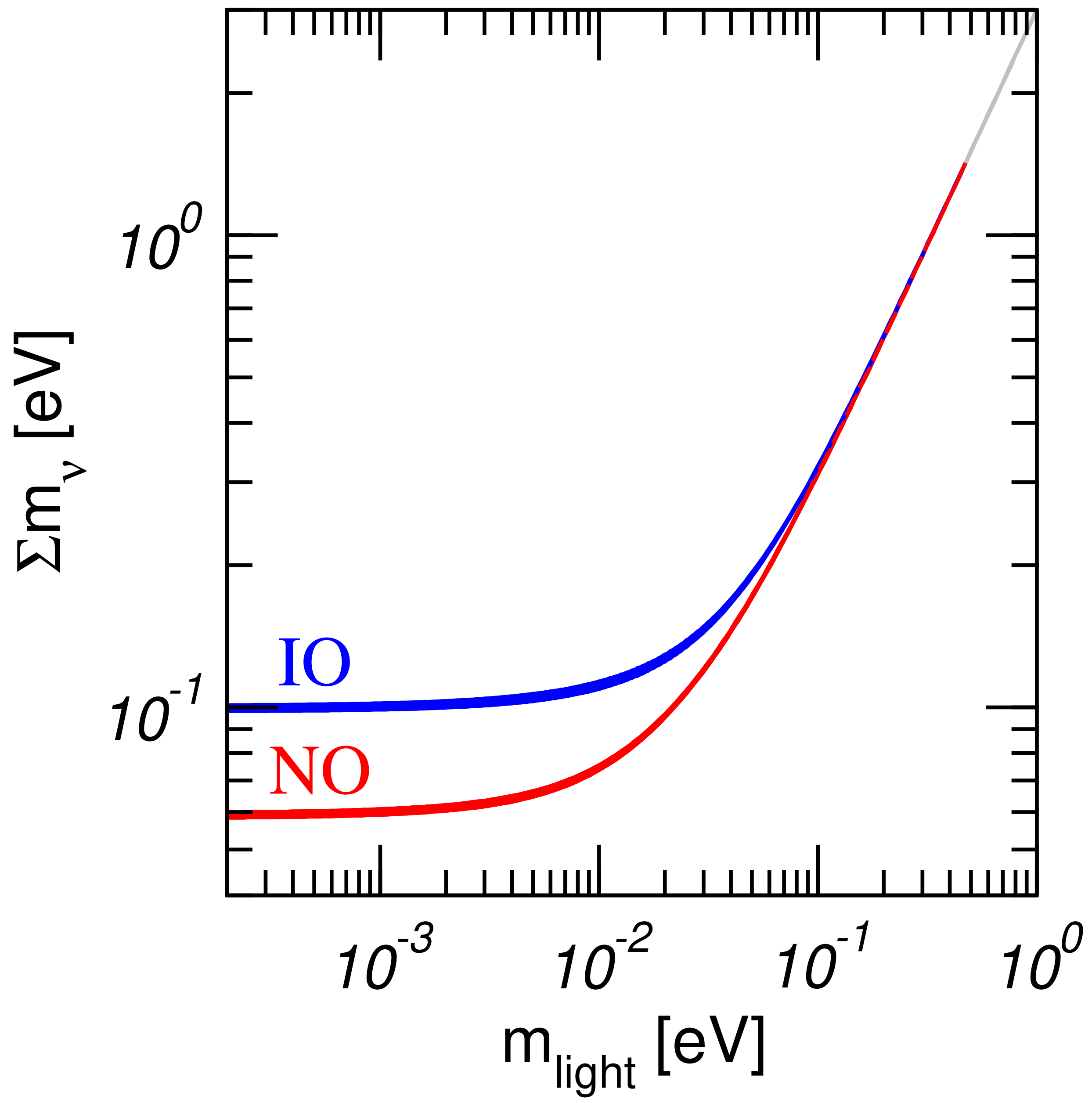
absolute neutrino mass

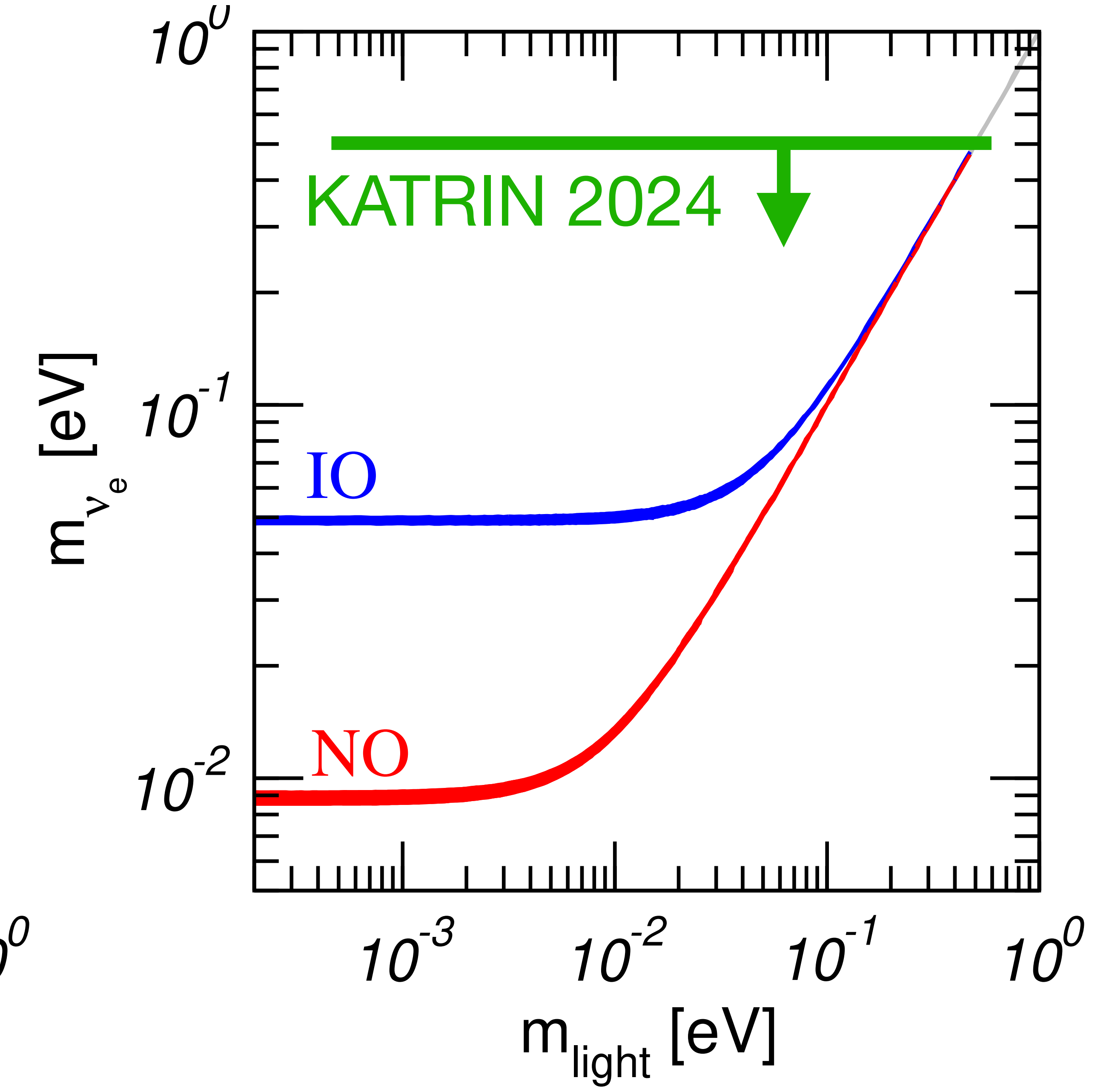
cosmology

$$\sum_i m_i \lesssim 0.1\,\text{eV}$$



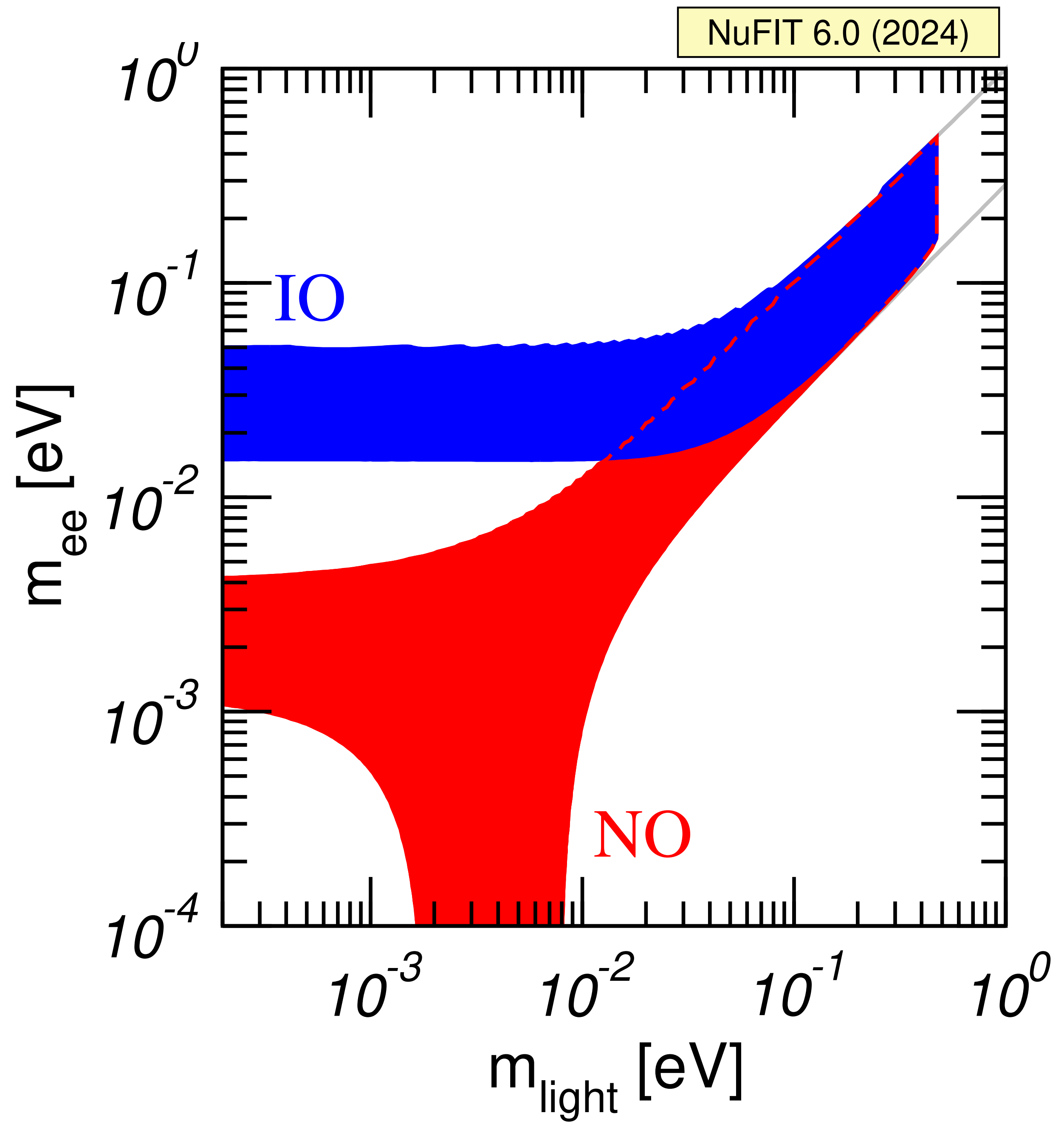
beta-decay spectrum
(KATRIN)

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2} < 0.45\,\text{eV}$$



neutrinoless double-beta decay
(assuming Majorana neutrinos)

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right| \lesssim 0.07\,\text{eV}$$



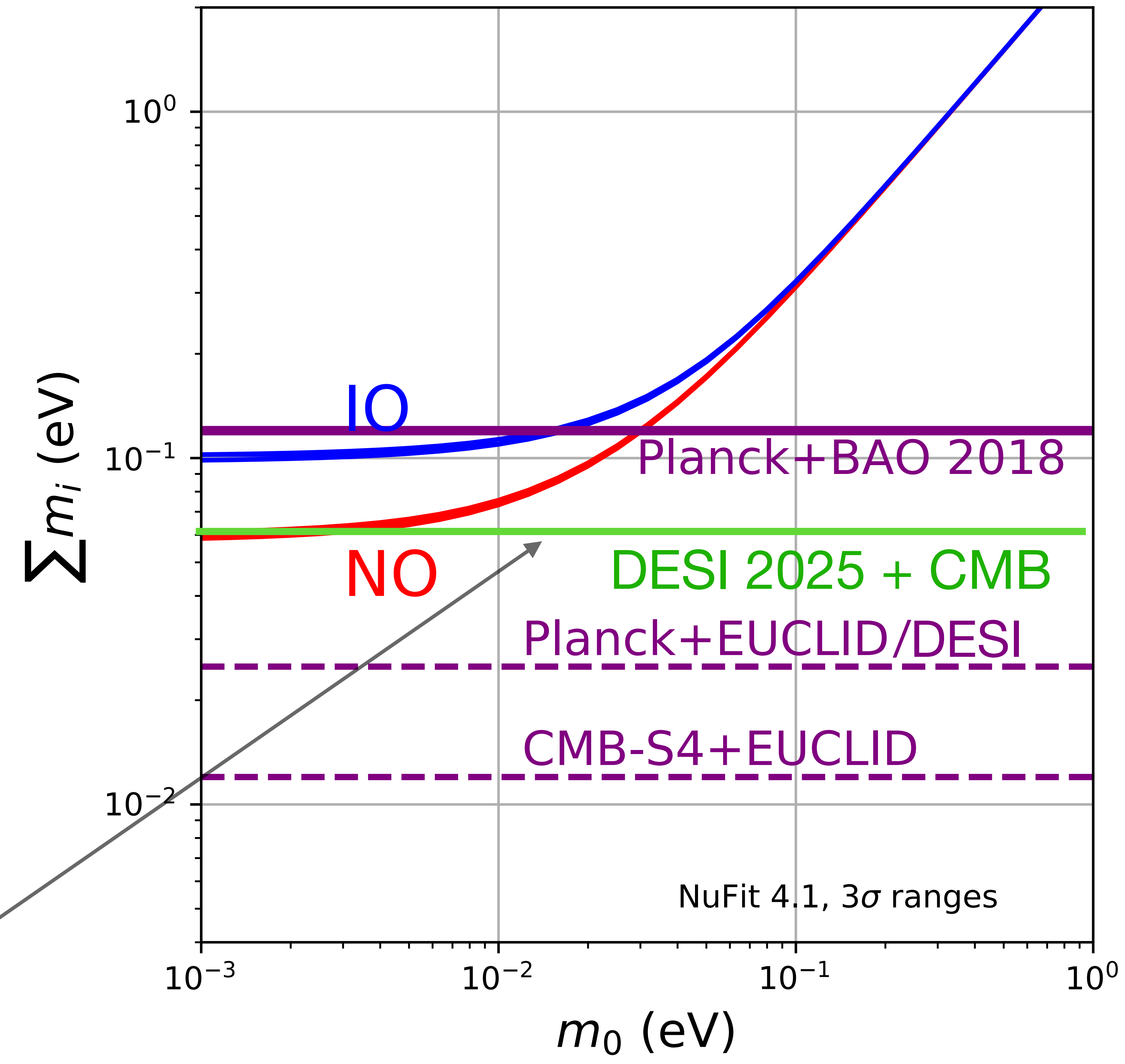
Neutrino mass from cosmology

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m^2_{21} + m_0^2} + \sqrt{\Delta m^2_{31} + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m^2_{32}| + m_0^2} + \sqrt{|\Delta m^2_{32}| - \Delta m^2_{21} + m_0^2} & \text{(IO)} \end{cases}$$

- minimal values predicted from oscillation data for $m_0 = 0$:

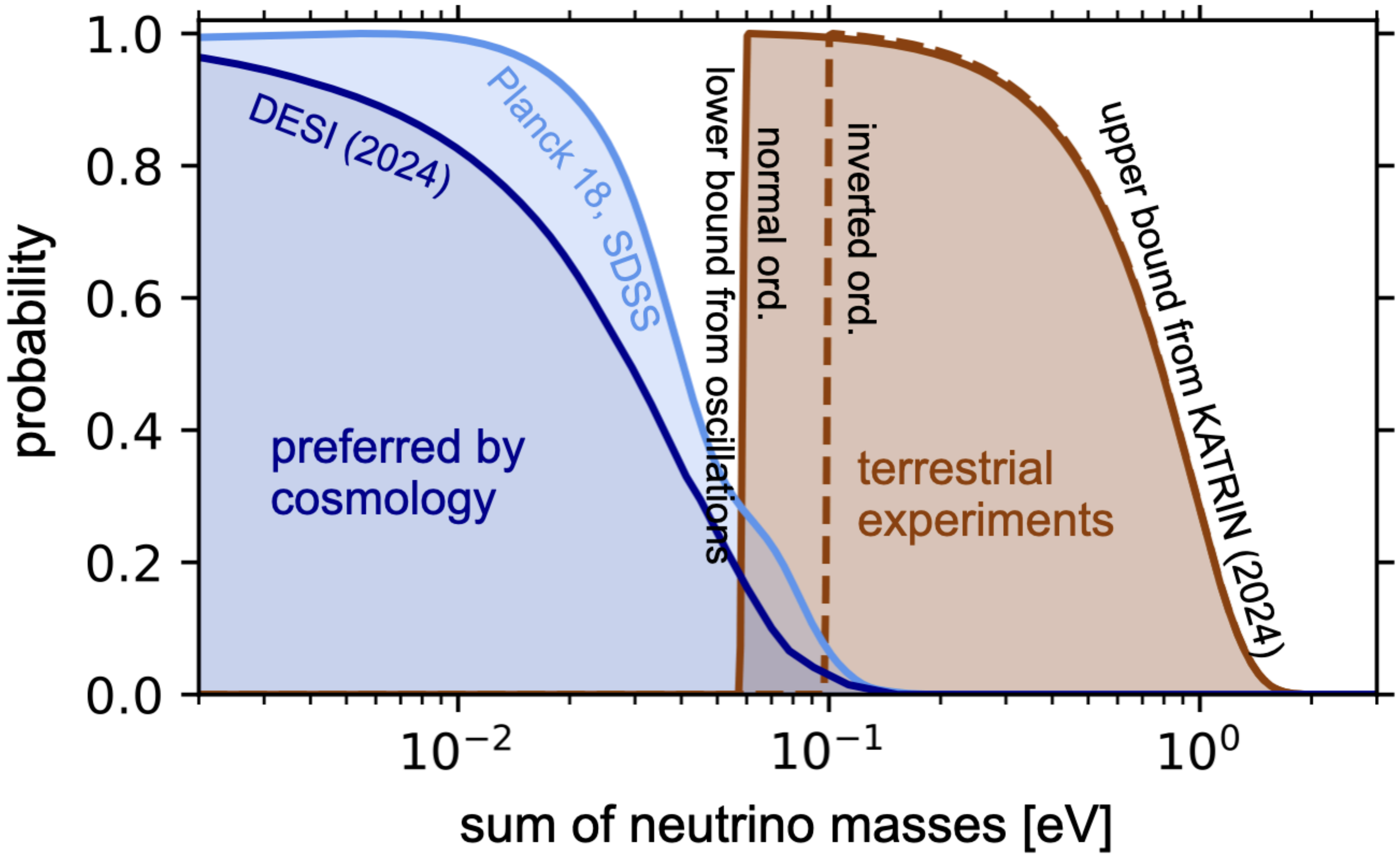
$$\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85\,\text{meV} & \text{(IO)} \\ 58.5 \pm 0.48\,\text{meV} & \text{(NO)} \end{cases}$$

- **Upper bounds from current data:**
  - $\Sigma m_\nu < 0.12\,\text{eV}\ (95\,\%\ \text{CL})$ Planck CMB+BAO 2018
  - $\Sigma m_\nu < 0.064\,\text{eV}\ (95\,\%\ \text{CL})$ DESI 2025 + CMB



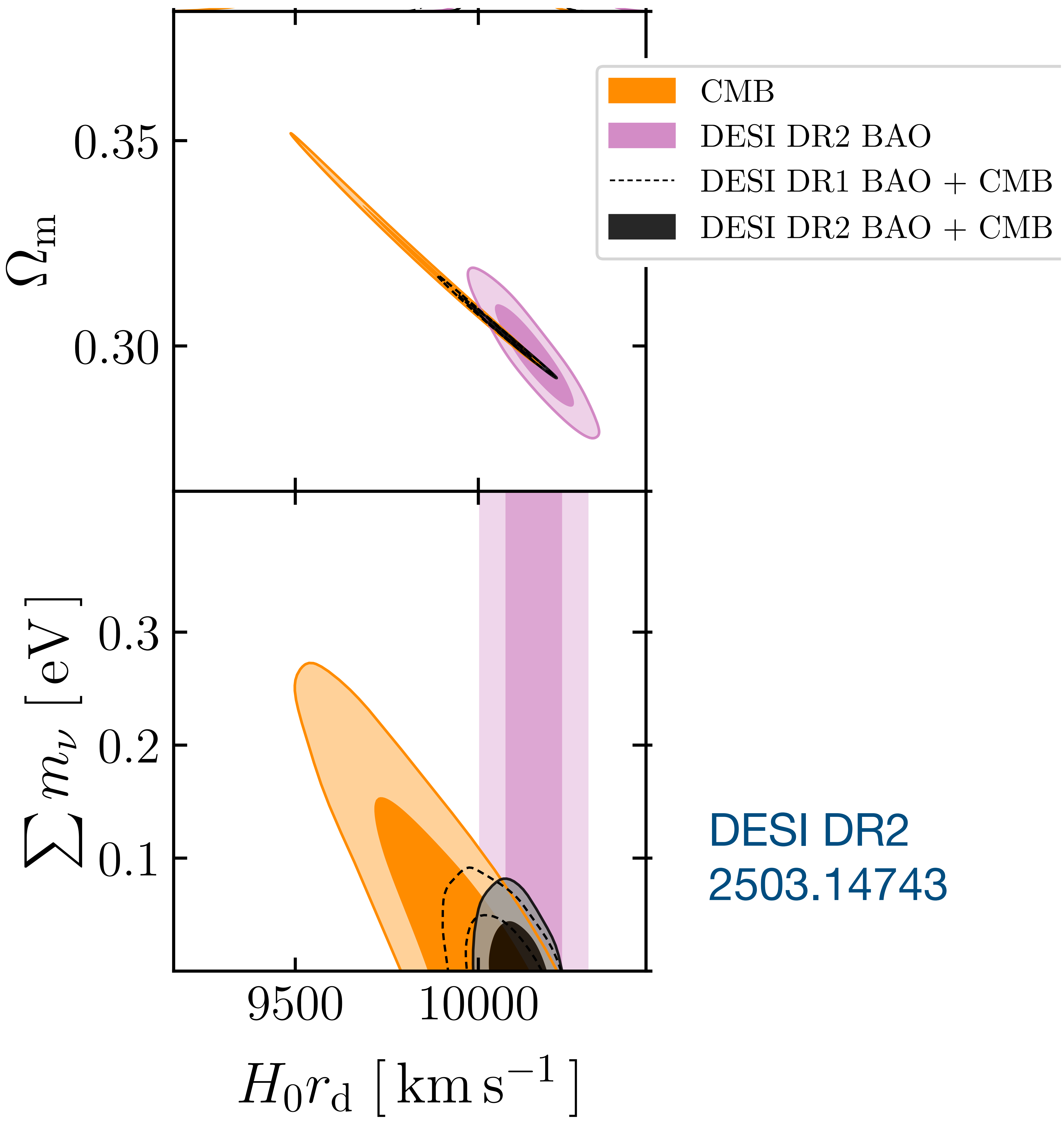
Tension between cosmology and laboratory?

updated from Gariazzo, Mena, TS, 2302.14159



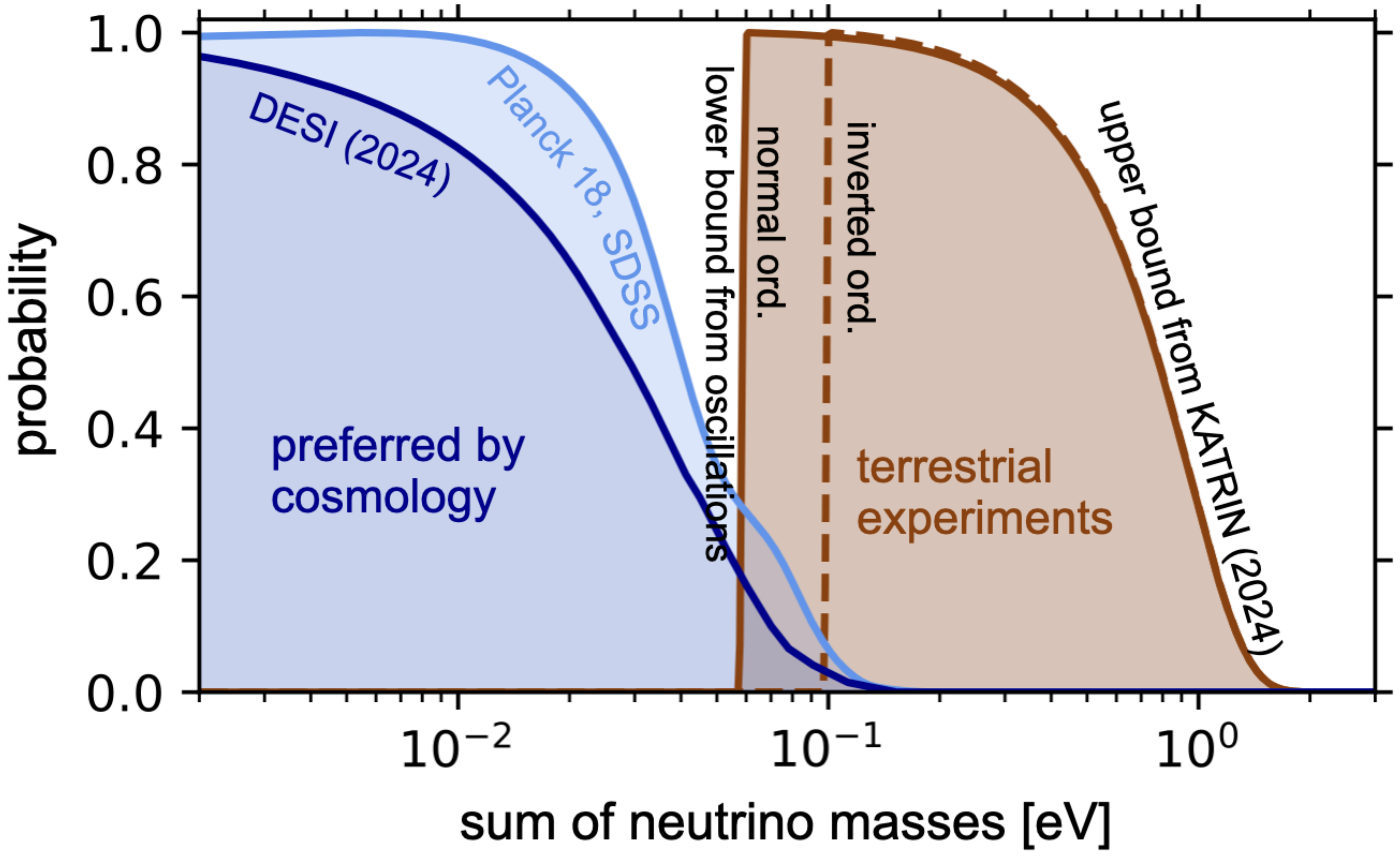
Tensions in cosmology

- Hubble tension
- CMB-BAO tension?
- Neutrino tension?



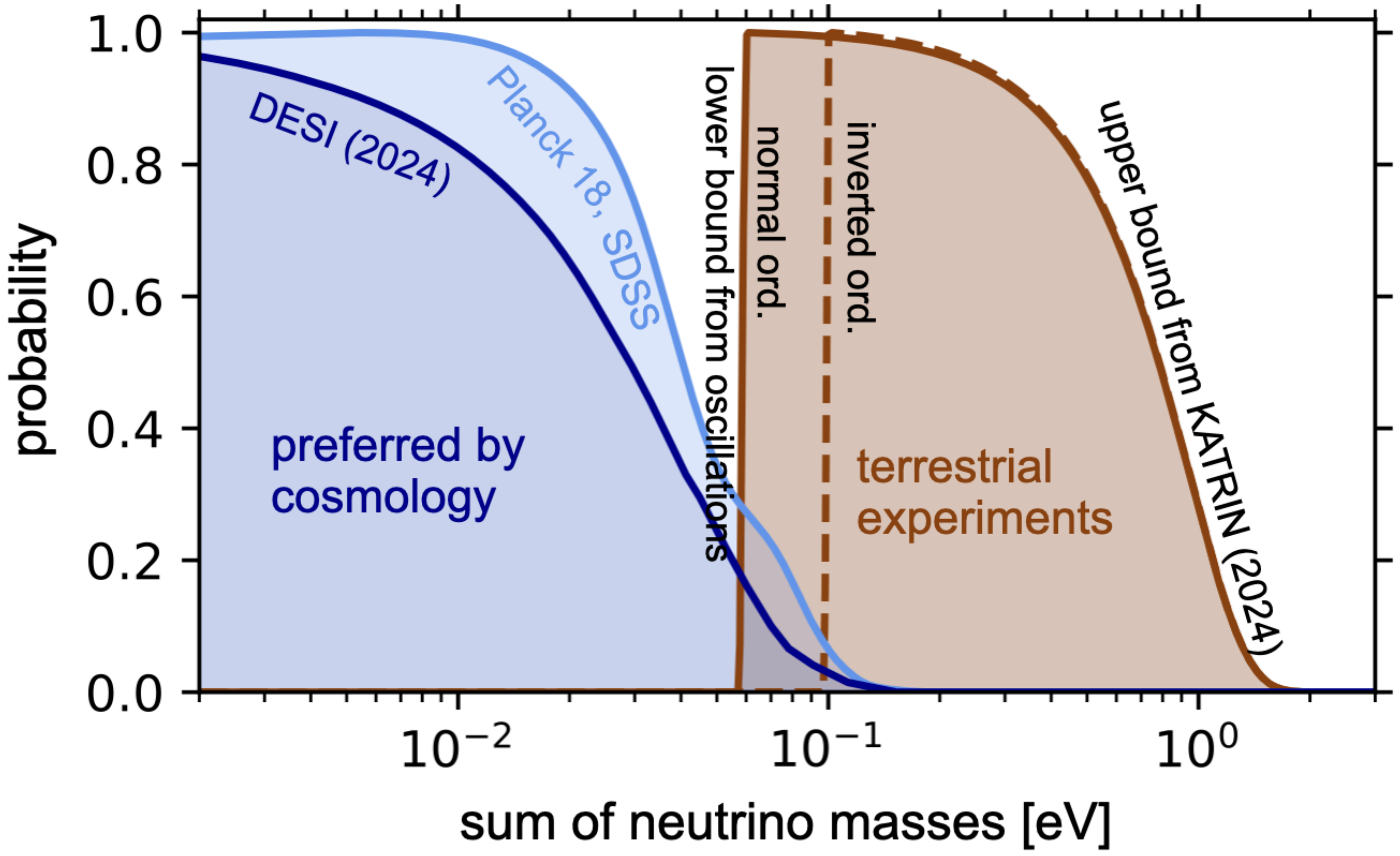
DESI DR2
2503.14743

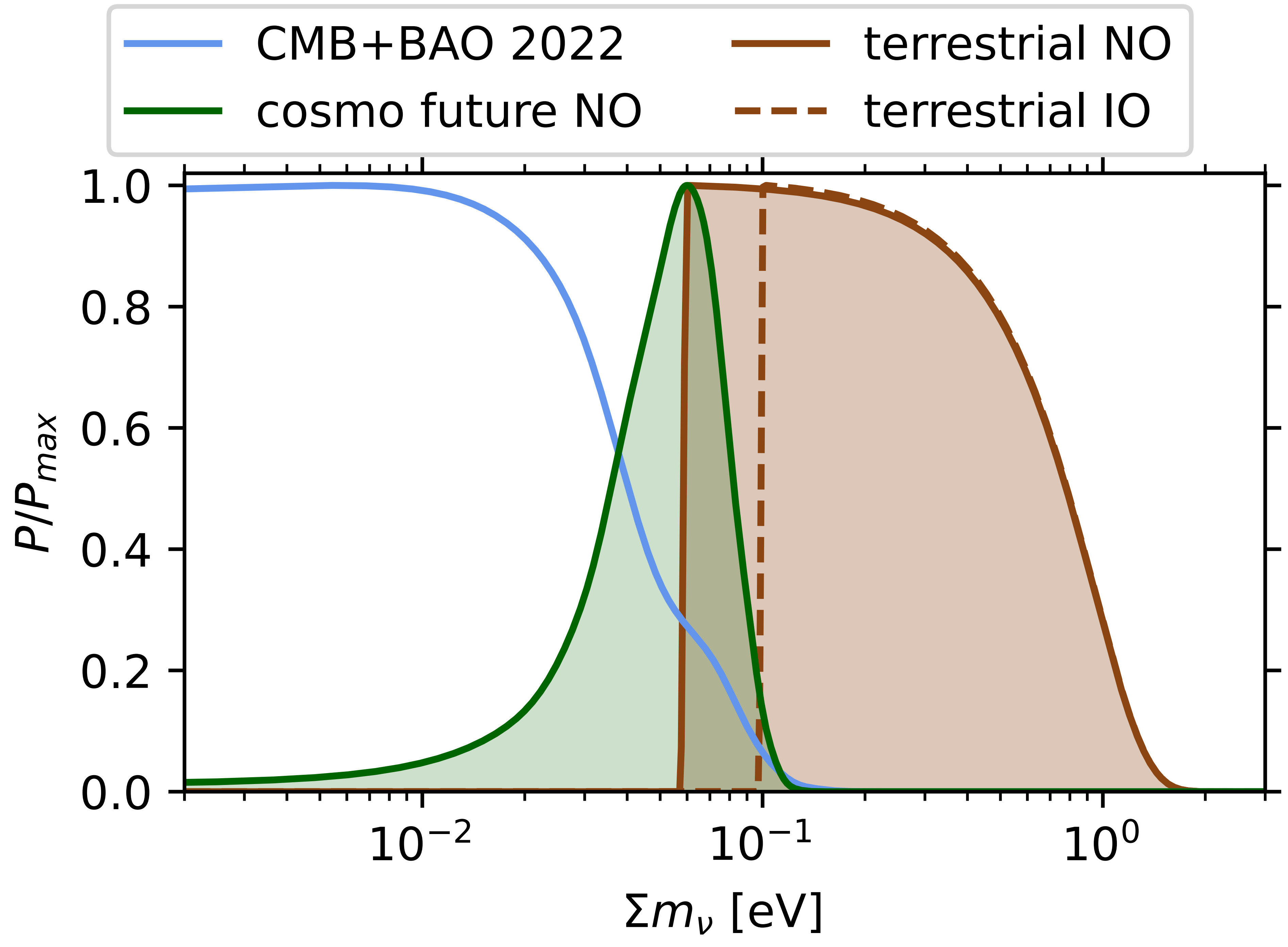
Mass ordering from cosmology?



Mass ordering from cosmology?

require first a positive neutrino mass signal from cosmology (without tensions)
only then we can consider NO vs IO hypothesis test





updated from Gariazzo, Mena, TS, 2302.14159

Cosmology bounds can be relaxed in non-standard scenarios

- dynamical dark energy

  Mena et al; Green, Meyers, 2407.07878; DESI 2025, 2503.14738: $\sum m_\nu < 0.14\,\mathrm{eV}$

- neutrino decay into dark radiation

  Chacko et al. 1909.05275; 2002.08401; Escudero et al., 2007.04994;
  Barenboim et al.,2011.01502; Chacko et al. 2112.13862: $\sum m_\nu < 0.42\,\mathrm{eV}$

- time dependent neutrino mass

  Lorenz et al. 1811.01991; 2102.13618; Esteban, Salvado, 2101.05804;
  Sen, Smirnov, 2306.15718, 2407.02462

- modified momentum distribution

  Cuoco et al., astro-ph/0502465; Barenboim et al., 1901.04352;
  Alvey, Sabti, Escudero, 2111.14870

- reduced neutrino density + dark radiation

  Beacom, Bell, Dodelson, 04; Farzan, Hannestad, 1510.02201; Renk, Stöcker et al., 2009.03286;
  Escudero, TS, Terol-Calvo, 2211.01729; Das, Dev et al., 2506.08085

incomplete!

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Example 1

- neutrino decay into dark radiation

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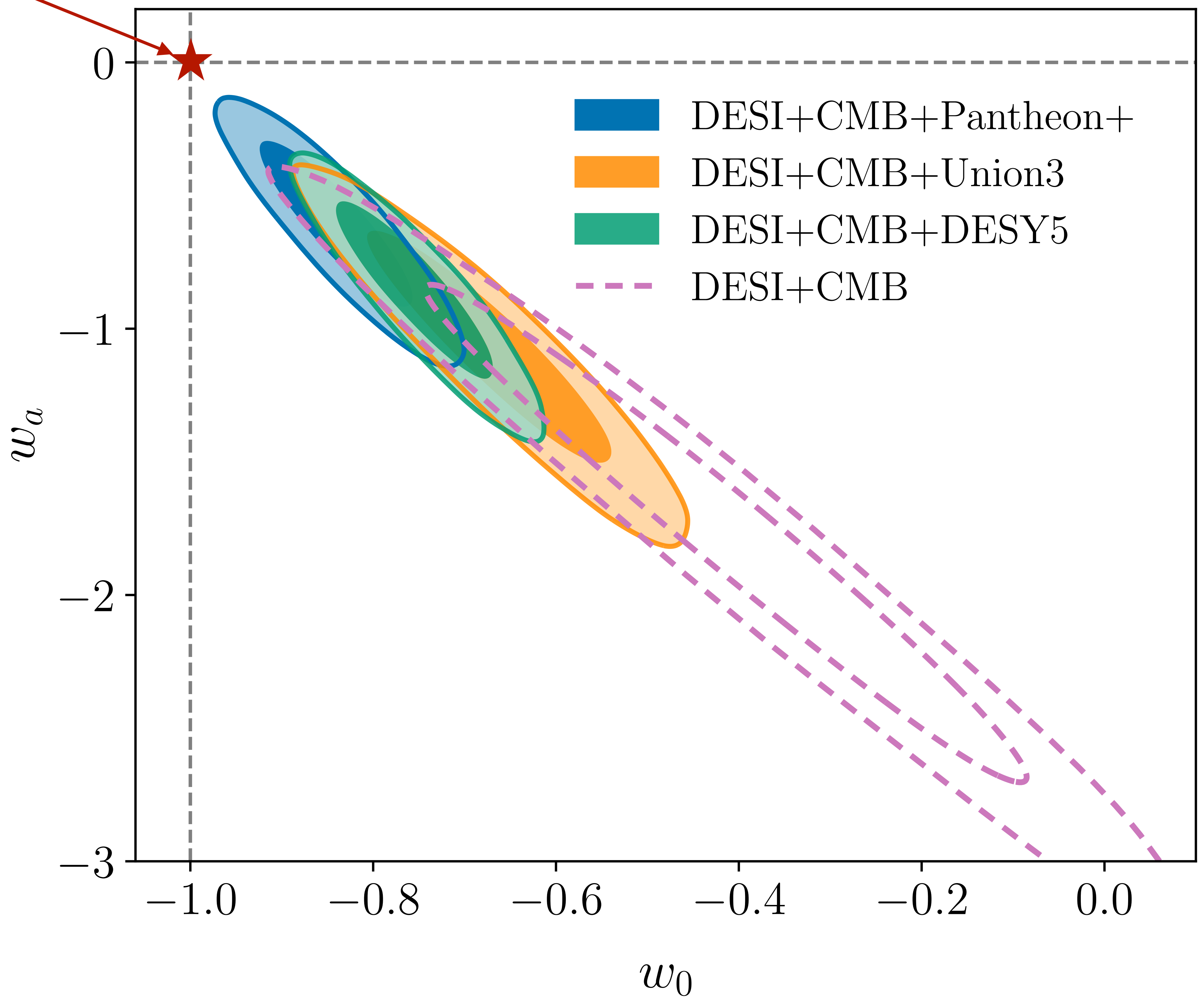
incomplete!

Example 1: hint for dynamical dark energy?

cosm . const . : $w_0 = -1, w_a = 0$

DESI DR2 2025 [2503.14738]



DE equation of state: $p = w\rho$

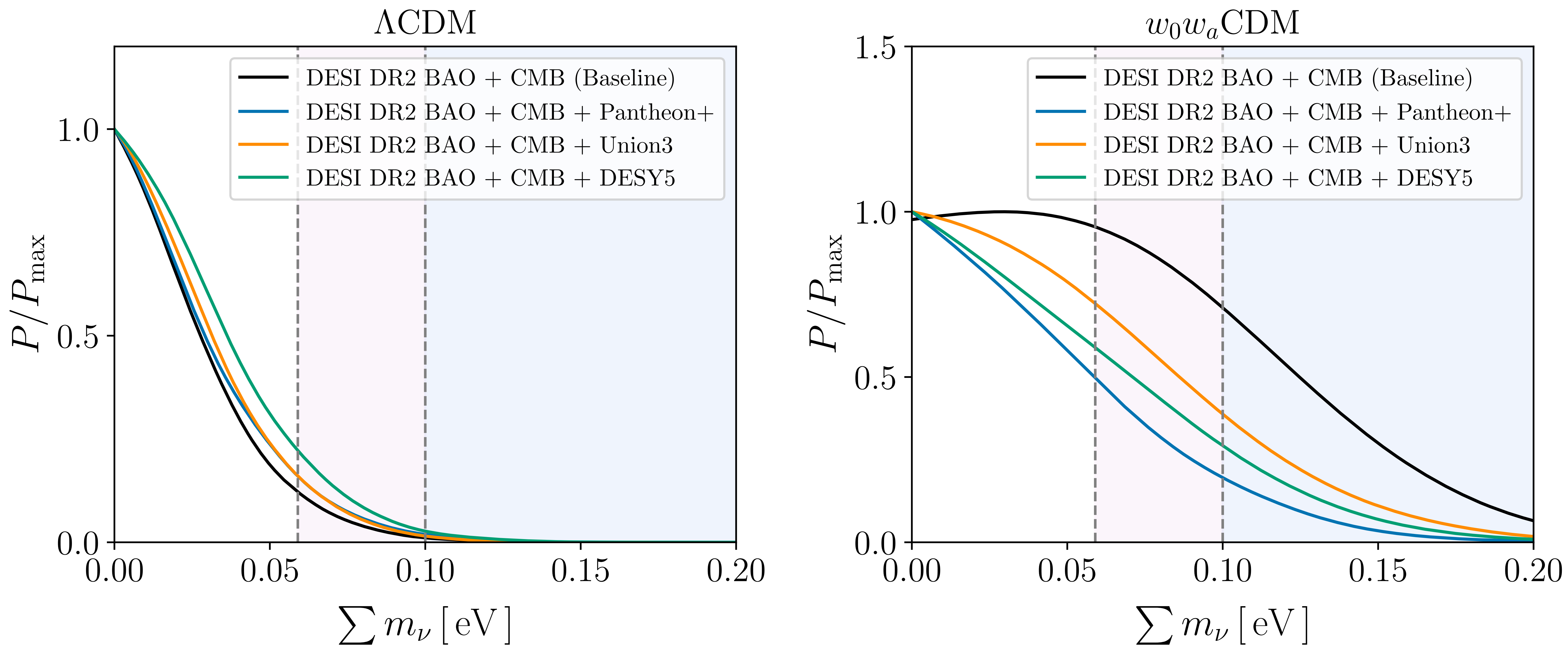
$$w(z) = w_0 + w_a \frac{z}{1+z}$$

$2.8\sigma - 4.2\sigma$ indication for deviation from cosmolog. const.

Example 1: hint for dynamical dark energy?

	$\sum m_\nu$ [eV]
ΛCDM+$\sum m_\nu$	
DESI BAO+CMB [Camspec]	< 0.0642
DESI BAO+CMB [L-H]	< 0.0774
DESI BAO+CMB [Plik]	< 0.0691

	$\sum m_\nu$ [eV]
$w_0 w_a$CDM+$\sum m_\nu$	
DESI BAO+CMB	< 0.163
DESI BAO+CMB+Pantheon+	< 0.117
DESI BAO+CMB+Union3	< 0.139
DESI BAO+CMB+DESY5	< 0.129



DESI DR2
[2503.14743]

Cosmology bounds can be relaxed in non-standard scenarios

- dynamical dark energy

  Mena et al; Green, Meyers, 2407.07878; DESI 2025, 2503.14738: $\sum m_\nu < 0.14\,\mathrm{eV}$

- neutrino decay into dark radiation

  Chacko et al. 1909.05275; 2002.08401; Escudero et al., 2007.04994;
  Barenboim et al.,2011.01502; Chacko et al. 2112.13862: $\sum m_\nu < 0.42\,\mathrm{eV}$

- time dependent neutrino mass

  Lorenz et al. 1811.01991; 2102.13618; Esteban, Salvado, 2101.05804;
  Sen, Smirnov, 2306.15718, 2407.02462

- modified momentum distribution

  Cuoco et al., astro-ph/0502465; Barenboim et al., 1901.04352;
  Alvey, Sabti, Escudero, 2111.14870

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  Escudero, TS, Terol-Calvo, 2211.01729; Das, Dev et al., 2506.08085

incomplete!

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incomplete!

Example 2

- reduced neutrino density + dark radiation

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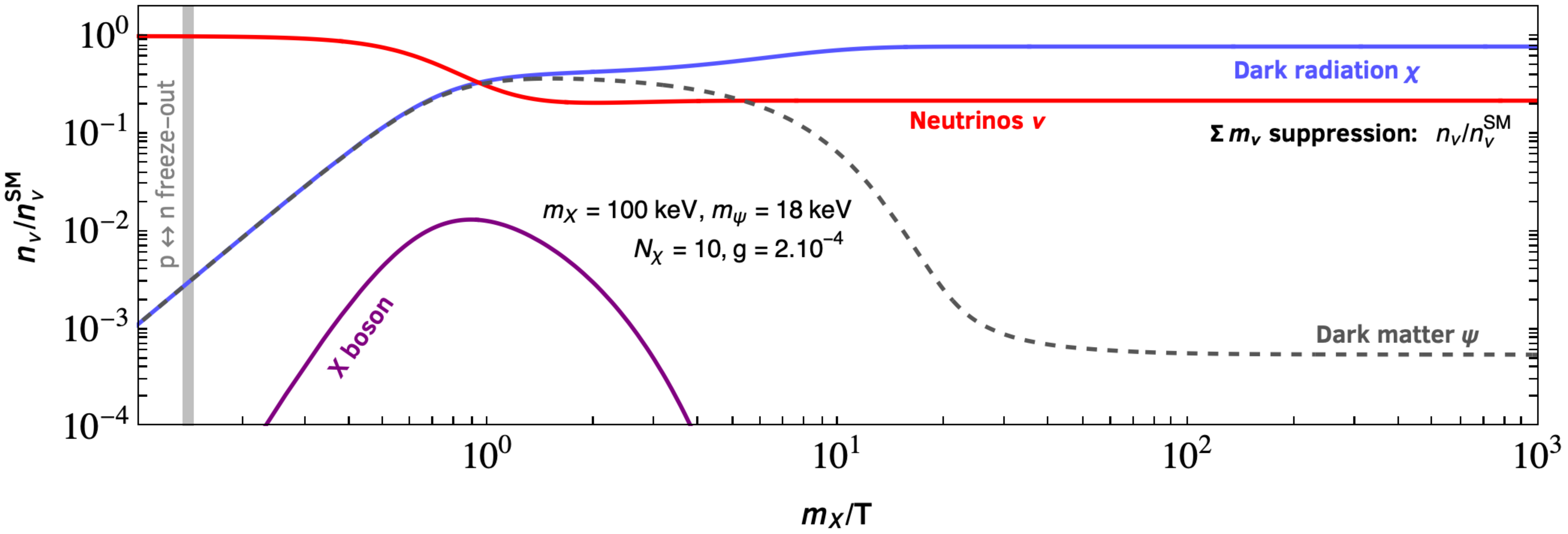
Example 2: light dark sector

Escudero, TS, Terol-Calvo, 2211.01729
Benso, TS, Vatsyayan, 2410.23926



- postulate a light dark sector with (many) massless sterile neutrinos
- equilibrate DS via Z' mediator with SM neutrinos btw BBN and recombination
- can accommodate a sterile neutrino DM candidate

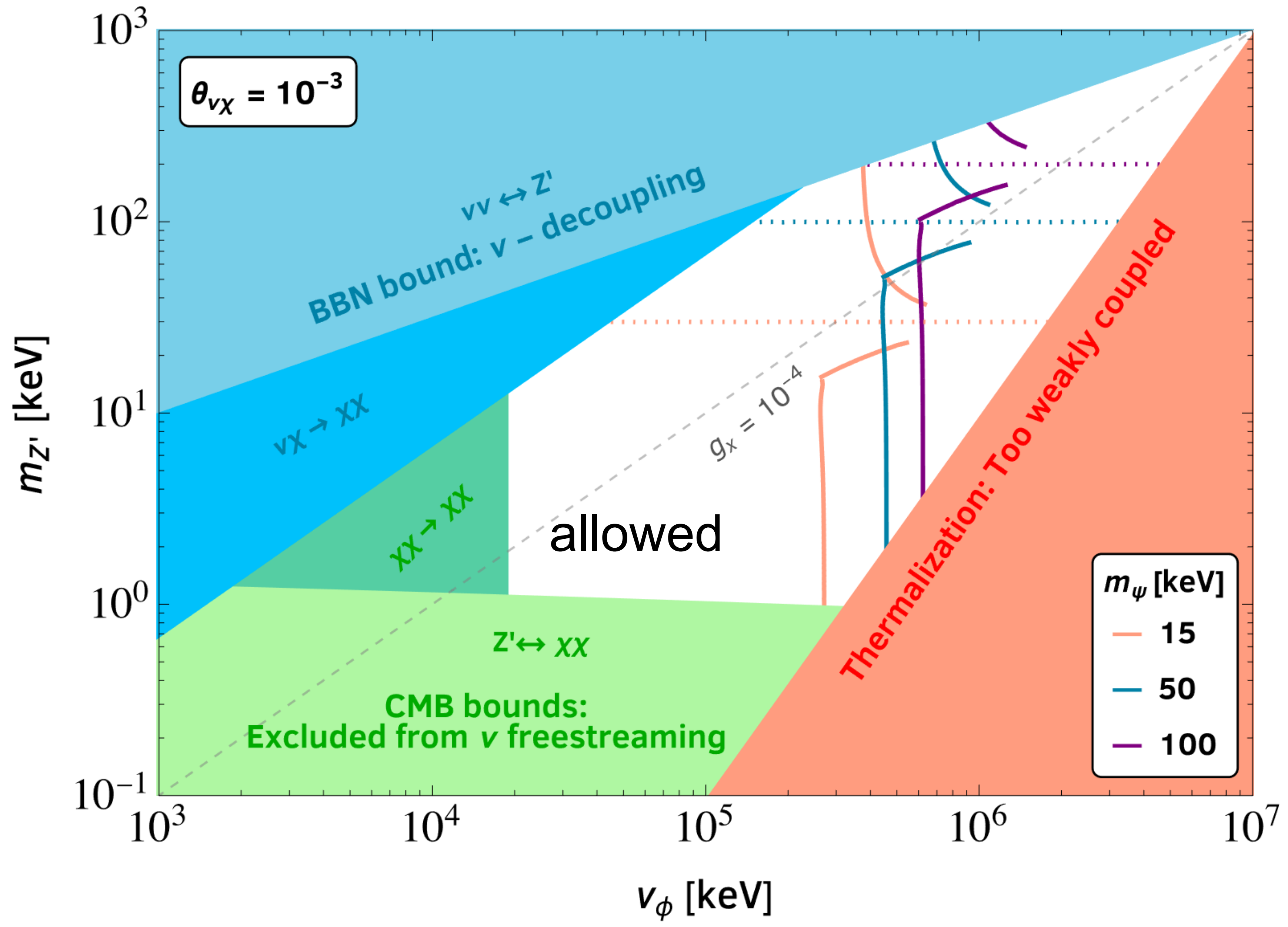
Example 2: light dark sector

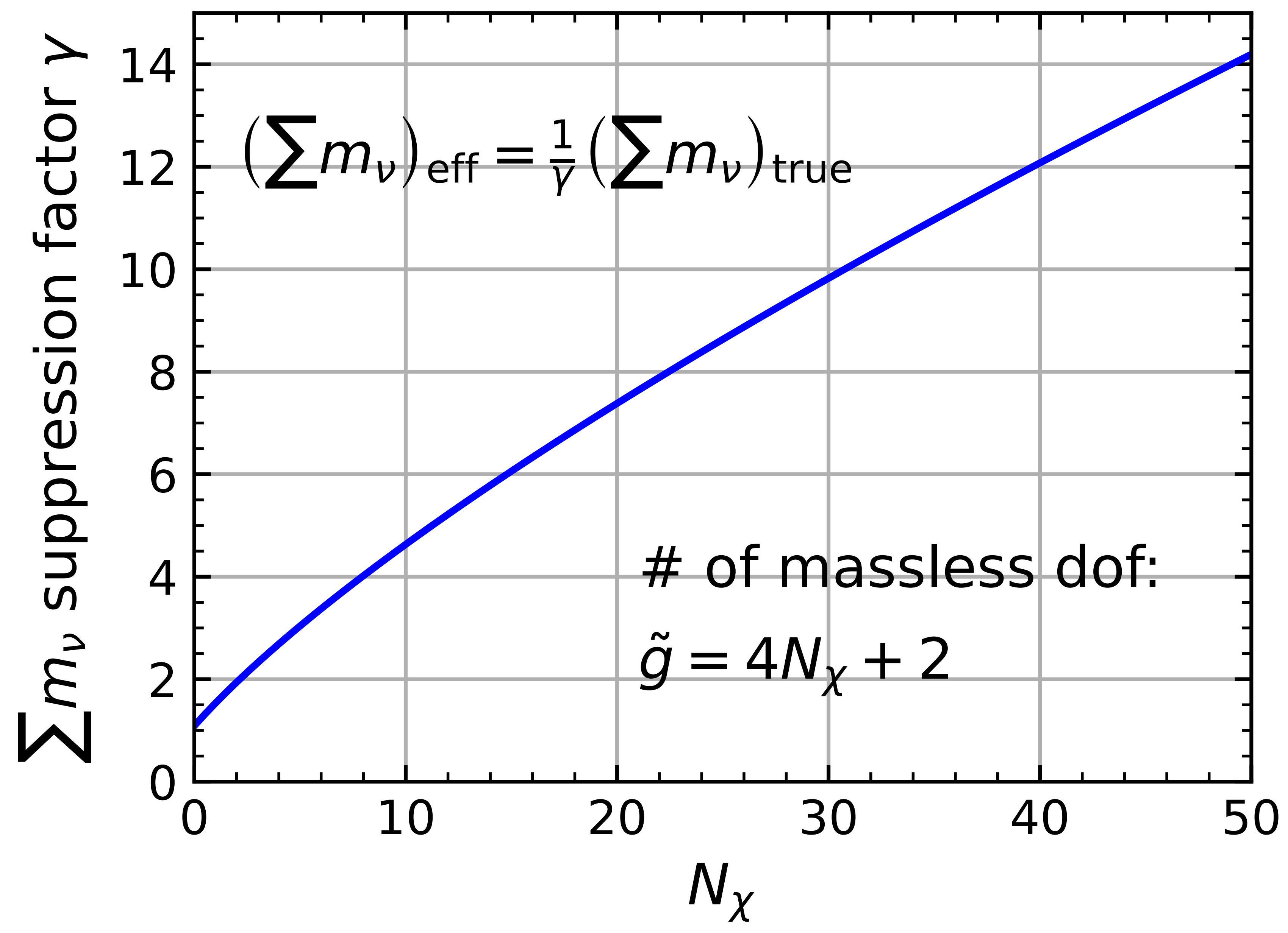
$$\theta_{\nu\chi} \simeq 10^{-3}\,,\; m_{Z'} \sim 10\,\mathrm{keV}\,,\; v_\Phi \sim 100\,\mathrm{MeV}$$

$$g_X = \frac{m_{Z'}}{v_\Phi} \sim 10^{-4}\,,\;\; m_{\mathrm{DM}} \simeq 50\,\mathrm{keV}$$

potential signatures:

- different neutrino mass in cosmo and lab
- $N_{\mathrm{eff}} > 3$ at CMB
- enhanced high-energy tail of SN neutrinos
- sterile neutrino oscillations
- warm DM signatures in structure formation





Escudero, TS, Terol-Calvo, 2211.01729
Benso, TS, Vatsyayan, 2410.23926

Summary

- **The neutrino challenge for theory**
  the unique position of $0\nu\beta\beta$ to test lepton number violation and the paradigm of neutrino mass from EFT based on the Weinberg operator

- **The success story of three-flavour oscillations**
  robust determination of 4.5 out of 6 oscillation parameters

- **Tensions** in the standard three-flavour paradigm / signs of new physics?
  - **short-baseline anomalies**: eV sterile neutrino oscillations do not provide an explanation, no explanation known for Gallium, LSND/MiniB require additional BSM physics
  - **the neutrino tension in cosmology**:
    exciting sensitivity to neutrino mass from cosmology, tension with oscillations emerging,
    Does it signal cosmology beyond ΛCDM or new physics in the neutrino sector or both?

Summary

thank you for your attention!

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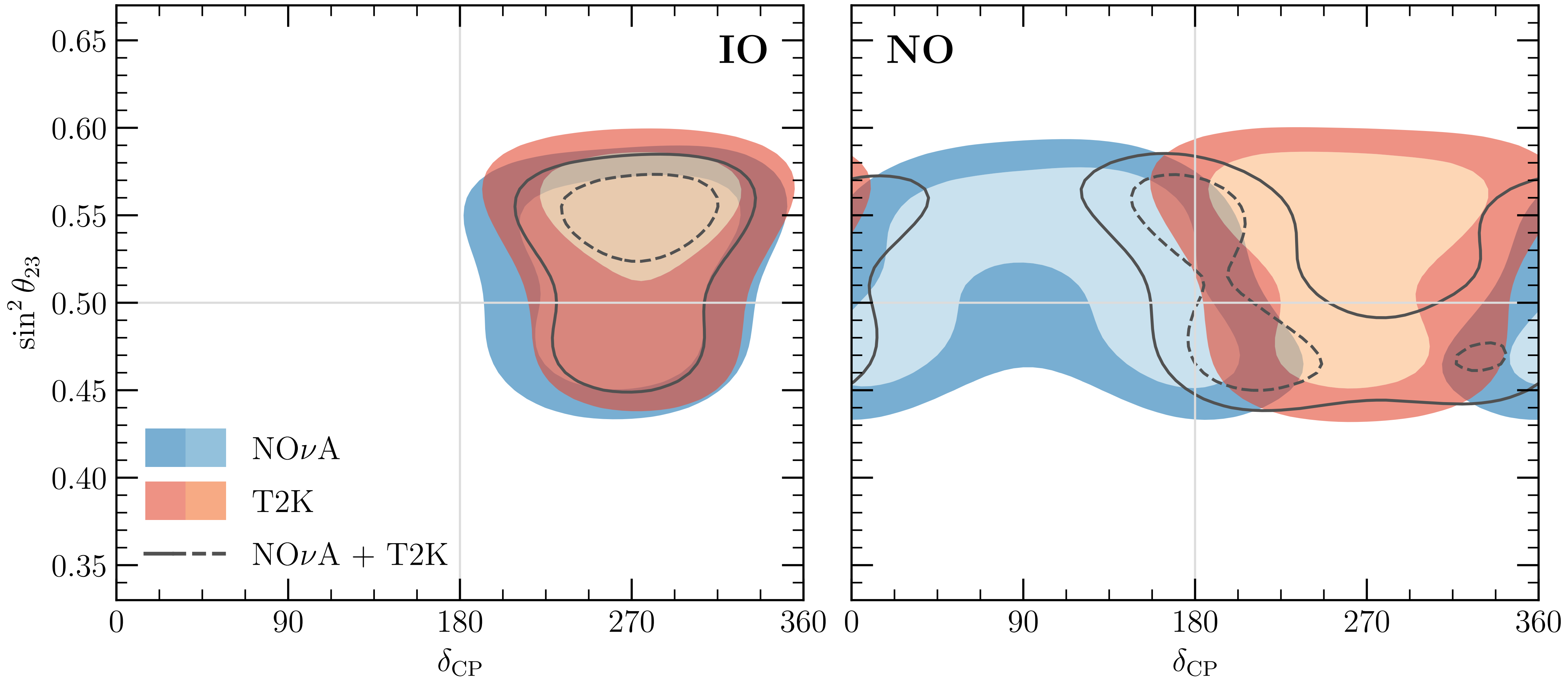
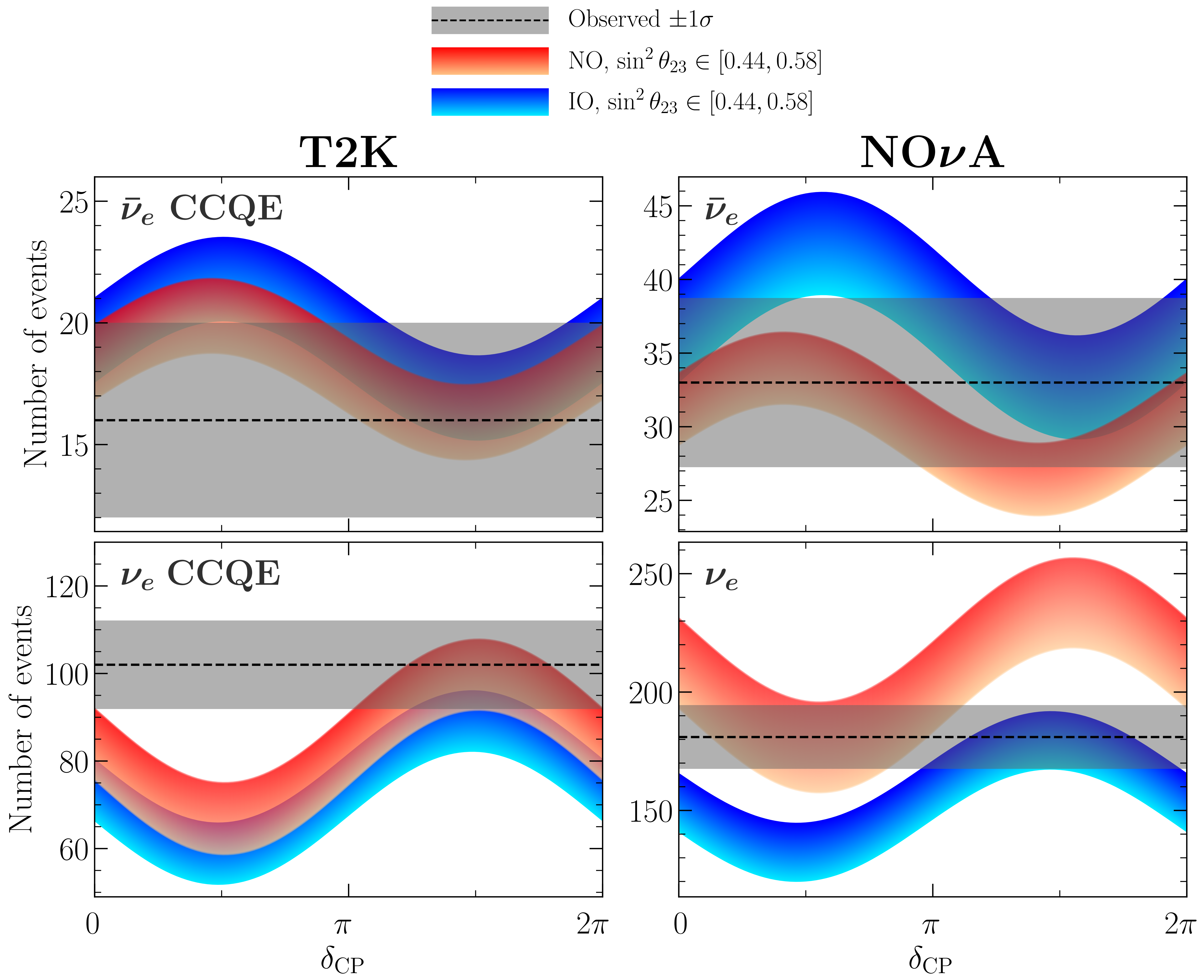
Backup

T2K and NOvA $\nu_\mu \to \nu_e$ appearance data

better consistency for inverted ordering





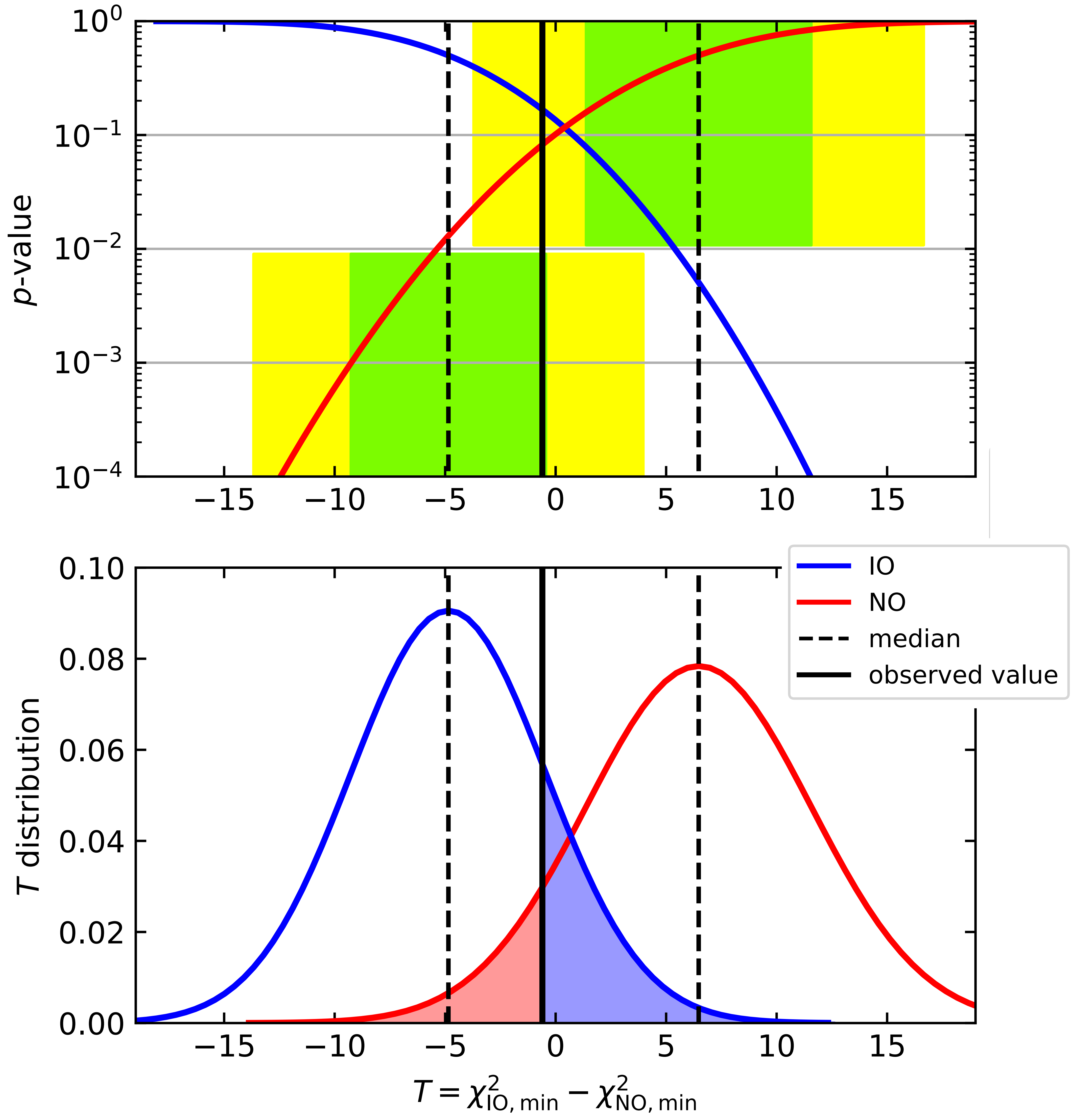
Esteban et al. (NuFit-6.0), 2410.05380

Mass ordering sensitivity

global data IC19 w/o SK

- median sensitivity:
  NO: 2.5σ, IO: 2.8σ

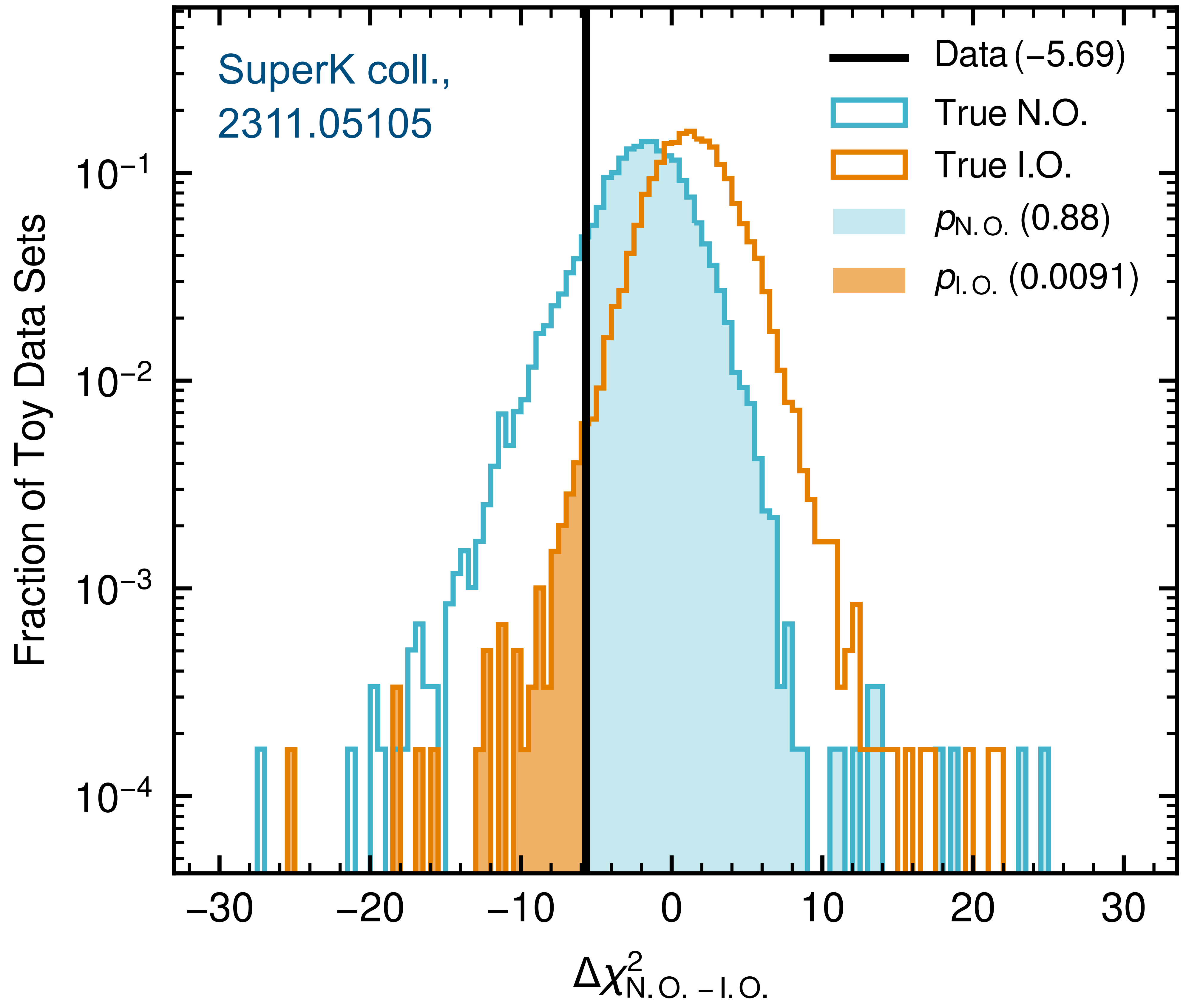
- observed p-values:
  NO: 1.7σ, IO: 1.4σ

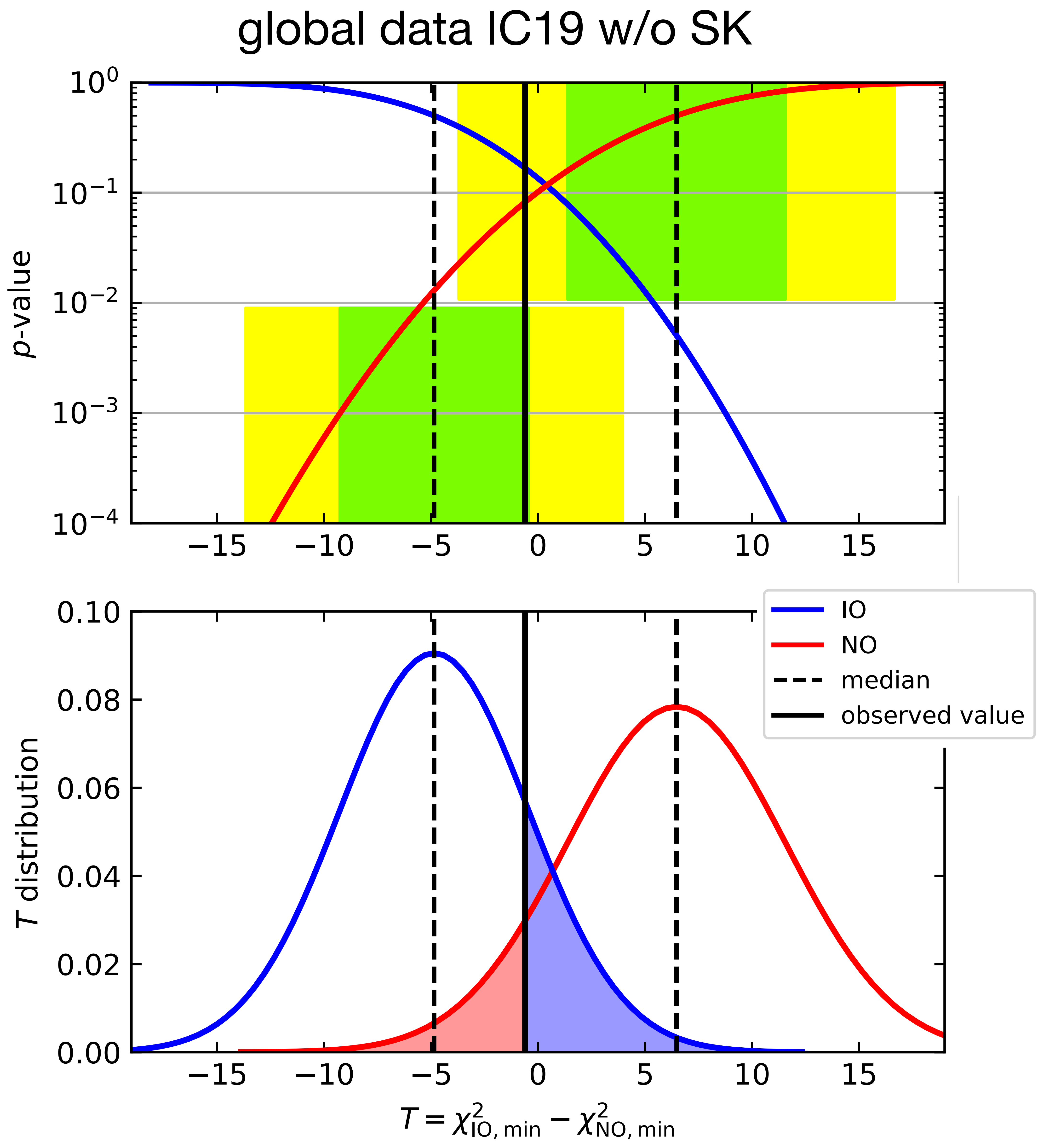


Esteban et al. (NuFit-6.0), 2410.05380

Adding SuperK

preference for NO with $\Delta\chi^2 \approx 5.7$



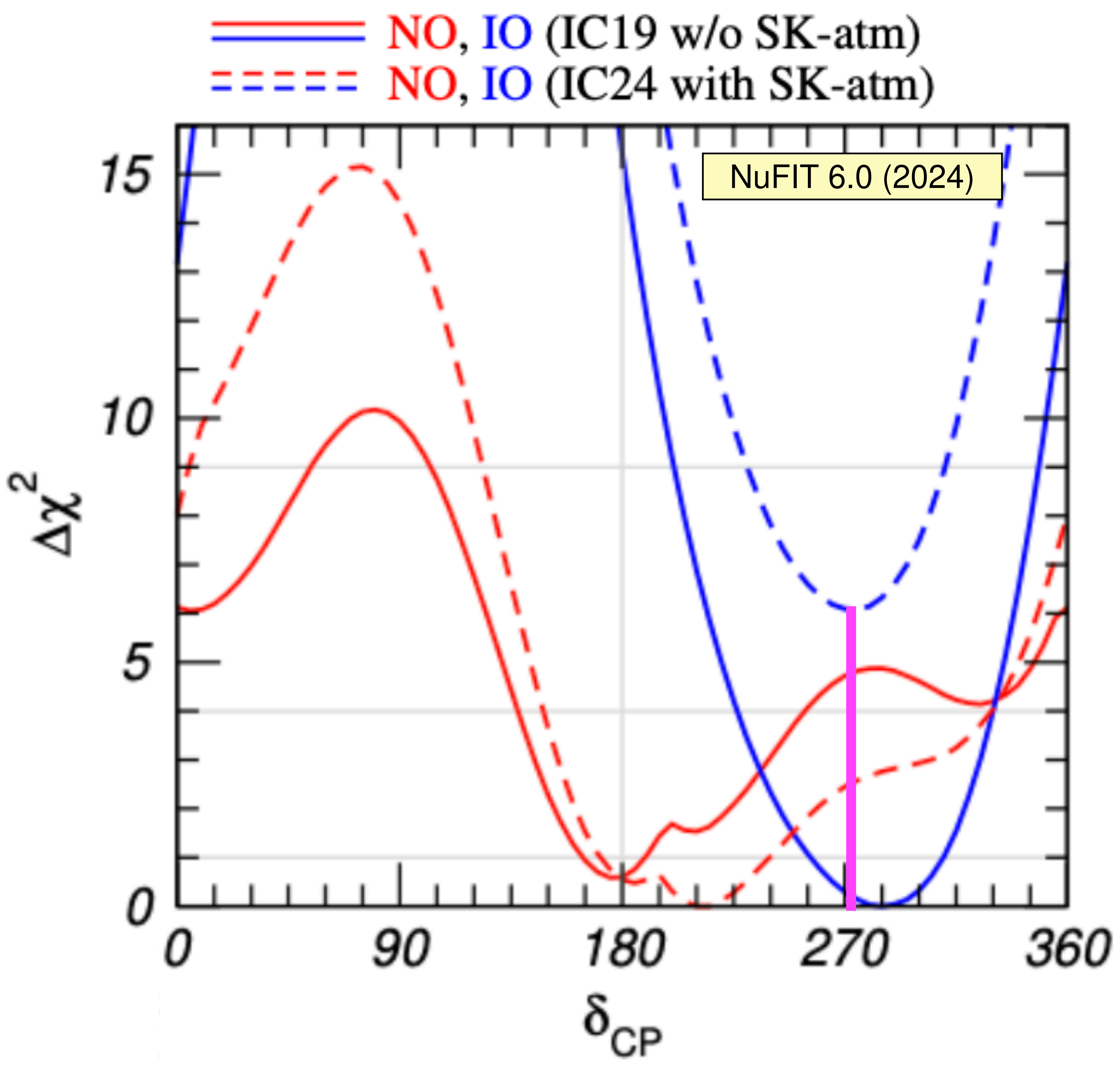


Esteban et al. (NuFit-6.0), 2410.05380

Global status mass ordering

- overall preference for normal ordering with $\Delta\chi^2_{\text{IO}-\text{NO}} \approx 6.1$

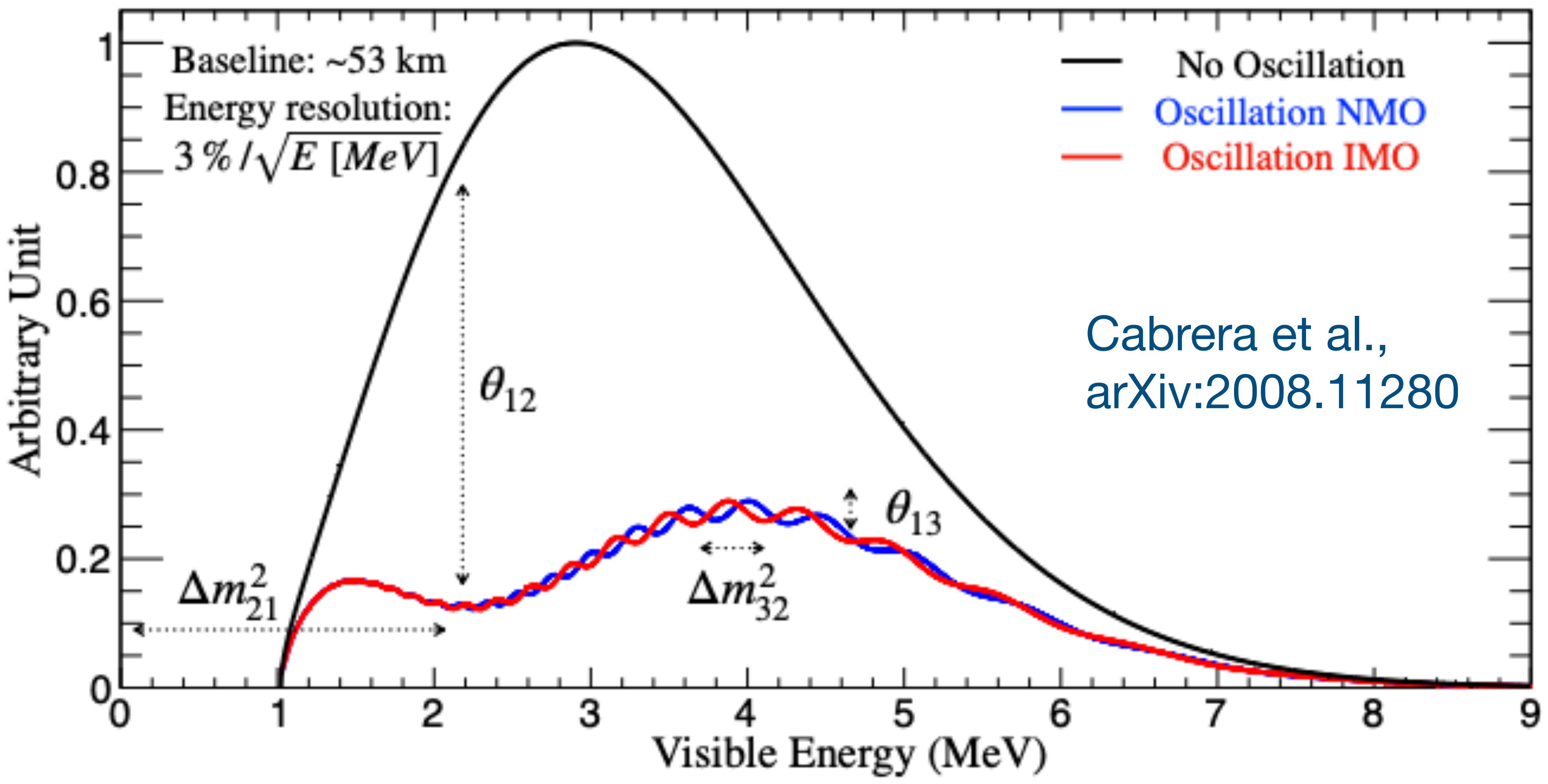
NuFit 5.3 (2024 pre-NU24): 9.1
NuFit 5.2 (2022): 6.4
NuFit 5.0 (2020): 7.1
Valencia (Tortola@Nu24): 7.1
Bari (Capozzi et al 2021): 6.5
Bari (Capozzi et al 2025): 5.0 (2.0 w/o atm)



SK: 484.2 kt yr [2311.05105]
IC24: 9.3 yr [2405.02163]
IC19: 3 yr [1902.07771]

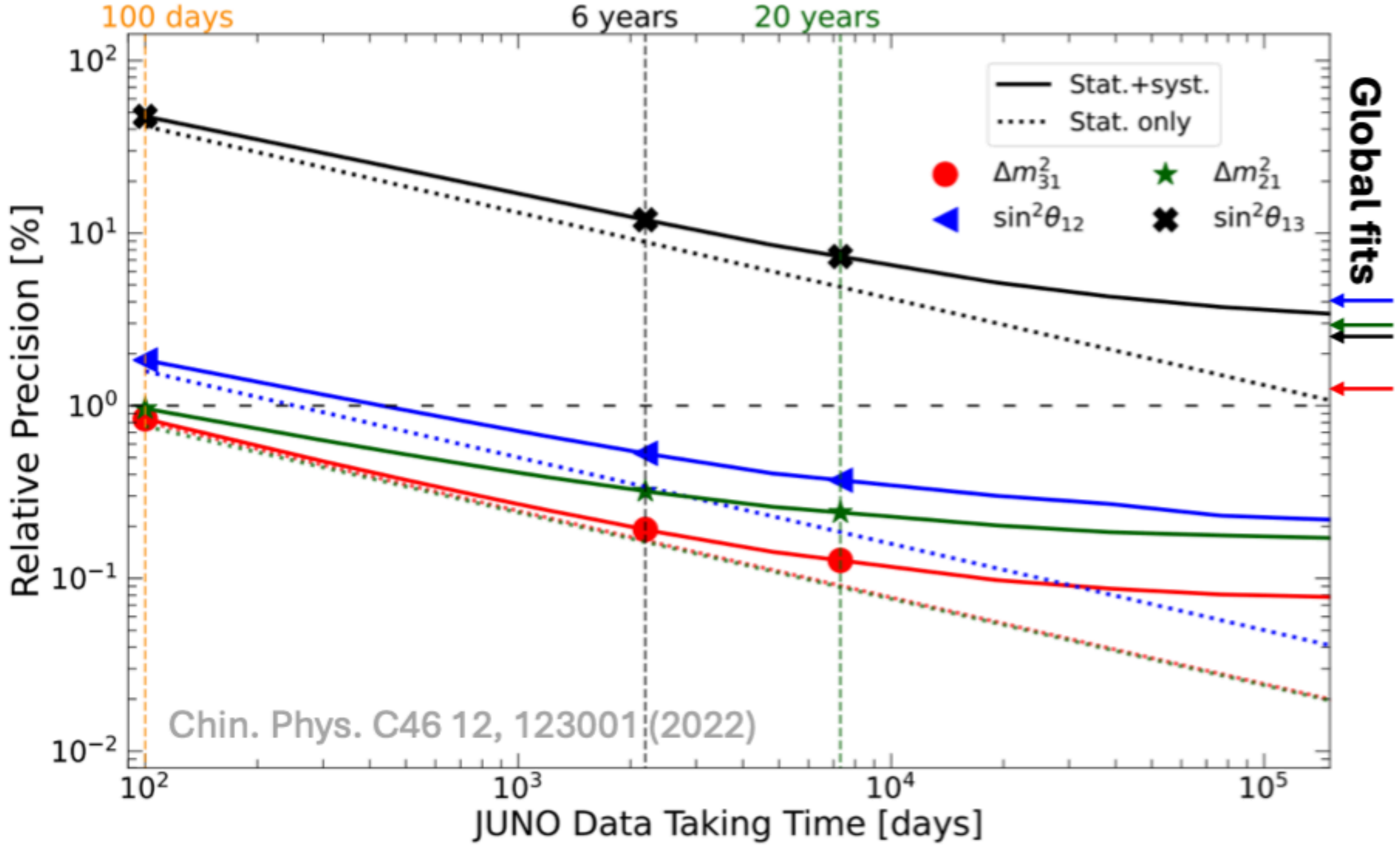
Oscillations — near term future: JUNO reactor experiment

- precision measurement of reactor neutrino spectrum at ~53 km



Cabrera et al., arXiv:2008.11280

- sub-percent precision on θ_{12}, Δm^2_{21} $|\Delta m^2_{31}|$

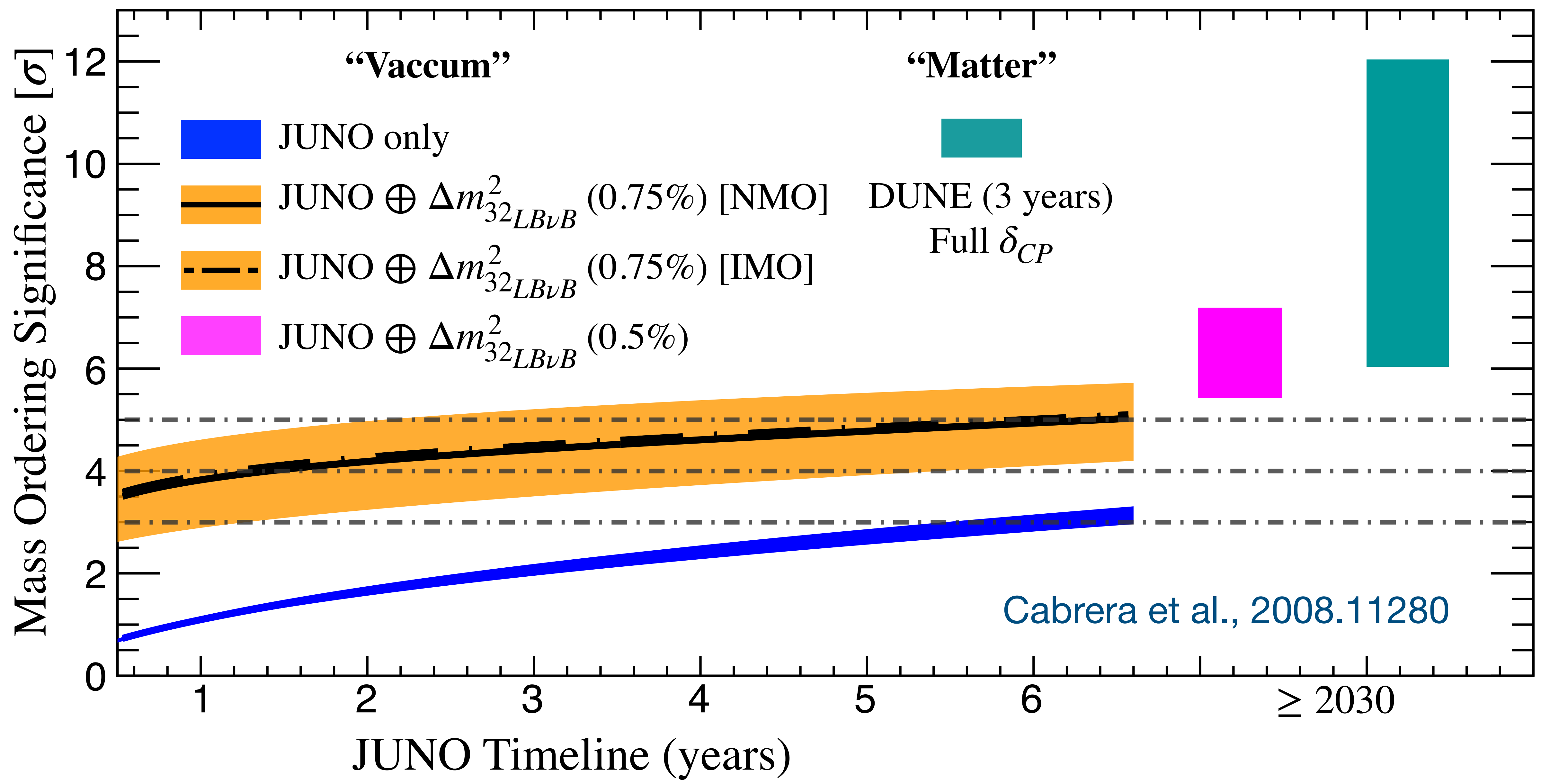


Mass ordering — near term future

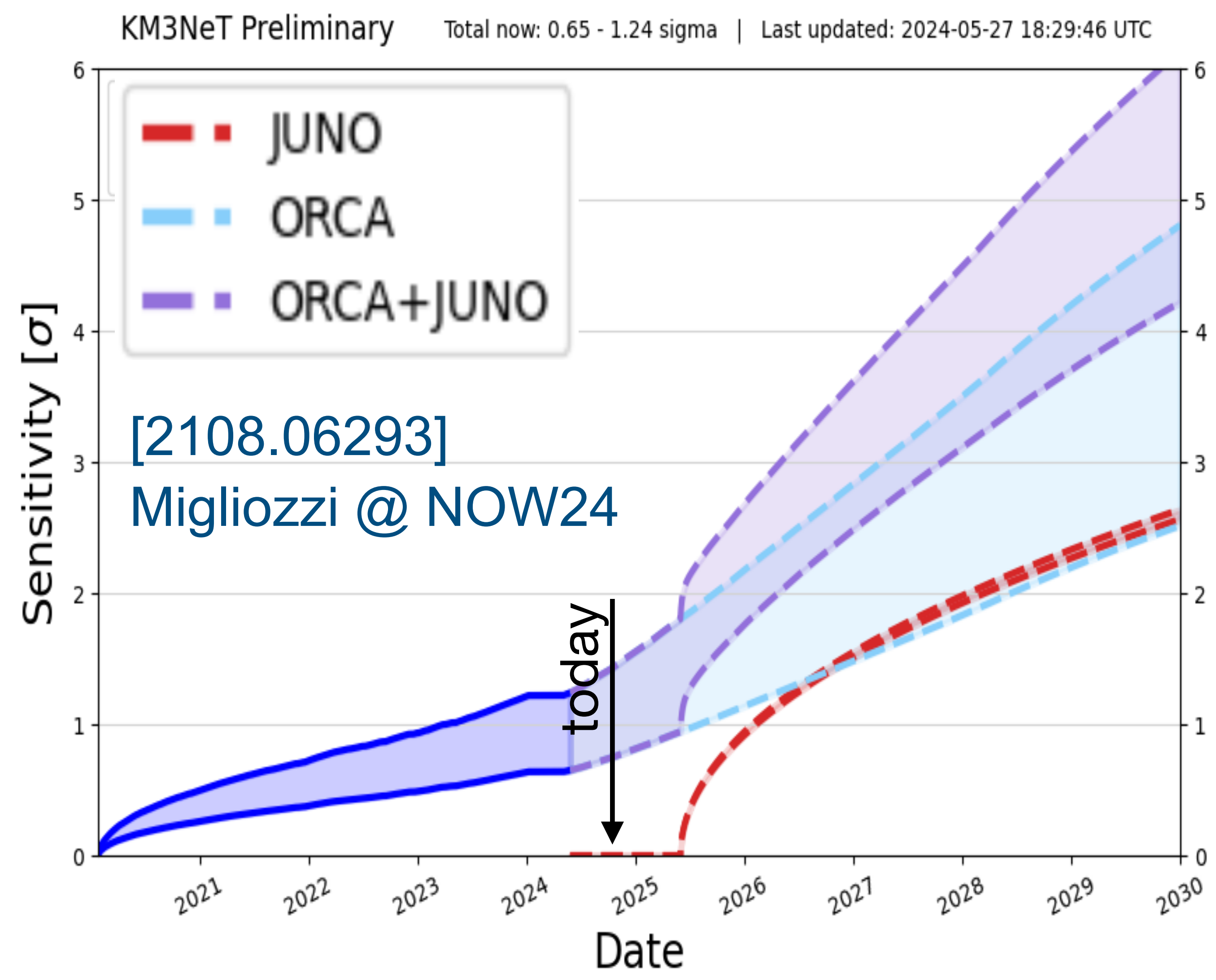
- determination by combining JUNO with LBL accelerators [Nunokawa, Parke Zukanovich, ’05] or atmospheric neutrinos [Blennow, Schwetz, ’13]

indep. determination of $|\Delta m^2_{31}|$ in ν_μ and ν_e disappearance

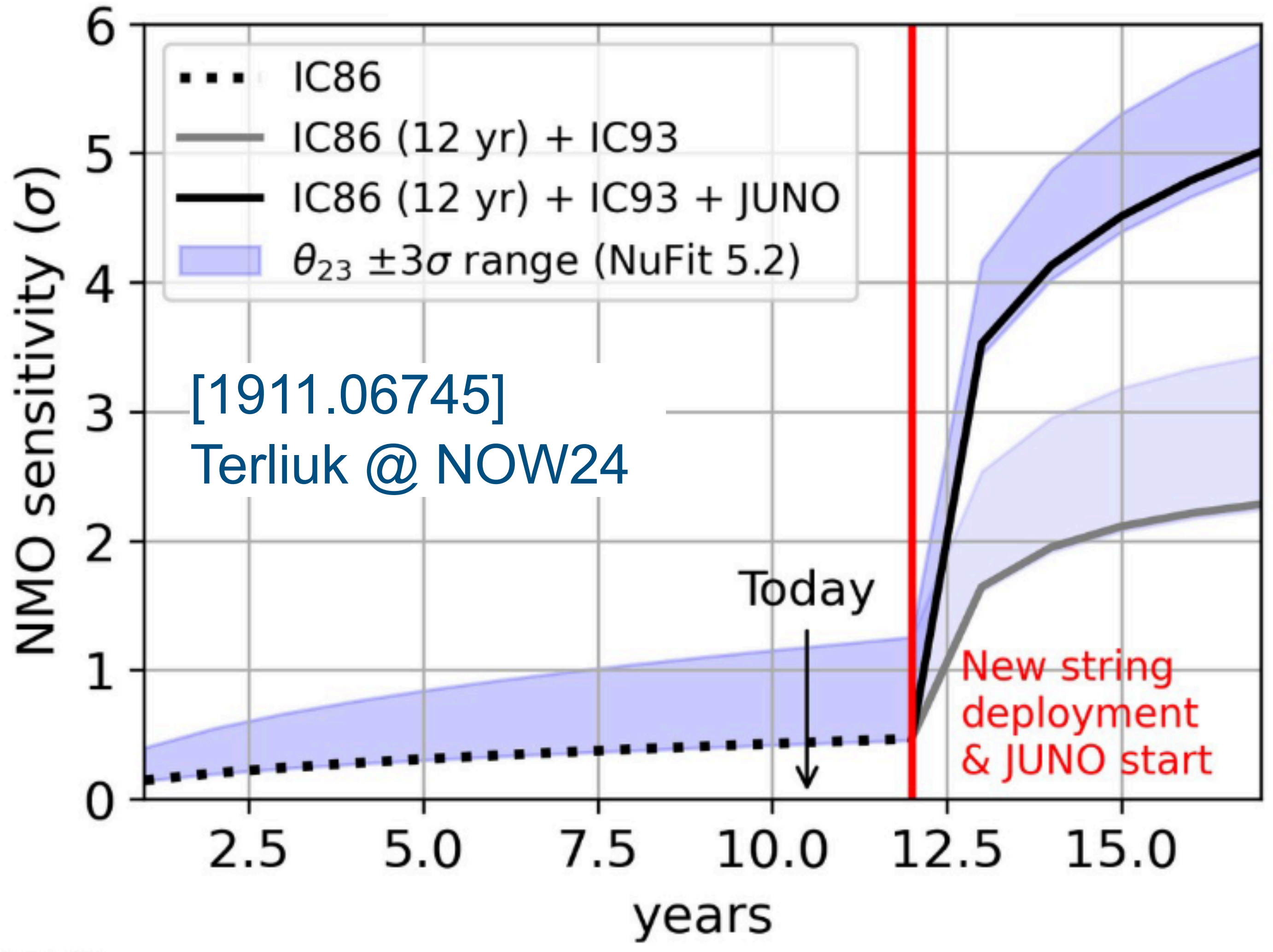
JUNO & long-baseline experiments



JUNO & KM3NET/ORCA



JUNO & IceCube

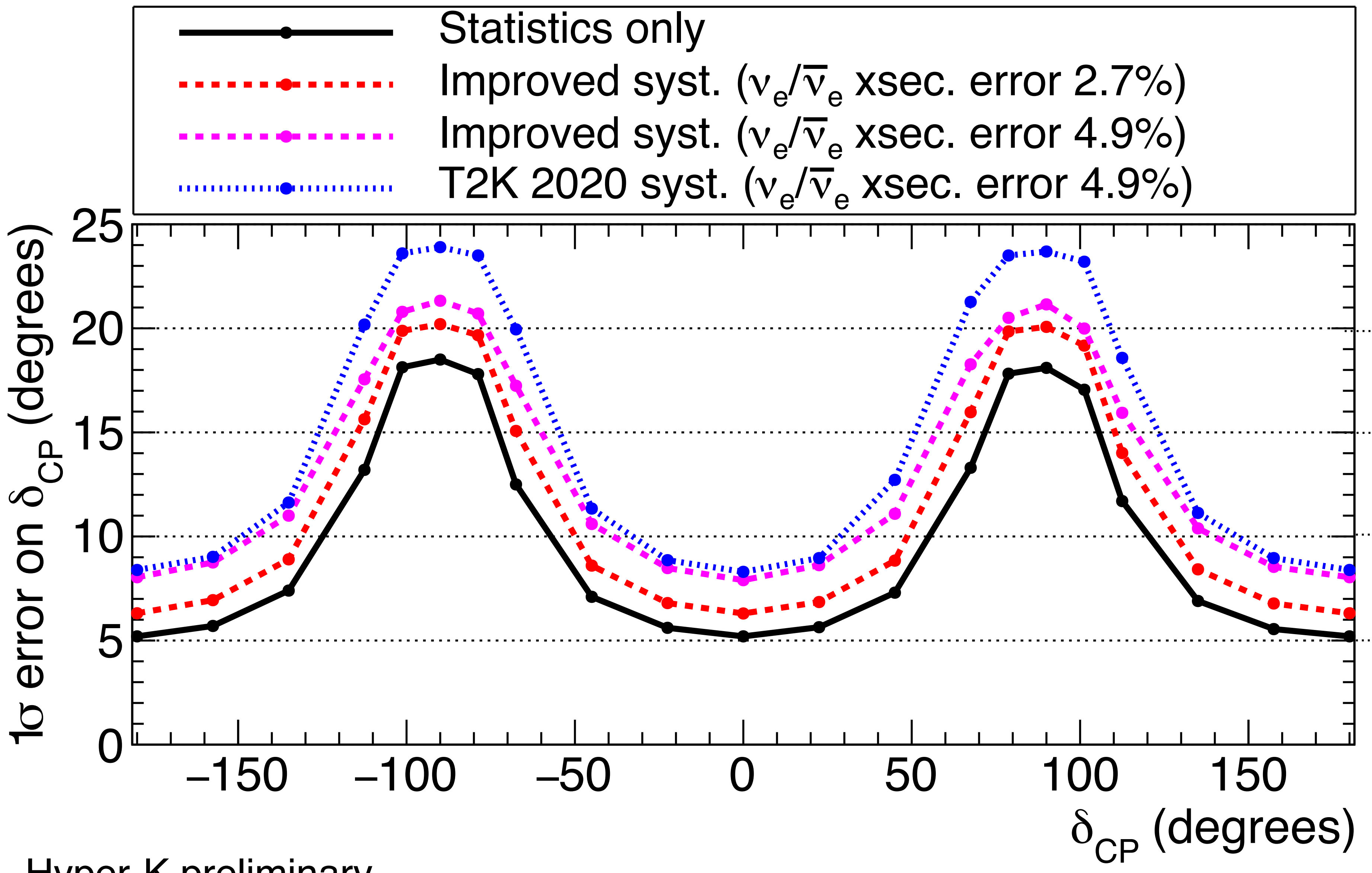


Karlsruher Institut für Technologie

Oscillations — long term: DUNE & HyperK: CP phase

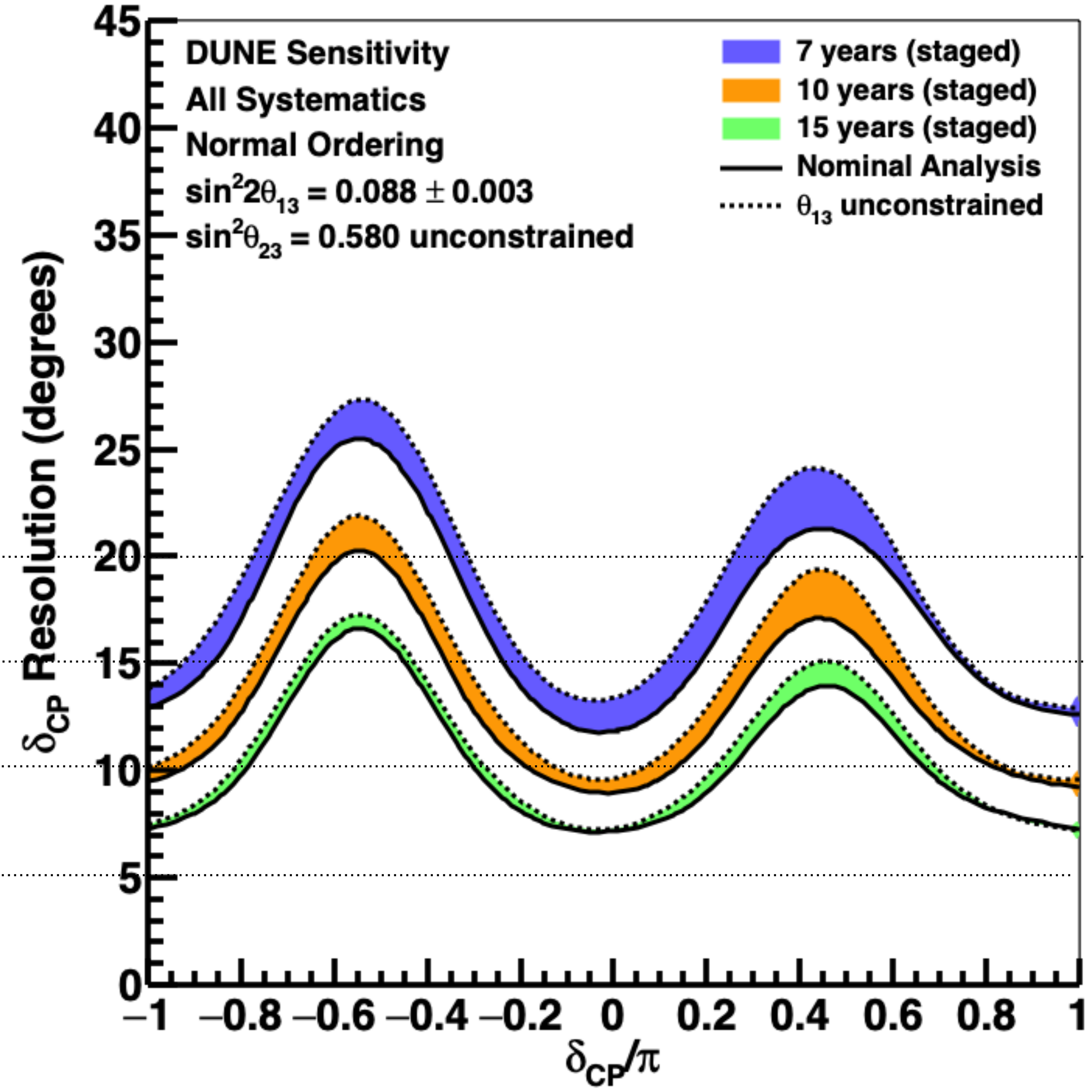
- 10° — 20° precision on δ_{CP} in ~10 years

HyperK, J. Wilson @ NOW24



Hyper-K preliminary
True normal ordering (known), HK 10 Years (2.7×10^{22} POT 1:3 ν:$\bar{\nu}$)
$\sin^2\theta_{13}=0.0218\pm0.0007$, $\sin^2\theta_{23}=0.528$, $\Delta m^2_{32}=2.509\times10^{-3}\mathrm{eV}^2/c^4$

DUNE coll. 2006.16043



Preference for negative neutrino mass?

$$\Delta\chi^2(m_\nu = 0) \lesssim 3\,, \quad \Delta\chi^2(\mathrm{NO}) \lesssim 6$$

DESI DR2 [arXiv:2503.14743]

Naredo-Tuero, Escudero, Fernandez, Marcano, Poulin, 2407.13831