Precision neutrino oscillometry in the light of JUNO

Image credit: magnific.com (adapted)

Eligio Lisi

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IRN Neutrino Meeting (IJCLab, Orsay, France), 1-2 June 2026

Based on Capozzi+, arXiv:2503.07752, PRD 111 (2025) 9, 093006 **(pre-JUNO)**

Neutrino masses and mixing: Entering the era of subpercent precision

Francesco Capozzi,[1,2] William Giarè,[3] Eligio Lisi,[4]
Antonio Marrone,[5,4] Alessandro Melchiorri,[6,7] and Antonio Palazzo[5,4]

and on Capozzi+, arXiv:2511.21650, PRD (2026) submitted **(post-JUNO)**

Updated bounds on the (1, 2) neutrino oscillation parameters after first JUNO results

Francesco Capozzi,[1,2] Eligio Lisi,[3] Francesco Marcone,[4,3] Antonio Marrone,[4,3] and Antonio Palazzo[4,3]

+ some comments about **prospective JUNO** results

OUTLINE:

- Intro and remarks on JUNO
- Results from osc. data fit (pre/post-JUNO)
- Prospective impact of further (~1 yr) data
- *[Absolute mass observables – extra slides]*

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3ν status (1 digit)

5 knowns:

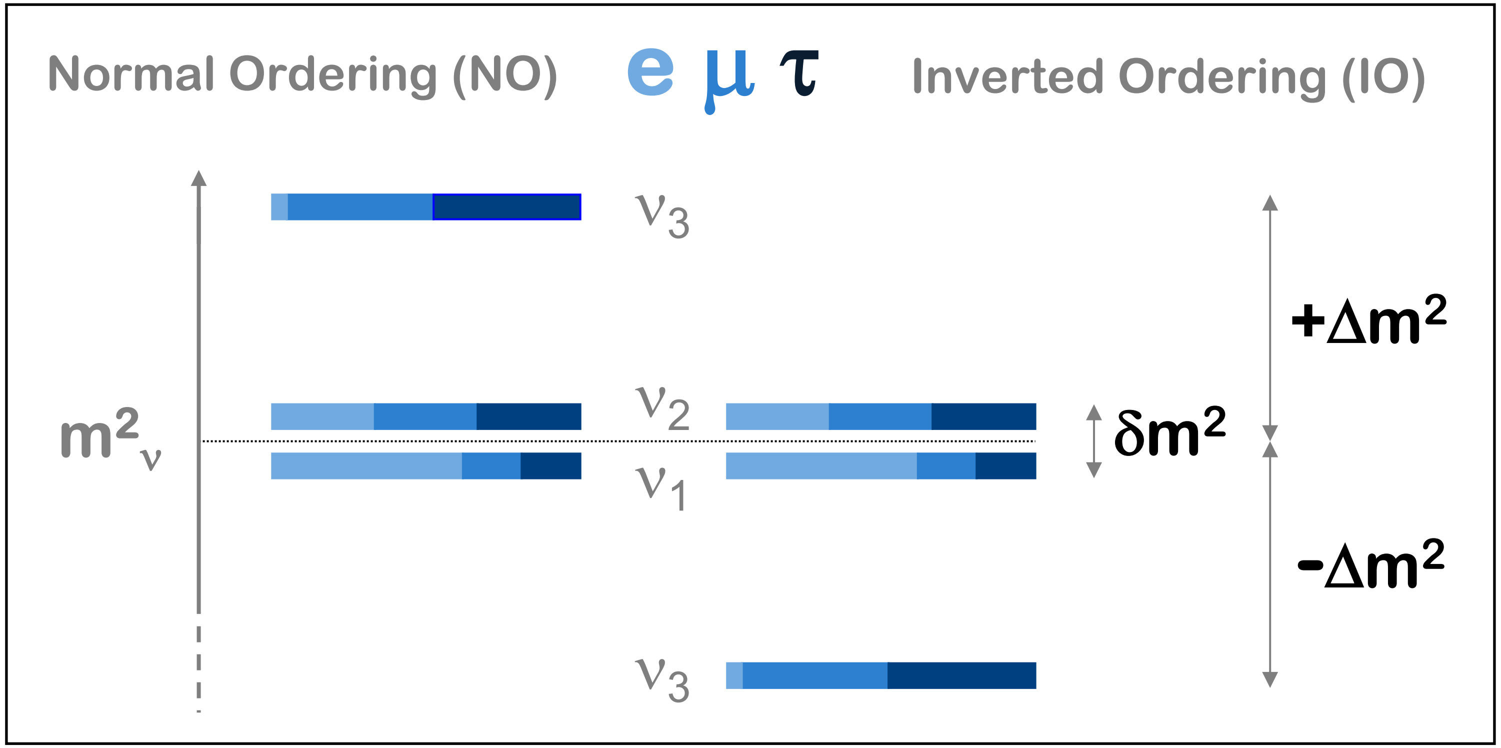
- $\delta m^2 \sim 7 \times 10^{-5}\ eV^2$
- $|\Delta m^2| \sim 2 \times 10^{-3}\ eV^2$
- $\sin^2\theta_{12} \sim 0.3$
- $\sin^2\theta_{23} \sim 0.5$
- $\sin^2\theta_{13} \sim 0.02$

Oscillations

5 unknowns:

Oscillations:
- δ **CPV** Dirac phase
- **sign(Δm^2)** → NO/IO
- θ_{23} **octant** degeneracy

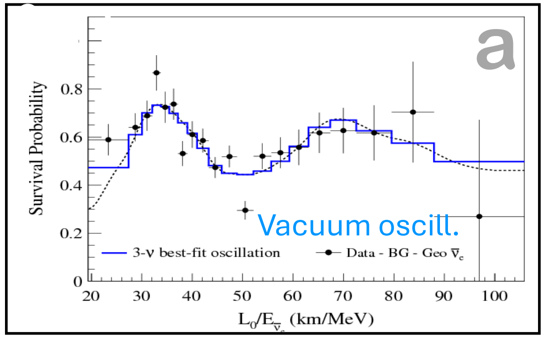
Non-oscillat.:
- **absolute mass** scale
- **Dirac/Majorana** nature



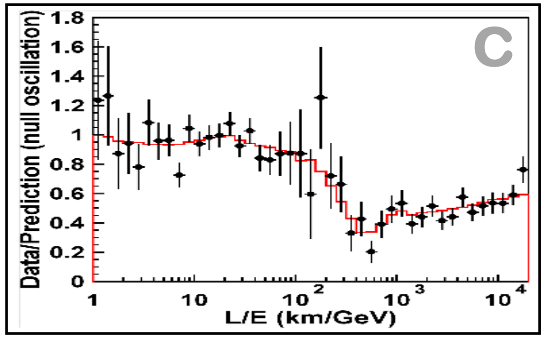
Each known parameter probed by at least two different kinds of experiments

3ν oscillations probed by many experiments in different flavor channels…

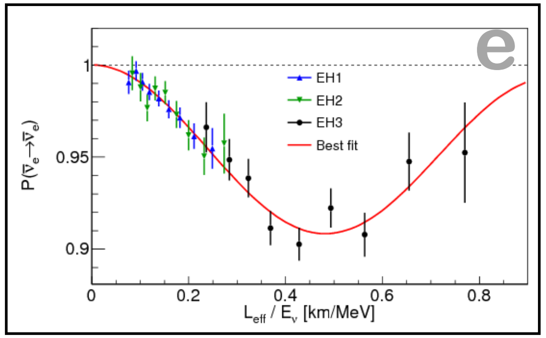
e→e (KamLAND, KL)



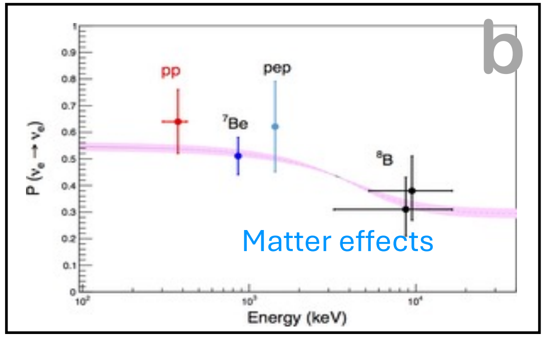
μ→μ (Atmospheric)



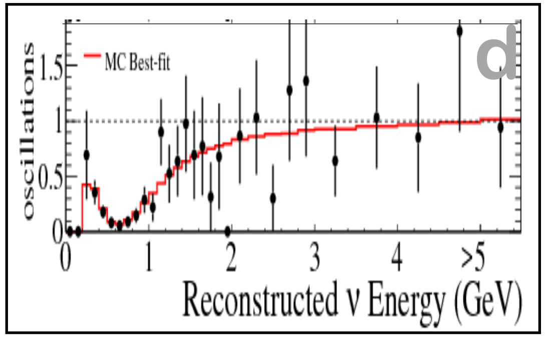
e→e (SBL Reac.)



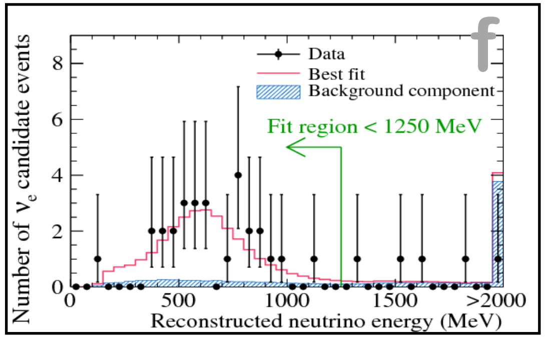
e→e (Solar)



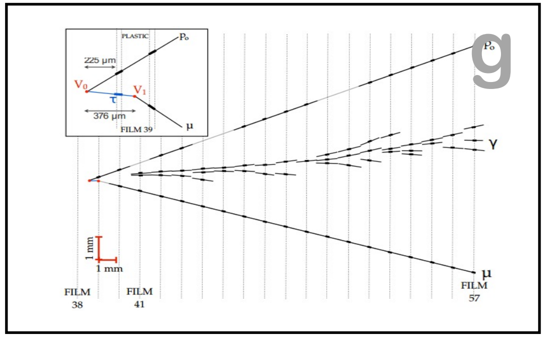
μ→μ (LBL Accel)



μ→e (LBL Accel)



μ→τ (OPERA, SK, DC)

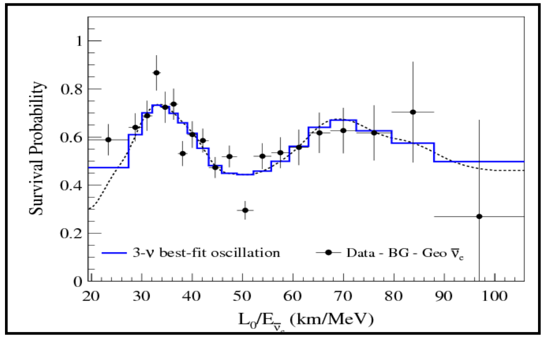


LBL = Long baseline (few x 100 km); **SBL = short baseline** (~1 km)

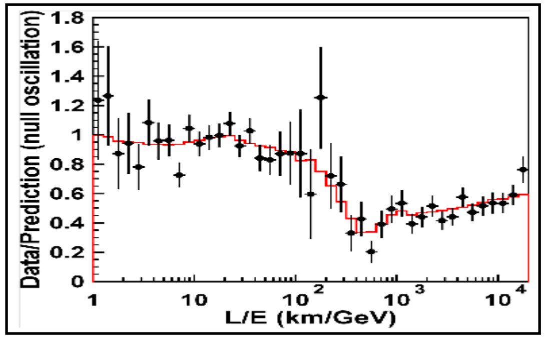
(a) KamLAND reactor [plot]; (b) Borexino [plot], Homestake, Super-K, SAGE, GALLEX/GNO, SNO; (c) Super-K atmosph. [plot], IC DeepCore, KM3, MACRO, MINOS etc.; (d) T2K (plot), NOvA, MINOS, K2K LBL accel.; (e) Daya Bay [plot], RENO, Double Chooz SBL reactor; (f) T2K [plot], MINOS, NOvA LBL accel.; (g) OPERA [plot] LBL accel., Super-K and IC-CD atmospheric.

Each oscillation frequency and amplitude governed by 2 (or 3) mass-mixing parameters

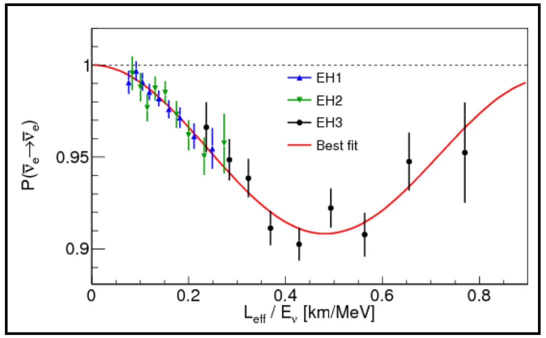
e→e (δm^2 , θ_{12})



μ→μ (Δm^2 , θ_{23})



e→e (Δm^2 , θ_{13})



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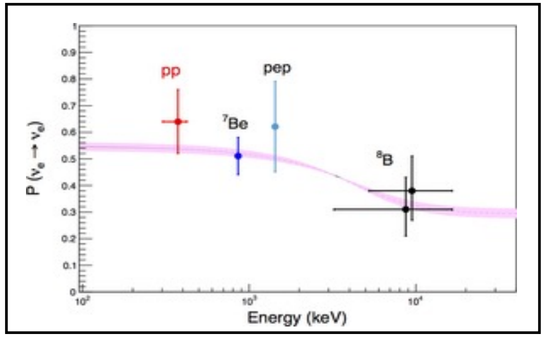

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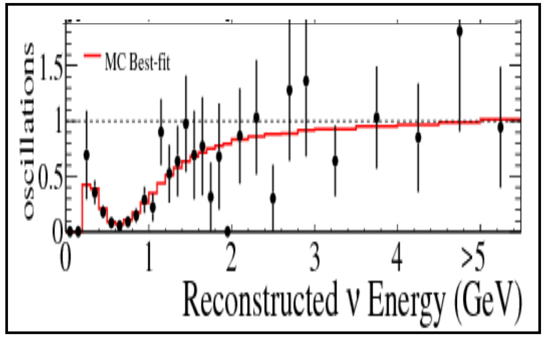
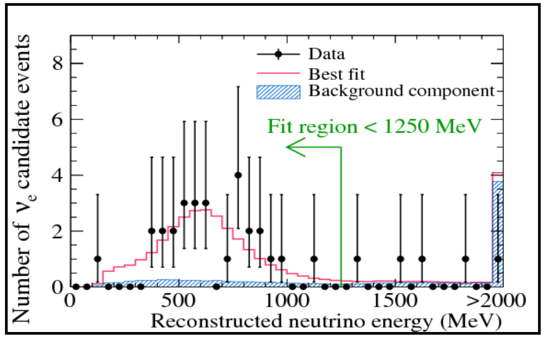
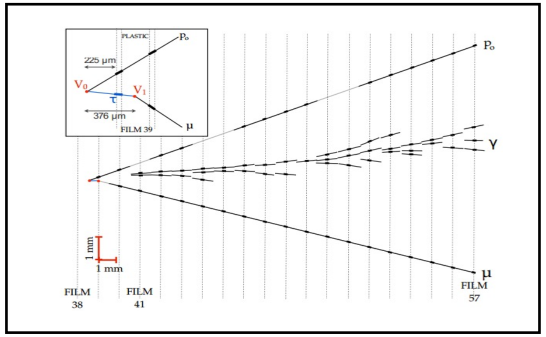


μ→e (Δm^2 , θ_{13} , θ_{23})



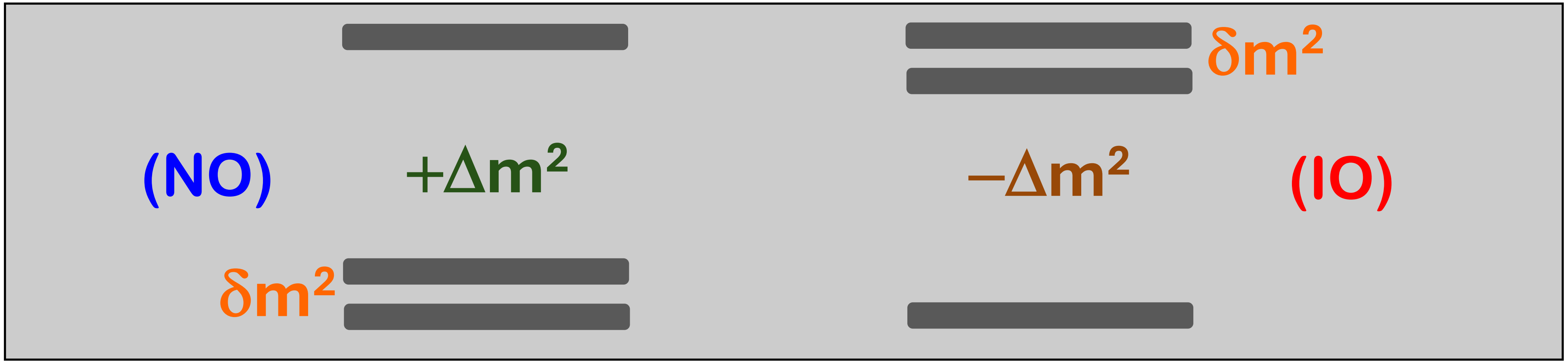
μ→τ (Δm^2 , θ_{23})



5 param.'s known & (over)constrained → consistency

Currently: focus on unknown par. & subleading effects, especially CPV via $\nu_\mu \to \nu_e$ in LBL accel. and atmos. expts and NO/IO mass spectrum via reactor + accel + atmos.

How do oscillation searches probe mass ordering?



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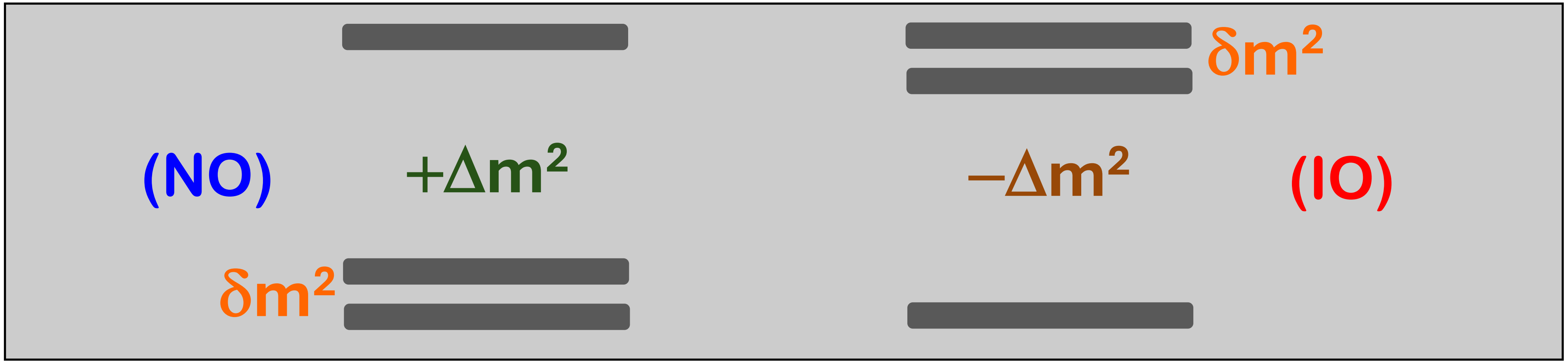

Observe **interference effects** of oscill. driven by $\pm\Delta m^2$ with oscill. driven by another quantity **Q** with known sign. Options:

$Q \sim \delta m^2$	medium-baseline reac. → JUNO "standalone"
$Q \sim G_F N_e E$	ν–matter effects → atmos & LBL accel. expts.
[$Q \sim G_F N_\nu E$	ν–ν collective effects → CC SN, difficult …]

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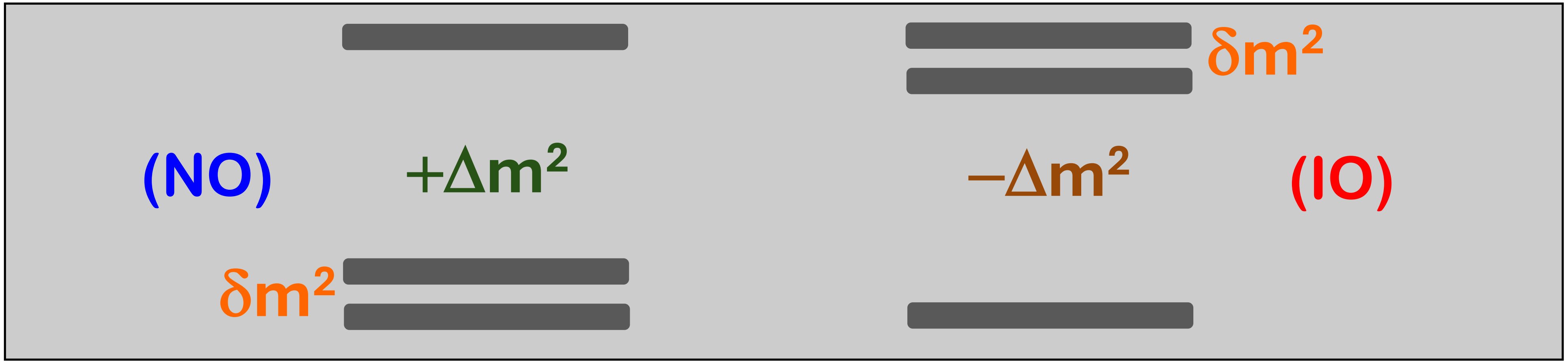

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[$Q \sim G_F N_\nu E$	ν–ν collective effects → CC SN, difficult …]

Additional tool: SYNERGY of $|\Delta m^2|$ data from different experiments,
e.g. two or more $|\Delta m^2|$ data from reactor + accelerator + atmospheric
should converge better in the true ordering than in the wrong one

Our notation about mass^2 splittings (→ JUNO's frequencies)

$$\delta m^2 = \Delta m^2_{21}$$

>0 by convention

$$\Delta m^2 = (\Delta m^2_{32} + \Delta m^2_{31})/2$$

May be >0 or < 0

α = sign(Δm^2) = +1 (NO) or -1 (IO)

(NO or IO)

$$\Delta m^2_{ee} = |\Delta m^2| + \tfrac{1}{2}\alpha(\cos^2\theta_{12} - \sin^2\theta_{12})\delta m^2$$

>0 by convention

$\Delta m^2_{ee} > 0$ convention consistent with JUNO's 1507.05613

Neutrino Physics with JUNO

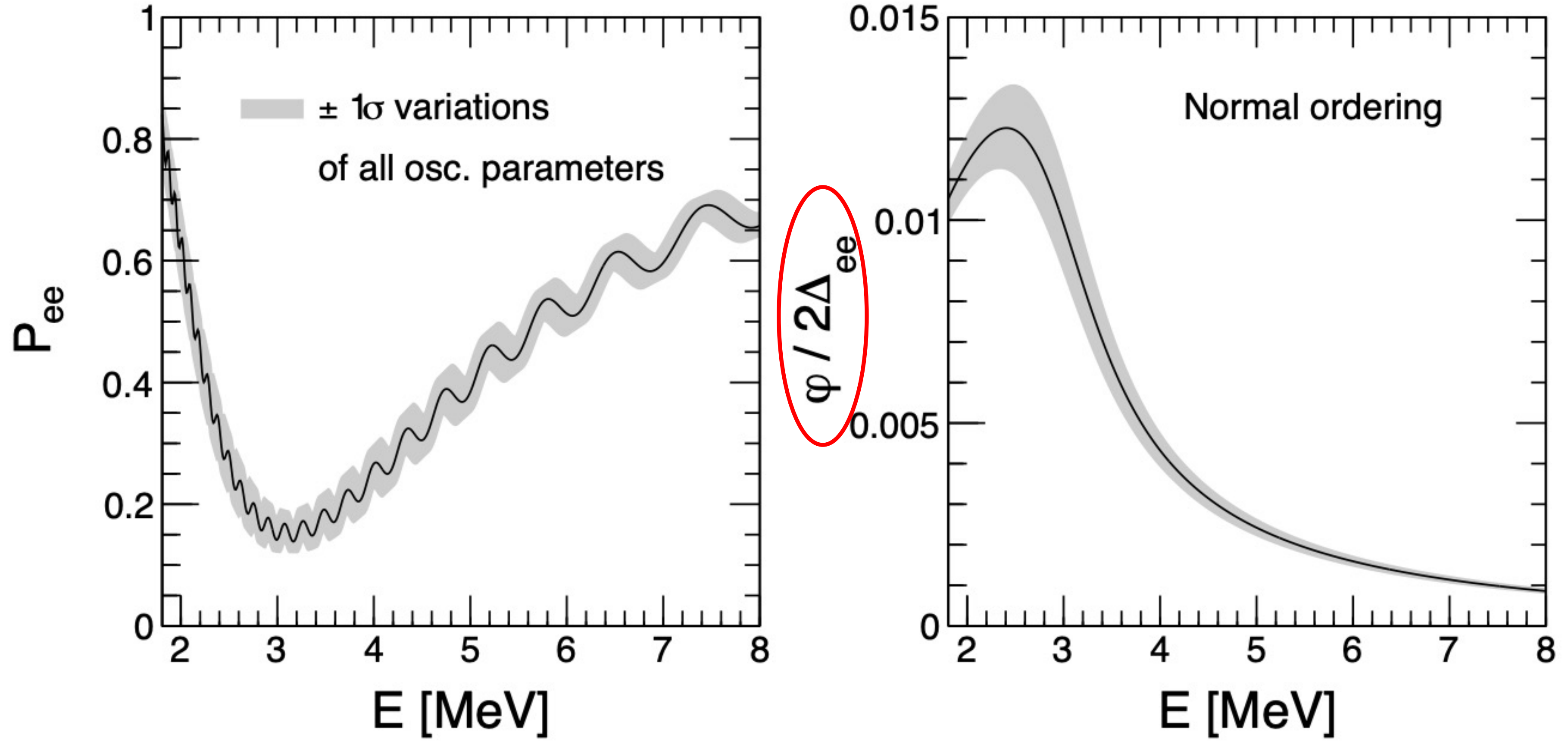
$$P_{\bar{\nu}_e \to \bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21} \quad (2.1)$$
$$= 1 - \frac{1}{2}\sin^2 2\theta_{13}\left[1 - \sqrt{1 - \sin^2 2\theta_{12}\sin^2\Delta_{21}}\cos(2|\Delta_{ee}| \pm \phi)\right] - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21},$$

JUNO only:

What matters for **"JUNO standalone"** NO/IO discrimination is the relative sign $\alpha=\pm1$ between the dominant L/E oscillation phase **$2\Delta_{ee}$** and the non-L/E phase ϕ (depending on **δm^2**). Timescale: 6-7 years?

Two very different L/E oscill.: δm^2 (slow) and Δm^2_{ee} (fast)

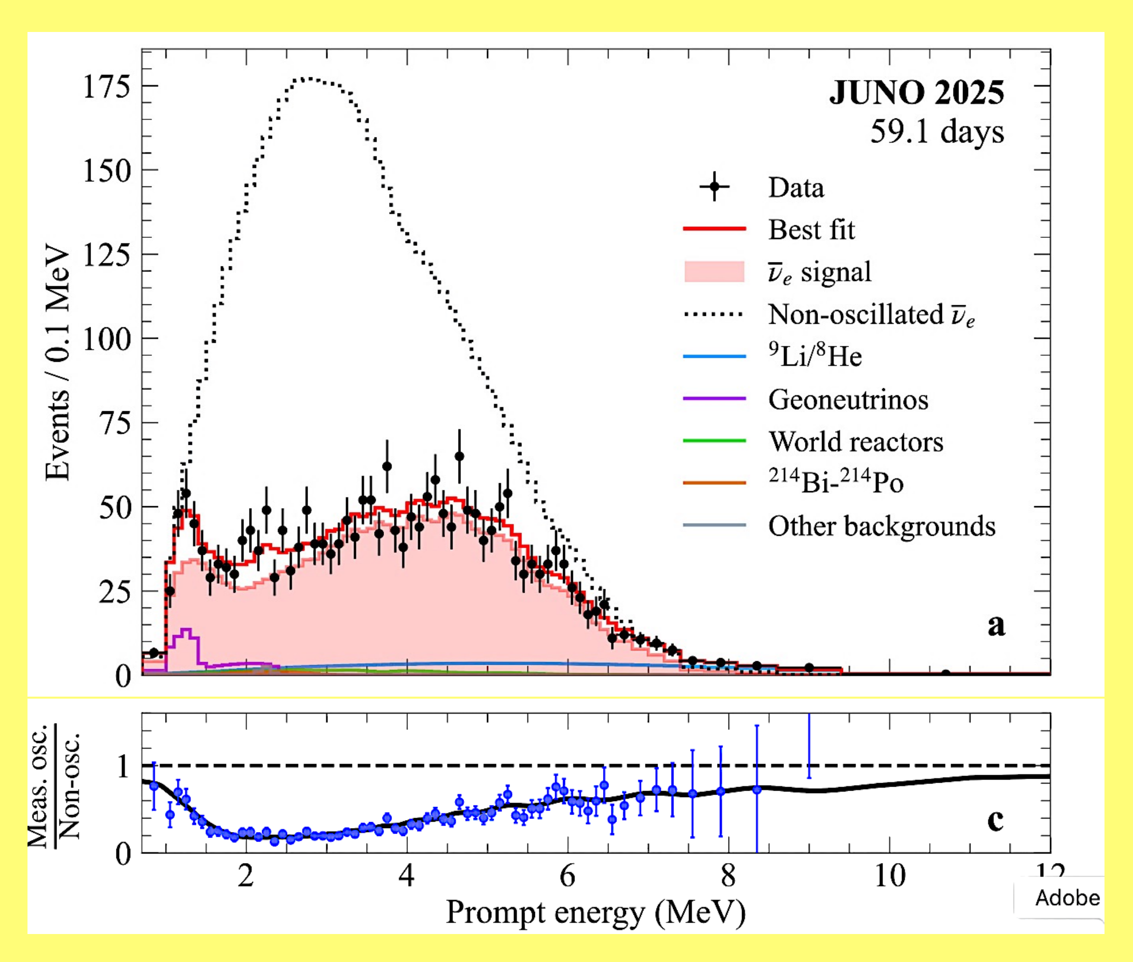
Fast oscill. driven by close waves: Δm^2_{31} , Δm^2_{32} → non-L/E phase*



Within **JUNO standalone**, finding the **mass ordering** amounts to find, besides the L/E slow wave (easy), also the **fast wave (~easy)** plus its **non-L/E modulation**

[H. von Helmoltz: "Sensations of Tone" (1863). See also 1601.07464, 2006.01648]*

JUNO 2-months data (2511.14593): slow oscillations seen; fast ones not yet...



...or "not clearly emerging" → current impact "only" on (1,2) oscillation parameters

→ JUNO first data constrain (δm^2, θ_{12}), NOT YET Δm^2

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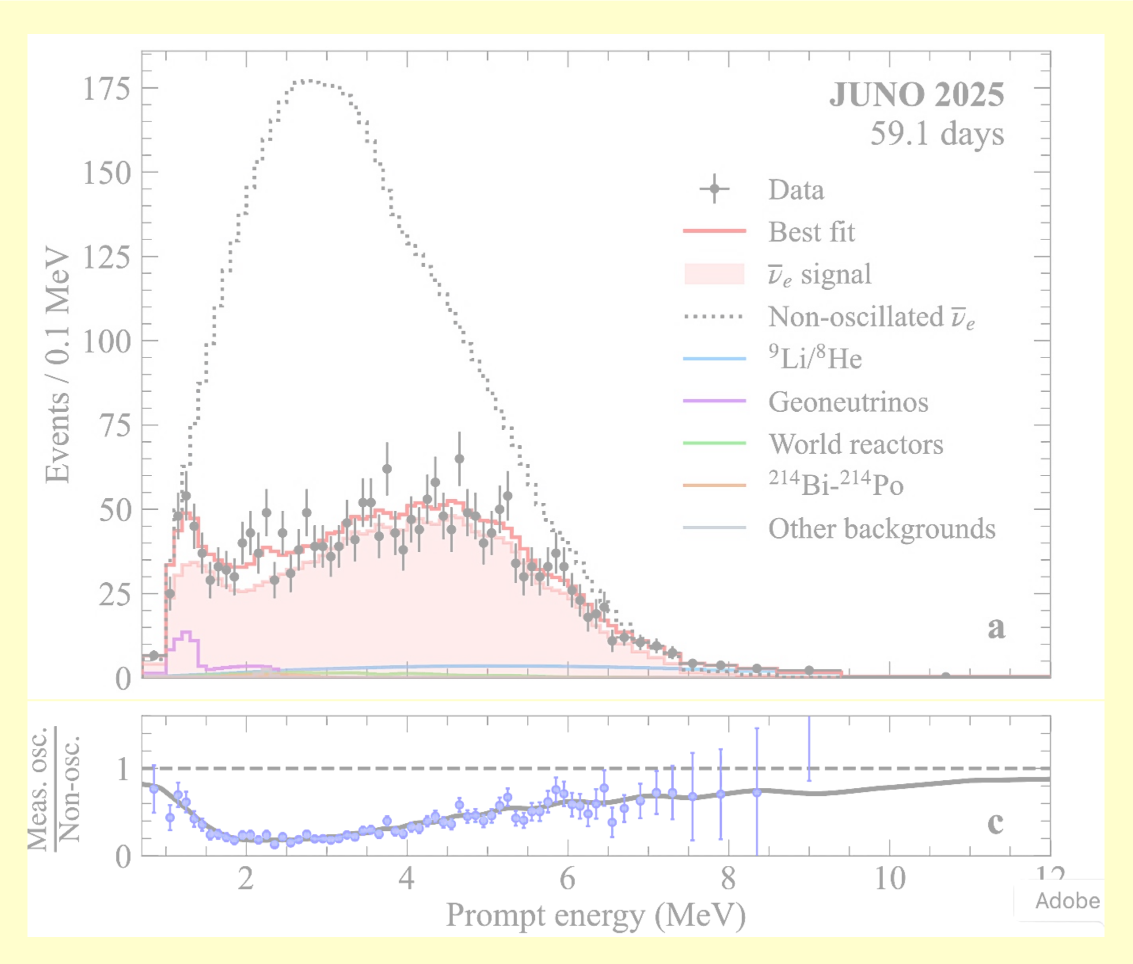

...or "not clearly emerging" → current impact "only" on (1,2) oscillation parameters.

But baby JUNO is growing fast, and will soon count 1, 2... and 3!

$\Delta m^2_{ee} > 0$ consistent with JUNO Coll. paper 1507.05613

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JUNO only:	What matters for **"JUNO standalone"** NO/IO discrimination is the relative sign $\alpha=\pm 1$ between the dominant L/E oscillation phase $2\Delta_{ee}$ and the non-L/E phase ϕ (depending on δm^2). Timescale: 6-7 years?
JUNO +XYZ expt(s)	What matters for **"JUNO + XYZ synergy"** NO/IO discrimination is the better consistency between different measurements of Δm^2_{ee} in "true" ordering w.r.t. to "wrong" ordering. Timescale: O(1) yr?

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- *[Absolute mass observables – extra slides]*

Global analysis of oscillation data → Useful analysis sequence:

LBL Accel + Solar + KL (KamLAND)

minimal set sensitive to all osc. param. δm^2, Δm^2, θ_{13}, θ_{23}, θ_{12}, δ, NO/IO

LBL Accel + Solar + KL + SBL Reactor

add sensitivity to Δm^2, θ_{13} and affect other parameters via correlations

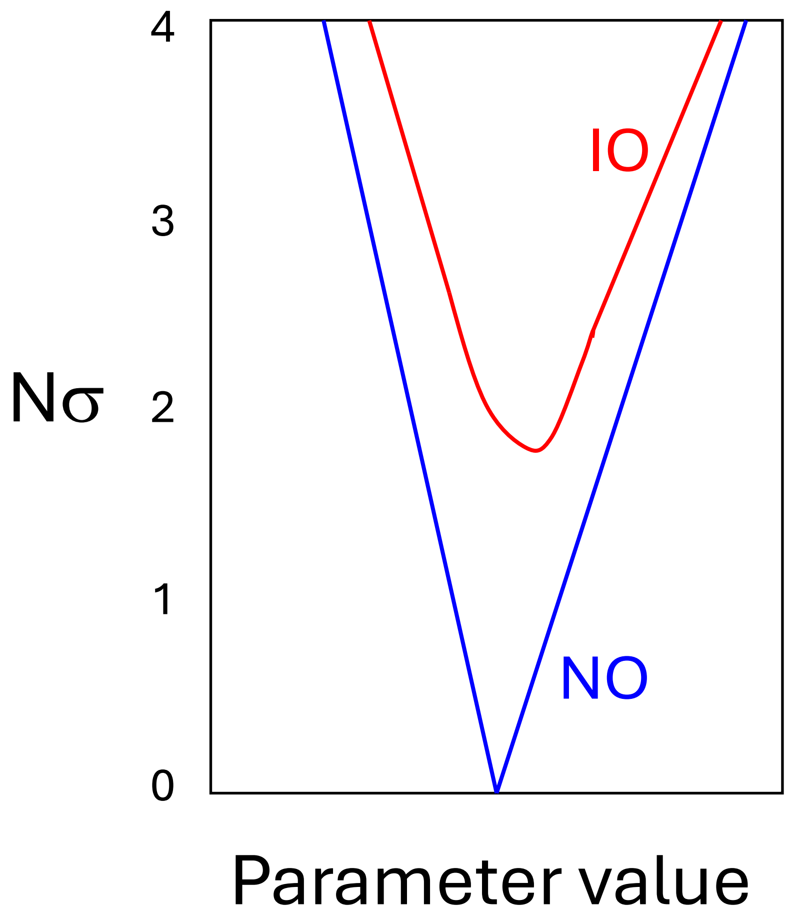
LBL Accel + Solar + KL + SBL Reactor + Atmosph.

add sensitivity to Δm^2, θ_{23}, δ, NO/IO (but: entangled information in atmos.)

[Some "synergy effects" on NO/IO already showing up since several years…]

$\Delta\chi^2$ statistics adopted for all datasets: $N\sigma = \sqrt{\Delta\chi^2}$ →

E.g.,

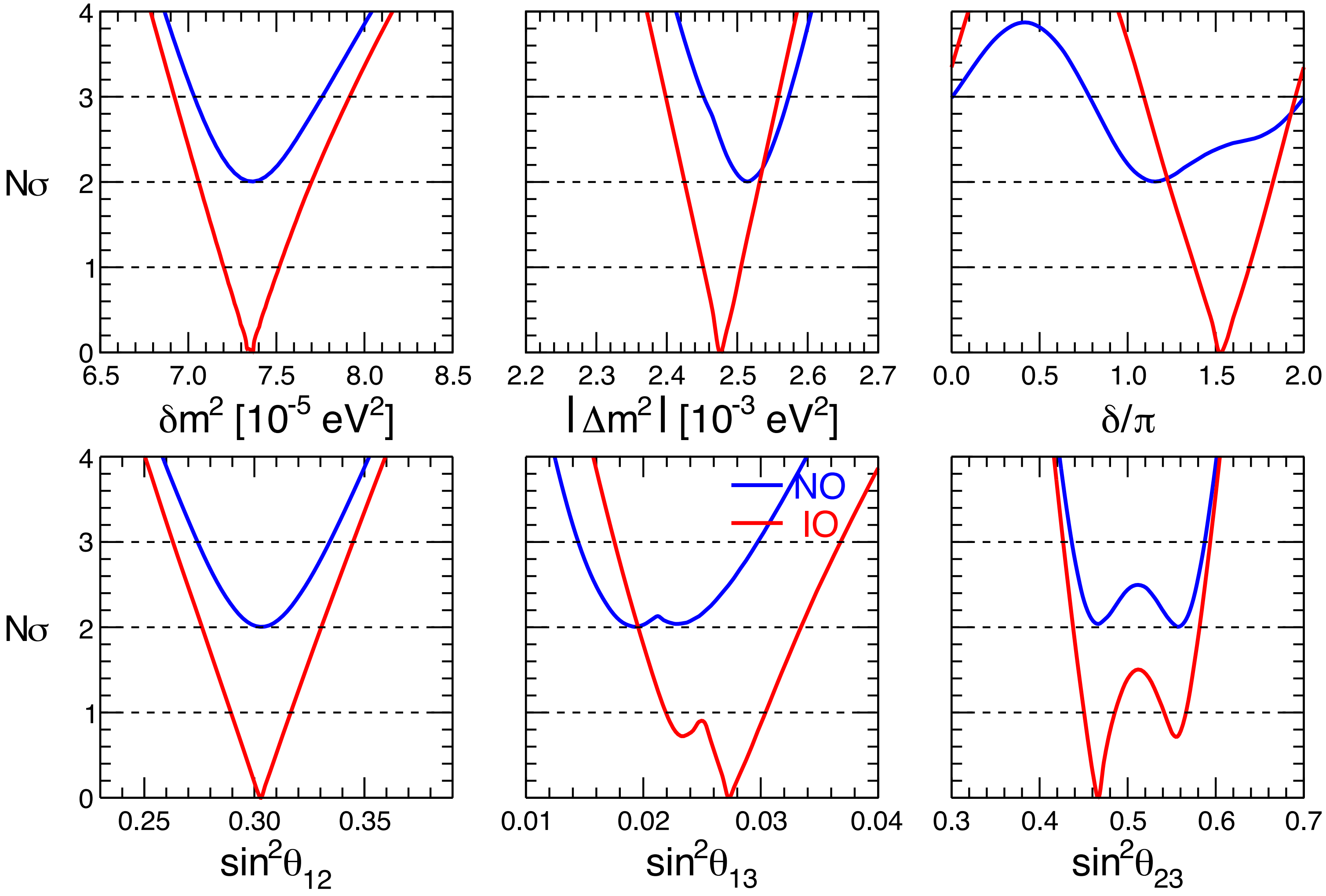


(Best-fit "perfectly gaussian" errors would lead to linear and symmetric bounds)

Let's discuss first pre-JUNO (1,2,3) param., then post-JUNO (1,2) ones

Pre-JUNO ⬇️

LBL Acc + Solar + KamLAND

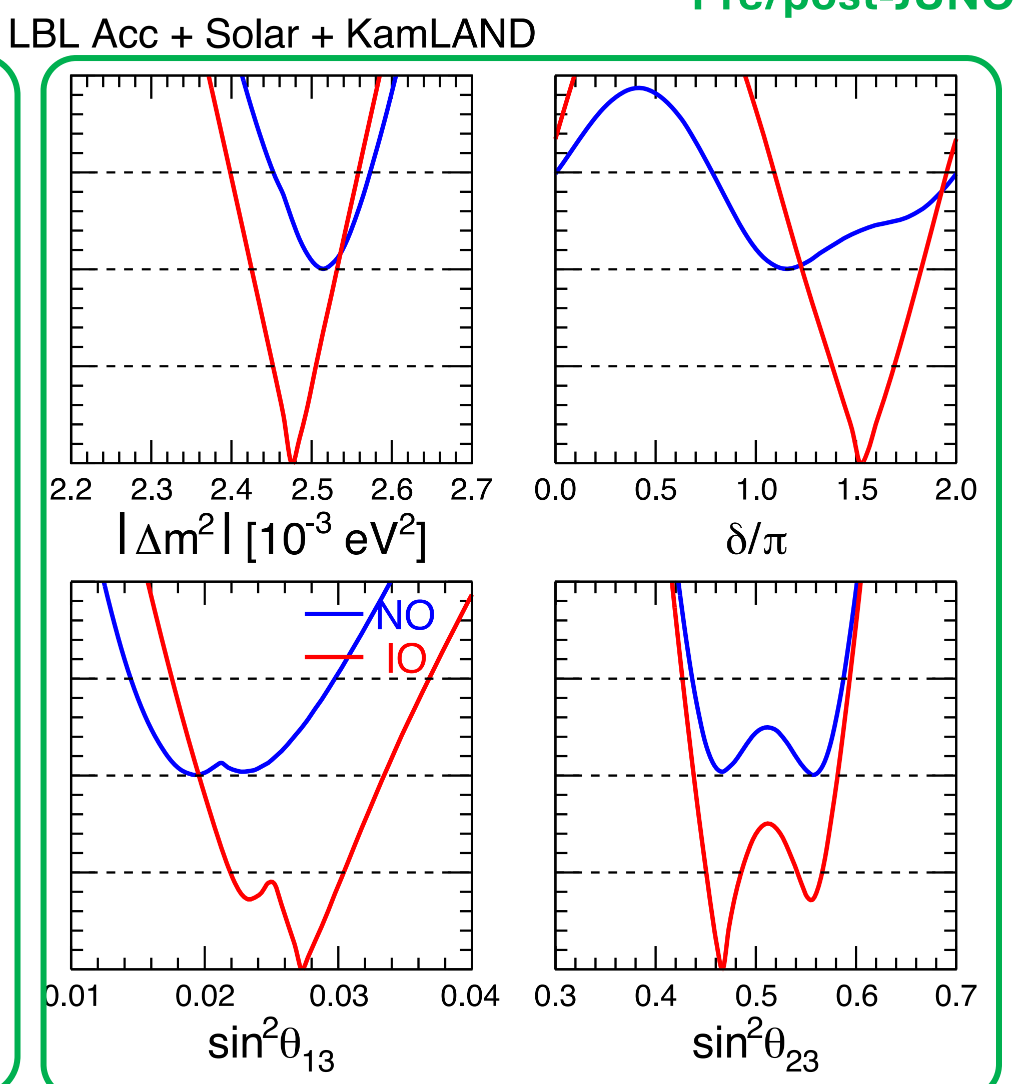


Capozzi+, arXiv:2503.07752

Pre-JUNO ⬇️

Pre/post-JUNO ⬇️

(1,2) parameters

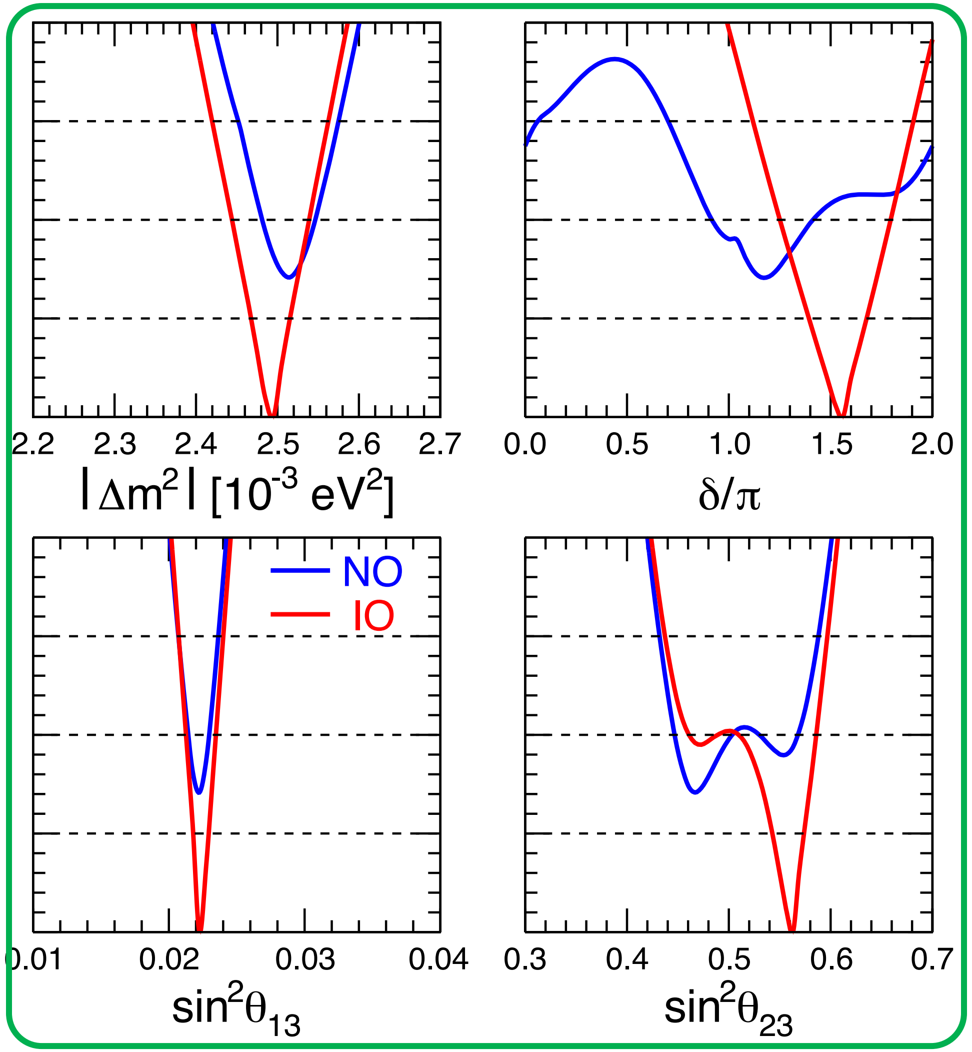


T2K and NOvA prefer NO separately, and IO in combination (at 2σ).

[Due to some tension]. **In IO, indications for CP violation > 3σ!**

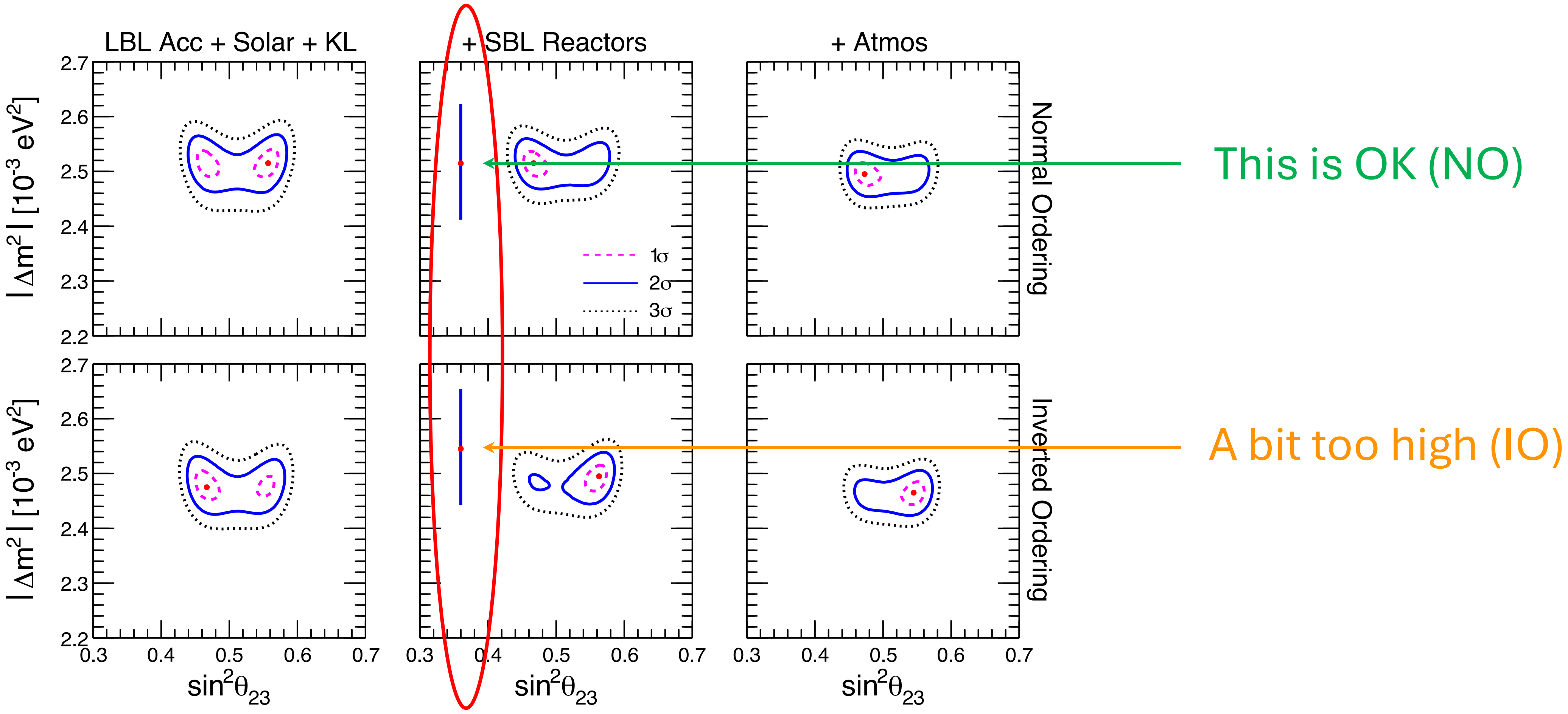
Pre/post-JUNO ⬇️

LBL Acc + Solar + KamLAND + SBL Reactors



Adding SBL reactors: Still preference for IO, but at lower CL (~1.4σ). Reason →

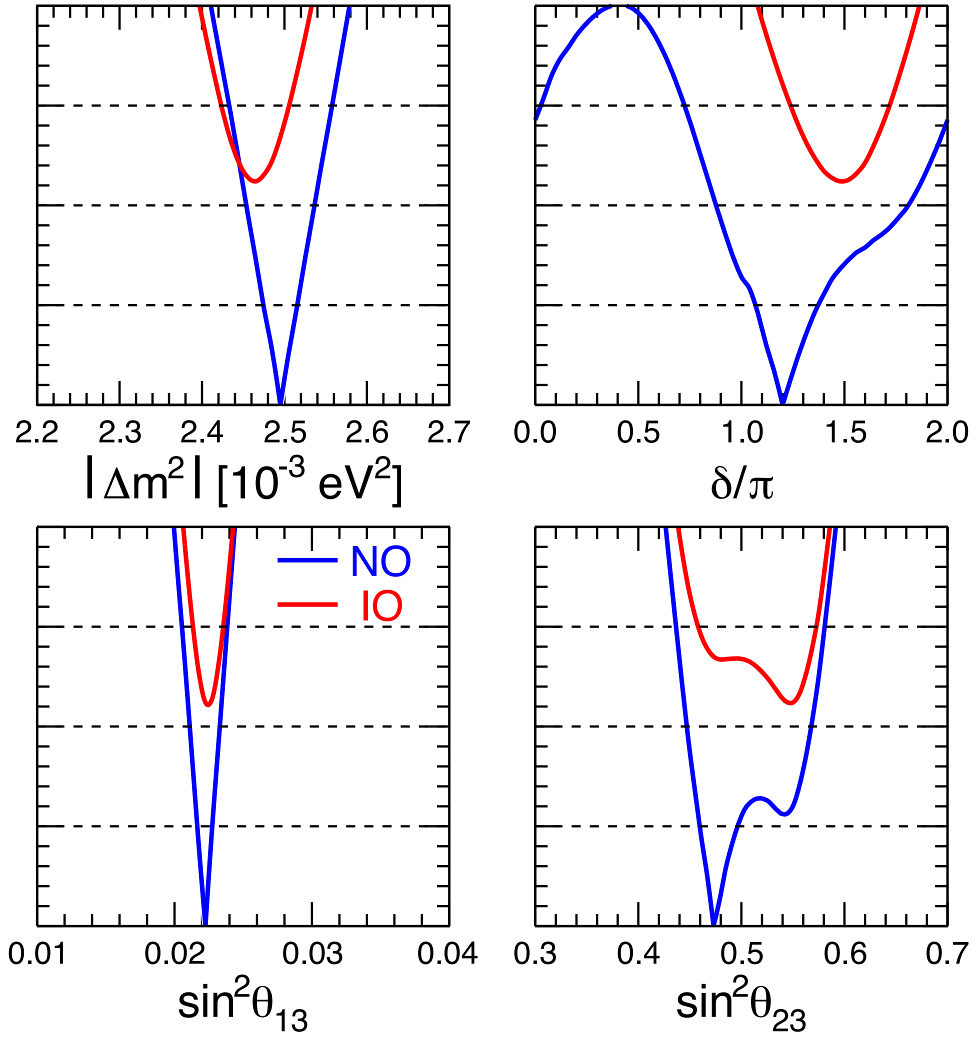
Standalone SBL reactor measurement of Δm^2 is more synergic with LBL accel. in **NO** than in **IO**



In addition, reac+acc more synergic with atmospheric data in NO wrt IO →

Pre/post-JUNO ⬇️

LBL Acc + Solar + KamLAND + SBL Reactors + Atmos



ALL DATA: Including atmospheric (SK+IC), overall preference flips from IO to NO (~2.2σ).

In NO: rather weak hints for CPV (~1.3σ) and first octant (~1.1σ)

Current hints on oscillation unknowns are slightly weaker than they used to be...

... while fractional accuracy of **known** parameters improved.

In particular, Δm^2 formally determined at the subpercent level, 1σ = 0.8%

	Parameter	Ordering	Best fit	1σ range	2σ range	3σ range	"1σ" (%)
Pre-JUNO	$\delta m^2/10^{-5}$ eV^2	NO, IO	7.37	7.21 – 7.52	7.06 – 7.71	6.93 – 7.93	2.3
	$\sin^2\theta_{12}/10^{-1}$	NO, IO	3.03	2.91 – 3.17	2.77 – 3.31	2.64 – 3.45	4.5
Pre/Post	$\lvert\Delta m^2\rvert/10^{-3}$ eV^2	NO	2.495	2.475 – 2.515	2.454 – 2.536	2.433 – 2.558	0.8
		IO	2.465	2.444 – 2.485	2.423 – 2.506	2.403 – 2.527	0.8
” ”	$\sin^2\theta_{13}/10^{-2}$	NO	2.23	2.17 – 2.27	2.11 – 2.33	2.06 – 2.38	2.4
		IO	2.23	2.19 – 2.30	2.14 – 2.35	2.08 – 2.41	2.4
” ”	$\sin^2\theta_{23}/10^{-1}$	NO	4.73	4.60 – 4.96	4.47 – 5.68	4.37 – 5.81	5.1
		IO	5.45	5.28 – 5.60	4.58 – 5.73	4.43 – 5.83	4.3
” ”	δ/π	NO	1.20	1.07 – 1.37	0.88 – 1.81	0.73 – 2.03	18
		IO	1.48	1.36 – 1.61	1.24 – 1.72	1.12 – 1.83	8
” ”	$\Delta\chi^2_{\mathrm{IO-NO}}$	IO−NO	+5.0				

But there are reasons to be **cautious about subpercent accuracy** levels...

E.g., correlated effects of ν **interaction uncertainties** in different expts need improvement

The **official SK+T2K analysis** estimates that neutrino interaction systematics in the water detector can **bias Δm^2 up to 1.5% at 1σ**.

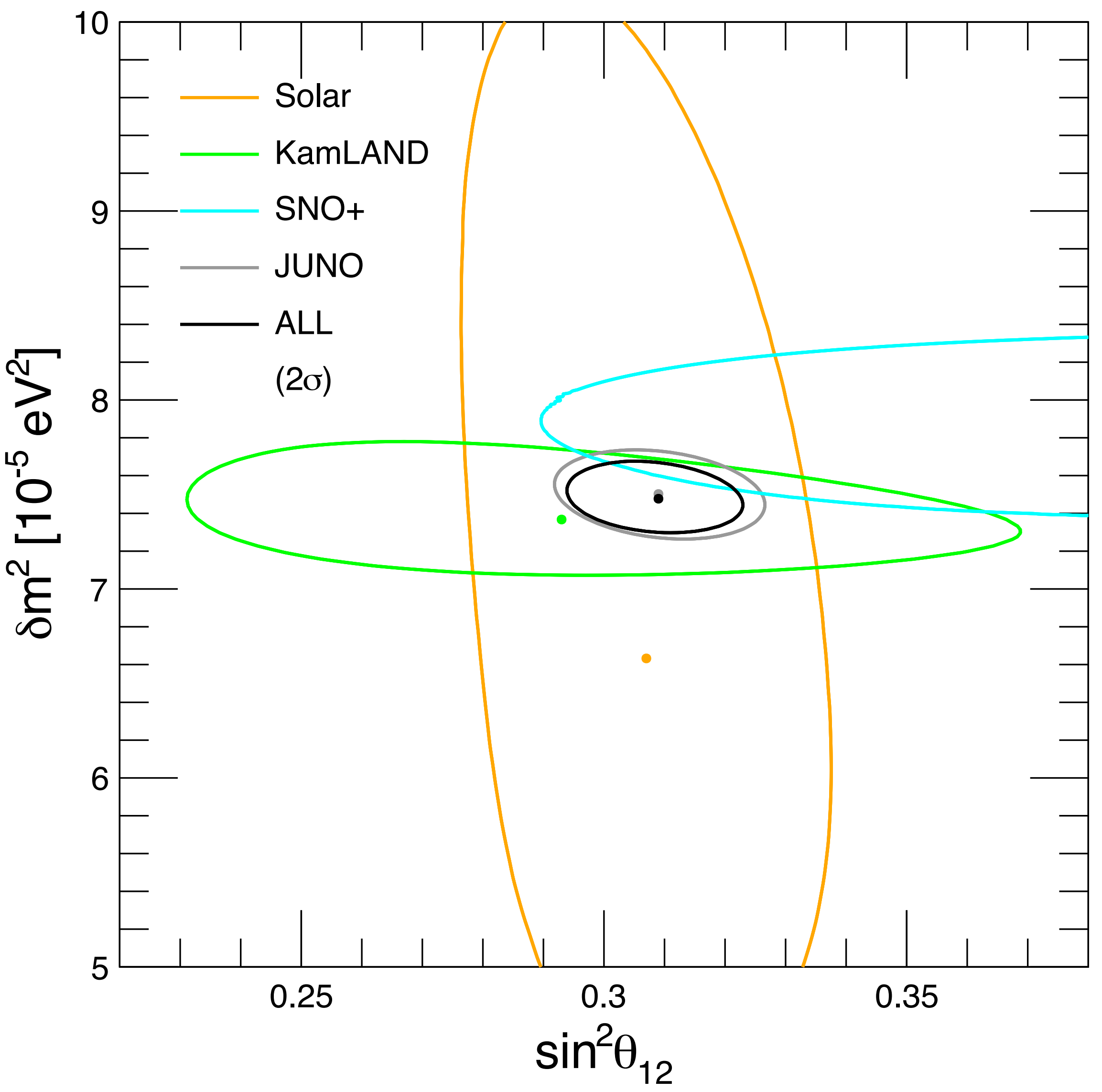
These systematics, being correlated among H_2O-based experiments, can't be reduced by combining their results:
SK+T2K +IceCube +KM3NeT +HK+...
(Adding their χ^2 maps is formally incorrect)

Common interaction systematics can be reduced only by improving nuclear models and related experimental constraints!

From SK+T2K official analysis (2405.12488):

Robustness studies—Simulated datasets [3], generated using alternative models and fit using the nominal model are used to measure how *p*-values and oscillation parameter constraints would be affected if the assumed model is incomplete (Appendix D). Fourteen simulated datasets are considered, corresponding to alternative neutrino interaction models and data-driven effects at both T2K ND and SK. These studies are used to estimate, for example, how the observed atmospheric down-going CC1π^+ data excess could bias the results if it originated from an unknown systematic effect. Some of the simulated datasets produce a visible shift in the preferred values for Δm^2_{32}. The uncertainty on Δm^2_{32} is therefore inflated by 3.6×10^{-5} eV$^2/c^4$ to account for these effects.

Post-JUNO (1,2) parameters δm^2, θ_{12}



Global analysis [Ref.]	Parameter	Best fit	"1σ" (%)
All data 2024	$\delta m^2/10^{-5}$ eV^2	7.37	2.3
[3]	$\sin^2\theta_{12}/10^{-1}$	3.03	4.5
w/ SNO+ 2025	$\delta m^2/10^{-5}$ eV^2	7.44	2.1
[This work]	$\sin^2\theta_{12}/10^{-1}$	3.06	4.4
w/ SNO+ & JUNO 2025	$\delta m^2/10^{-5}$ eV^2	7.48	1.3
[This work]	$\sin^2\theta_{12}/10^{-1}$	3.085	2.4

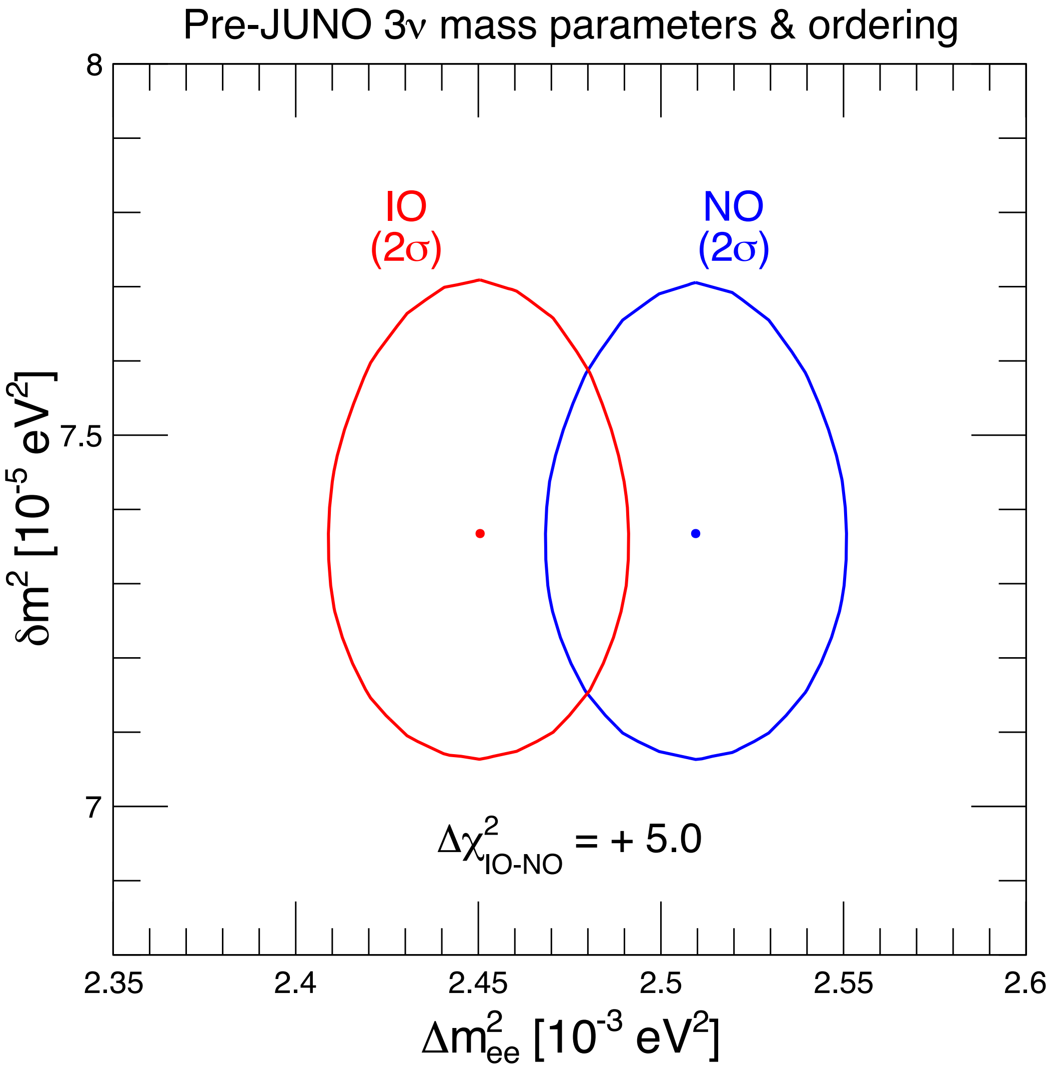
JUNO takes the lead!

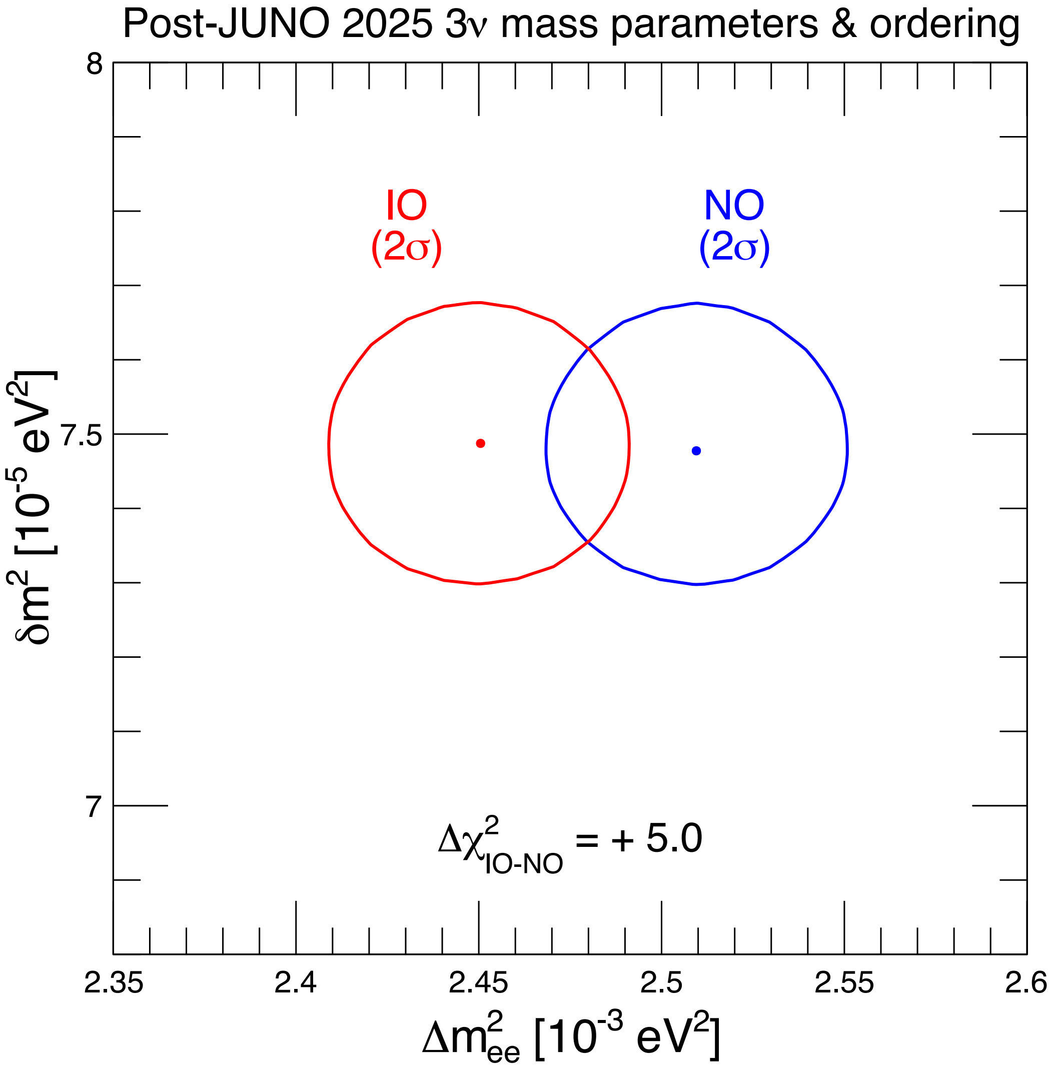
(almost ×**2** improvement on both)

Post-JUNO (1,2)-param:

$$\delta m^2/10^{-5}\text{eV}^2 = 7.48 \pm 0.10,$$
$$\sin^2\theta_{12}/10^{-1} = 3.085 \pm 0.073,$$
$$\rho = -0.20.$$

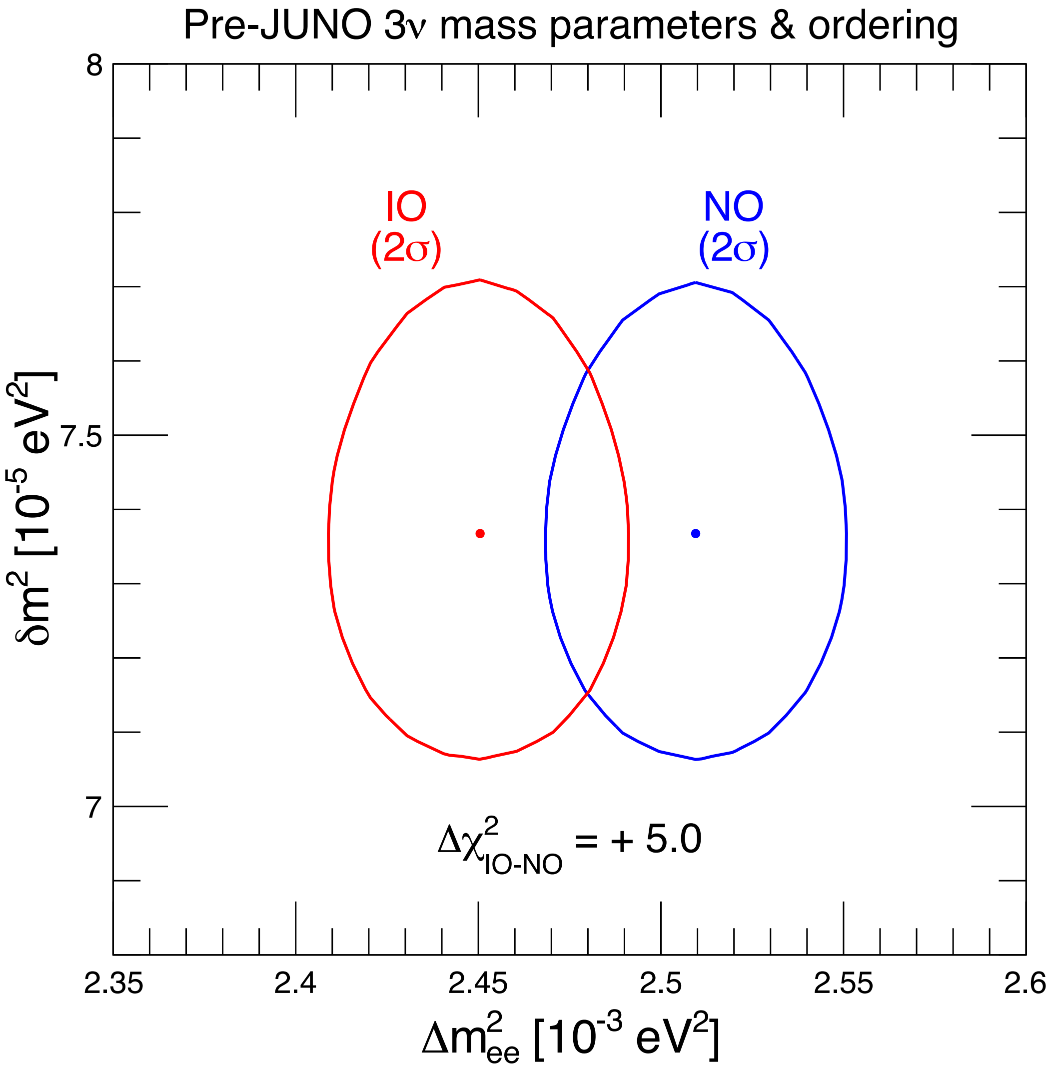
Squared mass parameters (δm^2, Δm^2_{ee}) before and after JUNO

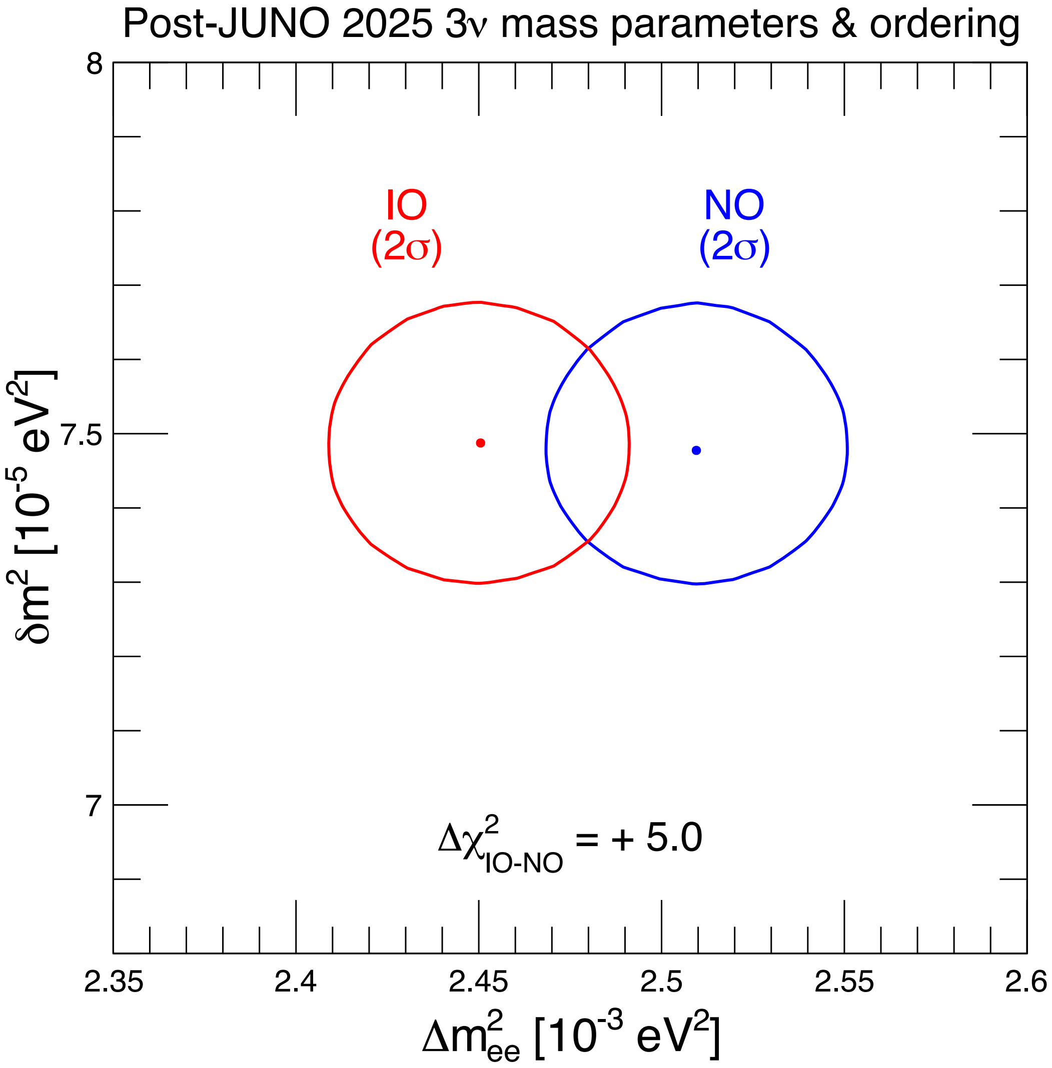




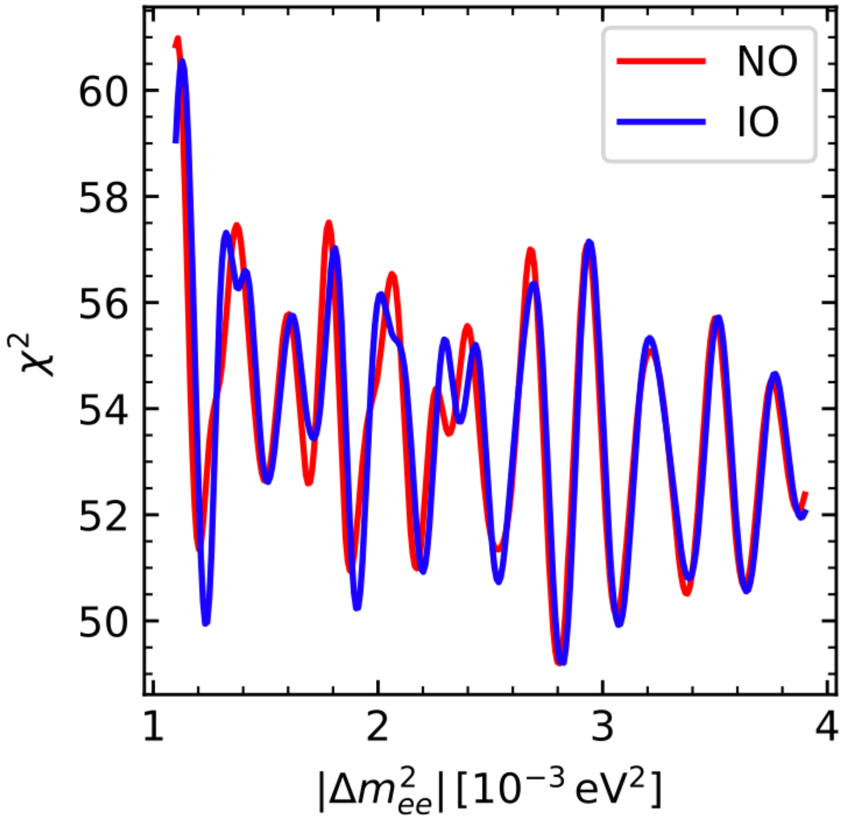
But the real "prey" is Δm^2_{ee} : not yet determined (or stable) from 1st JUNO data.

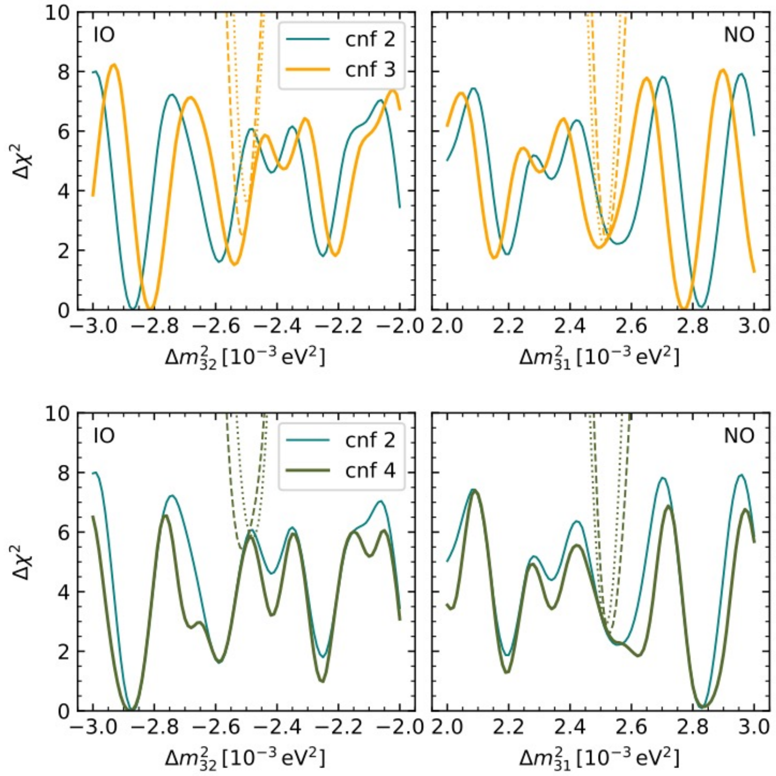
Current instability and degeneracy of Δm^2_{ee} in JUNO is known to phenomenologists...





... e.g. it is explicitly shown by Nu-Fit group in 2601.09791:

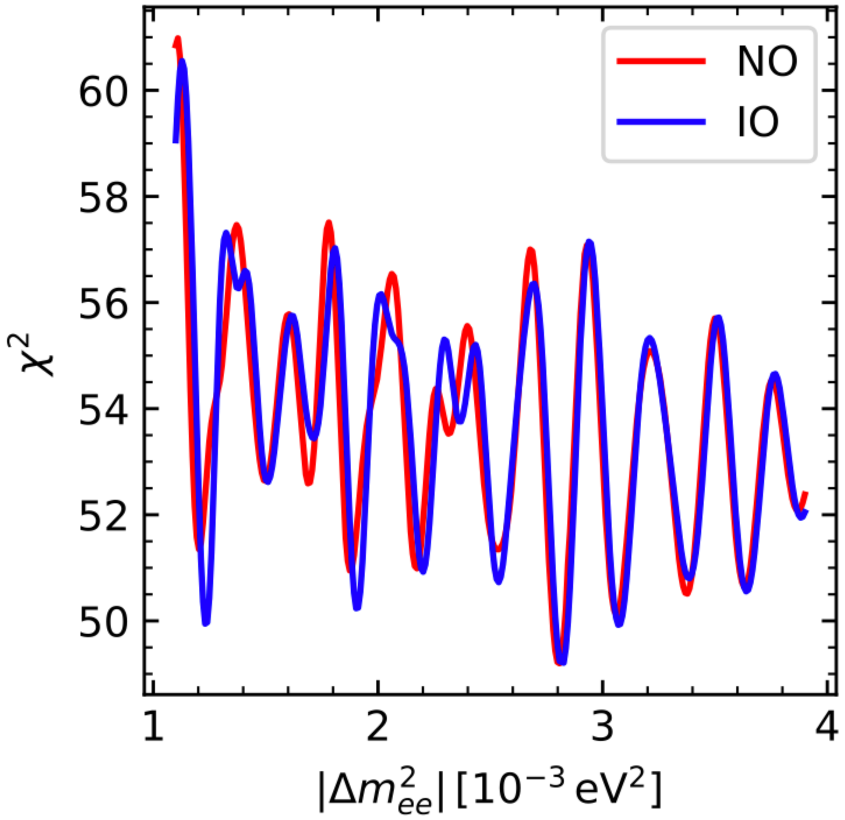


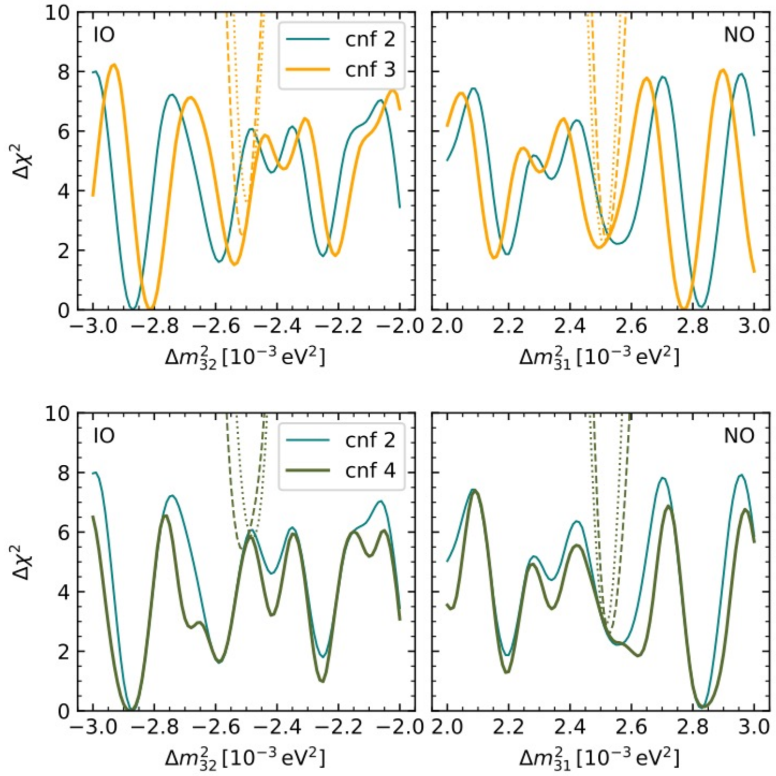


Low stat → ~Degenerate minima

Systematics → ~Displaced minima

... e.g. it is explicitly shown by Nu-Fit group in 2601.09791:





Low stat → ~Degenerate minima

Systematics → ~Displaced minima

But: convergence on a single -or highly preferred- Δm^2_{ee} minimum will not take long!

[Say, it may occur this Summer at Neutrino 2026]. **What may happen then?**

- Intro and remarks on JUNO
- Results from osc. data fit (pre/post-JUNO)
- Prospective impact of further (~1 yr) data
- *[Absolute mass observables – extra slides]*

Technical note: Any JUNO event spectrum fit leads to two slightly different best fits points for osc. parameters in NO and IO. See eg. Capozzi+ 1508.01392:

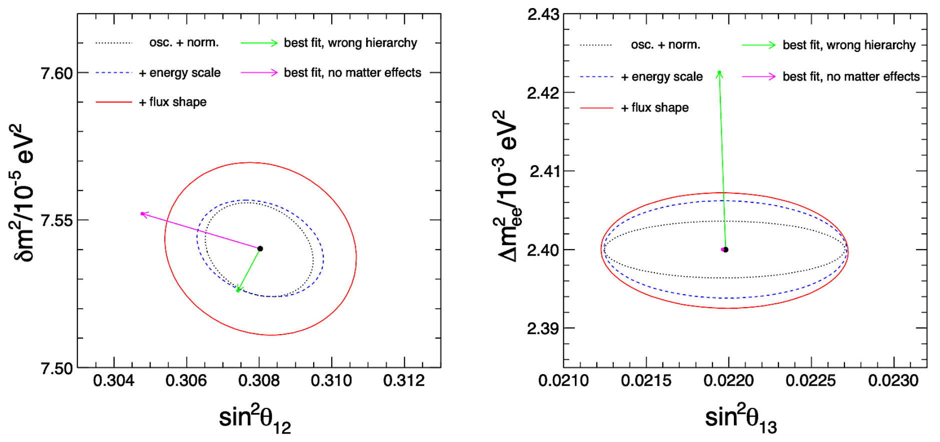


FIG. 16: As in Fig. 9, but with halved energy-scale and flux-shape uncertainties.

FIG. 17: As in Fig. 10, but with halved energy-scale and flux-shape uncertainties.

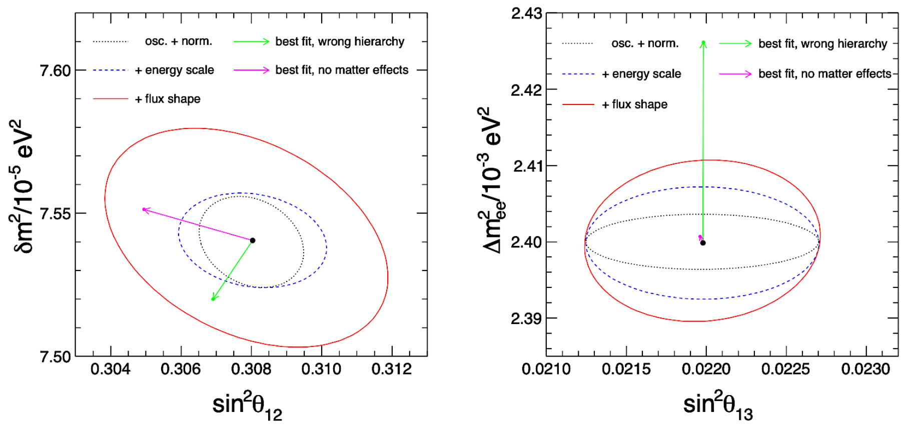


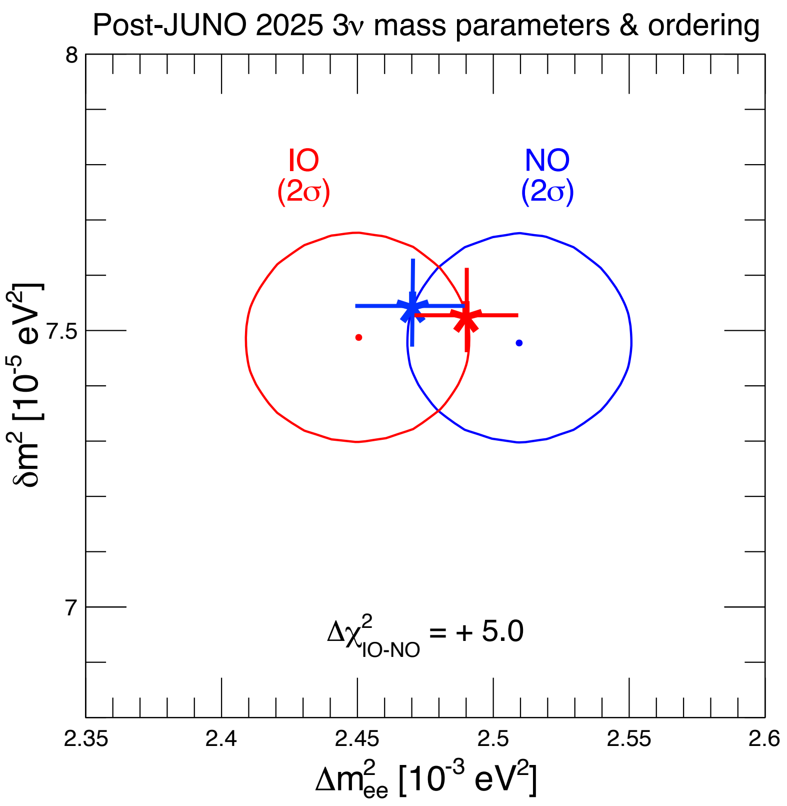
FIG. 9: Mass-mixing parameters (δm^2, s^2_{12}): 1σ contours for true NH and $T = 5$ y, as derived from fits including different systematic uncertainties. The arrows indicate the best-fit displacement in the cases of wrong hierarchy (green) and no matter effects (magenta).

FIG. 10: As in Fig. 9, but for the (Δm^2_{ee}, s^2_{13}) parameters.

Green arrows: shifts of best fits when passing from NO to IO assumption.

Shift of Δm^2 discussed in many papers. All parameter shifts depend little on fit details.

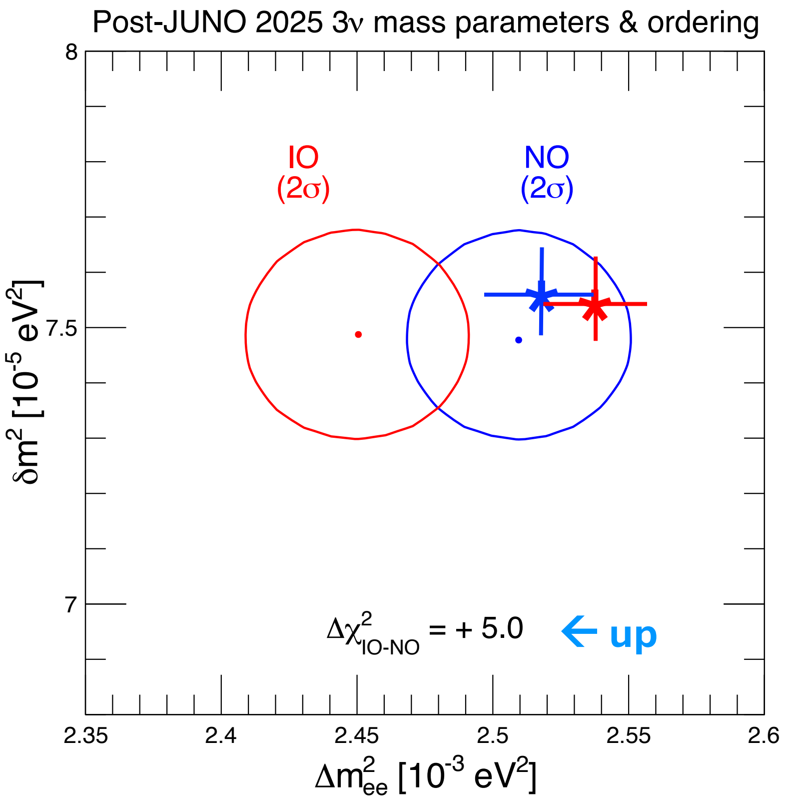
After one year, an educated guess about JUNO's <u>relative</u> best-fit points in NO and IO, together with their associated $\pm 2\sigma$ errors, might look like this one in the $(\delta m^2, \Delta m^2_{ee})$ plane:



Now, let's move around the hypothetical best-fit points!

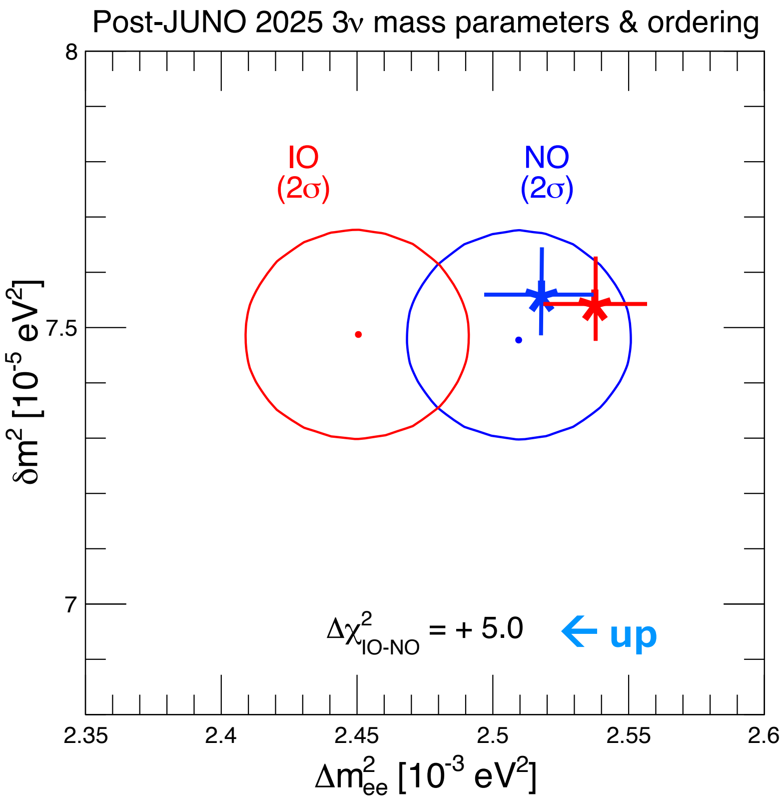
Examples of possible JUNO outcomes after ~1 yr

A synergy favoring NO

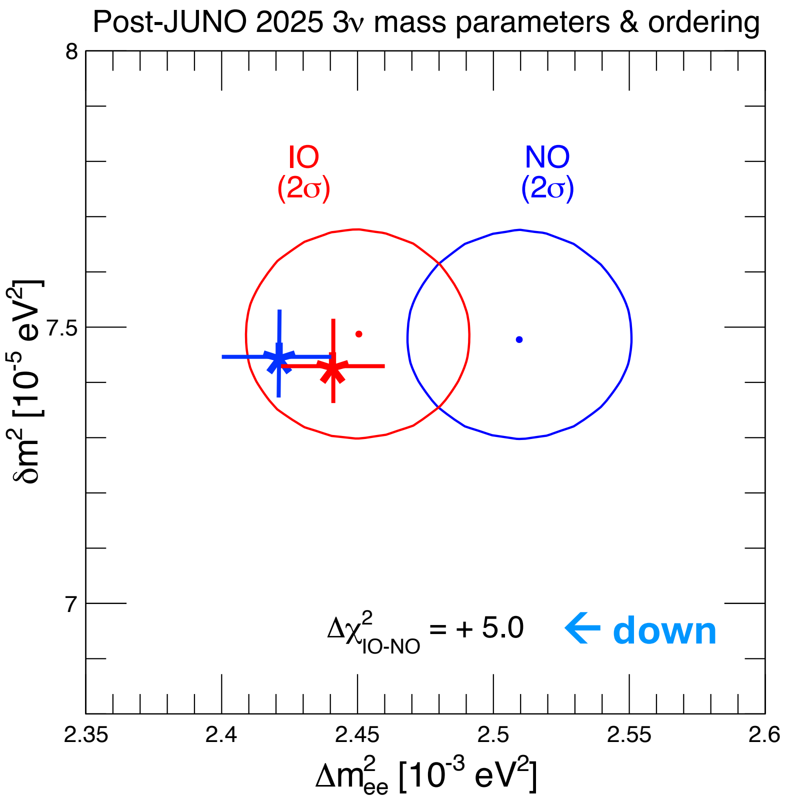


Examples of possible JUNO outcomes after ~1 yr

A synergy favoring NO



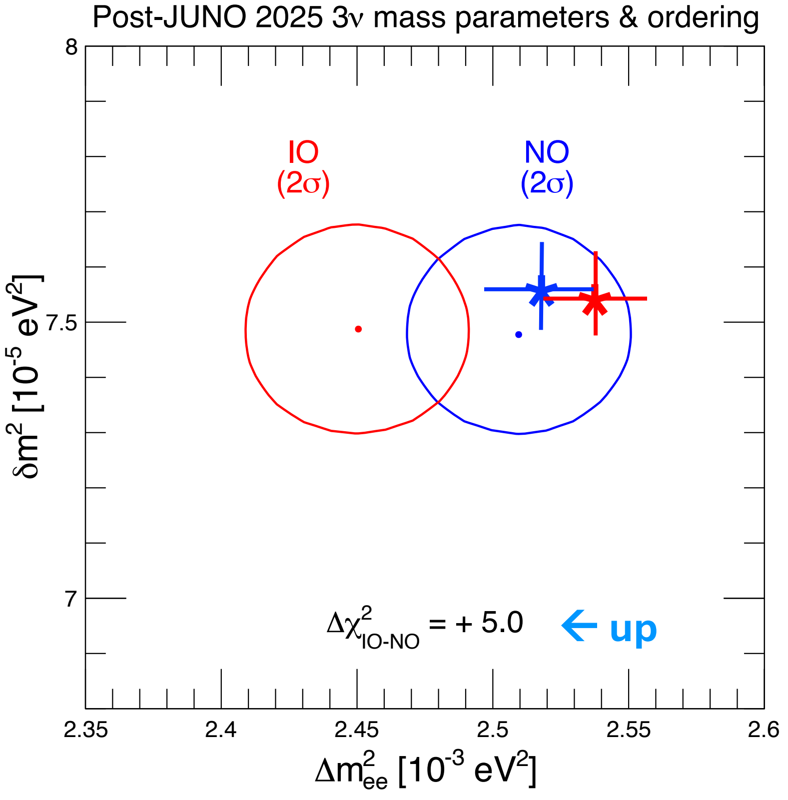
A synergy favoring IO



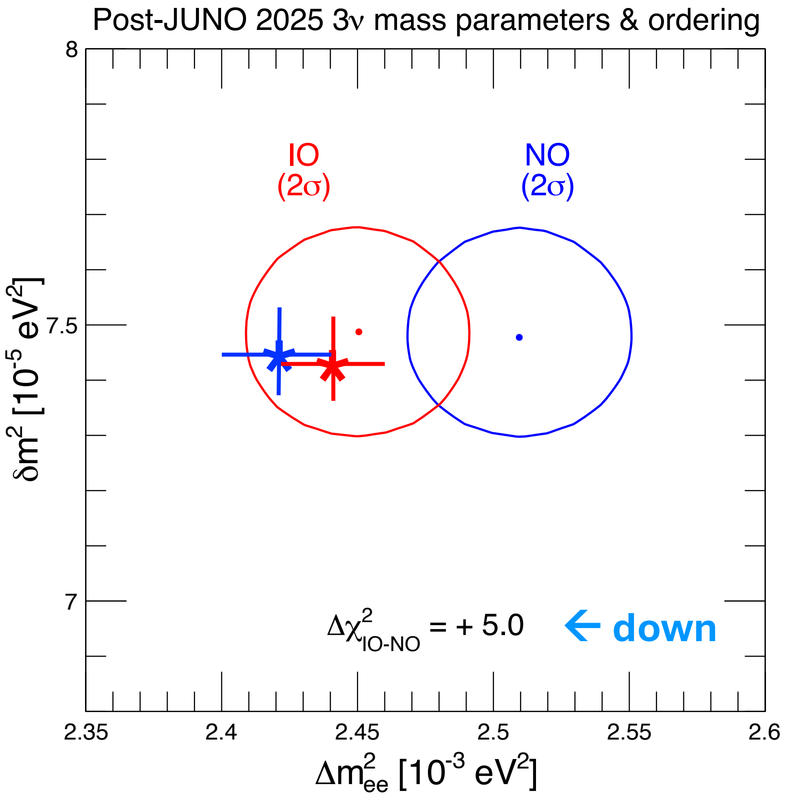
[But what about current NO favored...?]

Examples of possible JUNO outcomes after ~1 yr

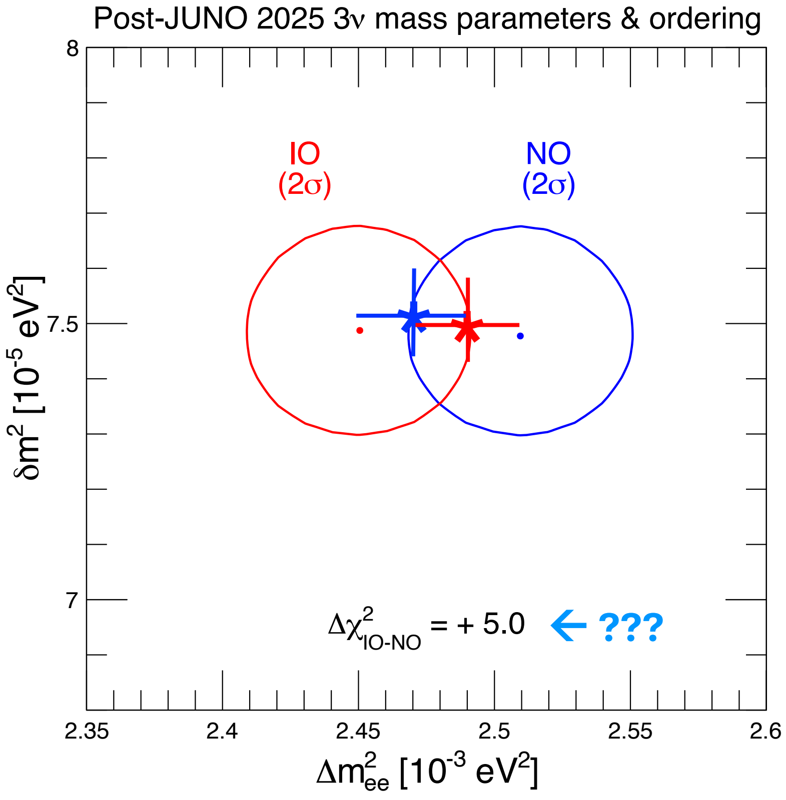
A synergy favoring NO



A synergy favoring IO

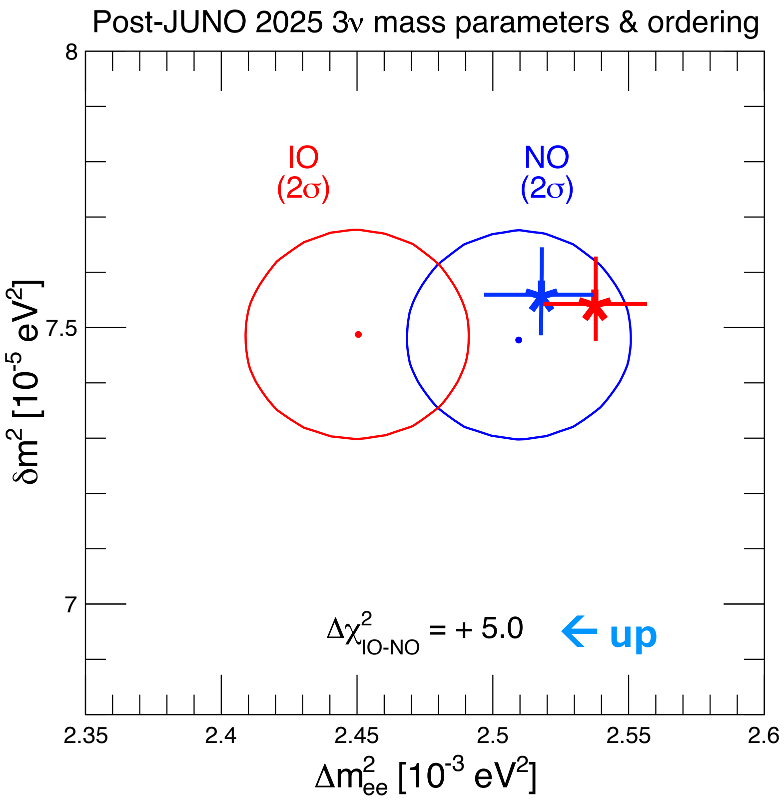


An undecided NO/IO...

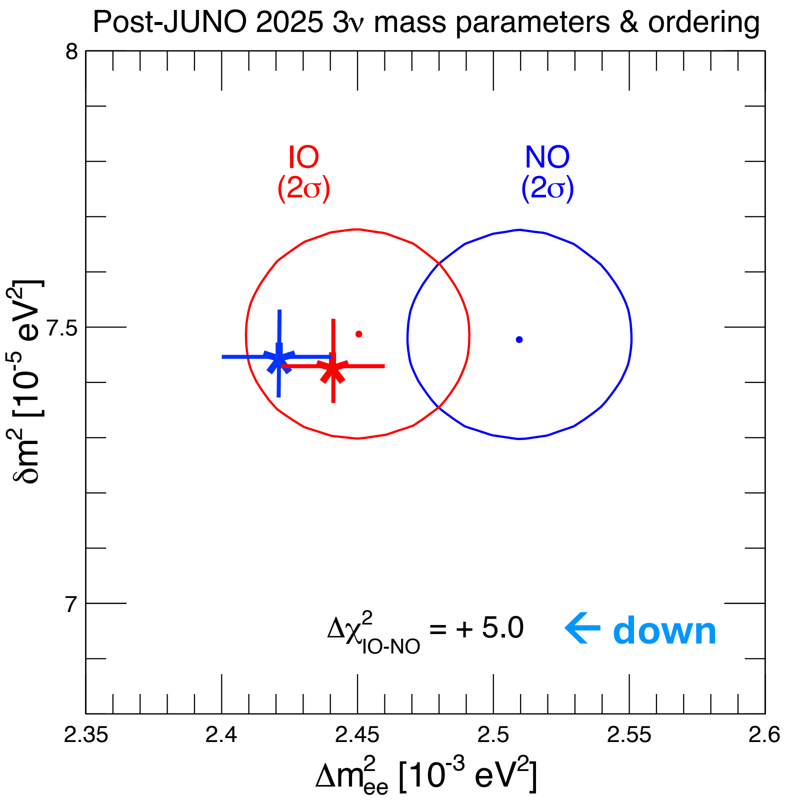


Examples of possible JUNO outcomes after ~1 yr

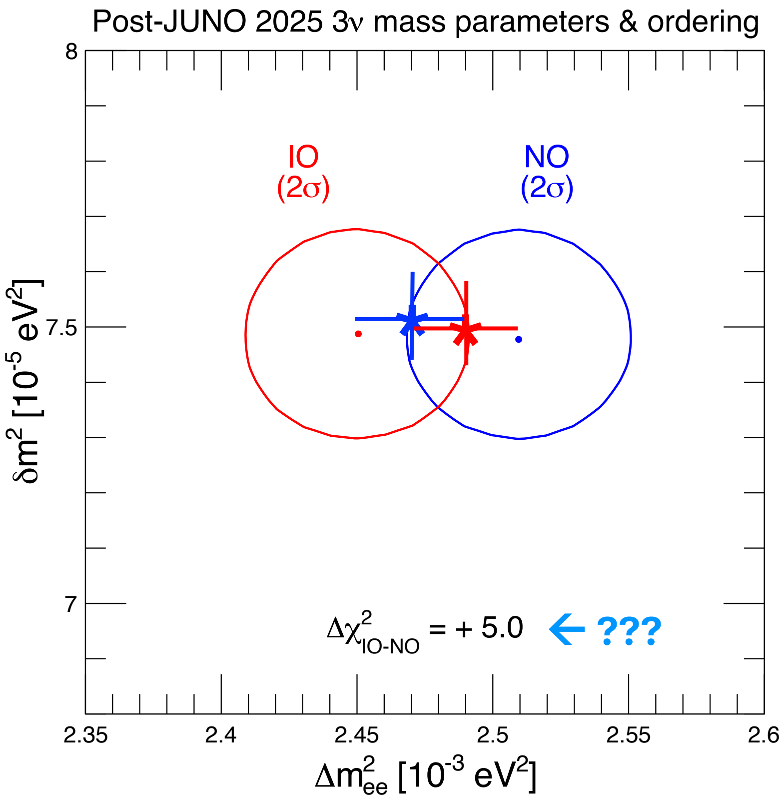
A synergy favoring NO



A synergy favoring IO

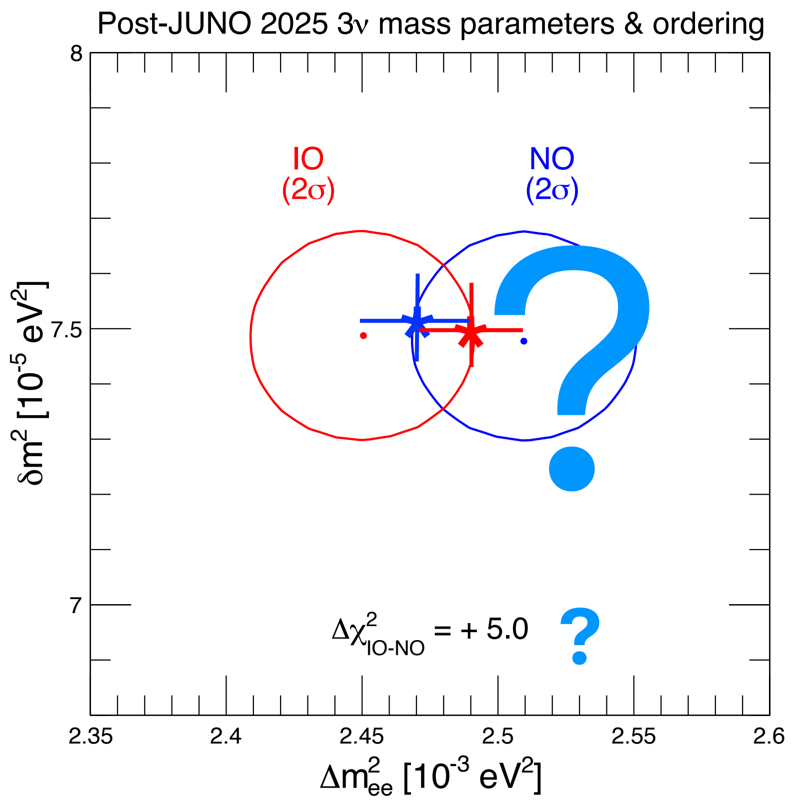


An undecided NO/IO...



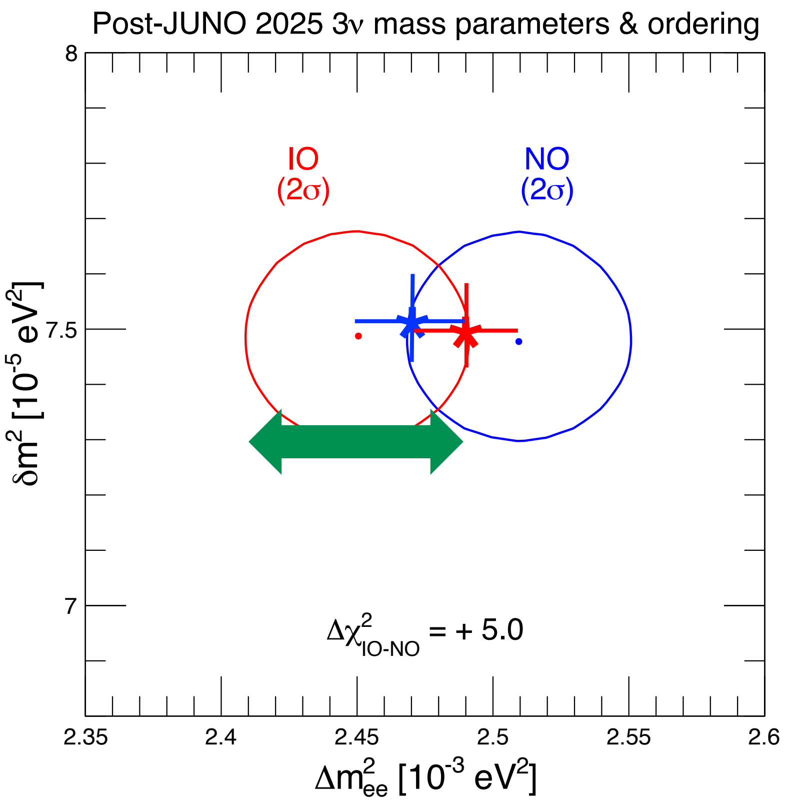
... with some cascade (correlated) effects on the other oscill. unknowns – difficult to anticipate!

So, it will be very interesting to see where first-year JUNO data will fall in this plane…
and, in the long term, compare with (convergent?) JUNO standalone results on NO/IO



Indications could converge towards the true mass ordering, or show up some tension(s) that might point towards something new, beyond standard 3ν oscillations…

... modulo interaction systematics in accelerator / atmospheric experiments, that might significantly bias the interpretation:



Arrows: the ±1.5% ν interaction error estimated in the official SK+T2K analysis

[while in JUNO: IBD reaction very well known, very small interaction systematics]

Precision frontier entering the sub% accuracy

5 knowns:

δm^2	$\sim 7 \times 10^{-5}\ eV^2$	*Oscillations*
$\lvert\Delta m^2\rvert$	$\sim 2 \times 10^{-3}\ eV^2$	
$\sin^2\theta_{12}$	~ 0.3	
$\sin^2\theta_{23}$	~ 0.5	
$\sin^2\theta_{13}$	~ 0.02	

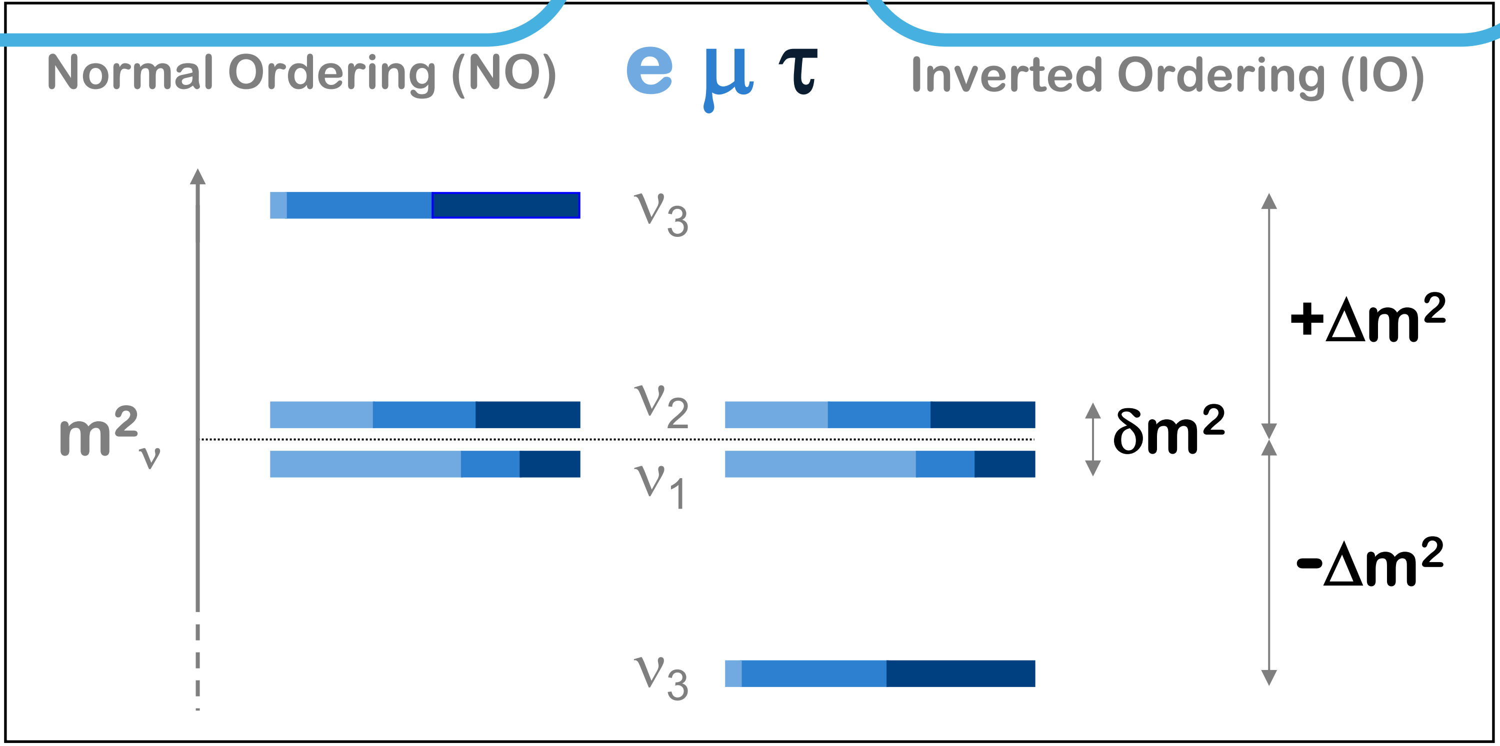
3ν recap

5 unknowns:

Oscillations:
- **δ CPV** Dirac phase
- **sign(Δm^2)** → NO/IO
- **θ_{23} octant** degeneracy

Non-oscillat.:
- **absolute mass** scale
- **Dirac/Majorana** nature

Discovery frontier quite open to different outcomes



JUNO will soon affect both frontiers - plus other neutrino expts in the pipeline. In general, remain open to possible surprises beyond the standard 3ν (and cosmological) frameworks

- Intro and remarks on JUNO
- Results from osc. data fit (pre/post-JUNO)
- Prospective impact of further (~1 yr) data
- *[Absolute mass observables – extra slides]*

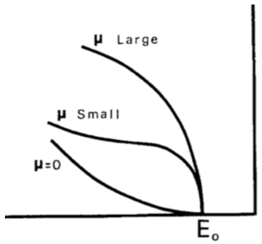
  ... if time allows

Absolute neutrino mass observables: (m_β , $m_{\beta\beta}$, Σ)

Probe absolute neutrino masses in different ways
May provide extra handles to distinguish NO vs IO

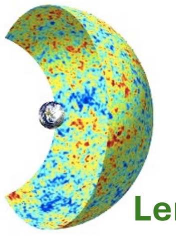
β decay (kinematics) - Sensitive to the "effective electron neutrino mass":

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



Cosmology (gravity) - Dominantly sensitive to sum of neutrino masses:

$$\Sigma = m_1 + m_2 + m_3$$



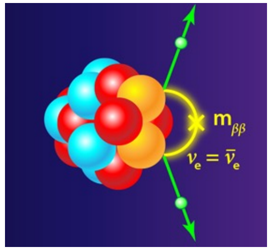
CMB

LSS

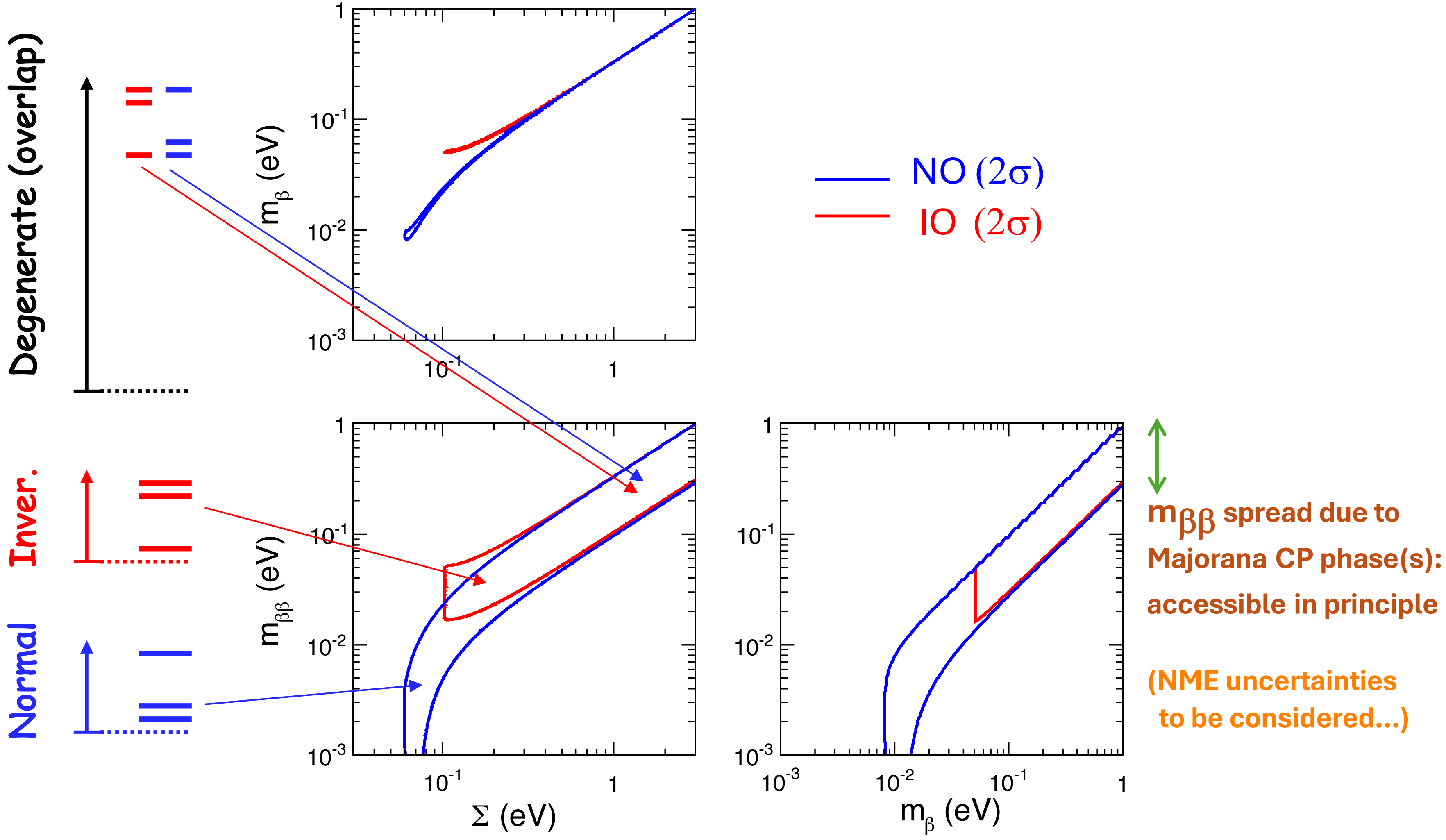
Lensing

0νββ decay: only if Majorana. "Effective Majorana mass" (+new CPV phases):

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$

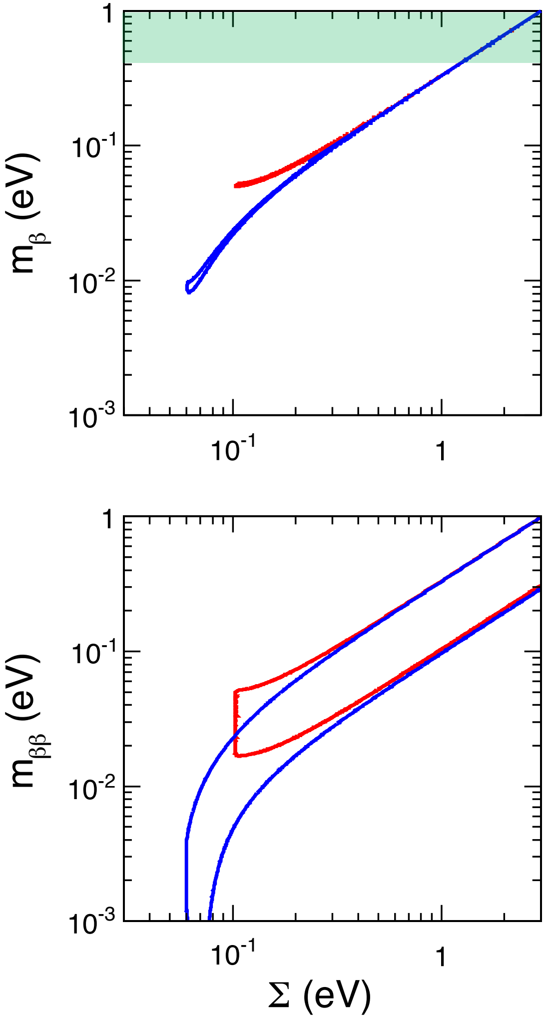


(m_β , $m_{\beta\beta}$, Σ) observables: bands allowed by oscillations in NO/IO



β: KATRIN

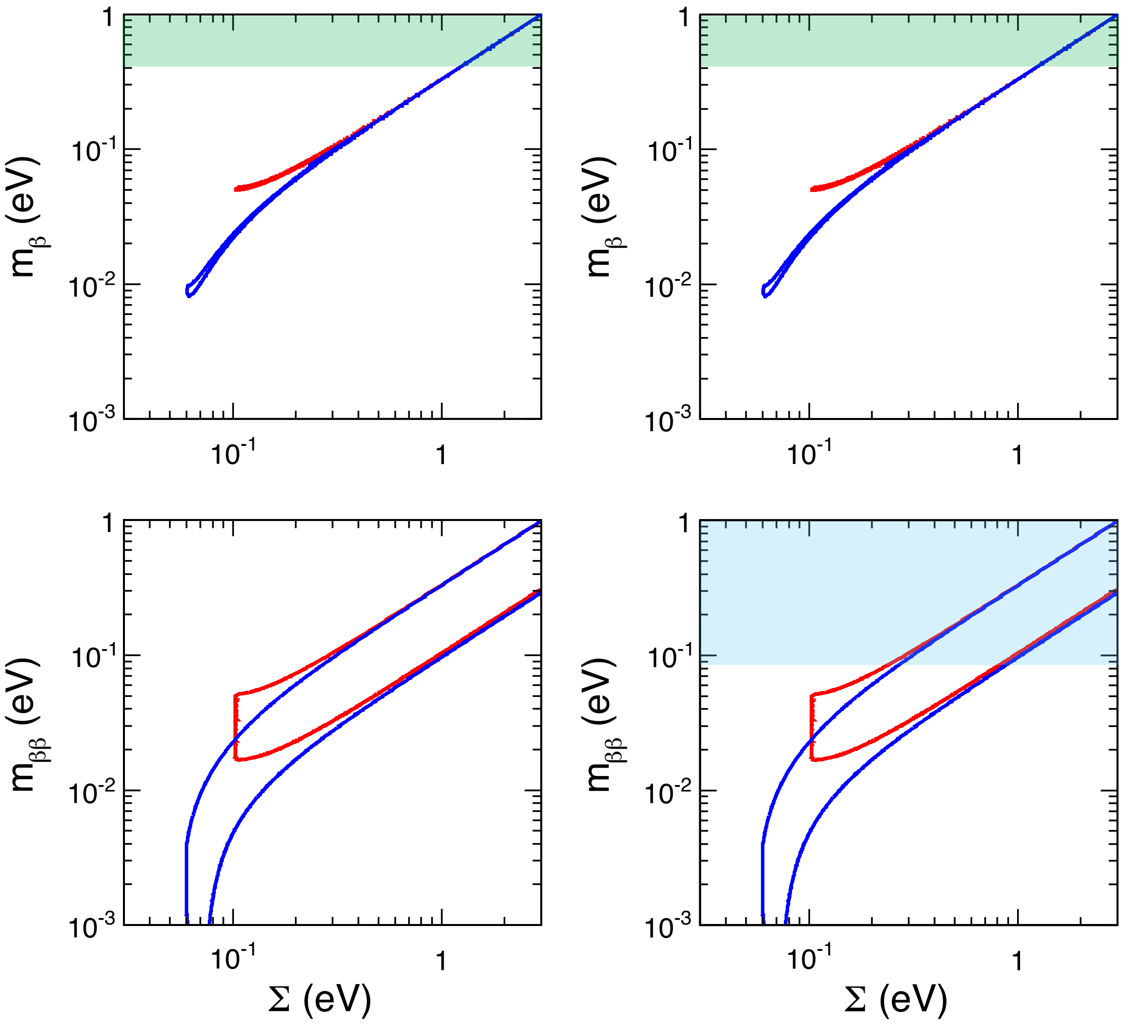
← No signal so far. Current upper bounds from β decay



β: KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

[+ nuclear model uncert.]



← **Current upper bounds from 0νββ decay including correlated NME uncertainties**

Cosmology: data tensions in the standard ΛCDM model

Possible systematics (e.g., lensing?)

Possible new physics (e.g., dynamical dark energy?)

TABLE IV: Results of the cosmological data analysis under three model assumptions: standard cosmology with neutrino masses (ΛCDM+Σ), an extended model accounting for lensing systematics (ΛCDM+Σ+A_{lens}), and a nonstandard cosmology with dynamical dark energy and neutrino masses ($w_0 w_a$CDM+Σ). The datasets used are listed in Section III C. For Planck, we consider both Plik and CamSpec likelihoods, which yield very similar results in all cases (shown explicitly only for ΛCDM+Σ). Upper bounds on Σ are reported at the 2σ level.

#	Model	Data set	Σ (2σ)
1	$\Lambda\text{CDM} + \Sigma$	Plik	< 0.175 eV
2		Plik+DESI	< 0.065 eV
3		Plik+DESI+PP	< 0.073 eV
4		Plik+DESI+DESy5	< 0.091 eV
5		camspec	< 0.193 eV
6		camspec+DESI	< 0.064 eV
7		camspec+DESI+PP	< 0.074 eV
8		camspec+DESI+DESy5	< 0.088 eV
9	ΛCDM+Σ+A_{lens}	Plik	< 0.616 eV
10		Plik+DESI	< 0.204 eV
11		Plik+DESI+PP	< 0.255 eV
12		Plik+DESI+DESy5	< 0.287 eV
13	$w_0 w_a$CDM+Σ	Plik	< 0.279 eV
14		Plik+DESI	< 0.211 eV
15		Plik+DESI+PP	< 0.155 eV
16		Plik+DESI+DESy5	< 0.183 eV

Wide range of bounds: $\Sigma < 0.2$ eV within factor of 3 (up/down)

Using the same data, limit depends on the underlying model (unlike beta decay))

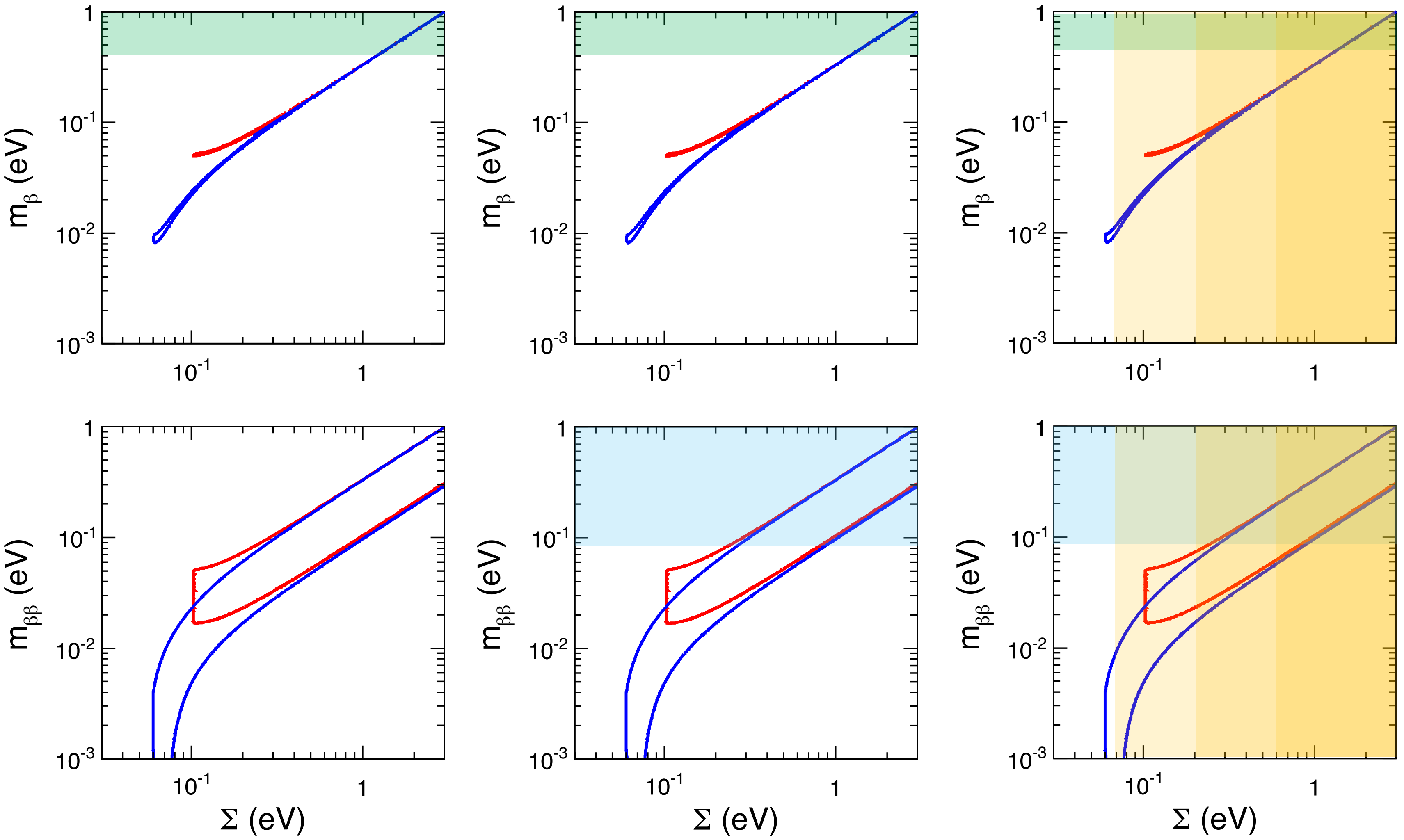
β: KATRIN

0νββ: KL-Zen, Exo, GERDA, Cuore...

Σ: Planck, BAO, lensing ...

[+ nuclear model uncert.]

[spread: model/data tension]



IO "under pressure" from cosmo data. But: lively debate after recent (too strong?) DESI constraints

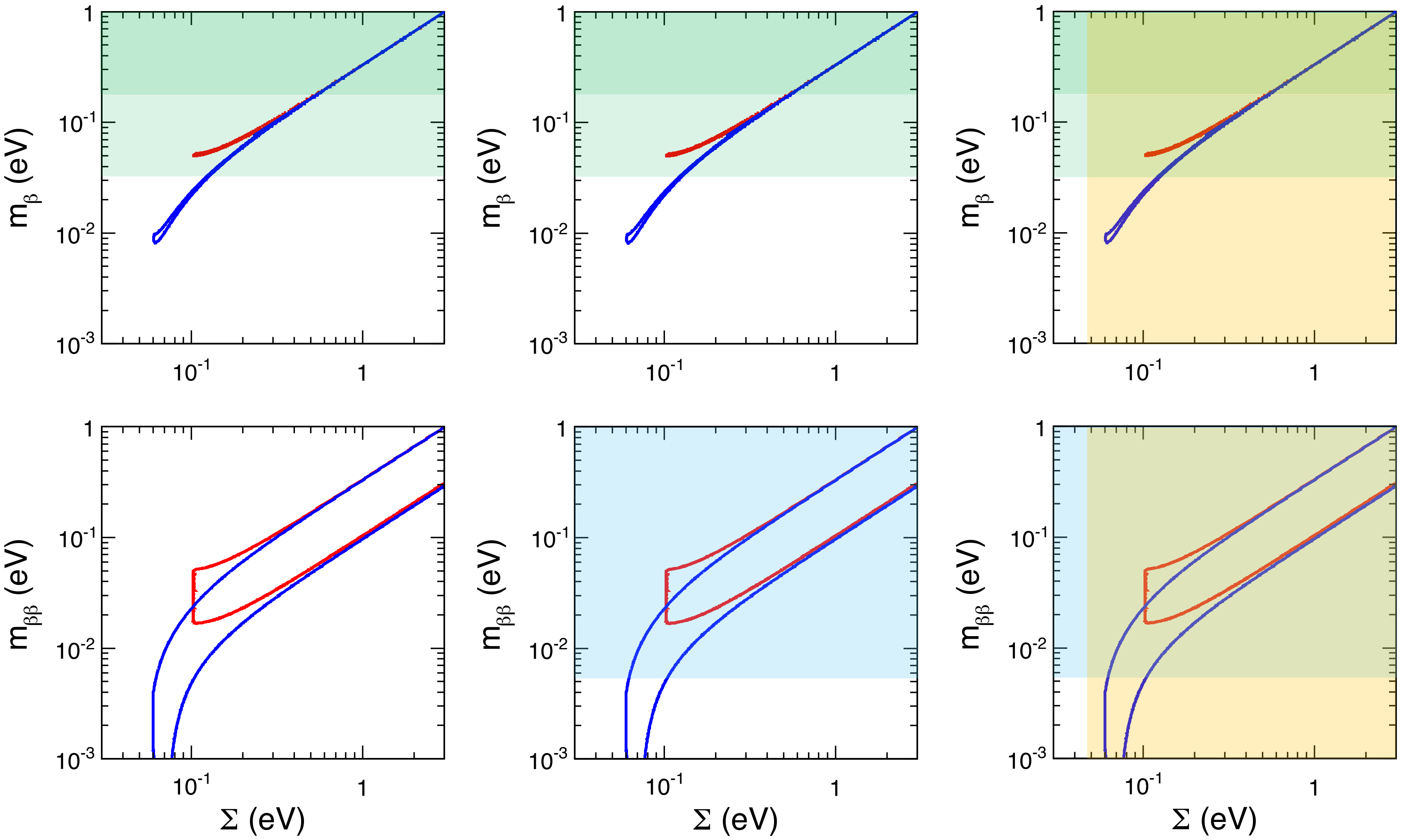
... systematics? dynamical dark energy? ... Our conservative view: **Σ < 0.2 eV** "within a factor of three"

FRONTIERS in 5-10 yrs?

β: ~0.2 eV (KATRIN) and hopefully below in ← **PROJECT-8 + Ho + ...**

0νββ: Well below IO limit @Ton scale **(LEGEND, NEXO, CUPID...)** w/ improved **NME**

Σ: complete covering seems possible within a "robust" **cosmo model**



Large phase space for possible mass discoveries in sub-eV range. **First claims on ν mass may come from cosmology, but laboratory detection via β decay or 0νββ decay (if Majorana) is mandatory, no matter how long it will take !**

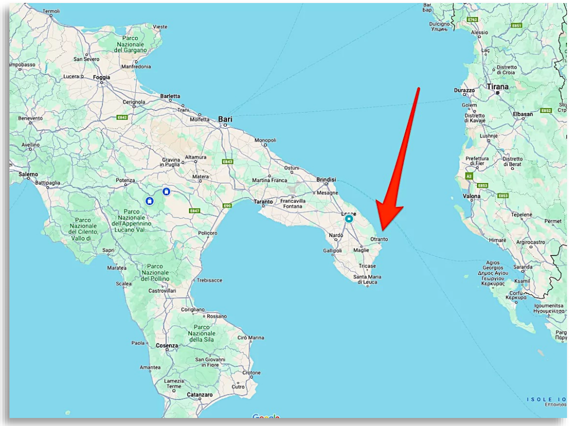
Developements in ν physics are bridging two infinities...

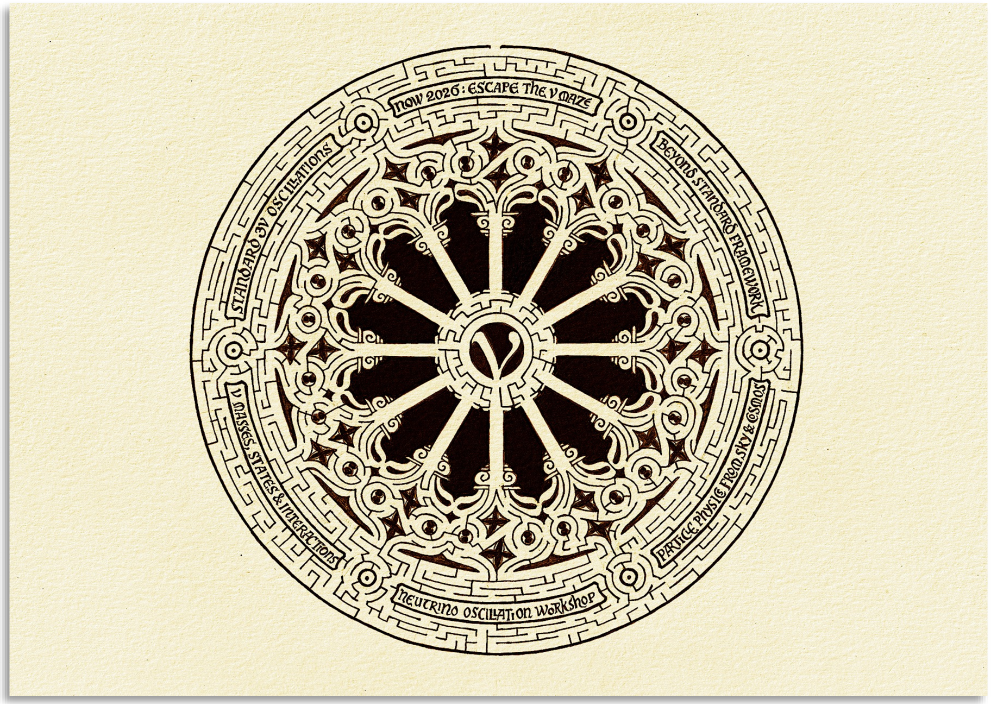
Developements in ν physics are bridging two infinities...

...although the emerging ν picture may need some time to get focused

If you are interested in focusing on the next ν developments, in the wider context of (astro)particle physics and cosmology, please join the

Neutrino Oscillation Workshop (NOW 2026), www.ba.infn.it/now
13th edition, Otranto (Lecce, Italy) 31/8 - 6/9 /2026

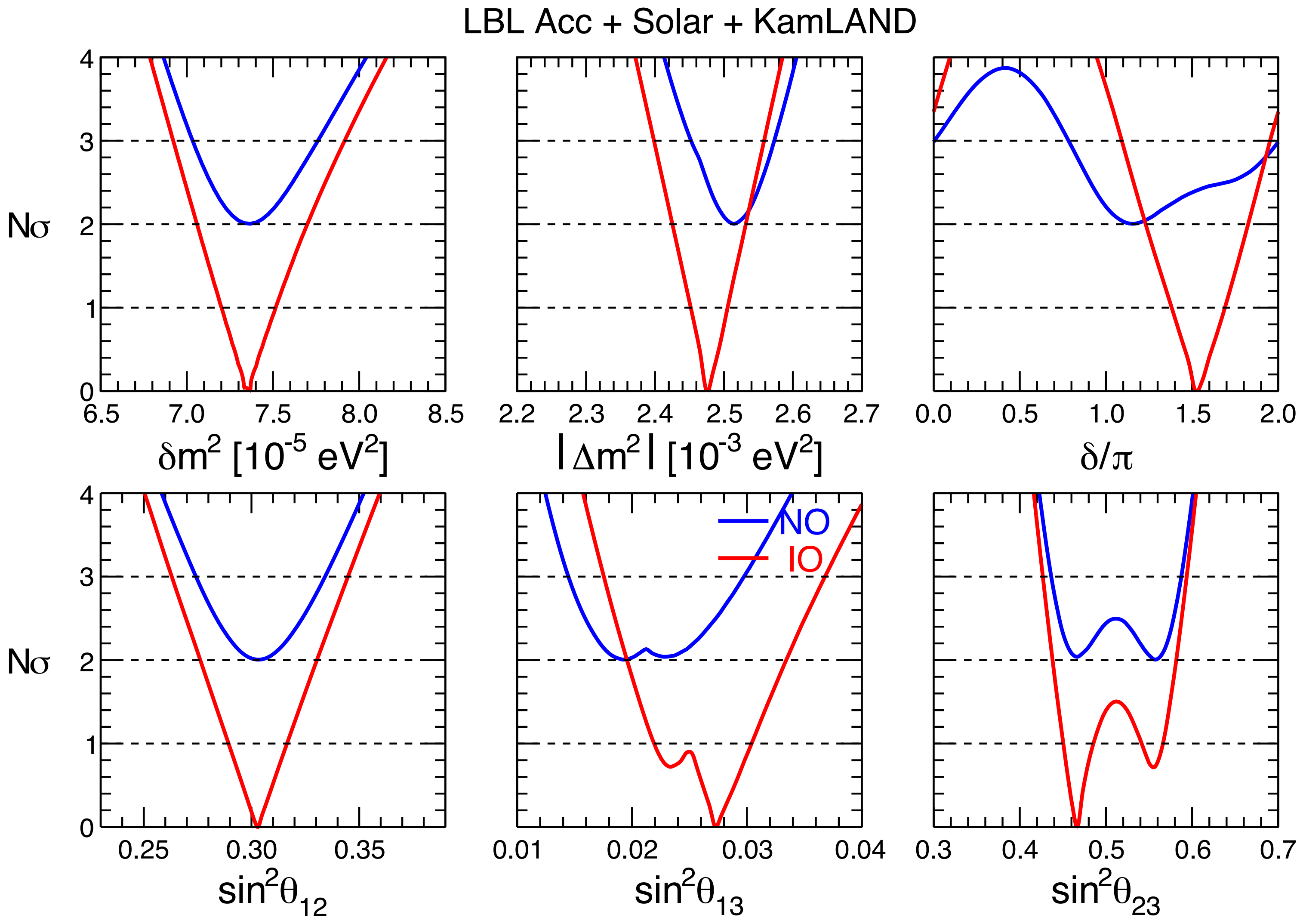




In your spare time ... print and solve the above ν maze:
start at the ν cusp & exit on top of the rose window.
You will need to cross all the five Workshop Sessions!


Thank you for your attention

BACK-UP SLIDES



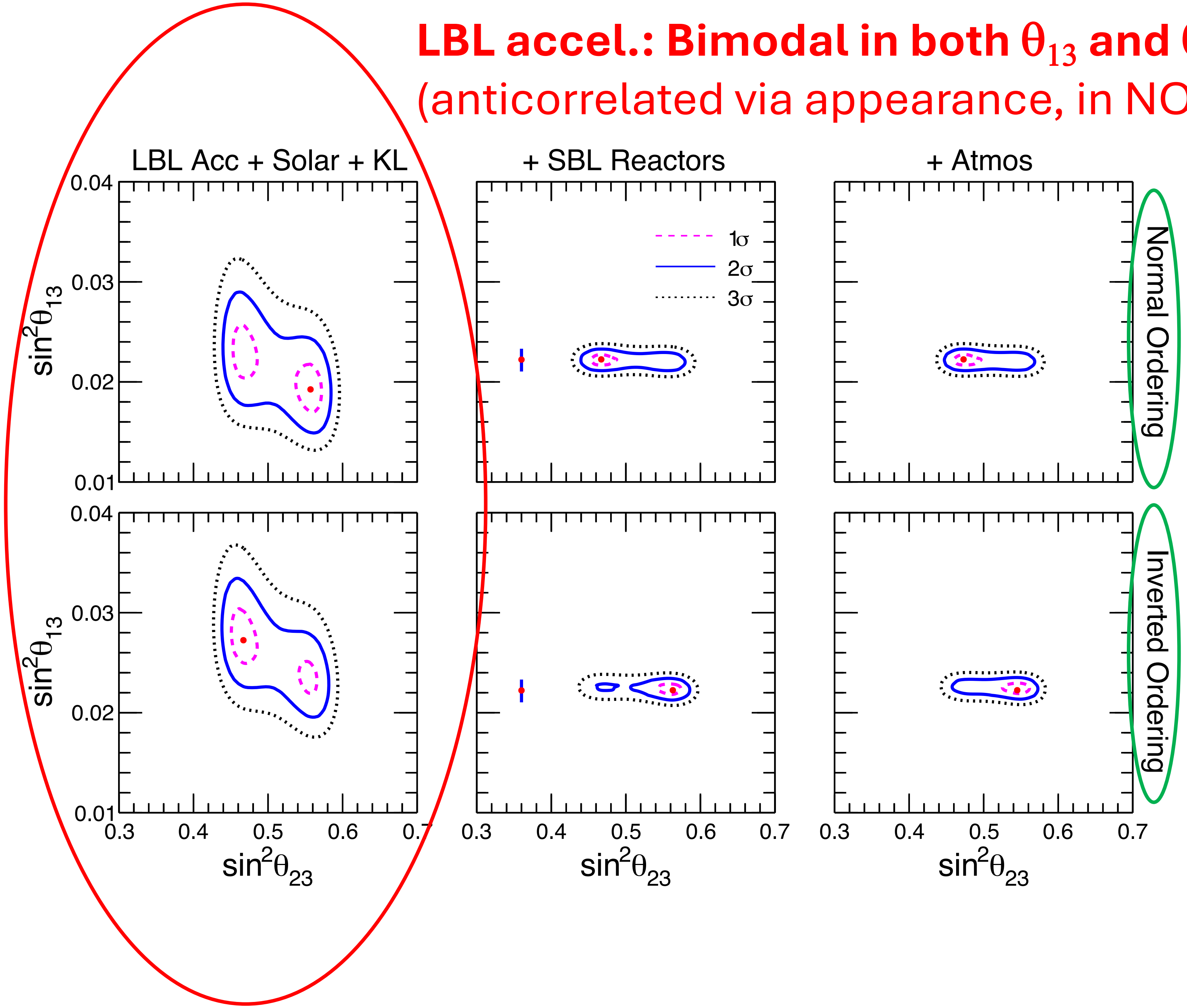
T2K and NOvA prefer NO separately, and IO in combination (at 2σ).

In IO, evidence for CP violation emerges at 3σ!

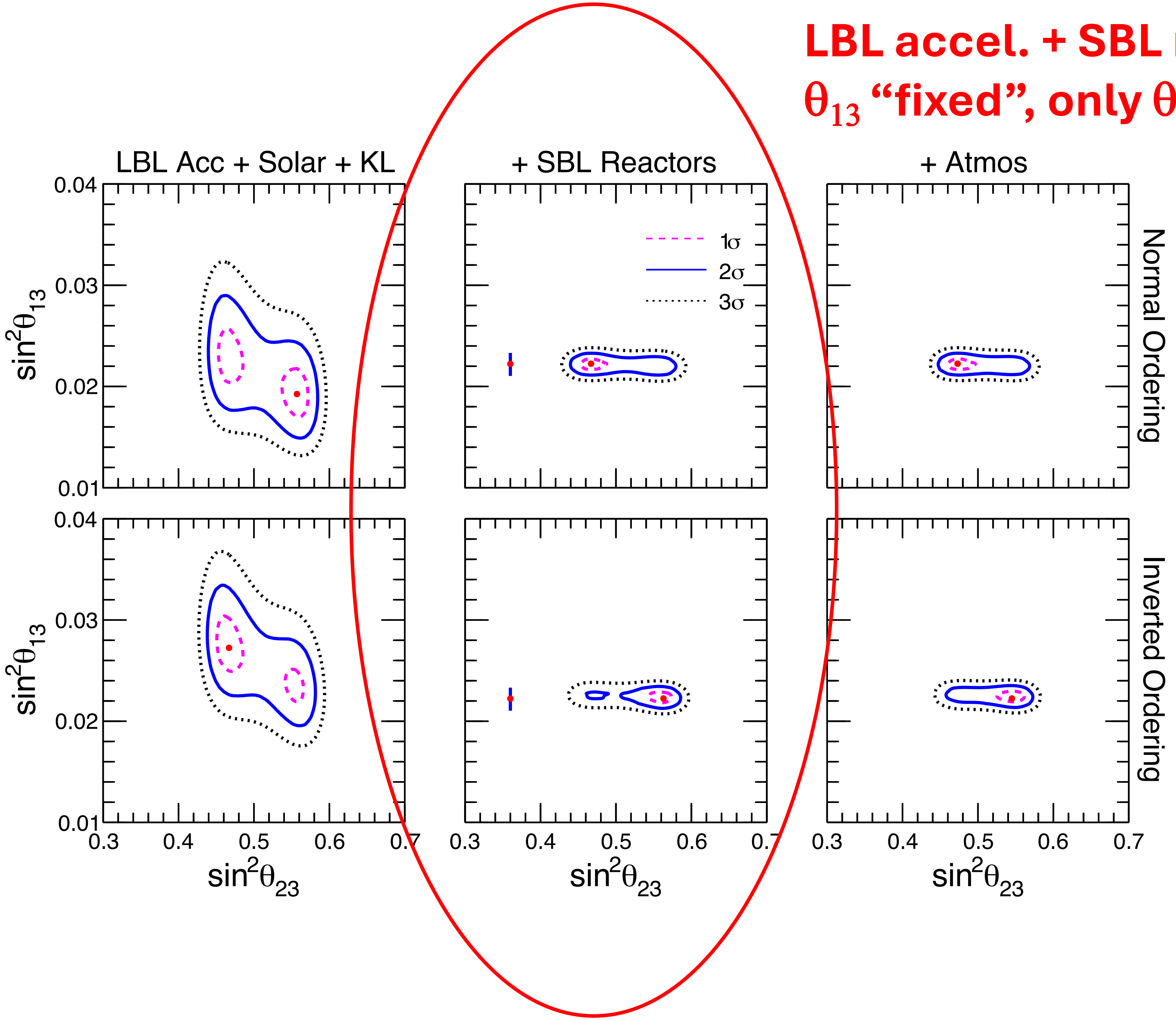
Note bimodal distribution of θ_{13} , related to θ_{23} octant ambiguity

LBL accel.: Bimodal in both θ_{13} and θ_{23}

(anticorrelated via appearance, in NO and IO)

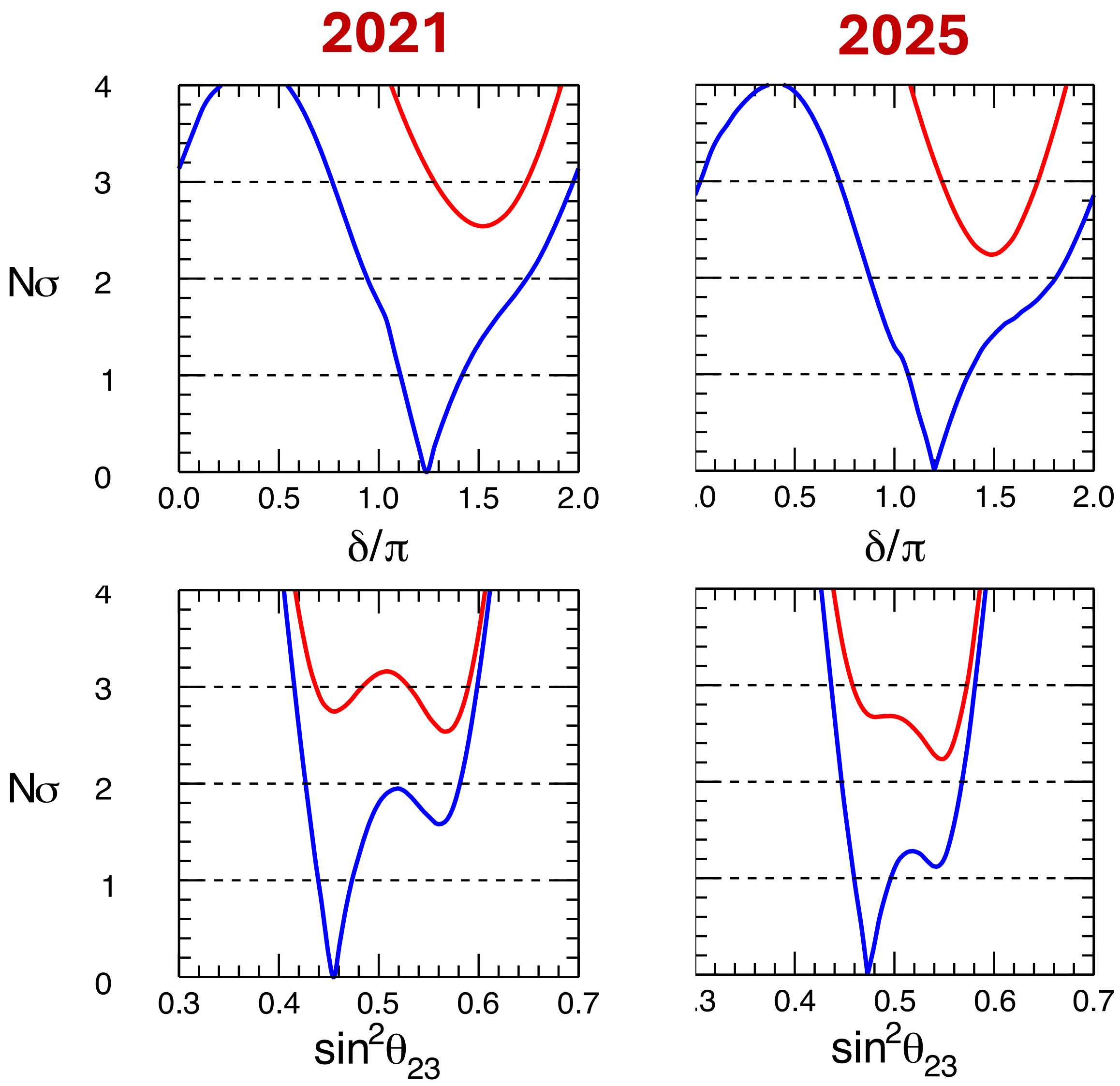


LBL accel. + SBL reactors
θ_{13} “fixed”, only θ_{23} bimodal



As noted, oscillation **unknowns** are somewhat more uncertain than in the past…

All hints on CPV, NO/IO, and octant are a bit weaker



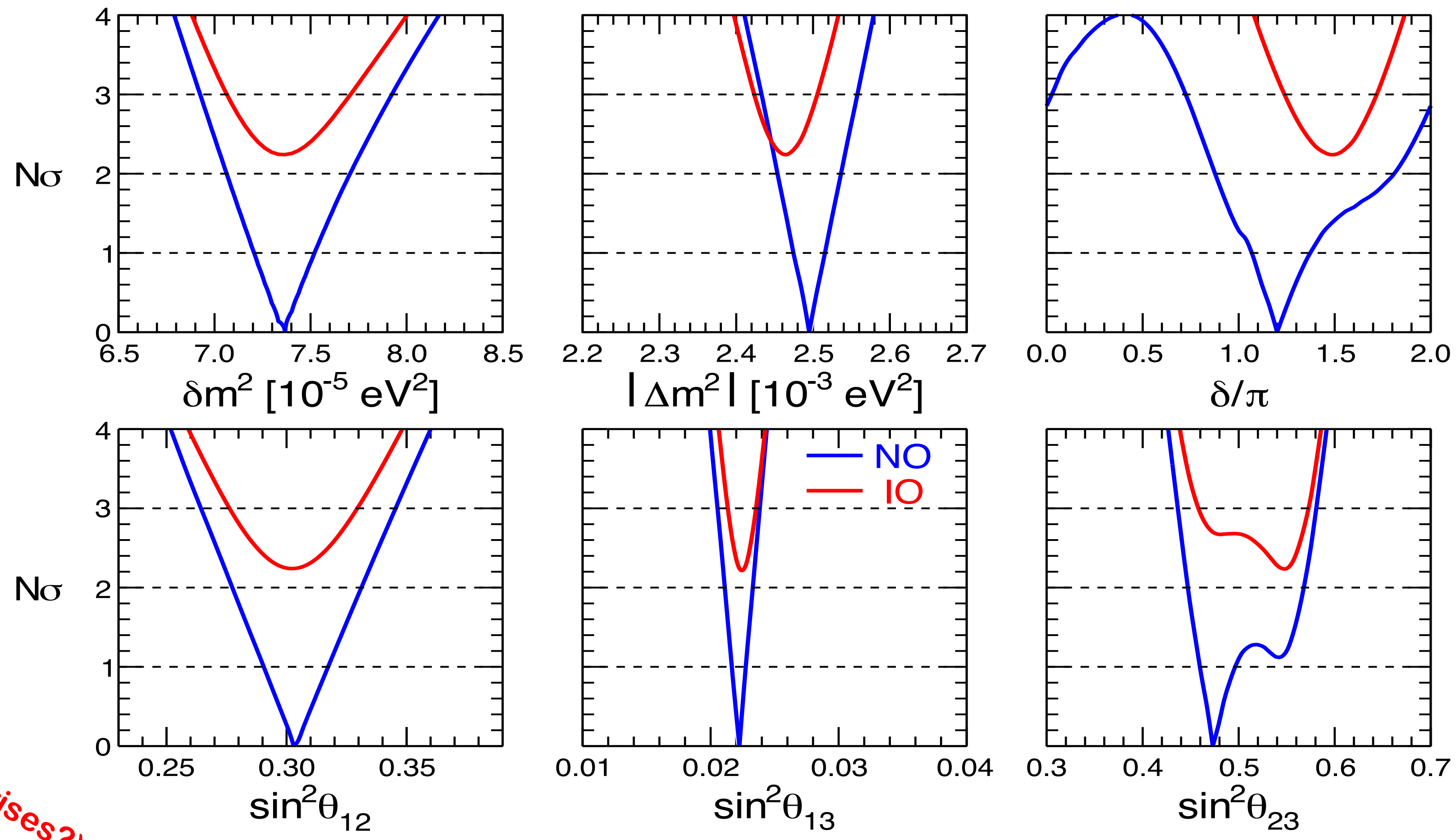
wrt 2021:

← 2025: Weaker hints for NO and CPV

← 2025: Closer and more degenerate octants

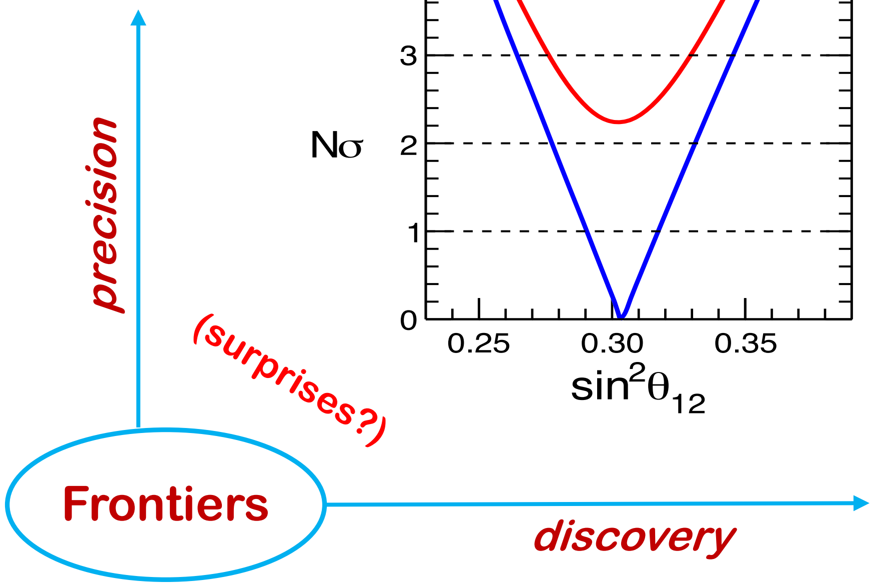
Status of known and unknown 3ν oscillation parameters [arXiv:2503.07752]

All ν oscillation data



1σ error of **known** parameters

$\lvert\Delta m^2\rvert$	0.8%
δm^2	2.3%
θ_{13}	2.4%
θ_{12}	4.5%
θ_{23}	~ 5%



Hints on oscillation **unknowns**

NO	$2.2\,\sigma$
$\sin\delta < 0$	$1.3\,\sigma$
$\theta_{23} < \pi/4$	$1.1\,\sigma$

How do $\nu_\mu \rightarrow \nu_e$ appearance searches probe CPV?

Volume 72B, number 3 PHYSICS LETTERS 2 January 1978

TIME REVERSAL VIOLATION IN NEUTRINO OSCILLATION

Nicola CABIBBO*
*Laboratoire de Physique Théorique et Hautes Energies, Paris, France***

Received 11 October 1977

We discuss the possibility of CP or T violation in neutrino oscillation CP requires $\nu_\mu \longleftrightarrow \nu_e$ and $\bar{\nu}_\mu \longleftrightarrow \bar{\nu}_e$ oscillations to be equal Time reversal invariance requires the oscillation probability to be an even function of time Both conditions can be violated, even drastically, if more than two neutrinos exist

For two neutrinos, no CPV:

$$\overset{(-)}{\nu}_e = \cos\theta_{12}\,\nu_1 + \sin\theta_{12}\,\nu_2$$

How do $\nu_\mu \rightarrow \nu_e$ appearance searches probe CPV?

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For two neutrinos, no CPV:

$$\overset{(-)}{\nu}_e = \cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2$$

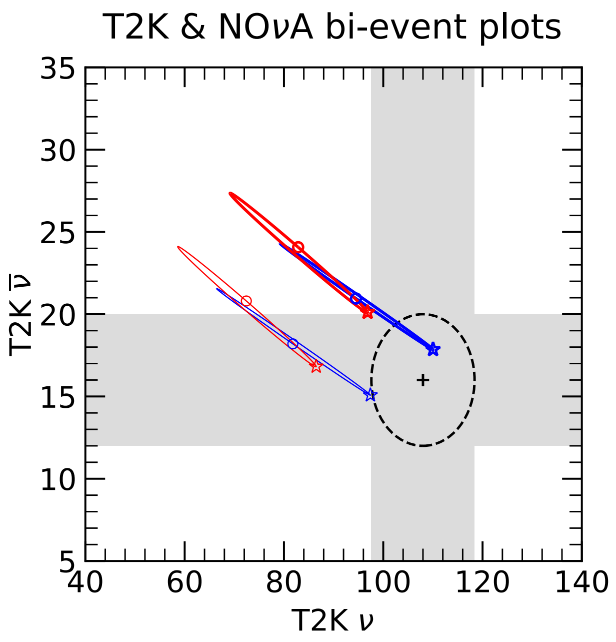
For three neutrinos: new possible CPV phase δ, tested via $\nu / \bar{\nu}$

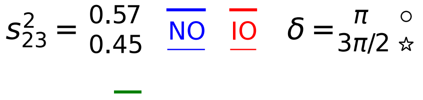
$$\overset{(-)}{\nu}_e = \cos\theta_{13}\,(\cos\theta_{12}\, \nu_1 + \sin\theta_{12}\, \nu_2) + e^{\pm i\delta} \sin\theta_{13}\, \nu_3$$

CPV is a genuine 3ν effect → all parameters (known+unknown) involved/entangled → difficult!

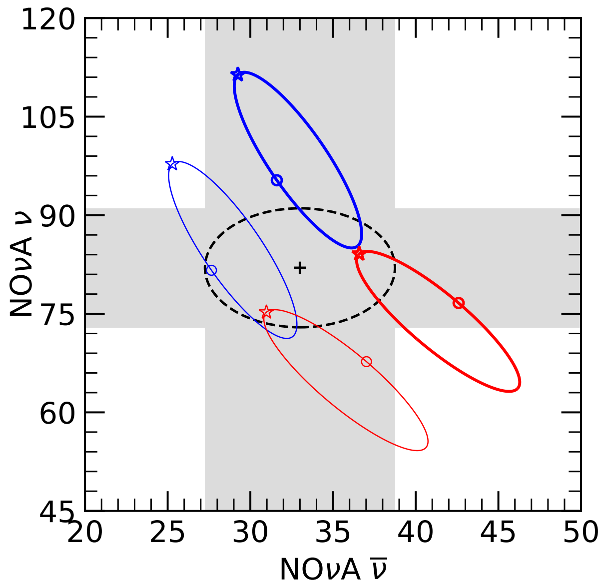
CPV currently tested in T2K, NOvA, atm. oscillations *(with some T2K-NOvA tension…)*

Integrated info on ν and ν̄, stat. errors only. [Not used in fits]





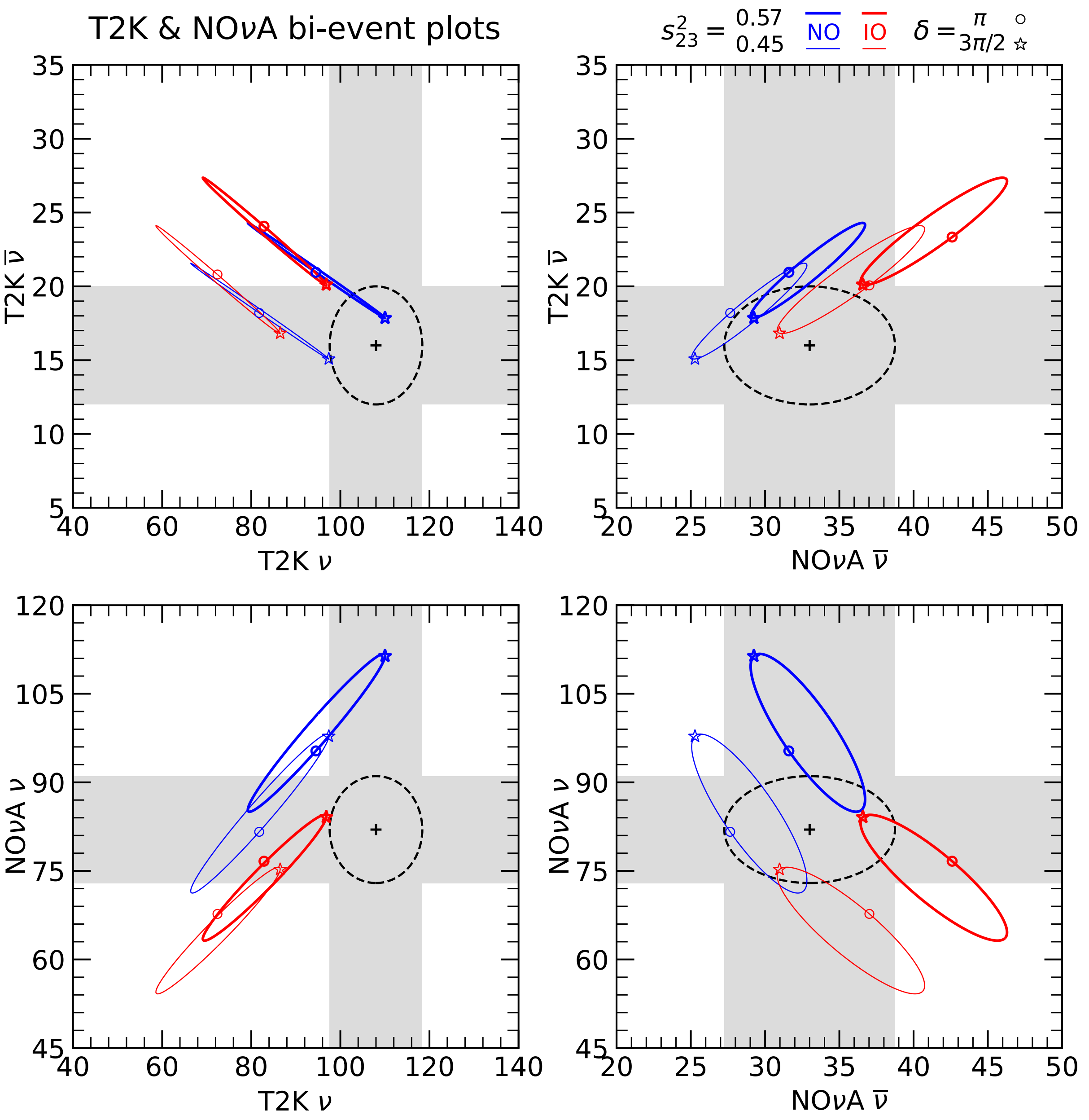
T2K (ν+ν̄) prefers:
NO
δ~3π/2 (~max CPV)
2nd octant



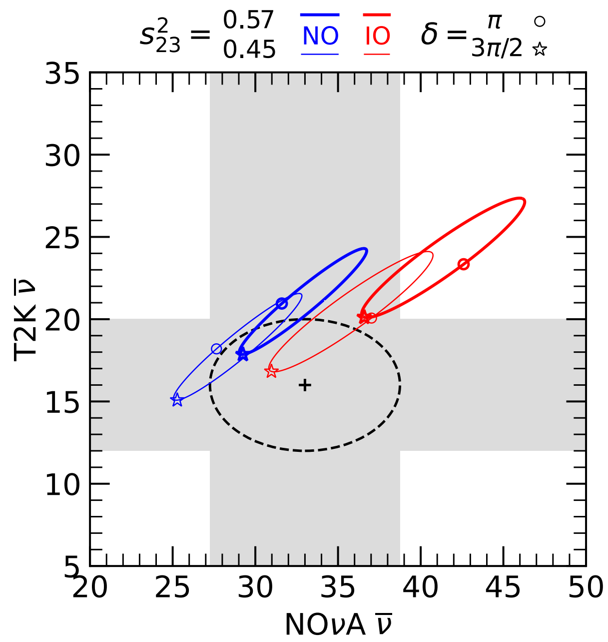
NOVA (ν+ν̄) prefers:
NO
CP conservation
octants ~degenerate

→ T2K and NOVA, separately: NO preferred; CP and octant ambiguous

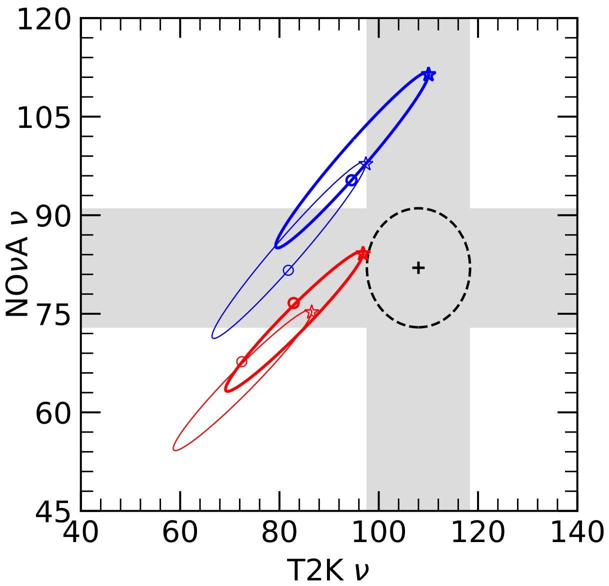
The same info can be reorganized in terms of T2K vs NOvA:



T2K & NOνA bi-event plots



T2K+NOvA (ν) prefer:
IO
δ~3π/2
1^{st} octant



T2K+NOvA ($\bar{\nu}$) prefer:
IO
δ~3π/2
2^{nd} octant

→ T2K and NOVA, jointly: IO and CPV preferred; octant ambiguous