Neutrino Mass Ordering ≥5σ?

P2IO NuBSM Workshop II
IJCLab — April 2022

Anatael Cabrera
CNRS/IN2P3
IJCLab (Orsay)
LNCA (Chooz)

status on neutrino oscillation knowledge…

Standard Model (3 families)
[leptons & quarks]
&
<u>unitary</u> **PMNS**$_{3x3}$(θ_{12},θ_{23},θ_{13},δ_{CP})
&
±Δm² & **+δm²**

no conclusive sign of any extension so far!!
(inconsistencies vs uncertainties)

must measure all parameters→characterise & test (i.e. over-constrain) ***Standard Model***

	today		
	best knowledge		NuFit-5.0
θ_{12}	3.0 %	SK⊕SNO	2.3 %
θ_{23}	5.0 %	NOvA+T2K	2.0 %
θ_{13}	1.8 %	DYB+DC+RENO	**1.5 %**
+δm²	2.5 %	KamLAND	2.3 %
|Δm²|	3.0 %	T2K+NOvA & DYB	1.3 %
Mass Ordering	**unknown**	SK et al	NMO **~3σ**
CP Violation	**unknown**	T2K+NOvA	**≲2σ**

(**now**)

(reactor-beam)

soon JUNO⊕DUNE⊕HK will lead precision in the field→ **sub-percent precision & CPV!**

NOTE: ORCA⊕PINGU⊕IceCube complementary (Mass Ordering & Δm² measurements)

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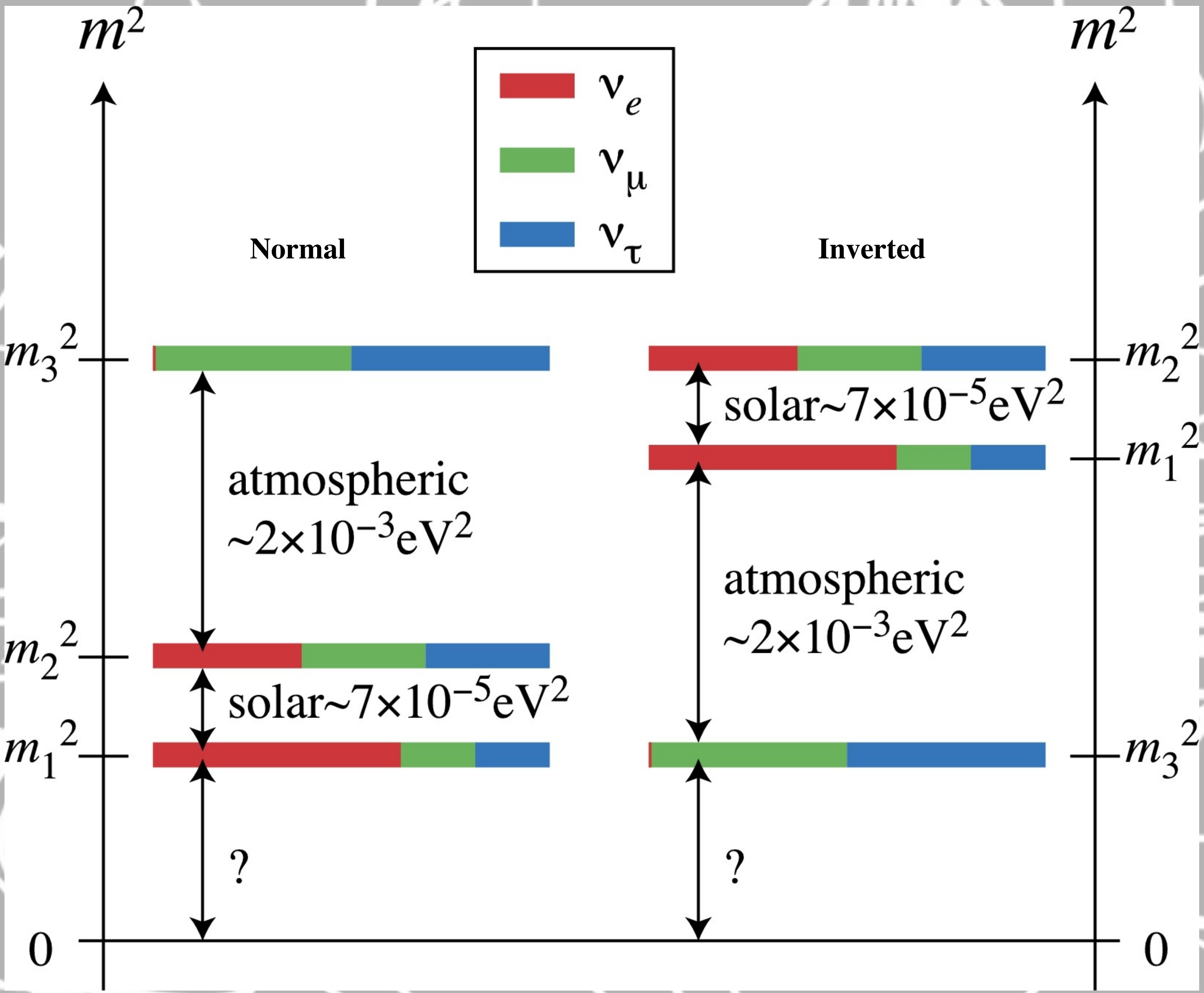

Mass Ordering means…

- **the lightest ν: $\nu_1(m_1)$ vs $\nu_3(m_3)$?**
- **important consequences to…**
  - the lightest known particle Universe
  - **Cosmology** [ν role in Universe formation]
  - **Particle Physics** [ex. ββ decay range]
- **discovery? test new physics!**
  - **Standar Model: incomplete!** [not known where it'd break first]

note: neutrino oscillations not sensitive to the ν absolute mass (other channels).

the Mass Ordering mystery…

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NuFit5.0

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The fate of hints: updated global analysis of three-flavor neutrino oscillations

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ABSTRACT: Our herein described combined analysis of the latest neutrino oscillation data presented at the Neutrino2020 conference shows that previous hints for the neutrino mass ordering have significantly decreased, and normal ordering (NO) is favored only at the 1.6σ level. Combined with the χ^2 map provided by Super-Kamiokande for their atmospheric neutrino data analysis the hint for NO is at 2.7σ. The CP conserving value $\delta_{CP} = 180°$ is within 0.6σ of the global best fit point. Only if we restrict to inverted mass ordering, CP violation is favored at the $\sim 3\sigma$ level. We discuss the origin of these results – which are driven by the new data from the T2K and NOvA long-baseline experiments–, and the relevance of the LBL-reactor oscillation frequency complementarity. The previous 2.2σ tension in Δm^2_{21} preferred by KamLAND and solar experiments is also reduced to the 1.1σ level after the inclusion of the latest Super-Kamiokande solar neutrino results. Finally we present updated allowed ranges for the oscillation parameters and for the leptonic Jarlskog determinant from the global analysis.

KEYWORDS: neutrino oscillations, solar and atmospheric neutrinos

NEUTRINO 2020

today's world data leads to…

NMO favoured to ~2.7σ (2020)

- **Super-Kamiokande** (most info so far)
- **1.6σ** (NOvA⊕T2K & DC⊕DYB⊕RENO)
- some **fragility?**

what are the leading experiments?

what's going to happen next?

NuFitv5.0: today's world knowledge — what about tomorrow?

today's NMO status…

Synergies and prospects for early resolution of the neutrino mass ordering

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P2iO institution
sabbatical @ P2iO institution

when can we **resolve (≥5σ)** the **neutrino Mass Order?**
[earliest time scale]

which experiments (i.e. the minimal set) to yield the **full resolution?**

what physics exploited to yield the **full resolution?**

MO to probe **new physics? (discovery potential)**

our studies goal…

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Synergies and prospects for early resolution of the neutrino mass ordering

Anatael Cabrera, Yang Han, ... Hongzhao Yu + Show authors

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Abstract

The measurement of neutrino mass ordering (MO) is a fundamental element for the understanding of leptonic flavour sector of the *Standard Model of Particle Physics*. Its determination relies on the precise measurement of Δm^2_{31} and Δm^2_{32} using either neutrino *vacuum oscillations*, such as the ones studied by medium baseline reactor experiments, or *matter effect modified oscillations* such as those manifesting in long-baseline neutrino beams (LBνB) or atmospheric neutrino experiments. Despite existing MO indication today, a fully resolved MO measurement ($\geq 5\sigma$) is most likely to await for the next generation of neutrino experiments: JUNO, whose stand-alone sensitivity is $\sim 3\sigma$, or LBνB experiments (DUNE and Hyper-Kamiokande). Upcoming atmospheric neutrino experiments are also expected to provide precious information. In this work, we study the possible context for the earliest full MO resolution. A firm resolution is possible even before 2028, exploiting mainly vacuum oscillation, upon the combination of JUNO and the current generation of LBνB experiments (NOvA and T2K). This opportunity is possible thanks to a powerful synergy boosting the overall sensitivity where the sub-percent precision of Δm^2_{32} by LBνB experiments is found to be the leading order term for the MO earliest discovery. We also found that the comparison between *matter* and *vacuum* driven oscillation results enables unique discovery potential for physics beyond the Standard Model.

Acknowledgements

Much of this work was originally developed in the context of our studies linked to the PhD thesis of Y.H. (APC and IJC laboratories) and to the scientific collaboration between H.N. (in sabbatical at the IJC laboratory) and A.C. Y.H. and A.C. are grateful to the CSC fellowship funding of the PhD fellow of Y.H. H.N. acknowledges CAPES and is especially thankful to CNPq and IJC laboratory for their support to his sabbatical. A.C. and L.S. acknowledge the support of the P2IO LabEx (ANR-10-LABX-0038) in the framework *"Investissements d'Avenir"* (ANR-11-IDEX-0003-01 – Project "NuBSM") managed by the Agence Nationale de la Recherche (ANR), France, where our developments are framed within the *neutrino inter-experiment synergy* working group. AC would like to thank also Stéphane Lavignac for useful comments and suggestions as feedback on the manuscript. The authors are grateful to JUNO's internal reviewers who ensured that the information included in this manuscript about that experiment is consistent with its official position as conveyed in its publications. We would like to specially thank the NuFit5.0 team (Ivan Esteban, Concha Gonzalez-Garcia, Michele Maltoni, Thomas Schwetz and Albert Zhou) for their kindest aid and support to provide dedicated information from their latest NuFit5.0 version. We also would like Concha Gonzalez-Garcia and Fumihiko Suekane for providing precious feedback on a short time scale and internal review of the original manuscript.

open-access — arXiv:2008.11280 updated shortly

most discussion based on…

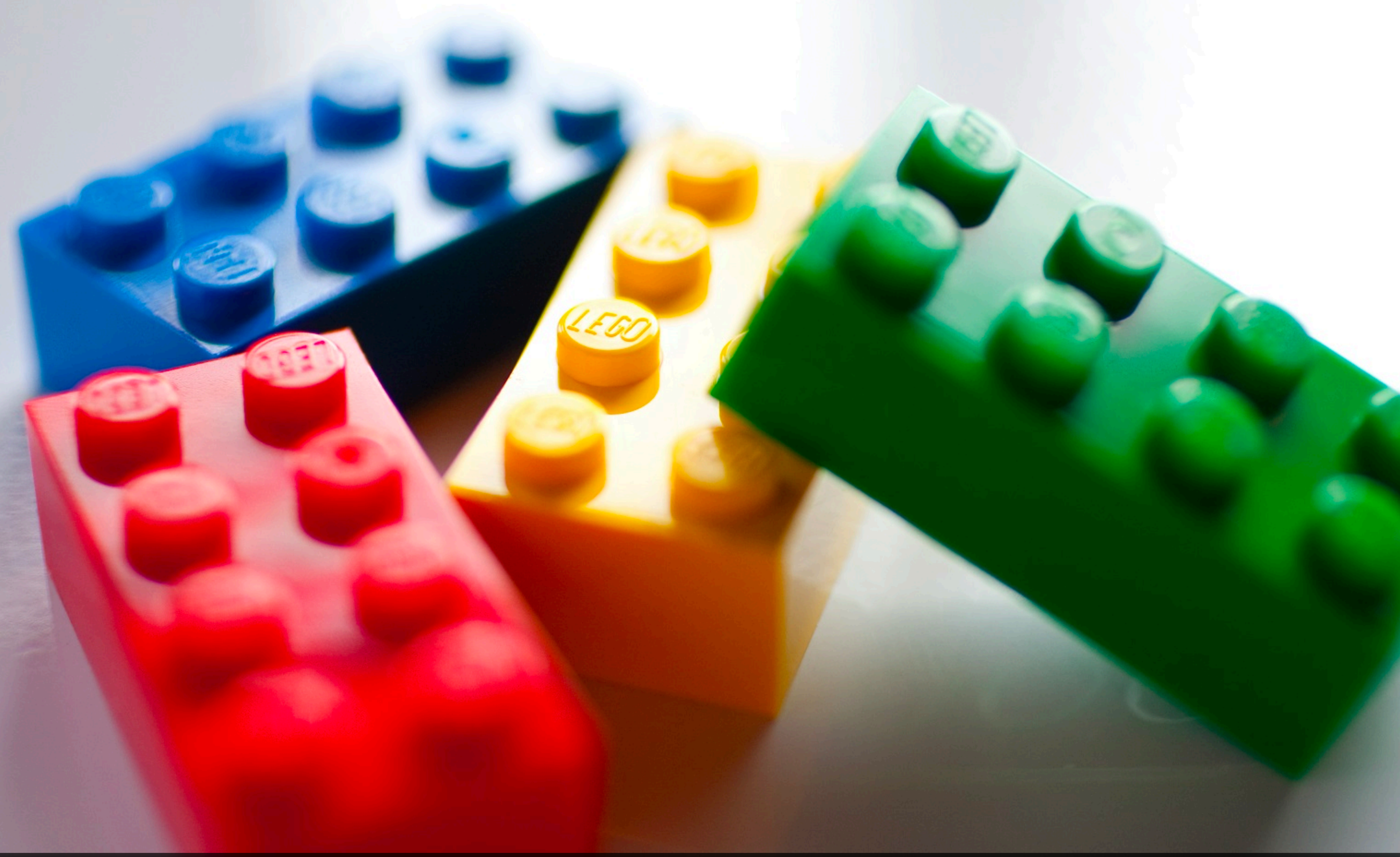
Université de Paris

Université de Paris
L'École Doctorale 560 STEP'UP
Laboratoire Astro-Particules et Cosmologie

Dual Calorimetry for High Precision Neutrino Oscillation Measurement at JUNO Experiment

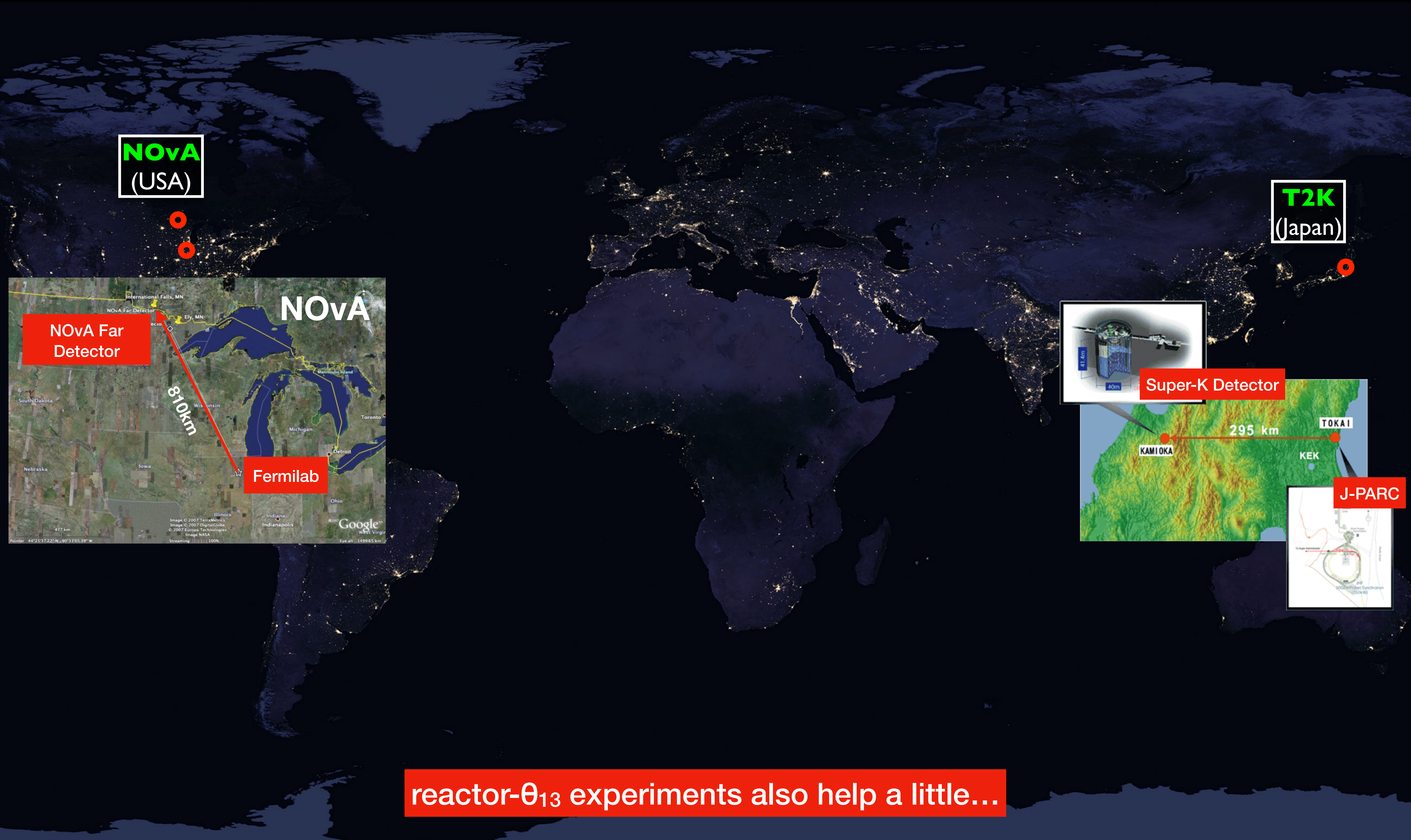
Par Yang HAN

born during our discussions…



the building blocks…

running experiments…



reactor-θ_{13} experiments also help a little…

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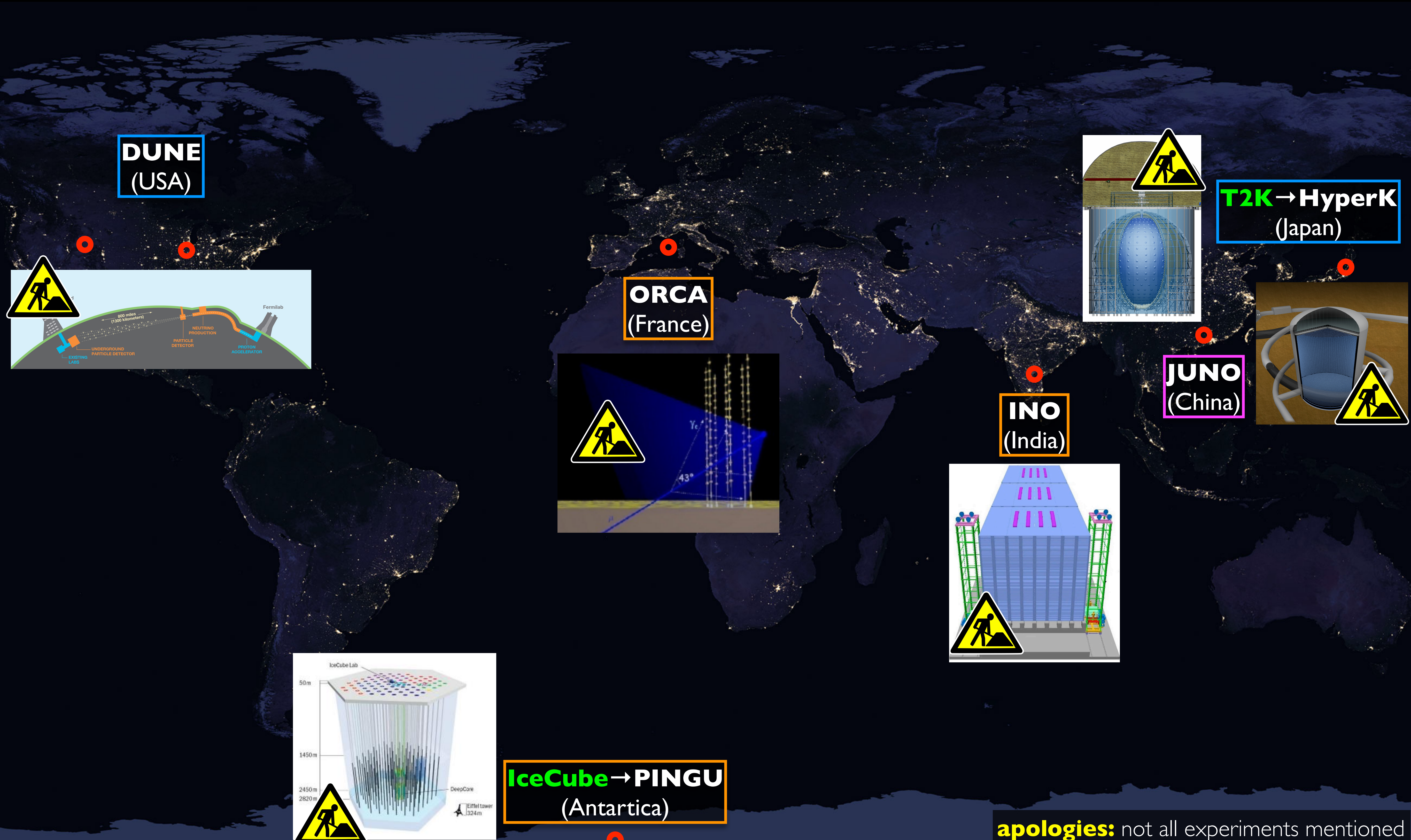
immintent experiments…



apologies: not all experiments mentioned

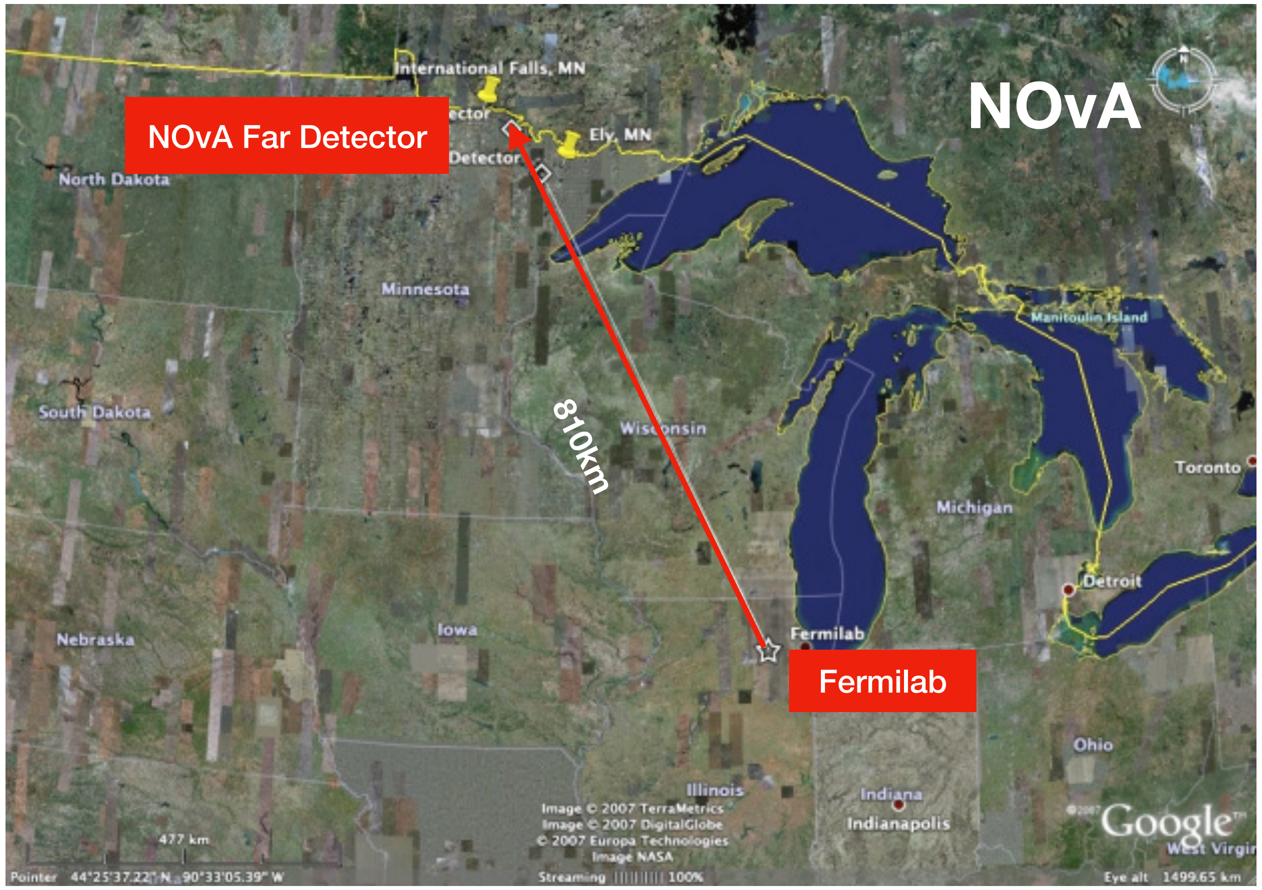
	direct sensitivity	nuisance	combined sensitivity
vacuum oscillation	ultra precise oscillation	θ_{13}?	Δm^2 with precision ≤1% & revolve CPV
matter effects	fake CPV (due to Earth)	CPV and θ_{23}	

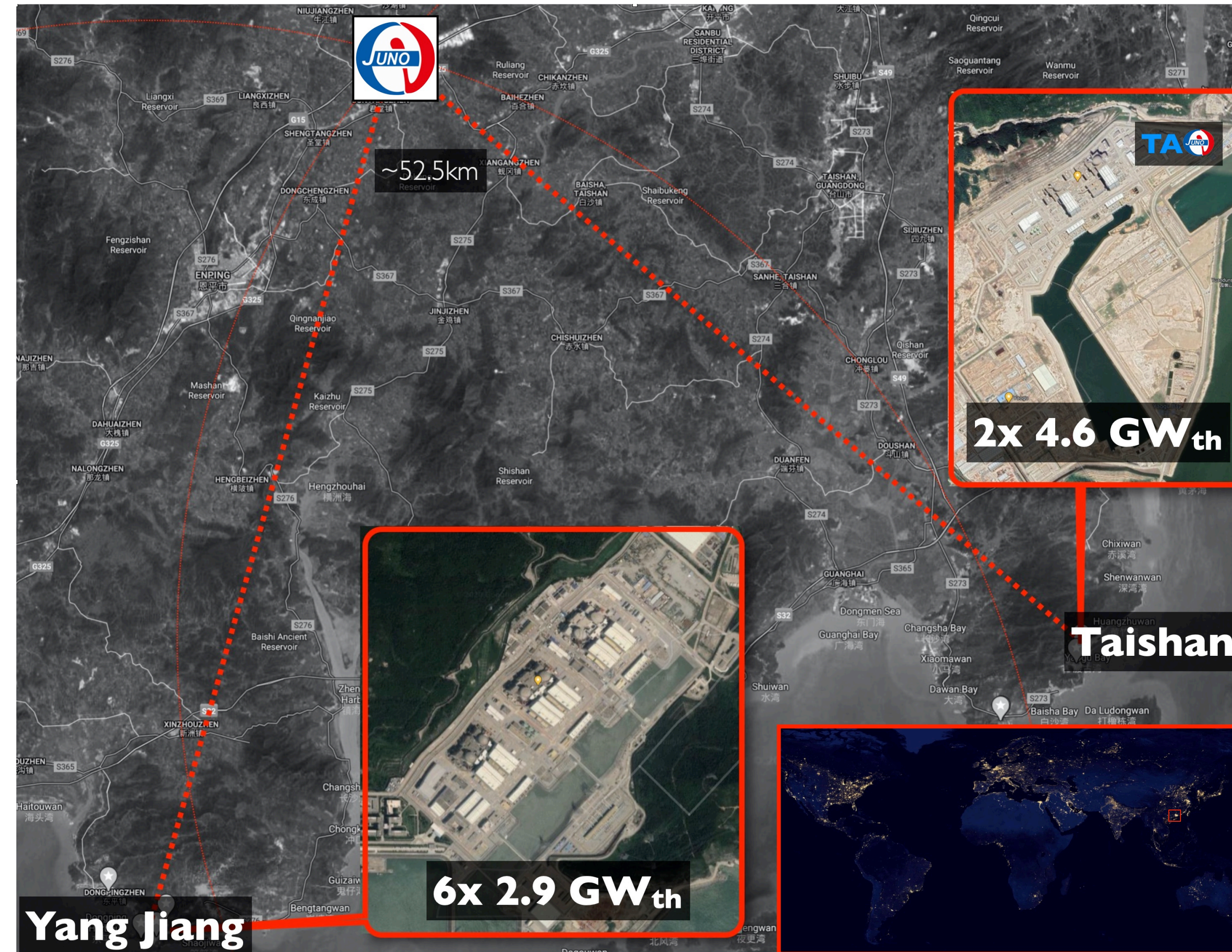
NuFitv5.0: maginilise today's world knowledge — CPV, θ_{23}, θ_{13}, …

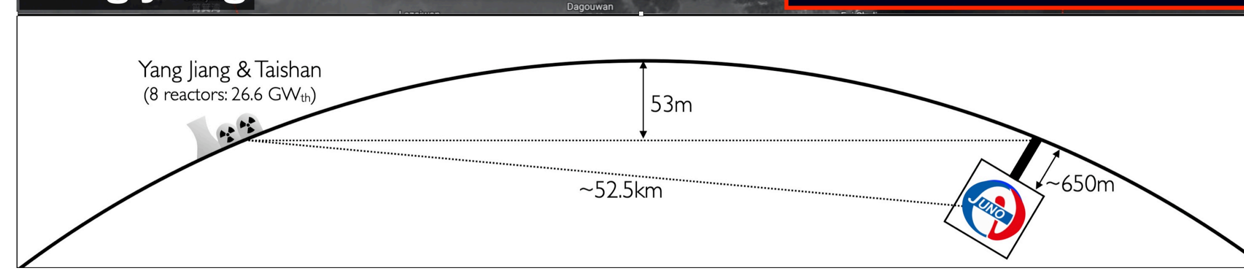
the building blocks…

Matter Effects Oscillations
(CP experiments→ ***fake*** CP-violation)

Vacuum Oscillations
(no CP-violation)







Appearance Channel [$\theta_{23}\oplus\theta_{13}$,$\boldsymbol{\delta_{CP}}$,**MO**]:

$\nu_\mu \rightarrow \nu_e$ [ν and anti-ν] — CPV & fake-CPV

Disappearance Channel [θ_{23},Δm^2_{32}]:

$\nu_\mu \rightarrow \nu_\mu$ "survival probability"

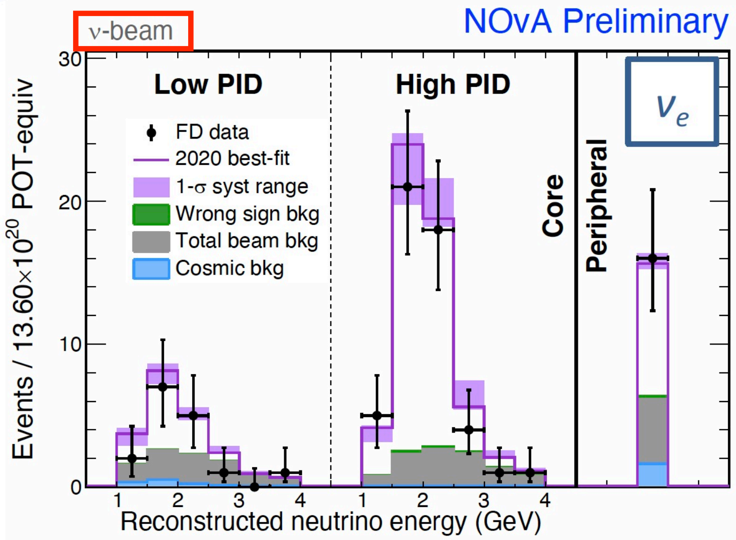
arXiv:2008.11280

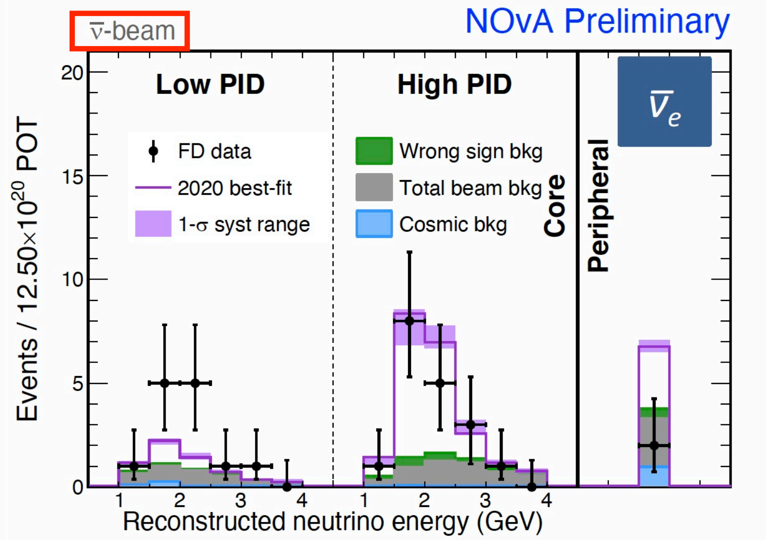
only 2 ways to measure…

NOvA & T2K: direct comparison of oscillation with neutrino & anti-neutrino

ν_e and $\bar{\nu}_e$ Data at the Far Detector

NEUTRINO 2020

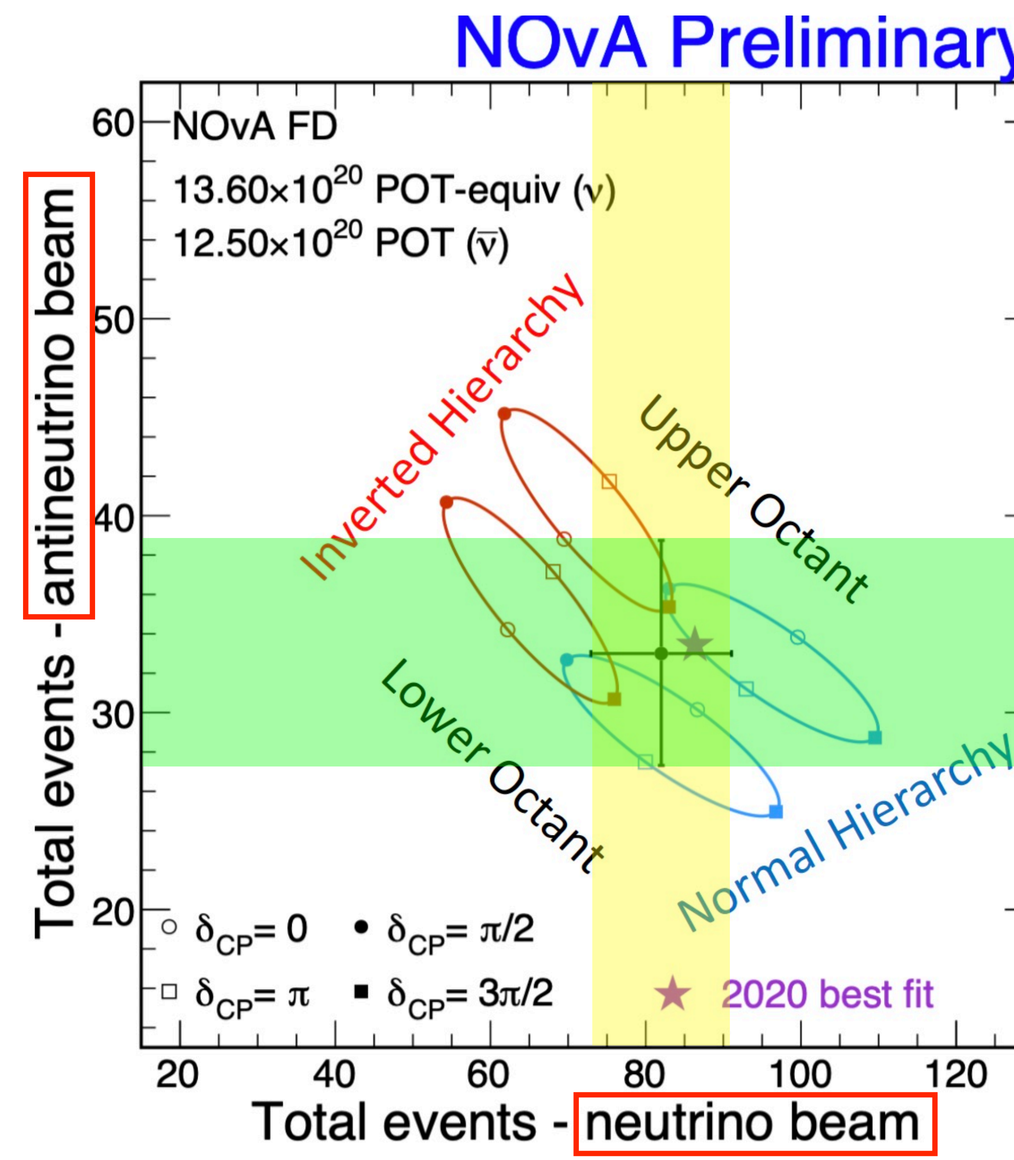




Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4σ evidence of $\bar{\nu}_e$ appearance

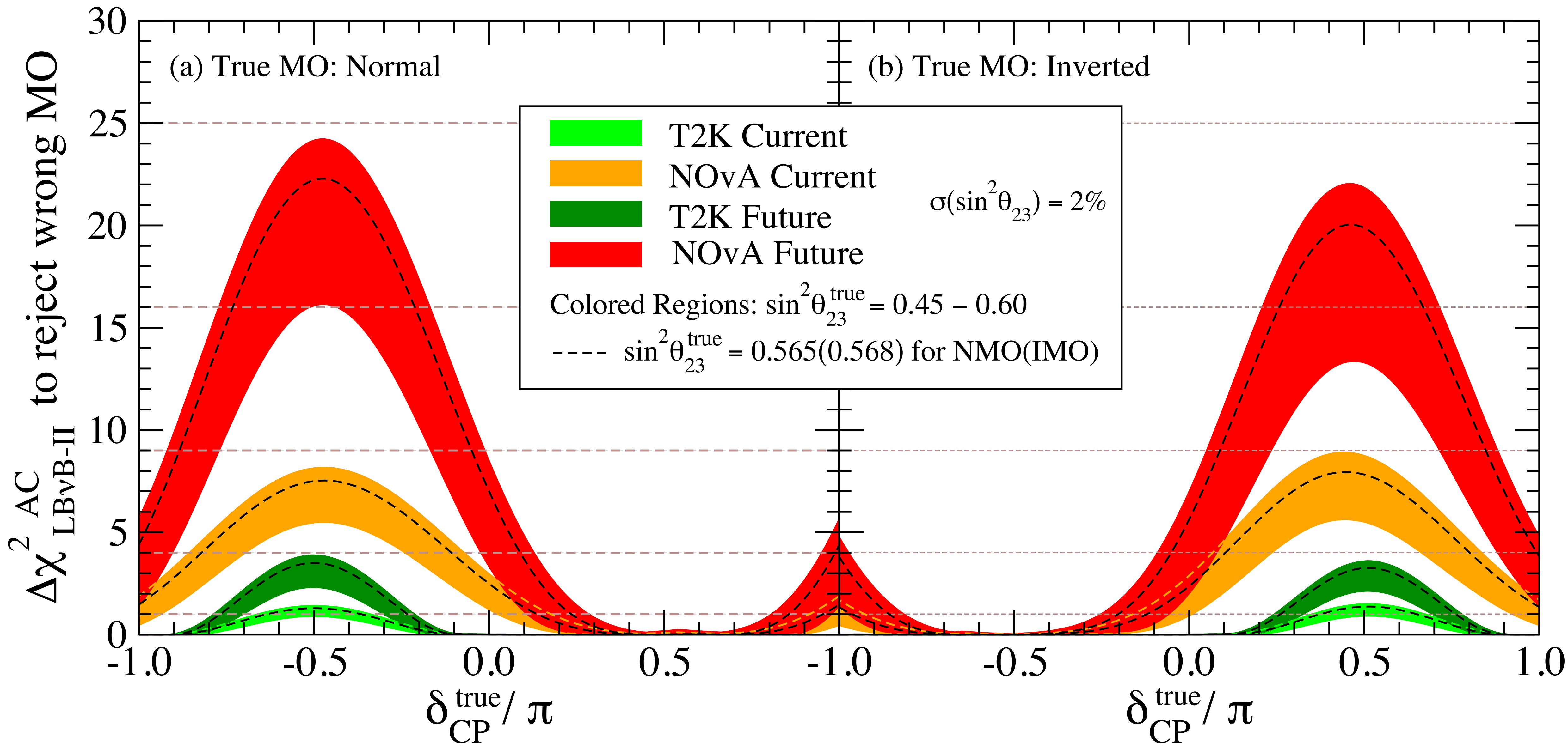


Appearance Channel [$\theta_{23} \oplus \theta_{13}$,$\boldsymbol{\delta_{CP}}$,**MO**]: $\nu_\mu \rightarrow \nu_e$ [ν and anti-ν]

Disappearance Channel [$\boldsymbol{\theta_{23}}$,$\boldsymbol{\Delta m^2_{32}}$]: $\nu_\mu \rightarrow \nu_\mu$ "survival probability" (not shown)

NOvA/T2K observables…

δ_{CP}, θ_{23} dependent



accelerator sensitivity now

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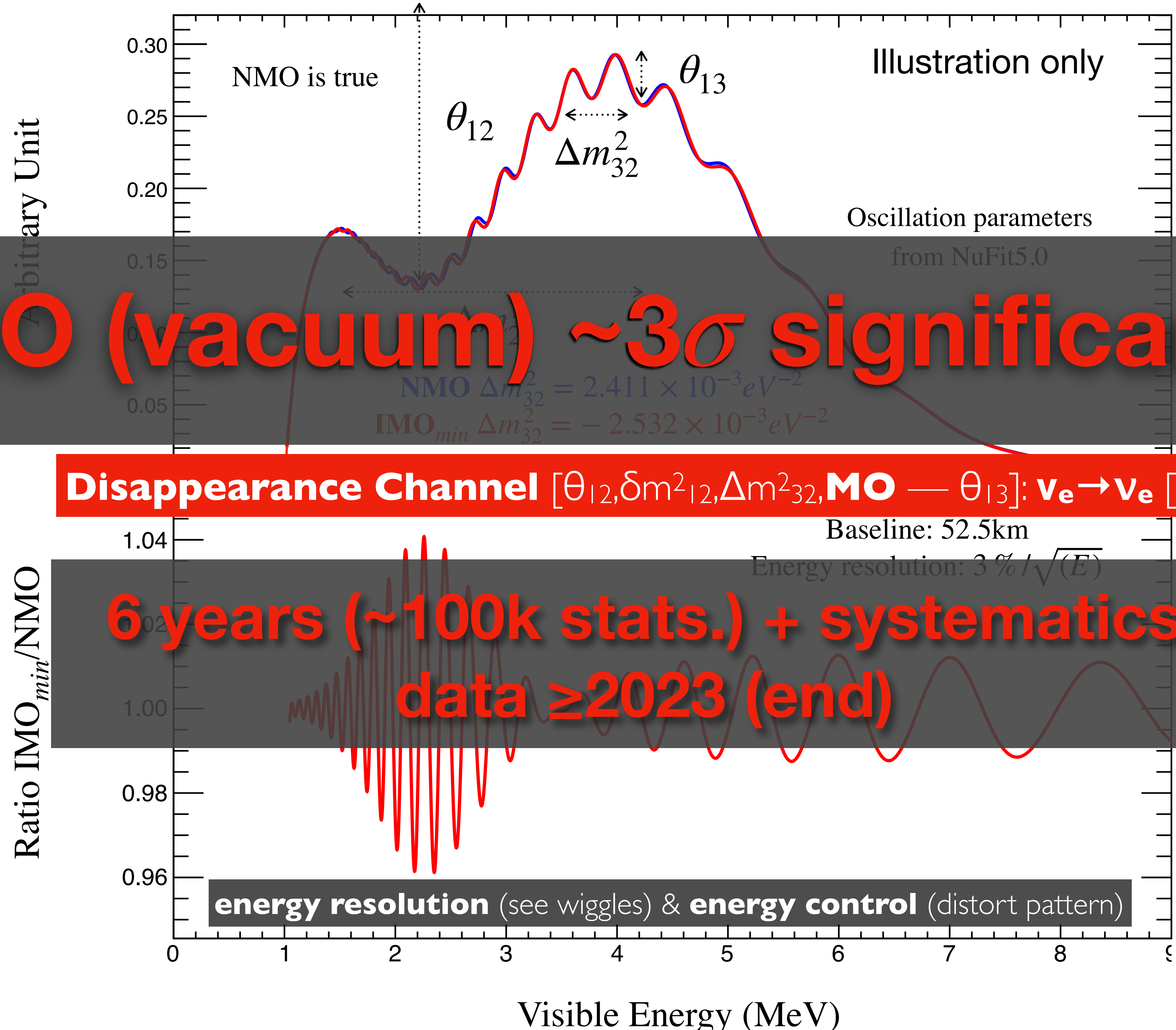
JUNO ultra-precise oscillometry: 2 oscillations & interference terms (hard physics)



MO (vacuum) ~3σ significance

Disappearance Channel [θ_{12},δm^2_{12},Δm^2_{32},**MO** — θ_{13}]: **$\nu_e \rightarrow \nu_e$** [anti-ν]

6 years (~100k stats.) + systematics
data ≥2023 (end)

energy resolution (see wiggles) & **energy control** (distort pattern)

the JUNO (hardest) way…

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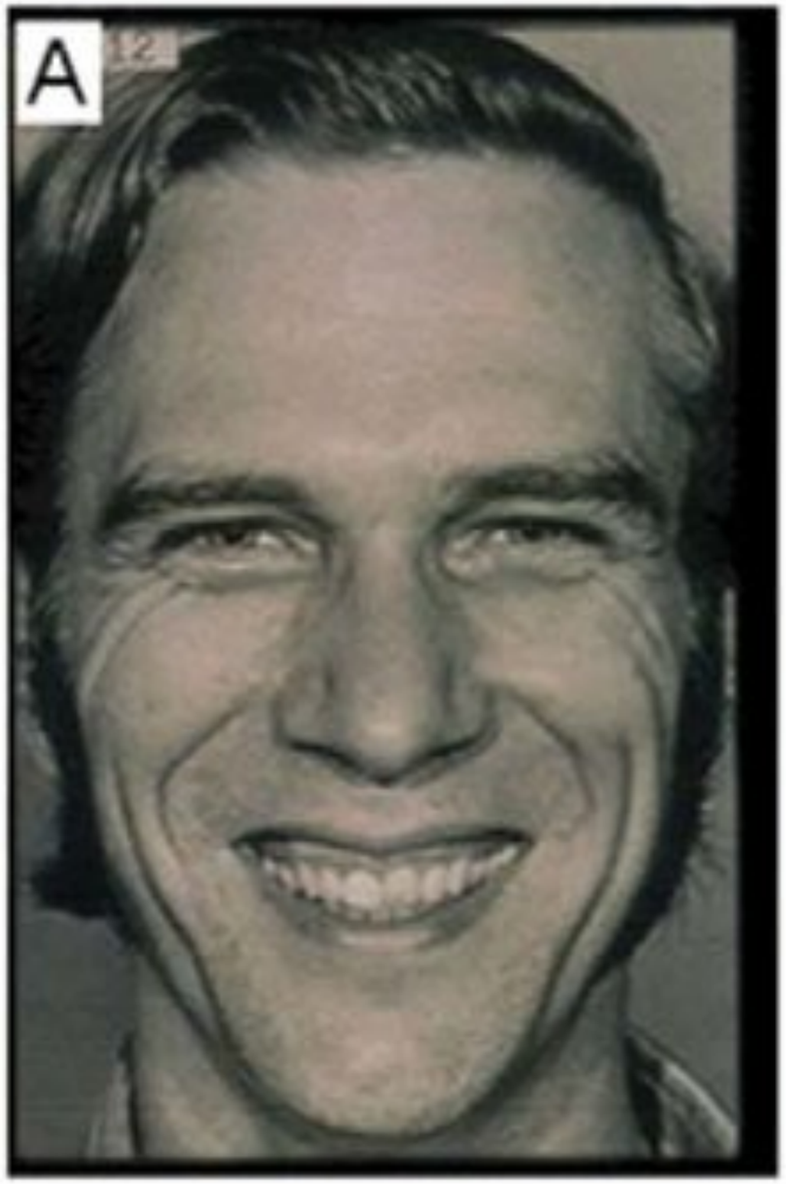
arXiv:2008.11280

- **T2K Appearance (≤2024) — no!**
- **NOvA Appearance (≤2026) — unlikely!**
- **JUNO (≥2022) — no!**

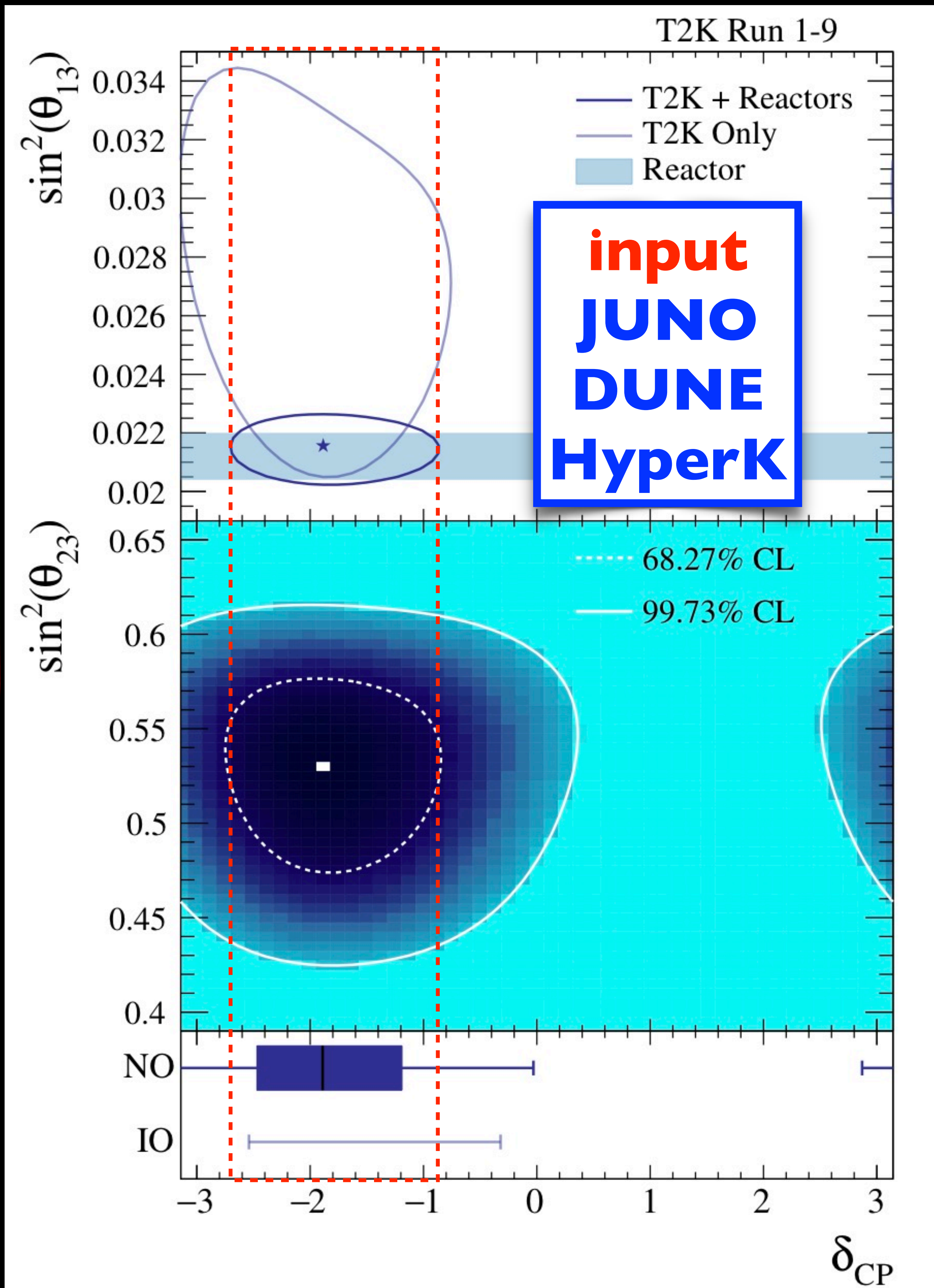
⟹ T2K + NOvA + JUNO = yes? → but no! (just adding)

⟹ T2K ⊕ NOvA ⊕ JUNO = yes! (synergies: appearance & disappearance)



still, ~5σ before 2030…

T2K⊕reactor powerful symmetry: CP-Violation



θ13 implications

powerful constraint

CPV phase vs θ13

[constrained by reactor]

CPV phase vs θ23

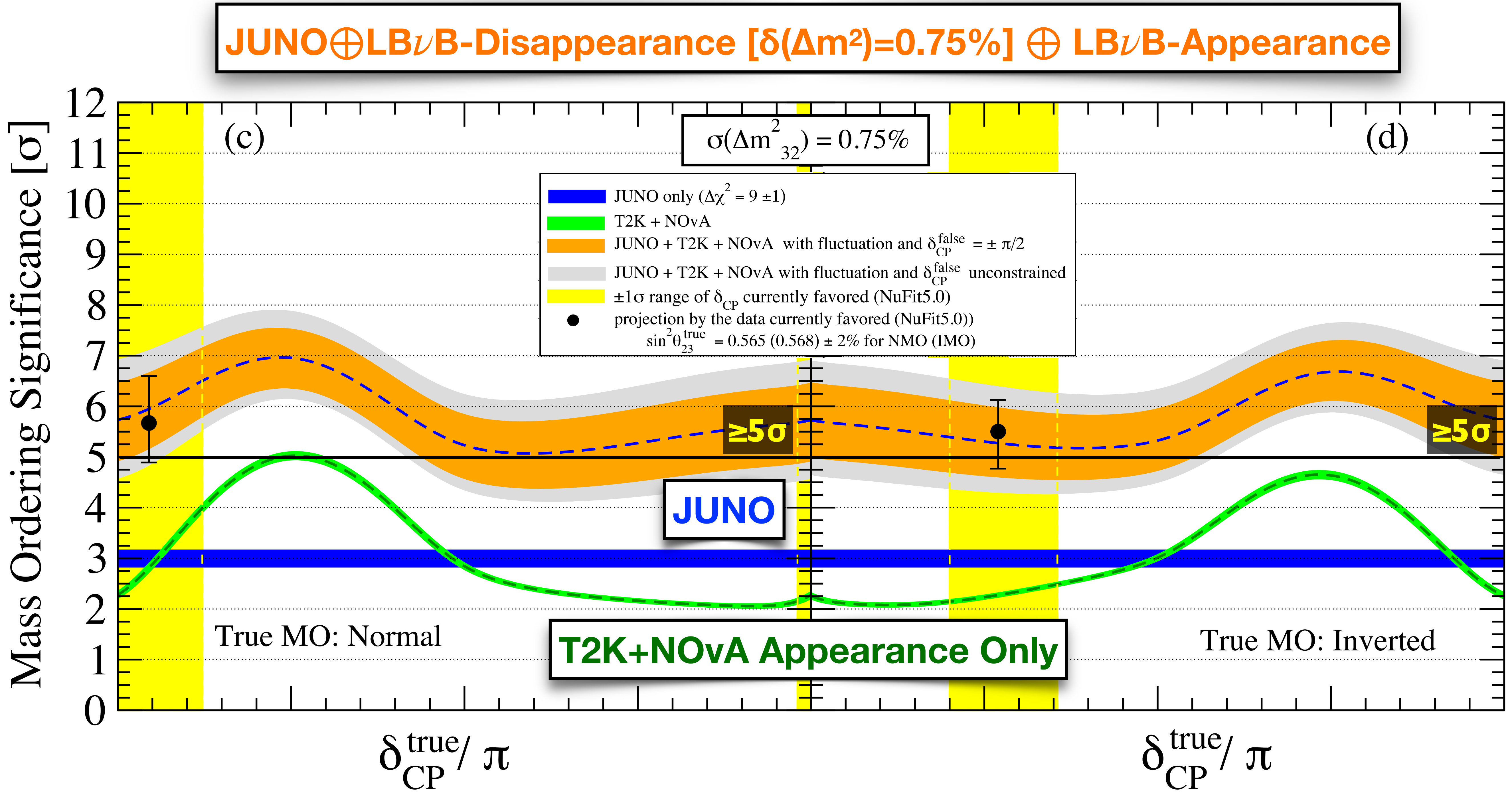
[octant ambiguity]

CPV phase vs (Atmospheric) Mass Ordering

	direct sensitivity	nuisance	sensitivity	combined sensitivity
JUNO	ultra precision oscillation	θ_{13}?	~3σ	$\delta(\Delta m^2)\leq 0.5\%$
NOvA	fake CPV (due to Earth)	mainly CPV (θ_{23} too)	~3-4σ (~800km baseline)	$\delta(\Delta m^2)\sim 1.0\%$
T2K			≤2σ (~250km baseline)	$\delta(\Delta m^2)\sim 1.0\%$
HyperK				$\delta(\Delta m^2)\sim 0.5\%$
DUNE			**>5σ !** (~1200km baseline)	$\delta(\Delta m^2)\sim 0.5\%$
Atmospherics		mainly θ_{23} (CPV too)	~3-6σ (many baselines)	$\delta(\Delta m^2)$ poor

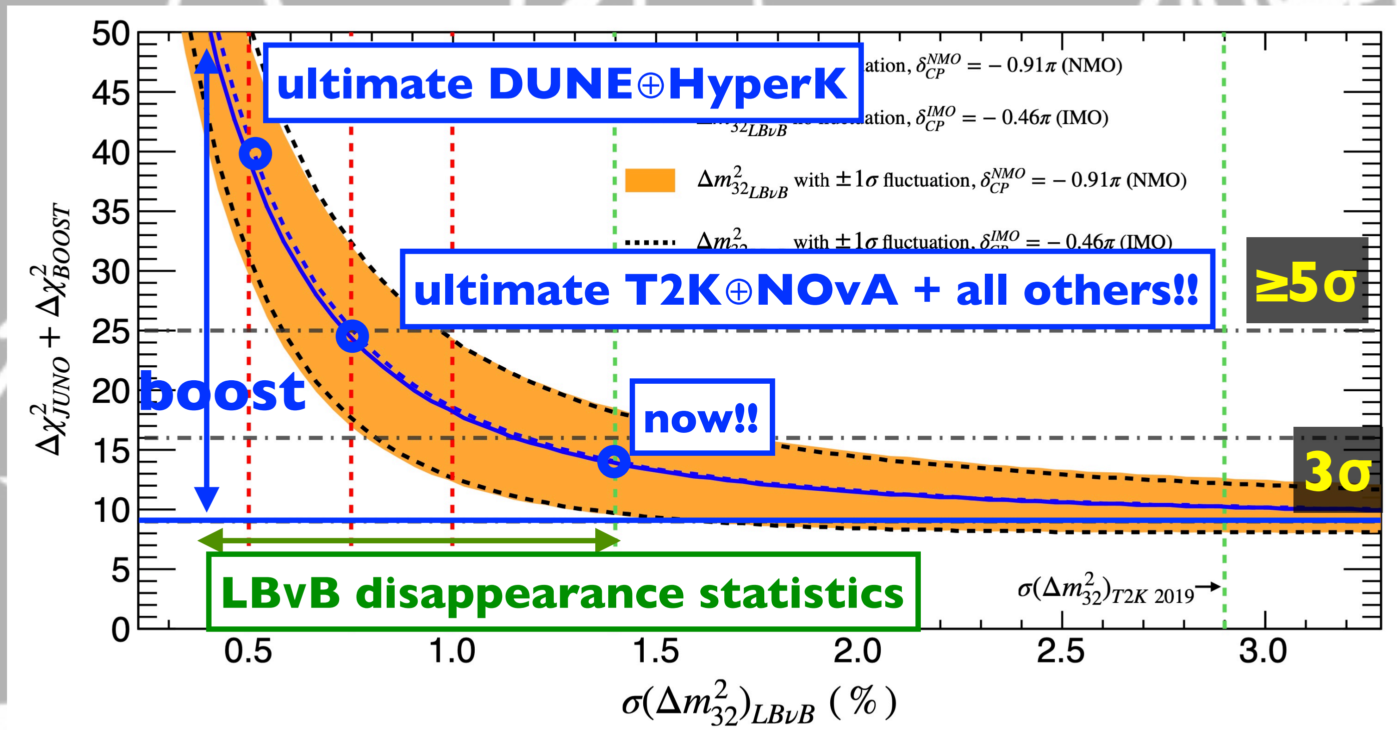
the building blocks…

arXiv:2008.11280



the power of synergies…

synergy I (JUNO vs NOvA⊕T2K): high precision disappearance Δm^2_{32} measurement

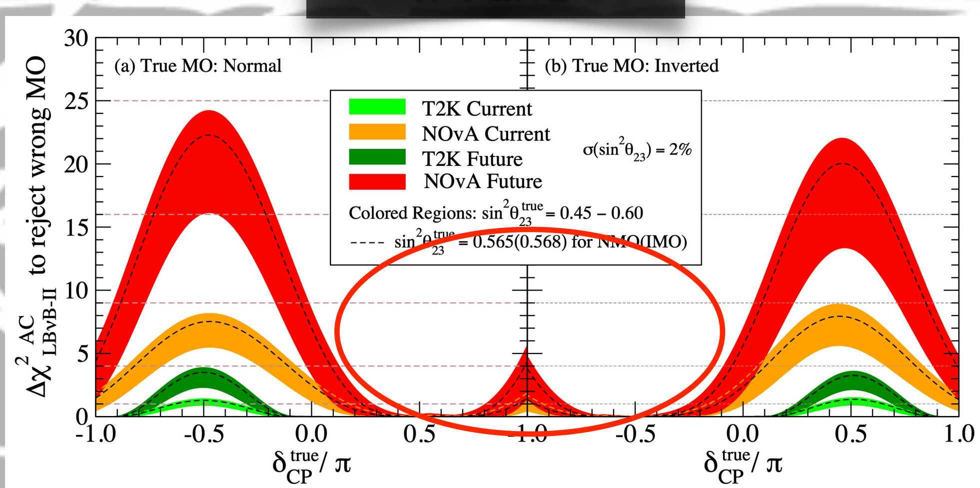


JUNO: unique vacuum oscillations (≥5σ!!!)

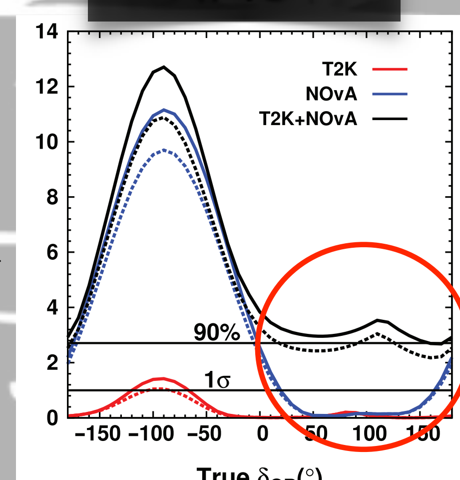
Δm² boosting is **blinded to matter-effect**

synergy II (NOvA vs T2K): MO⊕CPV complementary phase space discrimination

NOvA and T2K



NOvA⊕T2K



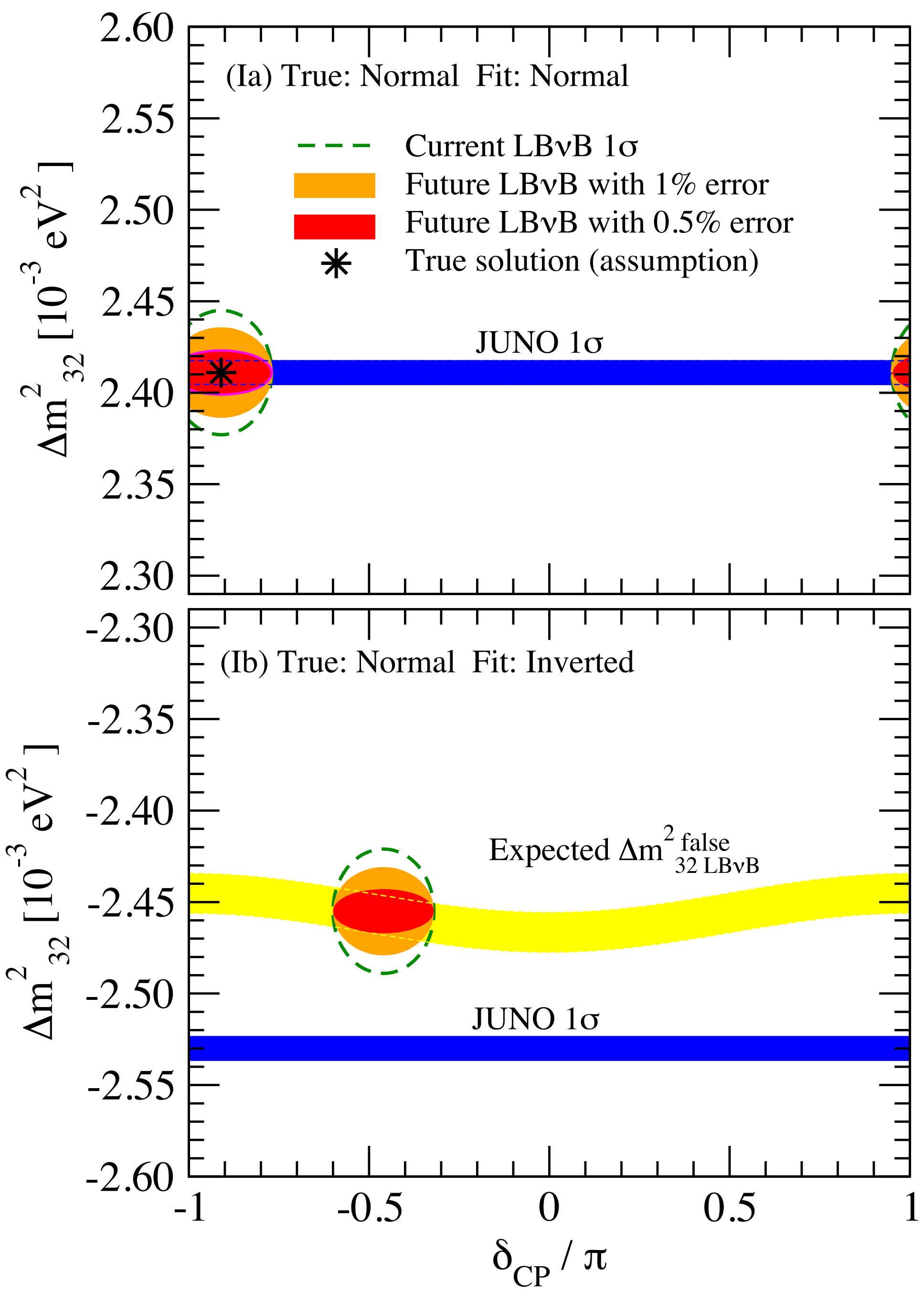
T2K @ PTEP (2015)

NOvA: strong matter effects

T2K: clean PMNS-CPV info

arXiv:2008.11280

Mass Ordering: JUNO⊕NOvA⊕T2K…



Δm^2_{32}[reactor] vs **Δm^2_{32}[LBvB]**

- **JUNO alone ~3σ**
  standalone JUNO (intrinsic): **"self Δm^2_{32}"**

JUNO alone

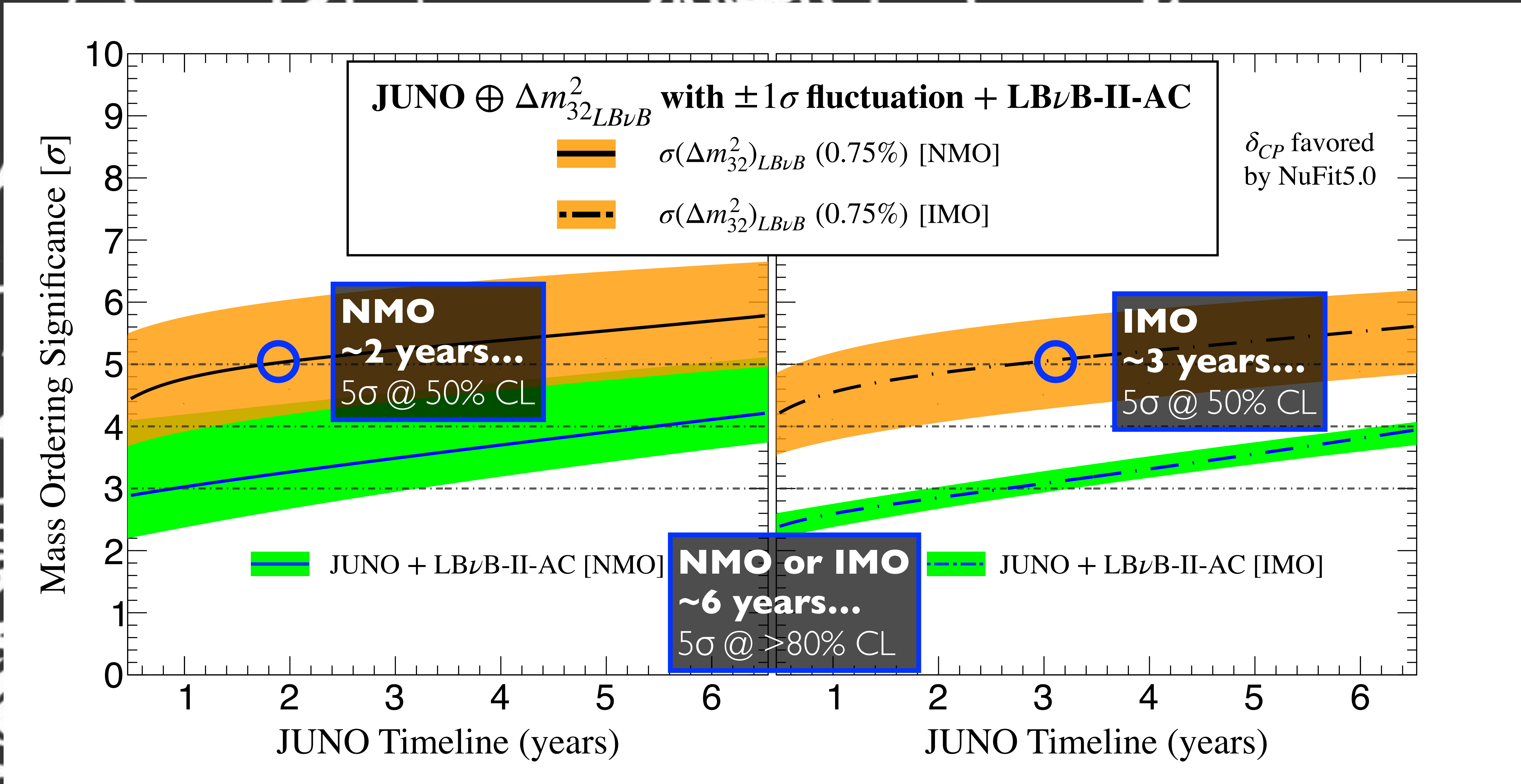
- **≥2026: JUNO⊕Δm^2_{32}[NOvA⊕T2K] ~5σ**
  JUNO exploits **Δm^2_{32}[NOvA⊕T2K]** via **PDG**

JUNO marginalised

- **≥2030: JUNO⊕Δm^2_{32}[DUNE⊕HyperK] >5σ**
  JUNO exploits Δm^2_{32}[DUNE⊕HyperK] via **PDG!**
  ⟹ **DUNE does not care about JUNO!! (too powerful)**

JUNO is world best Δm^2 (~0.1%!!)→ Accelerator experiments improving ≤1.0% NOvA⊕T2K

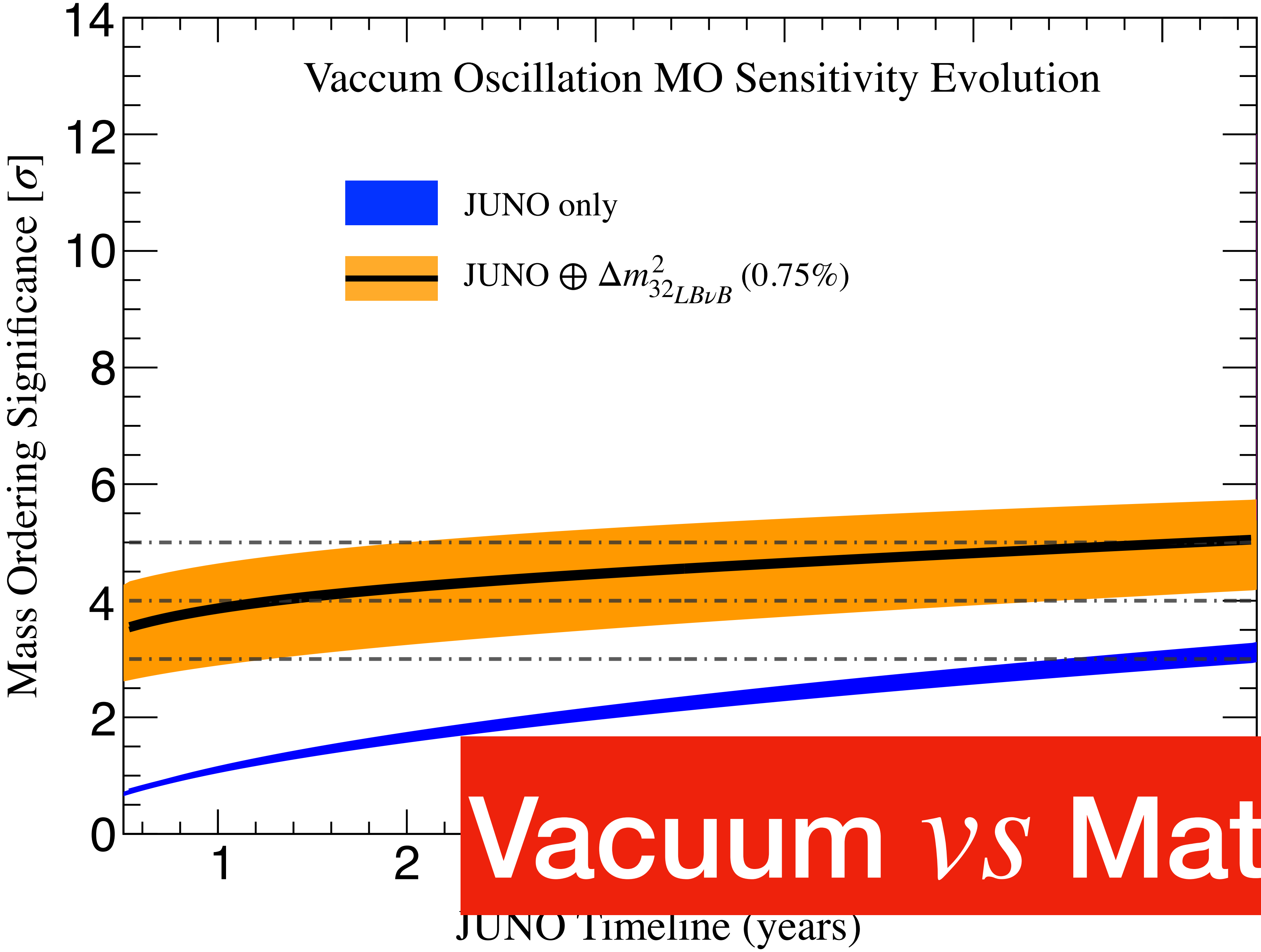
all about the **Δm^2 synergy**…



T2K data (2026) and NOvA data (2024)→ release most precise Δm^2_{32}

~5σ maybe even by ≥2026!! (if lucky)

arXiv:2008.11280



Vacuum *vs* Matter

first? MO @ **≥5σ possible** (≥90% CL) — follow JUNO [2028]

discovery: physics BSM?

time evolution… **new physics?**

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Synergies and prospects for early resolution of the neutrino mass ordering

Anatael Cabrera, Yang Han, ... Hongzhao Yu + Show authors

Scientific Reports **12**, Article number: 5393 (2022) | Cite this article

Abstract

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Acknowledgements

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atmospheric neutrinos were not covered — extra info→ even more significance!

correct? missing something?

arXiv:2008.11280

Earliest Resolution to the Neutrino Mass Ordering?

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We hereby illustrate and numerically demonstrate via a simplified *proof of concept* calculation tuned to the latest average neutrino global data that the combined sensitivity of JUNO with NOvA and T2K experiments has the potential to be the first fully resolved ($\geq 5\sigma$) measurement of neutrino Mass Ordering (MO) around 2028; tightly linked to the JUNO schedule. Our predictions account for the key ambiguities and the most relevant $\pm 1\sigma$ data fluctuations. In the absence of any concrete MO theoretical prediction and given its intrinsic binary outcome, we highlight the benefits of having such a resolved measurement in the light of the remarkable MO resolution ability of the next generation of long baseline neutrino beams experiments. We motivate the opportunity of exploiting the MO experimental framework to scrutinise the standard oscillation model, thus, opening for unique discovery potential, should unexpected discrepancies manifest. Phenomenologically, the deepest insight relies on the articulation of MO resolved measurements via at least the two possible methodologies *matter effects* and purely *vacuum* oscillations. Thus, we argue that the JUNO vacuum MO measurement may feasibly yield full resolution in combination to the next generation of long baseline neutrino beams experiments.

The discovery of *neutrino* (ν) *oscillations* phenomenon have completed a remarkable scientific endeavour lasting several decades that has changed forever our understanding of the phenomenology of the leptonic sector of the *standard model of elementary particles* (SM). A few modifications were accommodated to account for the new phenomenon [1]. This means the manifestation of massive neutrinos and leptonic mixing along with an embedded mechanism for the intrinsic difference between ν and $\bar{\nu}$ due to the violation of charge conjugation parity symmetry, or CP-violation (CPV); e.g. review [2].

Neutrino oscillations imply that the neutrino mass eigenstates (ν_1, ν_2, ν_3) spectrum is non-zero and non-degenerate, so at least two neutrinos are massive. Each mass eigenstate (ν_i; with i=1,2,3) can be regarded as a non-trivial mixture of the known neutrino flavour eigenstates (ν_e, ν_μ, ν_τ) linked to the three (e, μ, τ) respective charged leptons. Since no significant experimental evidence beyond three families exists so far, the mixing is characterised by the 3×3 so called *Pontecorvo-Maki-Nakagawa-Sakata* (PMNS) [3, 4] matrix, assumed unitary, thus parametrised by three independent mixing angles (θ_{12}, θ_{23}, θ_{13}) and one CP phase (δ_{CP}). The neutrino mass spectra are indirectly known via the two measured *mass squared differences* indicated as $\delta m^2_{21} (\equiv m^2_2 - m^2_1)$ and Δm^2_{32} $(\equiv m^2_3 - m^2_2)$, respectively, related to the ν_2/ν_1 and ν_3/ν_2 pairs. The neutrino absolute mass is not directly accessible via neutrino oscillations and remains unknown, despite major active research [5].

As of today, the field is well established both exper-

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our results (end of August 2020)

Physics potentials with a combined sensitivity of T2K-II, NOνA extension and JUNO

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Abstract

Leptonic CP violation search, neutrino mass hierarchy determination, and precision measurement of oscillation parameters for an unitary test of the neutrino mixing matrix are among the major targets of the ongoing and future neutrino oscillation experiments. The work explores the physics reach for these targets by around 2027, when the 3rd generation of the neutrino experiments starts operation, with a combined sensitivity of three experiments T2K-II, NOνA extension, and JUNO. It is shown that a joint analysis of these three experiments can conclusively determine the neutrino mass hierarchy. Also, it provides 5σ C.L. more or less to exclude CP conserving values if *true* $\delta_{CP} \sim \pm\frac{\pi}{2}$ and more than 50% fractional region of *true* δ_{CP} values can be explored with a significance of at least 3σ C.L. Besides, the joint analysis can provide unprecedented precision measurements of the atmospheric neutrino oscillation parameters and a great offer to solve the θ_{23} octant degeneracy in case of non-maximal mixing.

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confirmation (end of September 2020) [poster @ Nu2020]

validation↔agreement...

Combined sensitivity of JUNO and KM3NeT/ORCA to the neutrino mass ordering

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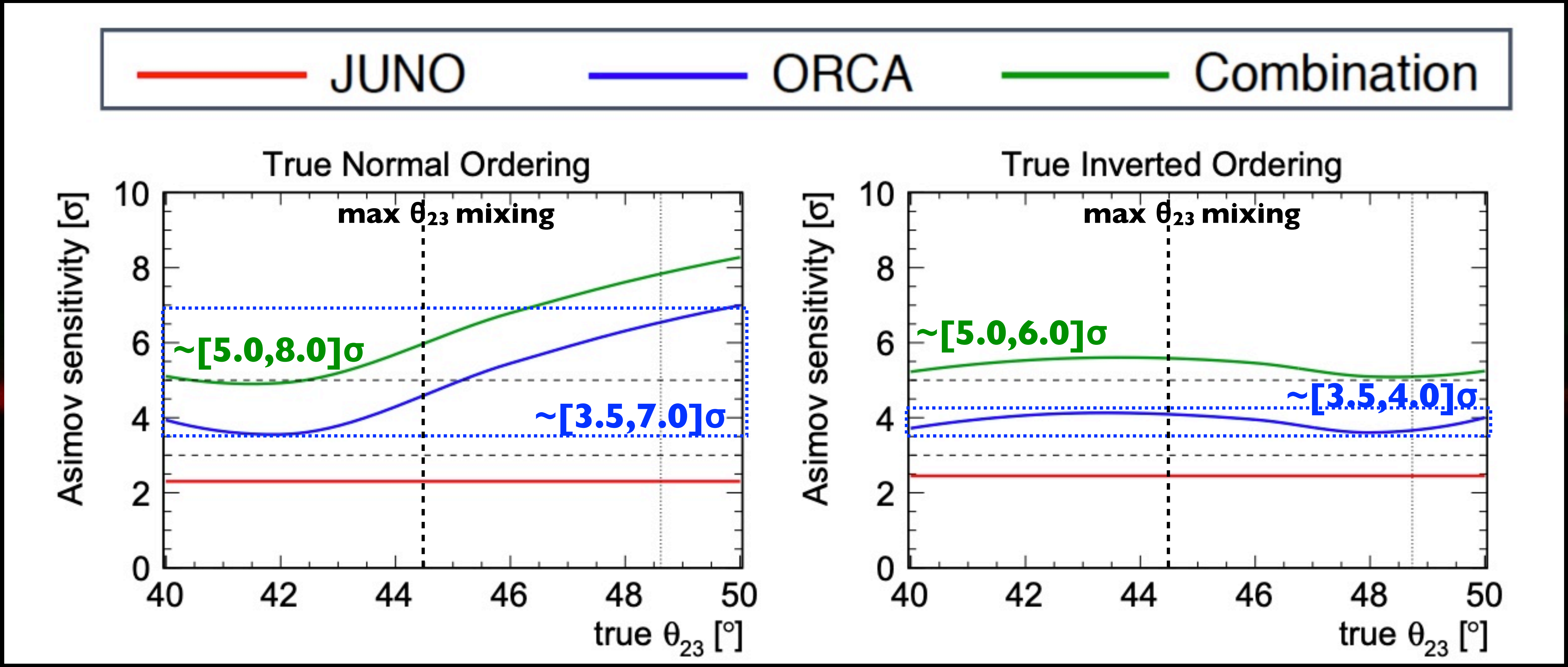
PINGU⊕JUNO (2019) & ORCA⊕JUNO (2022)

main nuisance: the θ_{23} octant…



θ_{23} octant ambiguity withholds much (up to ~2x in NMO) of the atmospheric potential…

•if *normal*-MO sensitivity (best): combined [5,8]σ

•if *inverted*-MO sensitivity (worse): combined [5,6]σ

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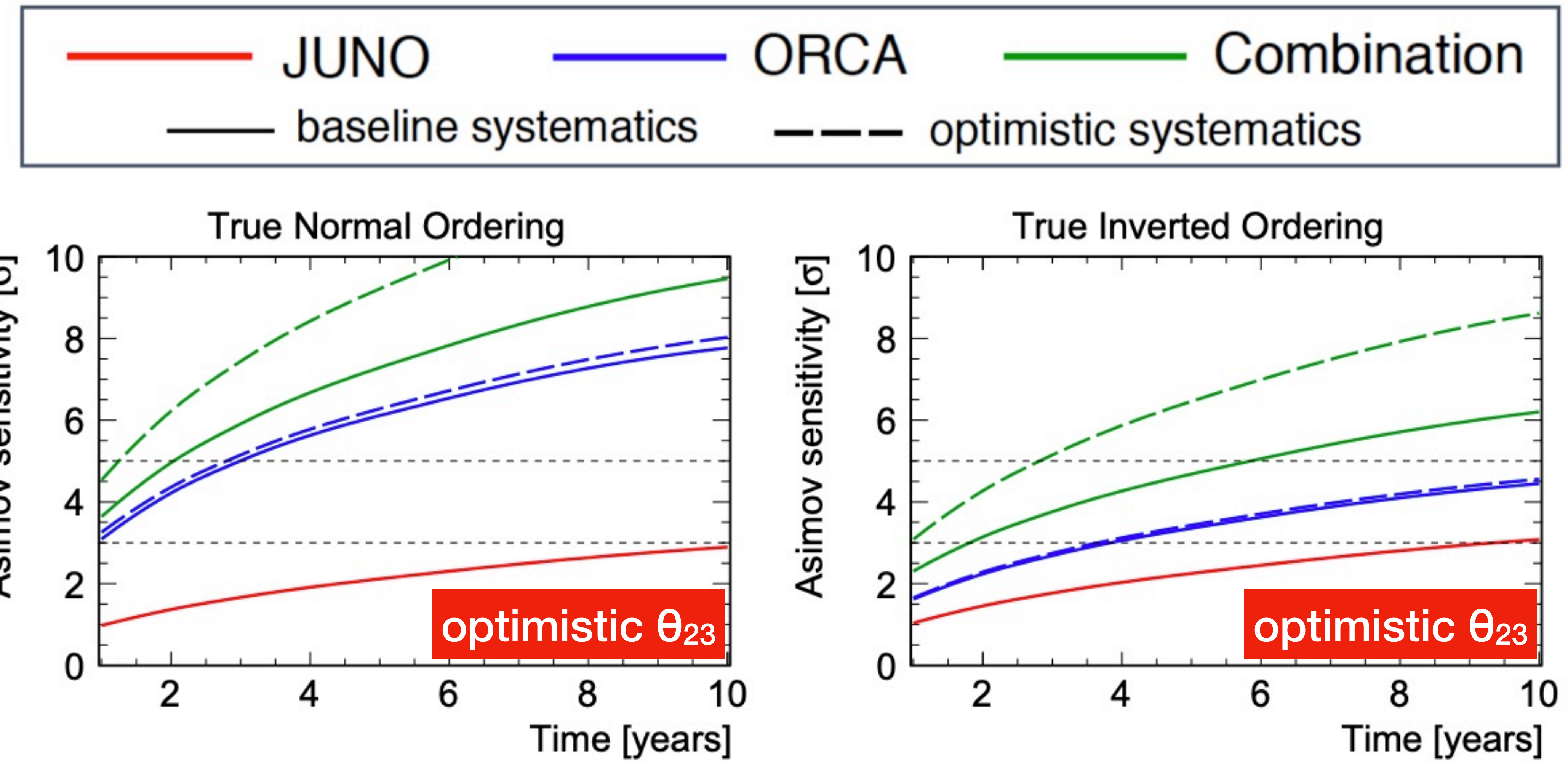
ORCA⊕JUNO sensitivity…

True NMO	JUNO, 8 cores	ORCA	Simple Sum	Combination
NO	2.3σ	6.5σ	6.9σ	7.8σ
IO	2.4σ	3.6σ	4.3σ	5.1σ



"time" assumes completed both JUNO and ORCA full array

combination goes beyond the simple sum of X^2… boosting term but less strong

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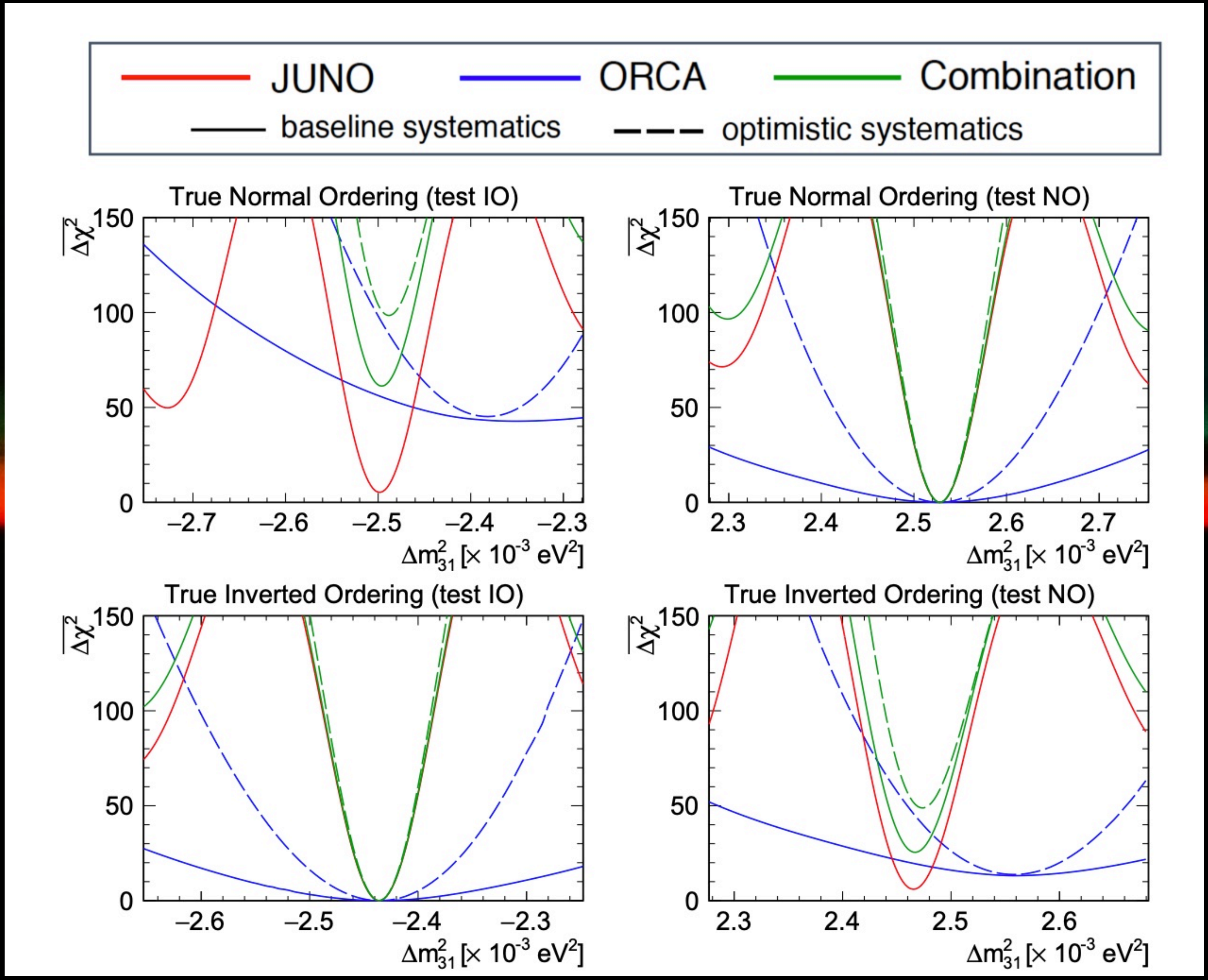
ORCA⊕JUNO: poorer boost



ORCA's intrinsic precision on Δm^2 is limited — instead JUNO is world best!

Mass Ordering: benefits from all…

many experiments with sensitivity…

now running (alphabetical)…

- **NOvA** — direct sensitivity
- **Reactor-θ13** — indirectly (via Δm^2)
- **SuperK** — direct sensitivity
- **T2K** — indirect sensitivity (via Δm^2 & CPV)

$\Longrightarrow$ see impact and details in **NuFit5.0**, Bari, Valencia, Madrid **global analyses**

forthcoming (alphabetical)…

- **DUNE** — direct sensitivity
- **HyperK** (atmospheric) — direct sensitivity
- **JUNO** — direct sensitivity
- **ORCA** — direct sensitivity
- **PINGU** — direct sensitivity
- **T2HK** — indirect sensitivity (via Δm^2 & CPV)

very exciting field — including CPV measurement

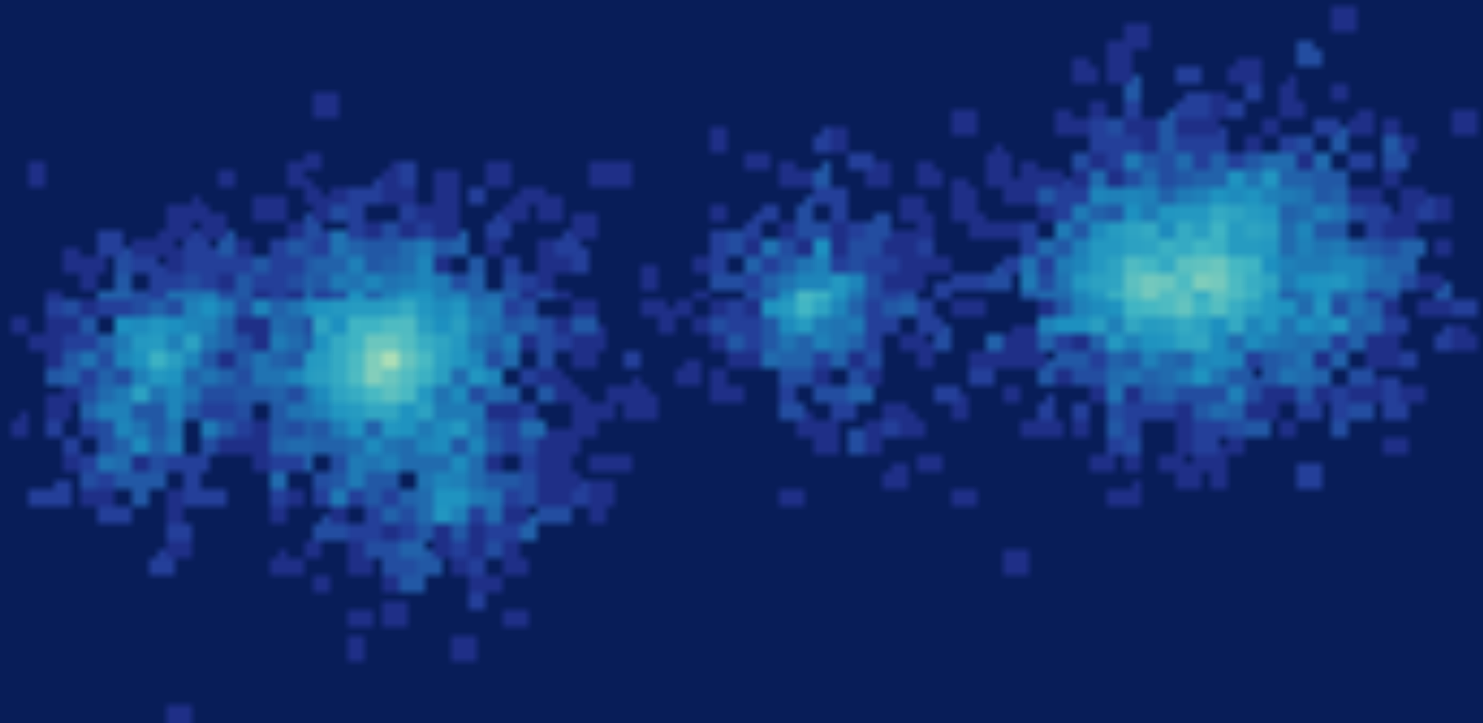
Neutrino Mass Ordering resolution…

- **fully resolved (≥5σ) by 2026-2028**: **<u>JUNO</u>⊕NOvA⊕T2K — plus atmospheric!**

- role of **atmospheric very important** — full exposure needed for statistical power.

- **first measurement** a mixture of **vacuum(JUNO)⊕matter(all others)**

- ultimate **vacuum(JUNO) vs matter(DUNE)**: **discovery?**



Дякую…
merci…
ありがとう…
danke…
고맙습니다…
obrigado…
спасибі…
grazie…
谢谢…
hvala…
gracias…
شكرا…
thanks…

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