Neutrino Mass Ordering 5σ?

IRN Meeting
June 2021

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LNCA (Chooz)

Physique des 2 Infinis et des Origines

status on neutrino oscillation knowledge…

Standard Model (3 families)
[leptons & quarks]
&
<u>unitary</u> **PMNS**$_{3x3}(\theta_{12},\theta_{23},\theta_{13},\delta_{CP})$
&
$\pm\Delta m^2$ & $+\delta m^2$

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		NuFIT4.0
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 %**
$+\delta m^2$	2.5 %	KamLAND	2.3 %
$\|\Delta m^2\|$	3.0 %	T2K+NOvA & DYB	1.3 %
Mass Ordering	**unknown**	SK et al	NMO **~3σ**
CP Violation	**unknown**	T2K+NOvA	**≲2σ**

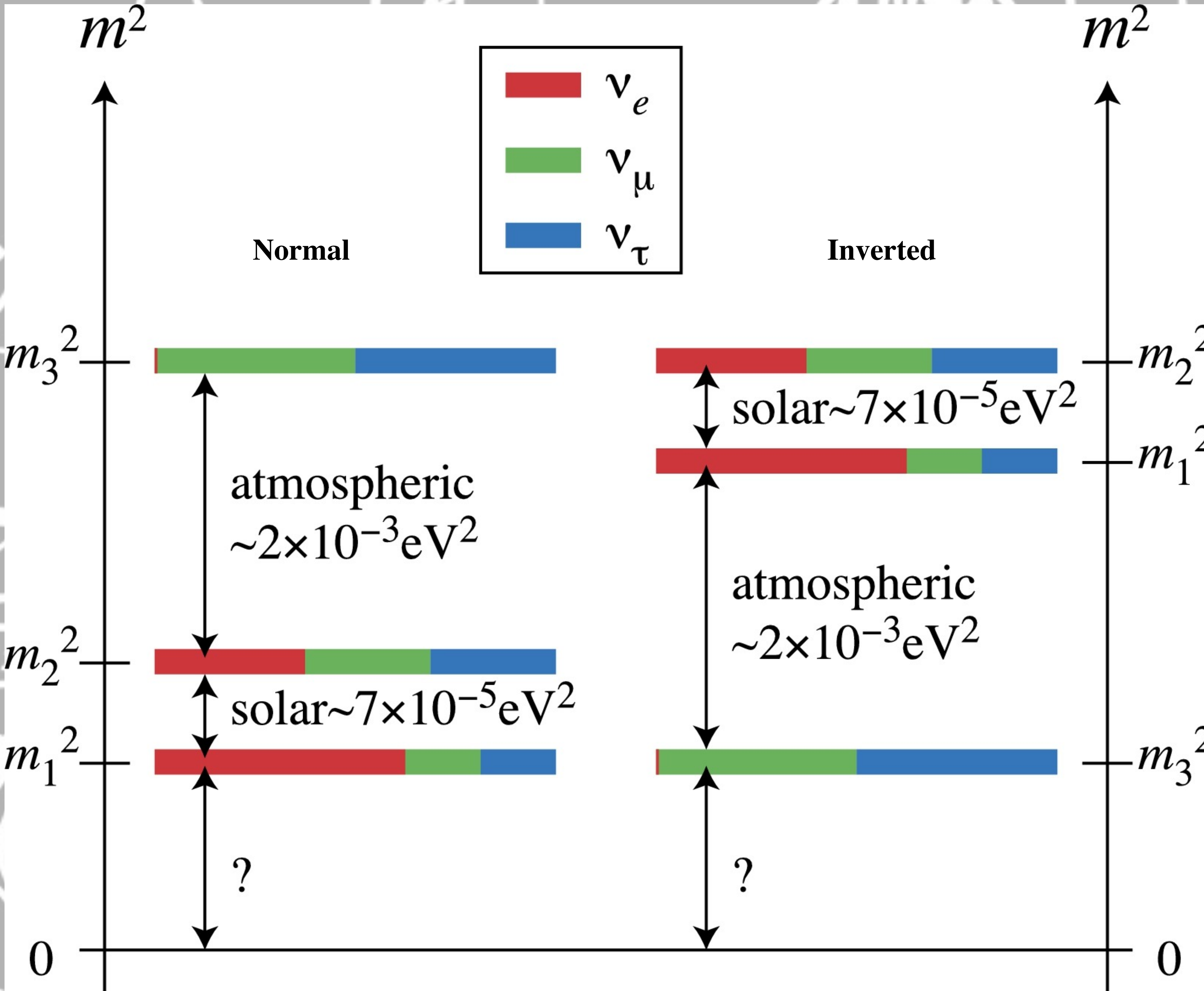
(**now**)

(reactor-beam)

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

NOTE: ORCA⊕PINGU⊕IceCube complementary (Mass Ordering & Δm^2 measurements)

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)



Mass Ordering means…

•the lightest ν: m_1 or m_3?

•important consequences to…

- **Cosmology**
  [ν role in Universe formation]
- **Particle Physics**
  [ex. ββ decay range]

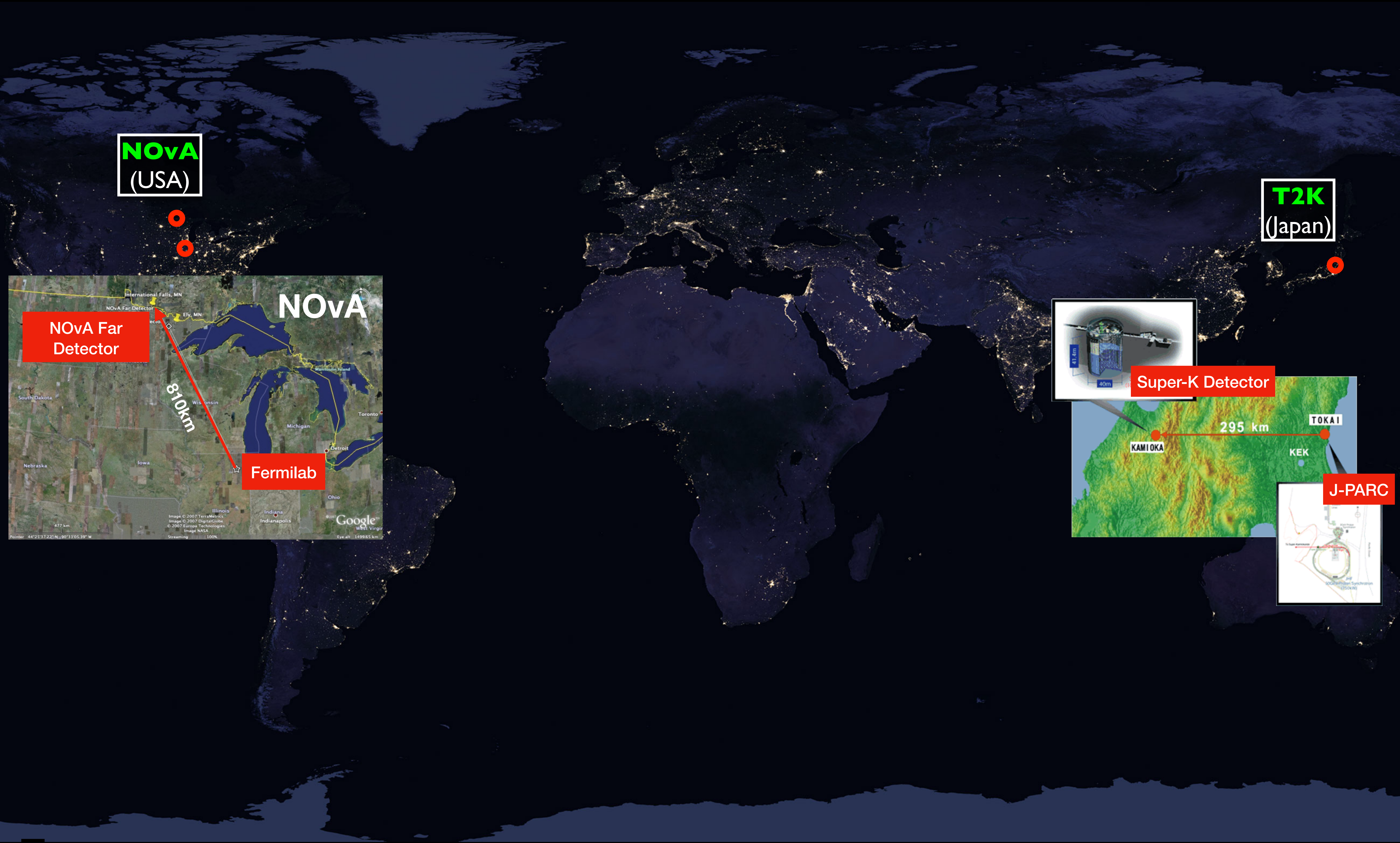
•discovery? test new physics!

- **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…

running experiments…



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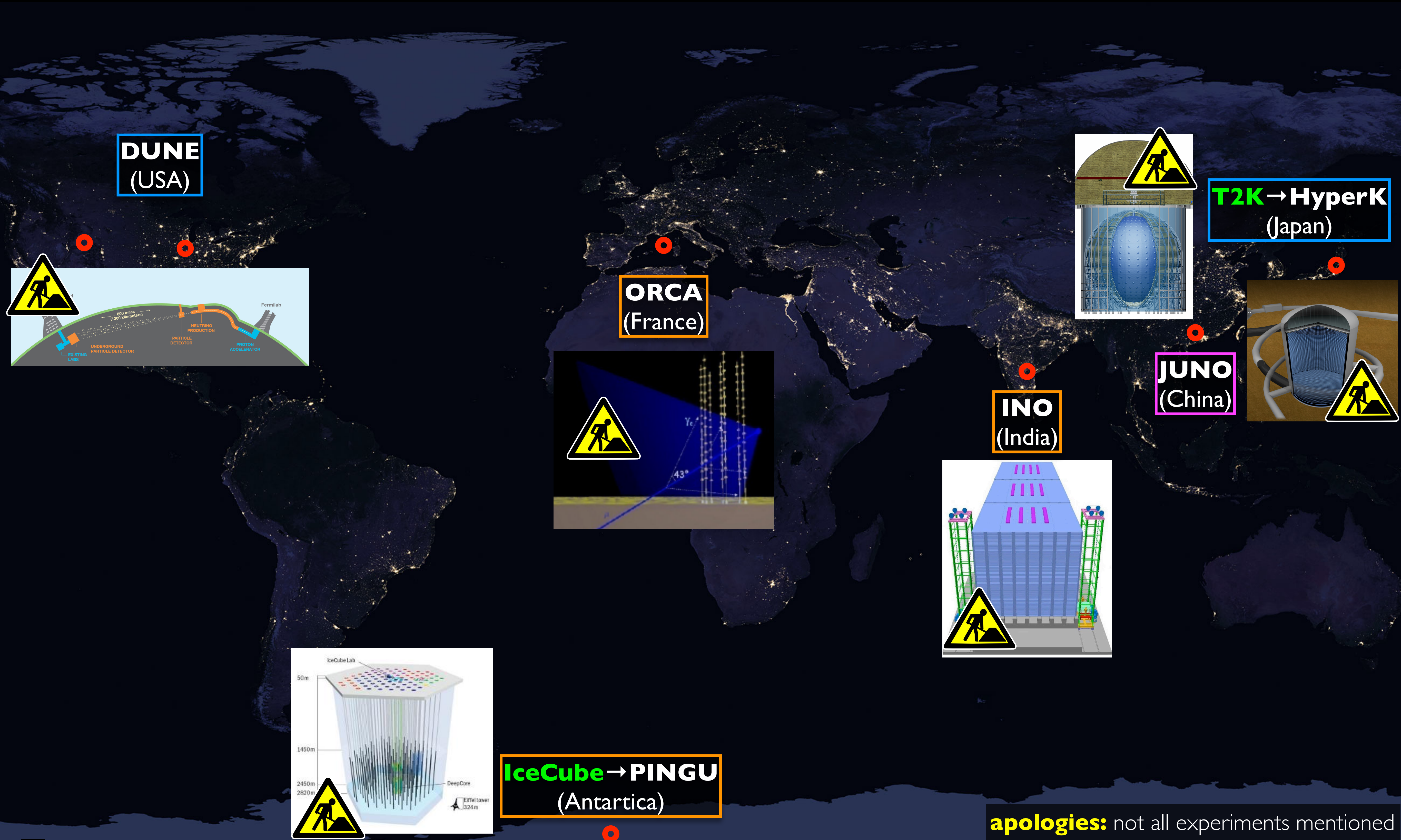
imminent experiments…



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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)

what are the leading experiments?

what's going to happen next?

today's NMO status…

arXiv:2008.11280

Earliest Resolution to the Neutrino Mass Ordering?

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

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

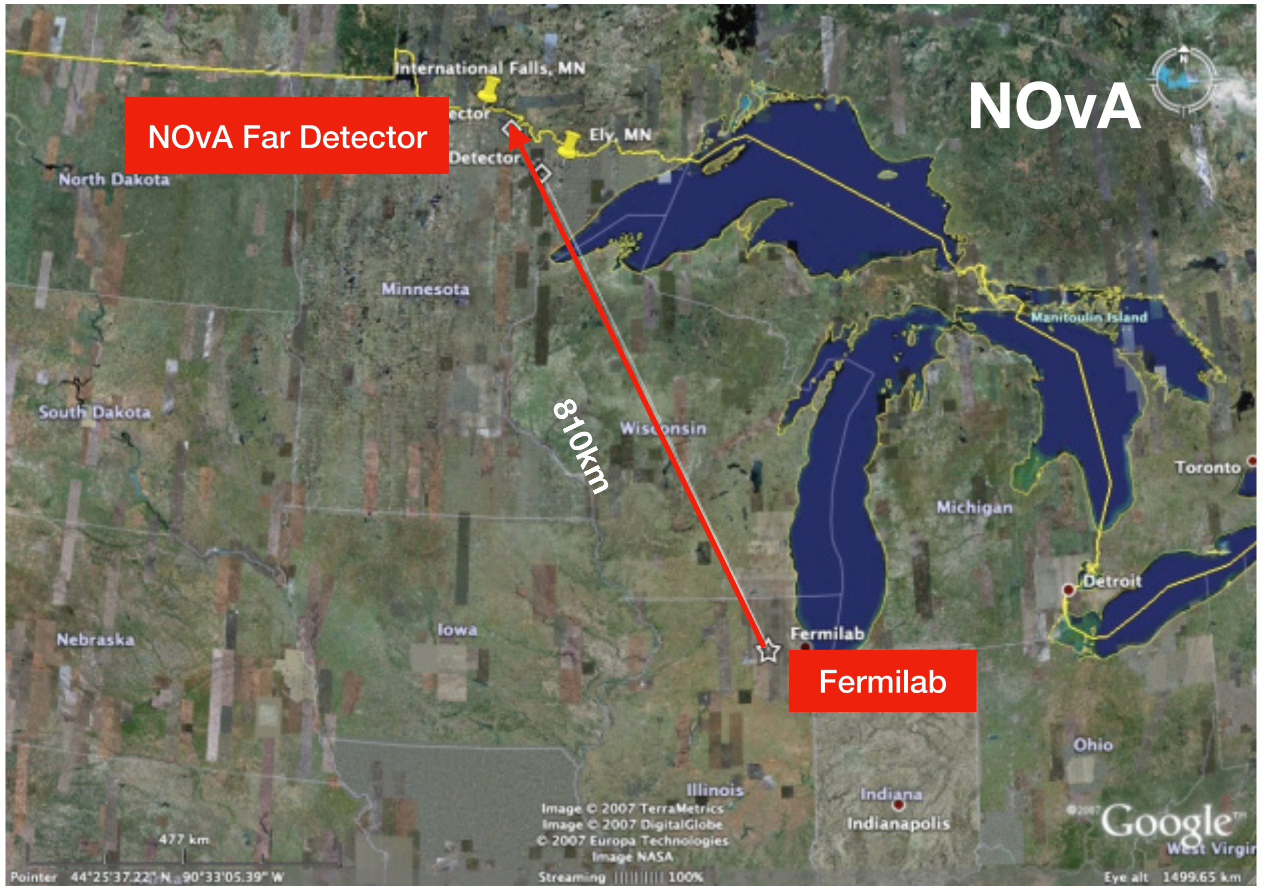
what physics exploited to yield the **full resolution?**

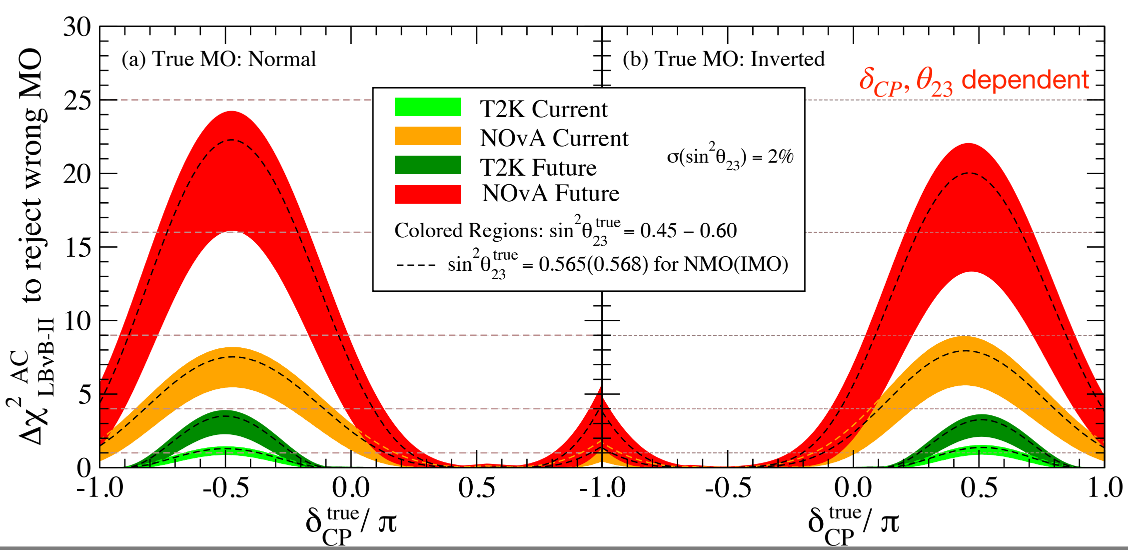
MO to probe **new physics? (discovery potential)**

our studies goal…

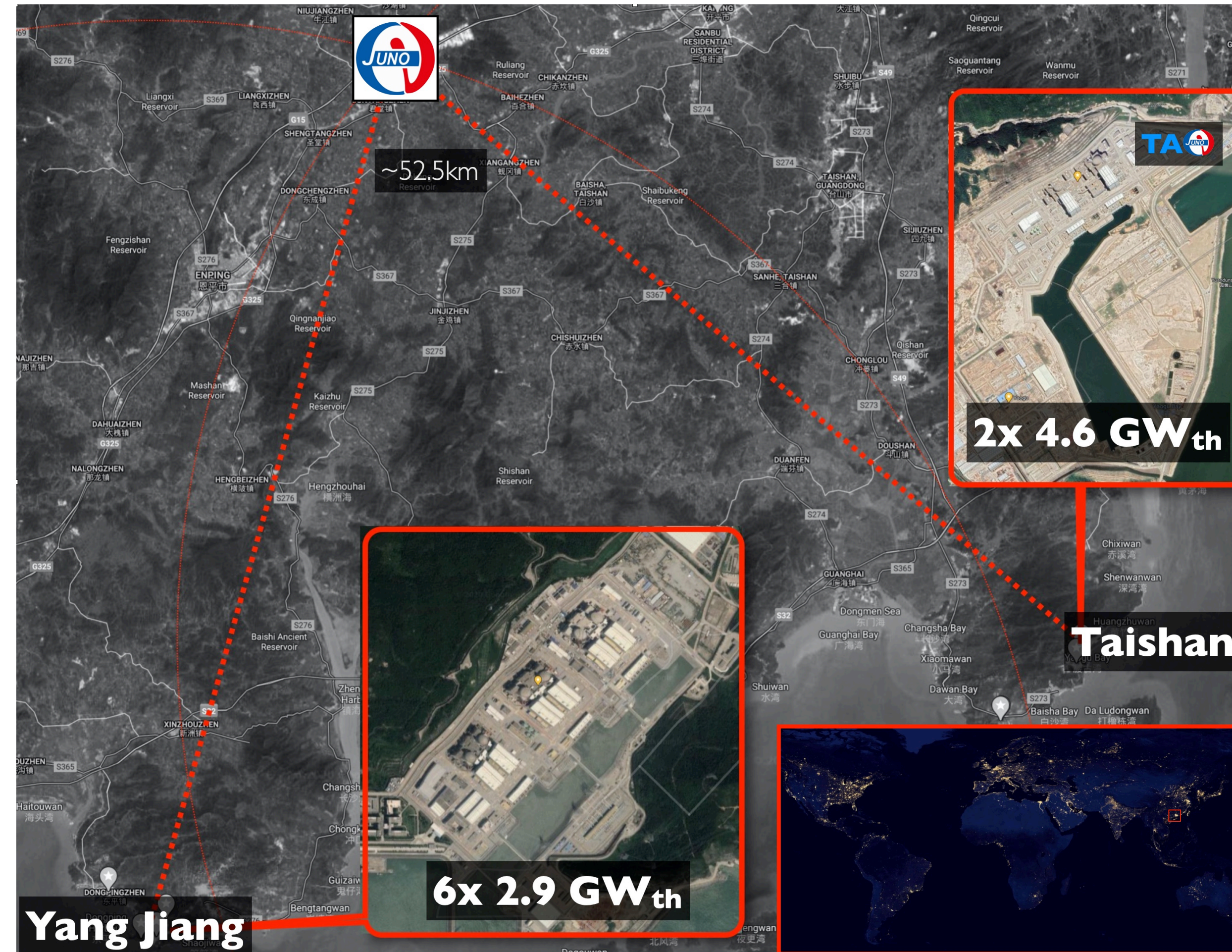
Physique des 2 Infinis et des Origines

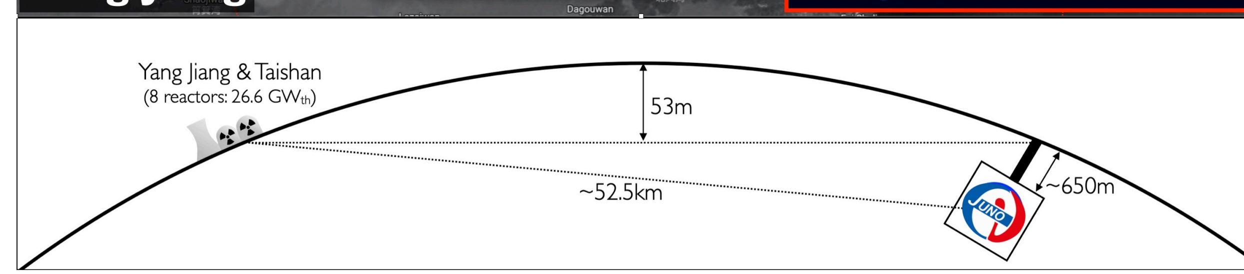
Matter Effects Oscillations
(CP experiments → ***fake*** CP-violation)





Vacuum Oscillations
(no CP-violation)





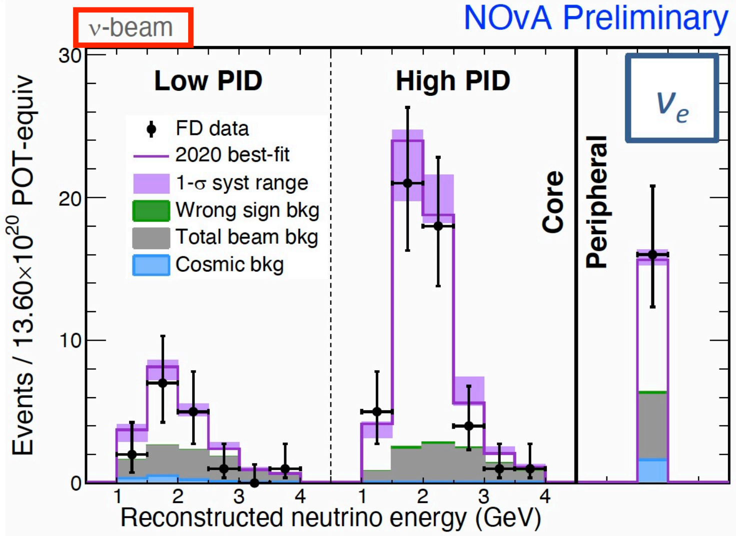
arXiv:2008.11280

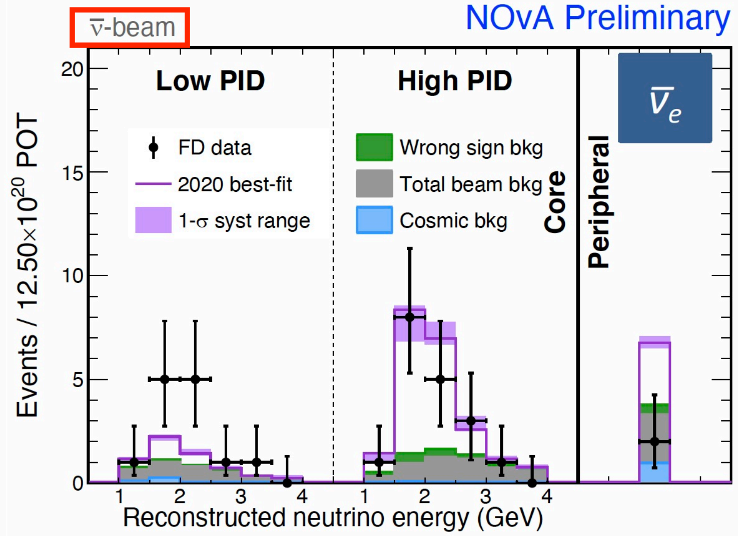
only 2 ways to measure…

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

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

NEUTRINO 2020

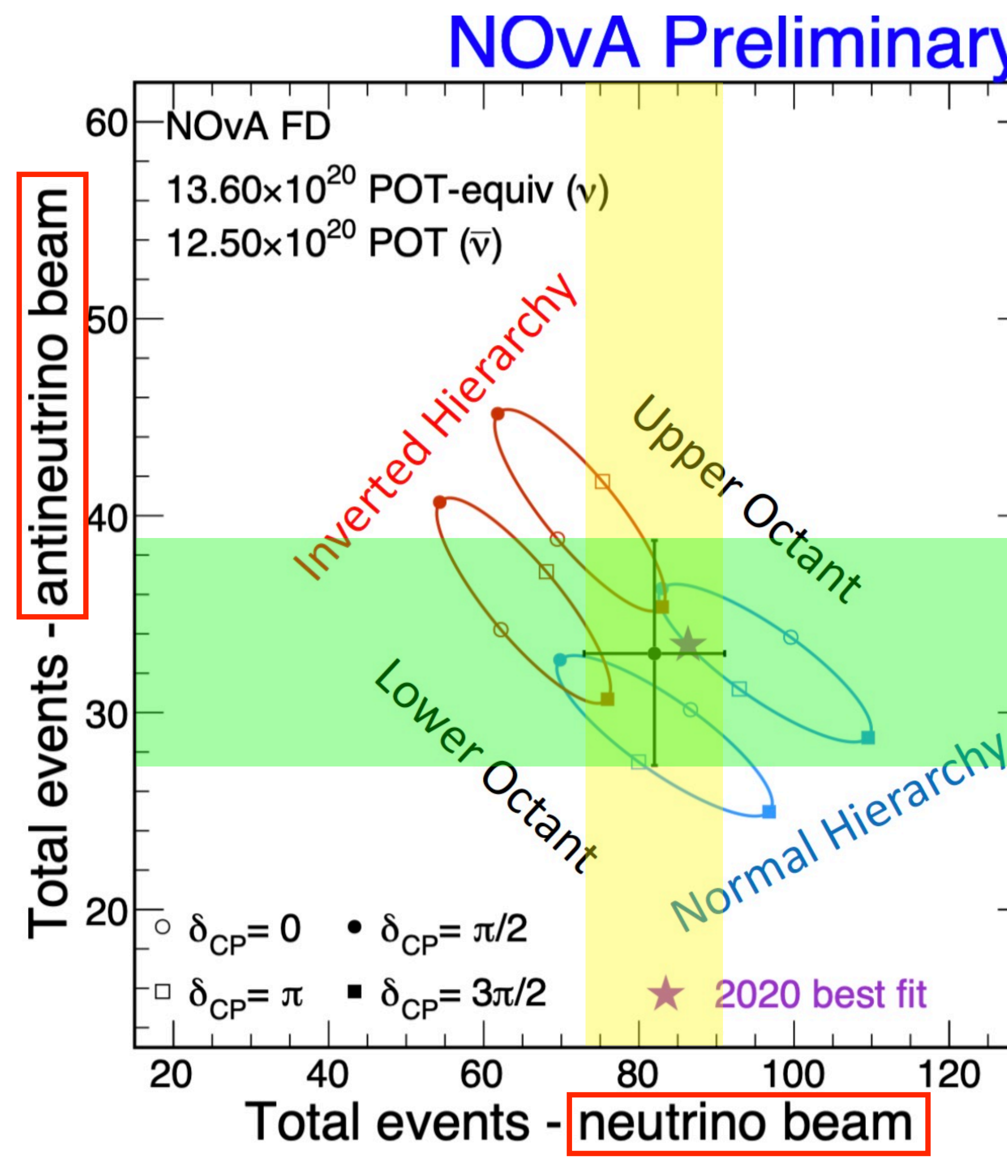




Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

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

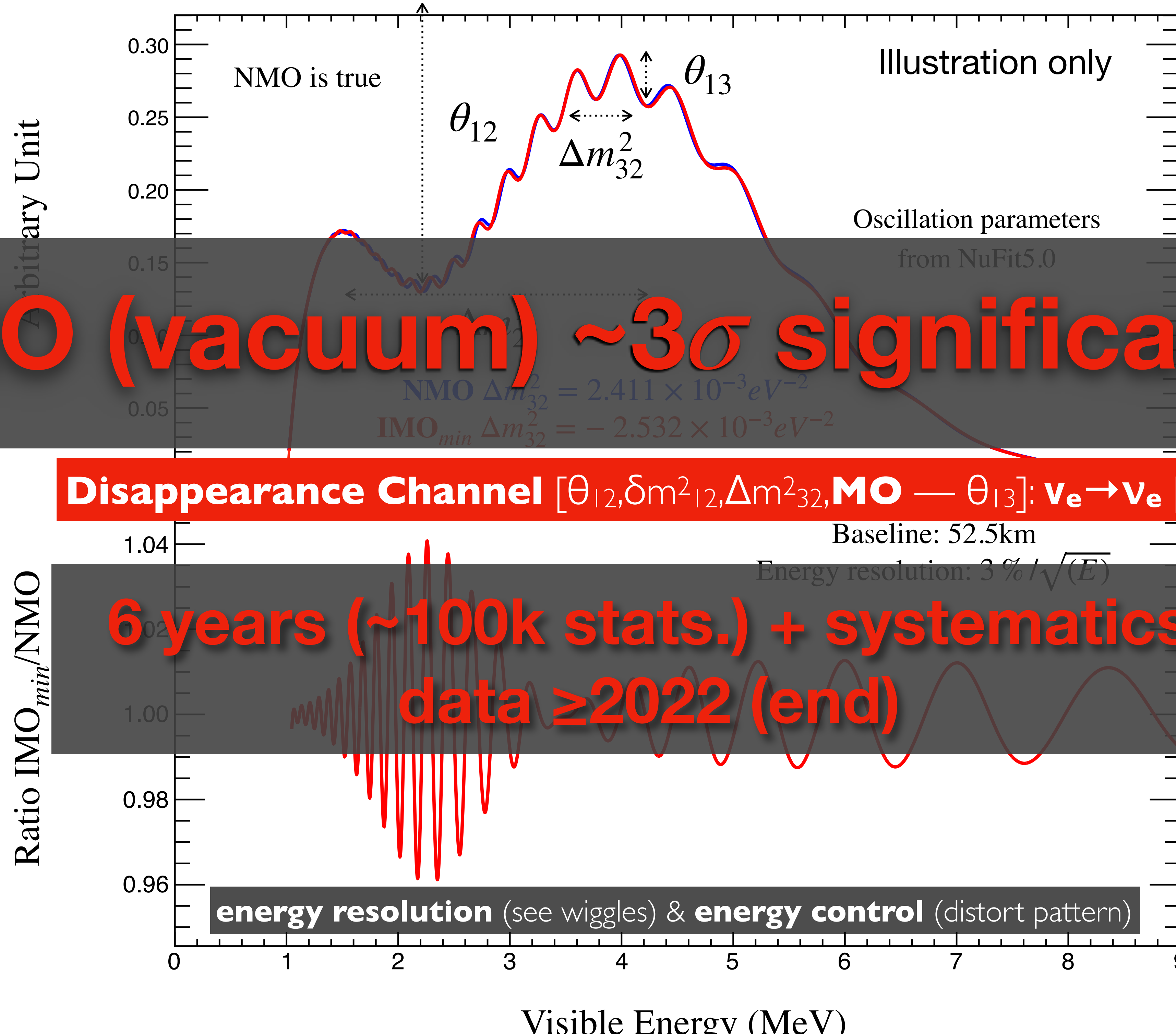


Appearance Channel [$\theta_{23} \oplus \theta_{13}$,$\boldsymbol{\delta_{CP}}$,**MO**]: $\nu_\mu \to \nu_e$ [ν and anti-ν]

Disappearance Channel [θ_{23},Δm^2_{32}]: $\nu_\mu \to \nu_\mu$ "survival probability" (not shown)

NOvA/T2K observables…

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 ≥2022 (end)

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

the JUNO (hardest) way…

in 2020…

Super-Kamiokande — no!

T2K (≤2024) — no!
little **≤2σ→** T2K designed for cleanest **δ(CP)**

NOvA (≤2026) — no!
not bad !! **≤4σ** (by 2026), only if lucky on δ(CP)!

JUNO (≥2022) — no!
not bad !! robust **~3σ** (by 2028) — careless of δ(CP)!!

by 2030…

DUNE(≥2028?) — yes!
stunning >5σ (by ~2030?) — careless of δ(CP)!!

Hyper-K(≥2028?) — no!
(like T2K) targets the cleanest δ(CP) [minimal matter effects]

atmospheric neutrino — critical! (extra info maybe **~5σ**)

atmospheric not addressed in our analysis (complex)→ reinforce our conclusions

resolution (≳5σ) anybody…?

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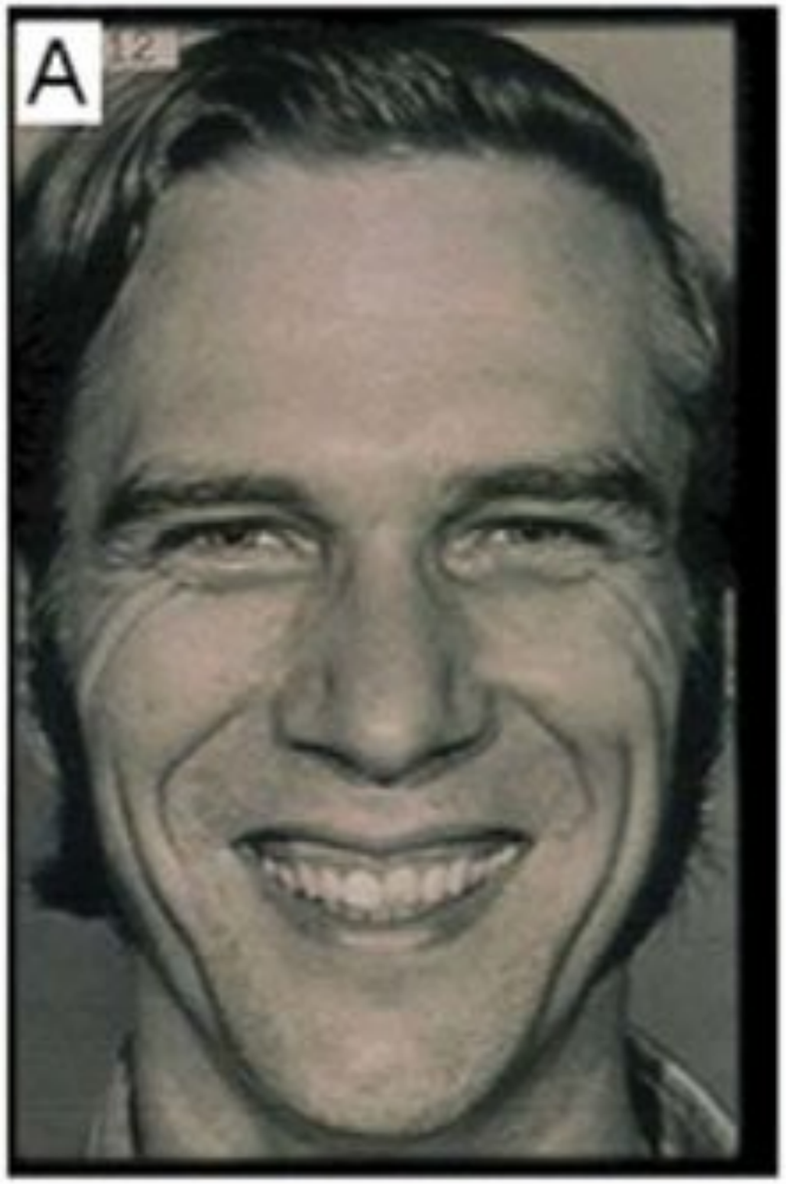
arXiv:2008.11280

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

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

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



still, ~5σ before 2030…

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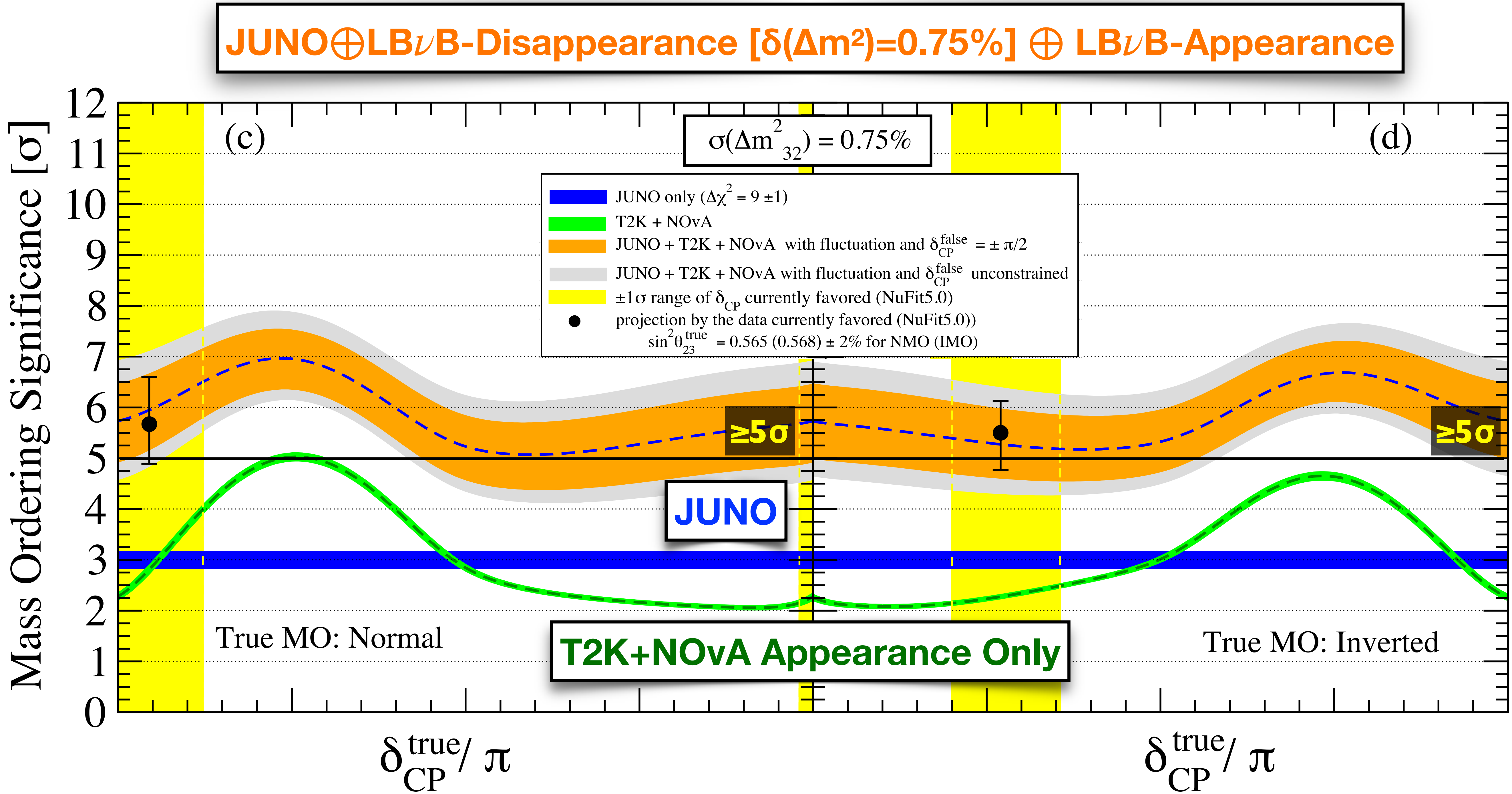
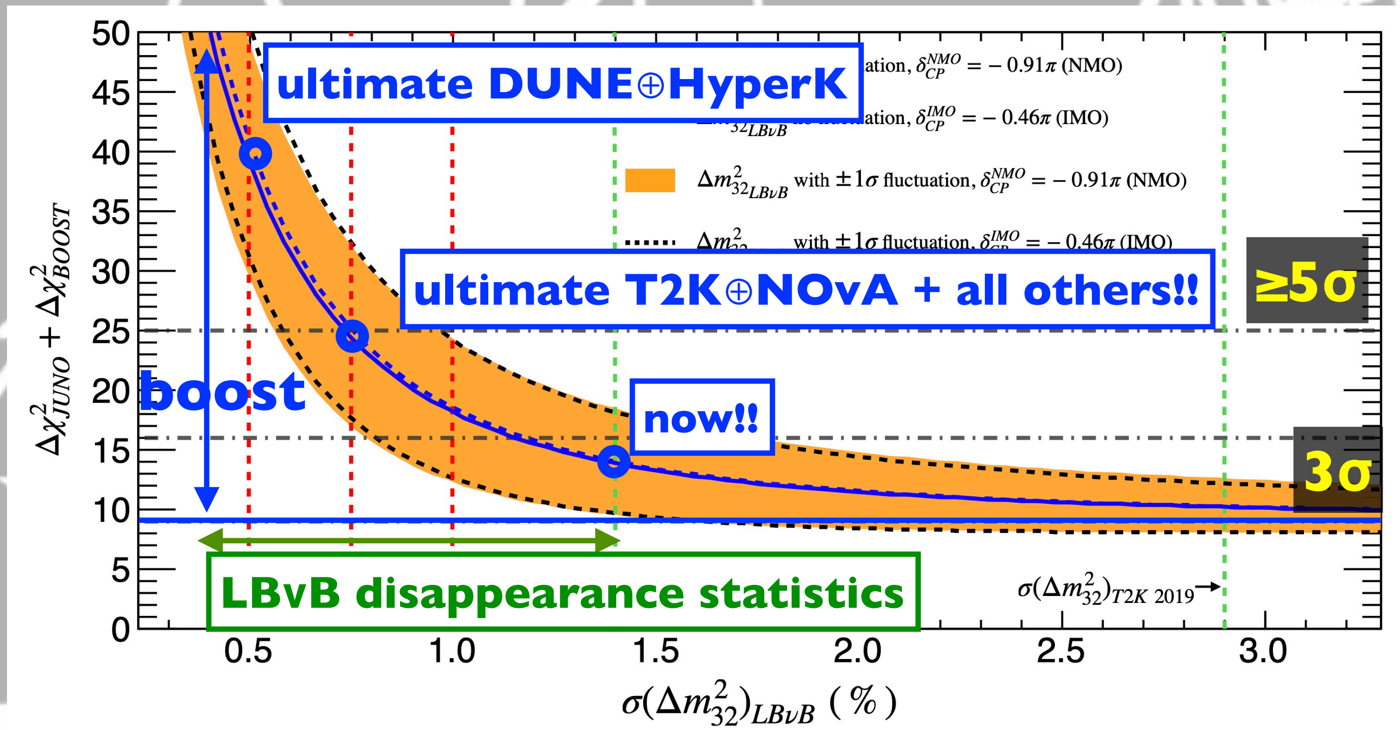


the power of synergies...

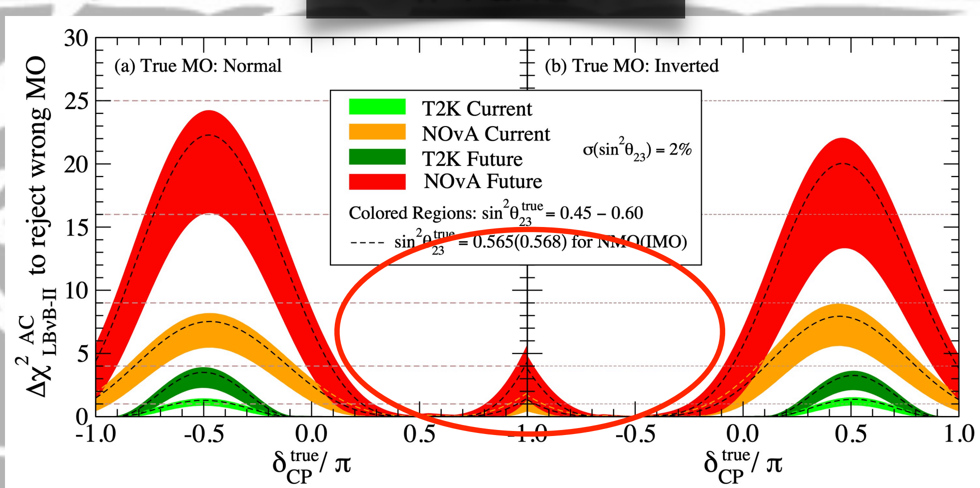
synergy I (JUNO vs NOvA⊕T2K): high precision disappearance Δm^2_{32} measurement



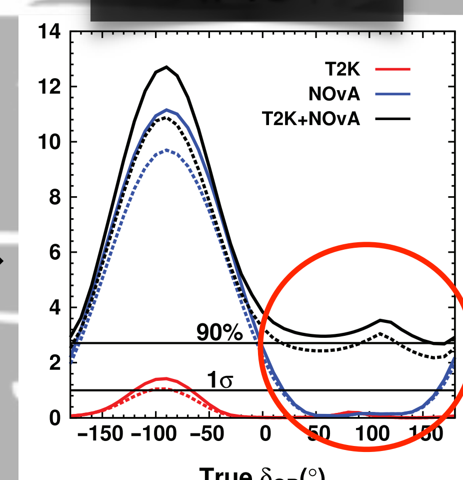
JUNO: unique vacuum oscillations (≥5σ!!!)

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 CPV information

arXiv:2008.11280

Mass Ordering: JUNO⊕NOvA⊕T2K...

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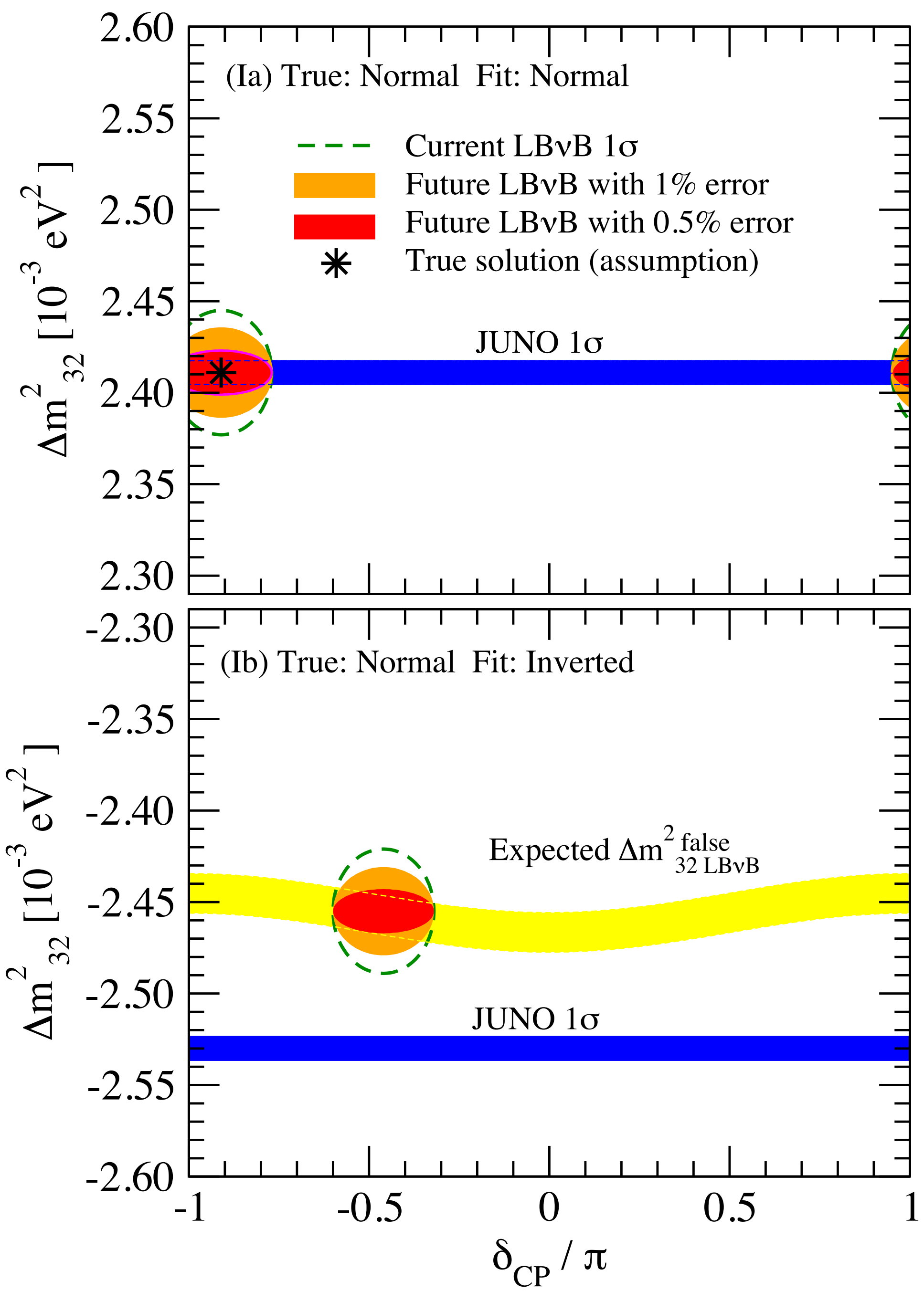

Δm^2_{32}[reactor] vs Δm^2_{32}[LBνB]

- **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)**

all about the **Δm² synergy**…

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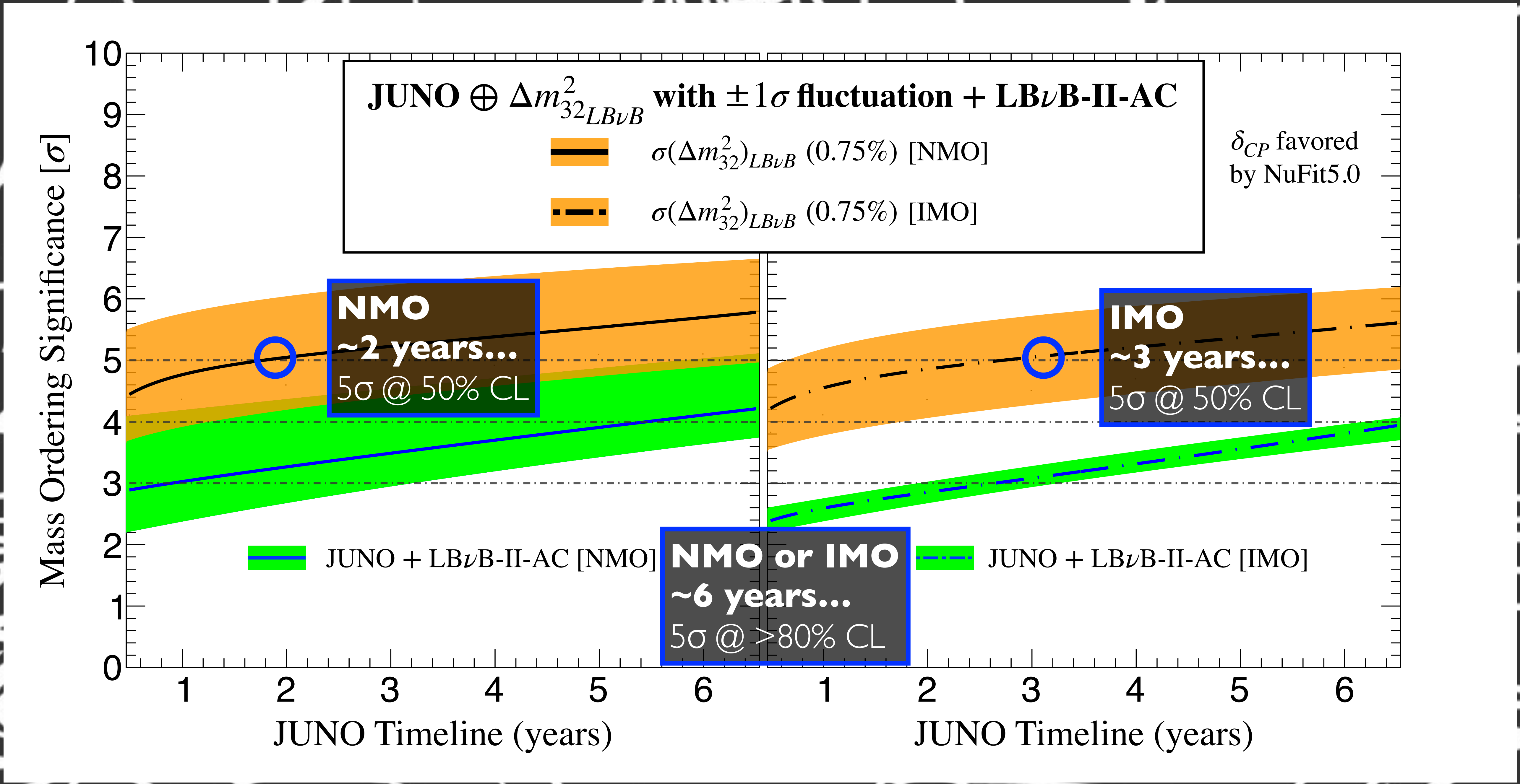
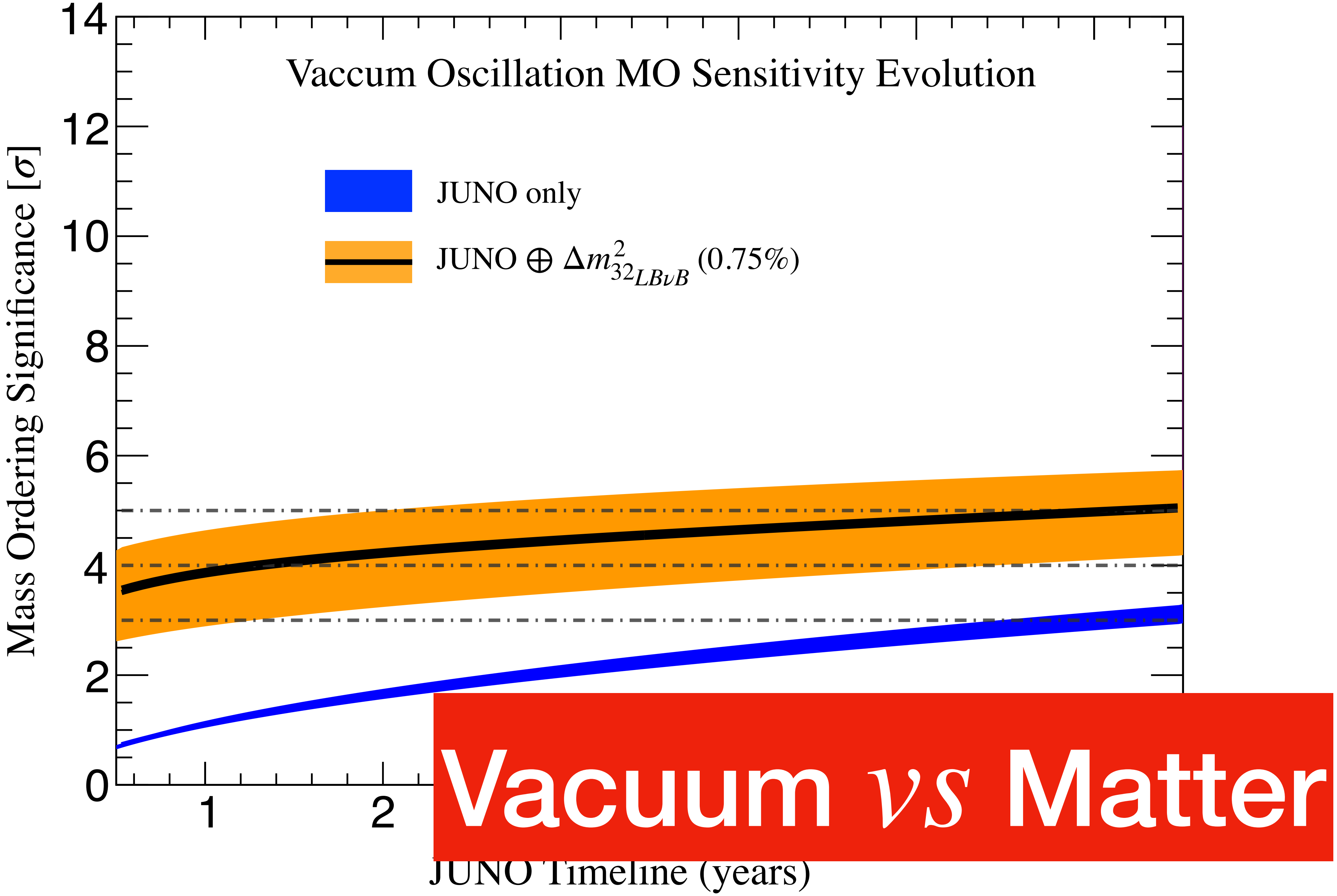


T2K data (2026) and NOvA data (2024) → release most precise Δm^2_{32}

~5σ maybe even by ≥2026!! (if lucky)

arXiv:2008.11280



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

discovery: physics BSM?

time evolution… **new physics?**

arXiv:2008.11280

Earliest Resolution to the Neutrino Mass Ordering?

Anatael Cabrera*[1,2,4], Yang Han†[1,2], Michel Obolensky[1], Fabien Cavalier[2], João Coelho[2], Diana Navas-Nicolás[2], Hiroshi Nunokawa‡[2,7], Laurent Simard[2], Jianming Bian[3], Nitish Nayak[3], Juan Pedro Ochoa-Ricoux[3], Bedřich Roskovec[3], Pietro Chimenti[5], Stefano Dusini[6a], Marco Grassi[6b], Mathieu Bongrand[8,2], Rebin Karaparambil[8], Victor Lebrin[8], Benoit Viaud[8], Frederic Yermia[8], Lily Asquith[9], Thiago J. C. Bezerra[9], Jeff Hartnell[9], Pierre Lasorak[9], Jiajie Ling[10], Jiajun Liao[10], and Hongzhao Yu[10]

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August 27, 2020 – v3.5

arXiv:2008.11280v1 [hep-ph] 25 Aug 2020

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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arXiv:2009.08585v2 [hep-ph] 4 Oct 2020

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]

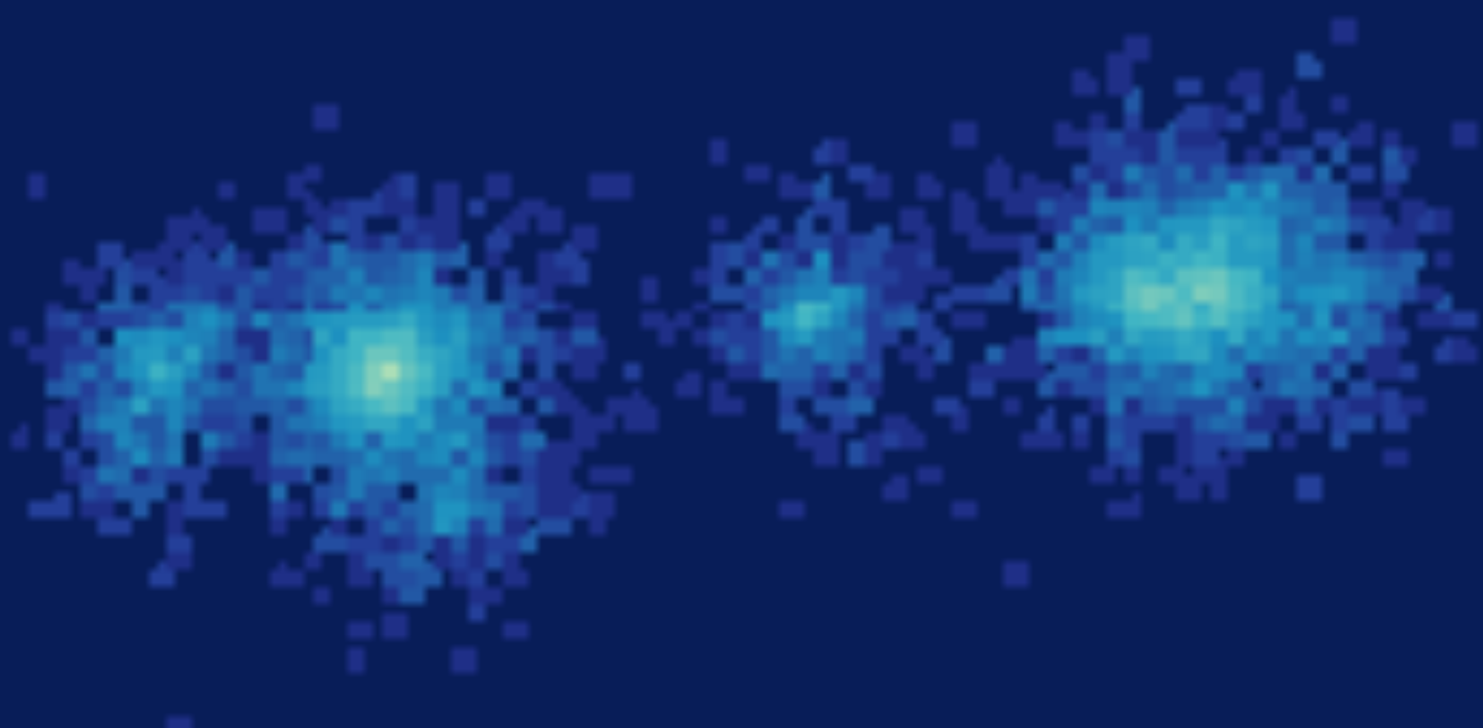
validation↔agreement…

Neutrino Mass Ordering resolution…

• **fully resolved (≥5σ) by ≥2026**: **JUNO⊕NOvA⊕T2K**
(current and extra **atmospheric neutrino**→even better)

• **first measurement** a mixture of **vacuum(JUNO)⊕matter(NOvA,T2K,etc), including atmospheric**

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



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

Physique des 2 Infinis et des Origines

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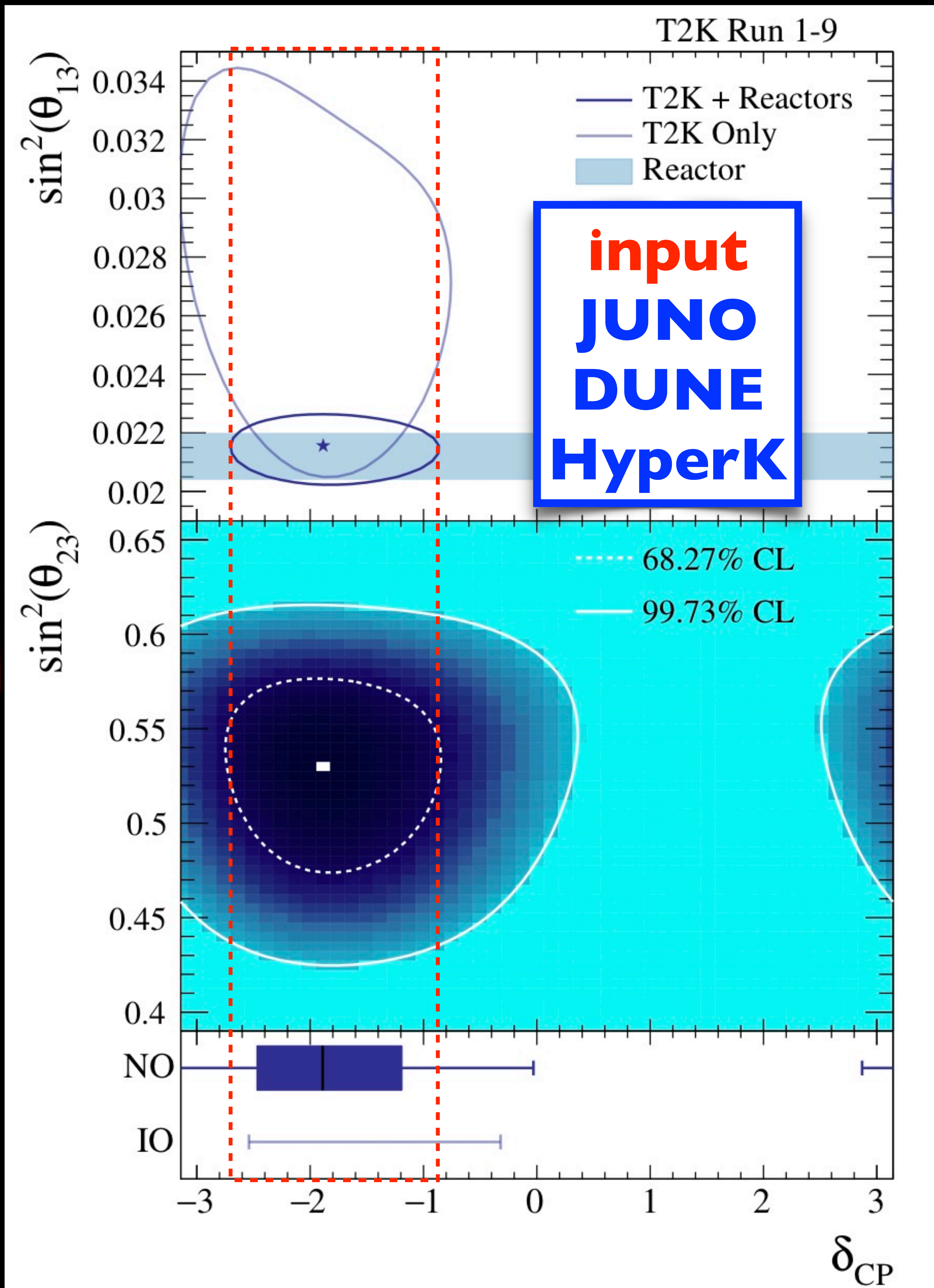
T2K⊕reactor best knowledge CP-Violation…



θ13 implications

powerful constraint

CPV phase vs θ13

[constrained by reactor]

CPV phase vs θ23

[octant ambiguity]

CPV phase vs (Atmospheric) Mass Ordering