neutrino oscillations

the latest on…

Conference FPCP
May-June 2023 — Lyon, France

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CNRS / Université de Paris-Saclay
IJCLab @ Orsay
LNCA @ Chooz

European Innovation Council

disclaimer…

- **this talk: general & news** — "non-experts" [**please ask**]
  - experimental view but not explaining all experiments

- **this talk** (reactor leaning) complementary to Sara Bolognesi's (accelerator leaning)

- skipping…
  - **absolute mass** [Stephane Lavignac]
  - **ββ** [Stefan Schoenert]
  - **beyond 3 neutrinos** [Julia Gehrlein] — **only a hint!!**
  - **short baseline** [Mark Ross-Lonergan]
  - **astrophysics** [Juan Pablo Yanez Garza]

what we **know**…

neutrino rather unique in ***Standard Model***… **discoveries!**

~50 years of neutrino oscillations…

huge experimental/theory effort

[discovery⊕establishment ⇔ Nobel 2015]

modification of the ***Standard Model of Particle Physics***

ingredients for **neutrino oscillations**…

neutrino massive

Non-degenerate mass spectrum (Δm^2)

⊕

neutrino mixing (no flavour-lepton#)

Mixing in the leptonic sector (θ)

=

Oscillation Probability

$P = f(\theta, \Delta m^2)$

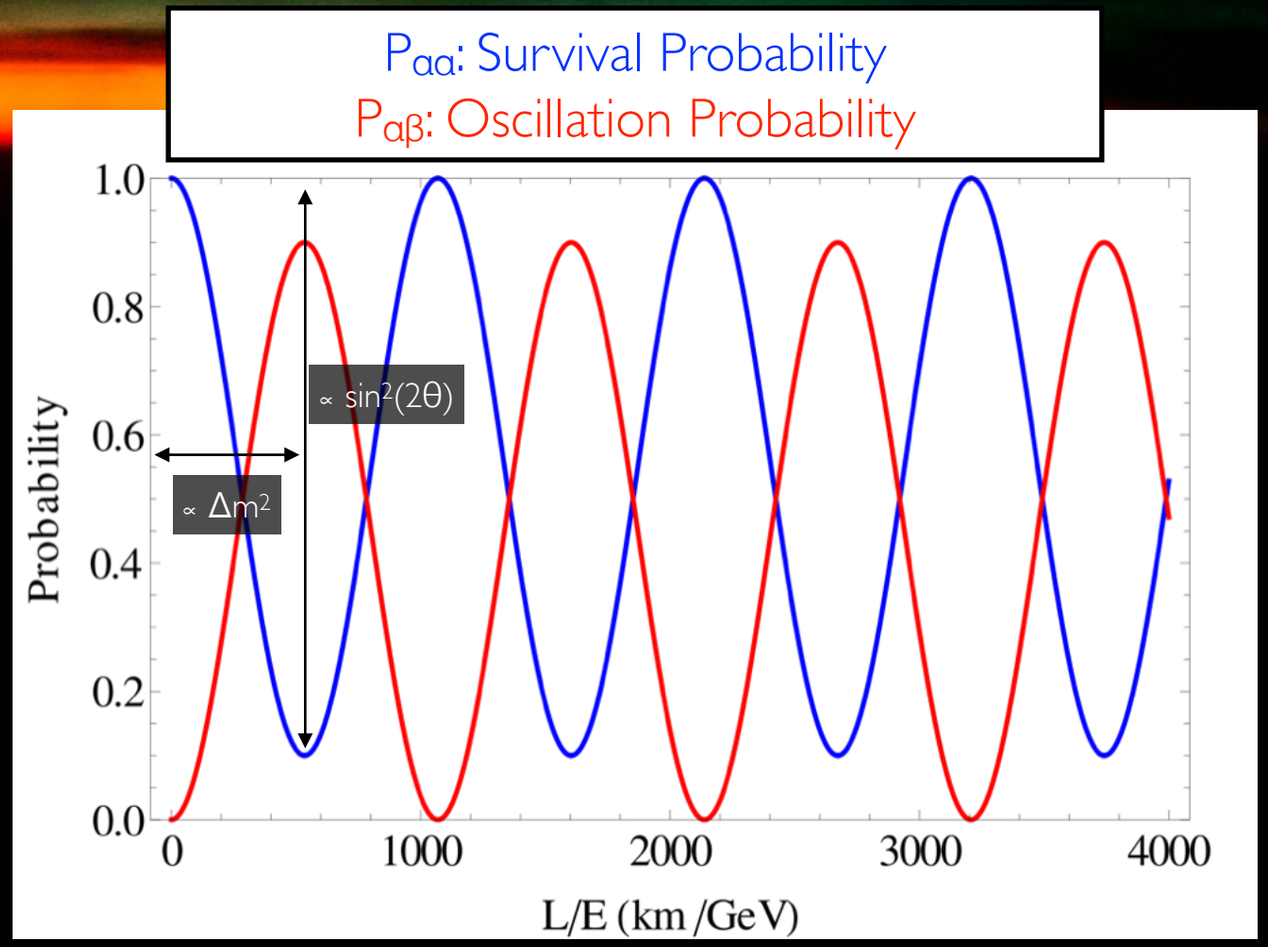
quantum interference (macroscopic)

UPMNS matrix (à la CKM)

ν_α (start with) & ν_β (none at first)

$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$

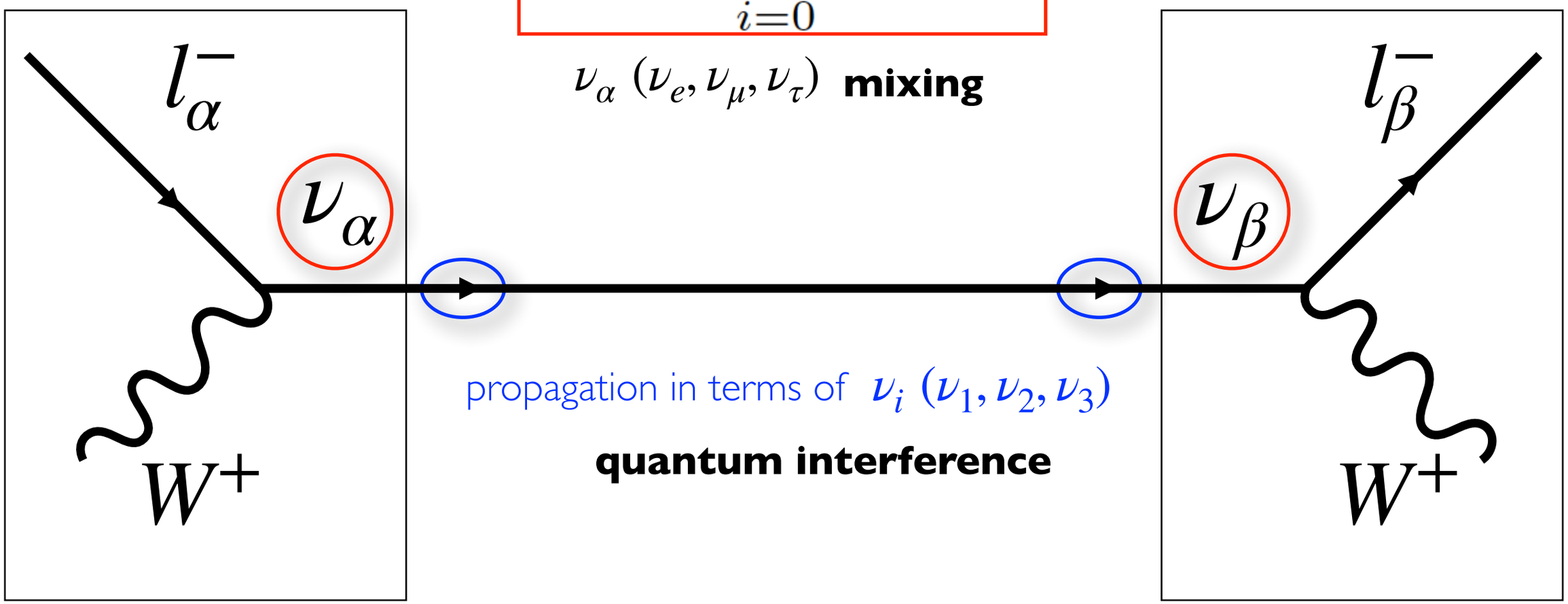
(its simplest manifestation)



diagrammatically…

$$|\nu_\alpha\rangle = \sum_{i=0} U_{\alpha,i}|\nu_i\rangle$$

ν_α $(\nu_e, \nu_\mu, \nu_\tau)$ **mixing**



propagation in terms of ν_i (ν_1, ν_2, ν_3)

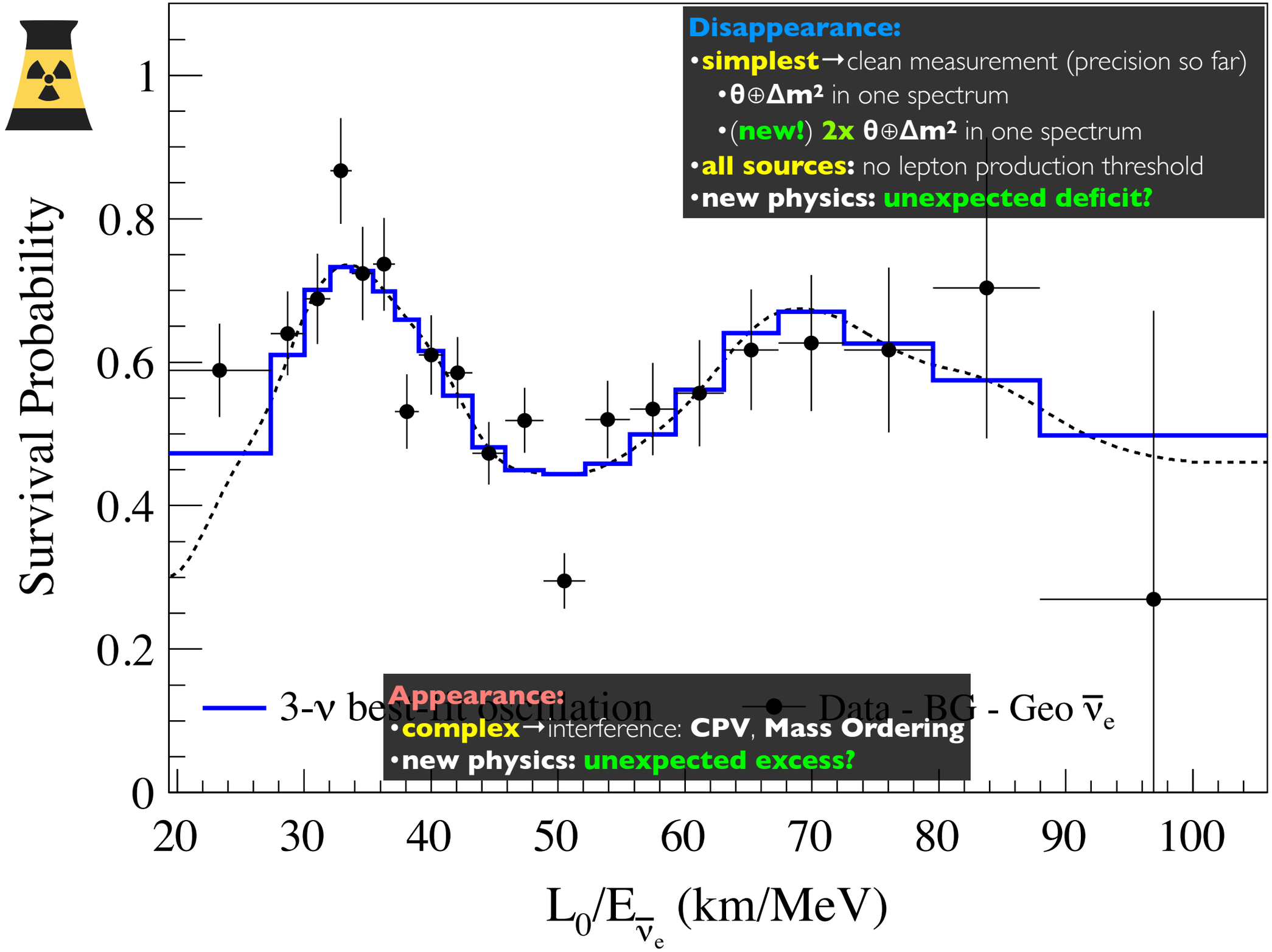
quantum interference

weak interaction
(production)

weak interaction
(detection)

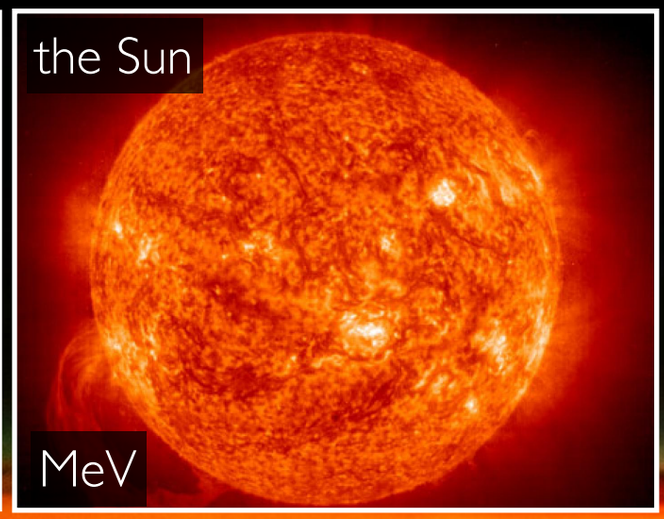
CC ($W^\pm$) sensitivity to **neutrino oscillations** while **NC (flavour blinded)** provide the **total flux**

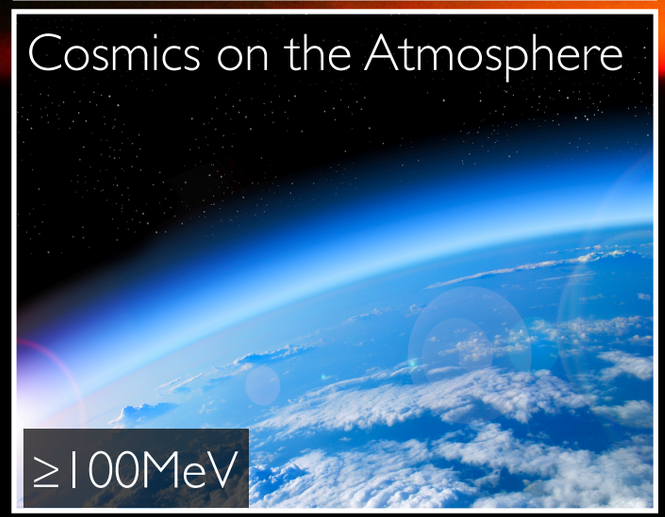
univocal neutrino oscillation signature…

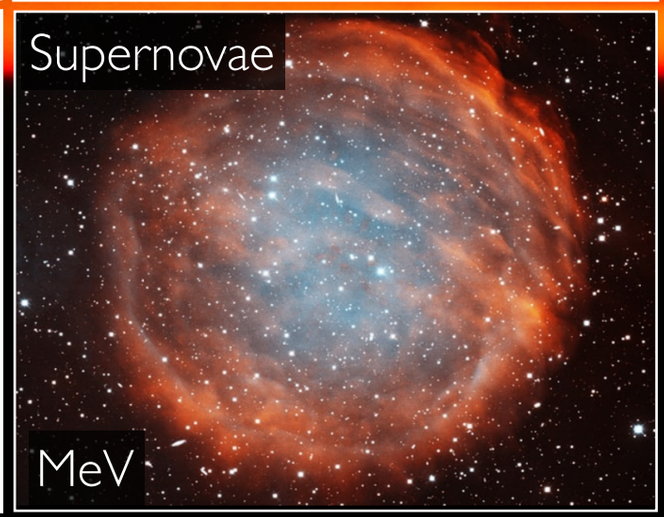


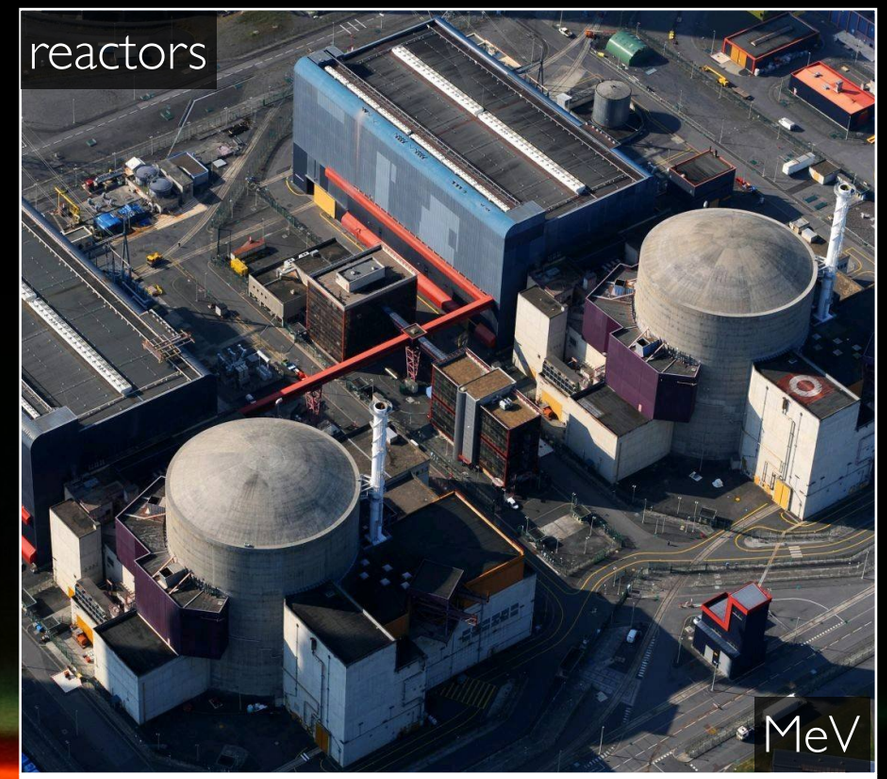
one of the most formidable spectral distorsion so far seen (KamLAND)

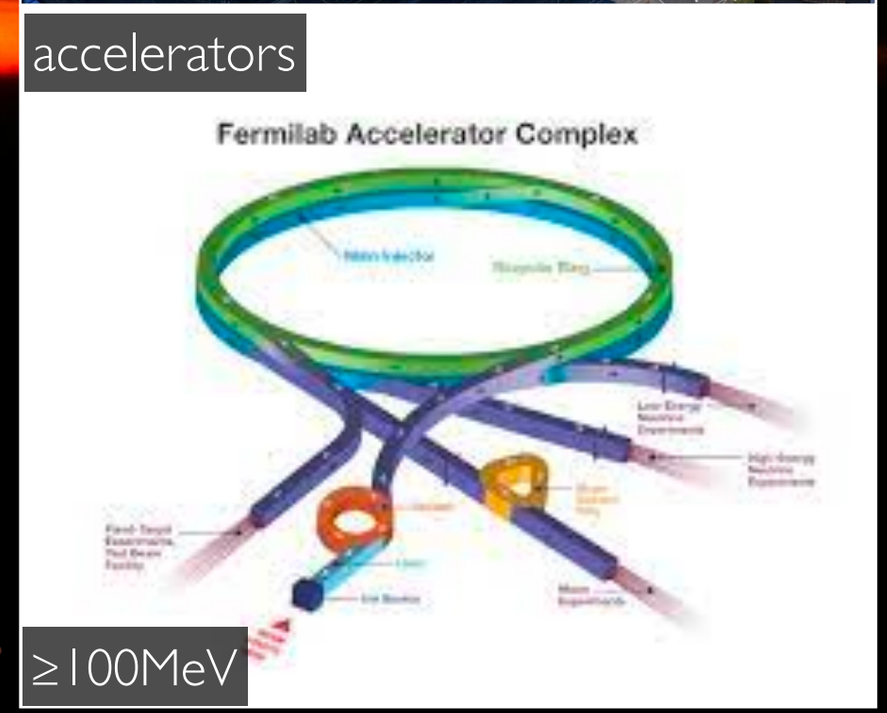
most used neutrino sources…











uncontrolled & poorer resolution L/E

controlled & high resolution L/E

status on neutrino oscillation knowledge…

Standard Model(3 families)
[leptons & quarks]
&
PMNS$_{3x3}$(θ_{12},θ_{23},θ_{13})
&
$\pm\Delta m^2$ ($\pm\Delta m^2_{23}$) & $+\delta m^2$ ($\pm\Delta m^2_{12}$)

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		global
θ_{12}	3.0 %	SK⊕SNO	2.3 %
θ_{23}	5.0 %	T2K⊕NOvA	2.0 %
θ_{13}	1.8 %	DYB⊕DC⊕RENO	**1.5 %**
$+\delta m^2$	2.5 %	KamLAND	2.3 %
$\lvert\Delta m^2\rvert$	3.0 %	T2K⊕NOvA DYB	1.3 %
Mass Ordering	**unknown**	SK et al	NO @ **~3σ**
CPV	**unknown**	T2K⊕NOvA	3/2π @ **≲2σ**

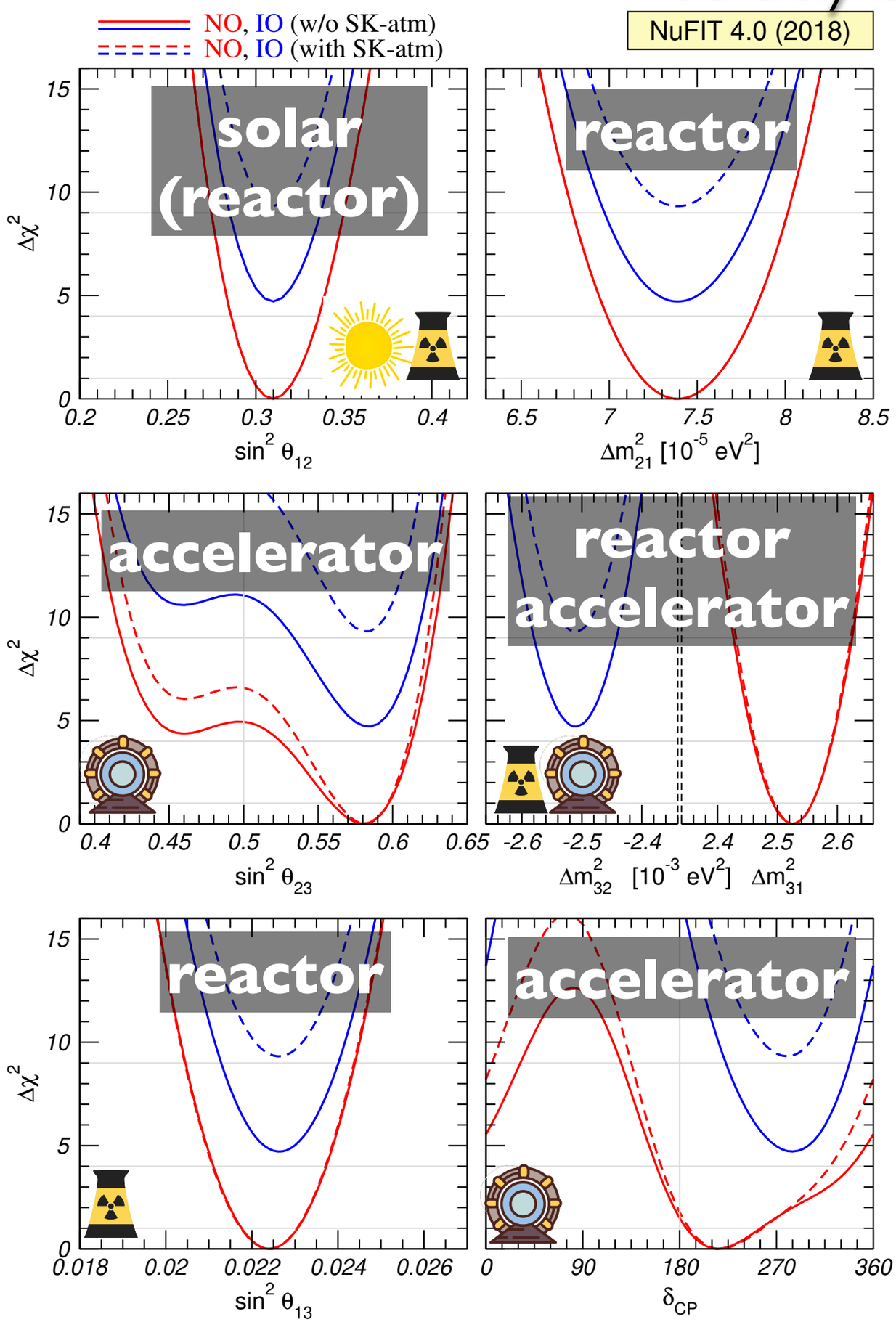
(**now**)

(reactor-beam)

JUNO⊕DUNE⊕HK will lead precision in the field→**Mass Ordering** & **CPV** **except θ_{13}!**

ORCA⊕PINGU⊕IceCube complementary for Mass Ordering & Δm^2 measurements

today's knowledge & prospects…



Normal/**Inverted** Mass Ordering

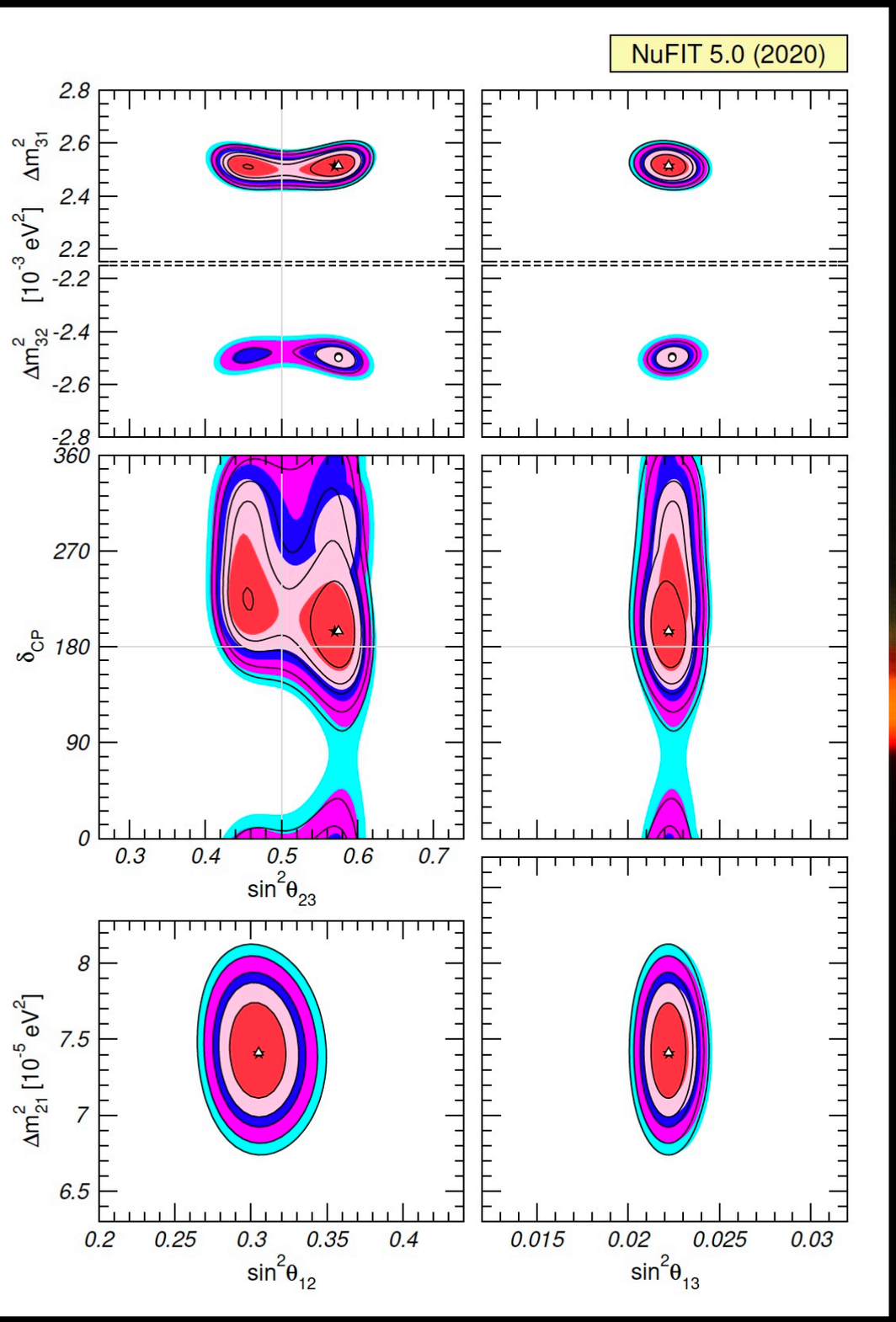
solar ≈ **SK⊕SNO⊕Borexino**
atmos ≈ **SK⊕IceCube** [**ORCA⊕PINGU**]
beam ≈ **T2K⊕NOvA** [**HyperK⊕DUNE**]
reactor ≈ **KamLAND⊕Reactor-θ13** [**JUNO**]

"solar" terms:
- **θ_{12}:** solar→JUNO
- **δm^2:** KamLAND→JUNO

"atmospheric" terms:
- **θ_{23}:** beam⊕atmos
- **Δm^2:** reactor⊕beam⊕atmos→JUNO
- **Mass Ordering:** all→JUNO⊕DUNE

θ13 terms (key for CPV & Mass Ordering)**:**
- **θ_{13}: Reactor-θ_{13}** (**DC⊕DYB⊕RENO**)

CPV(δ) term: beam

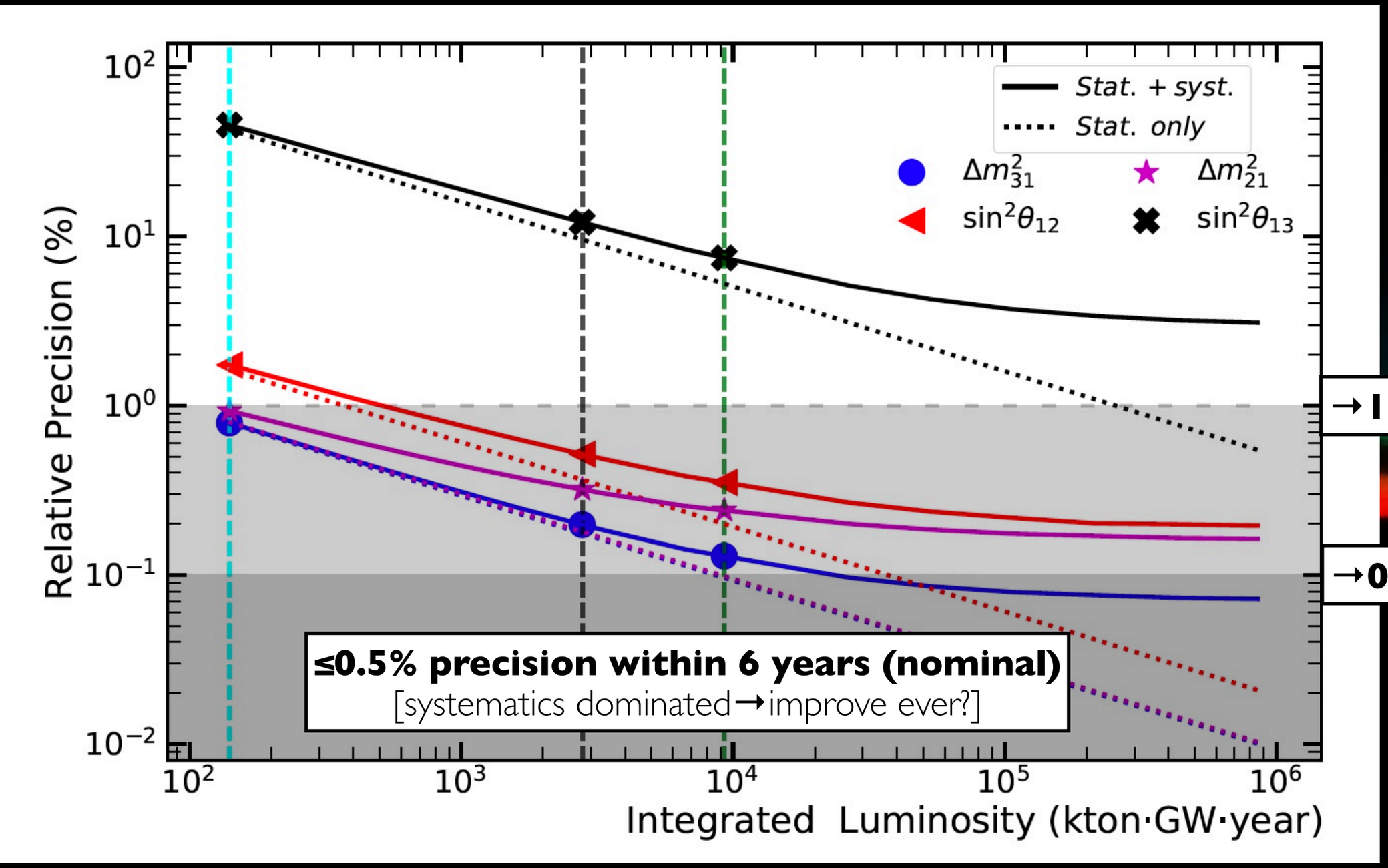


NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

JUNO precision (few months)…



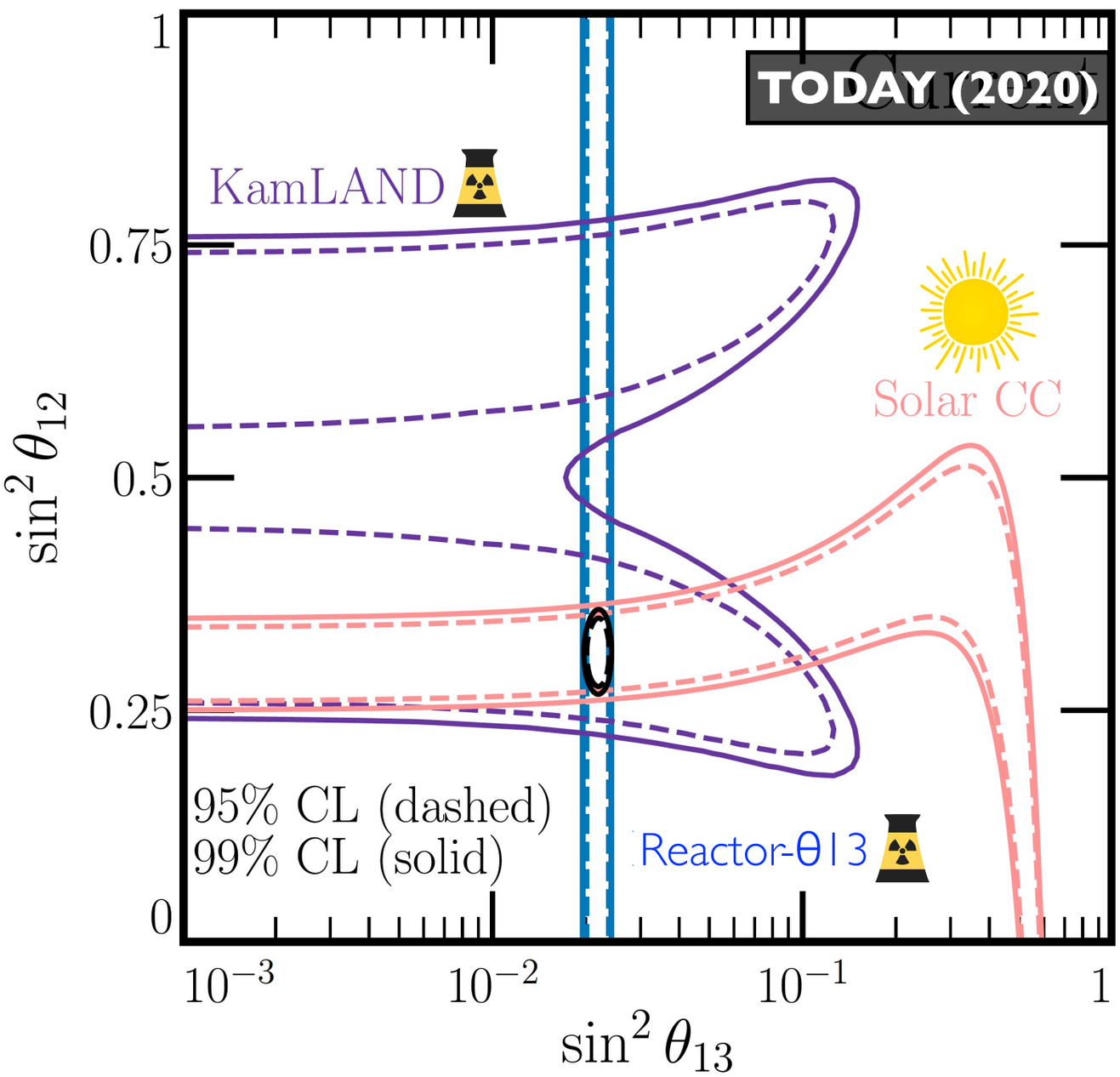
	Mass Ordering	$\lvert\Delta m^2_{32}\rvert$	$\lvert\Delta m^2_{21}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
6 years of data	3-4σ	$\sim 0.18\%$	$\sim 0.30\%$	$\sim 0.5\%$	$\sim 14\%$
20 years of data	5σ	$\sim 0.15\%$	$\sim 0.25\%$	$\sim 0.4\%$	$\sim 7\%$

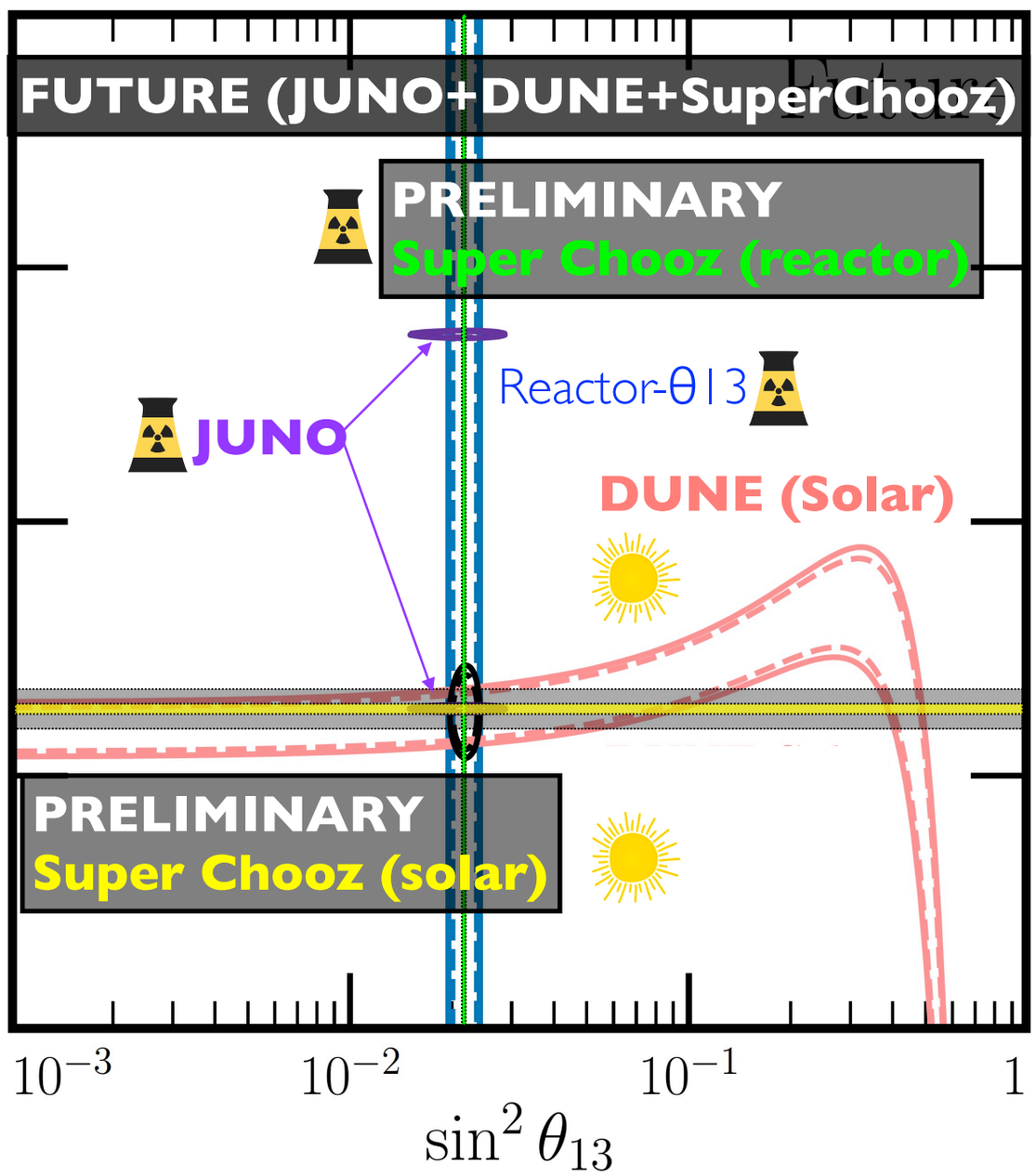
→ reactor-θ13 (input)

complementarity & synergies for ultimate precision…

Plot: hacked version from original in ***Ellis, Kelly & Weishi-Li at* arXiv:2008.01088**

Reactor-θ13: Daya Bay⊕Double Chooz⊕RENO

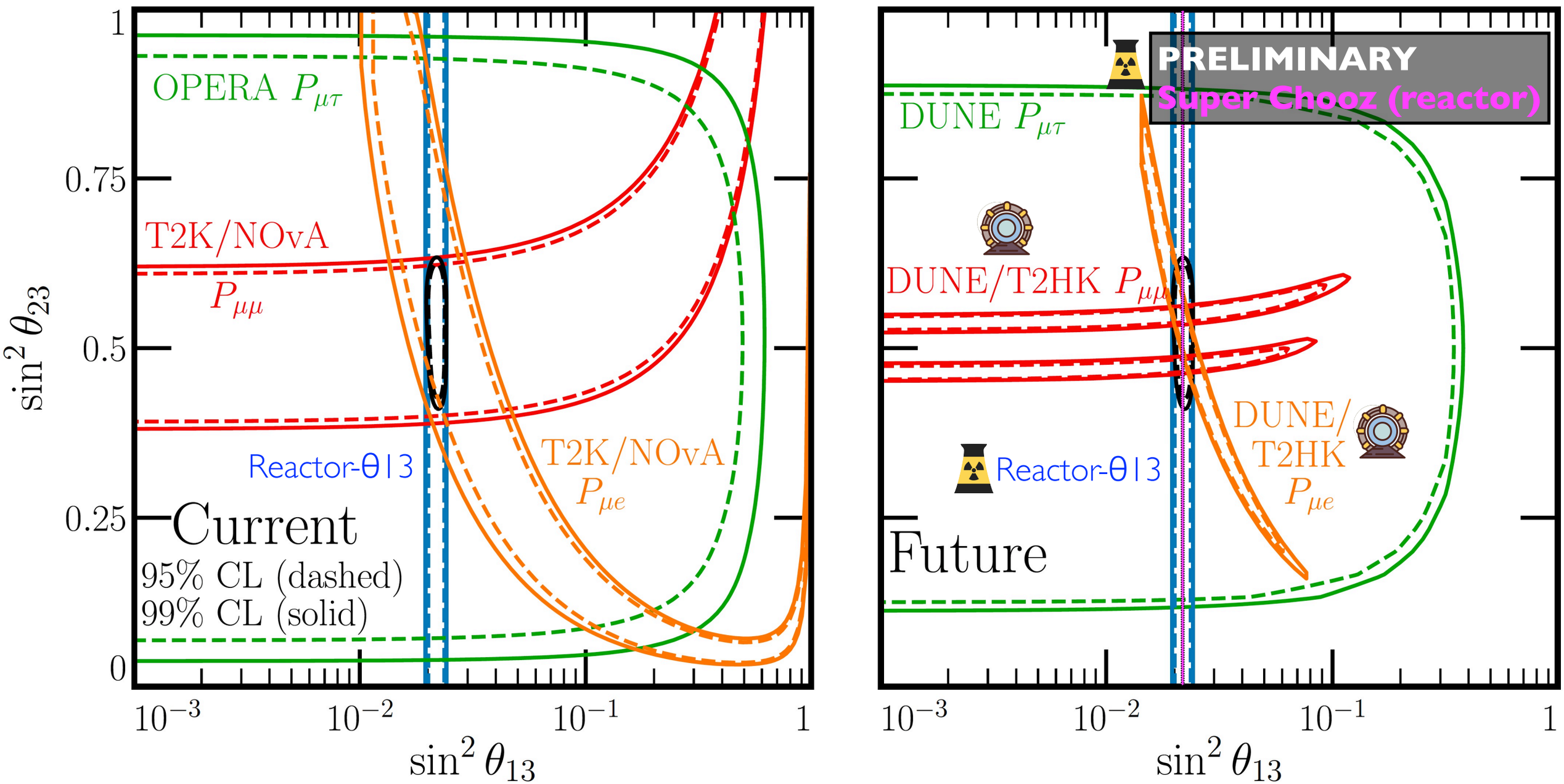




by 2030, θ12-θ13 plane fully dominated by <u>reactor experiments</u> — cross-check JUNO!

complementarity & synergies for ultimate precision…

Plot: hacked version from original in ***Ellis, Kelly & Weishi-Li at* arXiv:2008.01088**



by 2030, θ23 octant extremely hard (depending on θ23)→ improving θ13?

what we do **not know**…

***SM*v1.1**: knowns & unknowns…

Weak Flavour Neutrinos (**3**): **ν(e)**, **ν(μ)**, **ν(τ)** — observed **3!** (same as quarks)

Mass Neutrinos (**3**): **ν(1)**, **ν(2)**, **ν(3)** — assumed **≥3!** [tight cosmology constraints]

PMNS matrix (3x3; *a la CKM*): ***U***, *assumed* ***unitarity*** (→***violation?***) — discovery!

- mixing parameters (**3**): θ_{13}, θ_{12}, θ_{23} (octant?) — derived ***J*** [Jarlskog invariant]
- CP-violation parameter (**1**): **δ?** — unknown [*SM*]

JUNO
HyperK
DUNE
SuperChooz?

Mass Squared Differences (**2**): δm^2 (i.e. Δm^2_{12})
Δm^2 (i.e. Δm^2_{13} or Δm^2_{23})

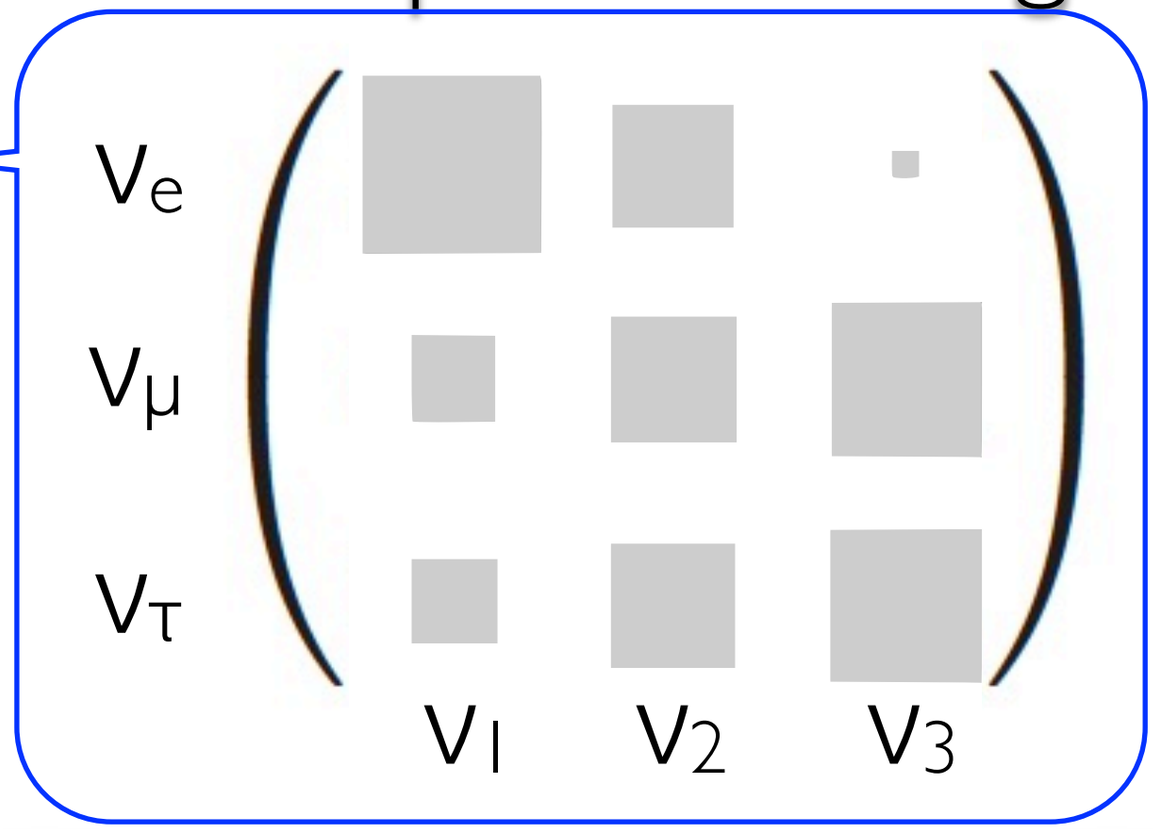
Mass Ordering (*MO*):
+δm^2 (solar data — observed!)
±?Δm^2 → which is the lightest neutrino ν(1) or ν(3)? — unknown [*SM*]

Mass Hierarchy (*MH*): **the mass of the neutrino?** — discovery!
[→why so much smaller than charged leptons?]

Neutrino Nature: **Majorana?** — discovery!

SM's leptonic mixing sector (PMNS)…

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



consider full matrix structure

(not just composition)

why shape?

- **large mixing** but a **small one**!
- **largest CP-violation** (SM)
- **any symmetry behind? [or Nature's caprice?]**

U_{3x3} unitary?

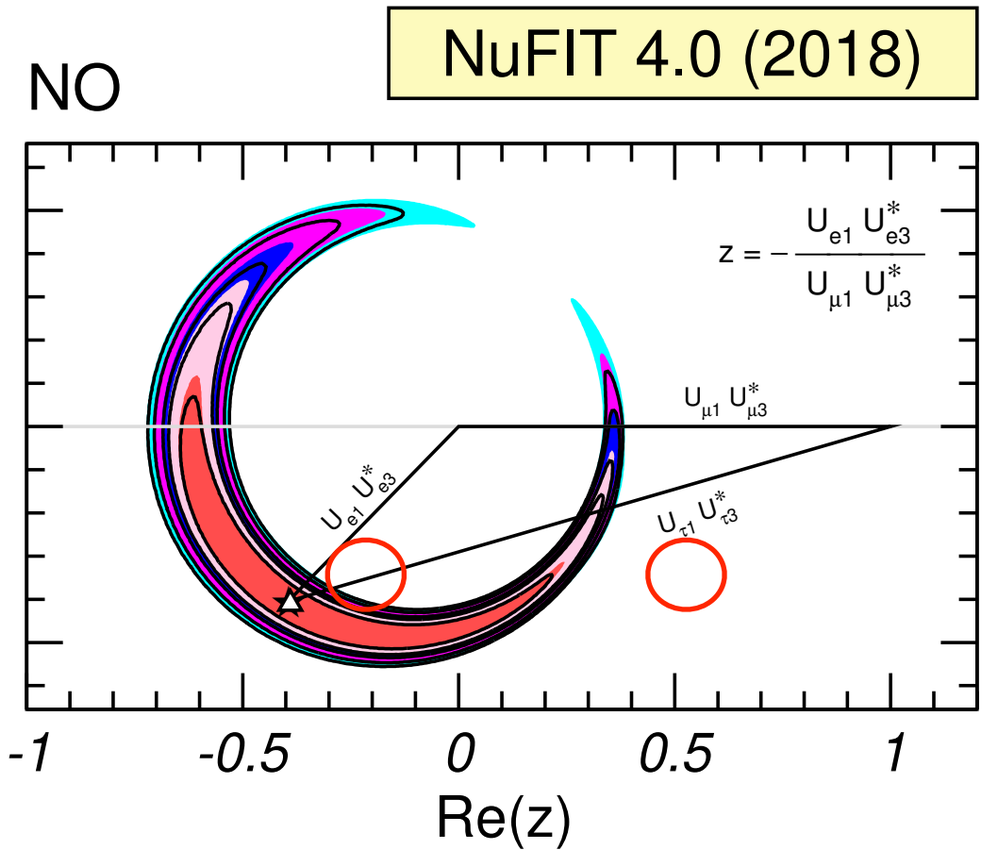
[assumed!!, not demonstrated]

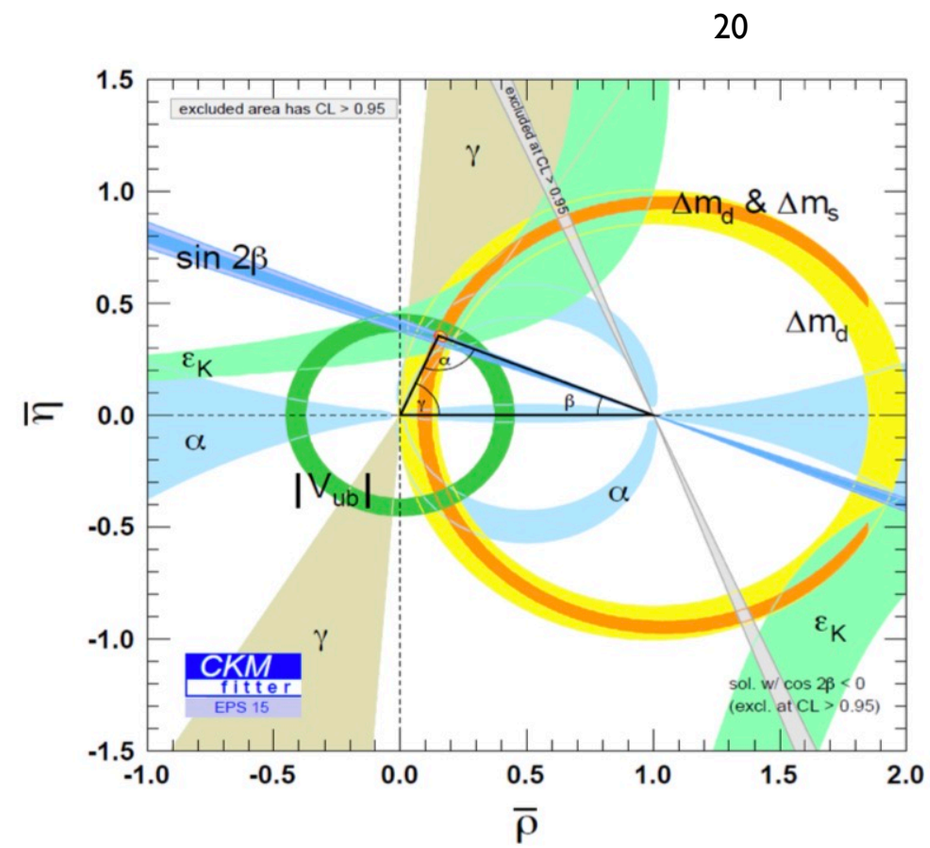
(BSM) any relation to CKM?

CP-violation (unknown)…

PMNS

CKM





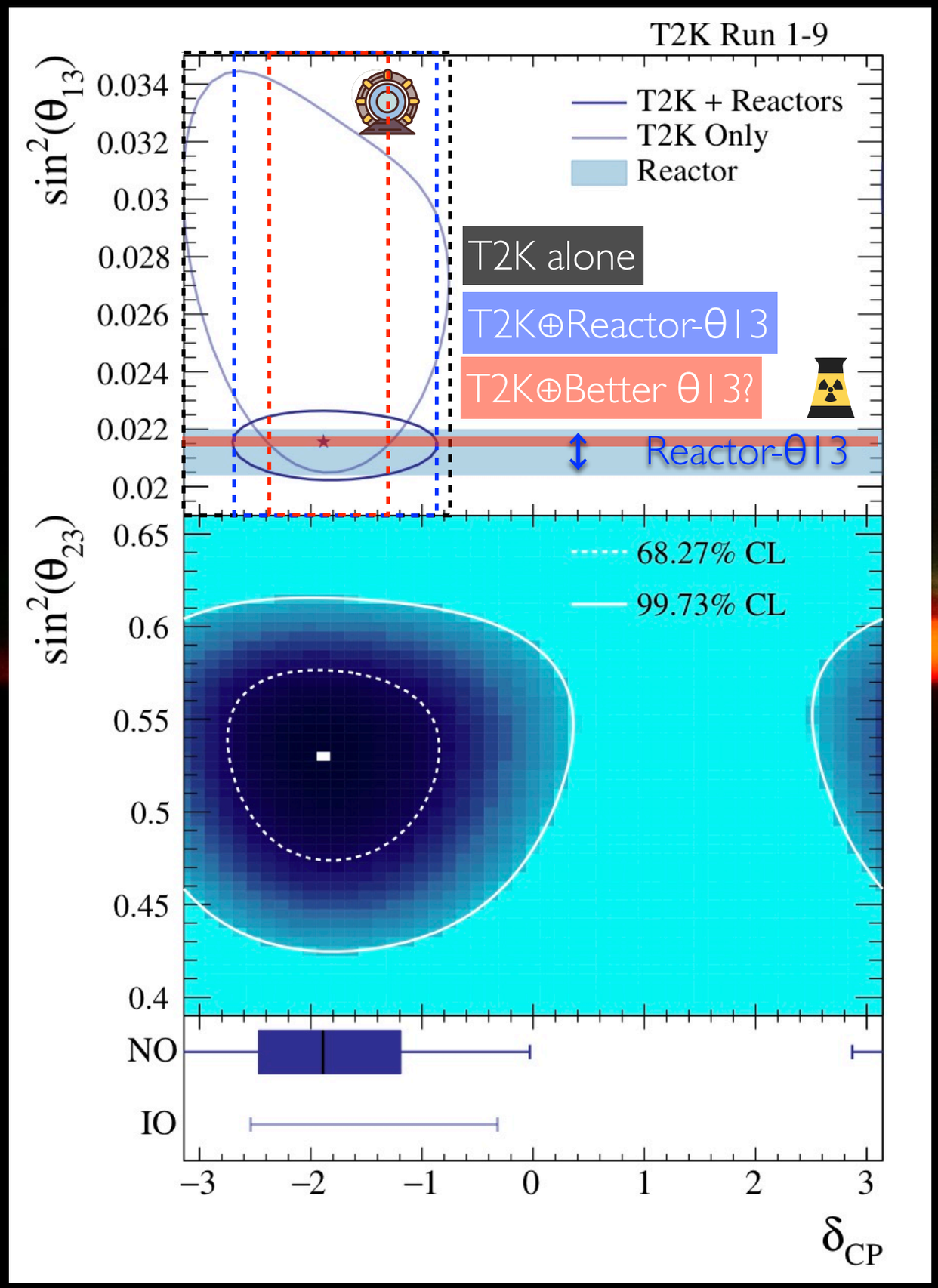
J(PMNS)≈3.33±0.06x10^{-2}

J(CKM)≈3.18±0.15x10^{-5}

CKM & PMNS triangles (CPV)

much larger CPV potential in PMNS — good news! we need CPV in the Universe to exist!

beam⊕reactor for CP-Violation…

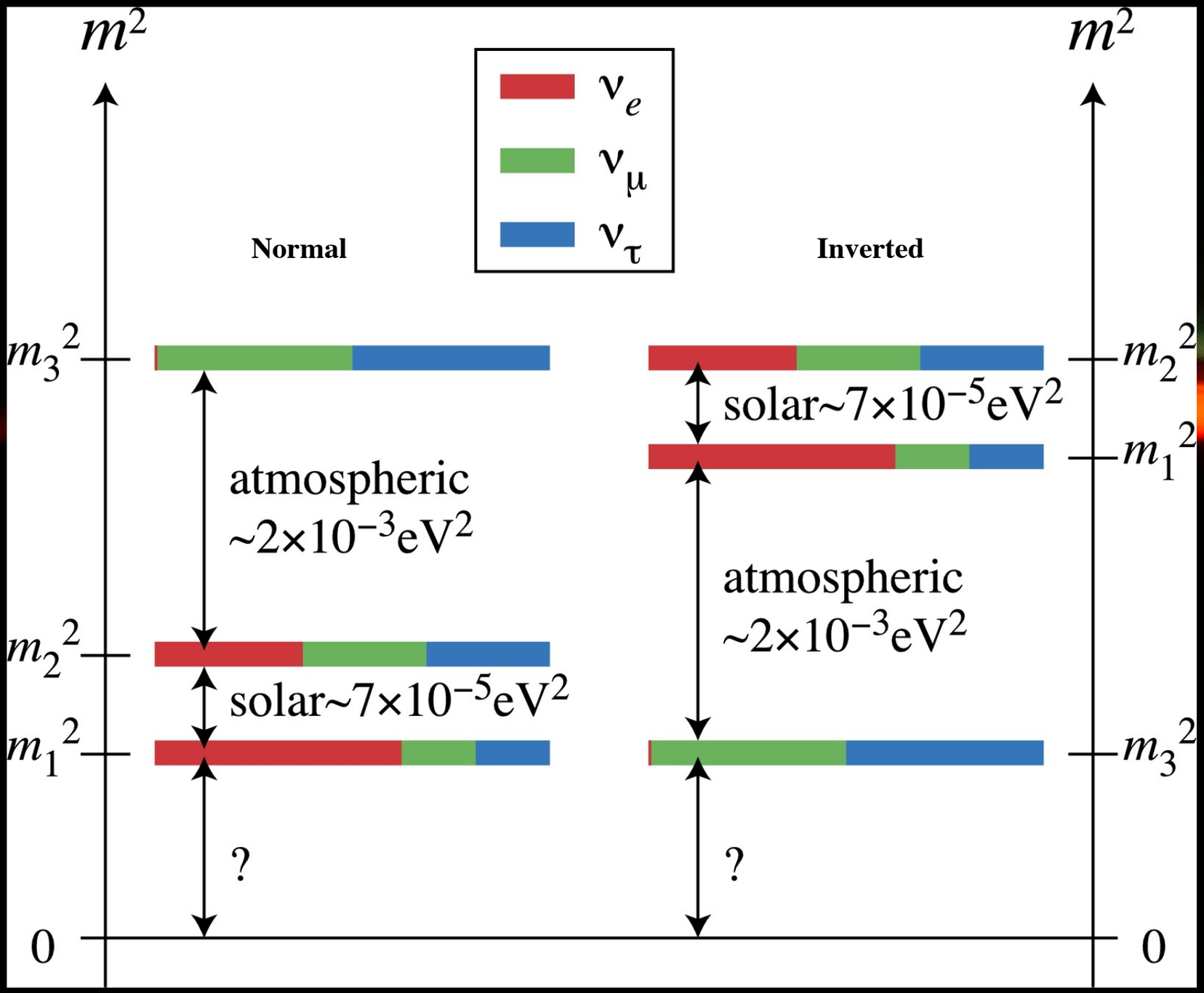


CPV phase vs θ13
[constrained by reactor]

CPV phase vs θ23
[octant ambiguity]

CPV phase vs (Atmospheric) Mass Ordering
[T2K blinded]

Mass Ordering (unknown)…



Mass Ordering means…

- **the <u>lightest</u> ν: $\nu_1(m_1)$ vs $\nu_3(m_3)$?**
- **important consequences to…**
  - the <u>lightest known particle</u> 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]

nature
SCIENTIFIC REPORTS

Synergies and prospects for early resolution of the neutrino mass ordering

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

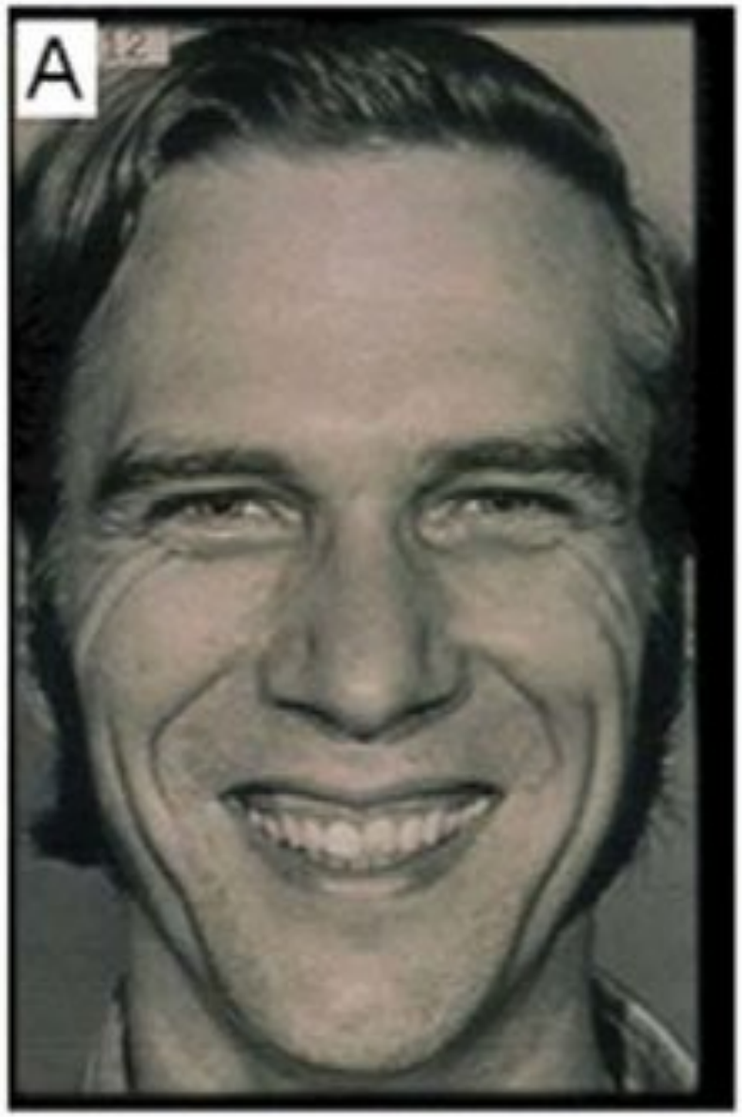
Scientific Reports **12**, Article number: 5393 (2022) | Cite this article

Today's global analysis: NMO@~3σ

- **T2K Appearance (≤2024) — no! [≤1σ]**
- **NOvA Appearance (≤2026) — unlikely! [≤4σ]**
- **JUNO (≥2024 + 6 years) — no! [≤3σ]**

⟹ T2K + NOvA + JUNO (≤6year) = unlikely! (just adding)

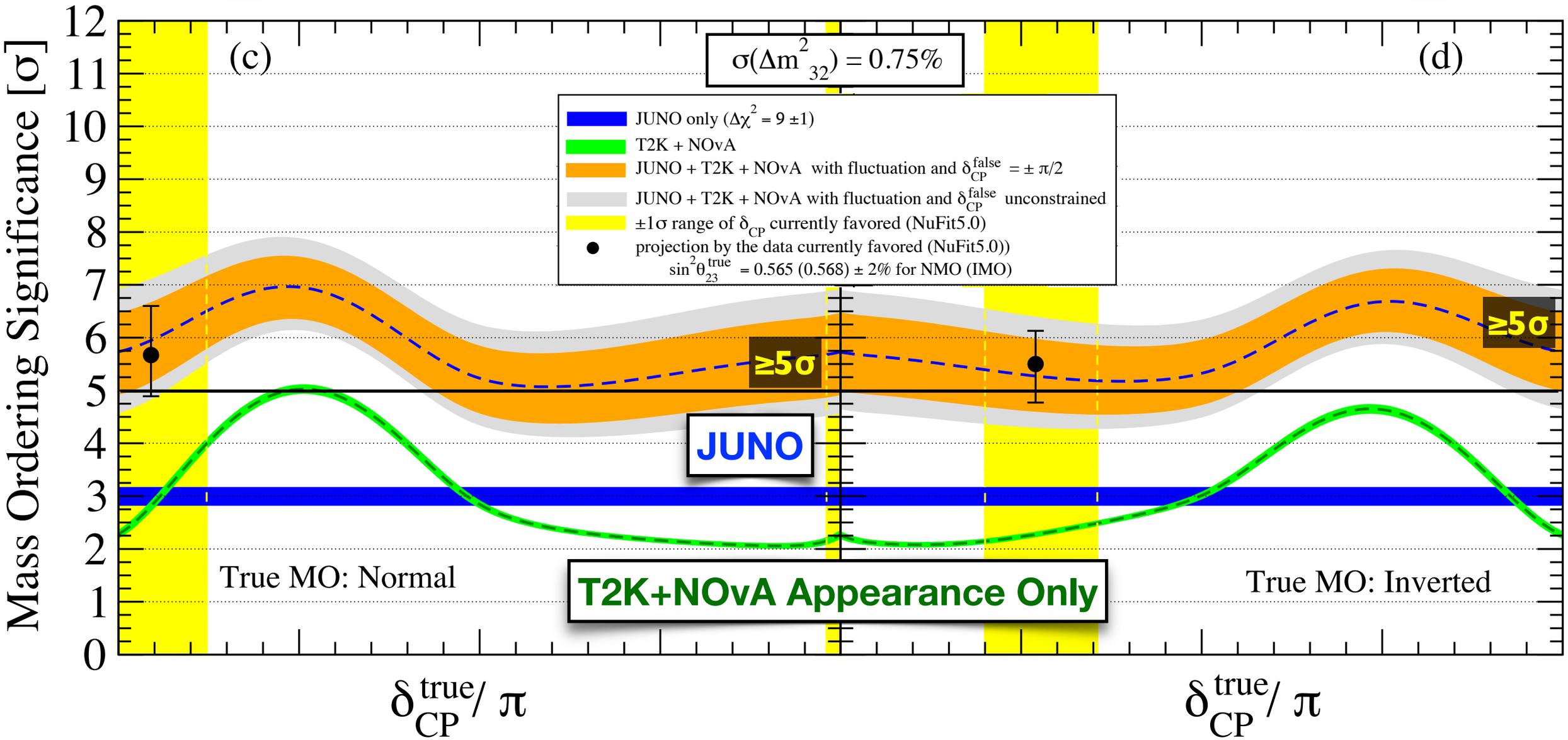
⟹ T2K ⊕ NOvA ⊕ JUNO (≤6year) = yes! (synergies: appearance⊕disappearance)



~5σ before 2030?

arXiv:2008.11280

JUNO⊕LBνB-Disappearance [δ(Δm²)=0.75%] ⊕ LBνB-Appearance



the power of synergies…

conclusions so far…

- **stunning evolution of the field** (worldwide & international)…
  ⟹ **several discoveries** (Nobel prizes) ⟹ modify the ***Standard Model***

- **historical effort construction & underground excavations** — ongoing
  LHC-like investments — even FNAL "goes neutrino"!!
  ⟹ **neutrino oscillations** controlled to ≲ **1%** by early 2030 — all parameters known!

- **standard oscillations** to become a **background** → **what's the new signal?**

more discoveries?

[redundancy ⊕ highest precision ⊕ test fundamental symmetries]

new **flagship** ν experiments…

enough?
(permille precision)

2 accelerator experiments **HyperK** & **DUNE** → **redundancy**
&
1 reactor experiment **JUNO** → **no cross-check!**

SUPERCHOOZ

exploring the opportunity…

neutrinos oscillation : standard picture (SM)

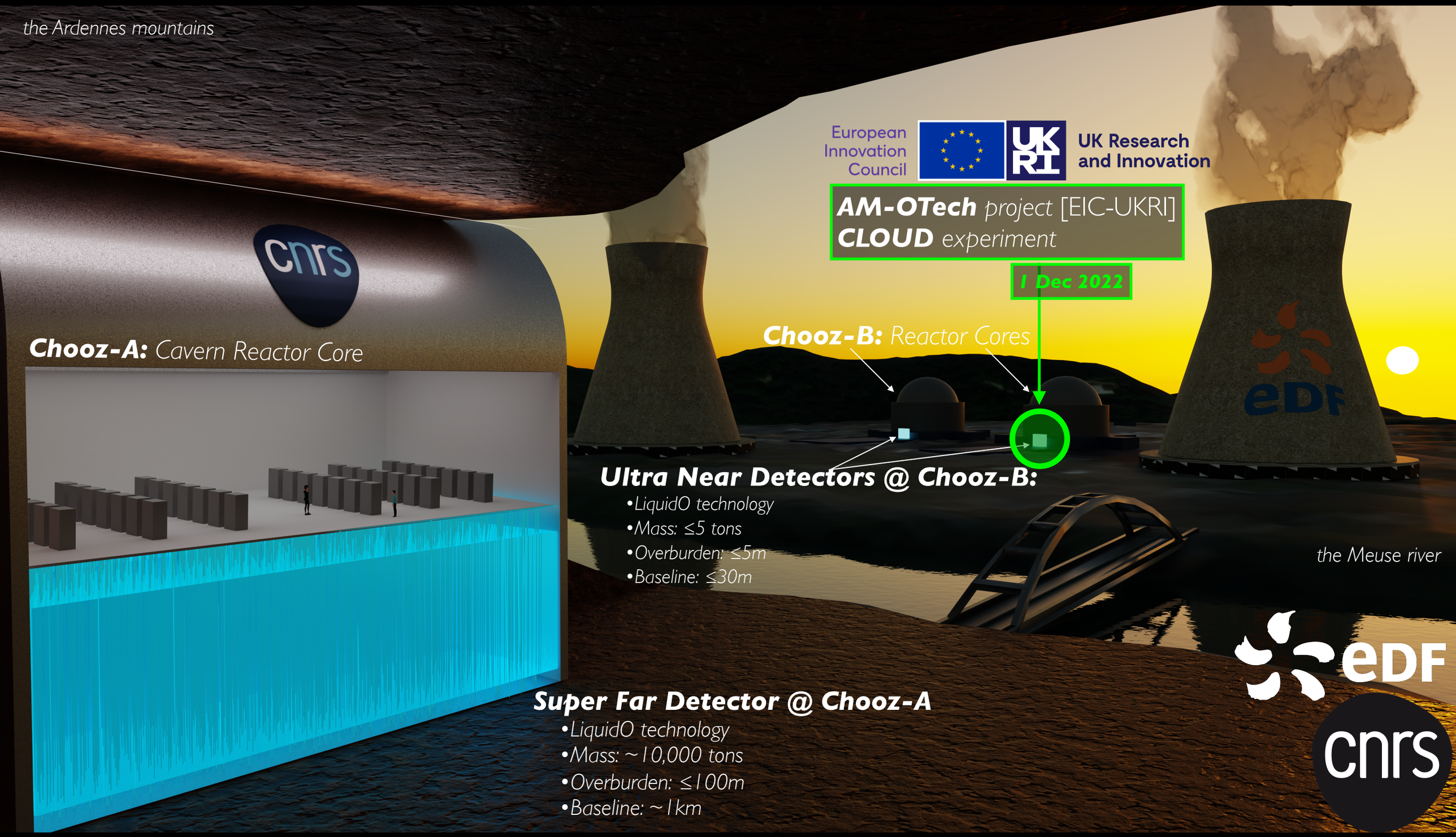
synergies with Hyperk-JUNO-DUNE!

neutrinos to probe BSM $\longrightarrow$ discoveries?

beyond today's paradigm!

SuperChooz rationale…

SuperChooz experimental setup…



HEP-European Physics Society (July 2019 @ Ghent Belgium)

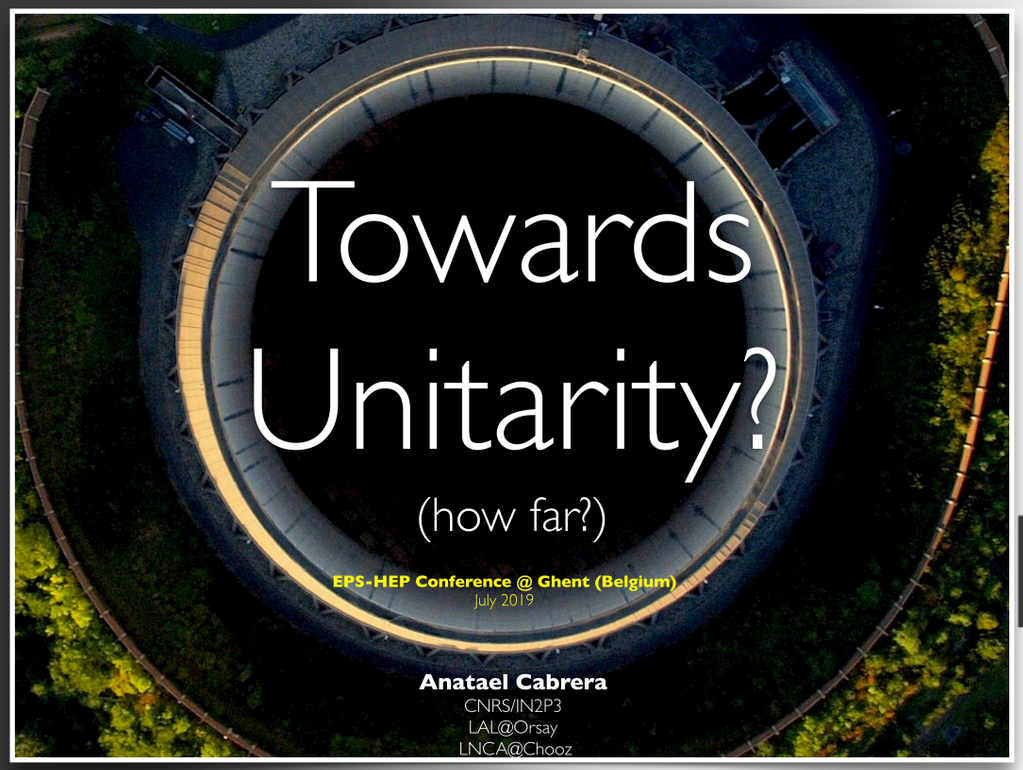
EP Seminar

The SuperChooz Experiment: Unveiling the Opportunity

by Dr Anatael CABRERA (IJCLab - IN2P3/CNRS)

Tuesday 29 Nov 2022, 11:00 → 12:00 Europe/Zurich

222/R-001 (CERN)



https://indico.cern.ch/event/1215214/

https://indico.cern.ch/event/577856/contributions/3421609/

https://zenodo.org/record/7504162

https://liquido.ijclab.in2p3.fr/

exploring since 2018…

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

questions…?

anatael@in2p3.fr

status on neutrino oscillation knowledge…

SuperChooz is designed cover the full ***SM picture*** (3 families) [synergy]

SuperChooz explore the ***SM***'s consistency/completeness → **BSM discovery?**

SuperChooz = SC

	today			**≥2030**		
	best knowledge		global	foreseen	dominant	source
θ_{12}	3.0 %	SK⊕SNO	2.3 %	≤0.5%	JUNO⊕**SC**	reactor⊕solar
θ_{23}	5.0 %	NOvA+T2K	2.0 %	≲1.0%?	DUNE⊕HK [**SC**]	beam (octant)
θ_{13}	1.8 %	DYB+DC+RENO	1.5 %	**≤0.5%**	**SC**	reactor
$+\delta m^2$	2.5 %	KamLAND	2.3 %	<0.5%	JUNO⊕**SC**	reactor⊕solar
$\lvert\Delta m^2\rvert$	3.0 %	T2K+NOvA & DYB	1.3 %	<0.5%	JUNO⊕DUNE⊕HK⊕**SC**	reactor⊕beam
Mass Ordering	**unknown**	SK et al	NMO @ ≤3σ	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CP	**violation?**	T2K+NOvA	3/2π @ ≤2σ	**@5σ?**	DUNE⊕HK [**SC**]	beam driven
CPT	**violation?**	—	—	**<1%?**	**SC**	reactor⊕solar
Unitarity	**violation?**	—	—	**<1%?**	**SC**	reactor⊕solar
Baryon#	**violation?**	—	—		JUNO⊕DUNE⊕HK⊕**SC**	

reactor⊕solar main channels of **SC**, but low energy **atmospherics** **under study…**

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?**

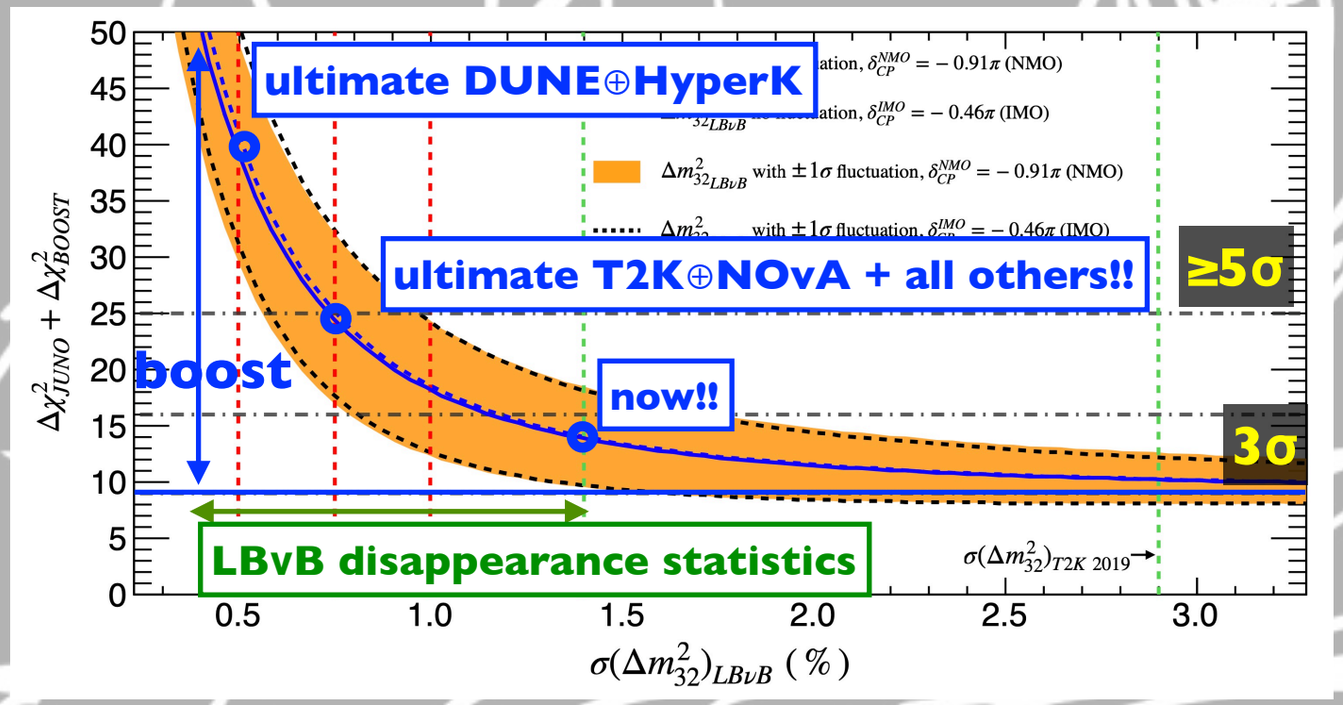
what are the leading experiments?

what's going to happen next?

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

today's NMO status…

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

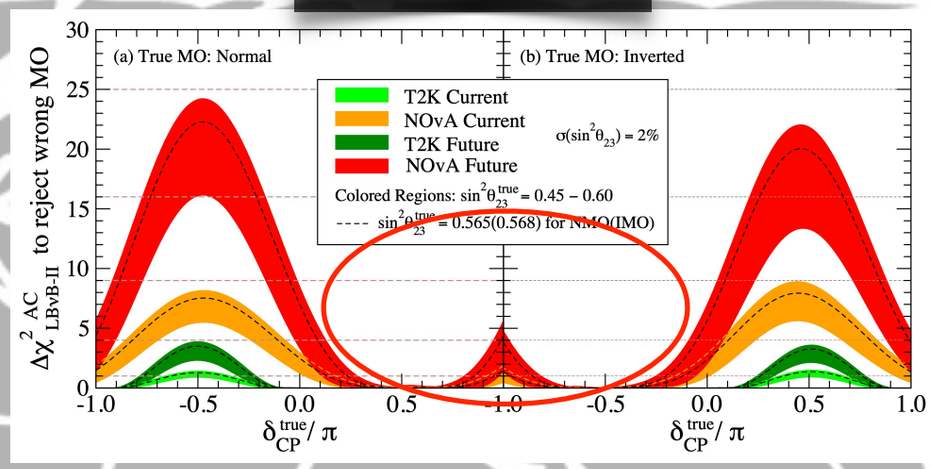


JUNO: unique vacuum oscillations (≥5σ!!!)

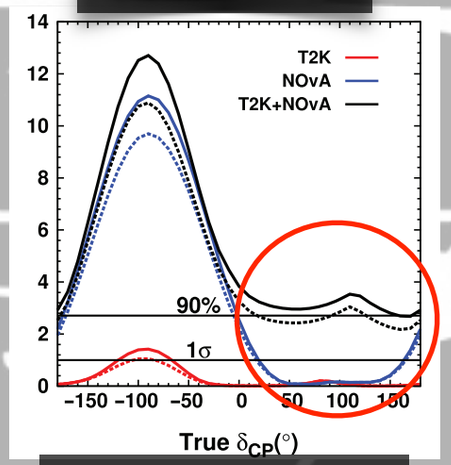
Δm^2 boosting is **blinded to matter-effect**

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

NOvA and T2K



NOvA⊕T2K



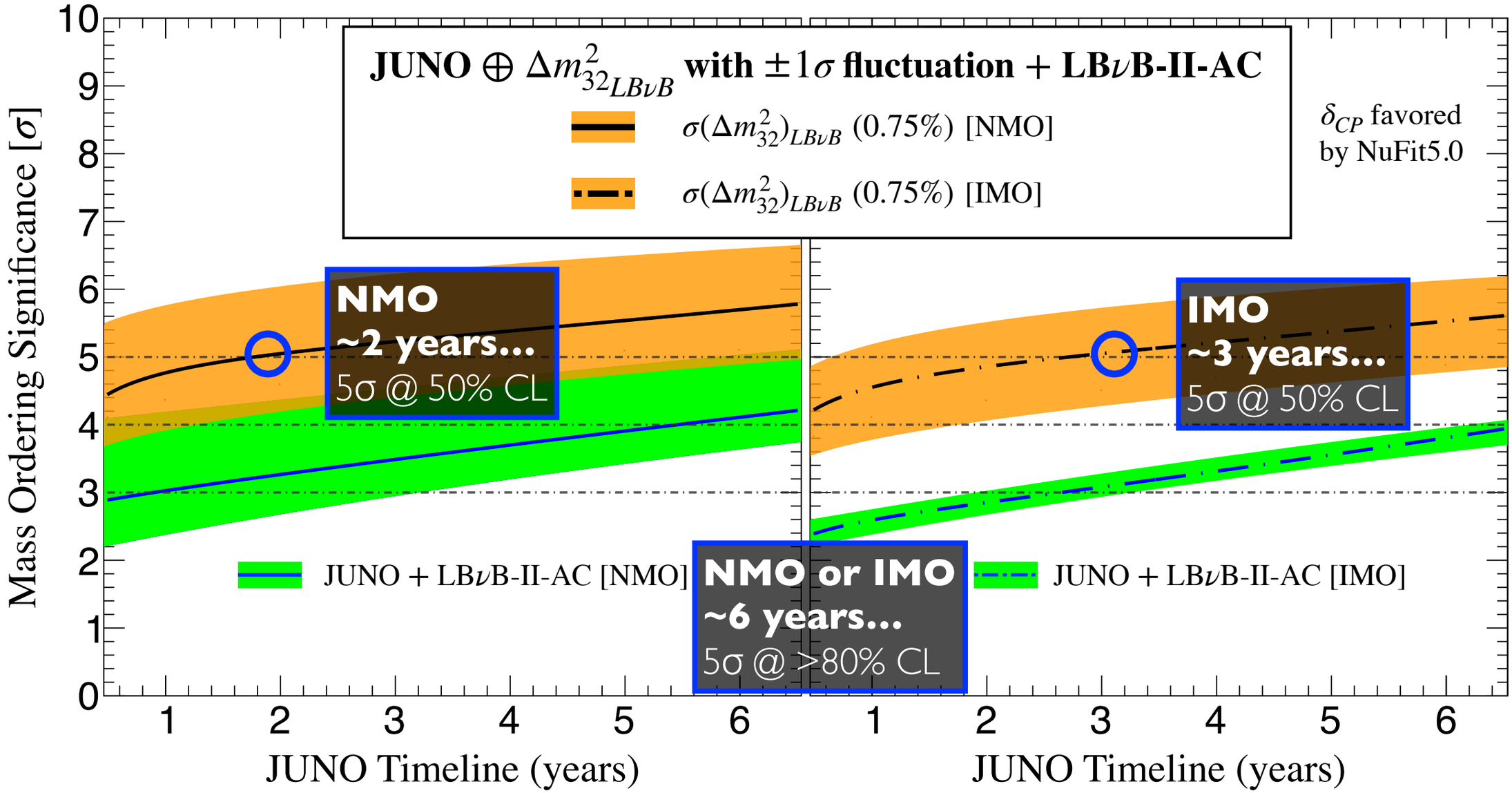
T2K @ PTEP (2015)

NOvA: strong matter effects

T2K: clean PMNS-CPV info

arXiv:2008.11280

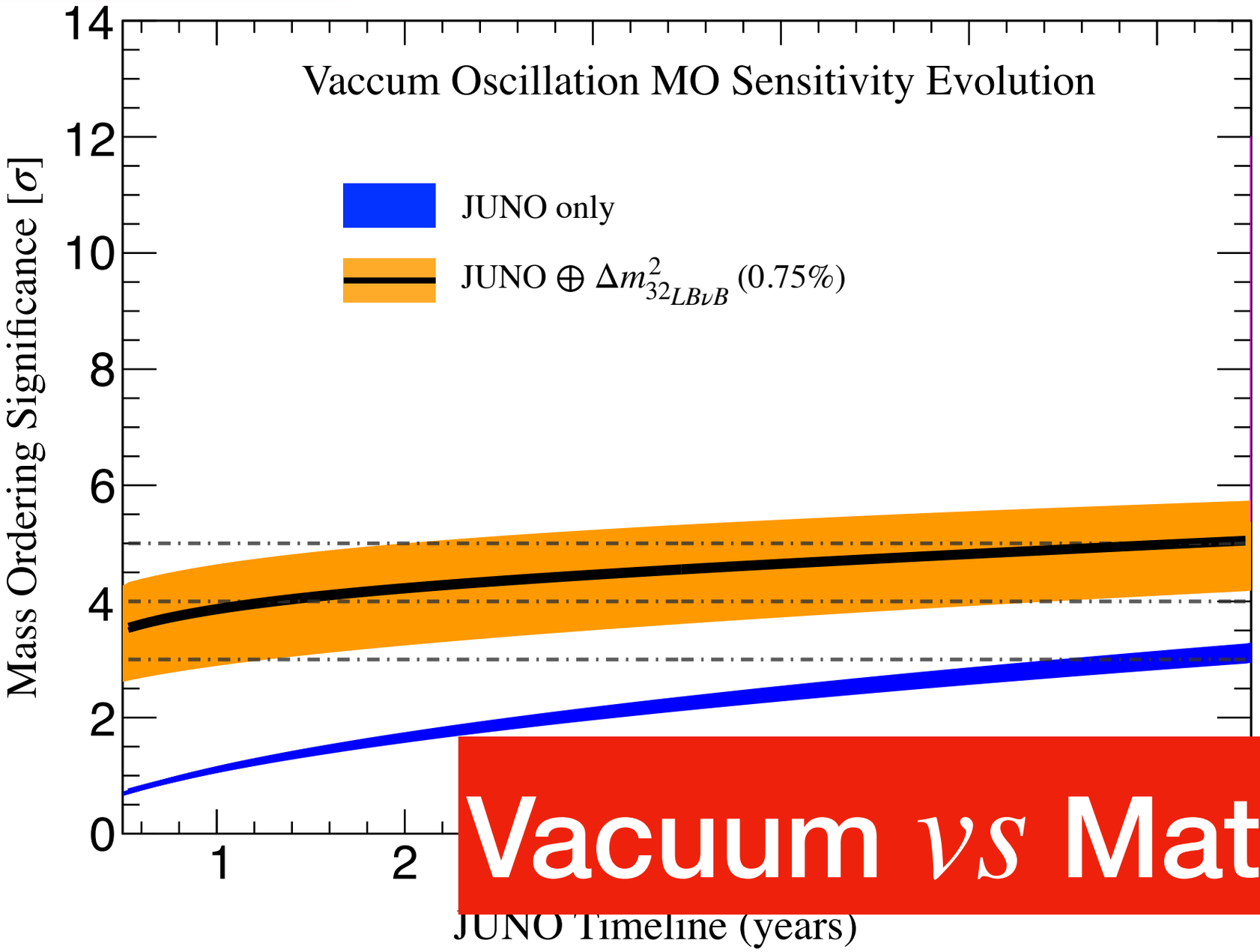
Mass Ordering: JUNO⊕NOvA⊕ T2K…



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?**

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)

⟹ 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