Neutrinos I

present and outlook...

IMFP-2021 @ Benasque (Spain)
7th September 2021

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disclaimer…

This description aims to provide a basic status of neutrino fundamental research. I will aim for **“neutrino in nutshell description”**; i.e. *all minimal information one needs to appreciate our field*. Due to time limitations, I am **forced to make some choices** (i.e. some sacrifices too). Here is the criteria…

- focus on the **experimental viewpoint**, with phenomenological considerations, but **minimal description of each experiment** (please ask later)

- **description biassed towards impact** (i.e. precision or discovery potential, etc), as opposed to follow historical (minimal) account(s) — much already in the literature

- **content tuned to overall programme** (avoid redundancies) relative to other talks (i.e. *my guess*), namely…
  Flavour Physics (J. Martin Camalich),
  Multi-messenger & Astro-Particle Physics (G. Sigl),
  Cosmology (E. Sanchez),
  Future Large Facilities Underground (C. Peña Garay), etc.

Apologies in advance, if I missed, or covered too superficially, your work; i.e. your experiment(s) and/or publication(s). You are nonetheless strongly invited to make comments at the end…

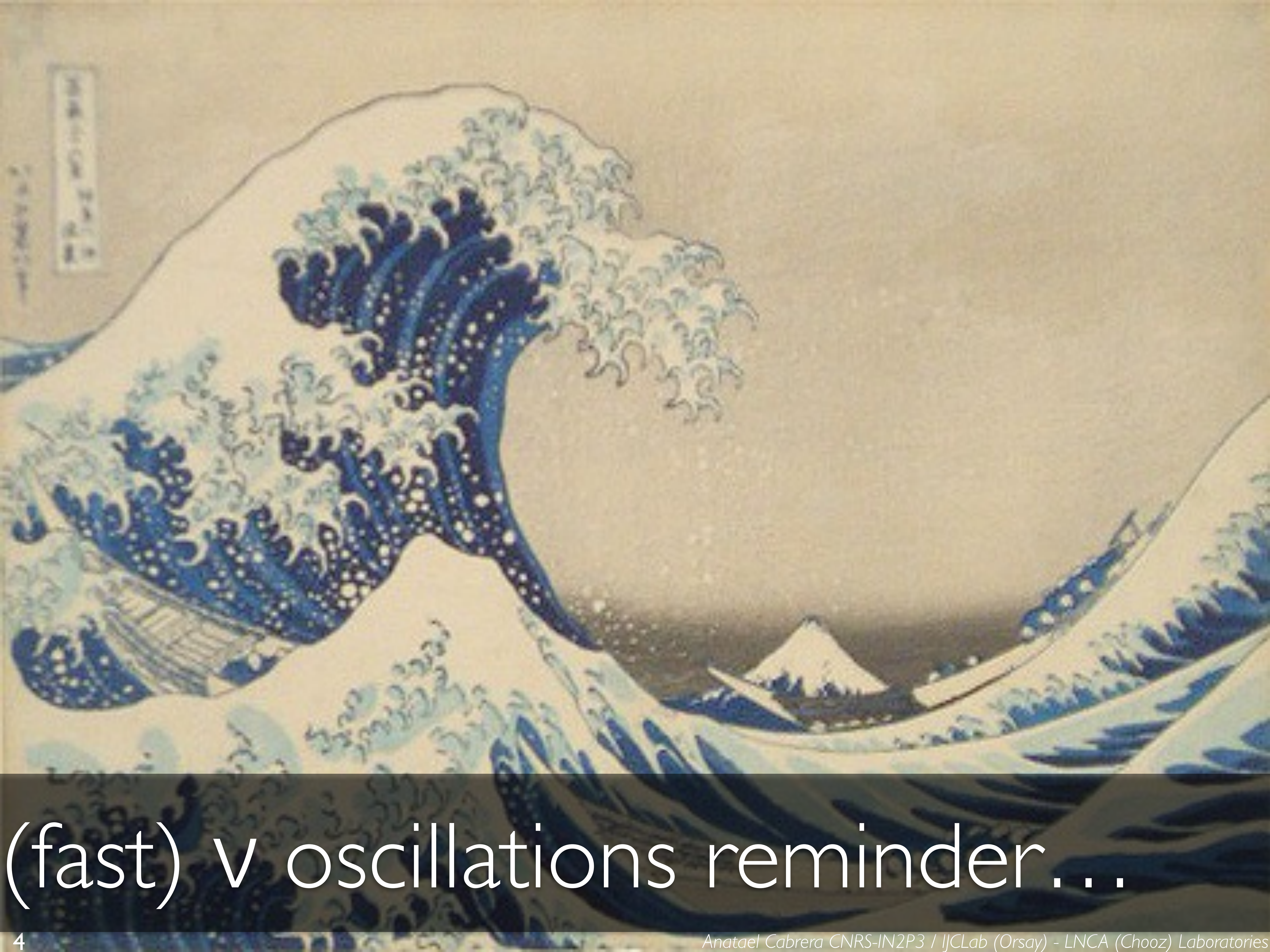
who I am?

work(ed/ing) on…

- **Double Chooz** experiment (dismantling now)
- **LiquidO** technology (R&D) & science prospect
- **JUNO** experiment — mainly ***Dual Calorimetry*** system
- **SuperChooz** explorations (new!)

and

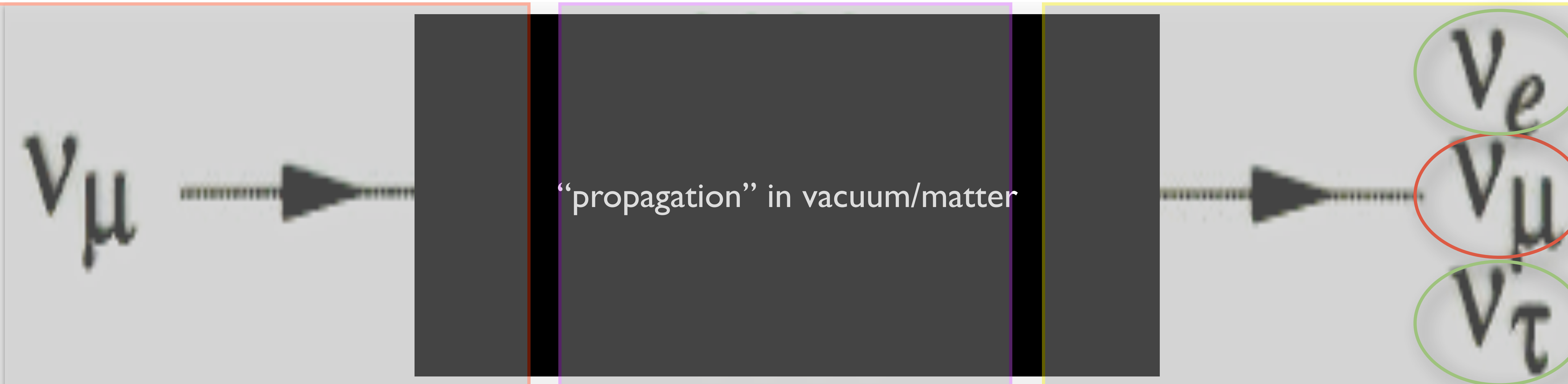
- **LNCA Underground Laboratory** (Chooz)



(fast) ν oscillations reminder…

neutrino oscillations: in a nutshell

disappearance experiment
appearance experiment



$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad (\alpha = e,\, \mu,\, \tau)$$

$$|\nu_\alpha(t>0)\rangle = \sum_i e^{-iE_it}U^*_{\alpha i}|\nu_i\rangle$$

$$\mathrm{P}(\nu_\alpha \to \nu_\beta) = |\langle\nu_\beta|\nu_\alpha(t)\rangle|^2 = \left|\sum_i U_{\beta i}e^{-iE_it}U^*_{\alpha i}\right|^2$$

production of ν_α
[mixing: from weak-space to mass-space]

propagation ν_i's
[Dirac/Schrödinger Eq.]

detection ν_α*
[mixing: back from mass-space to mass-space]

ingredients for neutrino oscillations…

Non-degenerate mass spectrum (**Δm^2**) ⊕ Mixing in the leptonic sector (**θ**) = Oscillation Probability **$P=f(\theta,\Delta m^2)$**

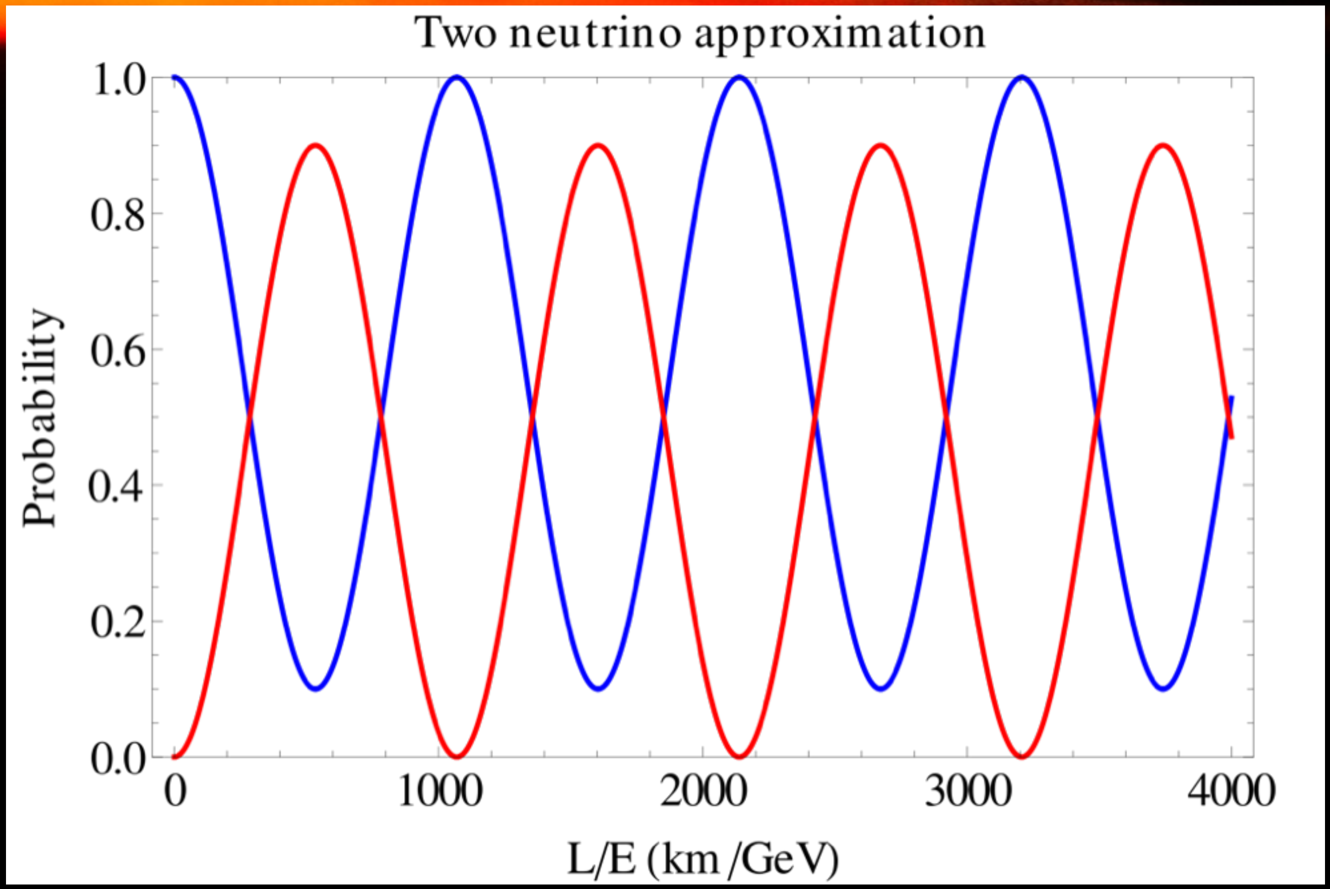
quantum interference (macroscopic)

UPMNS matrix (à la CKM)

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

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

Oscillation Probability
Survival Probability

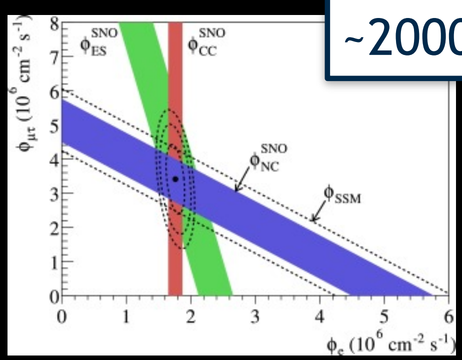


our history in a nut-shell…

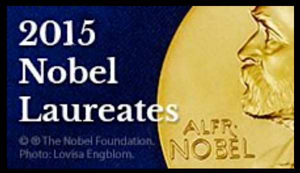
UNITARITY (assumed)

predictions: θ_{13} & CP-violation

solar anomaly ($\theta_{12} \oplus \delta m^2$)

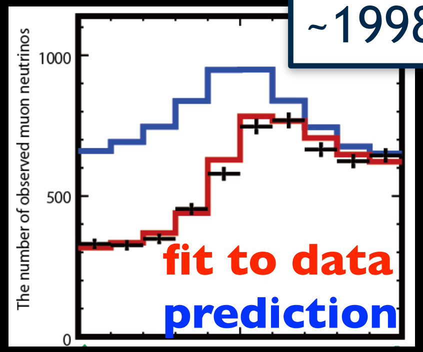


~2000

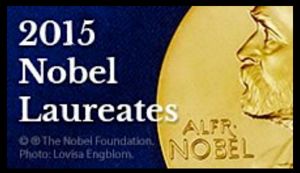


2015

atmospheric anomaly ($\theta_{23} \oplus \Delta m^2$)



~1998



large mixing! **large mixing!**

"reactor" oscillation (θ_{13})

CHOOZ

≤2000

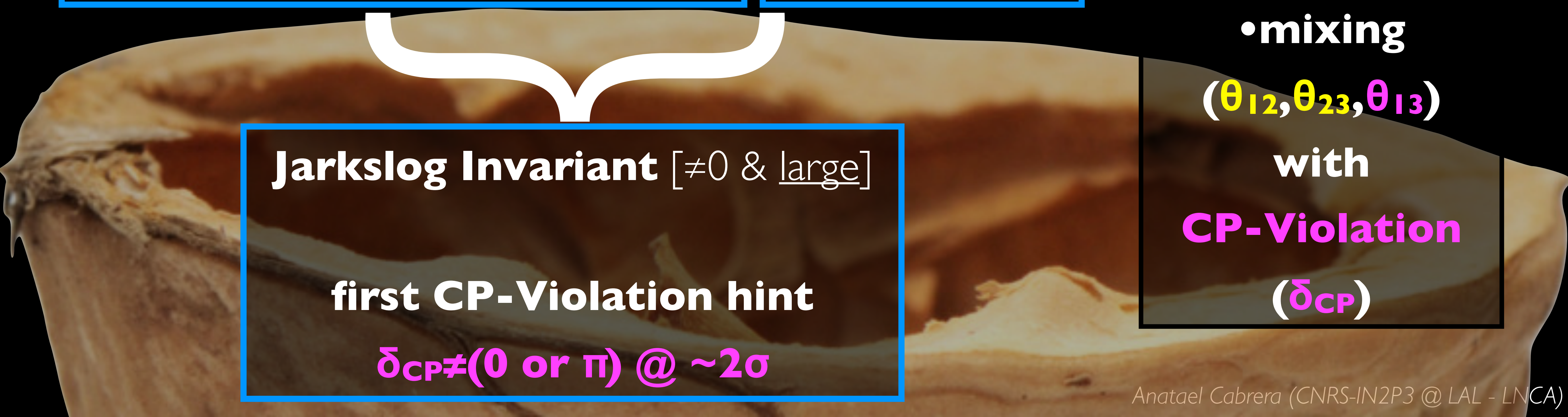
reactor-θ_{13}

2011-2012

small mixing

MODEL hypothesis: neutrino oscillations

- **3 types ν's**
- **ν massive (Δm^2 & δm^2)**
- **mixing (θ_{12},θ_{23},θ_{13}) with CP-Violation (δ_{CP})**



Jarkslog Invariant [≠0 & large]

first CP-Violation hint

$\delta_{CP} \neq (0 \text{ or } \pi)$ @ ~2σ

important to remember…

neutrino oscillation implies **massive** **neutrino physics**

$\Longrightarrow$ important modification to the ***SM***

ingredients & notation…

most points covered here!

Weak Flavour Neutrinos: **ν(e)**, **ν(μ)**, **ν(τ)**→ what we detect/production

Mass Neutrinos: **ν(1)**, **ν(2)**, **ν(3)**→ what propagates

PMNS matrix: ***U***→***unitarity*?** [else below parametrisation is wrong]

PMNS mixing parameters: **θ13**, **θ12**, **θ23**

CP-Violation parameters: **δ?** (within ***U***) and ***J*** [Jarkslog invariant]

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

Mass ordering:

+δm^2 (solar data)

±?Δm^2 (so far)→ the lightest neutrino**?** [ν(1) versus ν(3)]

Absolute mass scale: **m(ν)?**

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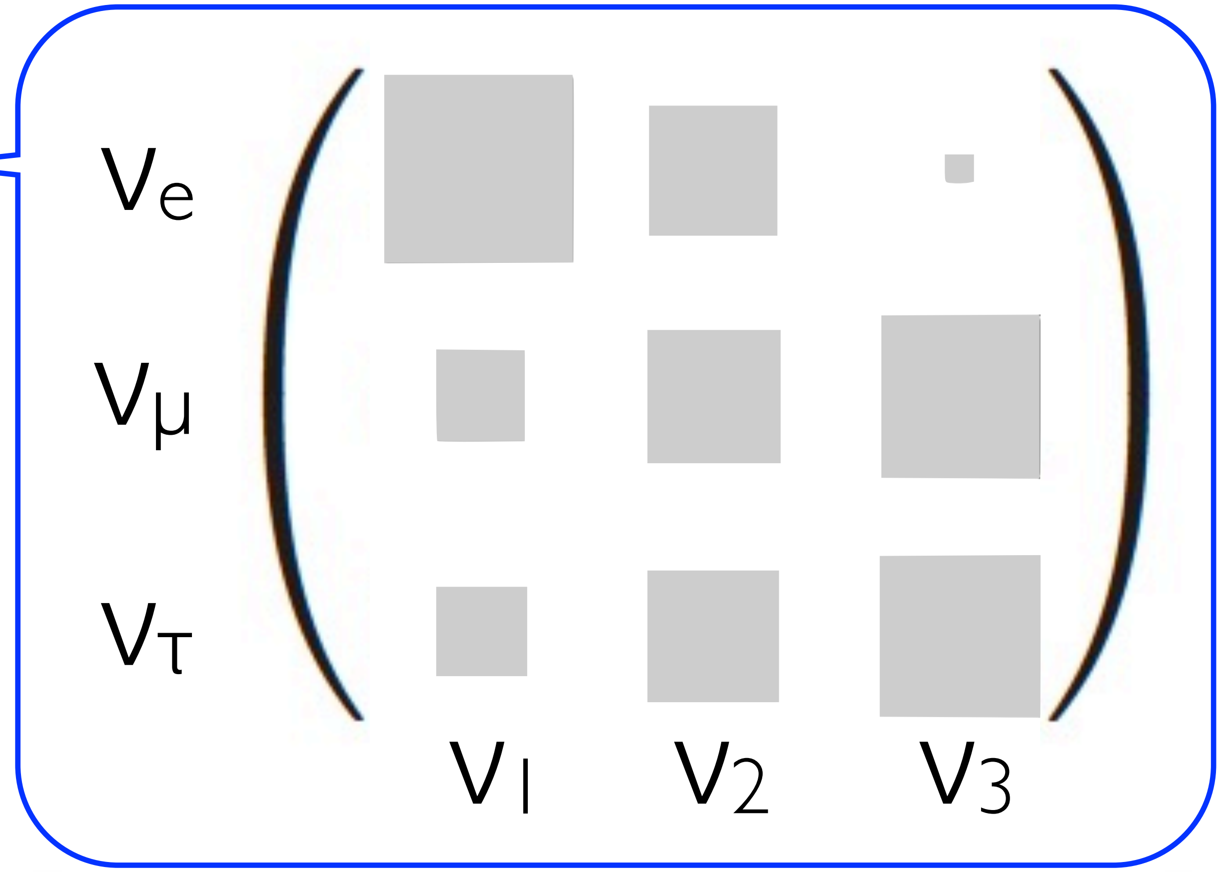
$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$



consider full matrix structure

(not just composition)

why shape?

- **large mixing** but **one (small)**!
- **largest CP-Violation** (SM)→ **Leptogenisis?**
- **any symmetry behind? [Nature's caprice/symmetry?]**
- **how is this related to the CKM (minimal mixing & little CPV)?**

U_{3x3} unitary?

[poorly constraint→assumed]

big picture…

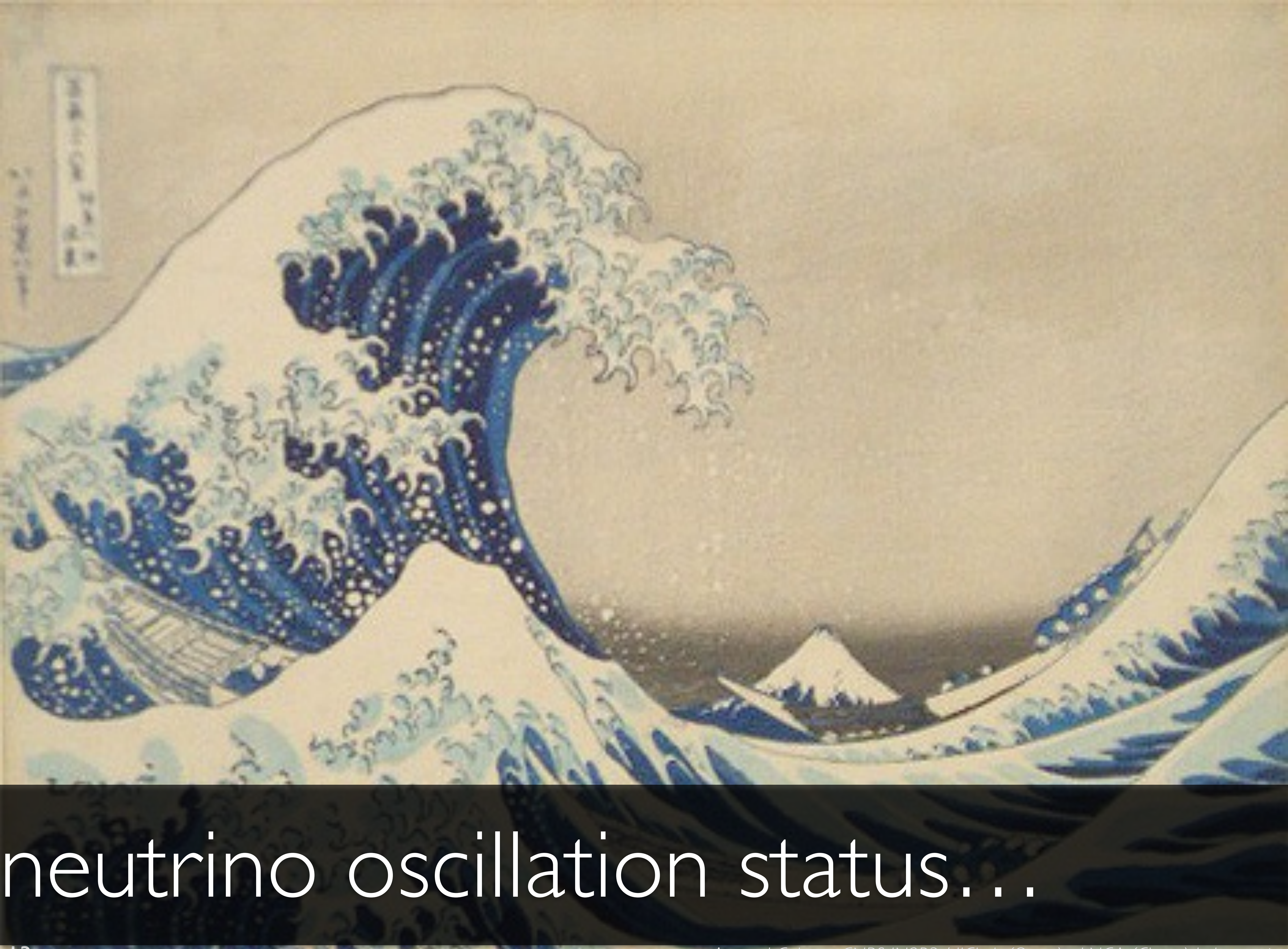
Jorge's talk: ***(Quark) Flavour Physics*** [i.e. CKM]

this talk: ***Leptonic Flavour Physics*** [i.e. PMNS] — most (but not only)

both about the ***SM*'s Flavour Sector**, which _may_ have a **common origin BSM?**

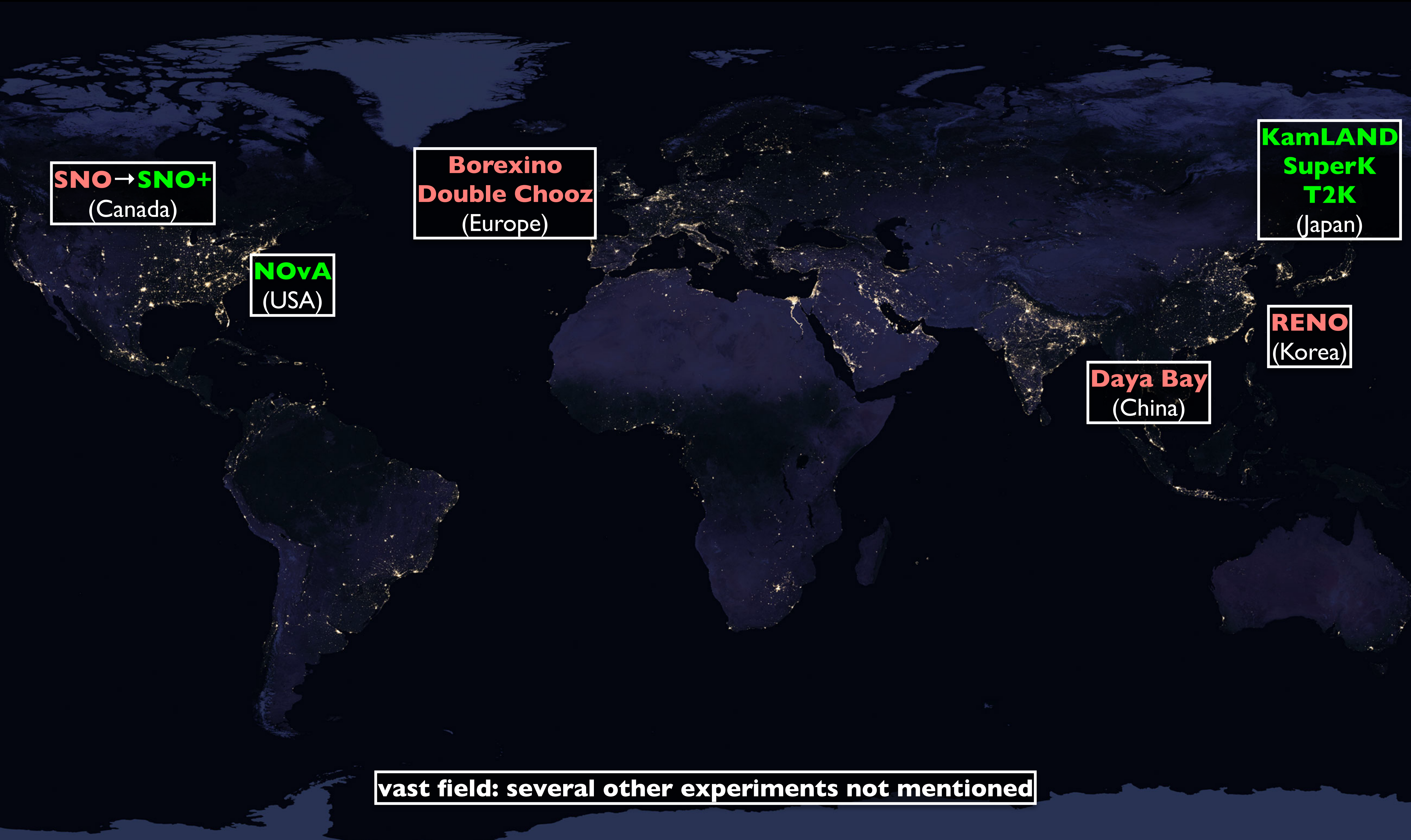
both wonder about ***our origin*** (i.e. via **CP-Violation**): **Baryogenesis** vs **Leptogenesis**.

could neutrinos be at **our most fundamental origin**?



neutrino oscillation status…

running experiments…



imminent experiments…

where are we now (~2020)?

status on neutrino oscillation knowledge…

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

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

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

	today		
	best knowledge		NuFIT5.0
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 %
$\lvert\Delta m^2\rvert$	3.0 %	T2K+NOvA & DYB	1.3 %
Mass Ordering	**unknown**	SK et al	NO @ **~3σ**
CPV	**unknown**	T2K	3/2π @ **≲2σ**

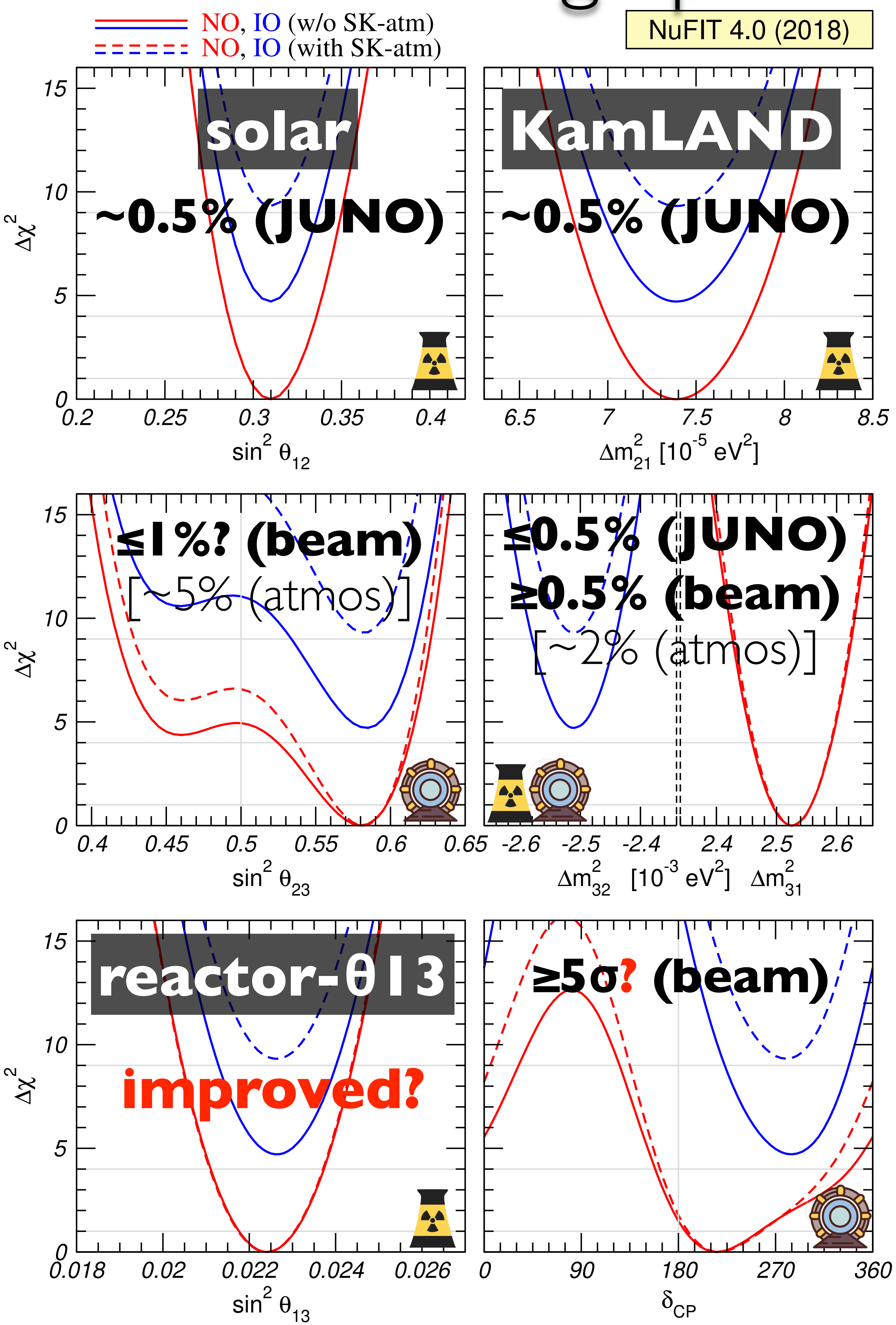
(**now**)

(reactor-beam)

JUNO⊕DUNE⊕HK will lead precision in the field (→ **CPV**) **except θ_{13}!**

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

high precision knowledge prospects…



Normal/Inverted Mass Ordering

beam ≈ **DUNE⊕HK[T2K⊕NOvA⊕MINOS]**
atmos ≈ **ORCA⊕PINGU⊕HK⊕IceCube⊕SK**

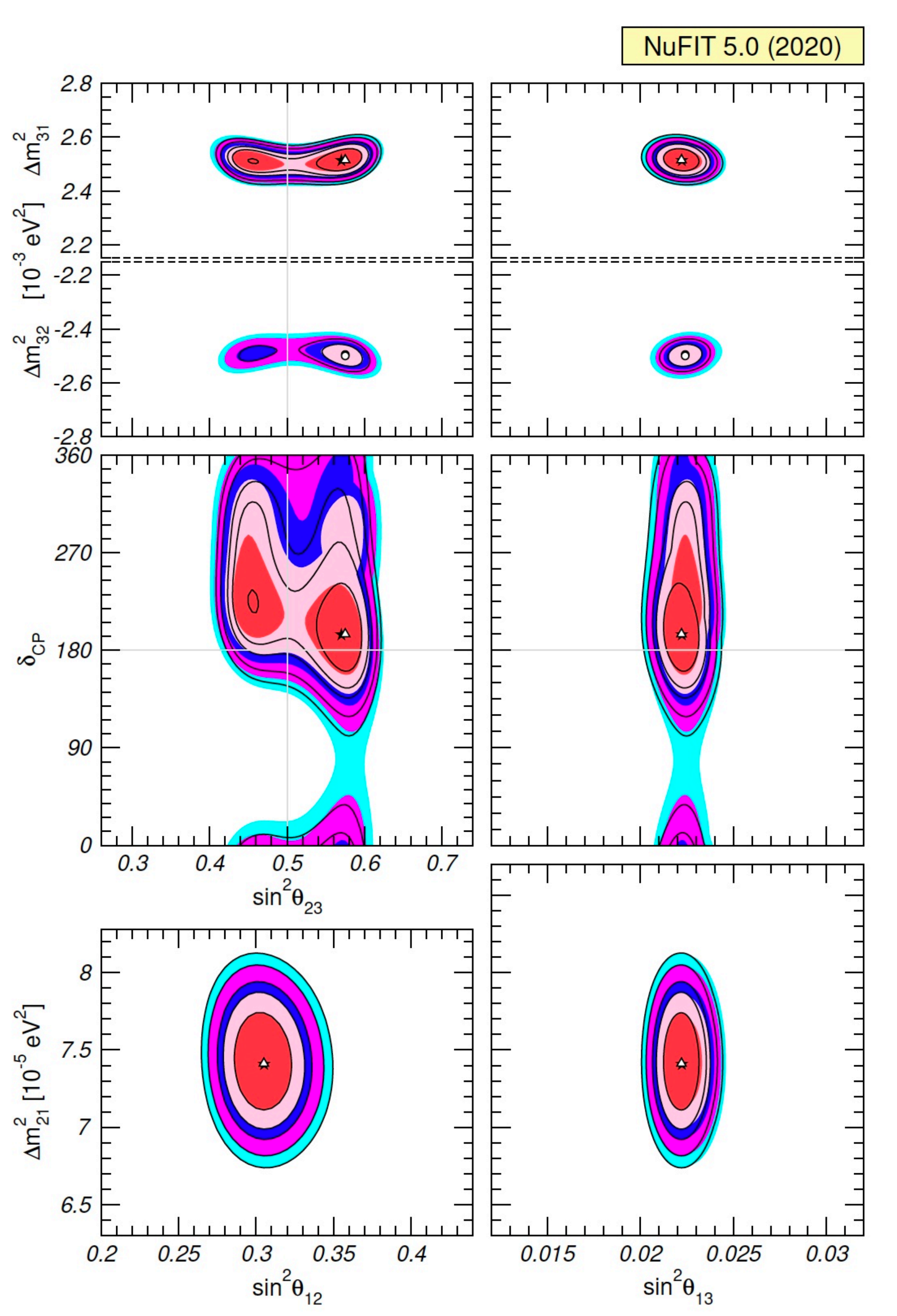
CPV term: beam* (directly)

"solar" terms:
- **θ_{12}:** JUNO [now solar]
- **δm^2:** JUNO [now KamLAND]

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

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

Unitarity conservation (assumed) **to few %**



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}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

		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}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

(vast) field complementarity…

accelerators: (**θ13**), **θ23**, **Δm²**, **δ?** and **±?**Δm² (matter effects mass ordering)

reactors: **θ13**, **θ12**, **δm²**, **Δm²** and **±?**Δm² (unique vacuum mass ordering)

atmospheric: **θ23**, **Δm²** and **±?**Δm² (matter effects mass ordering)

solar: **θ12**, **δm²** and **+**δm² (matter effects in the sun) — longest baseline

a few (very) **powerful synergies**:

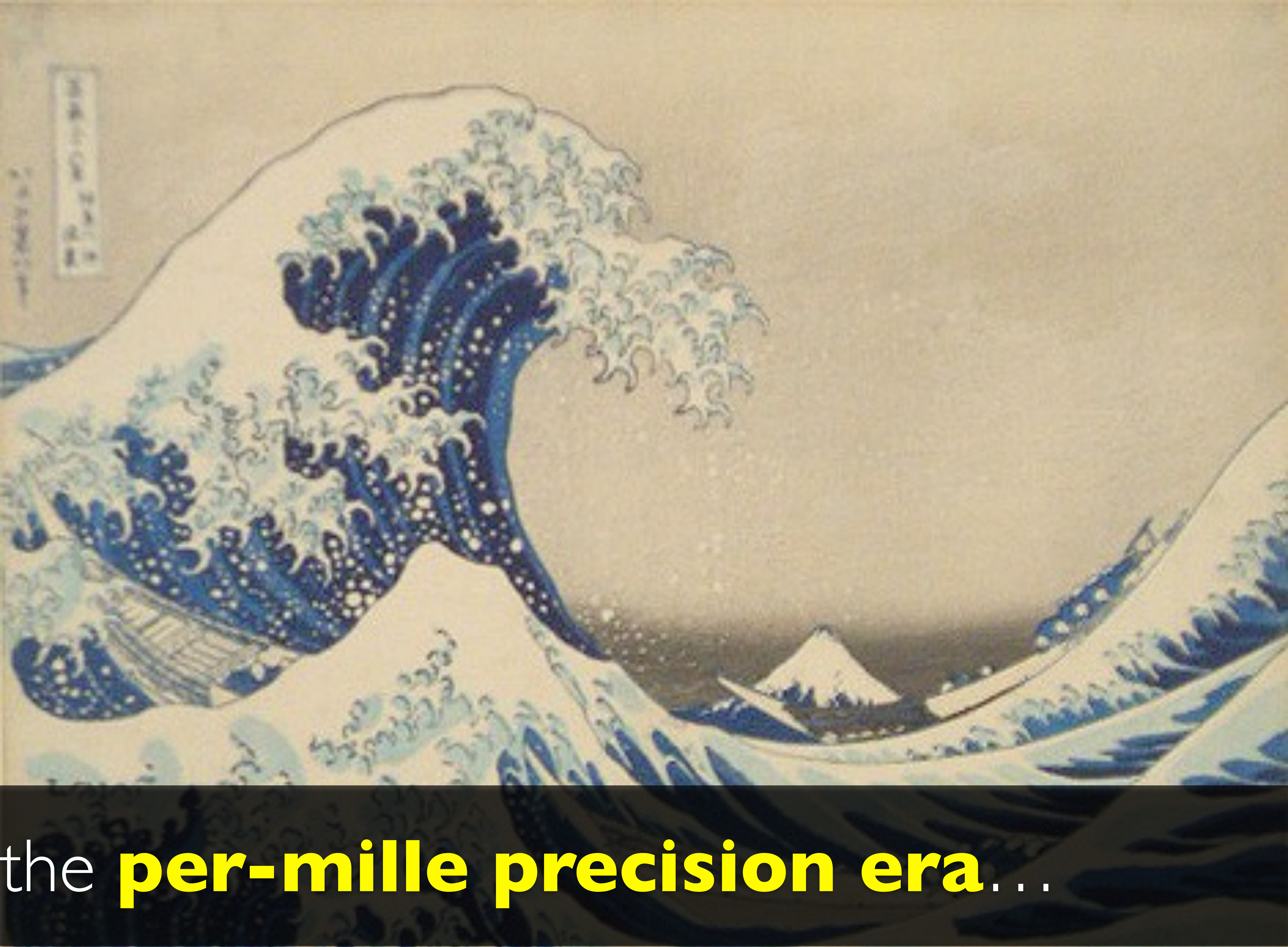
- reactor⊕accelerators(**θ13**): **δ?**
- reactor⊕accelerators(**Δm²**): **±?**Δm² Mass Ordering (a priori in vacuum)
- reactor⊕accelerators(**θ13**): **θ23**

issue! most experiment(s) bypass the **absolute flux (ϕ)** — **tough problem!** (uncertainty)

- **physics of source:** *solar*, *geo-neutrino*, *supernovae* (collapse vs remnant) and *astrophysics*, etc.
- much **BSM exploration hampered by poor ϕ knowledge**

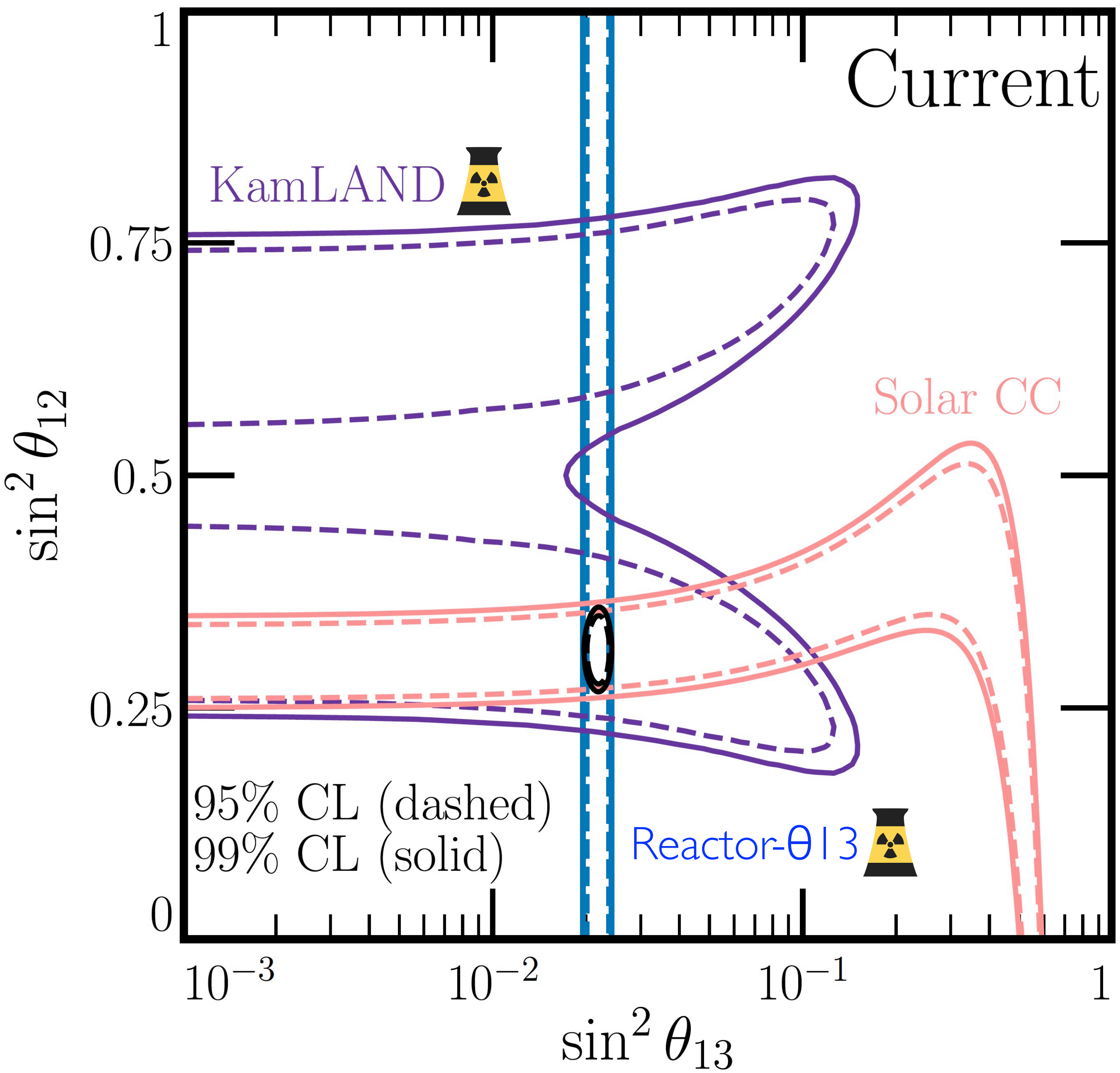
my talk(s) sub-division…

- first **per-mille precision measurements** (i.e. the **θ12-θ13** sector)
- first **Mass Ordering measurement** — Vacuum vs Matter
- first **CP-Violation measurement** and the **θ23-θ13** sector
- explorations of **Unitarity** — Conservation vs Violation



the **per-mille precision era**…

impact in **θ13-θ12** plane…



JUNO⊕Reactor-θ13 impact

matter / anti-matter consistency (CPT)

by 2030, θ12-θ13 sector fully dominated by <u>reactor experiments</u>
(today, it's rather true but some solar contribution)

the reactor…

Chooz-B nuclear reactor plant: 2x N4 reactors [4.2GW$_{\text{thermal}}$ each]

the ν discovery (1950's)…

Reines et al **detection strategy legacy**…

PMT ⇔ transparent medium

ν interaction: coincidence and/or tagging

overburden (μ-cosmic shielding)

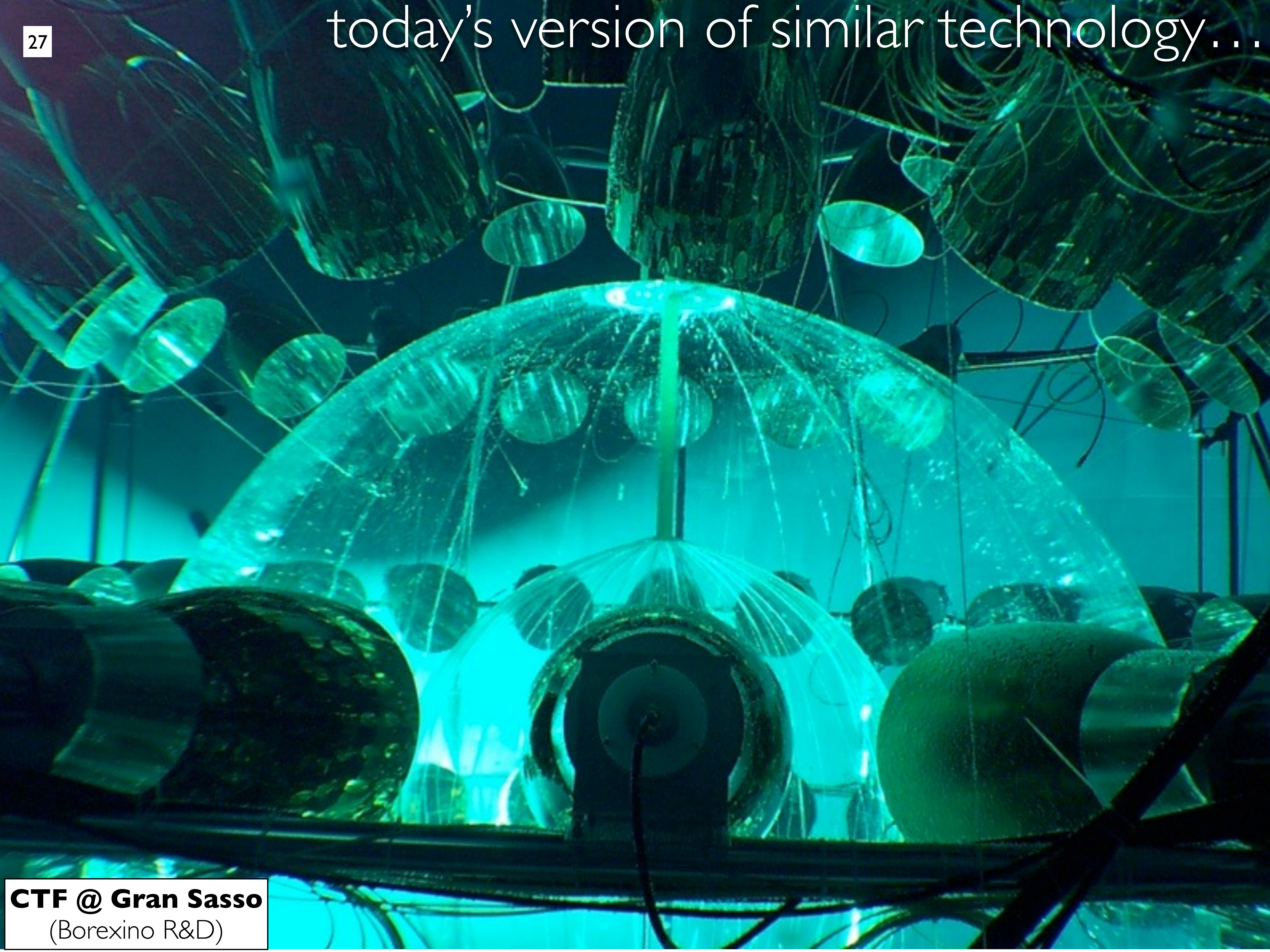
external shielding (radioactivity shielding)

loaded medium (^{113}Cd)→ non-native detection!

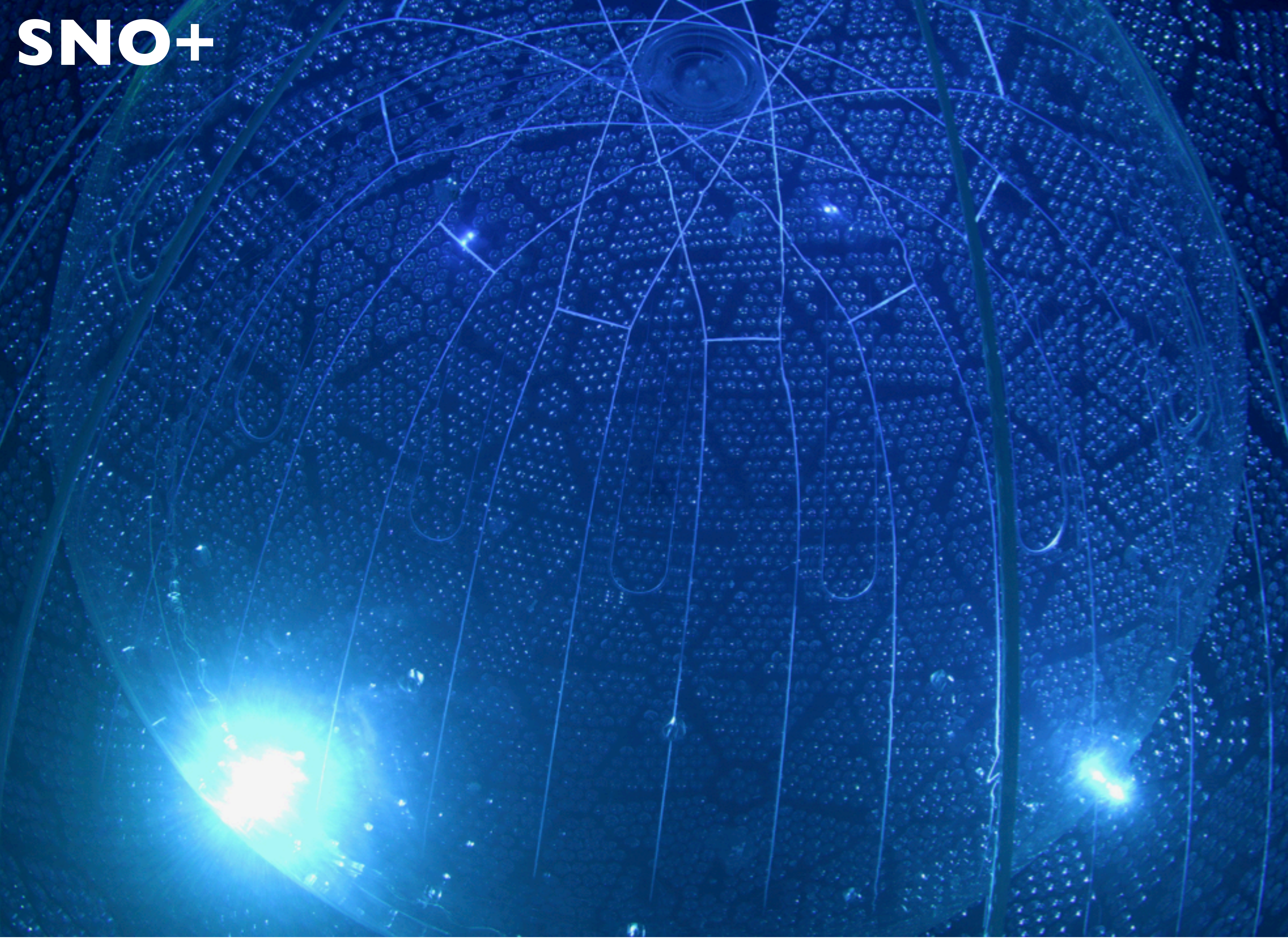
(reactor source) **signal modulation**

~70years ago → much the same still now!

today's version of similar technology…



CTF @ Gran Sasso
(Borexino R&D)



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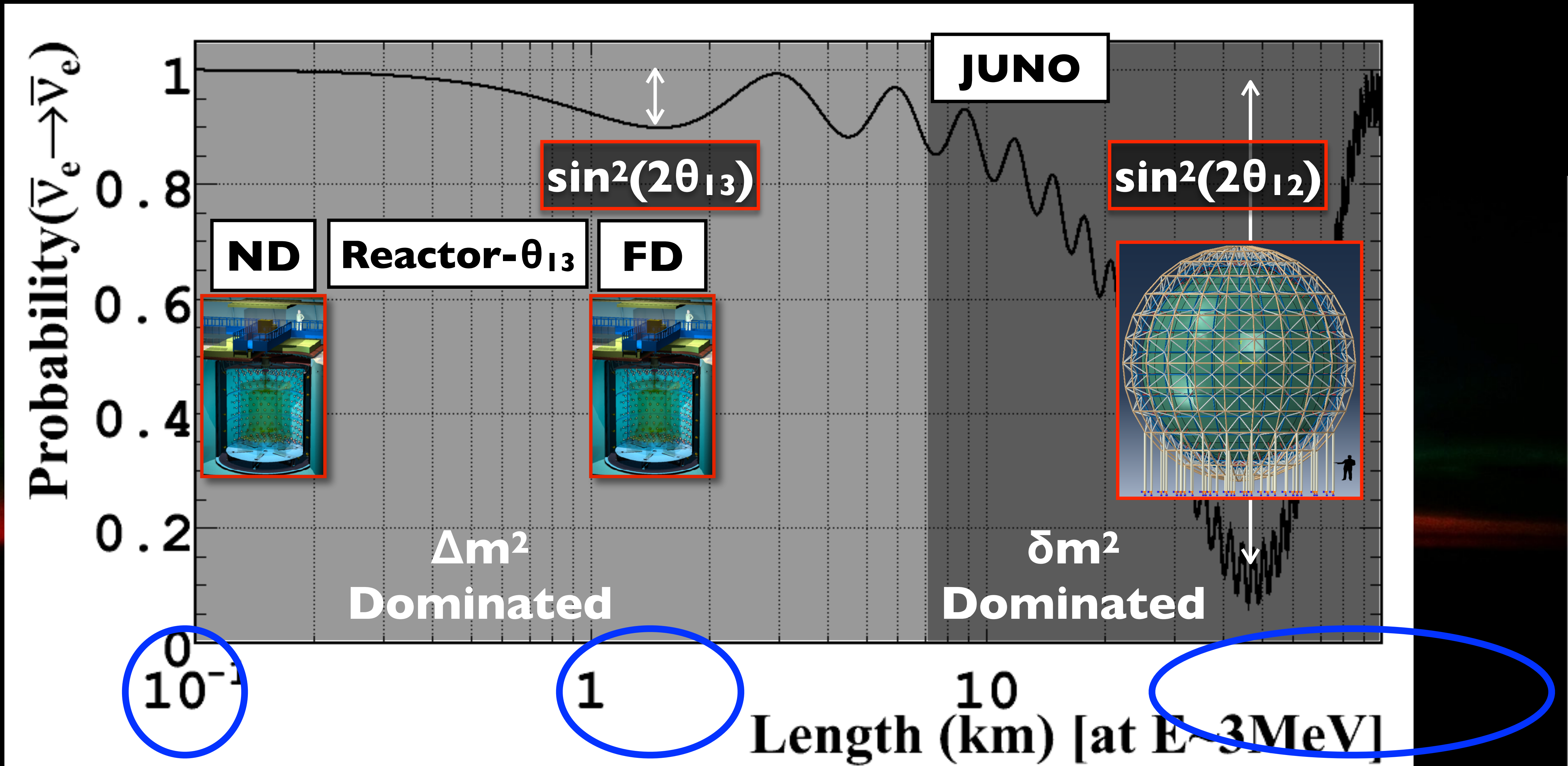
experimental setup…



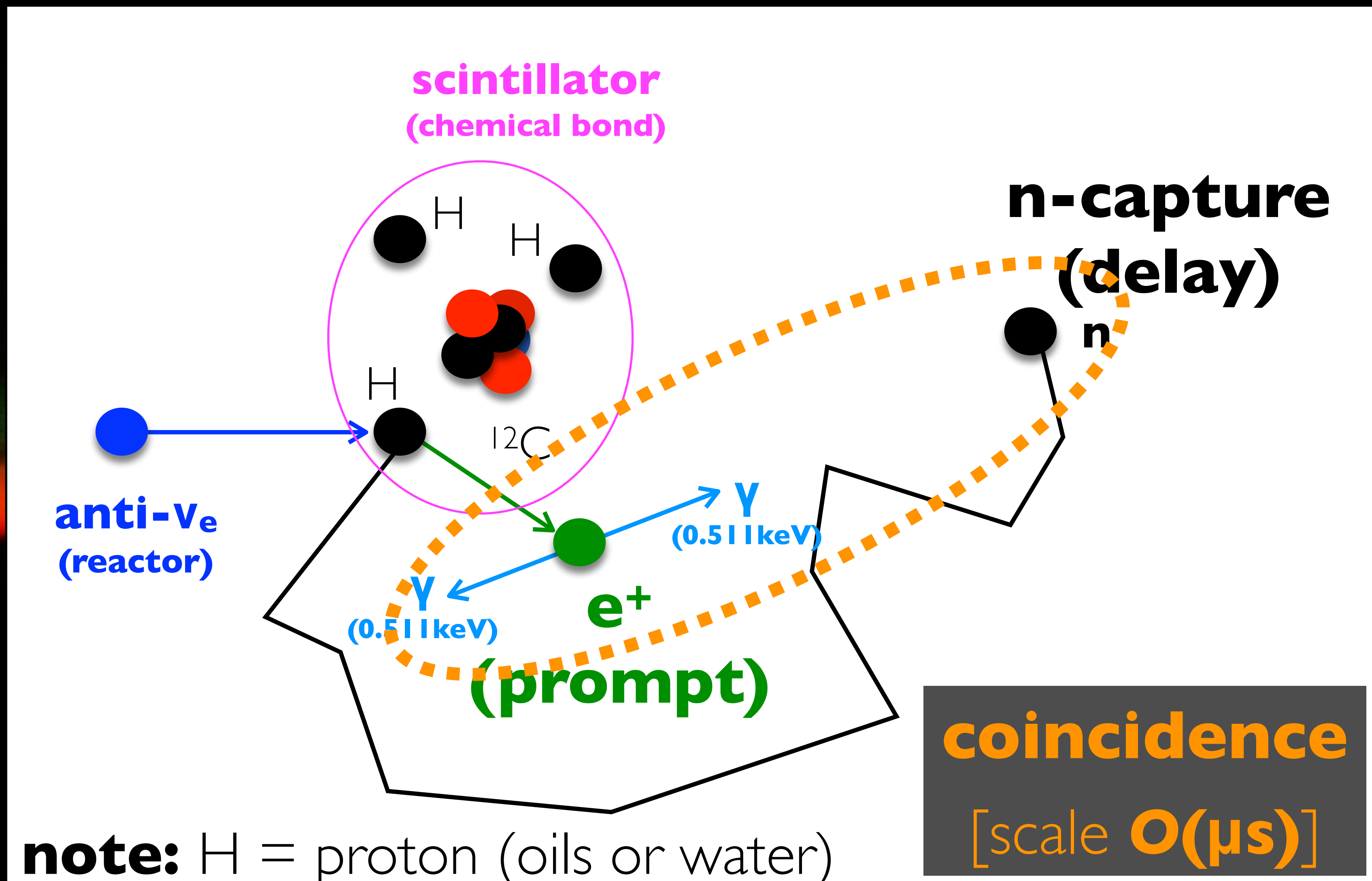
reactor: extreme source of neutrino (commercial→1GW≈2×10^{20}/s) — no running cost.
detector(s): transparent liquid scintillator (H is needed)
3 measurement regimes: depending on baseline (L):

- **zero-baseline** (L→~0km): **φ(reactor)** — and/or **new physics?**
- **short-baseline** (L→~1km): **θ13⊕Δm²** [multi-detector: ~~**φ(reactor)**~~]
- **long baseline** (L→≳50km): **θ12⊕δm²** and (**θ13⊕Δm²**, if enough resolution)

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n [CC *intetaction*]

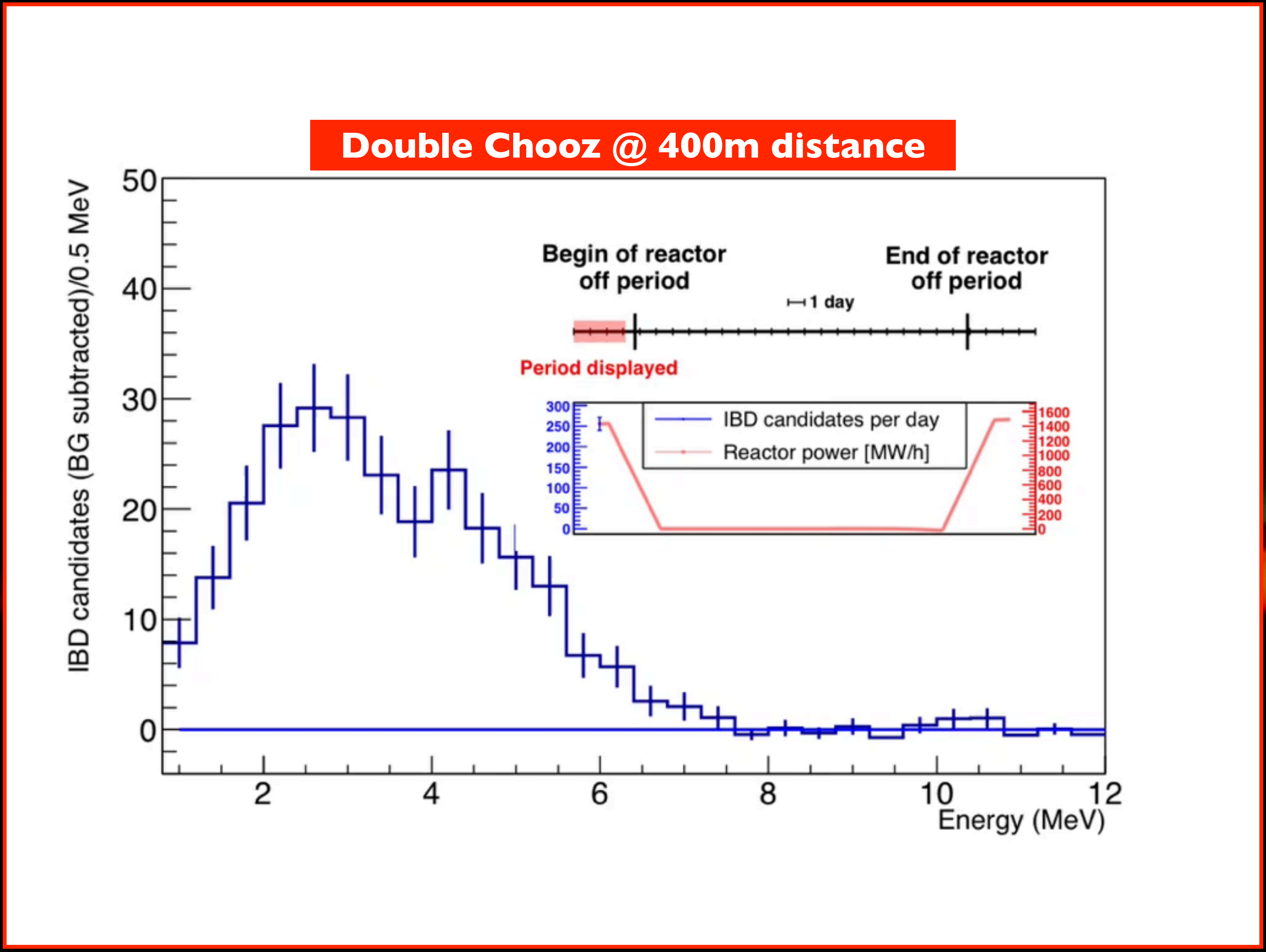
cross-section known to ~0.2% [↔lifetime of neutron]

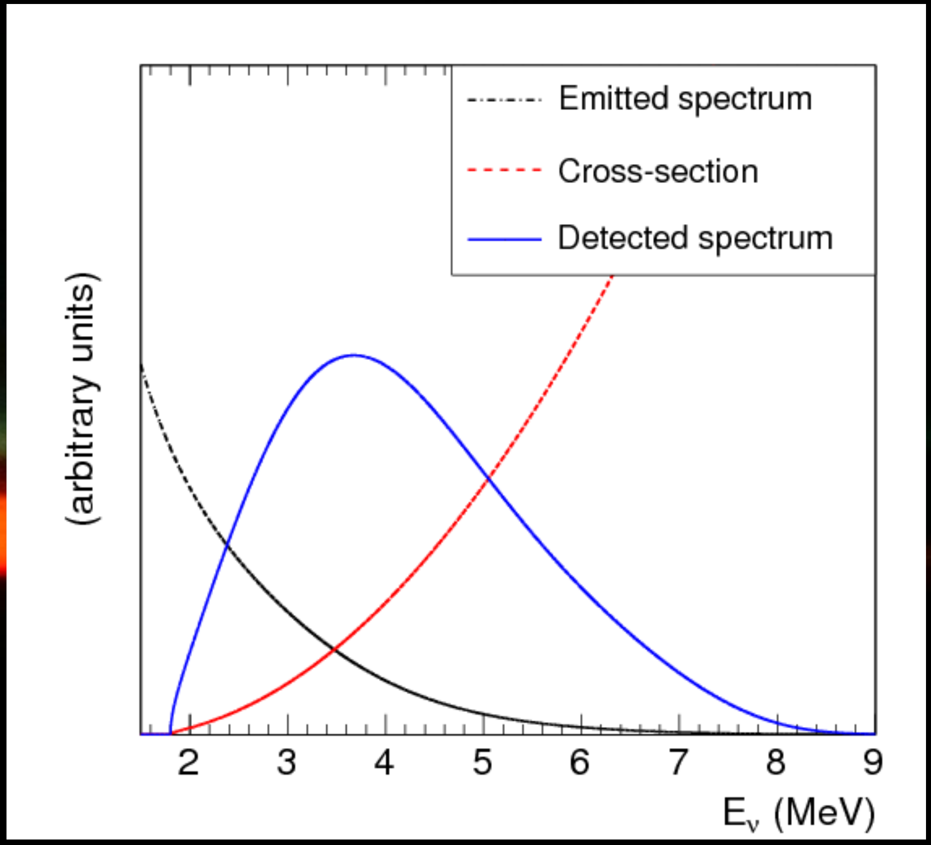


generally, **no e+ PID**

→ **γ** ≈ **e^-** ≈ **e^+** ≈ α ≈ **p-recoil** (fast-n)

reactor neutrino spectrum…





E(*neutrino*) = E(e+ *visible*) + ~0.8MeV [mass difference between p and n]

E(*neutrino*) can be controlled to order 0.1% precision

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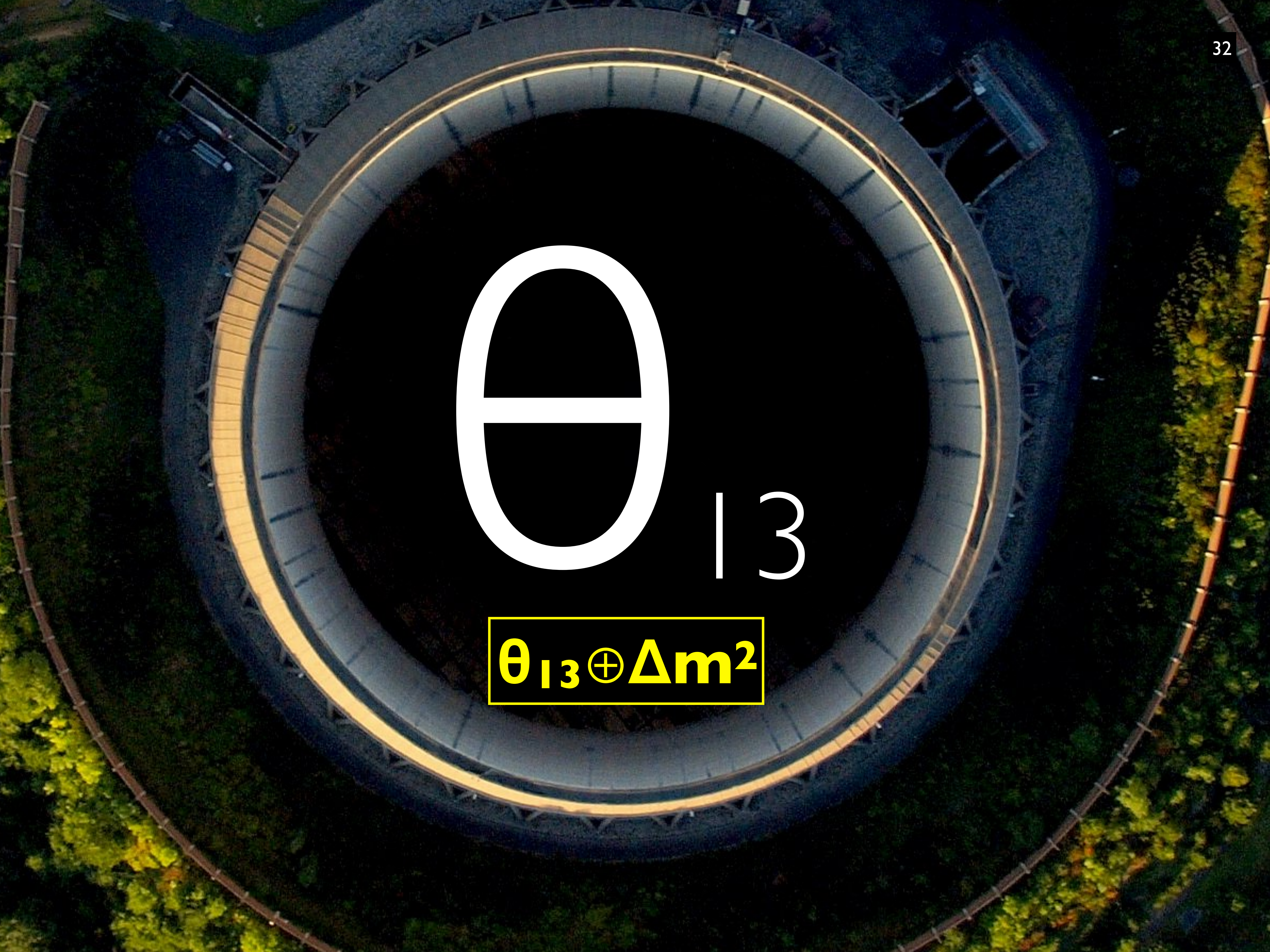


θ_{13}

$\boxed{\theta_{13} \oplus \Delta m^2}$

summary on today's θ13 knowledge/experiments…

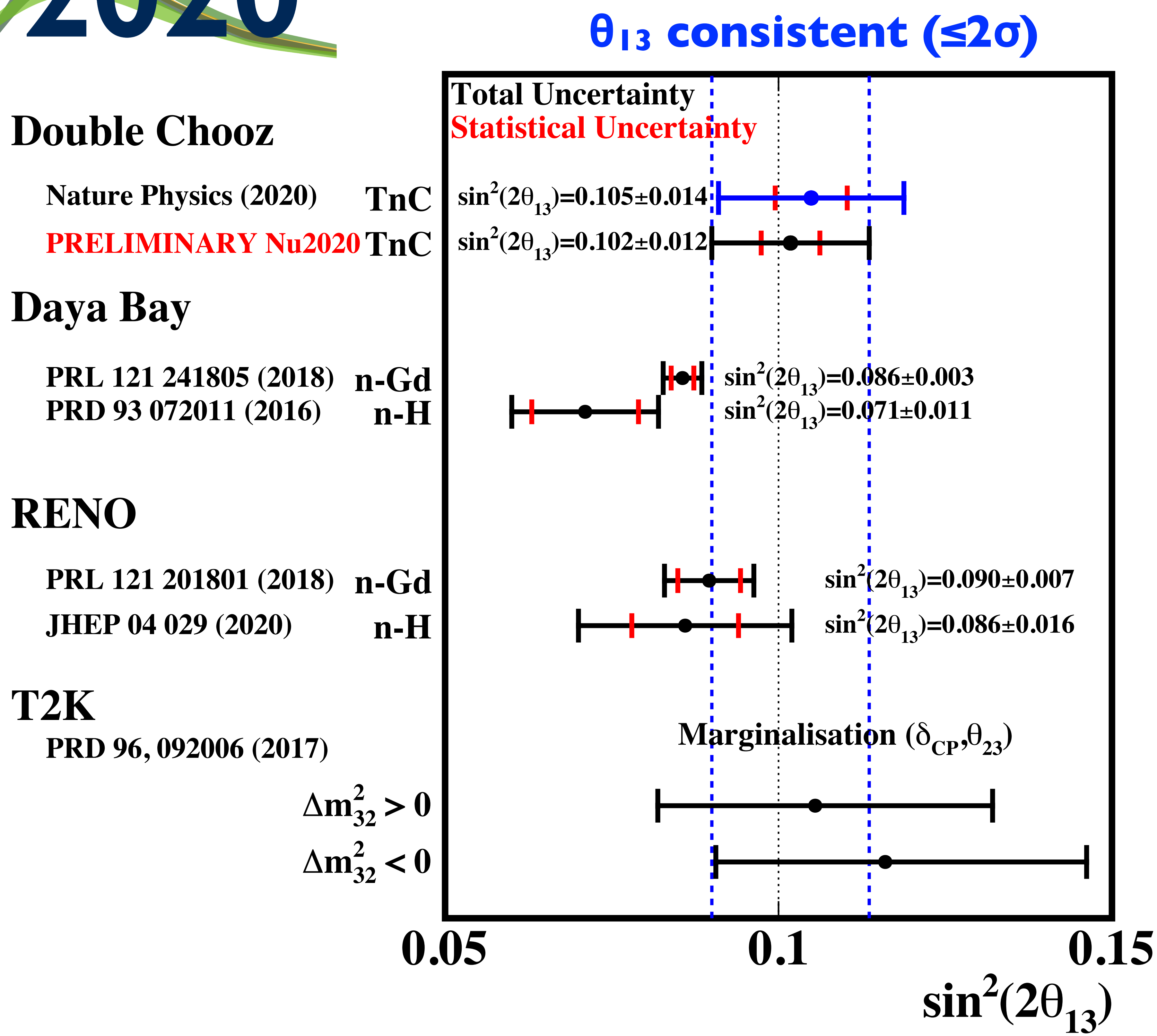
reactor-θ13 experiments: DC⊕DYB⊕RENO

•statistics: ≥10^5 (far) [<10^6]
•systematics: ~0.1% (each)
•energy control: ~0.5%

	<2010	reactor-θ13 [2010-2020]			cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	—	—	~100/day @ ≤1.5km
flux	~2.2%	~0.1%	~0.1%	<0.1%	near-to-far monitor (ideal: iso-flux)
BG	few %	~0.1%	~0.1%	<0.1%	overburden→few/day
detection	2.0 %	~0.1%	~0.1%	—	identical detectors
energy	few %	~0.5%	—	~0.5%	identical detectors

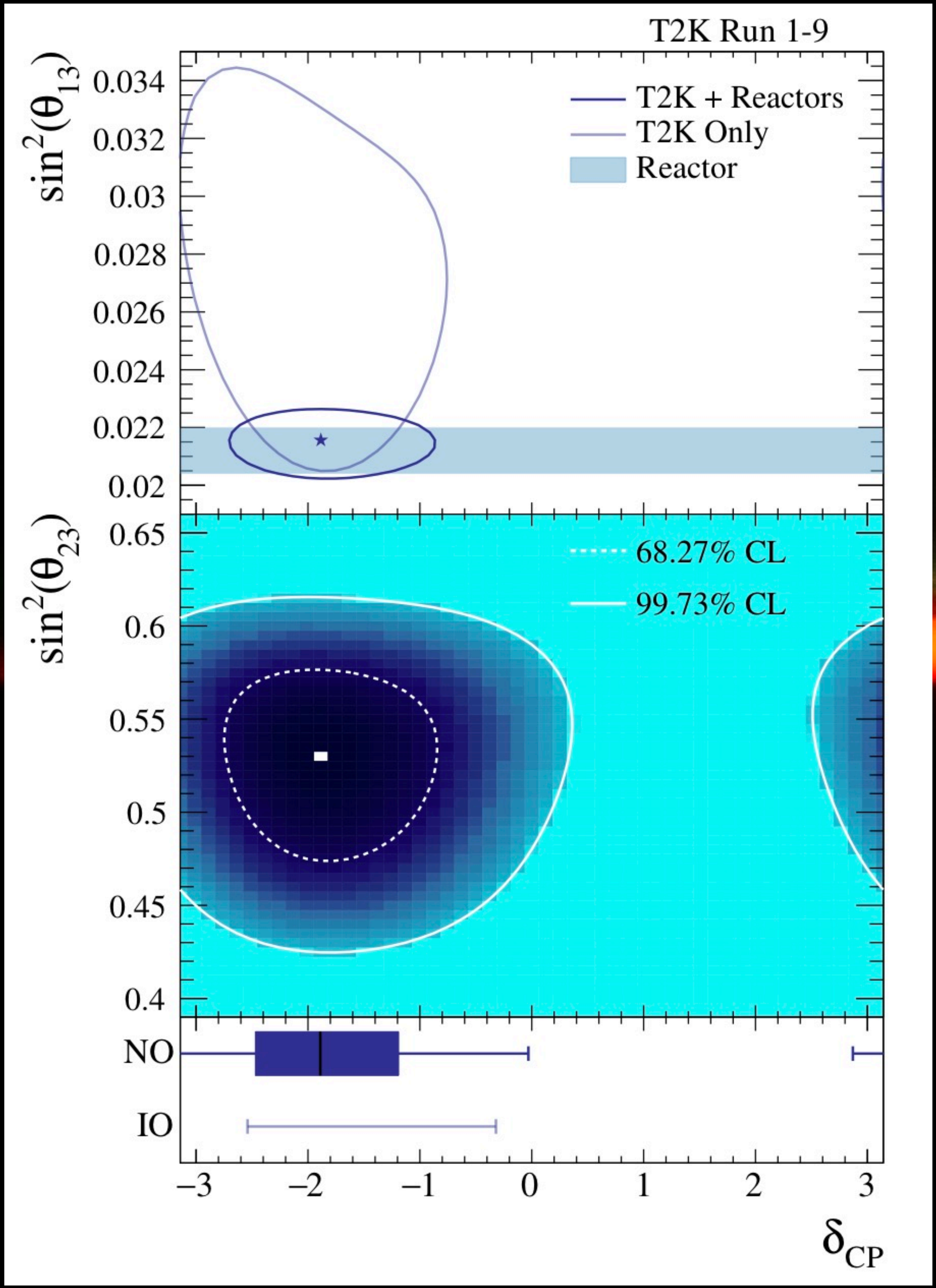
"naively extrapolating" from reactor-θ13 experiments…
•statistics: ~$10^{x?}$ (far) [>10^6]
•systematics: ~0.01%??!! (each)
possible to improve at all?

2020 world status in θ13…



minor tension (≤2σ) & slight increase (2016→2018)

T2K⊕reactor best knowledge CP-Violation…



θ13 implications

CPV phase vs θ13
[constrained by reactor]

CPV phase vs θ23
[octant ambiguity]

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

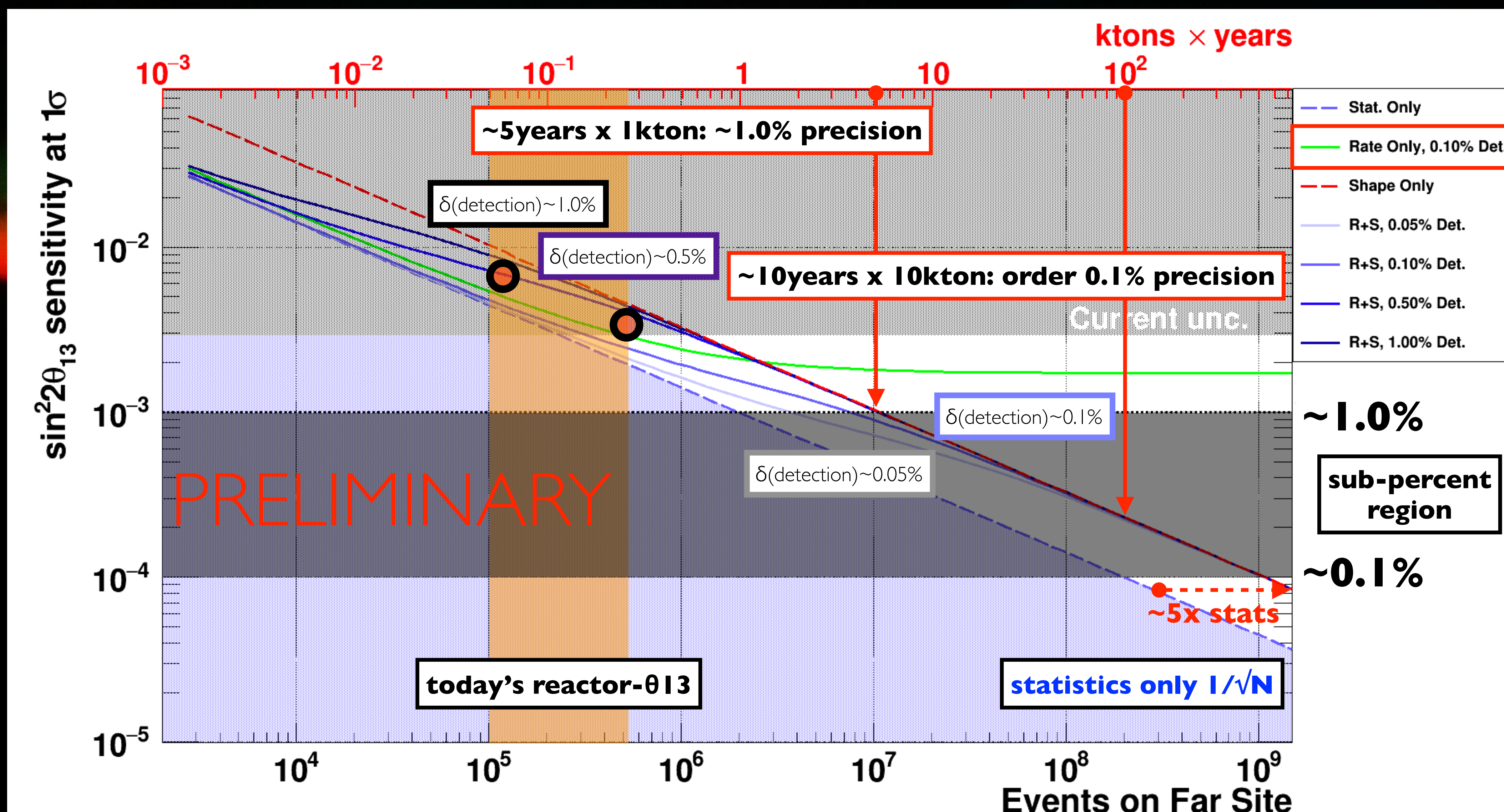

Yes?
(we don't know how...)
θ13
improvable?

review reactor θ13 sensitivity evolution…

reactor sensitive has potential to go well beyond today [DC⊕DYB⊕RENO]

•statistics: ≥10^7 (far) [≳20x today]
•detection systematics (~today: ~0.1%)
•energy control (<1% precision)
⇒ flux & BG systematics→ new techniques!!!

Today's reactor state of art knowledge
Power: 2x 4.2GW(thermal)
Baseline: ~1.1km
Detection efficiency: ~85%
Reactor duty-cycle: ~85% [refuel]



translator: 1 kton implies ~2x10^6 IBD/year→ **~4 IBD/min** [~50x today]

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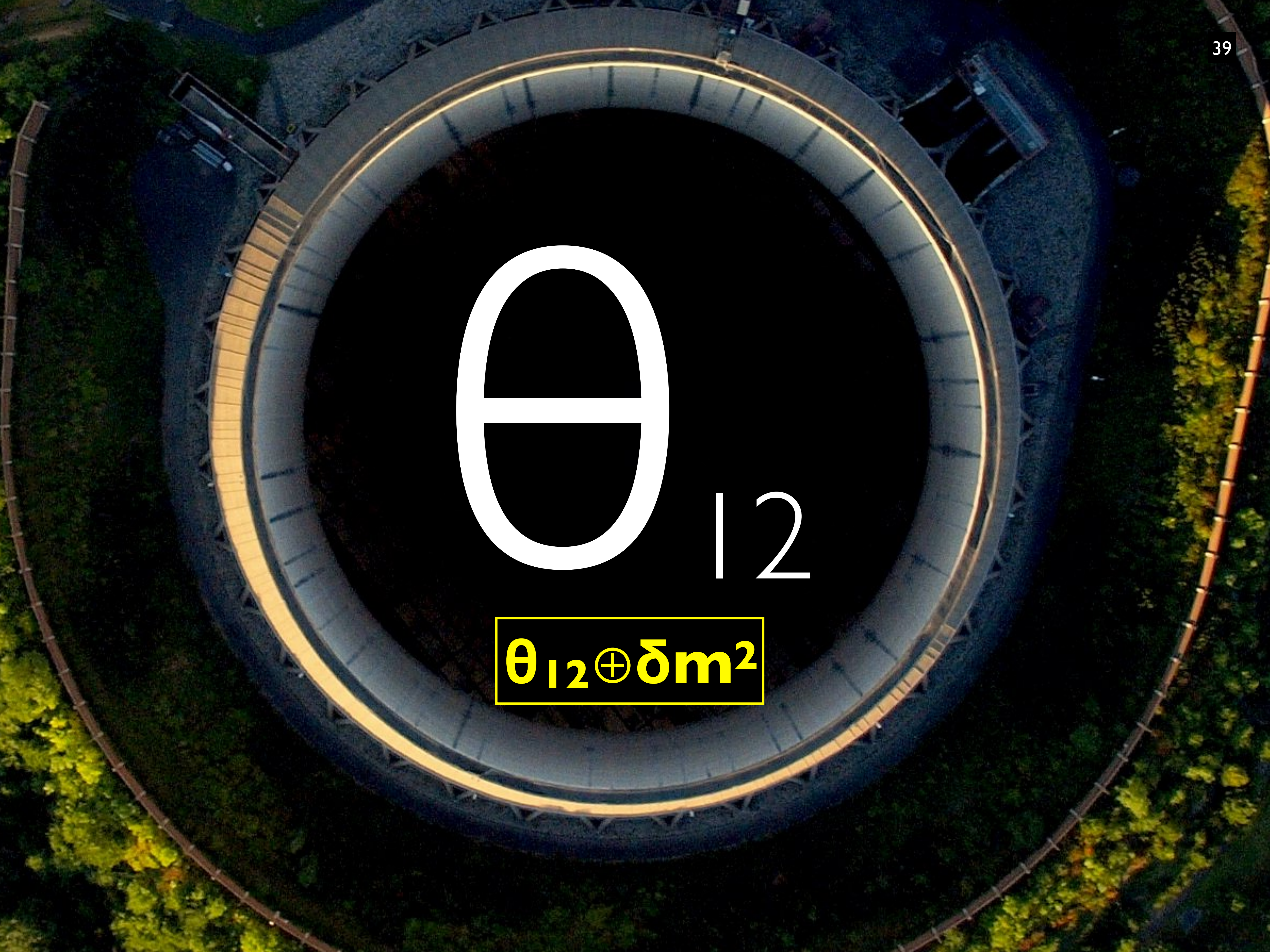
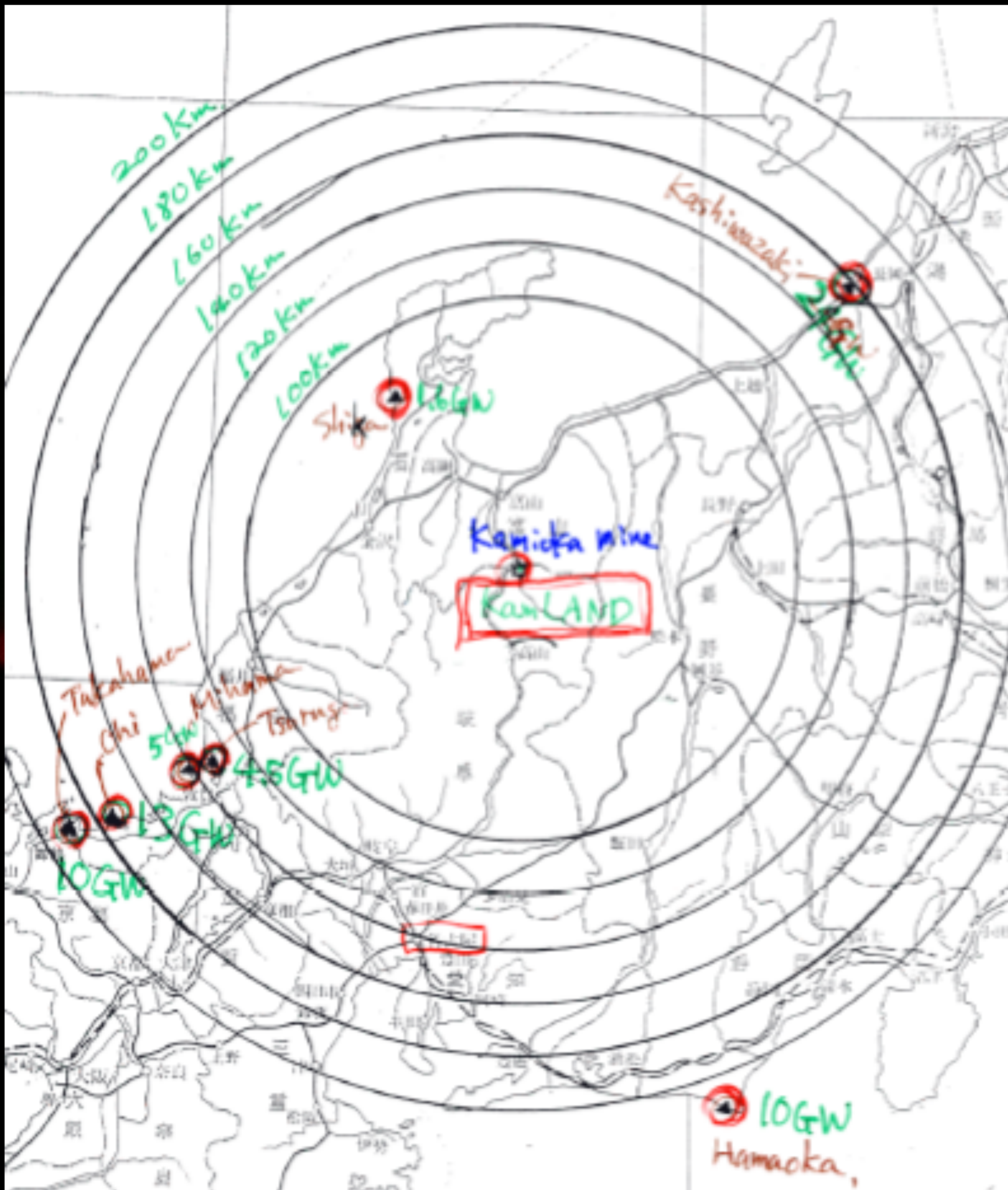
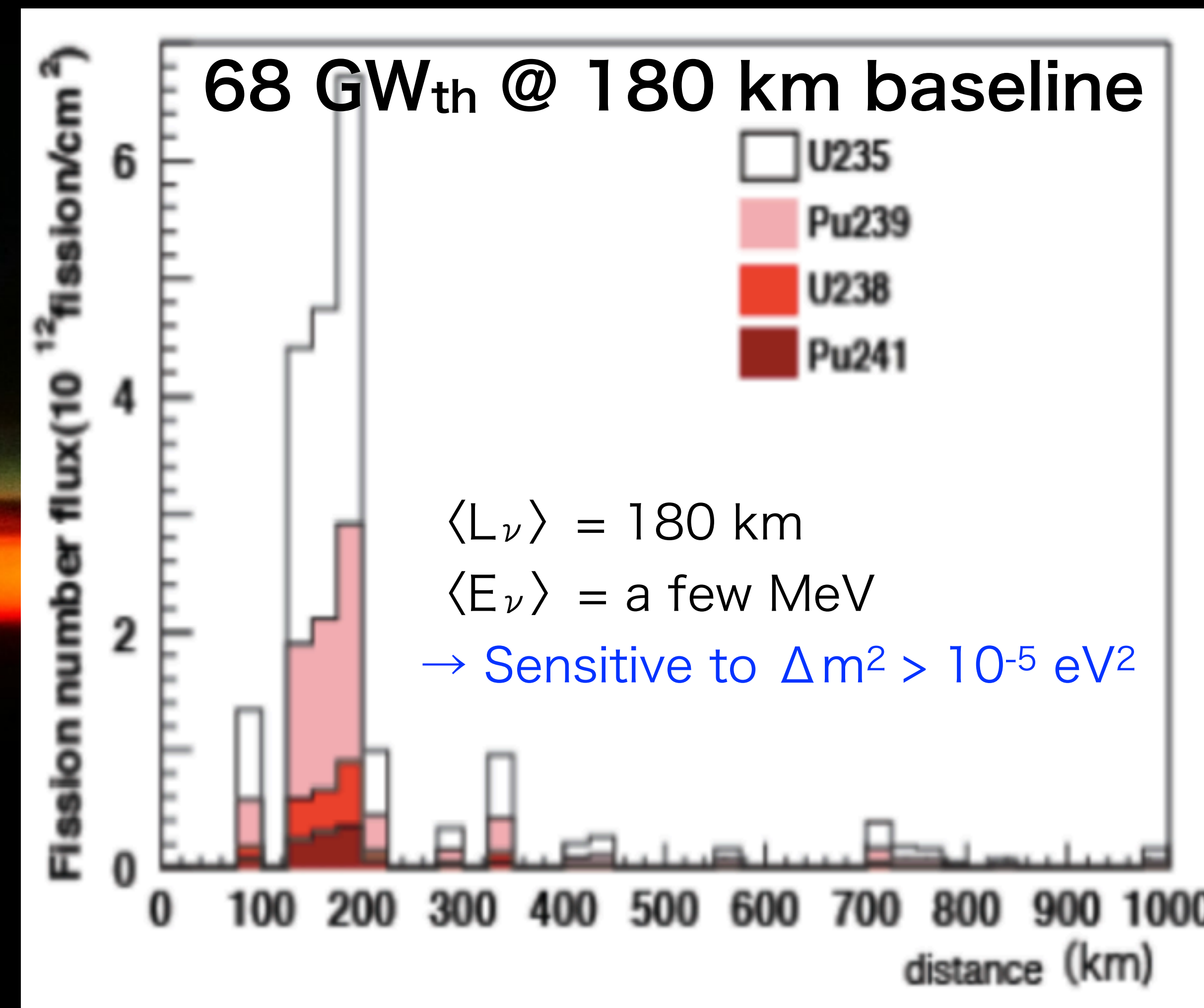
Super
ChooZ?


θ_{12}
$\boxed{\theta_{12} \oplus \delta m^2}$

(stunning) KamLAND experiment rationale…



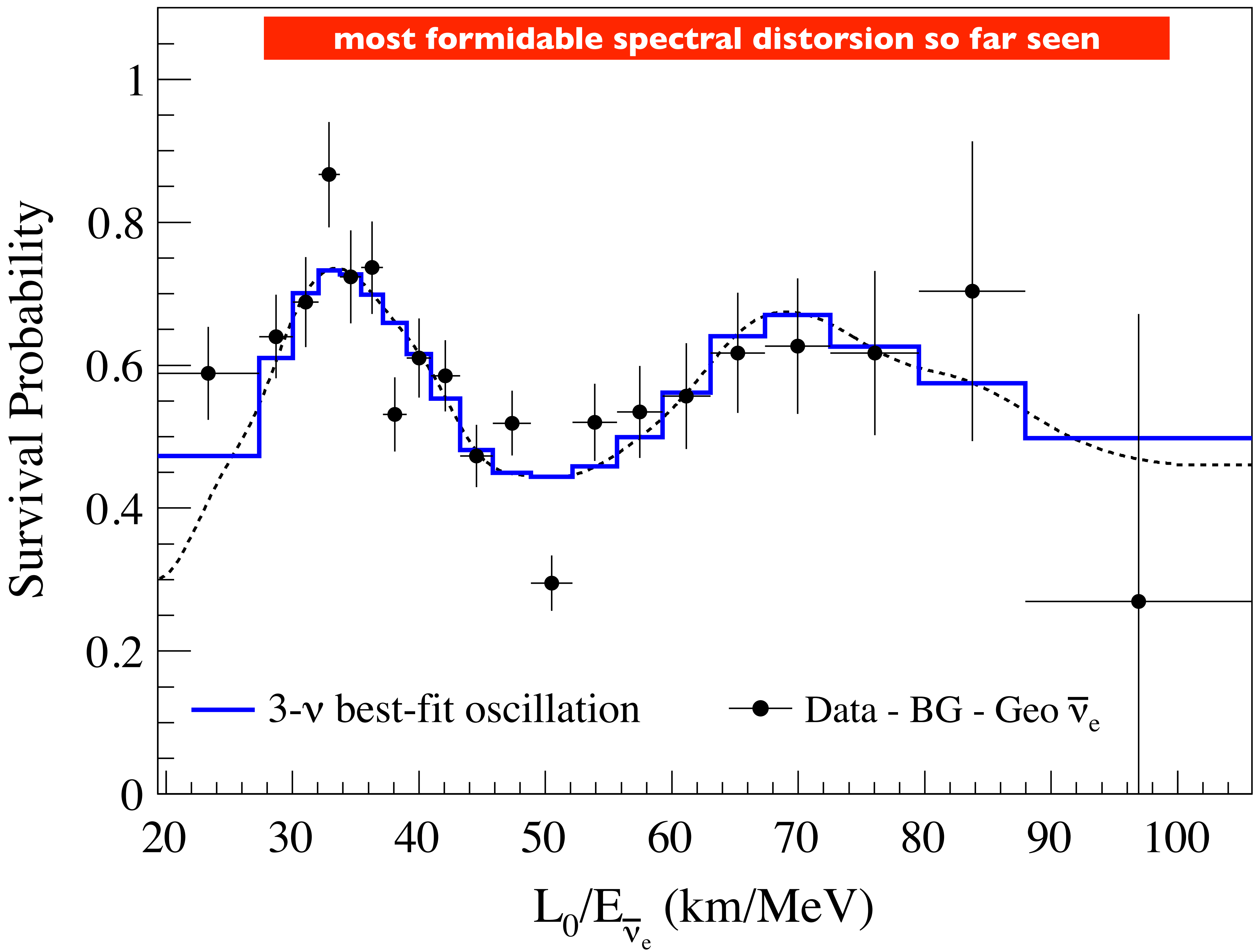


$\langle L_\nu \rangle$ = 180 km

$\langle E_\nu \rangle$ = a few MeV

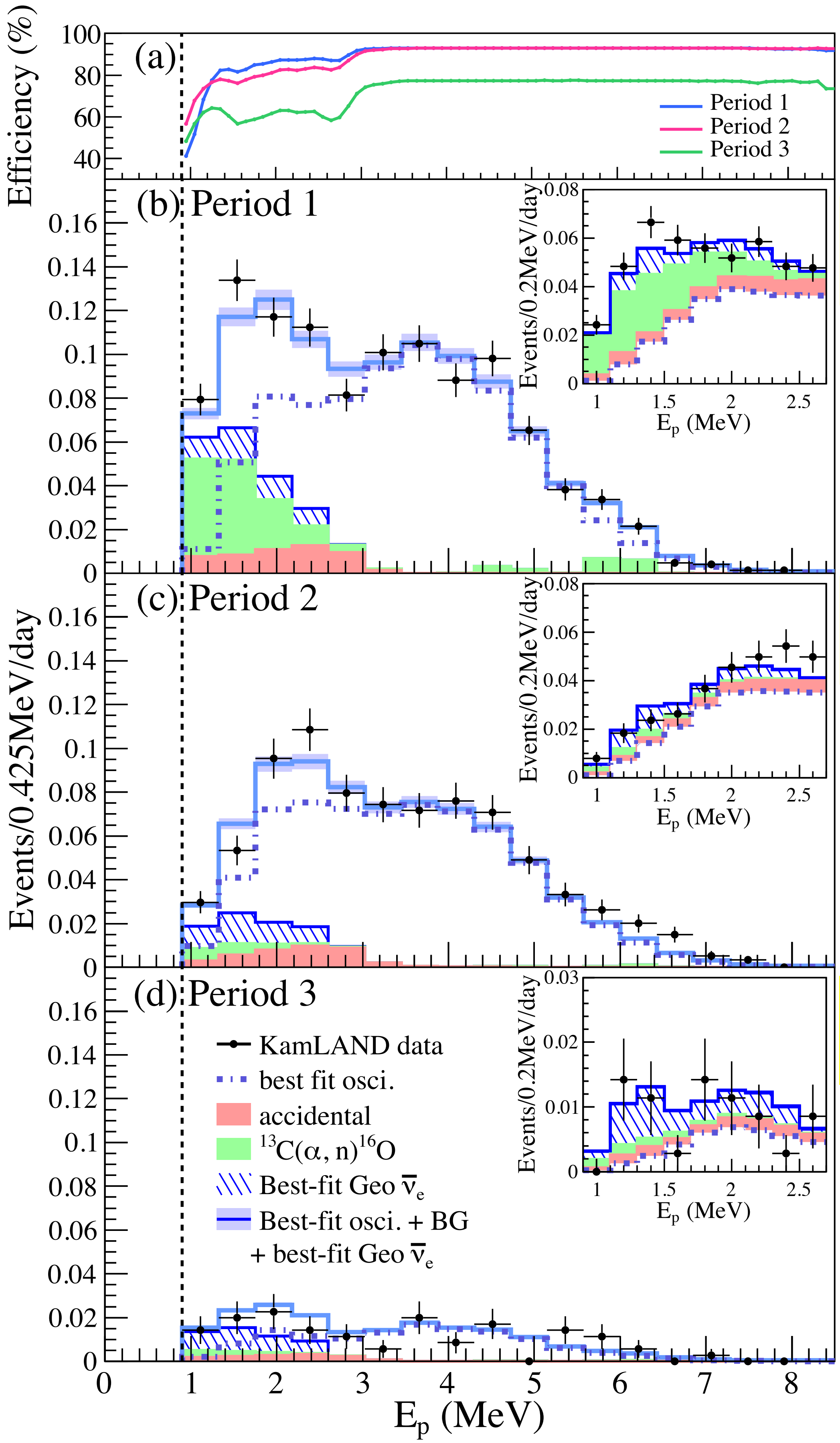
→ Sensitive to $\Delta m^2 > 10^{-5}$ eV^2

univocal neutrino oscillation signature…



KamLAND's spectral distortion (and reactor-off)…

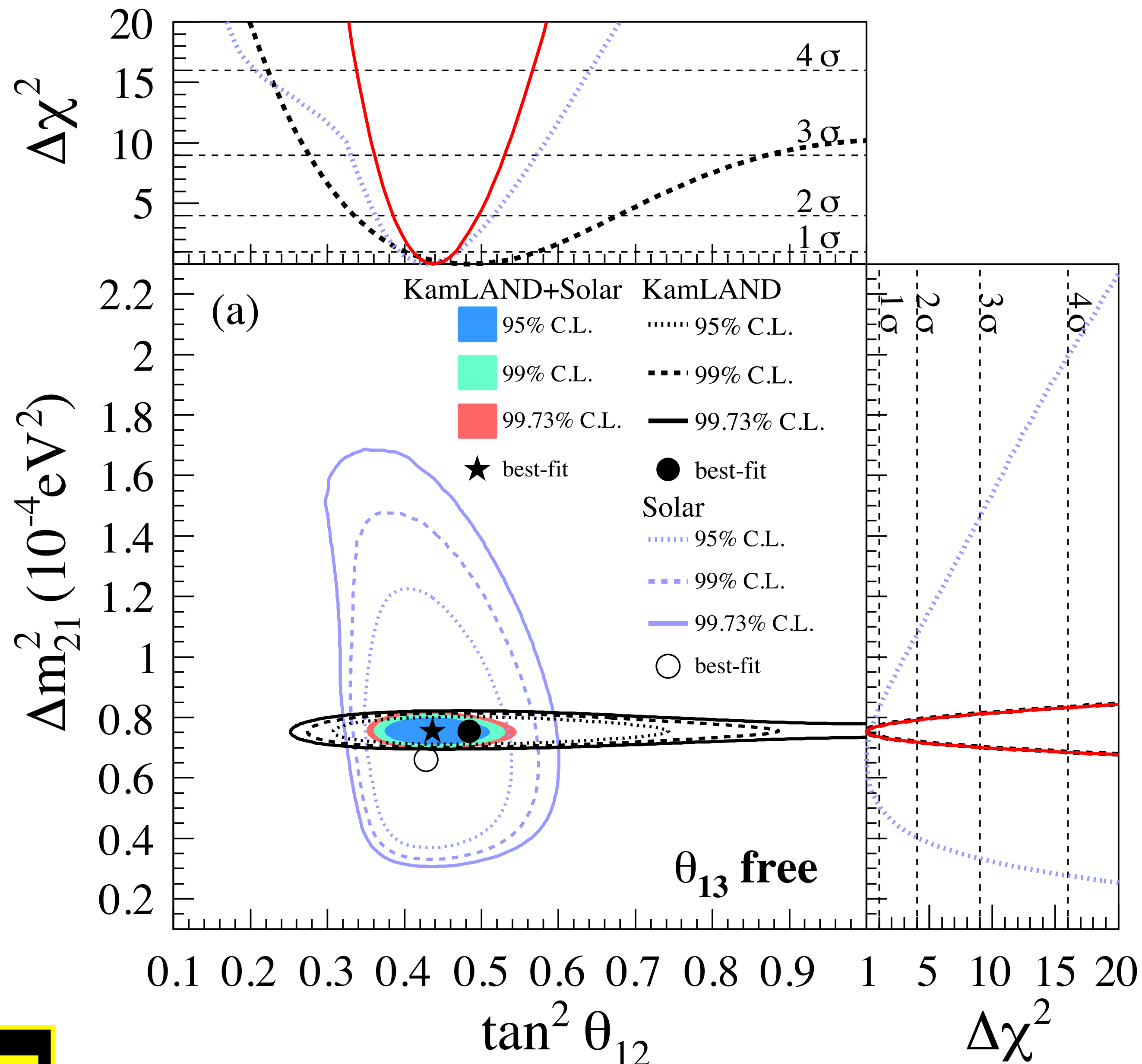
A. Gando et al., Phys. Rev. D 88, 033001 (2013).



ON

ON

~OFF



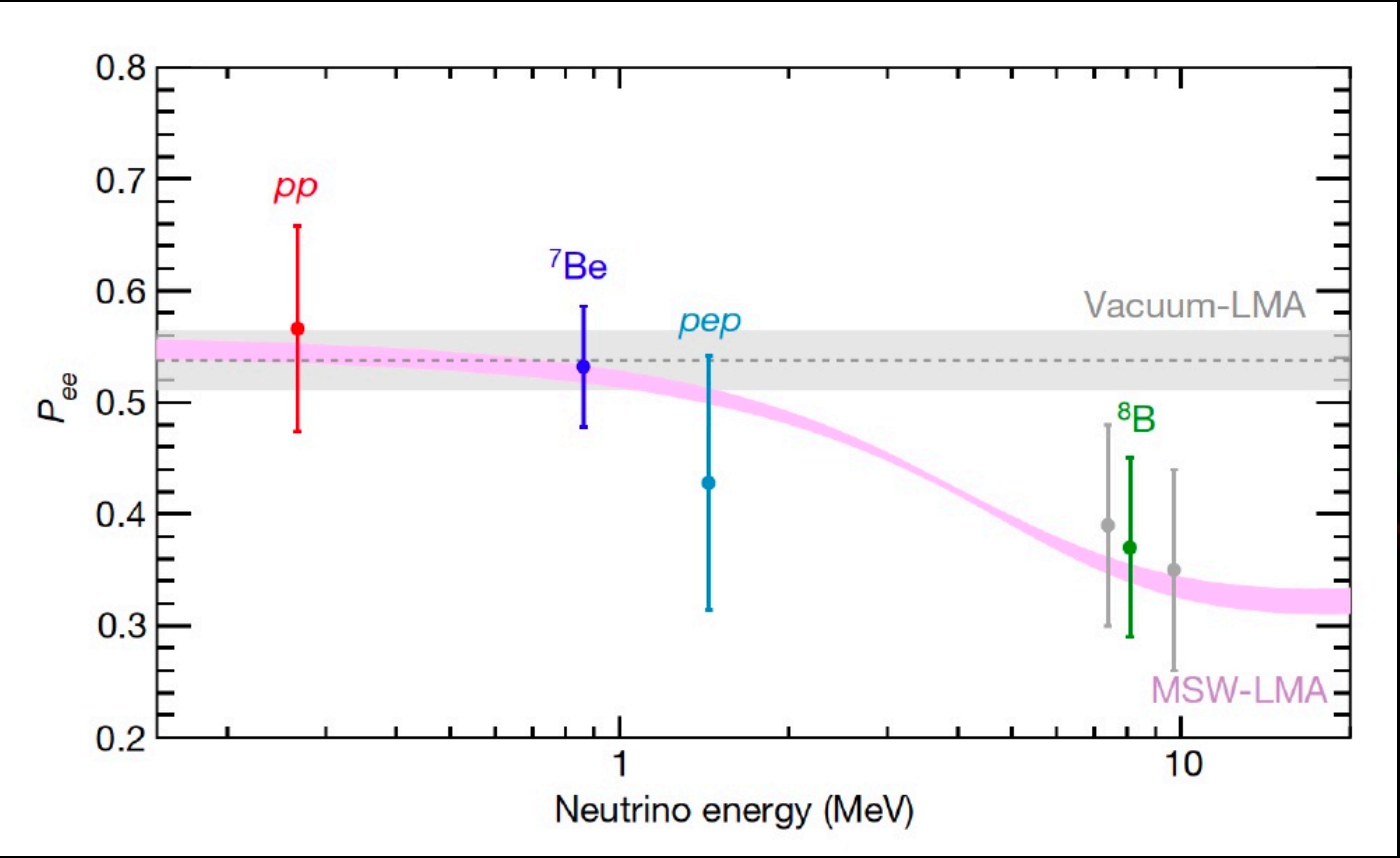
matter / anti-matter consistency (CPT)

Solar (SK⊕SNO) drives **θ_{12}**

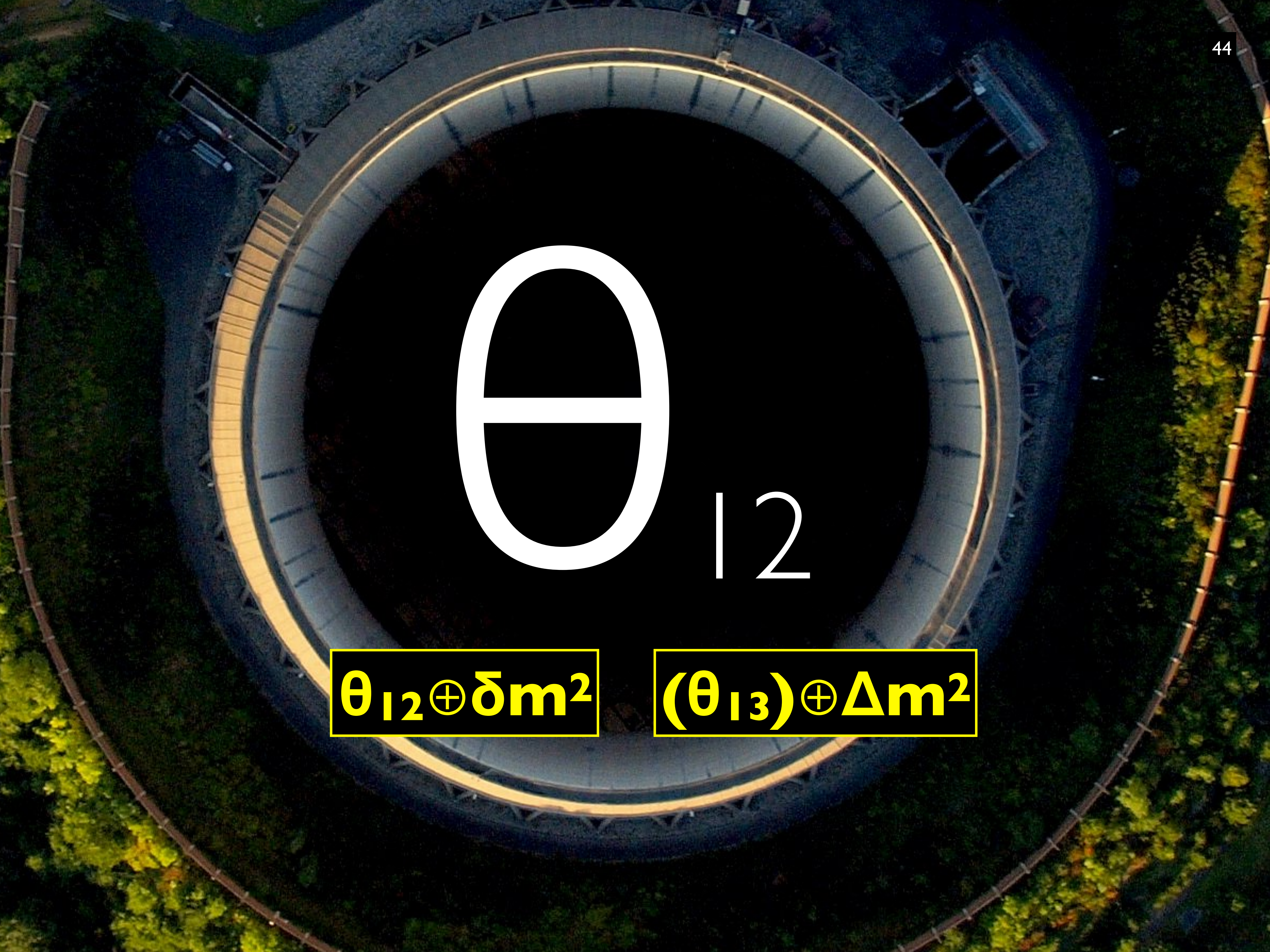
⊕

KamLAND drives **δm^2**

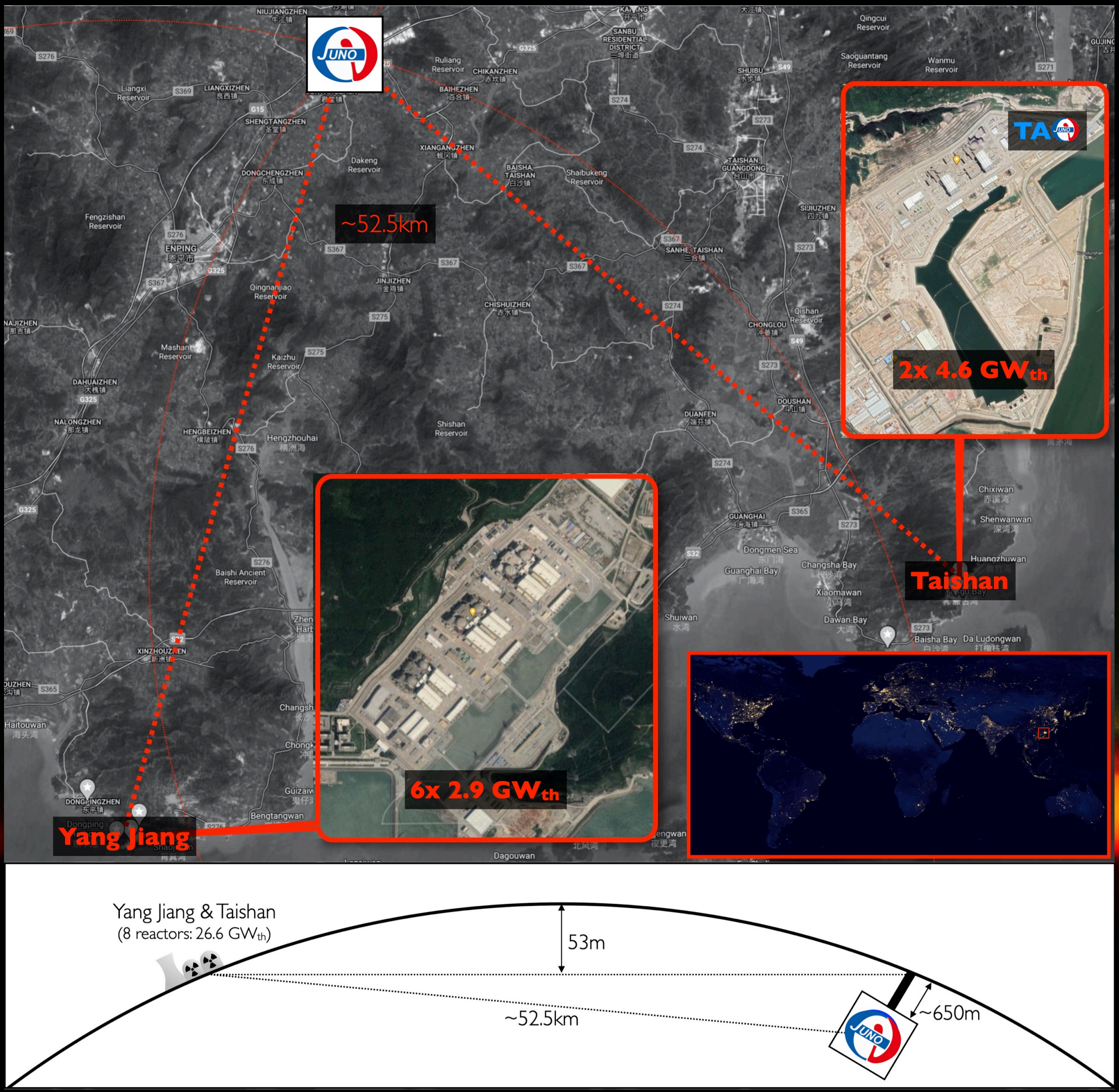
today's knowledge…

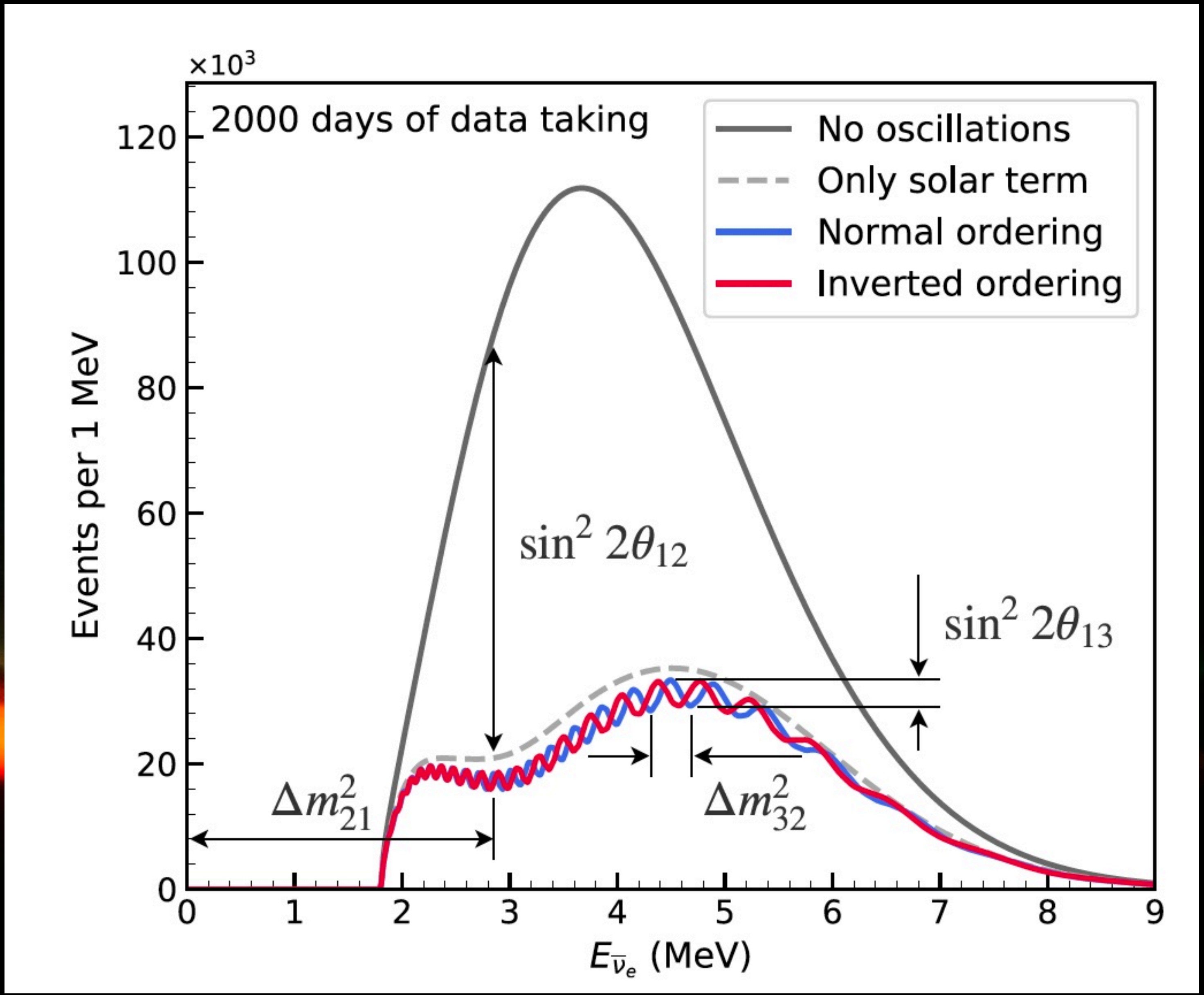


KamLAND + Solar (mainly: SK⊕SNO using ^{8}B and Borexino)→ "solar" parameters


θ_{12}
$\theta_{12} \oplus \delta m^2$
$(\theta_{13}) \oplus \Delta m^2$

JUNO experiment…



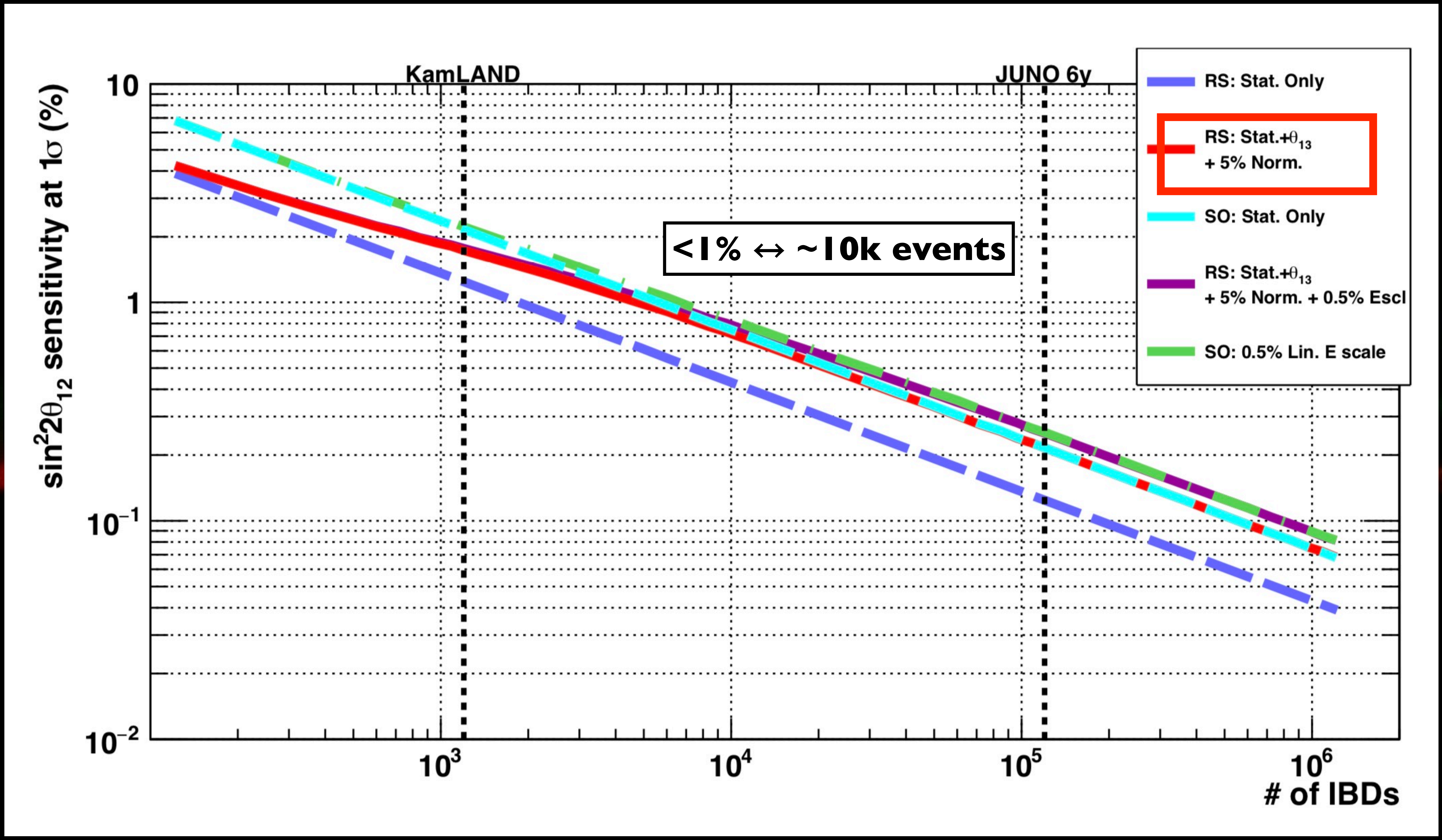


$\theta_{12} \oplus \delta m^2$ (slow)
$\theta_{13} \oplus \Delta m^2$ (fast)

simplistic schedule: **data-taking aim to start by ~late 2022**

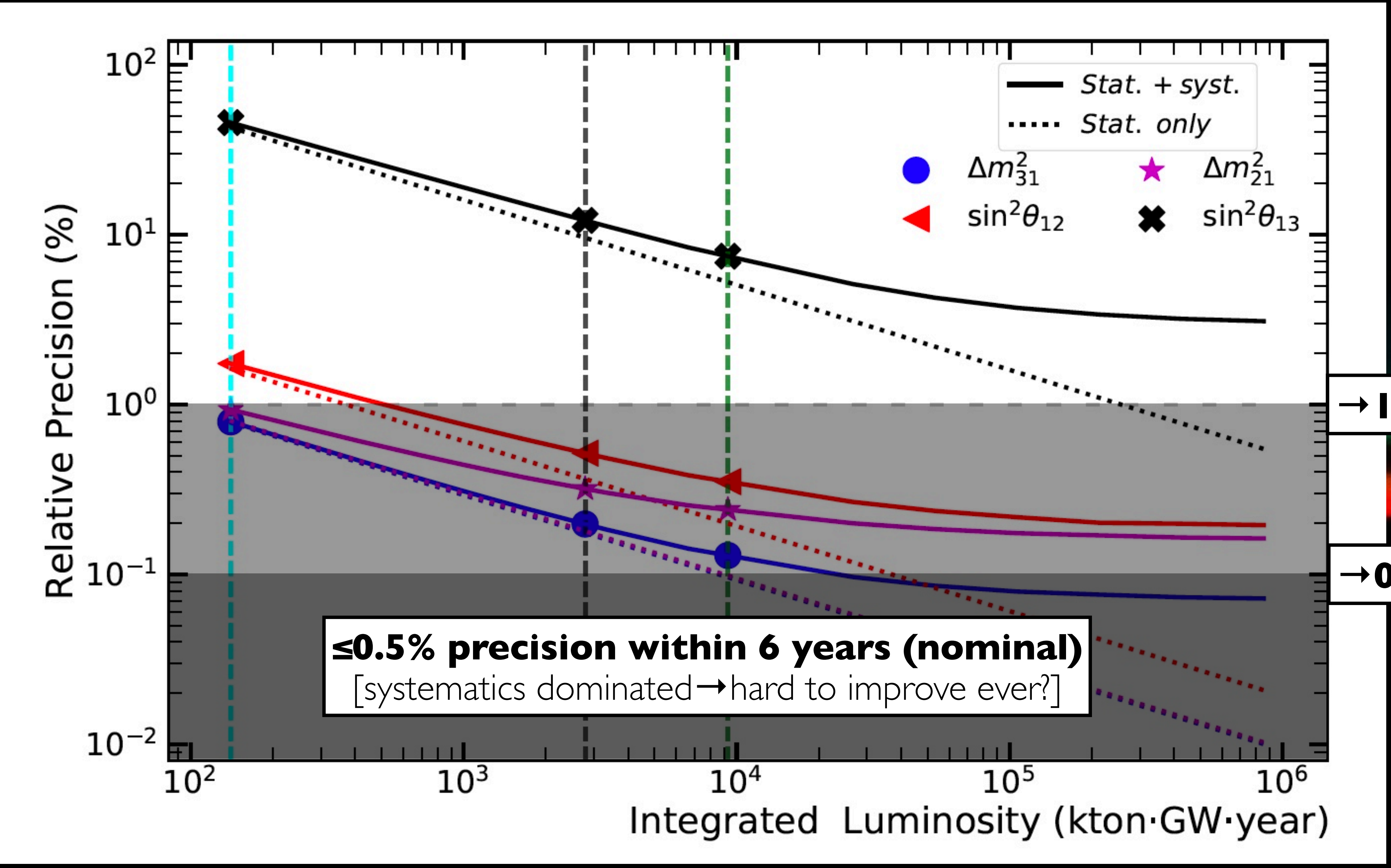
rate+shape sensitivity evolution…

consider all systematics with state of the art knowledge (KL, DC, DYB)



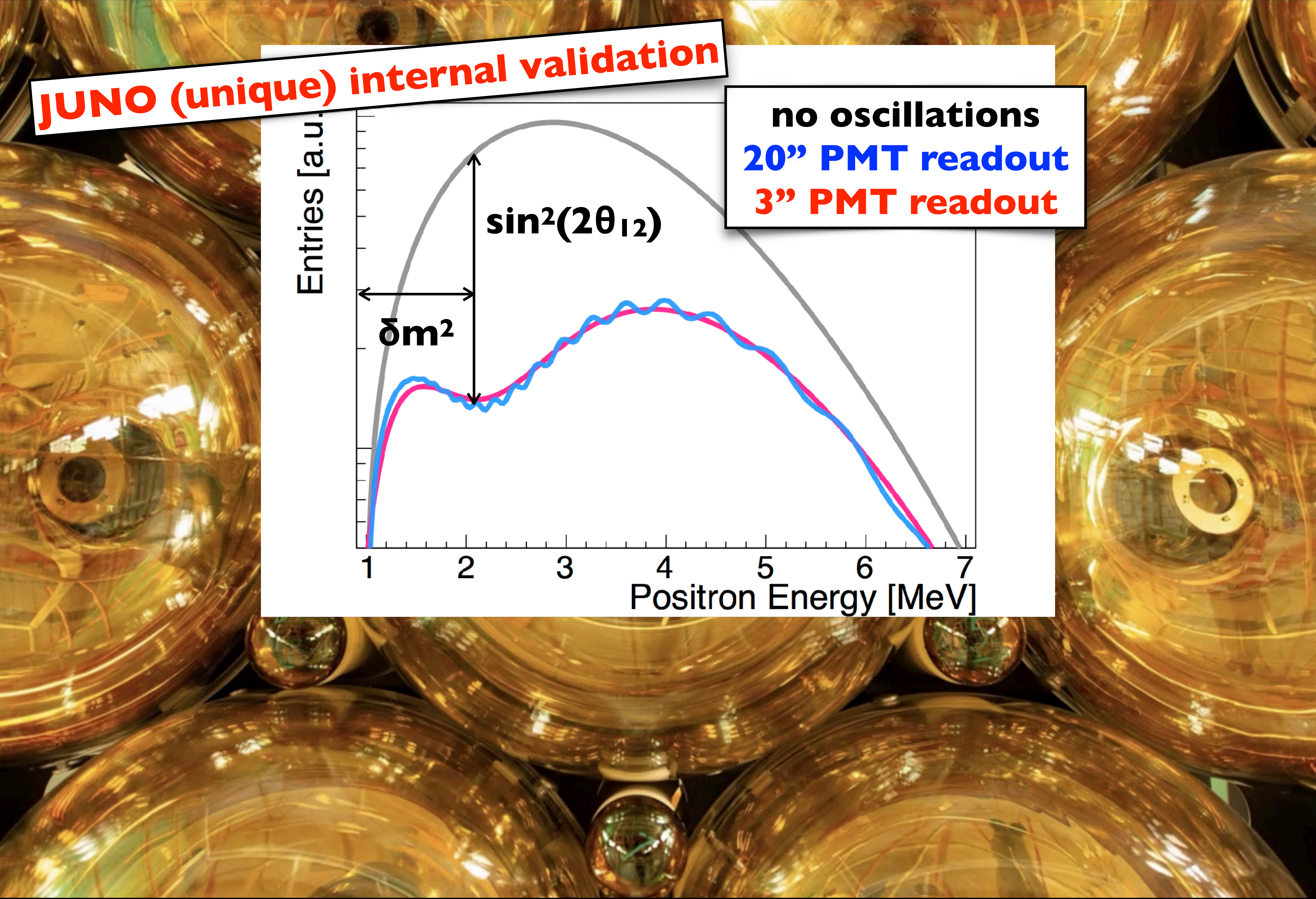
rate+**shape**→ negligible rate uncertainties

JUNO precision (IUPAP)…



	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)



intrinsic redundancy: **2 in 1 detector** (*Dual Calorimetry*)

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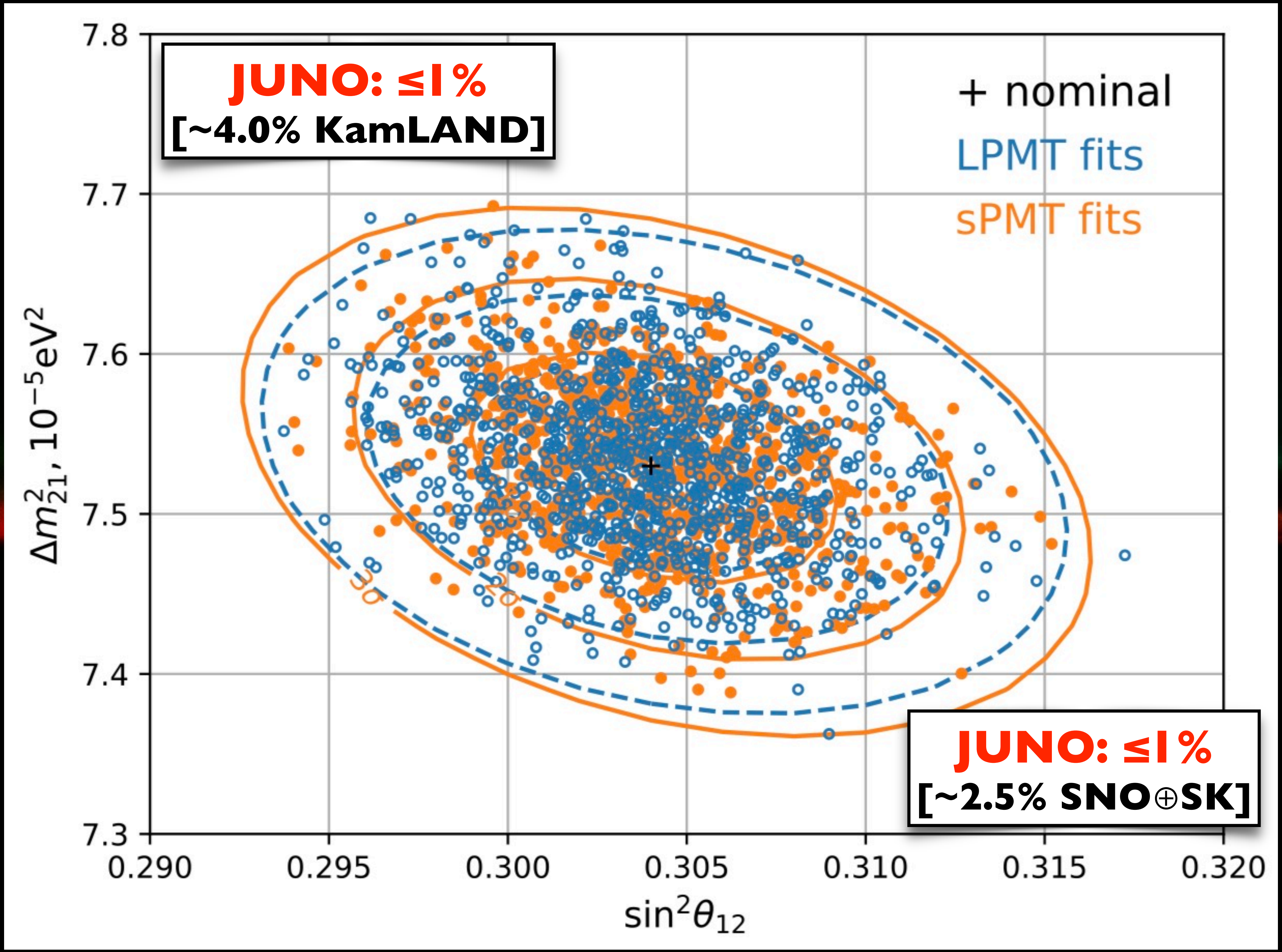
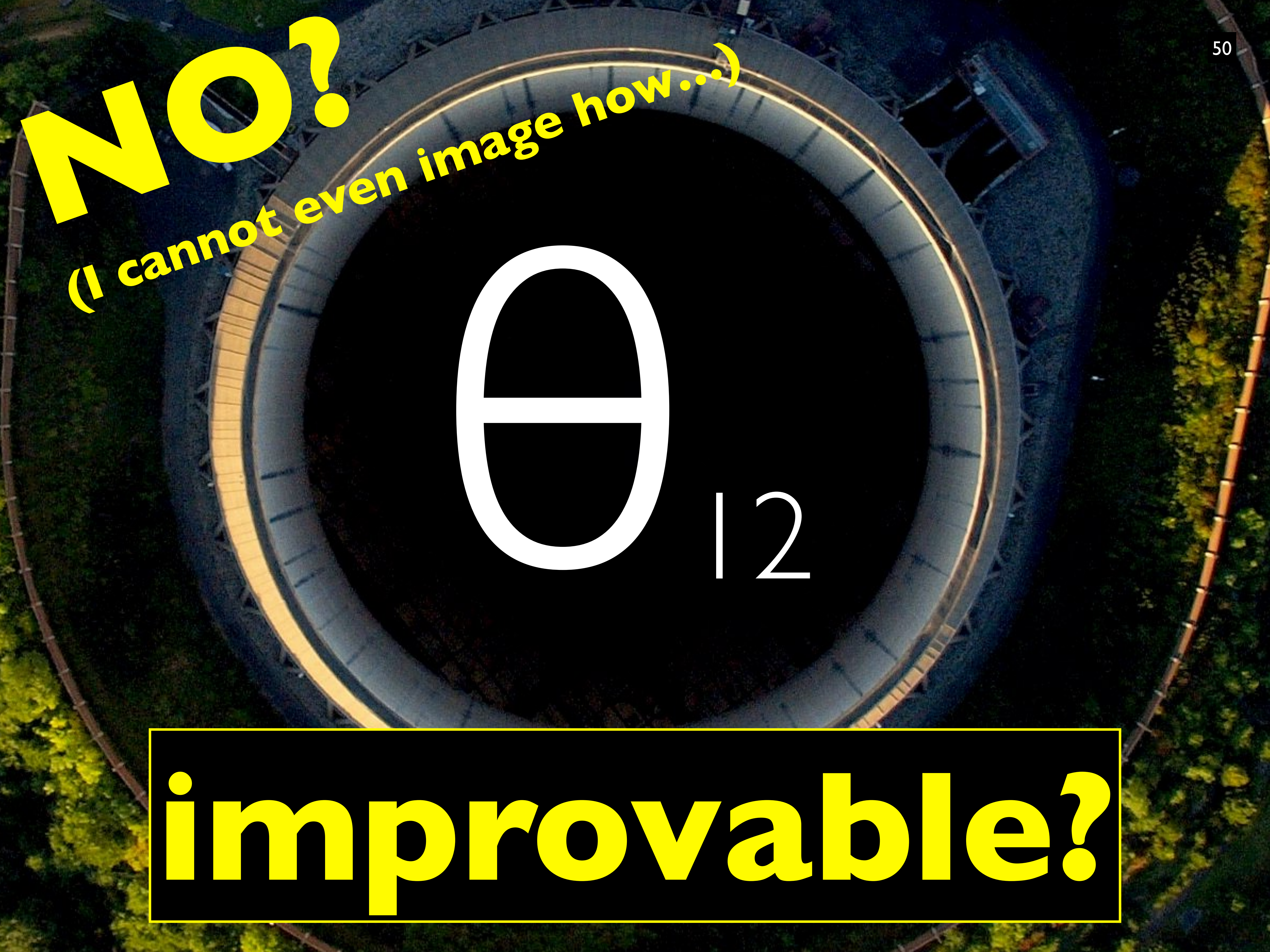
LPMT vs SPMT comparison…



readout explore θ12⊕δm² to per-mille precision (≤1%)


NO?
(I cannot even image how...)
θ_{12}
improvable?

the **Mass Ordering** (matter/vacuum)…

NuFit5.0 ≈ aggregate of the world data

Prepared for submission to JHEP — IFT-UAM/CSIC-112, YITP-SB-2020-21

arXiv:2007.14792v1 [hep-ph] 27 Jul 2020

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.

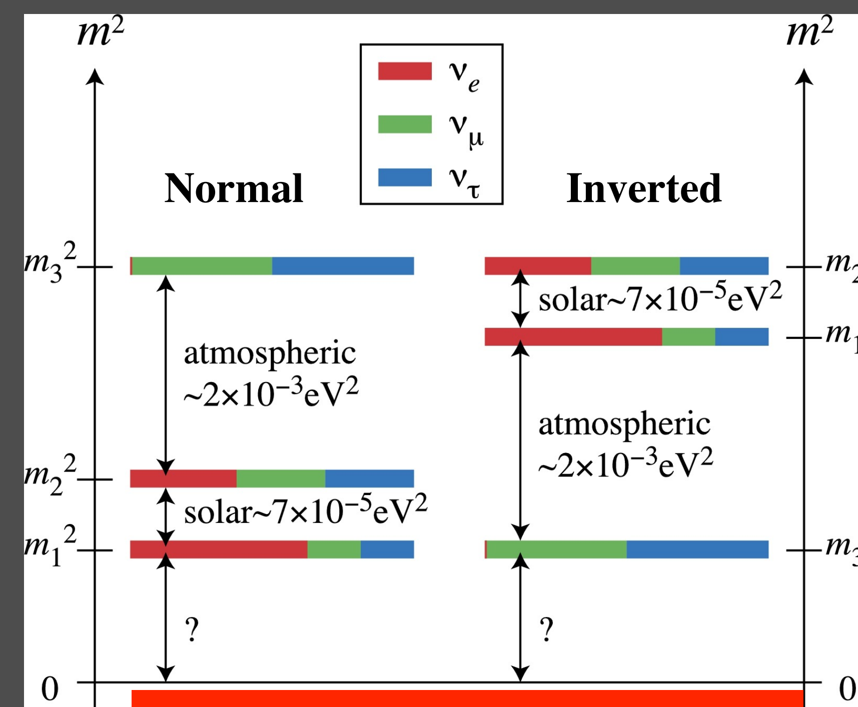
Keywords: neutrino oscillations, solar and atmospheric neutrinos

today's world data leads to…

NMO favoured to ~2.7σ (2020)

main experiments so far…

- SK
- NOνA⊕T2K
- DC⊕DYB⊕RENO

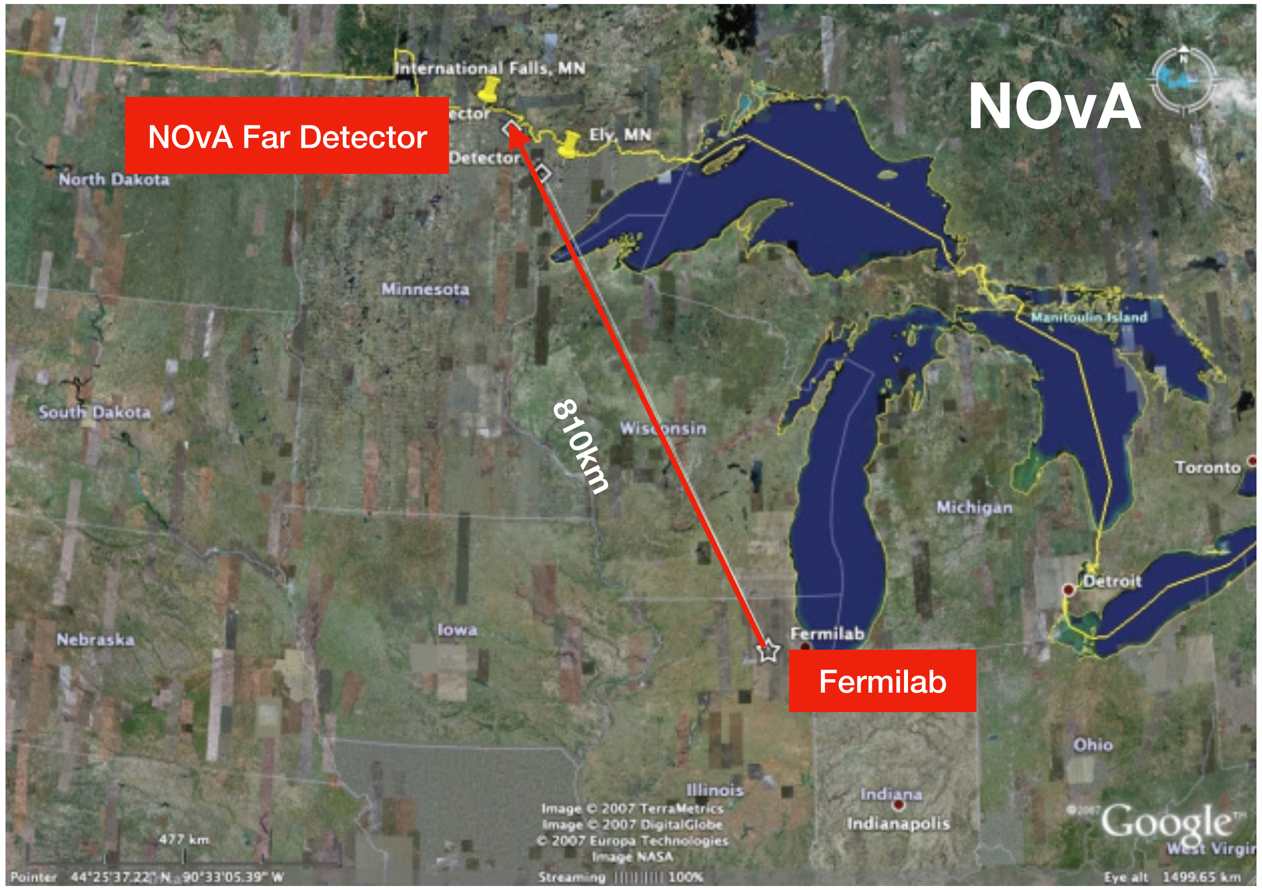


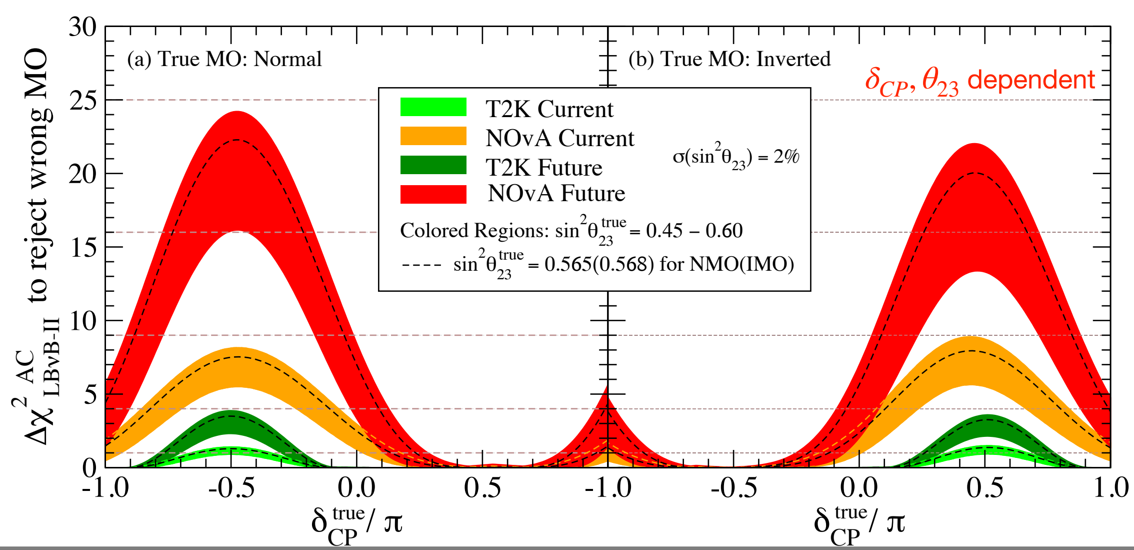
NO prediction by SM!!

NuFit consistent with other global-fit results by **Bari**, **Valencia**, etc groups

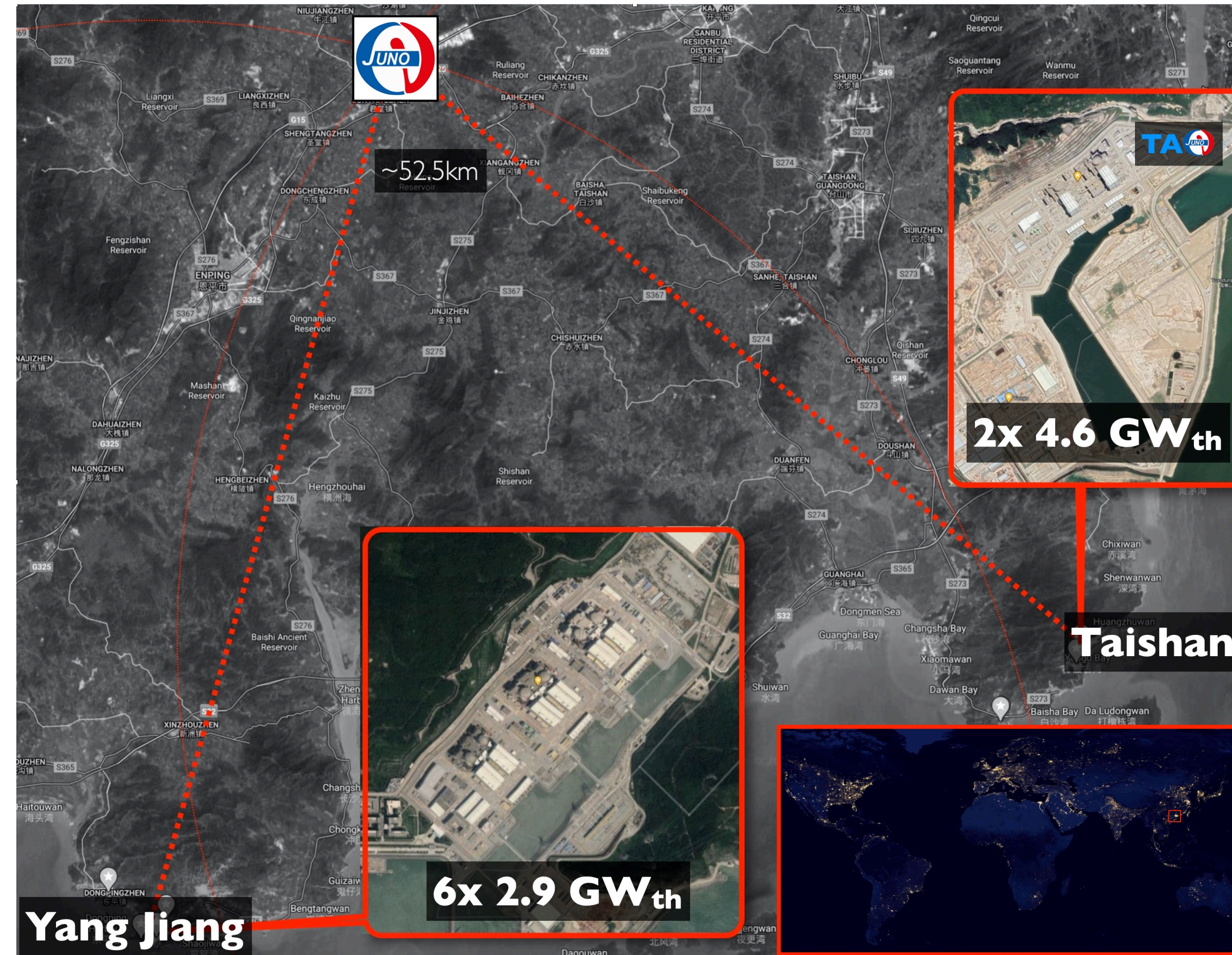
today's MO status…

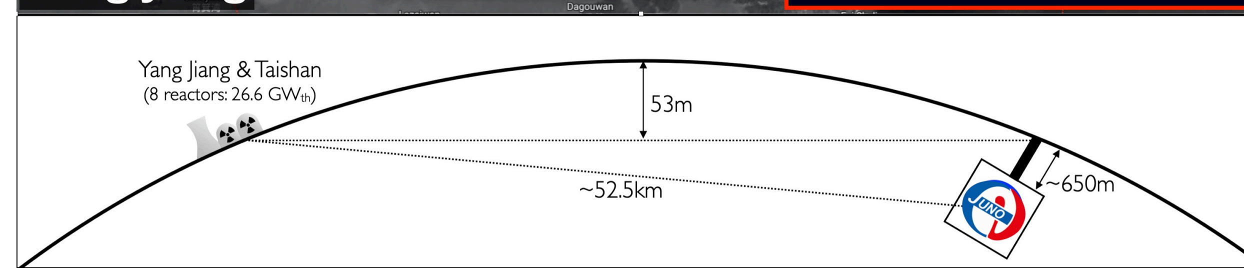
Matter Effects Oscillations
(CP experiments→ ***fake*** CP-violation)





Vacuum Oscillations
(no CP-violation)





arXiv:2008.11280

only 2 ways to measure…

accelerator experiments…

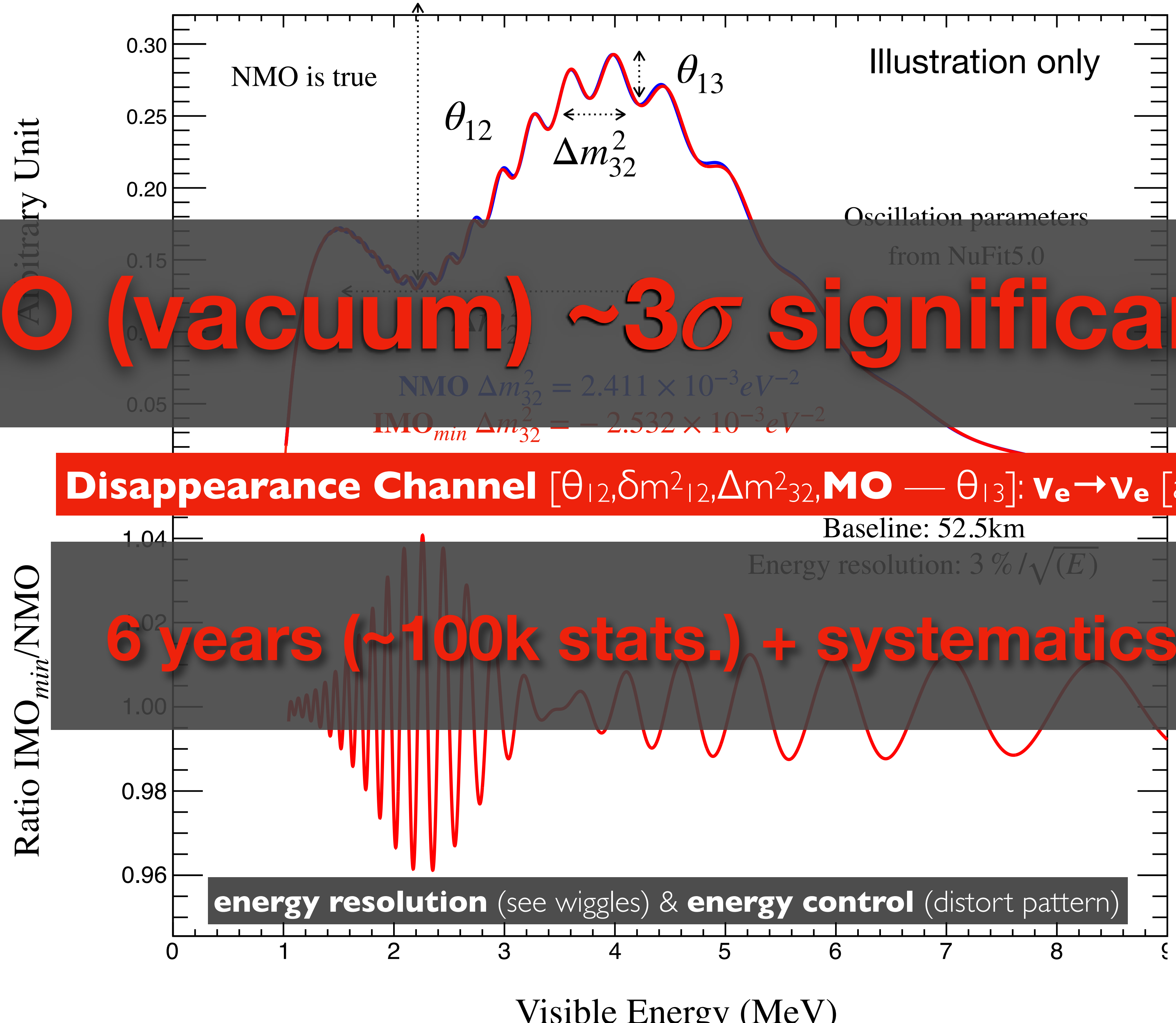
Disappearance Channel: $\boldsymbol{\nu_\mu \to \nu_\mu}$ "survival probability"

$\Longrightarrow$ measure [$\boldsymbol{\theta_{23}, \Delta m^2_{32}}$] — this is **MO blinded**

Appearance Channel: $\boldsymbol{\nu_\mu \to \nu_e}$ [done for both ν and anti-ν — **beam-mode**]

$\Longrightarrow$ measure [$\theta_{23} \oplus \theta_{13}$, $\boldsymbol{\delta_{CP}}$, **MO**] — strong dependence on **MO (matter effects)**

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

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

the JUNO (hardest) way…

Earliest Resolution to the Neutrino Mass Ordering?

Anataël 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]

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

when MO will be **resolved (≥5σ)?**

which experiments? (i.e. the minimal set)

what physics behind the resolution**?**

MO (binary outcome) be used to explore **BSM?**

See also arXiv:2009.08585 / arXiv:2107.12410

in 2020…

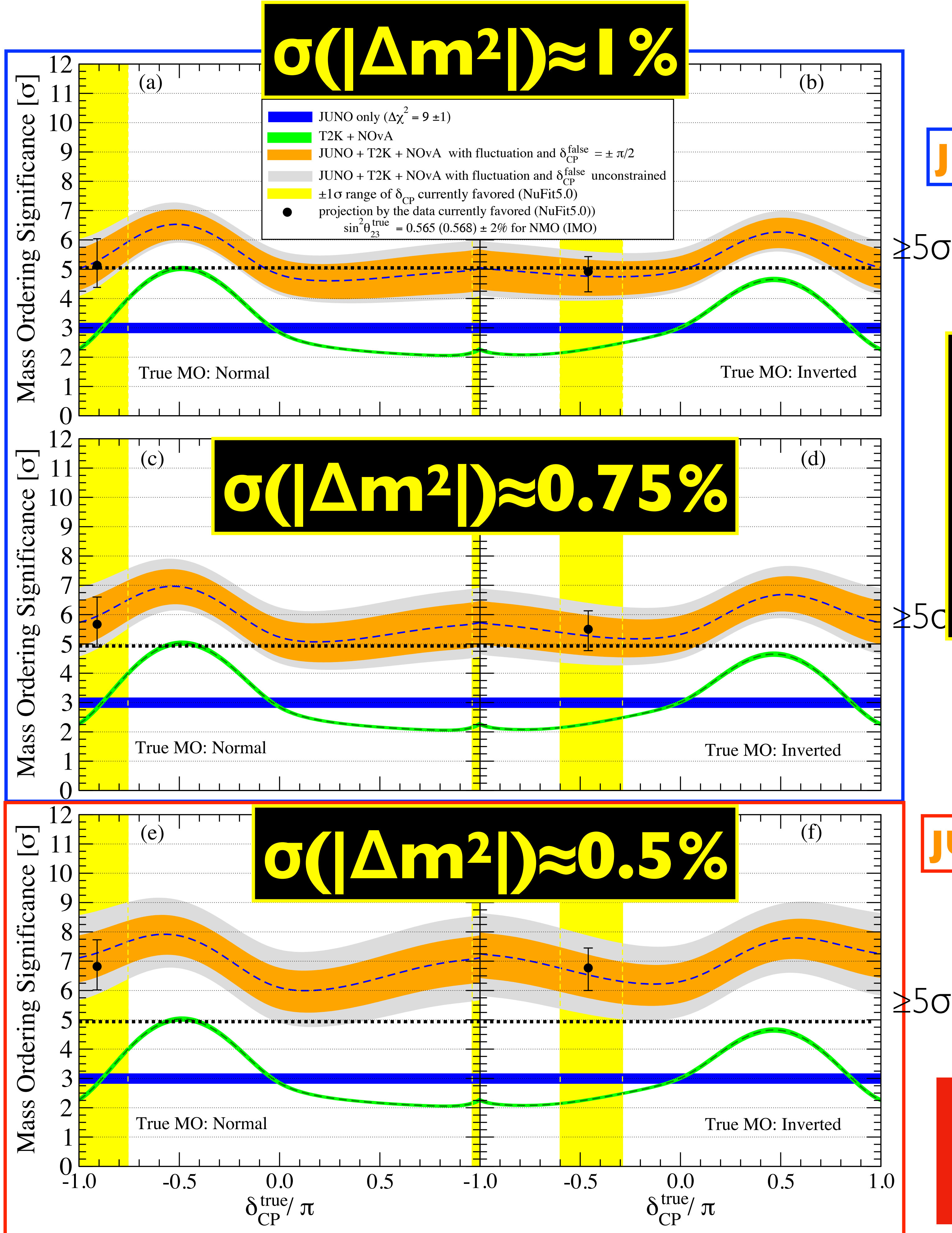
- **Super-Kamiokande (atmospheric) — no**
- **T2K (≤2024) — no**
  little **≤2σ**→ T2K designed for cleanest **δ(CP)**
- **NOvA (≤2026) — unlikely**
  not bad !! **≤4σ** (by 2026) — if lucky on δ(CP)
- **JUNO (≥2022) — unlikely**
  not bad !! **~3σ** (by 2028) — careless of δ(CP)!!

by 2030…

- **DUNE(≥2028?) — yes!!**
  stunning >5σ (2 years) — careless of δ(CP)!!
- **Hyper-K(≥2028?) — no!**
  (like T2K) targets the cleanest δ(CP)
  [minimal matter effects]
- **atmospheric neutrino — unlikely** (extra info)

NO prediction by SM!!

resolution (≳5σ) anybody…?



JUNO⊕NOvA⊕T2K

powerful synergy

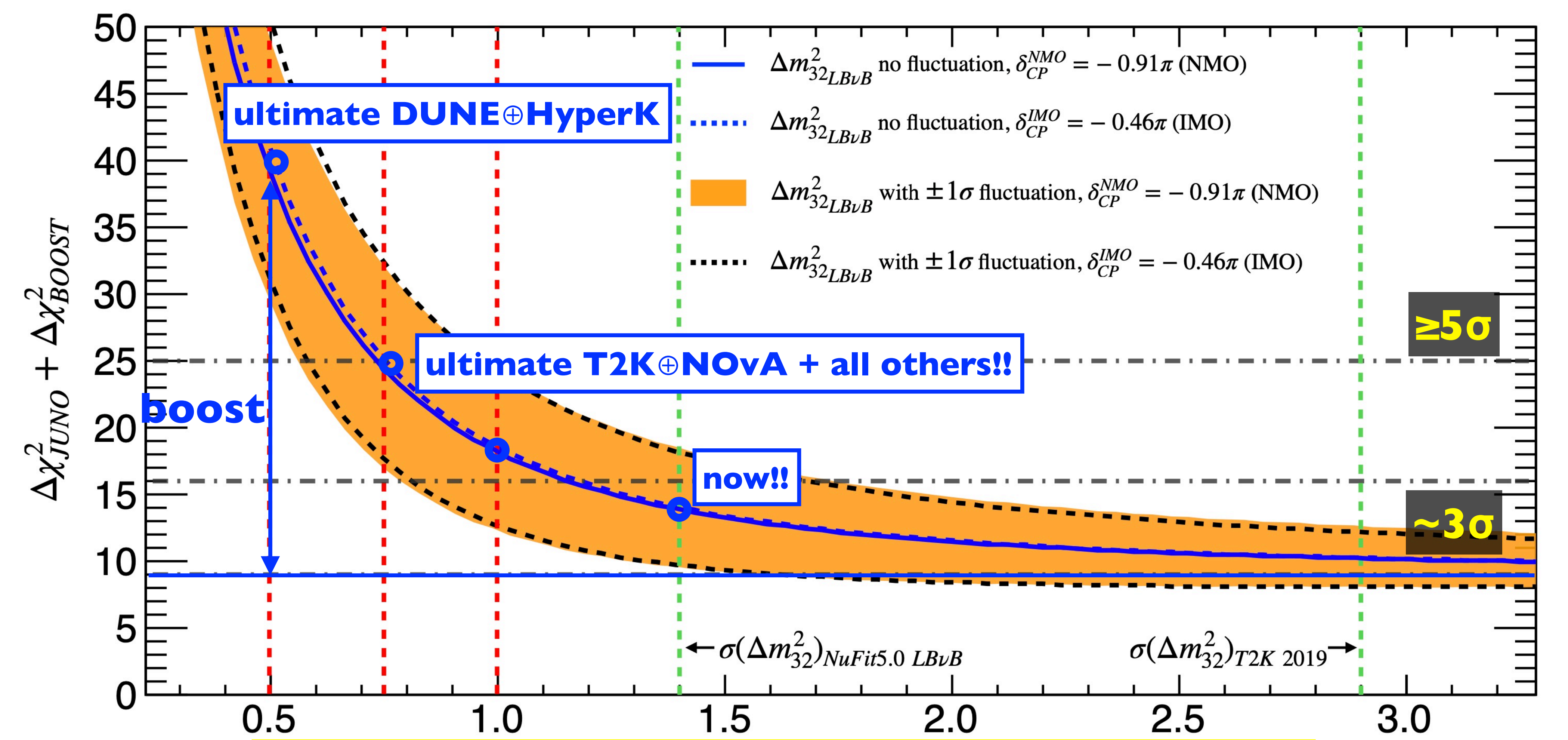
the **accelerator's σ(|Δm²|)** drives a **boost** in **JUNO's MO sensitivity!**

JUNO and Disapperance HK⊕DUNE

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

powerful synergy JUNO vs NOvA⊕T2K: high precision disappearance Δm^2_{32}…

JUNO: unique vacuum oscillations

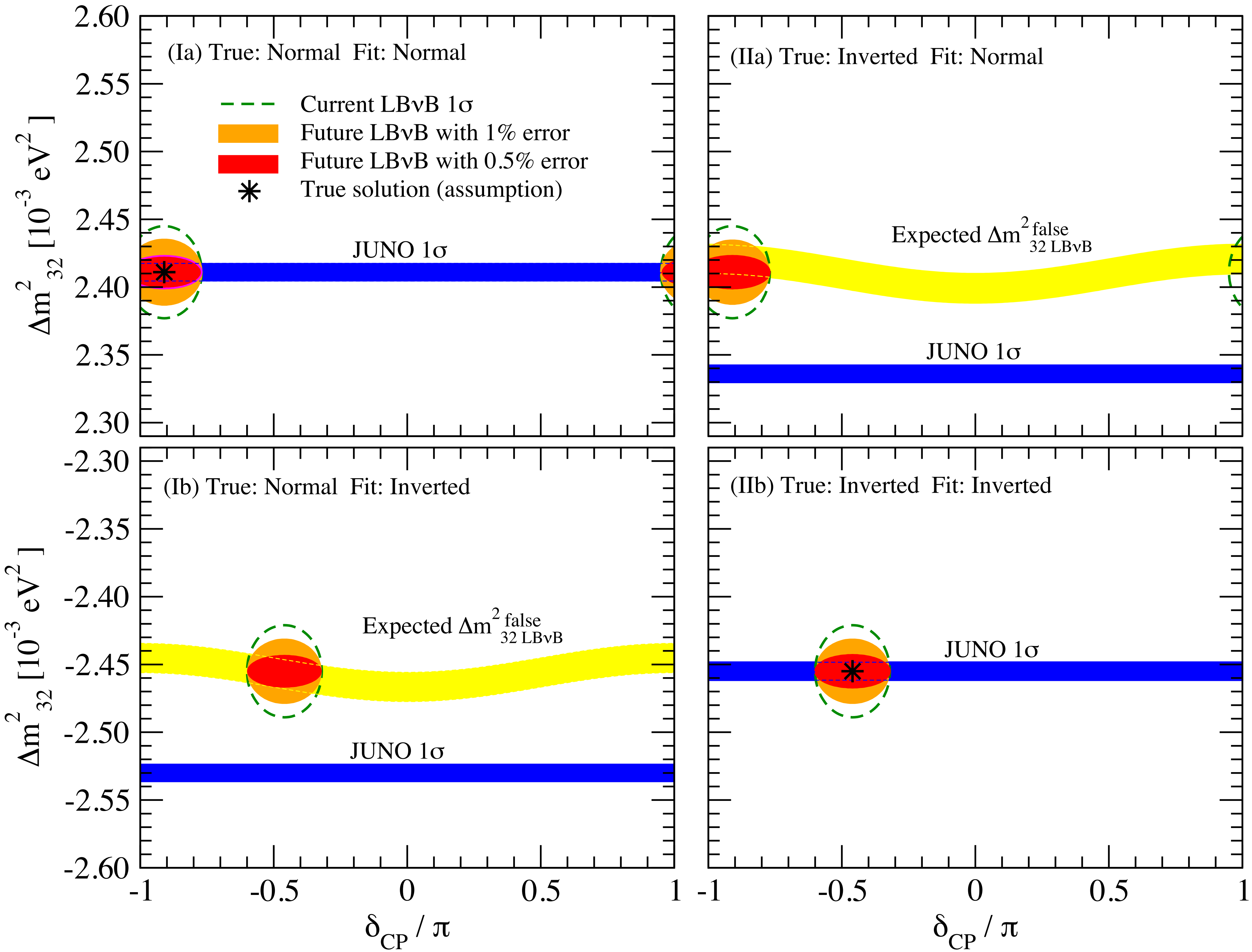


accelerator's σ(|Δm²|) (%)

JUNO MO sensitivity **boosted 3σ→≥5σ**
[leading order effect]

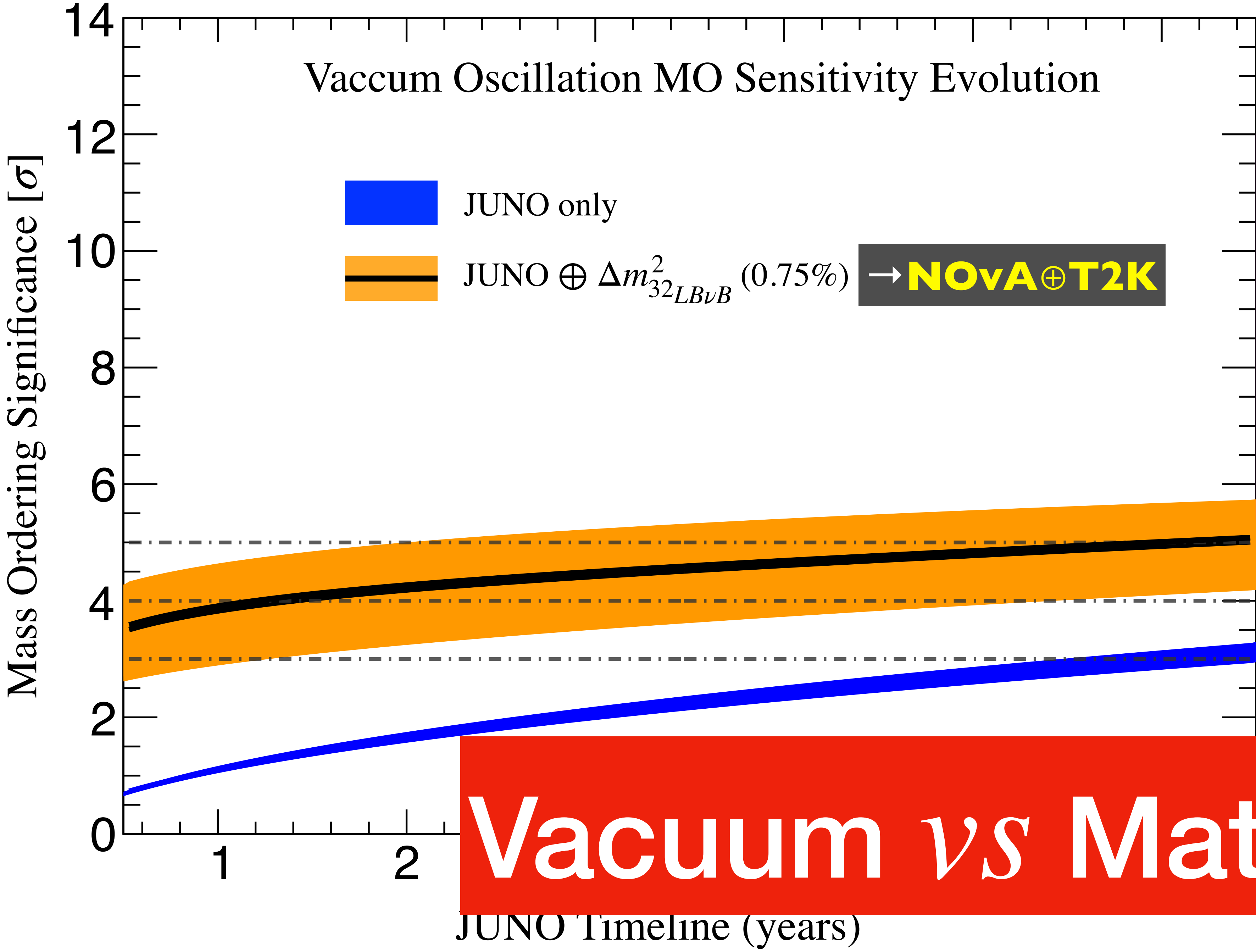
physics: extra discriminator due to **Δm^2_{32} solutions** slightly different (i.e. synergy) between reactor-accelerator but **only one true MO solution** forces equality
→powerful boosting with precision of Δm^2_{32}.

Mass Ordering JUNO (vacuum) boosting…



synergy JUNO⊕LBνB…

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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by 2030, mixing @ ~1% level…
(**no unknowns**)

the remaining challenges…

(my view — likely biassed somewhat)

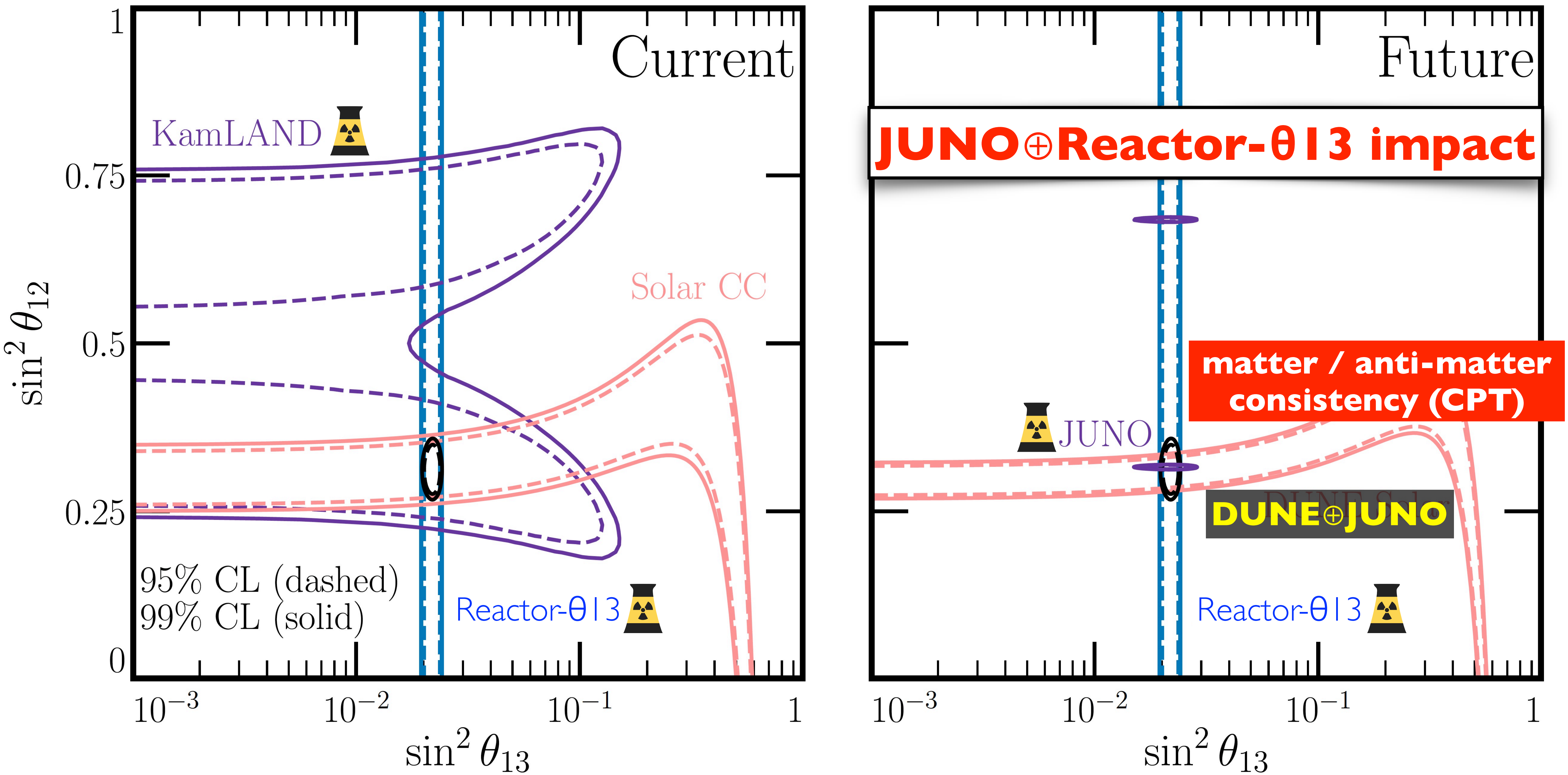
- **reactors:** likely **the most precise neutrino source** — tool for research — since the 50's (improving)
  - **improve absolute knowledge precision** (ex. flux cancels by <u>multi-detector</u>)→**discoveries?**
  - intrinsic limitations (no appearance, etc)→ **empower synergies with accelerators**, **solar**, etc.

- **θ12⊕δm² precision:** is likely hard to improve (**few per mille**) after JUNO — world best ≤1year of data

- **θ13⊕Δm² precision:** still improve for **θ13** — nobody knows how to!! [→**SuperChooz?**]
  - **θ13** is <u>one of the most intriguing parameter</u> of the PMNS (tiny term among many large terms)
  $\Longrightarrow$ **pointing to a feature(s) or symmetry? certainly this is BSM territory…**
  - understand meaning of **structure of the PMNS** (i.e. large mixing) — very different from CKM

- **JUNO⊕Accelerators:** smost powerful Mass Ordering measurements (2 independent):
  - ***vacuum*** — driven by **JUNO (unique)**
  - ***matter*** — driven by **DUNE (by far)**

impact in **θ13-θ12** plane…



by 2030, θ12-θ13 sector fully dominated by <u>reactor experiments</u>
(today, it's rather true but some solar contribution)