ν oscillations

(towards CP-violation)

France-China PPL workshop — May 2018
CPPM Marseille (France)

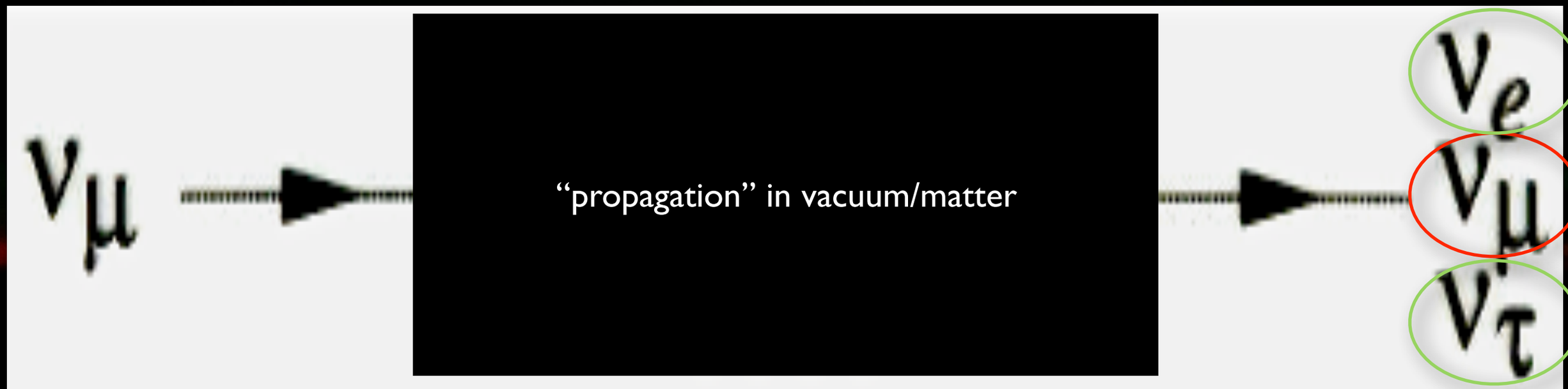
Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

neutrino oscillations manifestation…

Let's take ν_μ (a popular example) to start with…

disappearance
appearance



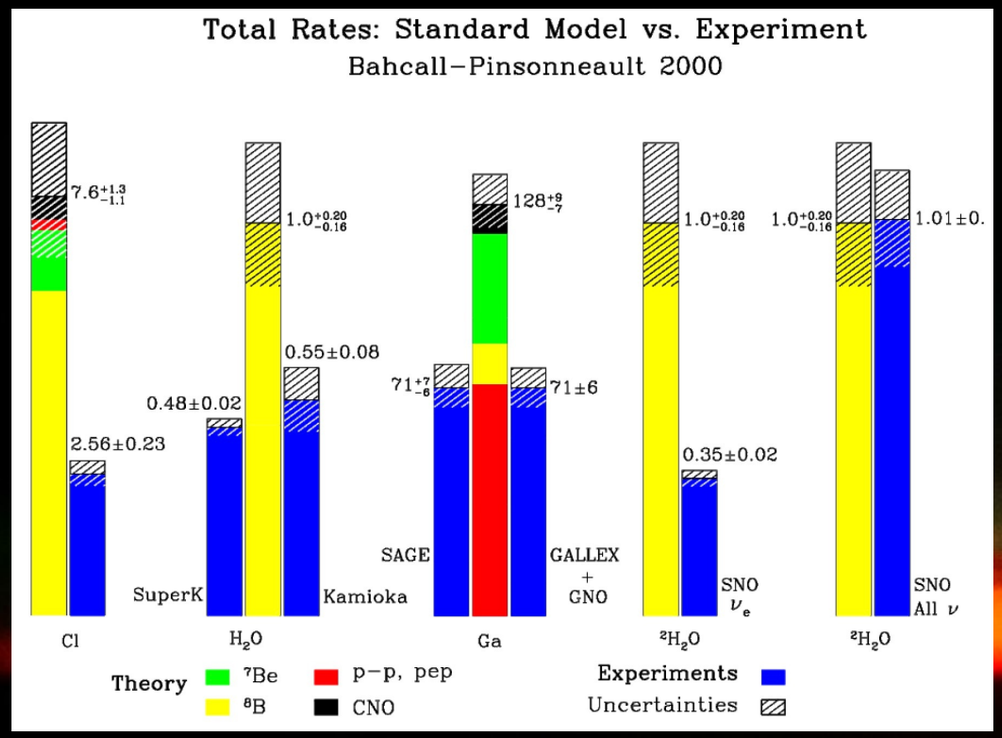
observation: both **disappearance** (the **anomalies**) & **appearance** (July 2013) have been seen

all observations (most!) consistent with 3ν oscillation model

(50 years quest) the historical starting point…

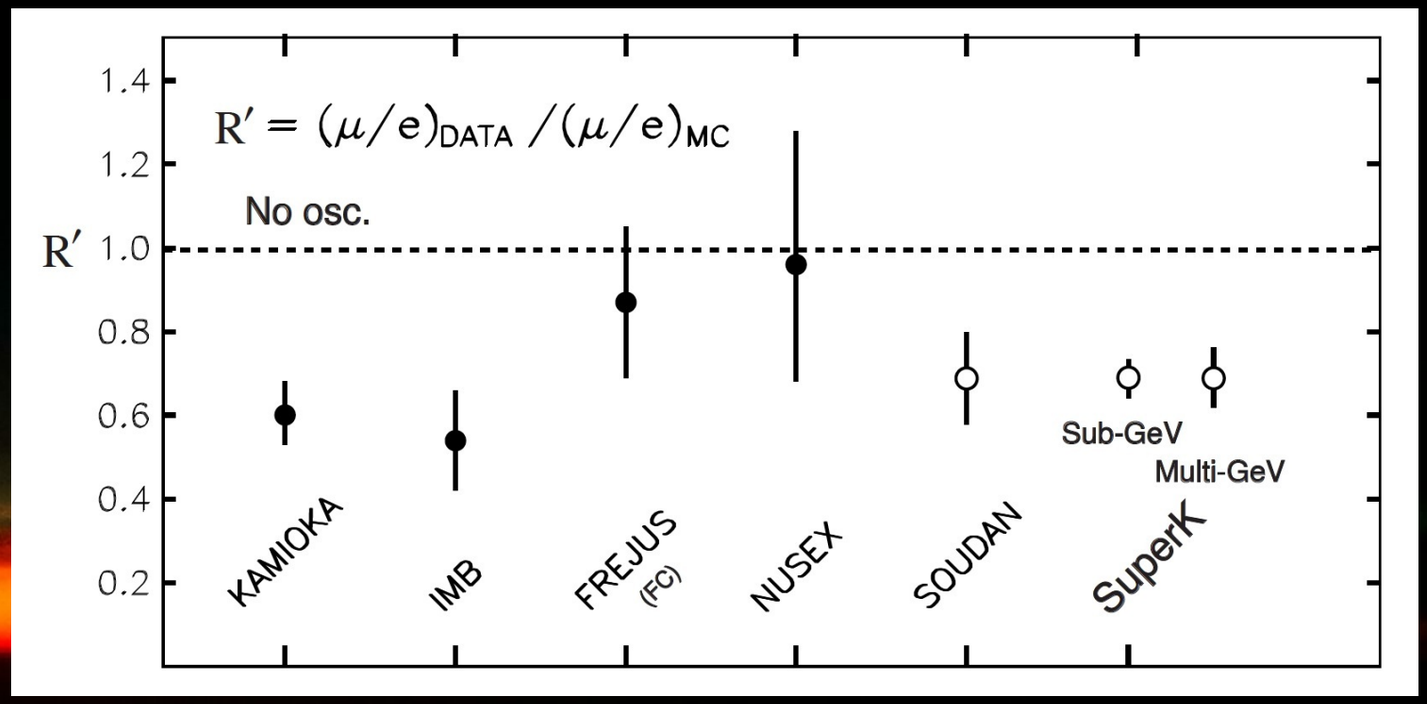
Solar Neutrino Anomaly

(deficit of solar-ν_e's)



Atmospheric Neutrino Anomaly

(deficit of atmospheric-ν_μ's)

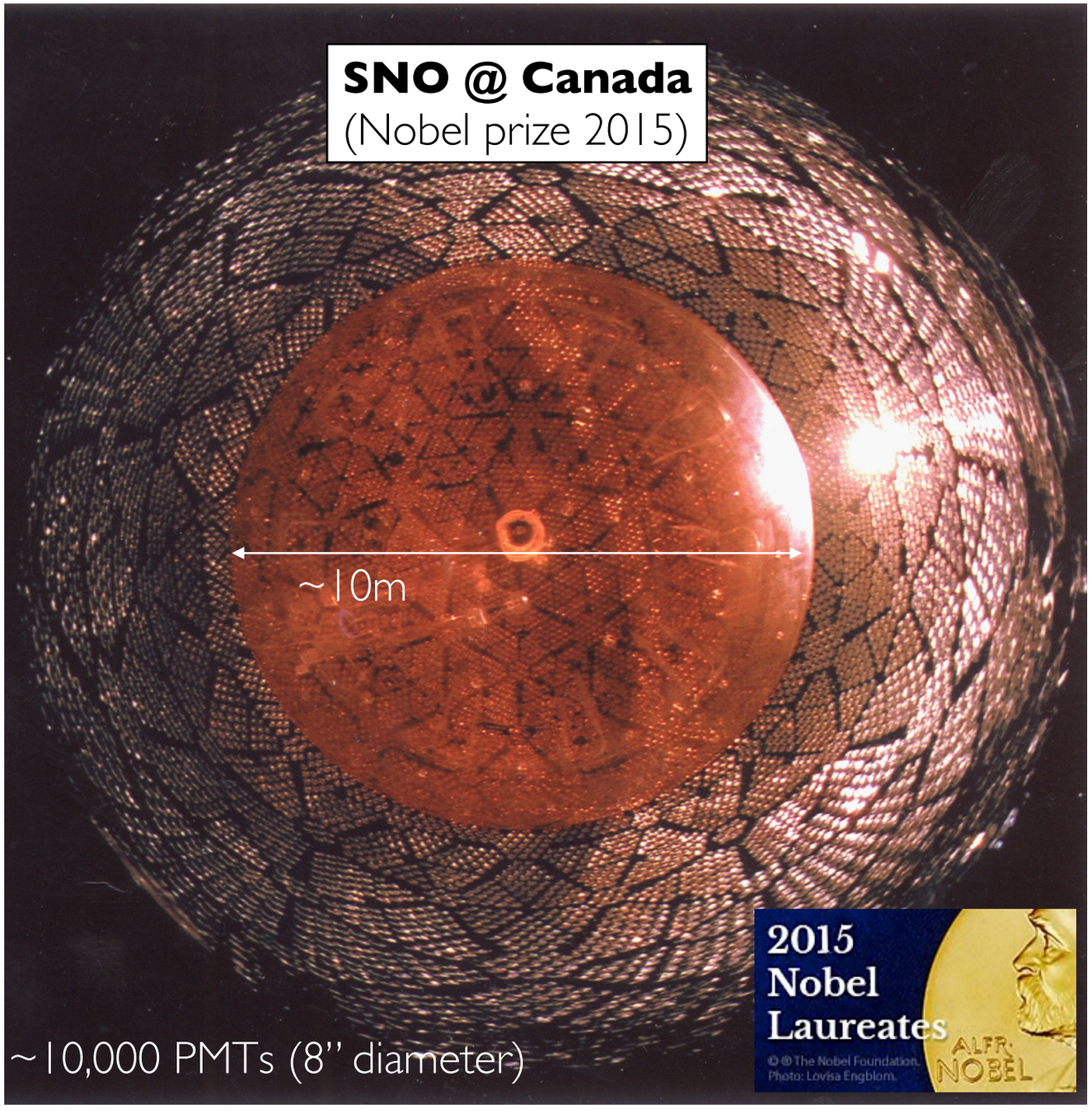


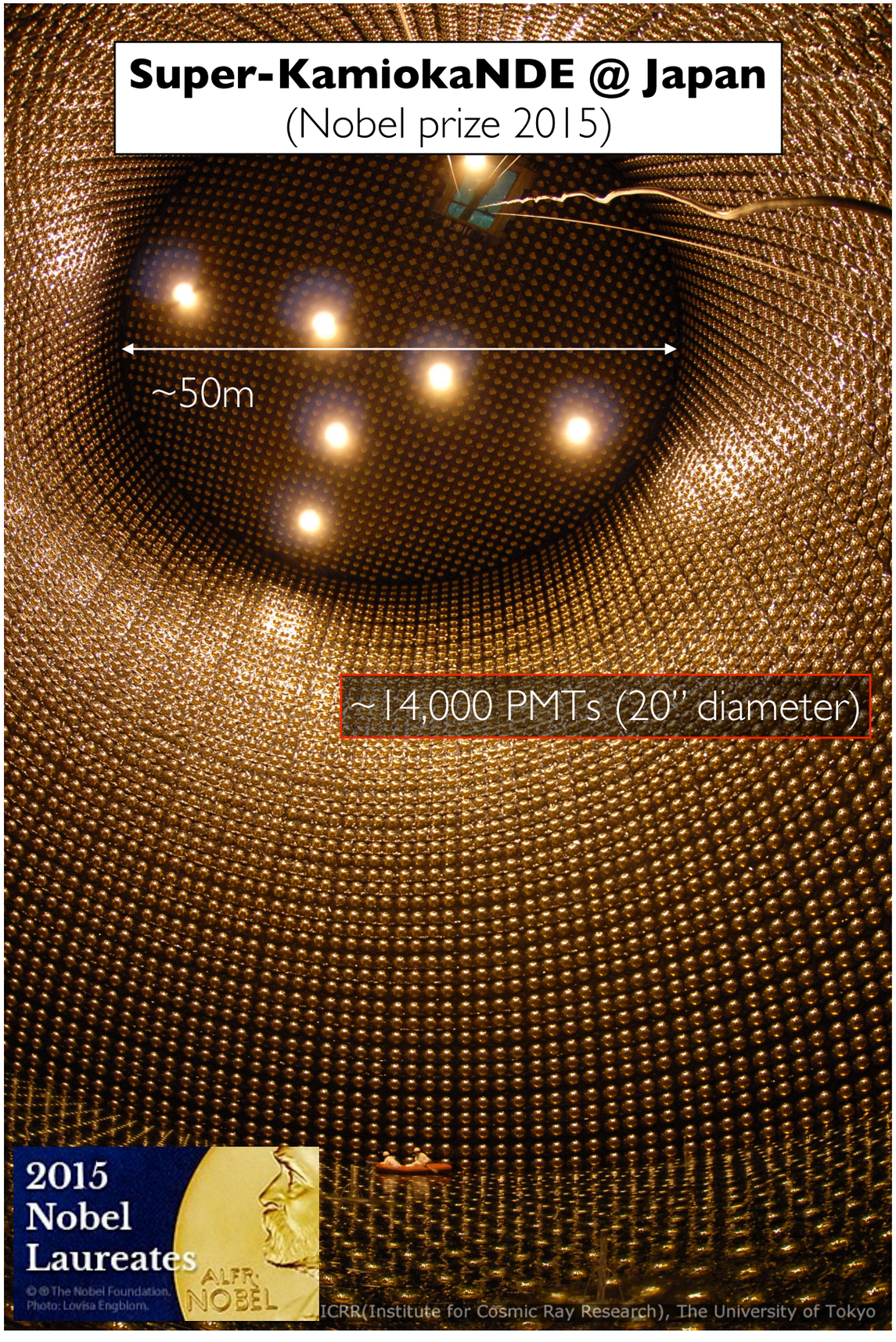
$\Longrightarrow$ both manifestations (or facets) of the one phenomenon **Neutrino Oscillations**

major implications to ν's phenomenology…

- **ν's are massive** → like other fermions [$\Longrightarrow$ why so light?]
- **mixing in leptonic sector** → more symmetrical quark-lepton behaviour

neutrino anomaly solution: **neutrino oscillations**...





many experiments: quest over ~50years
(huge experiments & theoretical challenge)

much owned to the Cowan+Reines technique
(discovery)

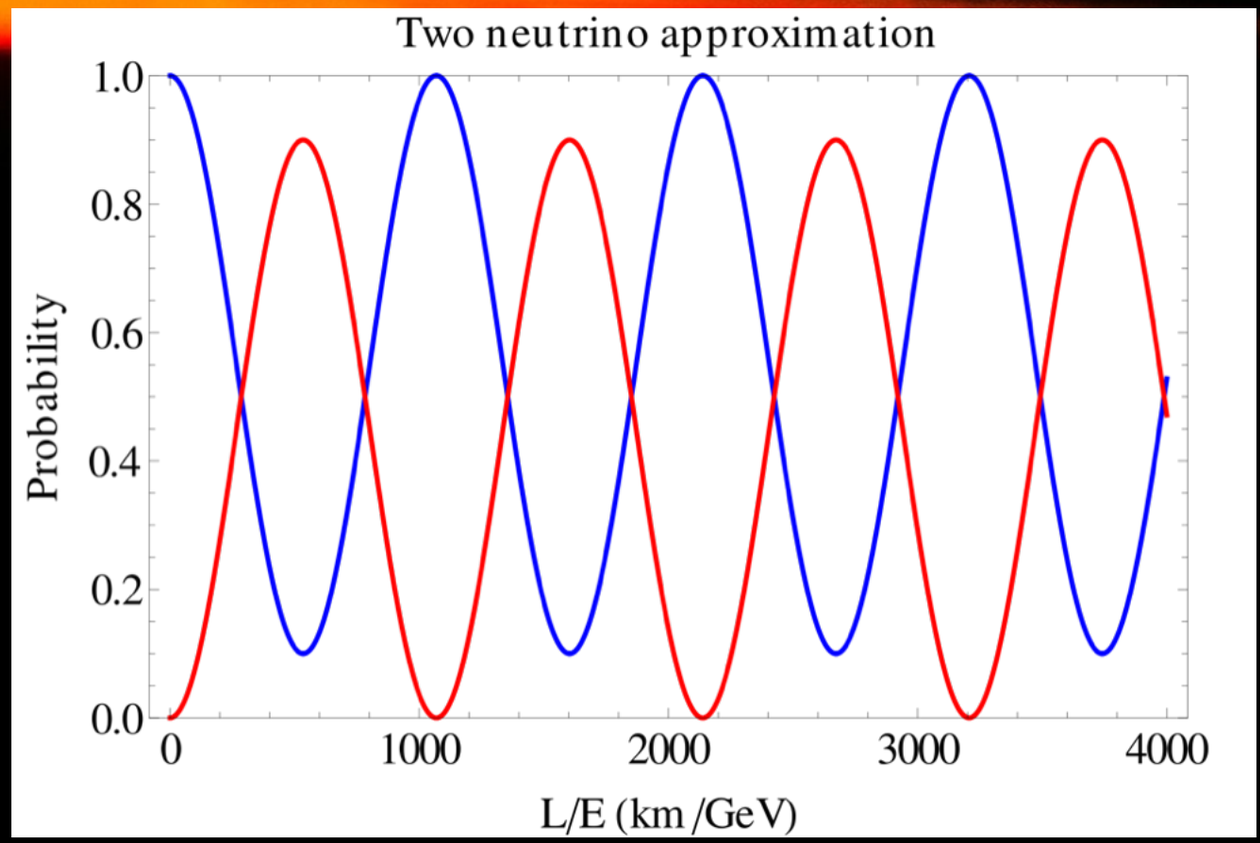
ingredients for neutrino oscillations…

leptonic Mixing (**θ**) ⊕ Non-degenerate **mass** spectrum (**Δm²**) = Oscillation Probability **P=*f*(θ,Δm²)**

Upmns matrix (à la CKM)	**quantum interference** (macroscopic)

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

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



"mixing": a common phenomenon…

$$\nu_\alpha = 0.5 \bullet \nu_1 + 0.5 \bullet \nu_2$$

"atmospheric" $\Longrightarrow$ θ_{23}~45° | θ_{13} & "dirac" δ_{CP} | "solar" $\Longrightarrow$ θ_{12}~33°

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{matrix} \Delta m^2_{31} \\ \text{sub-leading} \end{matrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{matrix} \Delta m^2_{31} \\ \text{sub-leading} \end{matrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{matrix} \Delta m^2_{21} \end{matrix}$$

atmos+LBL(dis) | Chooz+LBL(app) | solar+KamLAND

$P(\nu_\mu \to \nu_\mu)$ | $P(\nu_e \to \nu_e)$ & $P(\nu_\mu \to \nu_e)$ | $P(\nu_e \to \nu_x)$

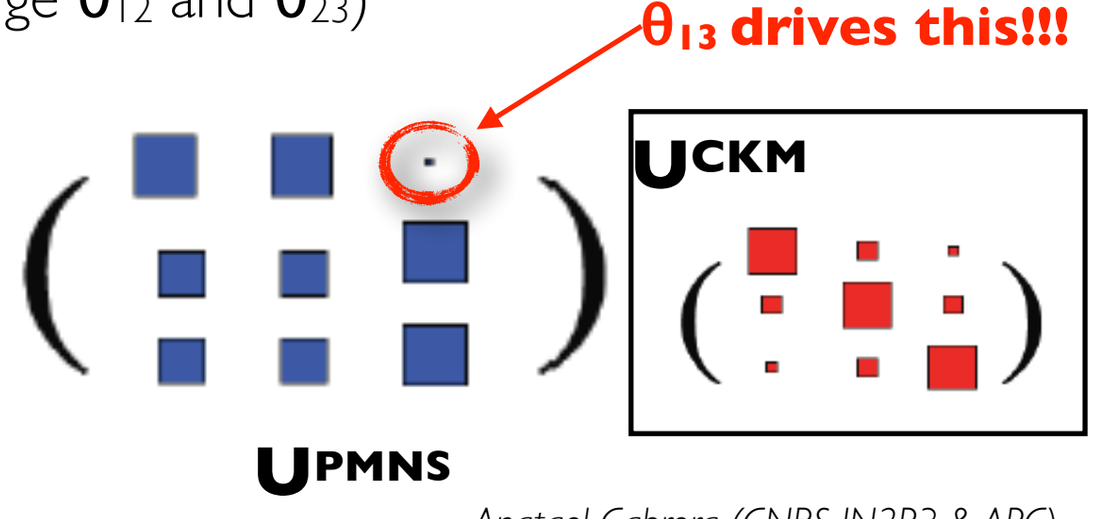
ATMOSPHERIC ANOMALY — **PREDICTION** — **SOLAR ANOMALY**

effective decoupling of "solar" & "atmospheric":

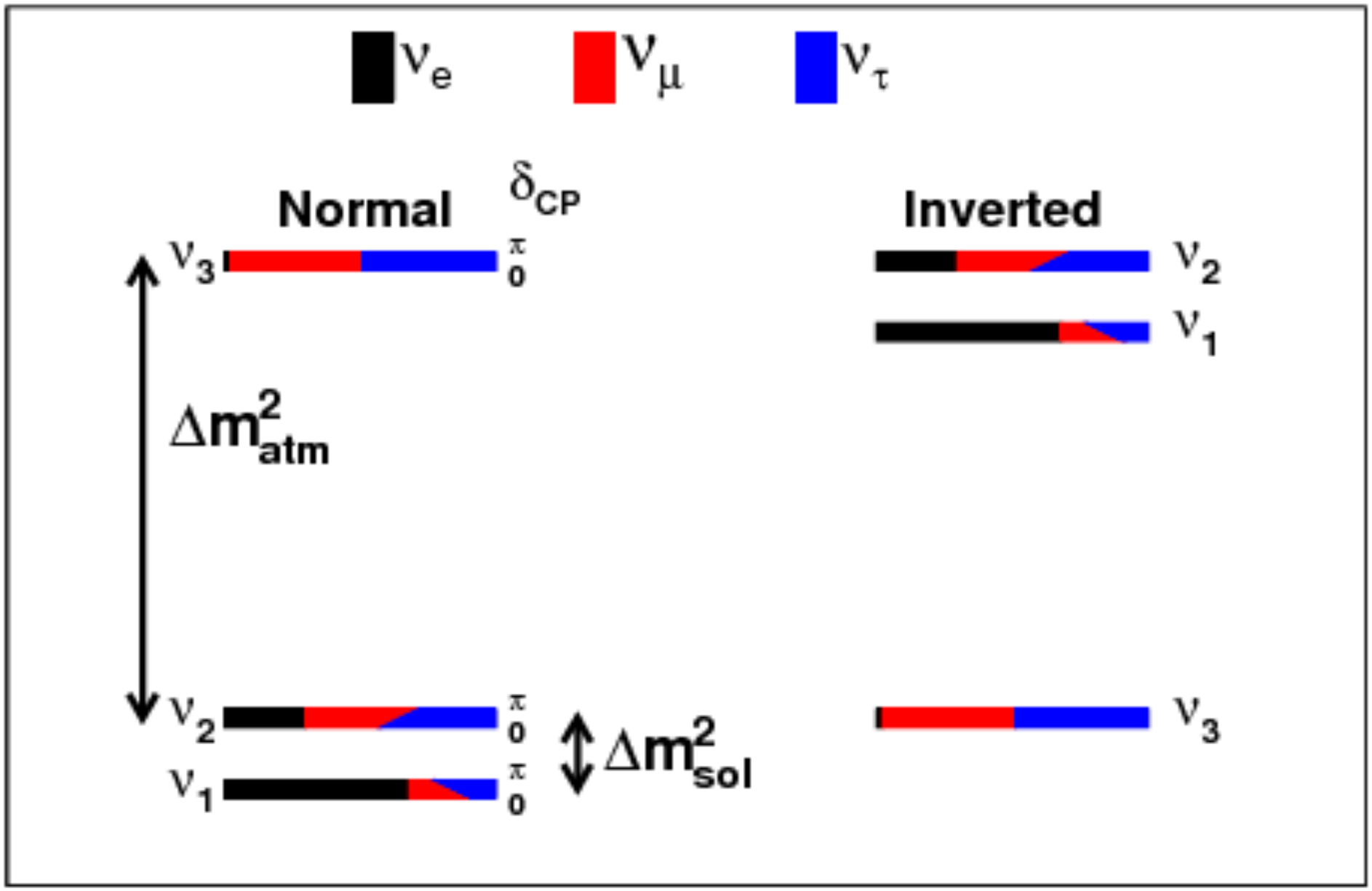
- δm^2 (order 10^{-5}eV^2) versus Δm^2 (order 10^{-3}eV^2)
- θ_{13} being small (relative to very large θ_{12} and θ_{23})

$(\nu_e,\nu_\mu,\nu_\tau)^T = U(\nu_1,\nu_2,\nu_3)^T$, where U^{PMNS} looks like

is U unitary? [if not→ 4th ν family]



(atmospheric) Mass Hierarchy/Ordering…



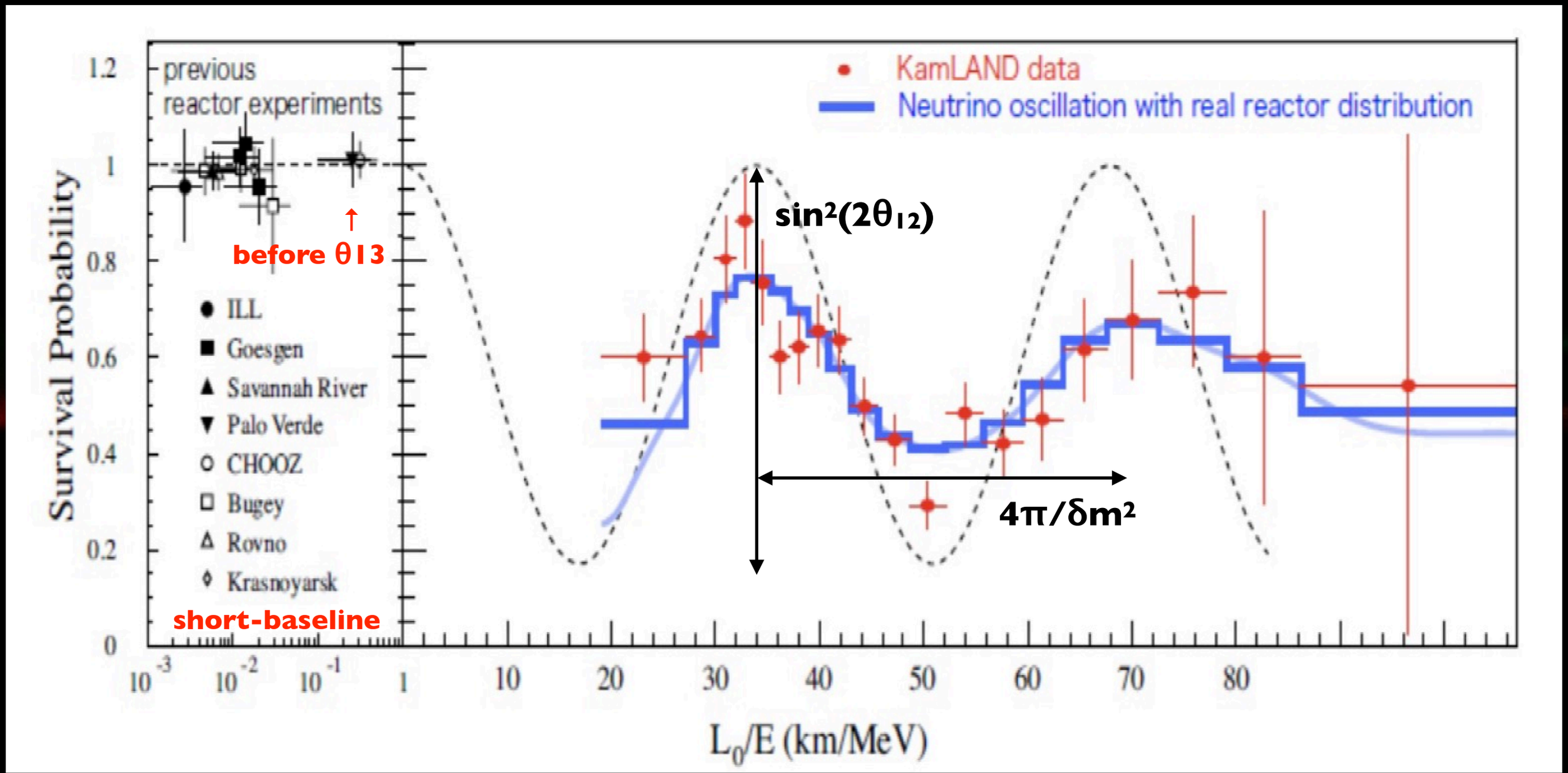
solar data: $+\delta m^2 \rightarrow m_1 < m_2$ [matter effects]

atmospheric data: ≈vacuum! [$\pm\Delta m^2$]

do we see oscillations?

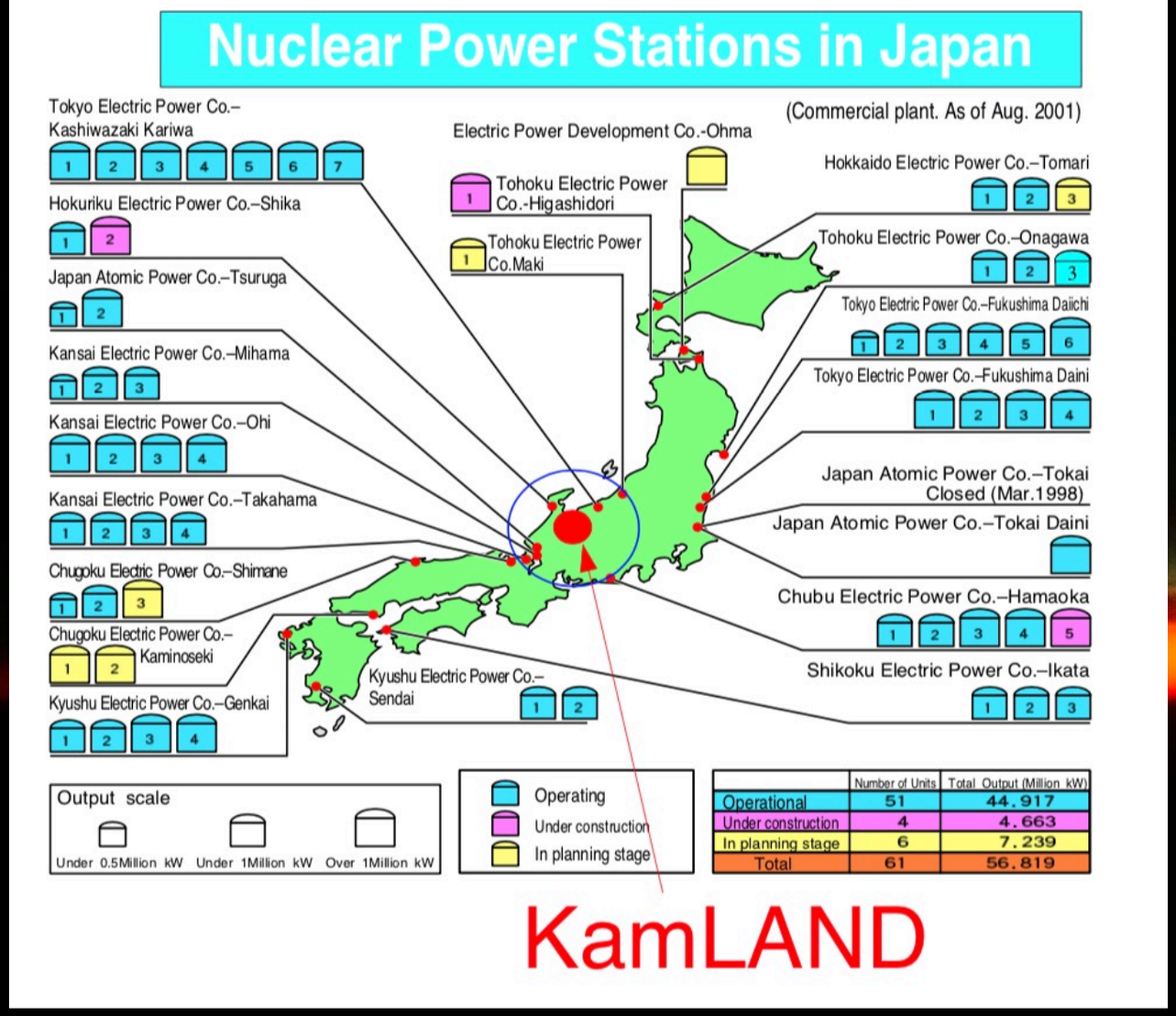
the latest KamLAND's $P(\nu_e \rightarrow \nu_e)$...

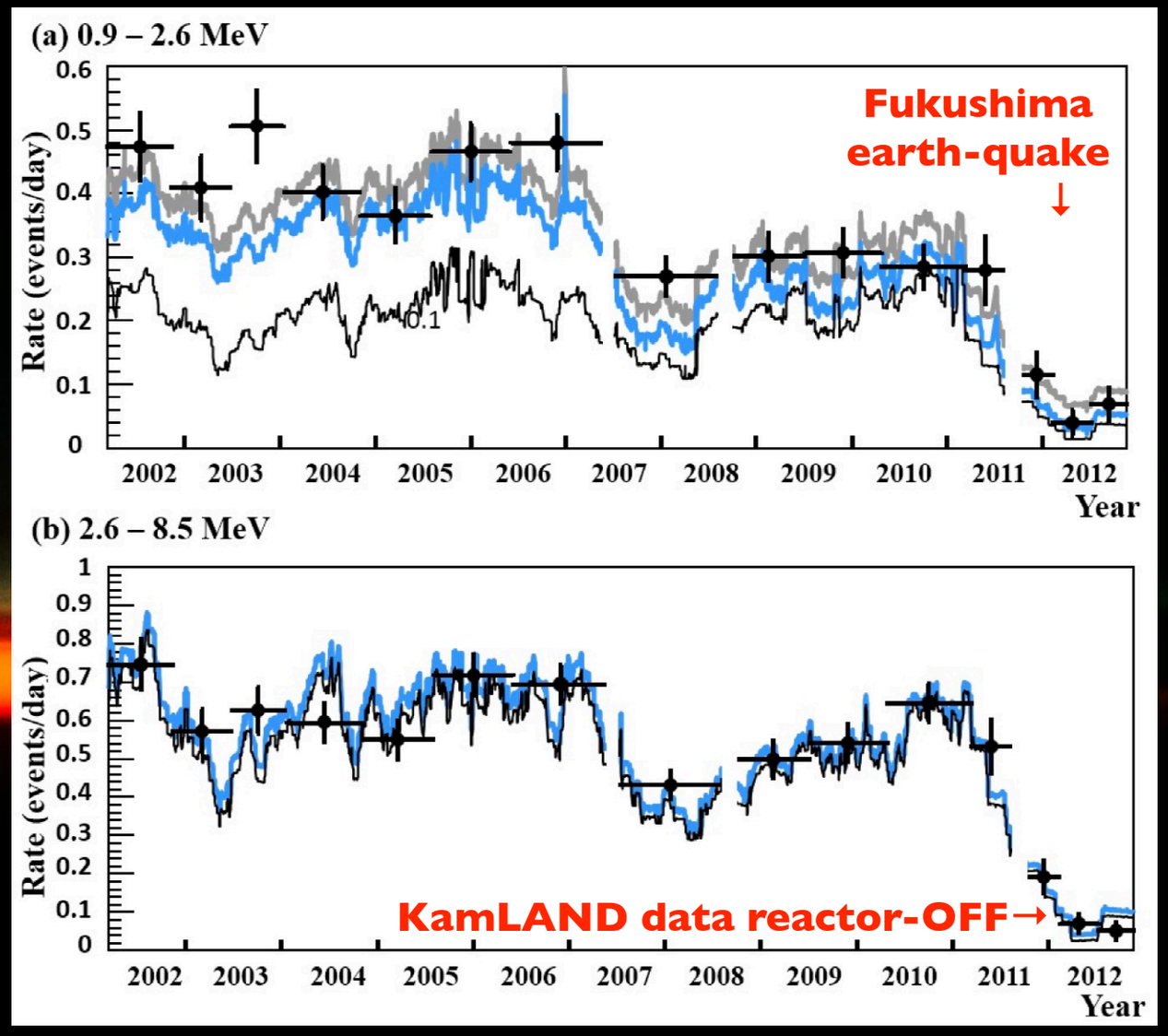
(to me) still the most beautiful E/L so far...?



average E/L over many reactors: visible oscillation over 100's km!

KamLAND strategic **position** & **time**…





~70GWth (~12% global)

<L> = (175±35)km

≲1.0 IBD/day

till Fukushima earth-quake

why CP-violation is important?

Anatael Cabrera (CNRS-IN2P3 & APC)

we live in a matter Universe (so it seems)…

matter / anti-matter asymmetry...

Big-Bang: equilibrium at first (same of both)

CP-Violation necessary ingredient!

$\Longrightarrow$ breaks the symmetry→ leads to our existence

CKM(quark): CPV far too small to explain...

$\Longrightarrow$ neutrino oscillation embeds CP-Violation (mixing)

are we byproduct of ν's?

ingredients to CP-violation…

Anatael Cabrera (CNRS-IN2P3 & APC)

3 main ingredients...

- **(sub-dominant) appearance transition: $\nu_\mu \rightarrow \nu_e$**
  $\Longrightarrow$ sensitive to CP-Violation
- **sizeable amplitude** [J-invariant]**: sub-dominant**
  $\Longrightarrow$ δm^2, Δm^2, θ_{12}, θ_{23}, θ_{13} combination
- **fake CP-violation due matter during oscillation**
  $\Longrightarrow$ sensitive to sign δm^2 and Δm^2 (Mass Hierarchy)

why & how $\nu_\mu \rightarrow \nu_e$?

Anatael Cabrera (CNRS-IN2P3 & APC)

why the $\nu_\mu \rightarrow \nu_e$ transition?

ν_e

$\nu_\mu \rightarrow$

ν_τ

ν_e **apparence**

ν_μ disappearance

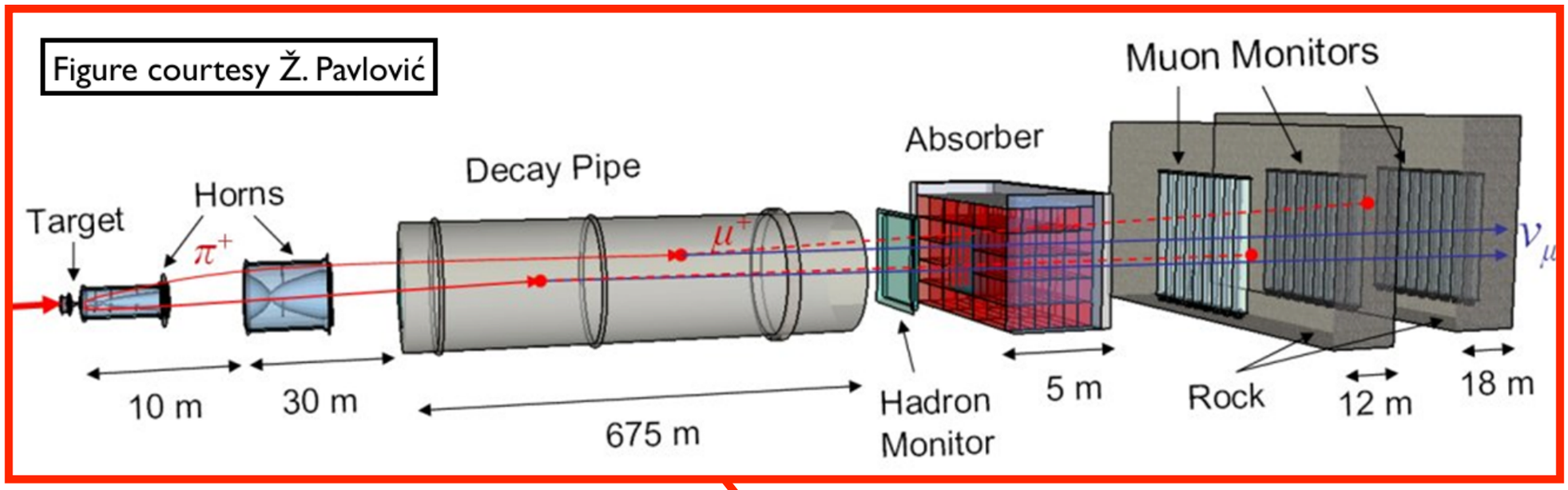
ν_τ

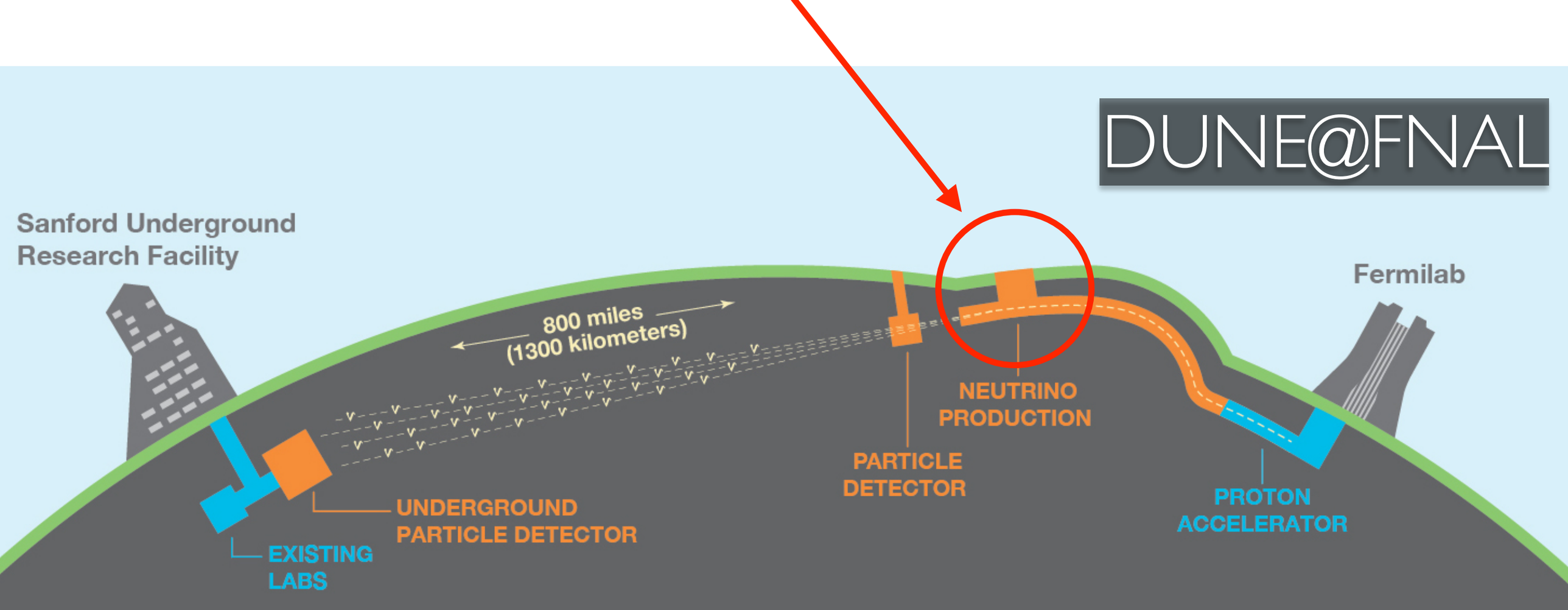
hard production
(ν_τ and ν_e)

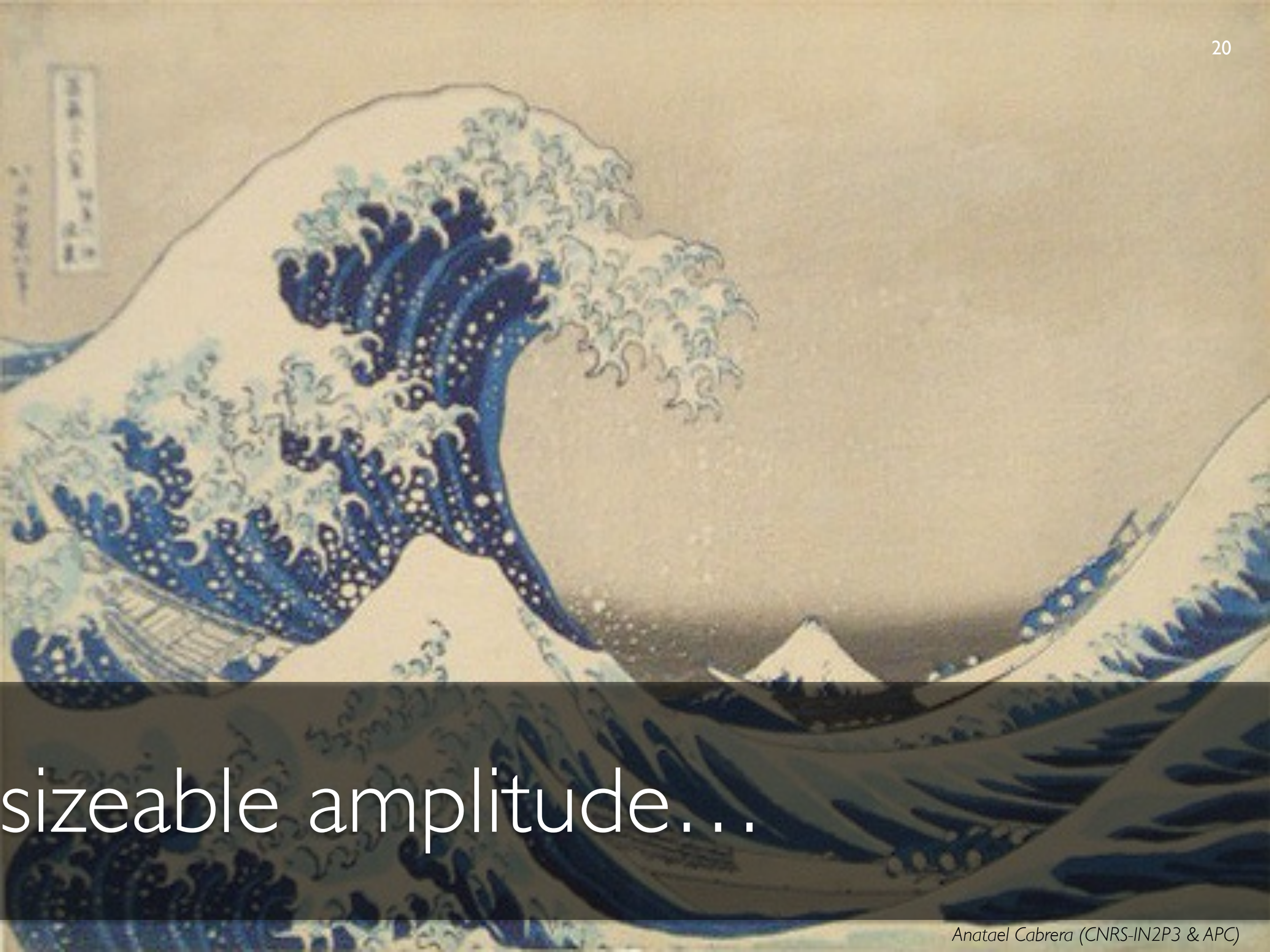
hard detection
(ask OPERA)

it's the **simplest** → higher luminosity/detection

π/K-decay neutrino beams…







sizeable amplitude…

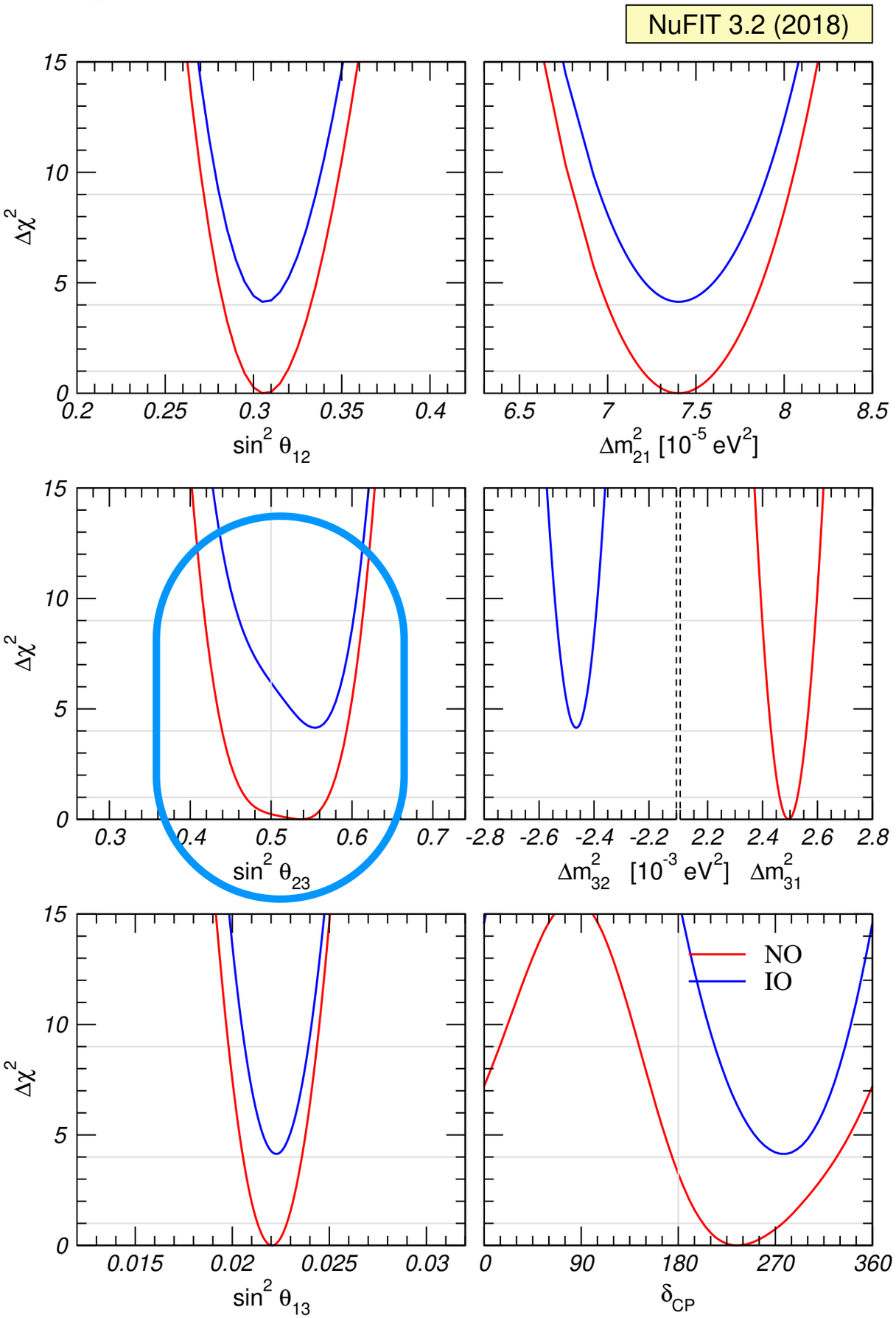
the Jarlskog invariant…

$$J(CP) = \cos\theta_{12}\cos^2\theta_{13}\cos\theta_{23} \times \sin\theta_{12}\sin\theta_{13}\sin\theta_{23} \times \sin\delta(CP)$$

J(CP) ≈ 3.3% [~10^{-5} in CKM]

$J_{CP} = c_{12}c_{13}^2c_{23}s_{12}s_{13}s_{23}\sin\delta$ is called Jarlskog invariant.

global knowledge before Nu2018 (MAY2018)…



θ13 terms:

- **θ_{13}:** reactor-θ_{13}

reactor-θ_{13}=DYB⊕DC⊕RENO

solar terms:

- **θ_{12}:** solar experiments (SNO)
- **δm^2:** KamLAND

atmospheric terms:

- **θ_{23}:** beam
- **Δm^2:** beam+reactor-θ_{13}

beam = T2K⊕NOvA[⊕MINOS]

atmos = SK⊕DeepCore

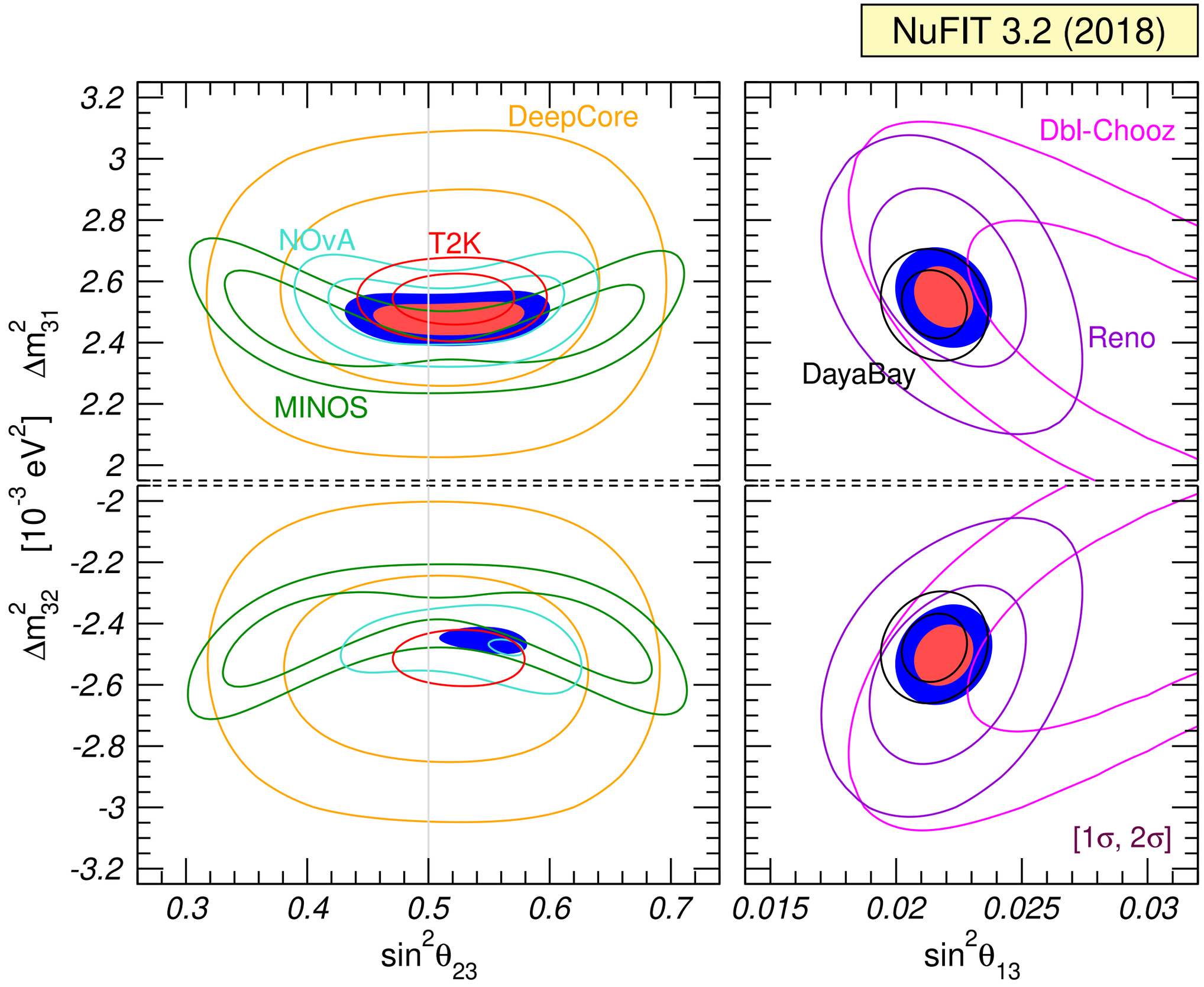
CPV term: beam (directly)

global knowledge before Nu2018 (MAY2018)…

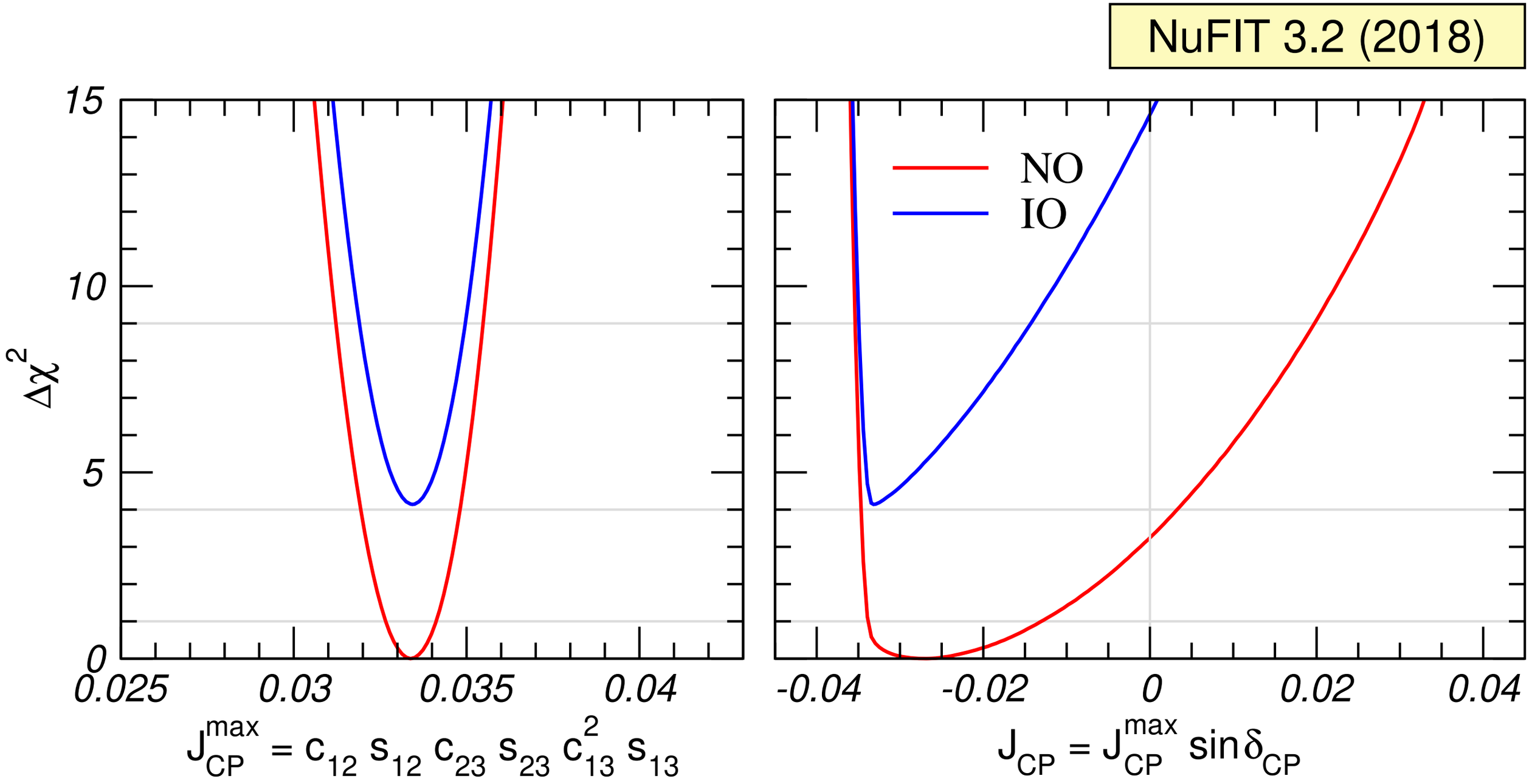
NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{\rm CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

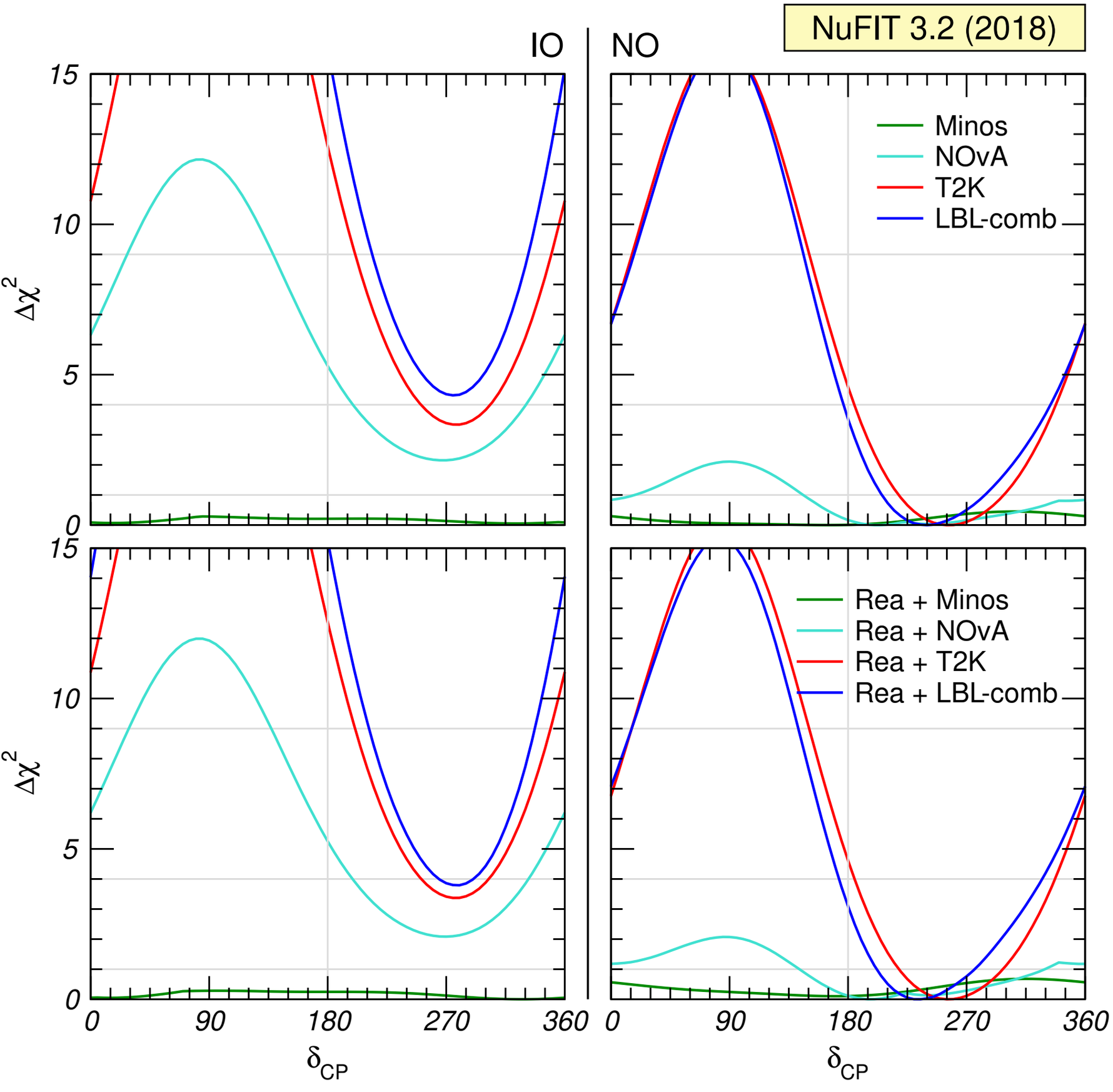
θ23 almost maximal → θ23-octant ambiguity…



the Jarlskog invariant→ CPV max. amplitude…



CP-violation first glimpses today…



CPV role:

- **θ_{13}:** reactor-θ_{13} (indirect contribution)
- **δ(CP):** beam

beam = T2K⊕NOvA

- **little aid by atmos**

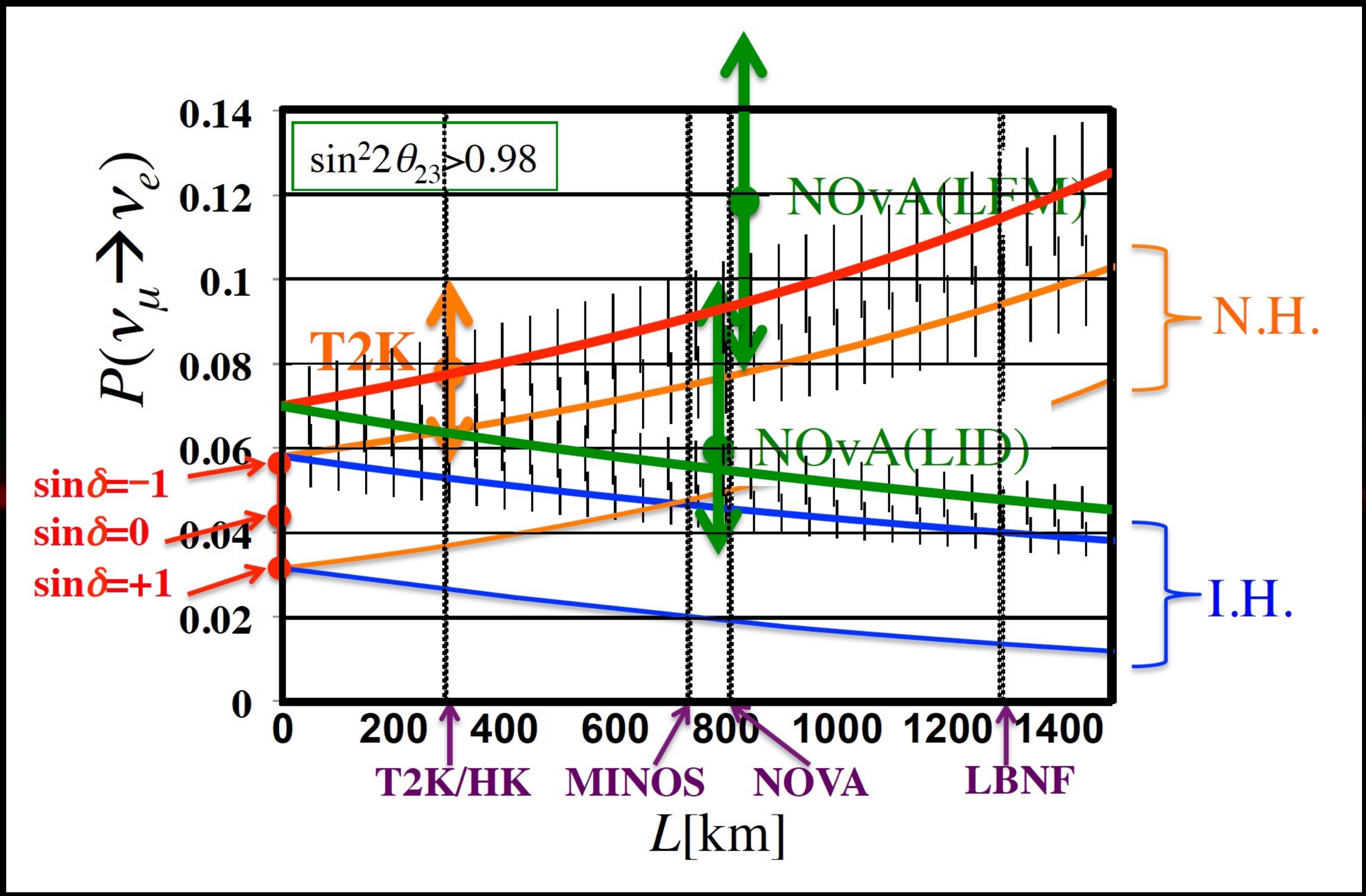
atmos = SK⊕DeepCore

“fake” CPV control…

Earth is matter: interact with ν's (propagation)…

anti-ν's no interaction…

"fake CPV" disentangling: Mass Hierarchy a must…



Suekane-san courtesy

and the future…?

3 main efforts world-wide...

- **JUNO experiment**

  $\Longrightarrow$ high precision (several) & Mass Hierarchy (vacuum)

- **beam experiments** [**DUNE** & **HyperK**]

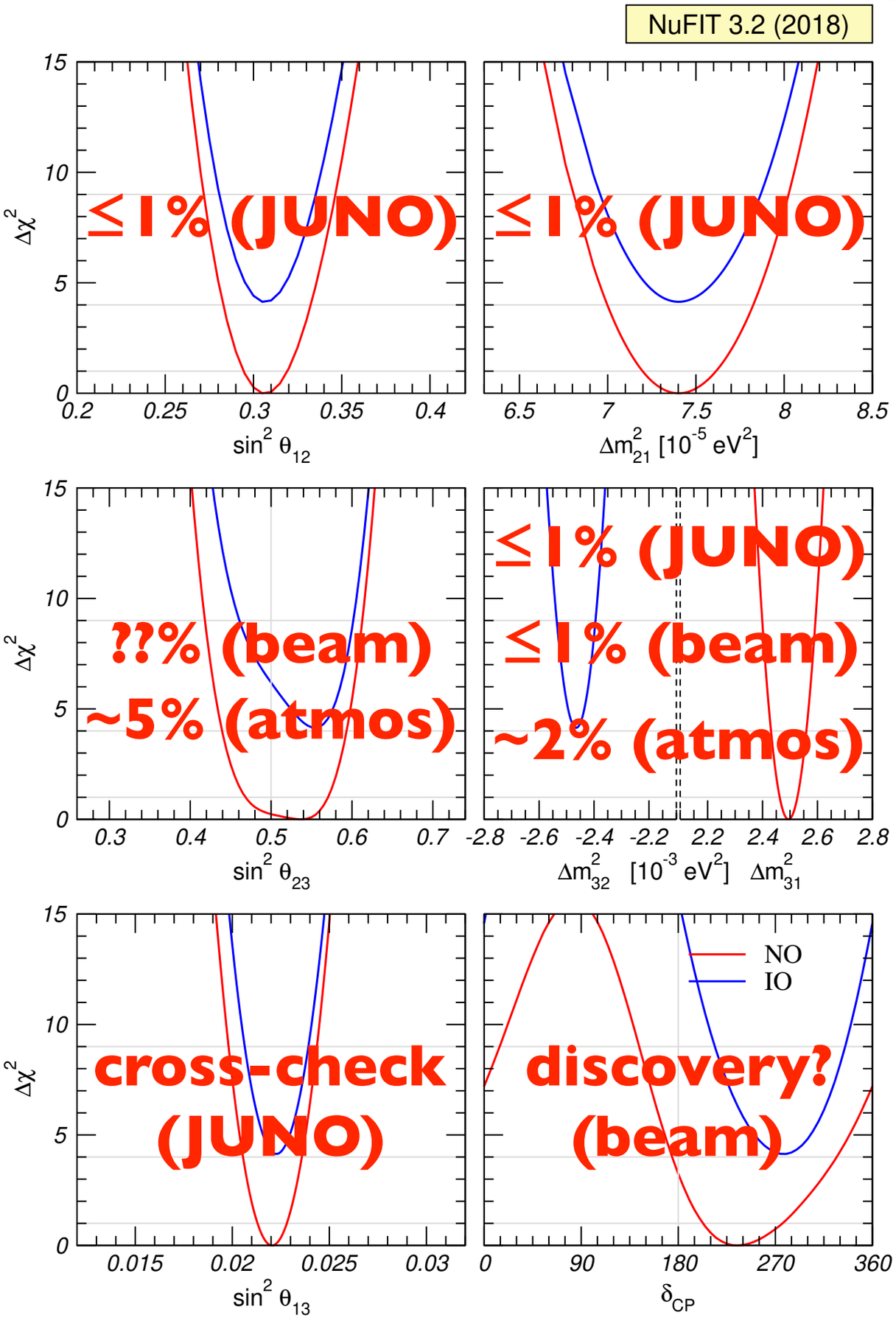
  $\Longrightarrow$ high precision (several) & Mass Hierarchy & **CPV**

- **atmospheric experiments** [**ORCA** & **PINGU**]

  $\Longrightarrow$ mainly Mass Hierarchy (matter effects)

disclaimer: 2β & ν(sterile) not covered

global knowledge future…



θ13 terms:

- **θ_{13}:** reactor-θ_{13}

reactor-θ_{13}=DYB⊕DC⊕RENO

JUNO: a cross-check (like DC now)

JUNO (~~solar~~) terms:

- **θ_{12}:** JUNO
- **δm^2:** JUNO

?? (~~atmospheric~~) terms:

- **θ_{23}:** beam*
- **Δm^2:** JUNO⊕beam*
- **sign[Δm^2]:** JUNO⊕beam⊕atmos

beam* = **DUNE⊕HK**

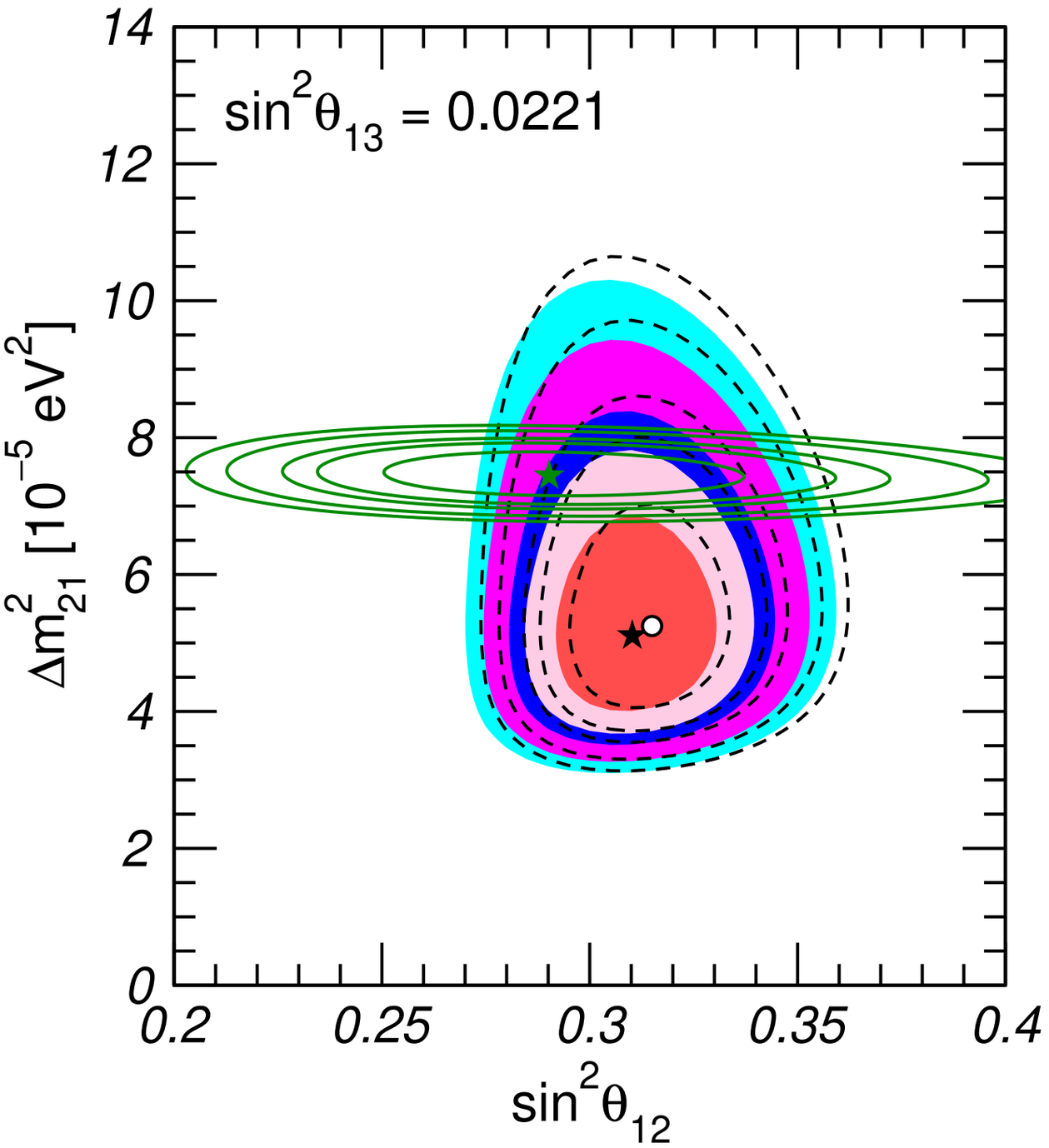
atmos = **ORCA⊕PINGU**

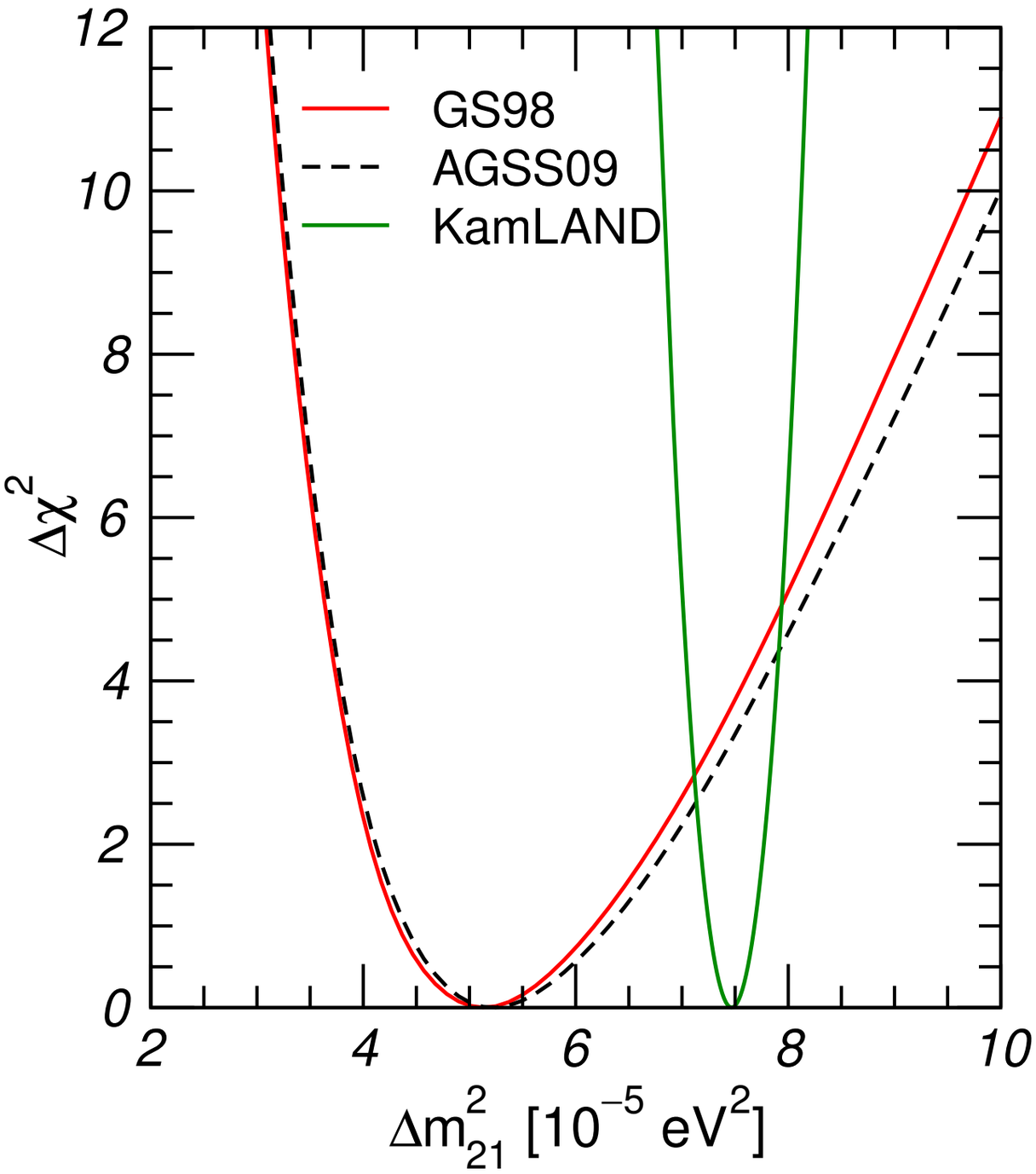
CPV term: beam* (directly)

stay watchful for consistency…

a δm^2 issue or astro/terrestrial effects…?

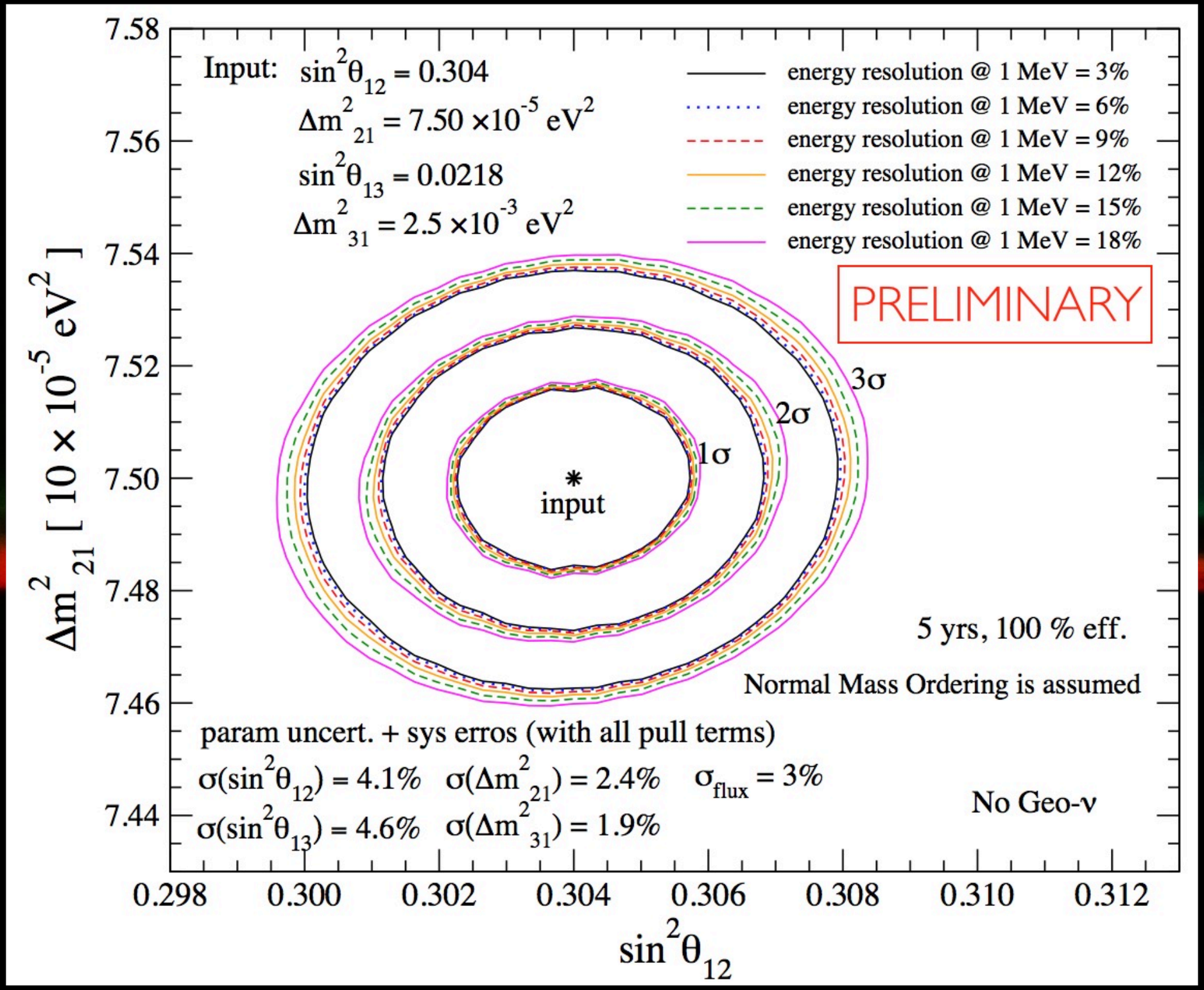
NuFIT 3.2 (2018)





ν(Sun) vs **anti-ν(reactor)**: difference?

JUNO internal redundancy on δm^2-θ_{12}…



SPMT⊕LPMT cross-check→ robust result

DC result @ CERN (SEPT-2016)…

Double Chooz
JHEP 1410, 086 (2014)

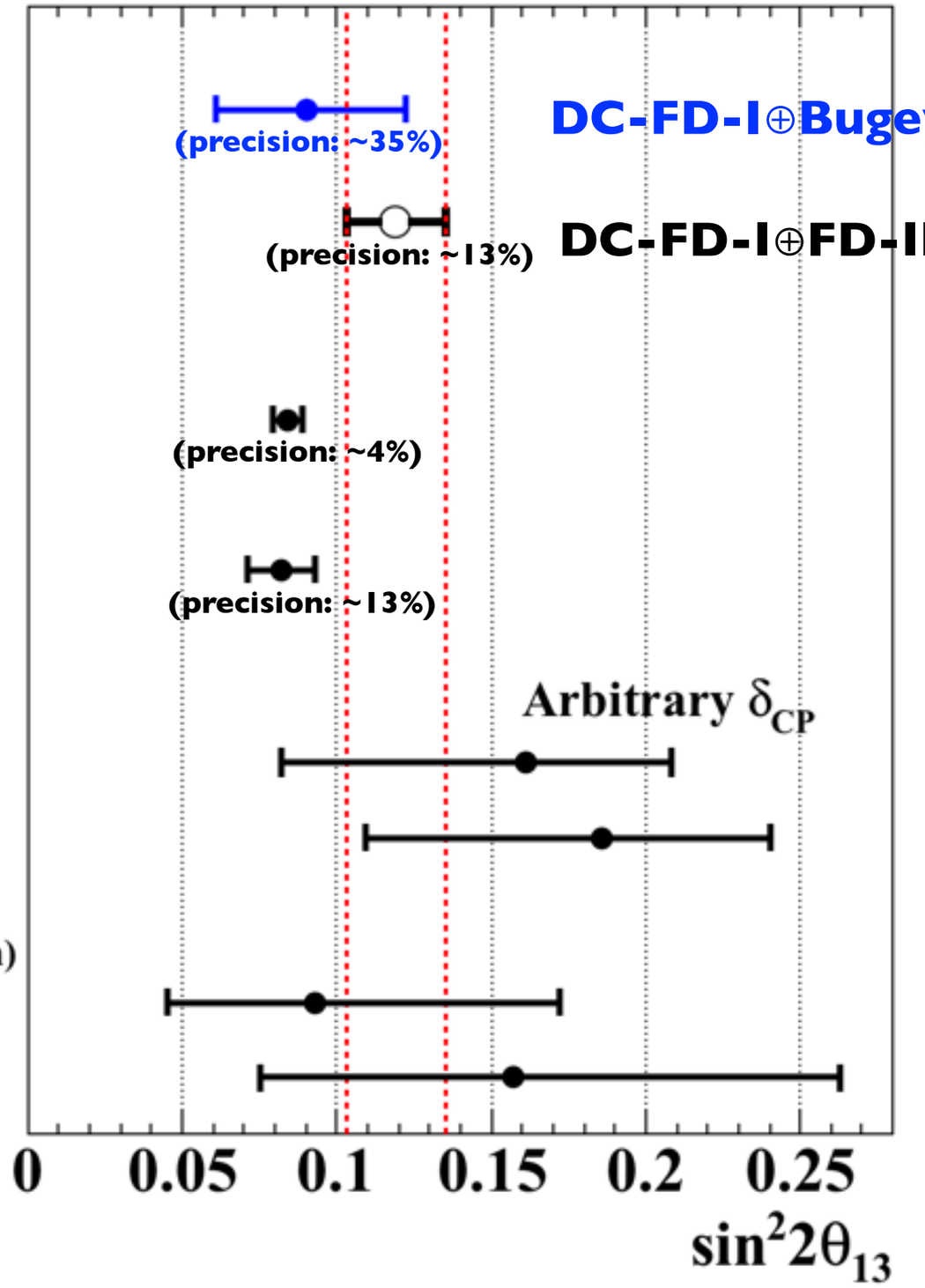
Preliminary **DC-IV**
(CERN seminar 2016)
$\sin^2(2\theta_{13})=(0.119\pm0.016)$

Daya Bay
PRL 115, 111802 (2015)

RENO
PRL 116 211801(2016)

T2K
PRD 91, 072010 (2015)
$\Delta m^2_{32} > 0$
$\Delta m^2_{32} < 0$

NOvA
Preliminary (private communication)
$\Delta m^2_{32} > 0$
$\Delta m^2_{32} < 0$



DC-IV-PRELIMINARY @ CERN

need to investigate carefully→ systematics @ ‰ level (complex)

Reactor-θ_{13} *(combining results)*

Daya Bay⊕Double Chooz⊕RENO

0th discussion/planning→@ Neutrino-2016, London (UK)

1st workshop→ October 2016 (Seoul, South Korea)
(systematics, results consistency)

2nd workshop→ June 2017 (Paris, France)
(further θ_{13} systematics consistency)

3rd workshop→ end 2018 (Hong Kong, China)

(likely) most precise input to θ_{13} for several decades…

what to remember?

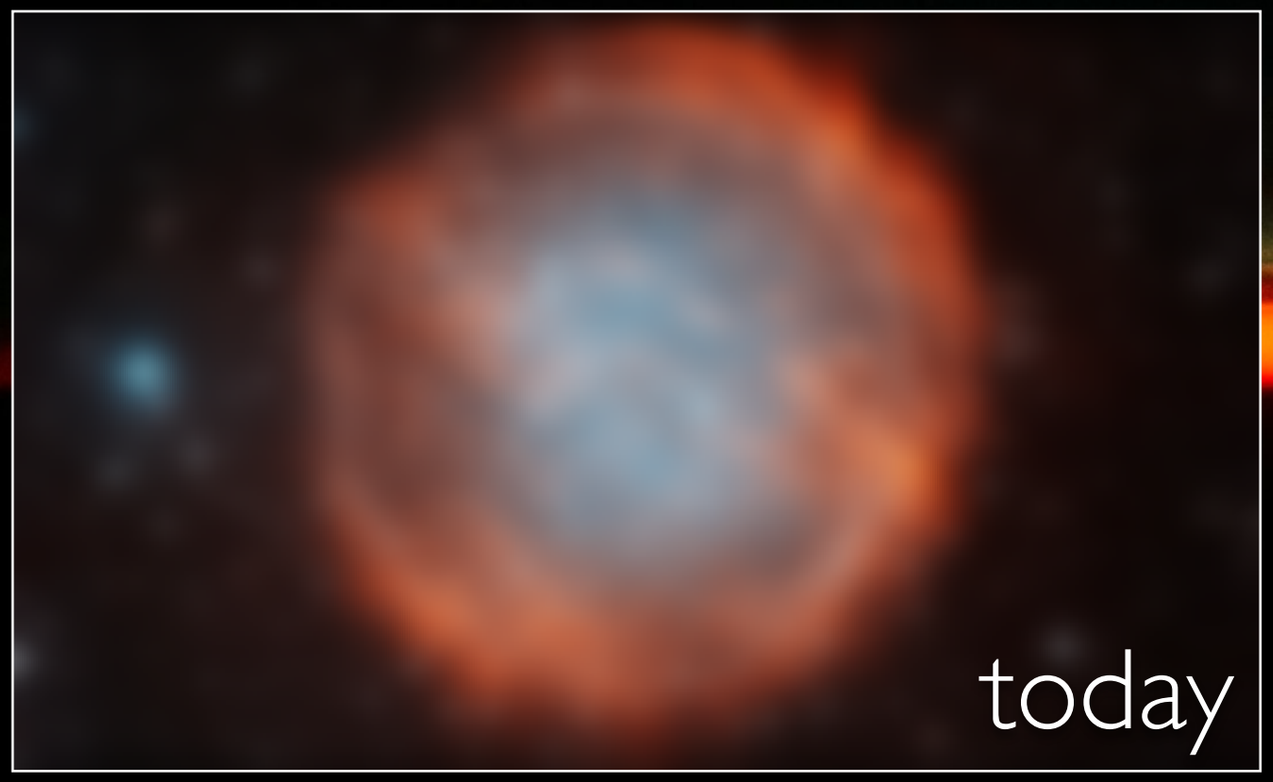
- **neutrino oscillation:** coherent solution to most data today (3**ν** model)…

- BIG step in precision upcoming >2020: **very mature programme**

- **better detectors→ surprises?**
  [i.e. discoveries beyond today's view]

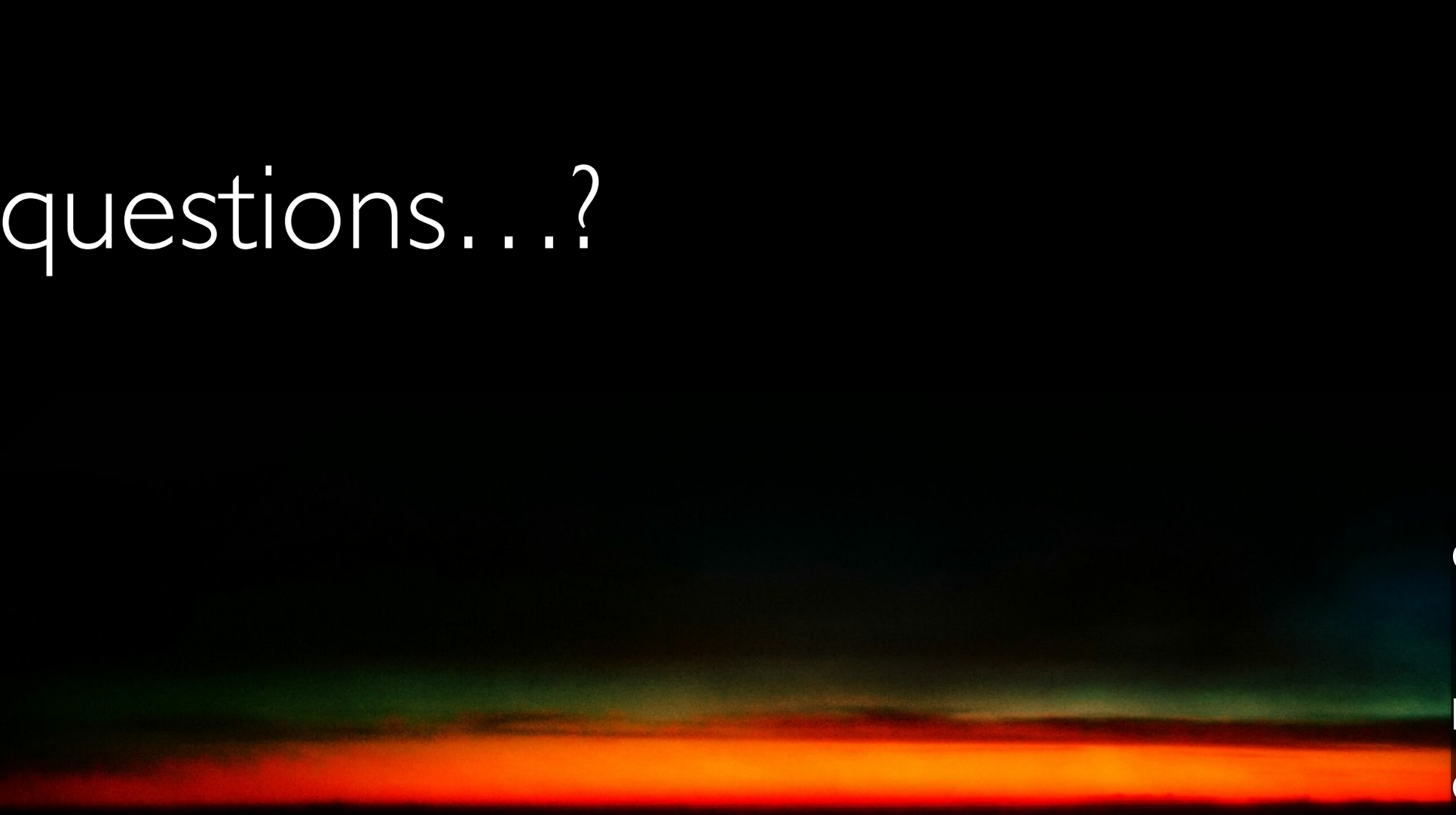
Nature always waiting **to be unravelled**…

(history of science → detection/instrumentation progress)



continue effort on detectors!!

questions…?



obrigado…
ありがとう…
merci…
danke…
고맙습니다…
Спасибо…
gracias…
grazie…
谢谢…
hvala…
thank you…

anatael@in2p3.fr