Neutrinos II

present and outlook...

IMFP-2021 @ Benasque (Spain)
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Anatael Cabrera
CNRS/IN2P3
IJCLab @ Orsay
(Université de Paris-Saclay)
LNCA @ Chooz

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
- ✗ •explorations of **absolute mass** & **ββ decay** **[apologies]**

ingredients & notation…

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]

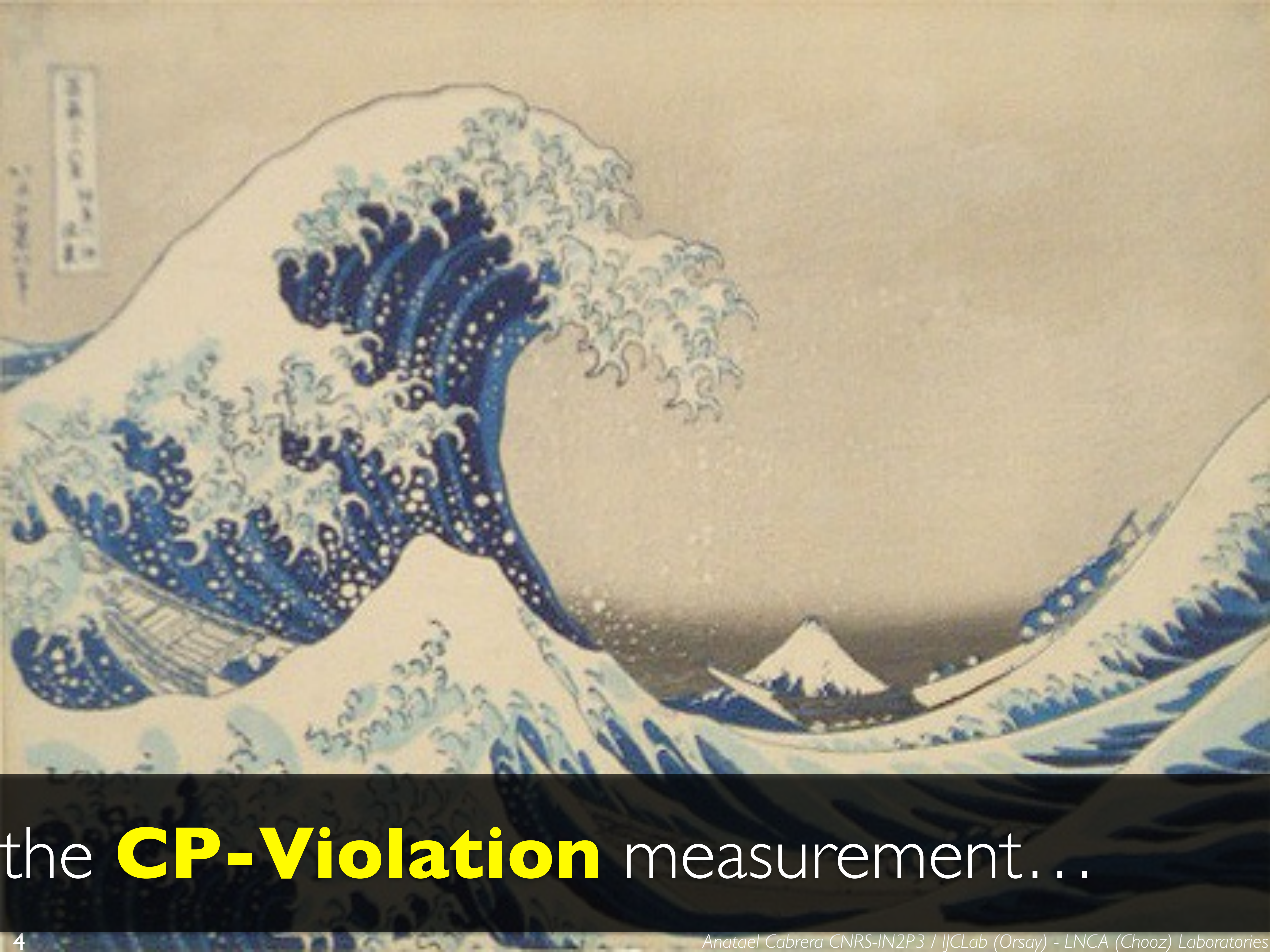
Mass Differences: **δm²** (i.e. Δm^2_{12}) and **Δm²** (i.e. Δm^2_{13} or Δm^2_{23})

Mass ordering:

+δm^2 (solar data)

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

Absolute mass scale: **m(ν)?**



the **CP-Violation** measurement…

accelerator experiments: 2 channels…

Disappearance Channel: $\nu_\mu \rightarrow \nu_\mu$ "survival probability" [mimic's directly the atmospheric anomaly mechanism,]

$\Longrightarrow$ measure [θ_{23},Δm^2_{32}] — this is **MO blinded**

Oscillation Probability order up to 100% [since θ23 may be maximal]

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

$\Longrightarrow$ measure [$\theta_{23} \oplus \theta_{13}$,$\delta_{CP}$,**MO**] — 4 unknowns & dependence on **MO (matter effects)**

Oscillation Probability order ≲3% [modulated by Jarkslog invariant]

$$
\begin{aligned}
P(\nu_\mu \to \nu_e) \simeq\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,
\end{aligned}
$$

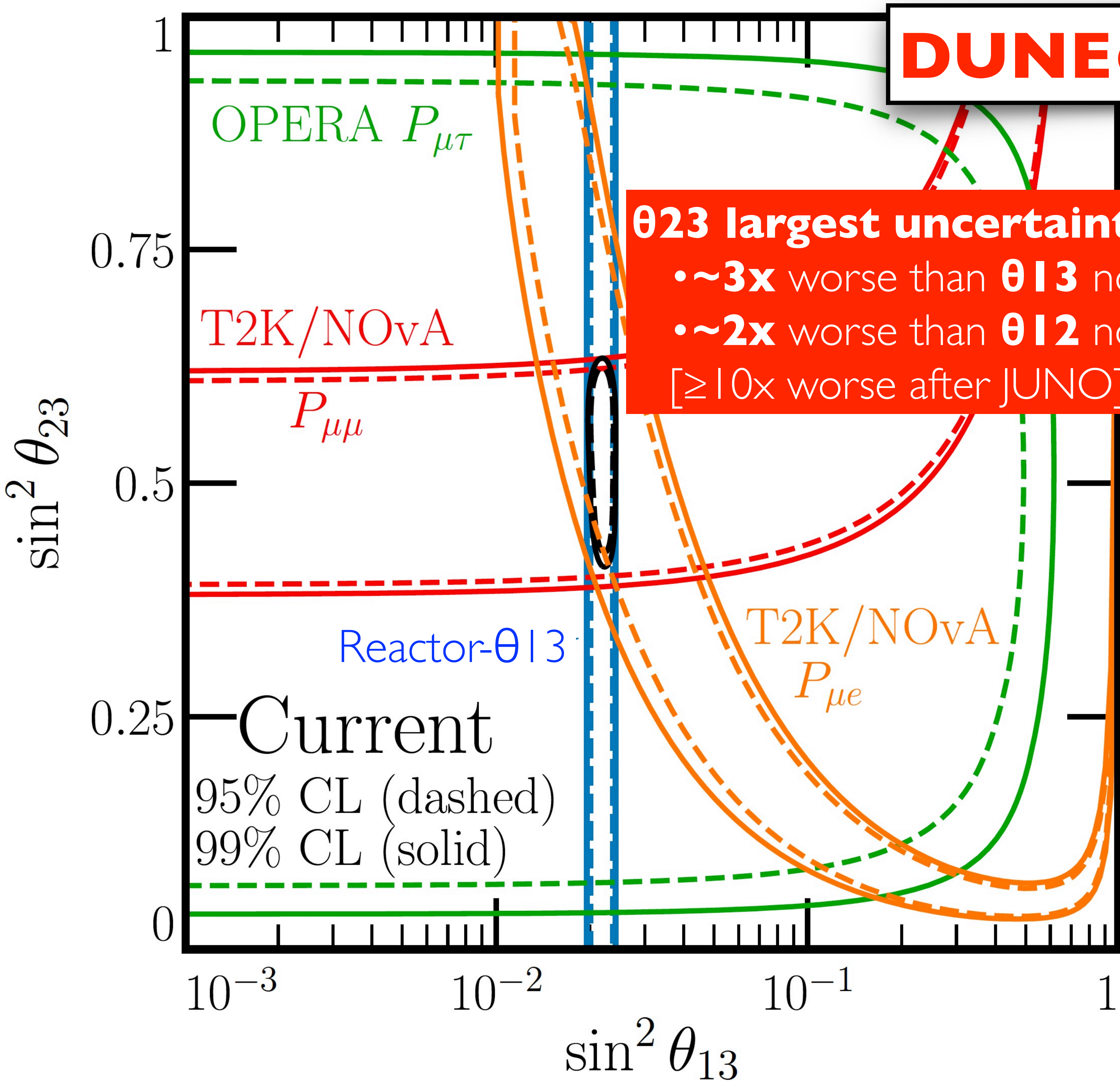
$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

measurement of **θ23** — dependence on **θ13**…

Reactor-θ13: Daya Bay⊕Double Chooz⊕RENO

DUNE⊕HyperK⊕Reactor-θ13 impact



θ23 largest uncertainty
- **~3x** worse than **θ13** now
- **~2x** worse than **θ12** now

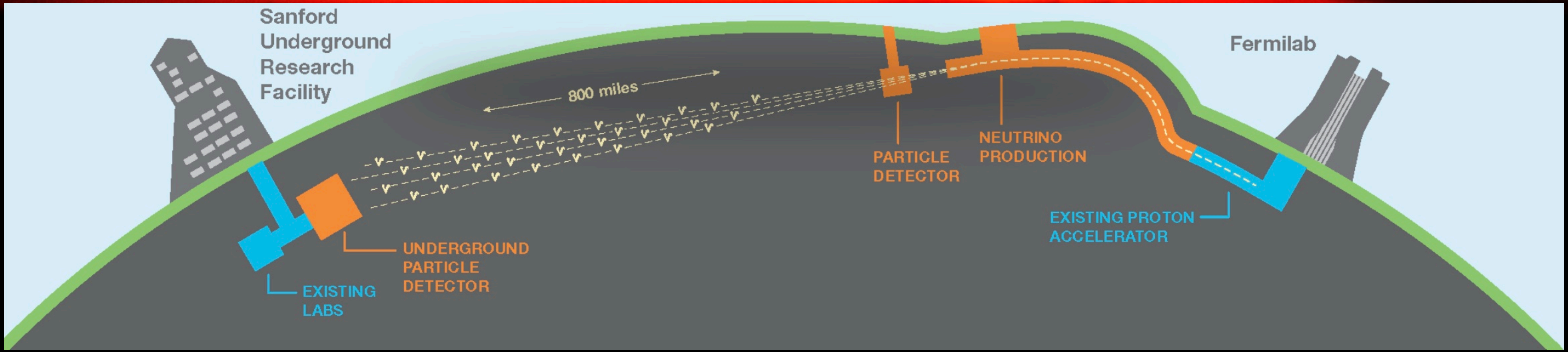
[≥10x worse after JUNO]

θ23 being **almost maximal** (not exclude) suffers from the so called "**octant ambiguity**" → larger uncertainty

phenomenologically, a maximal θ23 could embed the manifestation of a possible symmetry [θ13 being very small]

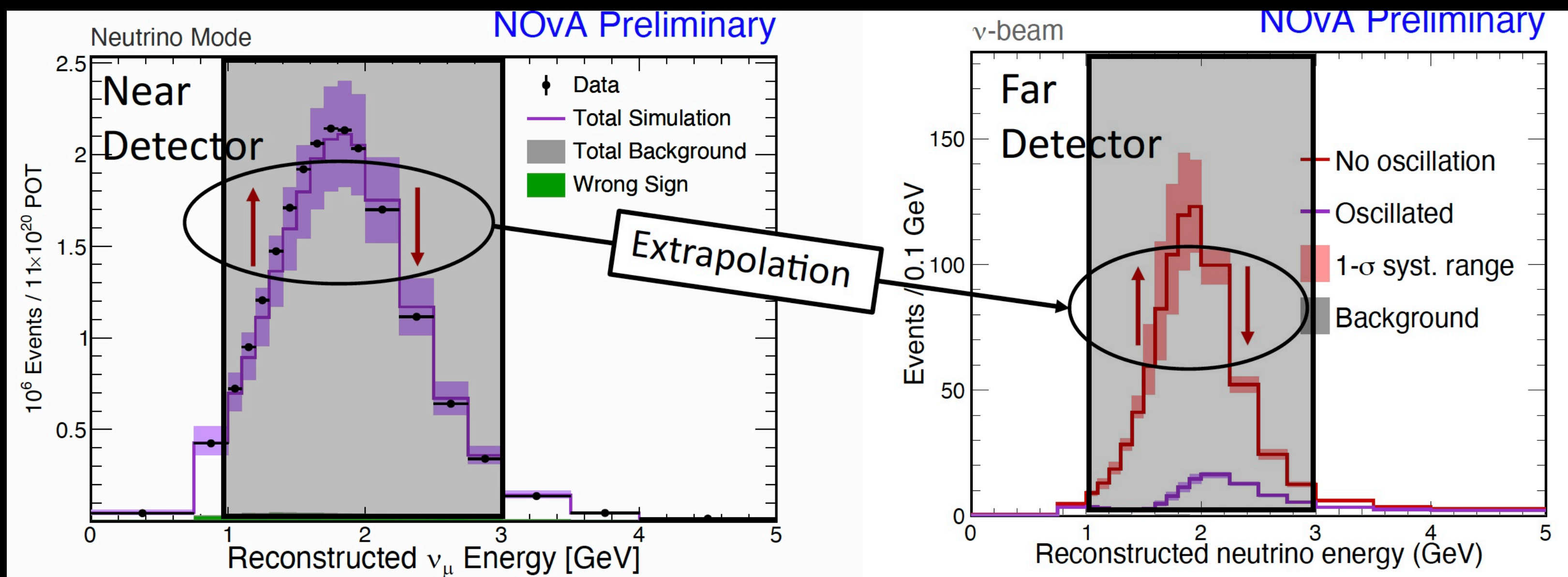
in-flight π-decay beam…

- **traditional beam divergent beam**
  - **on** (DUNE) and **off** (T2K / NOvA / HyperK) **axis**
  - **neutrino** and **anti-neutrino modes** (use "horn" current)
- **high beam power**→ towards **~MW**
- **near detector(s)…**
  - **monitoring for flux cancellation**
  - **cross-section measurement: signal and backgrounds**

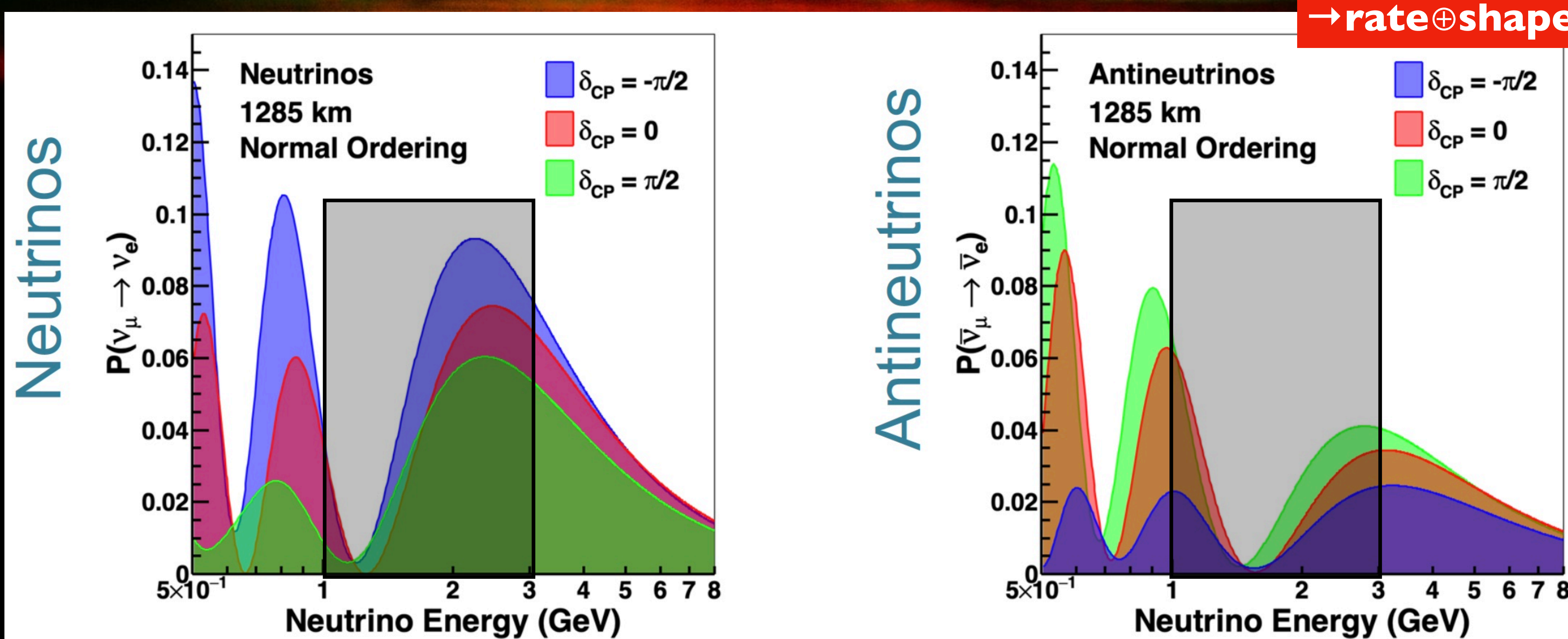


challenges (CPV): high statistics (~1000 events appearance)**, low systematics** (few %), etc

off-axis versus on-axis beams…

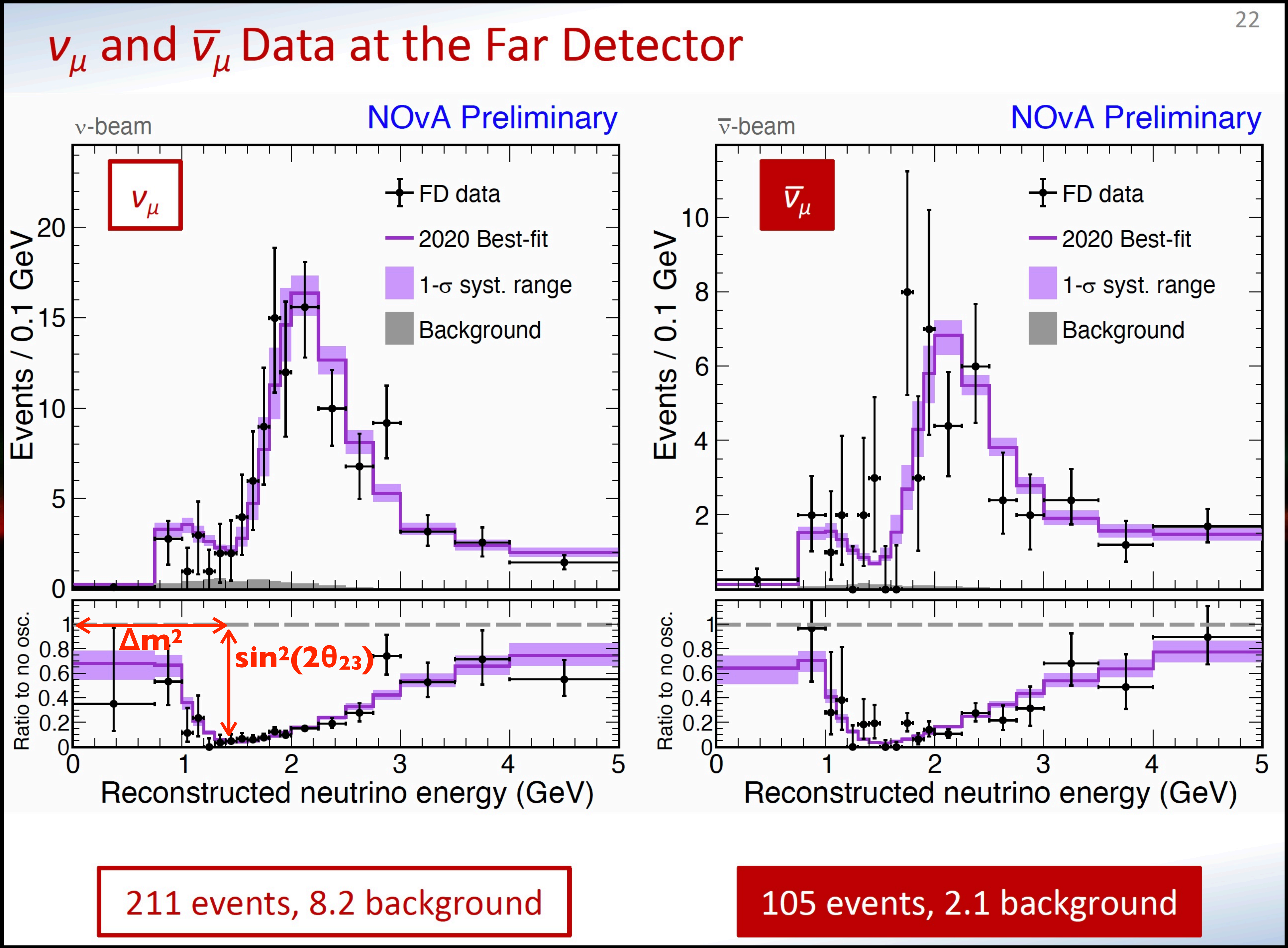


off-axis beam [narrow]
→rate main (some shape)



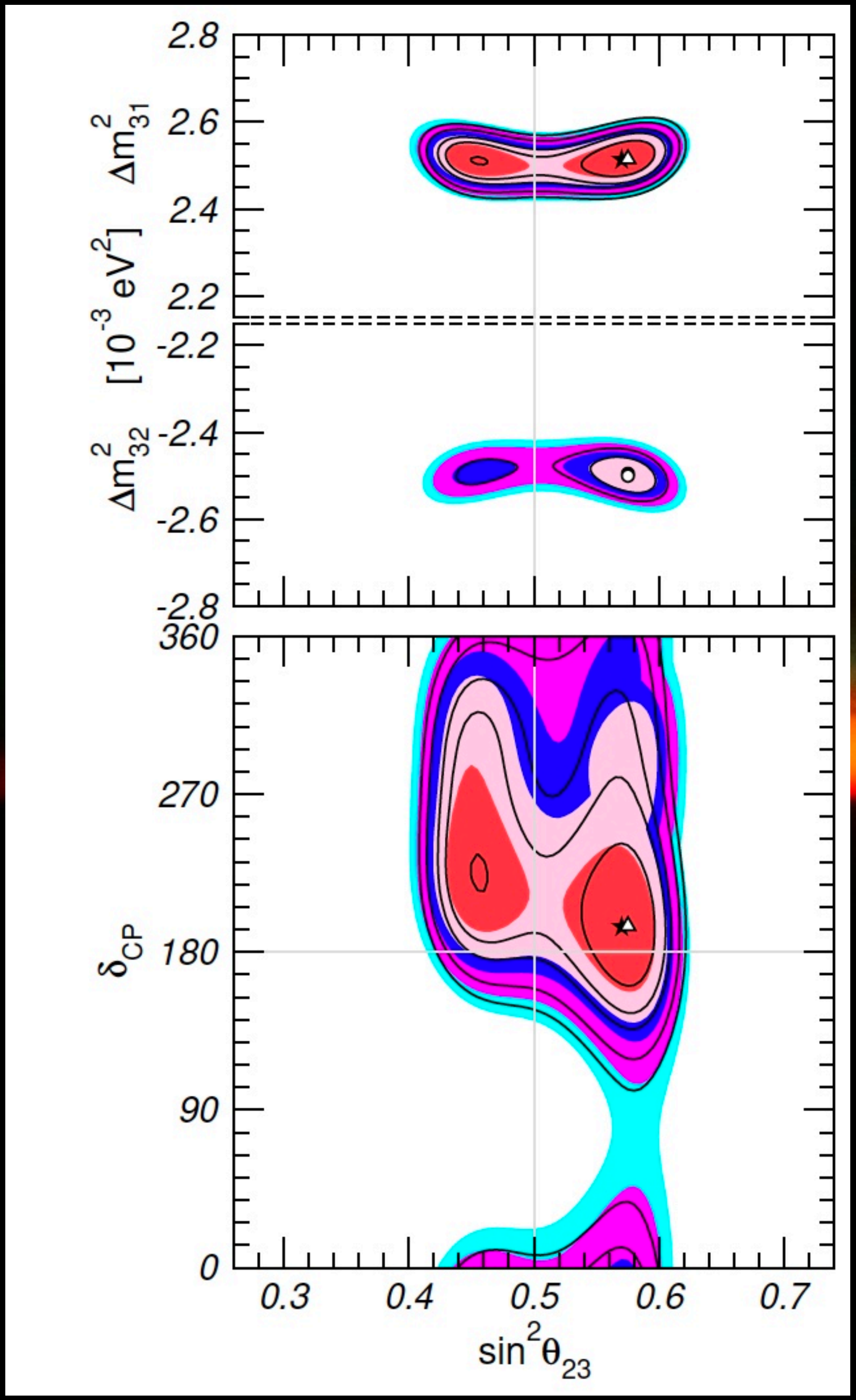
on-axis beam [narrow]
→rate⊕shape

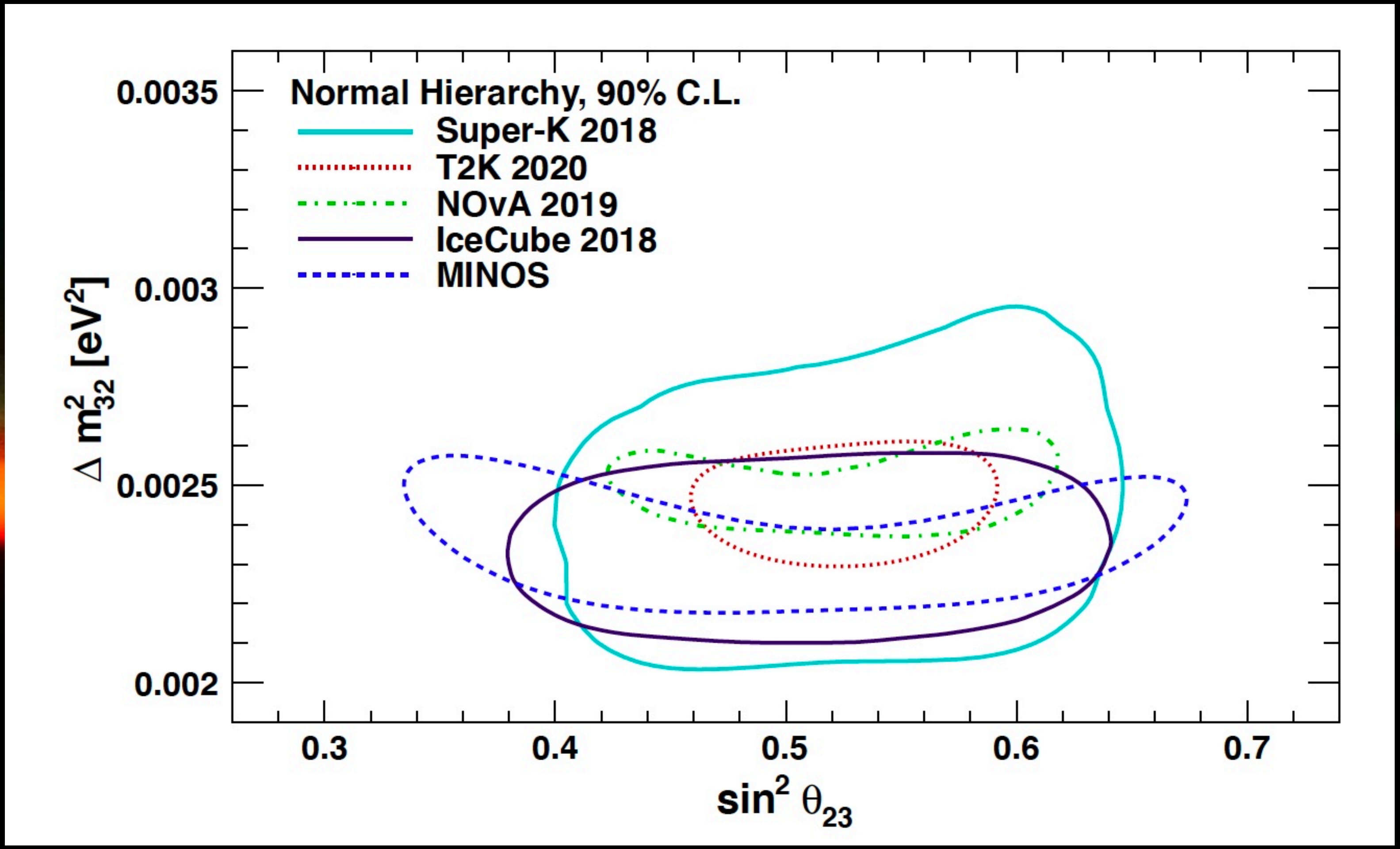
disappearance measurement (θ23)…



today's knowledge on θ23…

NuFit5.0





θ23 precision dominated by octant ambiguity

[beams⊕atmospherics]

PMNS' CP-violation…

key elements…

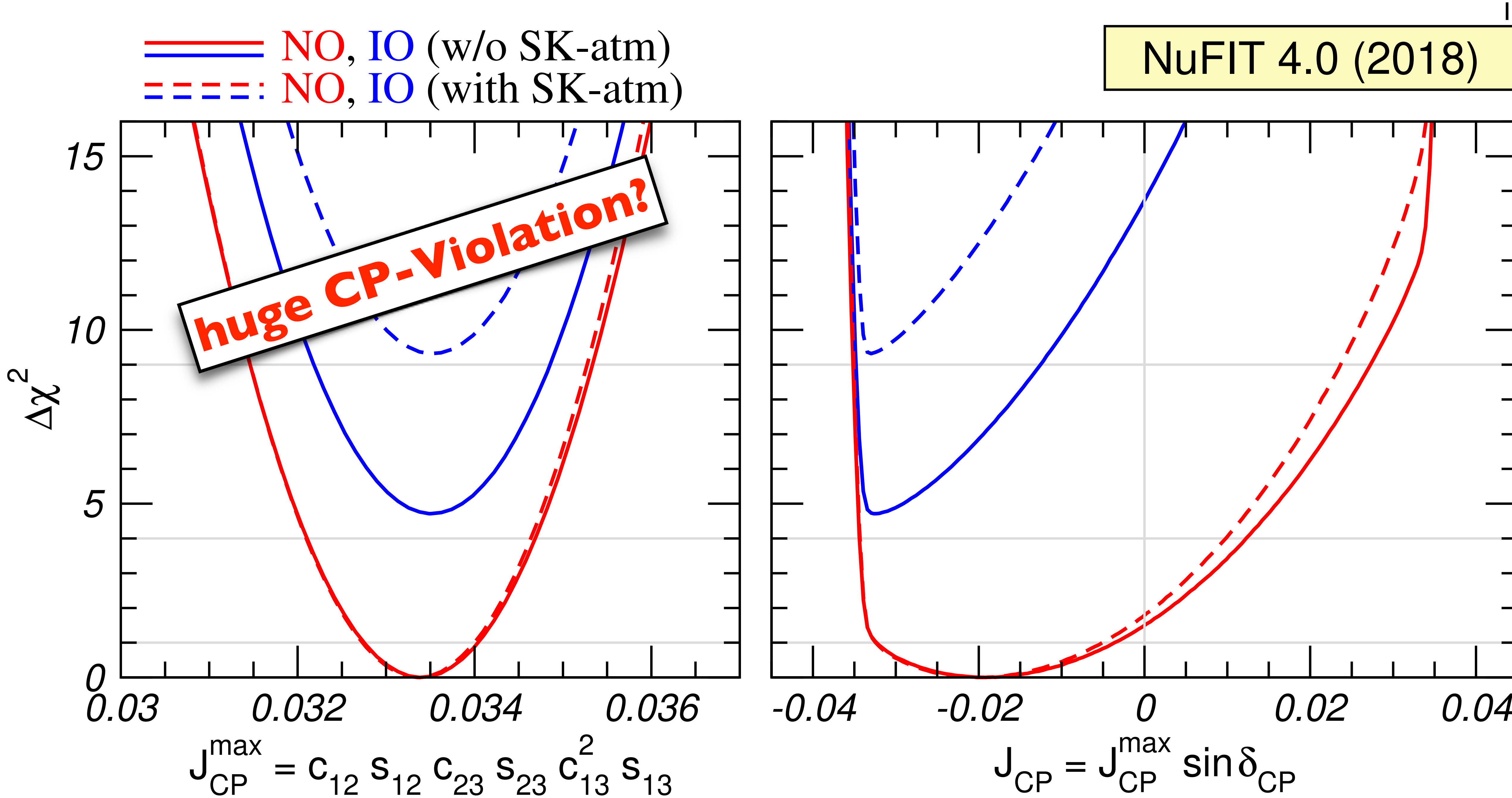
Jarkslog invariante: intrinsic **maximal CPV embedded in the PMNS** (CKM) matrix

$$J_{CP}^{max} = c_{12}\, s_{12}\, c_{23}\, s_{23}\, c_{13}^{2}\, s_{13}$$

PMNS CPV phase: modulation of J — as **sin(δ)** ⟹ CP conversation @ **0** & **π**

$$J_{CP} = J_{CP}^{max} \sin\delta_{CP}$$

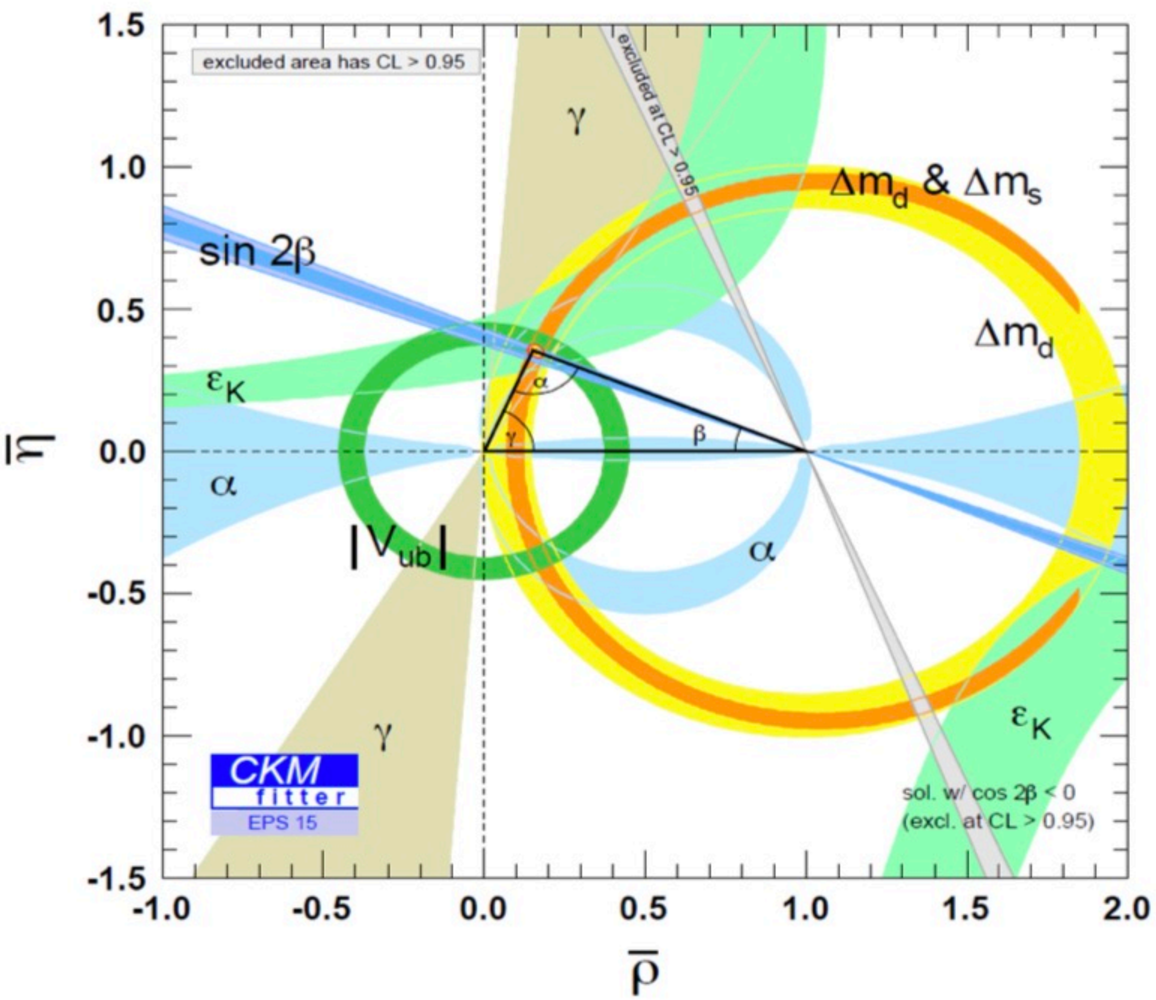
Fake CPV effects (i.e. non-PMNS CPV)**:** mainly **Mass Ordering** (matter) & **systematics** (mid-PID, etc)



J(PMNS)≈3.3x10^{-2}⇒ largest ever CPV possible

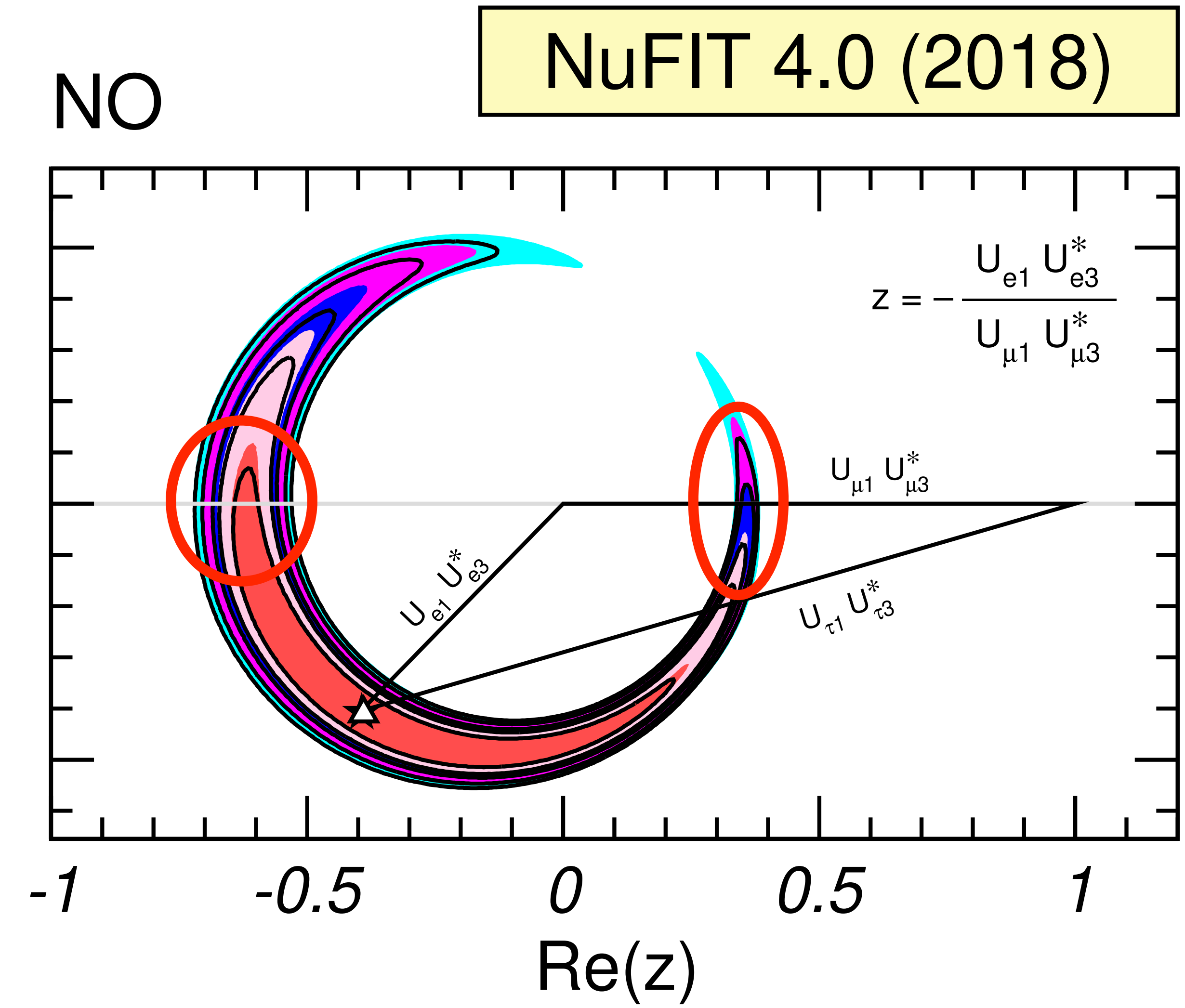
CP-Violation information….

CKM



J(CKM)≈3.18±0.15x10^{-5}

PMNS



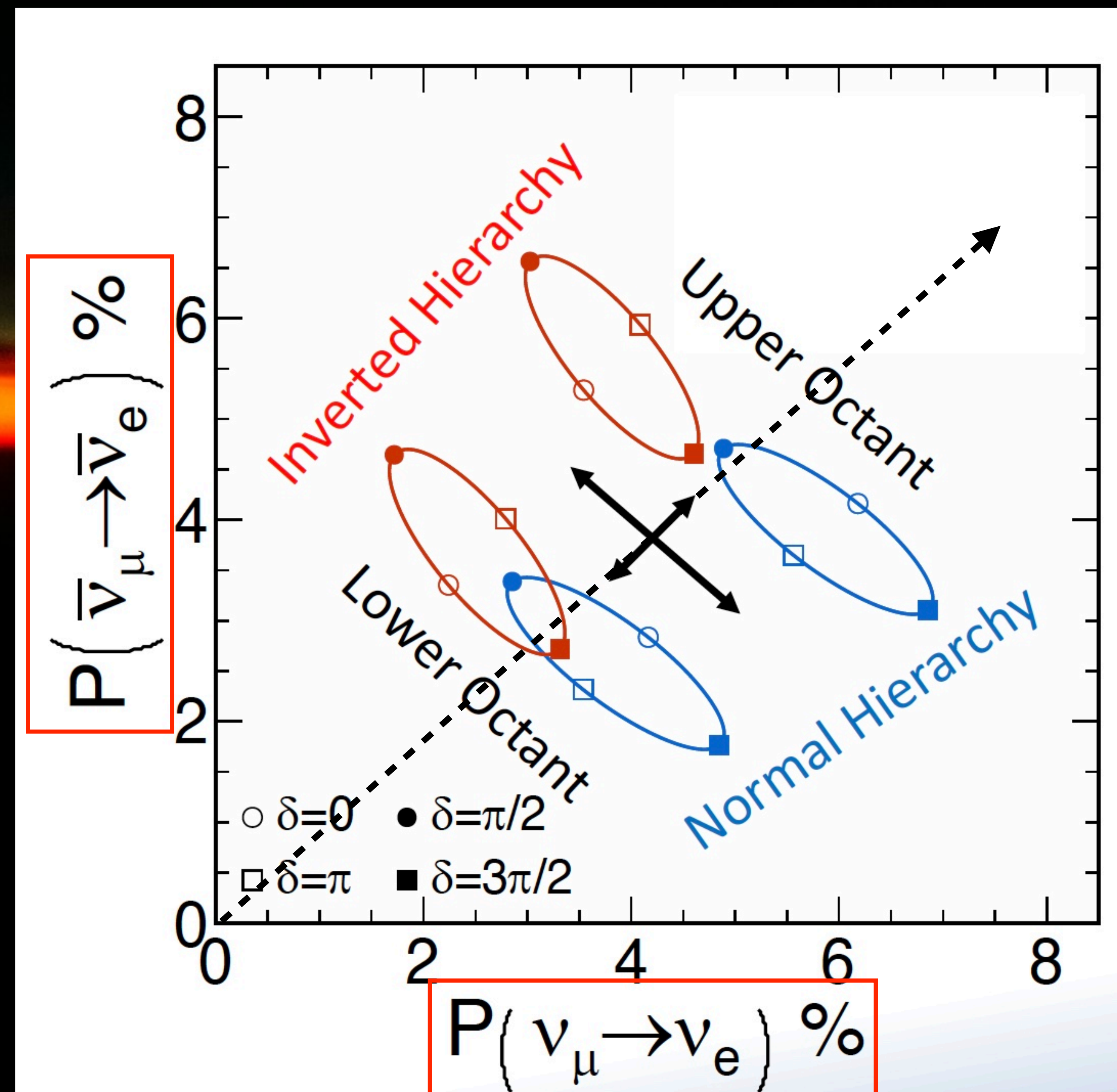
J(PMNS)≈3.33±0.06x10^{-2}

CP-Conversation disfavoured @ ~2σ
["infancy" era→ much to be done]

PMNS triangle (including CPV)…

measuring δ: bi-rate plots…

Appearance Channel ($\nu_\mu \to \nu_e$): 2 measurements [ν and anti-ν] for **4 a priori unknowns**
[$\theta_{23} \oplus \theta_{13}, \delta_{CP}$, MO]



CPV manifestation

difference probability for ν and anti-ν

δ_{CP}: elipses

MO: *off-diagonal* [conflic w δ]

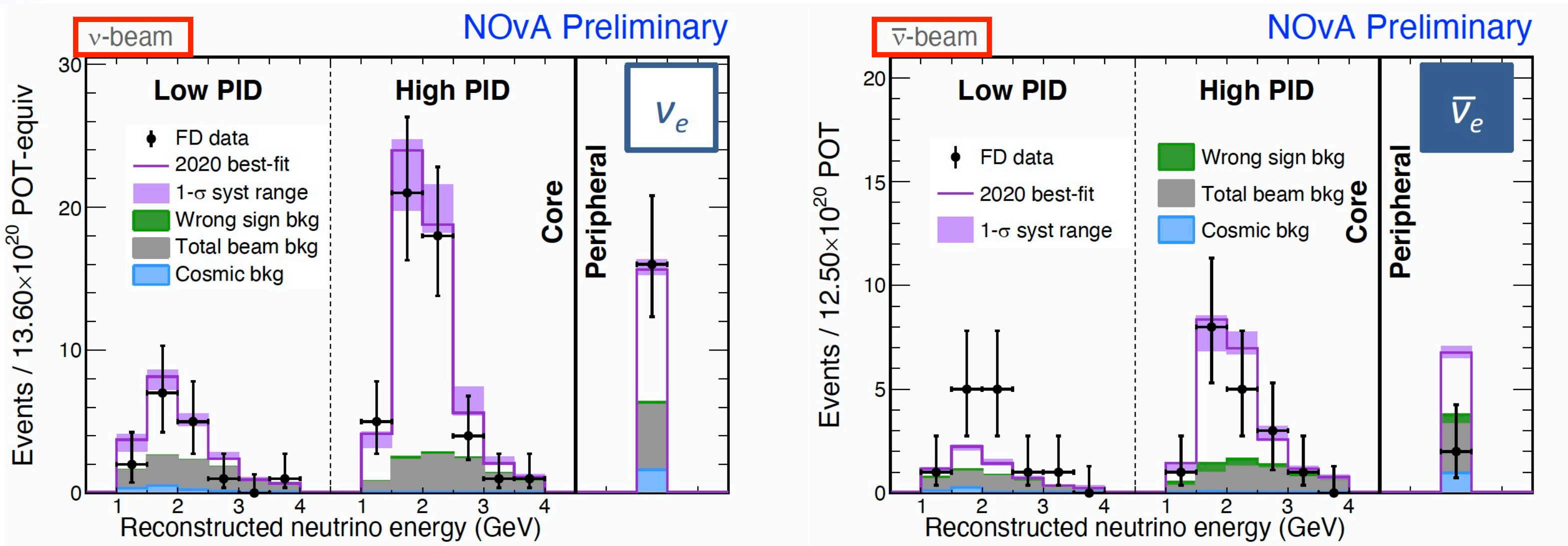
θ_{23} $\oplus\theta_{13}\to$ along diagonal

[reactors constrain **θ_{13}**]

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

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

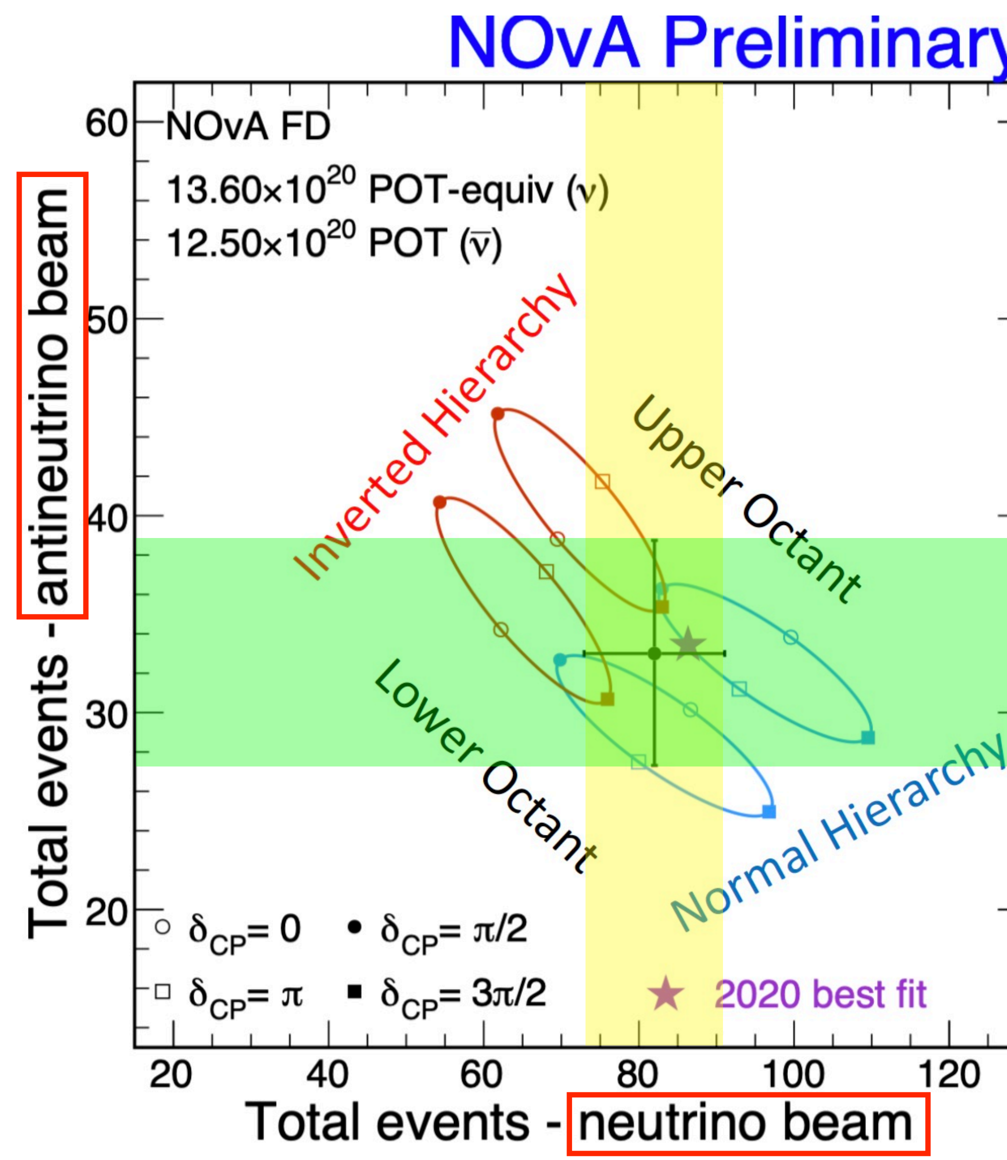
NEUTRINO 2020



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

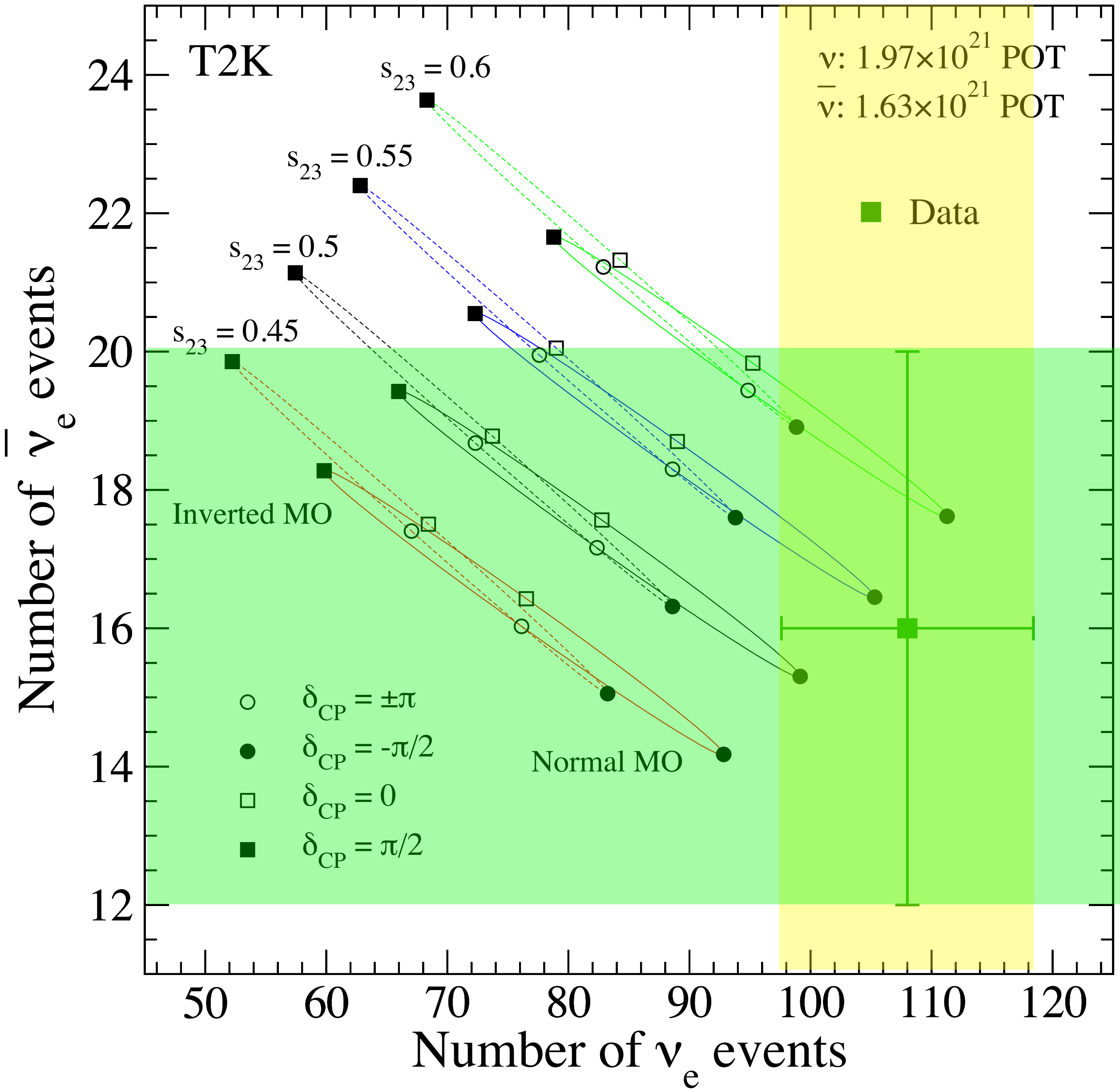
>4σ evidence of $\bar{\nu}_e$ appearance



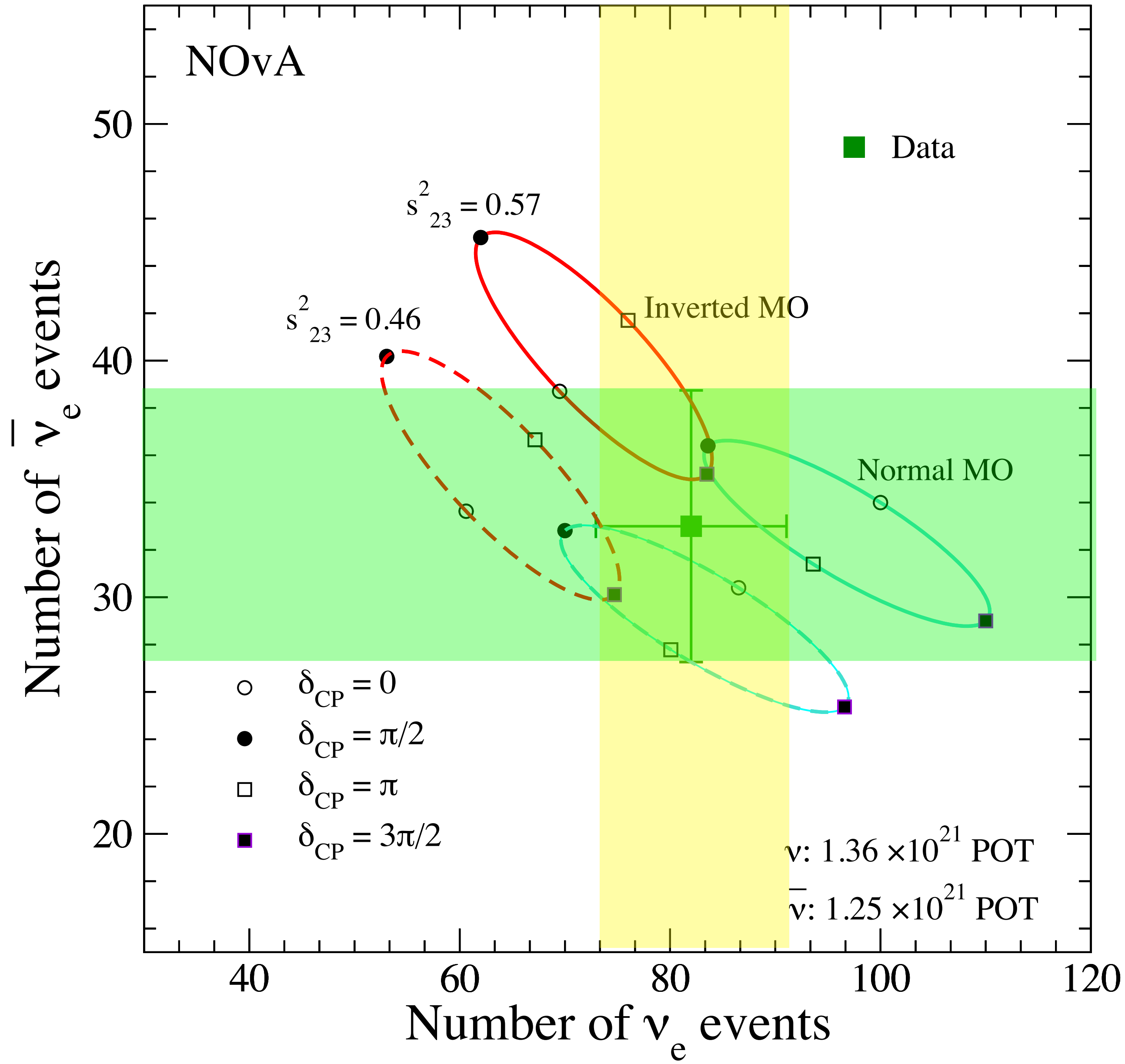
Appearance Channel ($\nu_\mu \rightarrow \nu_e$): 2 measurements [ν and anti-ν] for 4 a priori unknowns [$\theta_{23} \oplus \theta_{13}$, $\boldsymbol{\delta_{CP}}$, **MO**] but $\boldsymbol{\theta_{13}}$ marginalised by **reactor-θ13** and $\boldsymbol{\theta_{23}}$ measured via the ***Disappearance channel***

NOvA observables…

baseline ~250 km
[MO suppressed]



baseline ~800 km
[MO enhanced]



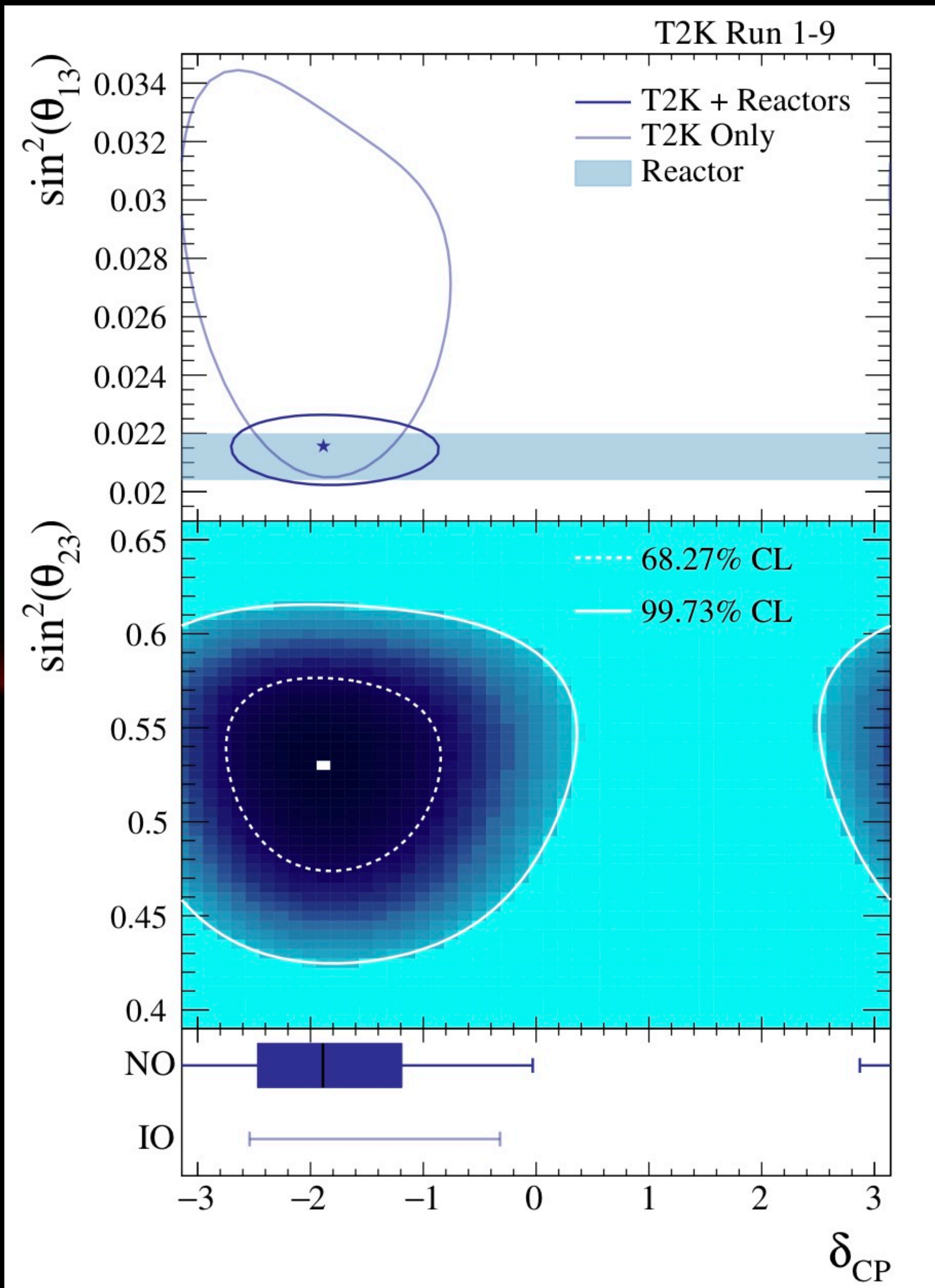
HyperK baseline ~250 km
[similar to T2K]

DUNE baseline ~1250 km
[MO further enhanced→separate elipses]

T2K versus NOvA…

δ_{CP}→ elipses (δ phase)
MO→ off diagonal [conflic w δ]
θ_{23} $\oplus\theta_{13}$→ along diagonal
[reactors constrain **θ_{13}**]

T2K⊕reactor best knowledge CP-Violation…

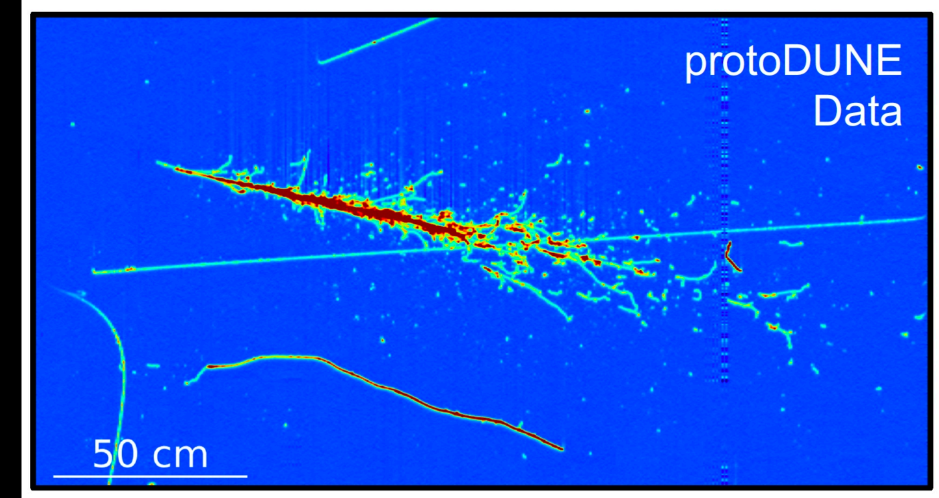


CPV phase vs θ13
[constrained by reactor]

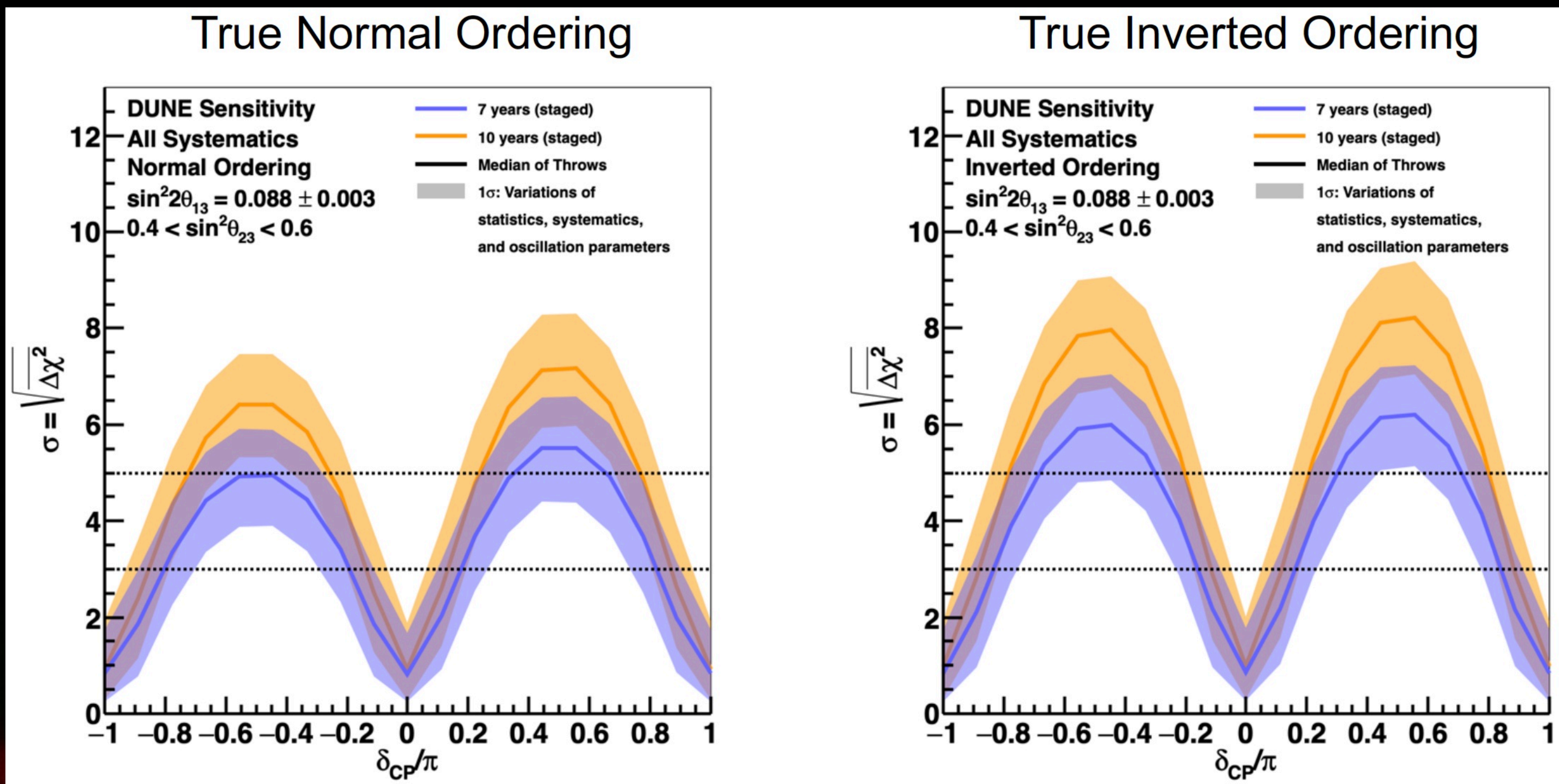
CPV phase vs θ23
[octant ambiguity]

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

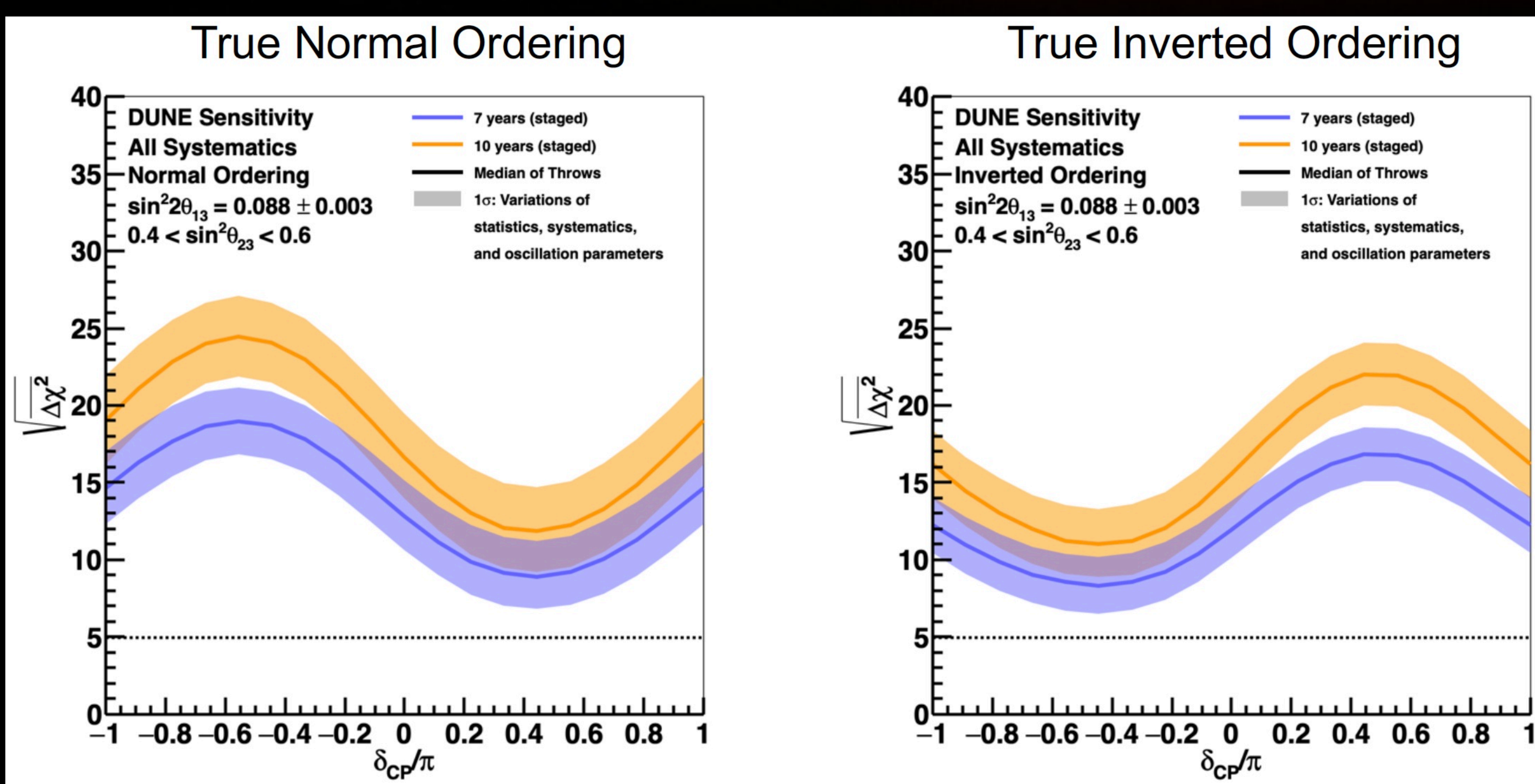
DUNE sensitivity…



CPV 's δ sensitivity…

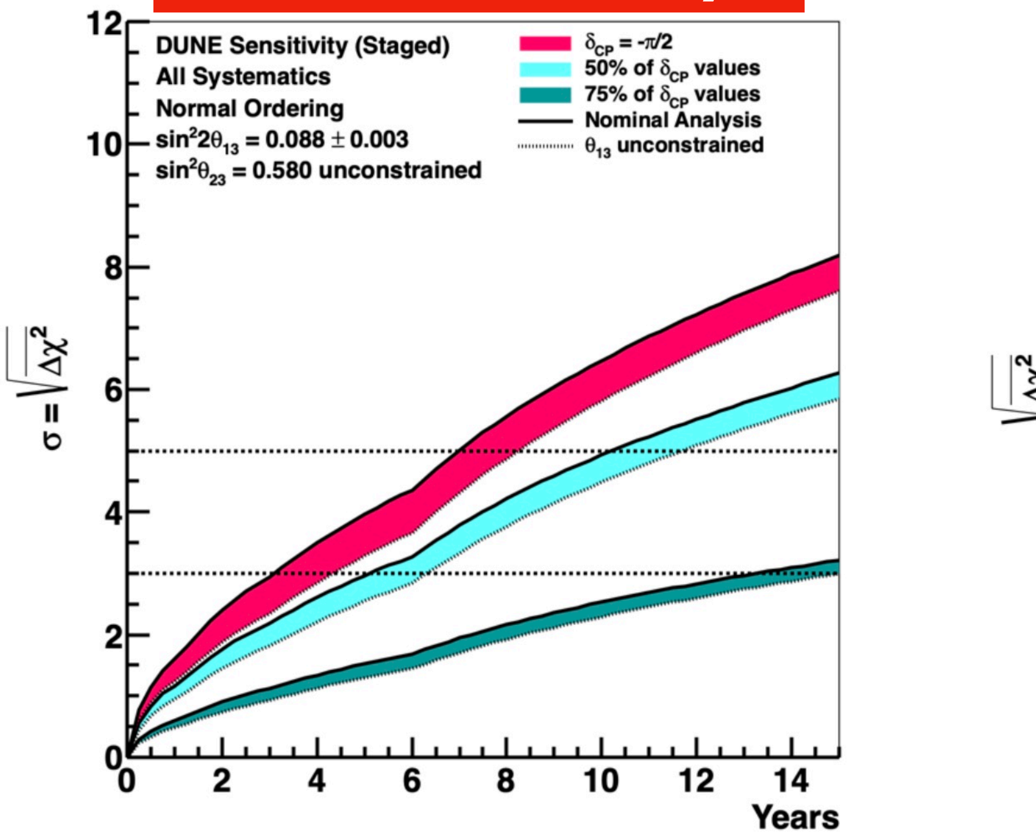


Mass Ordering (matter) sensitivity…

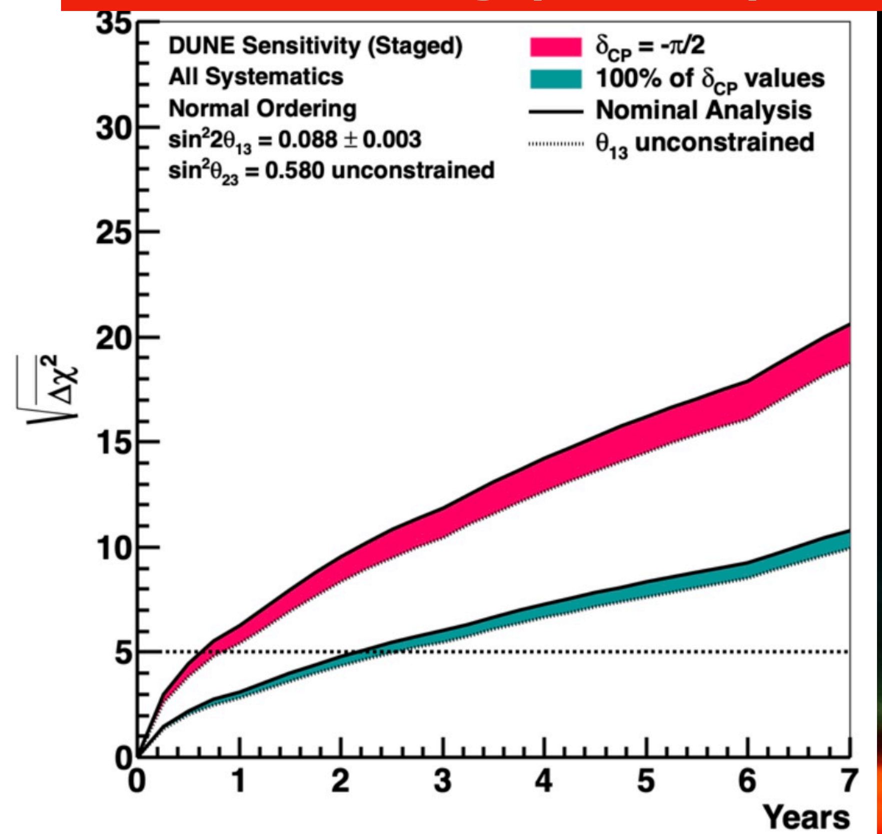


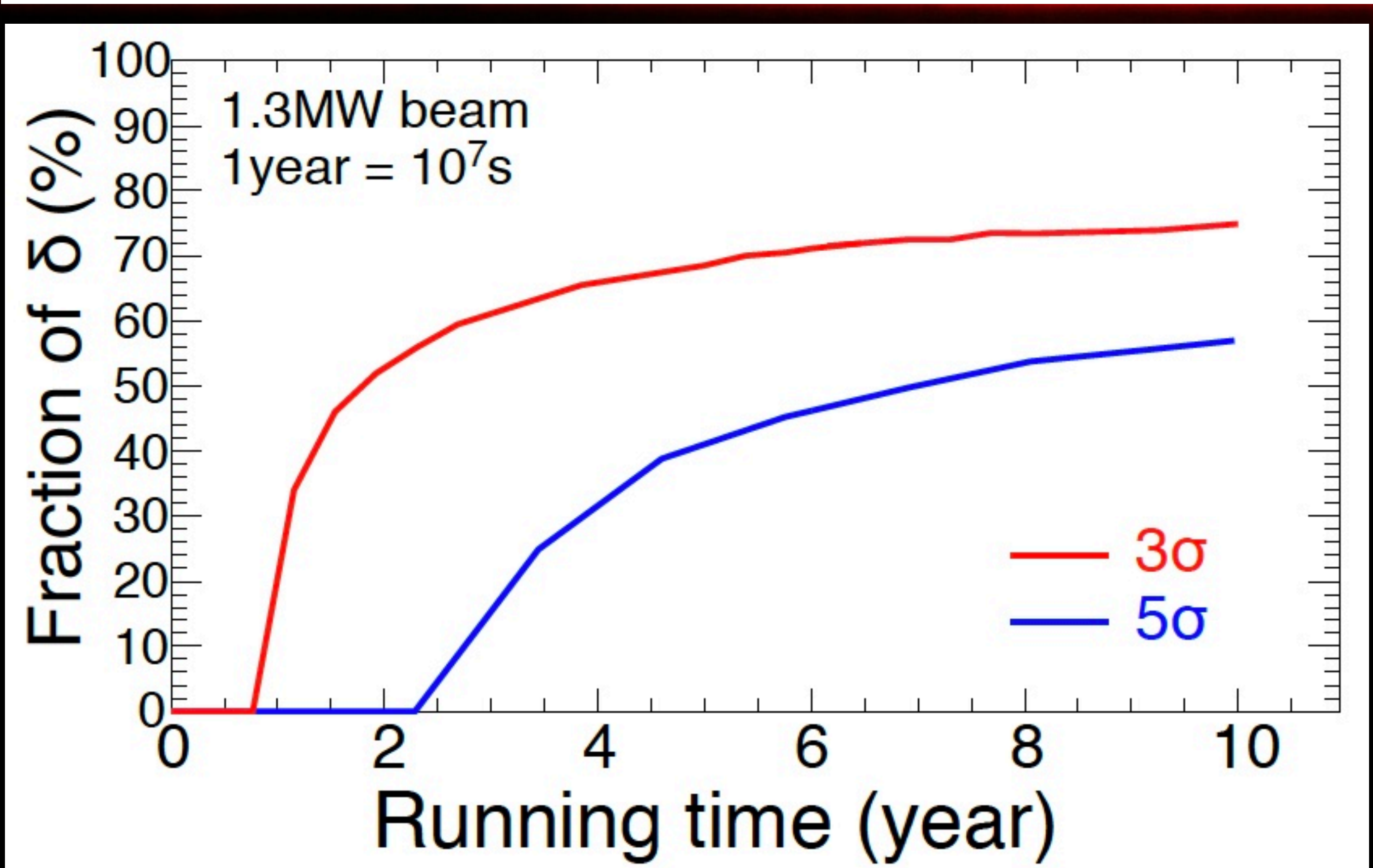
sensitivity time evolution…

CPV 's δ sensitivity…



Mass Ordering (matter) sensitivity…





HyperK: complementary to **DUNE**

detector: robust **Water-Cherenkov**
[DUNE: fancy **LAr**→R&D CERN et al**]**

Sorry: for briefness, I described less. HK sensitivity is similar to DUNE

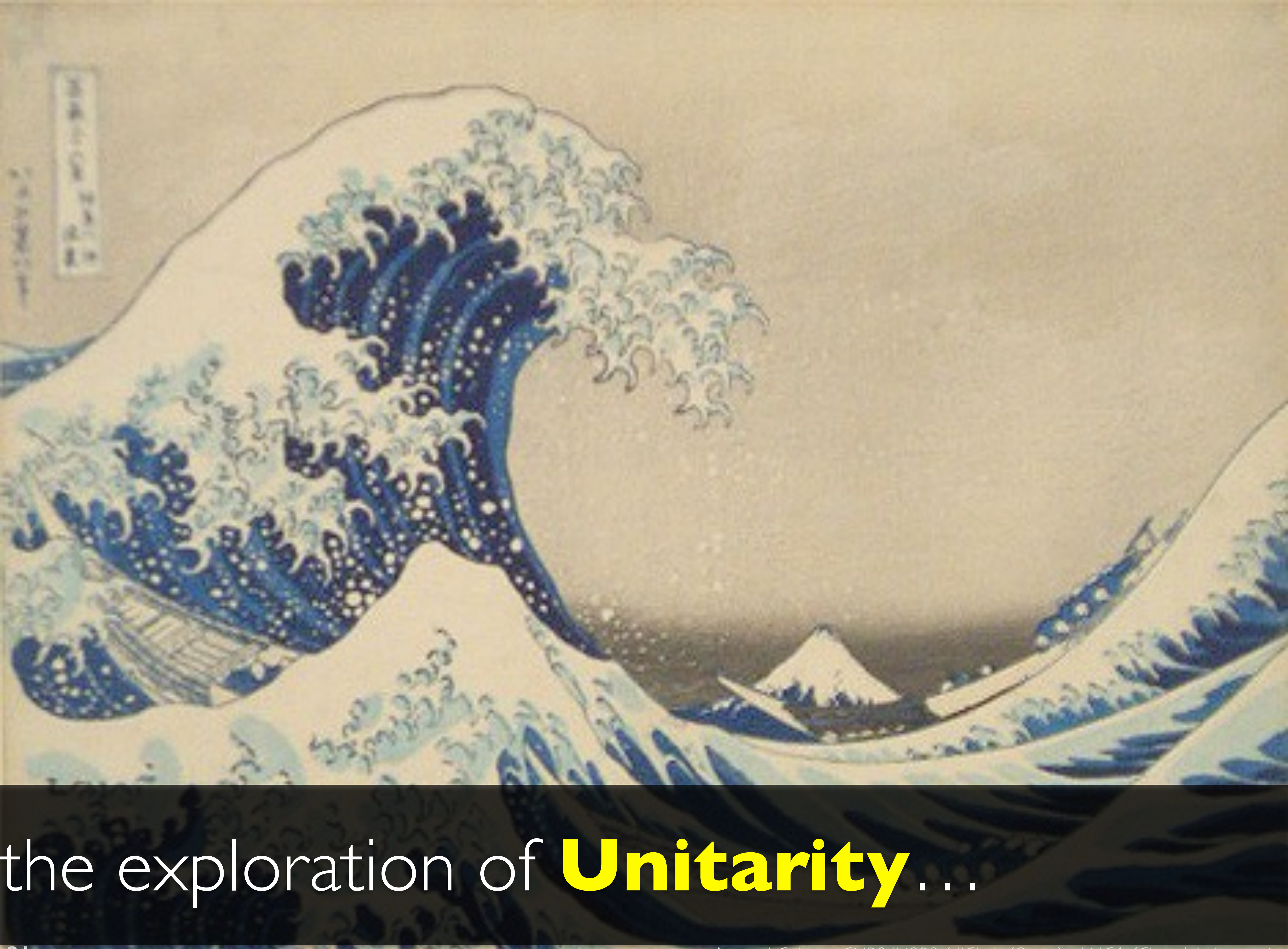
the bigger picture…

important to improving of both **θ13** (yesterday) and **θ23 [octant resolution]**

accelerator's the main observables are **δ** and **MO (matter)** — yesterday on **MO (vacuum)**

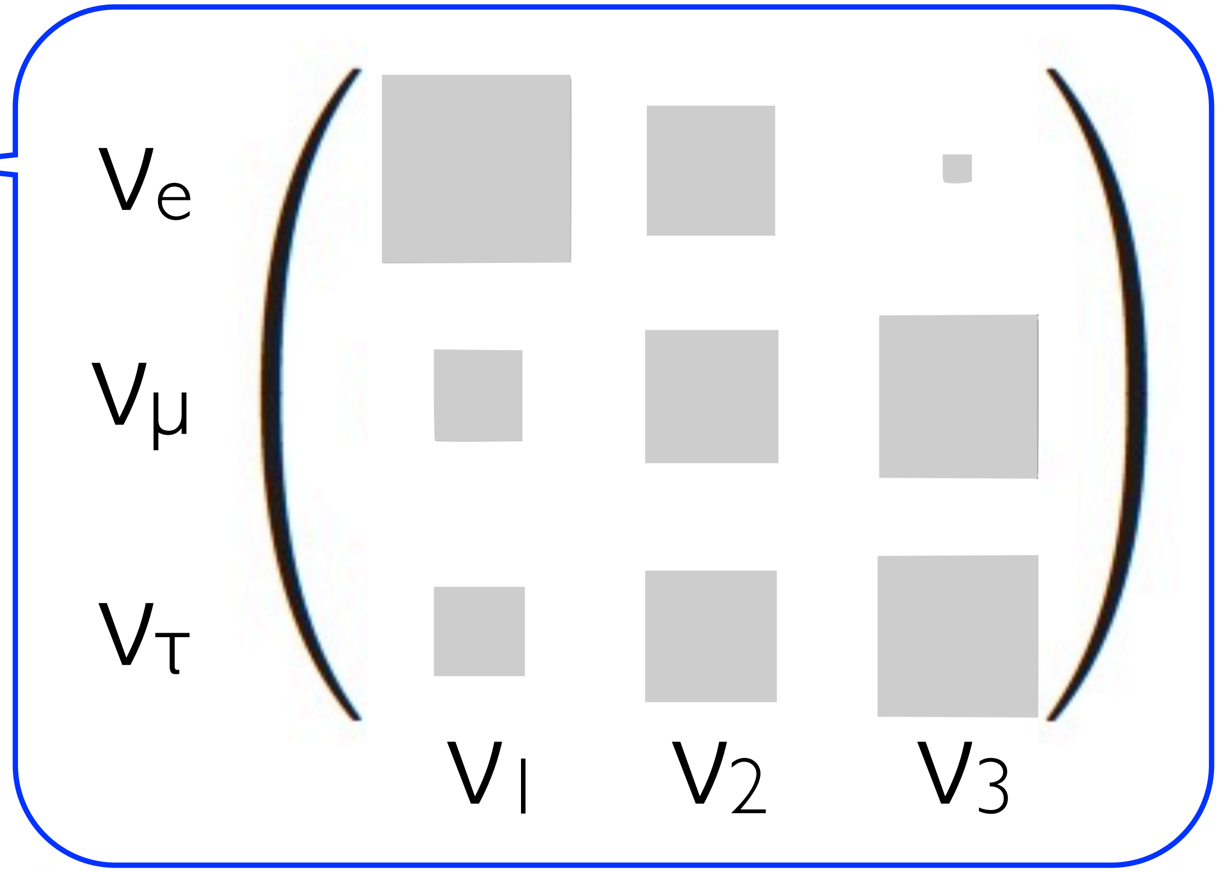
- both are will likely be **measured (≥5σ)** soon — **δ is harder if CP conserved**
- **beware:** ***SM*** mathematically (phenomenological) ready for both **δ** and **MO**
  - ***whether MO is normal or inverted***→ **SM is ready**
    [unless **MO(vacuum) ≠ MO(matter)**: **BSM manifestation**]
  - ***whether δ is violating or conserving***→ **SM is ready**
    [link to **Leptogenisis CPV via BSM** — not established model independently]
  - the **same is a priori rather true to the per-mille precision** (JUNO et al)

⟹ **no evident rupture** (or modification) in today's ***SM*** by future experiments (unless surprises)
[still **absolutely critical** measurements — huge effort]



the exploration of **Unitarity**…

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



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]

CKM vs PMNS…

u c t

d s b

ν_e ν_μ ν_τ

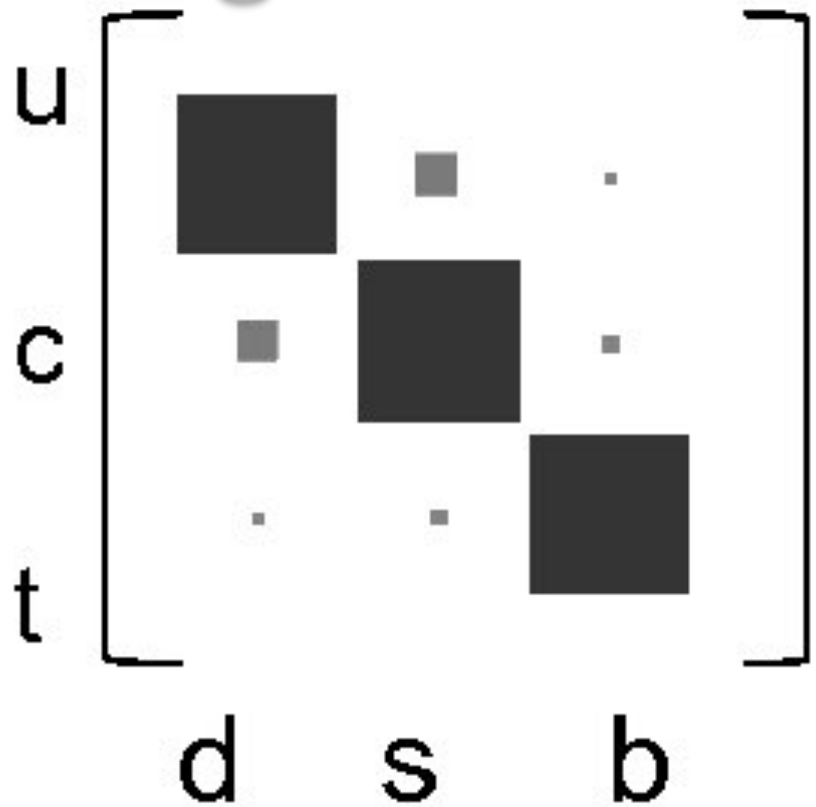
ν_1 ν_2 ν_3

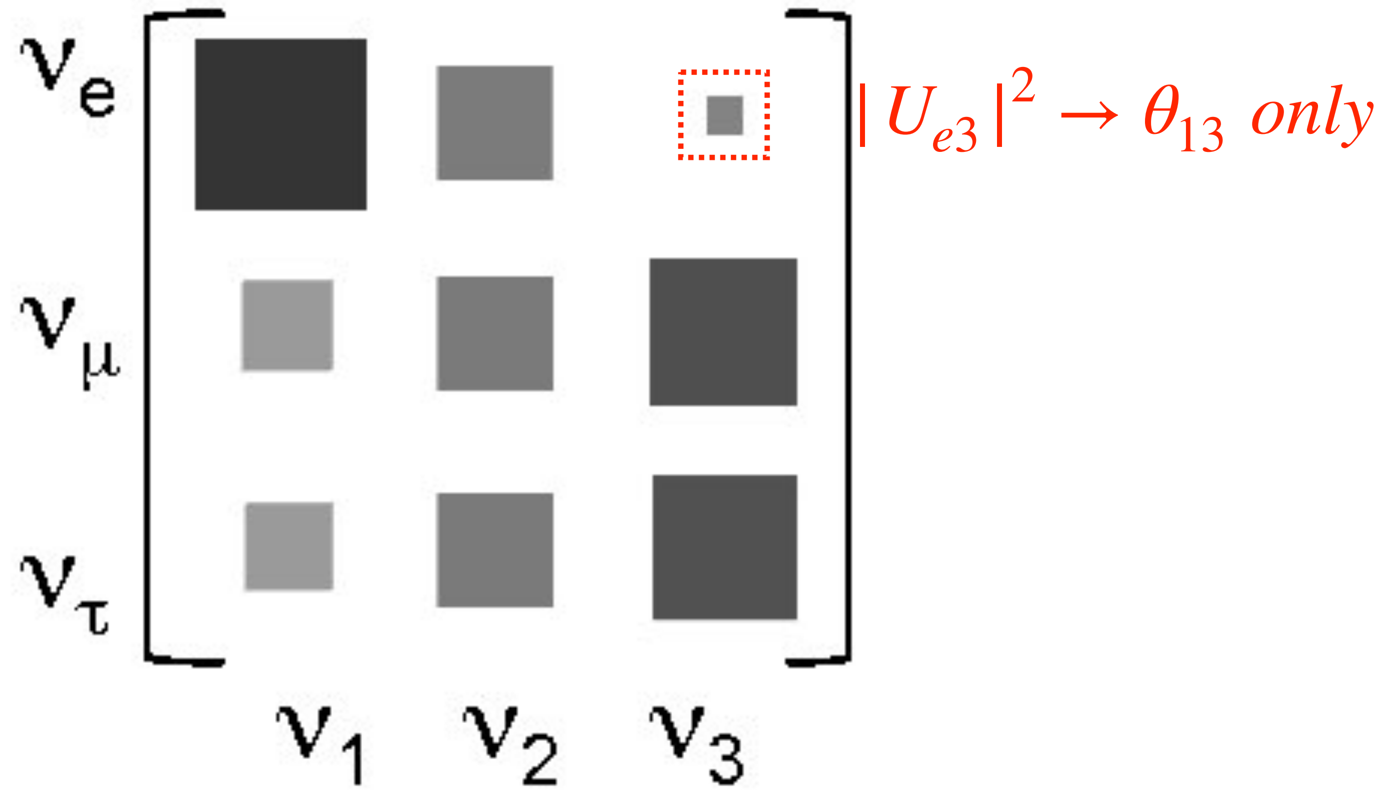
elegance
(symmetry)

stravaganzza
(anarchy?)

A. De Gouvea, H. Murayama, hep-ph/0301050; PLB, 2015.
L. Hall, H. Murayama, N. Weiner, hep-ph/9911341.

elegant CKM vs **PMNS extravaganza**...





CKM

$J_{max} \approx 3x10^{-5}$

- small CPV allowed
- small CPV measured

almost diagonal

- pattern exist (i.e. minimal mixing)
- off-diagonal is small

unitarity precision "top-row" [0.5‰]

- **deviation tiny?** (follow pattern)

PMNS

$J_{max} \approx 3x10^{-2}$

- larger CPV allowed [**$10^3\times$ the CKM**]
- maximal? CPV [T2K⊕reactors-θ13]

highly non-diagonal

- symmetry vs anarchy?
- only U_{e3} (θ_{13}) is small: why? **(meaningful vs caprice)**

unitarity precision "top-row" [~%]

- **larger deviations?**

much CPV to explain the observed Universe→ neutrino-based solution?

[link to heavy Majorana neutrinos CPV?]

unitarity is behind all our definitions…

UNITARITY implies…

- **IF 3 neutrino standard states — non-standard cases?**

[in agreement with quark's **3 families**]

$\Longrightarrow$ **2 mass difference: Δm^2 & δm^2**

$\Longrightarrow$ **3 independent mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$**

$\Longrightarrow$ **1 (Dirac) CP-Violating phase: δ_{CP}**

[*i.e. a 3x3 unitarity matrix may be complex*]

if 4 families, expect more Δm^2's, θ's or δ_{CP}'s → **3x3 *effective approximation***

testing **UNITARITY** → **testing for new families + more!!**

(regardless of kinematics)

significant unitarity violation means…

significant unitarity deviation ("*triangles*" or "*rows/columns*") imply the manifestation of…

1 •**new states** (**BSM** >3 families, sterile, etc)
or
2 •**new interactions** (**BSM**)
or
3 •**something totally new?** [**BSM**→ask your favourite theorist]
or
4 •**a combination of [1]⊕[2]⊕[3]** — hard (or impossible) to disentangle a priori

regardless, this means **discovery BSM!!** — a crack in the ***effective validity of the SM***…

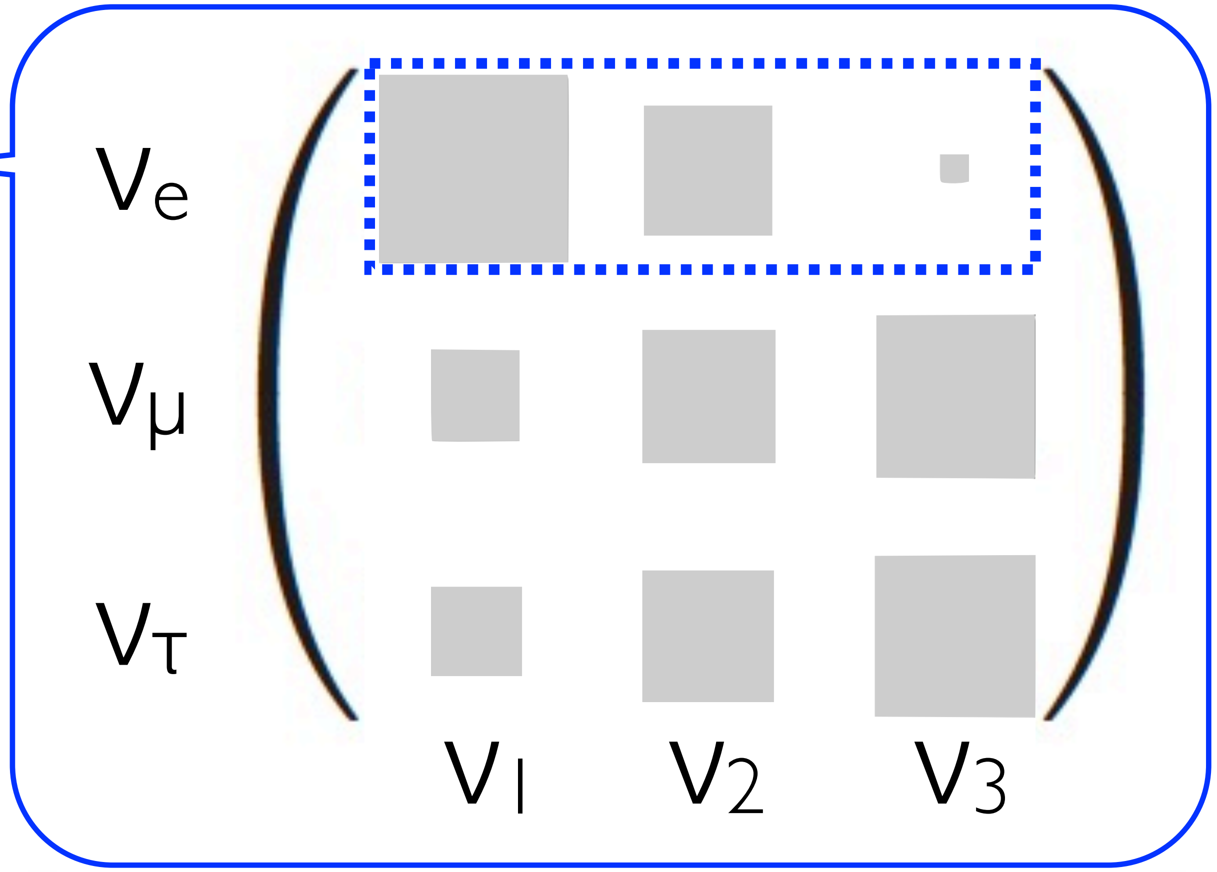
testing unitarity with neutrinos has some advantages (even more?)…

- **independent validation of CKM unitarity issues** (~4σ on "Cabibbo angle anomaly")
- unlike CKM, explorations with **NO QCD/QED correction(s)** (>experimental uncertainty)
- **neutrino uniqueness** (mass, neutral, etc)→enhanced sensitivity to **BSM** (→lot of phenomenology) [this is why neutrino is different…?]

note: exact theoretical prediction for unitarity conservation (must be 1)

test PMNS Unitarity…

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



⇒ **best precision?**

⇒ **good precision**

⇒ **poorest precision**

$$UU^\dagger = U^\dagger U = I$$

⇒ **many equations!!**
[“triangles” / “rows” / “columns”]

since no CPV (yet) ⇒ test Unitarity via the “rows”

$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$$

PMNS equivalent to the CKM’s “Cabibbo angle anomaly”

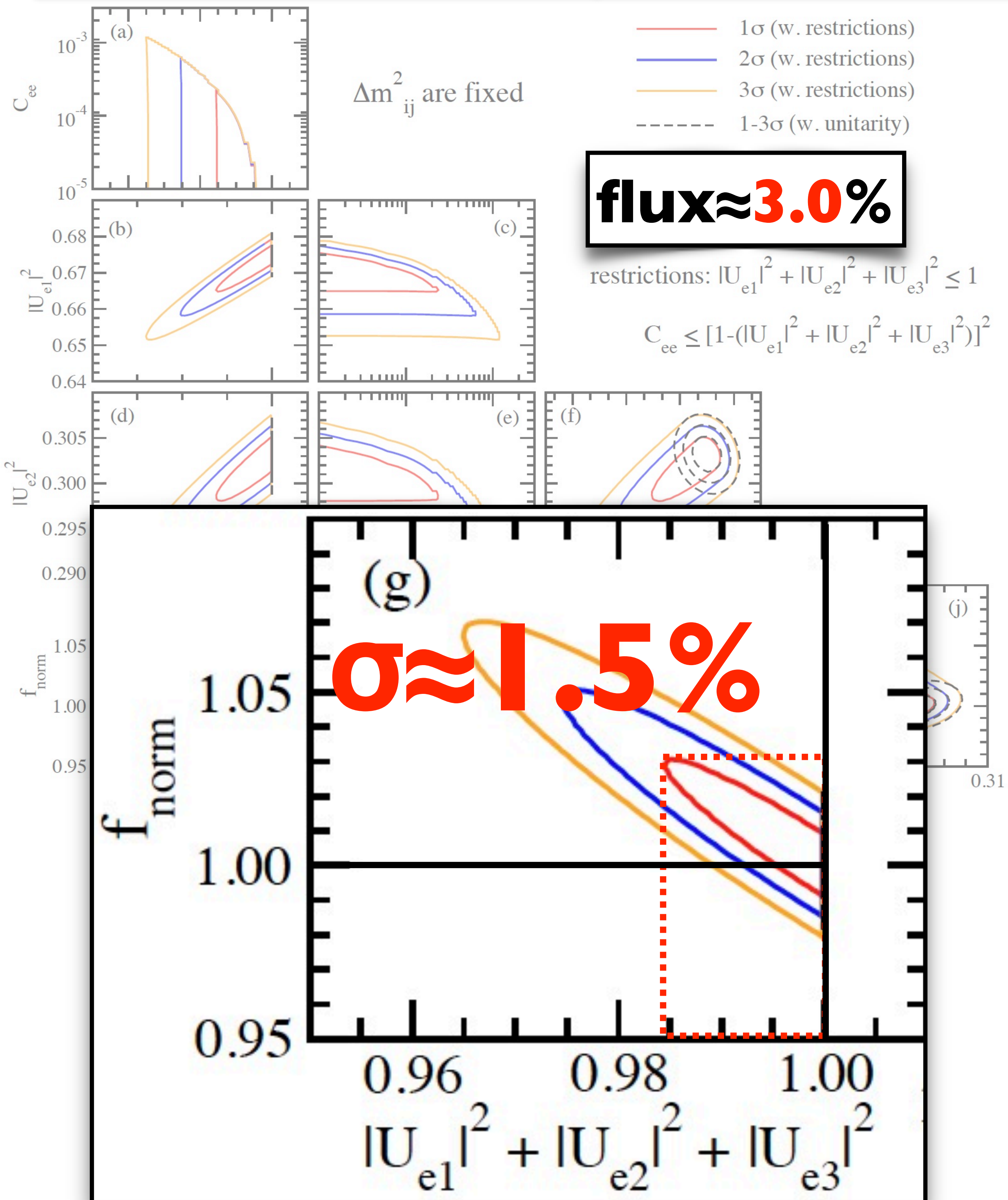
$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$

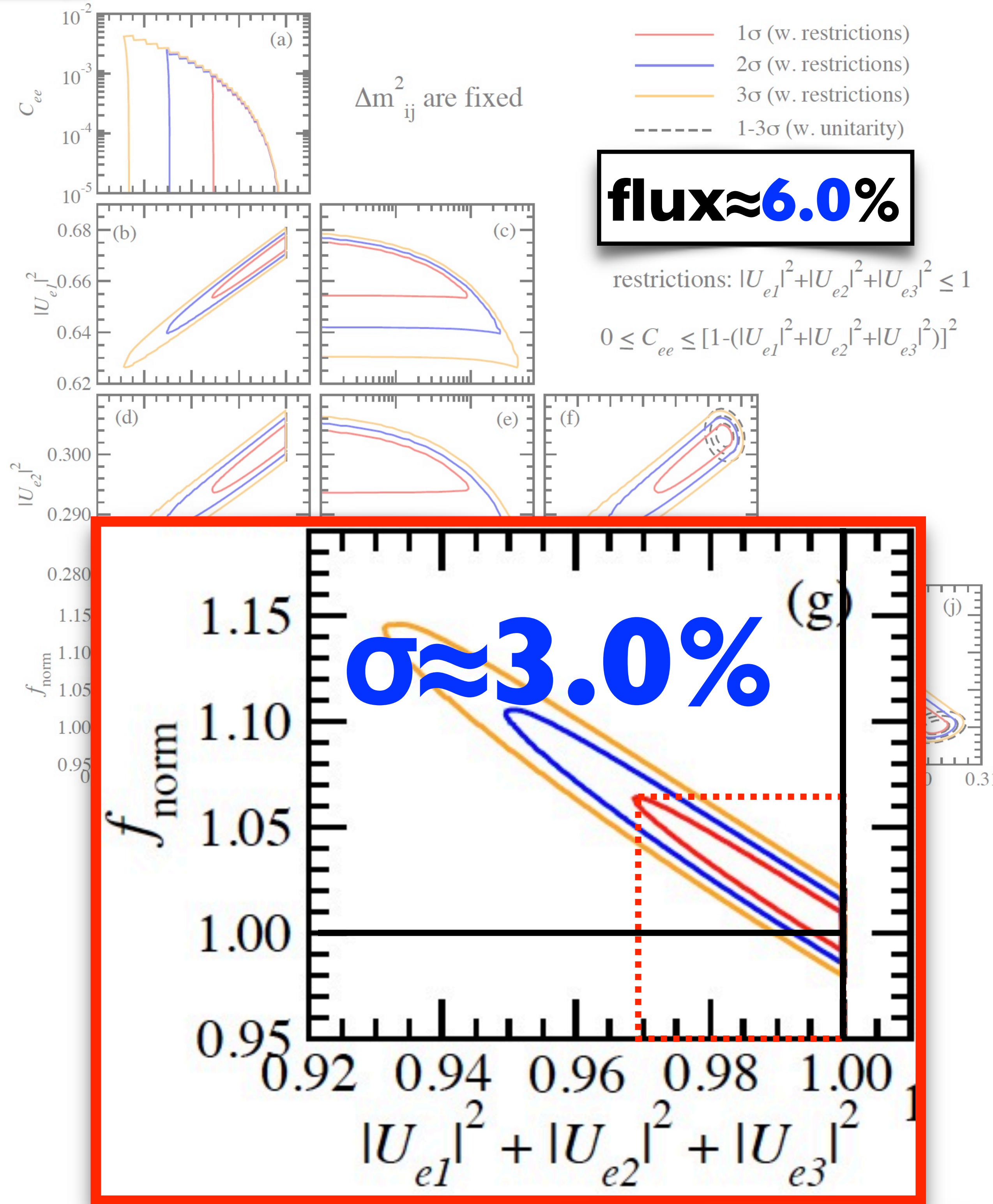
⇒ **explore “electron top-row”**

only θ_{12} and θ_{13} (unitary) — see Valencia parametrisation **(α_{11}): flux normalisation**

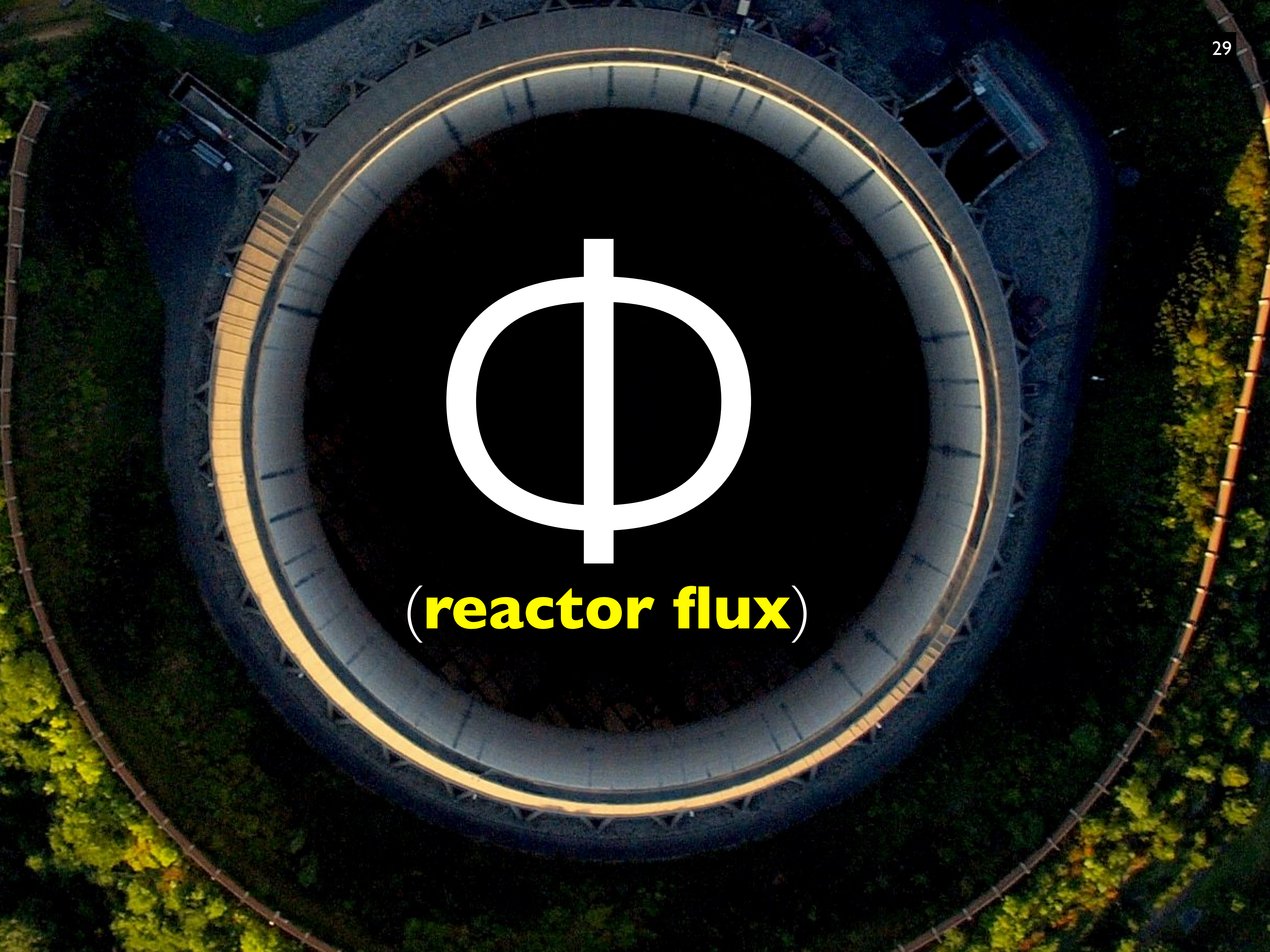
today's (**e-row**) **unitarity** knowledge…

H. Nunokawa *et al* (arXiv:1609.08623v2)

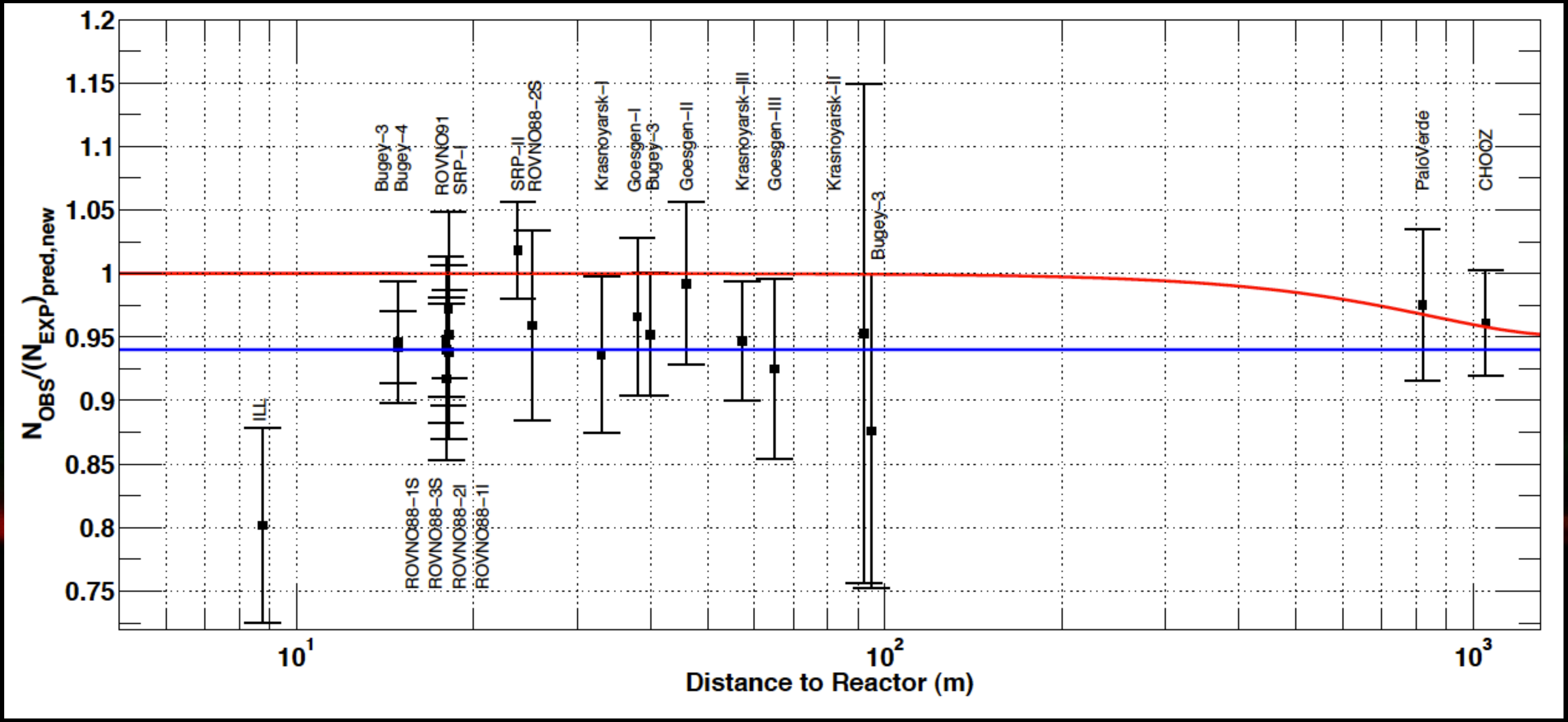




unitary explorations limited by absolute flux uncertainty


Φ
(reactor flux)

reactor flux discrepancy…



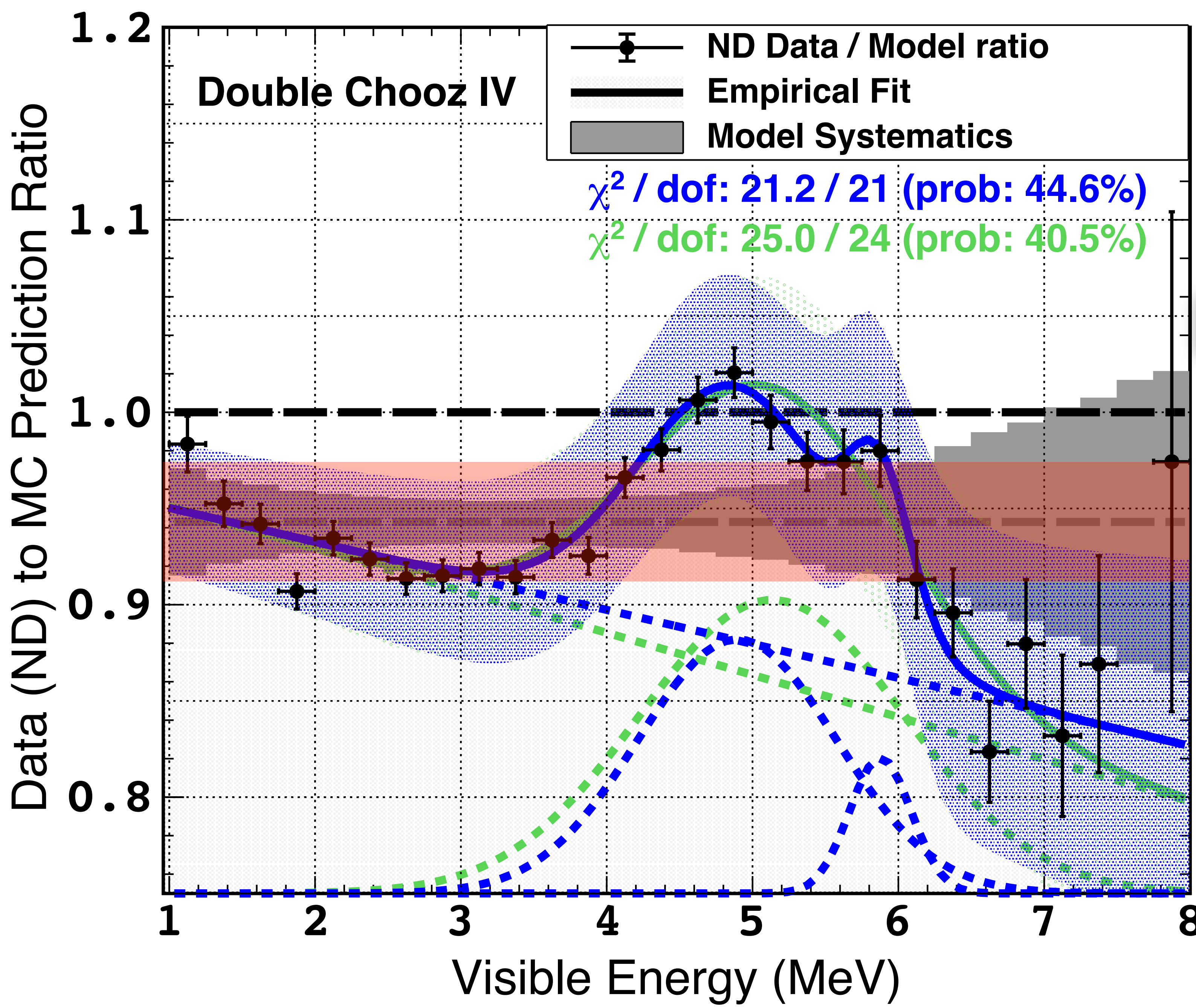
till 2011, excellent agreement to ILL-based (i.e. data) prediction (blue)

still excellent agreement among (all) experiments

now ≤7.0% mismatch between ILL-prediction and data

reactor flux uncertainty…

Hervé de Kerret *et al* (arXiv:1901.094451)



Φ(reactor) [exp] best precision (~0.9%)

R=0.925±**0.010**(exp)±**0.023**(model)

prediction fails to match both rate & shape!

[not just rate]

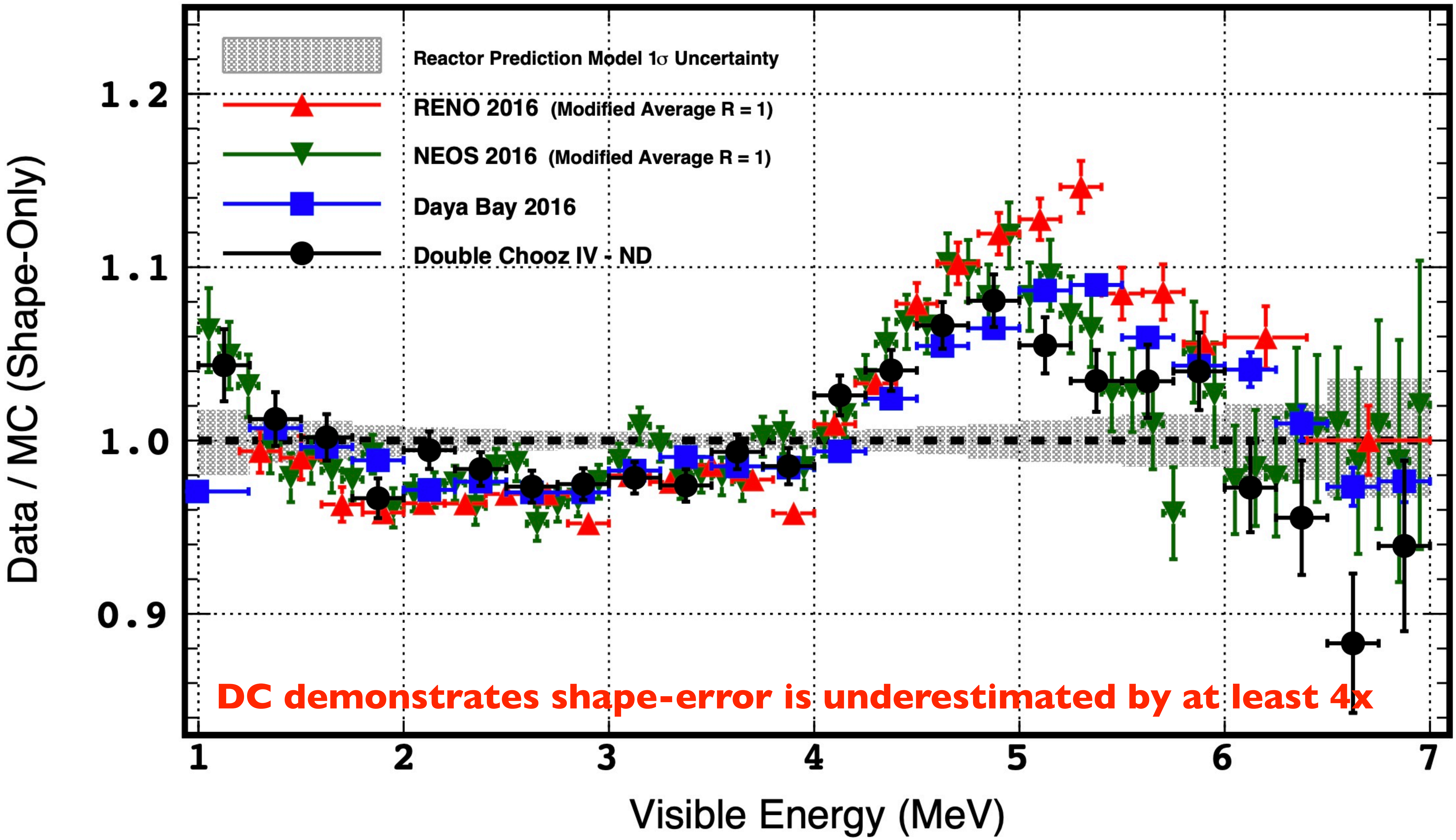
Total Uncertainty
~2.2%→6.0%?
[surely <10%]

nature physics

ARTICLE

First Double Chooz θ_{13} Measurement via Total Neutron Capture Detection

shape distorsion common across experiments…



only one experiment in tension: **Bugey3** (flat-ish) — spectral reference before **reactor-θ13**


No?
(till now we don’t know how)
Φ
improvable?

news! reactor ultimate flux…

solve the reactor "issue" (anomaly)?
(discrepancy data and ILL-prediction)

Reevaluating reactor antineutrino spectra with new measurements of the ratio between ^{235}U and ^{239}Pu β spectra

confirmed?

V. Kopeikin,[1] M. Skorokhvatov,[1,2] and O. Titov[1,*]
[1]*National Research Centre Kurchatov Institute, 123182, Moscow, Russia*
[2]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409, Moscow, Russia*
(Dated: May 31, 2021)

We report a reanalysis of the reactor antineutrino energy spectra based on the new relative measurements of the ratio $R = {}^{e}S_5/{}^{e}S_9$ between cumulative β spectra from ^{235}U and ^{239}Pu, performed at a research reactor in National Research Centre Kurchatov Institute (KI). A discrepancy with the β spectra measured at Institut Laue-Langevin (ILL) was observed, indicating a steady excess of the ILL ratio by the factor of 1.054 ± 0.002. We find a value of the ratio between inverse beta decay cross section per fission for ^{235}U and ^{239}Pu: $({}^{5}\sigma_f/{}^{9}\sigma_f)_{KI} = 1.45 \pm 0.03$, and then we reevaluate the converted antineutrino spectra for ^{235}U and ^{238}U. We conclude that the new predictions are consistent with the results of Daya Bay and STEREO experiments.

arXiv:2103.01684v2 [nucl-ex] 28 May 2021

R=0.925±0.010(exp)±0.023(model)→ **R≈1.0?**±0.010(exp)±0.0?(model)

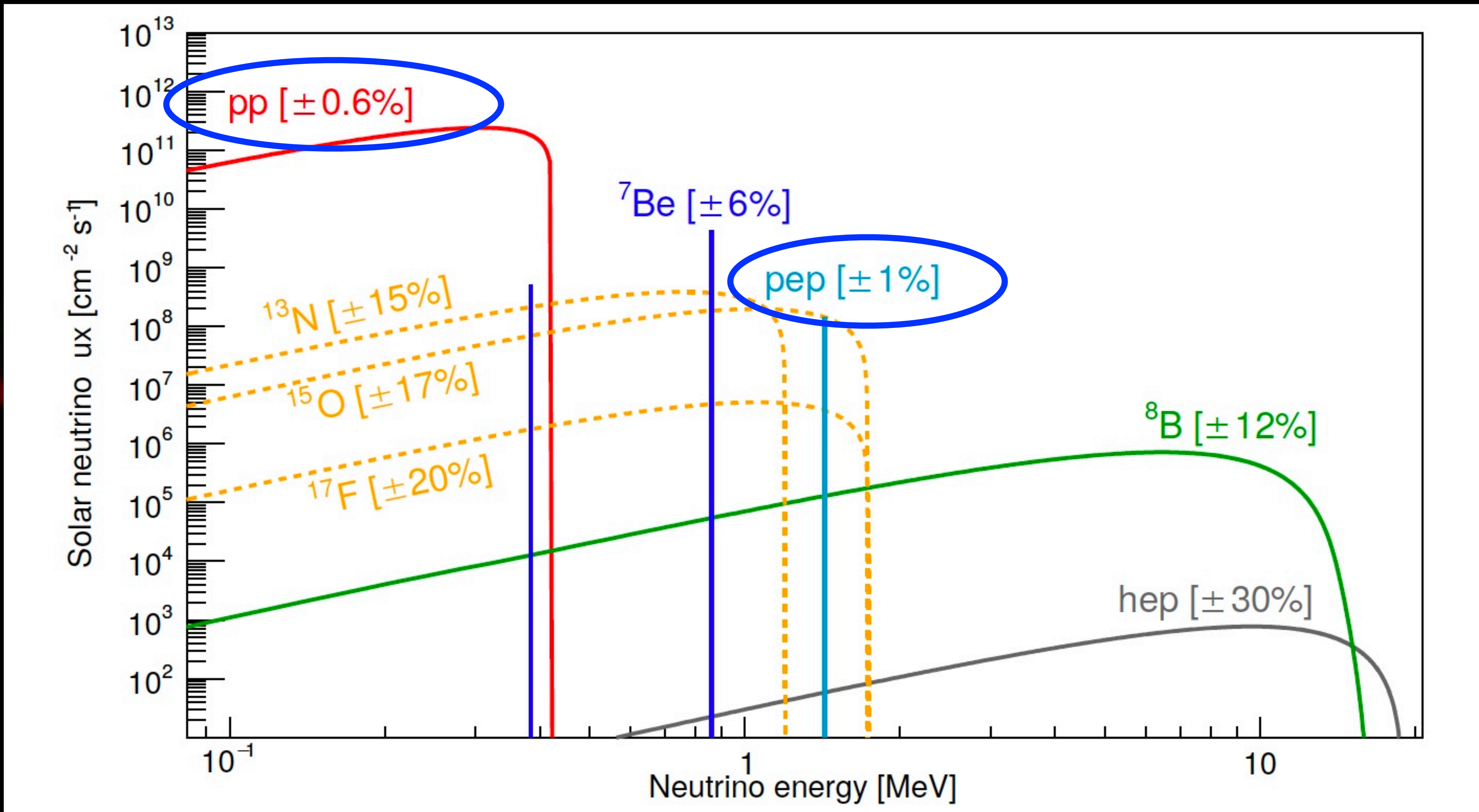
experiment flux uncertainty will drive?
(eventually dominated by thermal power)

Uncertainty (%)	ND
Proton Number	0.66
Thermal Power	0.47
TnC Selection	0.24
Background	0.18
Energy per Fission	0.16
θ_{13} Correction	0.16
Statistics	0.22
Total	0.97

→ irreducible!!

ultimate flux uncertainty: Sun…

ultimate flux uncertainty by reactor order 0.5% (thermal power)



accelerators flux uncertainties (order ≥5%)

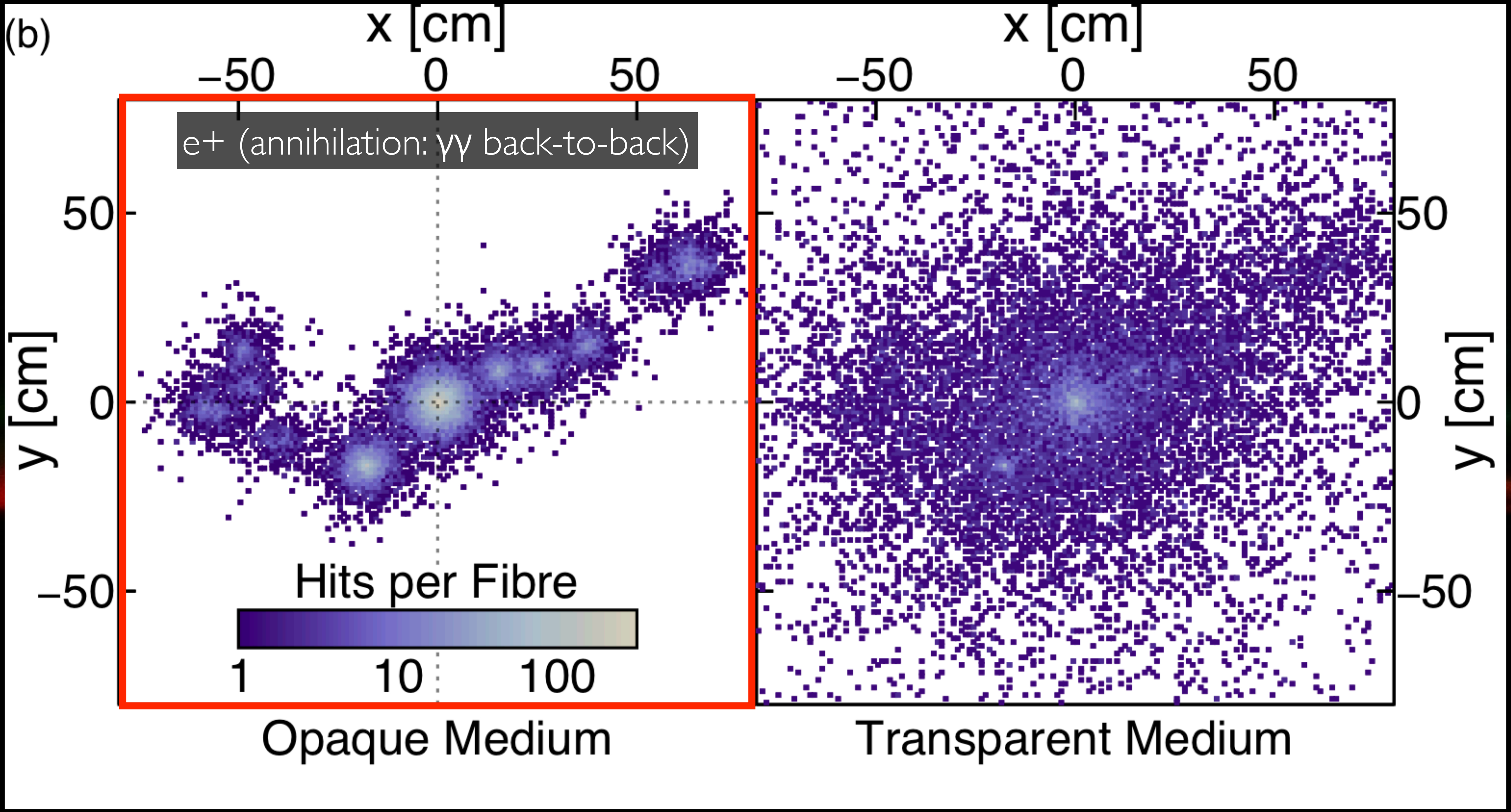
by 2030, mixing @ ~1% level…

(**no unknowns**)

still neutrino surprises…?

SuperChooZ?

LiquidO event-wise imaging…



opaque scintillator→stochastic light confinement (**self-segmentation**)

LiquidO: light "opaque" medium

[*stochastic light confinement*→imaging⊕topology & **PID**]

vocabulary: "opacity" ≈ "brutal translucency"

⇓

LiquidO ≈ "light TPC" ⊕ "4π ToF" (4D info)

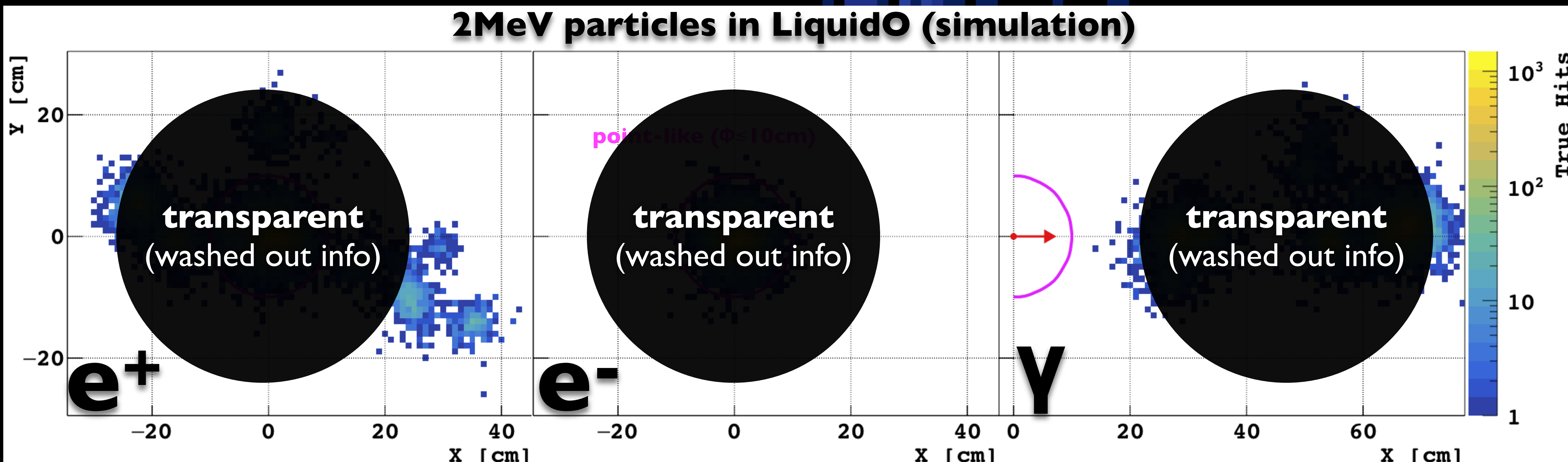
[highest duty-cycle & high acceptance→ minimal pile-up]

what's LiquidO?

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

LiquidO in a nut-shell…

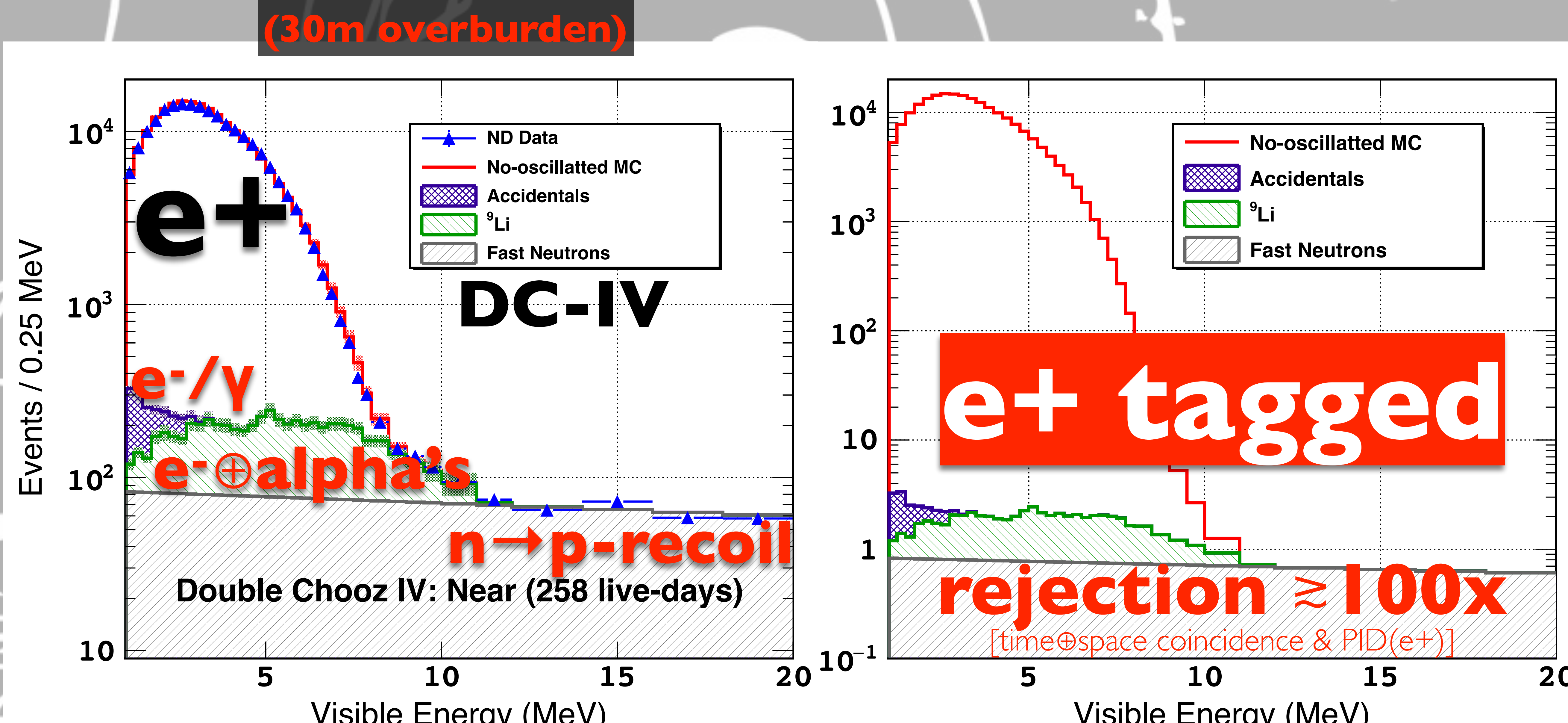
Imaging→powerful Particle-IDentification (PID)



LiquidO ≈ PID ⊕ (high) **Doping**

physics beyond detector "native composition" (H,C)

⟹ less shielding & no detector "buffer"



state of the art

Signal:Background ~30:1 (30m overburden)

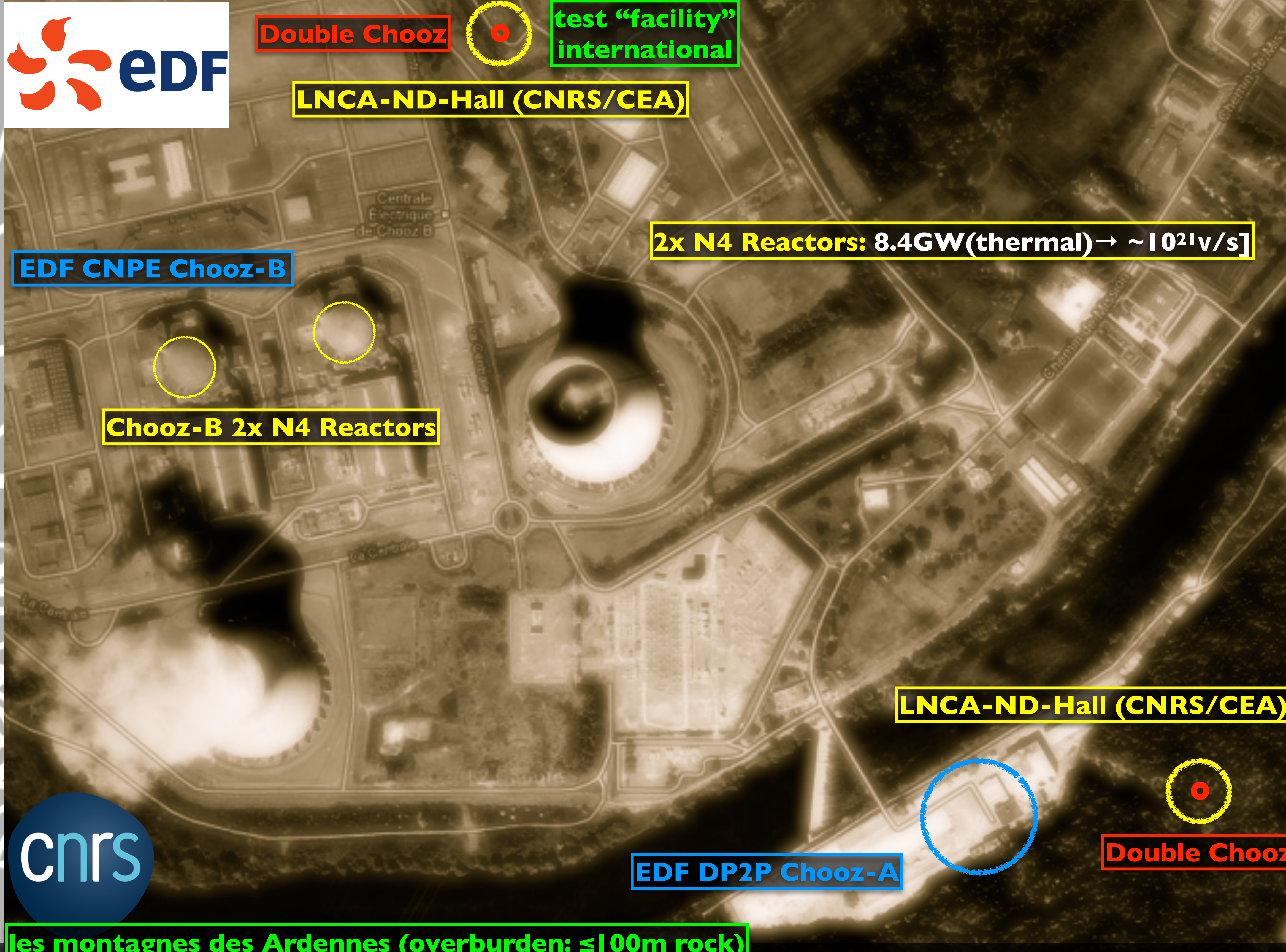
Background: few/day

LiquidO

Signal:Background ≳100×30:1

Background: few/year

towards background-less…

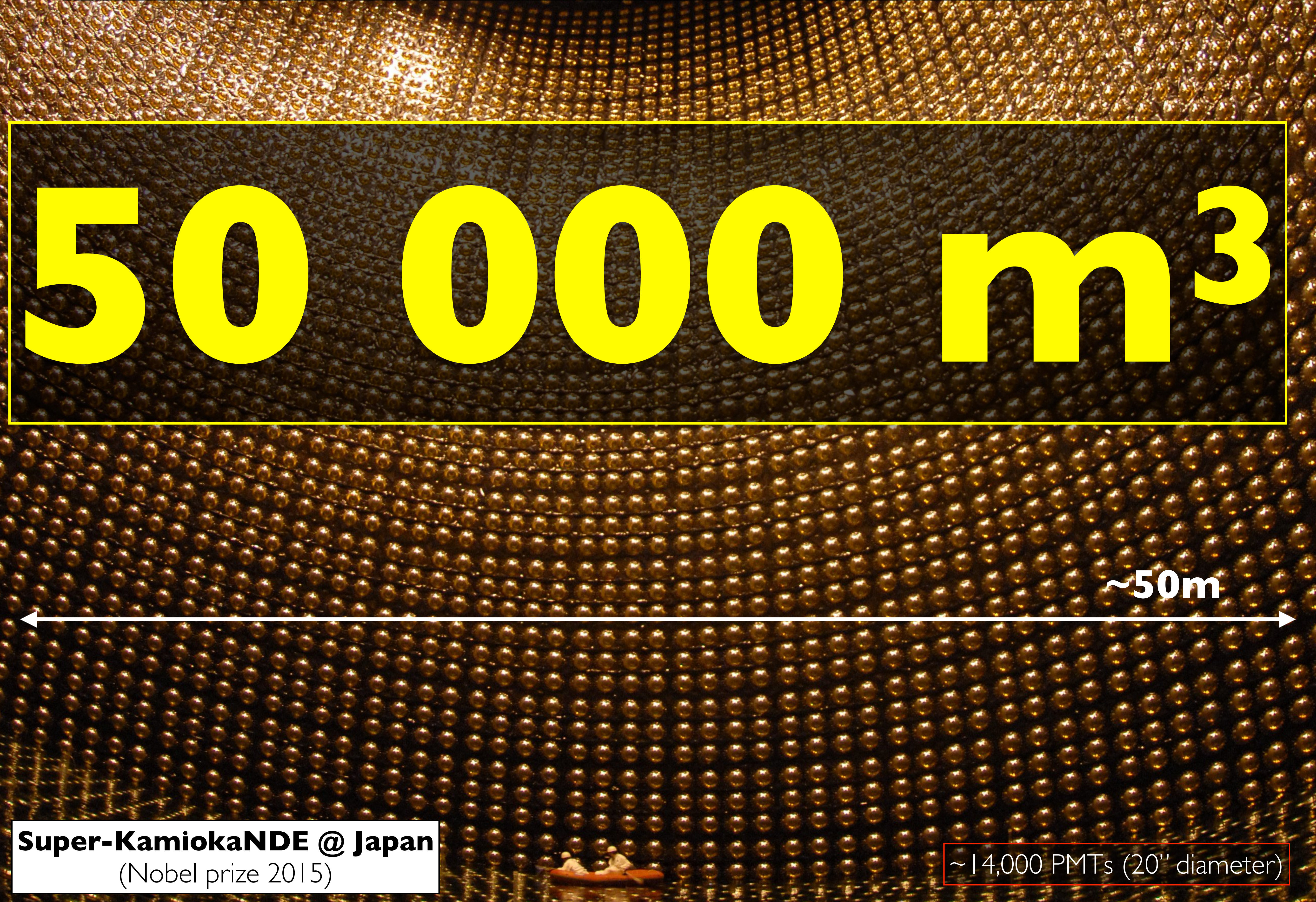


Europe's best reactor ν site…

an underground secret…

Chooz-A former nuclear reactor

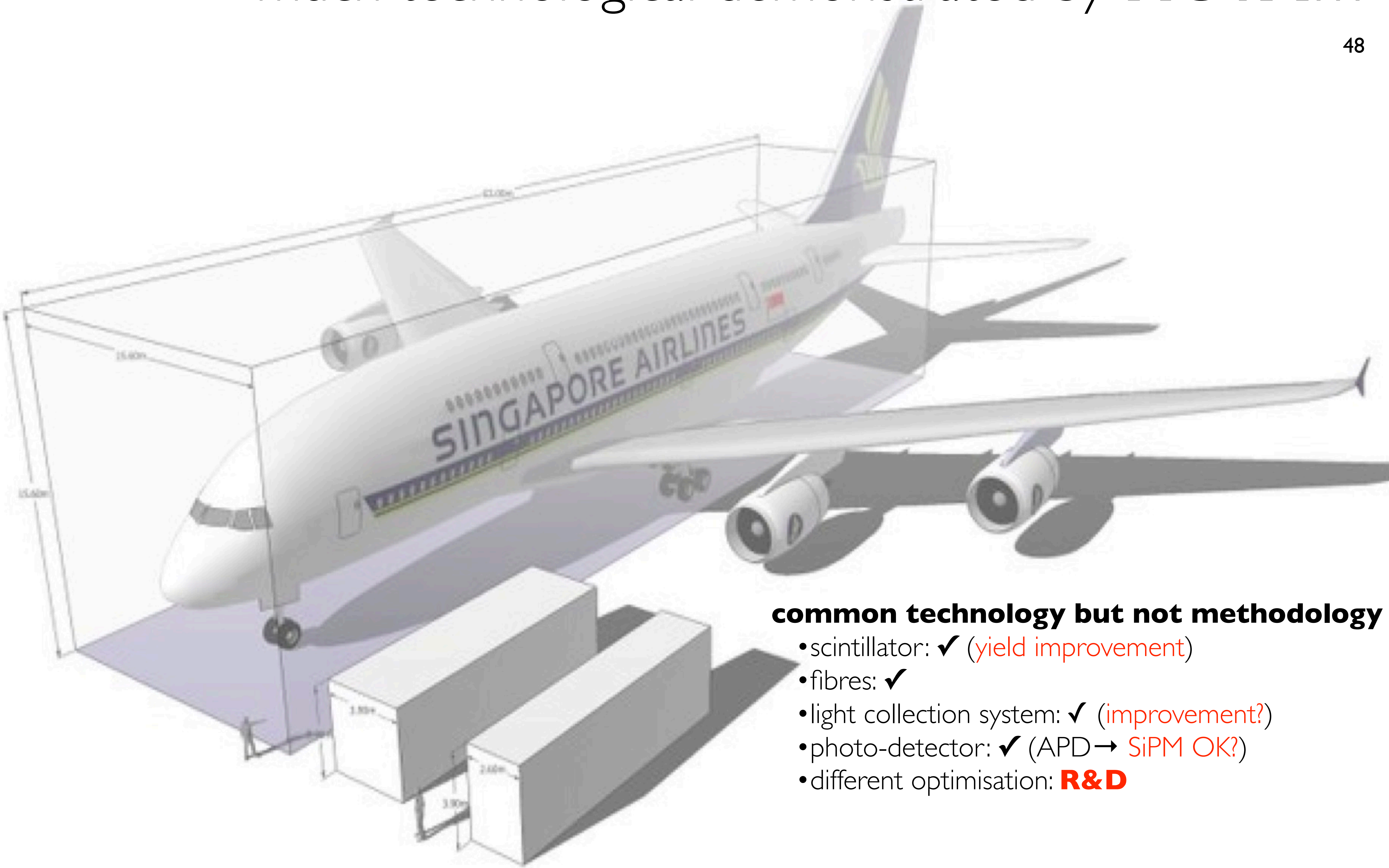
Super-Kamiokande (50kton)



two huge caverns already built of the size of **Super-Kamiokande** just next to **Chooz reactors**!
(unique site in France / Europe / World?)

recycling Chooz-A for science?

much technological demonstrated by **NOvA**...



common technology but not methodology

- scintillator: ✓ (yield improvement)
- fibres: ✓
- light collection system: ✓ (improvement?)
- photo-detector: ✓ (APD→ SiPM OK?)
- different optimisation: **R&D**

GeV OK!! But **~1MeV physics @ 10kton?**

(**R&D**)

the true goal…

change paradigm: use highest neutrino oscillation precision (JUNO⊕DUNE⊕HyperK + SuperChooz)

⟹ explore key SM uttermost fundamental symmetries (sub-percent level?)

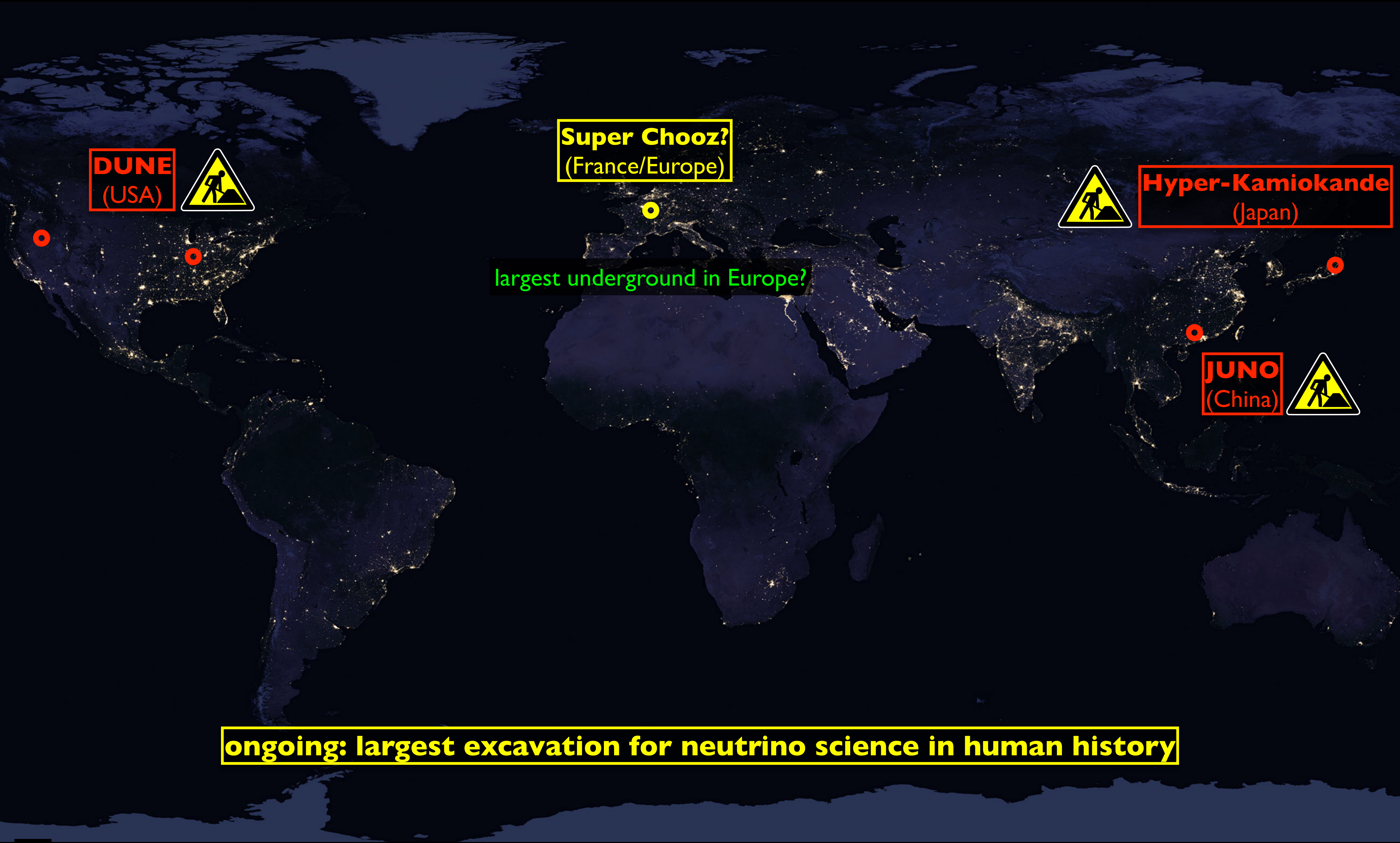
- **CPT violation?** [under investigation]
- **Unitarity violation?** [under investigation]

SuperChooz highest precision on θ13 (~10x? better than now) reinforce **JUNO⊕DUNE⊕HyperK**

thanks to LiquidO (again), **proton decay (multi-channel)** — including sign-tracking (under investigation)

other physics: supernova (core collapse & remnant), geo-neutrino, atmospheric (possible CPV?), etc.

SuperChooz ready since the 60's...



SuperChooZ?

flagship ν's in Europe?

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

the remaining challenges…

(my view — likely biassed somewhat)

- **accelerators:** stunning rich physics to explore the neutrino oscillation appearance channel→ **measure CPV**
    - **experiments reaching systematics** (at few % level) — very challenging
    - **improve absolute knowledge** (ex. flux cancels by multi-detector)→**discoveries?**
    - intrinsic limitations (systematics, etc)→ **empower synergies with reactors**, **solar**, etc.
- **$\theta 23 \oplus \Delta m^2$ precision:** still improve for **θ23** — it will with DUNE⊕HyperK
    - **θ23** is one of the most intriguing parameter of the PMNS (largest / maximal term) $\Longrightarrow$ **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
- **neutrino oscillation**[≤2030] reaching ≤1% precision — **complete and over-constant phenomenon**
    - **new paradigm:** neutrino oscillation to **probe BSM by exploring key SM symmetries**, etc. [motivation behind **SuperChooz exploration** — under brainstorming]
    - any better ideas?