Reactor ν

(today & future)

French-Ukrainian Workshop

19 Oct 2020, 08:45 → 23 Oct 2020, 14:25 Europe/Paris

200/Rdc-Auditorium - Auditorium P. Lehmann (IJCLab)

Anatael Cabrera
CNRS/IN2P3
IJCLab @ Orsay
LNCA @ Chooz

"**A long time ago in a galaxy far, far away**…"

Reines & Cowan (*et al*) around 1950

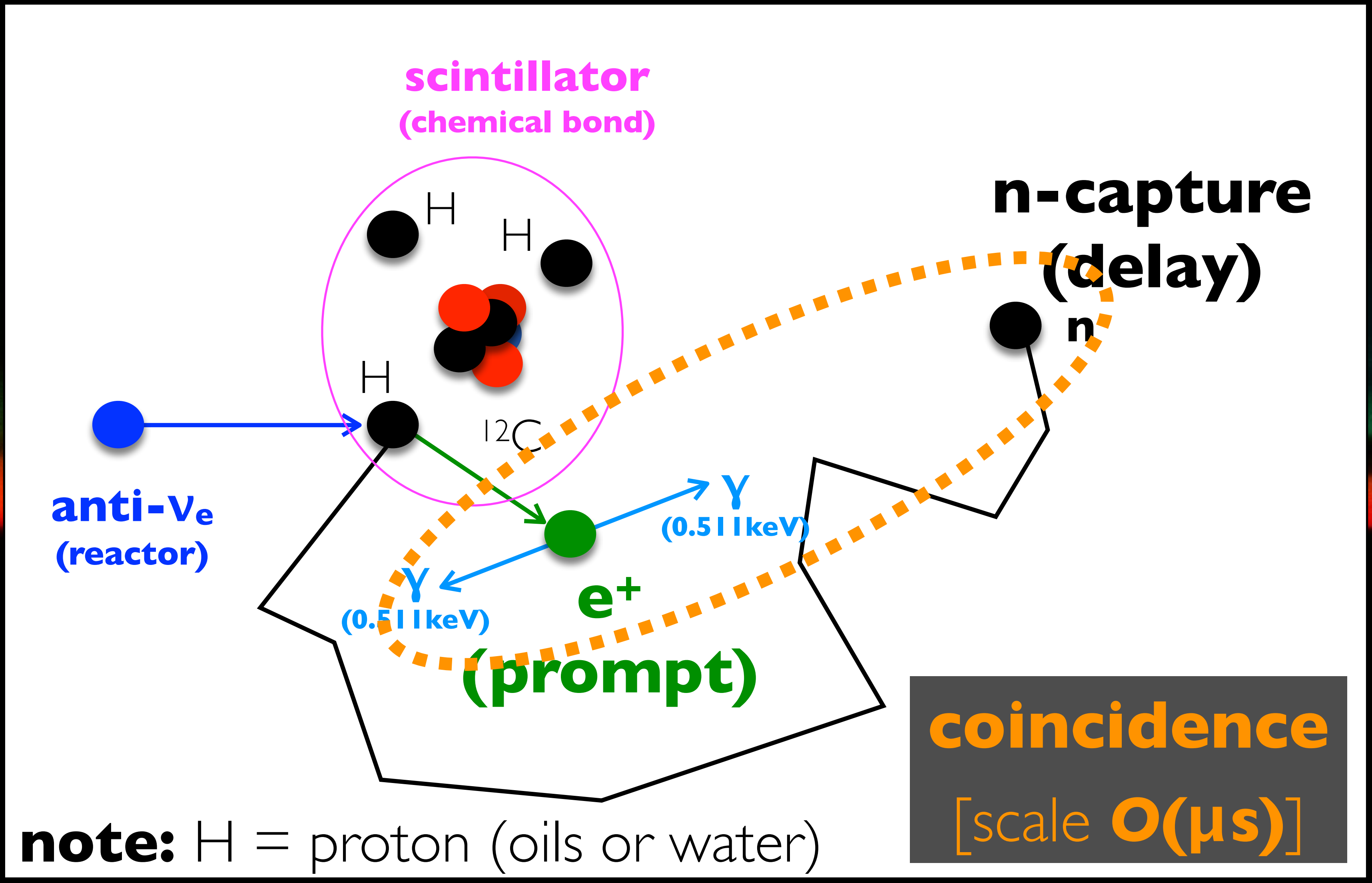
discover the neutrino (upon 1930's Pauli's hypothesis)
[Nobel prize 1995]

pave much of today's technological ground
[even ~70 years later, **dominant today**]

the ν discovery (1950's)…

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n



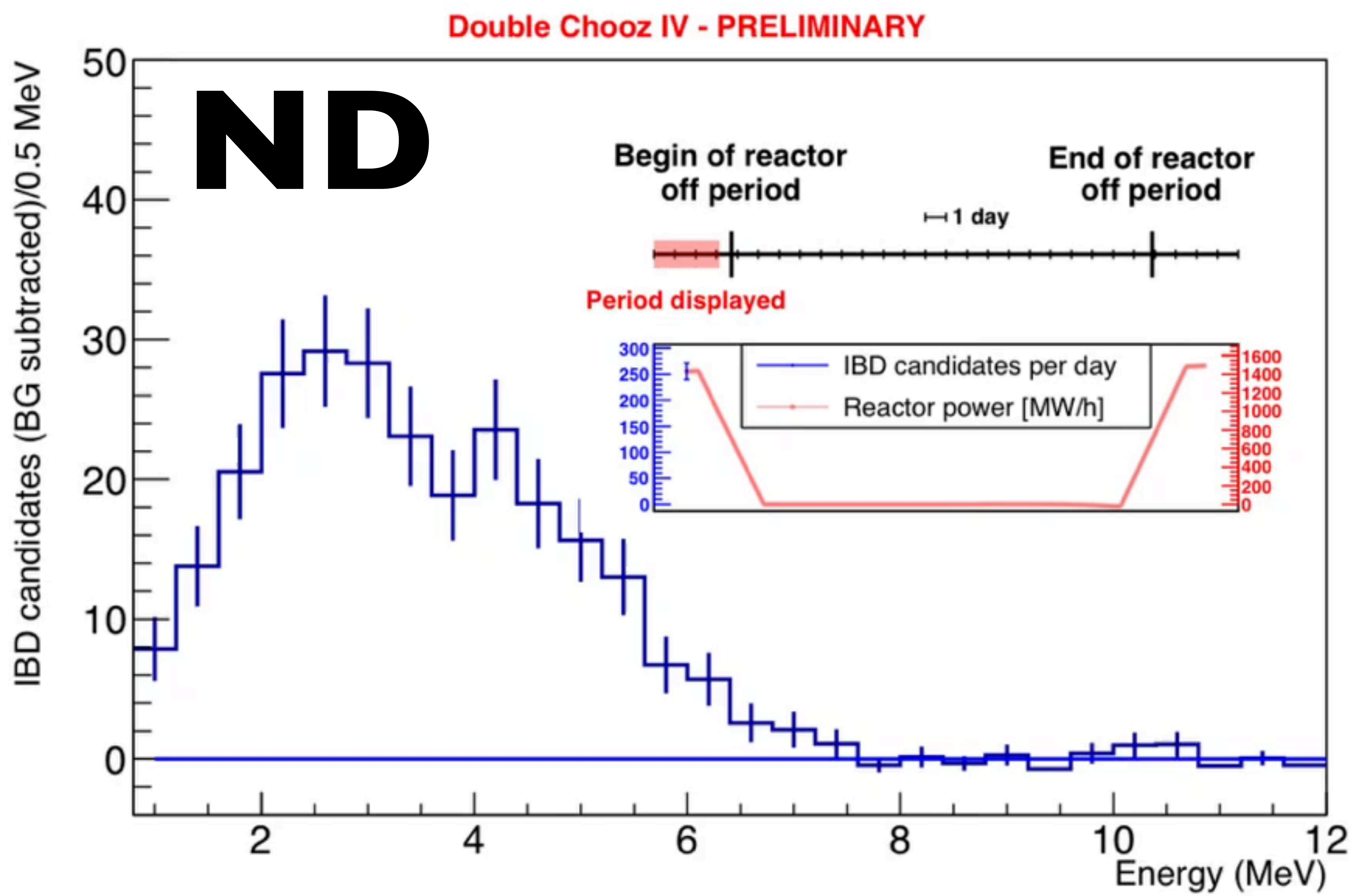
no e+ PID implies

$\gamma \approx e^- \approx e^+ \approx \alpha \approx$ **p-recoil** (fast-n)


v’s

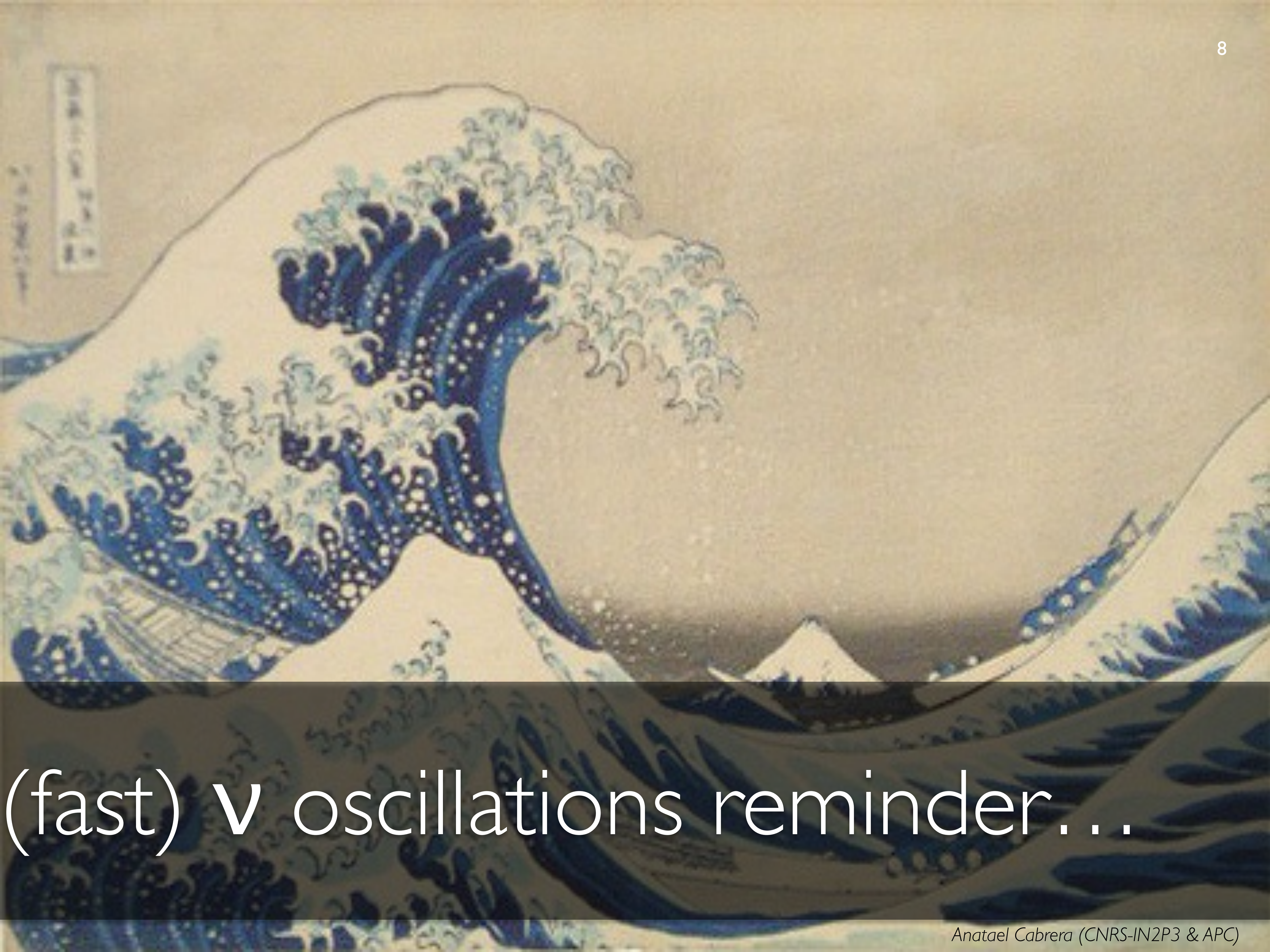
Double Chooz reactor-VETO: signal analysis…

rate(1 reactor) ≈ IBD per 3 min



BG subtracted


switch off the source for a while?
(the dream for a few)



(fast) ν oscillations reminder…

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)

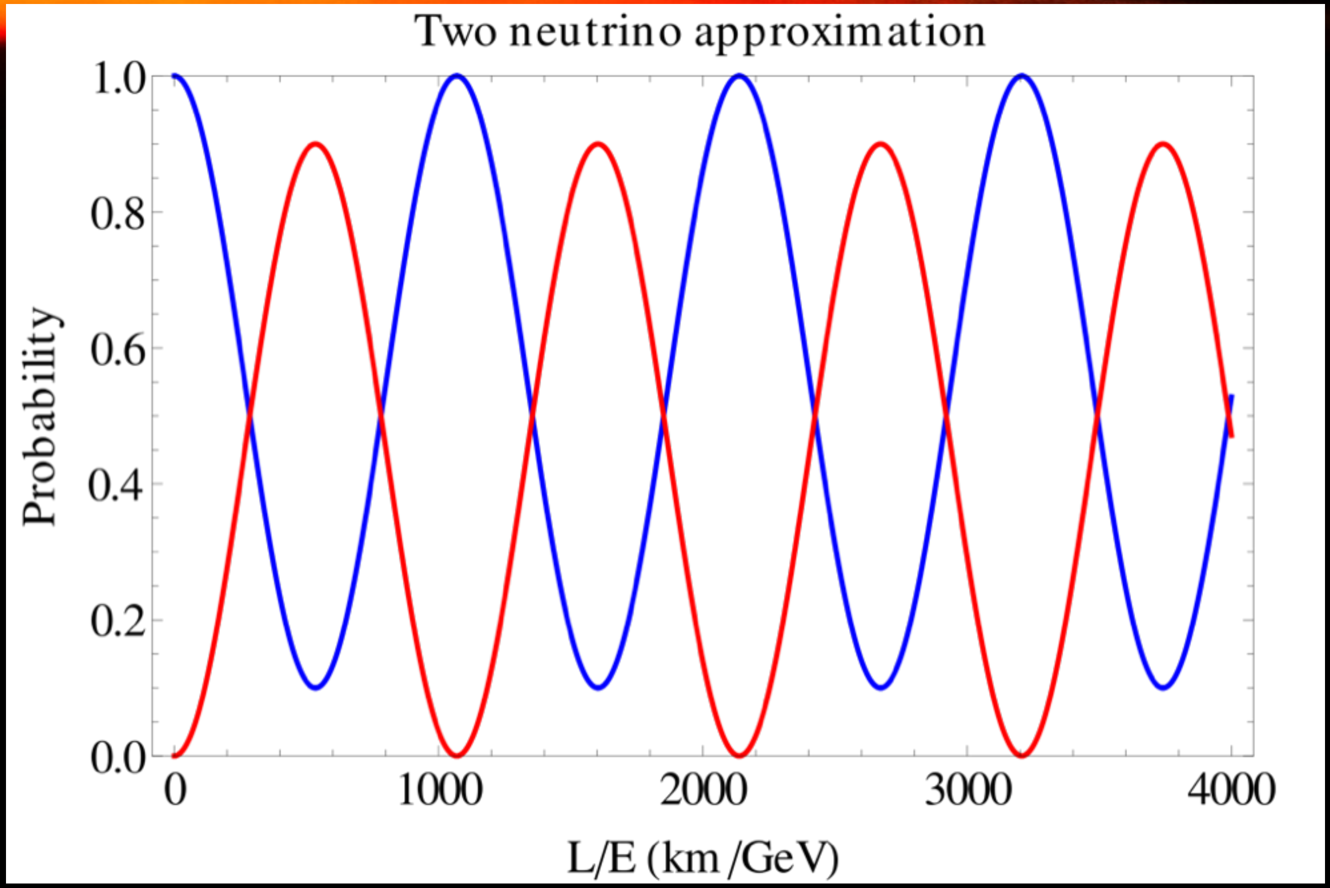
UPMNS matrix (à la CKM)

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

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

the simplest manifestation

Oscillation Probability
Survival Probability



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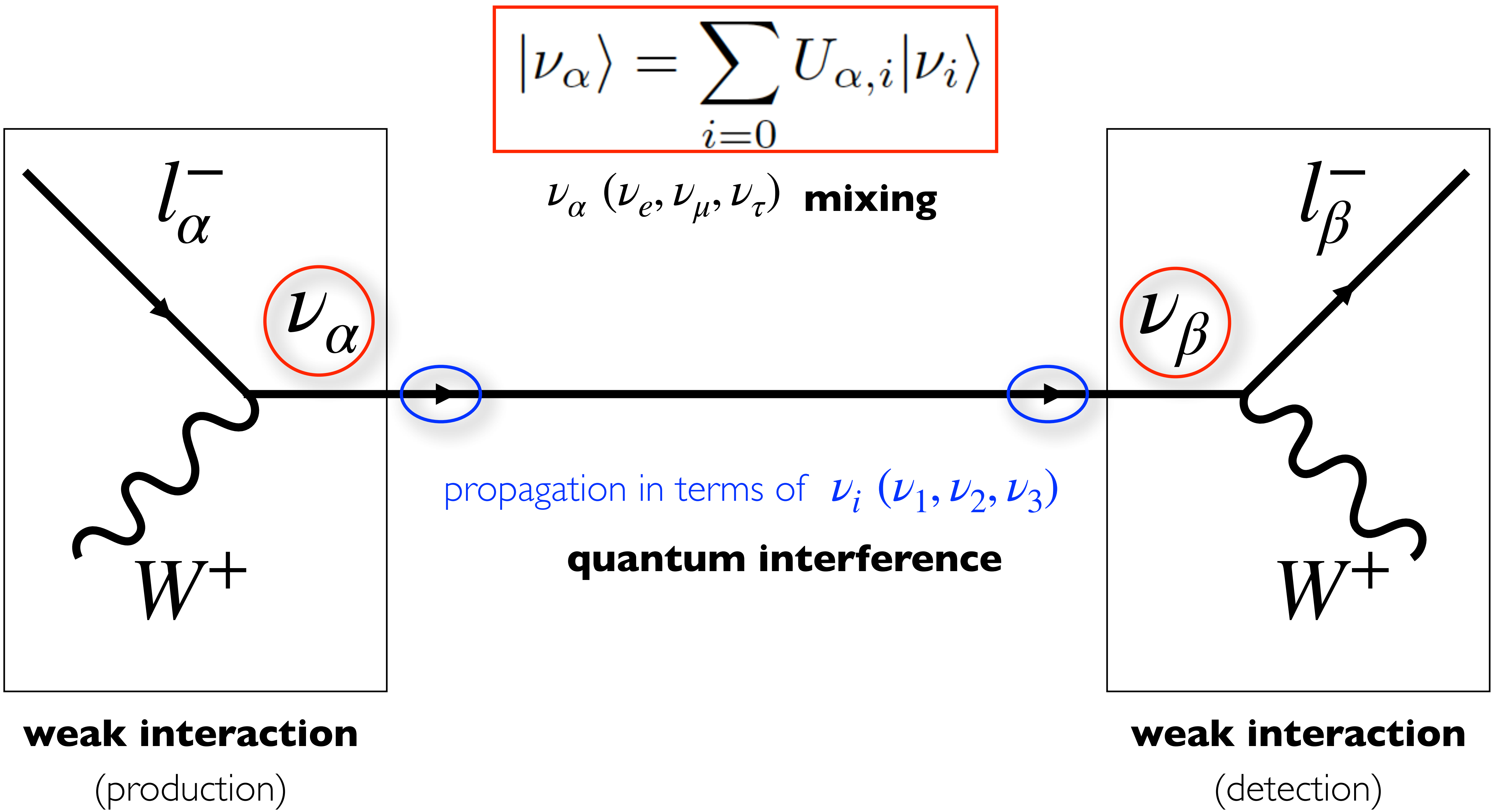
diagrammatically…



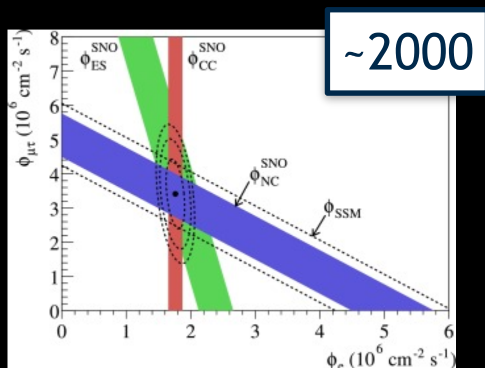

$\nu_\alpha = \nu_1 + \nu_2$

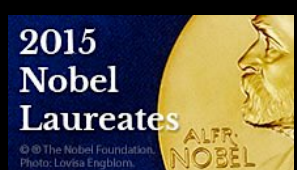
our history in a nut-shell…

UNITARITY (assumed)

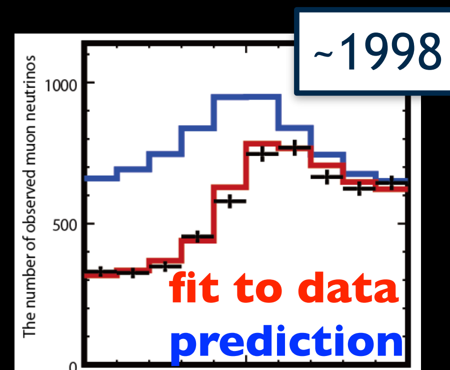
predictions: θ_{13} & CP-violation

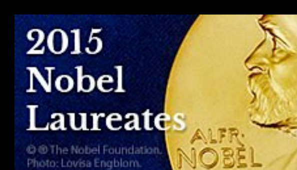
solar anomaly	atmospheric anomaly	"reactor" oscillation
$(\theta_{12} \oplus \delta m^2)$	$(\theta_{23} \oplus \Delta m^2)$	(θ_{13})





large mixing!





large mixing!

CHOOZ

≤2000

reactor-θ_{13}

2011-2012

small mixing

Jarkslog Invariant [≠0 & large]

first CP-Violation hint

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

MODEL hypothesis: neutrino oscillations

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

where are we now (~2020)?

status on neutrino oscillation knowledge…

Standard Model(3 families)
[leptons & quarks]
&
PMNS$_{3x3}$(θ_{12},θ_{23},θ_{13})
&
±Δm² & **+δm²**

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

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

	today			**≥2030**		
	best knowledge		NuFIT4.0	foreseen	dominant	technique
θ_{12}	3.0 %	SK⊕SNO	2.3 %	<1.0%	JUNO	reactor
θ_{23}	5.0 %	NOvA+T2K	2.0 %	≲1.0%	DUNE⊕HK	beam (octant)
θ_{13}	1.8 %	DYB+DC+RENO	**1.5 %**	**1.5 %**	DC⊕DYB⊕RENO	reactor
+δm²	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
|Δm²|	3.0 %	T2K+NOvA & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK	reactor⊕beam
sign(Δm²)	**unknown**	SK et al	NO @ ~3σ	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CPV	**unknown**	T2K	3/2π @ ~2σ	**@5σ?**	DUNE⊕HK⊕ALL	beam driven

(Nov 2018) (reactor-beam)

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

NOTE: ORCA⊕PINGU⊕IceCube complementary (Mass Ordering & Δm² measurements)

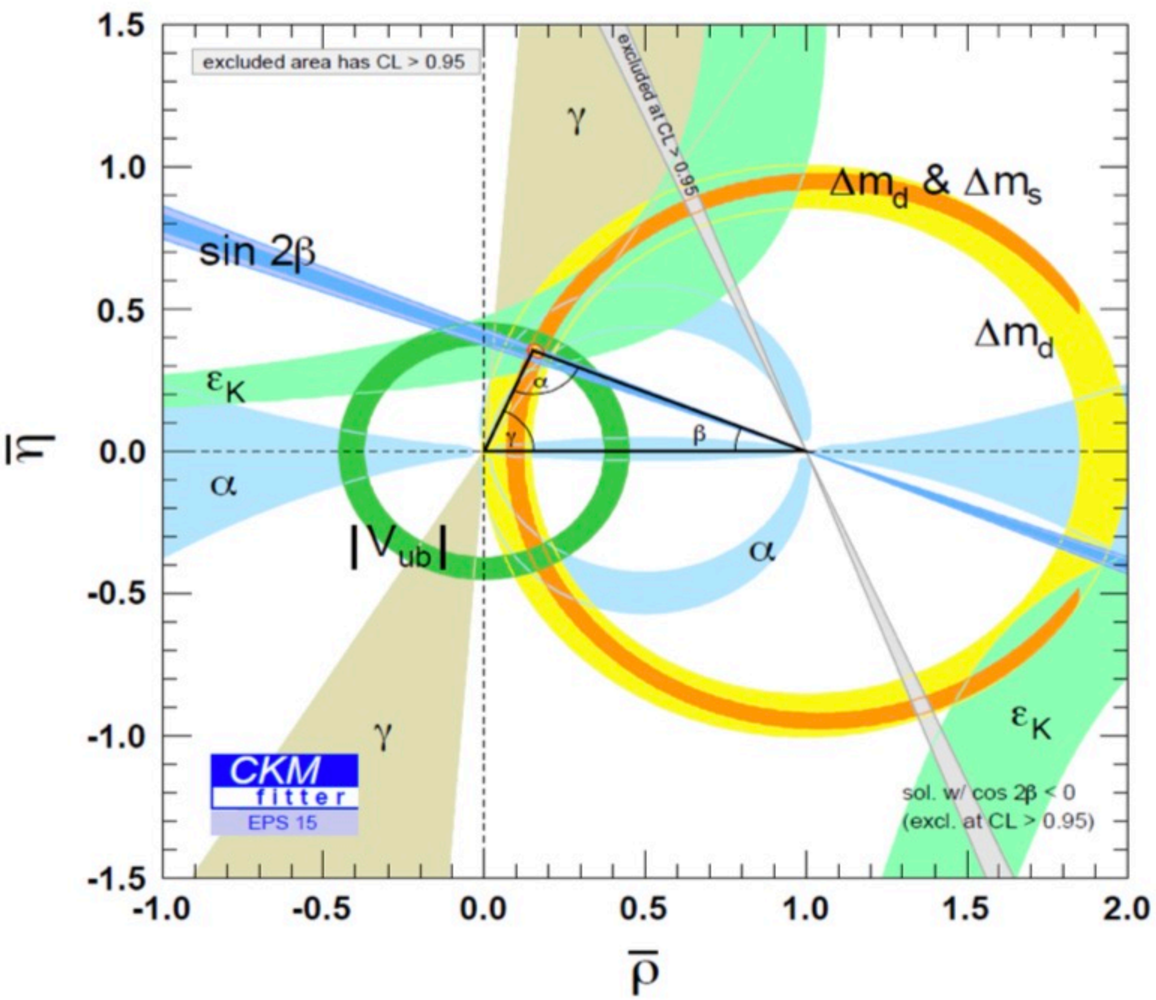
Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

by 2030, mixing @ ~1% level…

(**no unknowns**)

despite major success so far… ***challenges*** *leads* ***discoveries*** *(and fun)!!*

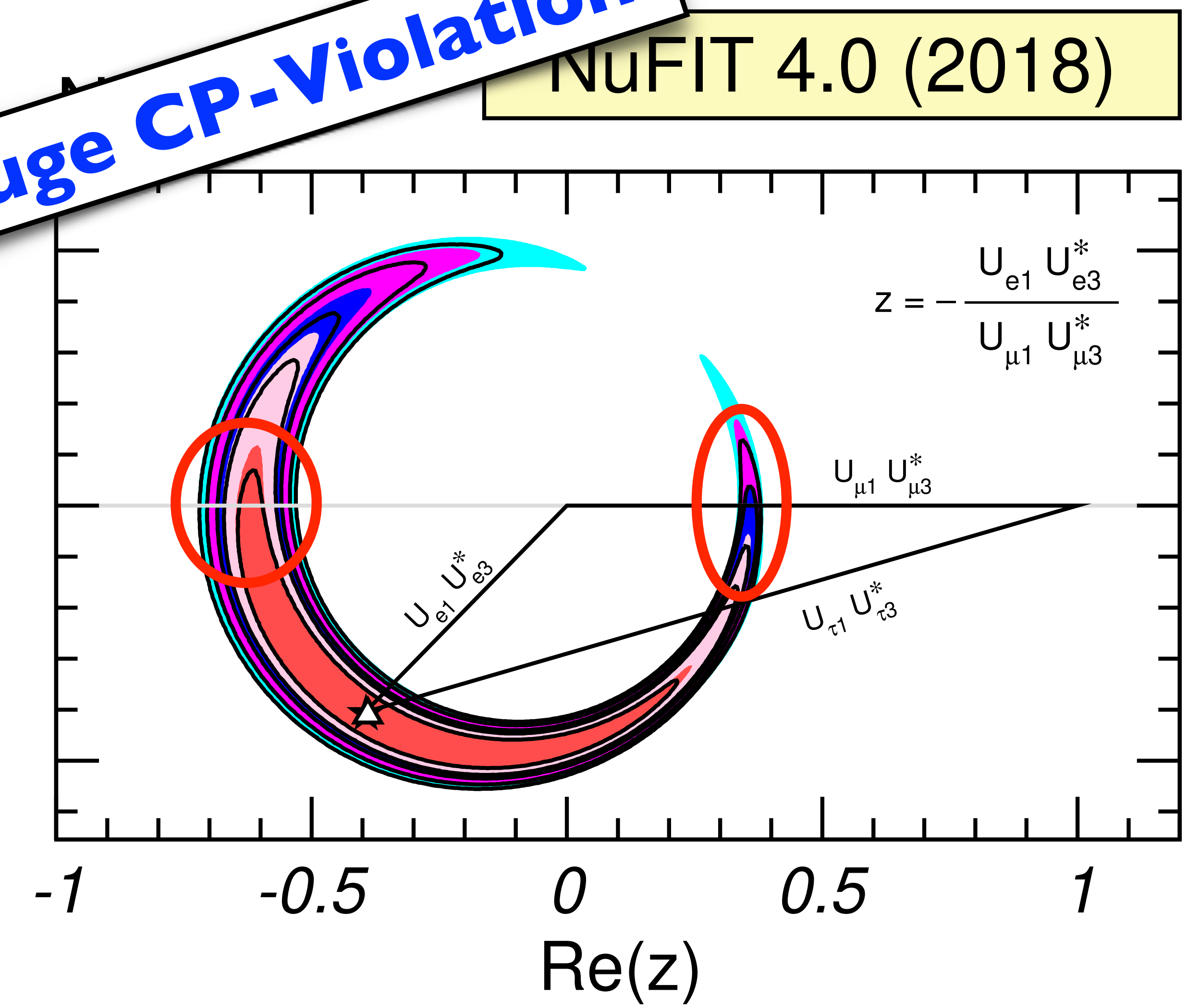
CKM



J(CKM)≈3.18±0.15x10^{-5}

PMNS

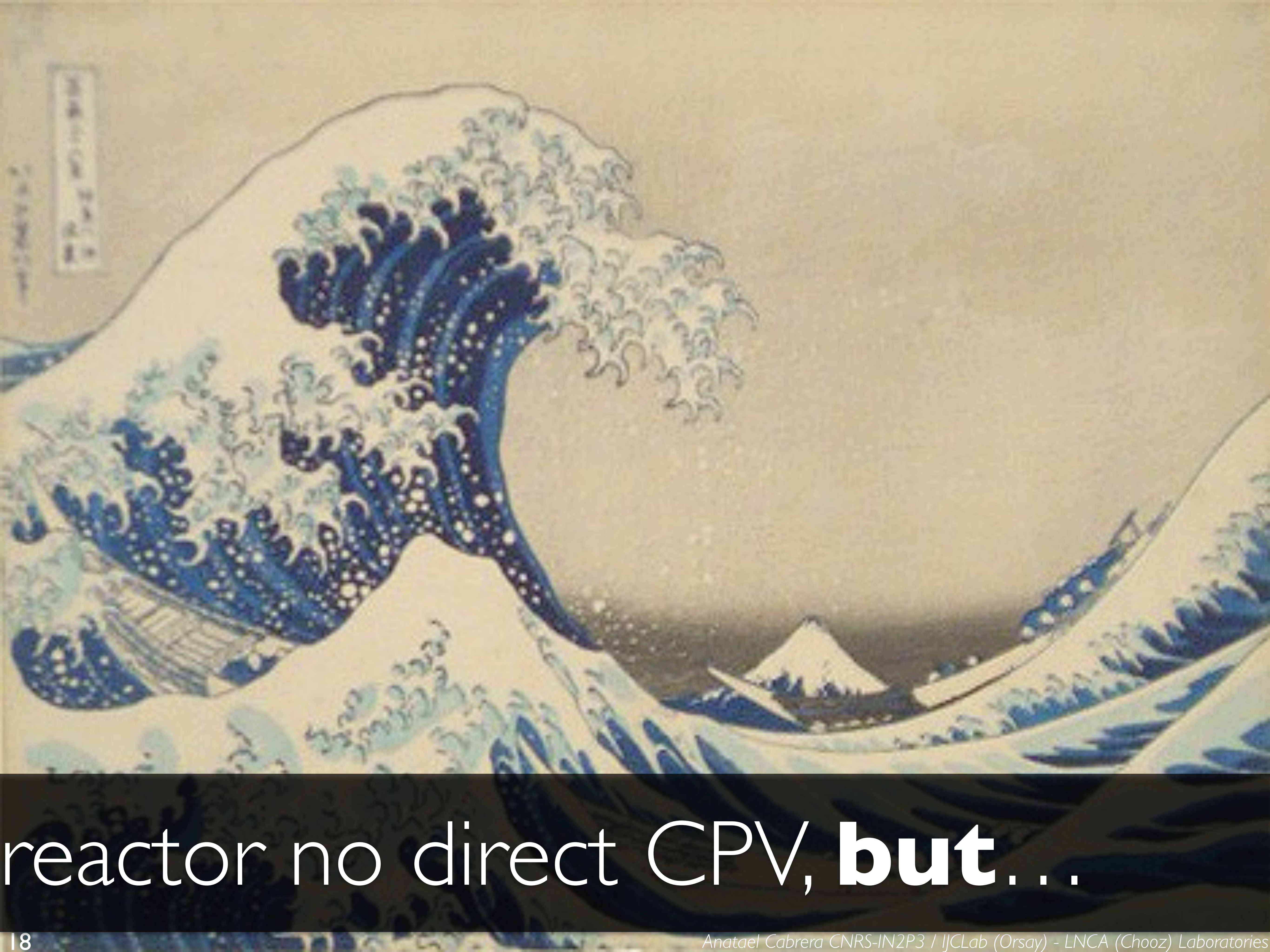
huge CP-Violation?



J(PMNS)≈3.33±0.06x10^{-2}

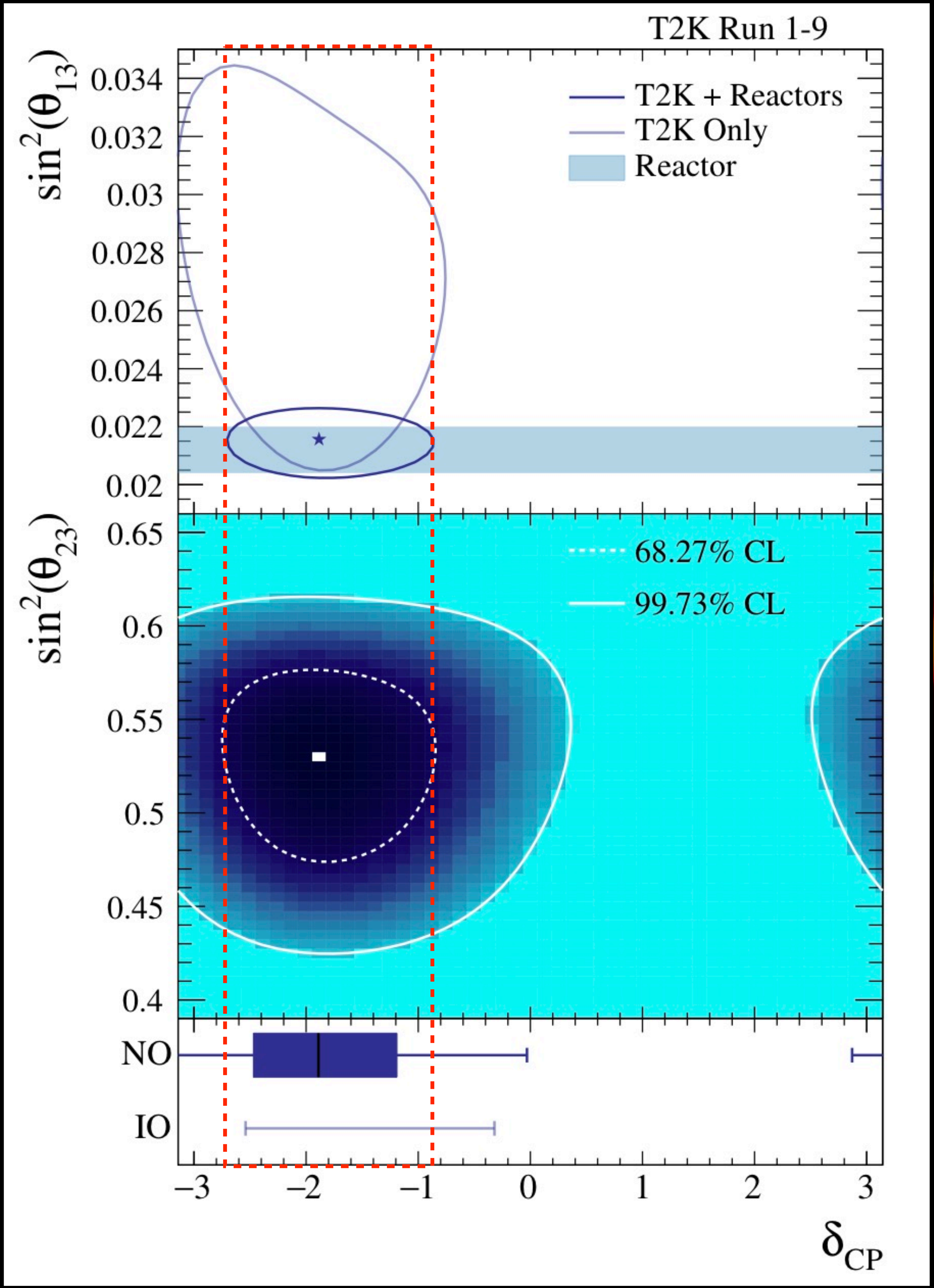
CP-Conversation disfavoured @ ~2σ
[“infancy” era→ much to be done]

PMNS triangle (including CPV)…



reactor no direct CPV, **but**…

T2K⊕reactor best knowledge CP-Violation…



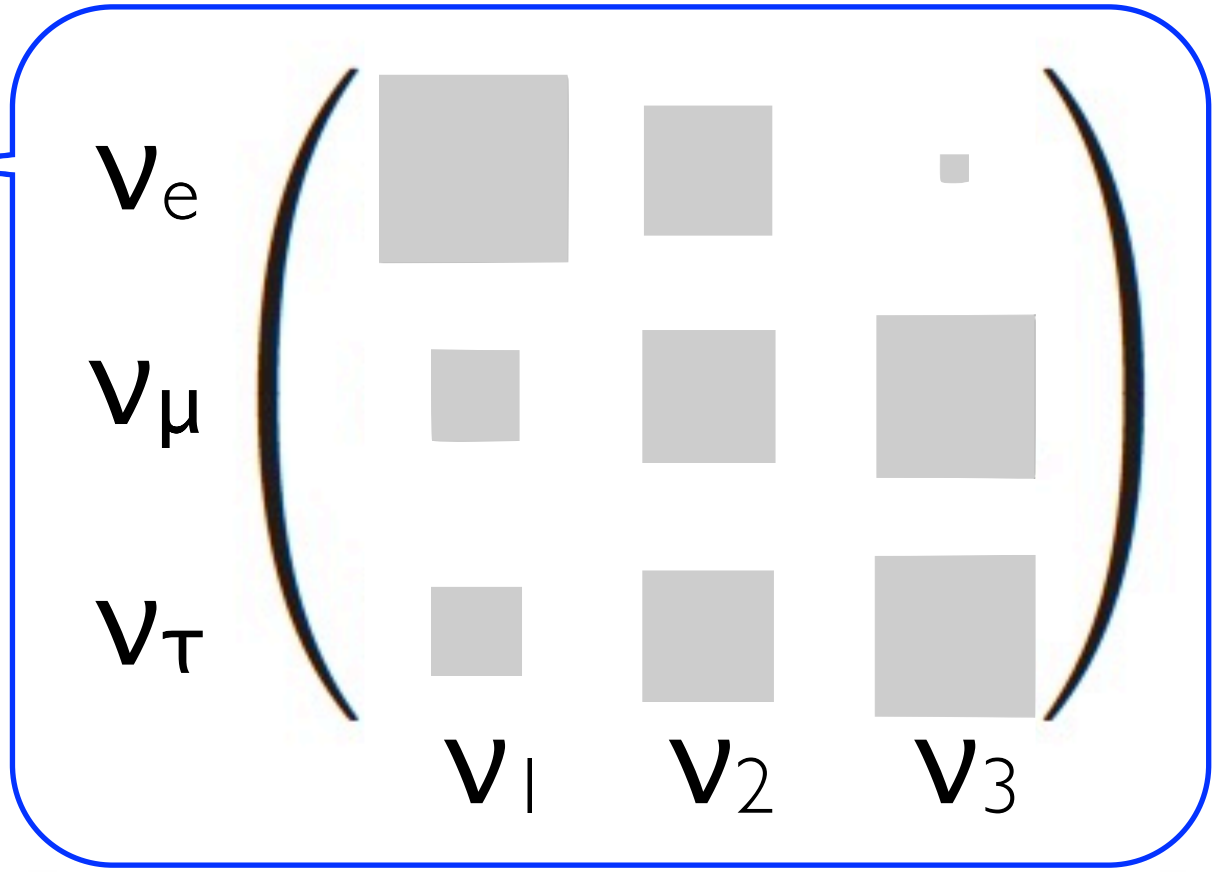
θ13 implications

CPV phase vs θ13
[constrained by reactor]

CPV phase vs θ23
[octant ambiguity]

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

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



consider matrix structure

(not just composition)

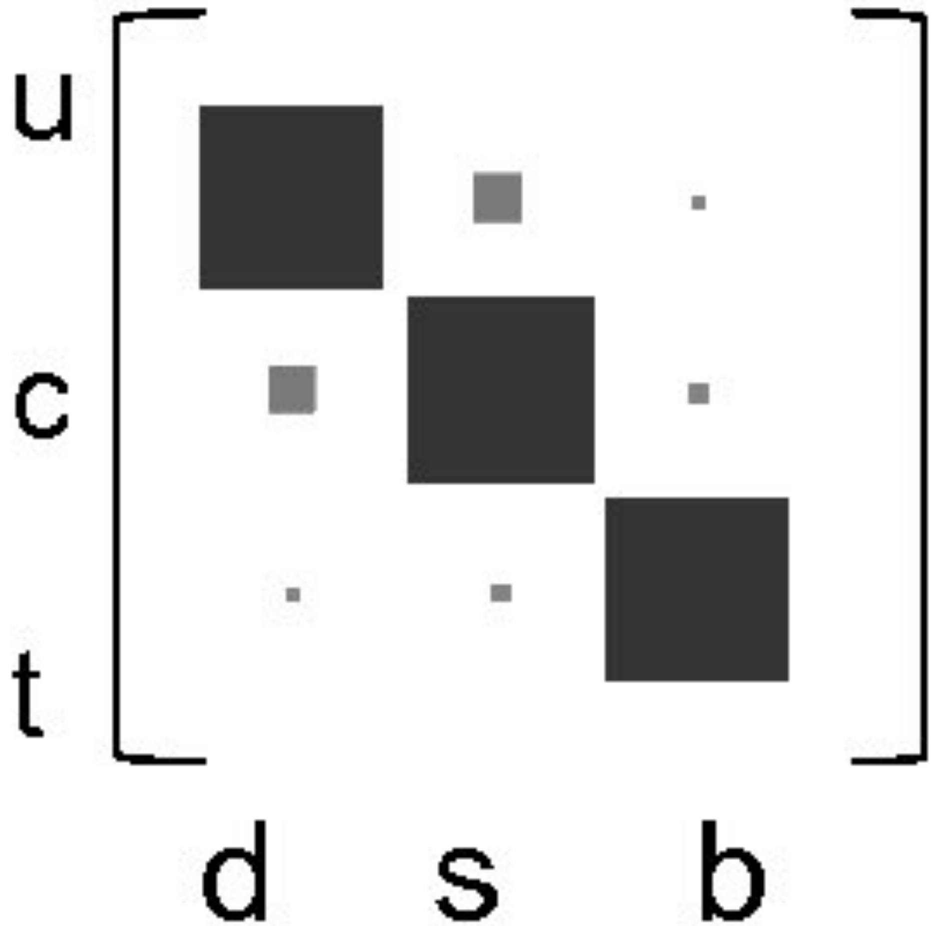
why shape?

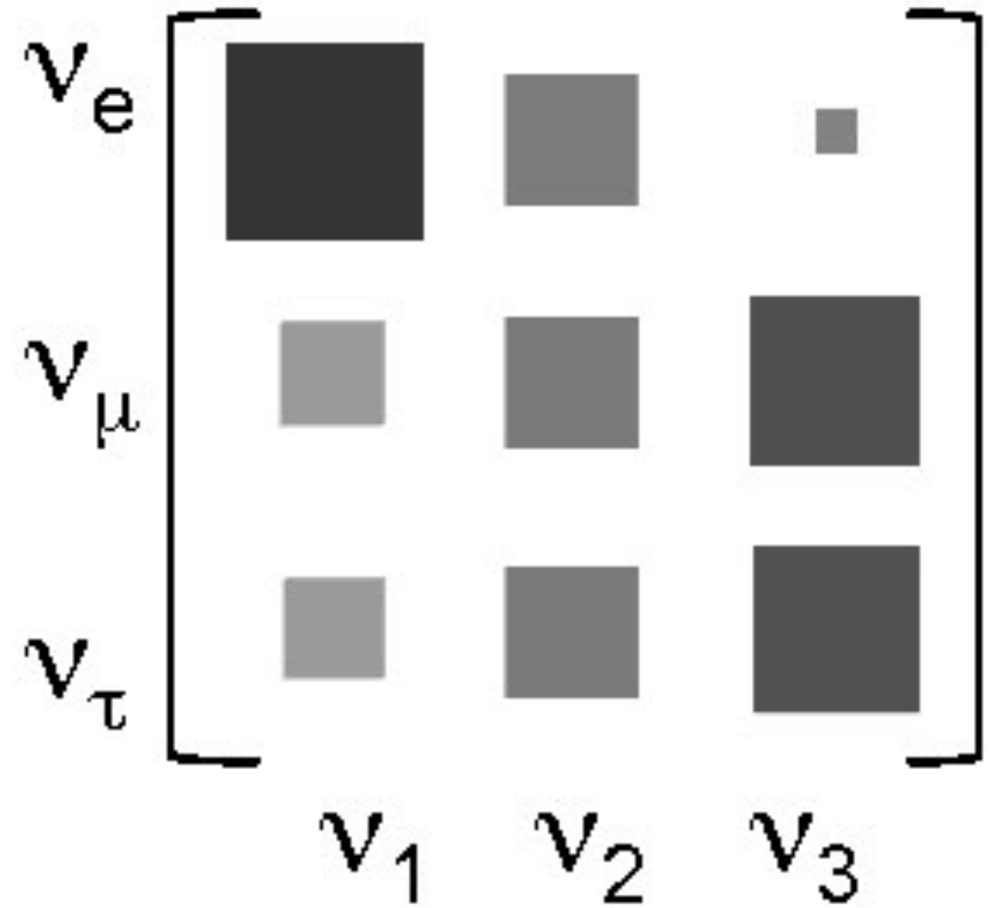
- **large mixing** but a **small one**!
- **largest CP-Violation** (SM)
- **any symmetry behind? [Nature's caprice?]**

U_{3x3} unitary?

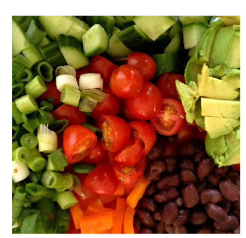
[next slides]

CKM vs PMNS…



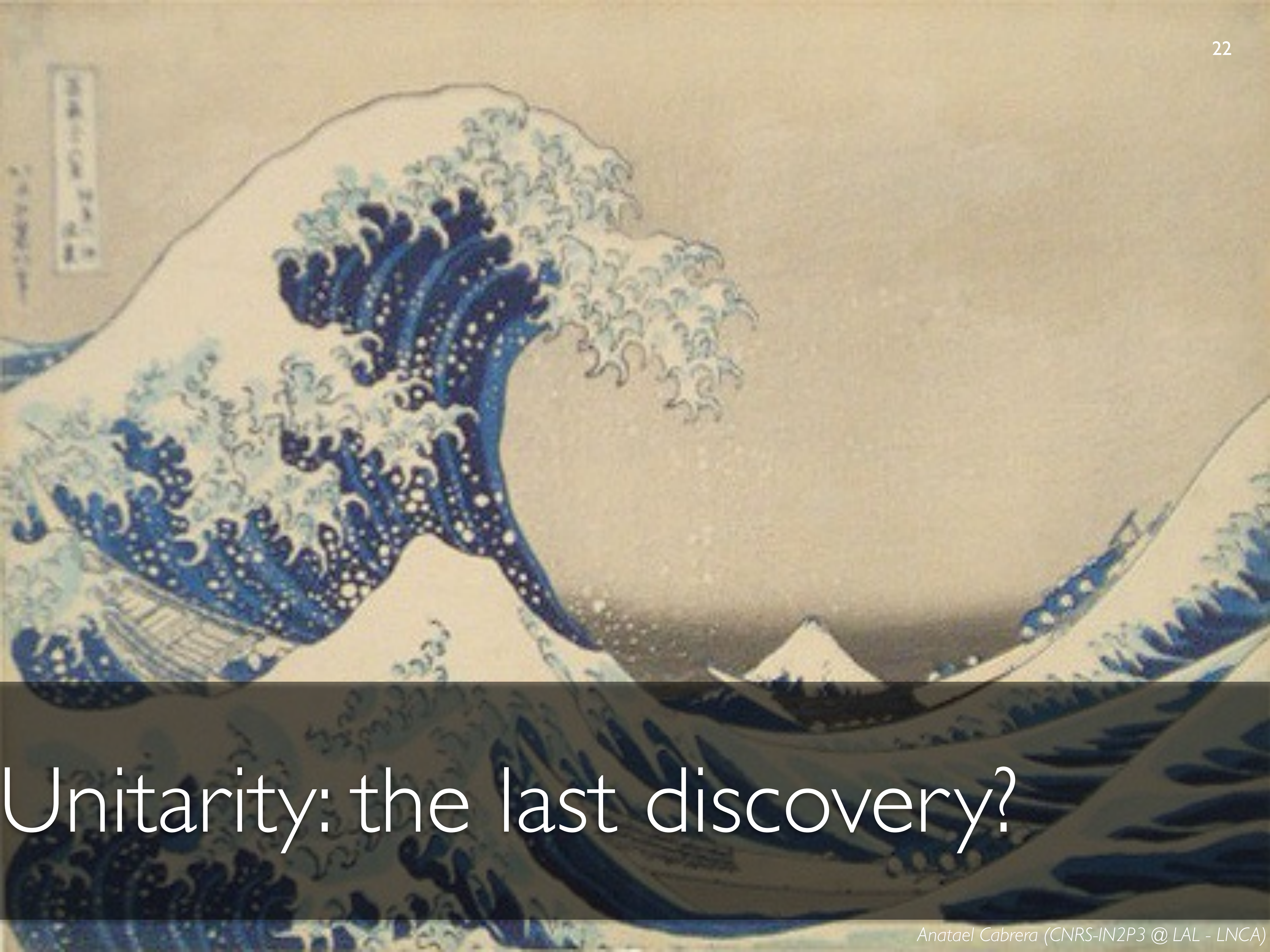


elegance
(symmetry)



stravaganzza
(anarchy?)

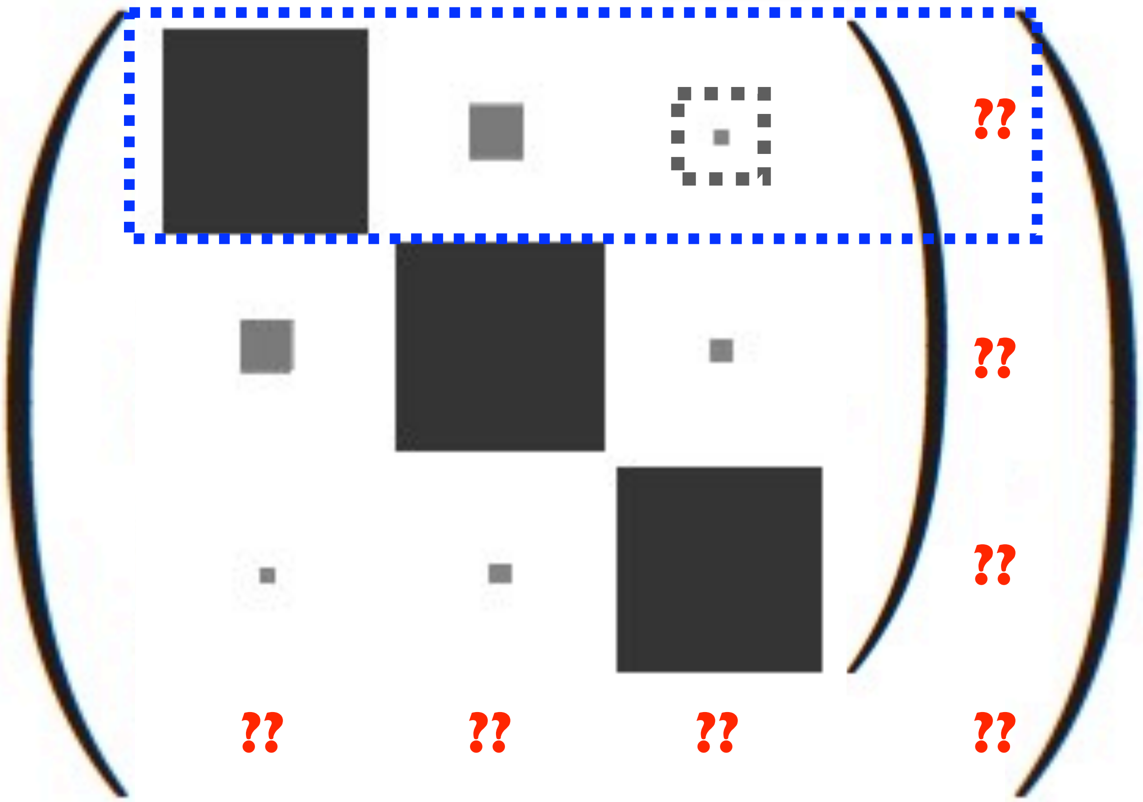
A. De Gouvea, H. Murayama, hep-ph/0301050; PLB, 2015.
L. Hall, H. Murayama, N. Weiner, hep-ph/9911341.



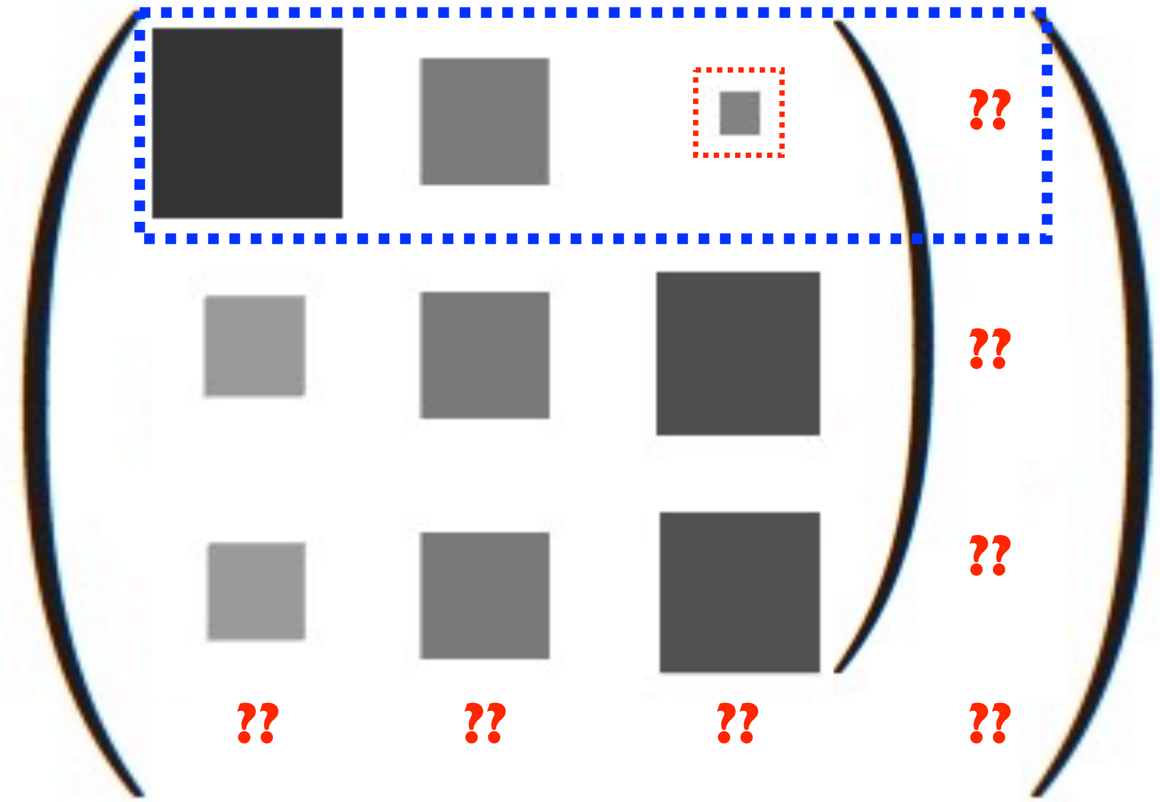
Unitarity: the last discovery?

unitarity violation implications…

0.37%



$|U_{e3}|^2 \rightarrow \theta_{13}$ *only*



if it existed ⇒ tiny!!(?)

(naive expectation)

if it existed ⇒ less tiny(?)

(naive expectation)

few % precision enough?

Unitarity Violation [major discovery]

non-standard ν states
and/or
non-standard ν interaction

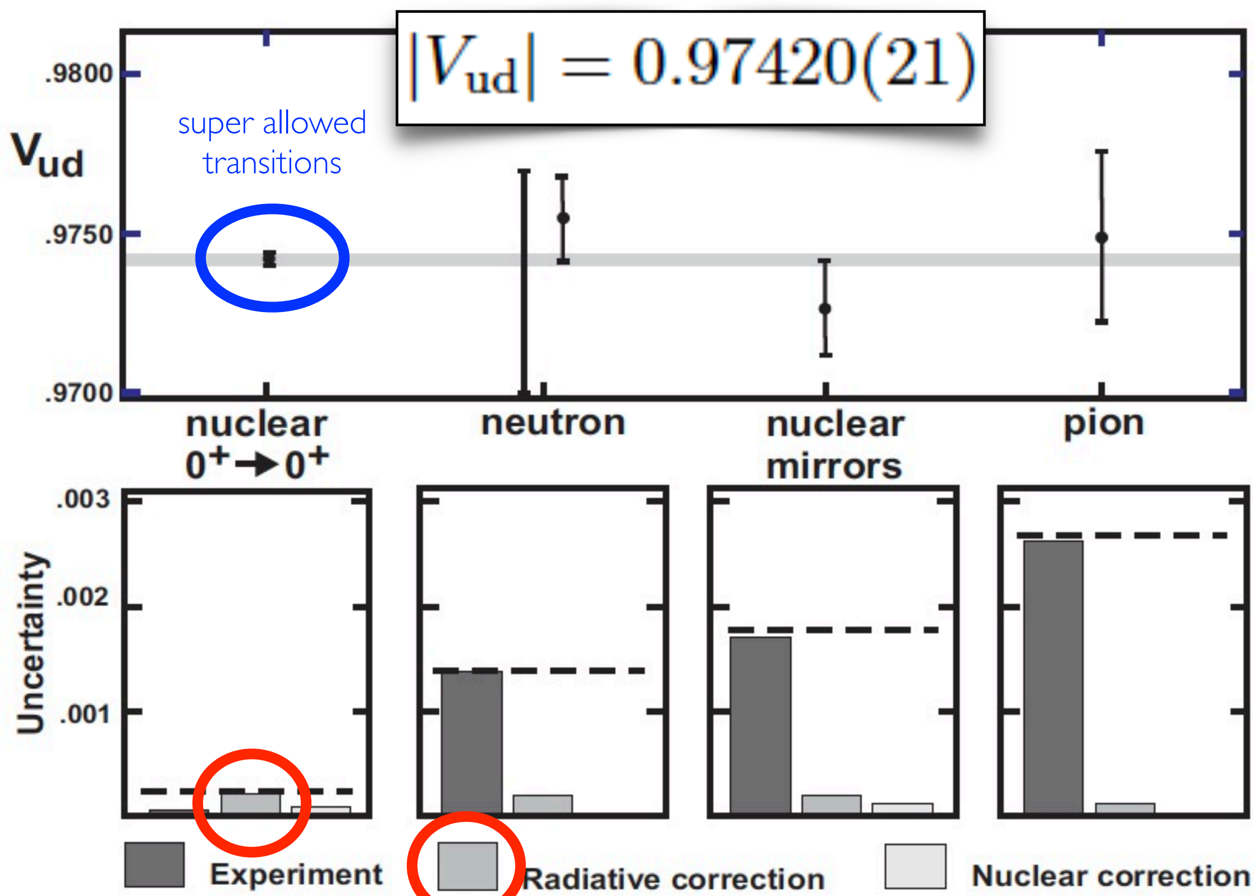
let’s quickly check the CKM…

CKM equivalent knowledge…

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99939(64)$$

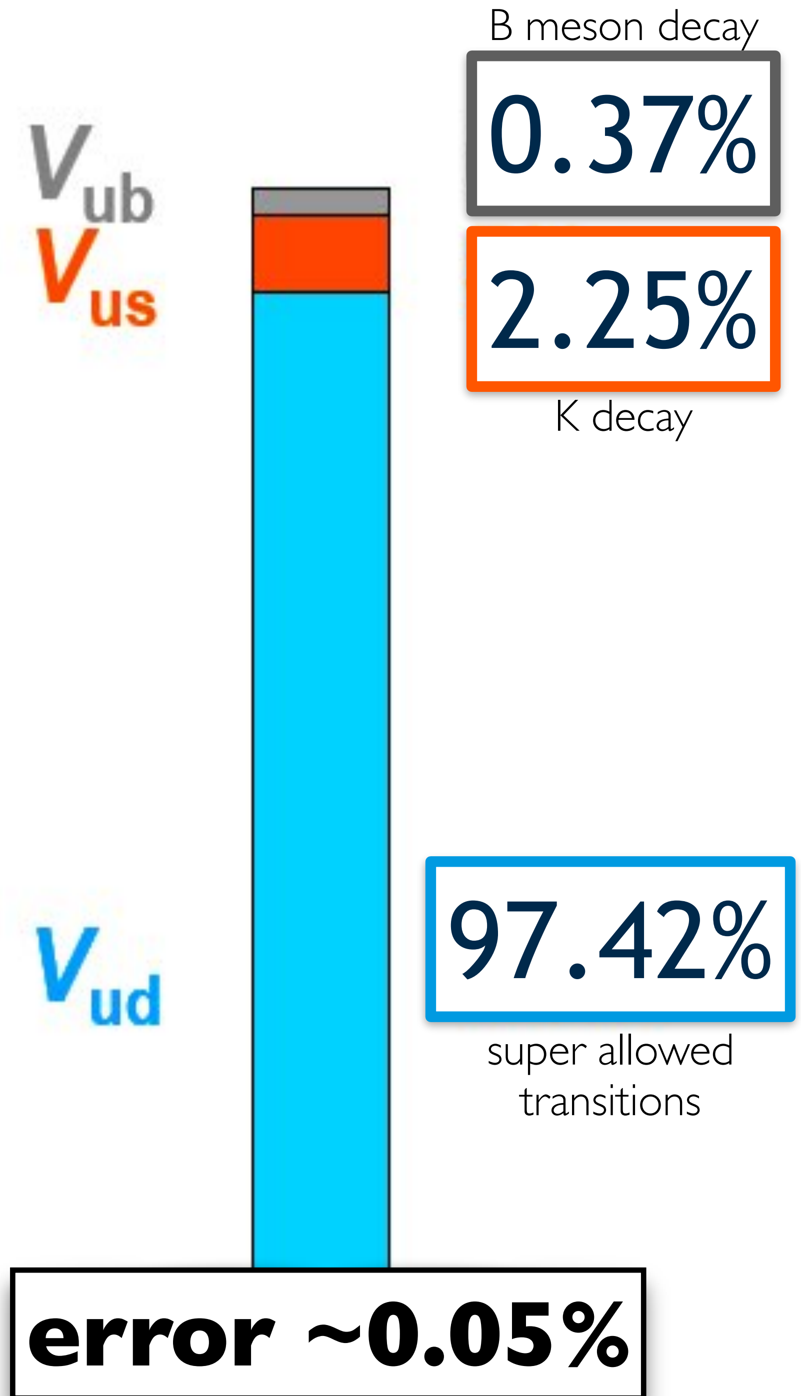
Hardy & Towner, arXiv 1807.01146 and Particle Data Group 2018

arXiv:1807.01146v1



2018 radiative correction (before 2006)

$$\sum |V_{ui}|^2 = 0.99939(47) \quad \rightarrow \quad 0.99842(47)$$



tension @ CKM??

[data or corrections]

Nathal Severins (Leuven)

https://indico.lal.in2p3.fr/event/5418/contributions/17551/

well definition theory/experimental problem

•perfect prediction ("symmetry")

•experimentally precision accessible?
[**challenge**]

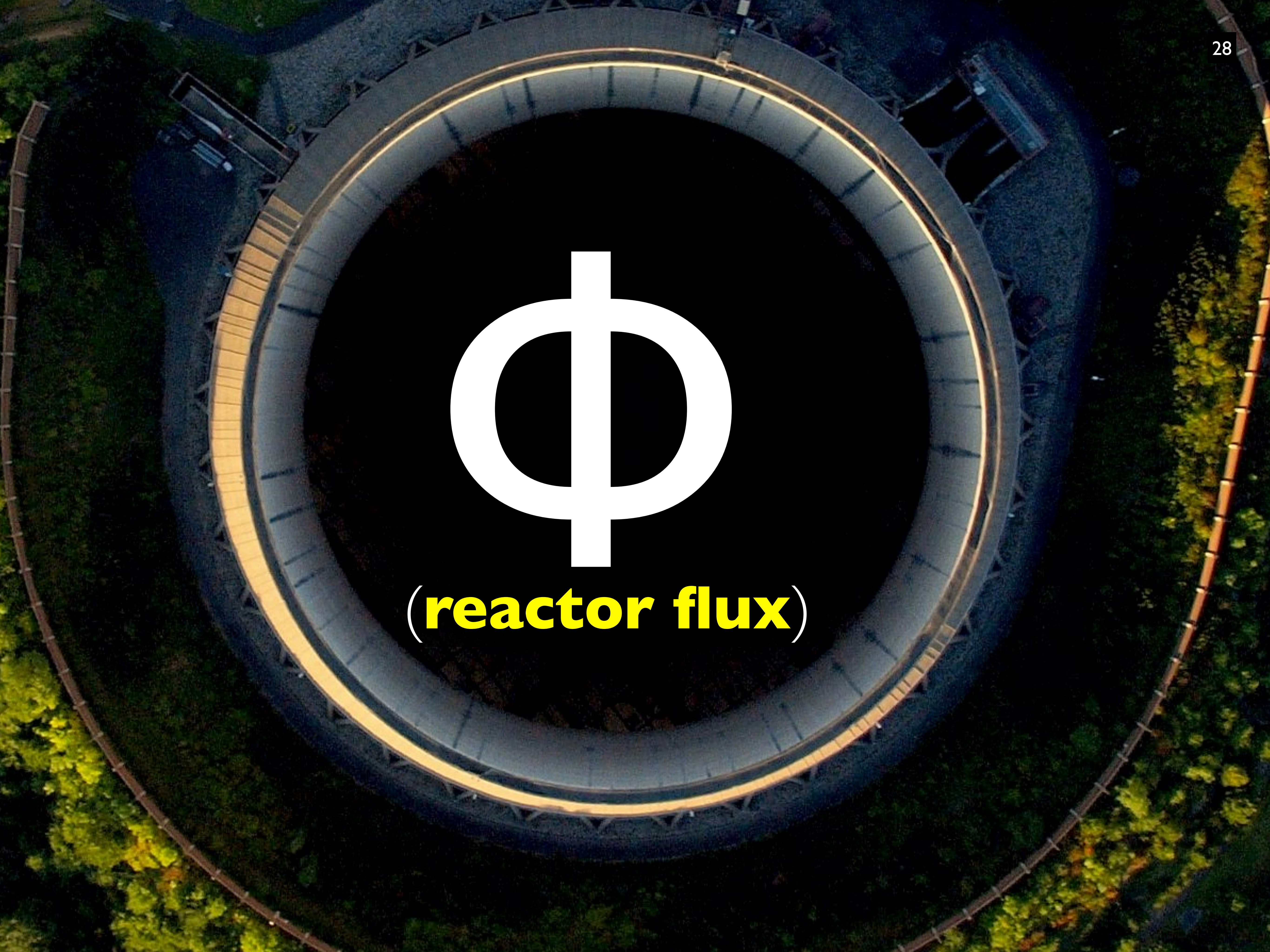
•neutrino: direct & clean probe
[no "slippery" corrections?]

major!! discovery potential
[building blocks of SM]

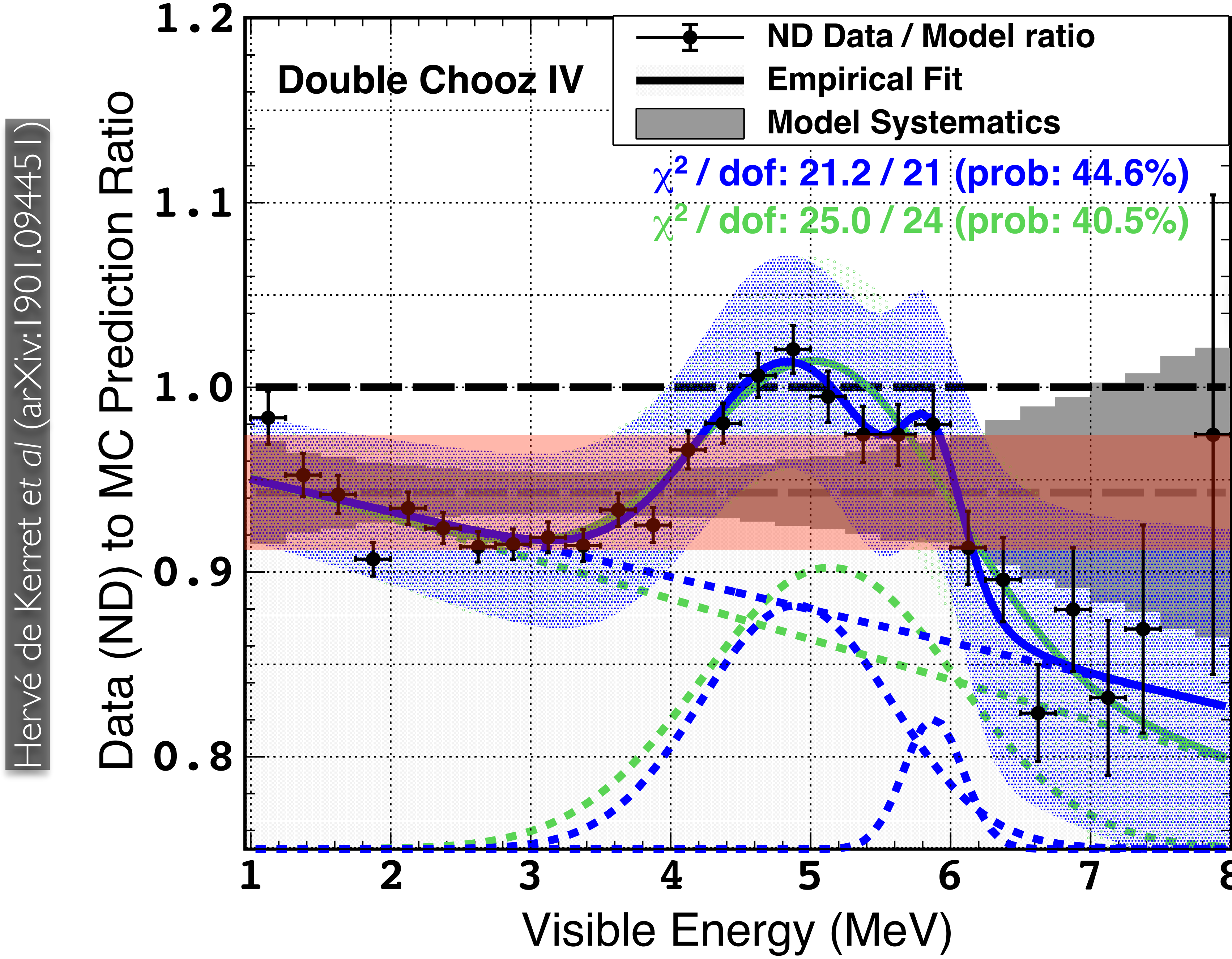
(if discovery) possible experimental redundancy

Unitarity violation test…


today's status…
present


ϕ
(reactor flux)

reactor flux uncertainty…



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]

Shape Uncertainty

~2.2%→**6.0%?**

[**≲10%**]

MC normalised to DYB-2017 (MCSpF per isotope)

nature physics

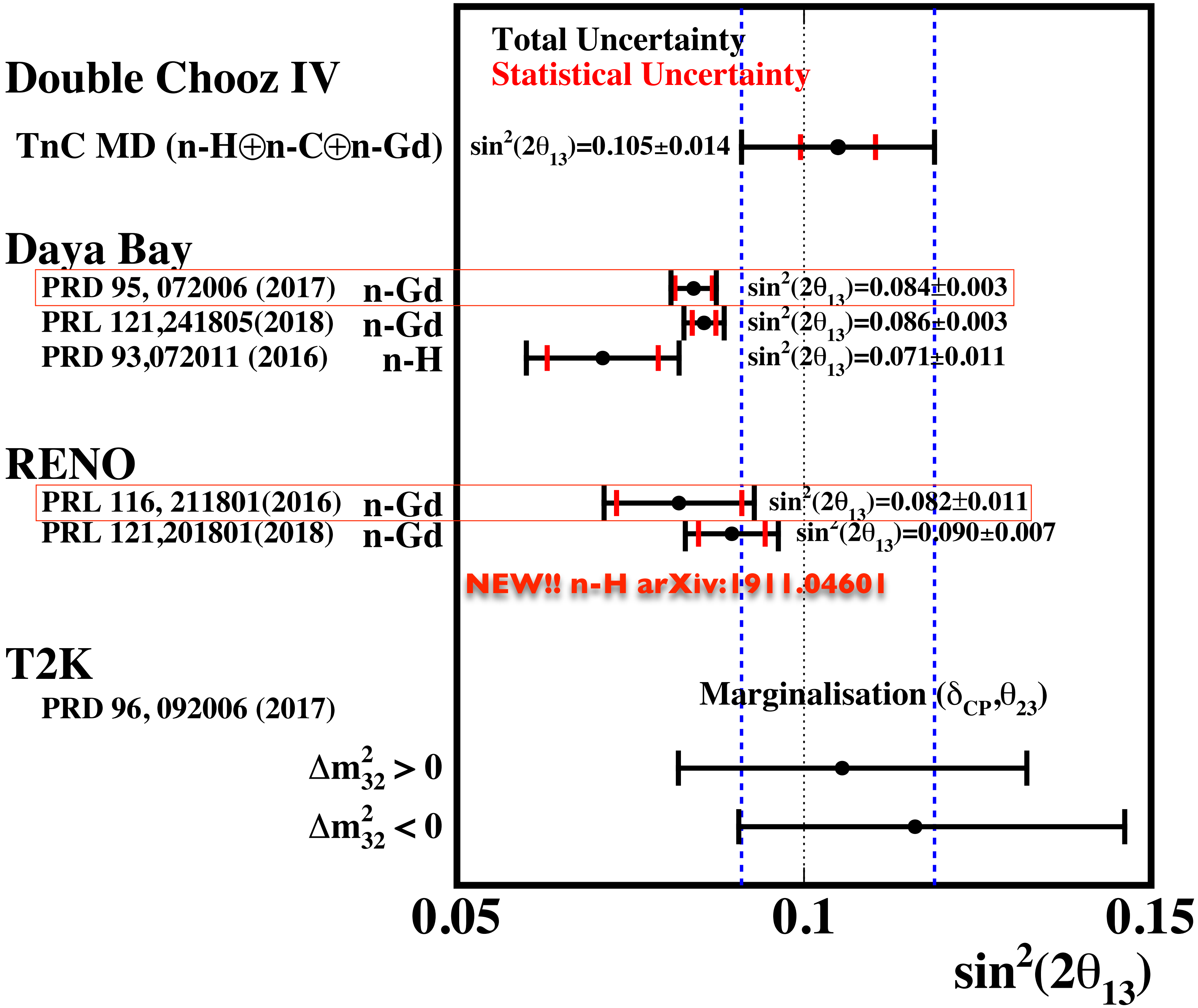
ARTICLE

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


NO?
(we don’t know how)
Φ
improvable?


θ_{13}

2019 world status in θ13…



Hervé de Kerret *et al* (arXiv:1901.09445 1)

slightly higher θ_{13}

before

(~2016)

↓

after

(@Nu2018)

NEUTRINO 2018 Heidelberg 4–9 June

nature physics

ARTICLE

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

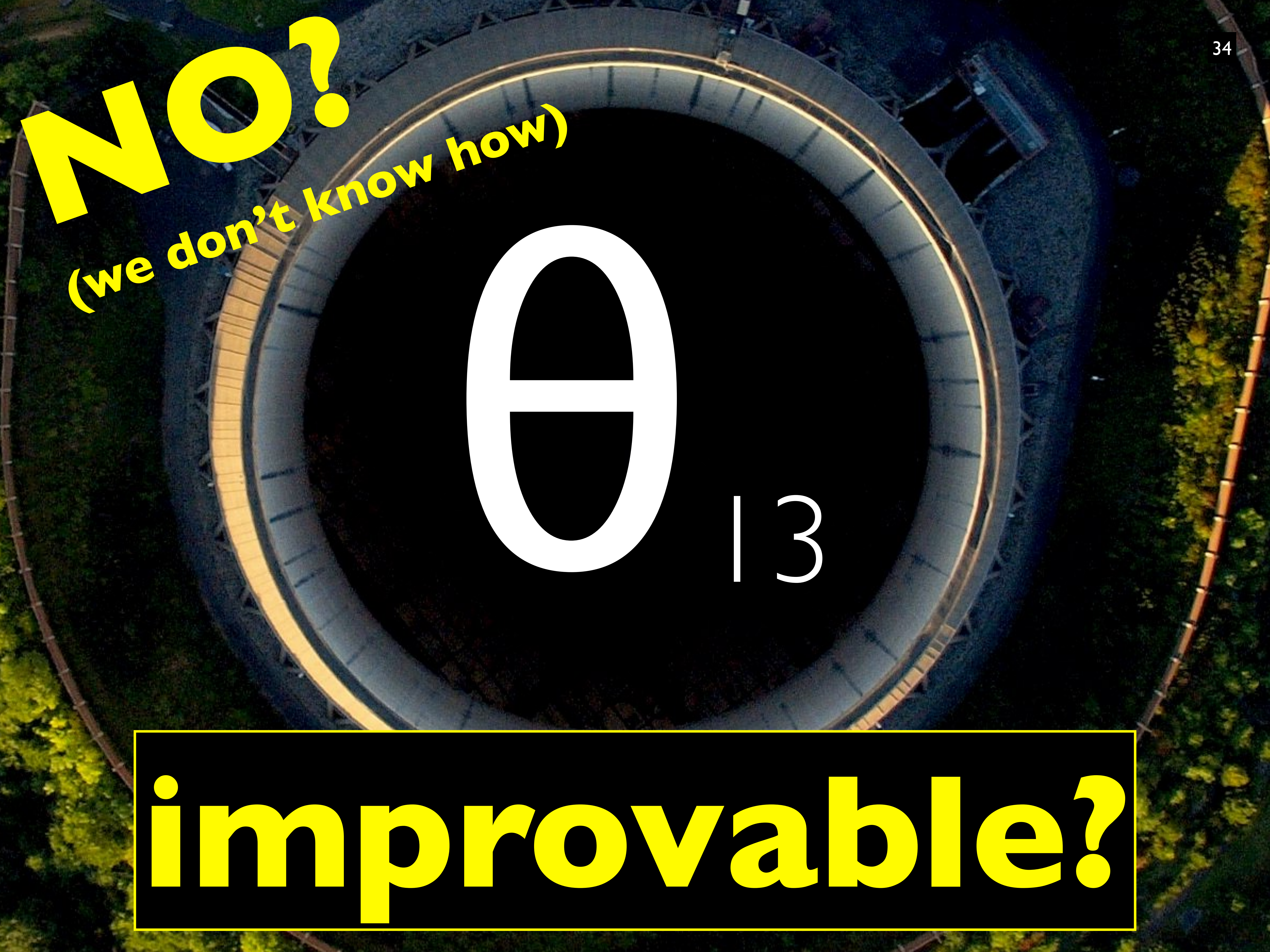
summary on today's θ13 knowledge/experiments…

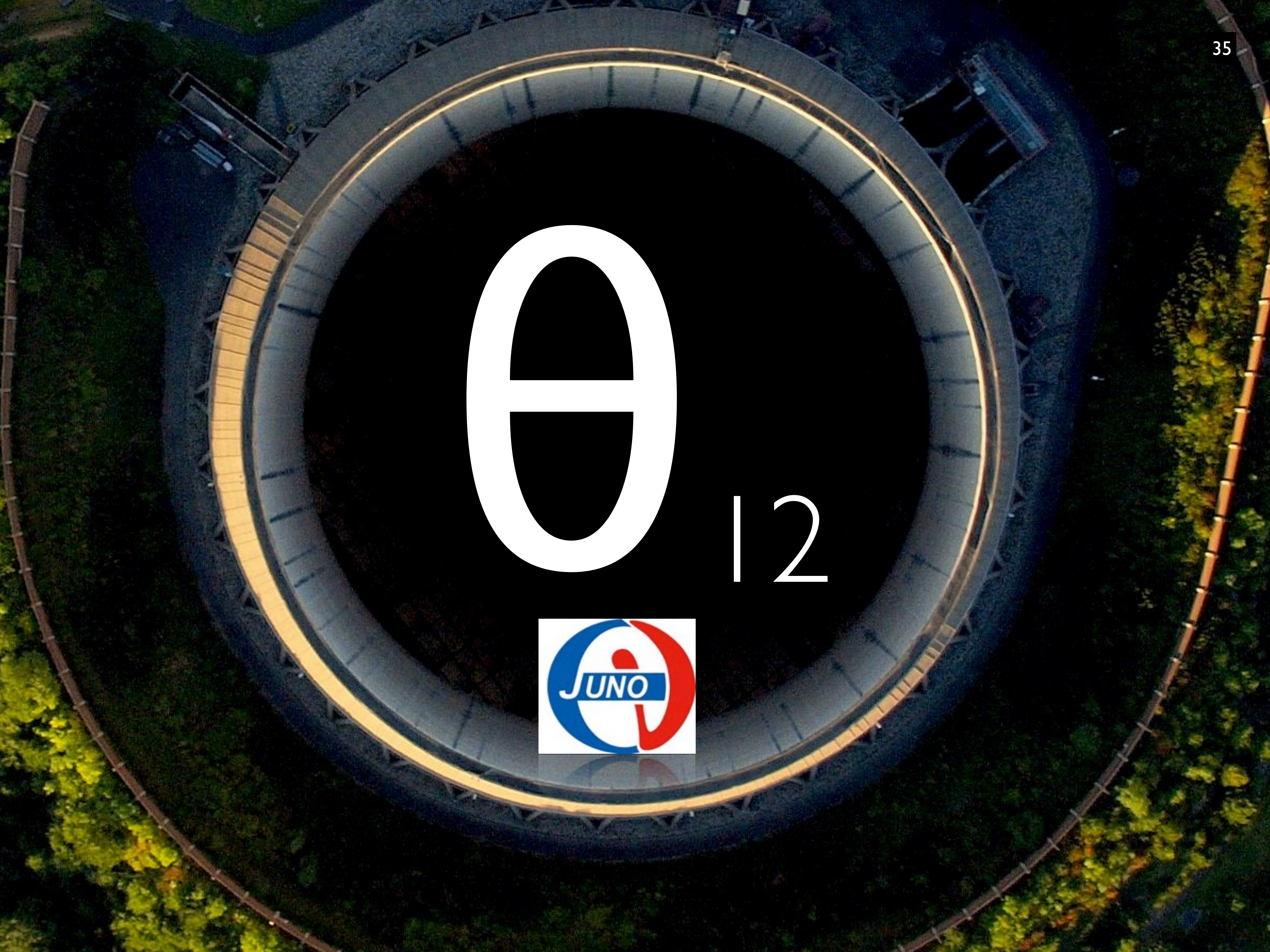
reactor-θ13 experiments
[DC⊕DYB⊕RENO]

•statistics: ~10^5 (far) [<10^6]
•systematics: ~0.1% (each)
•energy control: <1% precision

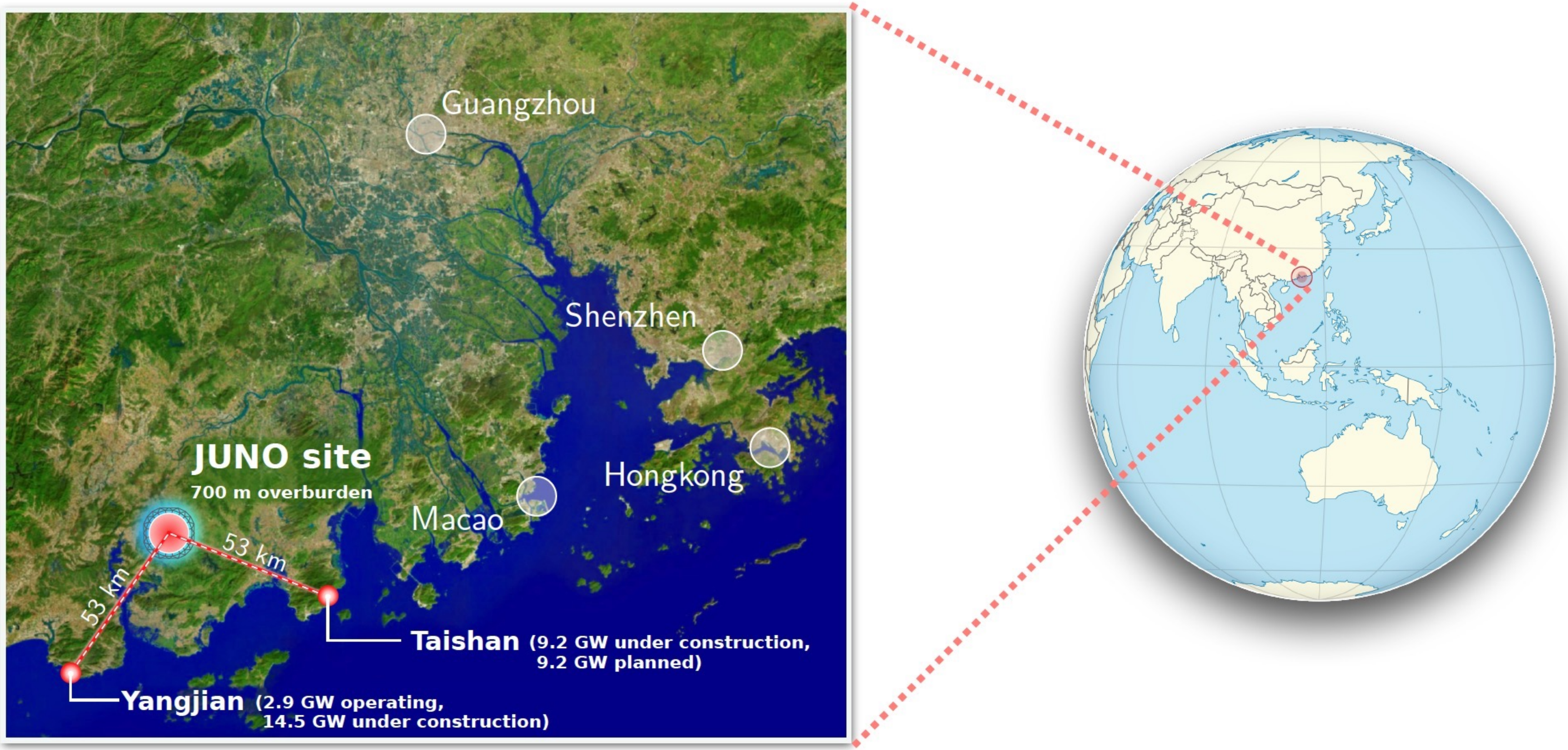
	<2010	today [2010-2020]			cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	—	—	~100/day @ 1.5km
flux	~2.2%	~0.1%	~0.1%	<0.1%	near-to-far monitor (ideal: iso-flux)
BG	few %	~0.1%	~0.1%	<0.1%	overburden → few/day
detection	2.0 %	~0.1%	~0.1%	—	identical detectors
energy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

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

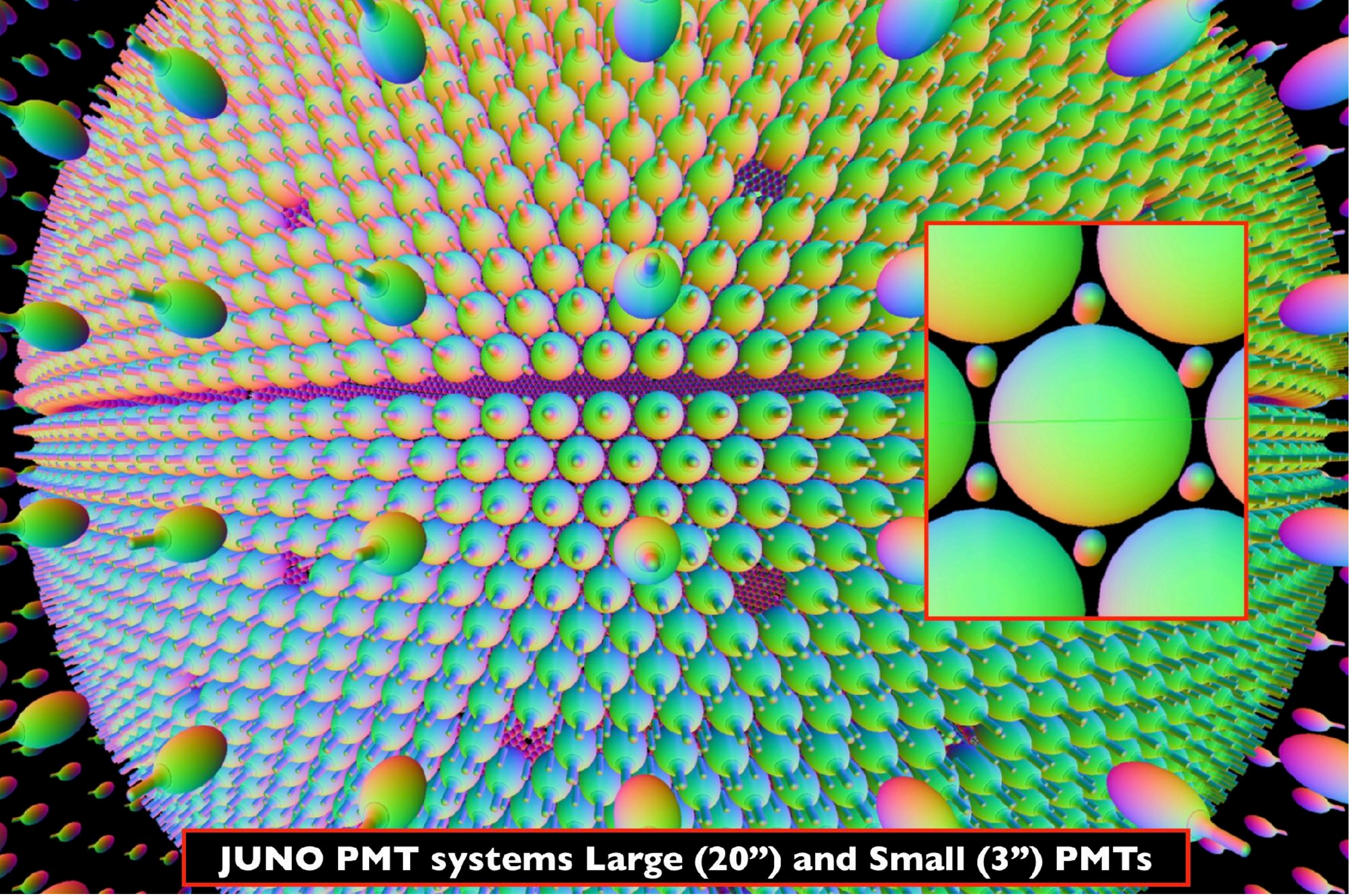

NO?
(we don’t know how)
θ13
improvable?


θ_{12}
JUNO

JUNO location…



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



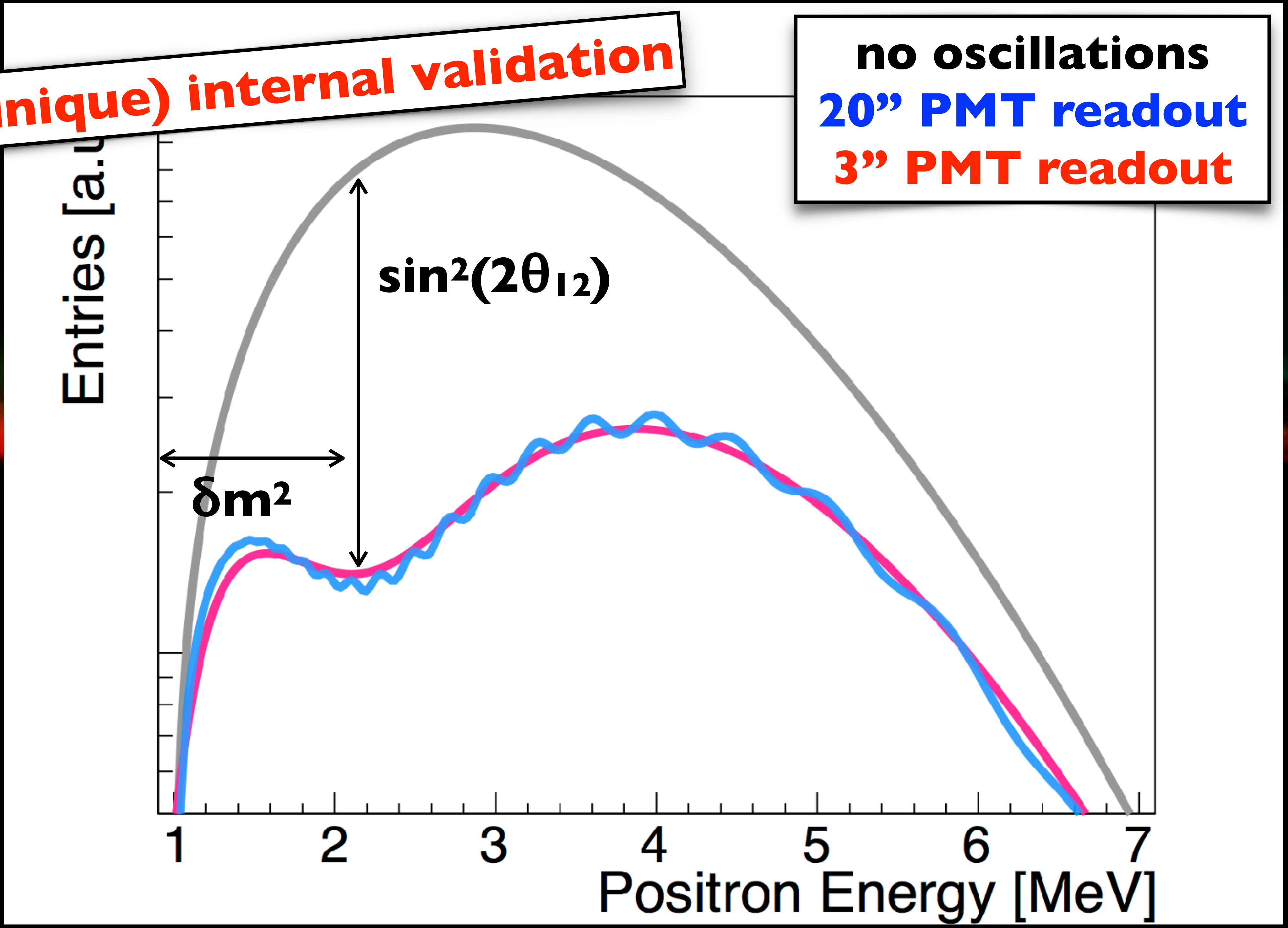
JUNO a photocathode colosso→ yield energy resolution!

Anatael Cabrera (CNRS-IN2P3 & APC)

"solar" oscillation measured by both PMT systems…

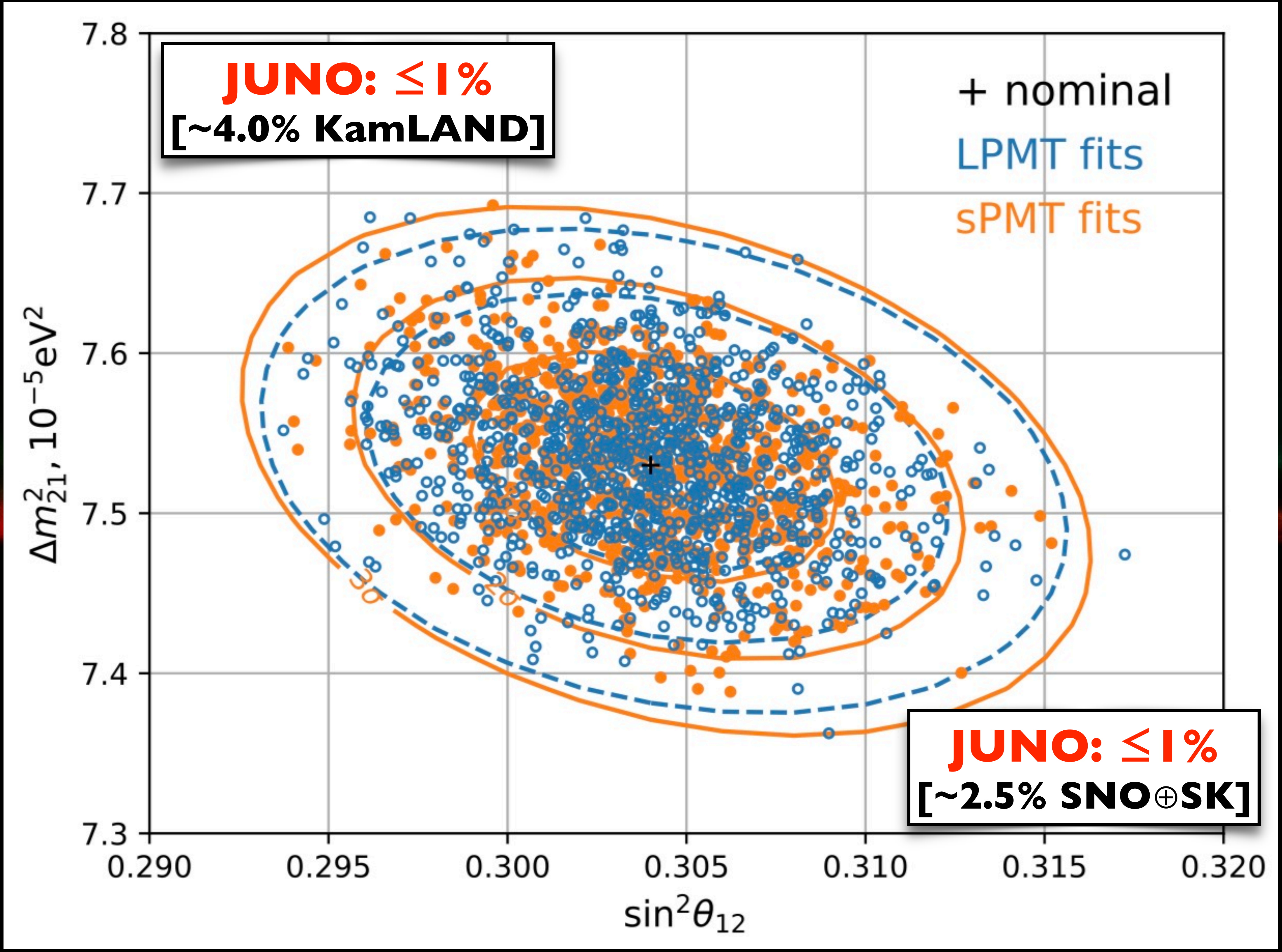
SPMT sees the "solar" oscillation

(fast oscillation washes out)



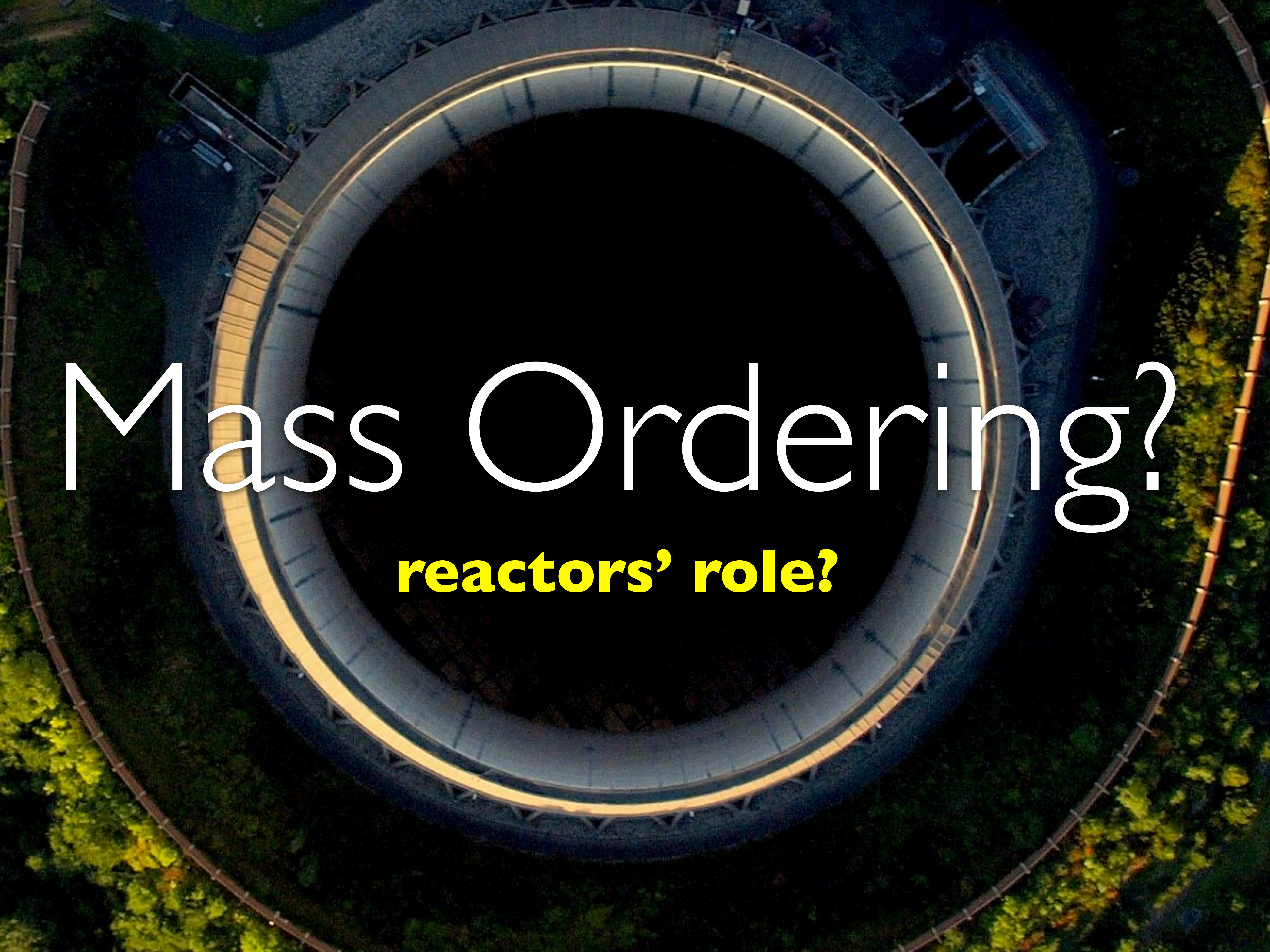
sensitivity: $\theta_{12} \oplus \delta m^2$

LPMT vs SPMT comparison…



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


only JUNO
θ_{12}
improvable?


Mass Ordering?
reactors' role?

Mass Ordering resolution [now at ~3σ]...

Earliest Resolution to the Neutrino Mass Ordering?

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

- **Mass Order** (likely) first measured (≥5σ by ~2028) thanks to **JUNO⊕NOvA⊕T2K** [extra Atmospherics]

- **DUNE** most powerful standalone experiment

- most interesting: exploit **MO**'s binary outcome for possible **BSM explorations**

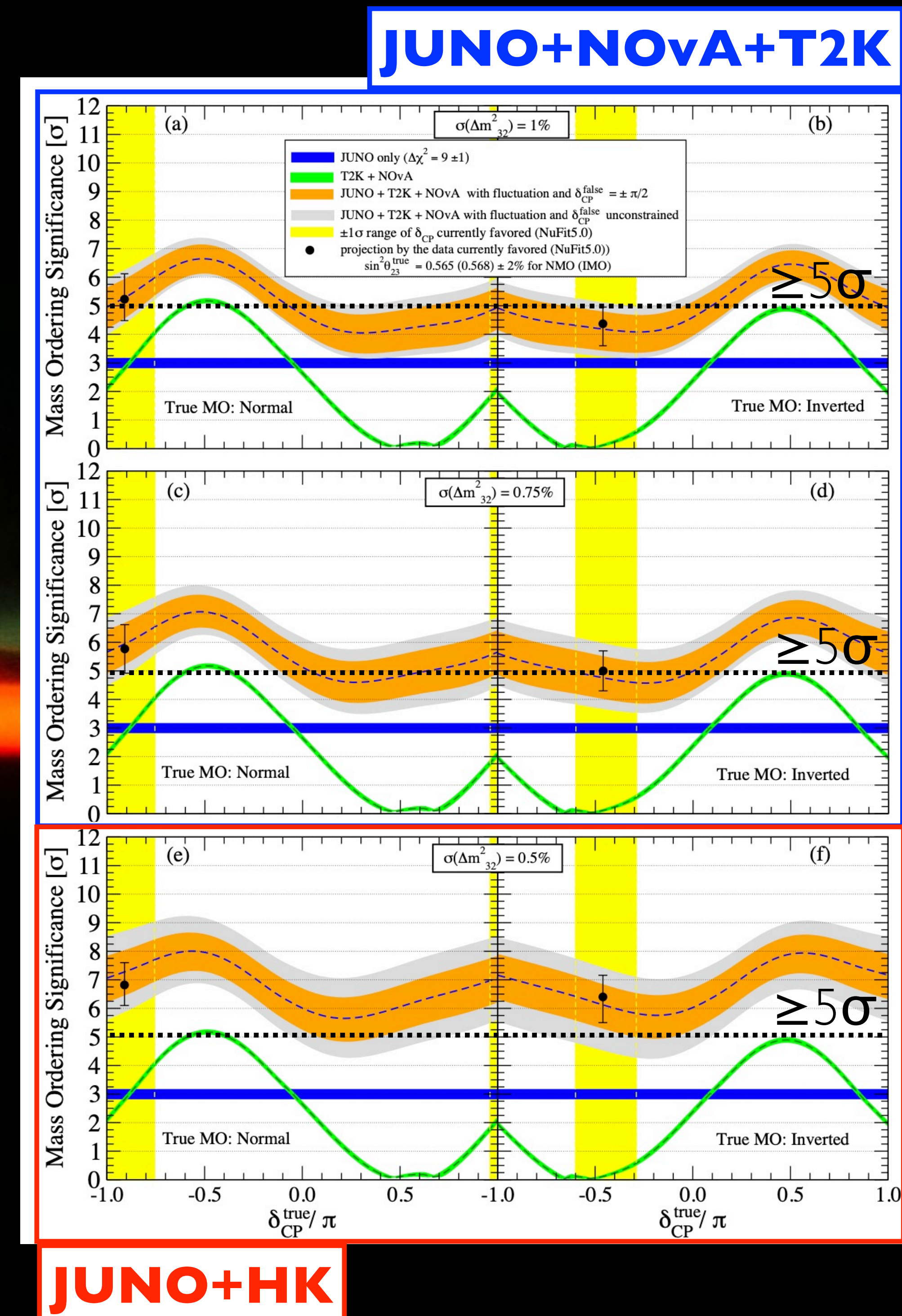
- the **ultimate & most powerful test**:

  DUNE (≥5σ — *matter effects*)

  vs

  JUNO⊕**HK** (≥5σ — *vacuum oscillations*)

⟹ **discrepancies may lead to discoveries!**



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


and beyond...
future

have the ν's left Europe…?

how to reduce BG with no more overburden?

lesson: avoid civil construction…

Liquid

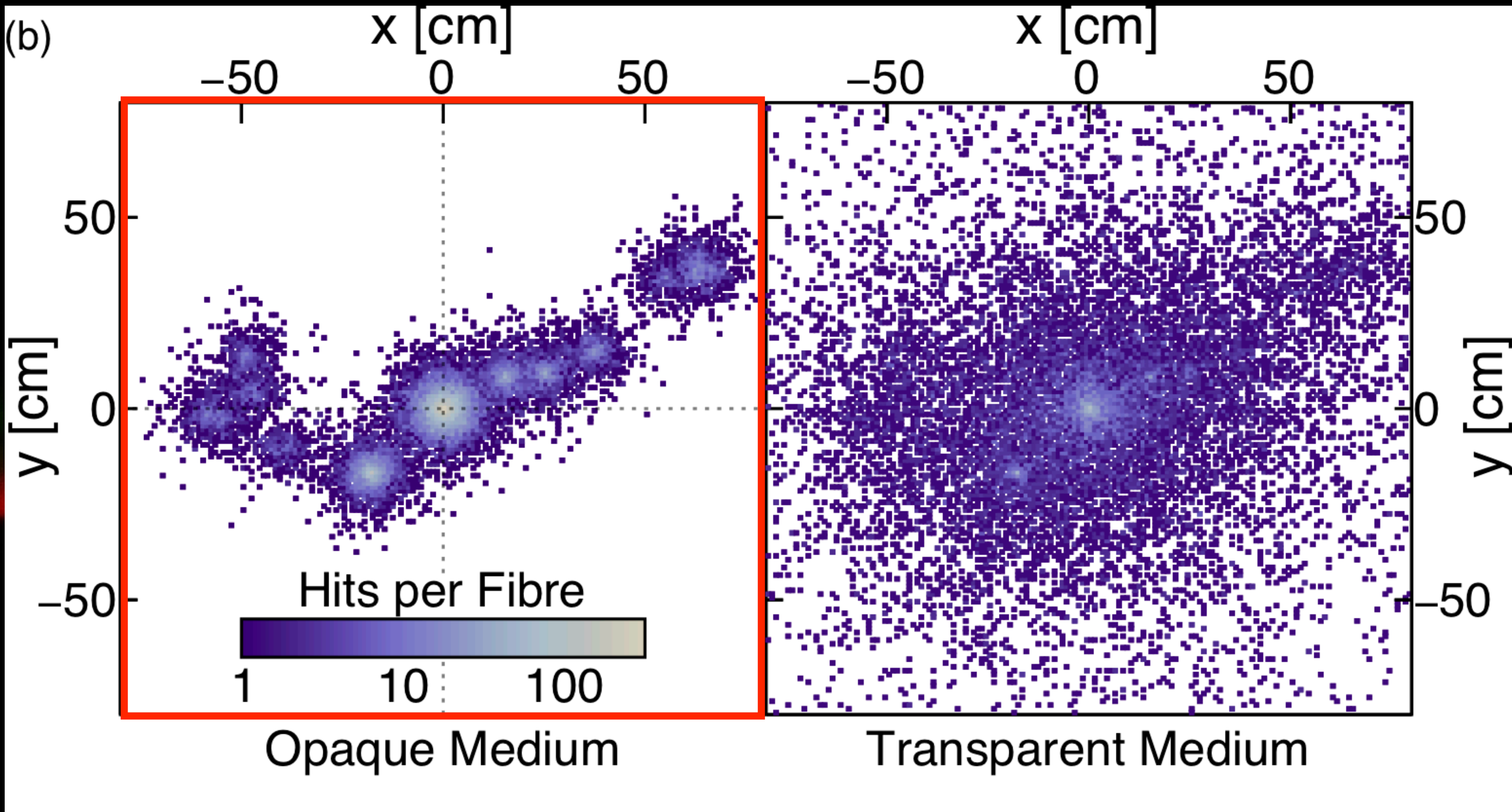
a novel neutrino detection

e+ tagging specialised

BG active rejection

[time⊕space coincidence & Particle-ID]

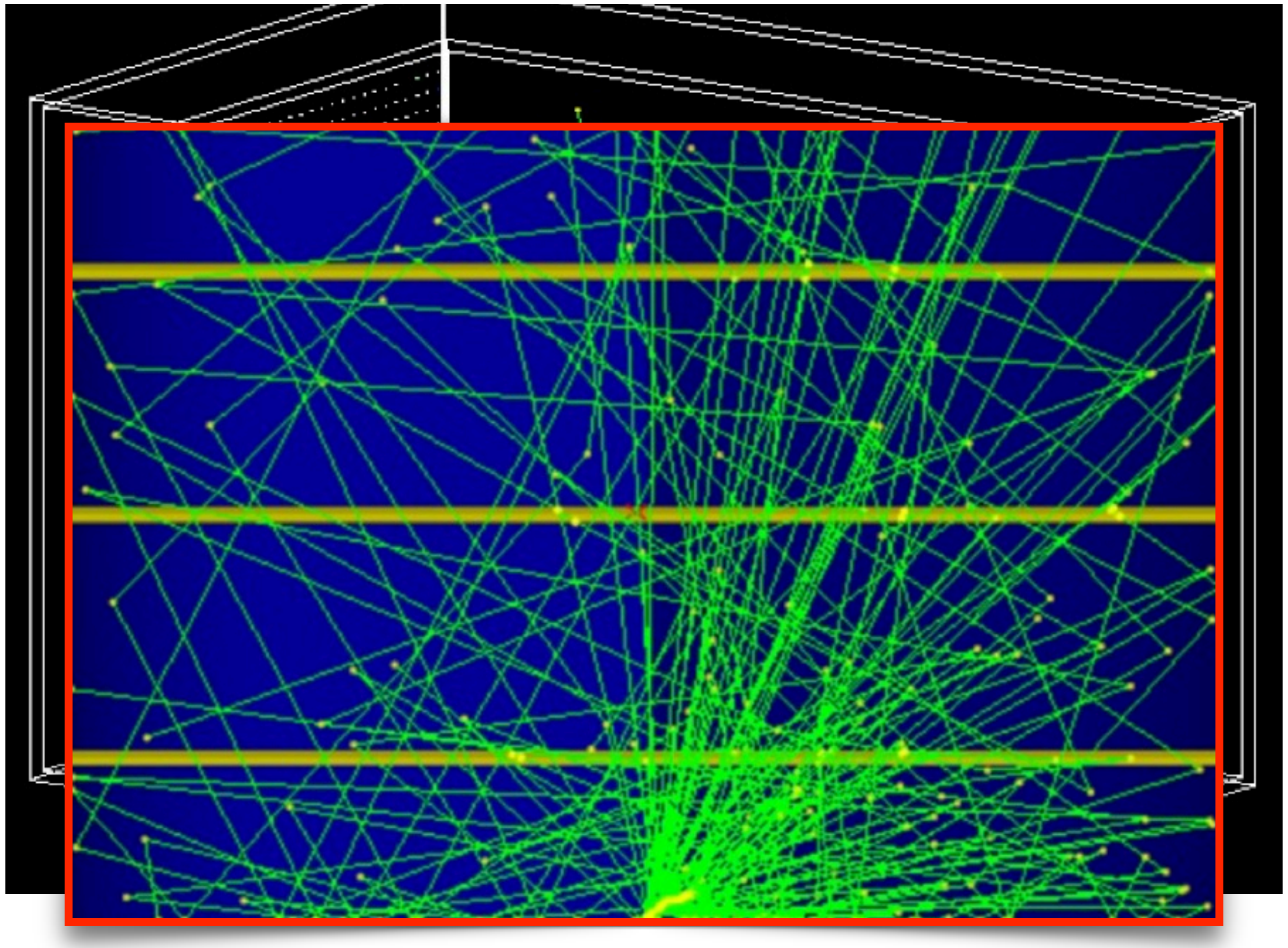
LiquidO event-wise imaging…



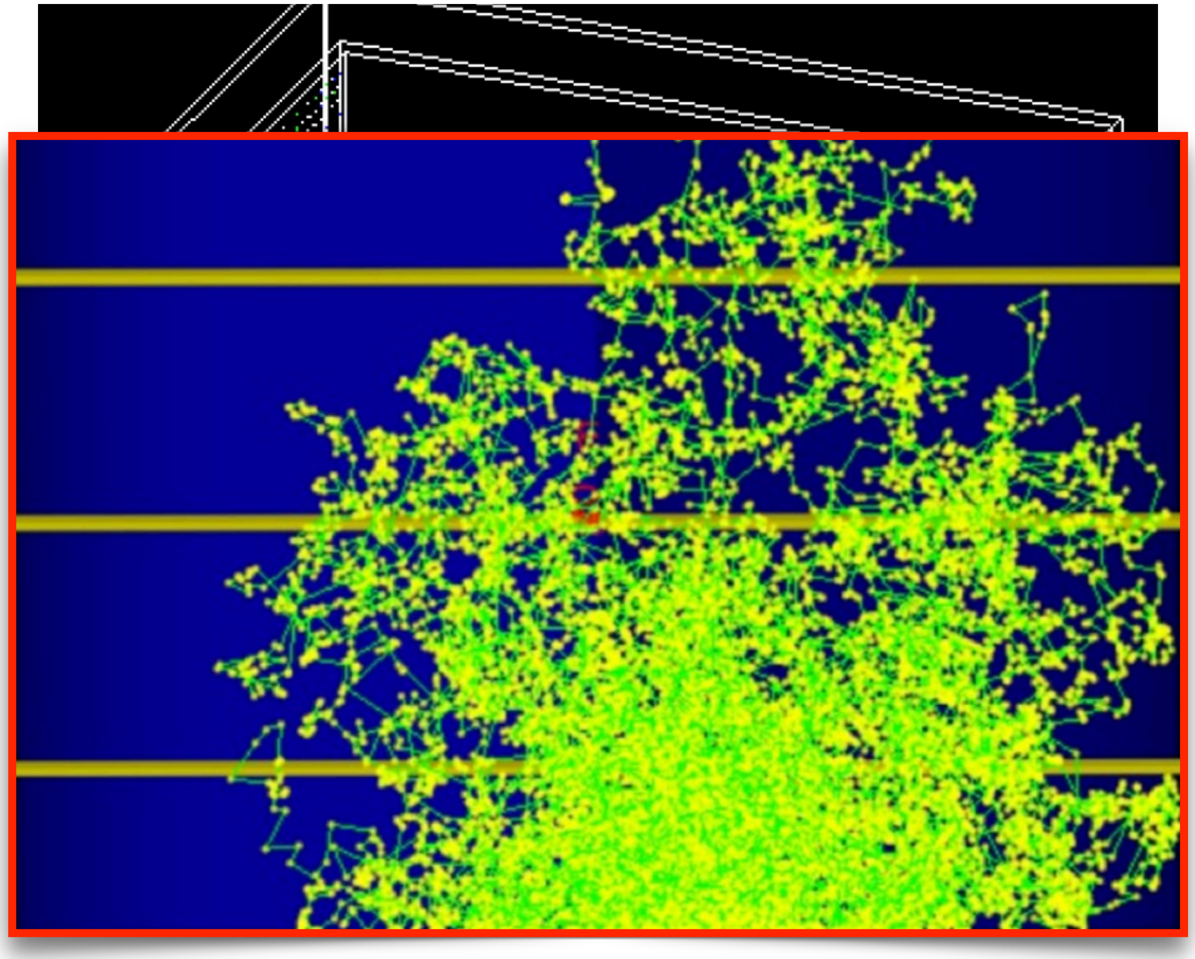
opaque scintillator→stochastic light confinement

(**self-segmentation**)

LiquidO recipe: just "bread & butter" physics…



today's technology

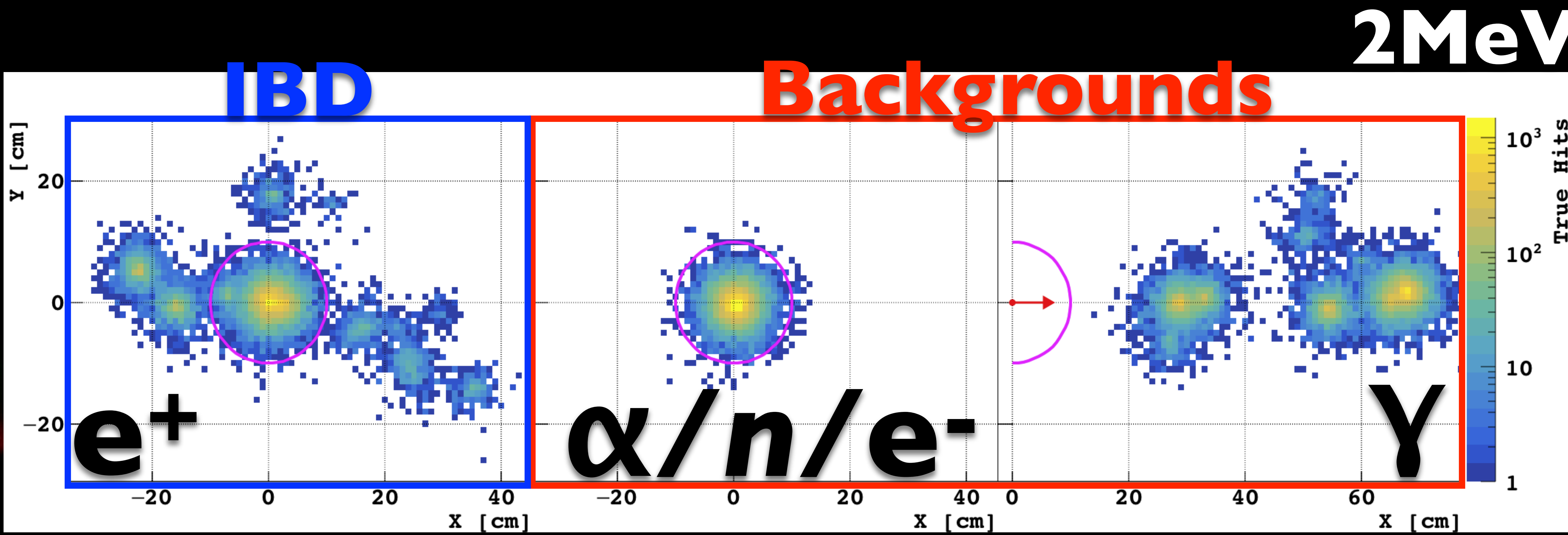


LiquidO technology

light ball size: scattering⊕fibres

(sampling optimisation)

powerful PID…



vertex resolution ≈ order mm

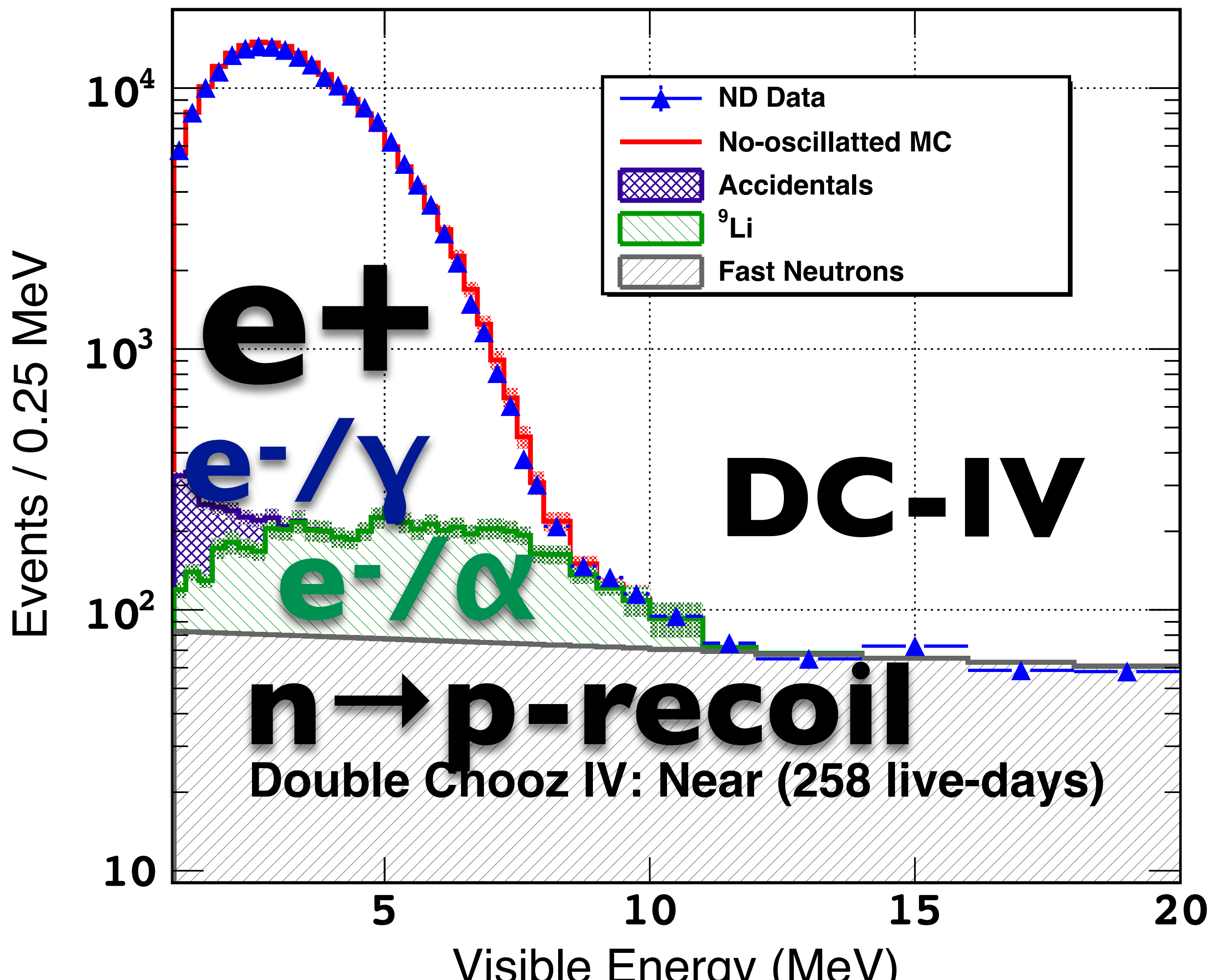
cosmogenic (^{9}Li & fast-neutrons)
accidentals (β^{-}, γ and α)

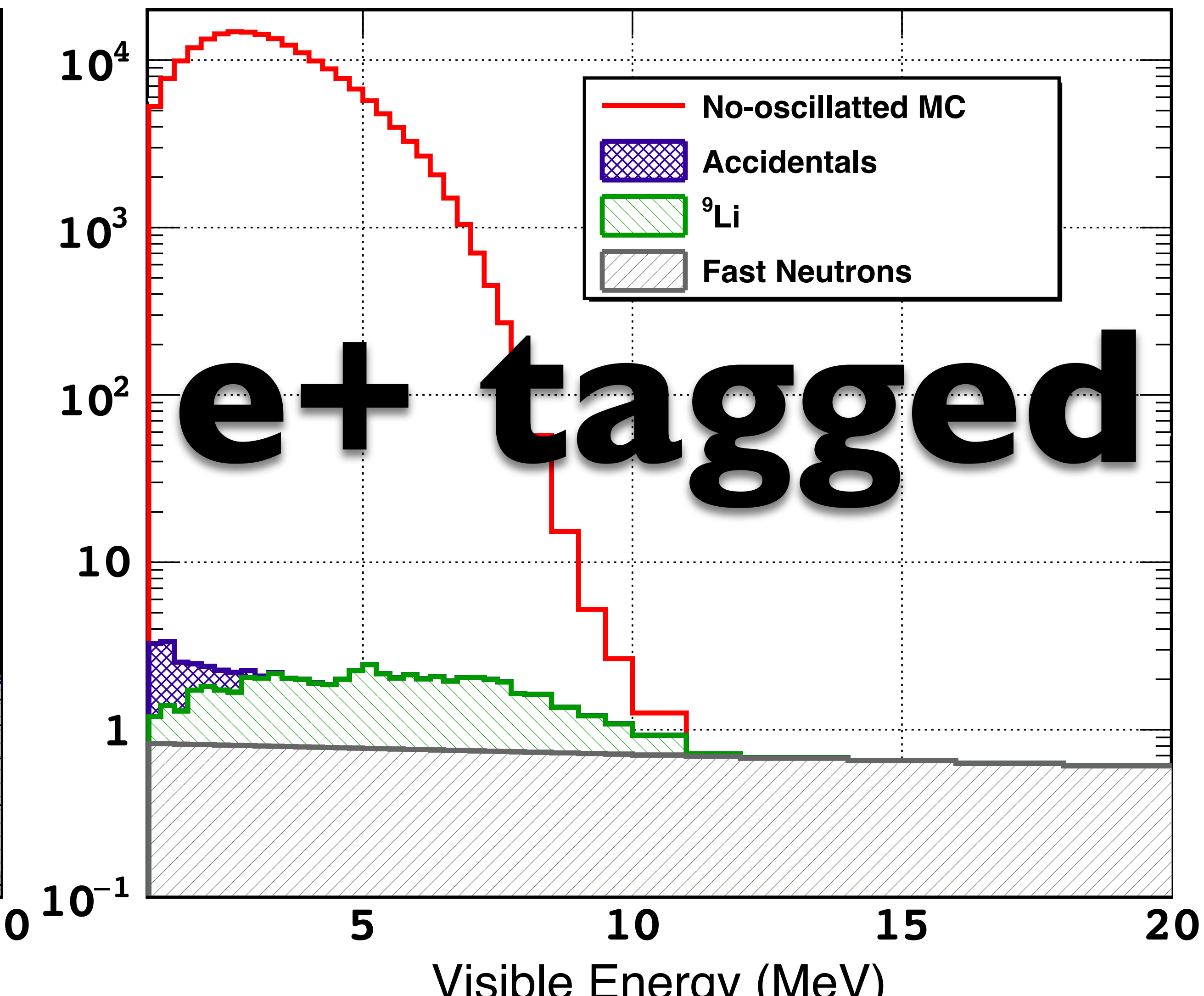
rejection ≳100x

[time⊕space coincidence & PID(e+)]

backup slide

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)





state of the art

Signal:Background ~20:1

Background rate few/day

LiquidO

Signal:Background ≥100x 20:1

Background rate few/year

LiquidO breakthrough possible?

LiquidO full release 2019…

Neutrino Physics with an Opaque Detector

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The discovery of the neutrino by Reines & Cowan in 1956 revolutionised our understanding of the universe at its most fundamental level and provided a new probe with which to explore the cosmos. Furthermore, it laid the groundwork for one of the most successful and widely used neutrino detection technologies to date: the liquid scintillator detector. In these detectors, the light produced by particle interactions propagates across transparent scintillator volumes to surrounding photo-sensors. This article introduces a new approach, called LiquidO, that breaks with the conventional paradigm of transparency by confining and collecting light near its creation point with an opaque scintillator and a dense array of fibres. The principles behind LiquidO's detection technique and the results of the first experimental validation are presented. The LiquidO technique provides high-resolution imaging that enables highly efficient identification of individual particles event-by-event. Additionally, the exploitation of an opaque medium gives LiquidO natural affinity for using dopants at unprecedented levels. With these and other capabilities, LiquidO has the potential to unlock new opportunities in neutrino physics, some of which are discussed here.

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Seminar@CERN — June 2019

Web: https://indico.cern.ch/event/823865/

Igniting publication — Aug 2019

LiquidO @ arXiv:1908.02859

- new detection principle
- **first experimental proof-of principle**
- vast neutrino physics prospect

Submitted for Publication

First Opaque Liquid Scintillator @ arXiv:1908.03334

SuperChooZ?

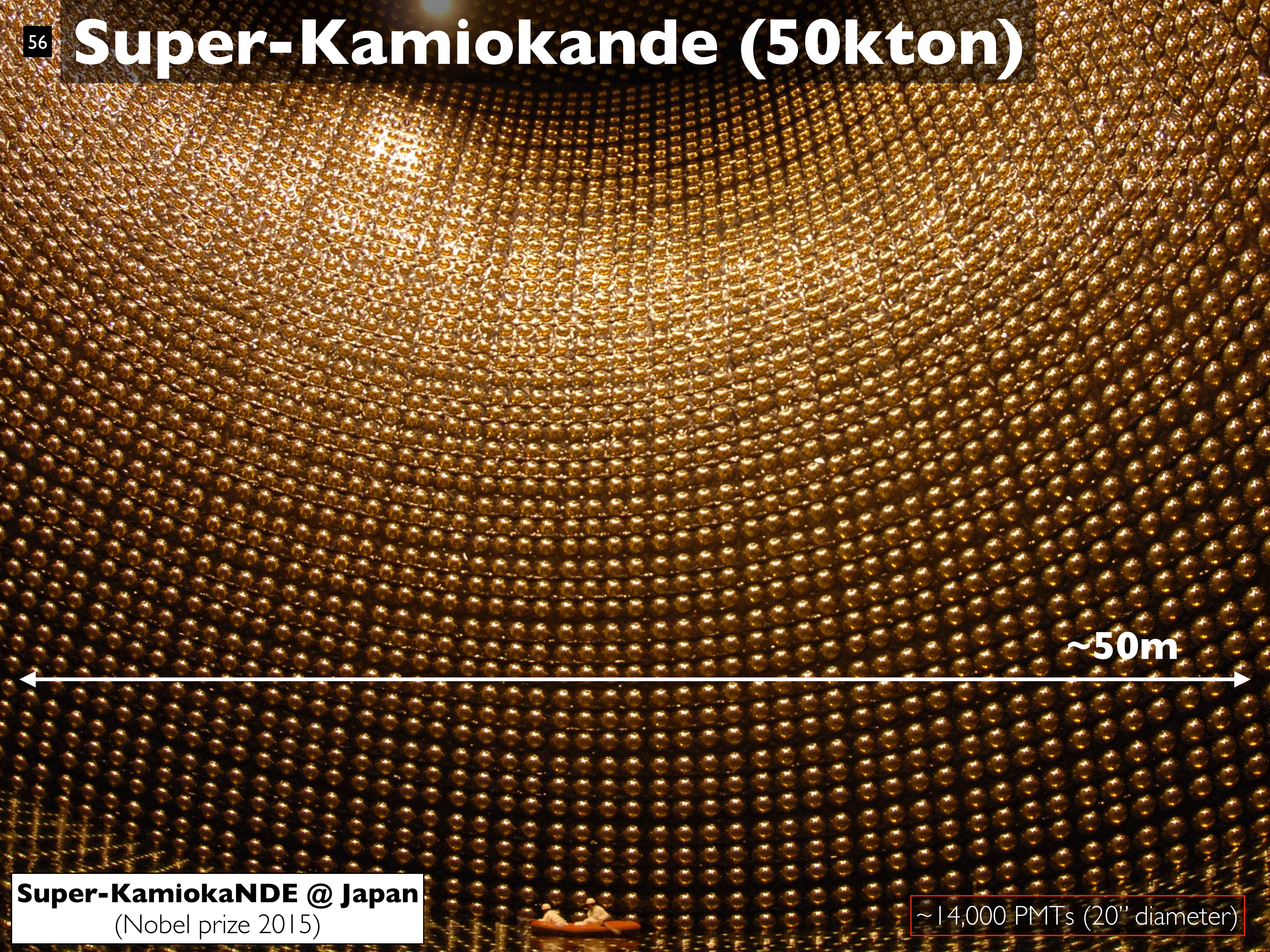
Europe's best reactor ν site…

a secret underground…

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?

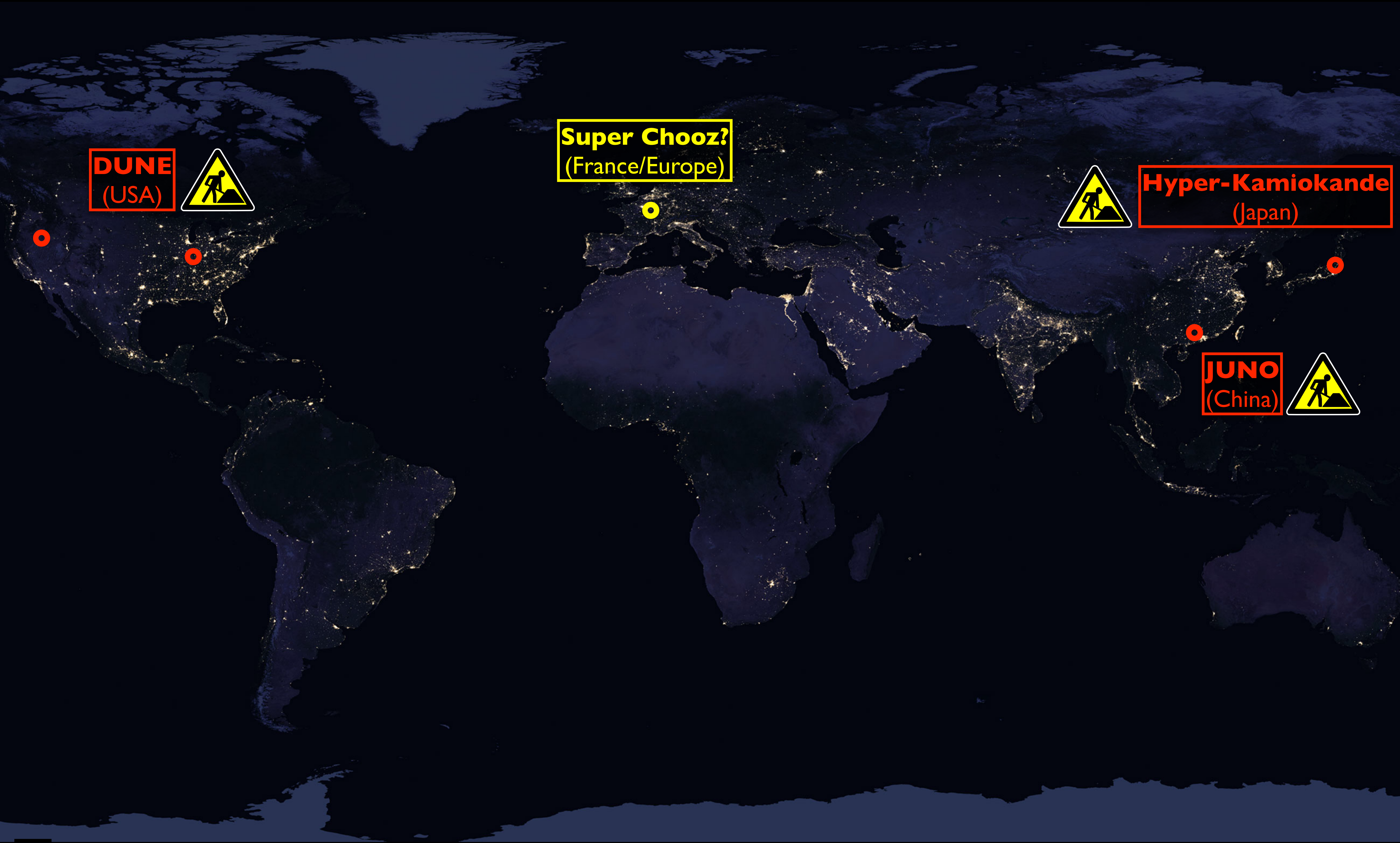
Super-Kamiokande (50kton)



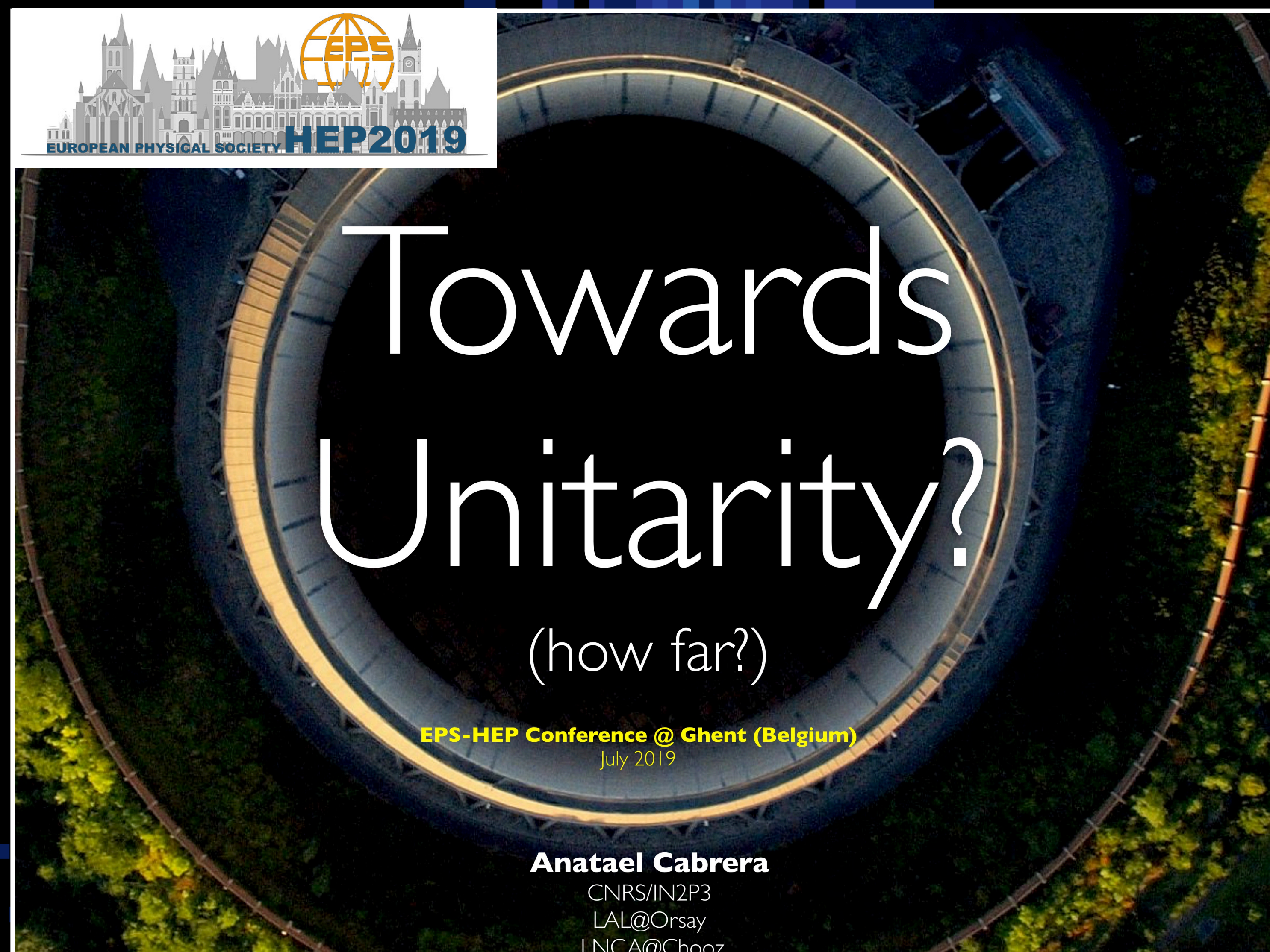
Super-KamiokaNDE @ Japan
(Nobel prize 2015)

~14,000 PMTs (20" diameter)

Super Chooz since the 60's…

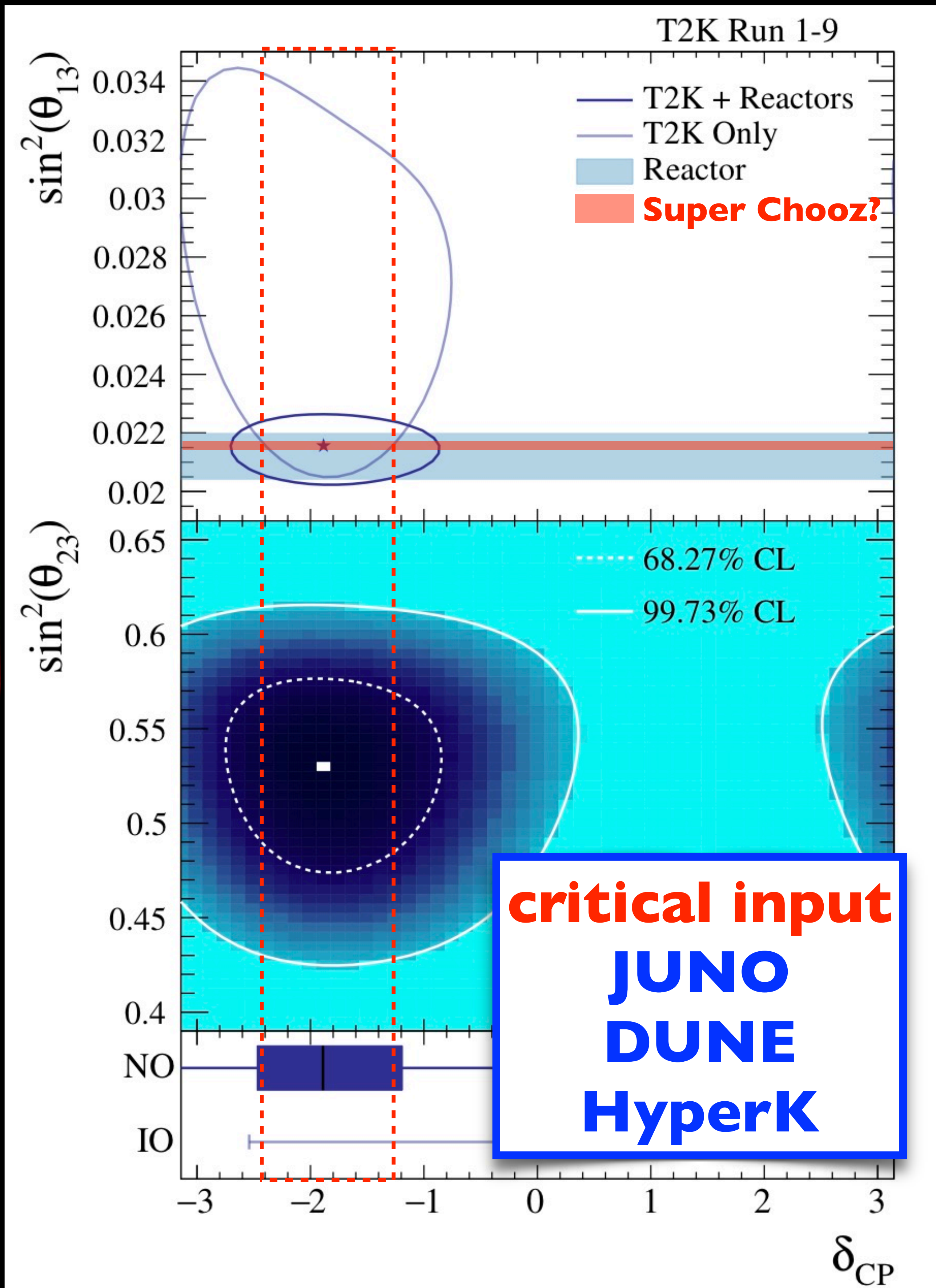


leptonic sector unitarity with LiquidO?



Conference @ HEP-European Physics Society (July 2019 @ Ghent Belgium)
Web: https://indico.cern.ch/event/577856/contributions/3421609/

T2K⊕reactor best knowledge CP-Violation…



θ13 implications

powerful constraint

CPV phase vs θ13

[constrained by reactor]

CPV phase vs θ23

[octant ambiguity]

CPV phase vs (Atmospheric) Mass Ordering

[T2K blinded]

solar neutrinos too…

Super Chooz = telescope of the sun's fusion!

MENU

neutrino reactor
θ13 et **Δm²** [**WB**]

neutrino solar
θ12 [**WB?**] — et **δm²**?

direct CPT violation?
[**WB-ν** & **BSM**]
direct Unitarity violation?
[**WB?** & **BSM**]

neutrino supernova
all channels [**WB?**]

proton decay
multi-cannel (model independent)
[**WB?** & **BSM**]

Super Chooz
(LiquidO ~10kton)

WB = world best
("?": under study still)

SuperChooZ?

stunning **opportunity**…

bring the ν's back to Europe…

historical opportunity for Europe science

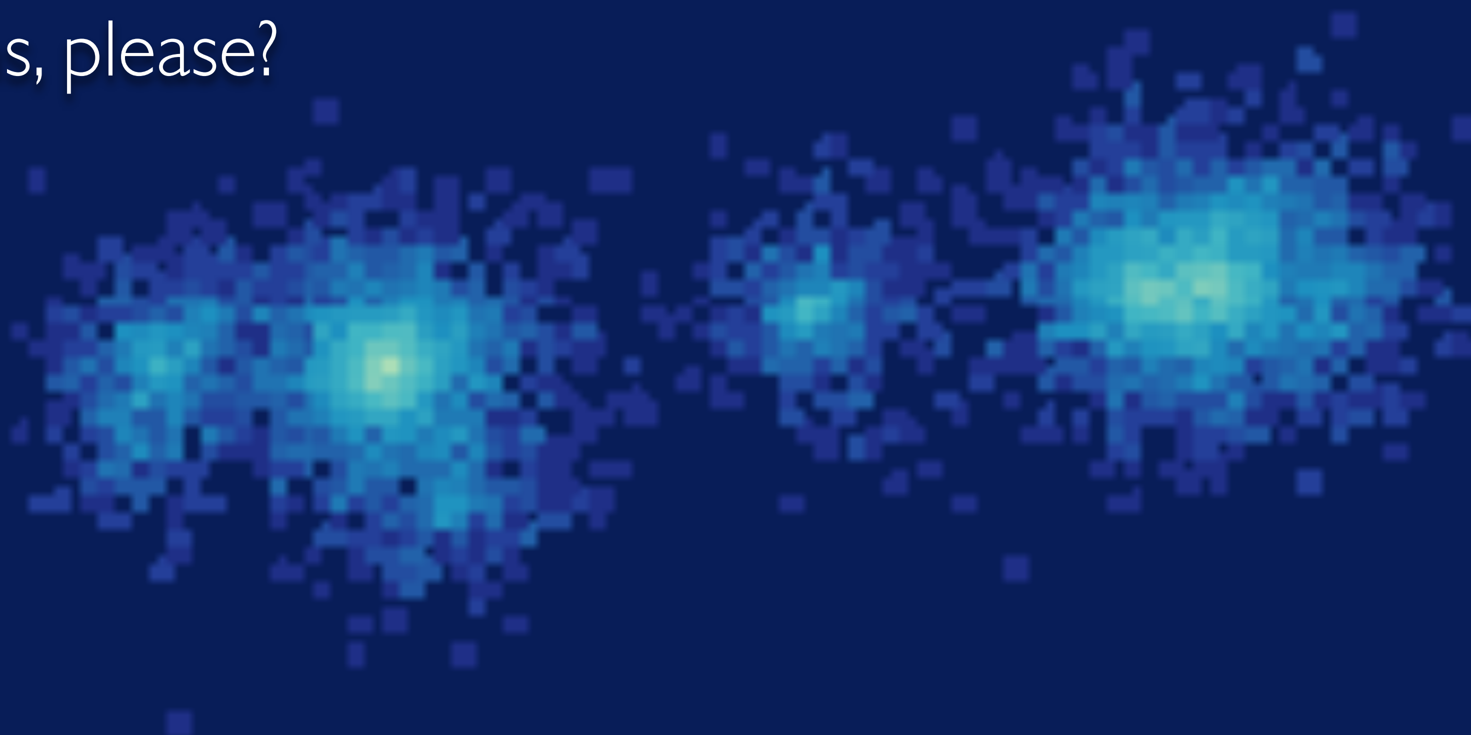
EDF+CNRS on the forefront…

since the ν discovery, **reactor ν's** remain one of the most powerful tools…

future knowledge (strongly) shaped by reactor ν…

Super Chooz: a powerful opportunity in Europe?

questions, please?



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

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