Reactor ν

(today & future)

Seminar @ RAL (UK)
November 2020

Seminars
Reactor Neutrino Potential in the era of the novel LiquidO Detection Technology
by Anatael Cabrera (CNRS-IN2P3)
Wednesday 18 Nov 2020, 11:30 → 12:30 Europe/London
Zoom

Anatael Cabrera
CNRS/IN2P3
IJCLab @ Orsay
LNCA @ Chooz

cnrs | université PARIS-SACLAY | FACULTÉ DES SCIENCES D'ORSAY | Université de Paris | IJCLab Irène Joliot-Curie

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

Reines & Cowan (*et al*) around 1950

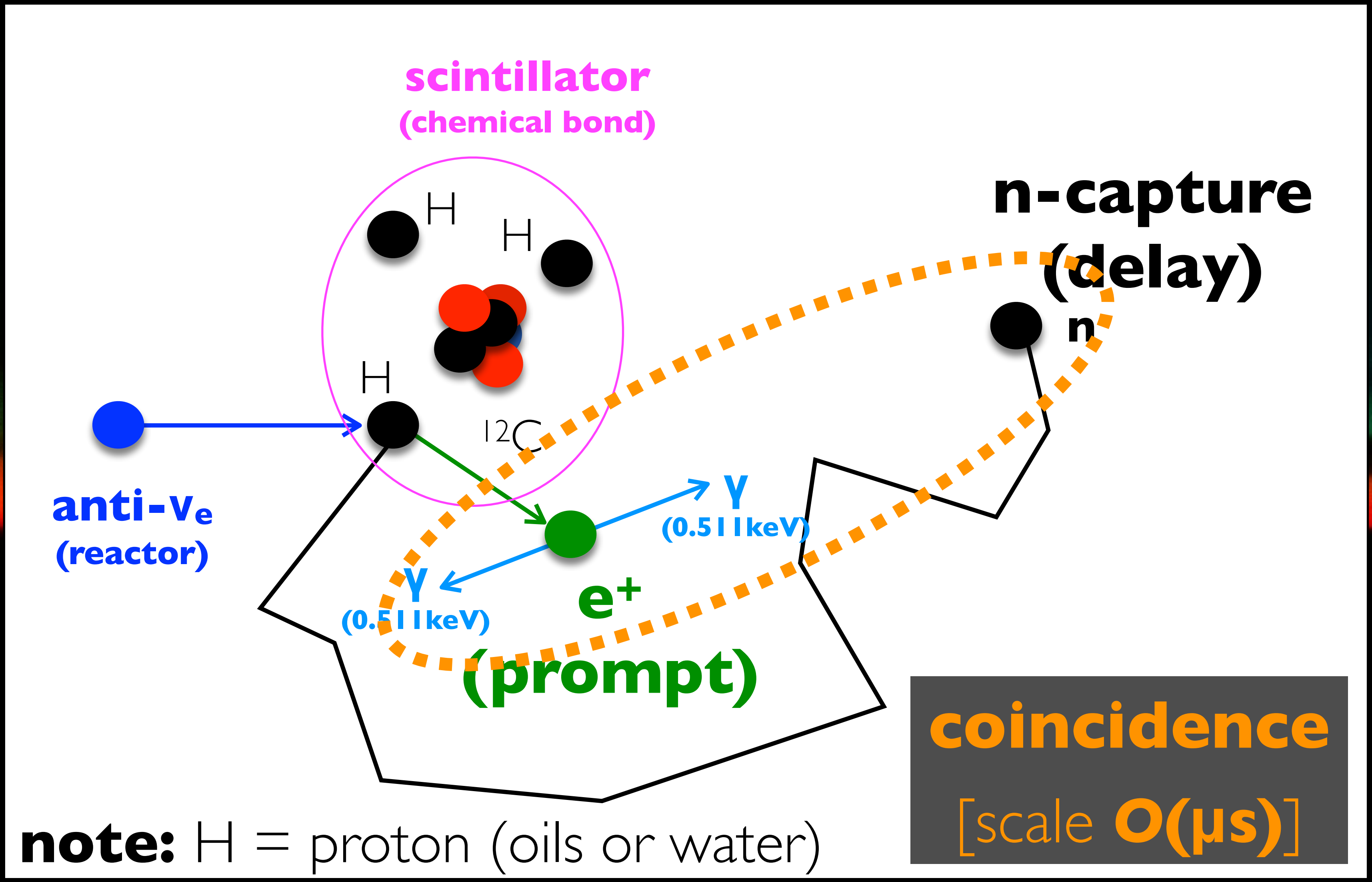
discover the neutrino (upon 1930’s Pauli’s hypothesis)
[Nobel prize 1995]

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



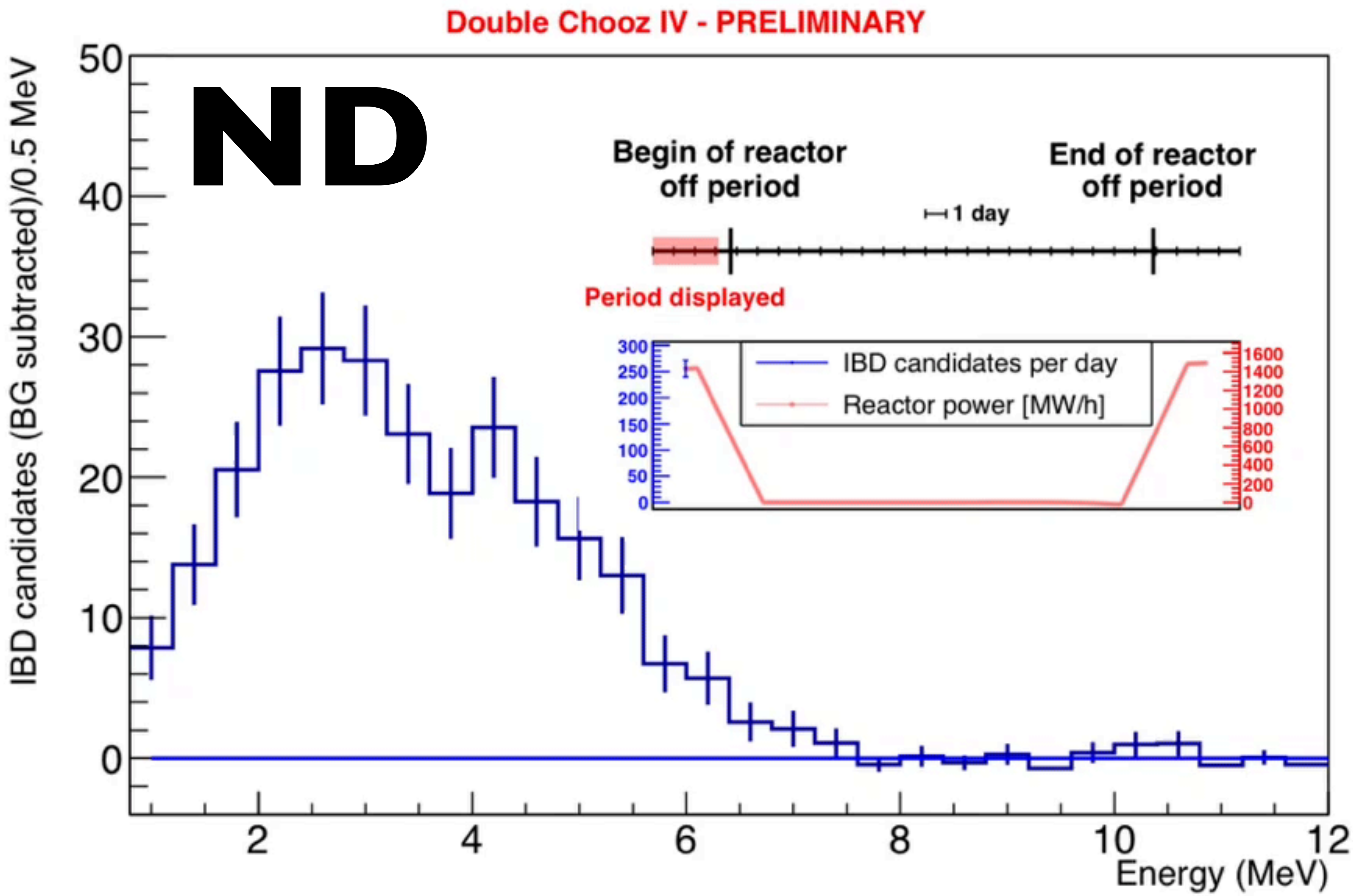
no e+ PID implies

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


V’s

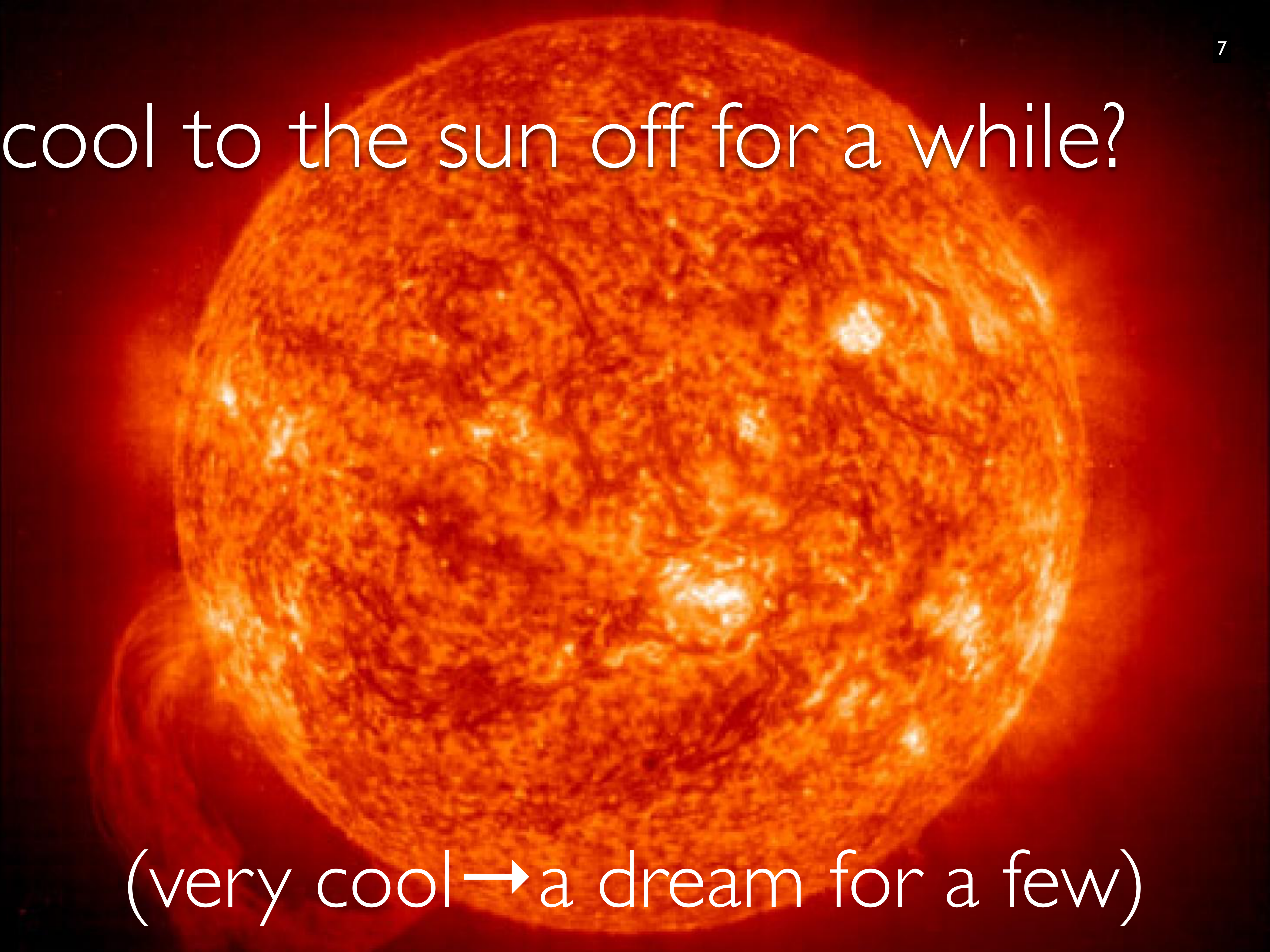
Double Chooz reactor-VETO: signal analysis…

rate(1 reactor) ≈ IBD per 3 min

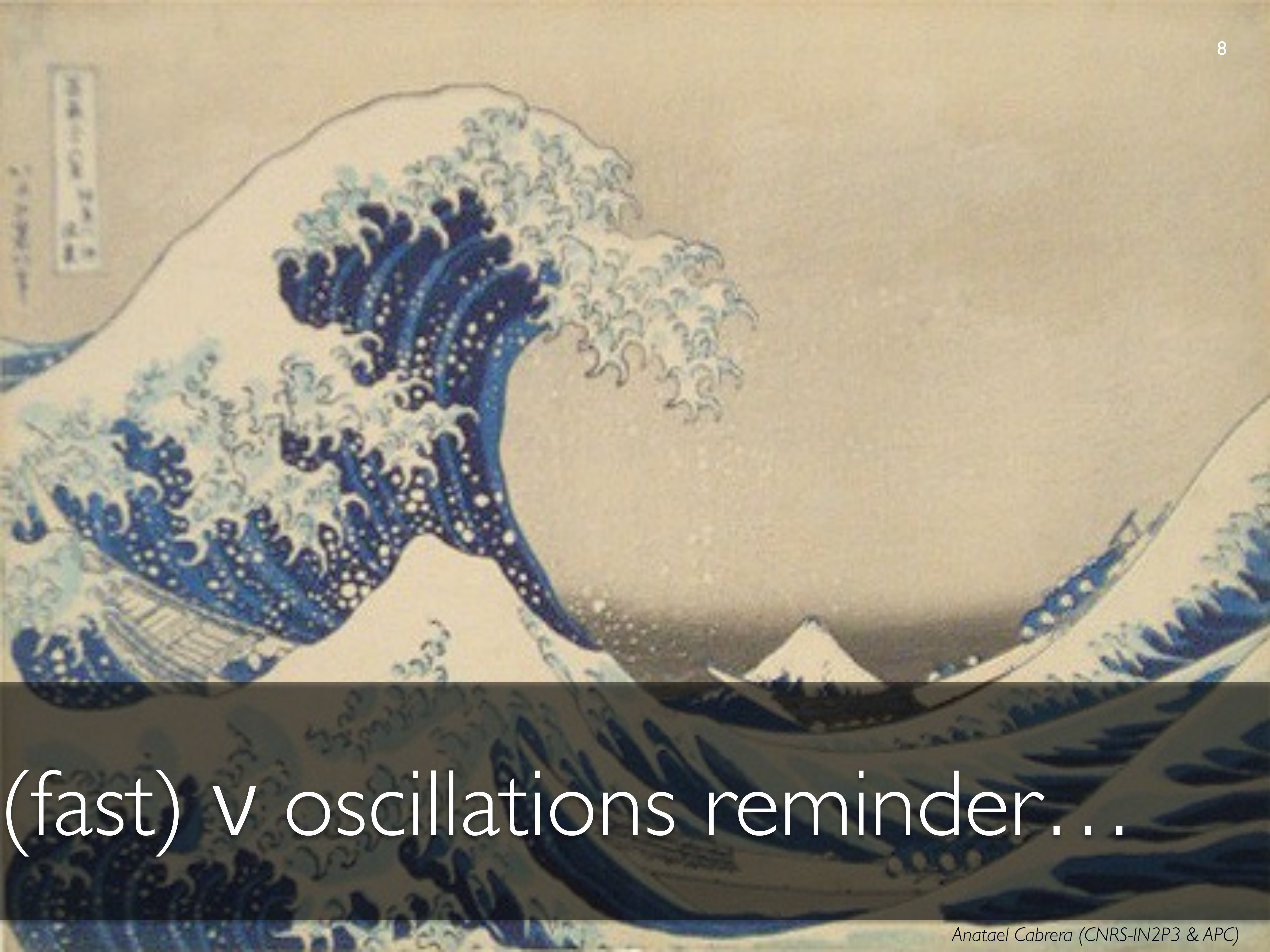


BG subtracted

cool to the sun off for a while?



(very cool→a 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=ƒ(θ,Δm²)**

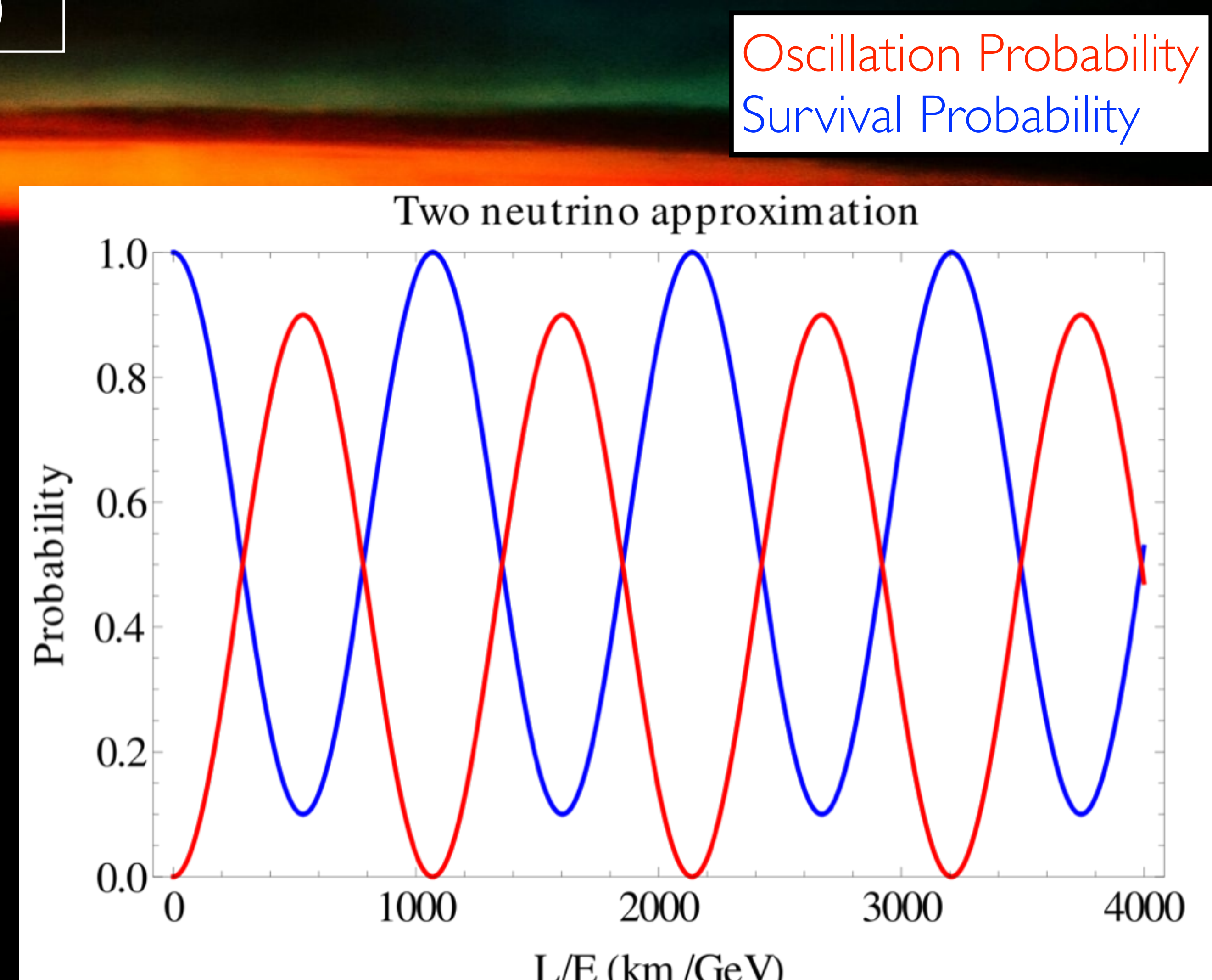
quantum interference (macroscopic)

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



APC)

where are we now (~2020)?

status on neutrino oscillation knowledge…

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

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 %	SNO	2.3 %	≲1.0%	JUNO	reactor
θ_{23}	5.0 %	NOvA	2.0 %	≲1.0%	DUNE⊕HK	beam (octant)
θ_{13}	1.8 %	DYB	**1.5 %**	**1.5 %**	DC⊕DYB⊕RENO	reactor
$+\delta m^2$	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
$\|\Delta m^2\|$	3.0 %	T2K & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK	reactor⊕beam
sign(Δm^2)	unknown	(SK *et al*)	NO @ ~3σ	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CPV	unknown	(T2K *et al*)	3/2π @ ~2σ	**@5σ?**	DUNE⊕HK⊕ALL	beam driven

(Nov 2018) (reactor-beam)

essentially JUNO⊕DUNE⊕HK will lead most of the field (**goal CPV**)→ **except θ_{13}!**

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

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		
	best knowledge		NuFIT4.0
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 %**
+δm²	2.5 %	KamLAND	2.3 %
|Δm²|	3.0 %	T2K+NOvA & DYB	1.3 %
sign(Δm²)	**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 & Δm² measurements)

status on neutrino oscillation knowledge…

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

	today			≥2030		
	best knowledge		NuFIT4.0	foreseen	dominant	technique
θ_{12}	3.0 %	SK⊕SNO	2.3 %	<1.0%	JUNO & **SC**	reactor
θ_{23}	5.0 %	NOvA+T2K	2.0 %	≲1.0%	DUNE⊕HK**[⊕SC⁇]**	beam (octant)
θ_{13}	1.8 %	DYB+DC+RENO	**1.5 %**	<1.0%	**Super Chooz (SC)**	reactor
+δm²	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
|Δm²|	3.0 %	T2K+NOvA & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK⊕**SC**	reactor⊕beam
Mass Ordering	**unknown**	SK et al	NMO @ ≲3σ	@5σ	JUNO⊕DUNE⊕HK (NOvA⊕T2K)	reactor⊕beam
CPV	**unknown**	T2K+NOvA	3/2π @ ≲2σ	**@5σ?**	DUNE⊕HK⊕**SC**	beam driven
CPTV	**assumed**	—	—	**<1%?**	**SC⁇ [studying]**	reactor+solar
Unitarity	**assumed**	—	—	**<1%?**	**SC⁇ [studying]**	reactor+solar

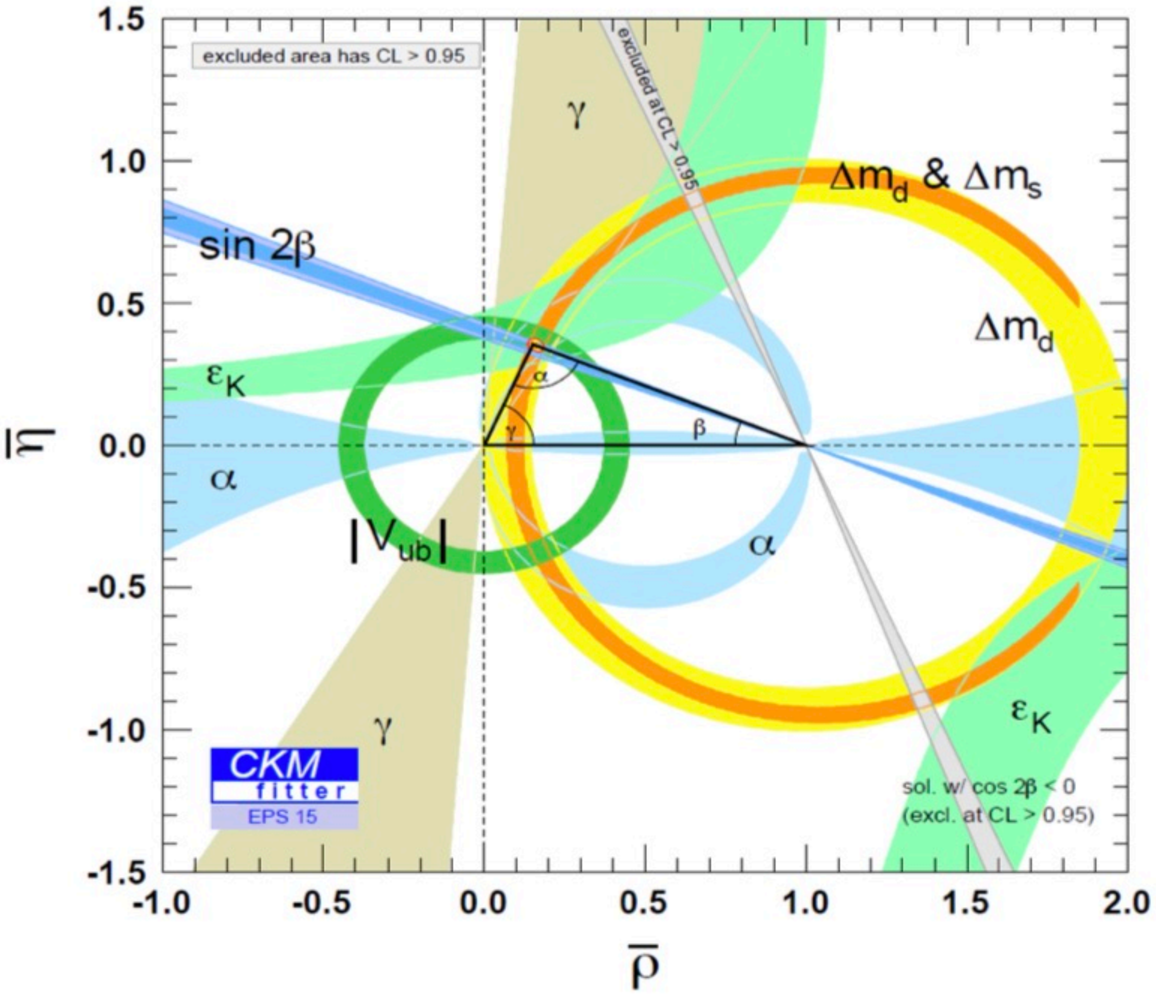
(reactor+solar+beam)

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

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

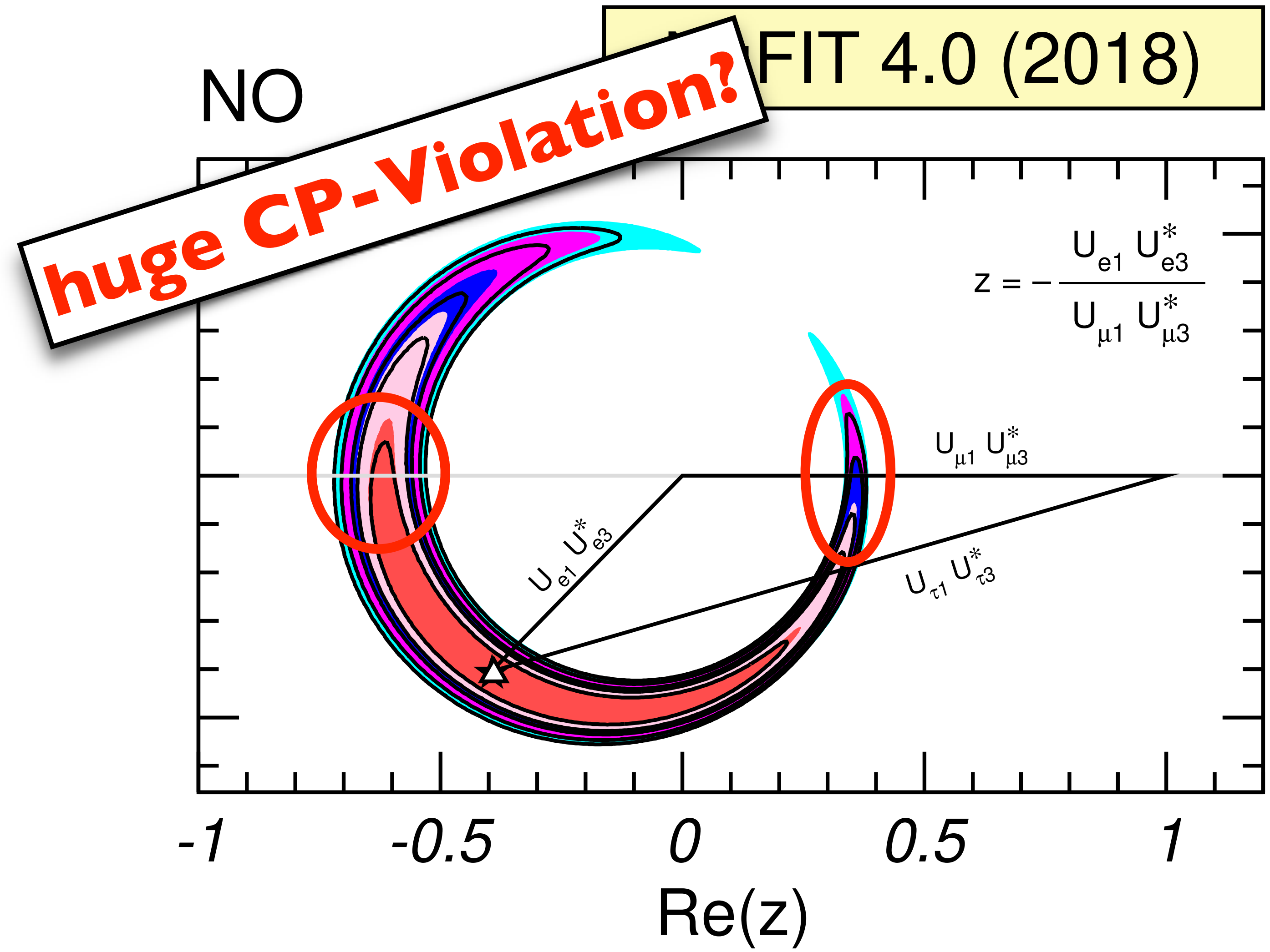
*despite major success so far… **challenges** leads **discoveries** (and fun)!!*

CKM



J(CKM)≈3.18±0.15x10^{-5}

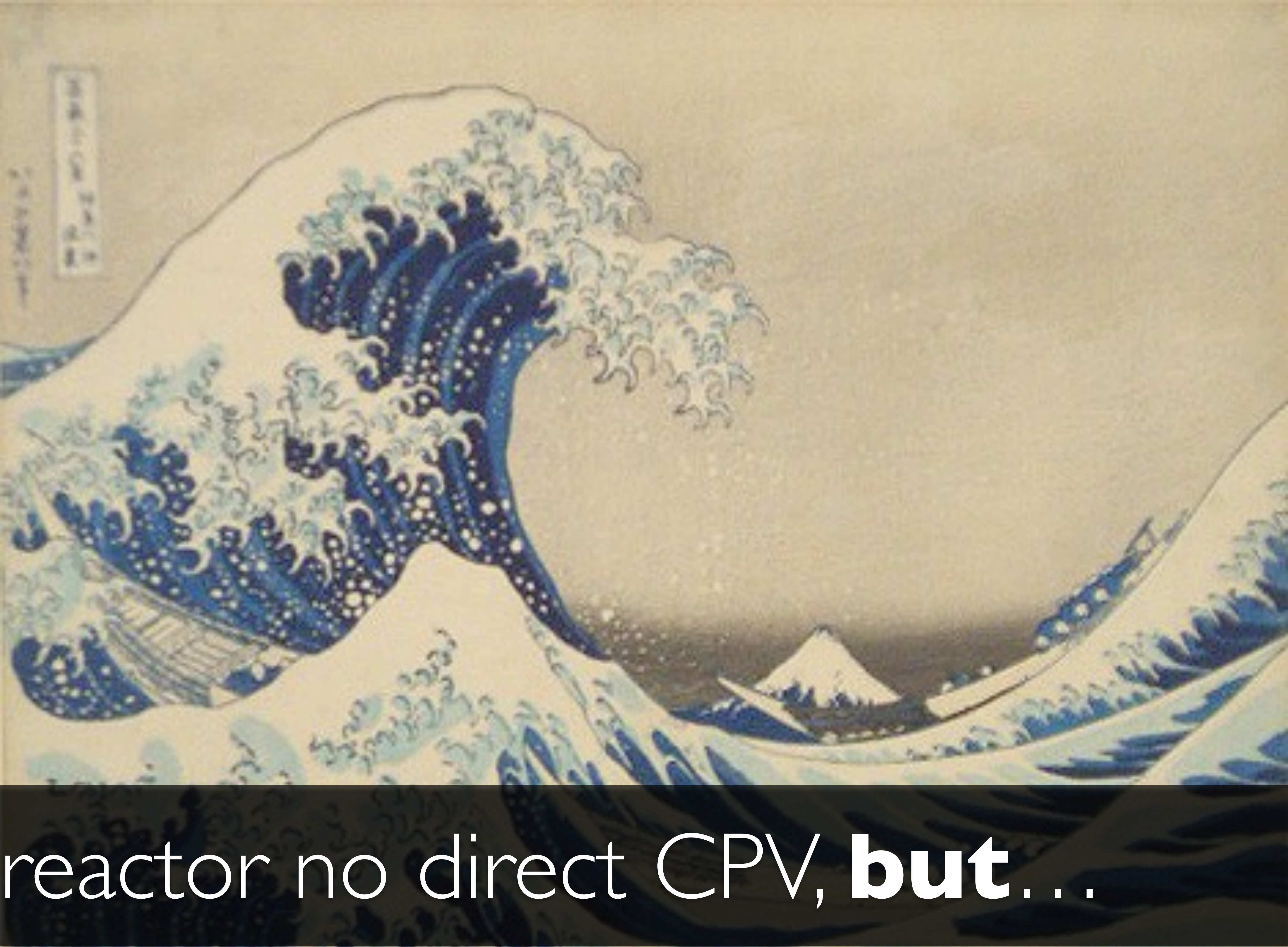
PMNS



J(PMNS)≈3.33±0.06x10^{-2}

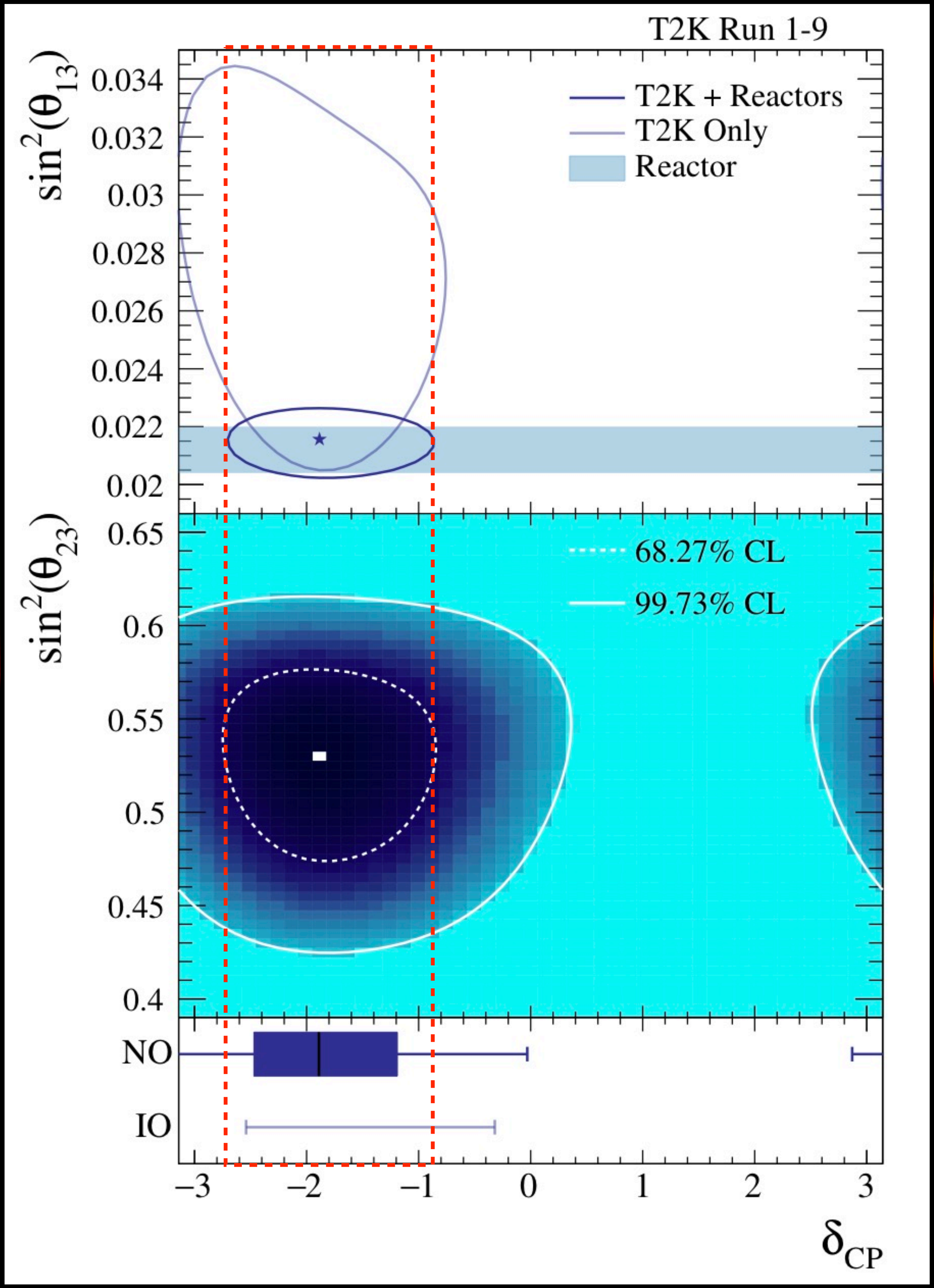
CP-Conversation disfavoured @ ~2σ
["infancy" era→ much to be done]

PMNS triangle (including CPV)…



reactor no direct CPV, **but**…

T2K⊕reactor best knowledge CP-Violation…



θ13 implications

CPV phase vs θ13

[constrained by reactor]

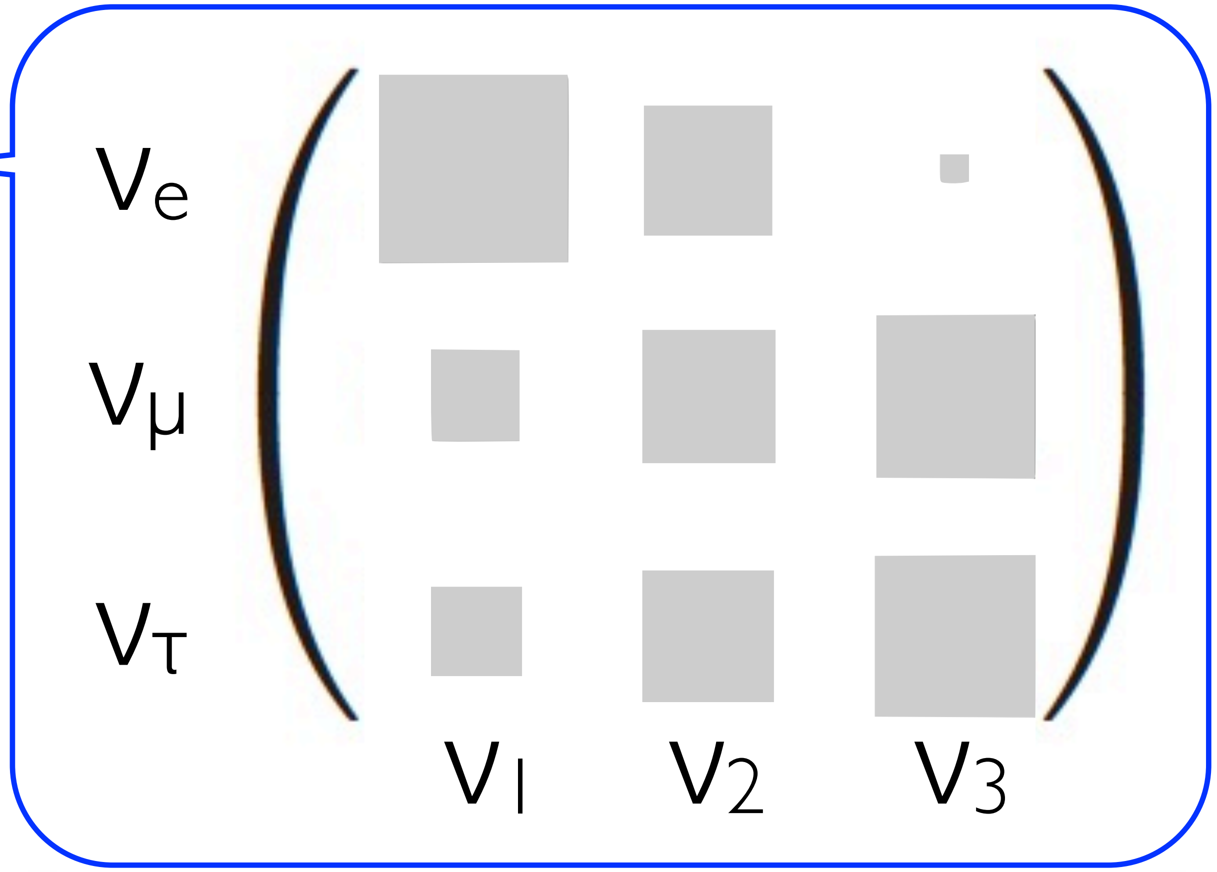
CPV phase vs θ23

[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…

u, c, t

d s b

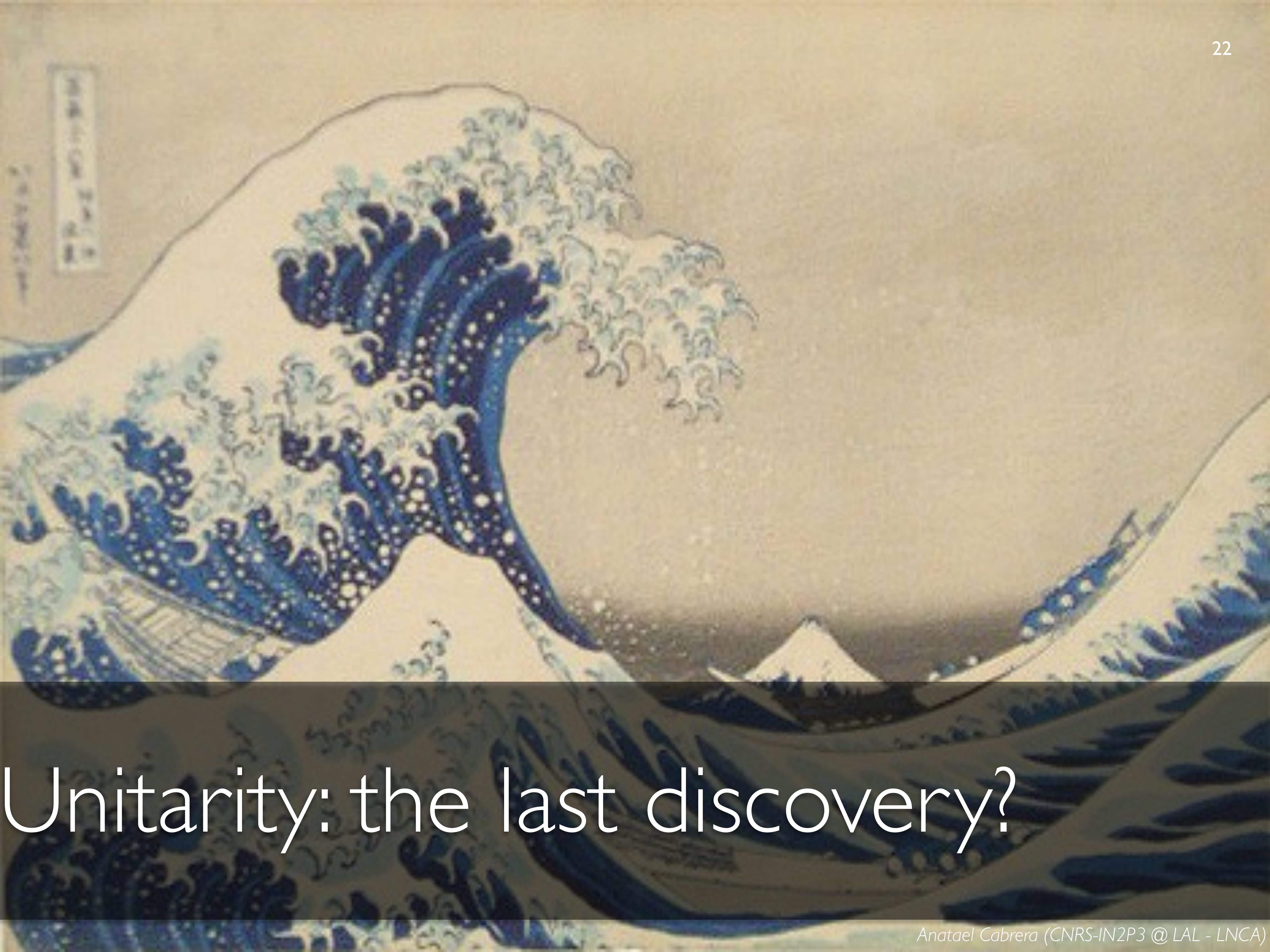
ν_e, ν_μ, ν_τ

ν_1 ν_2 ν_3

elegance
(symmetry)

stravaganzza
(anarchy?)

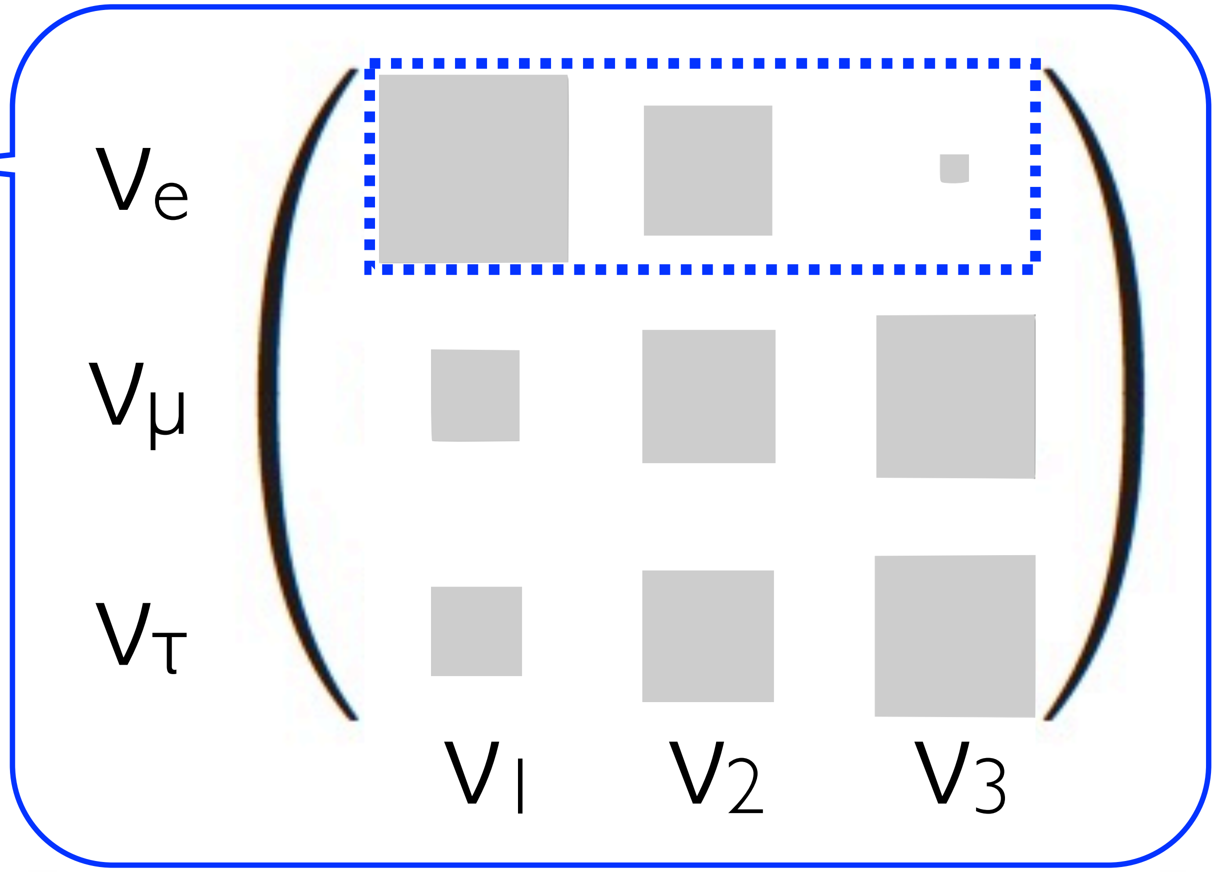
A. De Gouvea, H. Murayama, hep-ph/0301050; PLB, 2015.
L. Hall, H. Murayama, N. Weiner, hep-ph/9911341.



Unitarity: the last discovery?

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**

⇒ **OK precision**

⇒ **poorest precision**

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

⇒ **many equations!!**
[including the "triangles"]

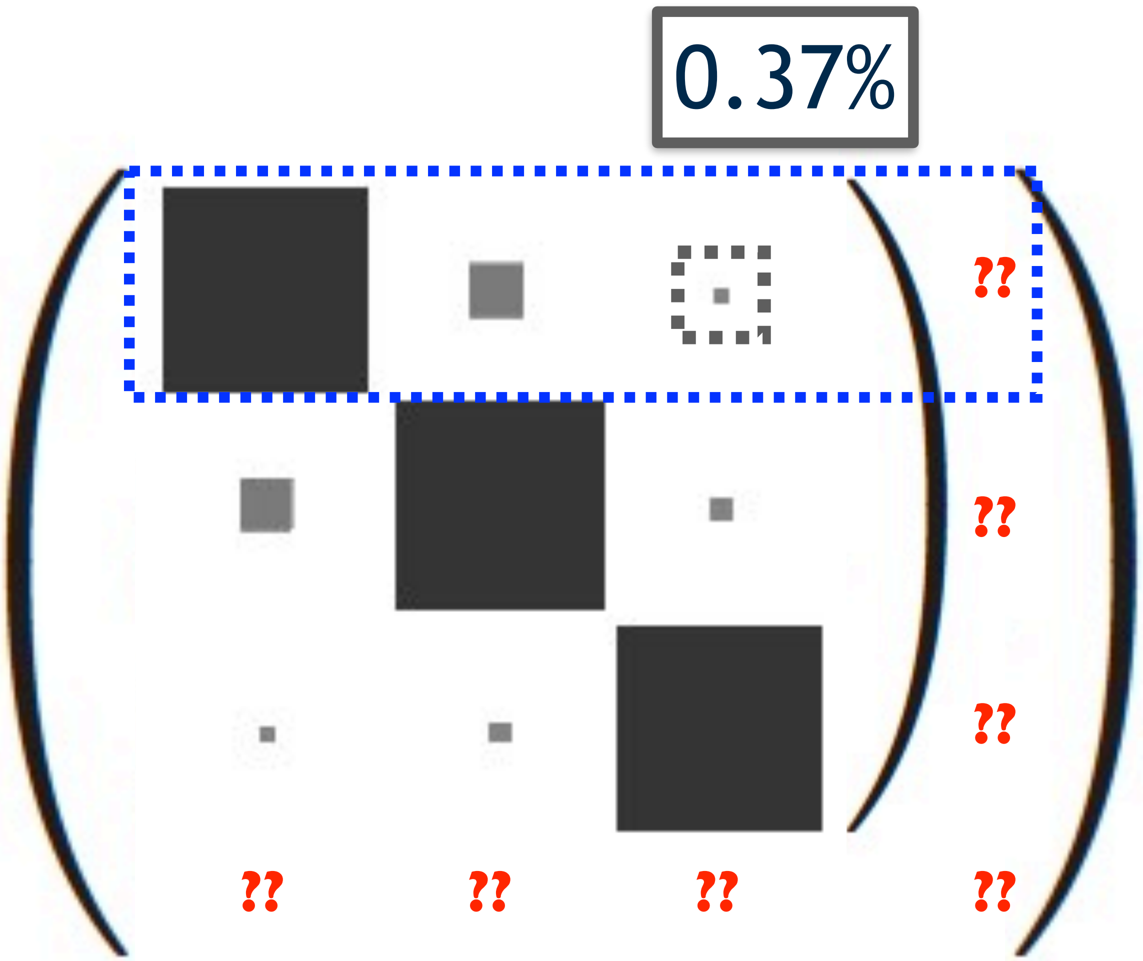
since no CPV (yet) ⇒ test PMNS Unitarity via "each row"

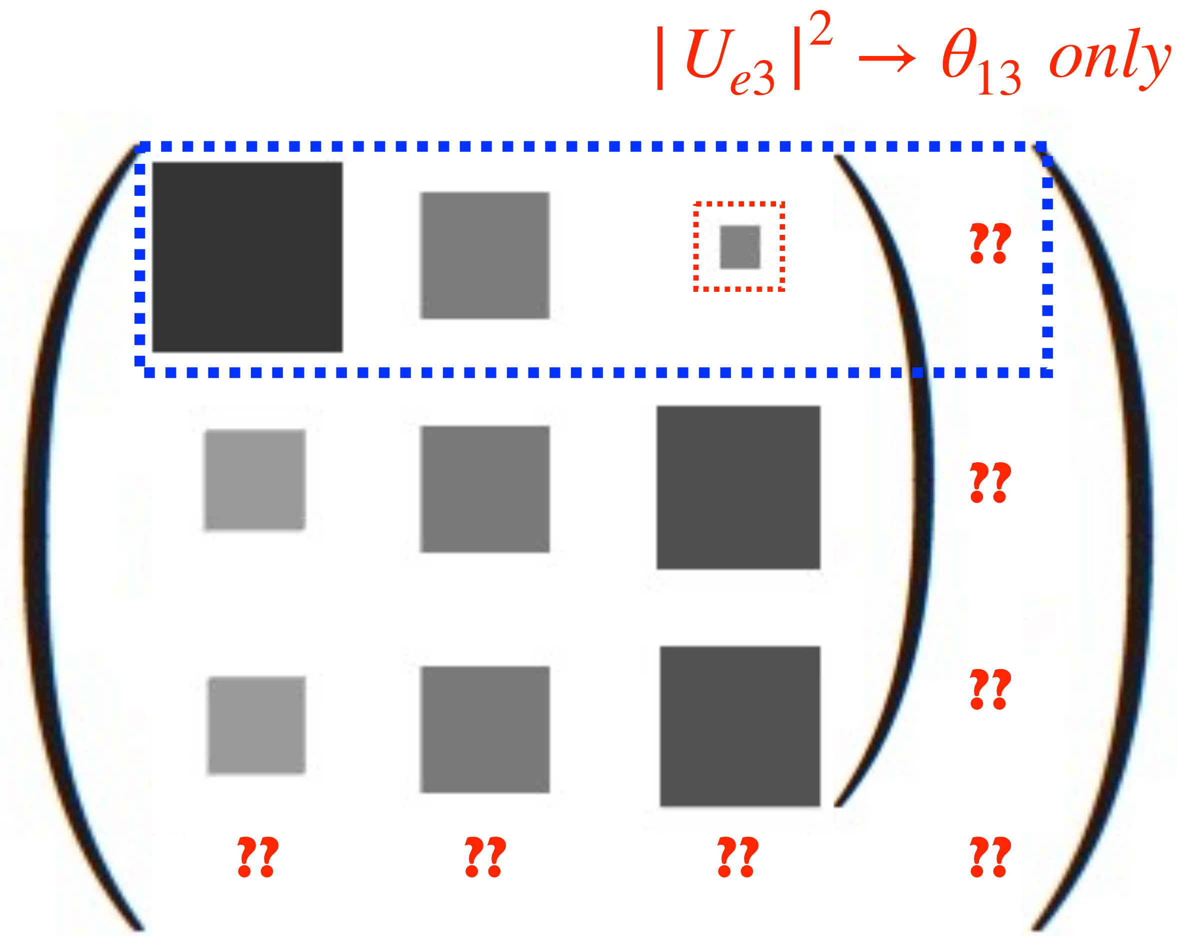
$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$$

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$ ⇒ **explore "electron top-row"**

only "θ_{12}" and "θ_{13}"

unitarity violation implications…





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

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]

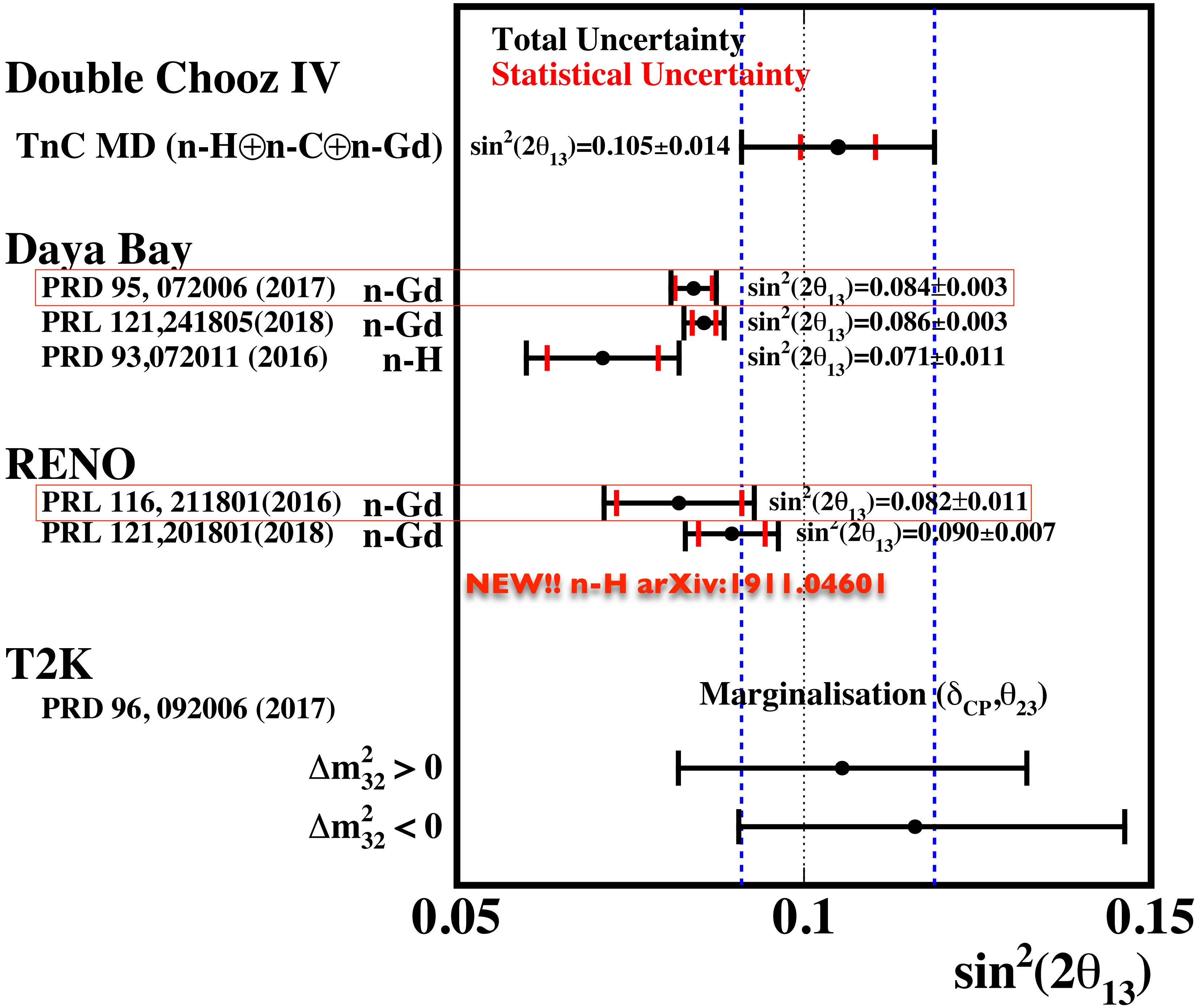
(if discovery) possible experimental redundancy

Unitarity violation test...


today's status...
present or imminently so...


θ_{13}

2020 world status in θ13…



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

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

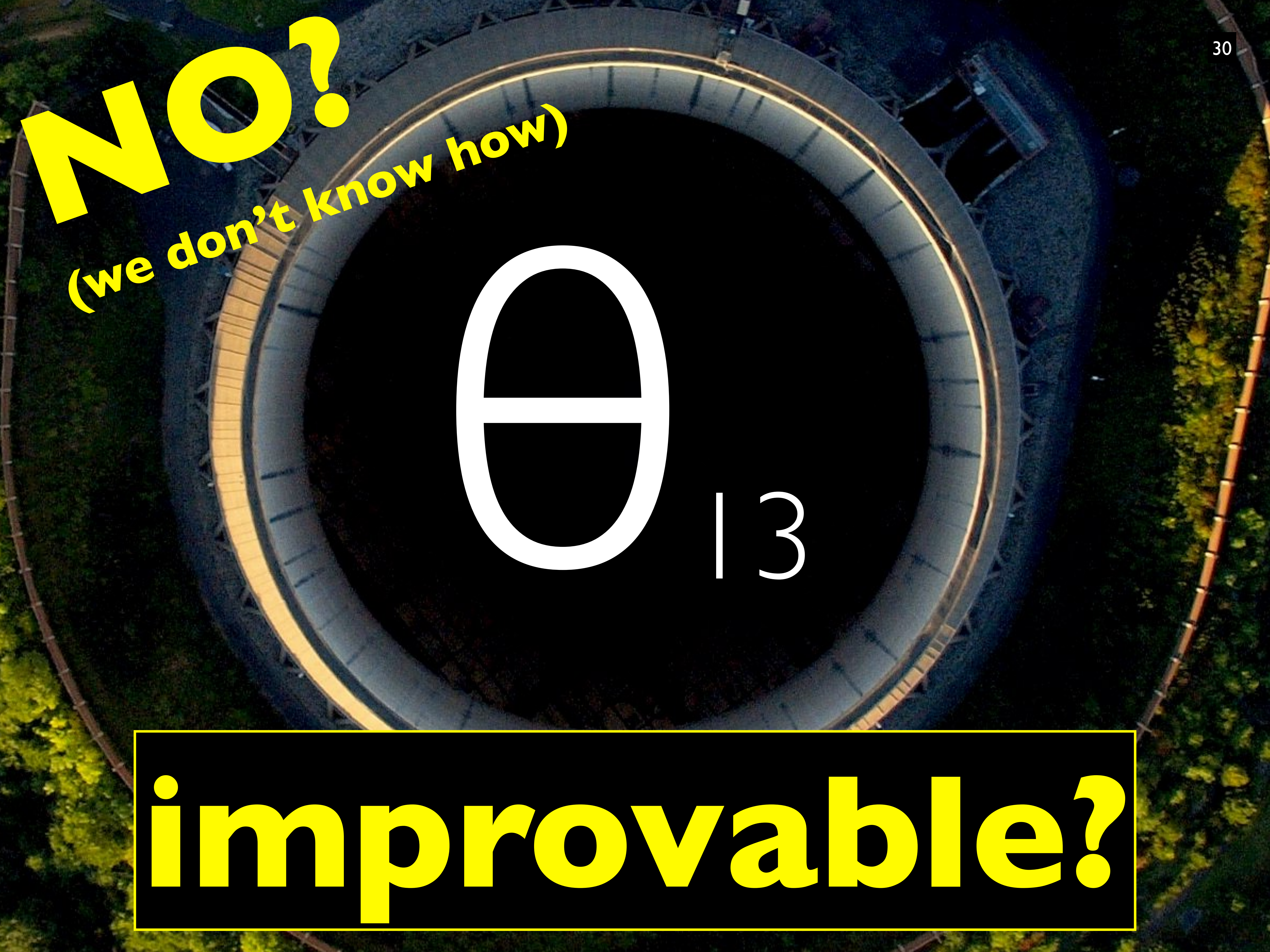
summary on today's θ13 knowledge/experiments…

reactor-θ13 experiments
[DC⊕DYB⊕RENO]

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

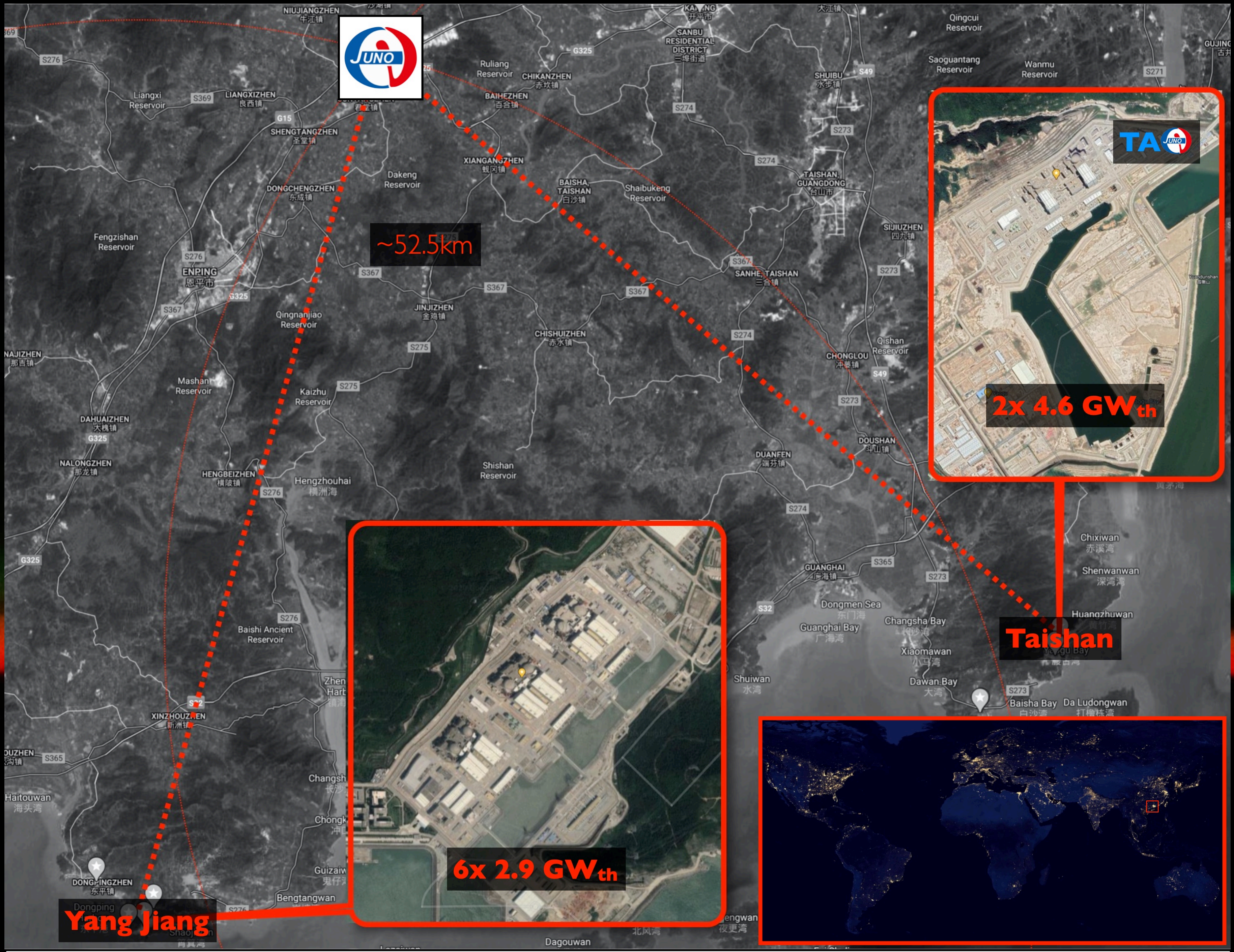
	<2010	today [2010-2020]			cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	—	—	~100/day @ 1.5km
flux	~2.2%	~0.1%	~0.1%	<0.1%	near-to-far monitor (ideal: iso-flux)
BG	few %	~0.1%	~0.1%	<0.1%	overburden→few/day
detection	2.0 %	~0.1%	~0.1%	—	identical detectors
energy	few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

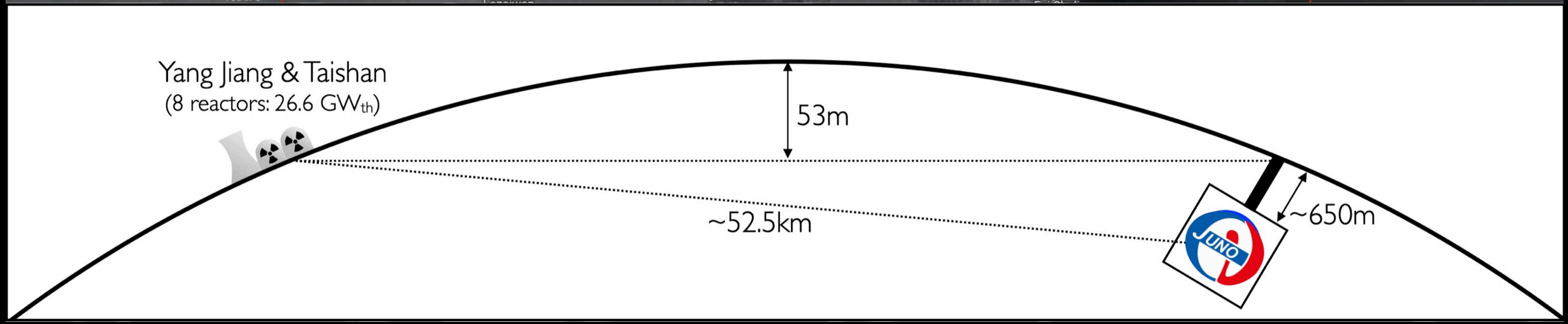
"naively extrapolating" from reactor-θ13 experiments…
•statistics: ~$10^{x?}$ (far) [>10^6]
•systematics: ~0.01%??!! (each)


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

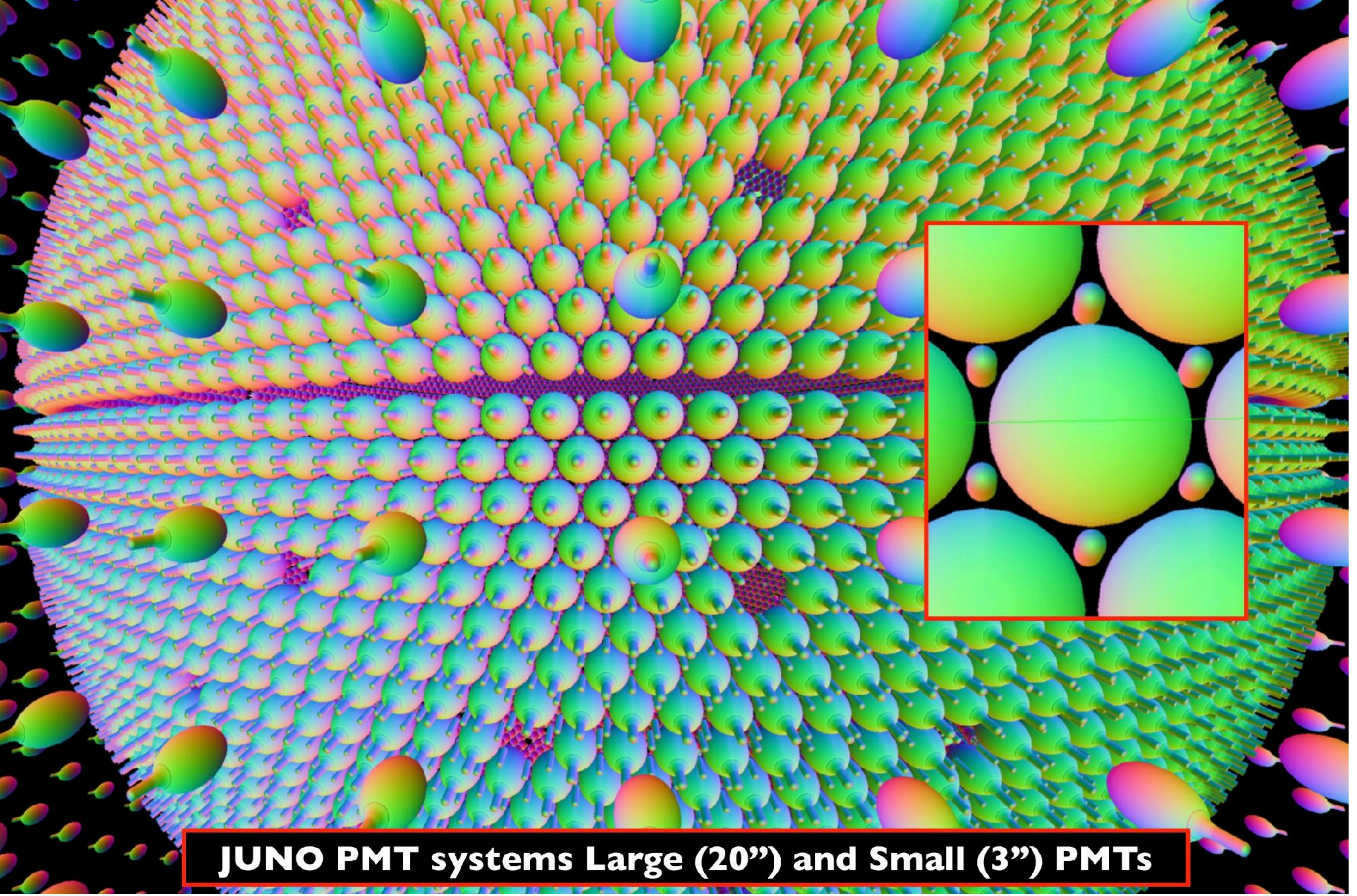

θ_{12}

JUNO location…





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



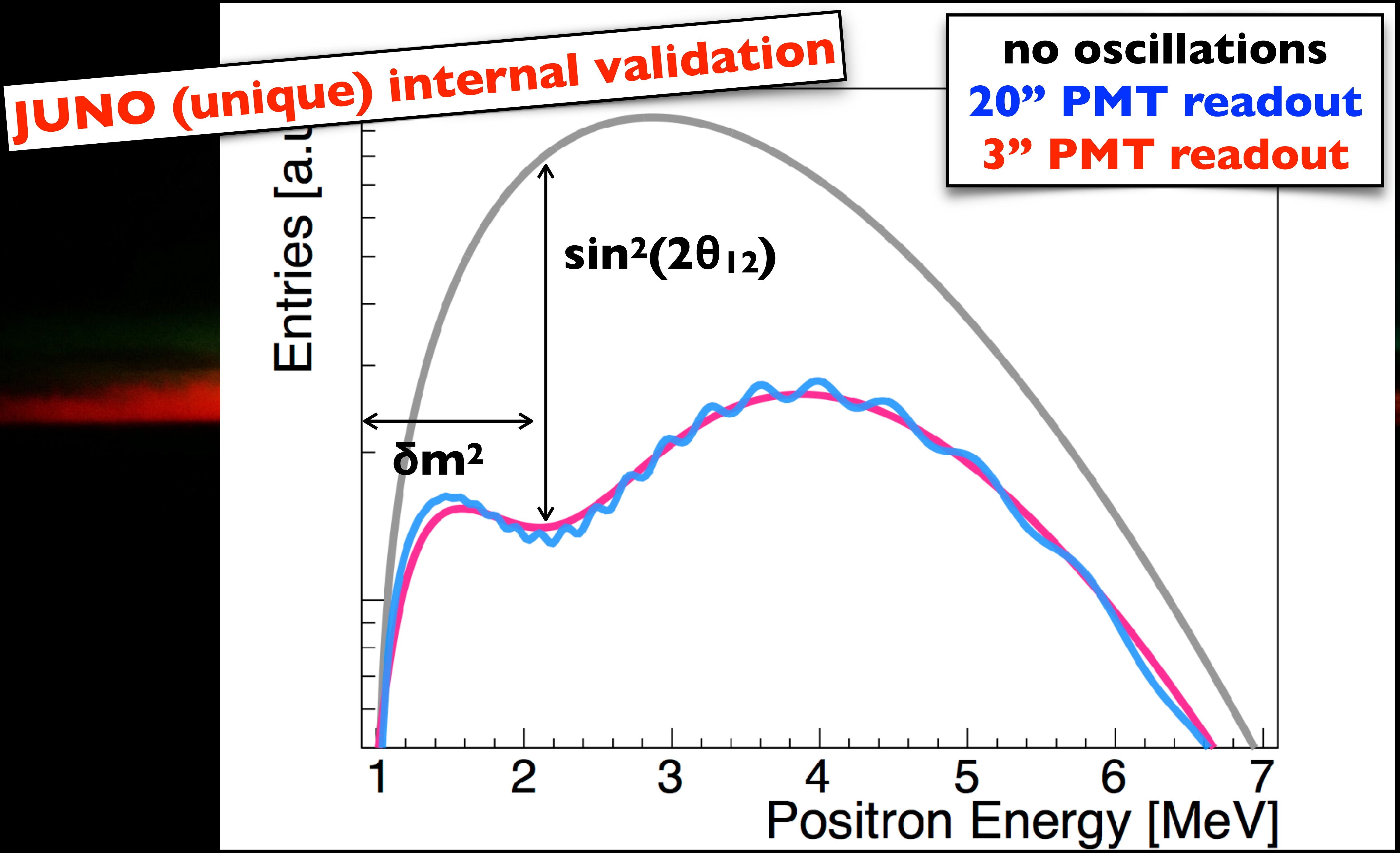
JUNO a photocathode colosso→ yield energy resolution!

Anatael Cabrera (CNRS-IN2P3 & APC)

"solar" oscillation measured by both PMT systems…

SPMT sees the "solar" oscillation

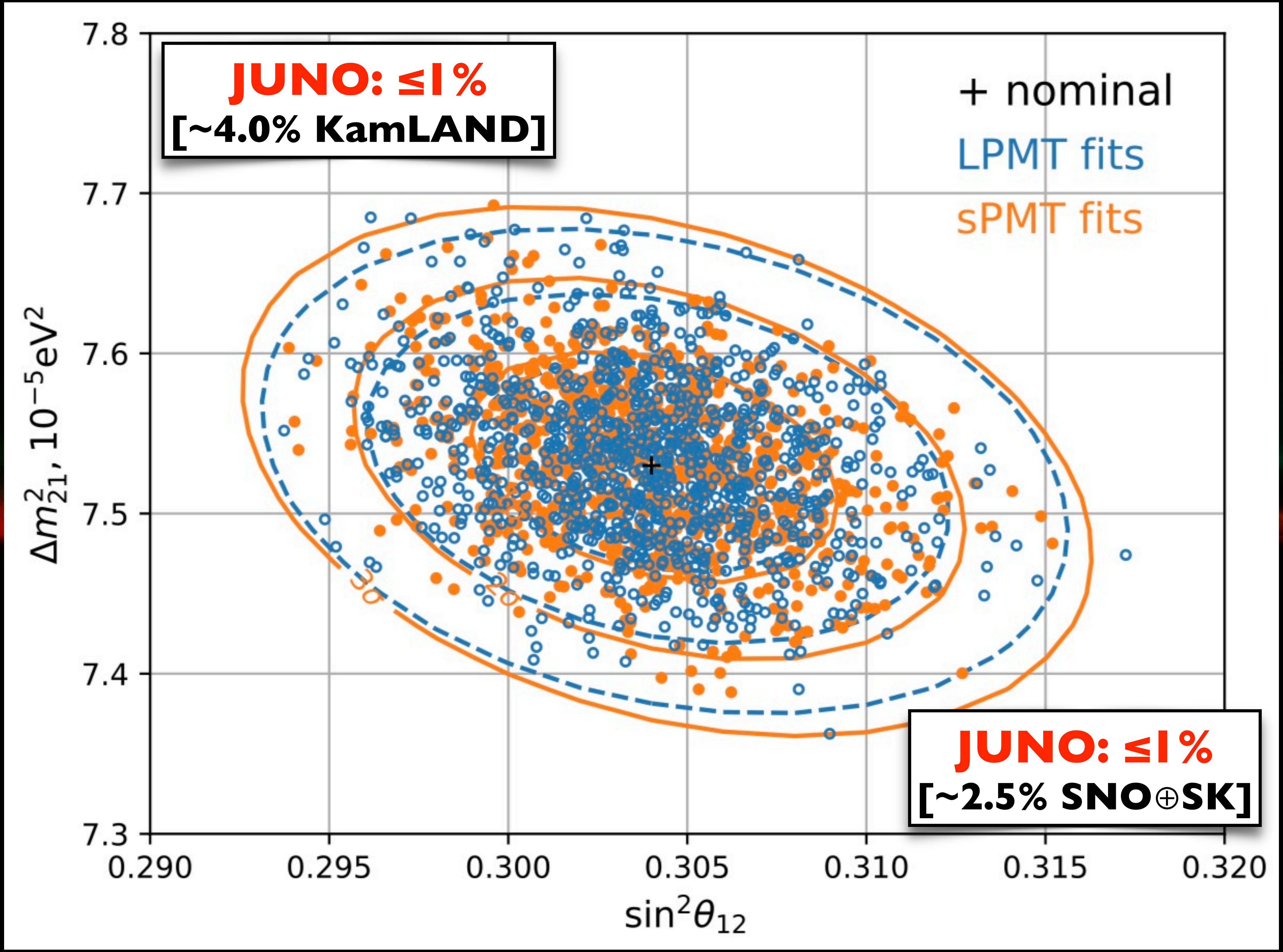
(fast oscillation washes out)



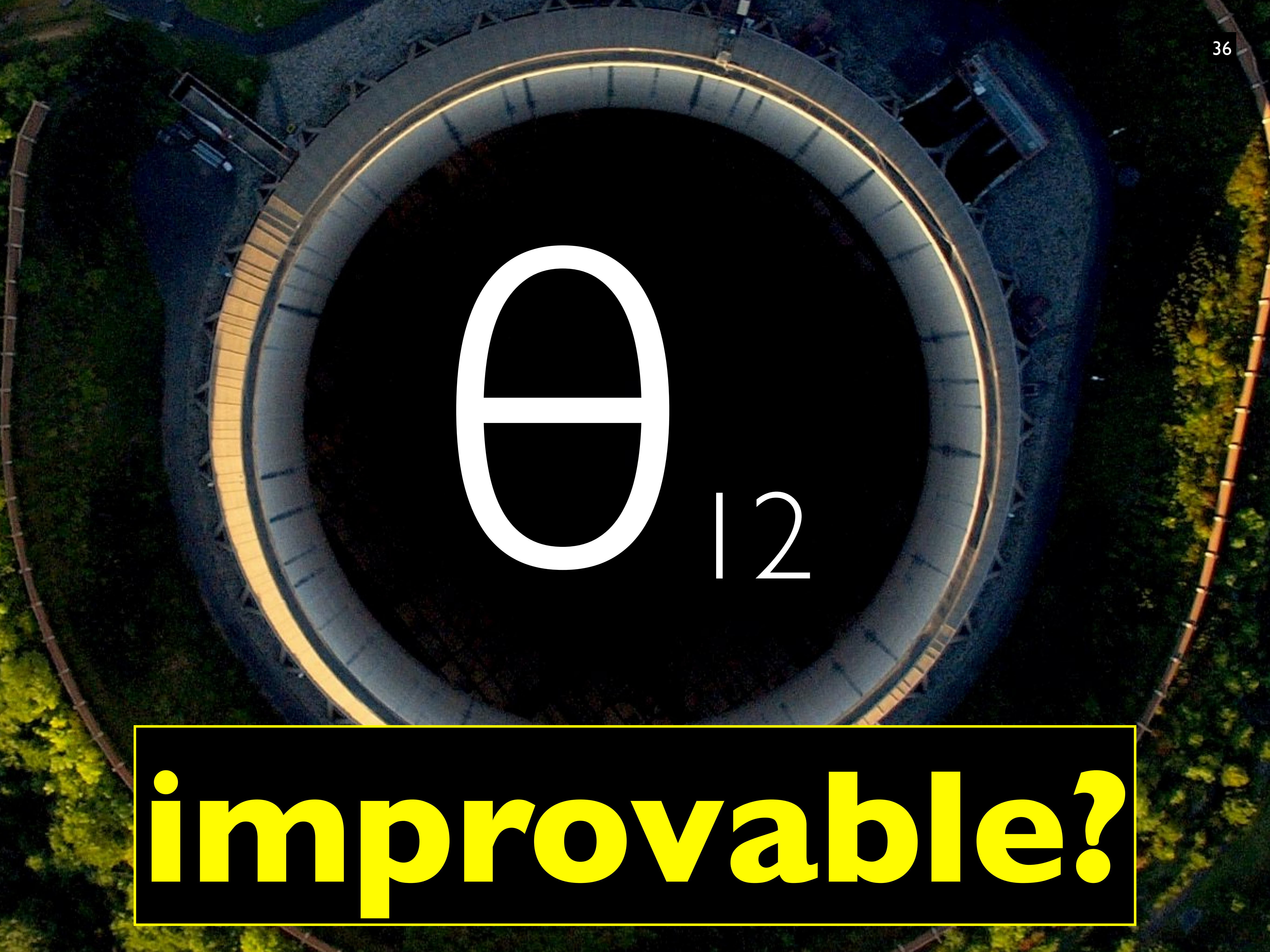
sensitivity: $\theta_{12} \oplus \delta m^2$

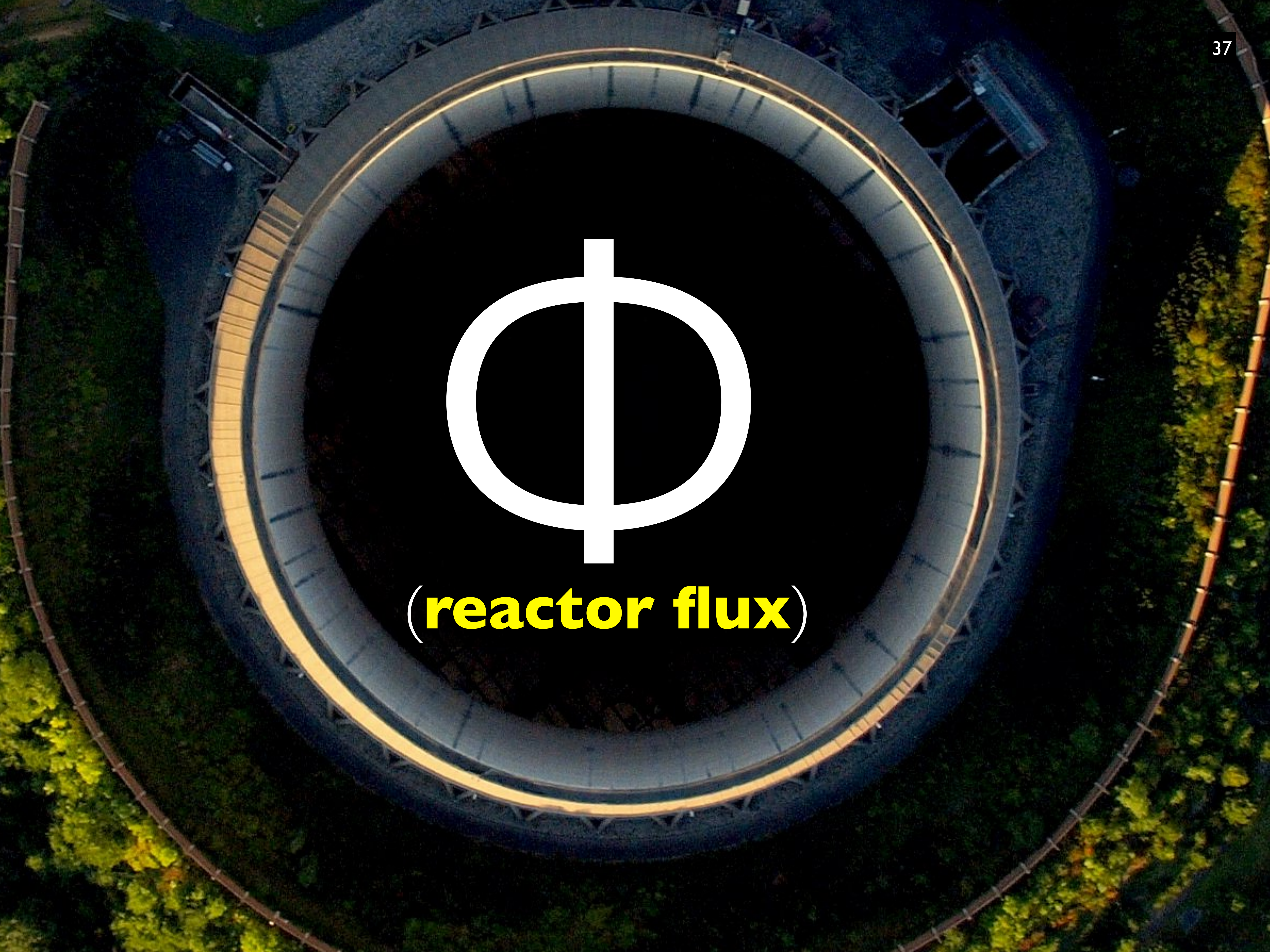
Anatael Cabrera (CNRS-IN2P3 & APC)

LPMT vs SPMT comparison…



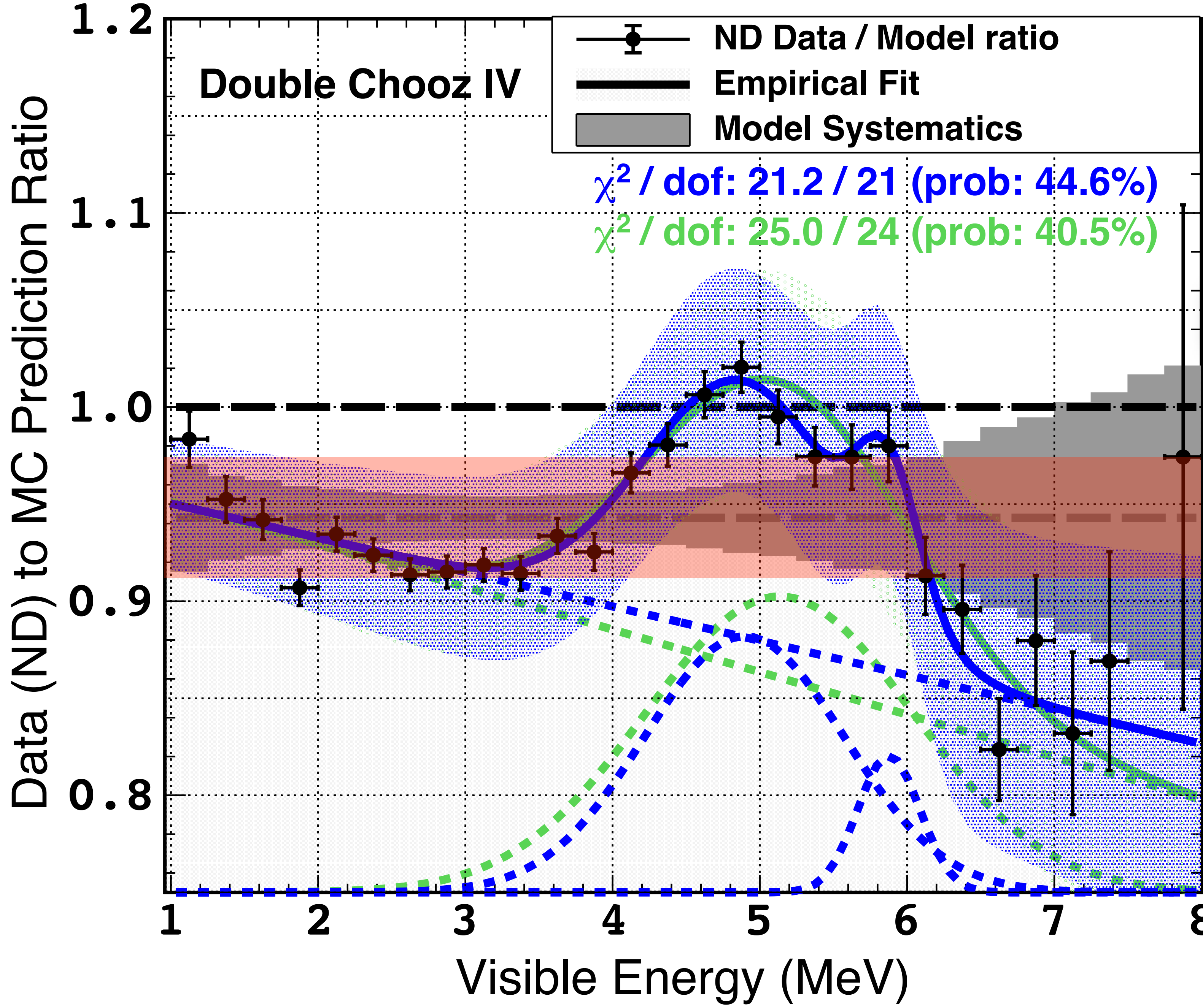
readout explore θ12⊕δm² to per-mille precision (≤1%)


θ_{12}
improvable?


Φ
(reactor flux)

reactor flux uncertainty…

Hervé de Kerret *et al* (arXiv:1901.09451)



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?

Unitarity?

Φ(reactor)

⊕

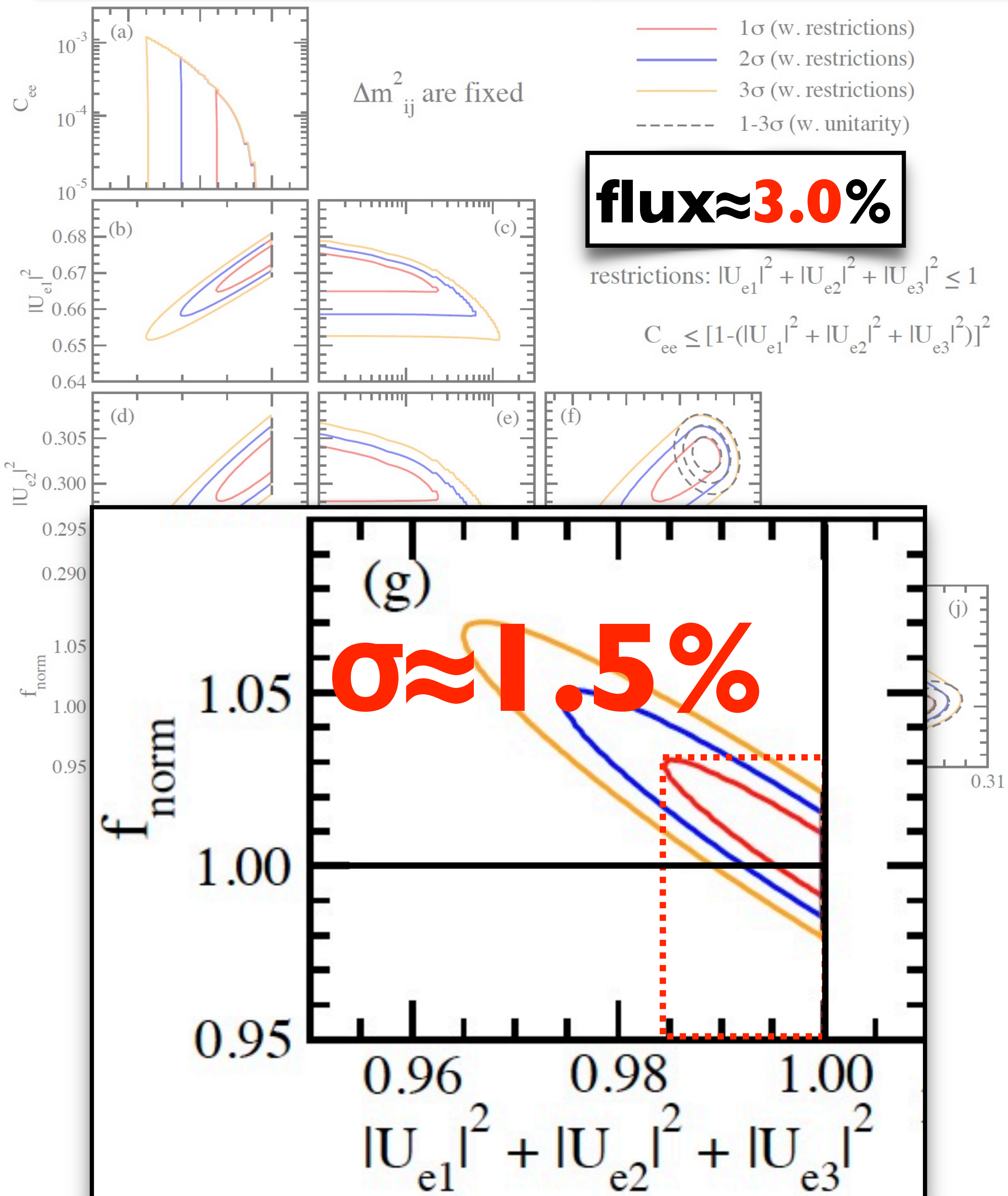
θ13(now)

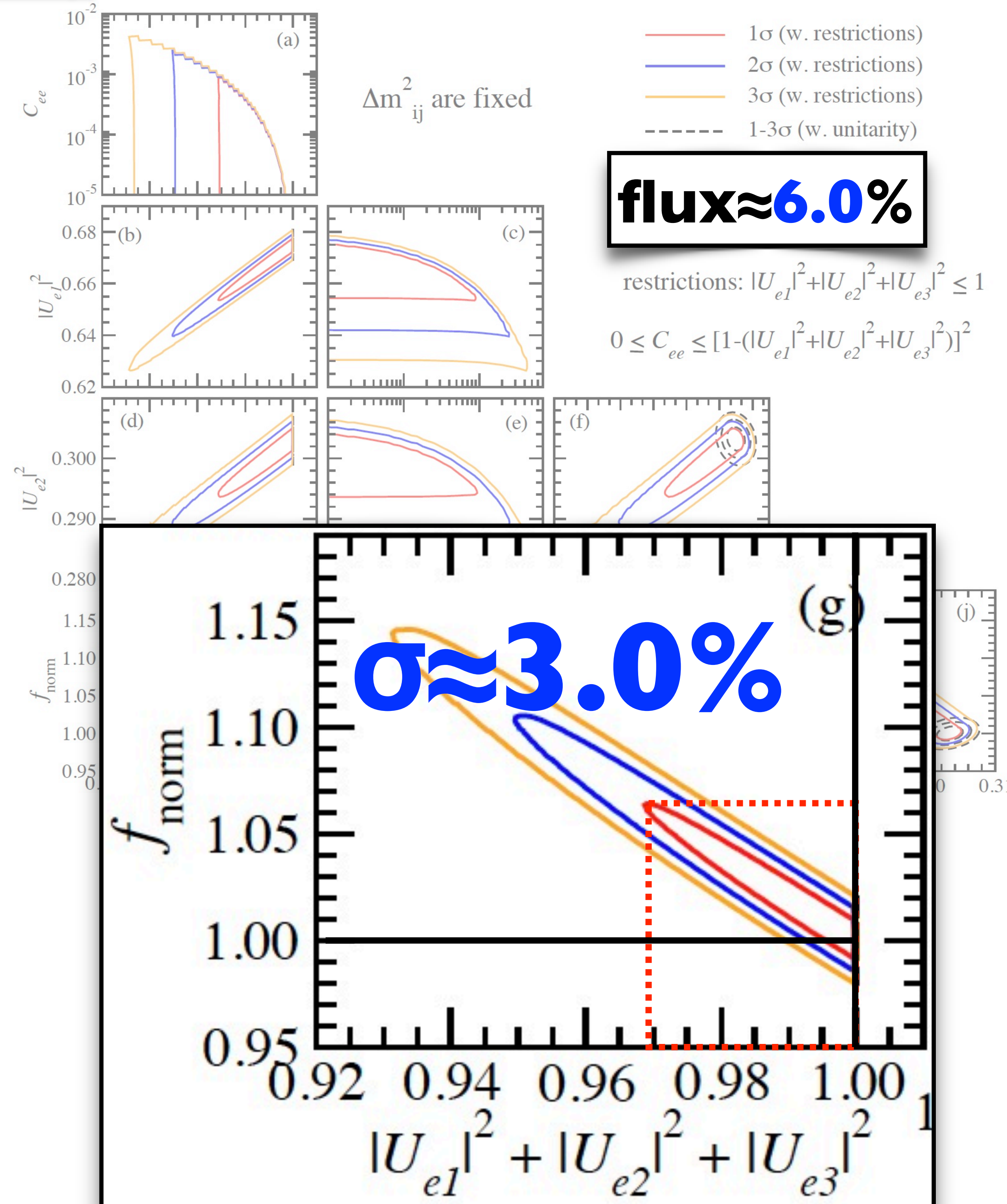
⊕

θ12(JUNO)

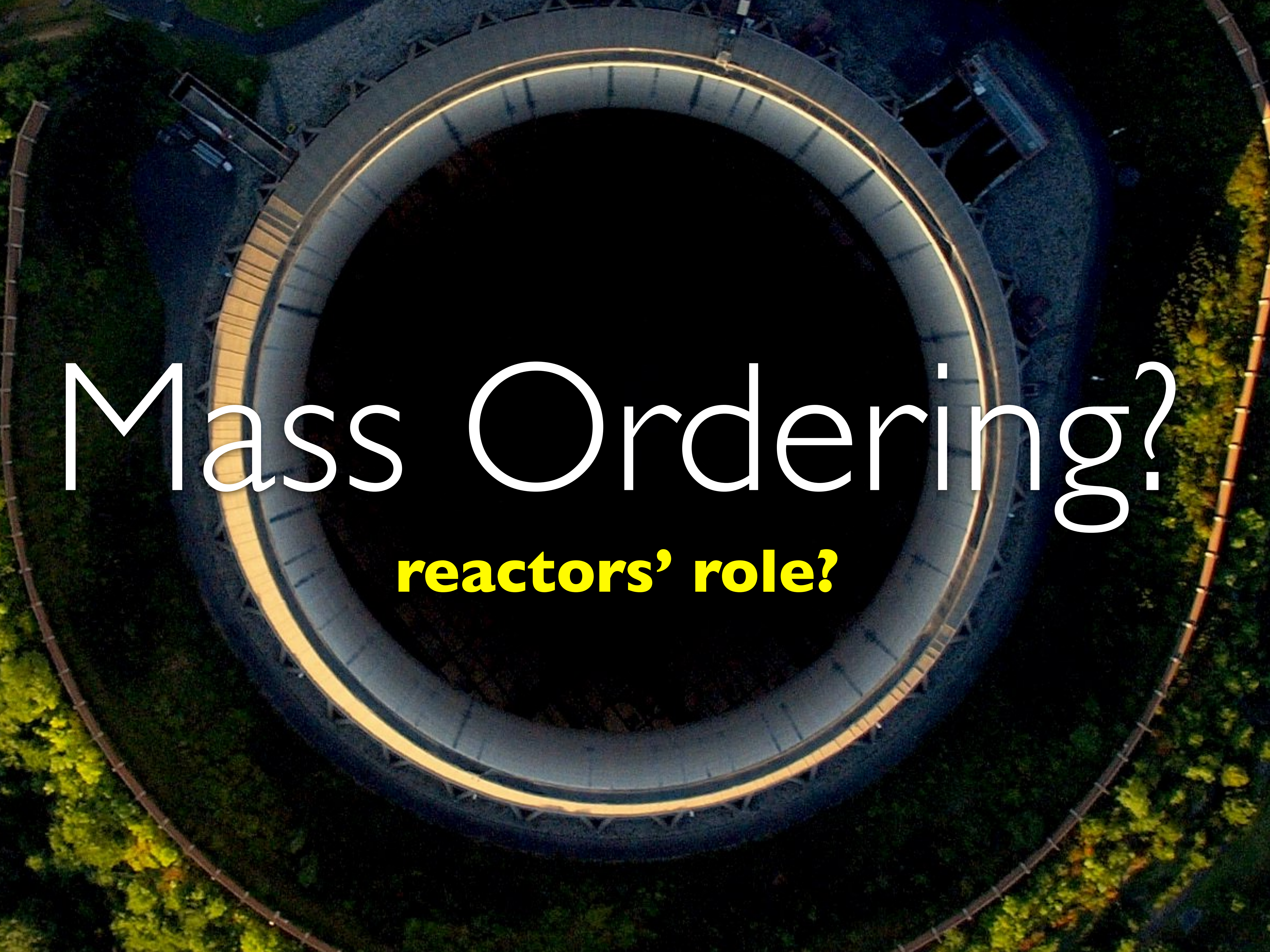
today's **e-row unitarity** knowledge…

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





even with JUNO, sub-perfect explorations IMPOSSIBLE!


Mass Ordering?
reactors' role?

NuFit5.0

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

The fate of hints: updated global analysis of three-flavor neutrino oscillations

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

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
- NOvA⊕T2K
- DC⊕DYB⊕RENO

JUNO will provide a ~3σ result in ≥2028

- **why important?**
- **too late & too little?**
- **ever enough?**

NOTE: almost impossible to ≥3σ alone!

today's MO status & JUNO…

Earliest Resolution to the Neutrino Mass Ordering?

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August 27, 2020 – v3.5

when can we **resolve (≥5σ)** the **neutrino Mass Order?**
[earliest time scale]

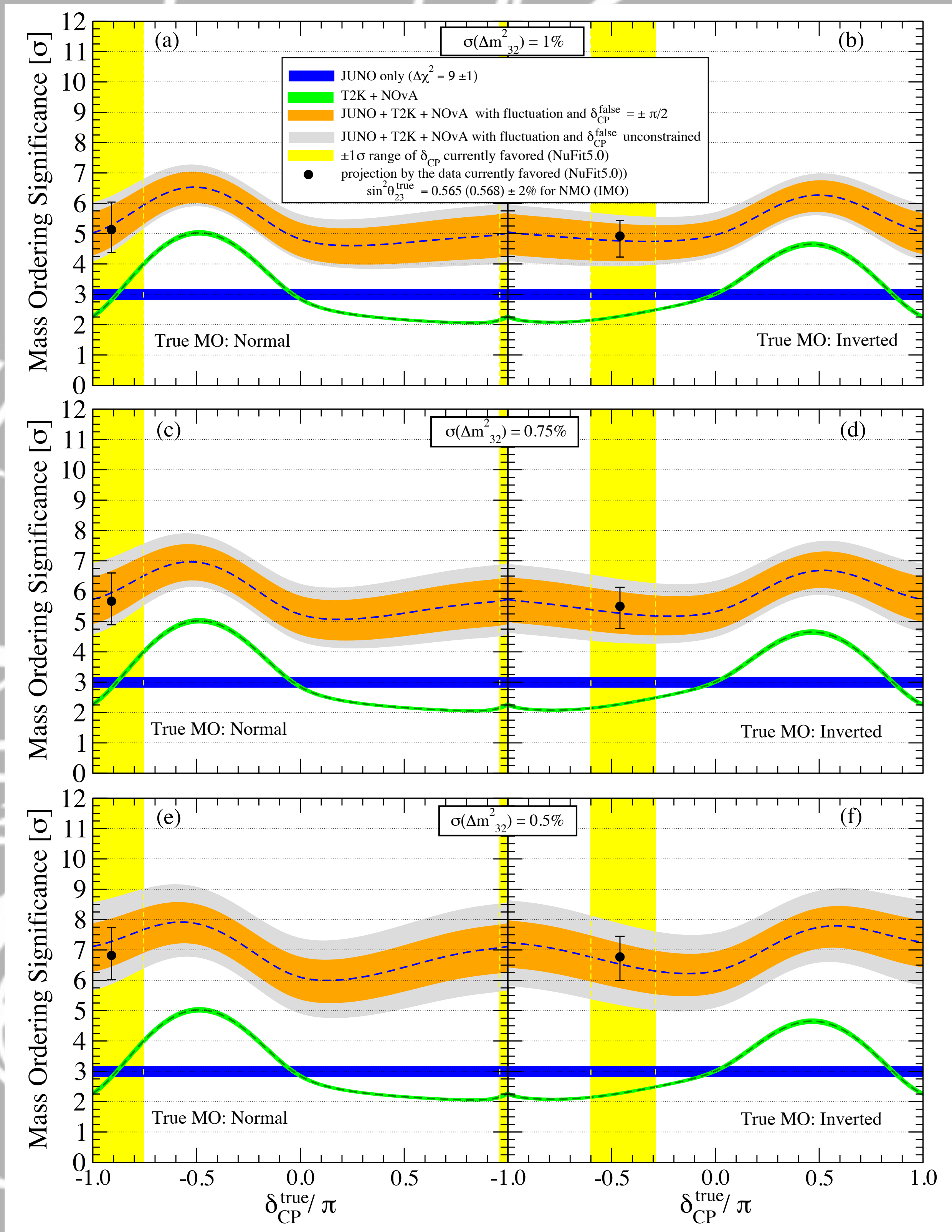
which experiments (many planned, but minimal set) can yield the **full resolution?**

what physics exploited to yield the **full resolution?**

implications beyond the Standard Model?

NuFit5.0 (July 2020): **Normal-MO favoured to ~3σ**

our paper's goal…



combination (JUNO⊕NOvA⊕T2K)

- **first MO measurement** @ **≥5σ possible** (≥90% CL)
- combined **both vacuum⊕matter MO** information [less clean but powerful]
- **JUNO schedule: ≥2028** [T2K / NOvA stopped ≤2026]
- **preparation 3rd beam generation** (DUNE & HyperK)
  →**DUNE** the most powerful standalone MO experiment

combination (JUNO⊕HyperK⊕DUNE)

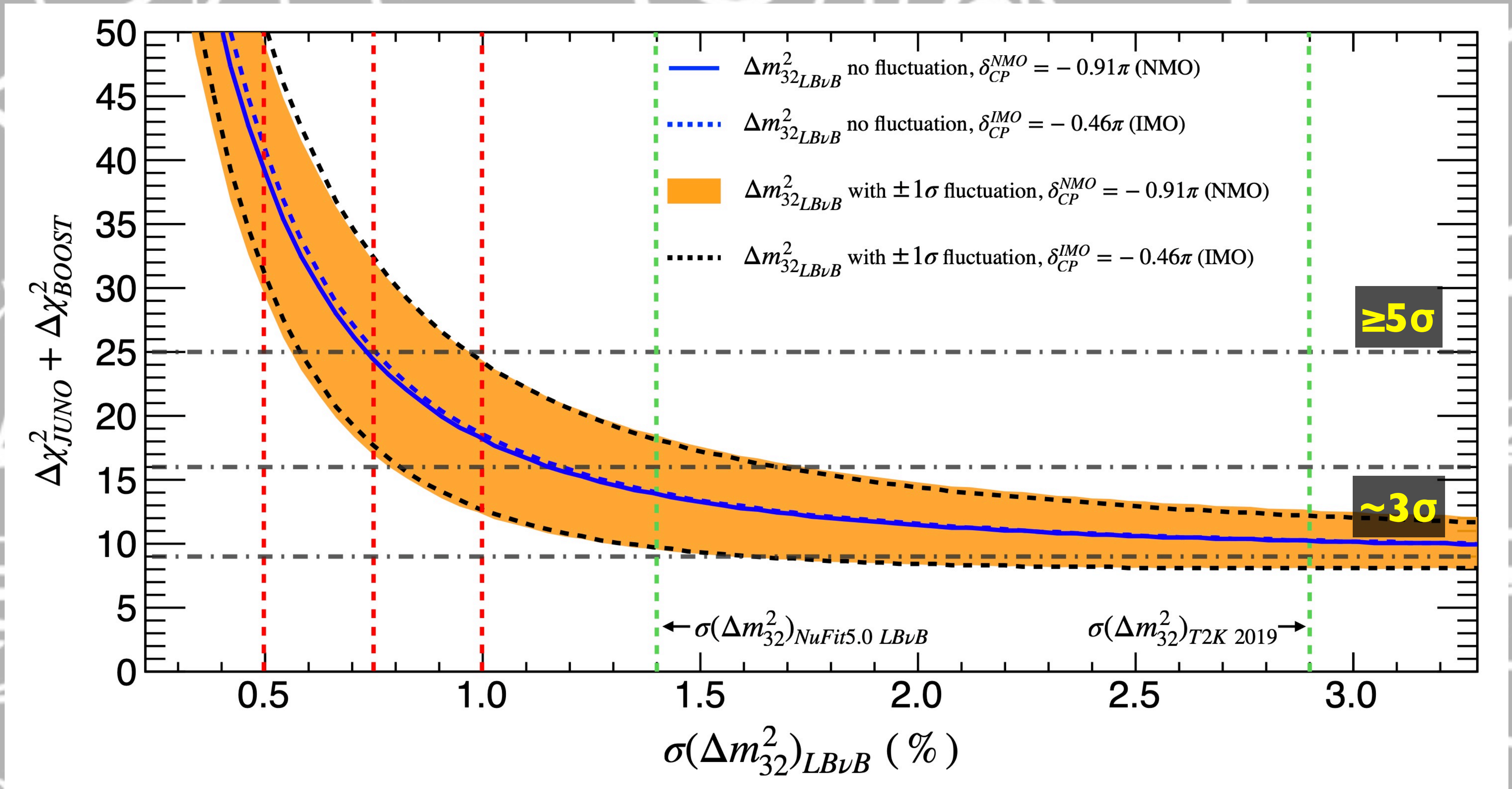
DUNE (CPV depends, but any — >2years data)
→**matter only ≥5σ MO**

JUNO⊕HyperK⊕DUNE(CPV rather insensitive)
→**vacuum only ≥5σ MO** (only Δm^2_{32} disappearance)

new physics? yes, if discrepancies found! **[→discovery!]**

JUNO⊕NOvA⊕T2K: MO ≥5σ by 2028

JUNO: unique vacuum oscillations



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 boosting…

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

NuFit5.0

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

The fate of hints: updated global analysis of three-flavor neutrino oscillations

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[e] *Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

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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

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

today's world data leads to…

NMO favoured to ~2.7σ (2020)

main experiments so far…
- SuperK
- NOvA⊕T2K
- DC⊕DYB⊕RENO

JUNO will provide a ~3σ result in ≥2028

JUNO critical upon combination
- **key player for discovery (≥5σ)!**
- **unique vacuum boost to ≥5σ!**
- **unique explorations BSM? (thinking)**

NOTE: almost impossible to ≥3σ alone!

today's MO status & JUNO…


and beyond…
the future…?

ν's left Europe next decade…?


how to reduce BG with no more overburden?
lesson: avoid civil construction (reactor!!)…

Liquid

a novel neutrino detection

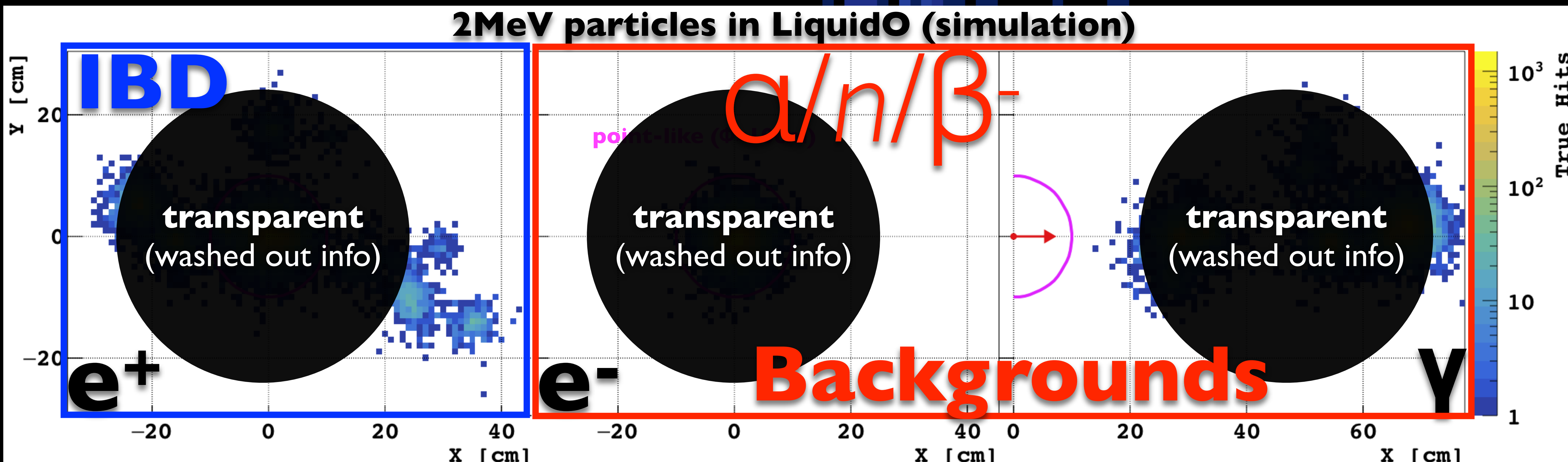
antimatter (e+) tagging

BG active rejection

[only "mundane" matter]

LiquidO active **Particle-ID**…

Imaging→powerful Particle-IDentification (PID)

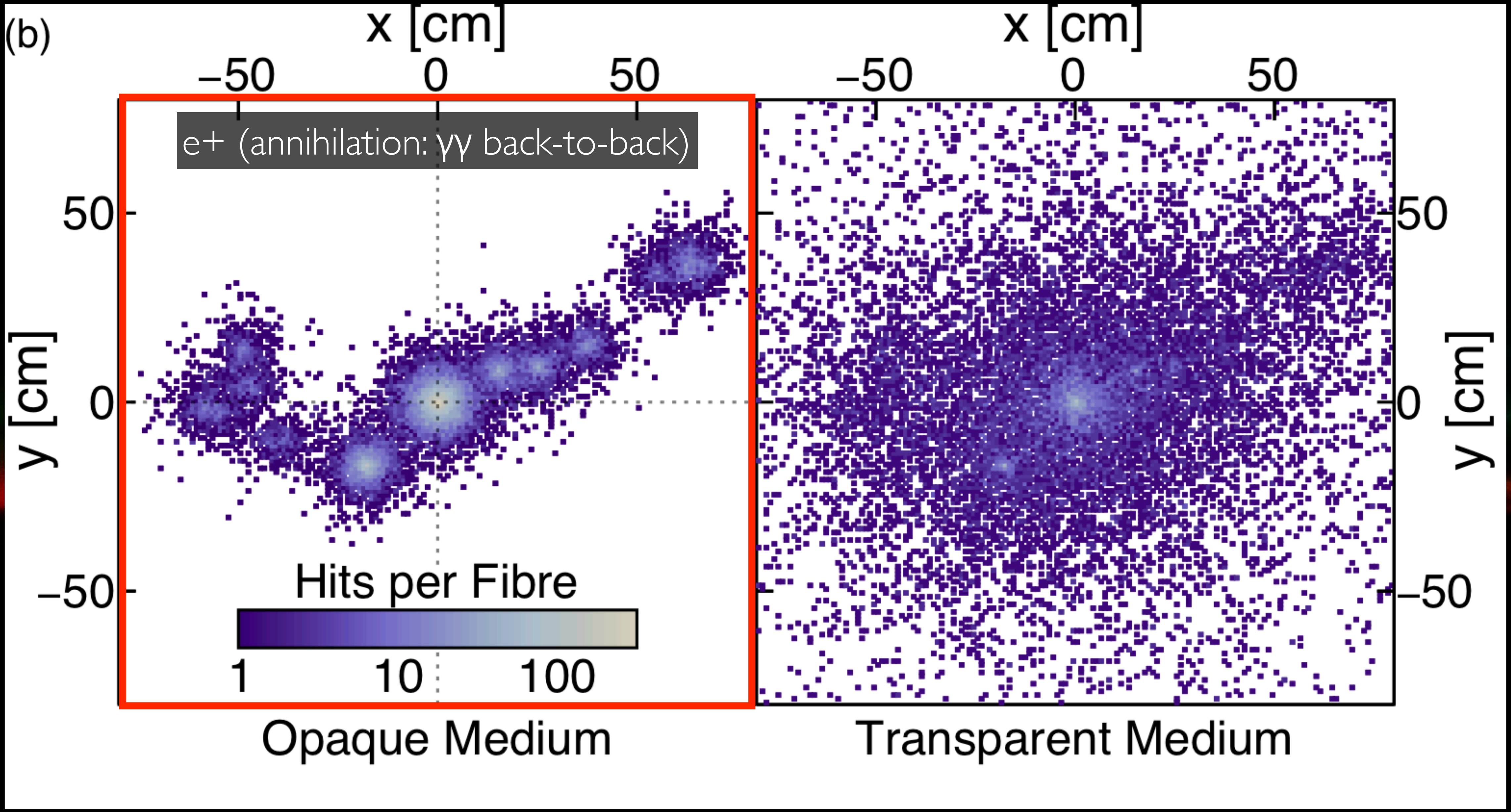


LiquidO ≈ PID ⊕ (high) **Doping**

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

diffusion⟹shaper images!

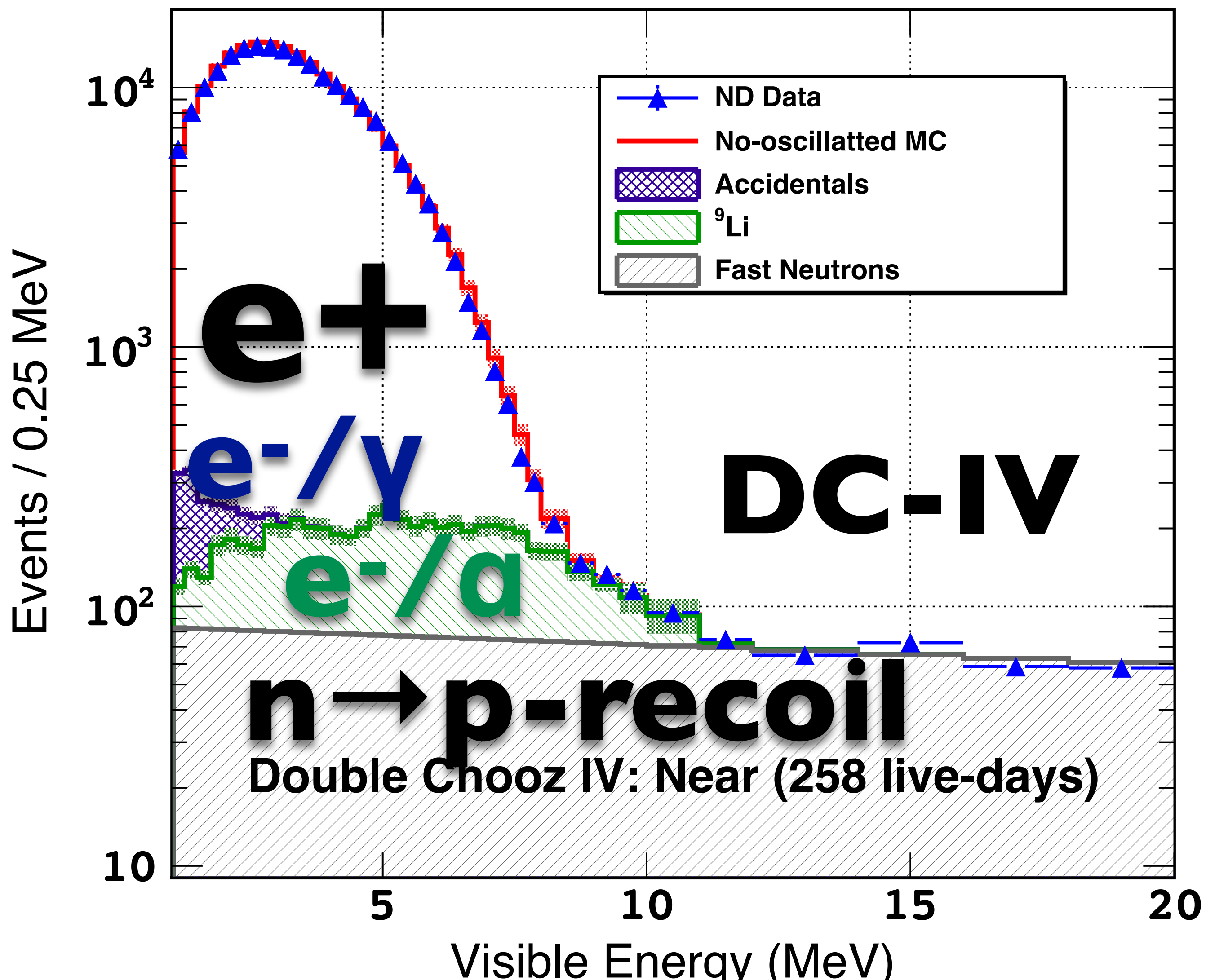
LiquidO event-wise imaging…

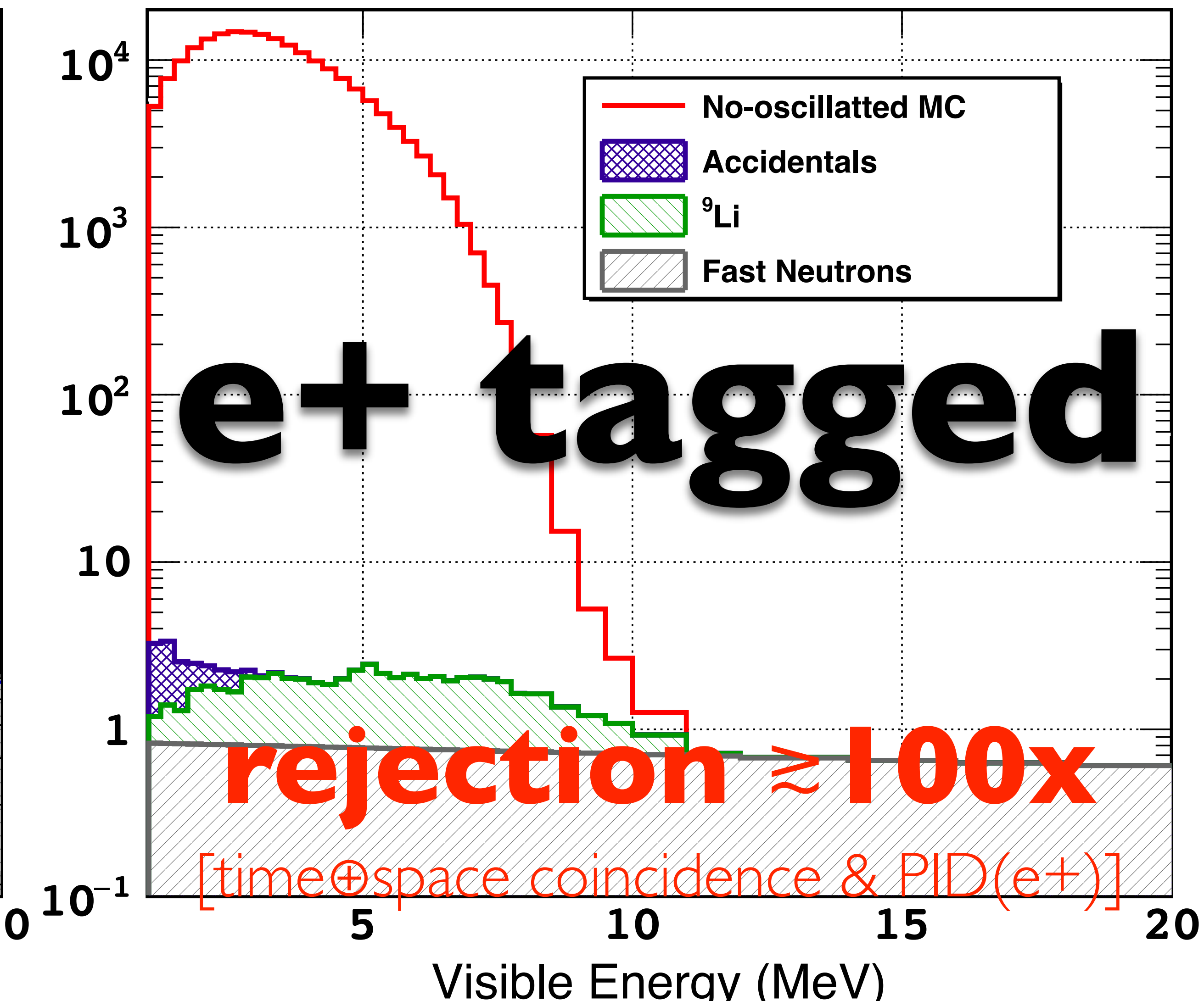


opaque scintillator→stochastic light confinement

(**self-segmentation**)

(30m overburden)





state of the art

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

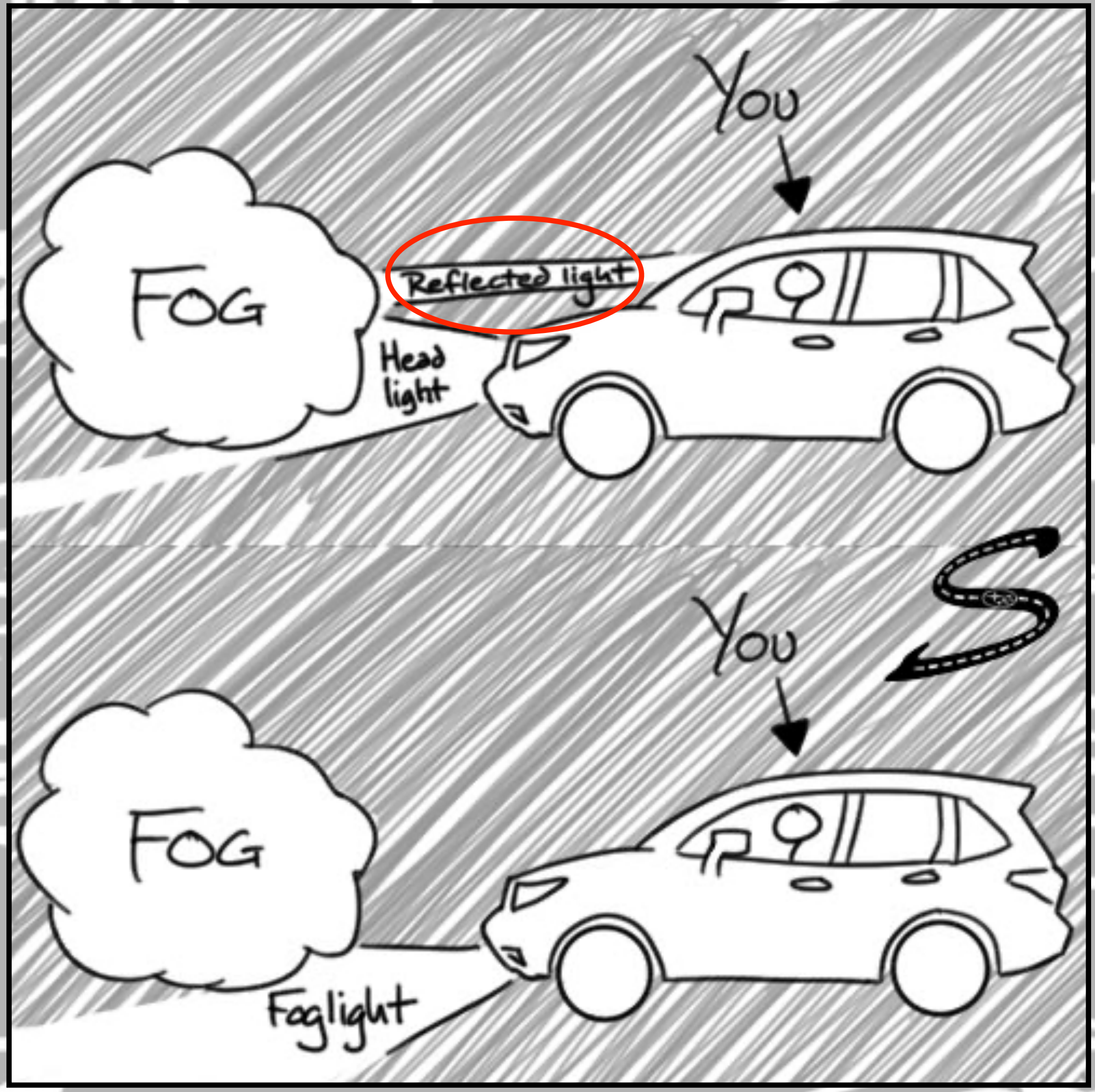
Background rate few/day

LiquidO

Signal:Background >100:1

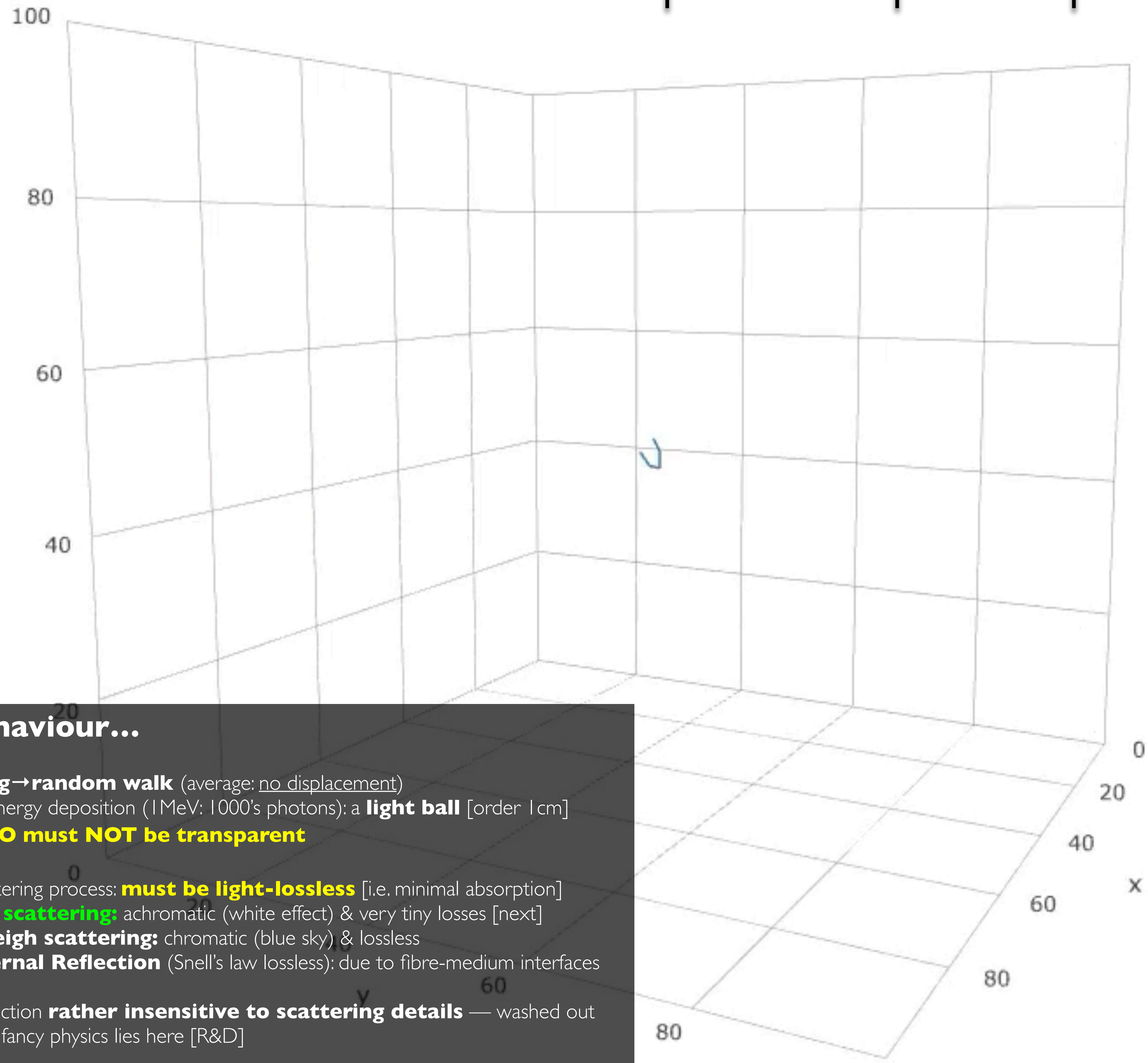
Background rate few/year

LiquidO breakthrough possible?



most basic principle..

the life of LiquidO optical photon…



photon's behaviour…

- **scattering→random walk** (average: no displacement)
- collective energy deposition (1MeV: 1000's photons): a **light ball** [order 1cm]

⟹ **LiquidO must NOT be transparent**

- overall scattering process: **must be light-lossless** [i.e. minimal absorption]
  - **Mie scattering:** achromatic (white effect) & very tiny losses [next]
  - **Raleigh scattering:** chromatic (blue sky) & lossless
  - **Internal Reflection** (Snell's law lossless): due to fibre-medium interfaces
- overall detection **rather insensitive to scattering details** — washed out
  - BUT fancy physics lies here [R&D]

LiquidO: unique stochastic light confinement (mainly lossless)

scattering…a “milky business”!

Computing the Scattering Properties of Participating Media Using Lorenz-Mie Theory

Jeppe Revall Frisvad[1] Niels Jørgen Christensen[1] Henrik Wann Jensen[2]

[1]Informatics and Mathematical Modelling, Technical University of Denmark
[2]University of California, San Diego

Figure 1: *Rendered images of the components in milk as well as mixed concentrations. The optical properties of the components and the milk have been computed using the generalization of the Lorenz-Mie theory presented in this paper. From left to right the glasses contain: Water, water and vitamin B2, water and protein, water and fat, skimmed milk, regular milk, and whole milk.*

Mie scattering (well known) used to study samples

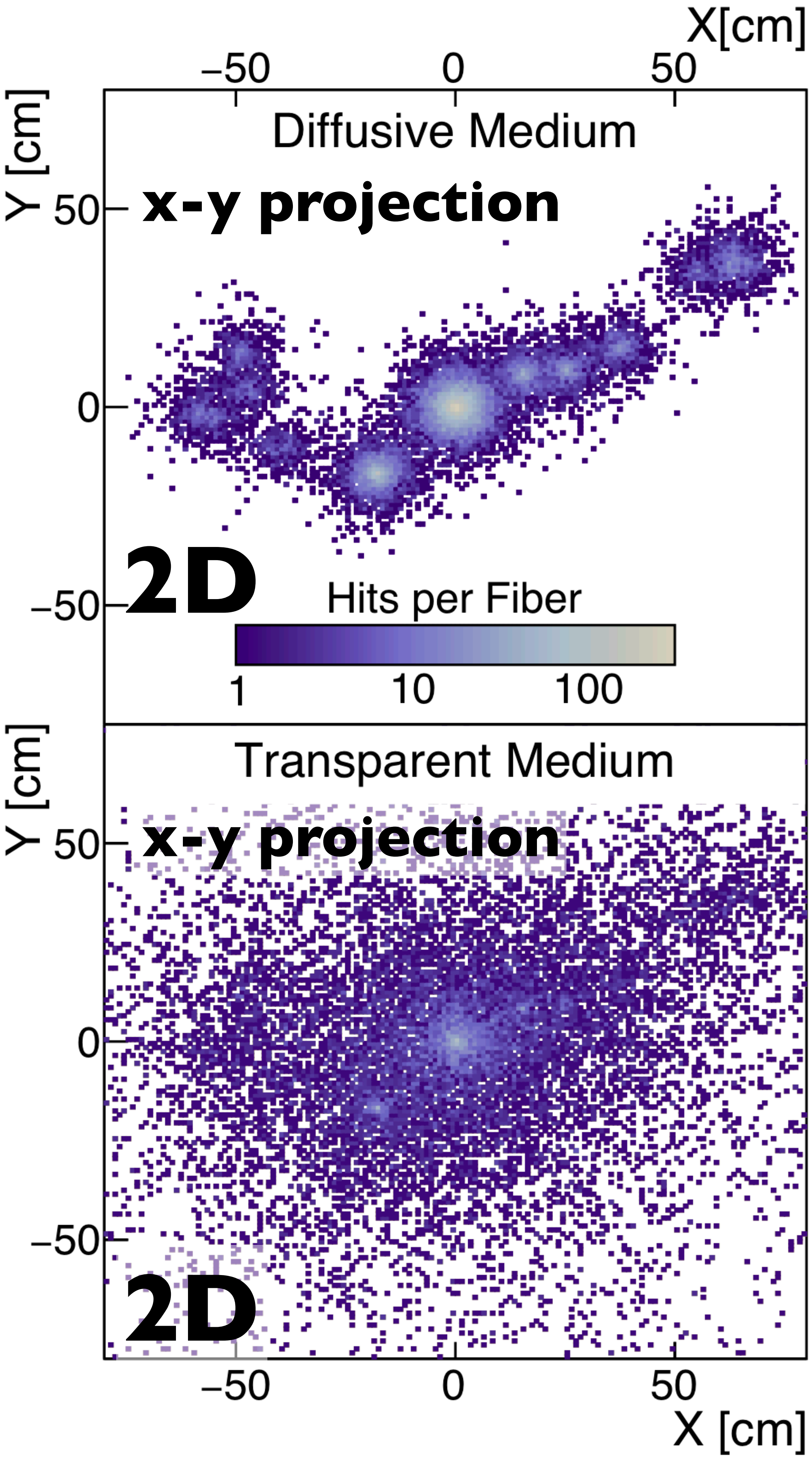
LiquidO **theorem**…

“milky” / “cloudy” / “waxy”

scintillator/cherenkov

(gas↔liquid↔solid)

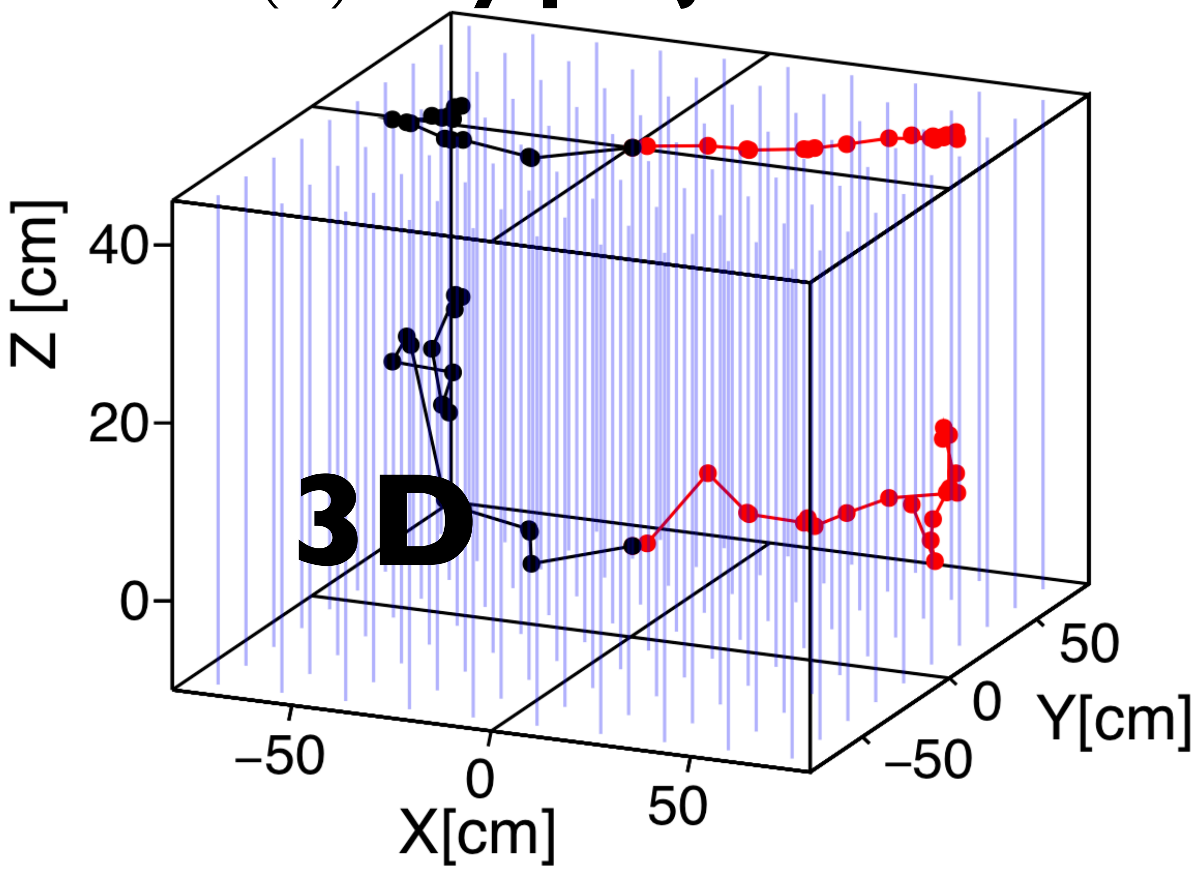
LiquidO's multi-axes…



LiquidO

up to 3 axes (unlike drift-TPC)→**needed?**

(↑) **x-y projection**



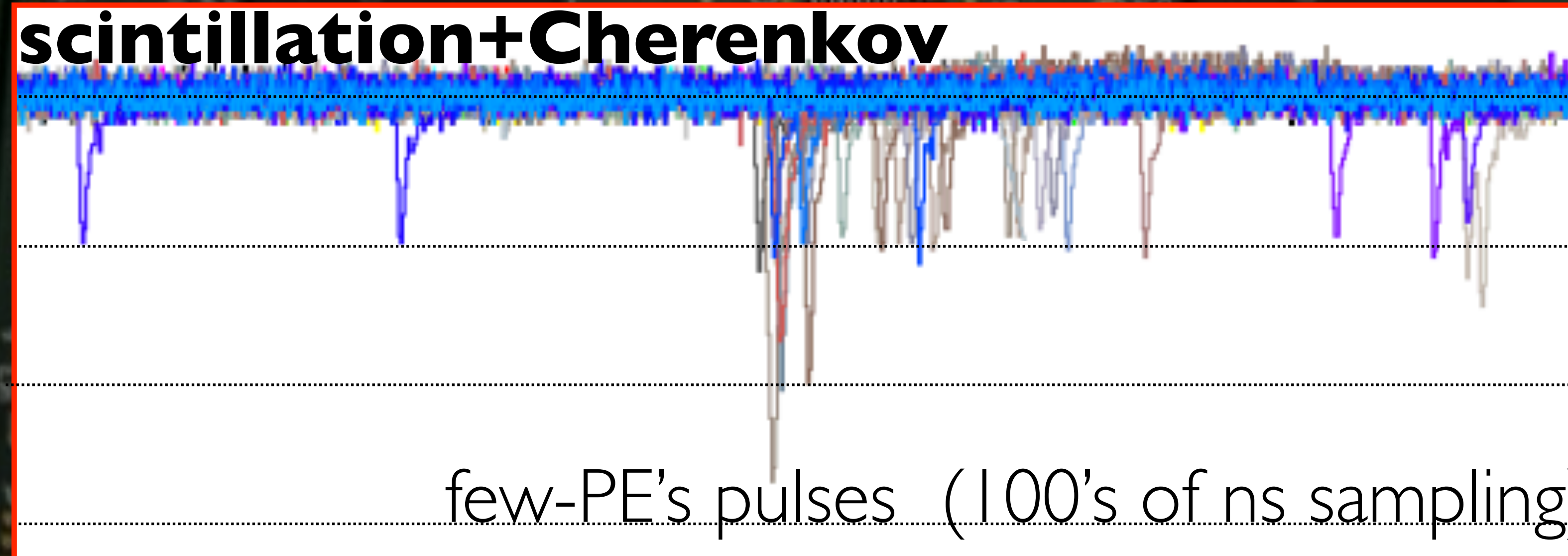
z projection (not yet fully exploited)

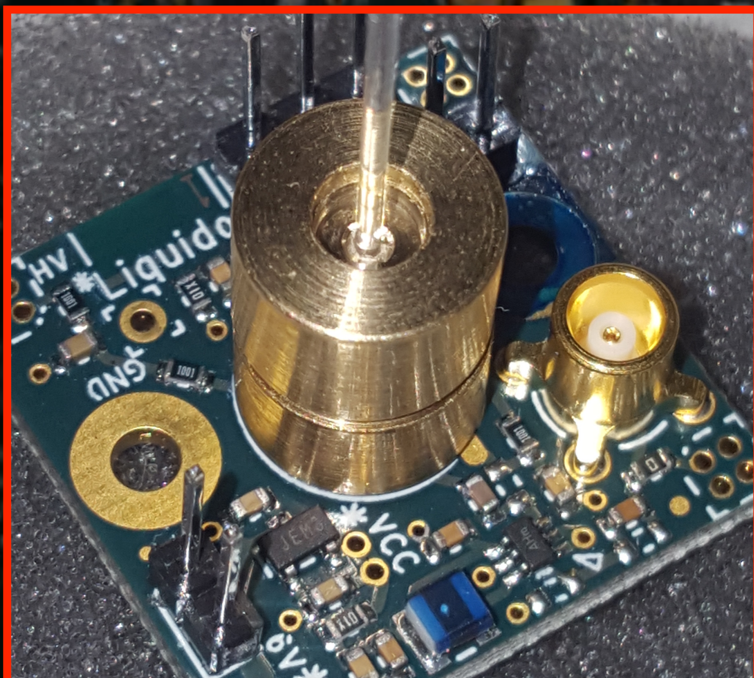
Transparent Scintillator⊕Fibres

light readout via "collectors"…


doping stability via solidification…
(beyond chemical stability)

our digitisation electronics…





~150ps per sample

(expected) **time resolution: ≤100ps/PE**

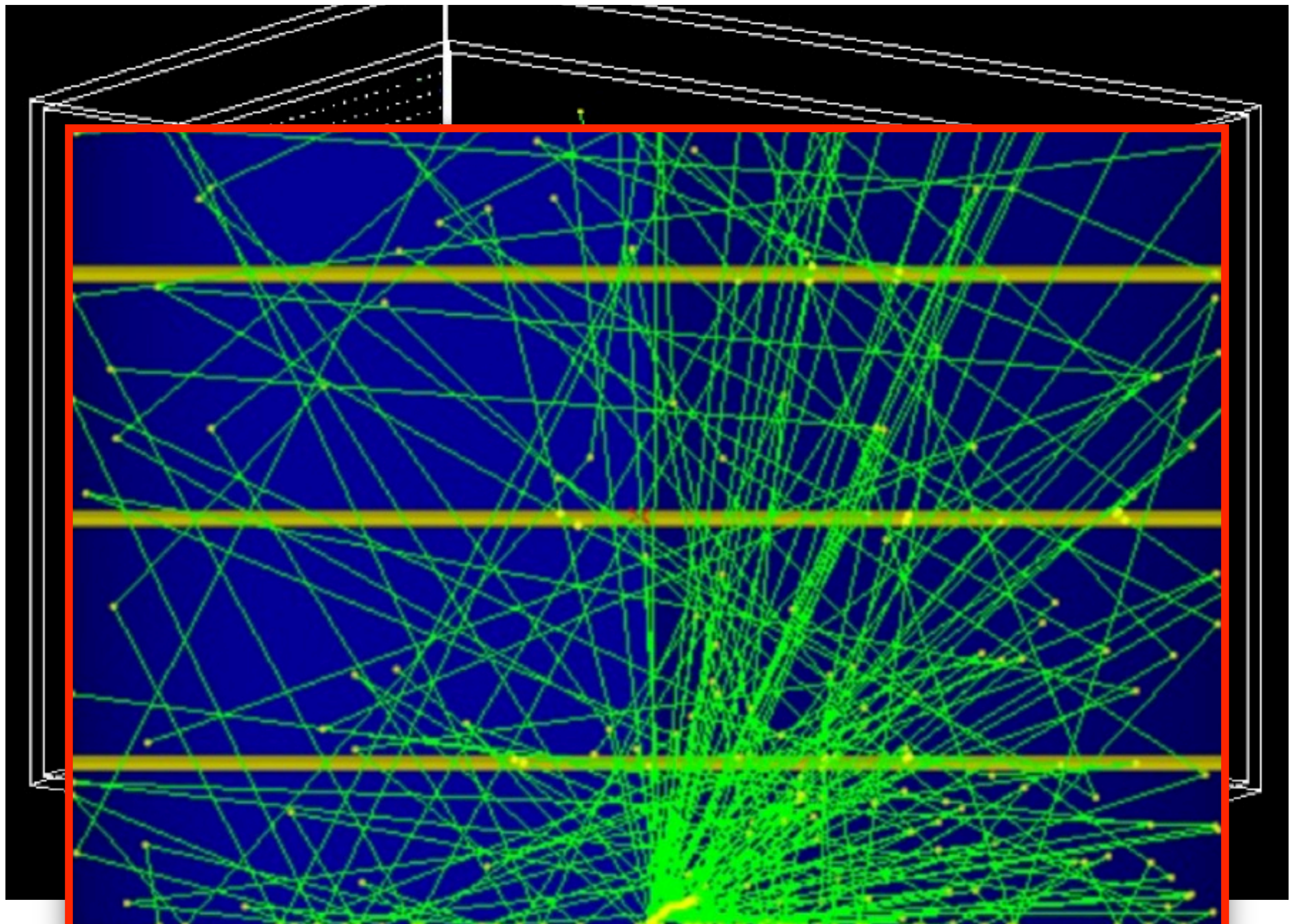
(i.e. ≤3cm/PE @ speed of light)

IEEE NSS (2014): The SAMPIC Waveform and Time to Digital Converter
NIM paper (2016): Measurements of timing resolution of ultra-fast silicon detectors with the SAMPIC Waveform Digitizer

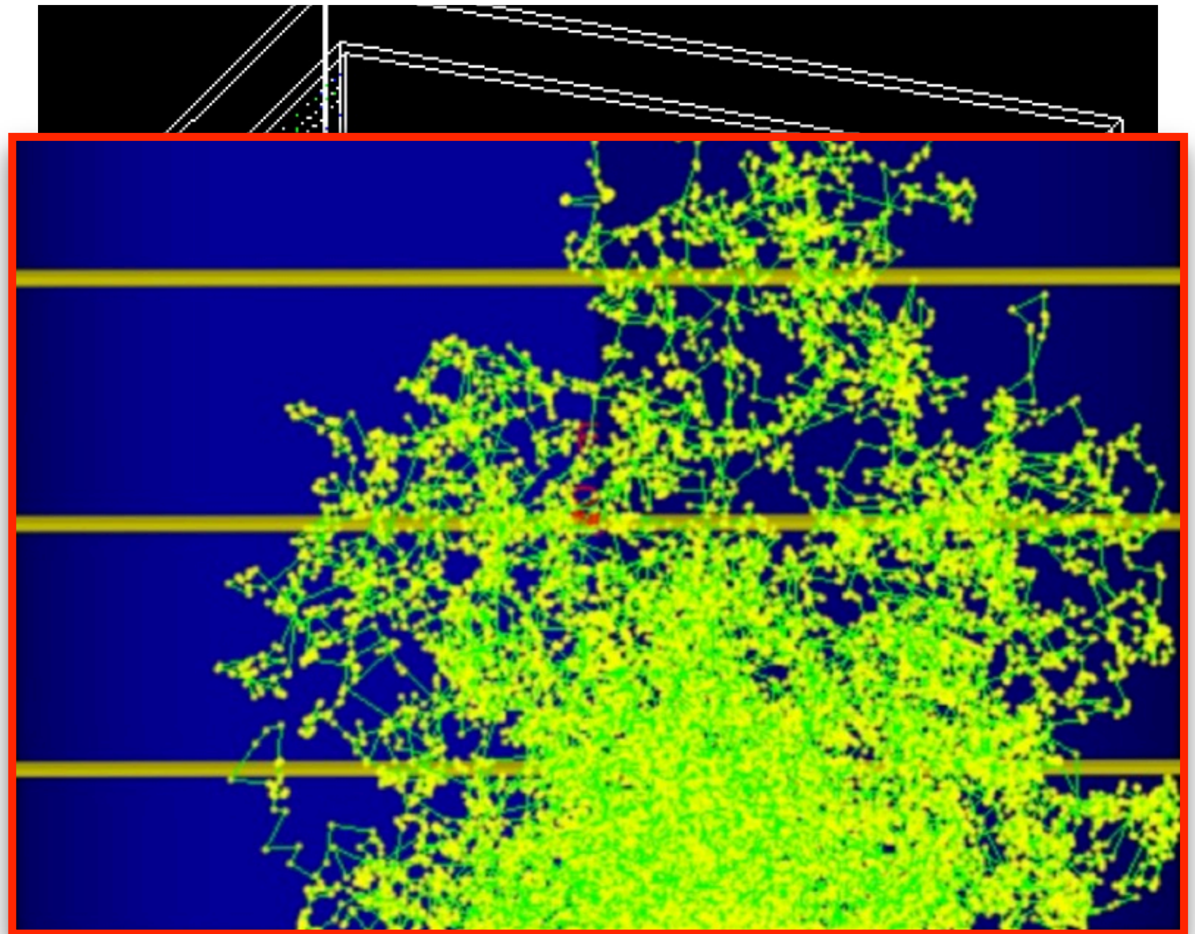
(instrumentation-wise)

LiquidO ≈ “light” TPC ⊕ 4π-ToF

LiquidO "bread & butter" physics…



today's technology



LiquidO technology

"ephemeral foam" of optical photons

light ball size: scattering⊕fibres

(stochastic light confinement)

LiquidO full release 2019…

Neutrino Physics with an Opaque Detector

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August 9, 2019

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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§Blaise Paschal Chaire Fellow.

1

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

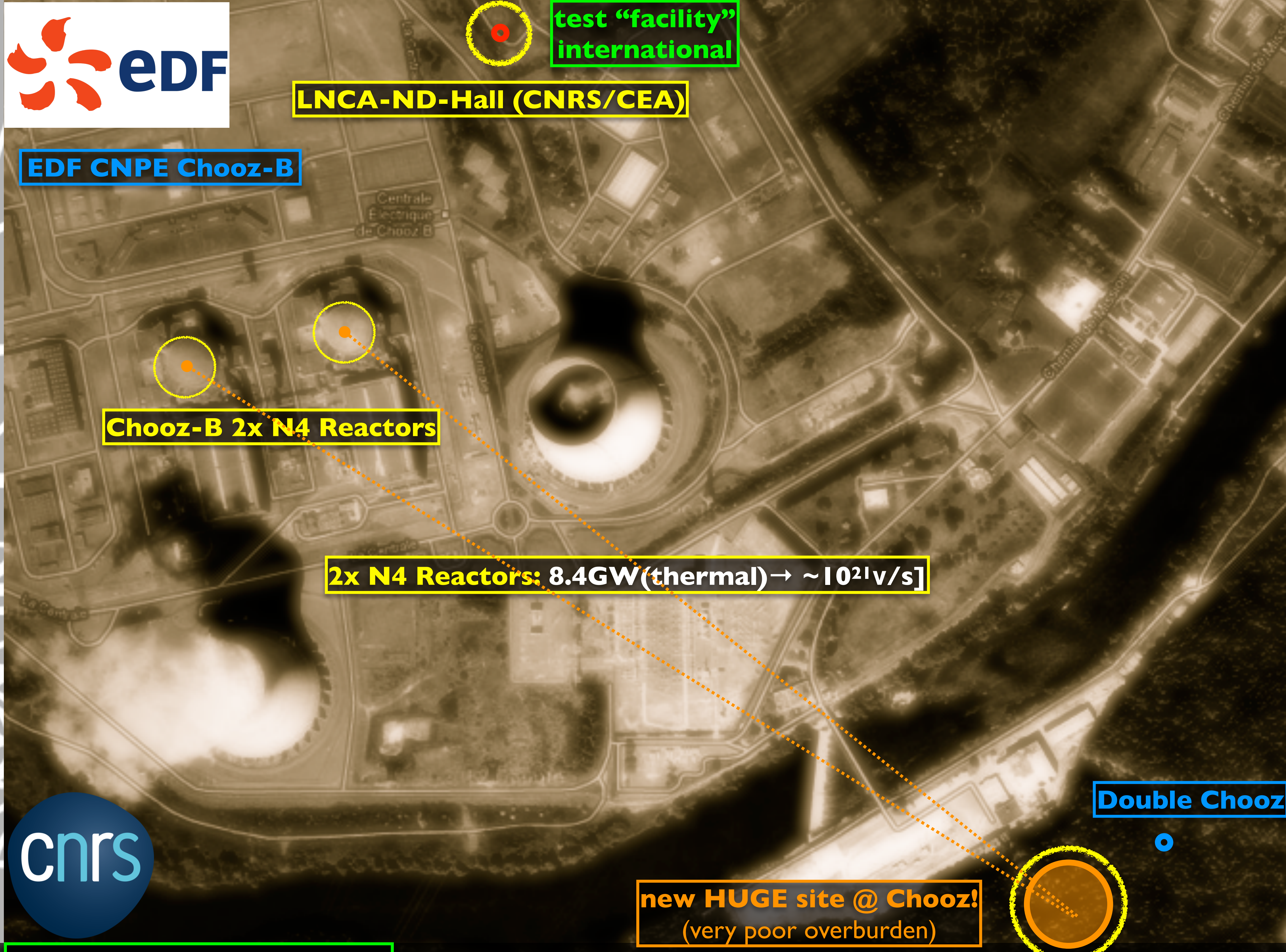
Submitted for Publication

First Opaque Liquid Scintillator @ arXiv:1908.03334

LiquidO

a novel neutrino detection

what can LiquidO do for us?



Europe’s best reactor ν site...

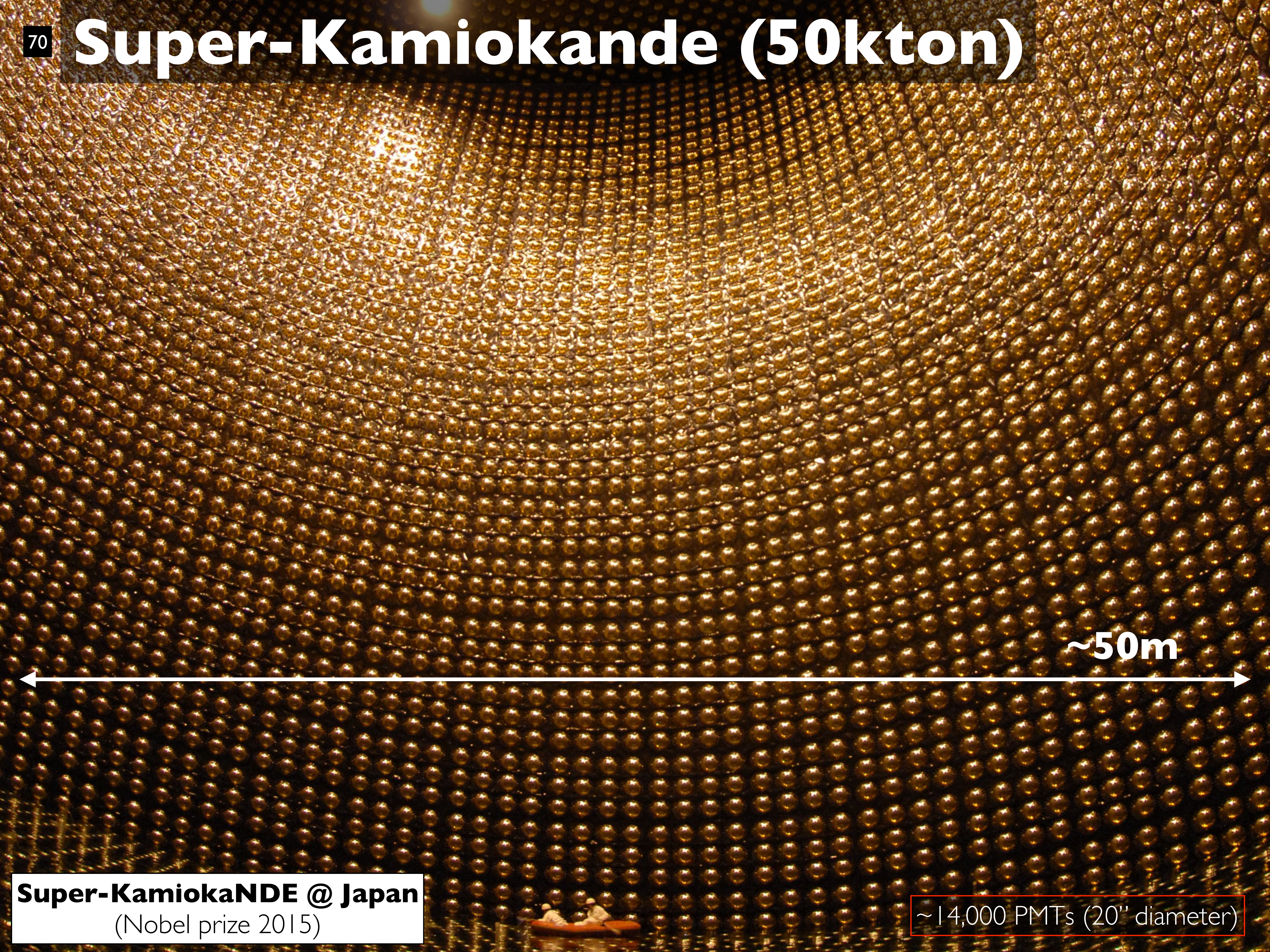
a secret underground…

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?

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

Super-Kamiokande (50kton)

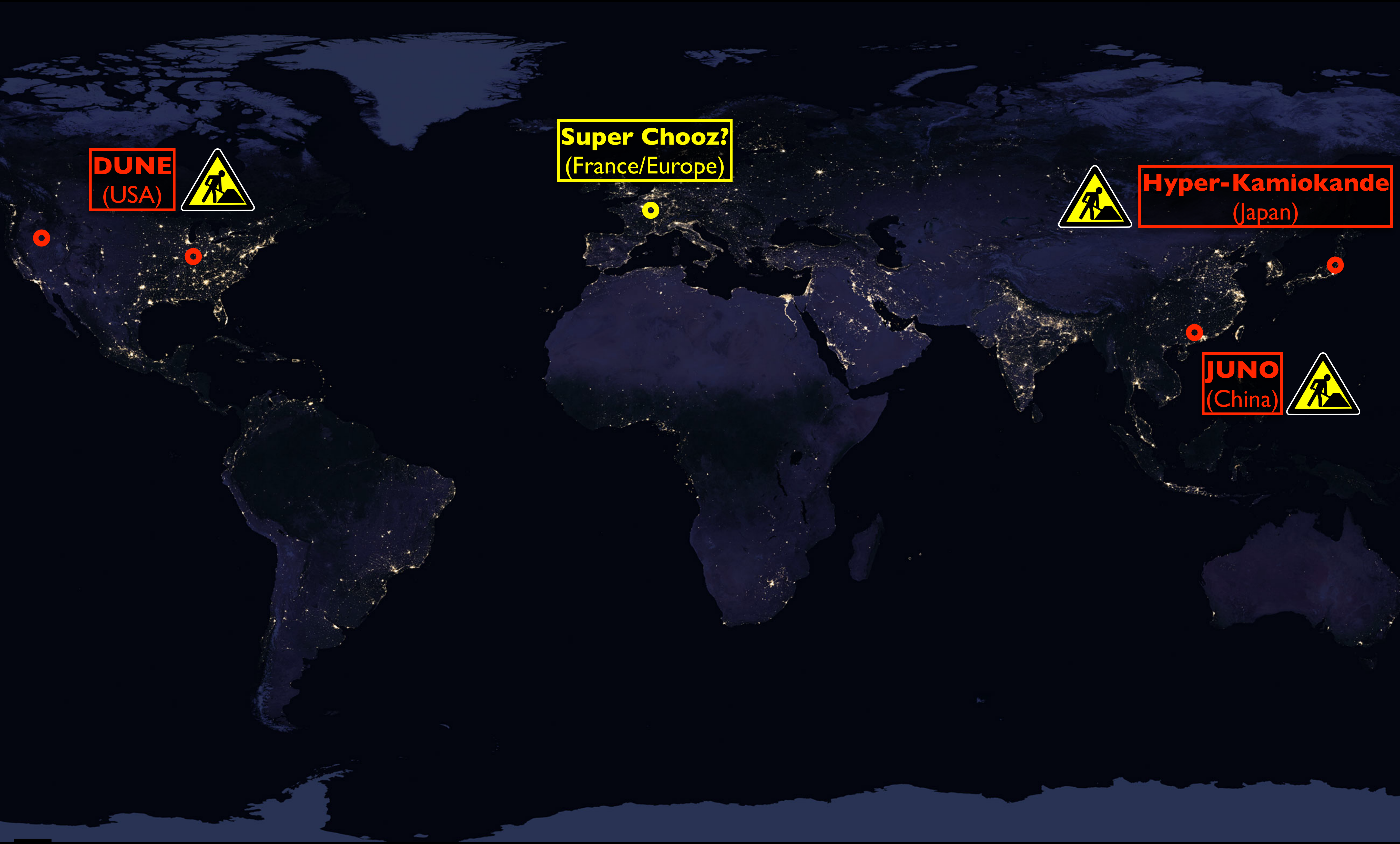


Super-KamiokaNDE @ Japan
(Nobel prize 2015)

~14,000 PMTs (20" diameter)

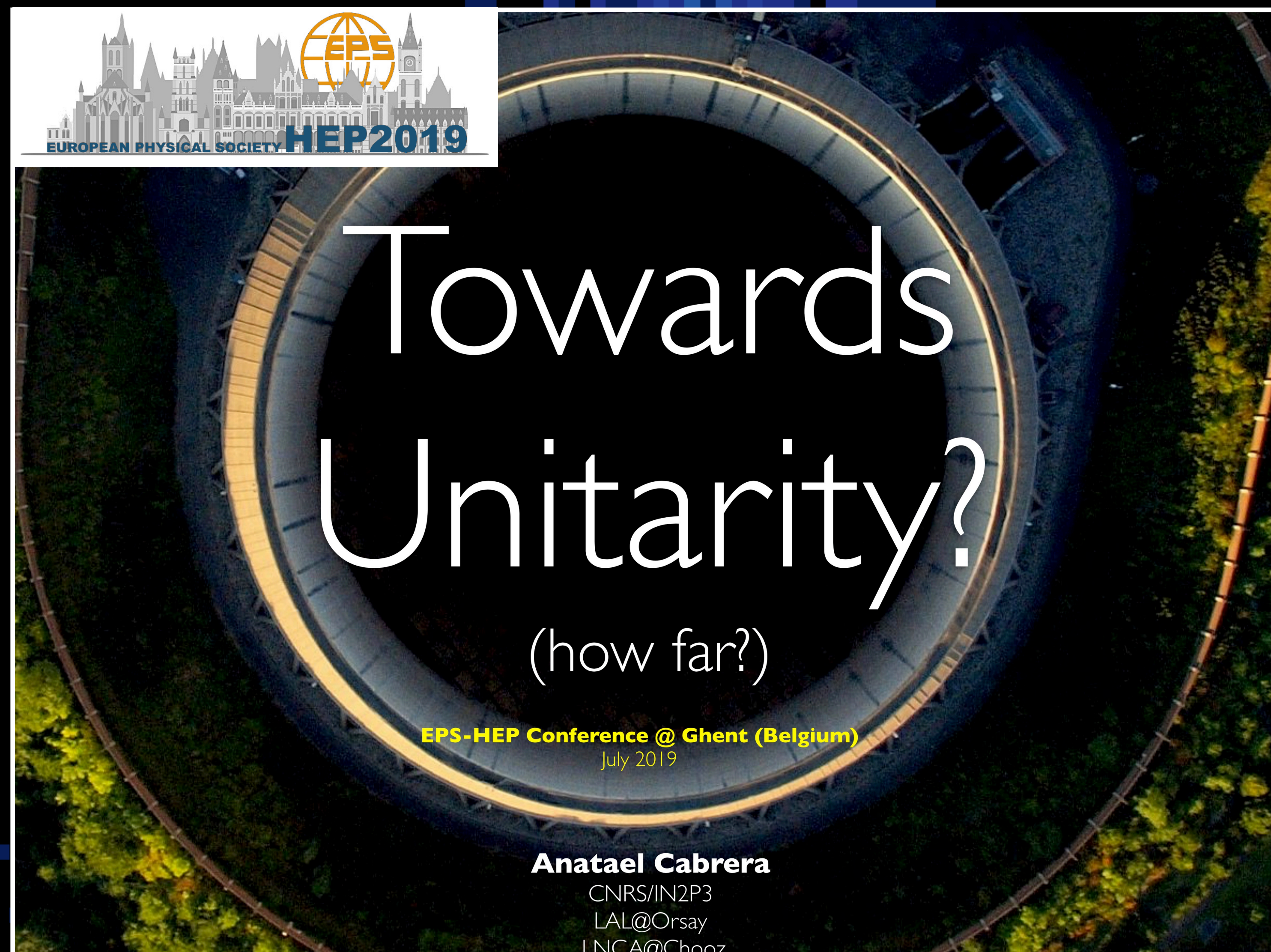
Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

Super Chooz since the 60's…



Europe’s best reactor ν site…

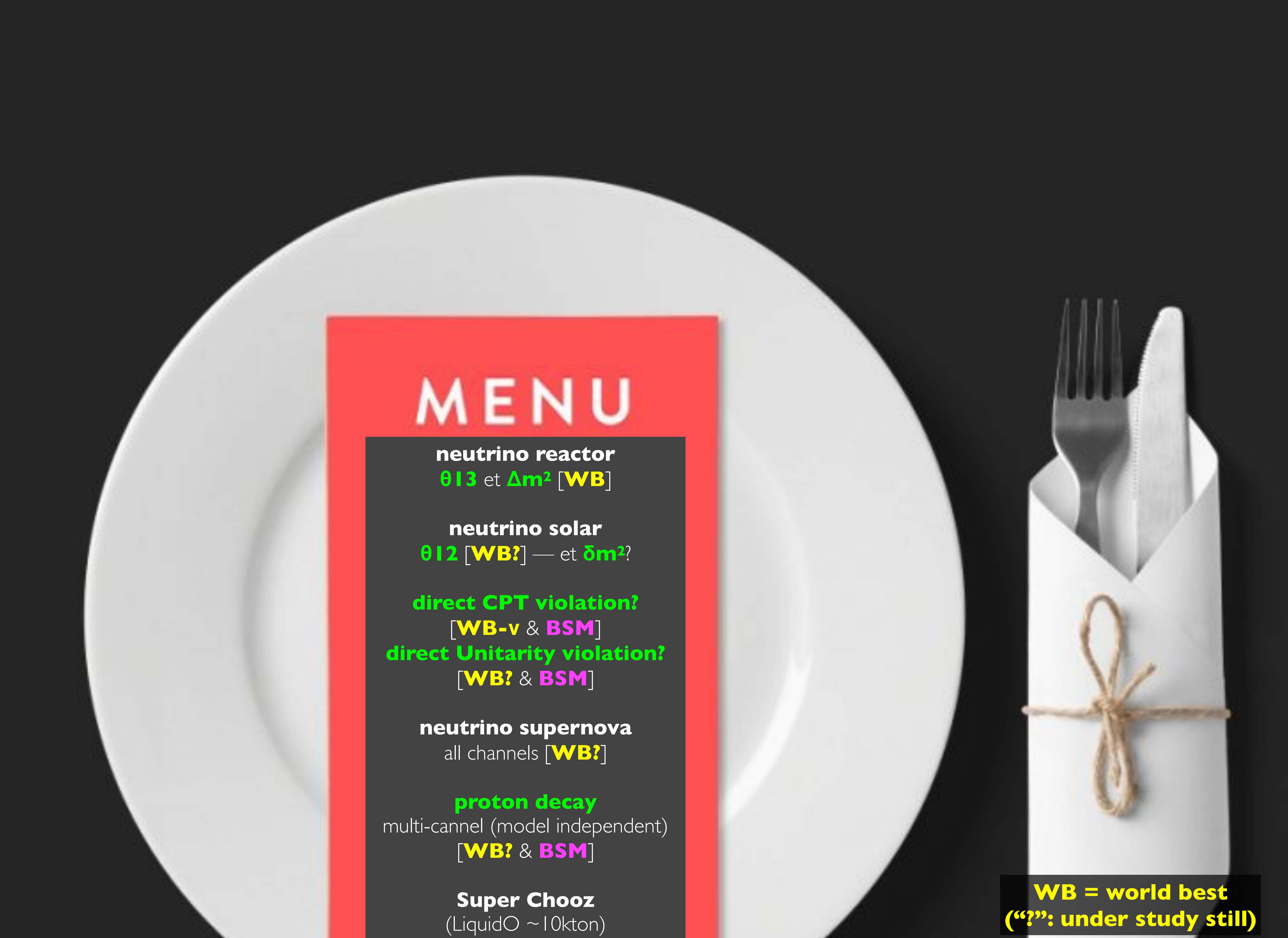
leptonic sector unitarity with LiquidO?



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

solar neutrinos too…

Super Chooz = telescope of the sun's fusion!



MENU

neutrino reactor
θ13 et **Δm^2** [**WB**]

neutrino solar
θ12 [**WB?**] — et **δm^2**?

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

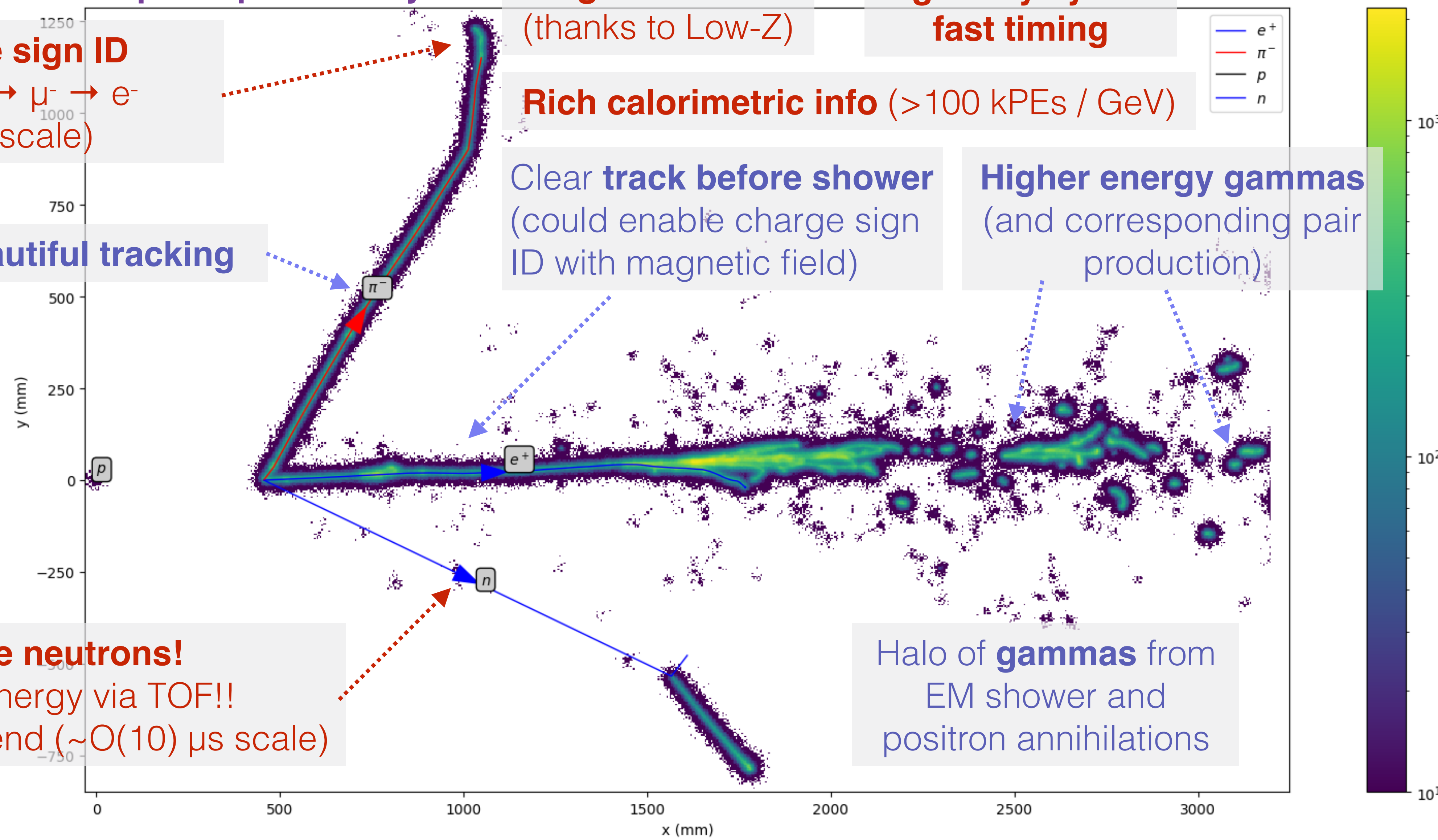
neutrino supernova
all channels [**WB?**]

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

Super Chooz
(LiquidO ~10kton)

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

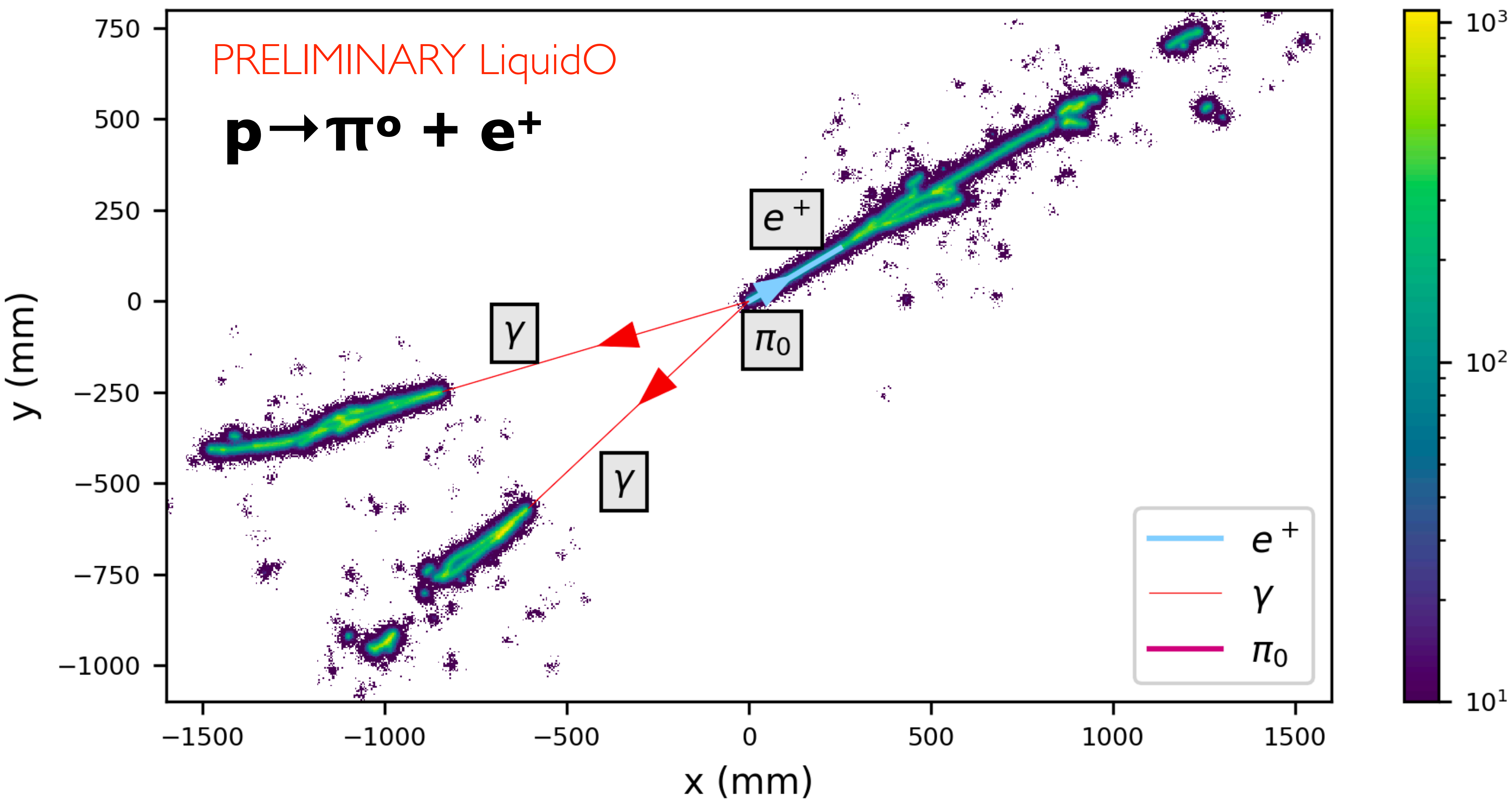
– LiquidO would reveal GeV-neutrino interactions in **extremely powerful** way:



(2 GeV electron antineutrino; 4mm fibre pitch and 1 mm scattering length; inefficiencies associated with photon detection are accounted for)

Imaging capabilities comparable to those of LArTPC + **Complementary features unique to LiquidO**

~1GeV neutrino…



proton-decay @ Super Chooz…

status on neutrino oscillation knowledge…

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

	today			≥2030		
	best knowledge		NuFIT4.0	foreseen	dominant	technique
θ_{12}	3.0 %	SK⊕SNO	2.3 %	<1.0%	JUNO & **SC**	reactor
θ_{23}	5.0 %	NOvA+T2K	2.0 %	≲1.0%	DUNE⊕HK**[⊕SC⁇]**	beam (octant)
θ_{13}	1.8 %	DYB+DC+RENO	**1.5 %**	<1.0%	**Super Chooz (SC)**	reactor
$+\delta m^2$	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
$\|\Delta m^2\|$	3.0 %	T2K+NOvA & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK⊕**SC**	reactor⊕beam
Mass Ordering	**unknown**	SK et al	NMO @ ≤3σ	@5σ	JUNO⊕DUNE⊕HK (NOvA⊕T2K)	reactor⊕beam
CPV	**unknown**	T2K+NOvA	3/2π @ ≤2σ	**@5σ?**	DUNE⊕HK⊕**SC**	beam driven
CPTV	**assumed**	—	—	**<1%?**	**SC⁇ [studying]**	reactor+solar
Unitarity	**assumed**	—	—	**<1%?**	**SC⁇ [studying]**	reactor+solar

(reactor+solar+beam)

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

SuperChooZ?

stunning **opportunity**…

EDF+CNRS exploring…

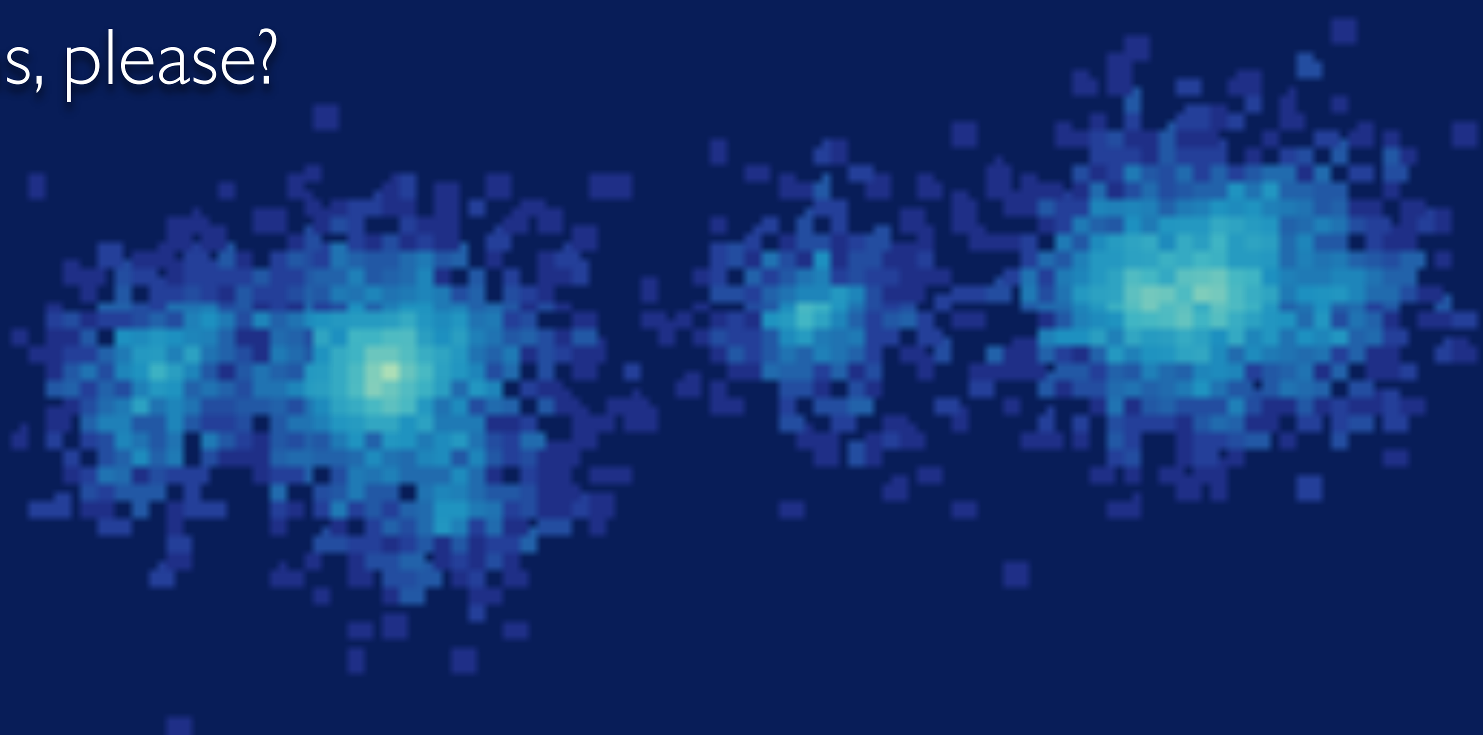
ν’s back to Europe…?

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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LiquidO (imaging⊕energy flow)⇒ **never before!**