Unitarity

(θ_{13} today & maybe beyond?)

how far with PMNS?

Seminar
November 2019

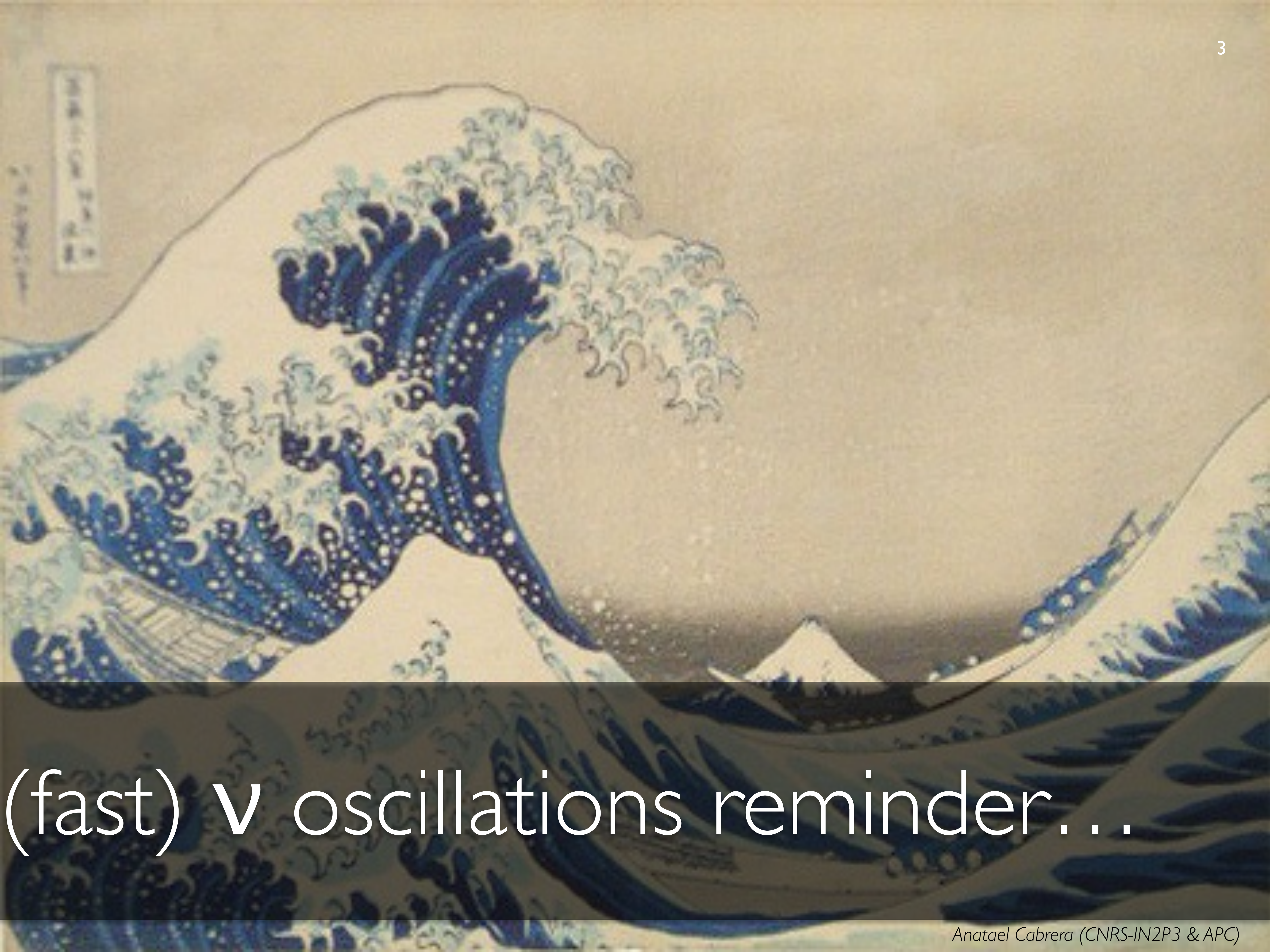
Anatael Cabrera
CNRS/IN2P3
LAL/FLUO @ Orsay
LNCA @ Chooz

~50 years of neutrino oscillations…

huge experimental effort→<u>well established</u>

[discovery ⇔ Nobel 2015]

what is/are the next goal?

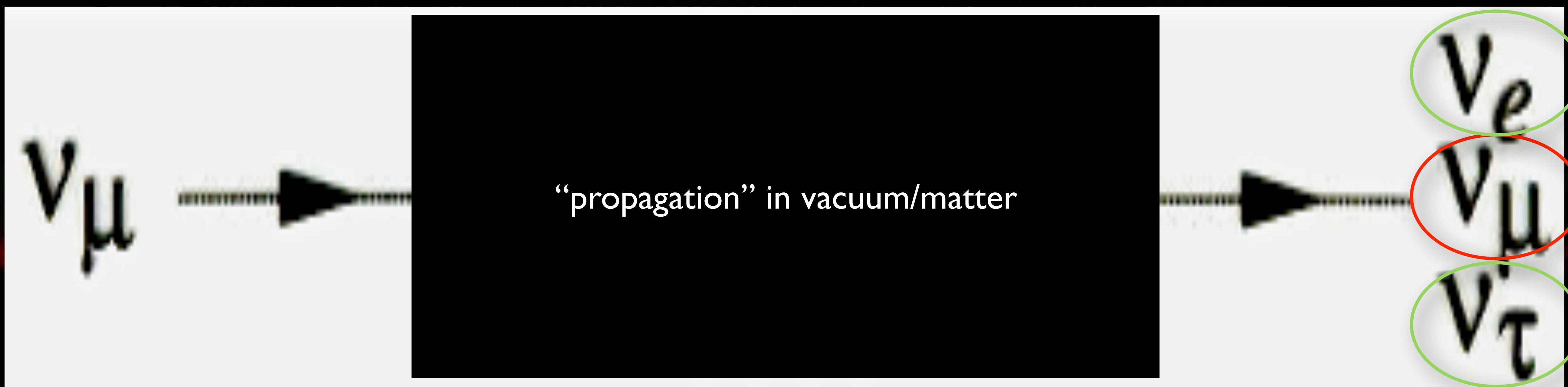


(fast) ν oscillations reminder…

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

ingredients for neutrino oscillations…

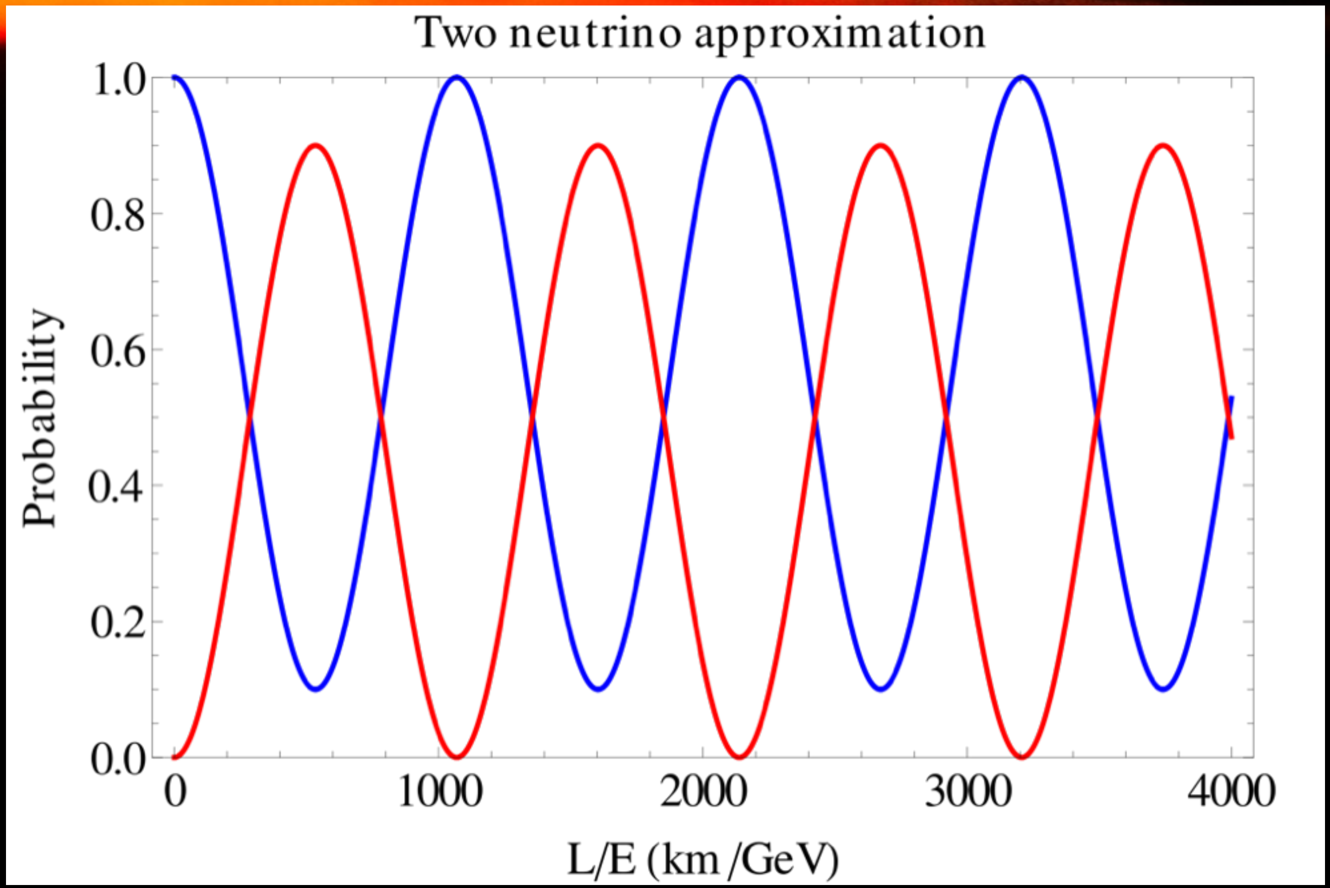
Non-degenerate mass spectrum (**Δm^2**) ⊕ Mixing in the leptonic sector (**θ**) = Oscillation Probability **$P=f(\theta,\Delta m^2)$**

quantum interference (macroscopic)

U_{PMNS} matrix (à la CKM)

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

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



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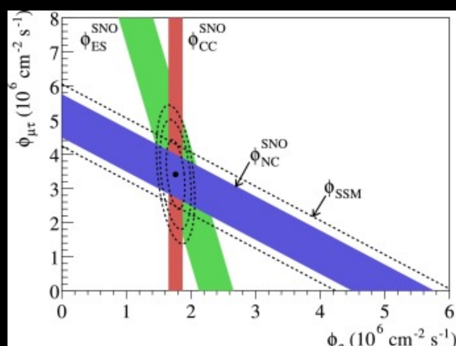
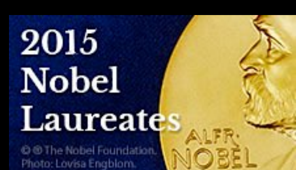
UNITARITY → demonstrate experimentally

our history…

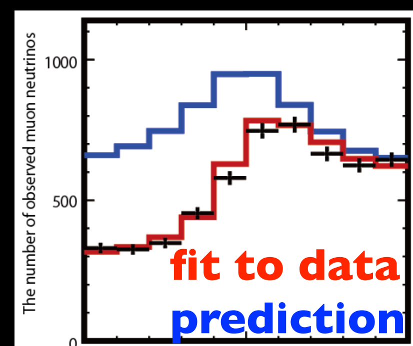
solar anomaly
$(\theta_{12} \oplus \delta m^2)$

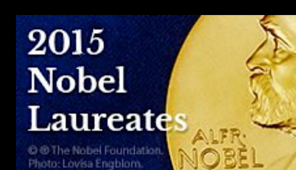




large mixing!

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





large mixing!

"reactor" oscillation
(θ_{13})

small mixing!

Jarkslog Invariant $[\neq 0]$

first CP-Violation hint
$(\delta_{CP} \neq (0 \text{ or } \pi)$ @ $\sim 2\sigma)$

MODEL hypothesis: neutrino oscillations

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

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"mixing": a common phenomenon…

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

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

$$\Delta m^2_{31} \qquad\qquad \Delta m^2_{31} \qquad\qquad \Delta m^2_{21}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

sub-leading | sub-leading

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

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

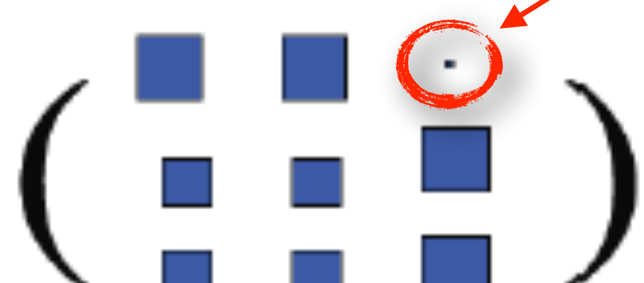
ATMOSPHERIC ANOMALY | **PREDICTION** | **SOLAR ANOMALY**

effective decoupling of "solar" & "atmospheric":

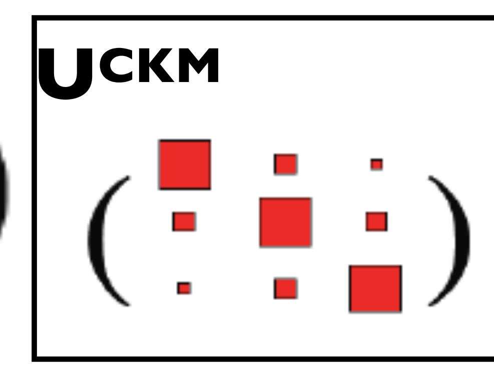
- δm^2 (order 10^{-5}eV^2) versus Δm^2 (order 10^{-3}eV^2)
- θ_{13} being small (relative to very large θ_{12} and θ_{23})

θ_{13} drives this!!!

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



U^{PMNS}



is U unitary? [key assumption]

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		
	best knowledge		NuFIT4.0
θ_{12}	3.0 %	SNO	2.3 %
θ_{23}	5.0 %	NOvA	2.0 %
θ_{13}	1.8 %	DYB	**1.5 %**
+δm²	2.5 %	KamLAND	2.3 %
|Δm²|	3.0 %	T2K & DYB	1.3 %
sign(Δm²)	**unknown**	SK	NO @ ~3σ
CPV	**unknown**	T2K	3/2π @ ~2σ

(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)

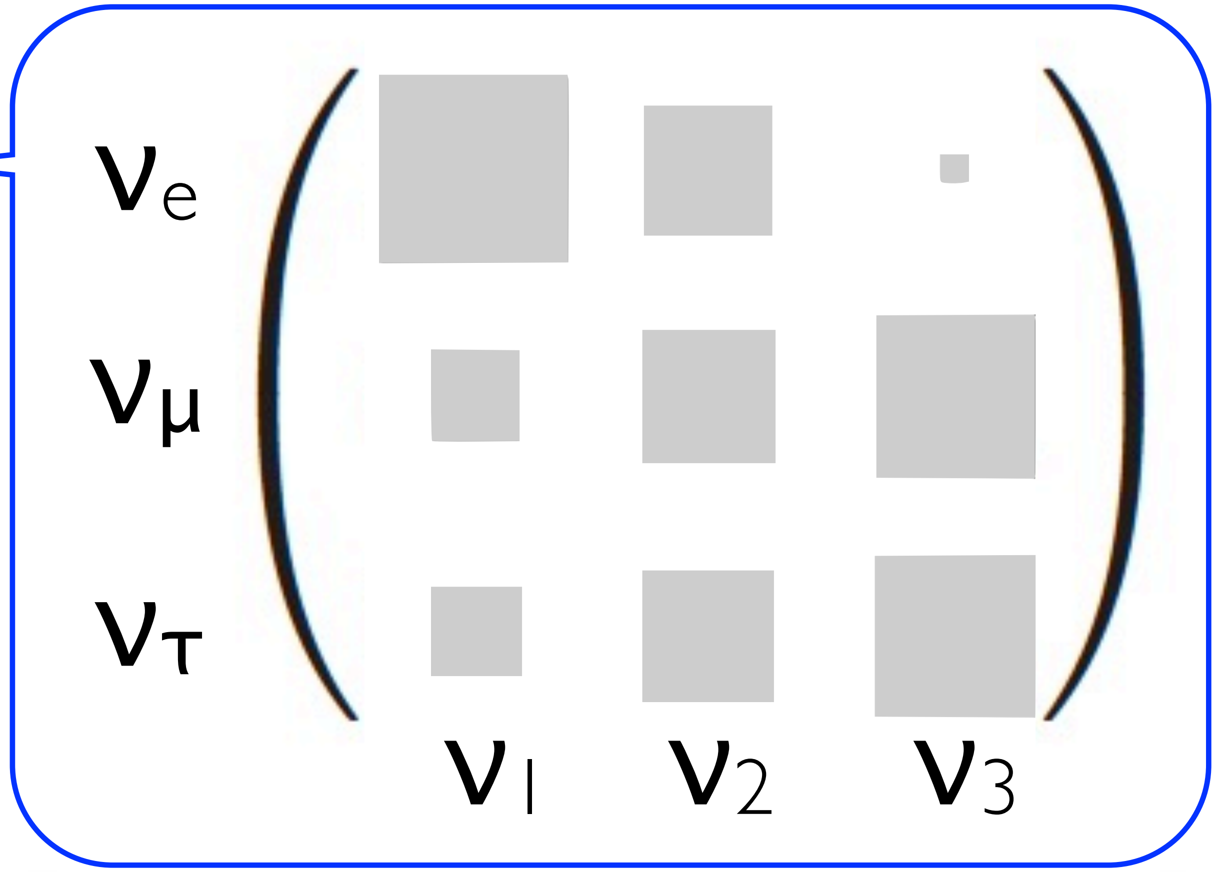
do we have all needed?

the "super" experiments era…

all done?

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

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



consider matrix structure

(not just composition)

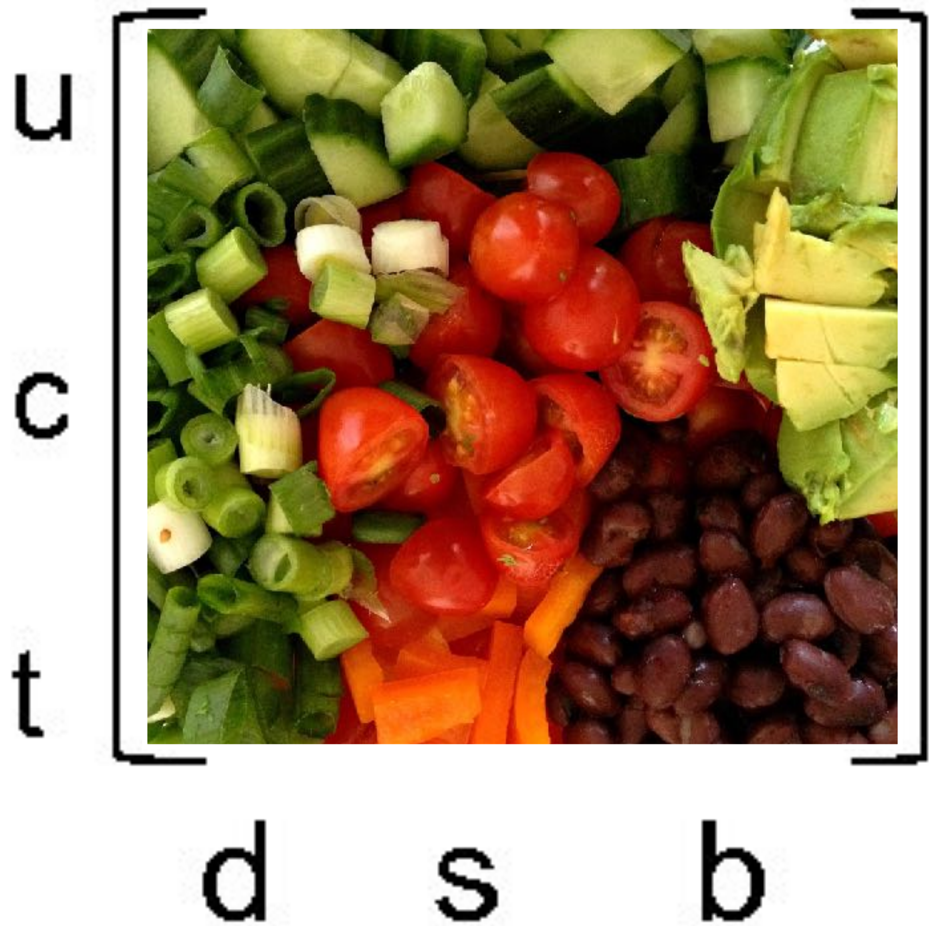
why shape?

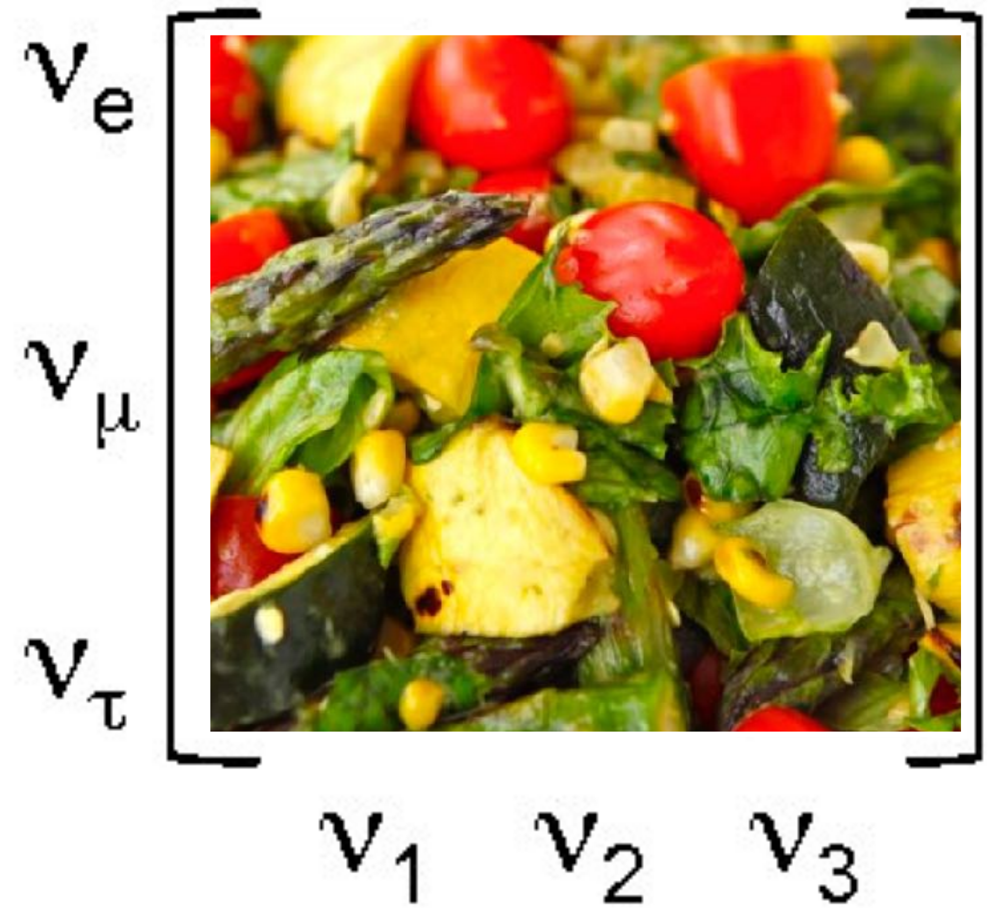
- **large mixing** but a **small one**!
- **largest CP-Violation** (SM)
- **any symmetry behind? [Nature's caprice?]**

U_{3x3} unitary?

[next slides]

CKM vs PMNS…





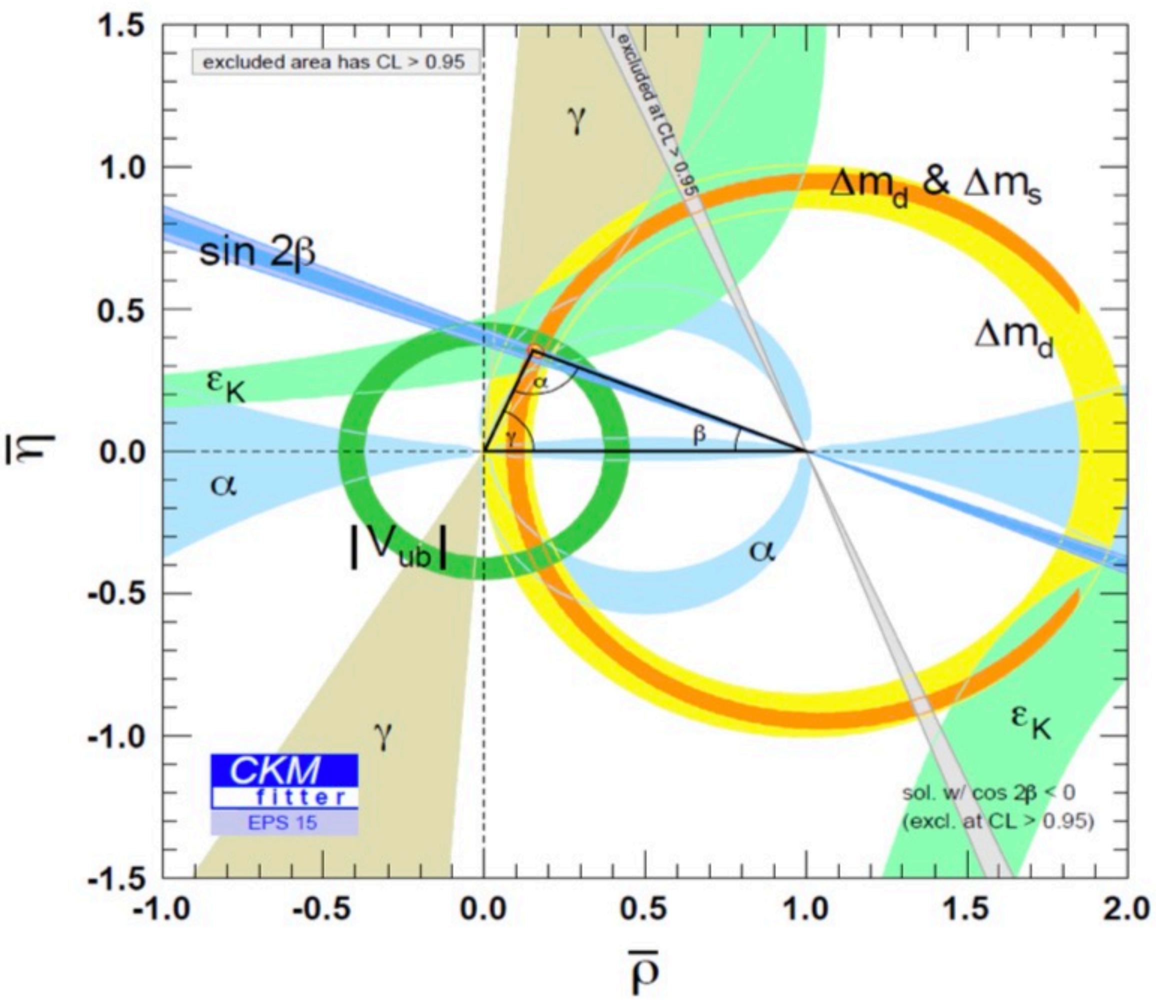
elegance
(symmetry)

stravaganzza
(anarchy?)

A. De Gouvea, H. Murayama, hep-ph/0301050; PLB, 2015.

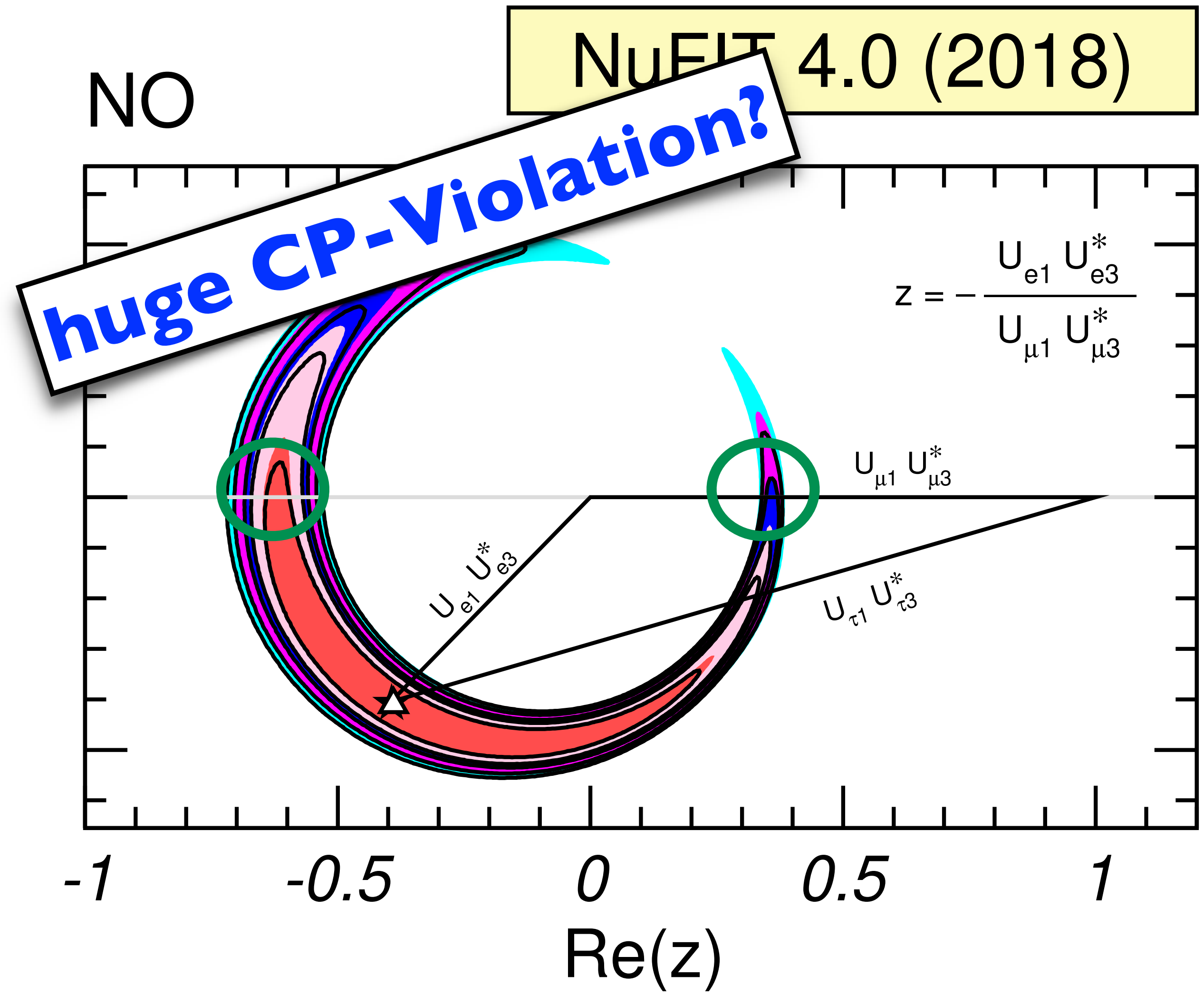
L. Hall, H. Murayama, N. Weiner, hep-ph/9911341.

CKM



$J(CKM) \approx 3.18 \pm 0.15 \times 10^{-5}$

PMNS



$J(PMNS) \approx 3.33 \pm 0.06 \times 10^{-2}$

CP-Conversation disfavoured @ $\geq 2\sigma$

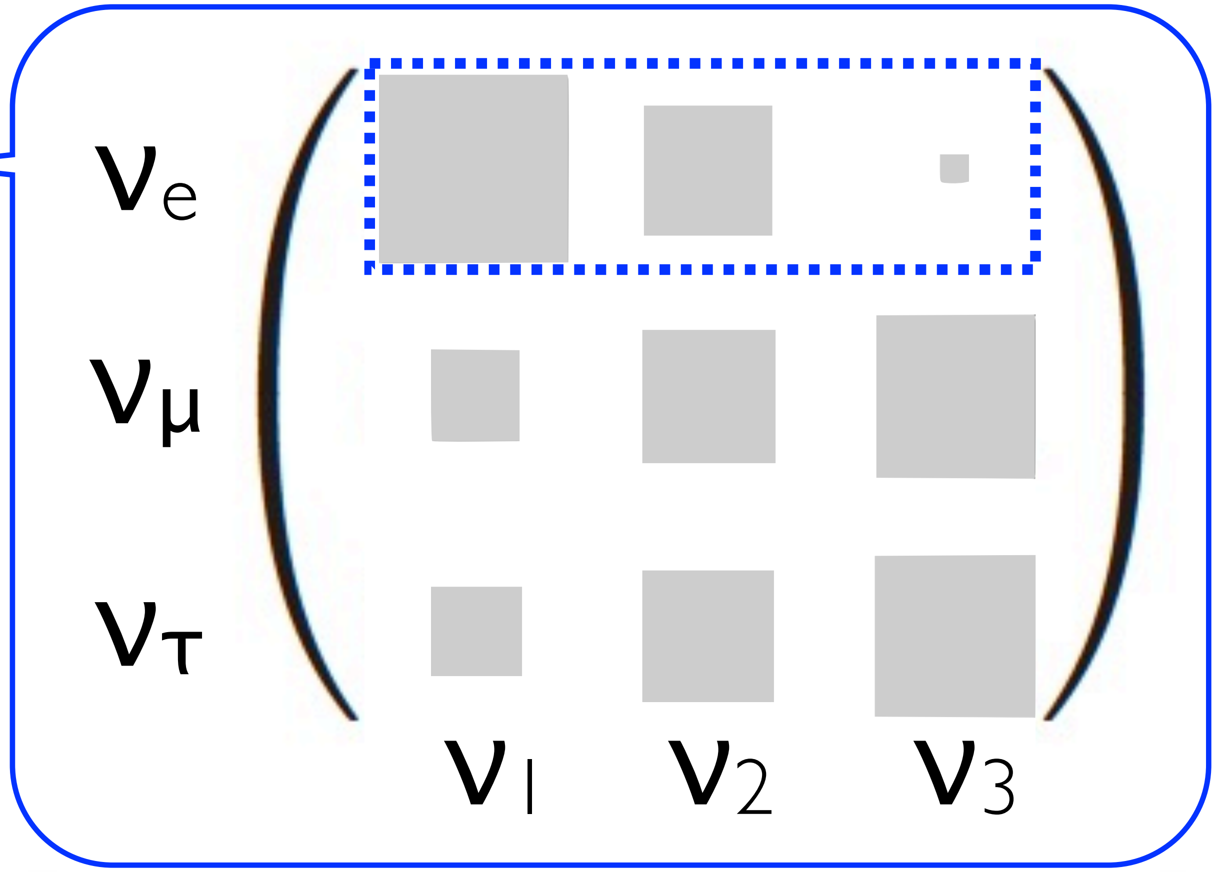
PMNS triangle (including CPV)…

Unitarity: the last discovery?

"discovery" here means "*going beyond today's model…*"

test PMNS Unitarity…

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}$$



⇒ **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}"

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

$$\begin{pmatrix} \boxed{c_{12}c_{13} \quad s_{12}c_{13} \quad s_{13}} e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

unitary representation

only "θ_{12}" and "θ_{13}" — very clean & best knowledge

- **θ_{13} is today most precise measurement [soon worst known though!]**
- **θ_{12} will be the most prise measurement by JUNO [next slides]**

when testing UNITARITY: you can no longer speak of θ_{ij} but U_{ij} instead

neutrino oscillation direct & clean probe
[no corrections or alike (yet!?)]

why Unitarity is important?

- as critical as θ_{12}, θ_{23}, θ_{13}, δ_{CP} ↔ part of their definition

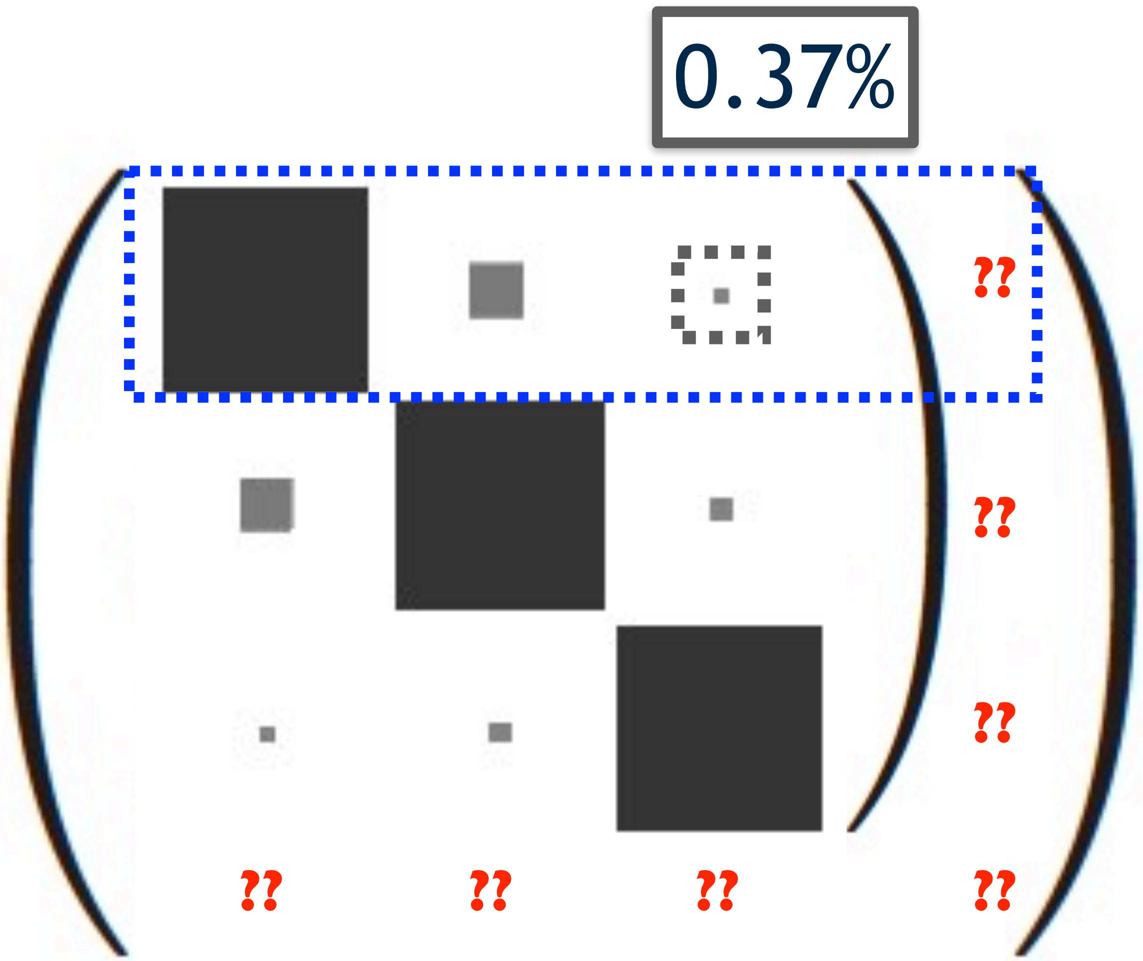
- so far **assumed!!**→**must test validity** [à la CKM]

- **Unitarity:** [the last discovery within "neutrino oscillation"?]
  - **δ_{CP}:**
    - **≠0 or π** very interesting but **foreseen in model** (i.e. not surprising)
    - **=0 or π** more(?) interesting (symmetry?) but **foreseen in model** (i.e. not surpr
    - **=x** (whatever value) **very important** but **little learnt if no prediction!**
  - $UU^\dagger$:
    - **=1 OK** [confirm & over-constrain SM]
    - **≠1 breakthrough! [i.e. NEW model]→ discovery beyond "SM"!!**

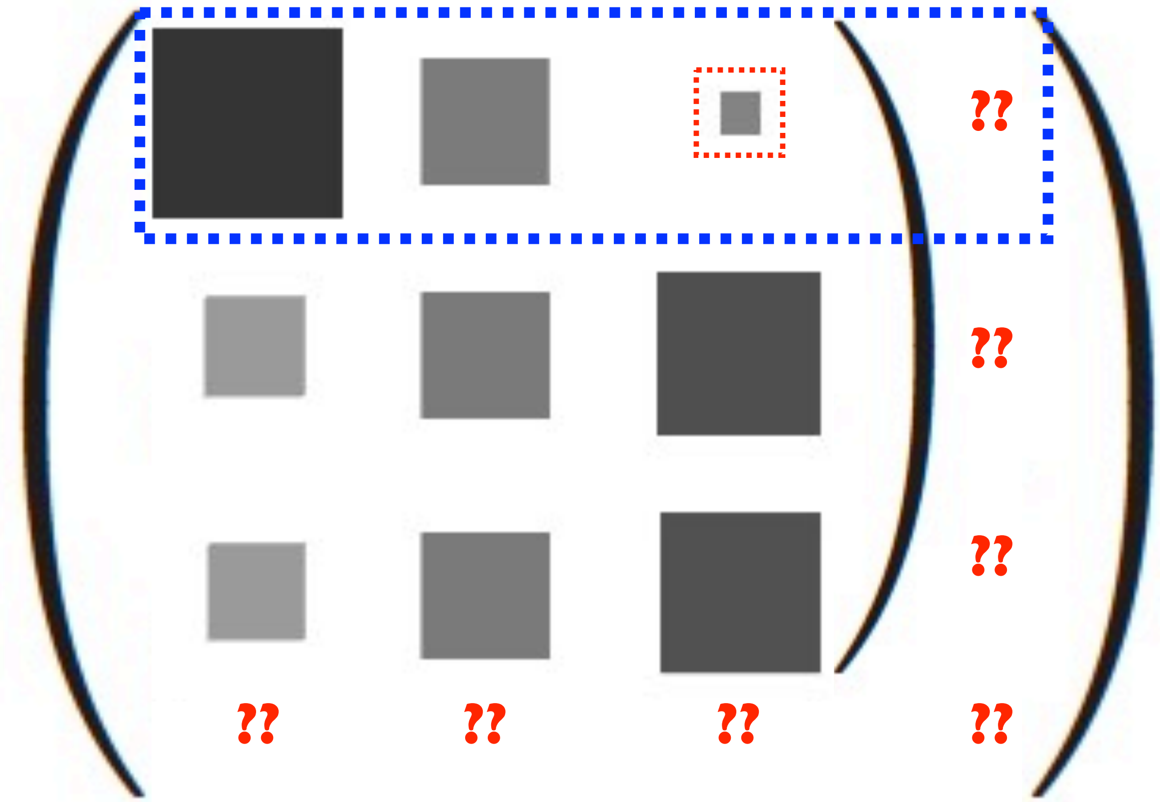
  [**perfect prediction ("1") protected by symmetry**]

Unitarity Violation→ 4th family? (~~kinematics~~) and/or NSI?
[i.e. major discovery]

unitarity violation implications…



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



if it existed ⇒ tiny!!(?)

(naive expectation)

if it existed ⇒ less tiny(?)

(naive expectation)

maybe few % precision enough!!

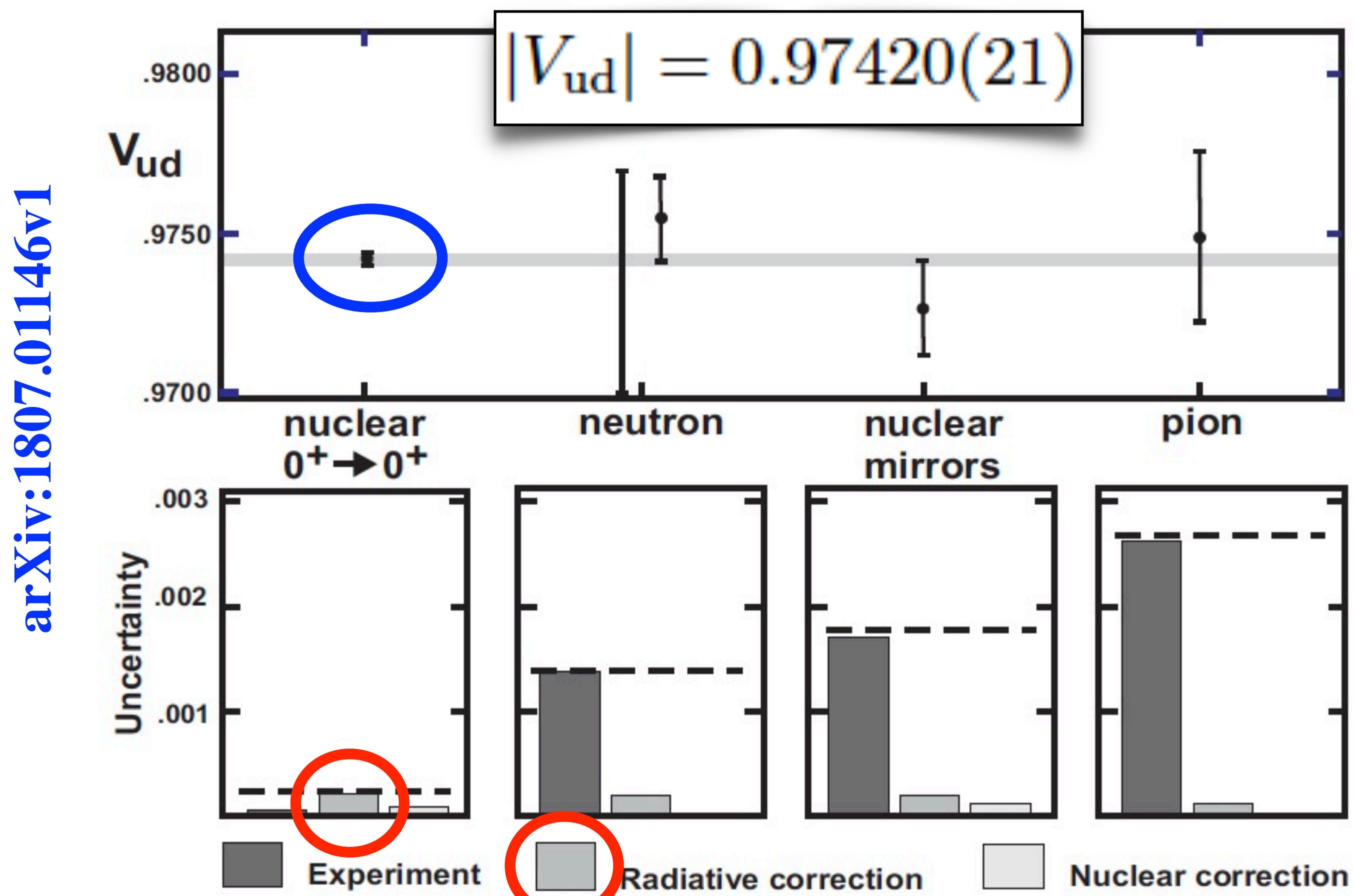
Unitarity Violation→ 4th family? (~~kinematics~~) and/or NSI?
[i.e. major discovery]

let’s quickly check the CKM…

CKM equivalent knowledge…

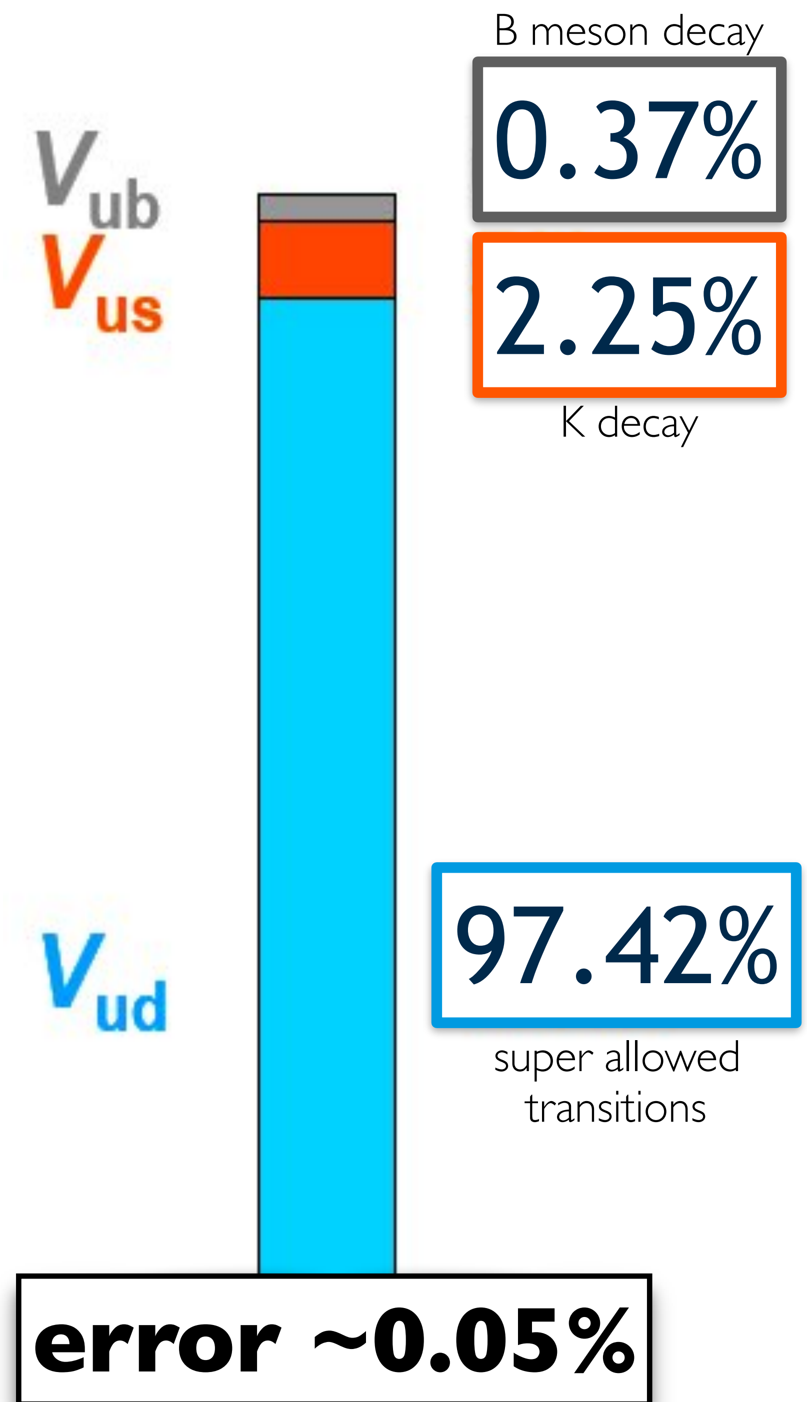
$$|V_{\rm ud}|^2 + |V_{\rm us}|^2 + |V_{\rm ub}|^2 = 0.99939(64)$$

Hardy & Towner, arXiv 1807.01146 and Particle Data Group 2018



2018 radiative correction (before 2006)

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

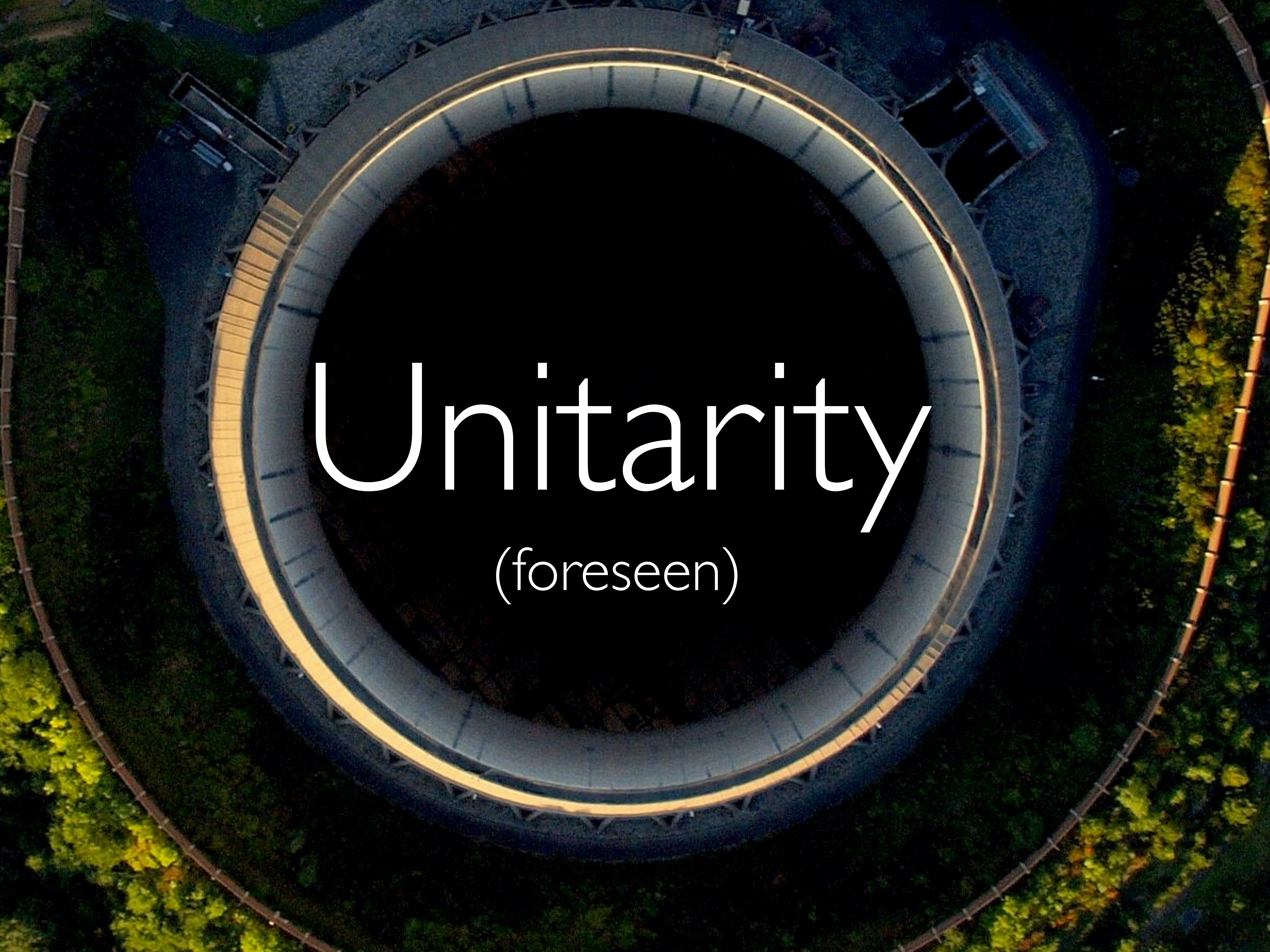


tension @ CKM??
[data or corrections]

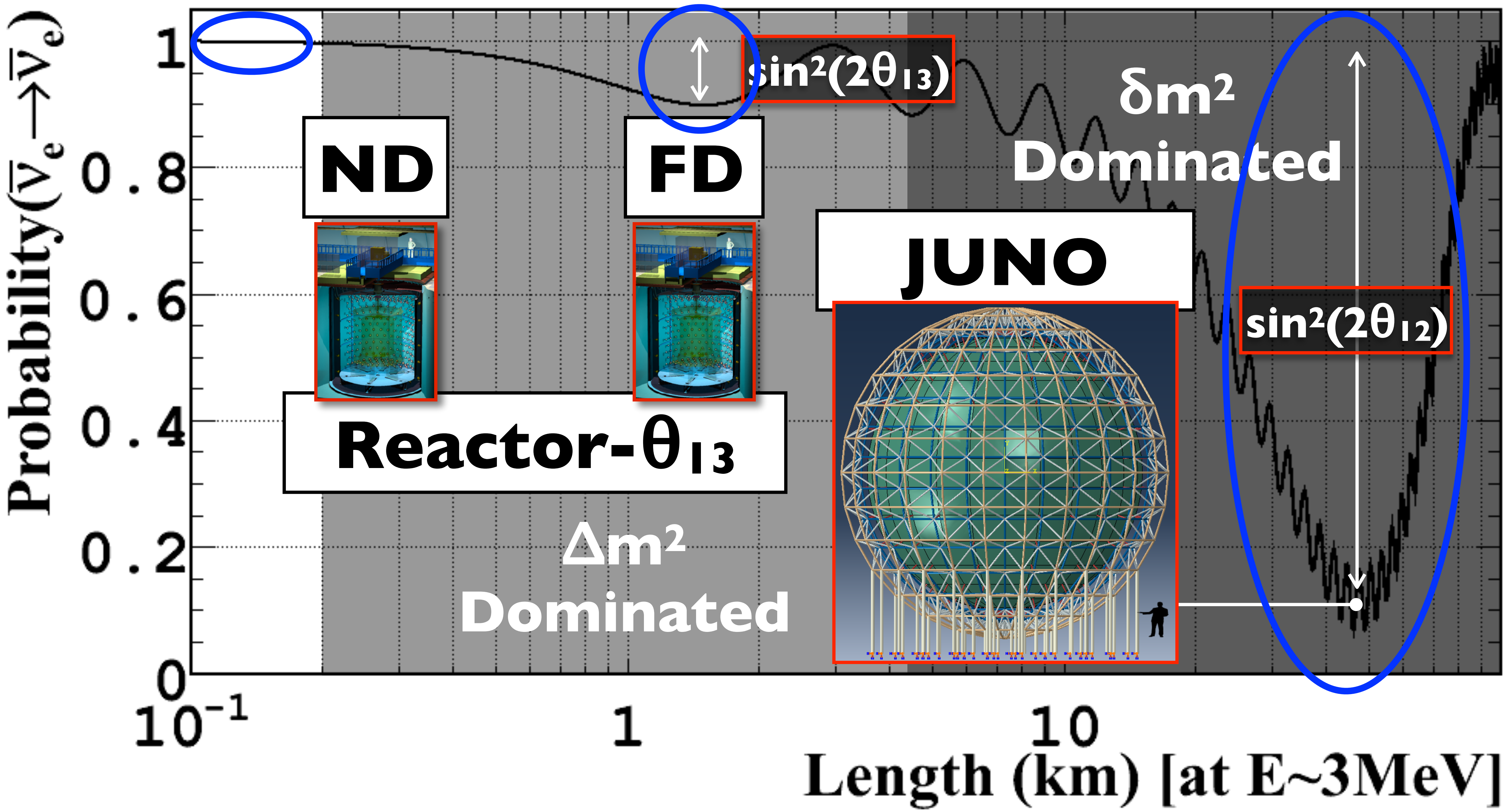
Nathal Severins (Leuven)
https://indico.lal.in2p3.fr/event/5418/contributions/17551/

Unitarity

(foreseen)



a long story short…



Unitarity: sensitive to **flux**, $\boldsymbol{\theta_{13}}$ and $\boldsymbol{\theta_{12}}$ [**all!**]

[non-unitary basis: "$\boldsymbol{\theta_{13}}$" & "$\boldsymbol{\theta_{12}}$" are meaningless]

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the electron-raw unitarity ingredients…

- **sensitive to θ12→ δ<1.0% [if unitary]**
  [**JUNO**, SNO, ~~KamLAND~~]

- **sensitive to θ13→ δ≈1.5% [if unitary]**
  [~~JUNO~~, ~~DUNE~~, **reactor-θ13**]

- **flux→ δ≳3.0% (6.0%)**
  [“ν” vs “non-ν reference”]

θ_{13}

summary on today's θ13 knowledge/experiments…

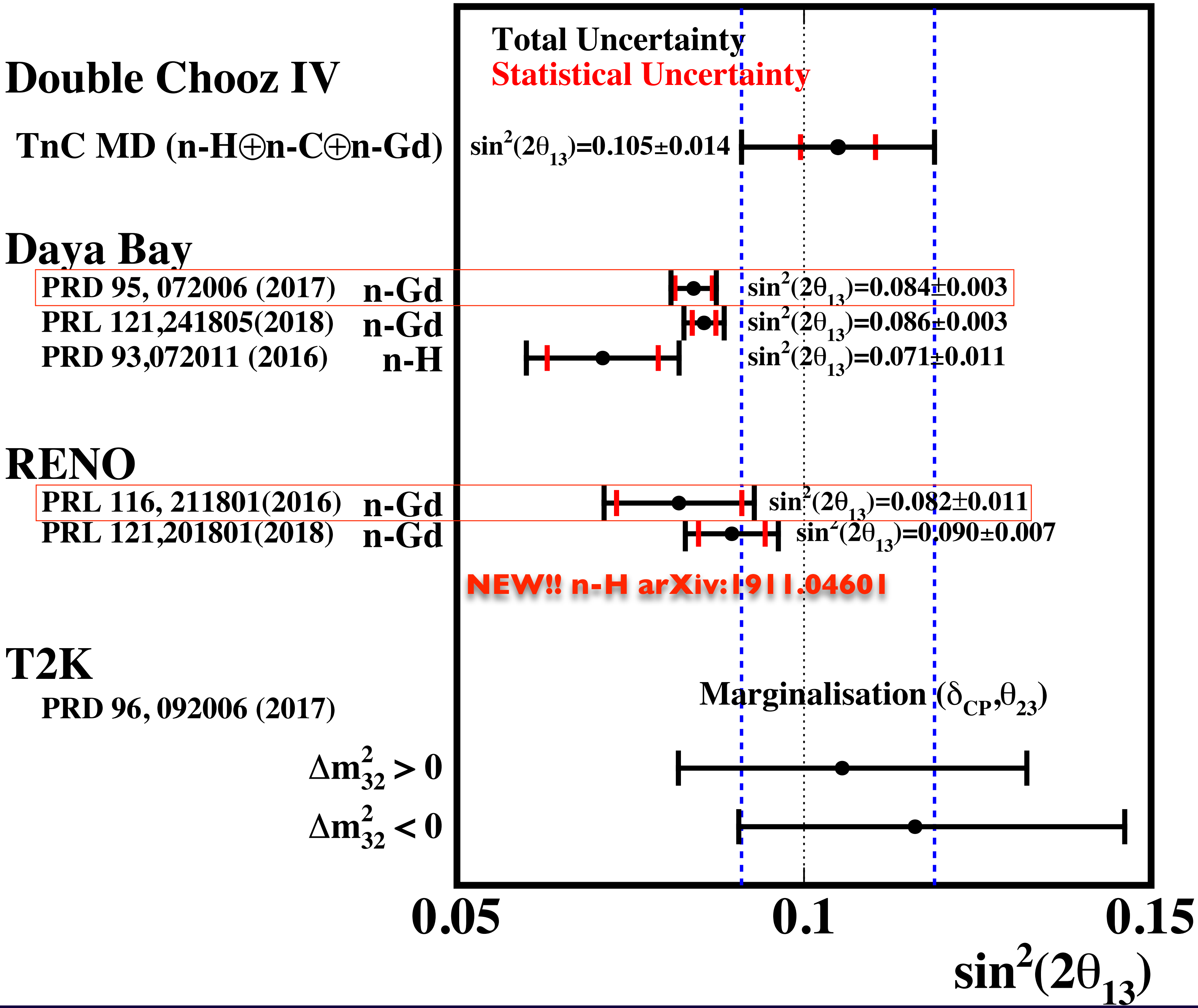
reactor-θ13 experiments
[DC⊕DYB⊕RENO]

•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)
possible at all?

2019 world status in θ13…



slightly higher θ_{13}

before
(~2016)
↓
after
(@Nu2018)

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

Submissions

nature physics

ARTICLE

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

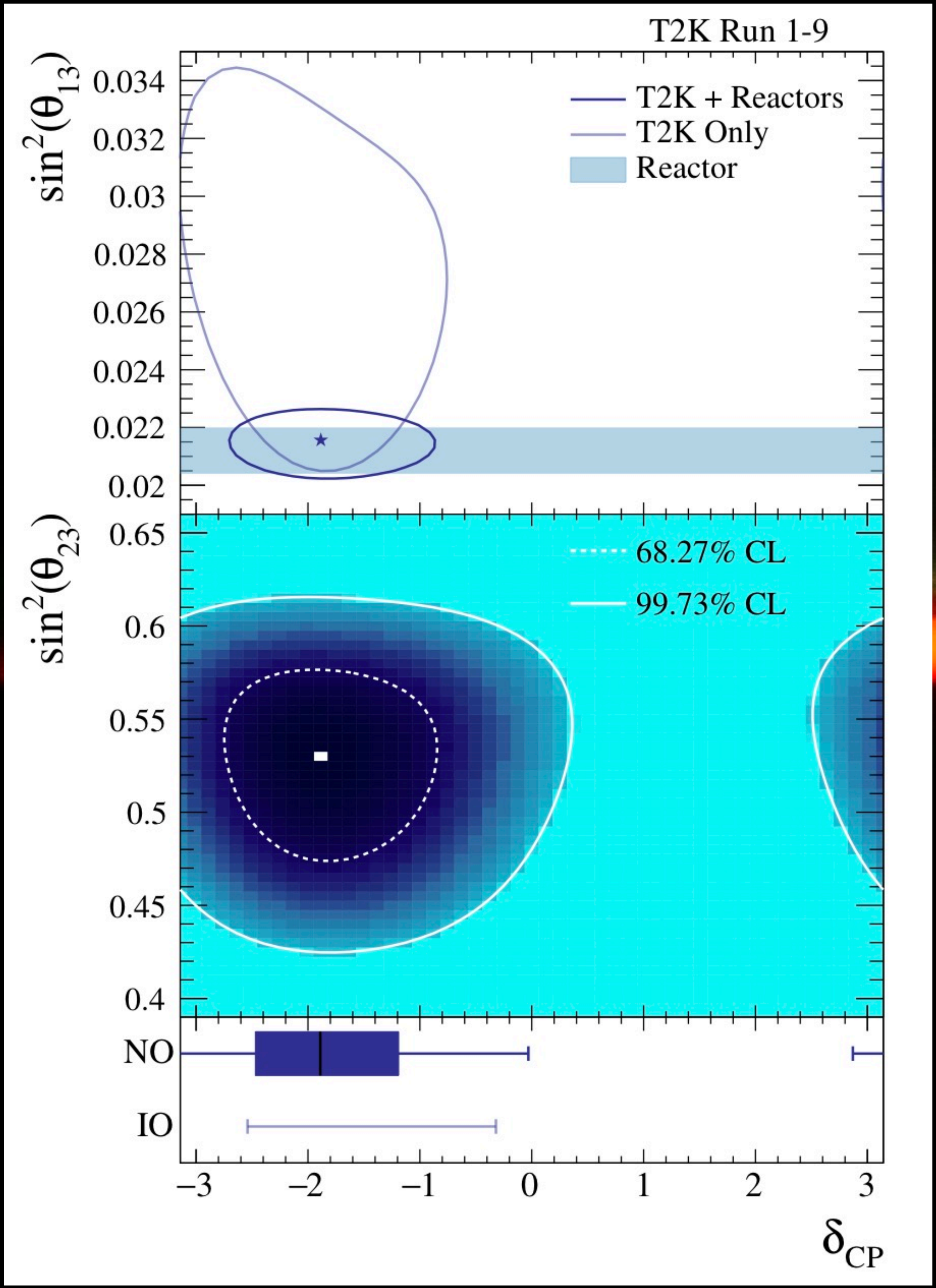
NO?

(we don't know how)

θ_{13}

improvable?

T2K⊕reactor best knowledge CP-Violation…



θ13 implications

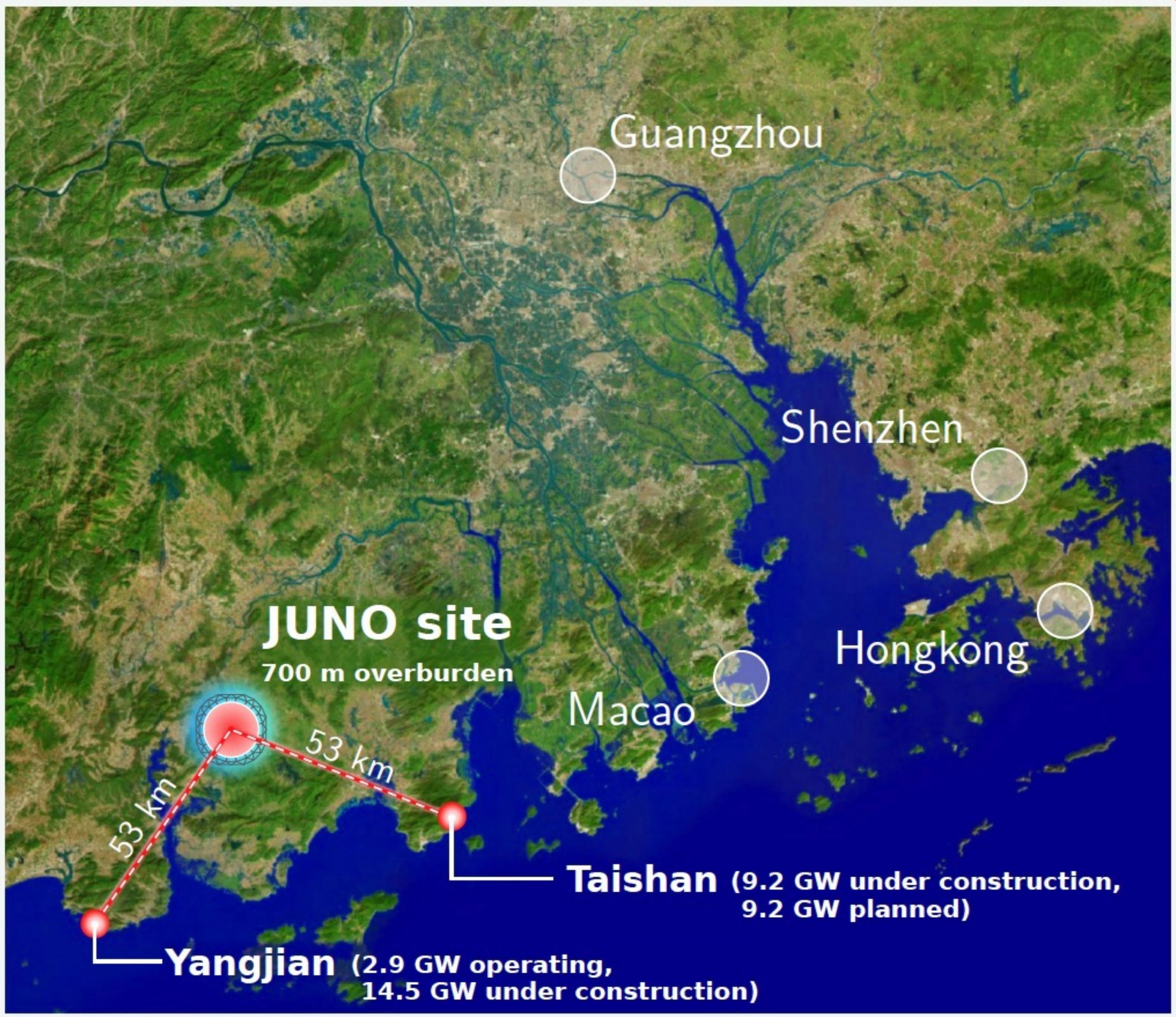
CPV phase vs θ13
[constrained by reactor]

CPV phase vs θ23
[octant ambiguity]

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

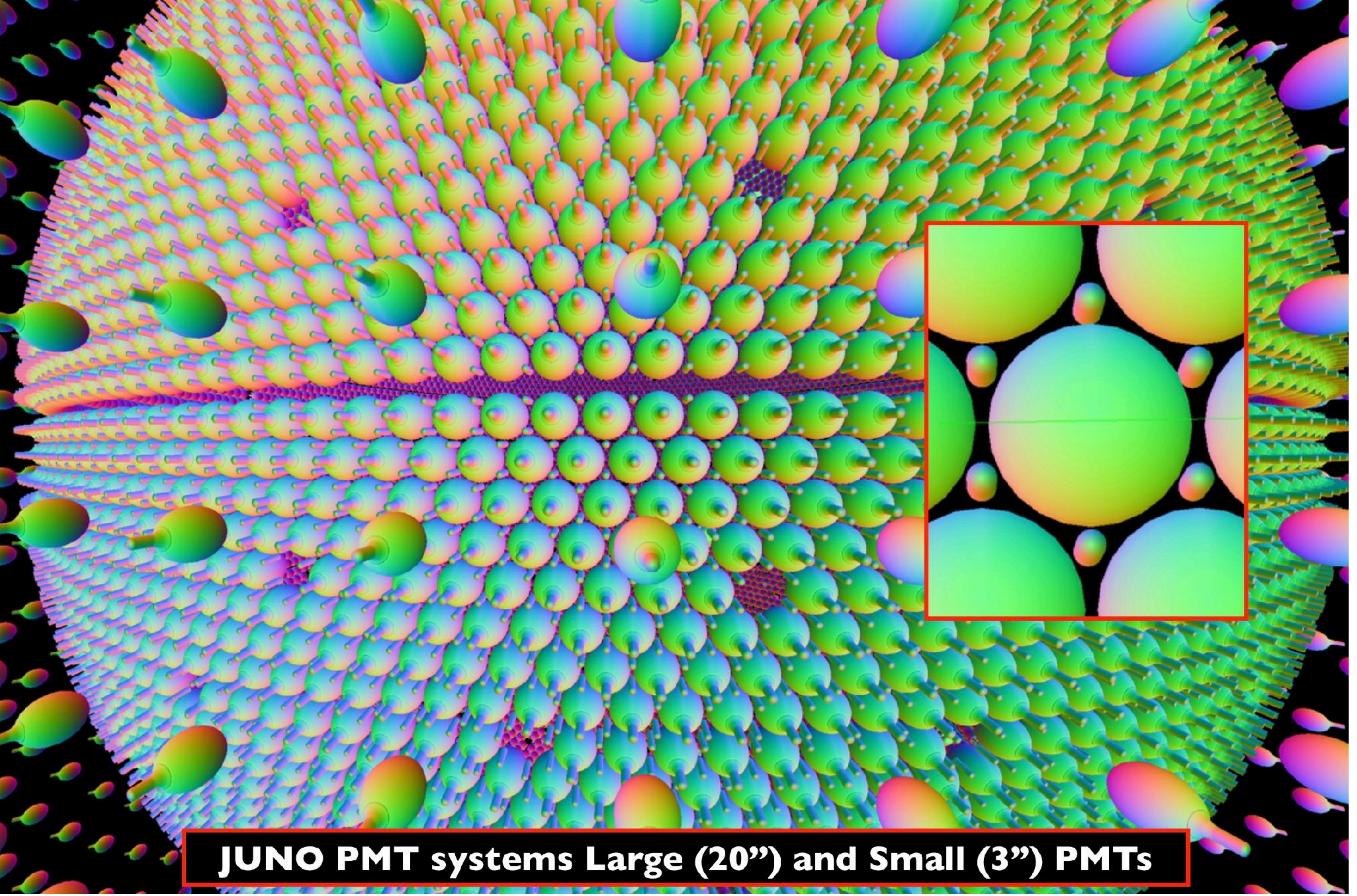
JUNO $= \theta_{12}$

JUNO location…



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

JUNO collaboration…



JUNO a photocathode colosso→ yield energy resolution!

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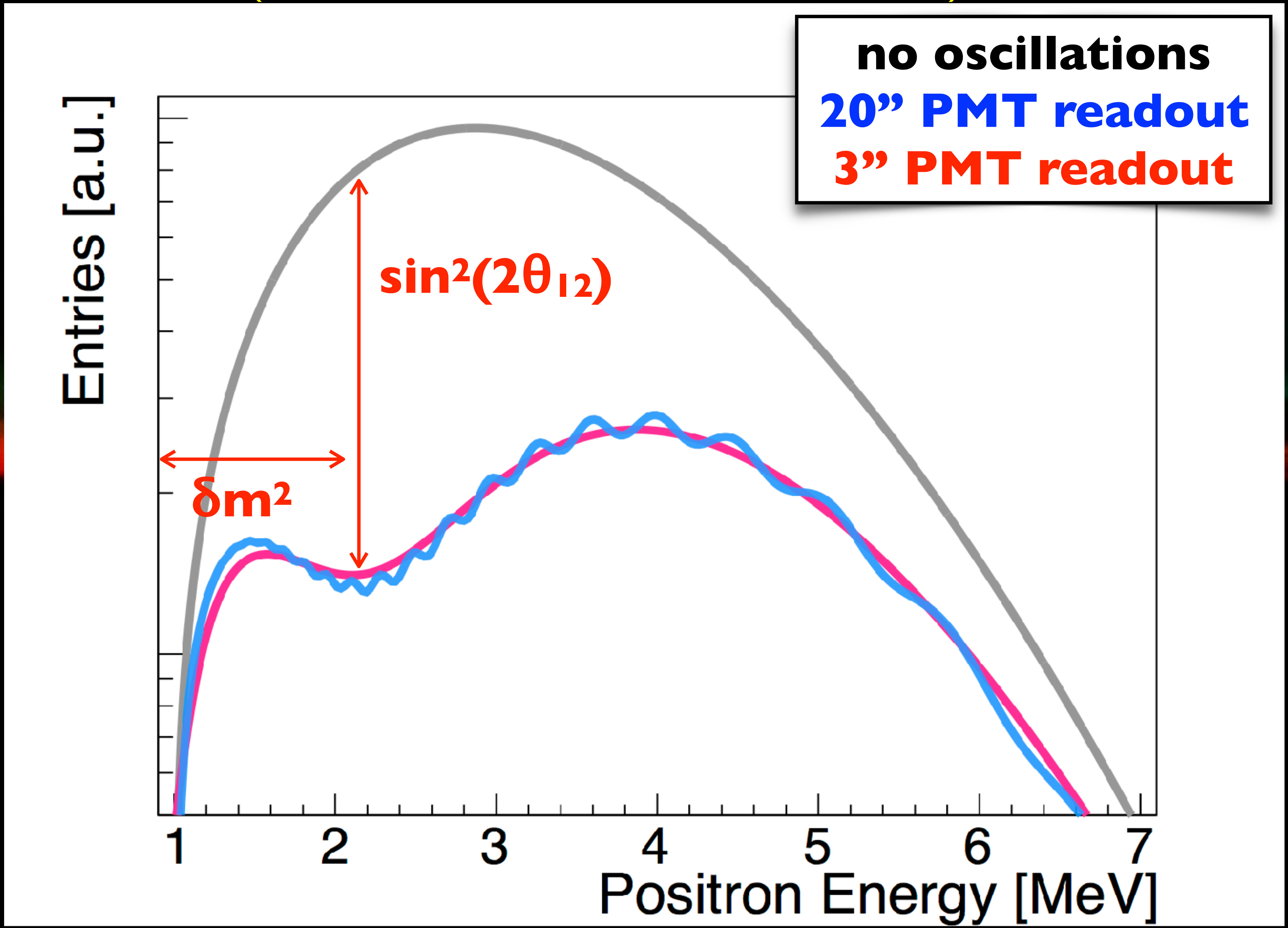
"solar" oscillation watch by 2 readouts…

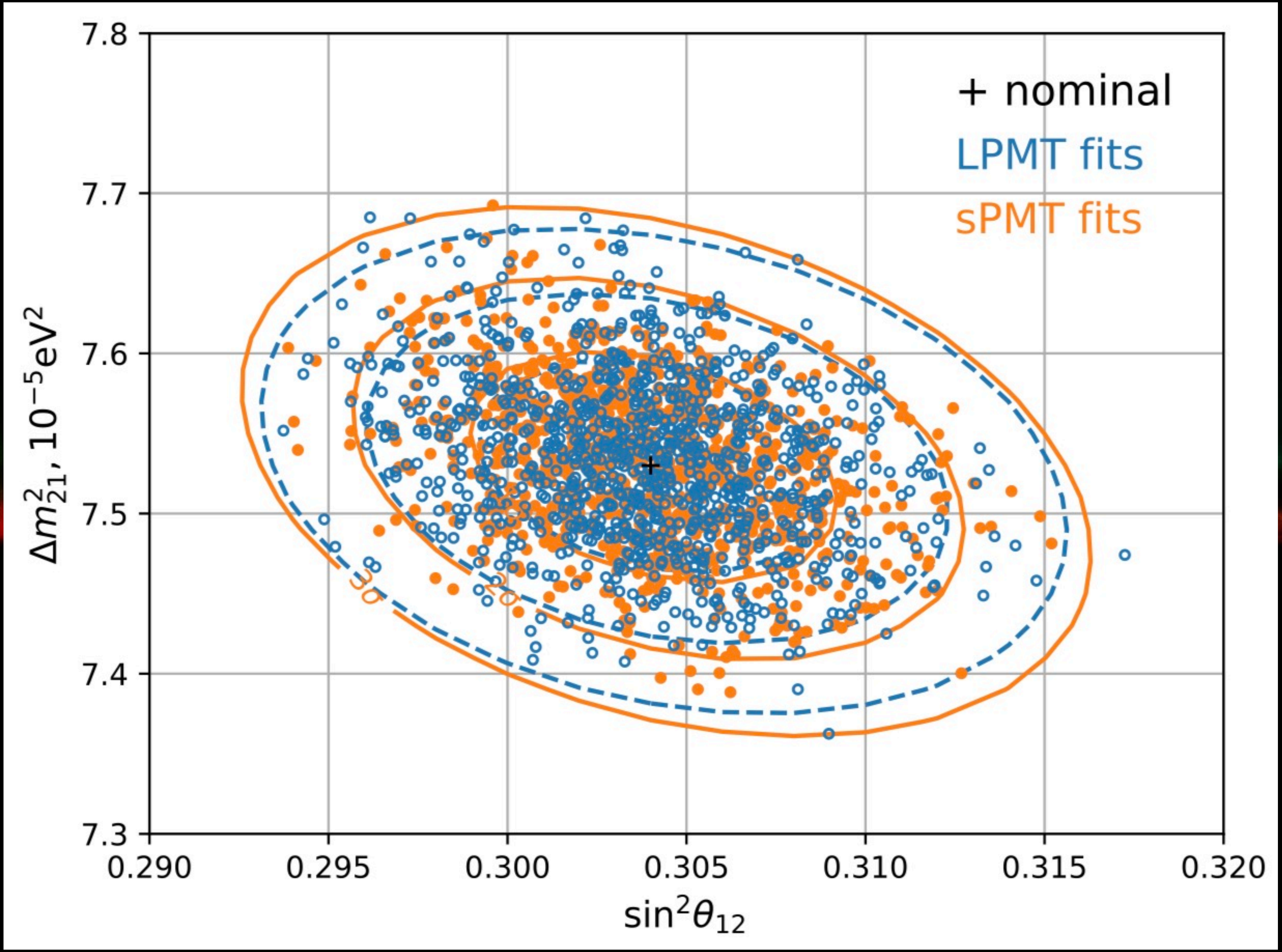
SPMT sees the "solar" oscillation

(fast oscillation washes out)



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

LPMT vs SPMT comparison…



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

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

unlikely

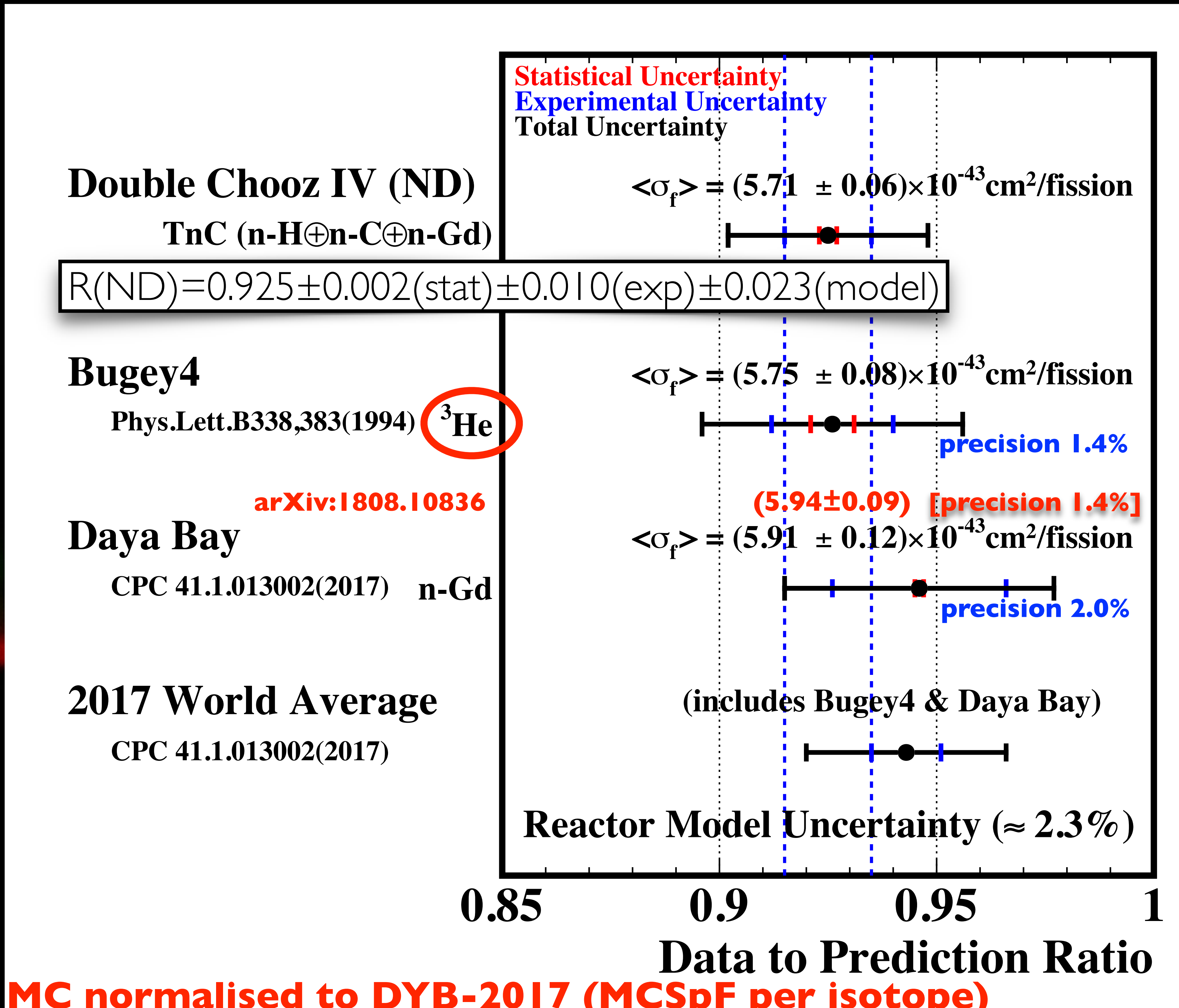
θ_{12}

improvable?

ϕ_{reactor}

2019 world reactor flux knowledge…

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



best world precision (9.7‰)

Mean Cross-Section per Fission

≈Φ(flux) [IBD σ known] δ≈0.2%

reactor flux data precision ≤1.0%

but ~7.0% ILL-based prediction mismatch!!

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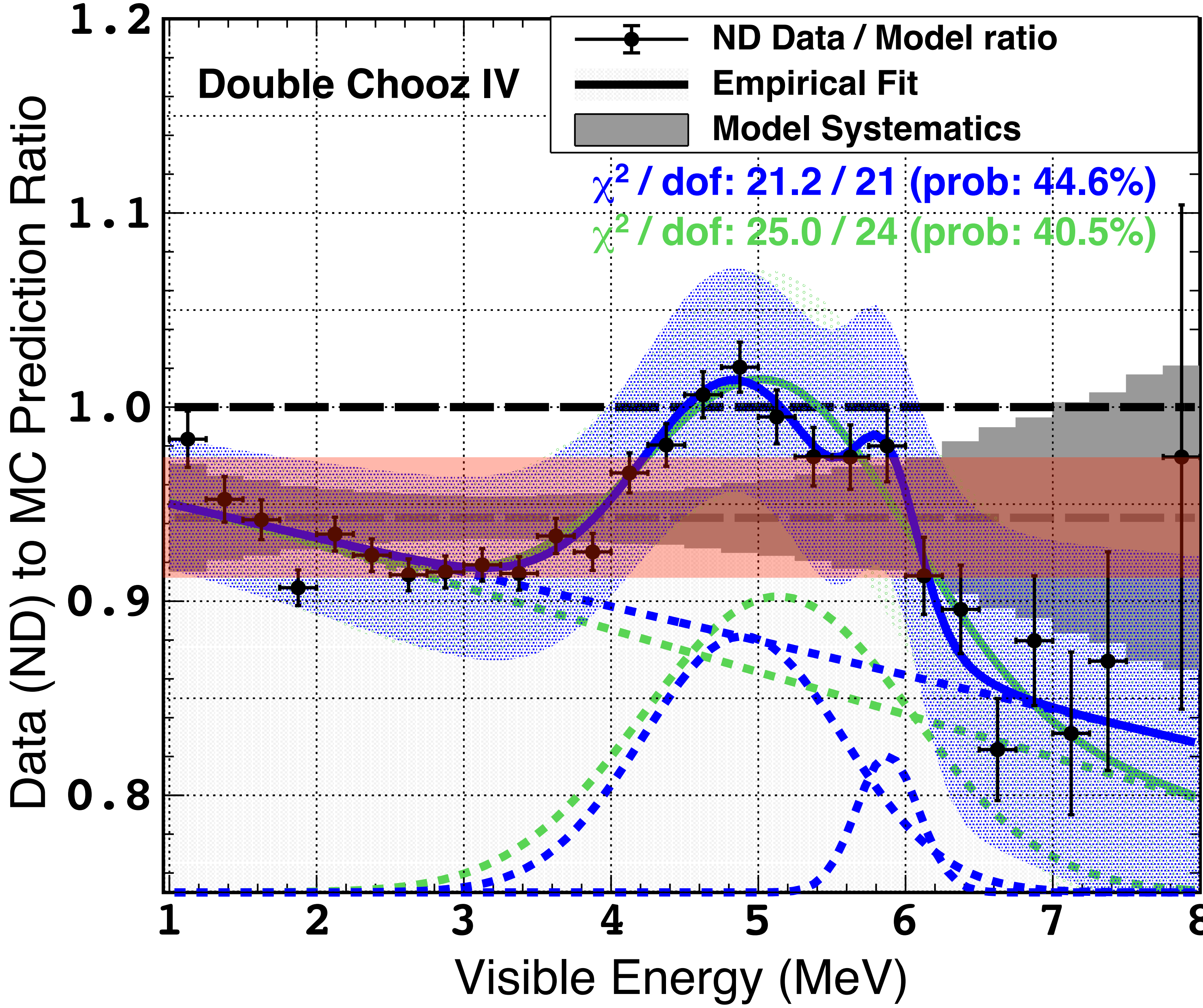
reactor flux uncertainty…

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



nor rate or shape understood

(unless new physics)

Uncertainty?

~3.0%→**6.0%**?

[≤10%]

Submissions

nature physics

ARTICLE

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

NO?
(we don't know how)

$\Phi_{reactor}$

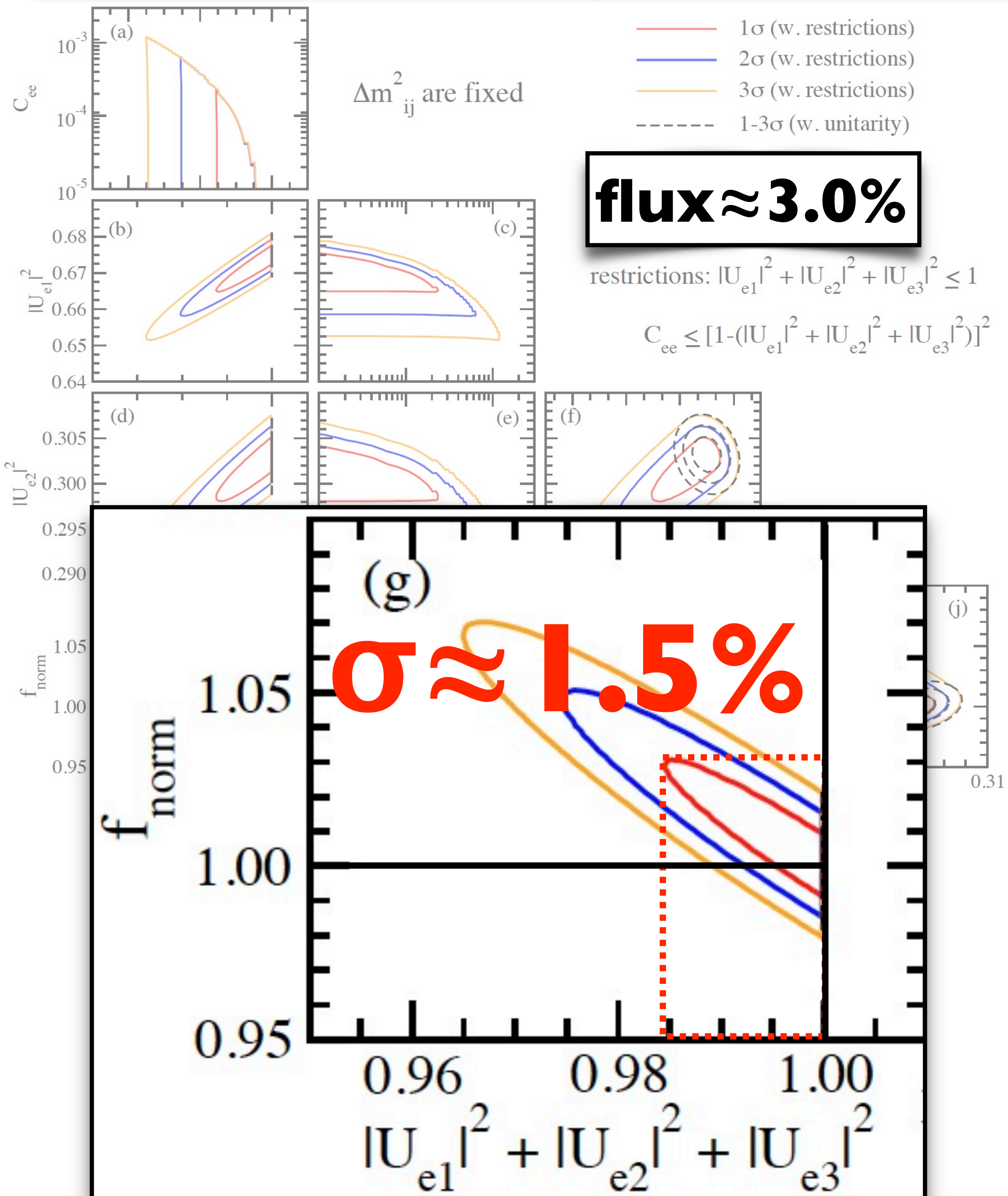
improvable?

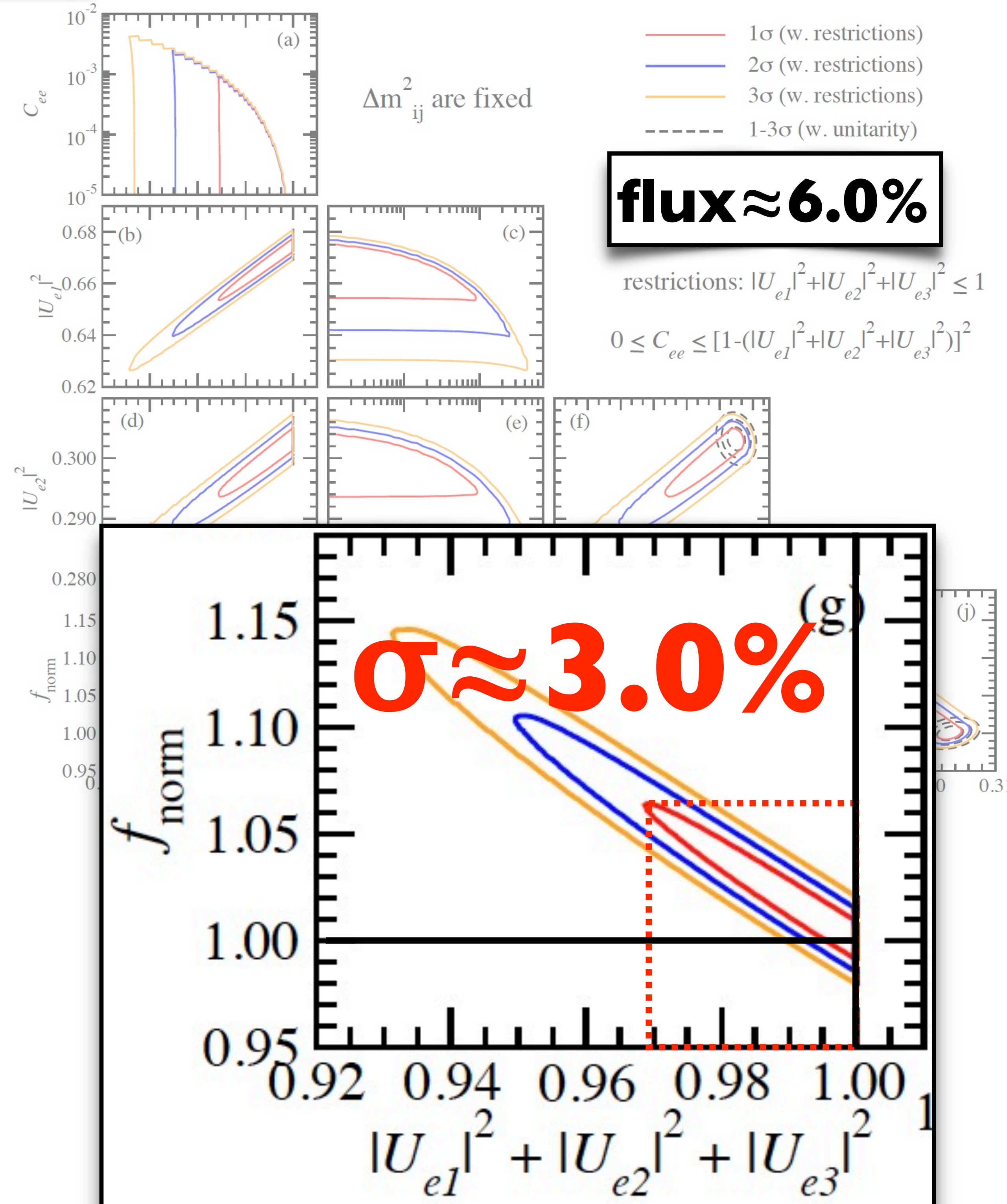
today's Unitarity knowledge…

Φ(reactor)⊕θ13(now)⊕θ12(JUNO)

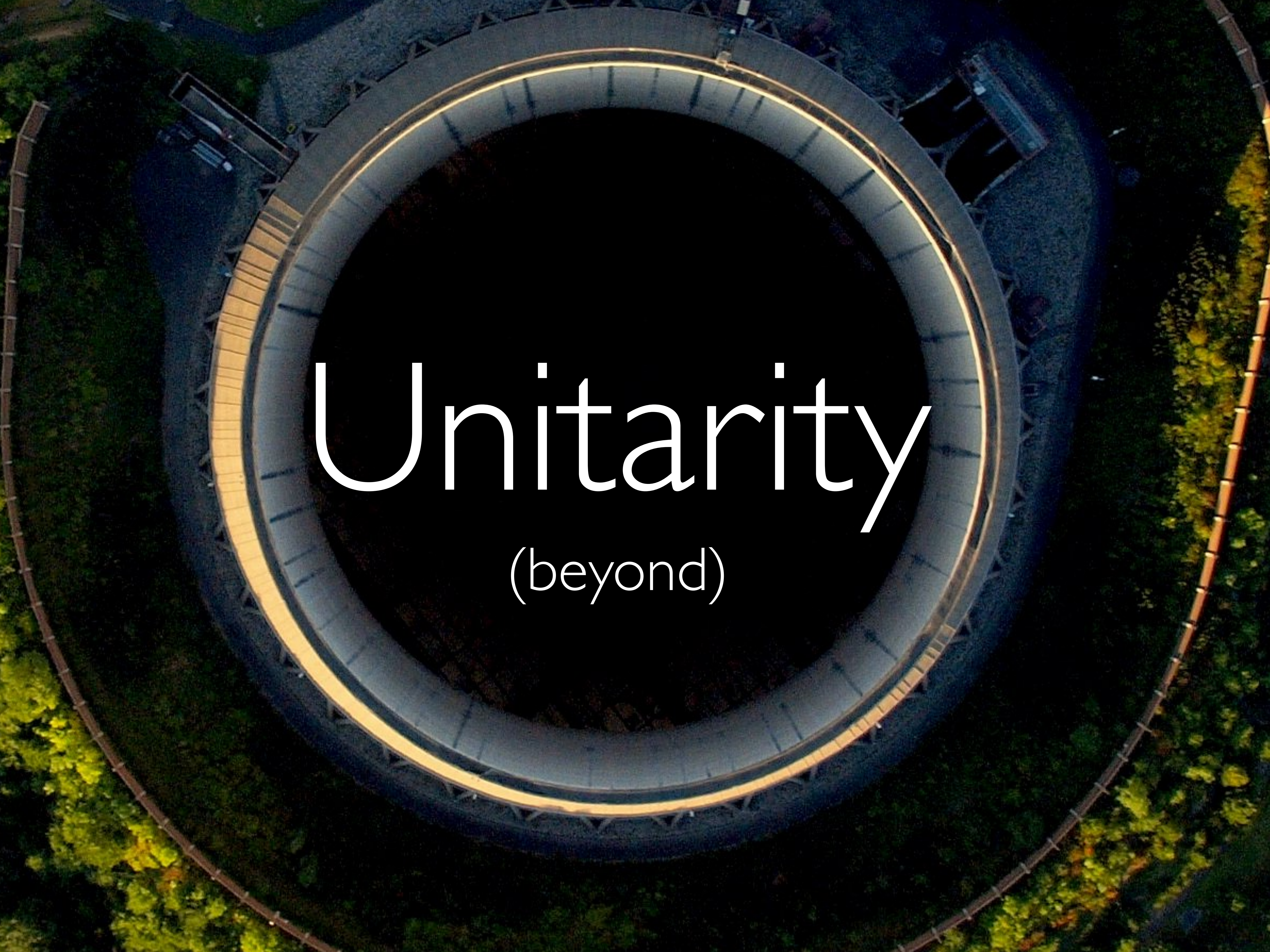
today's **top-row unitarity** knowledge…

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





even with JUNO, ≤1% precision very challenging


Unitarity
(beyond)

YES?

Unitarity

improvable?

the electron-raw unitarity ingredients…

- **sensitive to $\theta 12 \rightarrow \delta < 1.0\%$ [if unitary]**
  [**JUNO** + **improvable solar?**] **under study (appetiser)**

- **sensitive to $\theta 13 \rightarrow \delta \approx 1.5\%$ [if unitary]**
  [**improvable?**] **address here**

- **flux $\rightarrow \delta \gtrsim 3.0\%$ (more likely 6.0%)**
  [**improvable?**] **under study (not yet)**

today's unitary precision → flux normalisation critical

news!

θ_{13}

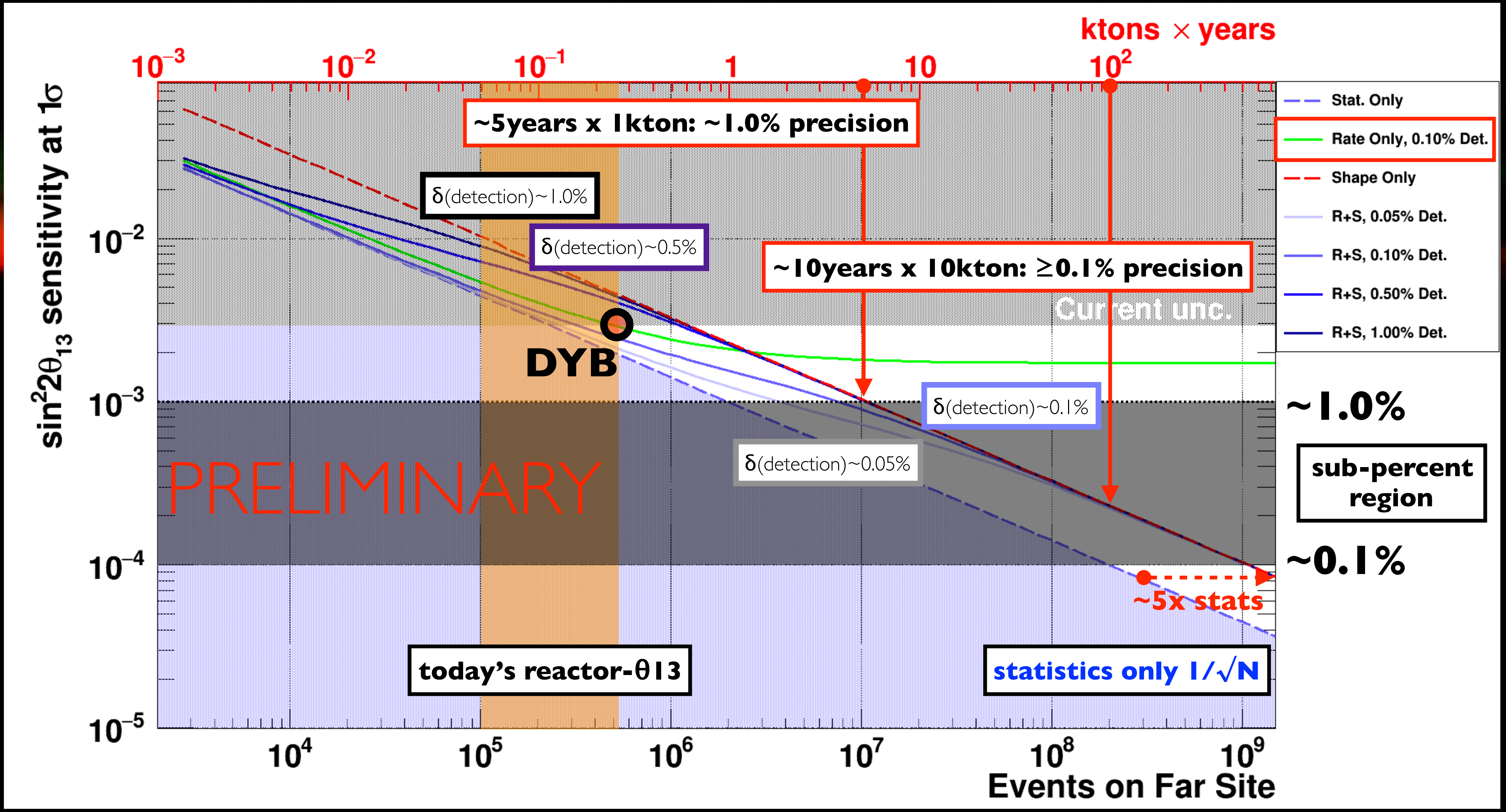
improvable!

review reactor θ13 sensitivity evolution…

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

•statistics: ≥10⁷ (far) [≳20x today]
•detection systematics (~today: ~0.1%)
•energy control (<1% precision)
⇒ flux & BG systematics→ new techniques!!

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



translator: 1 kton implies ~2x10⁶ IBD/year→ **~4 IBD/min** [~50x today]

improving possible...

<u>rate</u>+shape→rate+<u>shape</u>

(today) **(new)**

subtle by powerful difference!

(rate systematics→negligible)

From Double Chooz to Triple Chooz — Neutrino Physics at the Chooz Reactor Complex

P. Huber[a], J. Kopp[b], M. Lindner[c], M. Rolinec[d], W. Winter[e]

arXiv:hep-ph/0601266v1 31 Jan 2006

θ13 systematics: need for new techniques…

larger statistics→ shape-driven info (systematics) matters
is this good enough? no!!

- **detection:** believed impossible to improve [**irreducible**]
- **flux:** BIG trouble→**must fully cancel**
- **BG:** must suppress >10x→**more overburden?**

	<2010	today	>2025		cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	<0.01% (large)		**[25,250]k** IBD/day
detection	2.0 %	~0.1%	**~0.1%** just about possible	✓DC & ✓DYB	today's knowledge
energy	few %	~0.5%	—	**~0.5%**	today's knowledge
flux	~2.2%	**~0.1%**	**<0.01% (new)**		**full cancellation**
BG	few %	**~0.1%**	**<0.01% (new)**		**BG suppress >10x**

new techniques needed to yield δ(flux)→0 & δ(BG)→0!!

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

- **flux cancellation (!)**
- **BG elimination (!!!)**

tough requirements… possible?

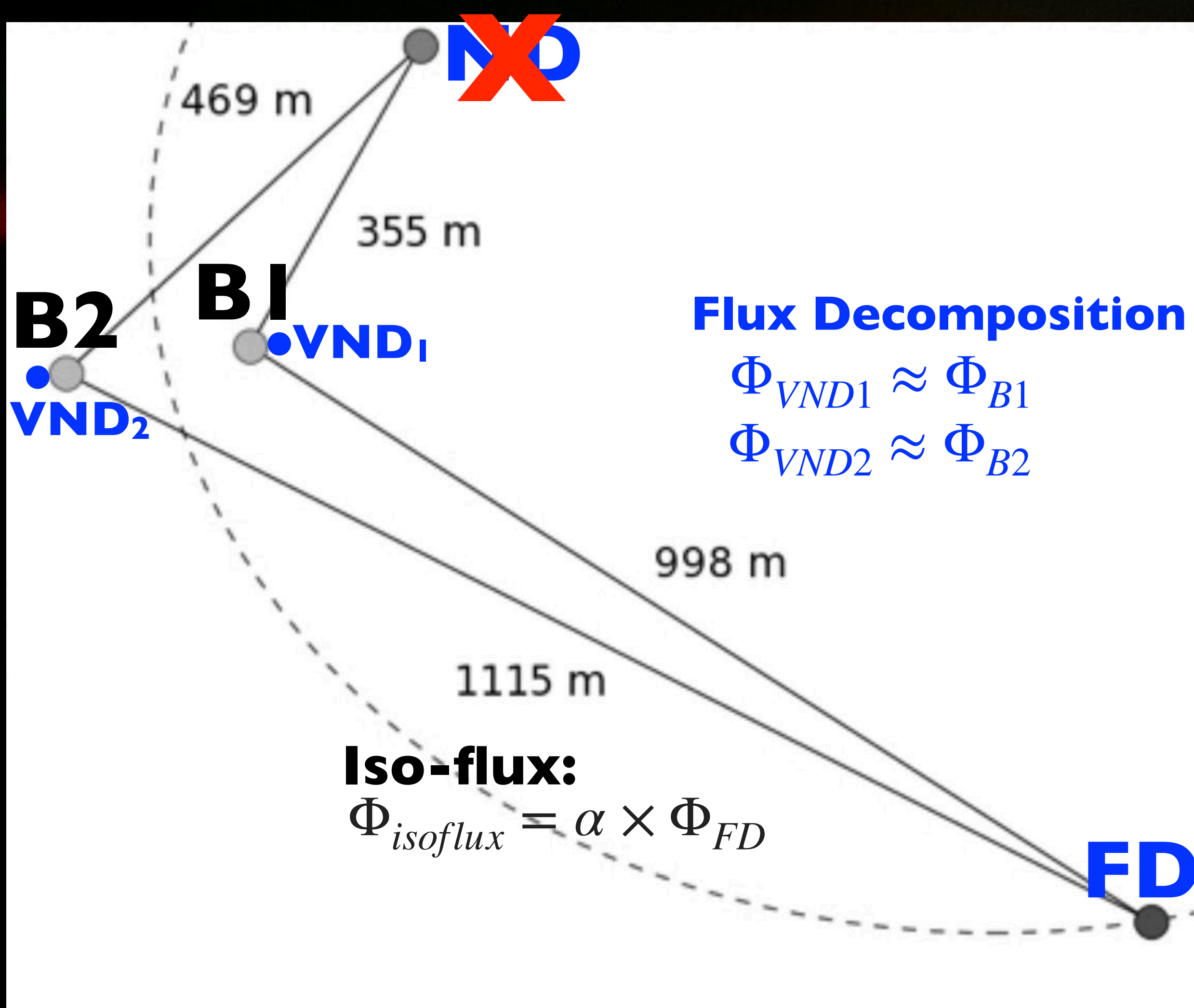
flux handled by the power of geometry…

today's flux knowledge converges: BIG ISSUE!

reactor prediction is <u>inaccurate</u> (few %)
[unsurprisingly more complex than we thought]

rate off by ~7% [deficit] & shape off by up to ~15% [distortion]

⇒our knowledge >6%(?) [claimed ≲3% is very unlikely]



monitor rate+shape cancels: how?

- **conventional ND: not good enough!**
  - →<u>degeneracy flux & θ13</u> (also far & small)
  - →slight offset to iso-flux
- **flux decomposition (L≲40m): perfect!**
  - →**very near detector** (**VND**) per reactor
  - →<u>huge statistics</u>: 1ton @ 20m: 8.2k IBD/day
  - →<u>no civil construction</u> [→**reactor space?**]

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

✓ • **flux cancellation**
• **BG elimination (!!!)**

tough requirements… possible?

how to reduce BG with no more overburden?

lesson: avoid civil construction…

Liquid

a novel neutrino detection

signal: e+

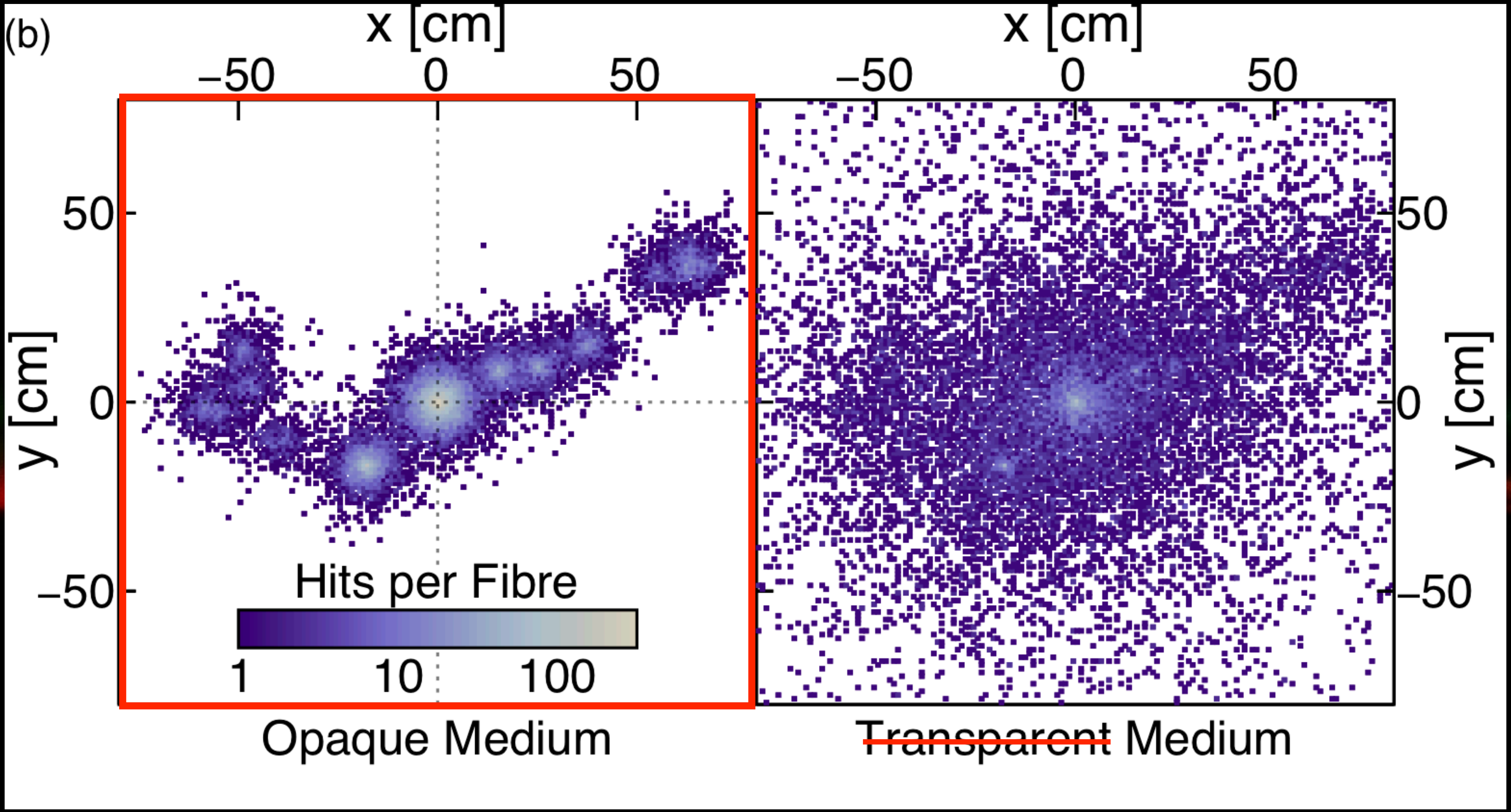
cosmogenic (^{9}Li & fast-neutrons)

accidentals (β^{-}, γ and α)

BG active rejection $\gtrsim$100x

[time⊕space coincidence & PID(e+)]

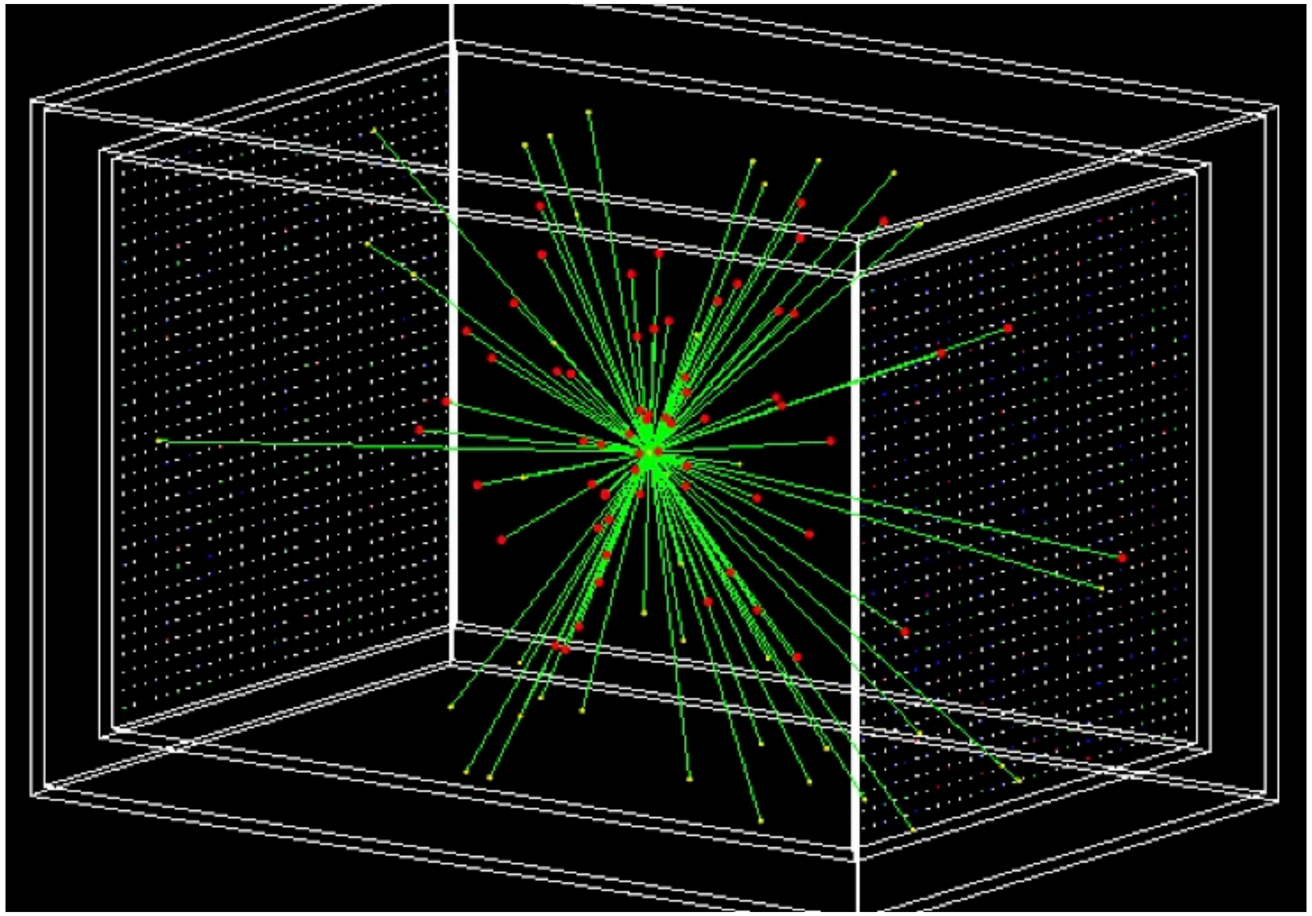
LiquidO event-wise imaging…



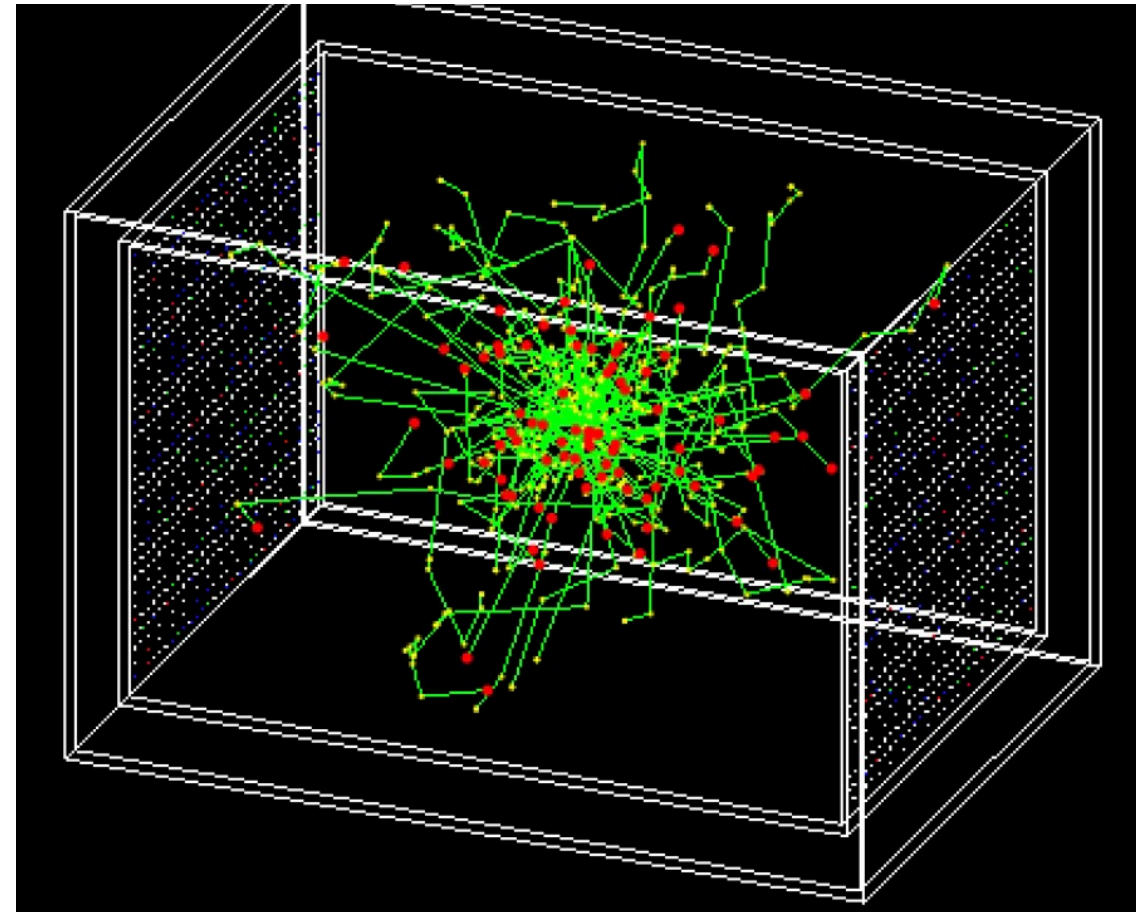
opaque scintillator→stochastic light confinement

(**self-segmentation**)

LiquidO recipe: just "bread & butter" physics…



today's technology



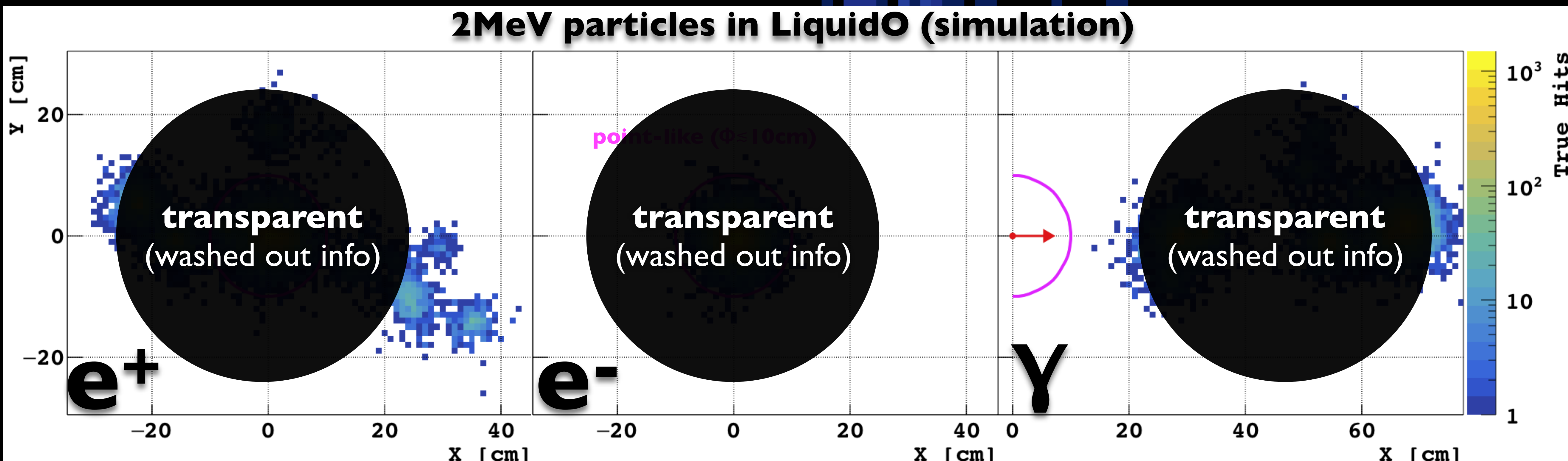
LiquidO technology

light ball size: scattering⊕fibres

(sampling optimisation)

LiquidO in a nut-shell…

Imaging→powerful Particle-IDentification (PID)

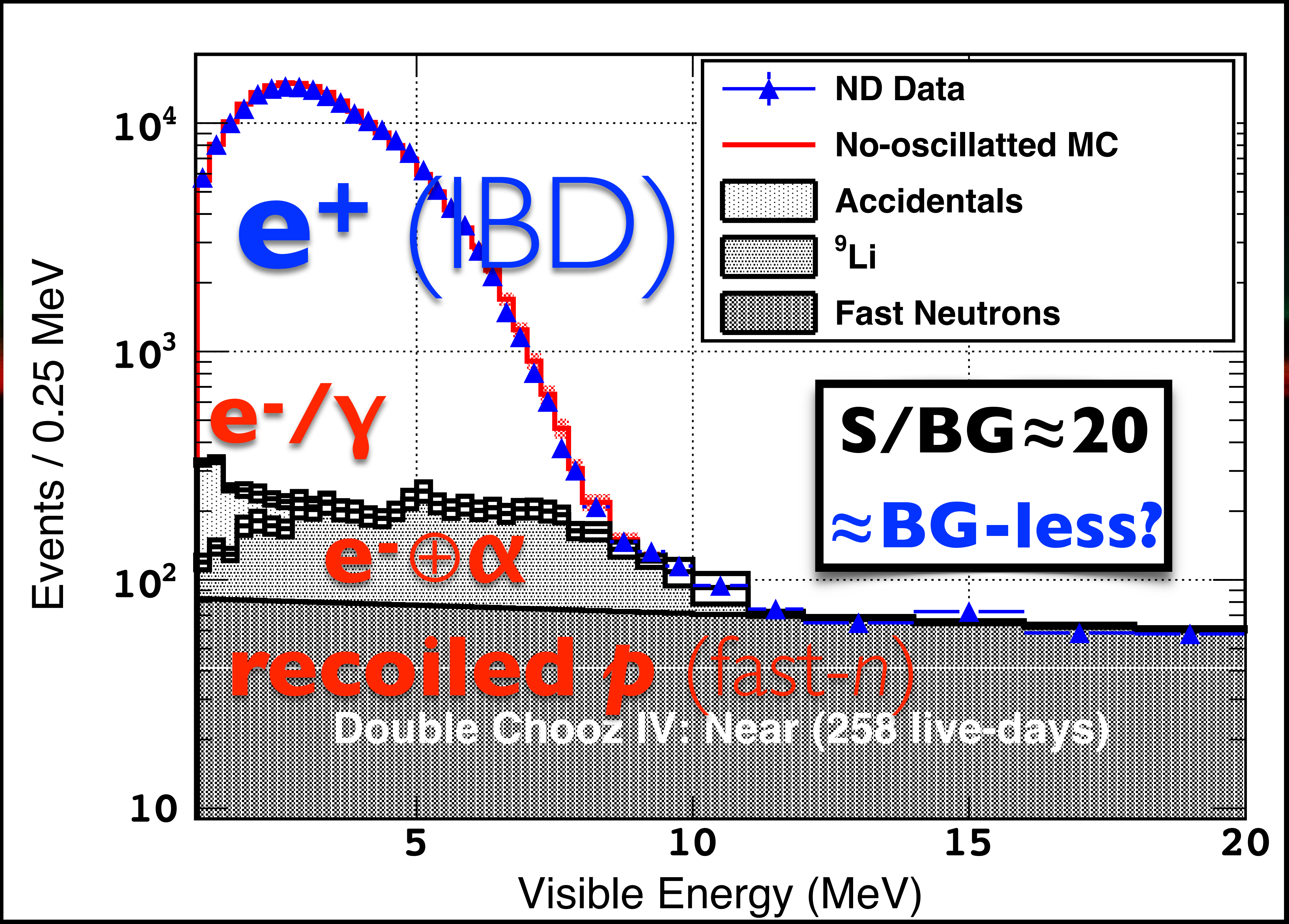


LiquidO ≈ PID ⊕ (high) Doping

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

diffusion⟹shaper images!

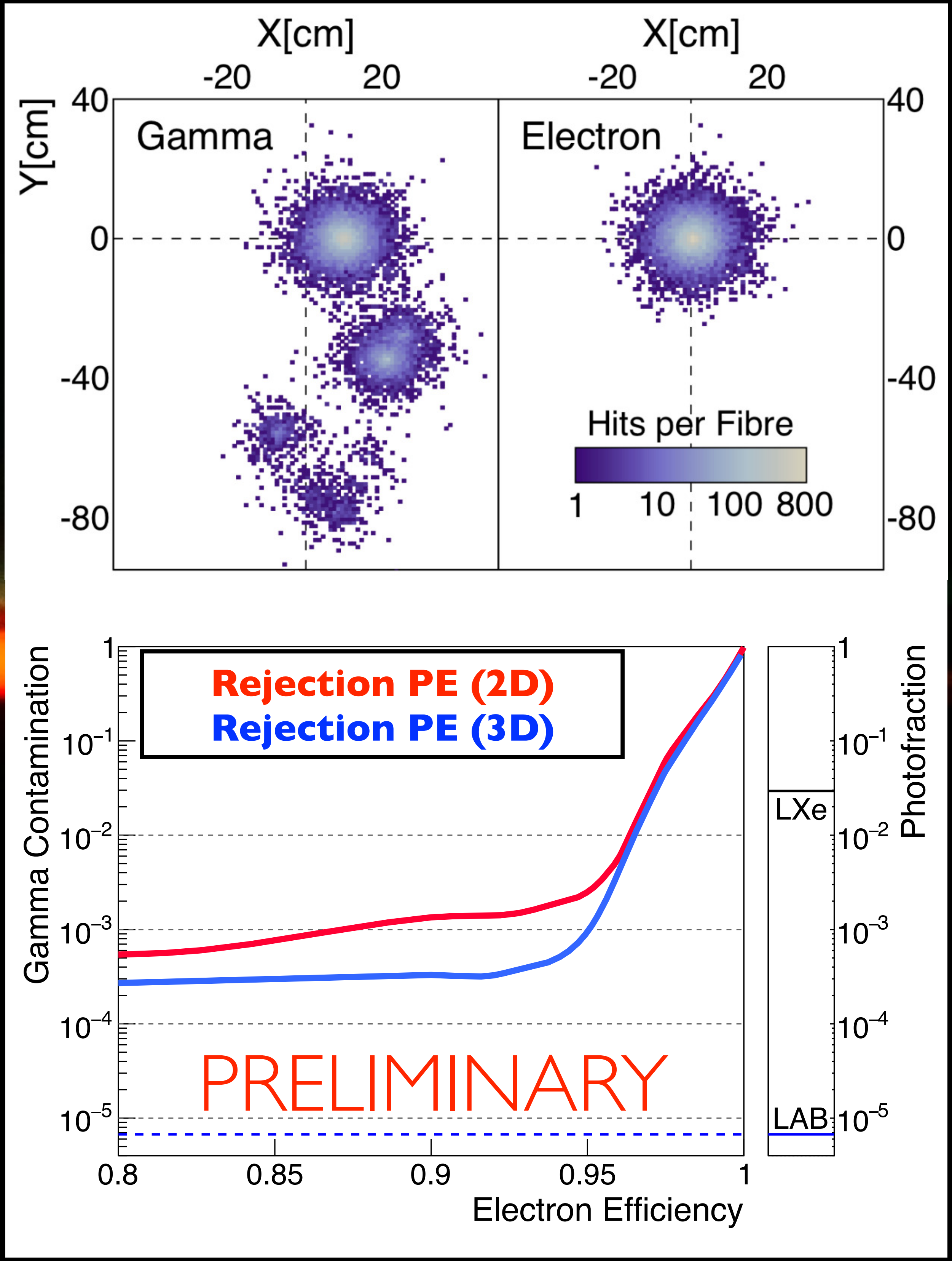
LiquidO→major active BG rejection
(born in reactor)



LiquidO: PID & background suppression…

Powerful PID:

- **≥10³ rejection** [2D only: no timing]
- **≥85% efficiency**



room to improve!

full release…

Neutrino Physics with an Opaque Detector

A. Cabrera*[1,9,10], A. Abusleme[15], J. dos Anjos†[3], T. J. C. Bezerra[18], M. Bongrand[9], C. Bourgeois[9], D. Breton[9], C. Buck[12], J. Busto[6], E. Calvo[5], E. Chauveau[4], M. Chen[16], P. Chimenti[11], F. Dal Corso[13], G. De Conto[11], S. Dusini[13], G. Fiorentini[7a,7b], C. Frigerio Martins[11], A. Givaudan[1], P. Govoni[2a,2b], B. Gramlich[12], M. Grassi[1,9], Y. Han[1,9], J. Hartnell[19], C. Hugon[6], S. Jiménez[5], H. de Kerret‡[1], A. Le Nevé[9], P. Loaiza[9], J. Maalmi[9], F. Mantovani[7a,7b], L. Manzanillas[9], C. Marquet[4], J. Martino[18], D. Navas[5], H. Nunokawa[14], M. Obolensky[1], J. P. Ochoa-Ricoux[8,15], G. Ortona[20], C. Palomares[5], F. Pessina[14], A. Pin[4], M. S. Pravikoff[4], M. Roche[4], B. Roskovec[8], N. Roy[9], C. Santos[1], A. Serafini[7a,7b], L. Simard[9], M. Sisti[2a,2b], L. Stanco[13], V. Strati[7a,7b], J.-S. Stutzmann[18], F. Suekane*§[1,17], A. Verdugo[5], B. Viaud[18], C. Volpe[1], C. Vrignon[1], S. Wagner[1], and F. Yermia[18]

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[3]Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, RJ, 22290-180, Brazil
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[10]LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France
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arXiv:1908.02859v1 [physics.ins-det] 7 Aug 2019

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.

*Contact: anatael@in2p3.fr and suekane@awa.tohoku.ac.jp.
†Also at Observatório Nacional. Rio de Janeiro, Brasil
‡Deceased.
§Blaise Paschal Chaire Fellow.

Seminar@CERN — June 2019

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

Igniting publication — Aug 2019

LiquidO @ arXiv:1908.02859

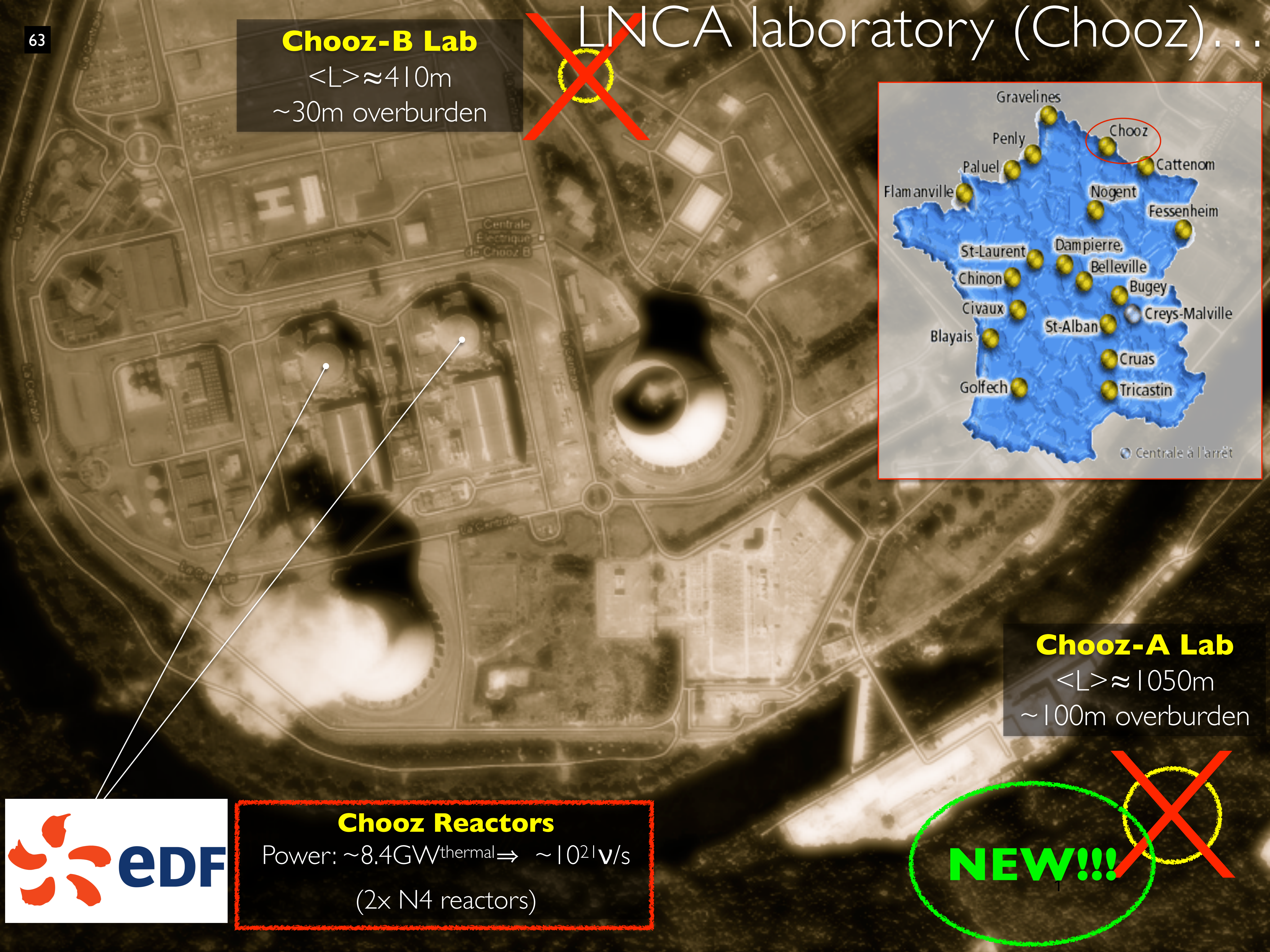
- new detection principle
- first experimental proof-of principle
- vast neutrino physics prospect

Submitted for Publication

First Opaque Liquid Scintillator @ arXiv:1908.03334

$\geq$10 000m^3 site ready?
($\leq$2km from powerful reactors)

LNCA laboratory (Chooz)...

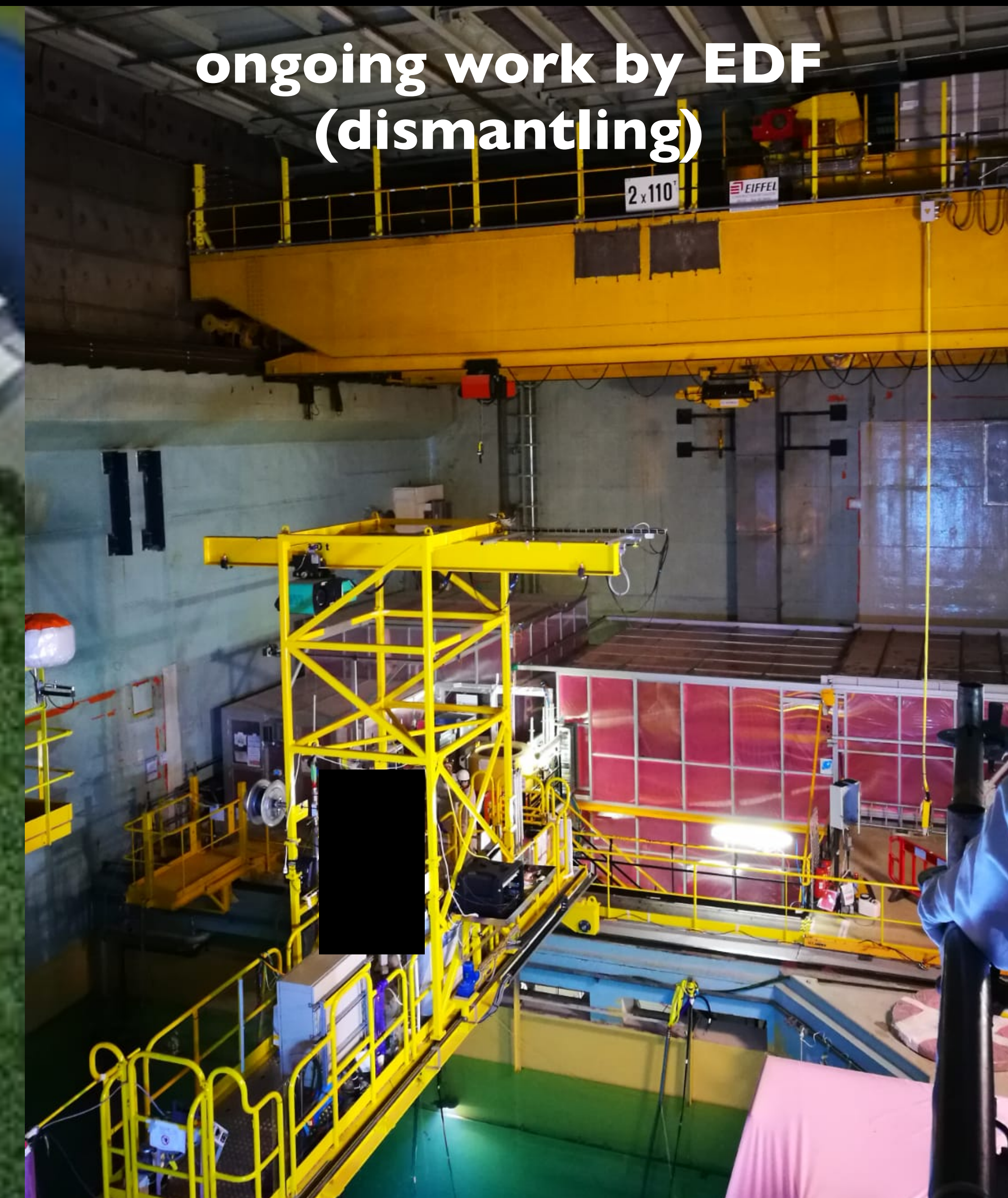


Chooz-B Lab
$\langle L\rangle \approx 410$m
~30m overburden

Chooz-A Lab
$\langle L\rangle \approx 1050$m
~100m overburden

Chooz Reactors
Power: ~8.4GW$^{\text{thermal}} \Rightarrow$ ~$10^{21}\,\nu$/s
(2x N4 reactors)

the Chooz-A underground system (former reactor)…



Cavern A: 20,000m³
[past: reactor Chooz-A]

Cavern B: 30,000m³
[past: fuel pool]

⇒ ≤10kton detector ⊕ water veto pool (which?)

Overburden: ~100m (**known BGs!**)

Civil Construction?

- minor refurbishment (remove structure)
- heavy cranes ready

Available? If so, around ≳2025


SuperChooZ?

much physics beyond θ_{13}…

full menu (under construction)

- **sub-percent precision on $\theta13$** [sin2(2θ13)] **& Δm^2(reactor)** [not shown yet]
  [aid DUNE⊕HK to improve **CP-Violation** & JUNO to measure **$\pm\Delta m^2$**(vacuum)]

- **burst & remnants supernovae ν_e, anti-ν_e and ν_x measurement**
  [10 kton & high efficiency]

- **multi-channel proton decay**
  [10 kton & high efficiency]

- **high precision reactor rate+shape spectra (B1 and B2) with VND's**
  [statistics & complementary to JUNO's TAO]
  ⇒demonstration of reactor monitor technology (high S/BG ~1ton detectors) [**industry?**]
  ⇒reactor spectral composition analysis upon switching ON/OFF (better reactor predictions?)

even more challenging thoughts…

- **measure solar neutrinos?**
  [unprecedented 10 kton precision with CC interactions]

- **measure θ_W via elastic scattering?** (interference CC & NC)
  [β^- BG is extreme challenge even with LiquidO but huge signal rate and ON/OFF helps]

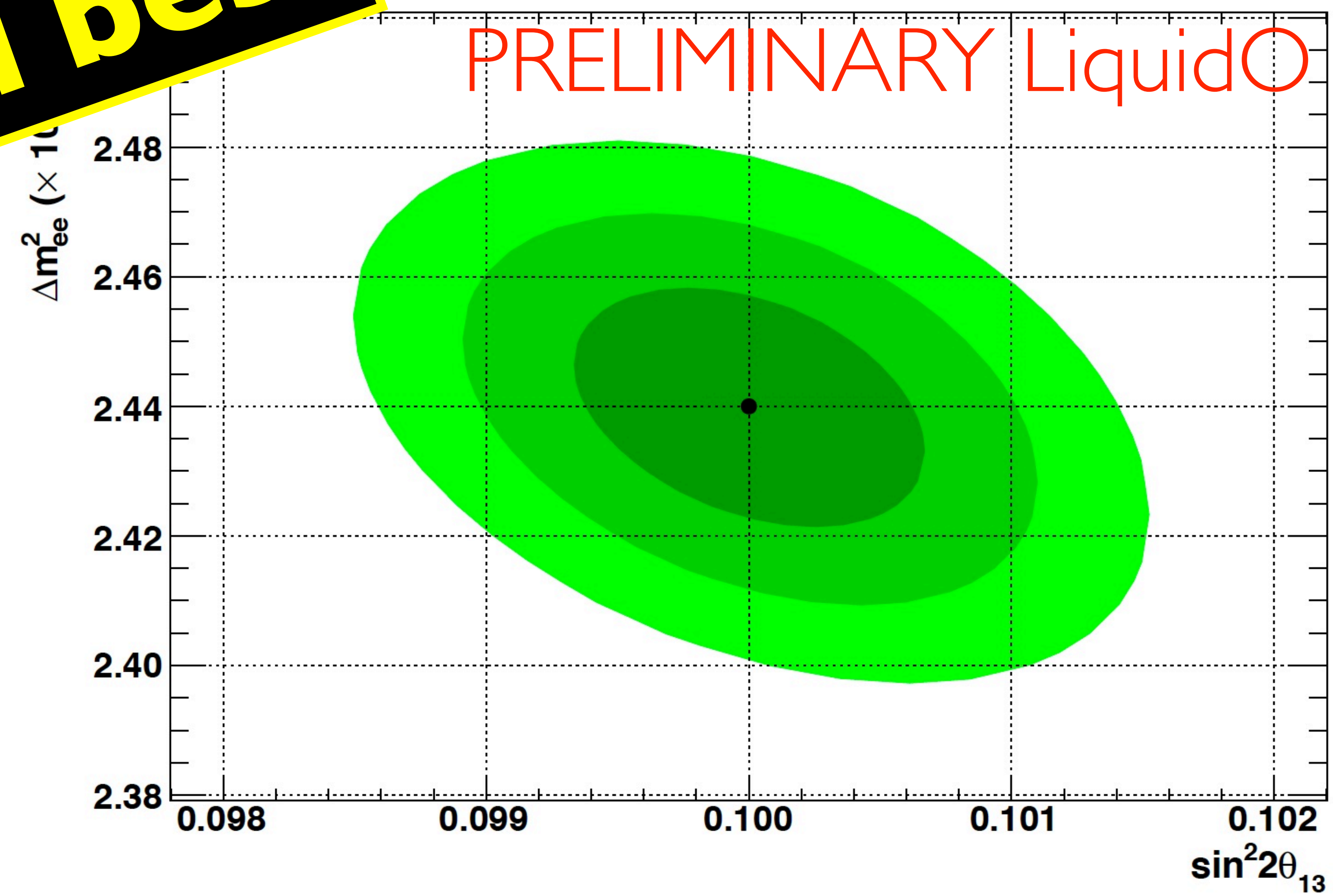
- [bad news] **geo-neutrinos unlikely** ⇒ huge reactor-IBD BG…

note: PMNS Unitarity test ("top-electron-row")→ solar & other constraints: **a full programme?**

overall θ13⊕Δm²(ee) sensitivity…

Input Δm^2_{ee} unc.	Output Δm^2_{ee} unc.	$\sin^2 2\theta_{13}$ unc.
1%	≤0.5%	≤0.5%
Free		

world best



[first time] sub-percent measurement of θ13⊕Δm²(ee)

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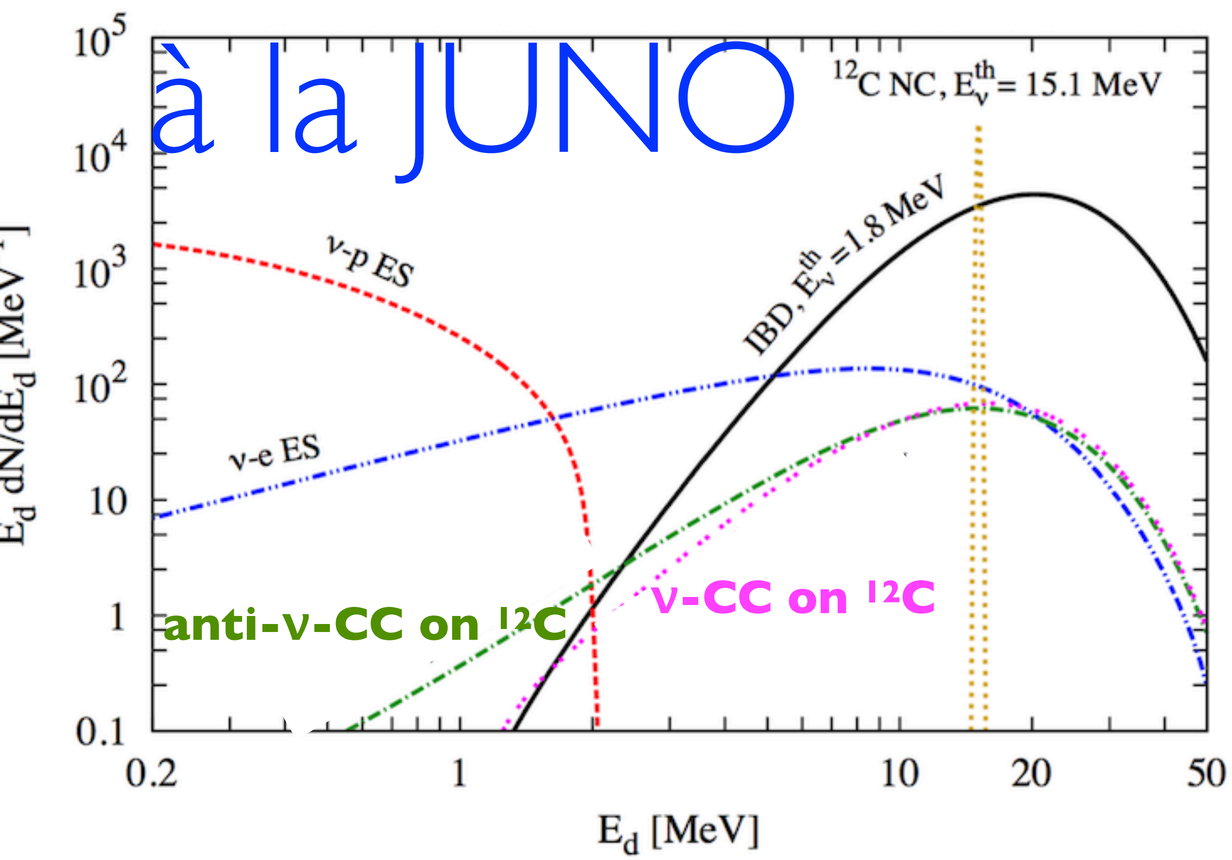
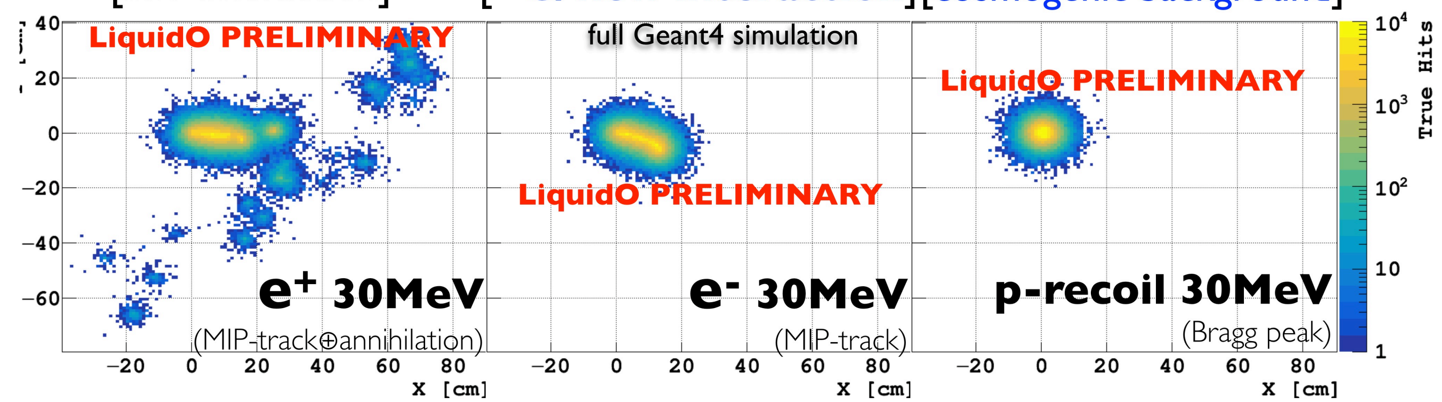
Supernova at 10 kParsec

$\langle E_{\nu_e}\rangle = 12$ MeV, $\langle E_{\bar{\nu}_e}\rangle = 14$ MeV and $\langle E_{\nu_x}\rangle = 16$ MeV.



Visible Energy [MeV]

e+ ⇔ anti-ν(e) [IBD interaction] | **e- ⇔ ν(e)** [**^{12}C/new interaction**][cosmogenic background] | **p-recoil**



IBD	**ES(e)**	**ES(p)**
ν CC (^{12}C)	**ν CC (^{12}C)**	**ES(e)** [low energy]
		fast-neutron (BG)
core-collapse relic	**core-collapse relic?**	**core-collapse huge BG!**

supernovae @ Super Chooz…

much physics beyond θ_{13}…

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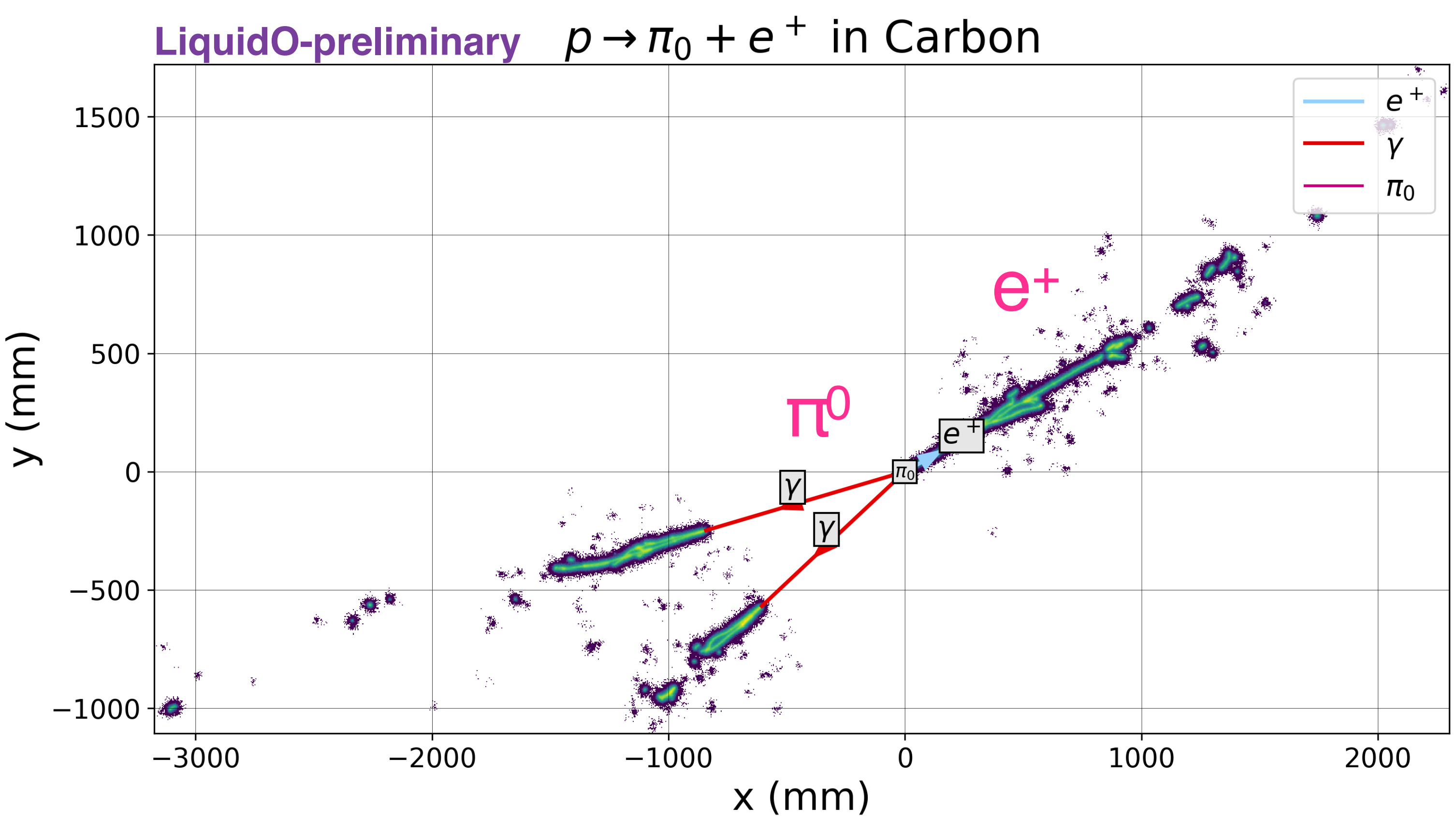
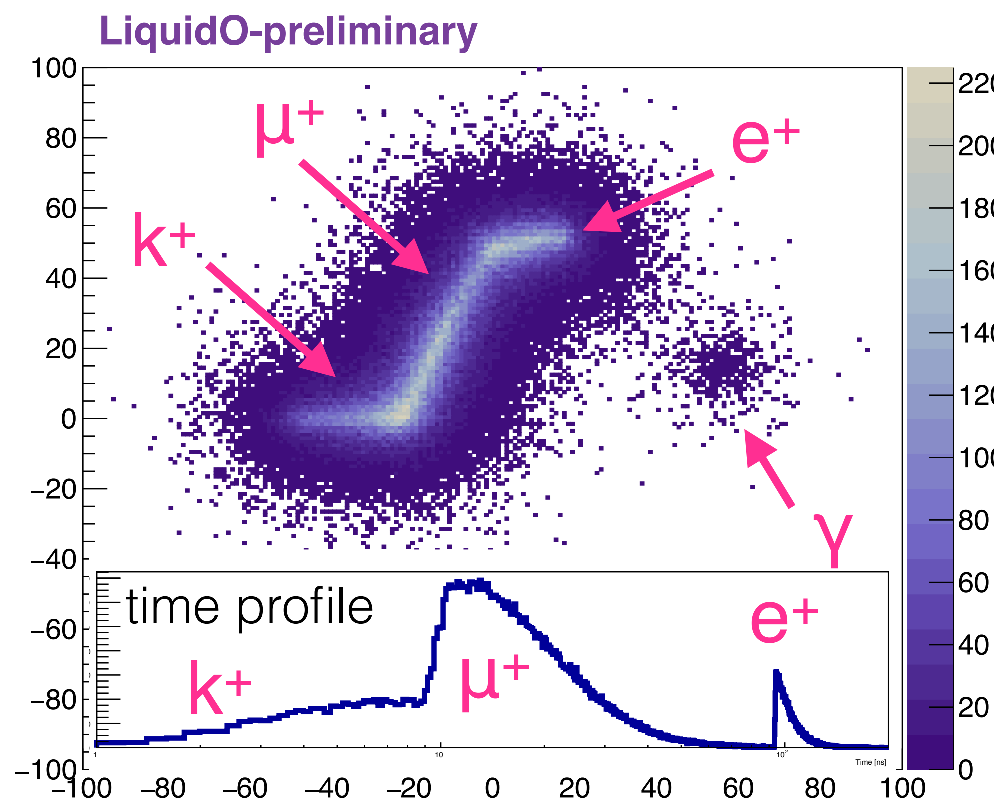
note: PMNS Unitarity test ("top-electron-row")→ solar & other constraints: **a full programme?**

- LiquidO sensitive to all channels
- Largest achievable density of free protons (organic scintillator)
- High efficiency (low energy threshold)
- **Full topological information** and sign-ID for some channels through final Michel electron (could do all if magnetise detector)

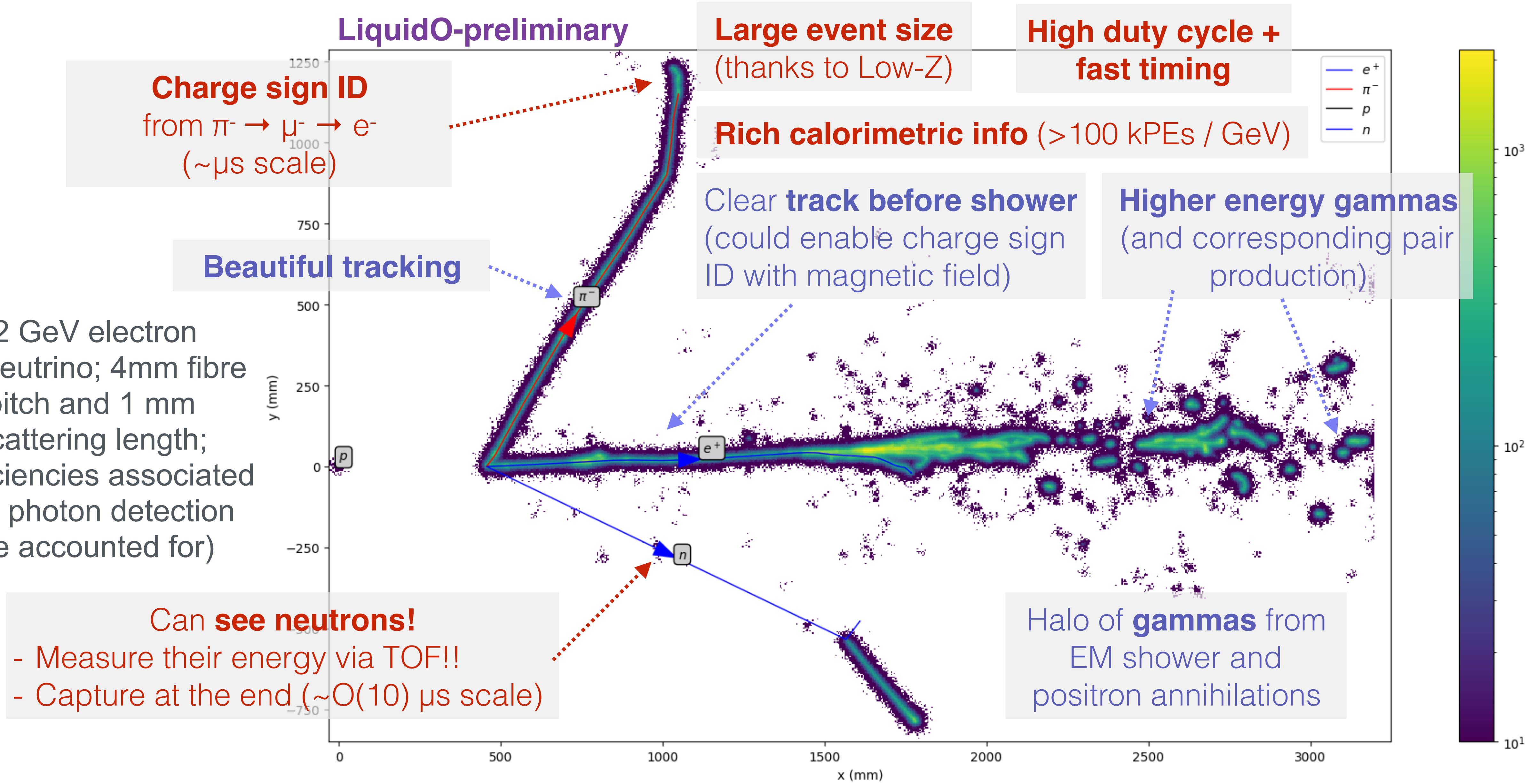
$$\boxed{p \to \bar{\nu} K^+} \qquad n \to \bar{\nu}\pi^0$$
$$p \to e^+ K^0 \qquad \boxed{p \to e^+\pi^0}$$
$$p \to \mu^+ K^0 \qquad p \to \mu^+\pi^0$$
$$p \to \bar{\nu}\pi^+ \qquad n \to \bar{\nu} K^0$$





proton decay… [much free-H]

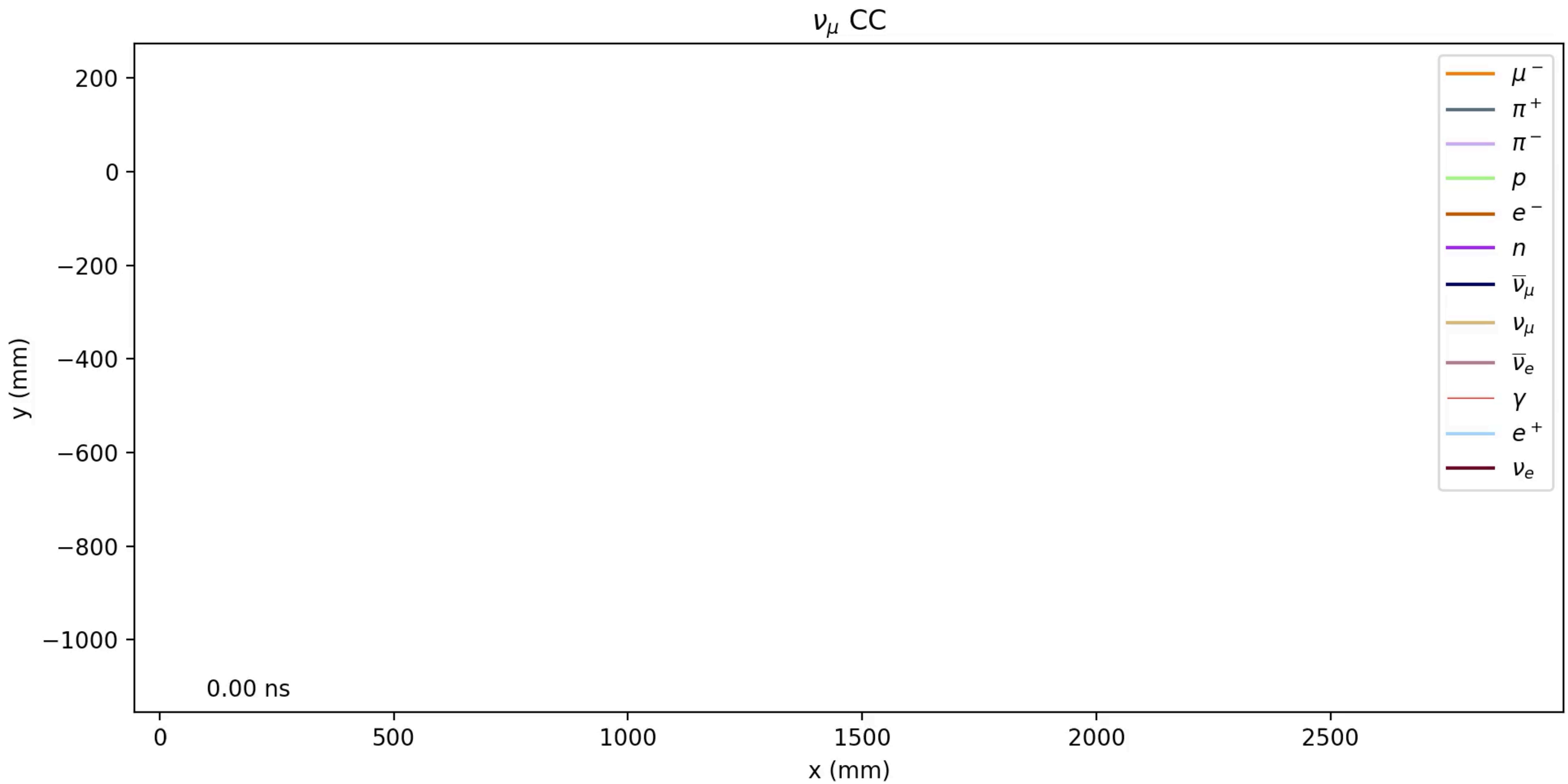
– LiquidO would reveal GeV-neutrino interactions in **extremely powerful** way:



(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**

atmospheric neutrino… [BG]



ν interaction: energy flow…

much physics beyond θ_{13}…

full menu (under construction)

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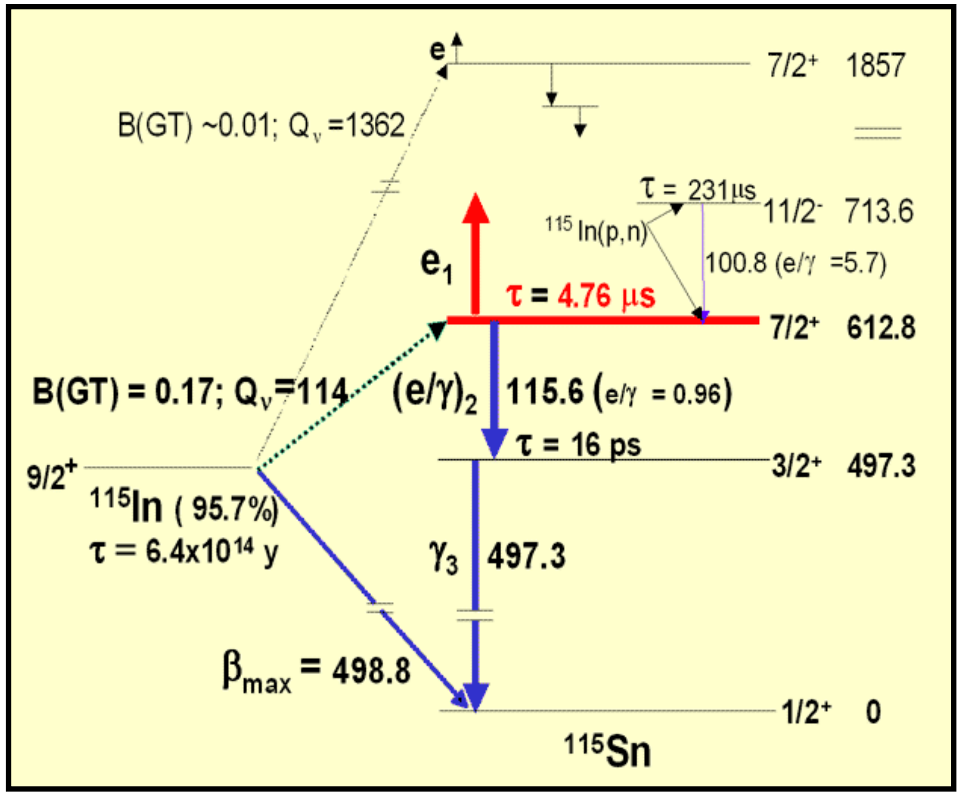
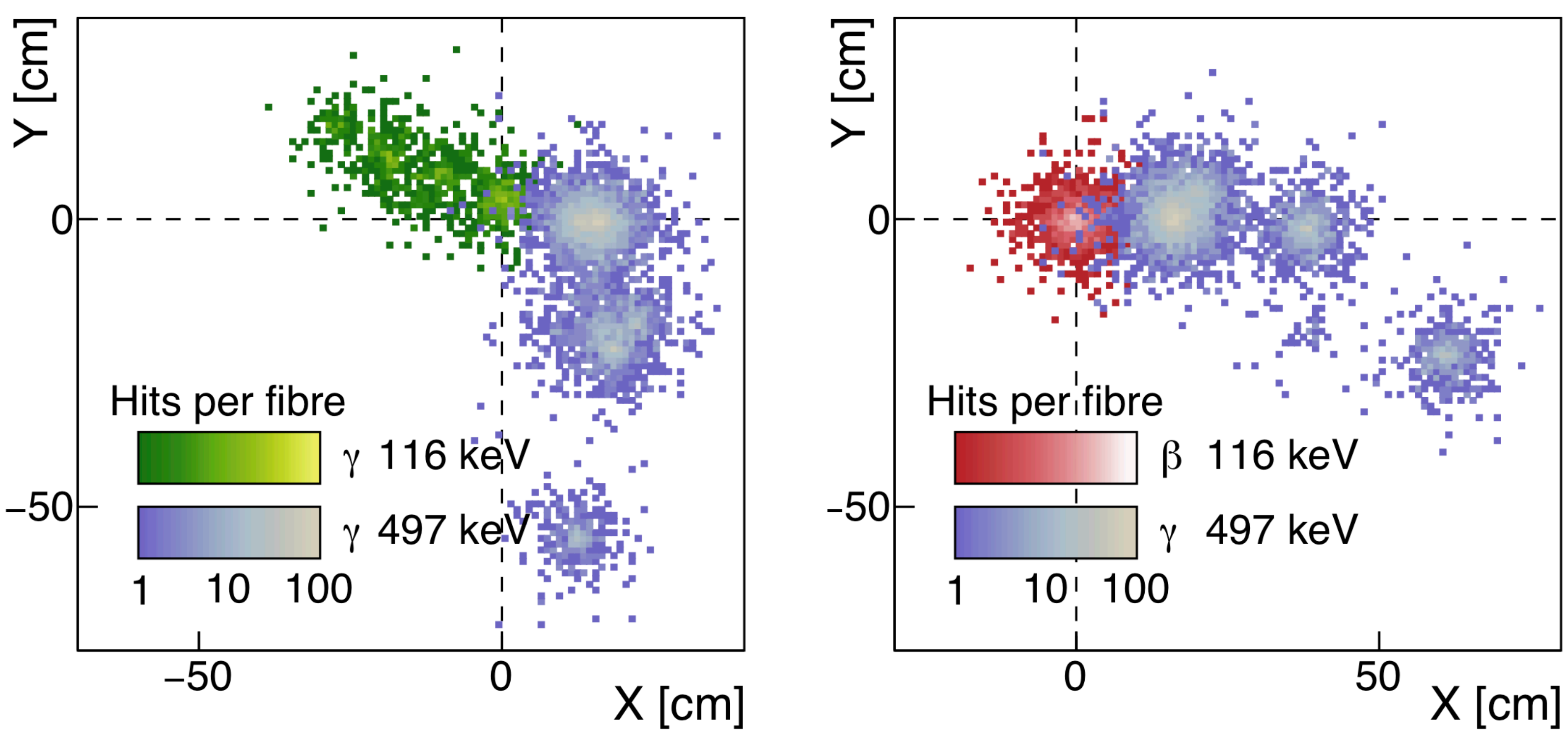


$$\nu_e + {}^{115}In \rightarrow \underbrace{e^-}_{\text{solar signal}} + \underbrace{\gamma + (\gamma / e^-)}_{\text{delayed tag } (\tau=4.76\,\mu s)} + {}^{115}Sn$$

Exploit capability to **load LS with In[^{115}In]**

CC ν-capture on ^{115}In tracks ν momentum (great for mono-energetic ν lines)

Higher cross section than ES interaction



Signal Tag

Delayed emission of

(e/γ) + γ

Fundamental for background rejection

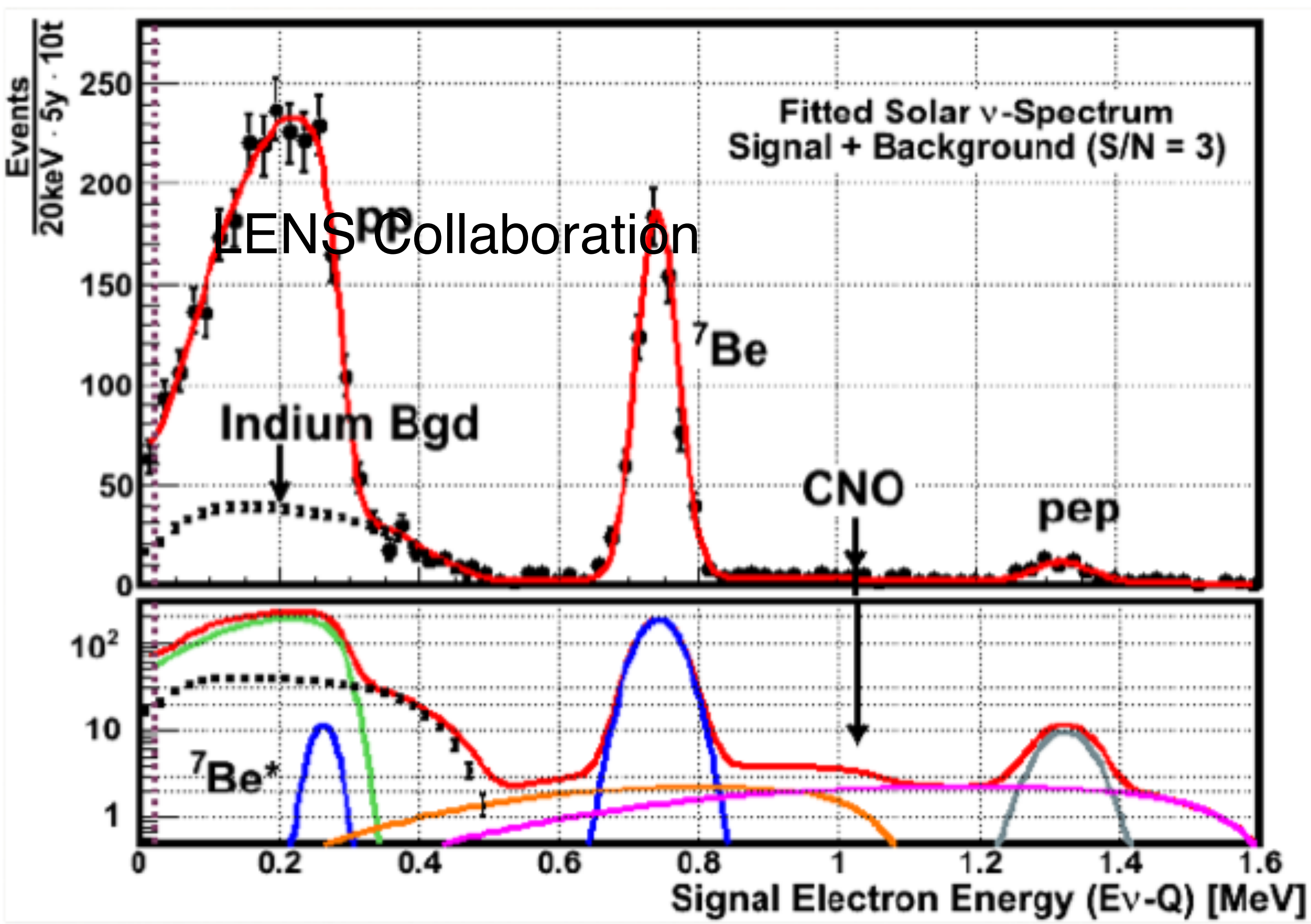
S

10% In-loading is quite feasible

Signal

CNO solar ν: few events/year/ton

pp solar ν: ~40 events/year/ton



Background Challenge

^{115}In is radioactive

: ~8·10^{12} β decays/year/ton

^{115}In β spectrum overlaps pp-ν signal

Bremsstrahlung from β decays could produce gamma tag backgrounds in accidental coincidence

BUT

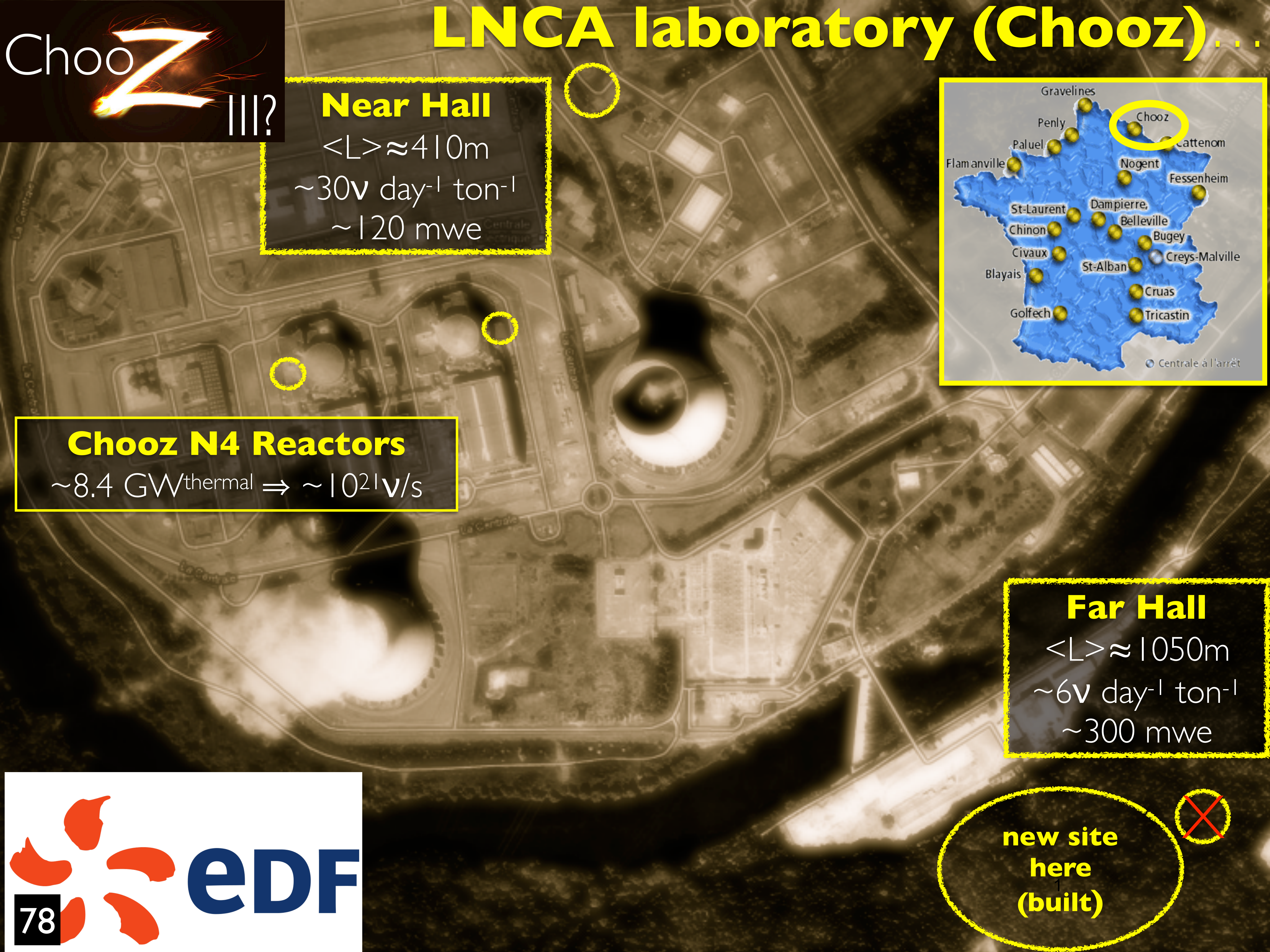
Above ^{115}In β endpoint, the delayed tag makes the signal **almost background-free** (only accidentals)

solar neutrino possible? [In load]

SuperChooZ!

under study…

LNCA laboratory (Chooz)...



Near Hall
<L>≈410m
~30ν day^{-1} ton^{-1}
~120 mwe

Chooz N4 Reactors
~8.4 GW^{thermal} ⇒ ~$10^{21}\nu$/s

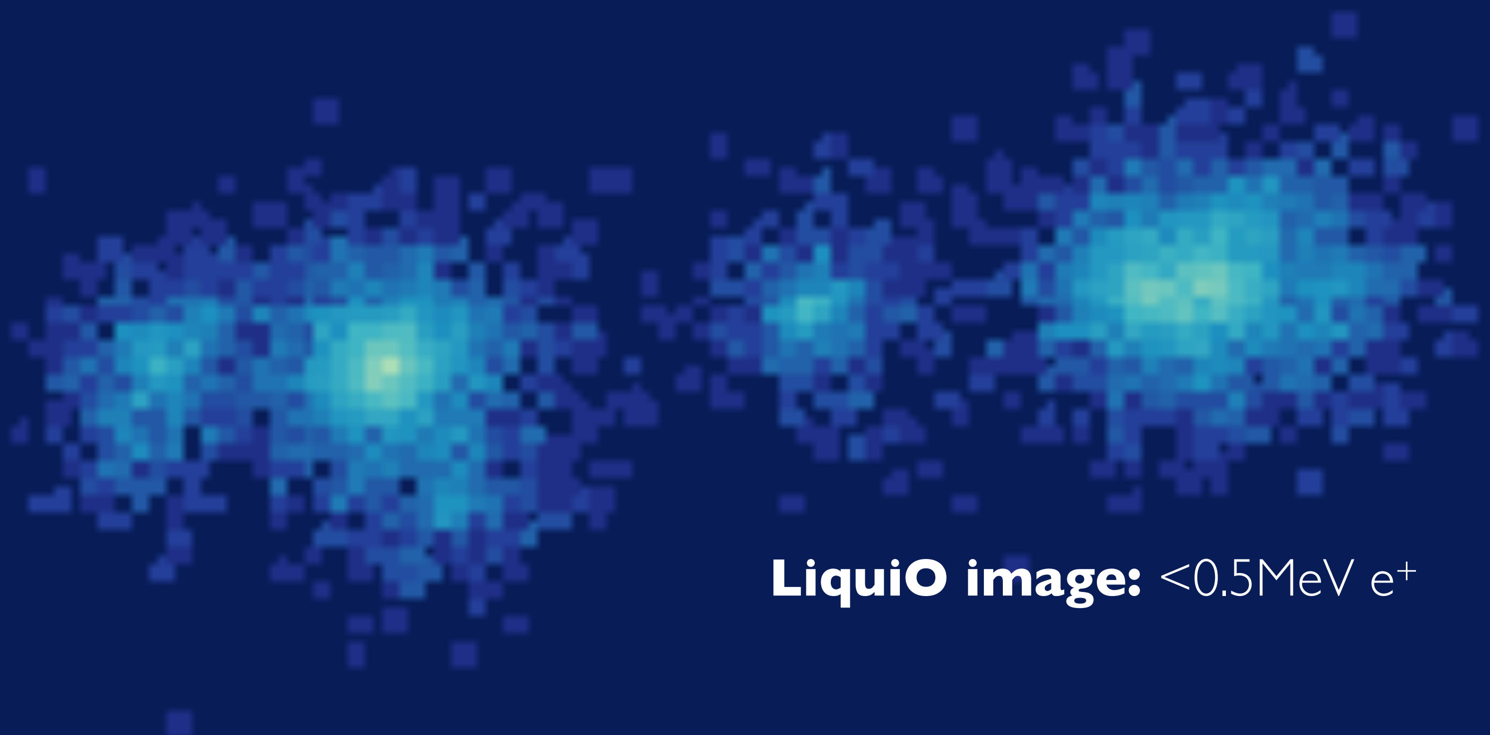
Far Hall
<L>≈1050m
~6ν day^{-1} ton^{-1}
~300 mwe

new site here (built)

conclusions…

- **PMNS unitarity is a must [several inputs]**
  - unique discovery potential — BSM physics?
- **benefit from >2025 sub-percent era**
  - starts JUNO θ12 — not enough!
  - needs per-mille precision on θ13 —now possible!
  - major improvement in flux prediction? [hard!!]
- **LiquidO [still R&D] powerful tool…**
  - a hypothetical **Super Chooz project?**
- **must continue thinking… do we have it all?**

Unitarity must be addressed… (experimentally)



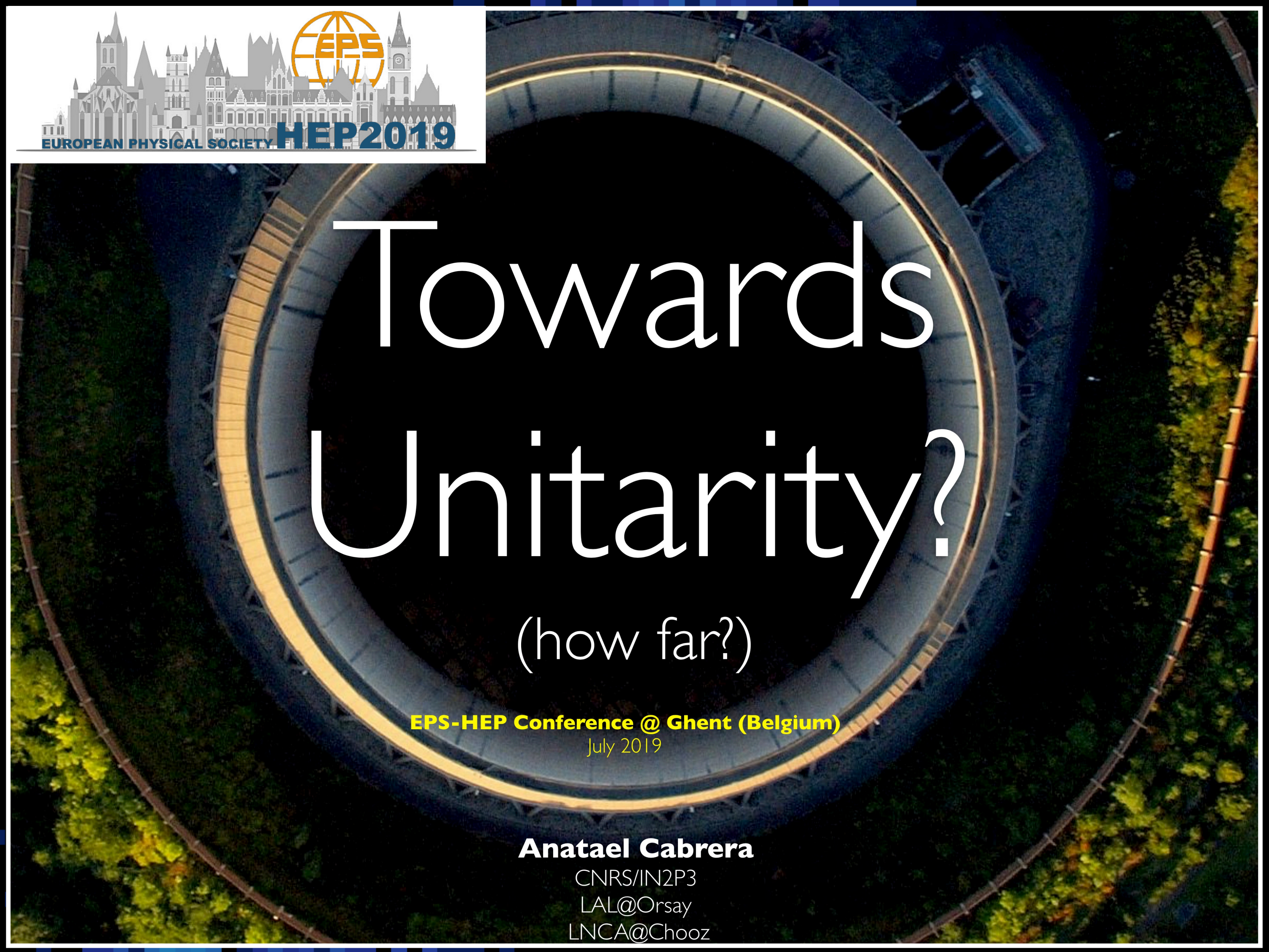
LiquiO image: <0.5MeV e^+

paper in soon!!

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

anatael@in2p3.fr

leptonic sector unitarity with LiquidO?



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