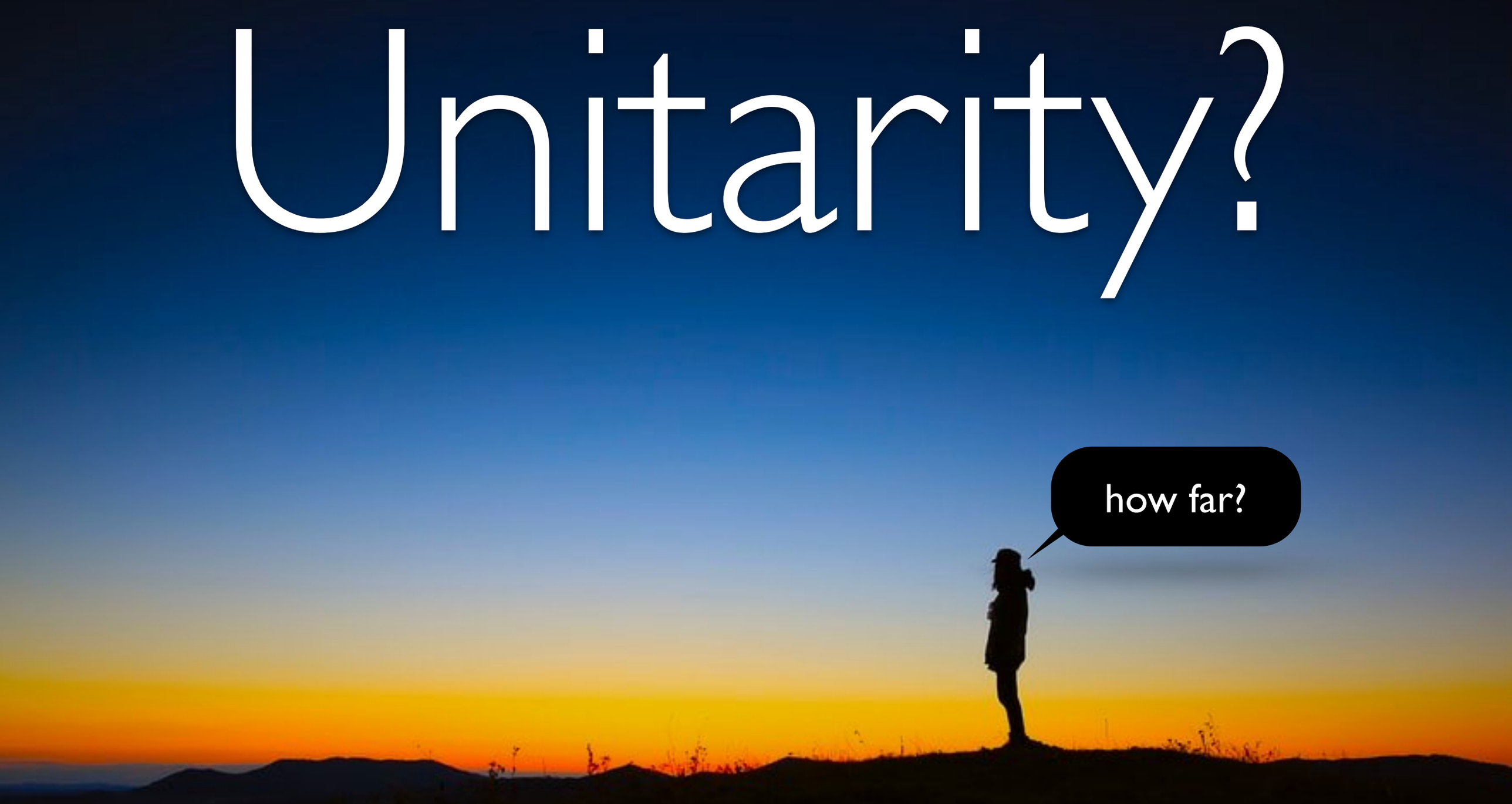
Unitarity?



CNRS/IN2P3 Prospect (France)
October 2019

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

High Precision Neutrino Unitarity Possible?

CNRS/IN2P3 2020 Prospect on Neutrino Physics

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tight collaboration with H. Nunokawa (PUC Rio, Brasil)

our contribution & team…

PMNS matrix…

mixing needed for neutrino oscillations

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

9 complex terms → θ_{12}, θ_{23}, θ_{13}, δ_{CP} parameters

[assumed unitarity 3x3]

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \Longrightarrow \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

SM : no prediction on PMNS matrix

(all to be measured)

status on neutrino oscillation knowledge…

Standard Model(3 families)
[leptons & quarks]
&
PMNS$_{3\times3}(\theta_{12},\theta_{23},\theta_{13})$
&
$\pm\Delta m^2$ & $+\delta m^2$

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
$\lvert\Delta m^2\rvert$	3.0 %	T2K & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK	reactor⊕beam
sign(Δm^2)	**unknown**	SK	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}!**

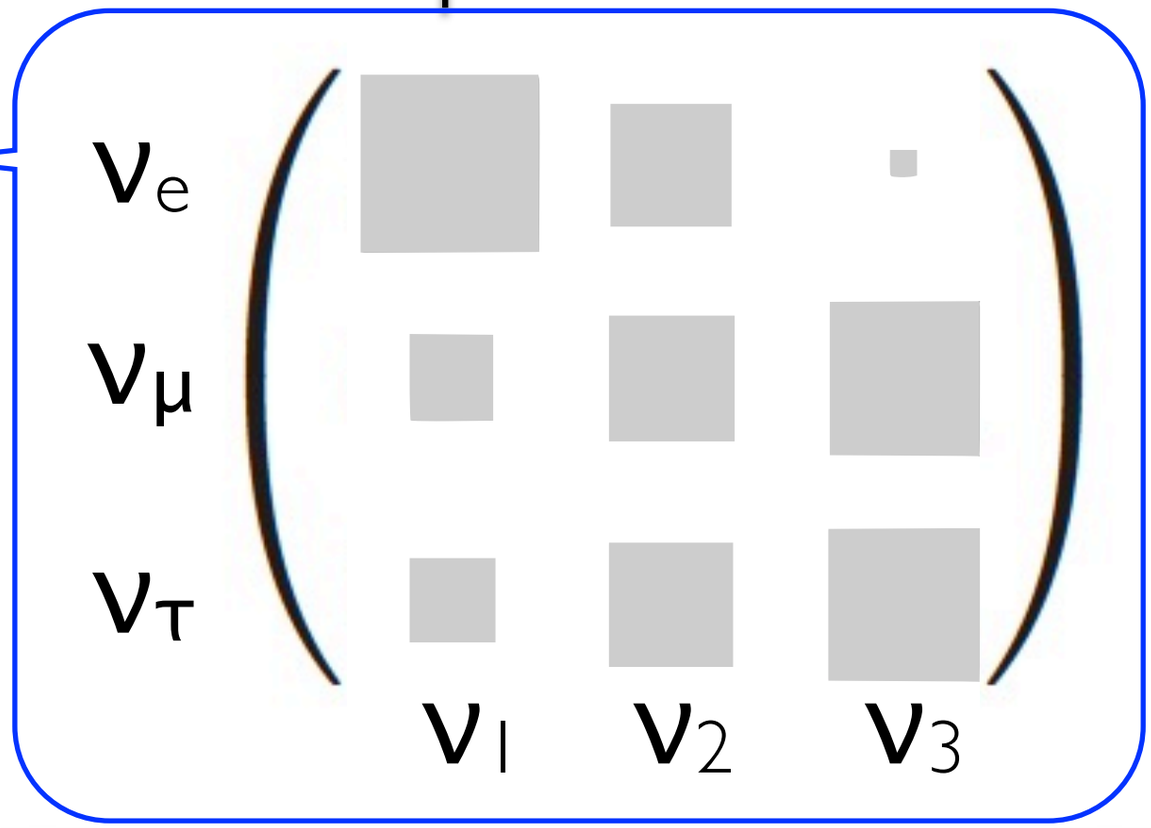
NOTE: ORCA⊕PINGU⊕IceCube complementary (Mass Ordering & Δm^2 measurements)

all done?

by 2030, all @ ~1% level…

what's special about the PMNS matrix?

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



consider matrix structure

(not just composition)

why shape?

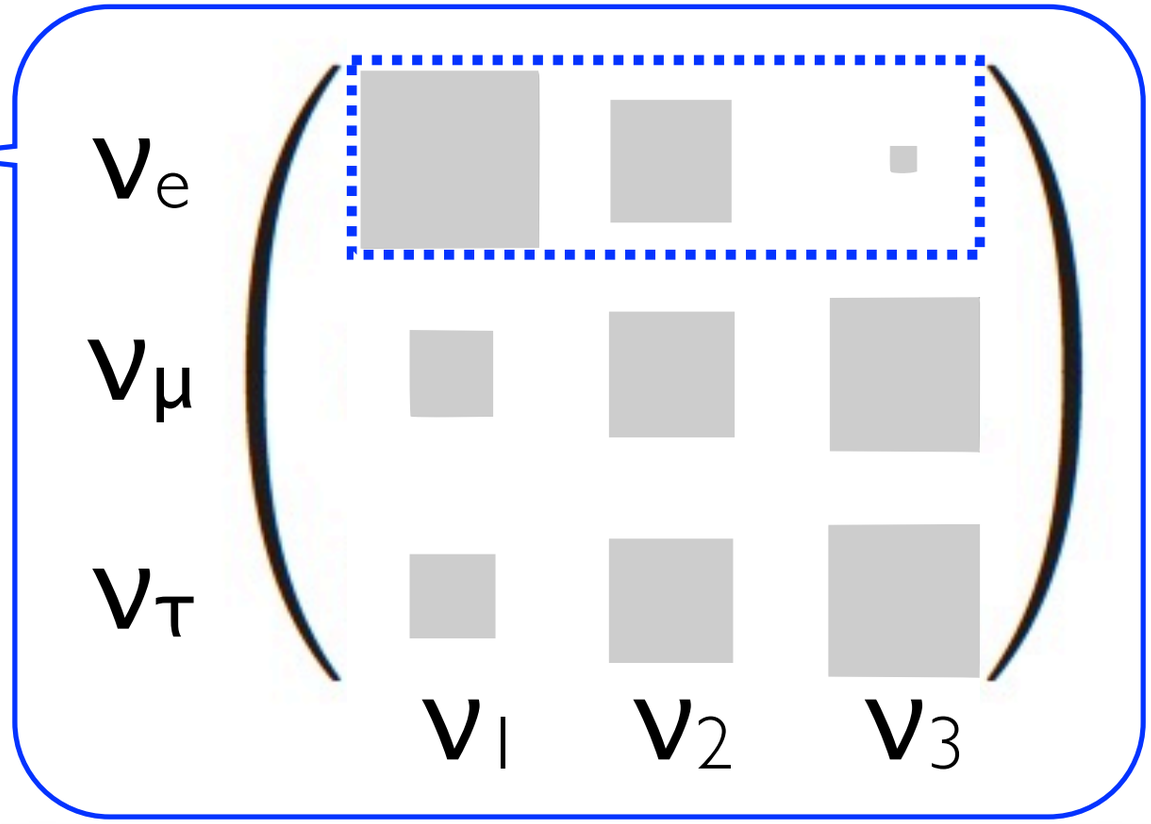
- maximal mixing — but θ13 small?
- largest CP-Violation (SM)
- symmetry behind?

U_{3x3} unitary?

[next slides]

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"]

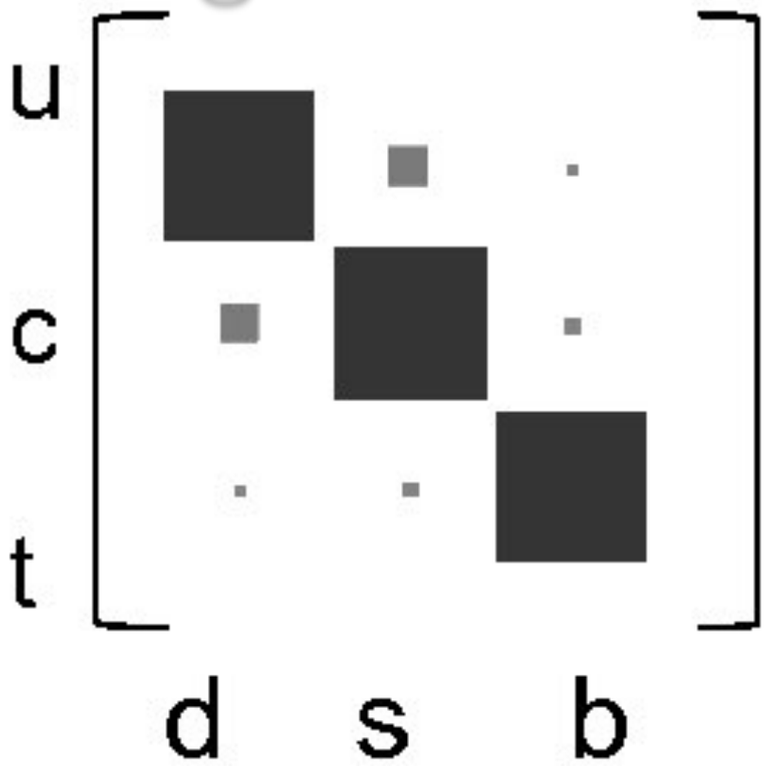
since no CPV (yet) ⇒ test PMNS Unitarity via "each row"

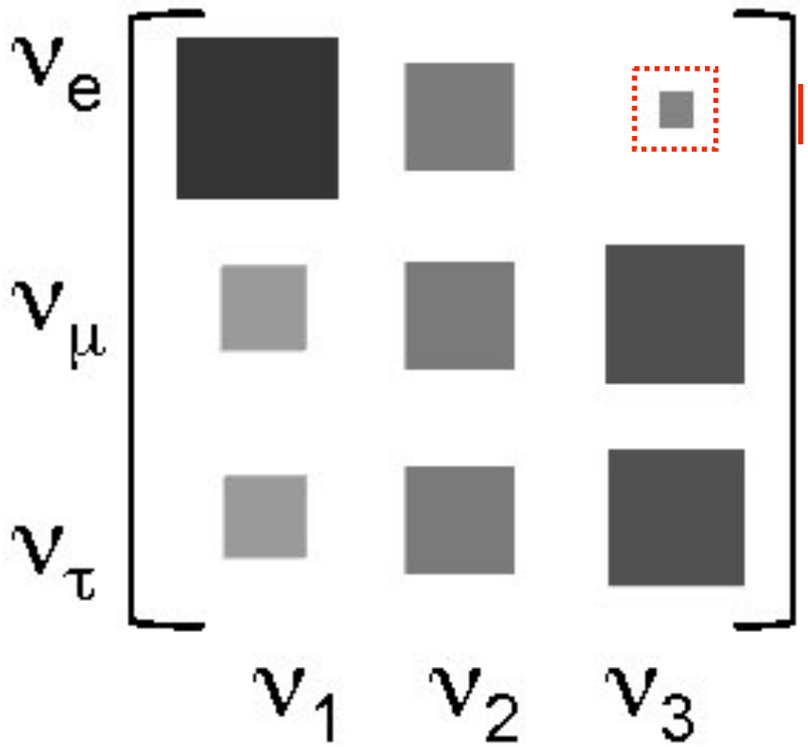
$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$$

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

only "θ_{12}" and "θ_{13}"

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

→less clear pattern (any?) **(anarchy vs symmetry)**

→only U_{e3} or θ_{13} is small!! **(meaningful vs caprice)**

unitarity precision "top-row"

→**large deviations?** (consistent)

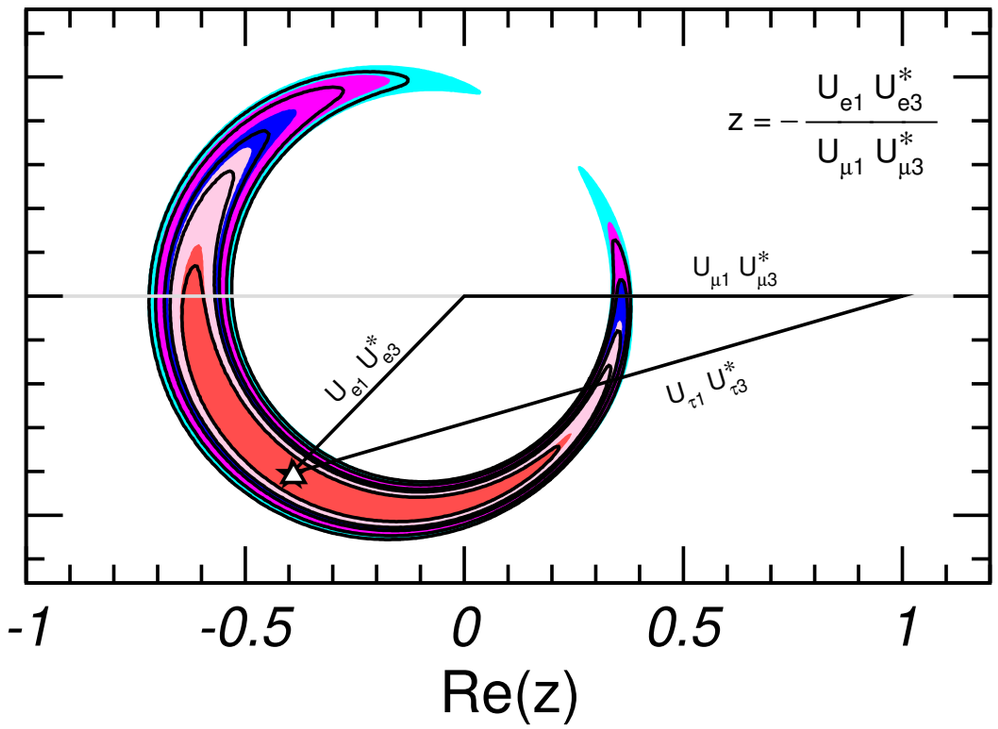
much CPV to explain the observed Universe→ PMNS only hope?

[link to heavy Majorana neutrinos CPV?]

PMNS

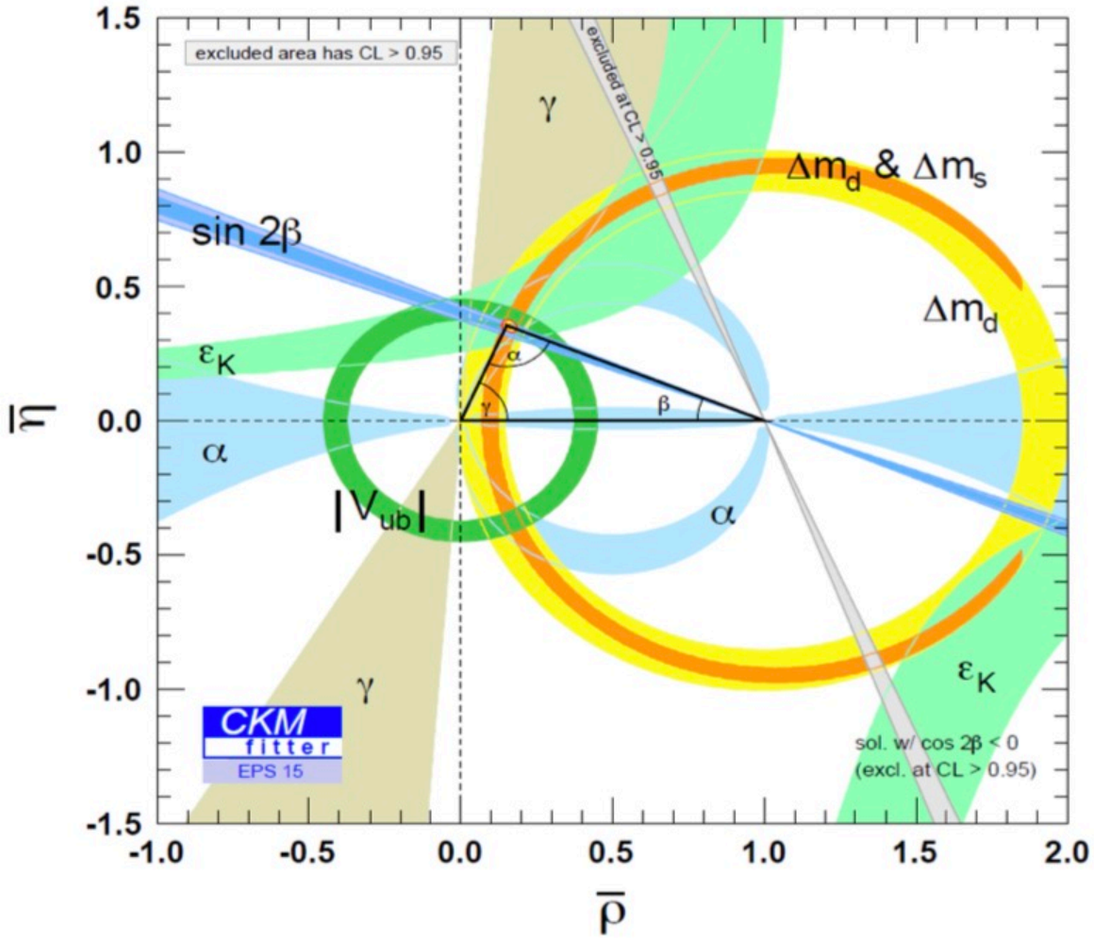
NuFIT 4.0 (2018)

NO



J(PMNS)≈3.33±0.06x10^{-2}

CKM



J(CKM)≈3.18±0.15x10^{-5}

PMNS triangle (including CPV)…

why Unitarity is important?

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

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

- **the last discovery within "neutrino oscillation"?**
  - δ_{CP}:
    - ≠0 <u>interesting</u>, but foreseen in model
    - =0 <u>more</u>? [→symmetry?] <u>interesting</u>, but foreseen in model
    - =**x** [whatever value?] <u>very important</u> but **no prediction**!

  - $UU^\dagger$:
    - ≠1 **breakthrough**→ NO model→**BSM discovery!!**
    - =1 OK [confirm & over-constrain SM]

    [perfect prediction protected by symmetry]

Unitarity Violation→ 4th family? (~~kinematics~~) and/or NSI?

" the electron-raw unitarity ingredients…

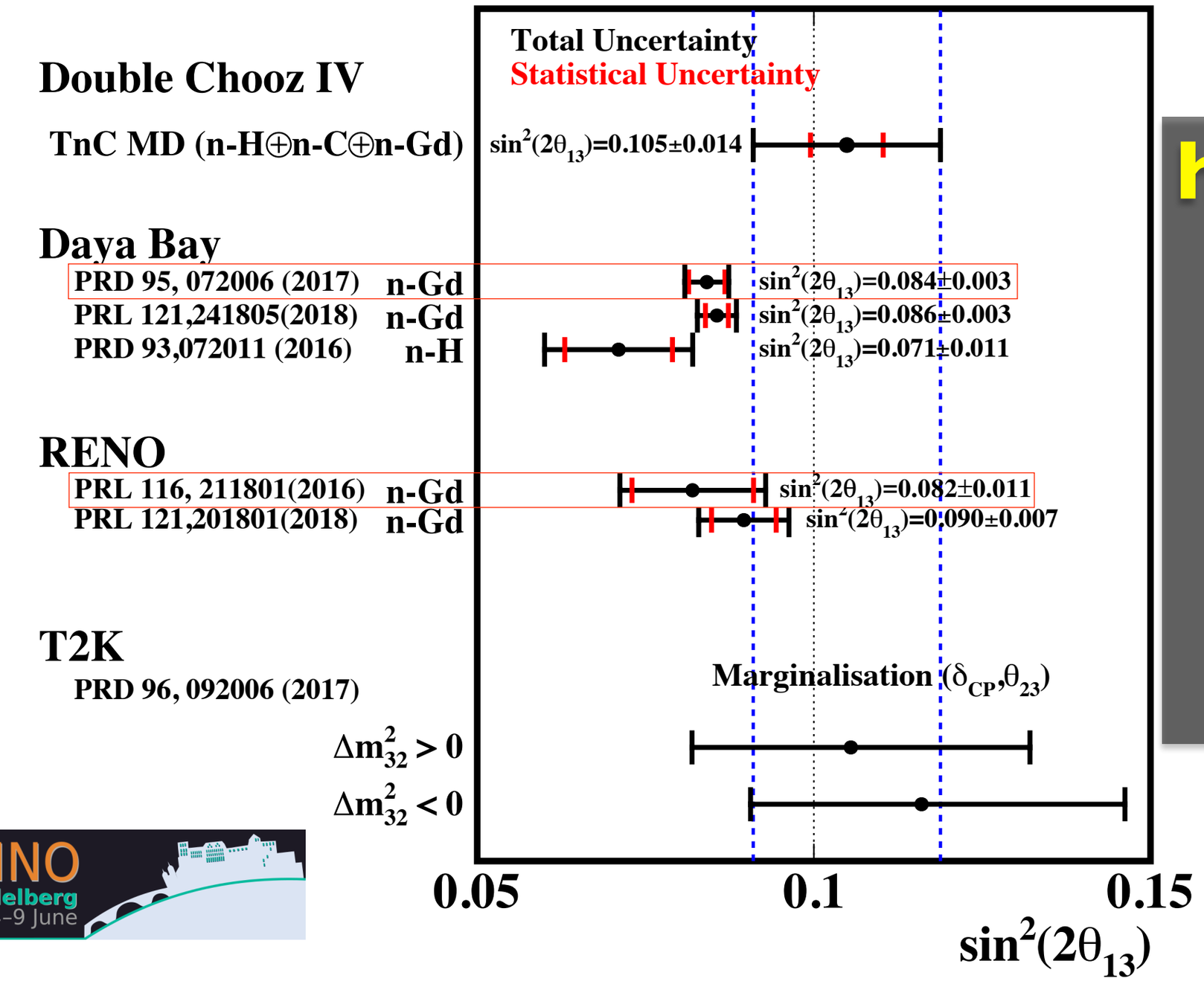
- **sensitive to θ12 → δ<1.0% [unitarity]**
  [**JUNO**, SNO, KL]

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

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

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

status in θ13…



higher θ_{13}

before
(~2016)
↓
after
(@Nu2018)

NEUTRINO 2018 Heidelberg 4–9 June

Submissions

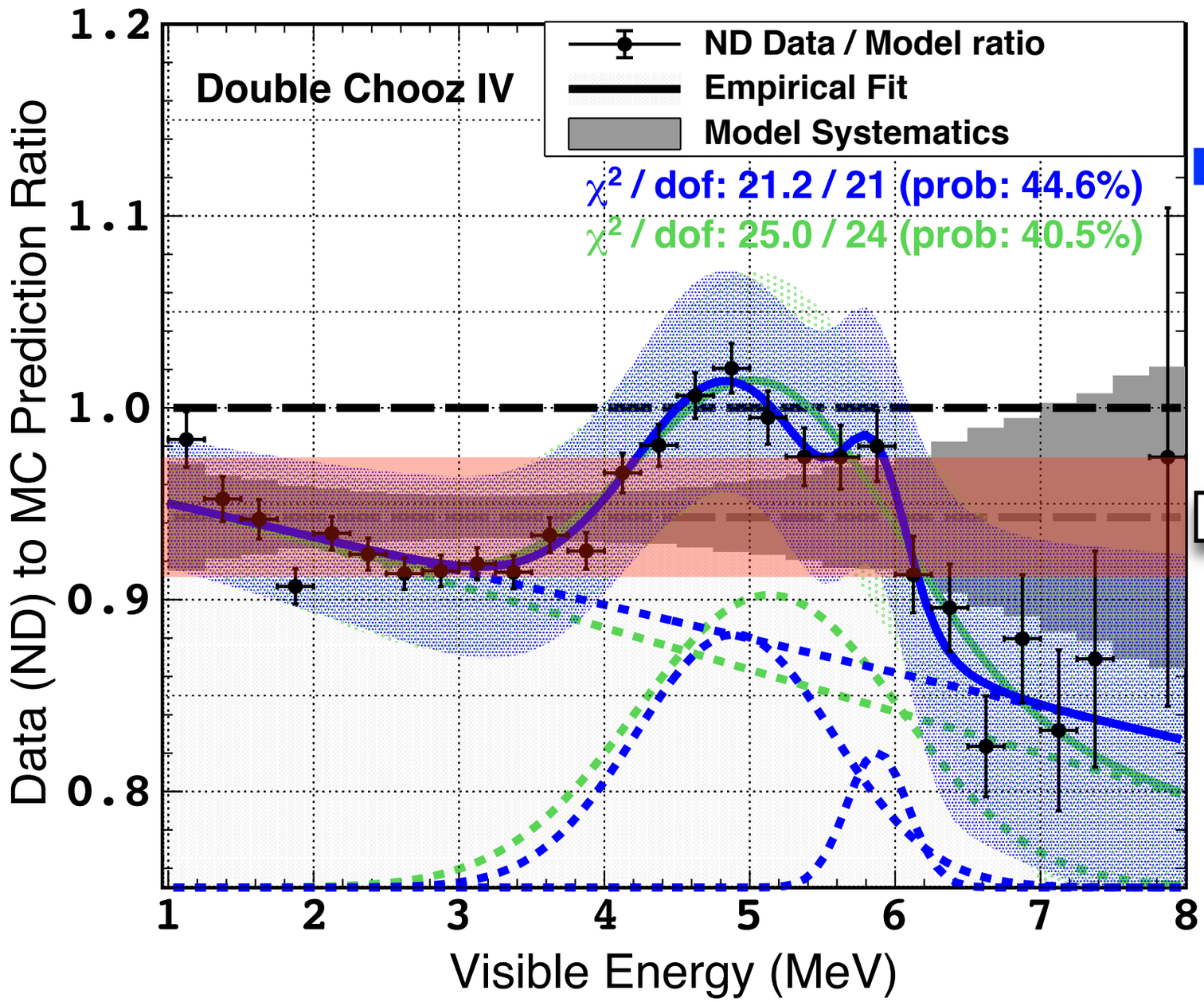
nature physics

ARTICLE

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

reactor flux knowledge…

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



reactor flux
nor rate or shape
understood
(unless new physics)

R=0.925±0.010(exp)±0.023(model)

Uncertainty?
~3.0%→**6.0%**?
[≤10%]

Submissions

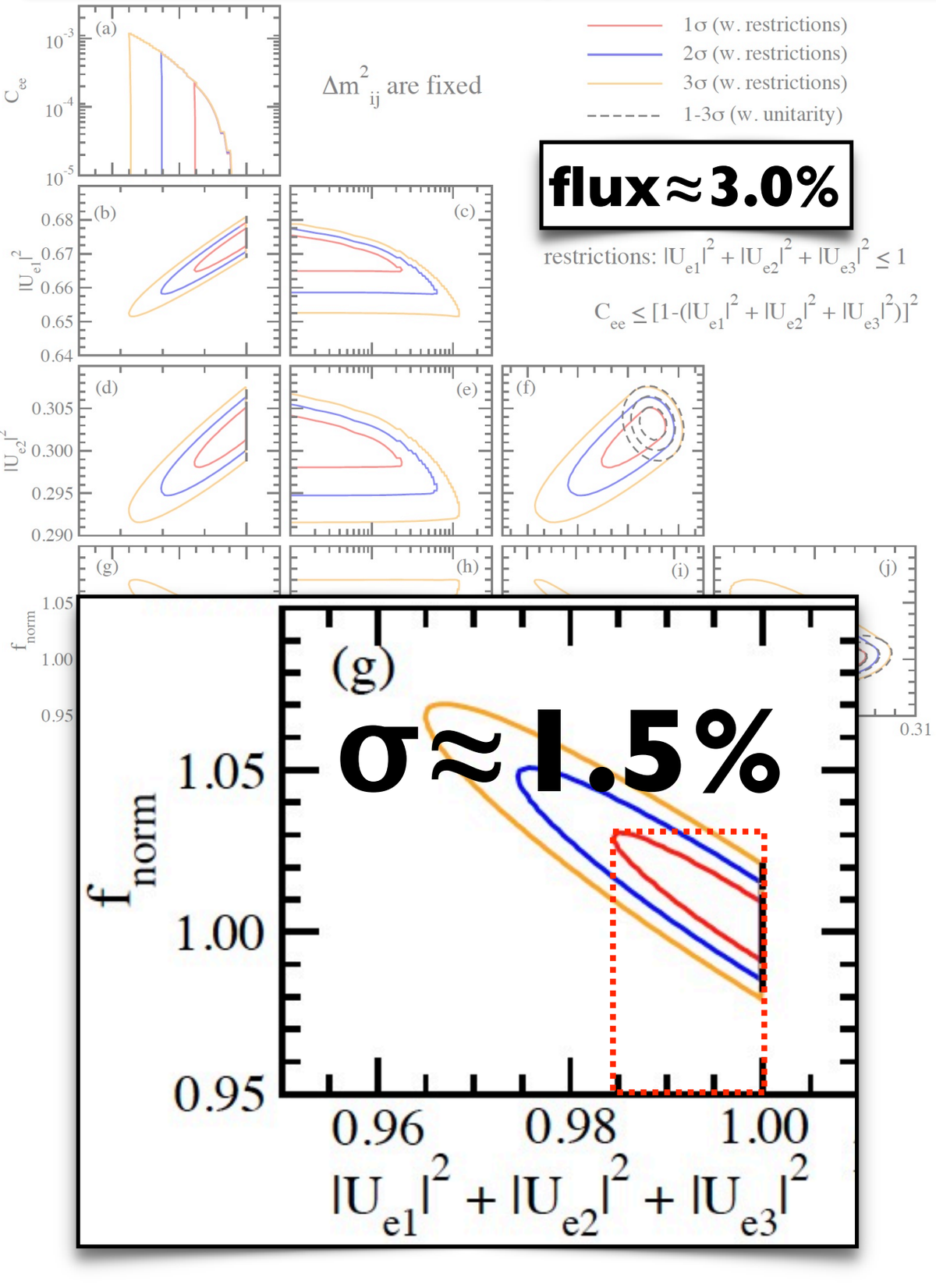
nature physics

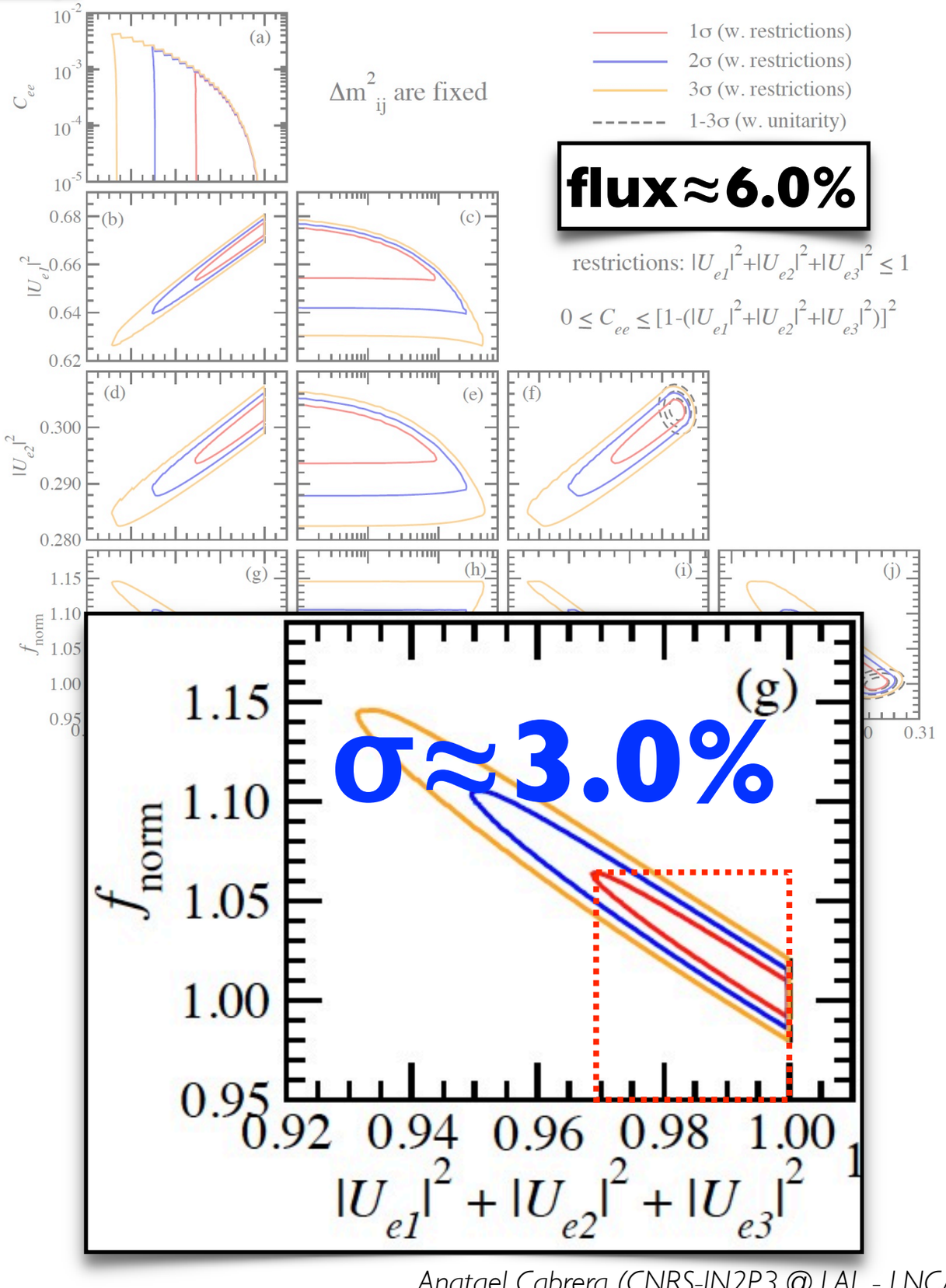
ARTICLE

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

today's top-row unitarity knowledge…

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



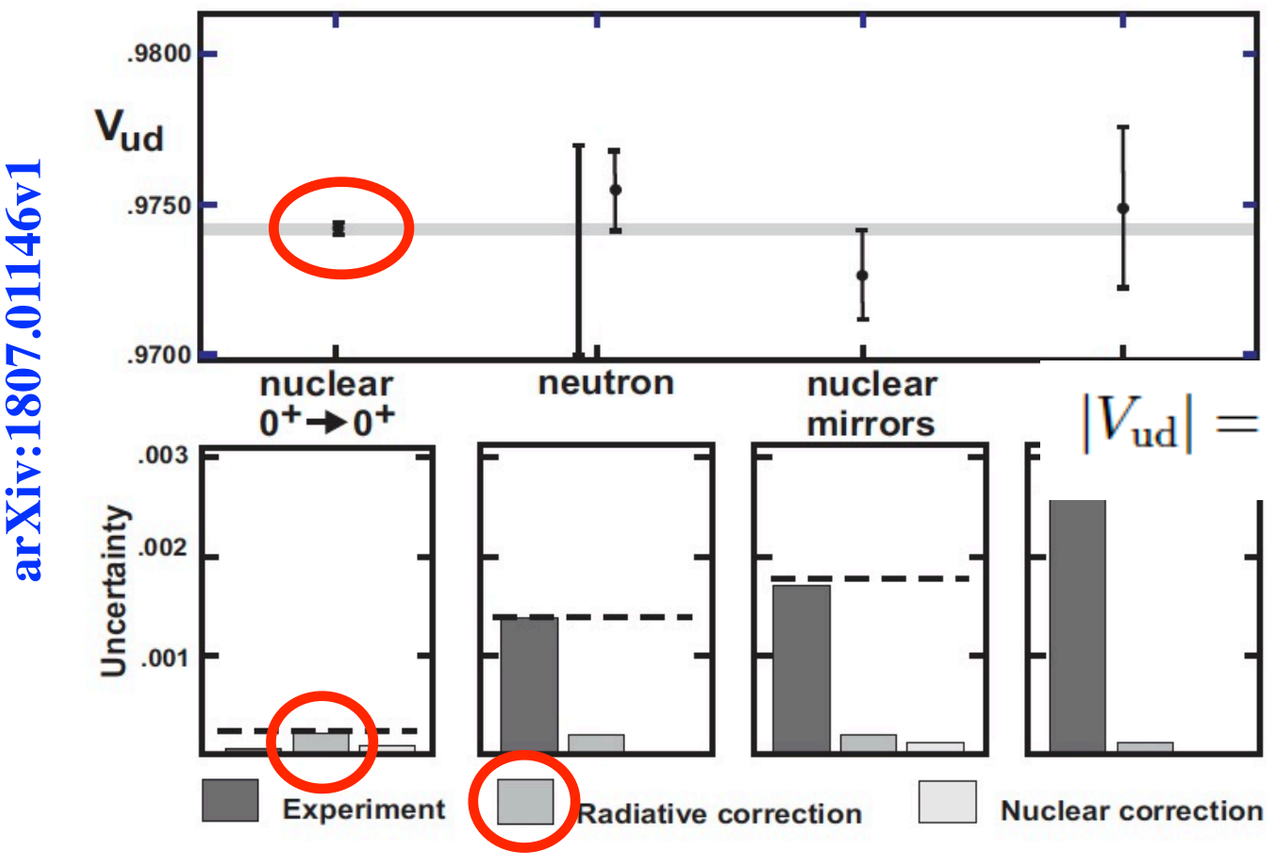


how about @ CKM?

V_{ud} (nuclear β-decay) = 0.97417(21)
V_{us} (kaon-decay) = 0.2253(14)
V_{ub} (B meson decay) = 0.0037(5)

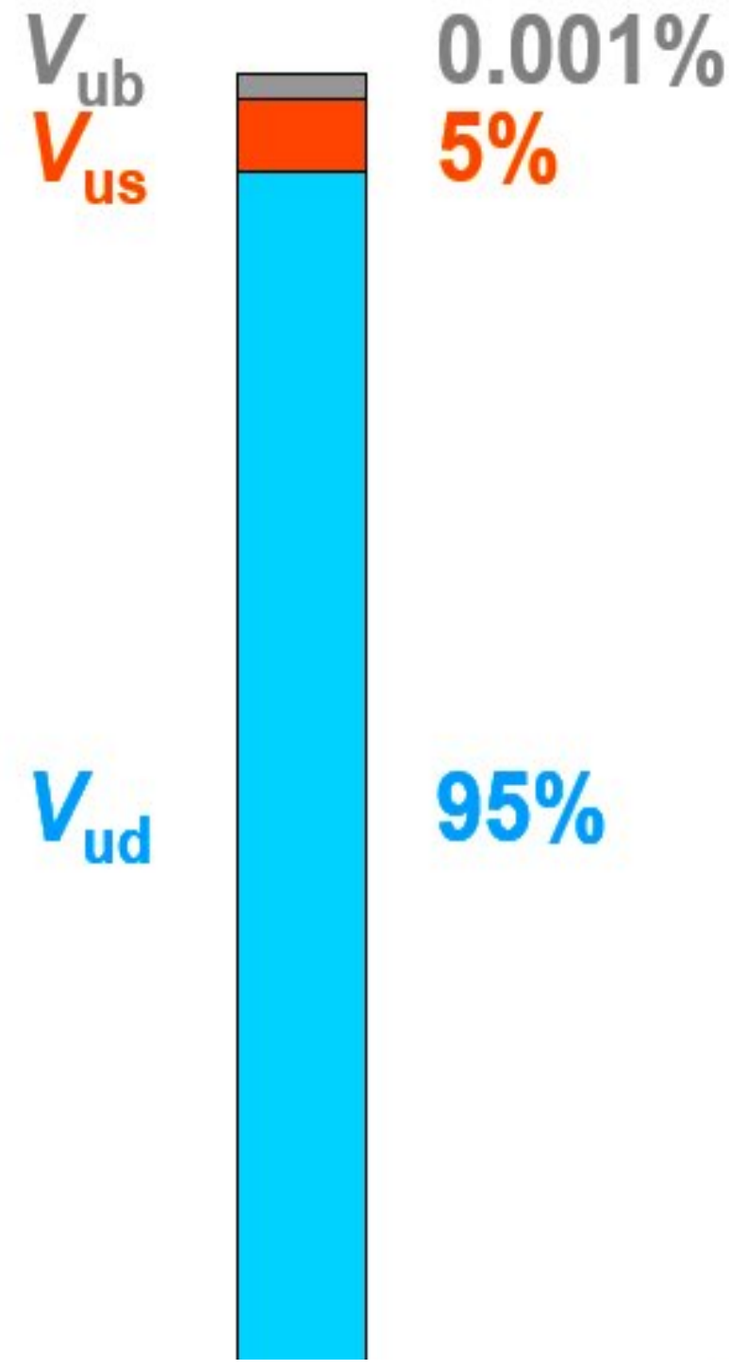
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.99939(64)$$

Hardy & Towner, arXiv 1807.01146 and Particle Data Group 2018



arXiv:1807.01146v1

$$|V_{ud}| = 0.97420(21).$$



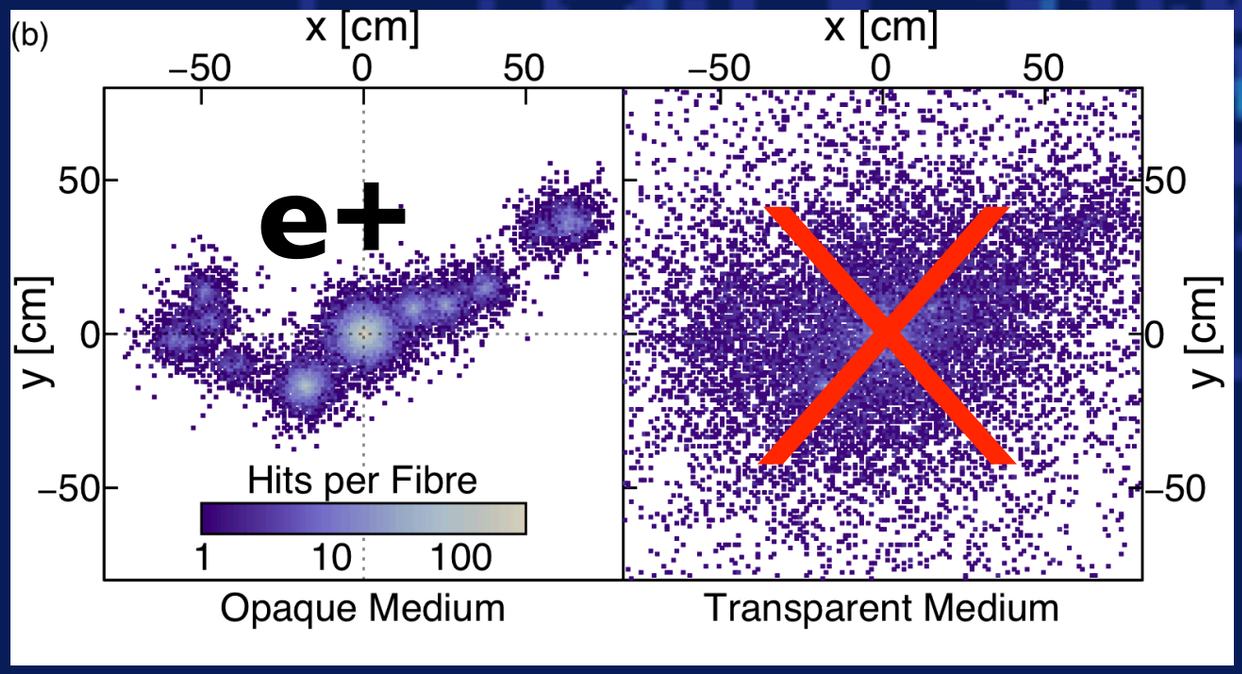
$$\sum |V_{ui}|^2 = 0.99939(47) \quad \to \quad 0.99842(47)$$ **tension @ CKM?**

improve Unitarity? [under study]

towards **Super Chooz**...

physics: Unitarity, proton-decay, supernovae, solar?
[$\theta_{13} \oplus |\Delta m^2_{ee}|$, etc]

new detector?



LiquidO technology

Release @CERN: https://indico.cern.ch/event/823865
Publication: arXiv:1908.02859

new laboratory?

up to 50,000 m^3

LNCA laboratory (Chooz)...

Choo Z III?

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

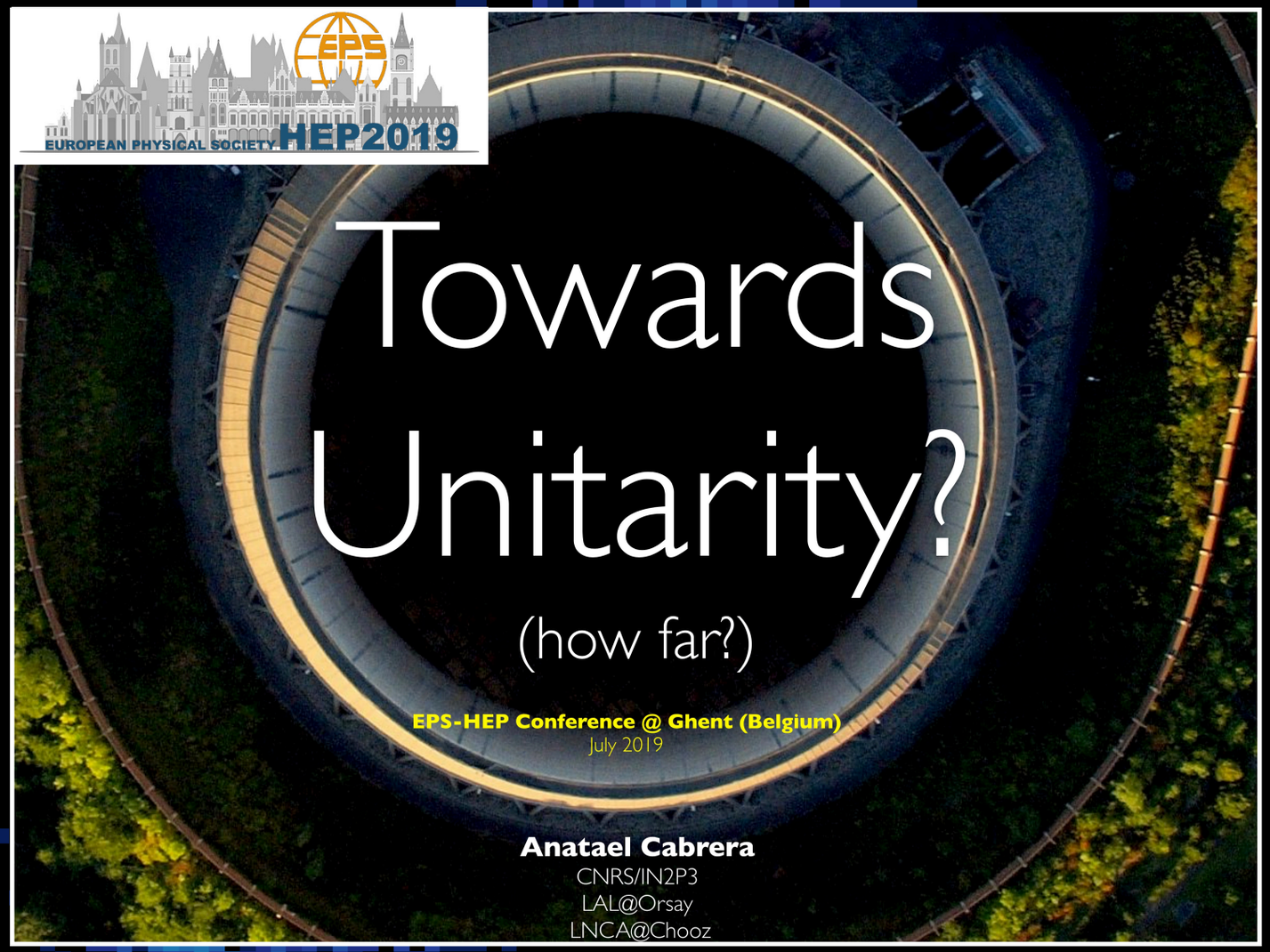
Chooz N4 Reactors
~8.4 GW^{thermal} ⇒ ~10^{21}ν/s

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

new site here (built)

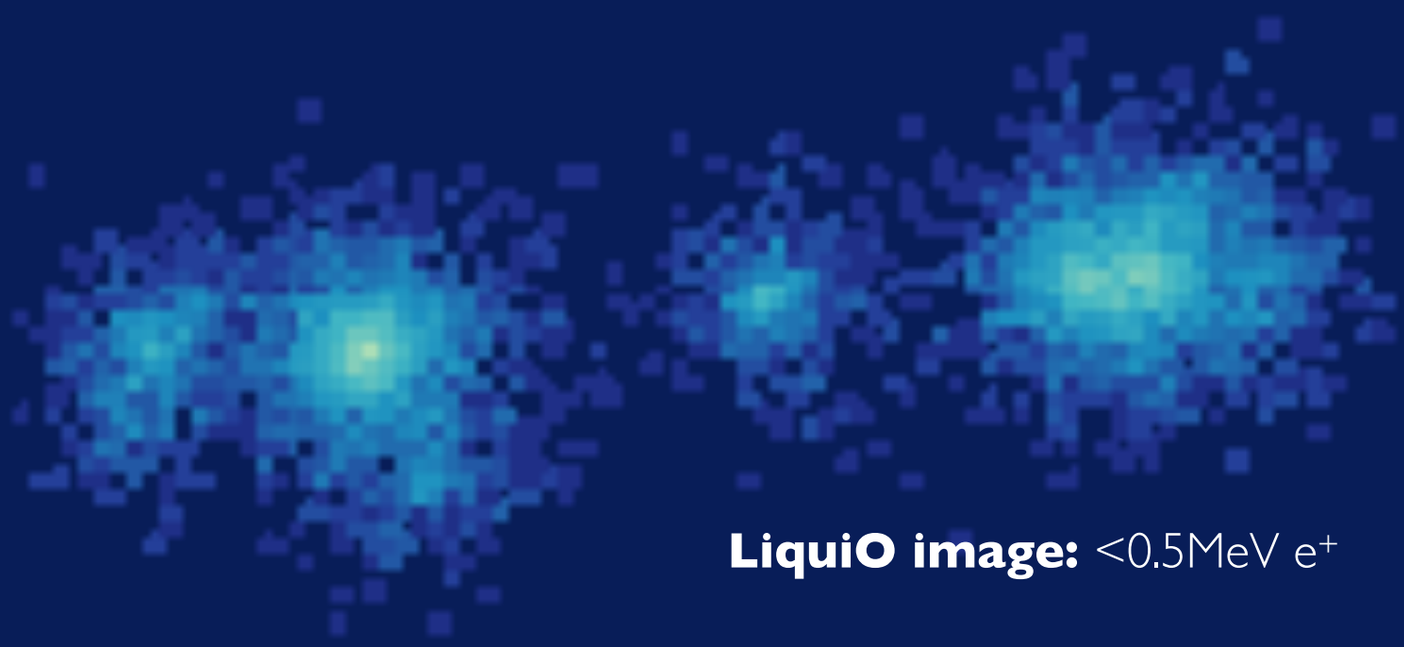
eDF

leptonic sector unitarity with LiquidO?



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

Unitarity must be addressed…
(experimentally)



LiquiO image: <0.5MeV e^+

full results soon!

[paper in preparation]

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

anatael@in2p3.fr