Unitarity

the next step…?

Erice — September 2022

much work with ***Prof. H. Nunokawa***

Anatael Cabrera
CNRS-IN2P3 / IJCLab / Université Paris-Saclay
Orsay, France

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		global	foreseen	dominant	source
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
Mass Ordering	**unknown**	SK et al	NO @ **~3σ**	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CPV	**unknown**	T2K	3/2π @ **≲2σ**	**@5σ?**	DUNE⊕HK⊕ALL	reactor⊕beam

(**now**) (reactor-beam)

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

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

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

what's the **next goal?**

neutrino oscillation $\lesssim 1\%$ (by 2030) $\rightarrow$ **how much more precision?**

today's **"signal"** (i.e. neutrino oscillations precision) $\Longrightarrow$ tomorrow's **"background"**
what's tomorrow's **"signal"** (i.e. **next goal**)?

neutrino oscillations: **done?**

SMv1.1: knowns & unknowns…

Weak Flavour Neutrinos (**3**): **ν(e)**, **ν(μ)**, **ν(τ)** — observed **3!** (same as quarks)

Mass Neutrinos (**3**): **ν(1)**, **ν(2)**, **ν(3)** **—** assumed **≥3!** [cosmology constraints ≤4]

PMNS matrix (3x3; *a la CKM*): ***U***, *assumed* ***unitarity*** (→***violation?***) — discovery!

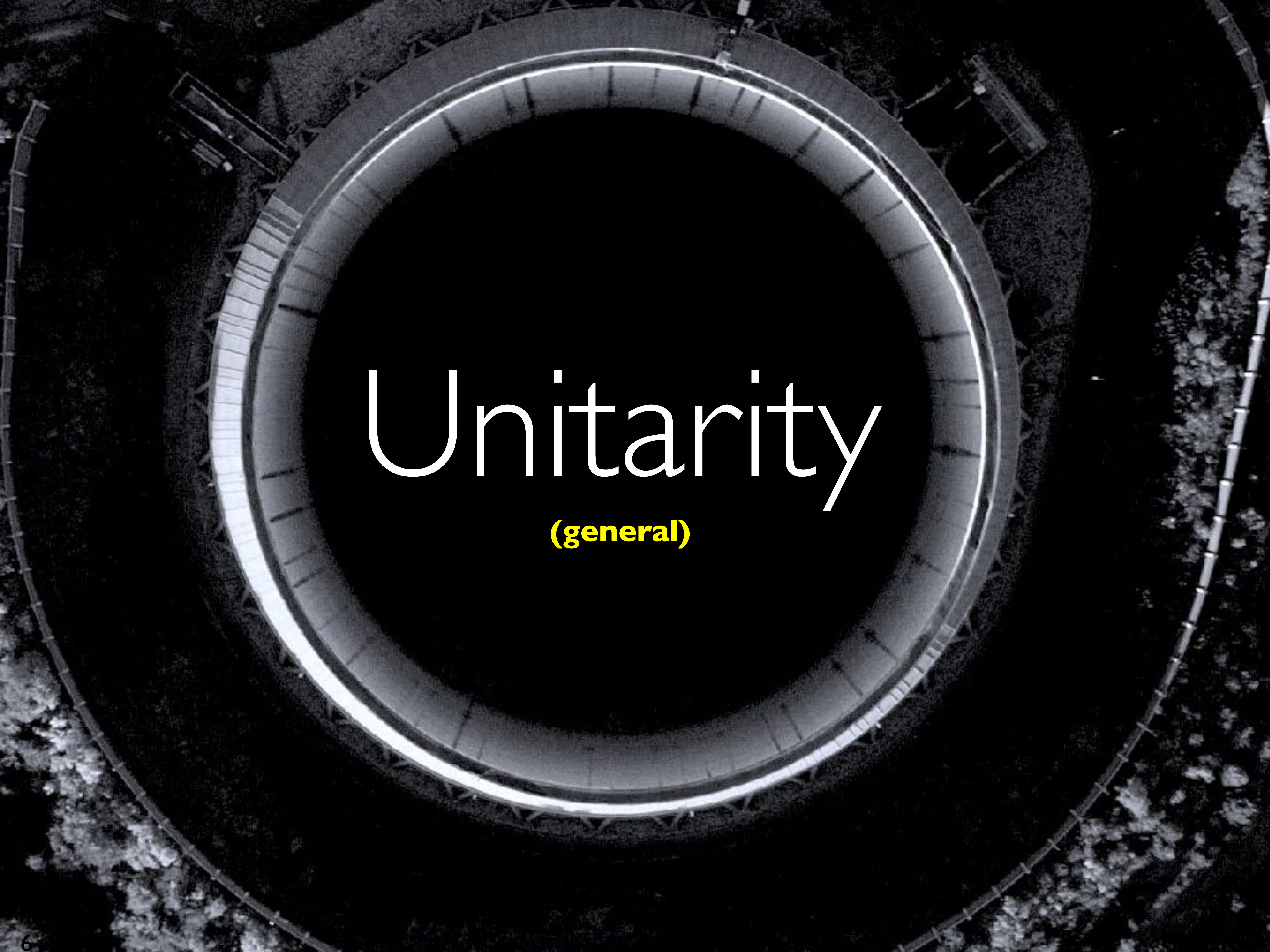
- mixing parameters (**3**): **θ_{13}**, **θ_{12}**, **θ_{23}** (octant**?**) — derived ***J*** [Jarlskog invariant]
- CP-violation parameter (**1**): **δ?** — unknown [*SM*]

Mass Squared Differences (**2**): **δm^2** (i.e. Δm^2_{12})
Δm^2 (i.e. Δm^2_{13} or Δm^2_{23})

Mass Ordering (*MO*):
+δm^2 (solar data — observed!)
±?Δm^2 → which is the lightest neutrino ν(1) or ν(3)**?** — unknown [*SM*]

Mass Hierarchy (*MH*): **the mass of the neutrino?** — discovery!
[→why so much smaller than charged leptons?]

Neutrino Nature: **Majorana?** — discovery!



Unitarity

(general)

PMNS with / without **Unitarity**...

unitary needed for **probability conservation** of the SM predictions — must be **conserved**

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

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

$\Longrightarrow$ $f(\theta_{13}, \theta_{12}, \theta_{23}, \delta)$

upon Unitarity imposition

- **3 real mixing angles**
- **1 complex phase** (Dirac)
- **2 complex phases** (Majorana)

$\Longrightarrow$ PMNS must meet **9 equations**

a priori **18 parameters** PMNS (3x3)

- 9 real
- 9 complex

unitary PMNS: parametrisation

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

Unitarity conditions: **2 types**…

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

⇒ ϕ precision ≤6%

sources:

- **reactors (→θ_{13})**
- **solar (→θ_{12})**

⇒ ϕ precision ≤10%

sources:

- **accelerators (→θ_{23})**
- **atmospherics (→θ_{23})**

⇒ ϕ poor precision

sources:

- **not easy** (to say the least)

a **unitary PMNS** (same for CKM) must…

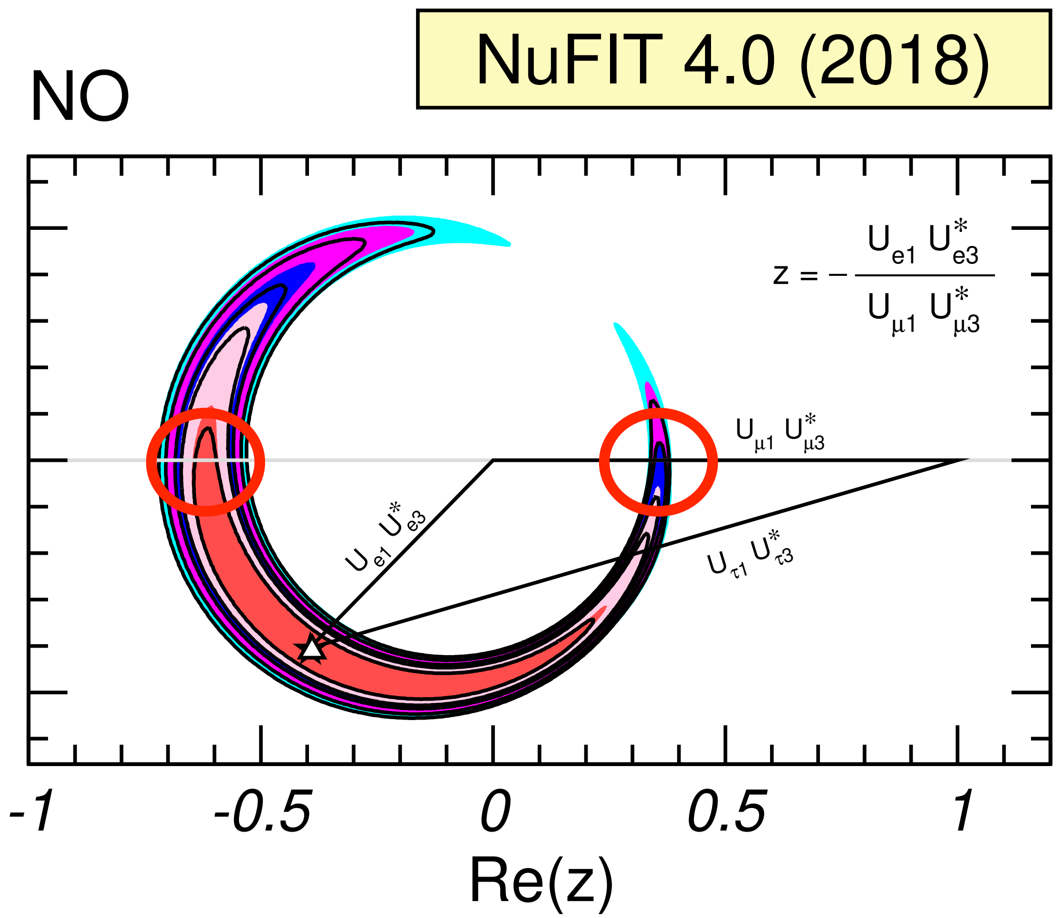
- **normalisation conditions** [refer to "lepton universality" in CKM]
  - each row unitary (3)
  - each column unitarity (3)
- **triangle closure conditions**
  - close all triangles (6)

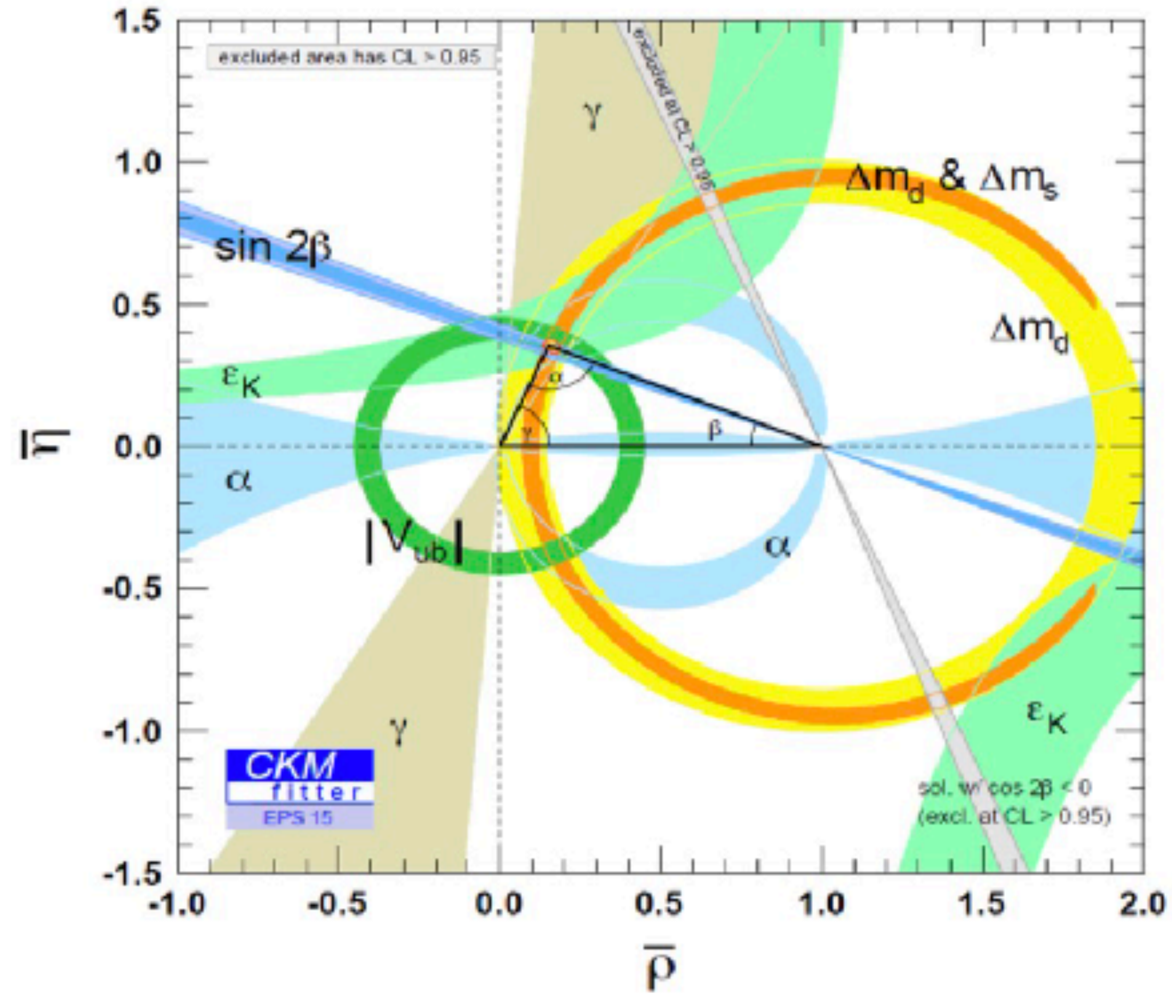
issue!! depends on CP-violation phase (δ) knowledge **[unknown for ν's]**

Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

PMNS

CKM





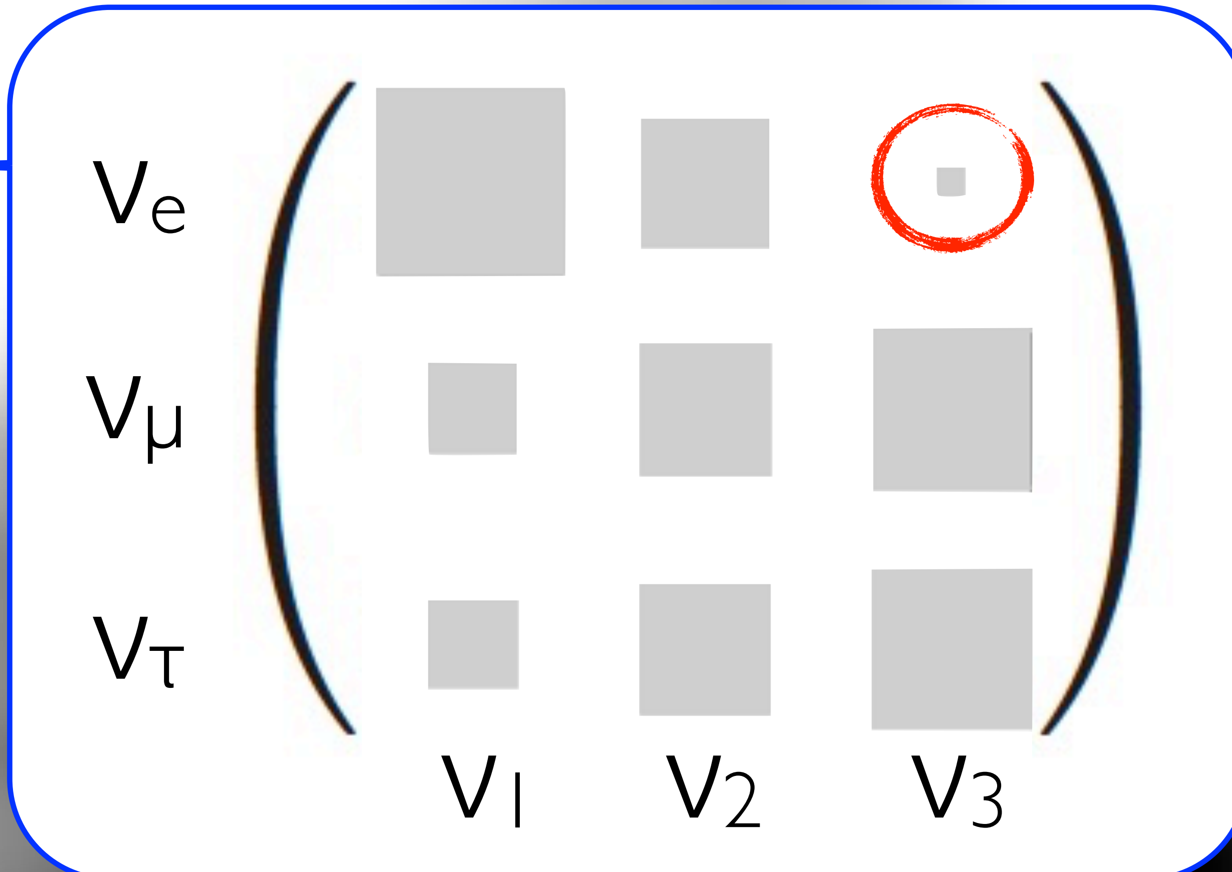
J(PMNS)≈3.33±0.06x10^{-2} **J(CKM)≈3.18±0.15x10^{-5}**

PMNS huge CPV potential: ~10^3 more than CKM — sin(δ_{CP})

PMNS triangle (→CP-violation)…

Unitarity: the structure of **PMNS**?

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



consider the full matrix structure

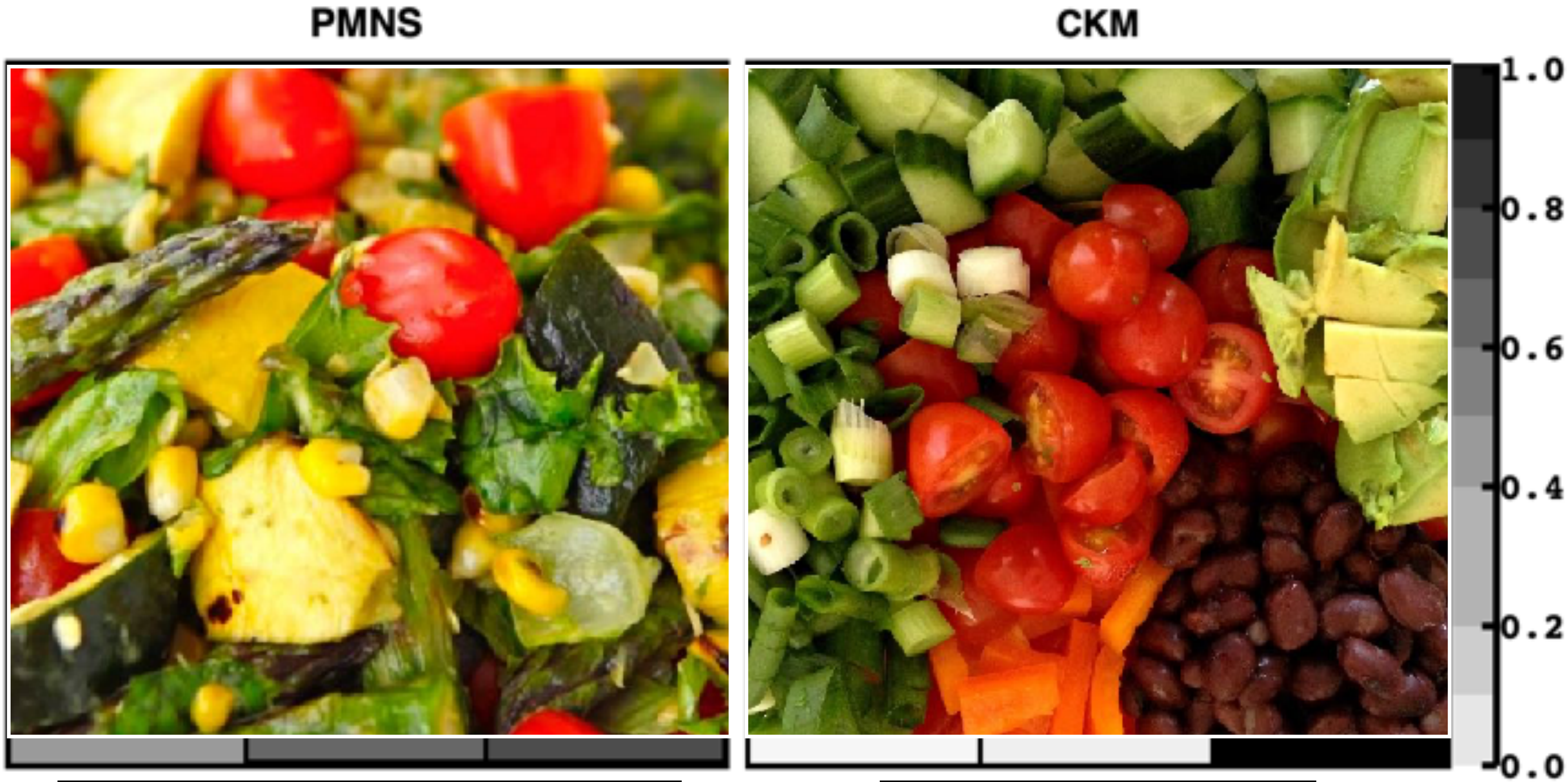
(not merely each of its elements)

why shape? ⟹ **U_{3x3} unitary?**

- **large mixing** but a **small one**!
- **largest CP-violation** (SM)
- **any symmetry behind?**

[assumed!!, not demonstrated]

what is the **PMNS** telling us…?



stravaganzza
(anarchy?)

elegance
(symmetry)

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

Unitarity: the completeness of the ***SM***…

SM "v1" ≈ theory of "Universe" [wo gravity for now] with…

- **3 gauge interactions**
- **3 families** (leptons & quarks) with **mixing** (PMNS / CKM)
- fermions: Dirac and massive
- *renormalised effective QFT* — Loretz / CPT / etc invariant

what **building blocks** are sensitive **Unitarity**? [***beyond SM***]

- **new families** → **≥4** families in the Universe?
- **new interactions** → **≥4** gauge interactions in the Universe?
- **missing phenomenology?** [no change in families or interactions]

⟹ **effective Unitarity violation**: the ***SM* incompleteness** manifestation

Unitarity with **neutrinos**: is it **advantageous**?

the **advantage of using neutrinos** to probe **Unitarity violation**…

- **new families**→ ≥4 lepton families in the Universe?
  [**mixing**: new states **active/sterile** and **regardless of kinematics**]

- **new interactions**→ beyond **weak-only** interaction?
  [**negligible EM/QCD corrections** — or minimal]

- **missing phenomenology?** [no change in families or interactions]
  [even if we have now **no clue**!!]

⟹ **effective Unitarity violation** ⟹ major **discovery** (regardless)

probing ***SM* "building-block symmetries"** key **path to progress**!

Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

Unitarity

(with reactor neutrinos)

this talk relies somewhat on Pedro's (mainly), Andrea's and Alberto's to minimise redundancies

Unitarity via the **electron-row**…

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

⇒ ϕ precision ≤6%

sources:
- **reactors (→θ_{13})**
- **solar (→θ_{12})**

unitary PMNS violation test via the **electron-row normalisation**

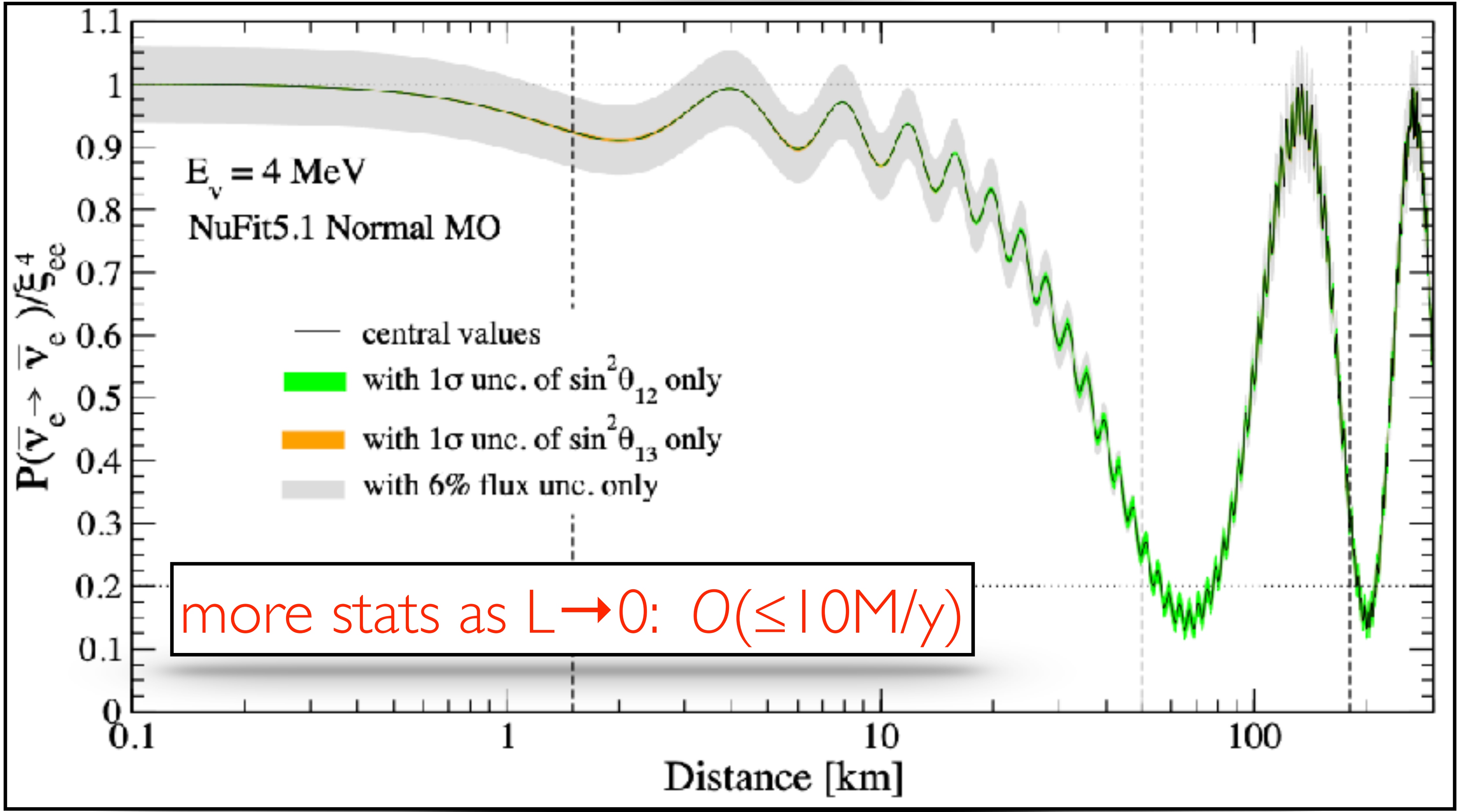
experimental observables…

- **absolute flux (ϕ)** @ baseline **L→0** [no oscillation — else **discovery!**]
- **“θ13” oscillation** @ baseline **L ≈ 1km** [vacuum oscillation]
- **“θ12” oscillation** @ baseline **L ≈ 50km** [vacuum oscillation]

$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$ **⇒ explore the “electron-row”**

a priori only “θ_{12}” and “θ_{13}”…

Unitarity violation with reactors: **how?**



unitary PMNS violation test via the **electron-row normalisation**

- **absolute flux (ϕ)** @ baseline **L→0** : **δϕ [≤6%]**
- **θ13 oscillation** @ baseline **L ≈ 1km** : **δϕ [≤6%]** ⊕ **$\delta\theta_{13}$ [≤3.2%]**
- **θ12 oscillation** @ baseline **L ≈ 50km** : **δϕ [≤6%]** ⊕ **$\delta\theta_{13}$ [≤3.2%]** ⊕ **$\delta\theta_{12}$ [≤4%]**

non-Unitarity basis (V): violation searches…

$$\begin{bmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{bmatrix}$$

⇒ ϕ precision ≤6%

sources:
- **reactors (→θ_{13})**
- **solar (→θ_{12})**

Similar formulations…
- M. Blennow *et al* **arXiv:1609.08637**
- F. Escrihuela *et al* **arXiv:1503.08879**

$$\begin{bmatrix} \xi_{ee} & 0 & 0 \\ \xi_{\mu e} & \xi_{\mu\mu} & 0 \\ \xi_{\tau e} & \xi_{\tau\mu} & \xi_{\tau\tau} \end{bmatrix} \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix}$$

CKM tension
(≥4σ's!!)

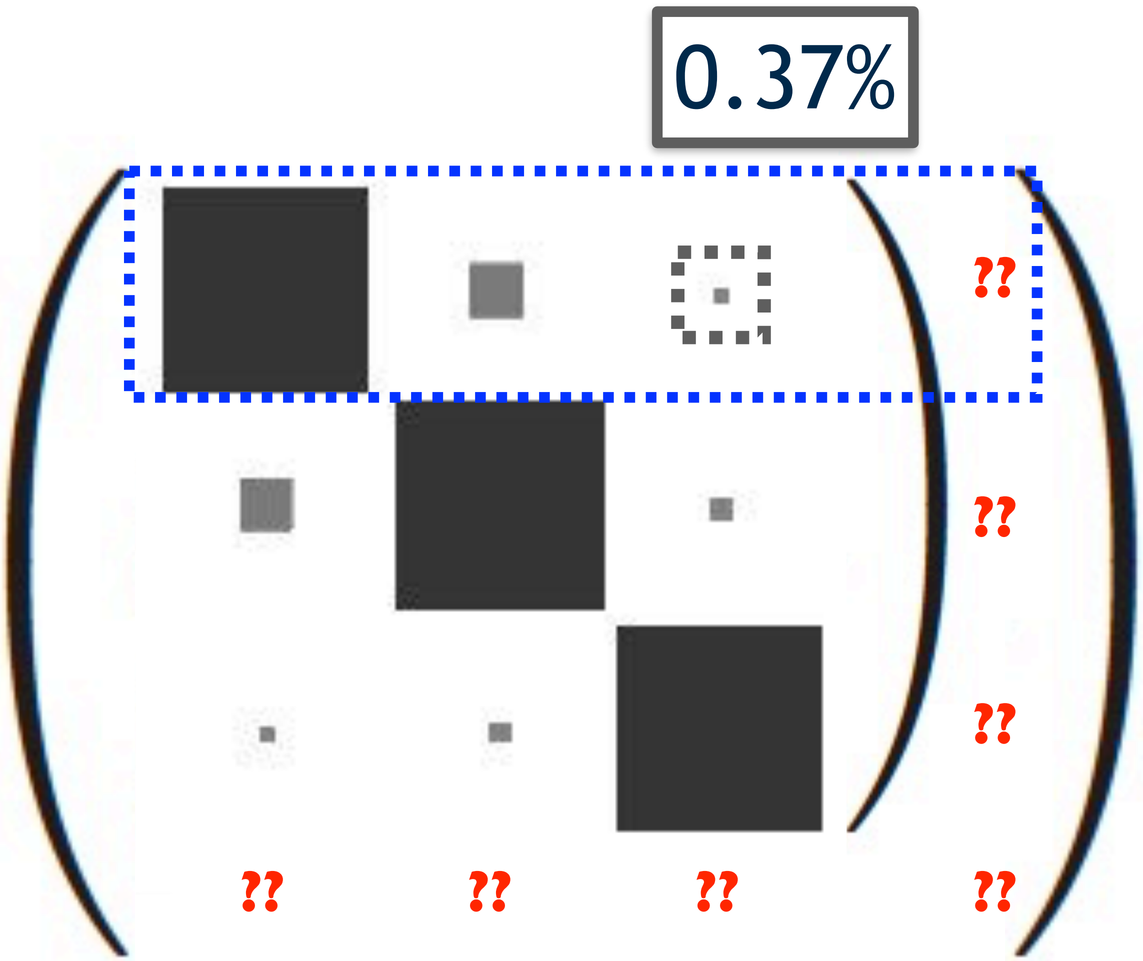
$$1 - (|V_{e1}|^2 + |V_{e2}|^2 + |V_{e3}|^2) = 1 - \xi_{ee}^2$$

explore the deviation (or violation) from unitarity
unitarity violation ⇒ absolute flux deviation

$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$ ⇒ **by unitarity definition (*SM*)**

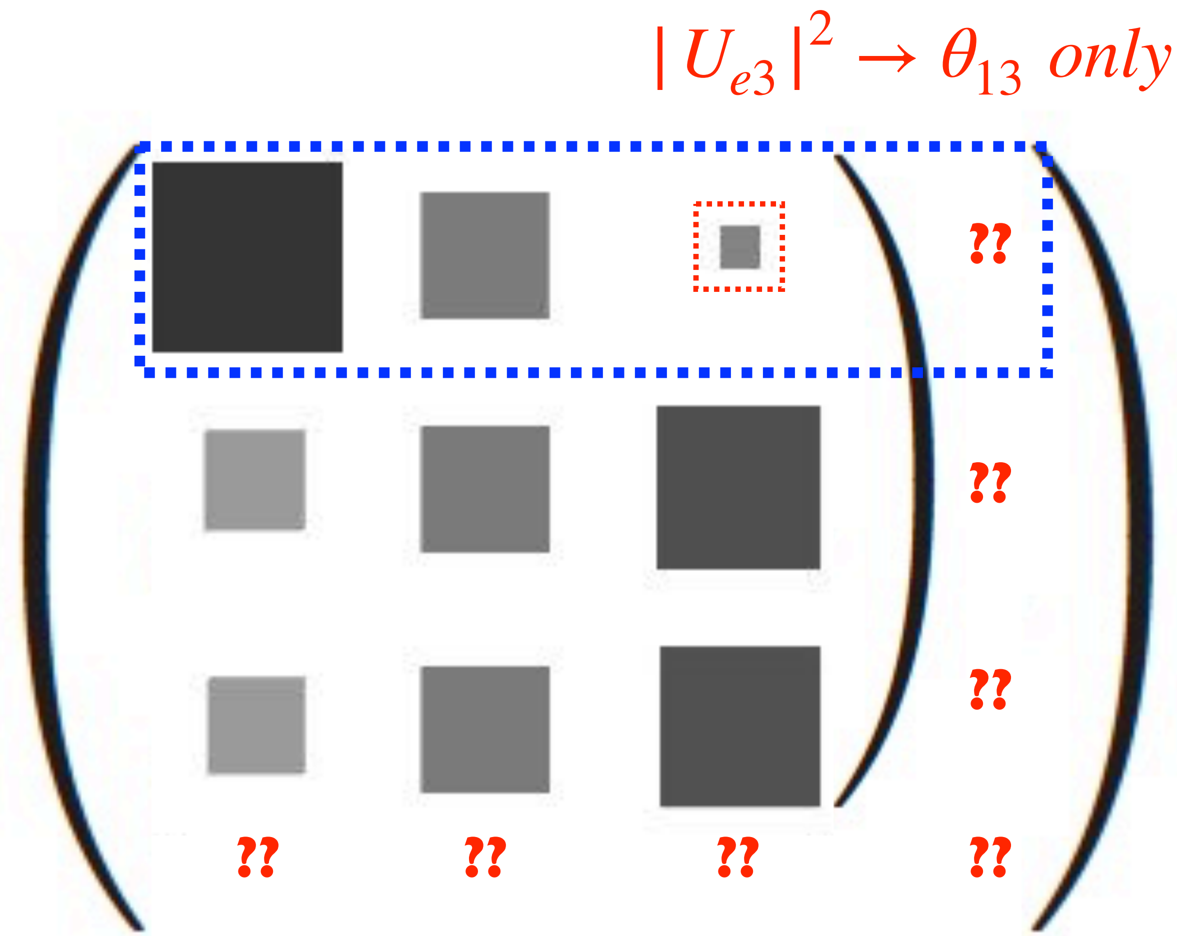
a priori only "θ_{12}" and "θ_{13}"…

unitarity violation implications…



if it existed ⇒ tiny!!(?)

(naive expectation)



if it existed ⇒ less tiny(?)

(naive expectation)

few % precision enough?

Unitarity Violation [major discovery]

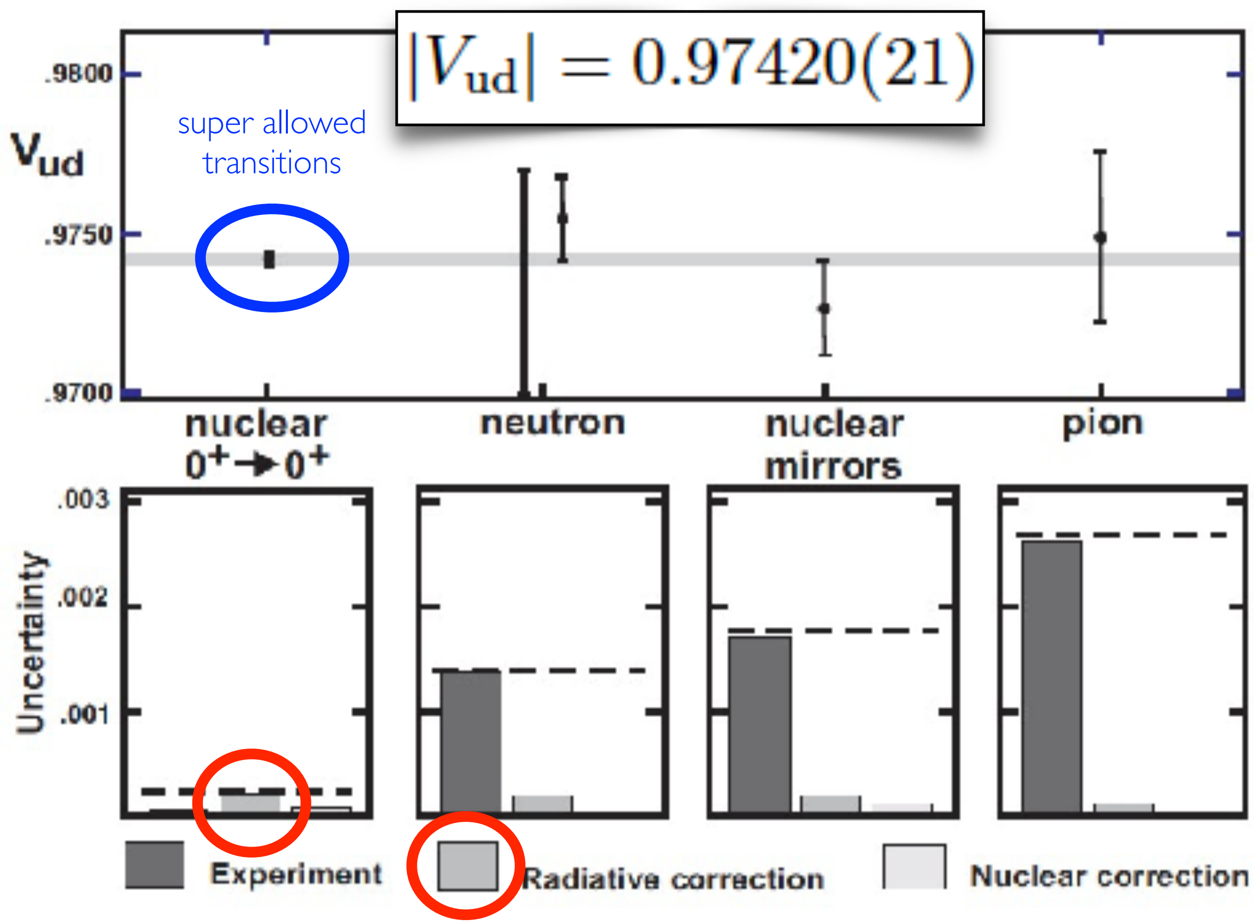
non-standard ν states
and/or
non-standard ν interaction

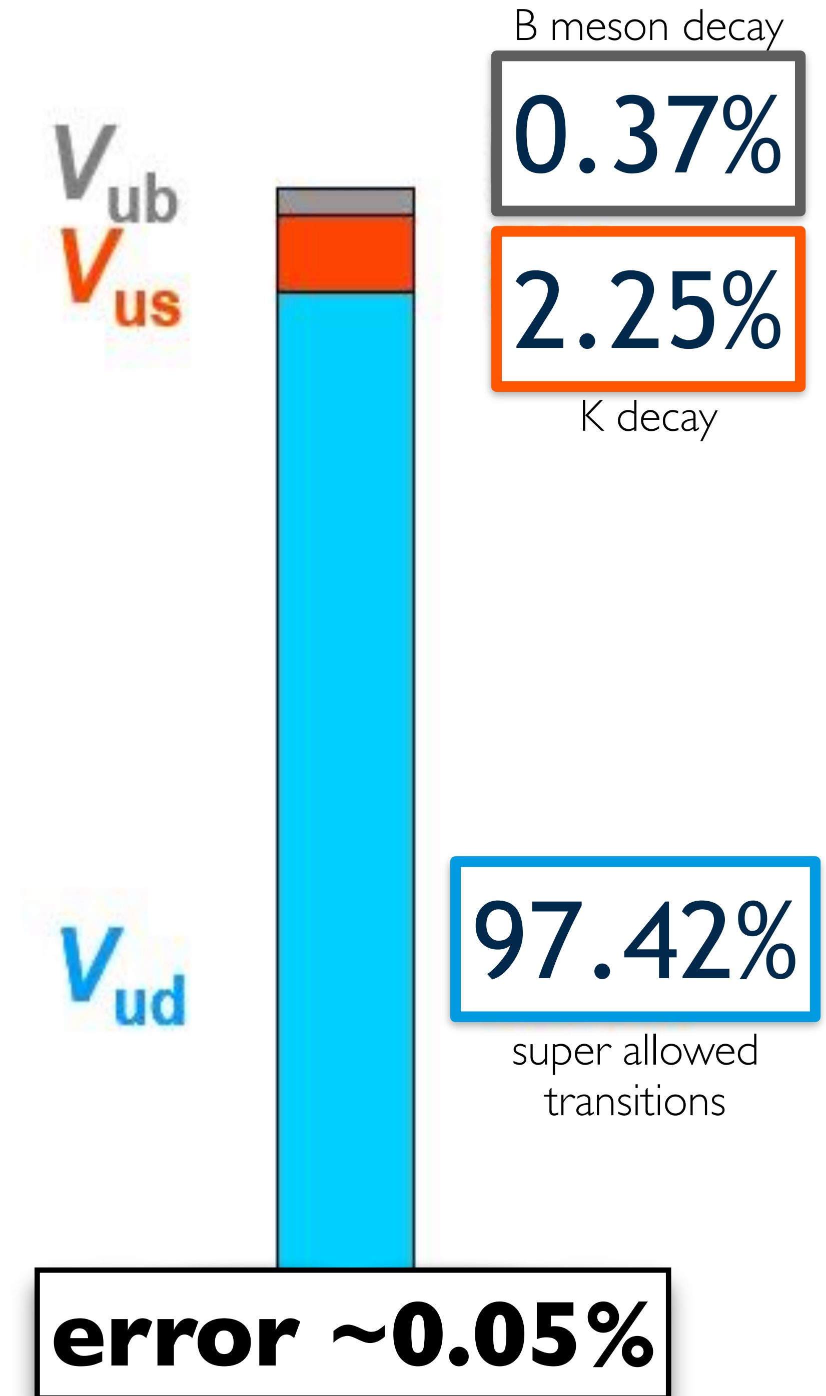
CKM equivalent knowledge…

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

Hardy & Towner, arXiv 1807.01146 and Particle Data Group 2018

arXiv:1807.01146v1





2018 radiative correction (before 2006)

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

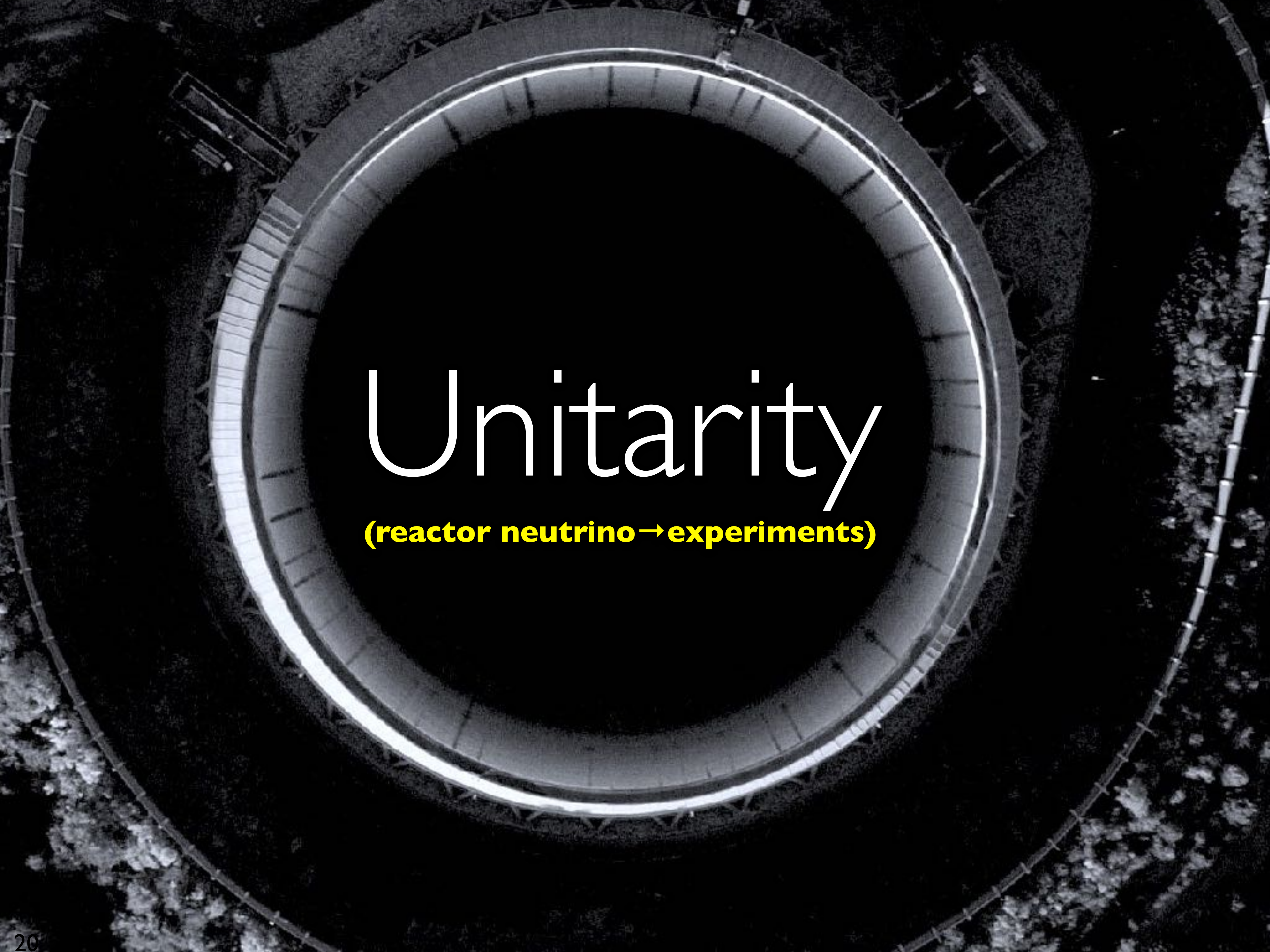
tension @ CKM??

[data or corrections]

Nathal Severins (Leuven)

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

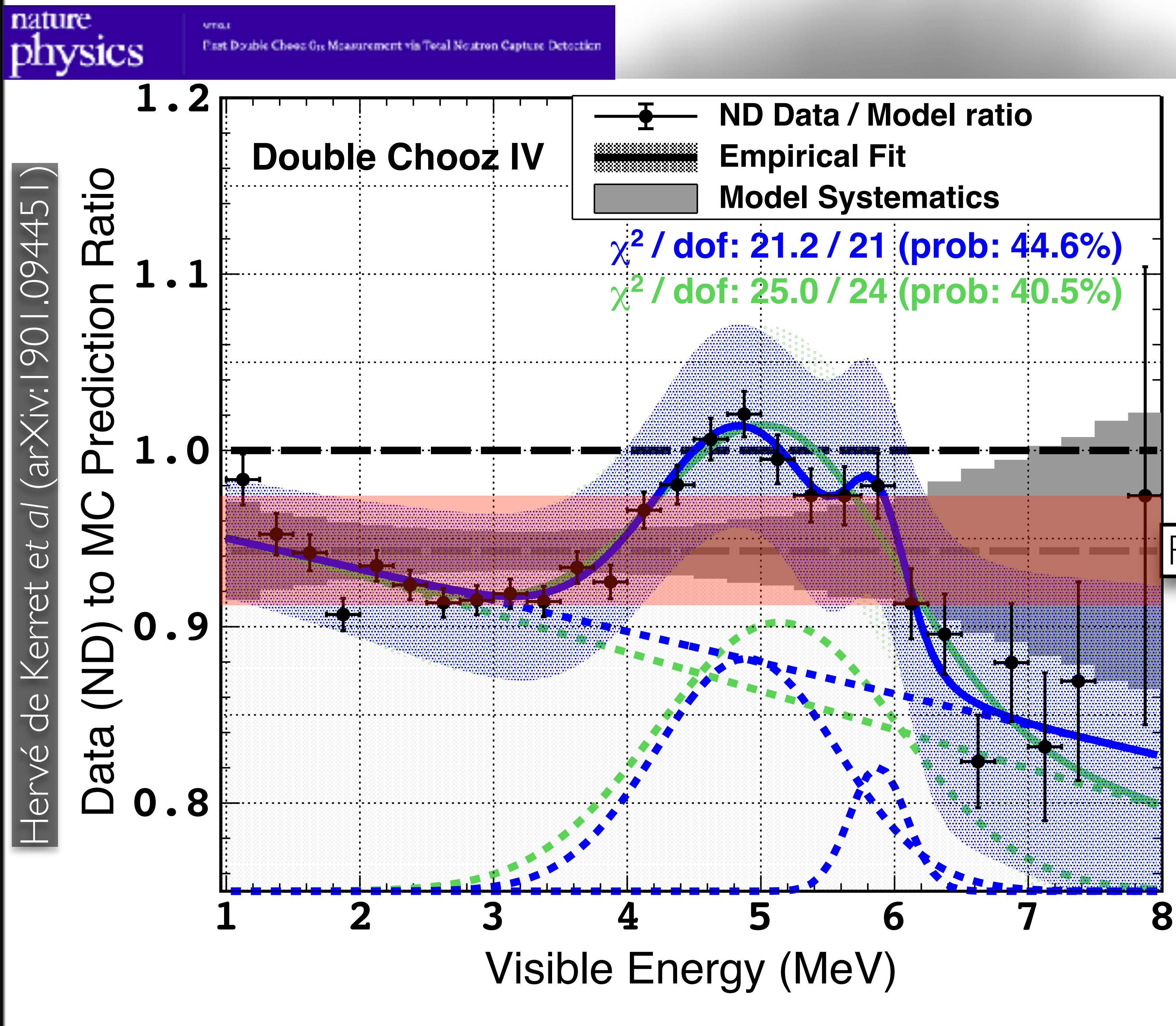
ECFA NuPECC ApPEC JENAS-2019 Joint ECFA-NuPECC-ApPEC Seminar October 14-16, 2019 - LAL Orsay, France



Unitarity

(reactor neutrino→experiments)

today's reactor **φ(absolute)** knowledge…



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

δΦ(reactor): ~1.0%
[world precision]

but biased up to 7%!!

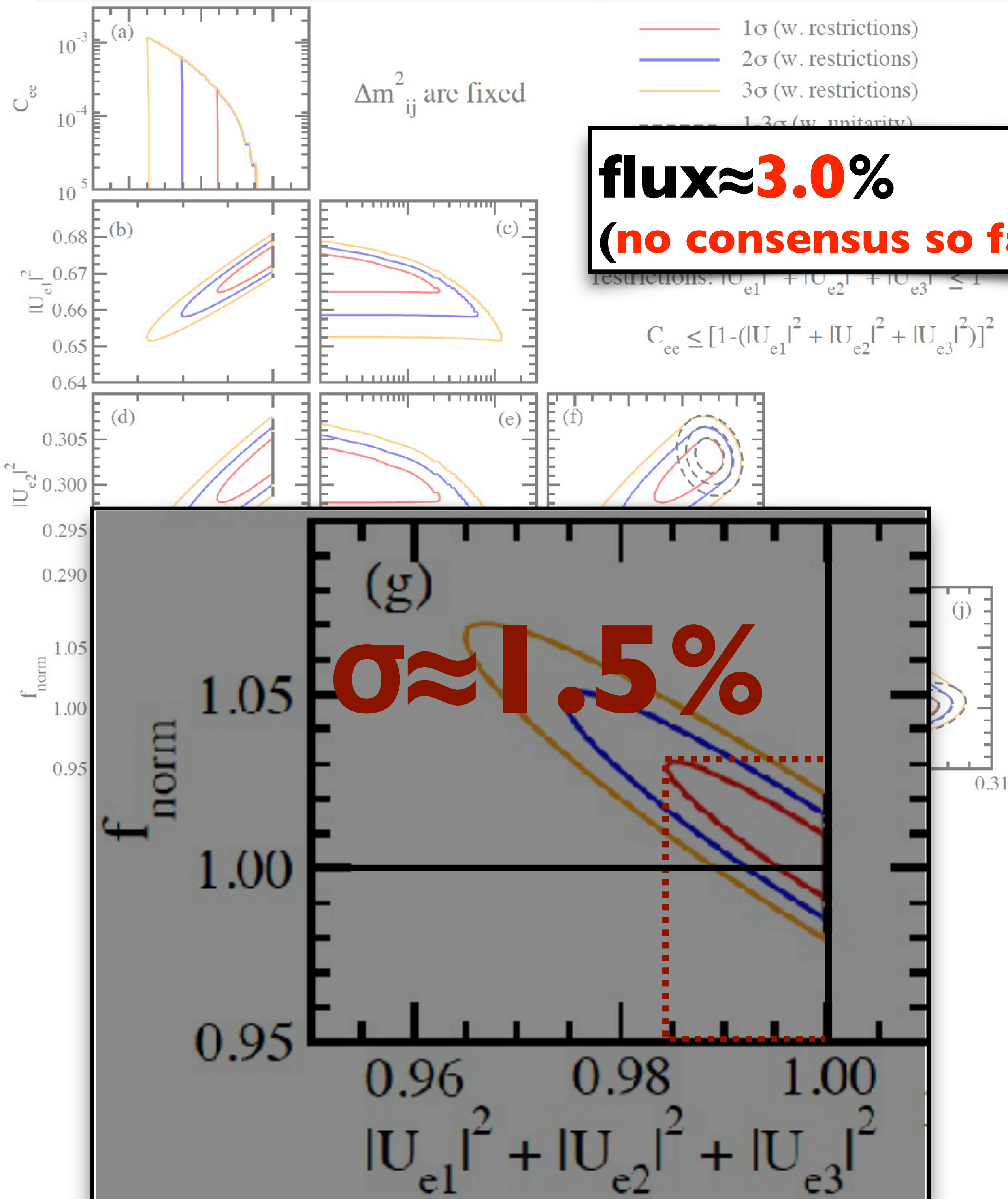
Uncertainty
~2.3%→**≤6.0%**
[surely <10%]

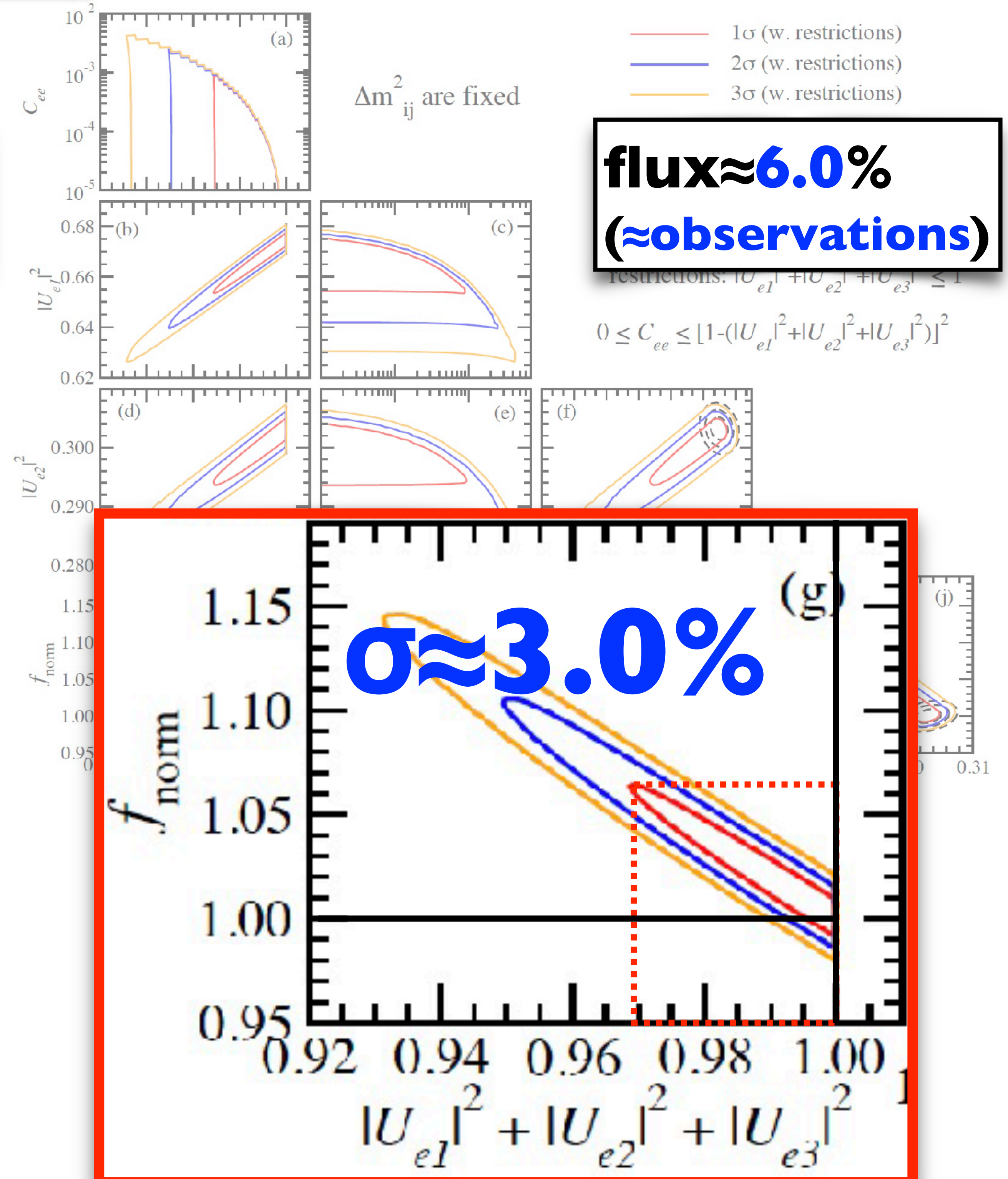
reactor flux poorer precision (rate or shape)

⟹ (long story short) unlikely new physics — unfortunately

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

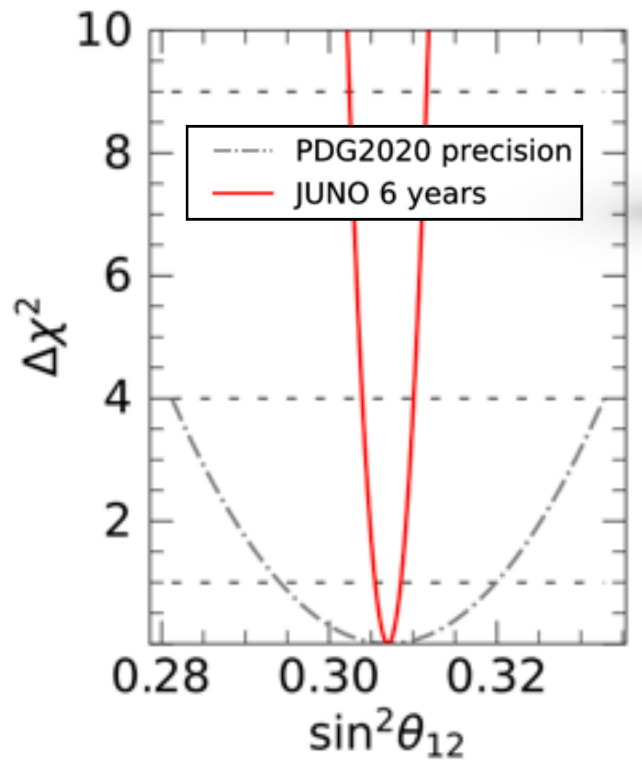
H. Nunokawa *et al* (arXiv:1609.08623v2)





unitary explorations limited by absolute flux uncertainty

at **longer baselines** (more uncertainties)…

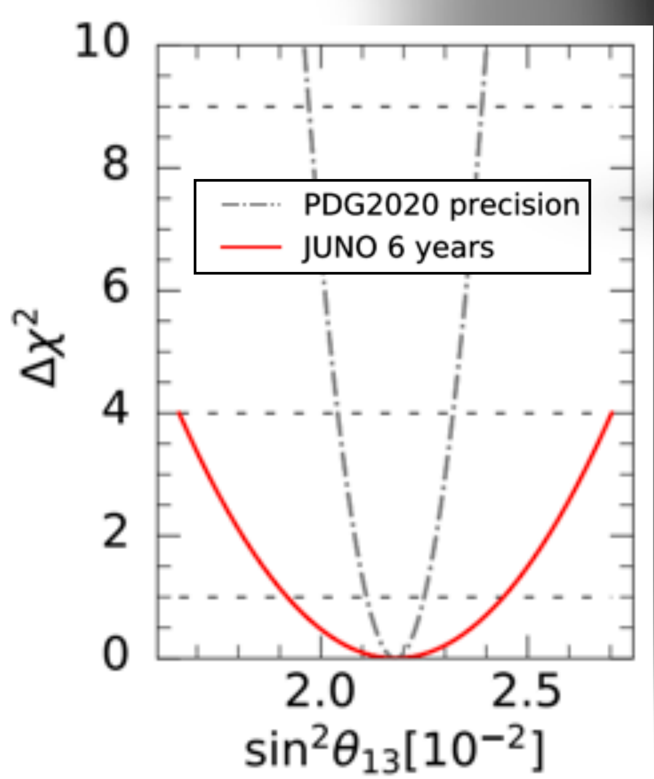


JUNO (10x better)

⇒ **JUNO major improvement 4.2%→≤0.5% (6 years)**

but measuring Unitarity **L≈50km**…

- **lower stats** *O*(<25k/year)
- systematics from **θ13** and **ϕ(absolute)** [no near-derector]



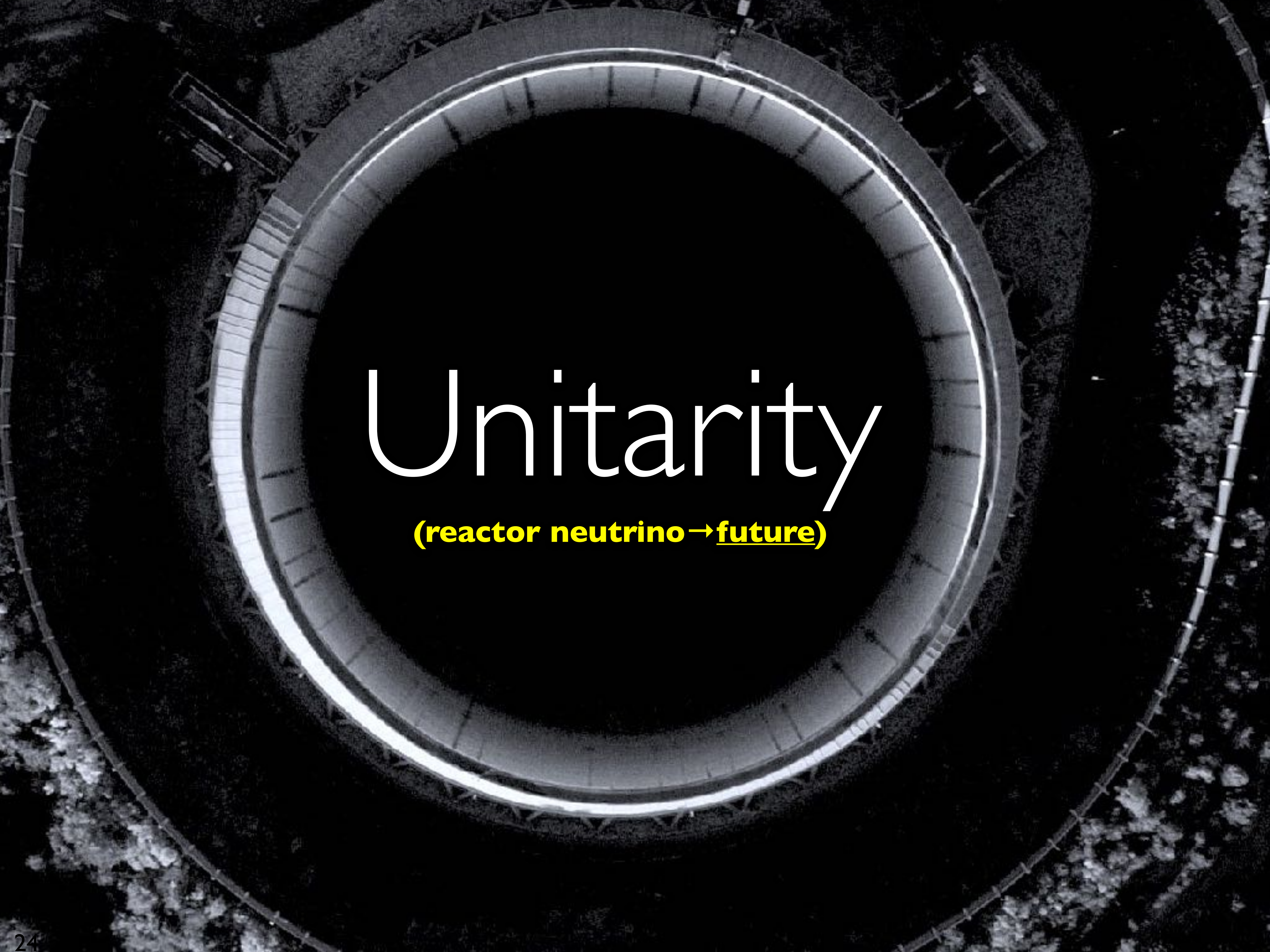
nothing can improve θ13
(**PDG2020 largely representative**)

⇒ **~3.0% (Daya Bay ⊕ Double Chooz ⊕ RENO)**

but measuring Unitarity **L≈1km**…

- good **stats**
- still systematics from **ϕ(absolute)** [no near-derector]

unitary explorations limited by absolute flux uncertainty

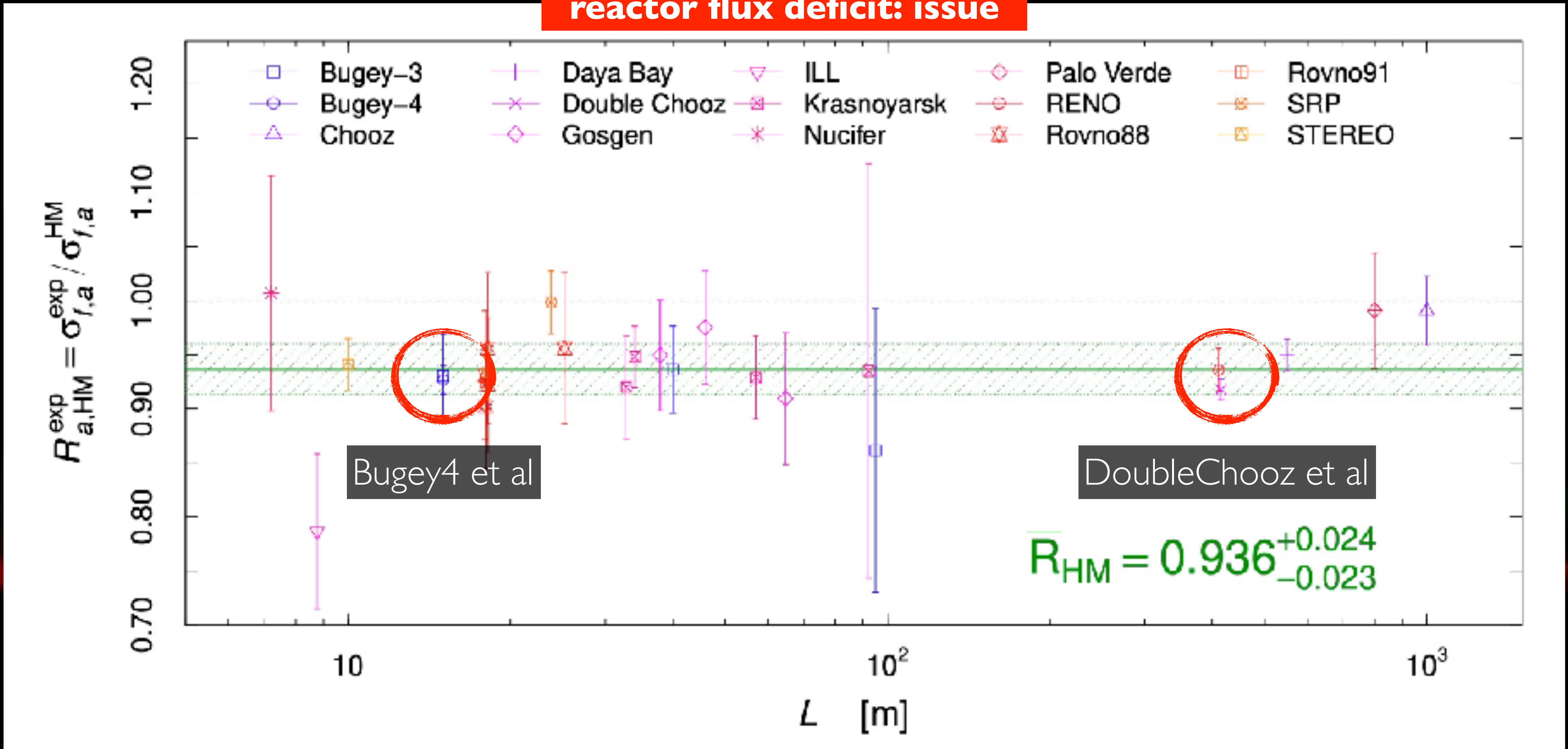


Unitarity

(reactor neutrino→<u>future</u>)

reactor flux (rate-only) discrepancy…

reactor flux deficit: issue



generally excellent agreement <u>among all experiments</u>

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

(≥2011) ~7.0% mismatch between ILL-prediction and data

≥2021 reactor flux improvement…

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

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

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

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

solve much of the"issue": enough?
(less discrepancy data and ILL-prediction)

DoubleChooz: R=0.925±**0.010**(exp)±**0.023**(model)⟹ **R→1** but **still issues!**

prediction: any remaining bias? [how to be sure?]
what's the uncertainty? [so far not right]

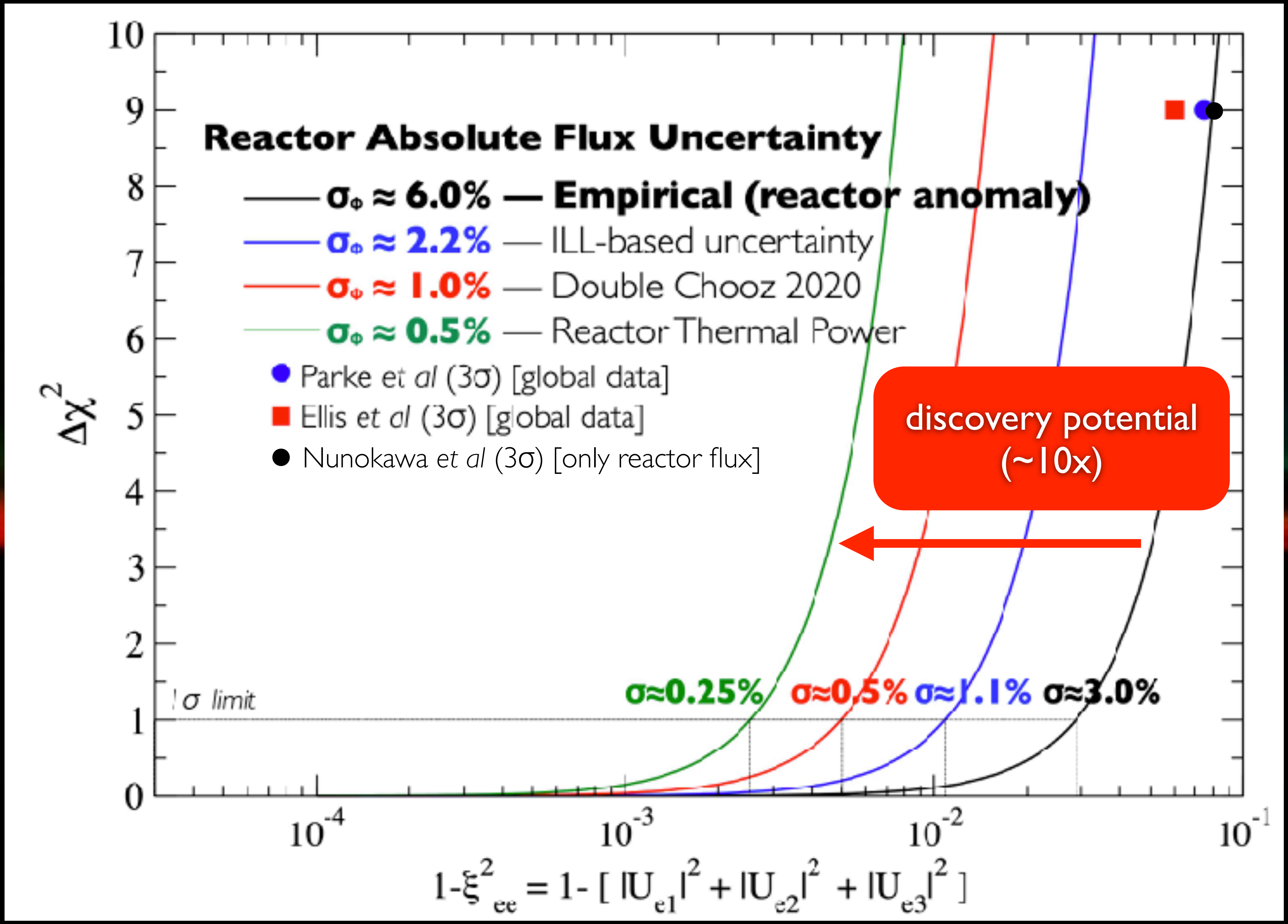
experiment flux uncertainty:
(ultimatedly dominated by thermal power)

DoubleChooz uncertainty: ~**1.0%**
Bugey4 uncertainty: ~**1.4%**
DYB uncertainty: **~1.5%**

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

→ irreducible!!

Unitarity knowledge potential…



must improve the reactor flux uncertainty → discovery potential!

much work & new data for the control of the uncertainties→ **possible?**

https://liquido.ijclab.in2p3.fr/nucloud/

C L O U D

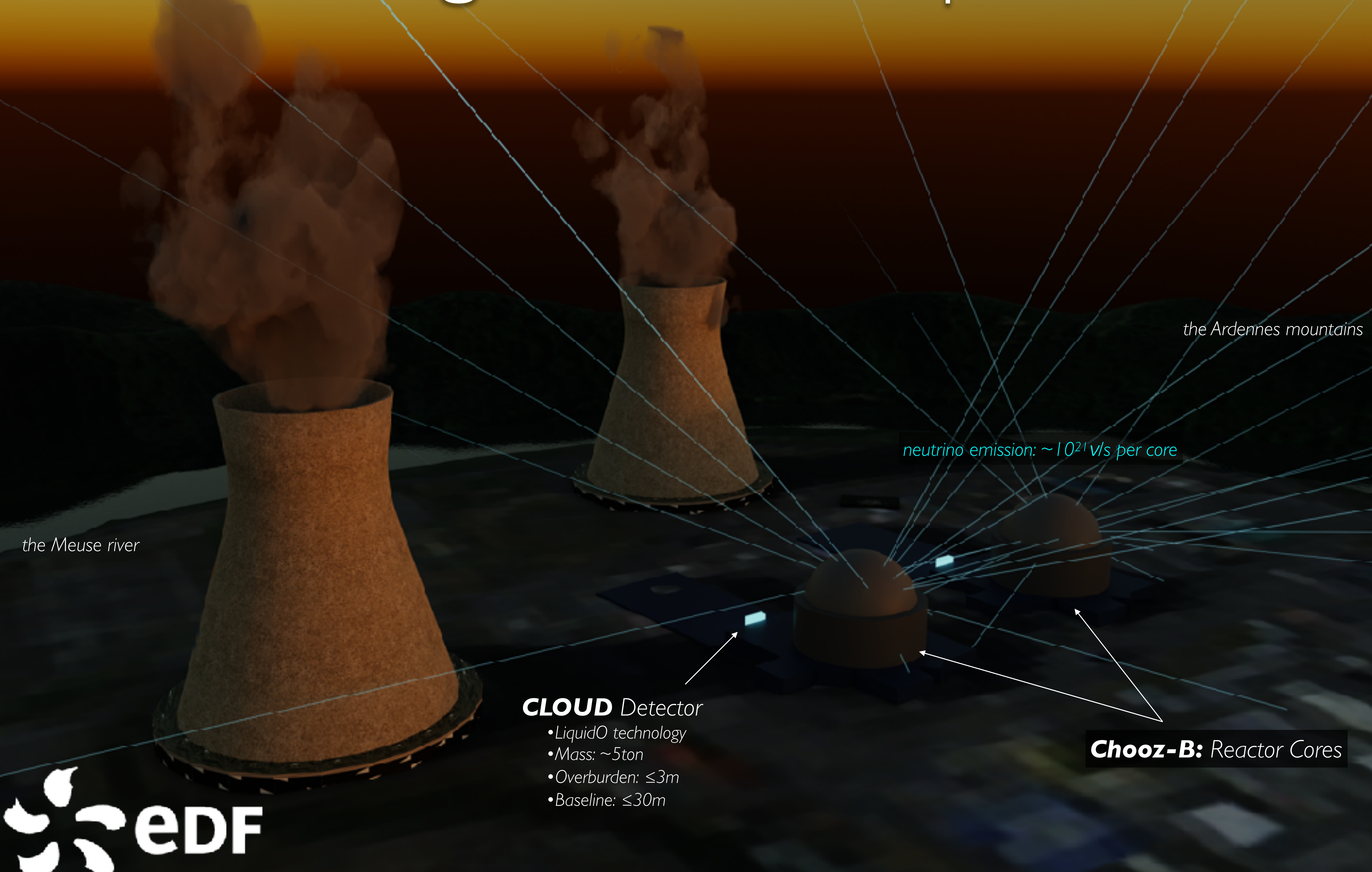
European Innovation Council

UK Research and Innovation

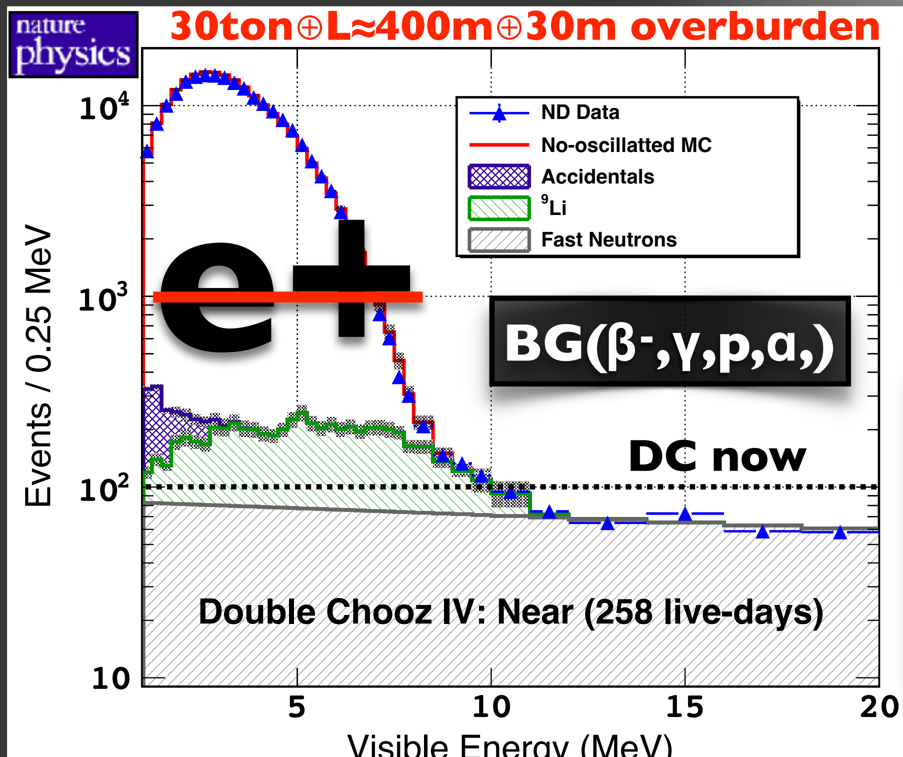
first LiquidO-based experiment…

CLOUD = "**C**hooz **L**iquid**O** **U**ltranear **D**etector"
[project: "**AntiMatter-OTech**"]

Chooz's 3rd generation experiment…



CLOUD background control…




Article Published: 20 April 2020

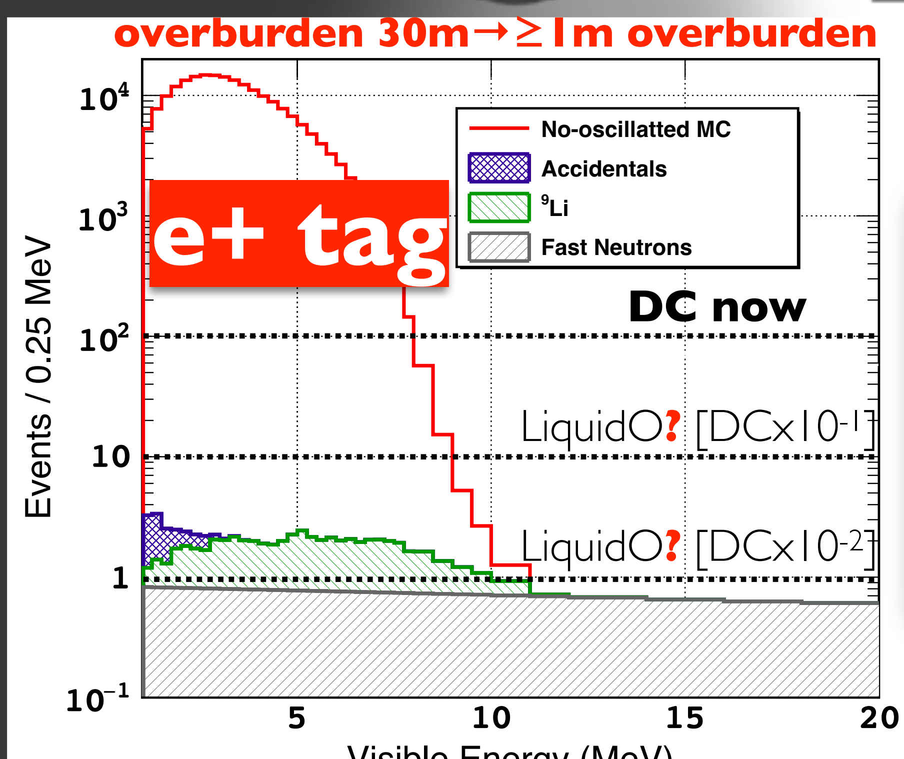
Double Chooz θ_{13} measurement via total neutron capture detection

The Double Chooz Collaboration

Nature Physics 16, 558–564 (2020) | Cite this article

DC-ND:
Signal ≈ 816 ν/day
BG(β-,α,γ,p) ≈ 39 day^{-1} ("*some per day*")

S/BG≈21(≤30)



CLOUD:
Signal(e+) ≥10,000 ν/day [**≥5M ν/year**]

BG(DC) ≈ **≥10x BG(LiquidO)→ few per year?!**

S/BG ≥100? similar configuration
[demonstration pilot project]

vast scientific programme...

European Innovation Council

UK Research and Innovation

C L O U D

scientific programme to be released soon — innovation (protected)

Innovation Programme (confidential for now) — "Antimatter-OTech"
Fundamental Science Programme (soon)

- **EDF** (France) — **first time in neutrinos!**
- **CIEMAT** (Spain)
- **IJCLab**/Université Paris-Saclay (France)
- **J-G Universität Mainz** (Germany)
- **Subatech**/Nantes Université (France)
- **Sussex University** (UK)

—

- **Charles University** (Czech Republic)
- **INFN-Padova** (Italy)
- **UC-Irvine** (US)
- **Universidade Estadual de Londrina** (Brasil)
- **PUC-Rio** de Janeiro (Brasil)
- **Queen's University** (Canada)
- **University of Zaragoza** (Spain)
- **Tohoku University** / **RCNS** (Japan)

CLOUD collaboration (EDF⊕13 institutions over 10 countries)

SuperChooz exploration…

https://liquido.ijclab.in2p3.fr/superchooz/

SuperChooz Pathfinder agreement between CNRS⊕EDF… [last Sunday!]

LiquidO Consortium (They/Them) • You
Detection in Fundamental Particle Physics & Innovation
1d • Edited •

Fantastic news at the #LiquidO (LiquidO Consortium) this week...

We are delighted to announce that our #detection #technology has the potential to open a new era of #neutrino #fundamental #science at the EDF #ChoozB #nuclear #reactor, located at the heart of #Europe, with the official start of the #SuperChooz #Pathfinder project (https://lnkd.in/efej2nqn) upon the signature (tweeter: https://lnkd.in/em4t2i_s) of the dedicated agreement between the directions of EDF (Cédric Lewandowski: announced at https://lnkd.in/ePEy5c94) and Centre national de la recherche scientifique (Reynald Pain #CNRS-#IN2P3) on the 7th of September 2022.

#LiquidO capabilities and performance are needed for the #SuperChooz (tweeter: https://lnkd.in/evT4VQ5W) to face an unprecedented #neutrino #detection challenge in the horizon of 2030 with a new experimental setup using 3 LiquidO detectors: 2 small "ultra-near detectors" (#UND) and 1 huge "super-far detector" (#SFD). If proved feasible, the ~10 kton #SFD would be located in one of the caverns of the '60s' #ChoozA #nuclear #reactor becoming available upon the dismantlement by the #DP2D department of EDF.

The #UND framework, along with the #LiquidO's performance demonstration, will be addressed as part of the approved #Europe-based #pilot #project "#AntiMatter #OTech" project (https://lnkd.in/ezf37Baz) funded by the #EIC(https://lnkd.in/eu3jxYjb) and the #UKRI starting officially from December 2022. Both #SuperChooz and #LiquidO are scientifically led by Anatael Cabrera.

Further details at our new(!!) LiquidO's website (https://lnkd.in/eVYaBpiG), where our history and present in terms of #R&D developments and projects in both #fundamental #research and #innovation are described.

IJCLab⊕Subatech teams — Octobre 2020

CNRS/IN2P3 direction — March 2022

EDF⊕CNRS exploration…

anatael@in2p3.fr

collaboration with **LiquidO, AM-OTech, CLOUD, EDF,** and **SuperChooz** teams…

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

publication(s) under preparation
(much more)

CLOUD

https://liquido.ijclab.in2p3.fr/

Unitarity violation searches a **powerful way to probe the SM (in)completeness**

- **any deviation** (significance?) may lead to **discoveries (even and specially model-less)**
- validating its **unitarity conservation experimentally** is a must — overconstrain the ***SM***

reactor neutrino remains **one of the most powerful** ways to probe **Unitarity** (**violation/conservation**)

- **absolute flux knowledge** is at stake — again!! [neutrino oscillations discovery: solar / atmospheric anomalies]
- new **CLOUD experiment** (L→0): **improving possible?** (beyond's DoubleChooz's precision?)