Reactor ν

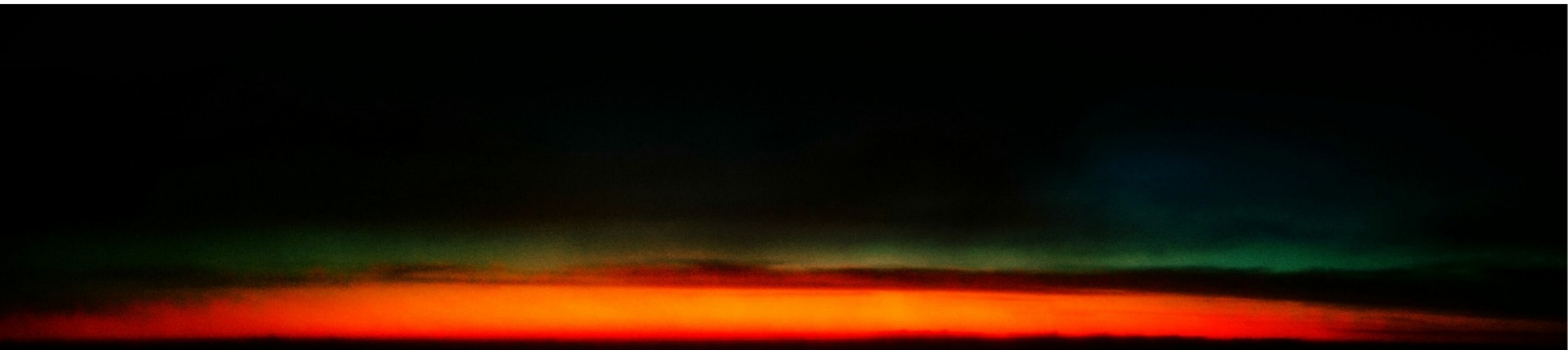
present and outlook...

VSON School (Vietnam)
19th July 2022

Anatael Cabrera
CNRS/IN2P3
IJCLab @ Orsay

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

disclaimer…



This description aims to provide basis of neutrino oscillation with reactor neutrinos based on the **experimental challenges** we faced / are facing now (including an outlook) while highlighting the topics **where reactors have the largest impact**…

Hence, this description will benefit from all other lectures for complementary information

not follow a strict chronological account

standard 3 active neutrino oscillation paradigm

who I am?

working on…

- **Double Chooz** experiment (dismantling now)

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*** [Jarkslog 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*]

?

discovery!

reactors' sensitivity…

<u>directly sensitive</u> to: **θ_{13}**, **θ_{12}**, **δm^2**, **Δm^2**, **$\pm$?**Δm^2 (mass ordering) via **vacuum oscillations**

by ≥2030: the world's knowledge of **all those parameters** will be driven by reactors
[key **input** for other experiments: accelerators, atmospheric, solar, etc]

indirect (i.e. **synergies**) boosting the **combined sensitivity** for **δ** and **θ_{23}**

issue! ϕ(reactor) exhibits <u>several inconsistent features</u> (⟶ unsettled debate still)

beyond standard neutrino

main achievements so far…

Discovery of the neutrino

[evidence (not reactor) for **solar anomaly** & **atmospheric anomaly**]

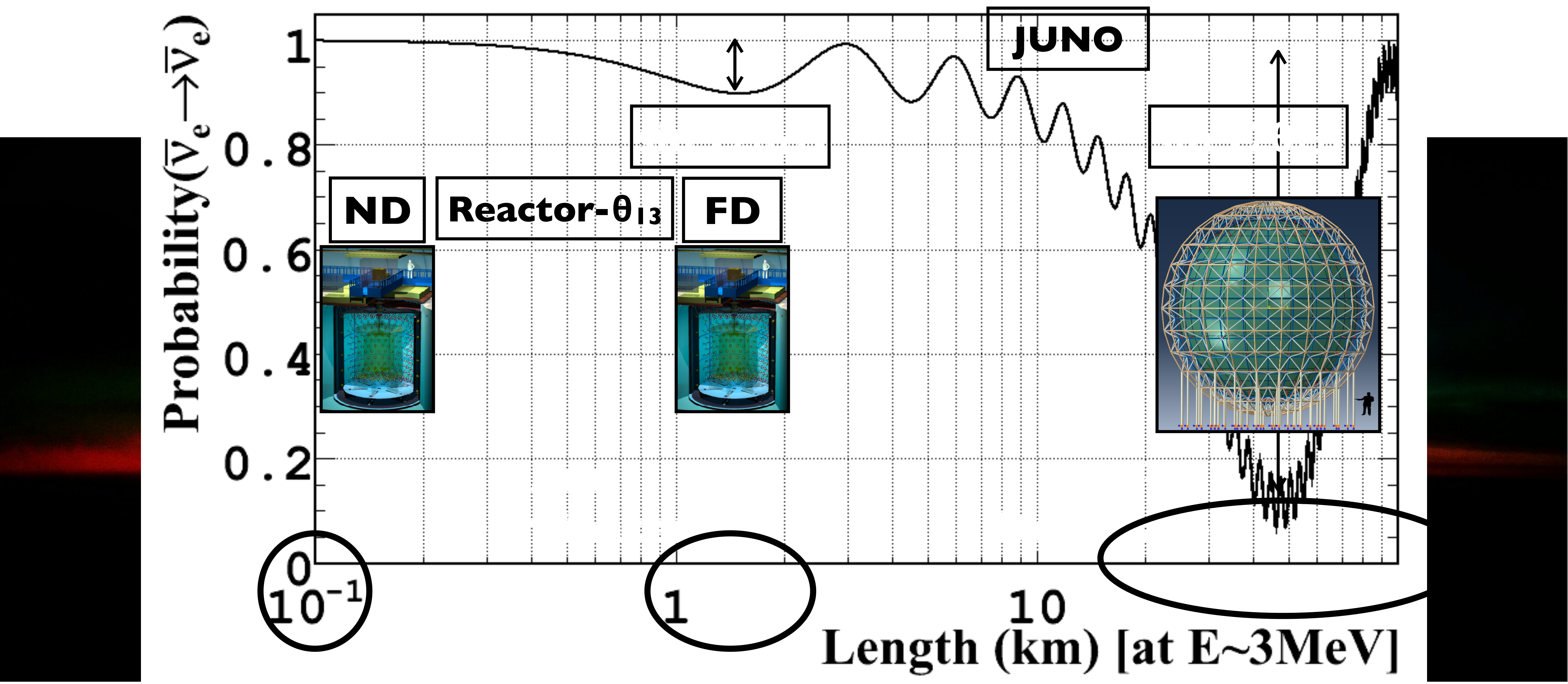
- **1990-2000:**
  - CHOOZ & Palo Verde support ***atmospheric anomaly*** Kamiokande's ν(μ)→ν(τ) [→SuperK]
  - (byproduct) direct (stringent) limit on **θ13** (till 2011)

- **2000-2010:**
  - KamLAND demonstrates the **LMA** solution of the "***solar anomaly***" [key for discovery]
  - (byproduct) most spectacular spectral distortion seen so far (**θ12** and **δm²**)

- **2010-2020:**
  - Daya Bay⊕Double Chooz⊕RENO: **first measure the *predicted* θ13** —T2K evidence too
  - (synergy) critical for **first ≤2σ constraints on δ** by T2K and NOvA
  - (byproduct Double Chooz): **φ(reactor) issue!**→ reactor knowledge**?** vs sterile at ~1eV^2**?**

? **What else?**

experimental setup…



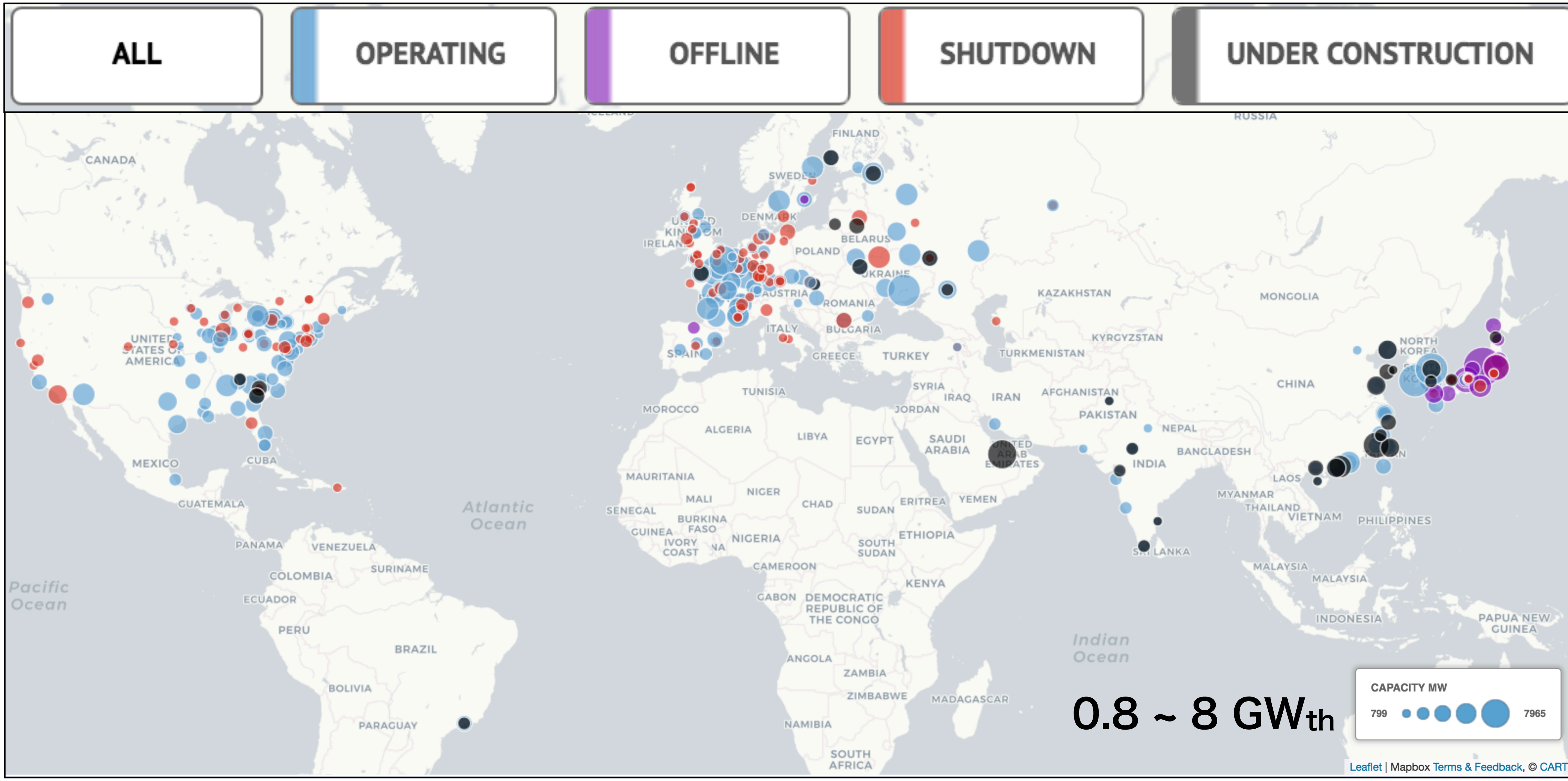
new physics?

the reactor…

Chooz-B nuclear reactor plant: 2x N4 reactors [4.2$GW_{thermal}$ each]

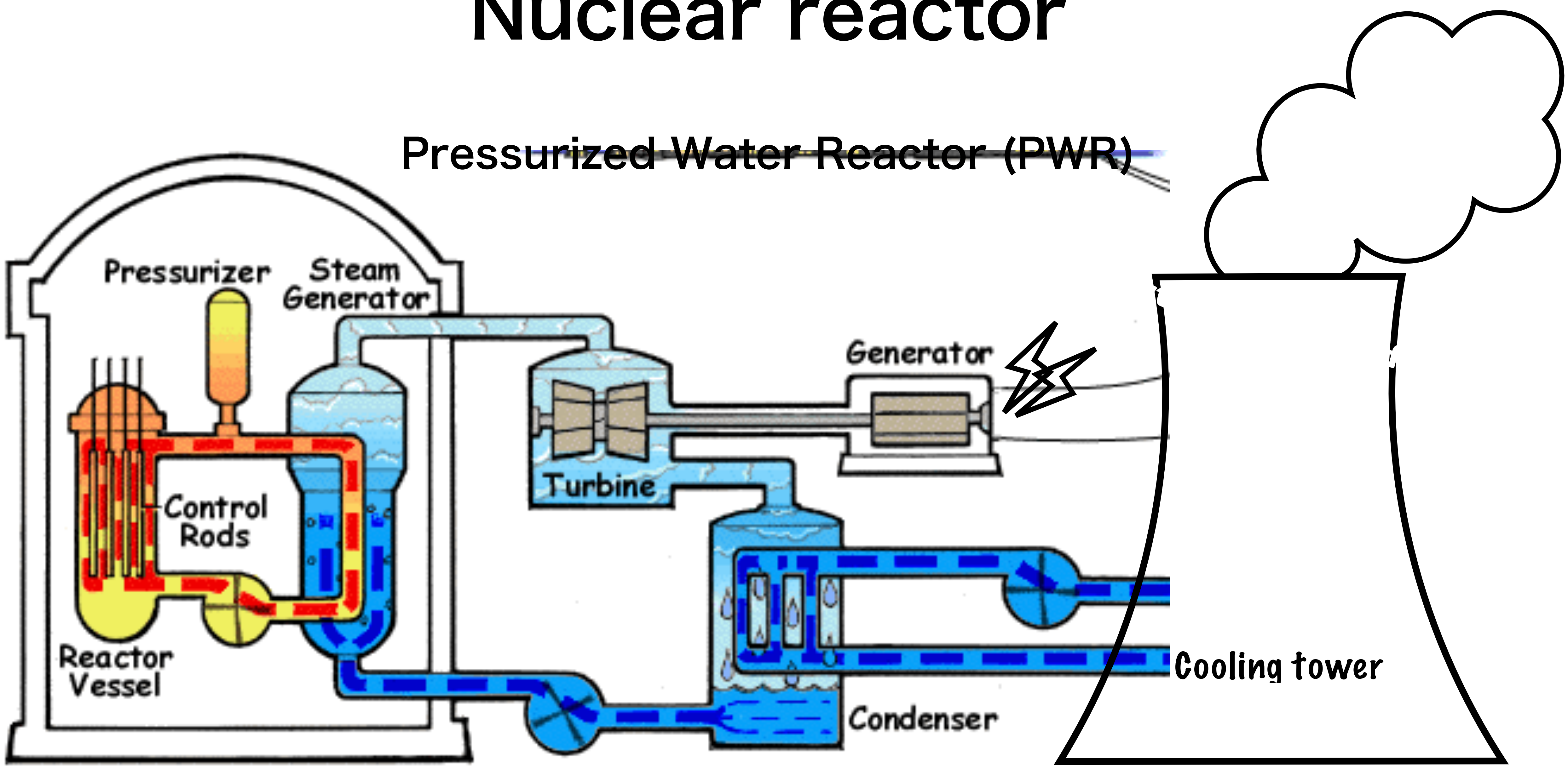
Nuclear reactors in the world

https://www.carbonbrief.org/mapped-the-worlds-nuclear-power-plants



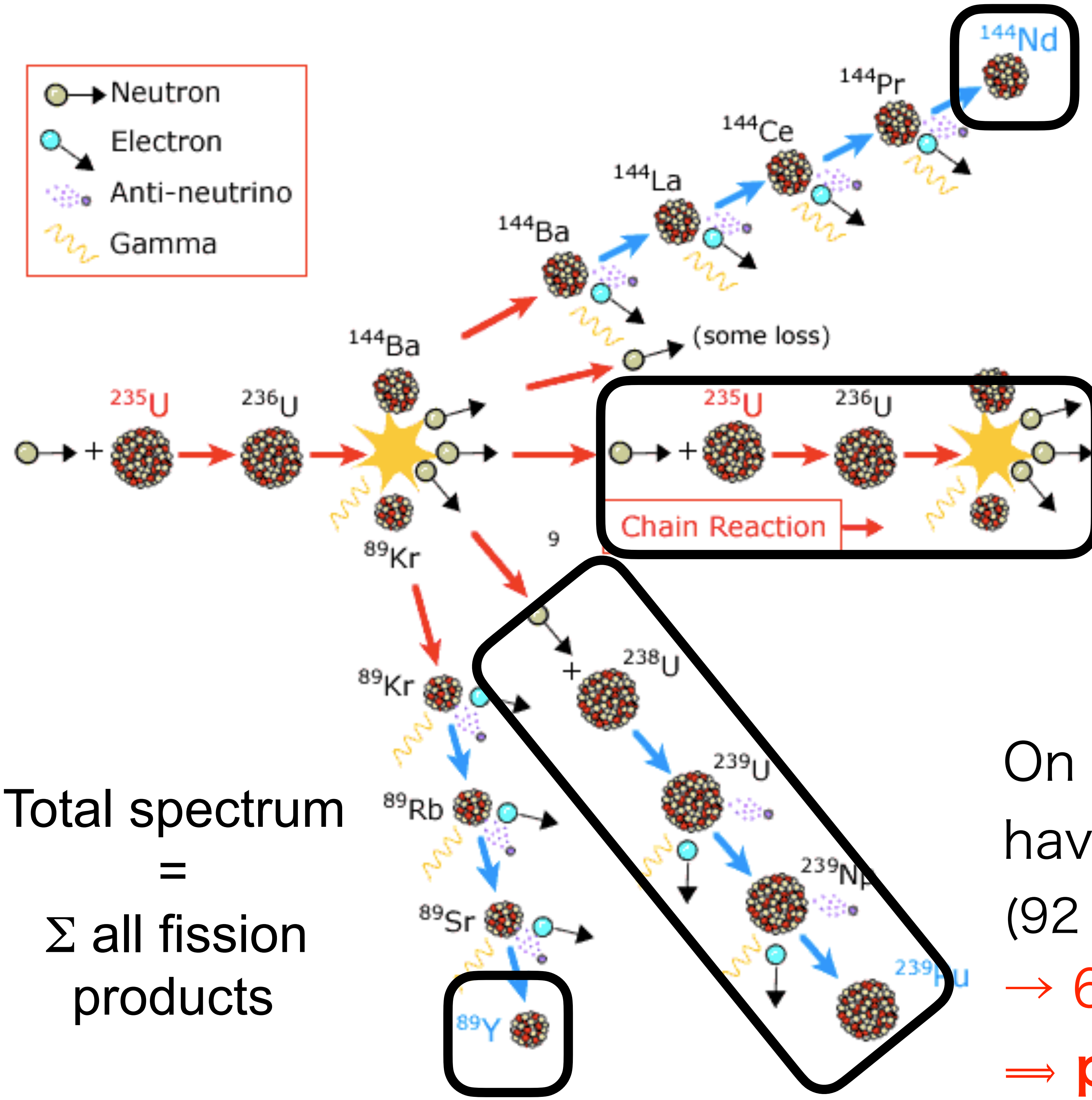
- 440 operable reactors. 55 reactors under construction (Apr. 2020)
- Reactor's share of total electricity supplies in the world is ~10%

Nuclear reactor



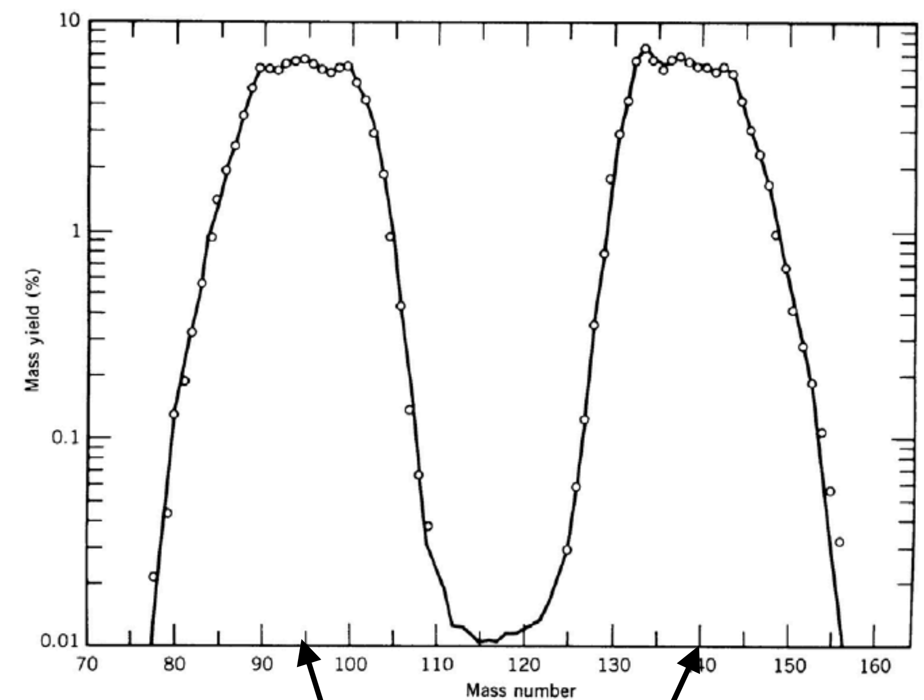
- Nuclear fuel is 3-4% of Uranium-235 (others are Uranium-238) provided by mining, milling, conversion to UF_6 & enrichment
- Heat from nuclear fission is used to provide steam for a generator
- Control rods are used to control the fission rate
- As a by-product, reactor core is an electron anti-ν source

$\bar{\nu}_e$ production in reactors



Total spectrum
=
Σ all fission products

Fission products from ^{235}U



$^{94}_{40}\mathrm{Zr}$ $^{140}_{58}\mathrm{Ce}$

On average, fission products have 98 protons & 136 neutrons (92 p & 144 n, originally in ^{235}U + n)

→ 6 n have to β^- decay into 6 p,

⇒ **product ~6 ν's & ~2 n's**

Reactor neutrino flux

Energy & neutrinos emitted per fission

$$^{235}U + n \rightarrow A + B + 6.1e^{-} + 6.1\,\bar{\nu}_e + 202\text{ MeV} + 2.4n$$

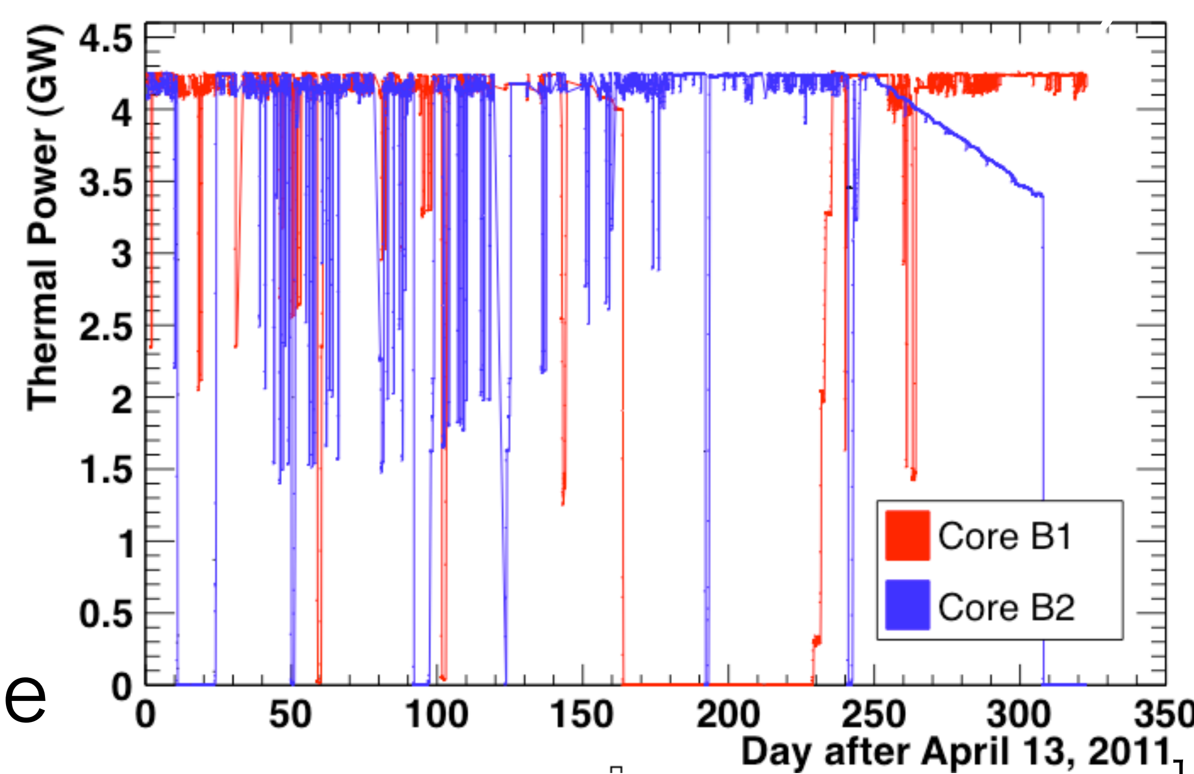
Neutrino flux of commercial reactor (~3 GW on average)

- $3\ GW_{th} = 3 \times 10^9$ J/s = 1.9×10^{22} MeV

  → Neutrino flux is ~ $6 \times 10^{20}\ \bar{\nu}_e/s$

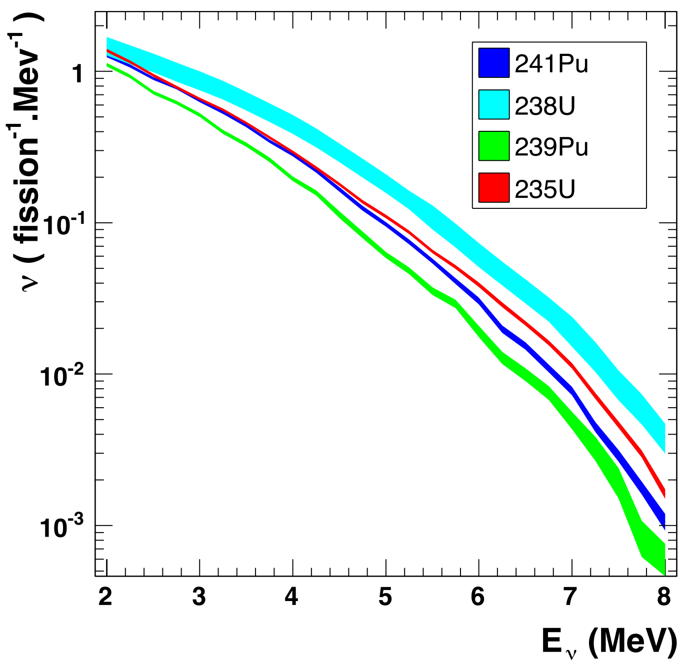
Thermal power

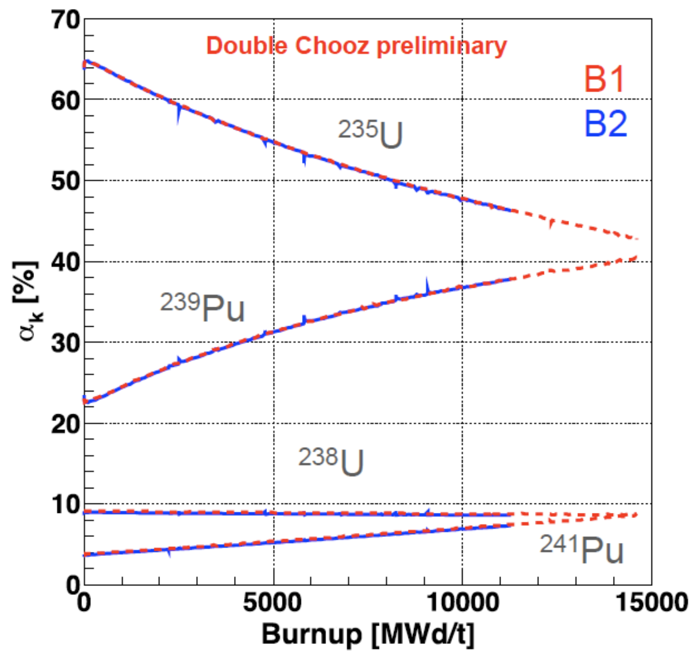
- Can be obtained from a power company to estimate ν flux prediction
- Thermal power vs time in Chooz reactor for example



Reactor neutrino spectrum

Reference spectra weighted by fuel evolution

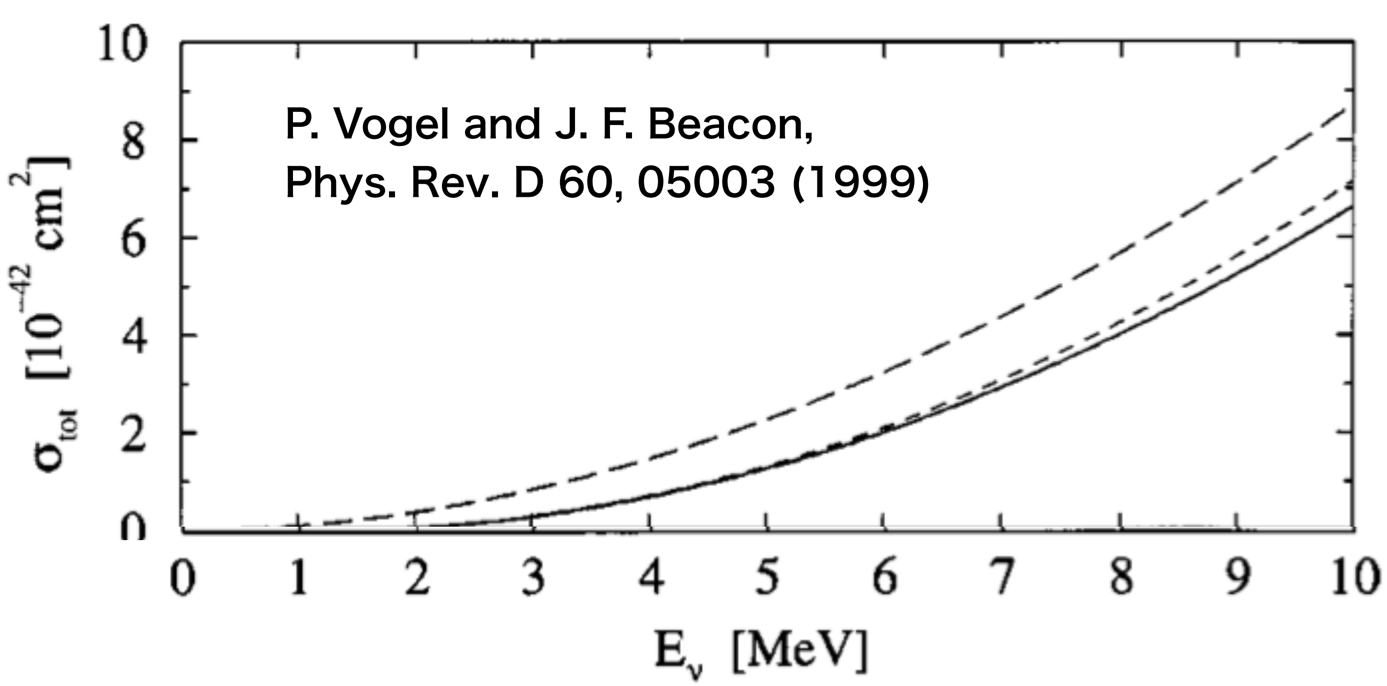


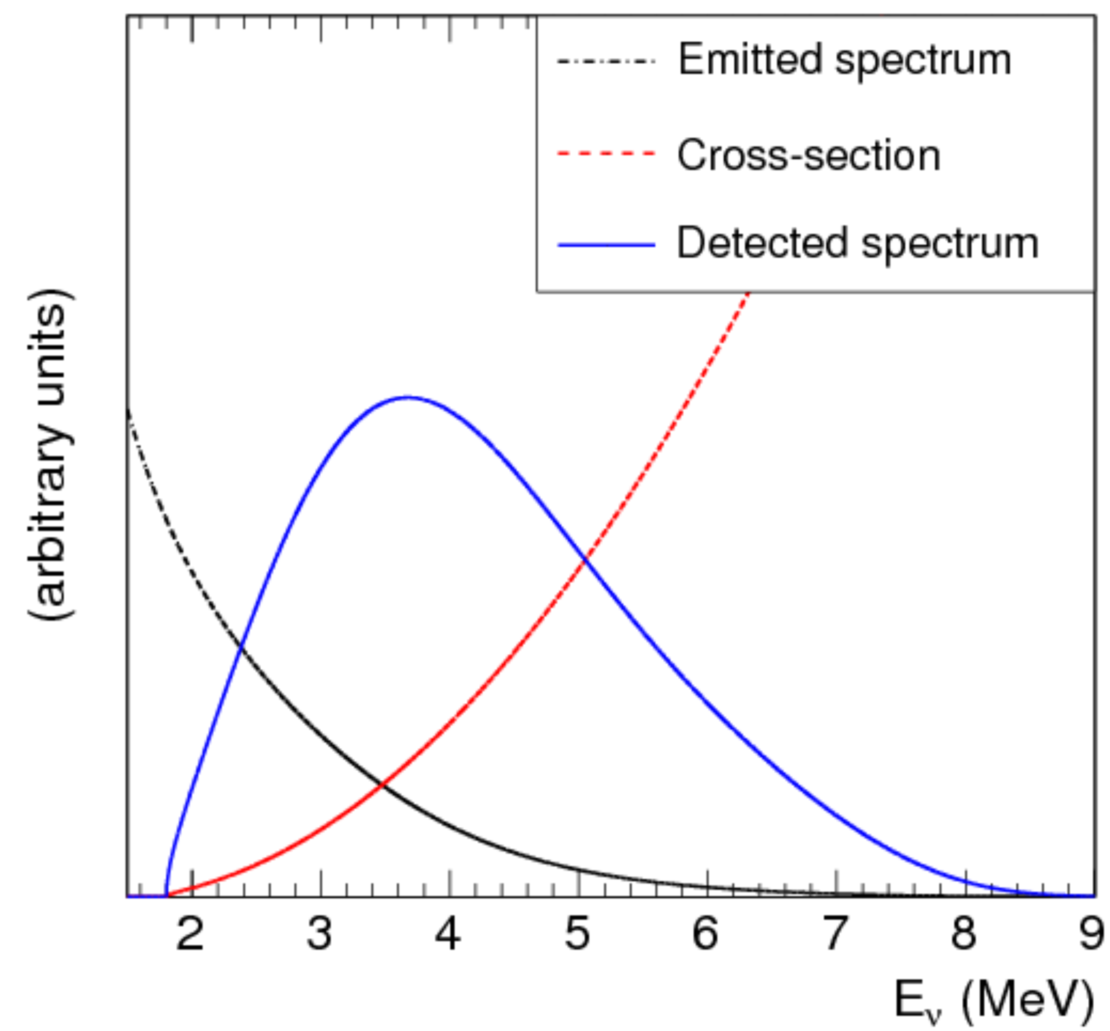


×

=

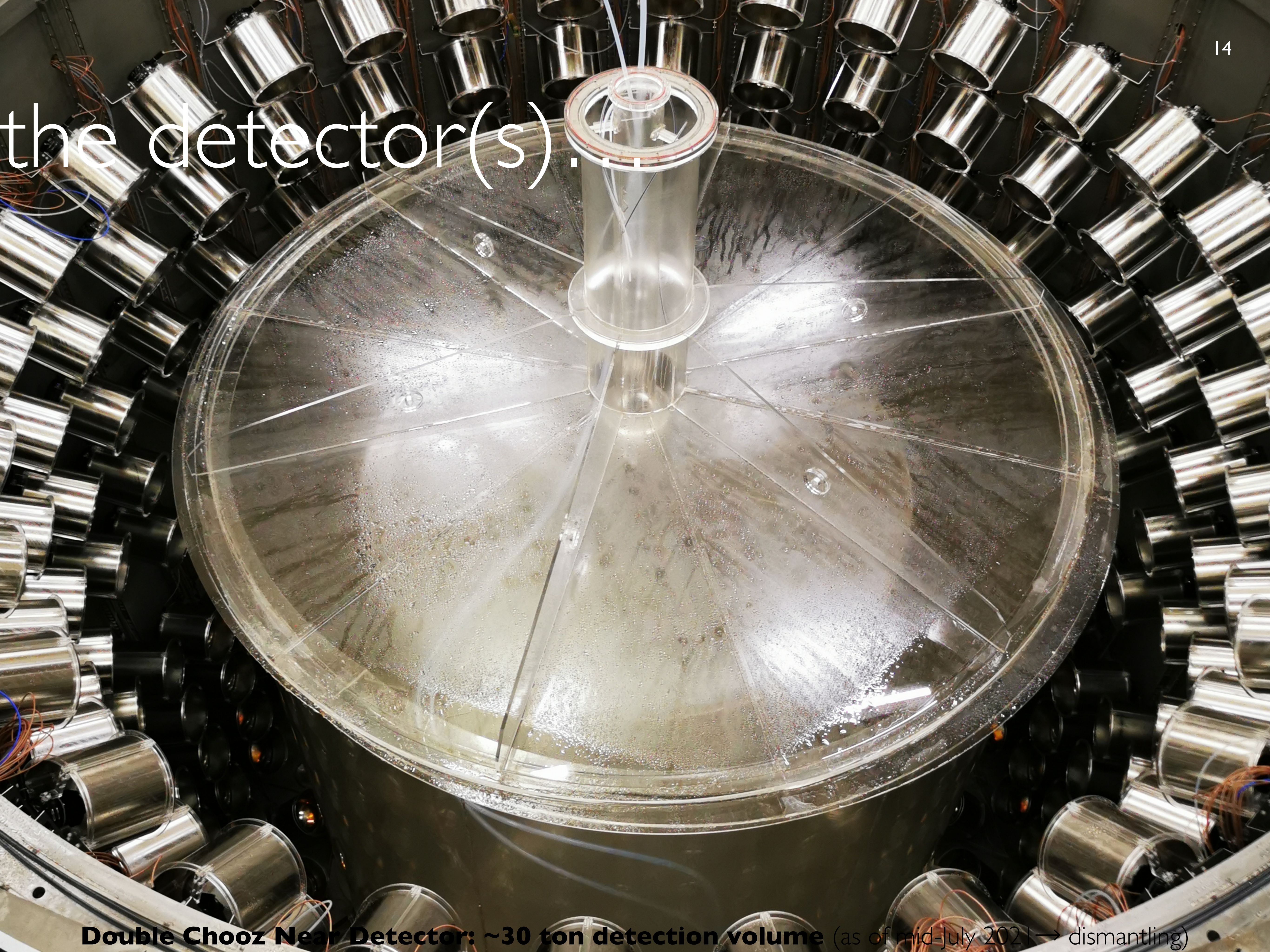
Total cross section as a function of energy





Energy spectrum peaks
at 3.5 ~ 4 MeV

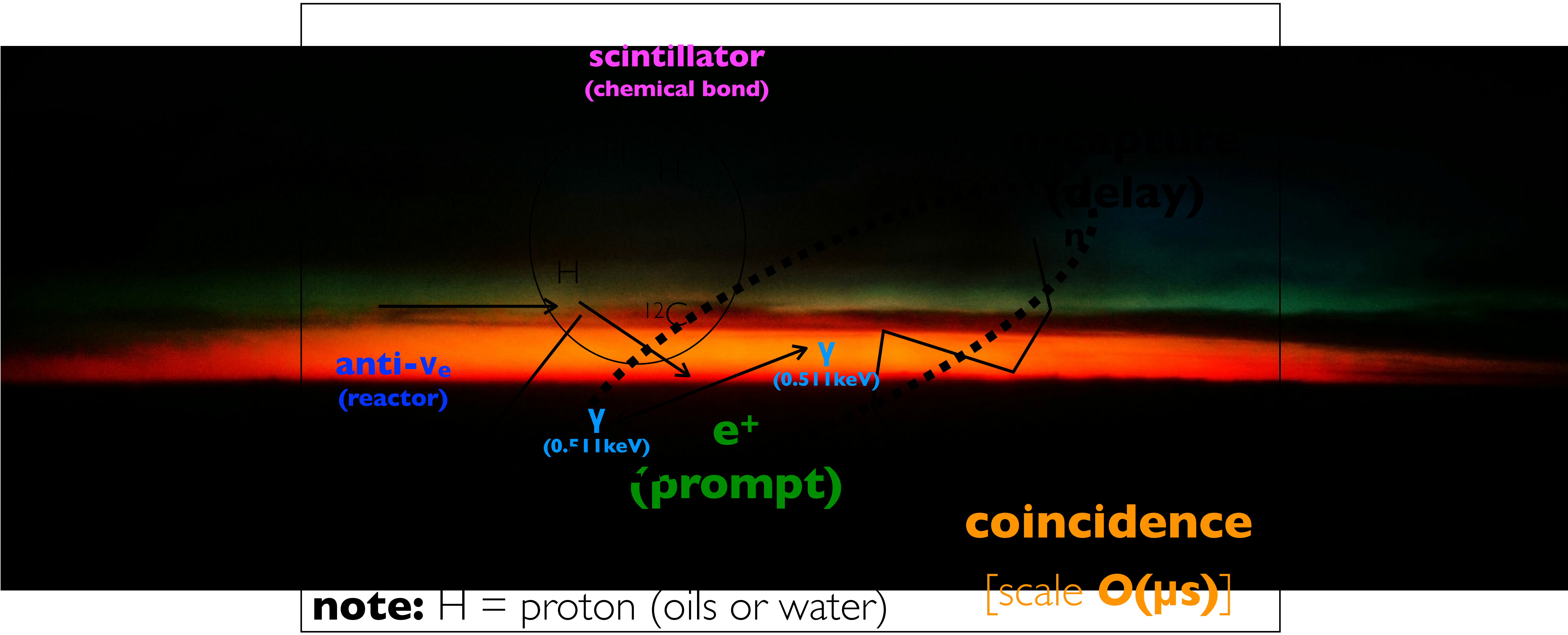
the detector(s)...



Double Chooz Near Detector: ~30 ton detection volume (as of mid-July 2021 → dismantling)

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n

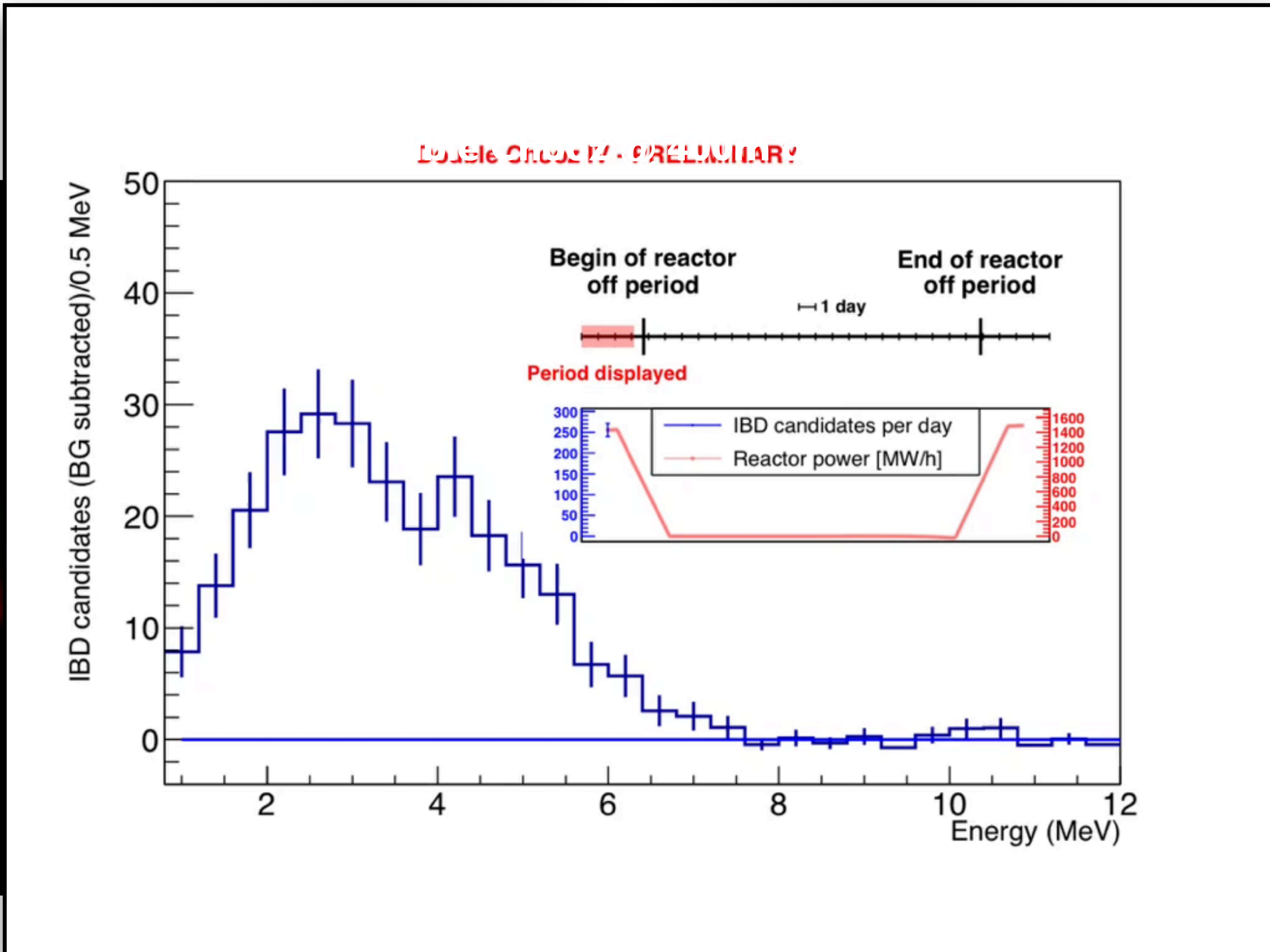


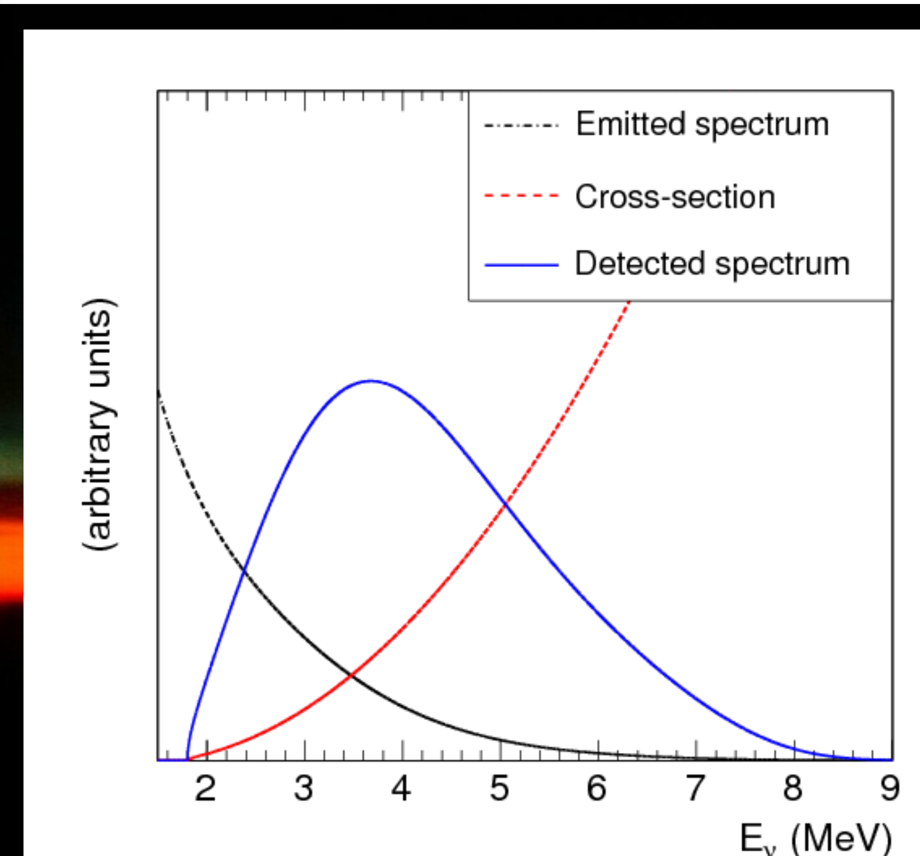
no e+ PID

e^+


V's

reactor neutrino spectrum…

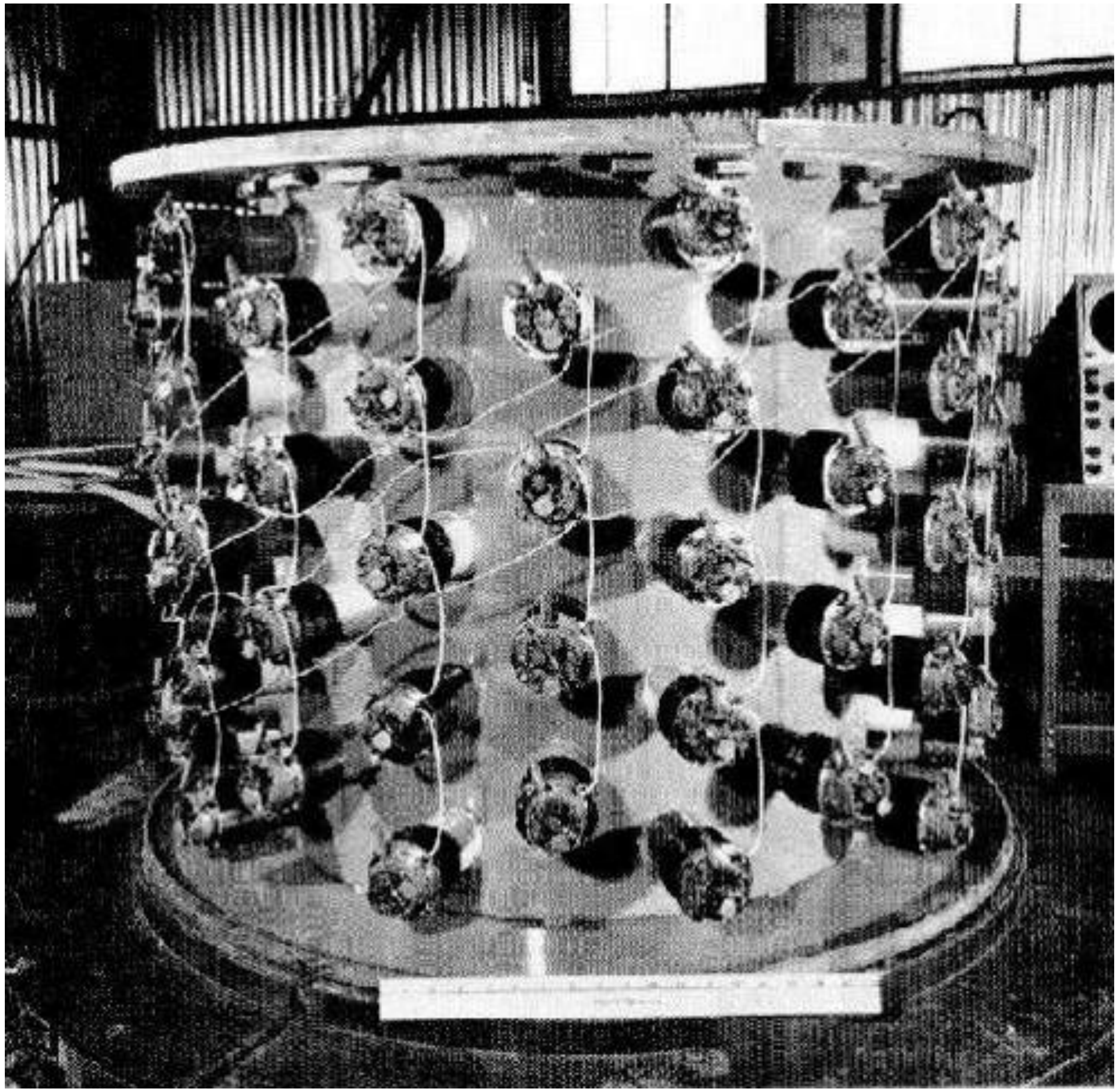




Double Chooz near-detector spectrum during ON-OFF-ON transition

the ν discovery (1950's)...

Reines & Cowan detector (300kg)…



today's inspiration!

Reines et al **detection strategy legacy**…

PMT ⇔ transparent medium

ν interaction: coincidence and/or tagging

overburden

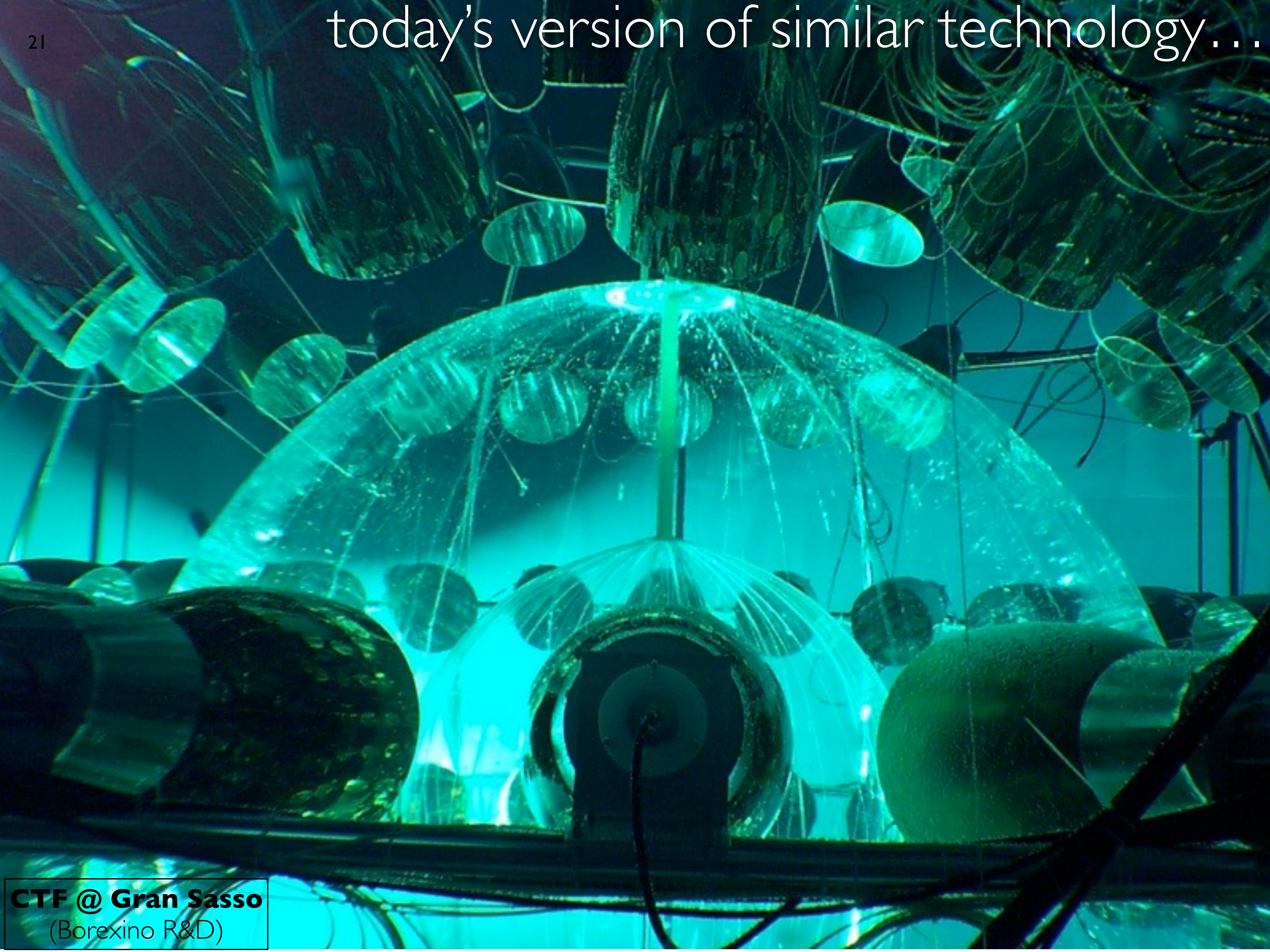
external shielding

loaded medium (^{113}Cd)

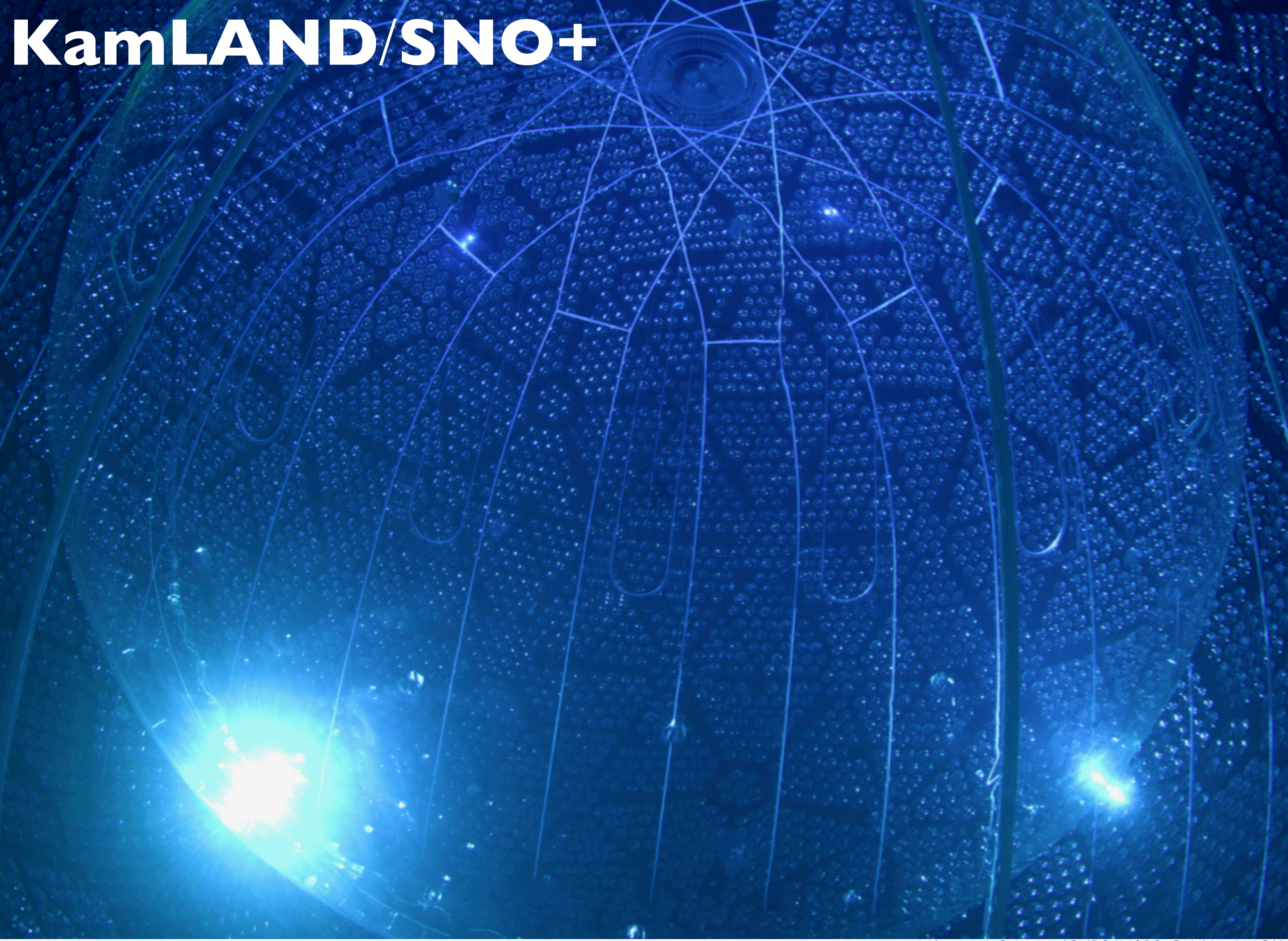
signal modulation

~70years ago → much the same still now!

today's version of similar technology…



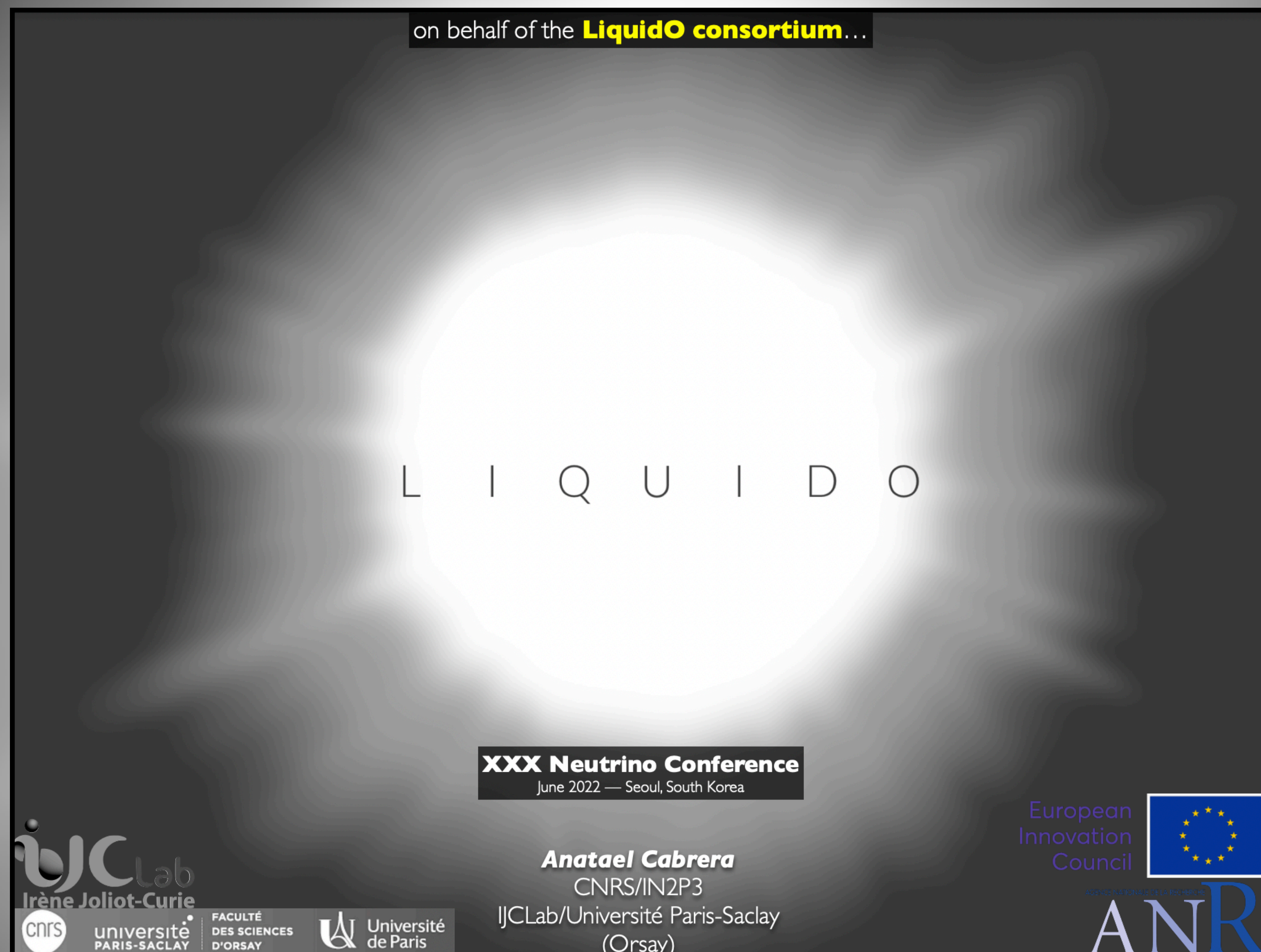
KamLAND/SNO+



Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

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

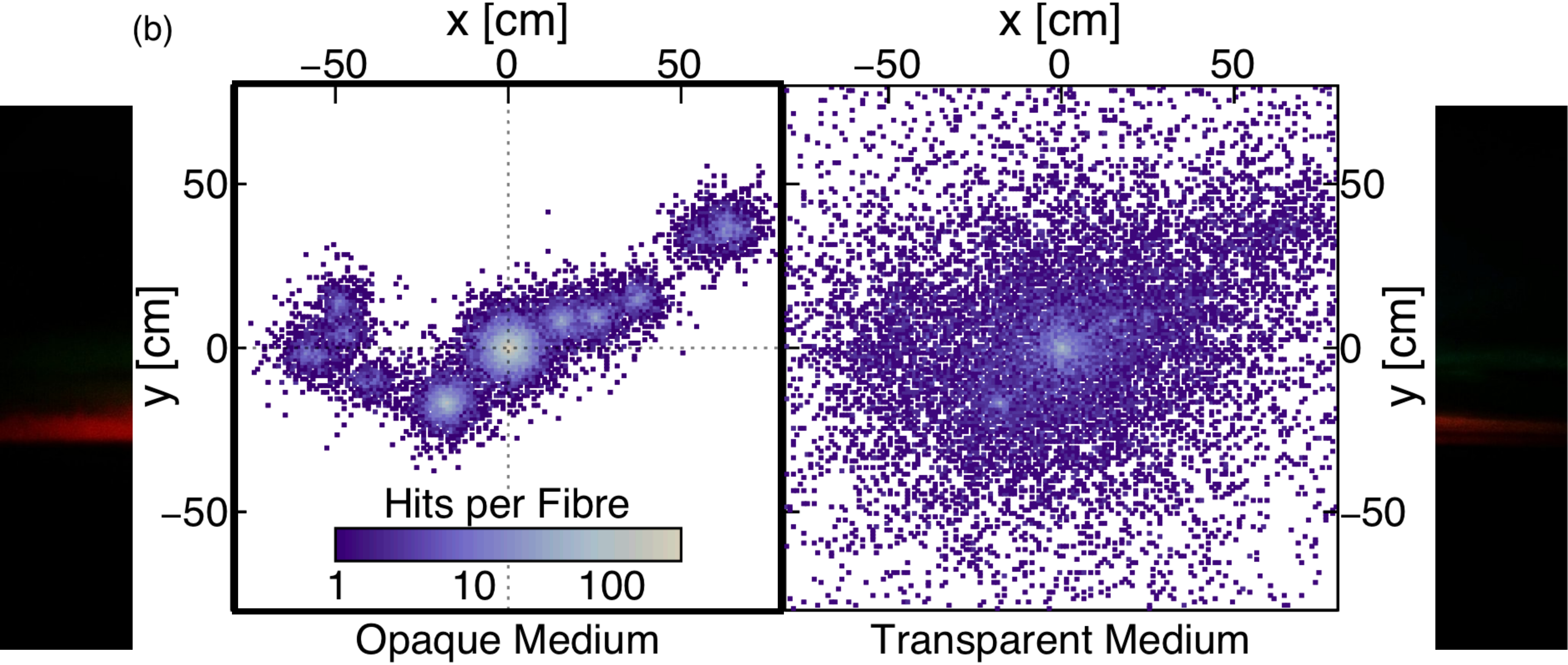
under construction



results release with the **latest experimental results** @ **Neutrino 2022** conference (June 2022)

https://media.neutrino2022.org/talk/talk_session_apply/108/20220603220651_33.pdf

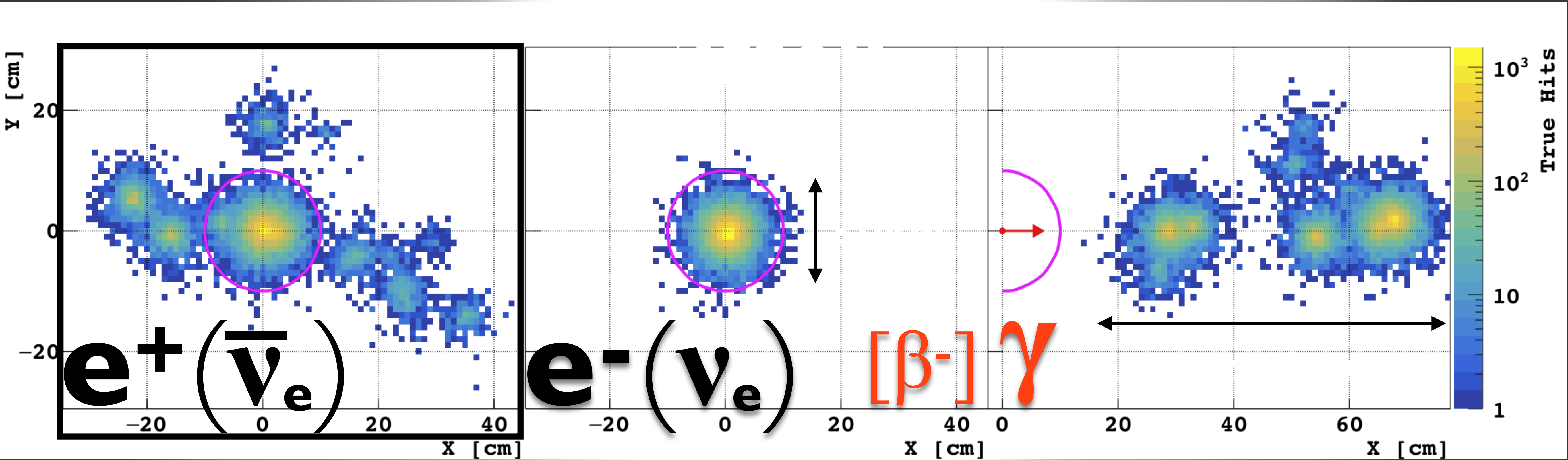
LiquidO event-wise imaging…



self-segmentation

unprecedented PID @ 1MeV…

potential: red… …rden / shielding



(reactor) opaque scintillation & (native) self-segmentation

needless segmentation: problematic @ 1MeV (pollution, cost⊕complex, etc)

~1MeV: reactor, geoneutrino, solar, ββ-decay, etc

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

status on neutrino oscillation knowledge…

no conclusive sign of any extension so far!!

(inconsistencies vs uncertainties)

&

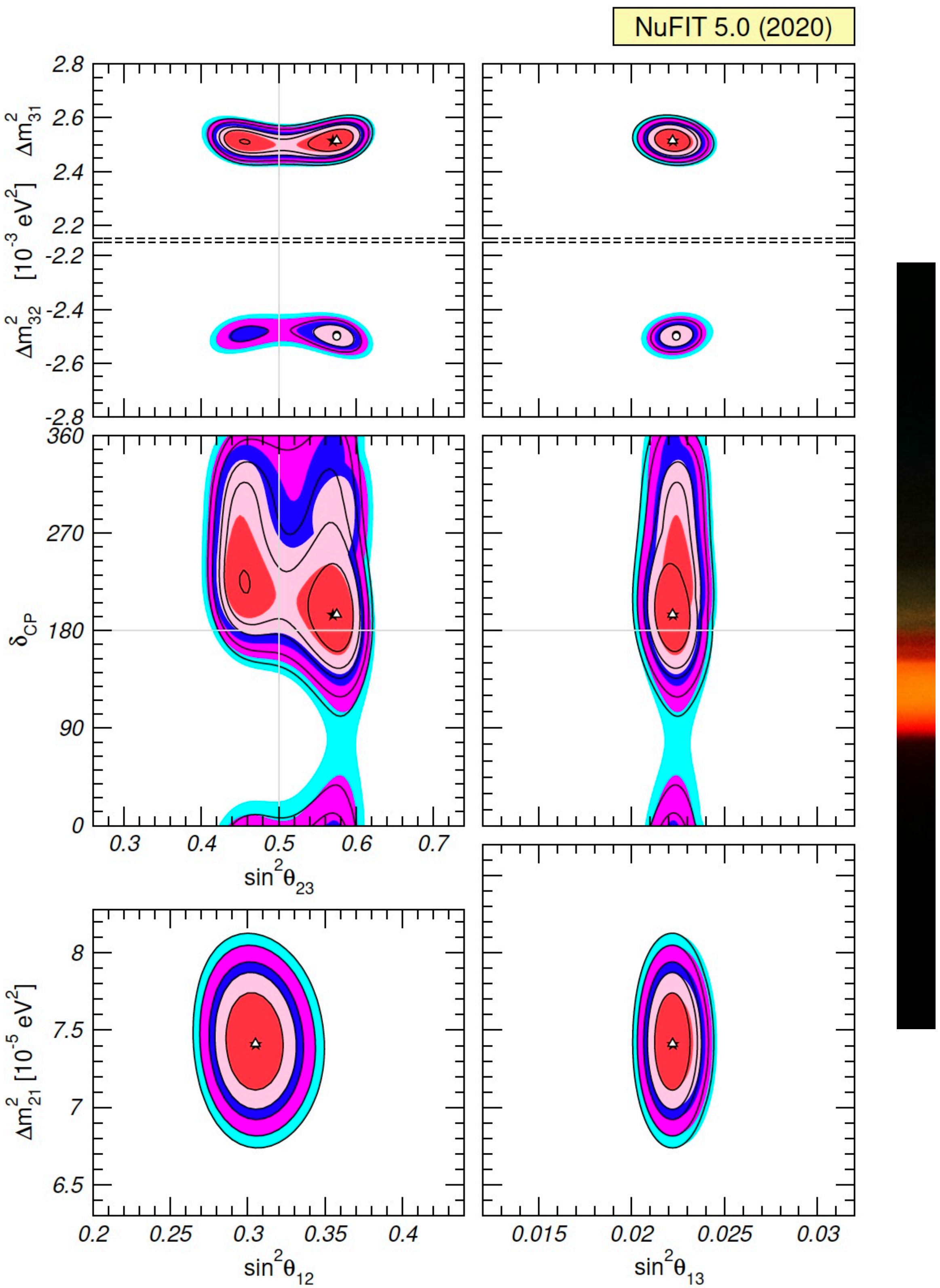
±Δm² & +δm²

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

	today				≥2030	
	best knowledge		NuFIT5.0	foreseen	dominant	technique
θ_{12}	3,0 %	SK⊕SNO	2,3 %	<1.0%	JUNO	reactor
|Δm²|	3,0 %	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	beam driven

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

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

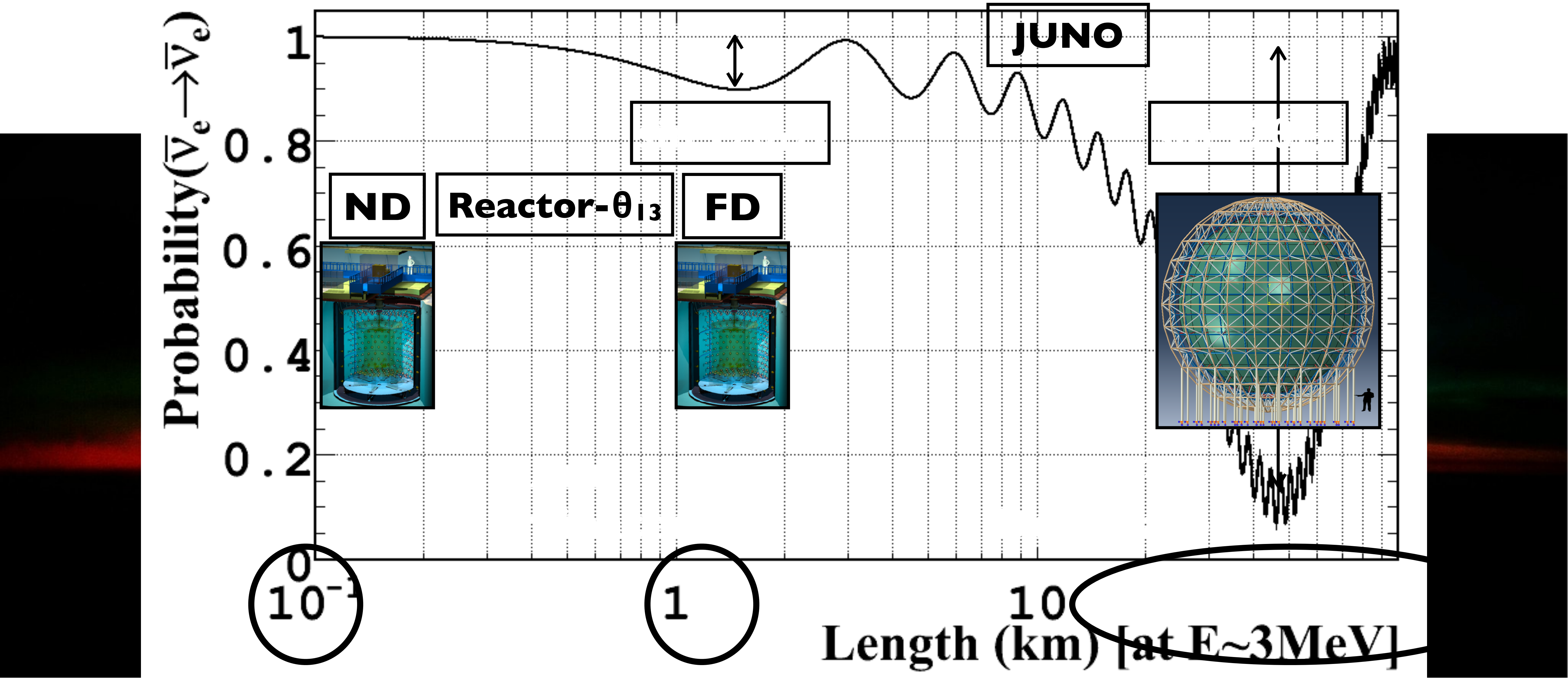


NuFIT 5.0 (2020)

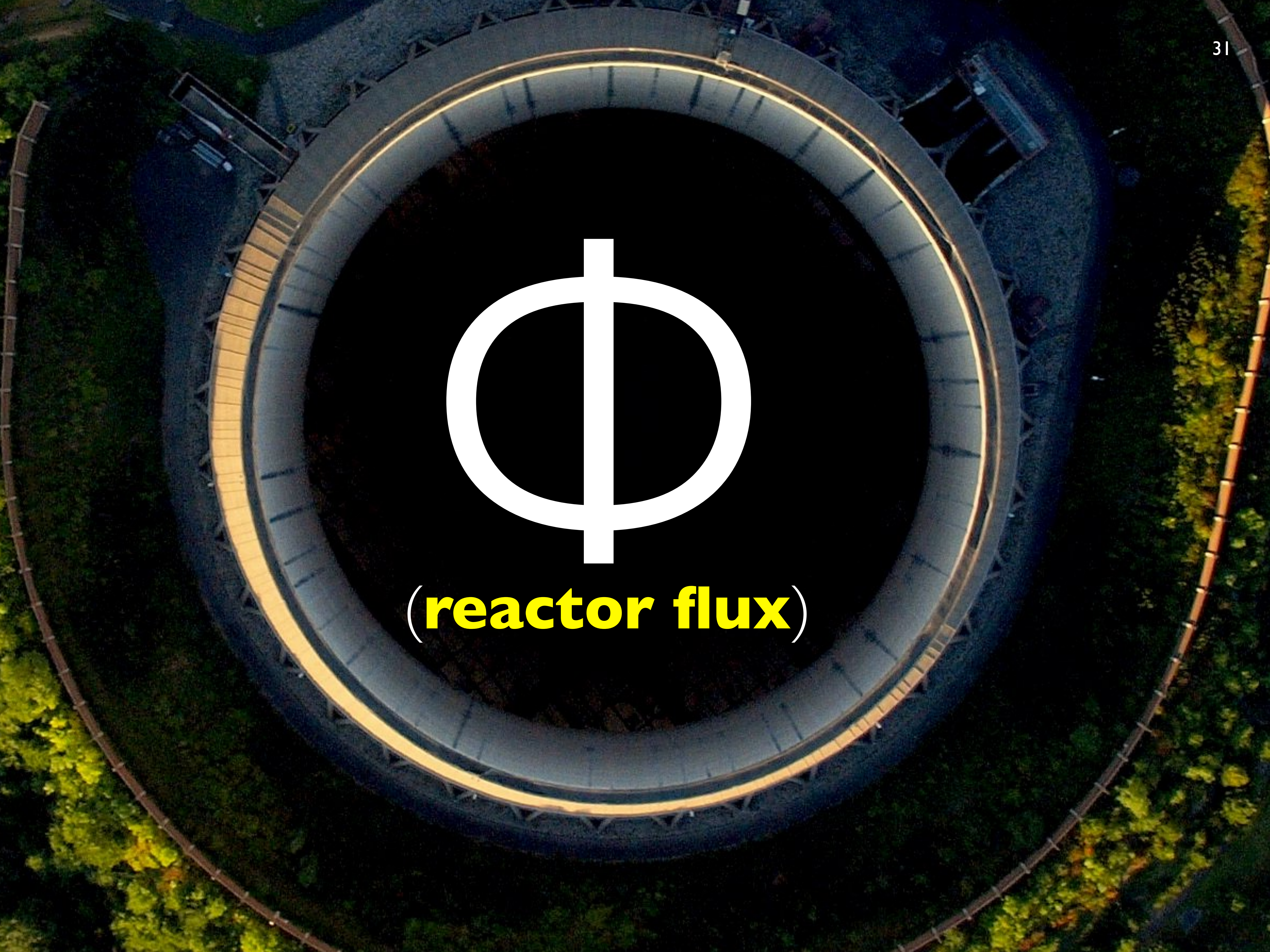
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

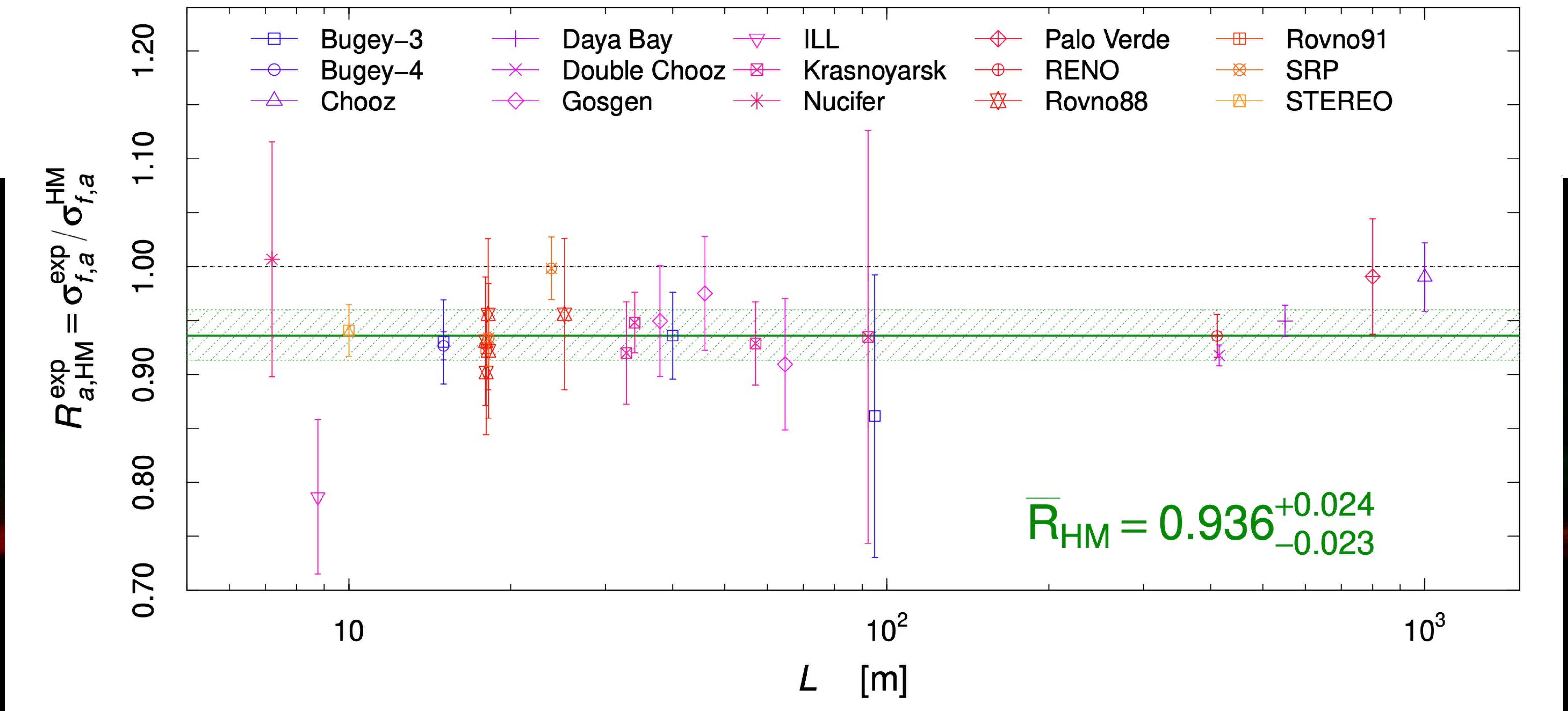
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ eV^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ eV^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

experimental setup…



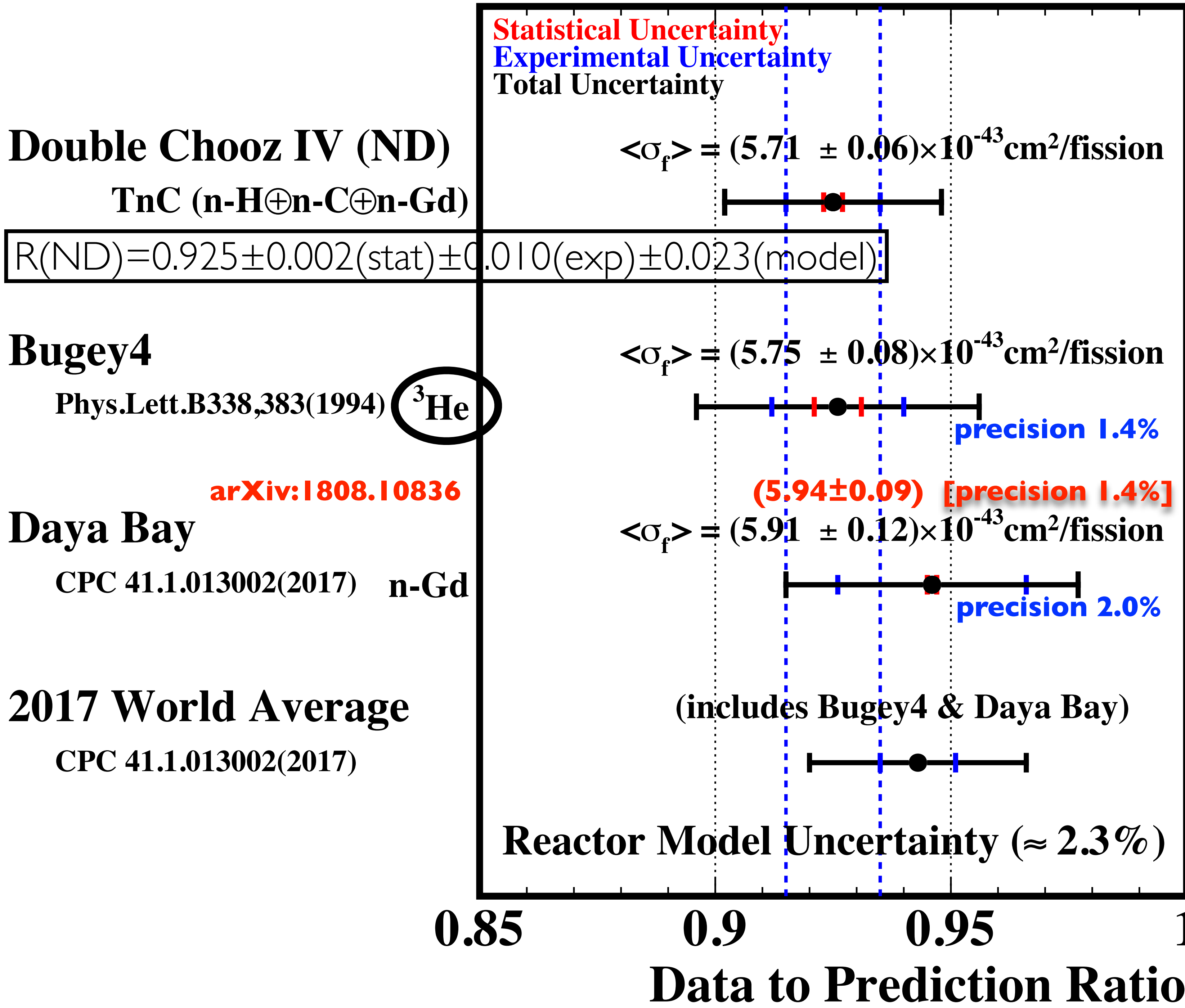
new physics


Φ
(**reactor flux**)

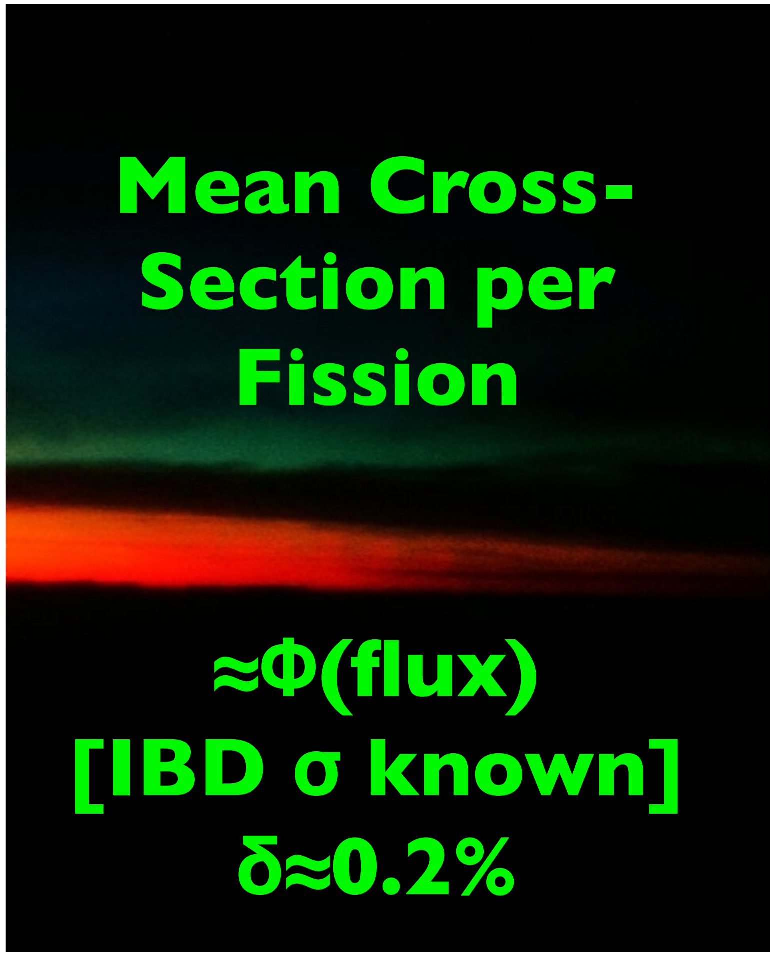


now ≤7.0% mismatch between ILL-prediction and data

2019 world reactor flux knowledge…



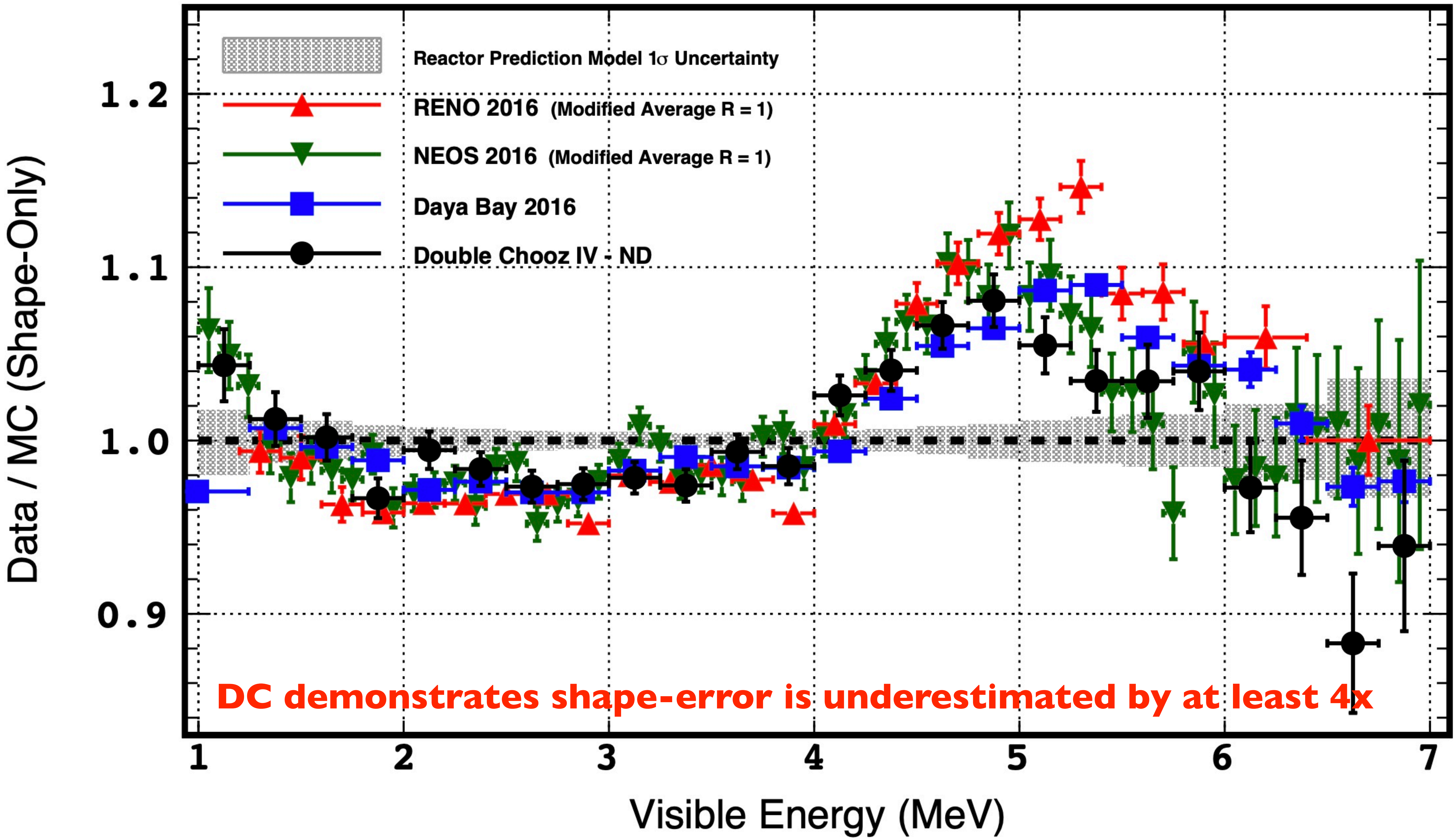
best world precision



MC normalised to DYB-2017 (MCSpF per isotope)

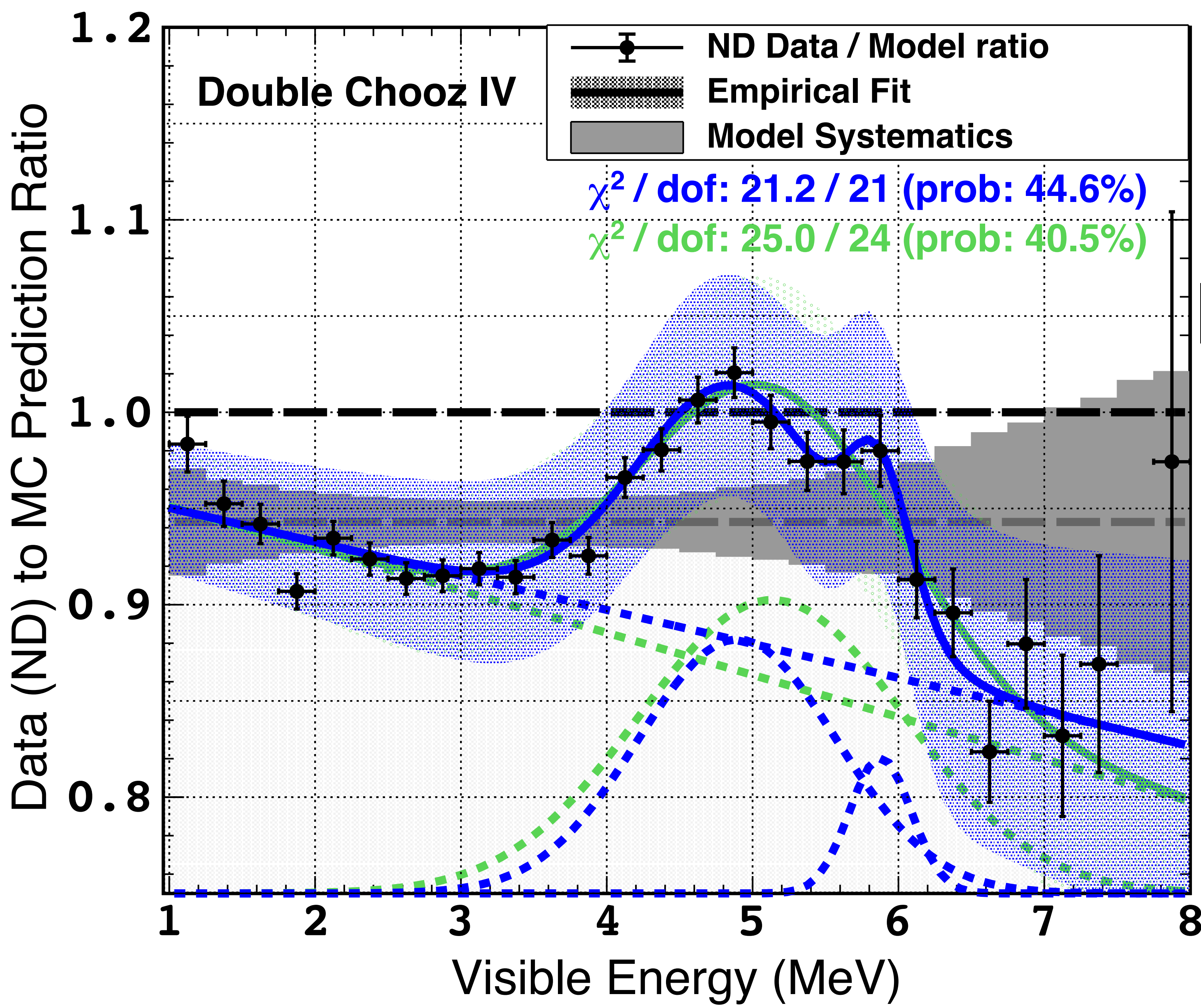
reactor flux (data) precision <1.0%

shape distorsion common across experiments…



only one experiment in tension: **Bugey3** (flat-ish) — spectral reference before **reactor-θ13**

reactor flux uncertainty…



Φ(reactor) [exp] best precision (~0.9%)

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

prediction fails to match both rate & shape!

[not just rate]

Shape Uncertainty

~2.2%→6.0%?

[**surely <10%**]

nature physics

ARTICLE

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


Yes?
(we don't know how)
Φ
improvable?

reactor ultimate flux…

solve the reactor "issue" (anomaly)?
(discrepancy data and ILL-prediction)

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 $R = {}^eS_5/{}^eS_9$ 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

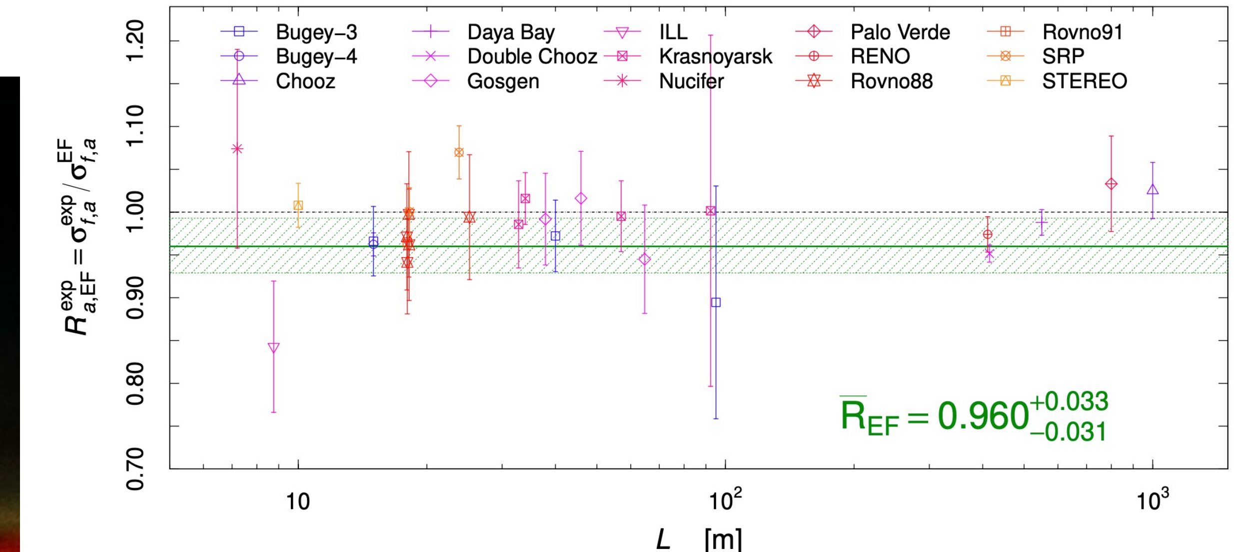
R=0.925±**0.010**(exp)±**0.023**(model)⟶ R≈1.0?±**0.010**(exp)±**0.0?**(model)

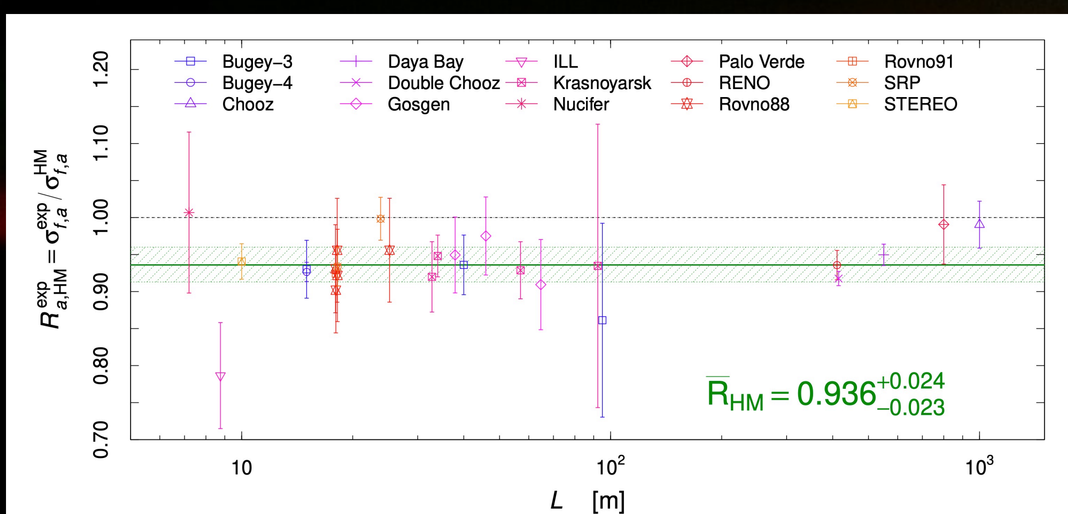
experiment flux uncertainty will drive?

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

reducible!!

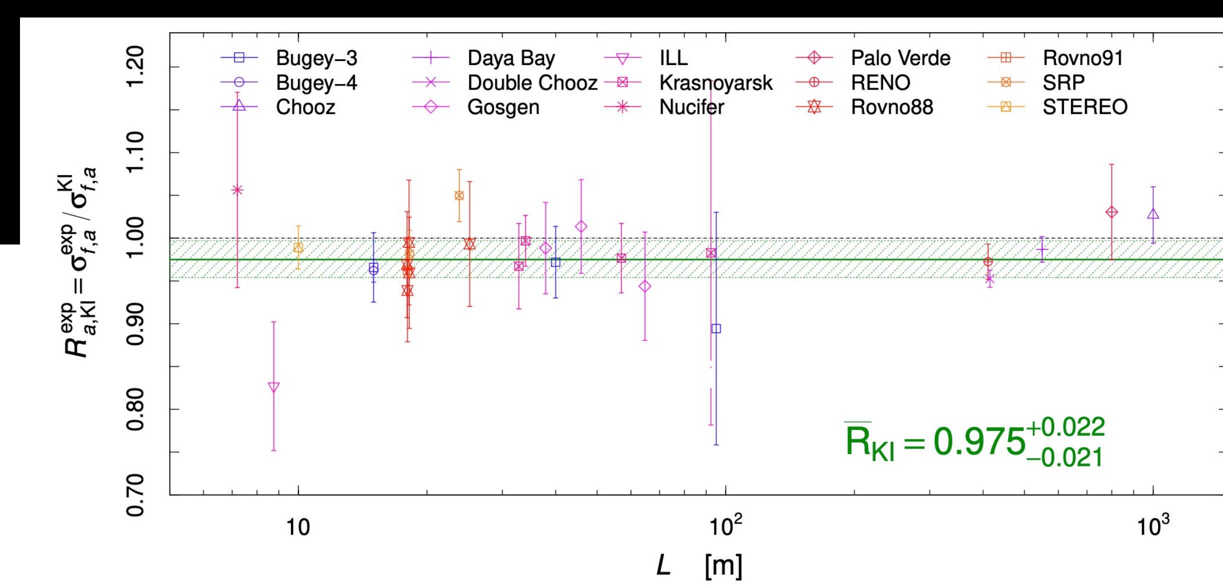
≥2020 improvements…





≥2020 ab initio estimation

→uncertainties fully understood?



first LiquidO's experiment…

European Innovation Council

UK Research and Innovation

C L U D

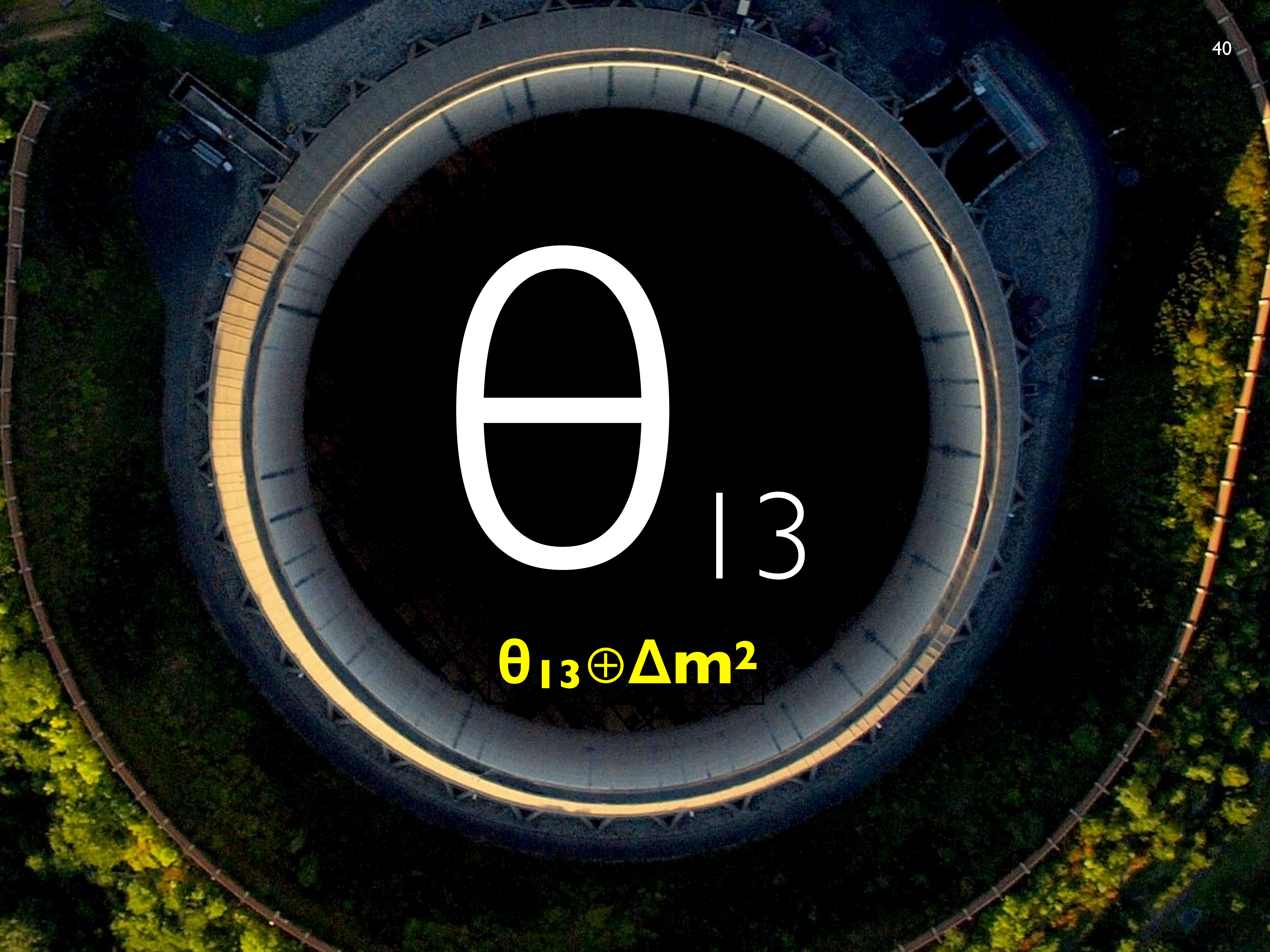
Innovation … **-OTech”**
Fundamental

- **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)

—

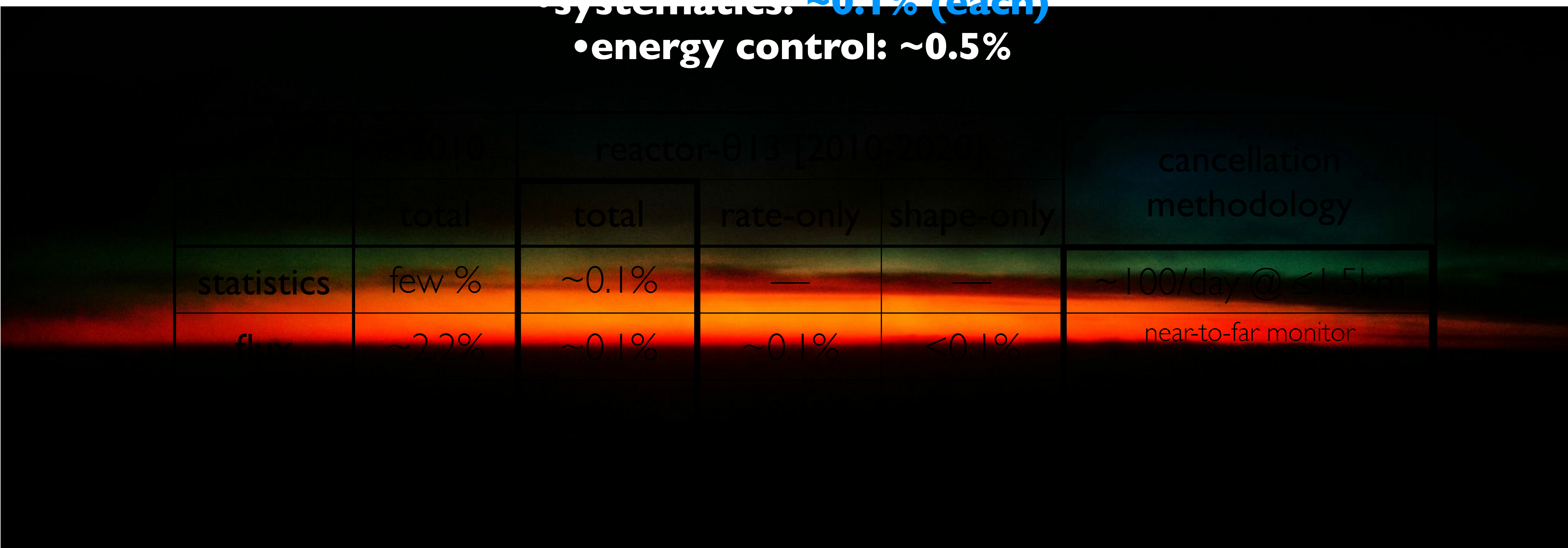
- **Charles University** (Czech Republic)
- **INFN-Padova** (Italy)
- **UC-Irvine** (US)
- **Universidade Estadual de Londrina** (Brasil)
- **PUC-Rio** de Janeiro (Brasil)
- **Queen's University** (Canada)
- **University of Zaragoza** (Spain)
- **Tohoku University** / **RCNS** (Japan)

CLOUD collaboration (EDF⊕13 institutions over 10 countries)


θ_{13}
$\theta_{13} \oplus \Delta m^2$

summary on today's θ13 knowledge/experiments…

reactor-θ13 experiments: DC⊕DYB⊕RENO



•systematics: ~0.1% (each)
•energy control: ~0.5%

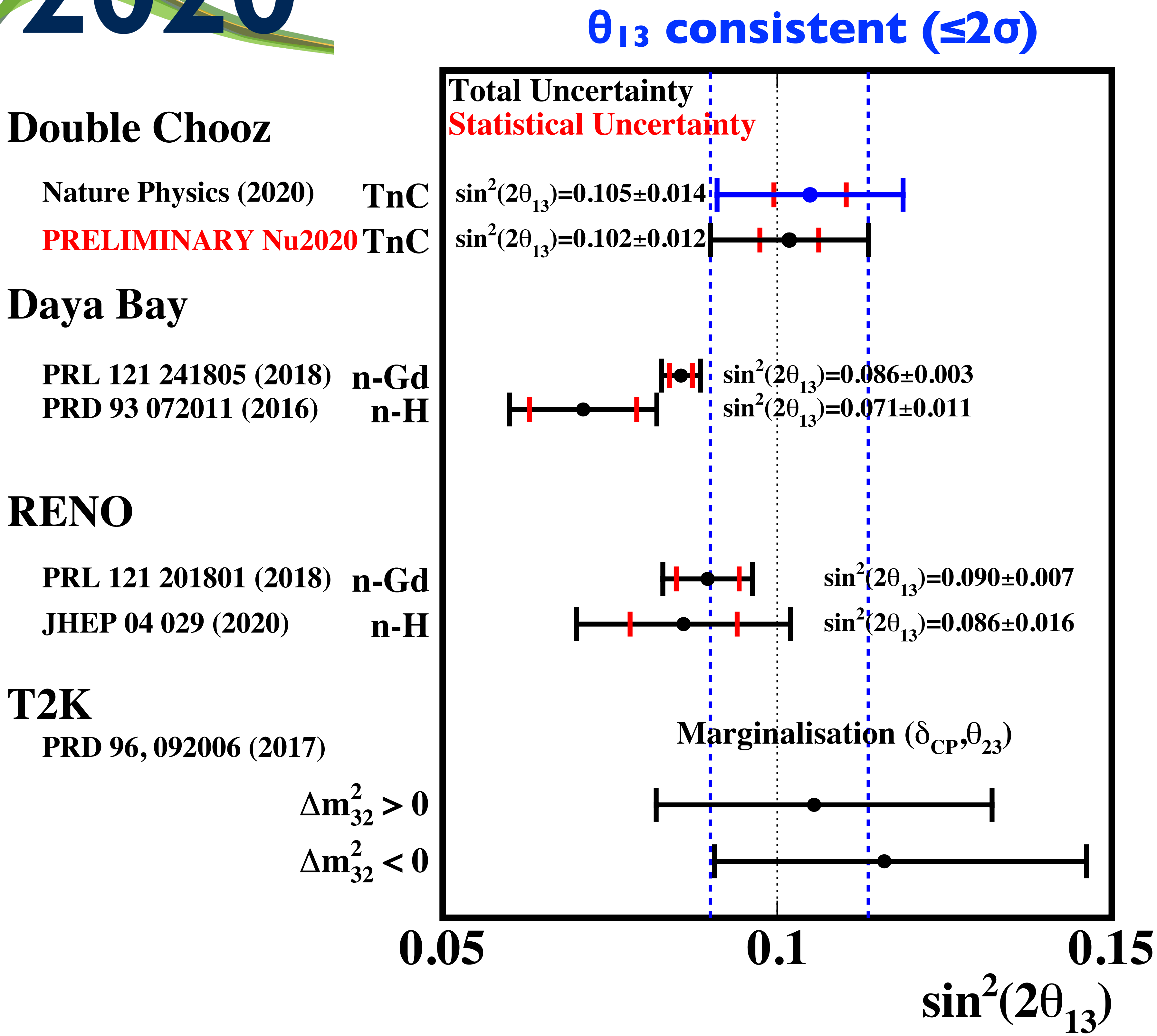
	2010	reactor-θ13 [2010-2020]			cancellation methodology
	total	total	rate-only	shape-only	
statistics	few %	~0.1%	—	—	~100/day @ ≤1.5km
flux	~2.2%	~0.1%	~0.1%	<0.1%	near-to-far monitor
[illegible]					

"naively extrapolating" from reactor-θ13 experiments…

~0.01%??!!
possible to improve at all?

NEUTRINO 2020

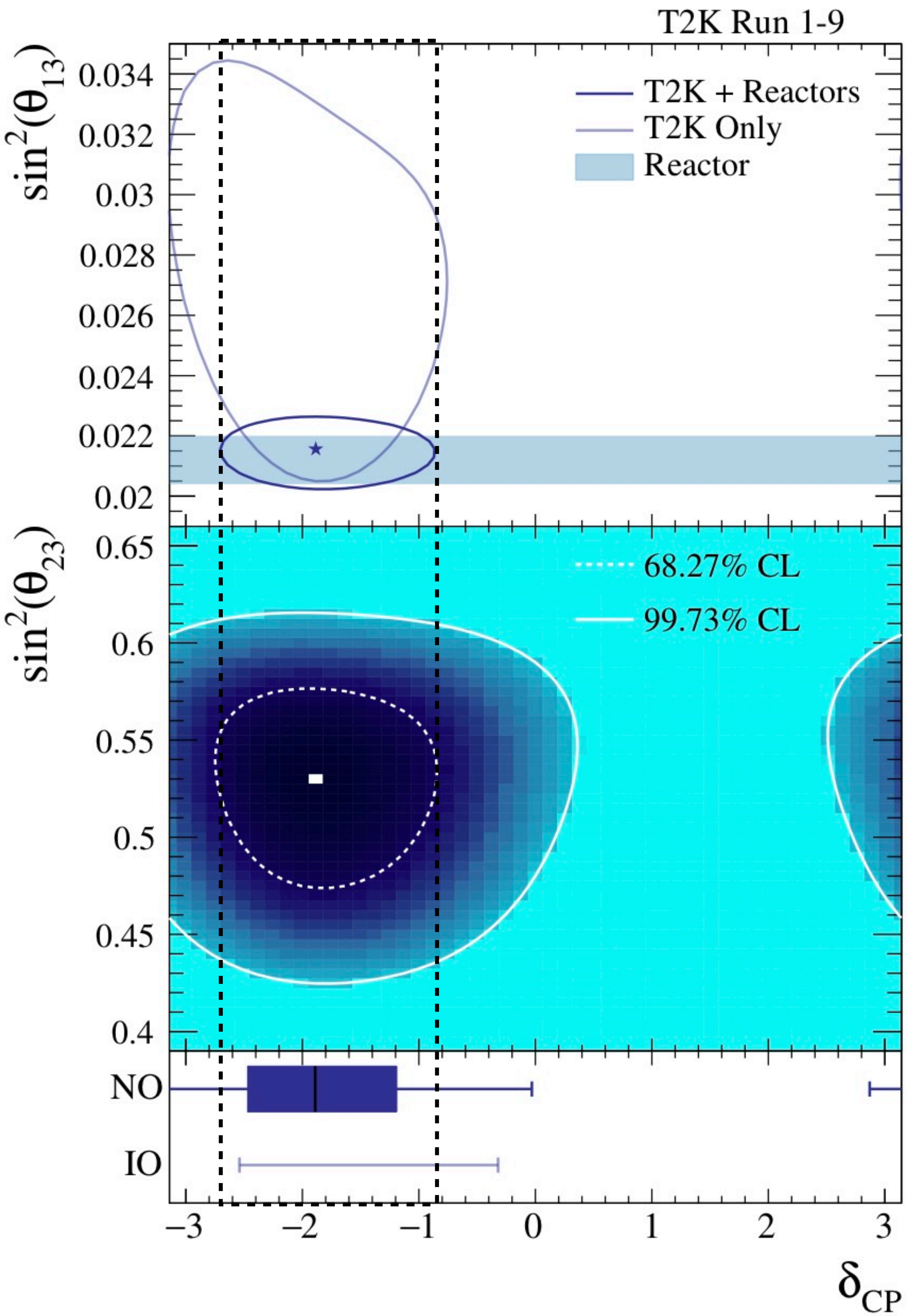
2020 world status in θ13…



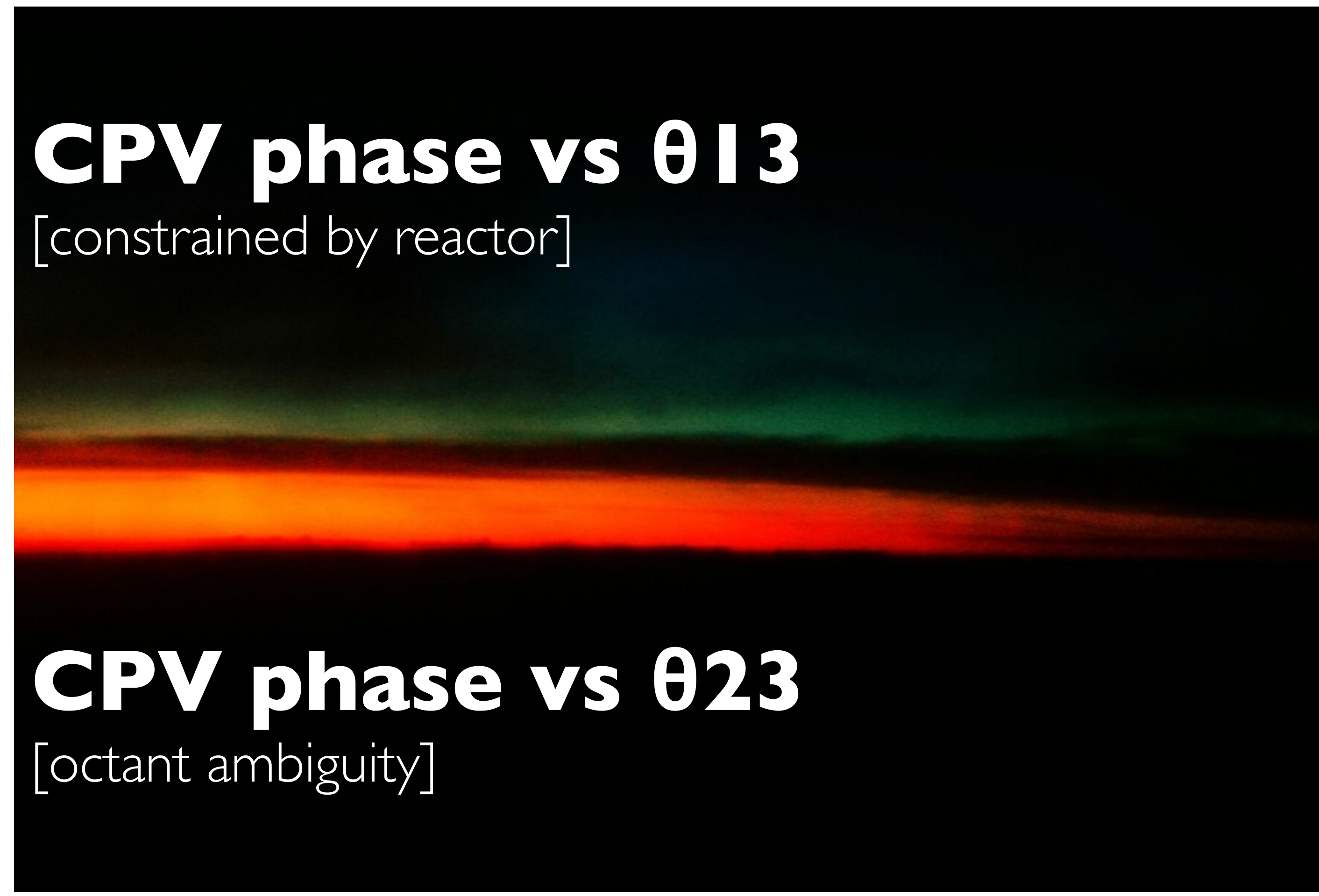
minor tension (≤2σ) & slight increase (2016→2018)

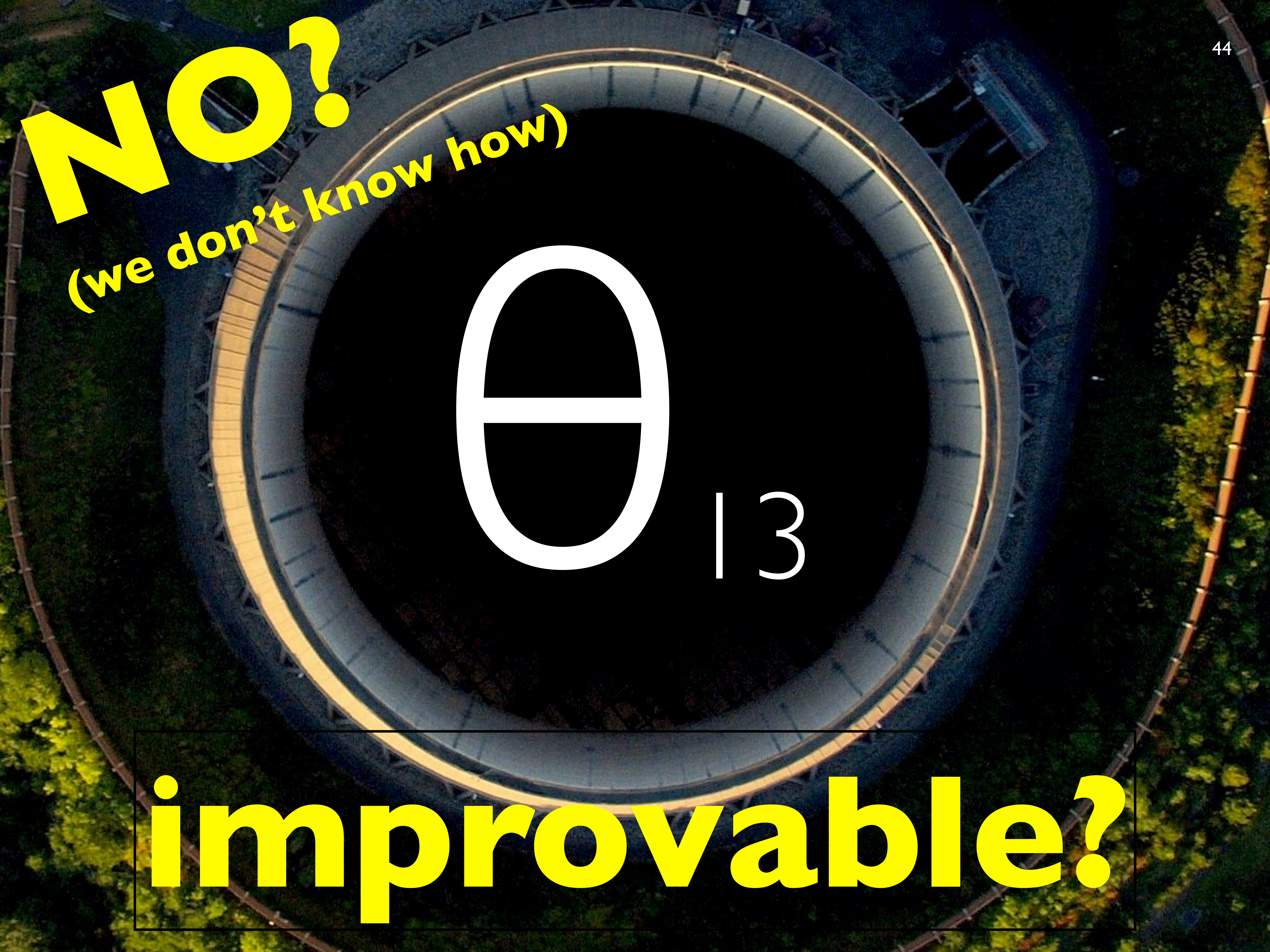
Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

T2K⊕reactor best knowledge CP-Violation…

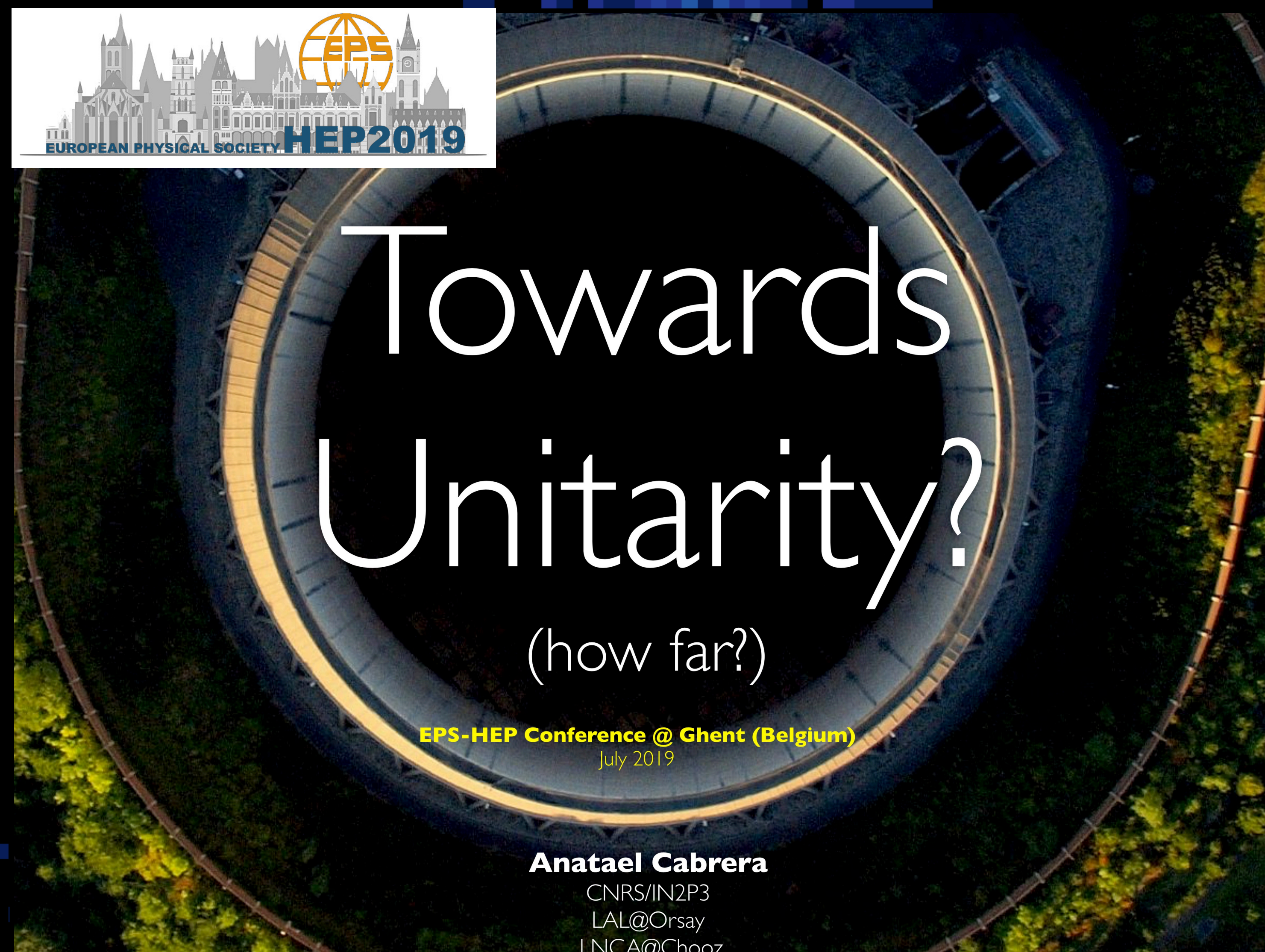


θ13 implications




NO?
(we don't know how)
θ_{13}
improvable?

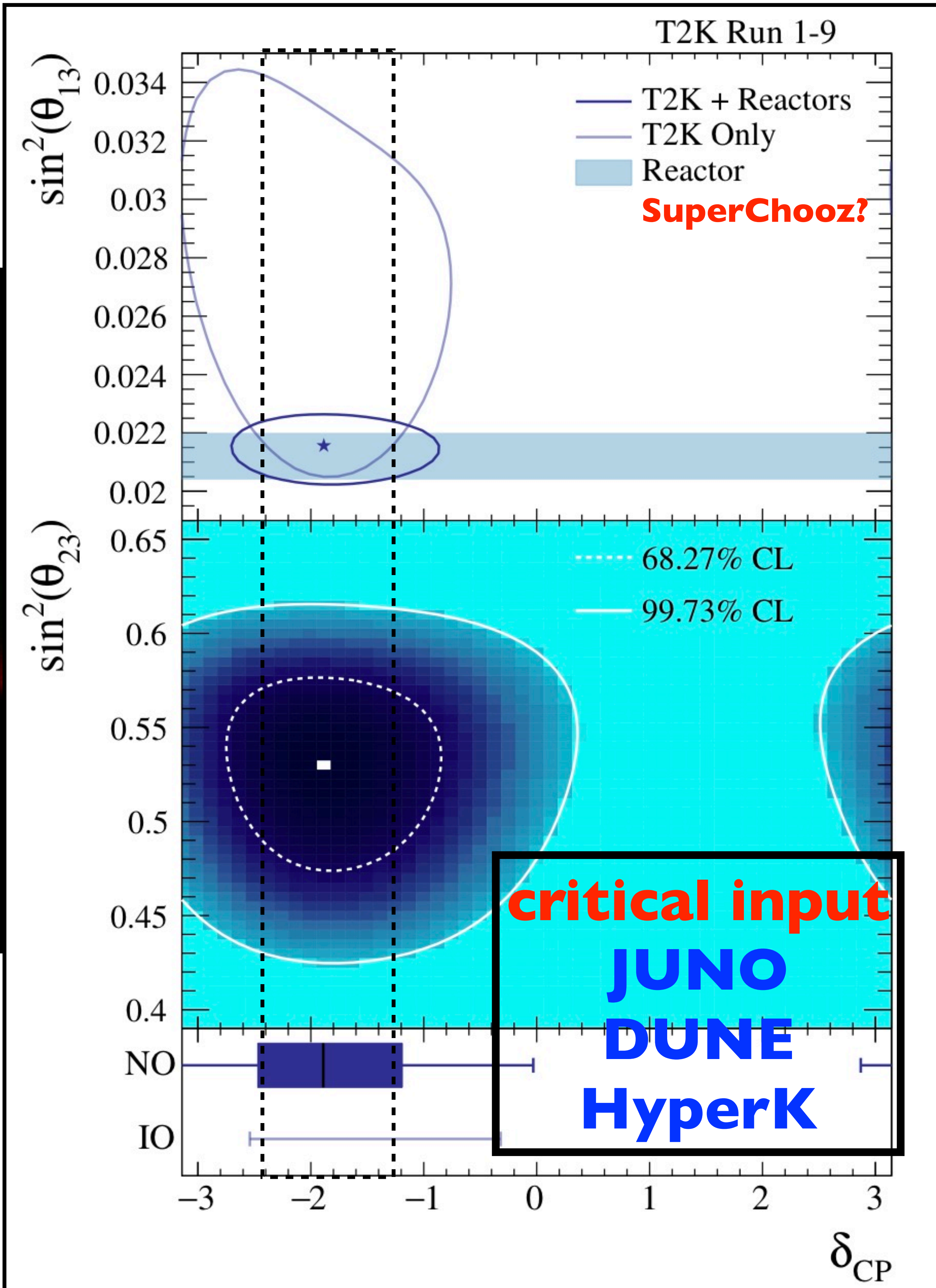
leptonic sector unitarity with LiquidO?



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


SuperChooZ?

T2K⊕reactor best knowledge CP-Violation…



θ13 implications

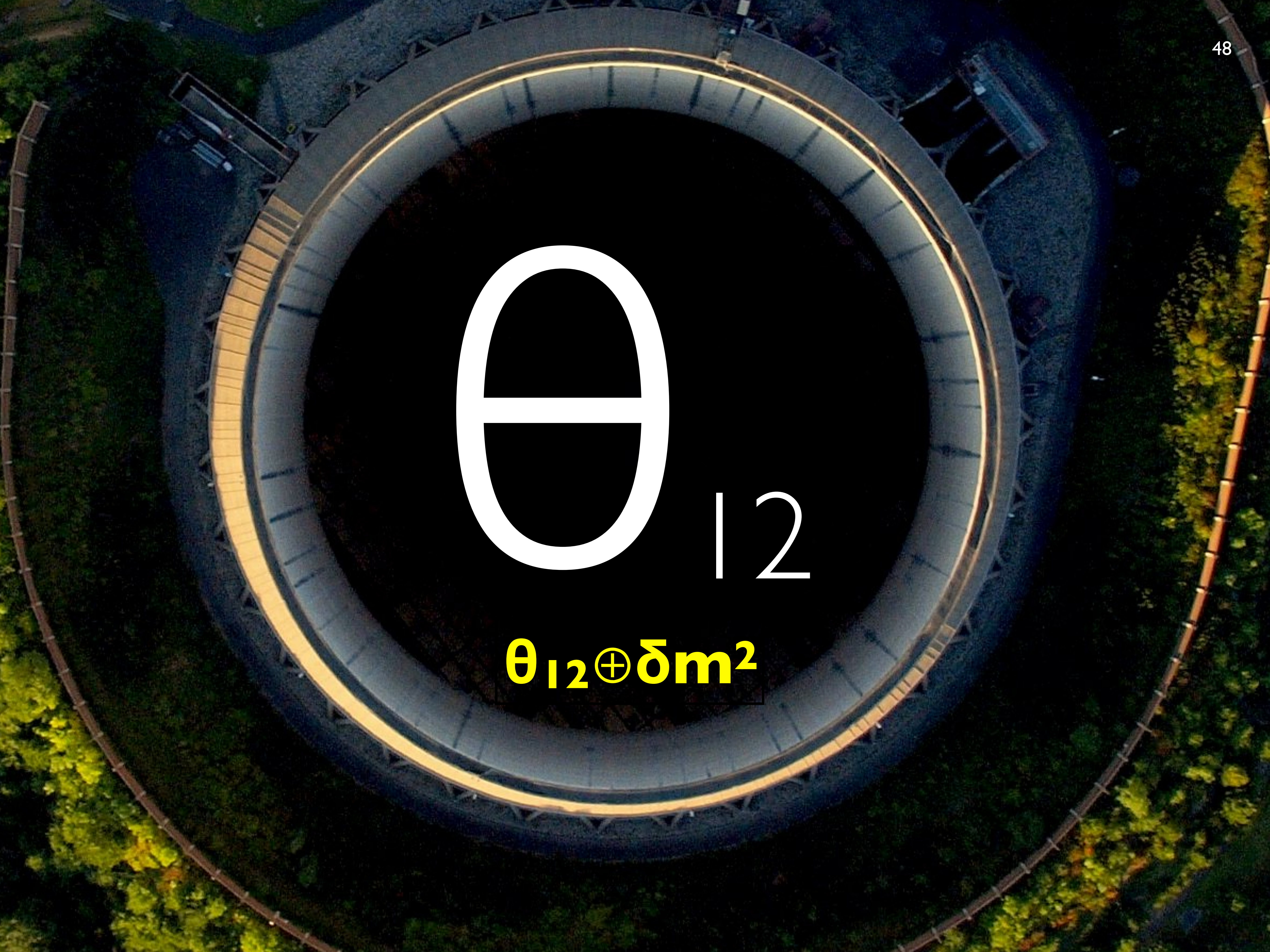
powerful constraint

CPV phase vs θ13

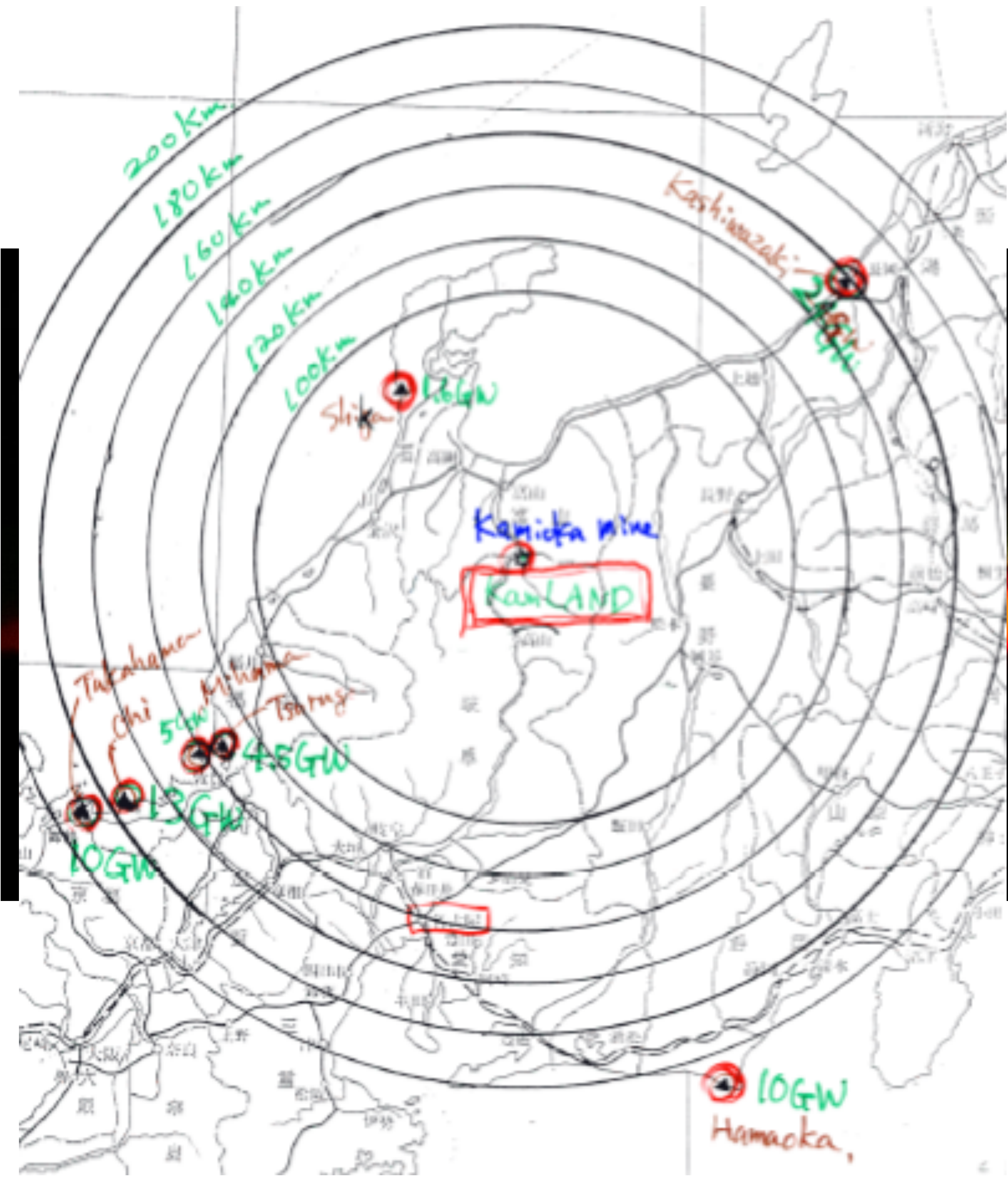
[constrained by reactor]

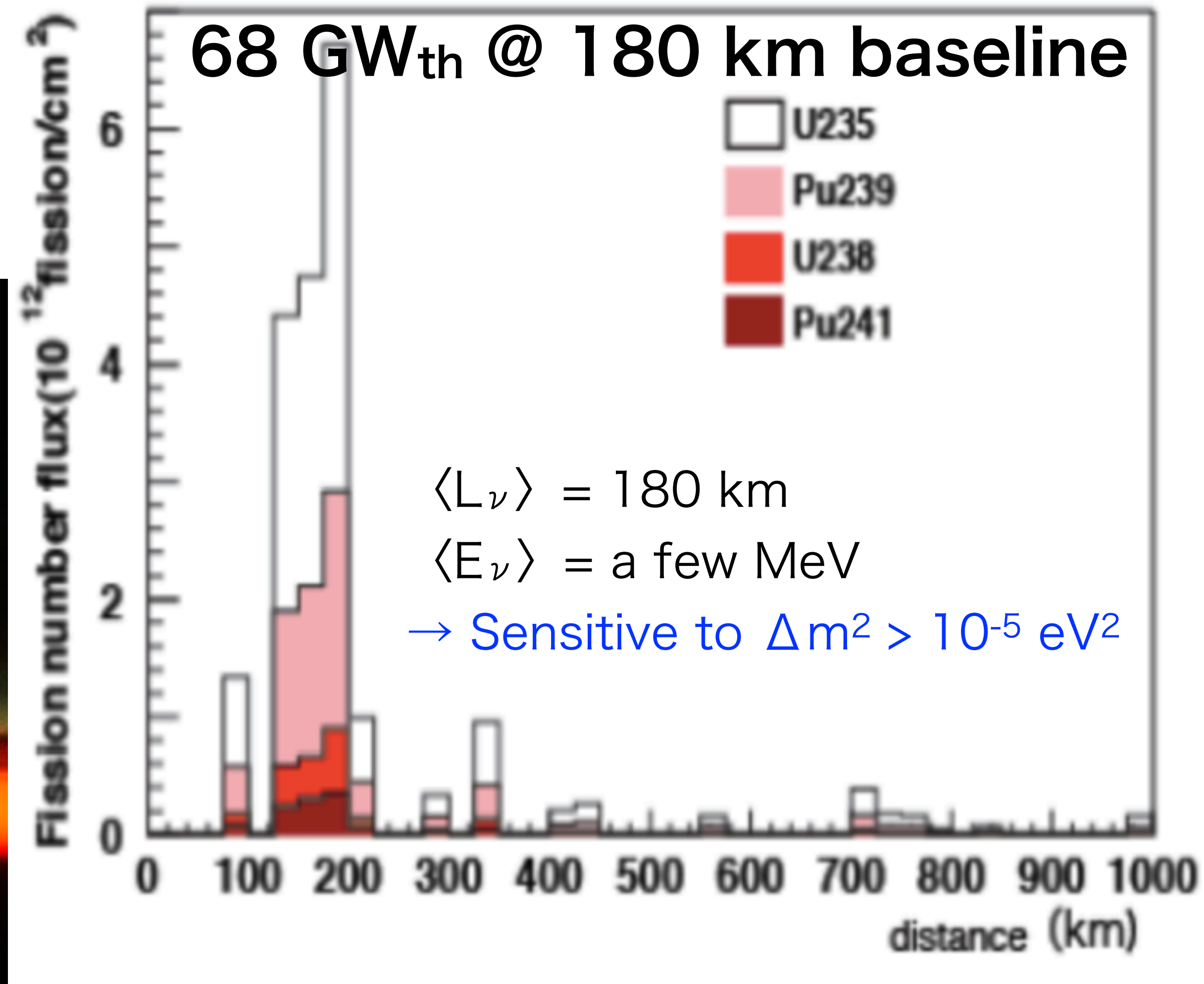
CPV phase vs θ23

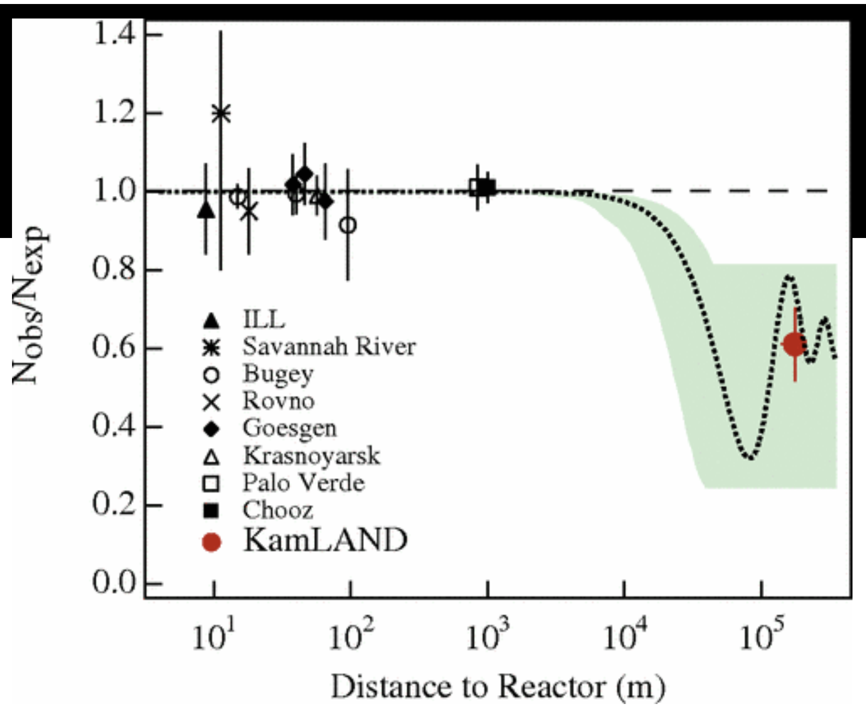
[octant ambiguity]


θ_{12}
$\theta_{12} \oplus \delta m^2$

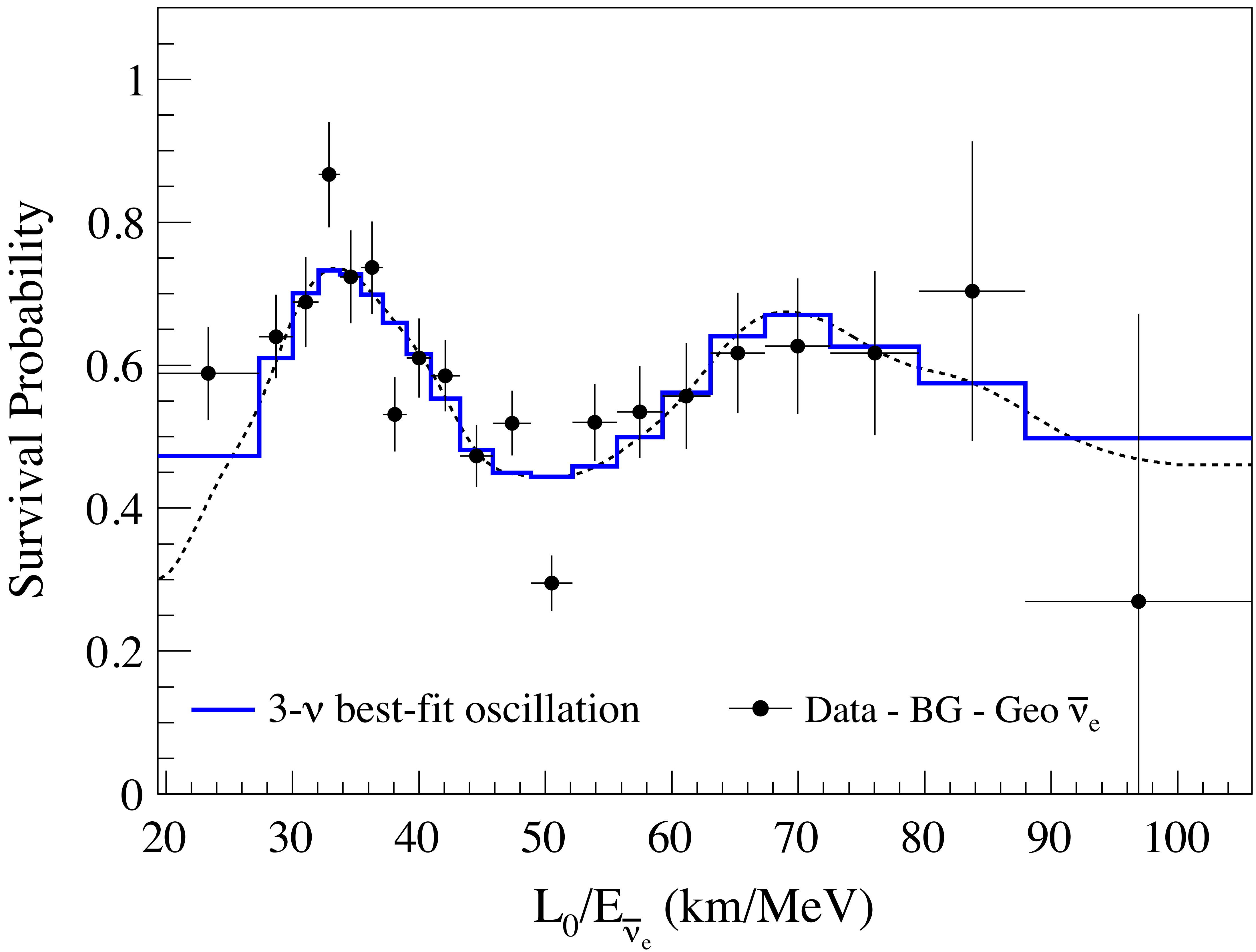
(stunning) experiment rationale...





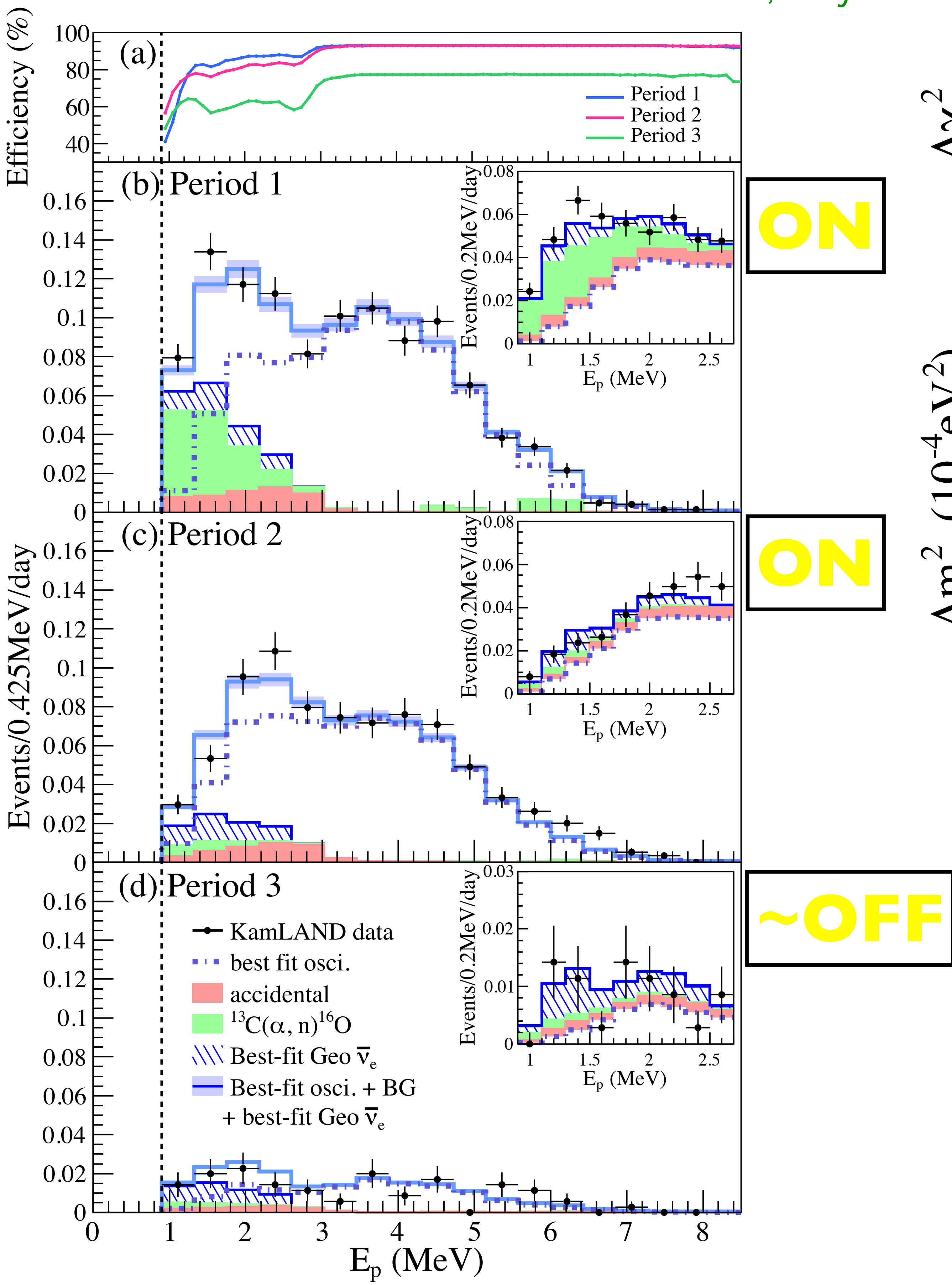


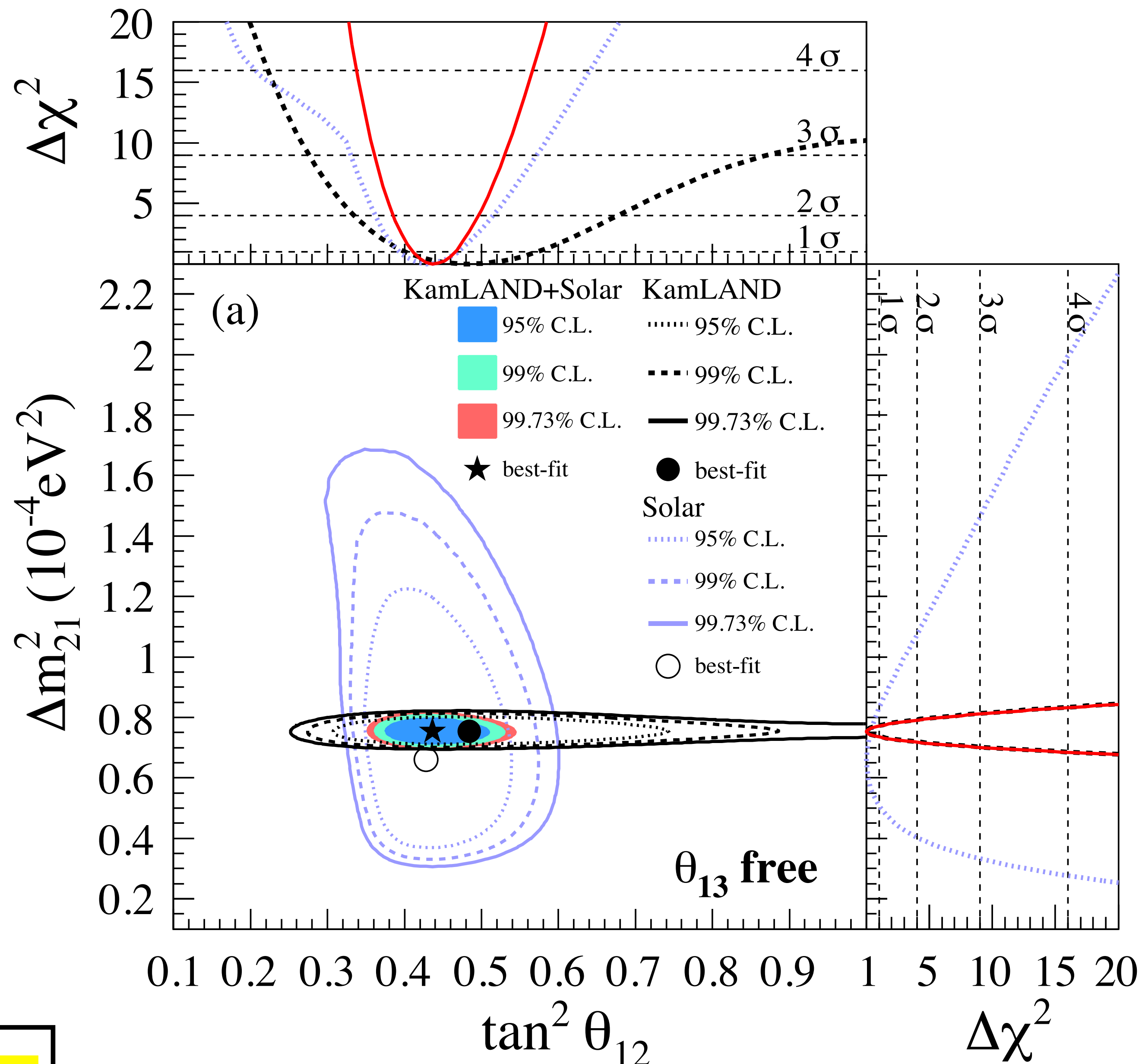
univocal neutrino oscillation pattern…



KamLAND's spectral distortion (and reactor-off)…

A. Gando et al., Phys. Rev. D 88, 033001 (2013).





solar drives **θ_{12}**

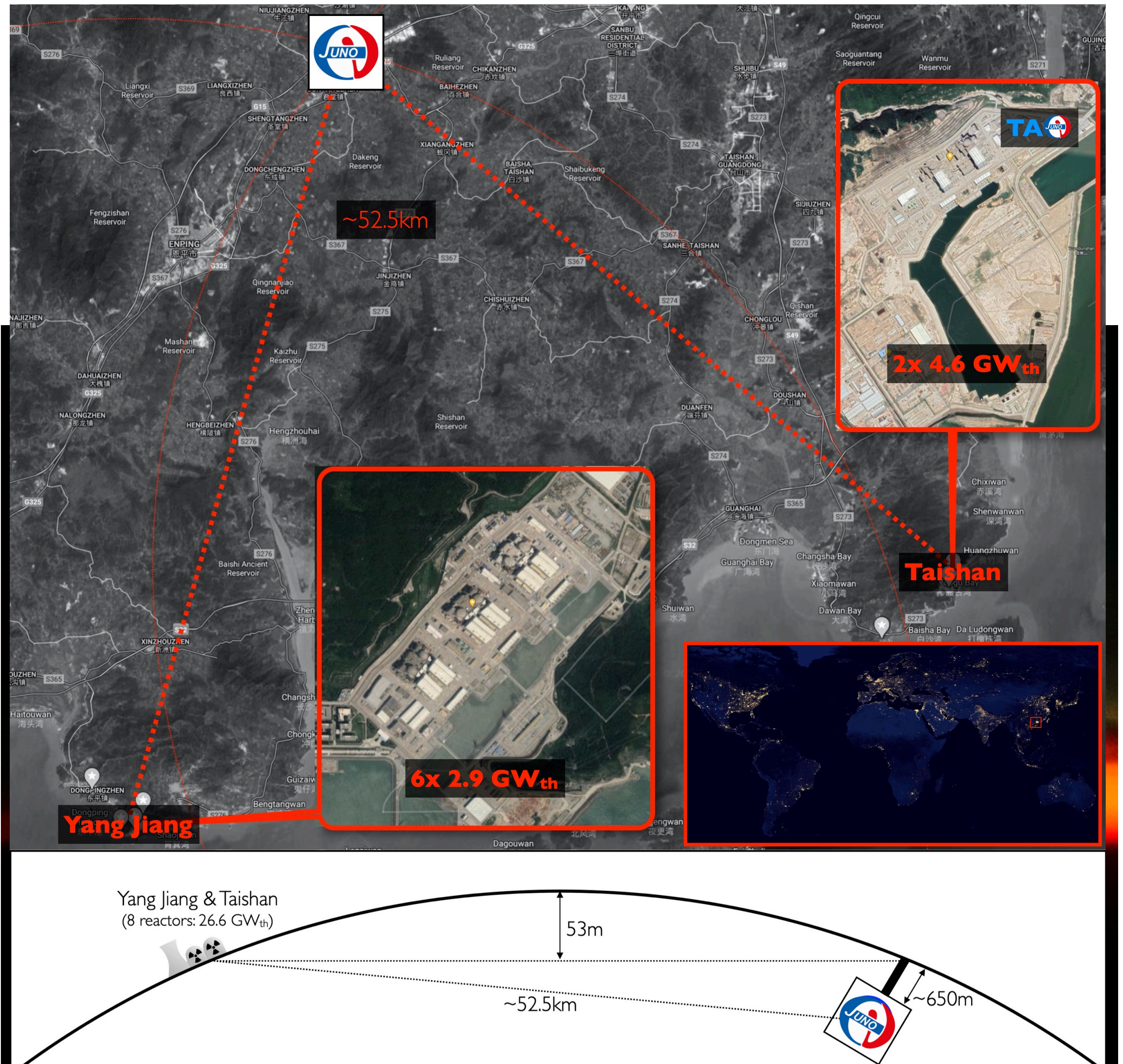
$\oplus$

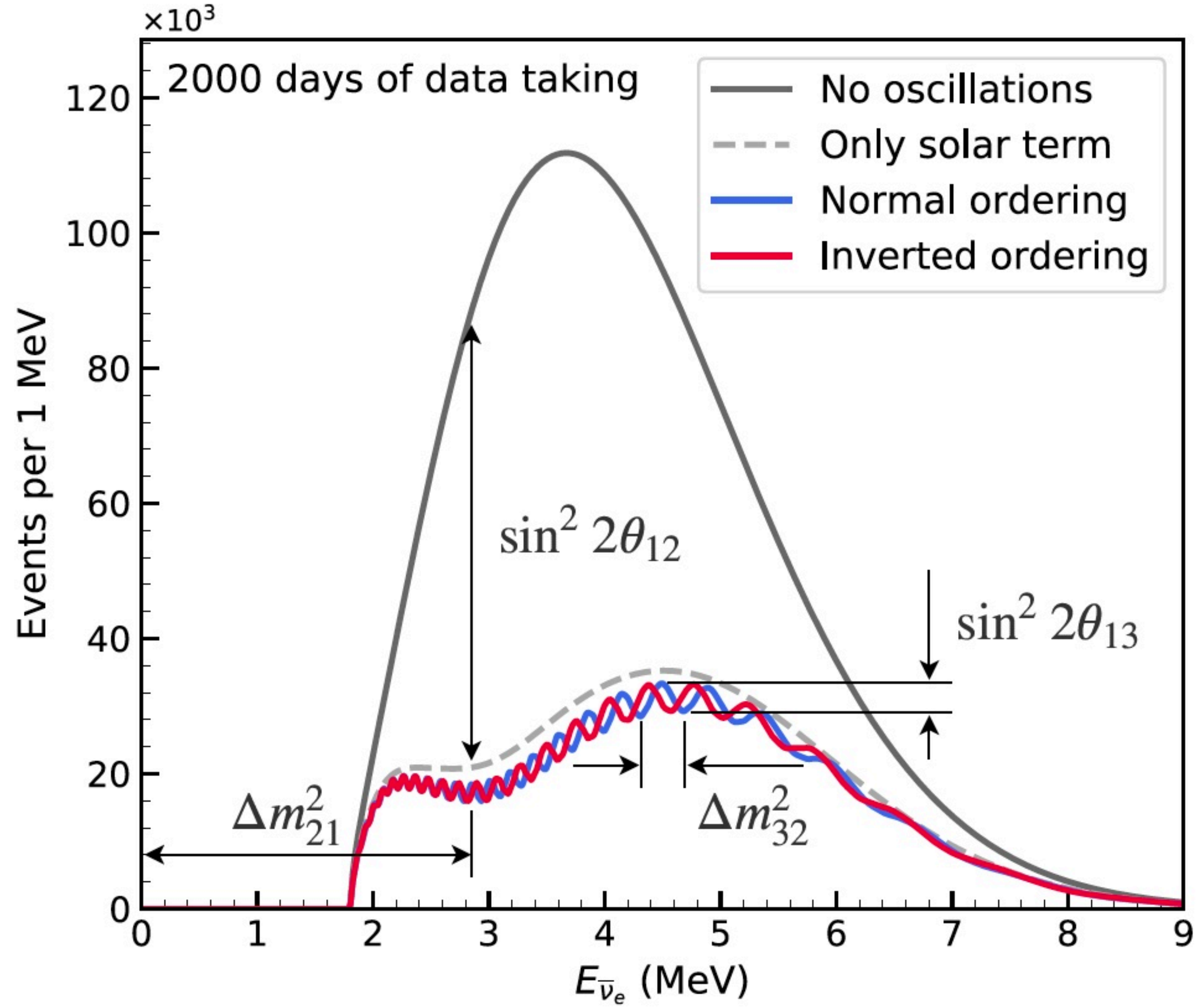
KamLAND drives **δm^2**


θ_{12}
improvable?


θ_{12}
$\theta_{12} \oplus \delta m^2$
$(\theta_{13}) \oplus \Delta m^2$

JUNO location…



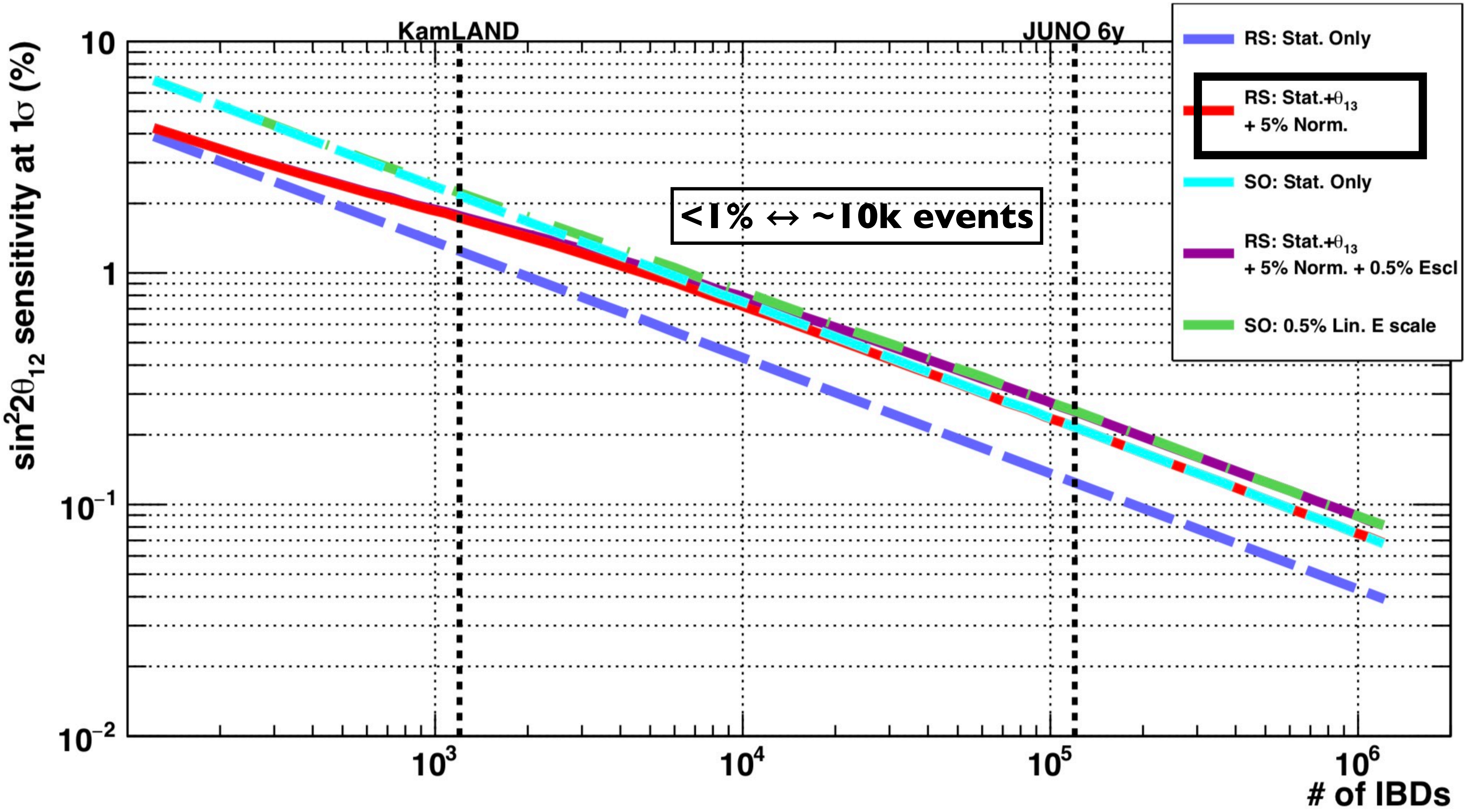


$\theta_{12} \oplus \delta m^2$ (slow)
$\theta_{13} \oplus \Delta m^2$ (fast)

~late 2022

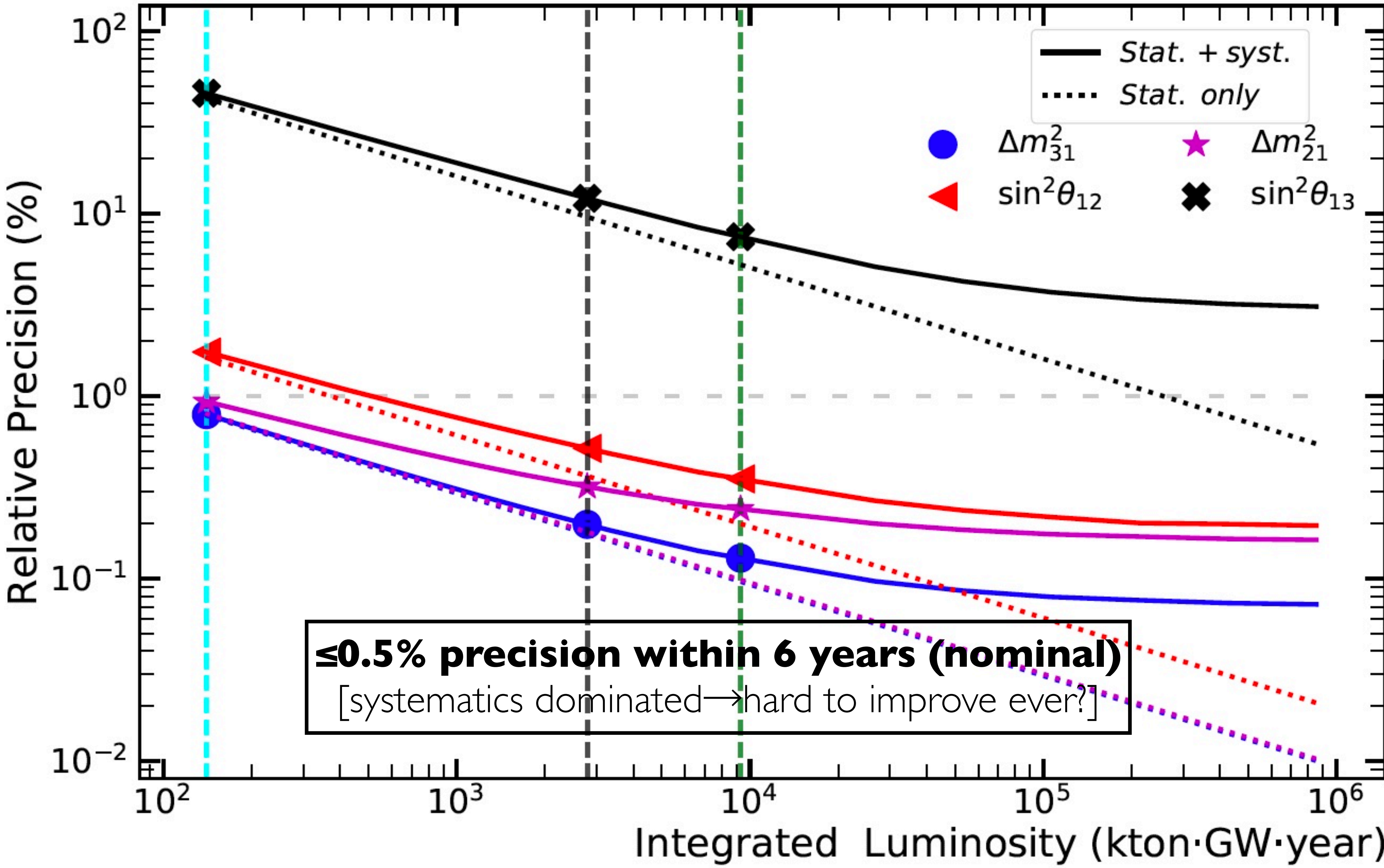
rate+shape sensitivity evolution…

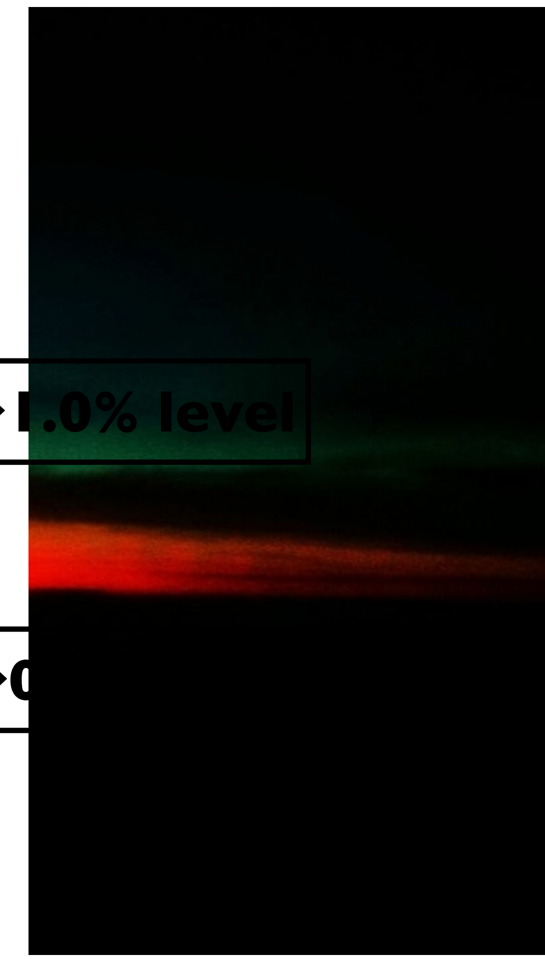
consider all systematics with state of the art knowledge (KL, DC, DYB)



rate+**shape**→ negligible rate uncertainties

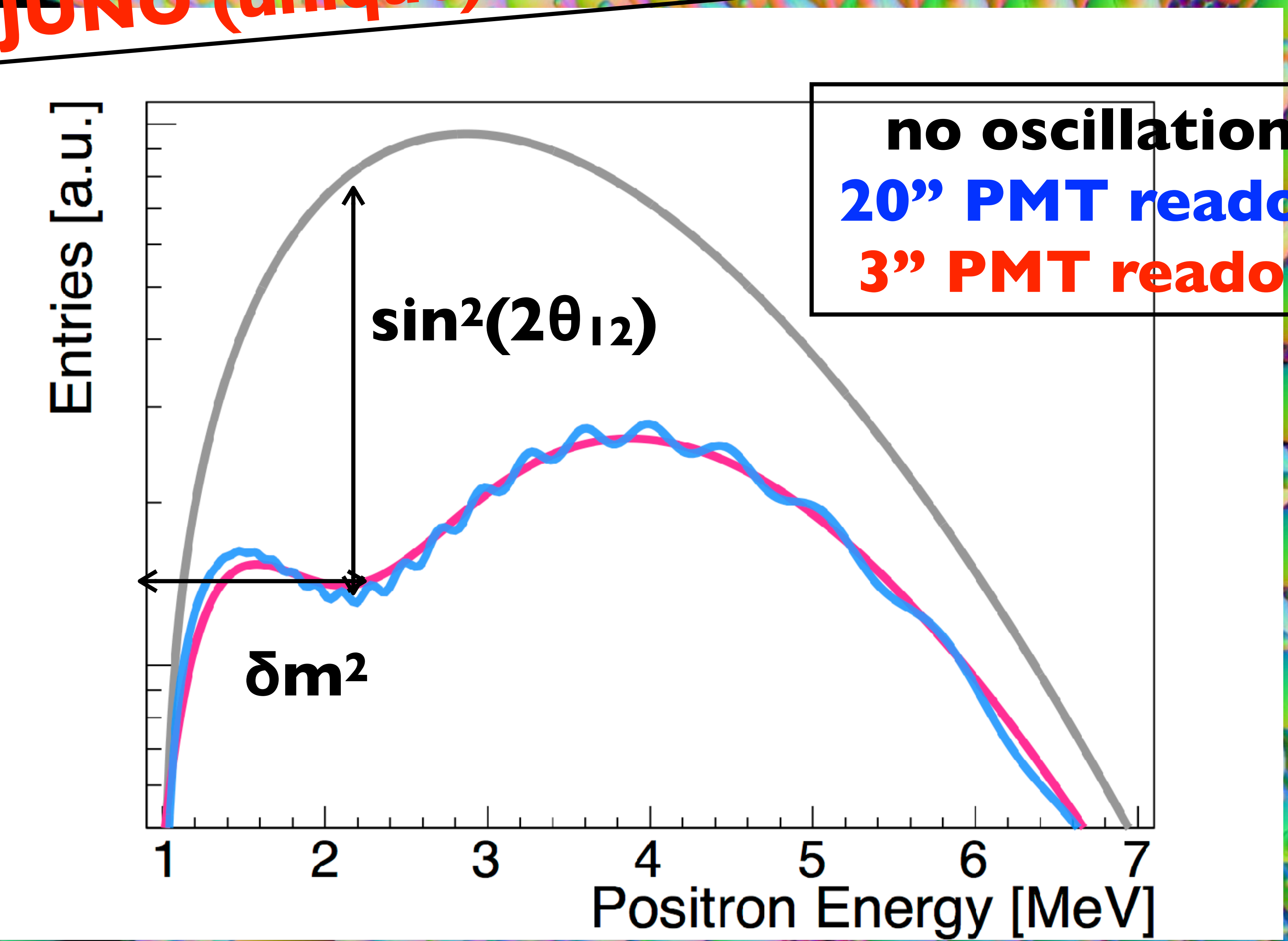
JUNO precision…

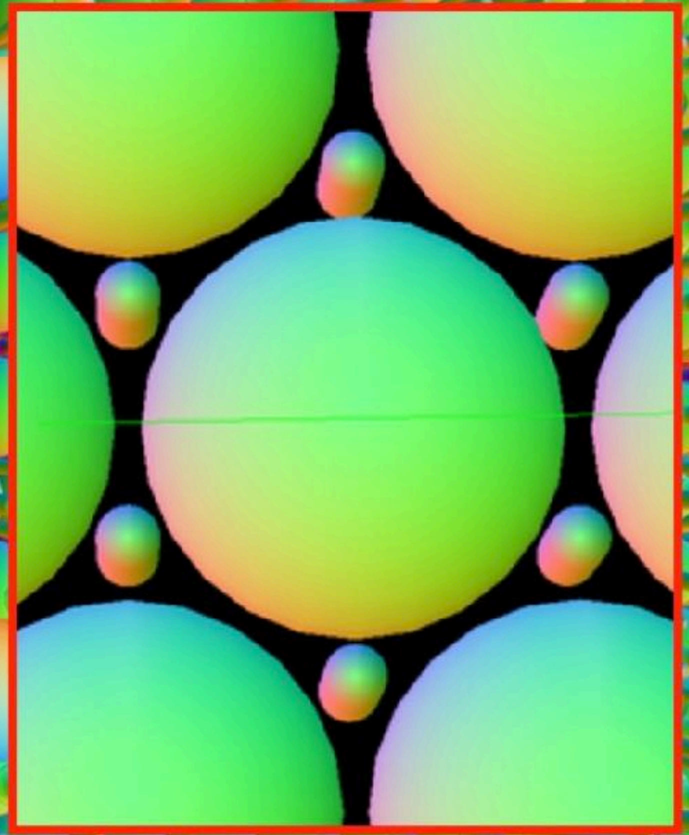




	Mass Ordering	$\lvert\Delta m^2_{32}\rvert$	$\lvert\Delta m^2_{21}\rvert$	$\sin^2\theta_{12}$	$\sin^2\theta_{13}$
6 years of data	3-4σ	$\sim 0.18\%$	$\sim 0.30\%$	$\sim 0.5\%$	$\sim 14\%$
20 years of data	5σ	$\sim 0.15\%$	$\sim 0.25\%$	$\sim 0.4\%$	$\sim 7\%$

JUNO (unique) internal validation



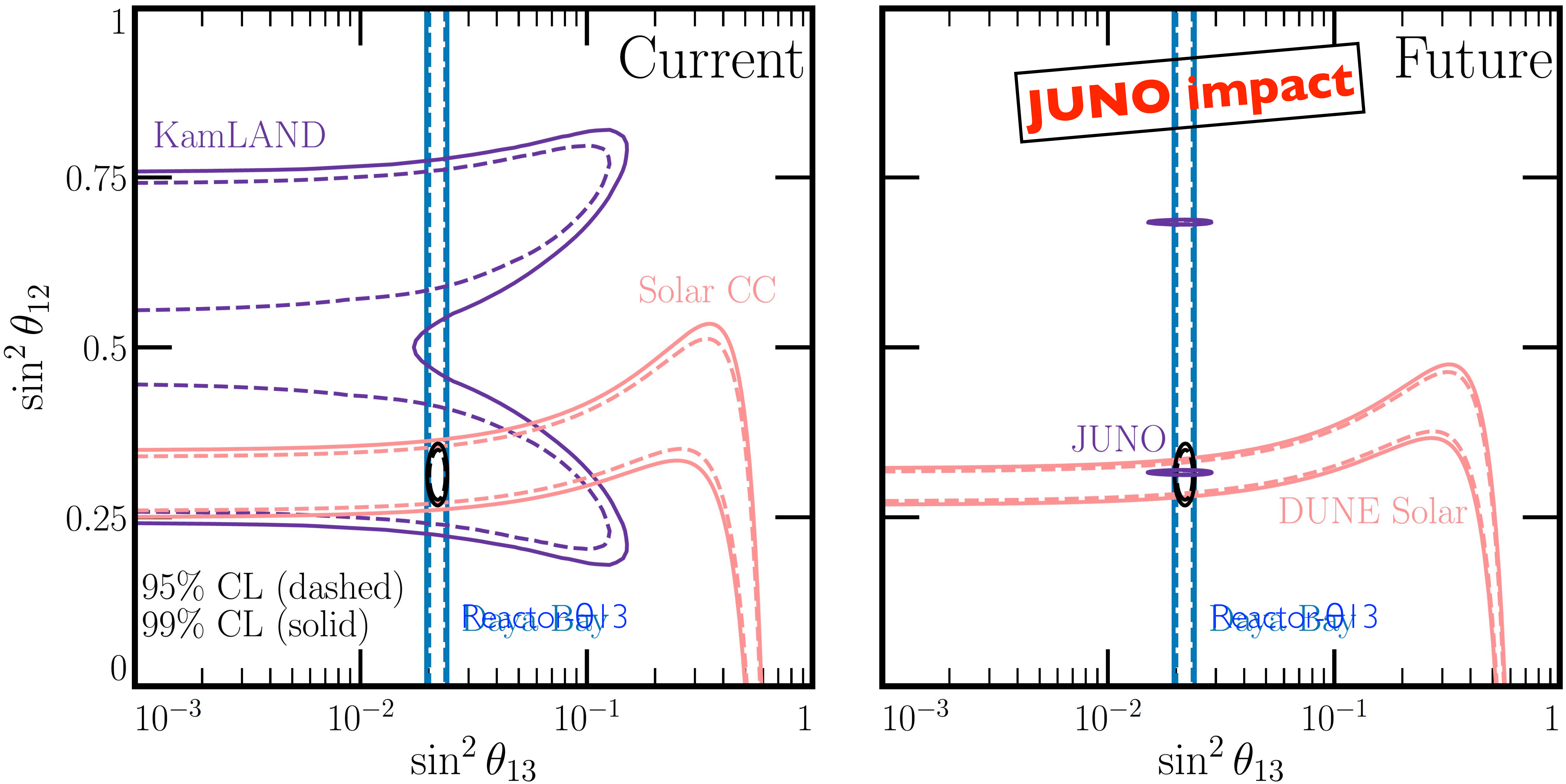


JUNO PMT systems Large (20”) and Small (3”) PMTs

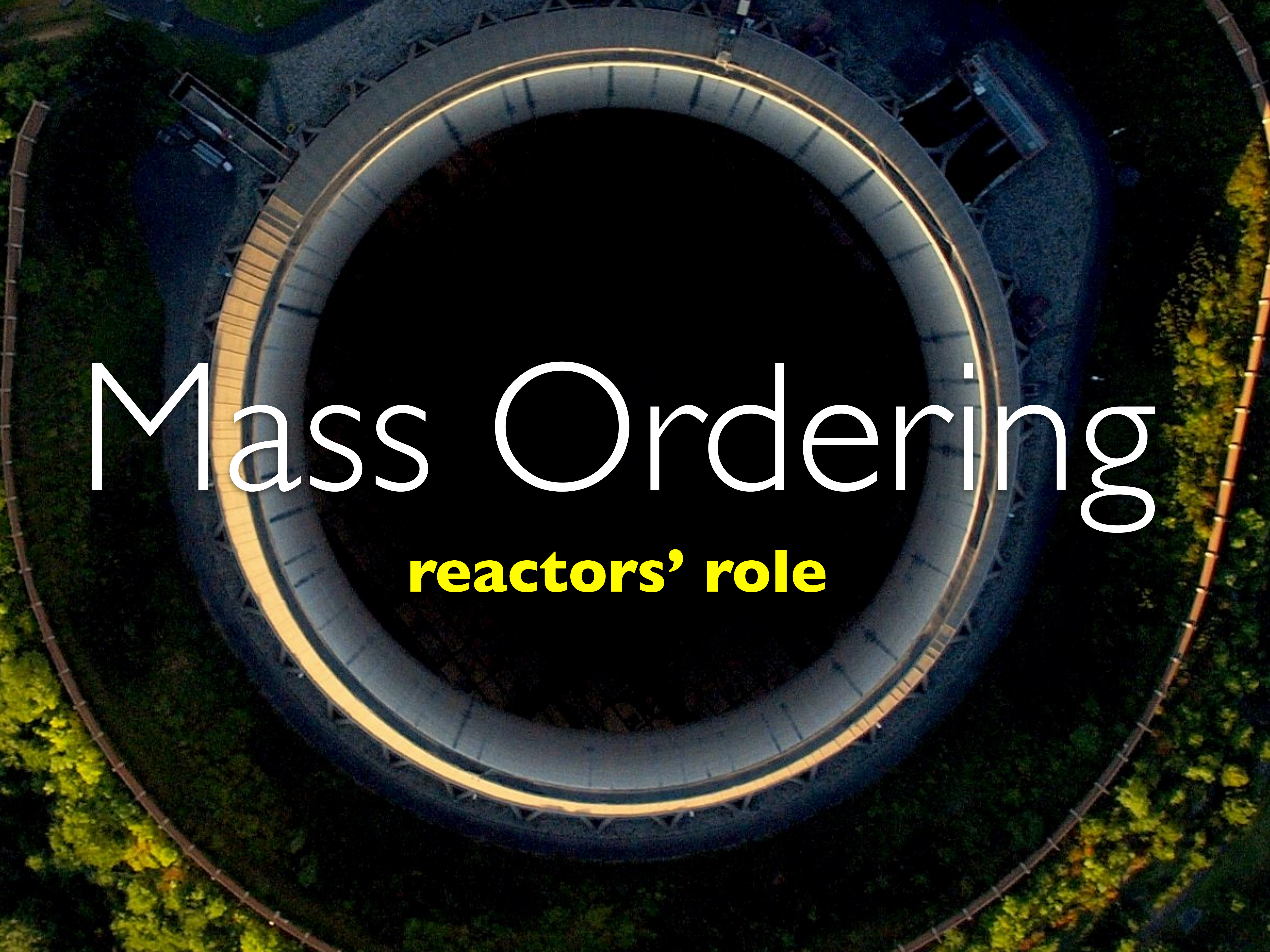
JUNO intrinsic redundancy→ 2 in 1 detectors within

Anatael Cabrera (CNRS-IN2P3 & APC)

reactor impact in **θ13-θ12** plane…



Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)


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

Ivan Esteban,[a] M. C. Gonzalez-Garcia,[a,b,c] Michele Maltoni,[d] Thomas Schwetz,[e] Albert Zhou[e]

[a] *Departament de Fisíca Quàntica i Astrofísica and Institut de Ciencies del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*
[b] *Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, 08010 Barcelona, Spain.*
[c] *C.N. Yang Institute for Theoretical Physics, State University of New York at Stony Brook, Stony Brook, NY 11794-3840, USA*
[d] *Instituto de Física Teórica UAM/CSIC, Calle de Nicolás Cabrera 13–15, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[e] *Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

E-mail: ivan.esteban@fqa.ub.edu, maria.gonzalez-garcia@stonybrook.edu, michele.maltoni@csic.es, schwetz@kit.edu, albert.zhou@kit.edu

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

NEUTRINO 2020

today's world data leads to…

NMO favoured to ~2.7σ (2020)

- **Super-Kamiokande** (most info so far)
- **1.6σ** (NOvA⊕T2K & DC⊕DYB⊕RENO)
- some **fragility?**

what are the leading experiments?

what's going to happen next?

NuFitv5.0: today's world knowledge — what about tomorrow?

today's NMO status…

	direct sensitivity	nuisance	combined sensitivity
vacuum oscillation (reactor)	ultra precise oscillation	θ_{13}?	Δm^2 with precision ≤1% & resolve CPV
matter effects (~~reactor~~)	fake CPV (due to Earth)	CPV and θ_{23}	

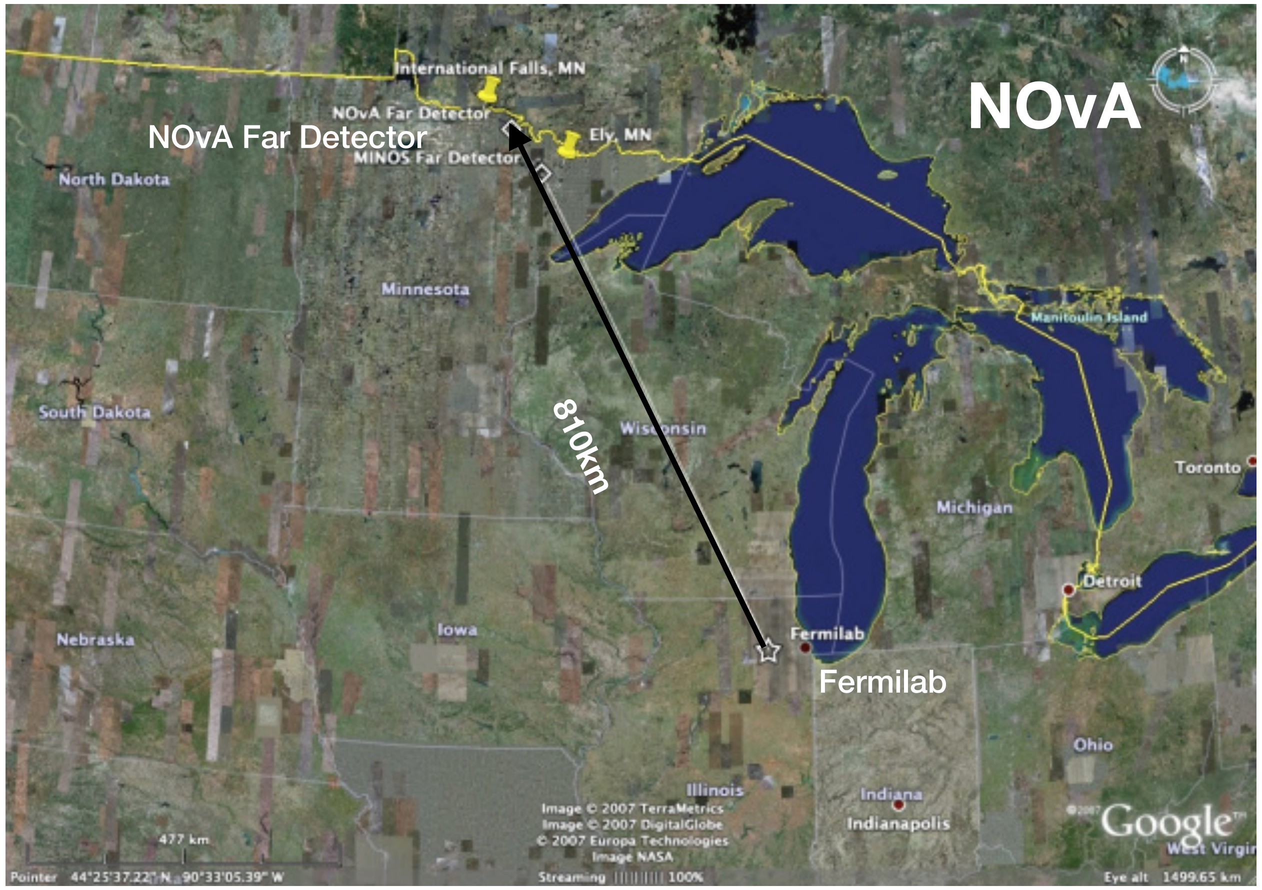
NuFitv5.0: maginilise today's world knowledge — CPV, θ_{23}, θ_{13}, …

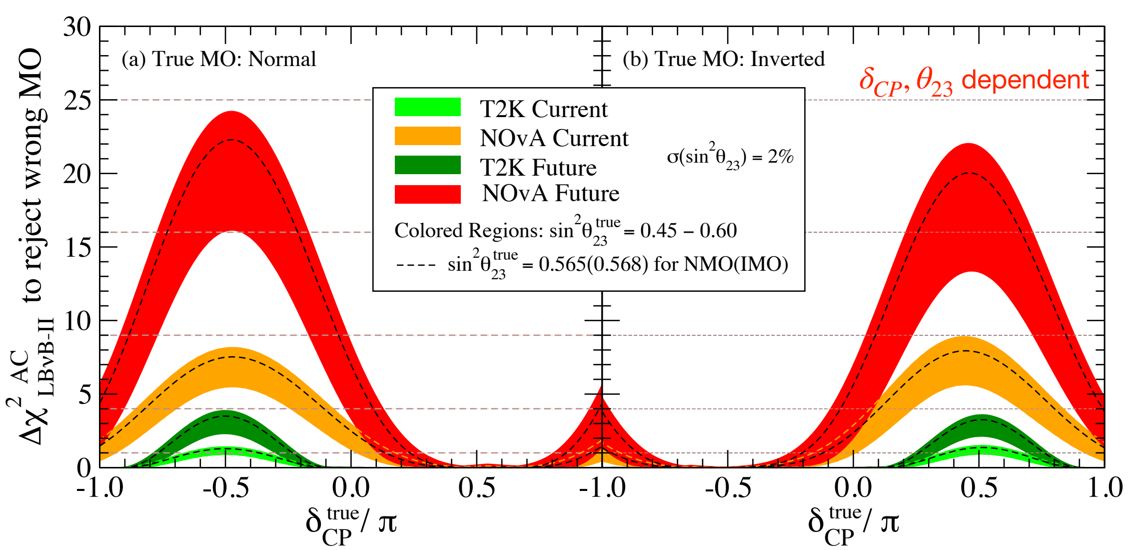
the building blocks…

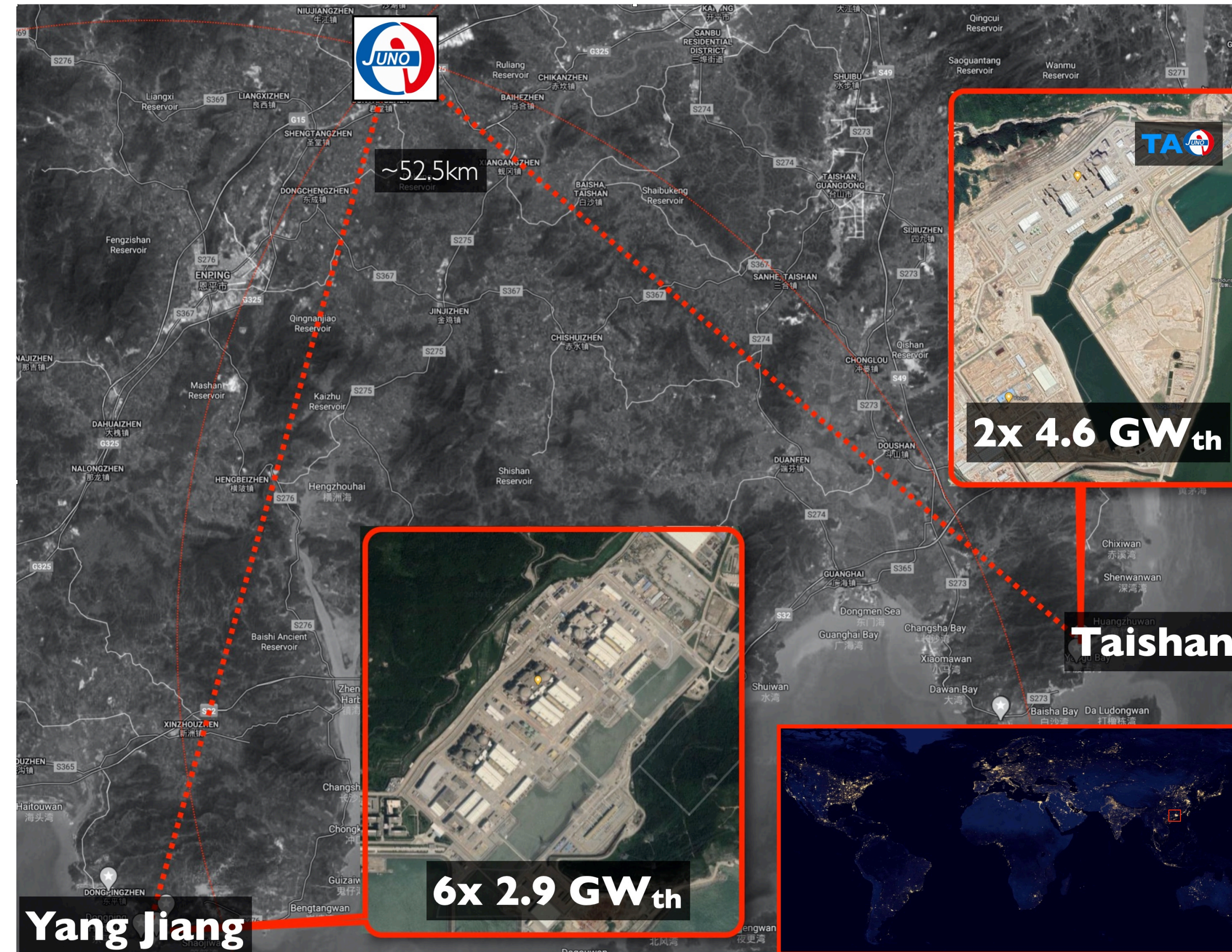
Anatael Cabrera CNRS-IN2P3 / IJCLab (Orsay) - LNCA (Chooz) Laboratories

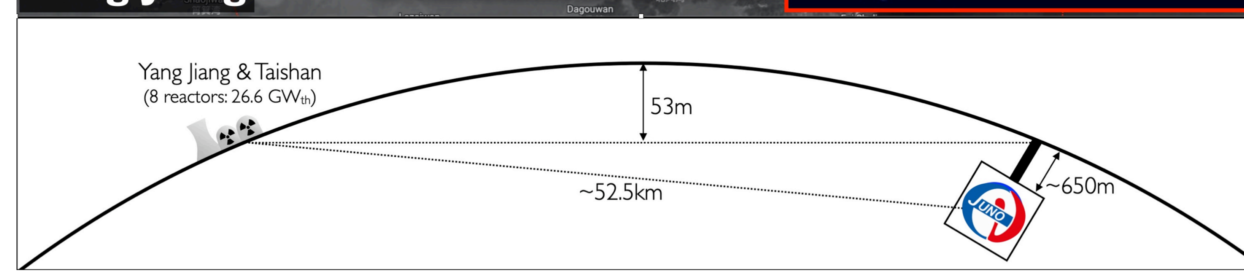
	direct sensitivity	nuisance	sensitivity	combined sensitivity
JUNO	ultra precision oscillation	θ_{13}?	~3σ	$\delta(\Delta m^2)\leq 0.5\%$
NOvA	fake CPV (due to Earth)	mainly CPV (θ_{23} too)	~3-4σ (~800km baseline)	$\delta(\Delta m^2)\sim 1.0\%$
T2K			≤2σ (~250km baseline)	$\delta(\Delta m^2)\sim 1.0\%$
HyperK				$\delta(\Delta m^2)\sim 0.5\%$
DUNE			**>5σ !** (~1200km baseline)	$\delta(\Delta m^2)\sim 0.5\%$
Atmospherics		mainly θ_{23} (CPV too)	~3-6σ (many baselines)	$\delta(\Delta m^2)$ poor

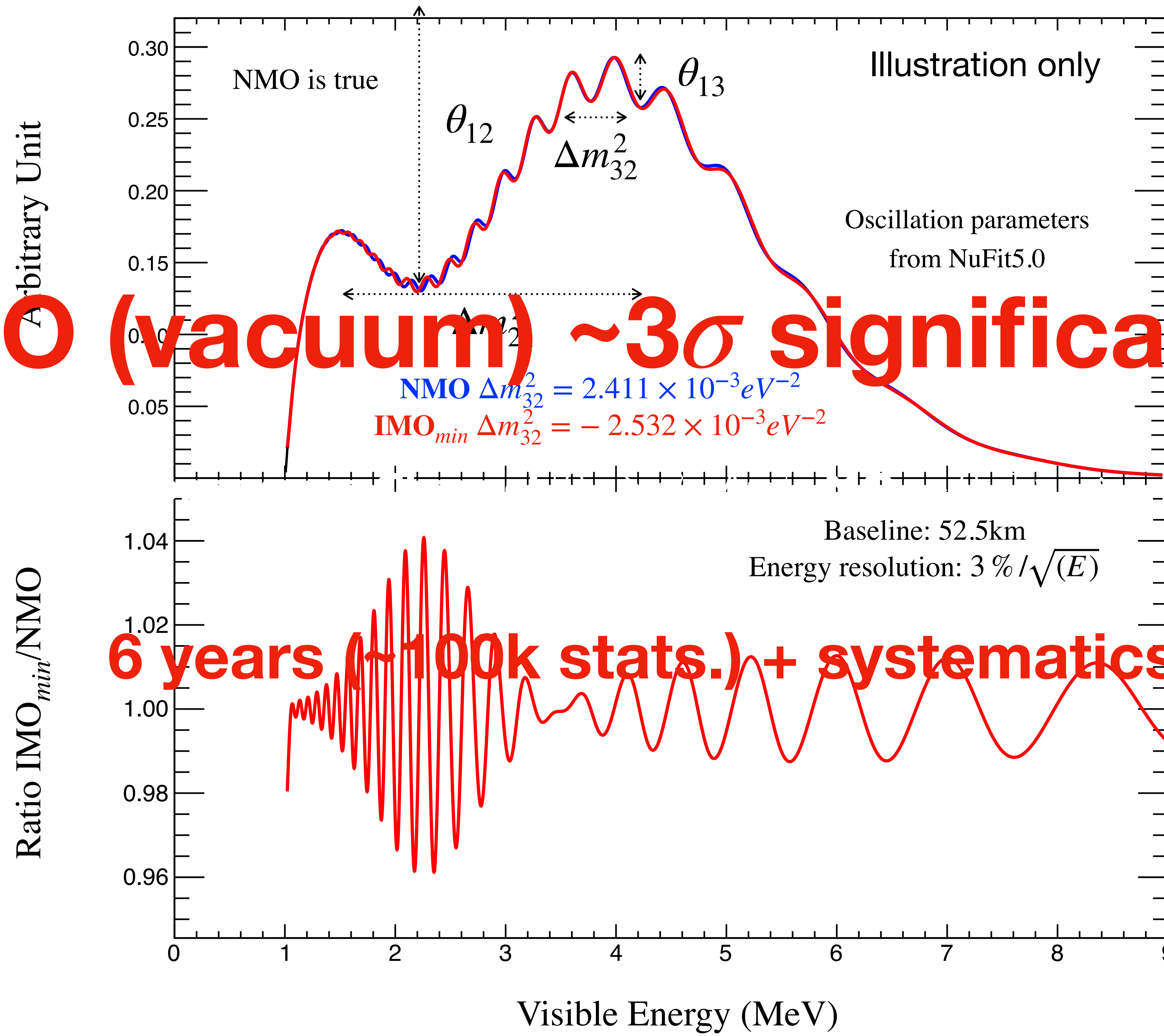
the building blocks…


NOvA
NOvA Far Detector
International Falls, MN
Ely, MN
MINOS Far Detector
North Dakota
Minnesota
South Dakota
Wisconsin
810km
Manitoulin Island
Toronto
Michigan
Detroit
Nebraska
Iowa
Fermilab
Fermilab
Ohio
Illinois
Indiana
Indianapolis
Google


(a) True MO: Normal
(b) True MO: Inverted
δ_{CP}, θ_{23} dependent
T2K Current
NOvA Current
T2K Future
NOvA Future
$\sigma(\sin^2\theta_{23}) = 2\%$
Colored Regions: $\sin^2\theta_{23}^{true} = 0.45 - 0.60$
---- $\sin^2\theta_{23}^{true} = 0.565(0.568)$ for NMO(IMO)
$\Delta\chi^2{}^{AC}_{LBvB-II}$ to reject wrong MO
δ_{CP}^{true}/π
δ_{CP}^{true}/π


JUNO
~52.5km
TAO
2x 4.6 GW$_{th}$
Taishan
6x 2.9 GW$_{th}$
Yang Jiang


Yang Jiang & Taishan
(8 reactors: 26.6 GW$_{th}$)
53m
~52.5km
~650m
JUNO



MO (vacuum) ~3σ significance

6 years (~100k stats.) + systematics

nature
SCIENTIFIC REPORTS

scientific reports

Article | Open Access | Published: 30 March 2022

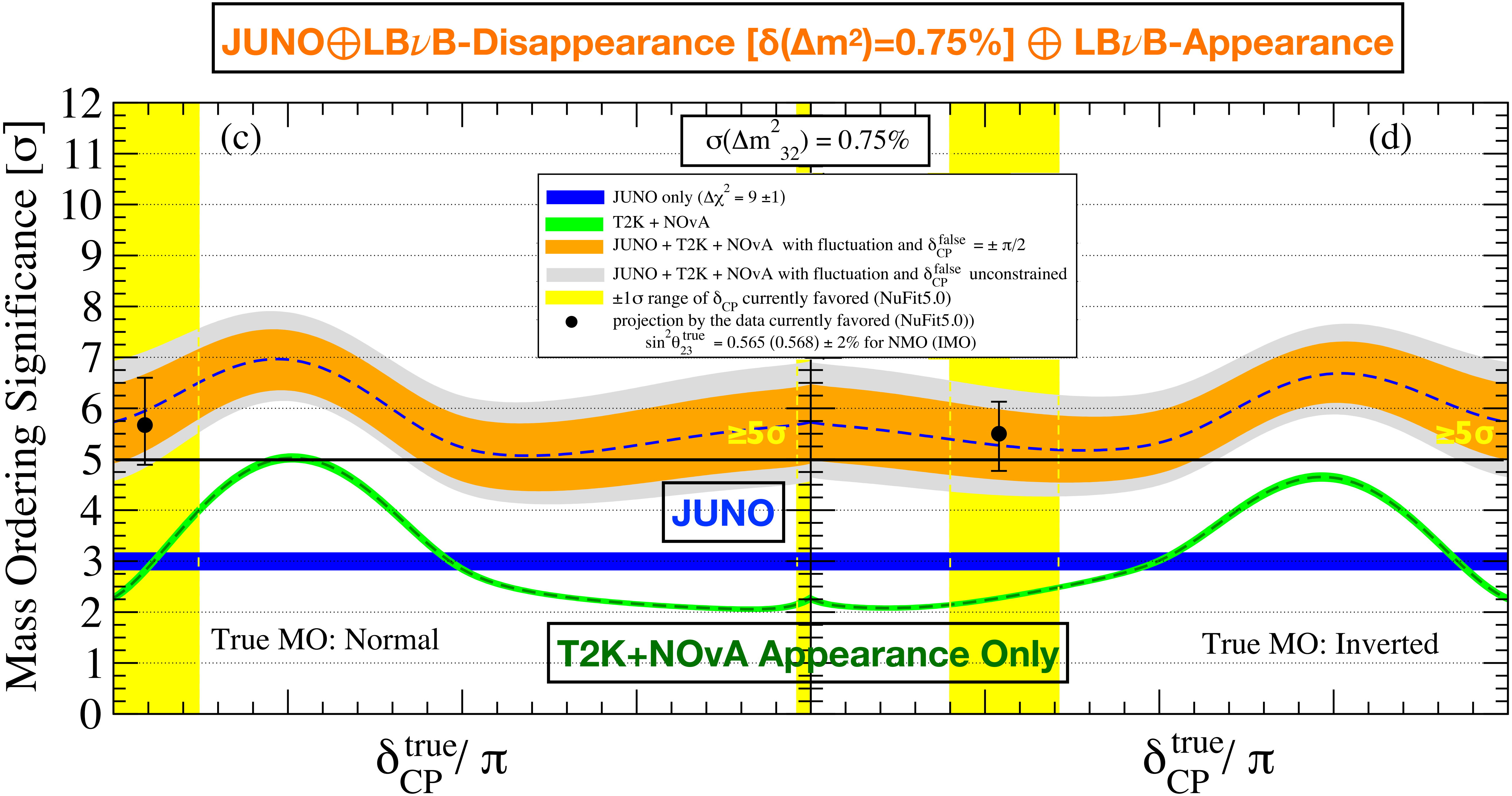
Synergies and prospects for early resolution of the neutrino mass ordering

Anatael Cabrera, Yang Han, ... Hongzhao Yu + Show authors

Scientific Reports **12**, Article number: 5393 (2022) | Cite this article

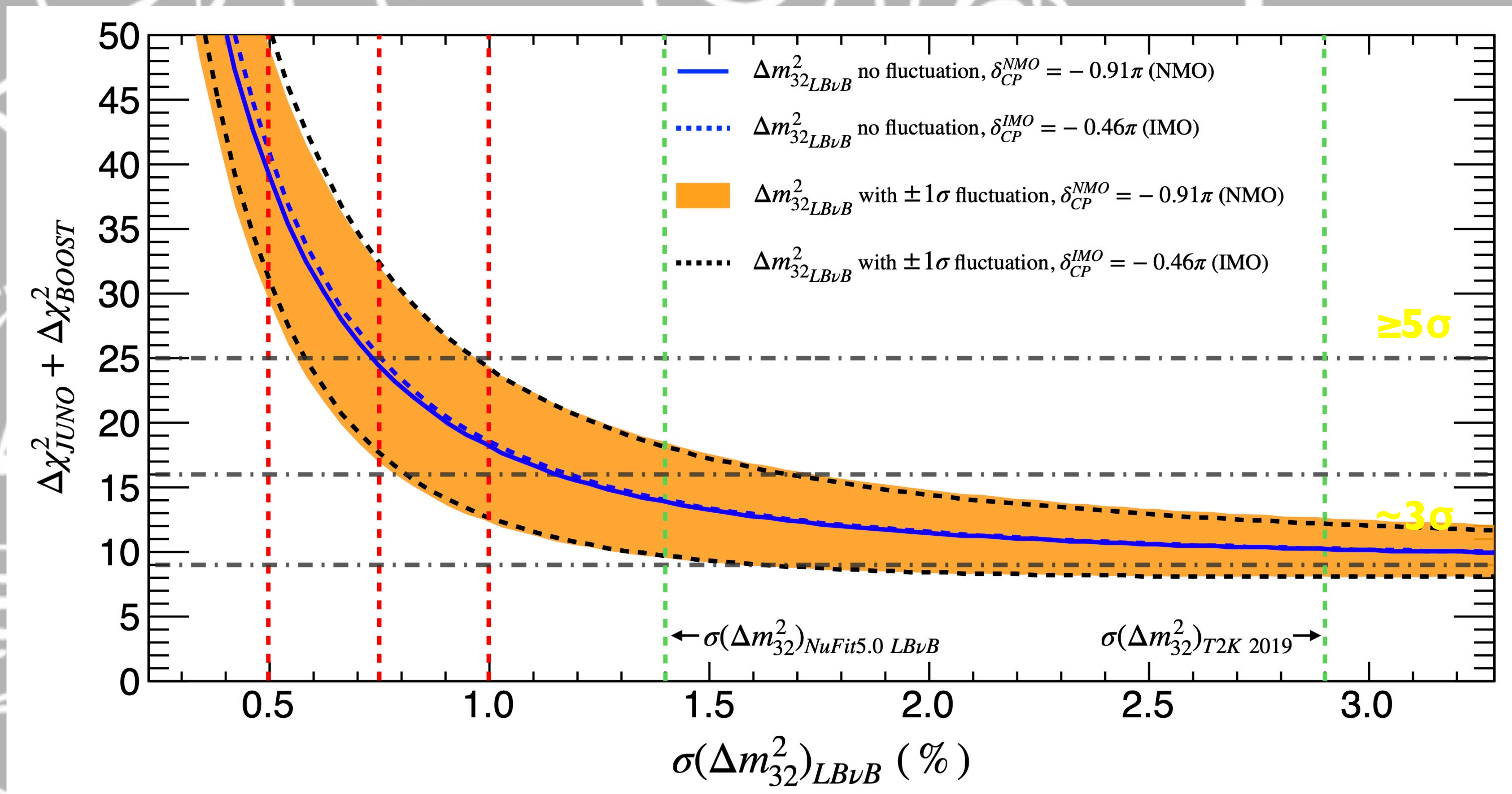
Abstract

The measurement of neutrino mass ordering (MO) is a fundamental element for the understanding of leptonic flavour sector of the *Standard Model of Particle Physics*. Its determination relies on the precise measurement of Δm^2_{31} and Δm^2_{32} using either neutrino *vacuum oscillations*, such as the ones studied by medium baseline reactor experiments, or *matter effect modified oscillations* such as those manifesting in long-baseline neutrino beams (LBνB) or atmospheric neutrino experiments. Despite existing MO indication today, a fully resolved MO measurement ($\geq 5\sigma$) is most likely to await for the next generation of neutrino experiments: JUNO, whose stand-alone sensitivity is $\sim 3\sigma$, or LBνB experiments (DUNE and Hyper-Kamiokande). Upcoming atmospheric neutrino experiments are also expected to provide precious information. In this work, we study the possible context for the earliest full MO resolution. A firm resolution is possible even before 2028, exploiting mainly vacuum oscillation, upon the combination of JUNO and the current generation of LBνB experiments (NOvA and T2K). This opportunity is possible thanks to a powerful synergy boosting the overall sensitivity where the sub-percent precision of Δm^2_{32} by LBνB experiments is found to be the leading order term for the MO earliest discovery. We also found that the comparison between *matter* and *vacuum* driven oscillation results enables unique discovery potential for physics beyond the Standard Model.


JUNO⊕LBνB-Disappearance [δ(Δm²)=0.75%] ⊕ LBνB-Appearance
Mass Ordering Significance [σ]
(c)
(d)
σ(Δm²₃₂) = 0.75%
JUNO only (Δχ² = 9 ±1)
T2K + NOvA
JUNO + T2K + NOvA with fluctuation and δ_CP^false = ± π/2
JUNO + T2K + NOvA with fluctuation and δ_CP^false unconstrained
±1σ range of δ_CP currently favored (NuFit5.0)
projection by the data currently favored (NuFit5.0))
sin²θ₂₃^true = 0.565 (0.568) ± 2% for NMO (IMO)
≥5σ
≥5σ
JUNO
True MO: Normal
T2K+NOvA Appearance Only
True MO: Inverted
δ_CP^true/ π
δ_CP^true/ π

powerful synergy JUNO vs NOvA⊕T2K: high precision disappearance Δm^2_{32}…

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…

Mass Ordering resolution [now at ~3σ]…

- **DUNE** most powerful standalone experiment

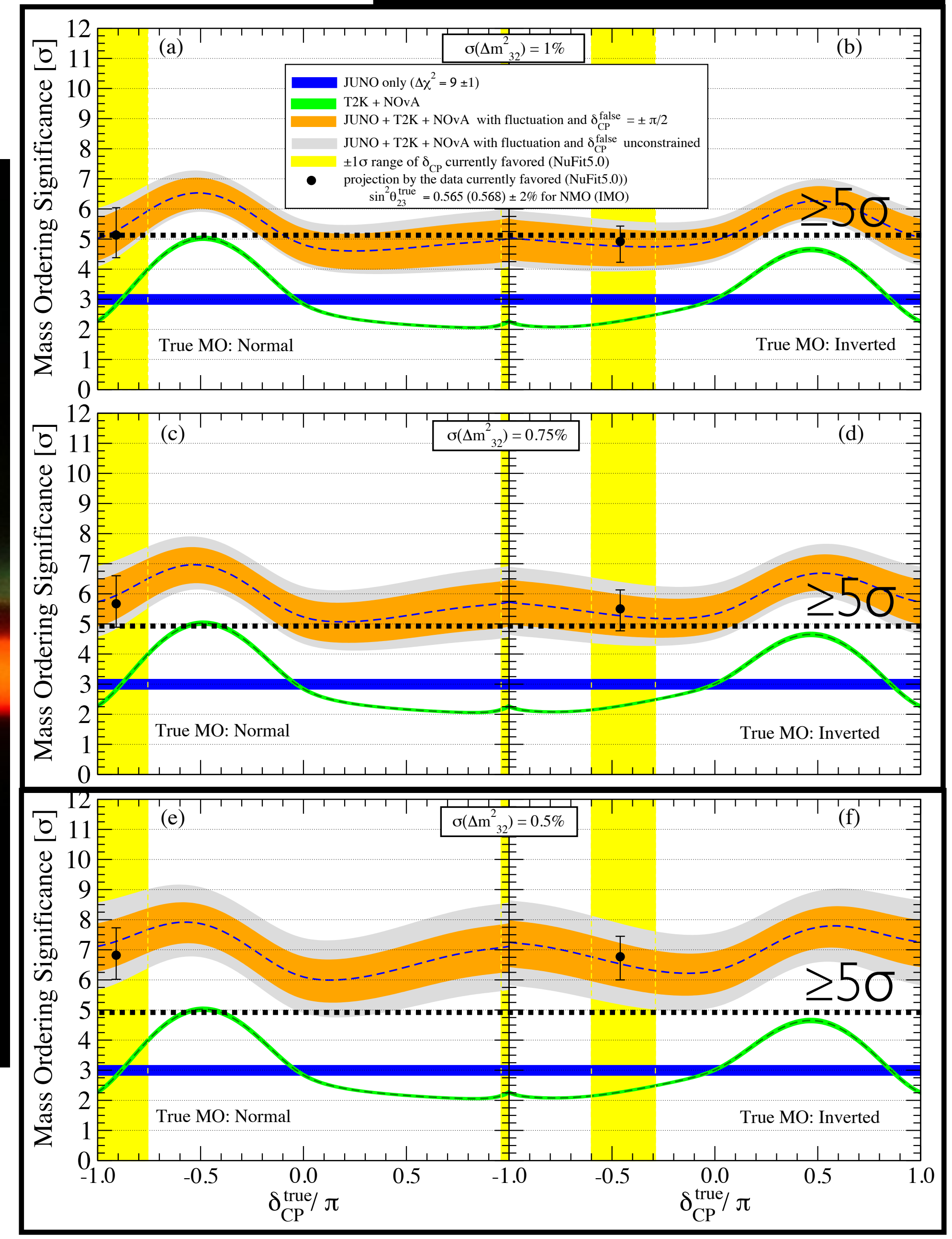
- most interesting: exploit **MO**’s <u>binary outcome</u> for possible **BSM explorations**

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

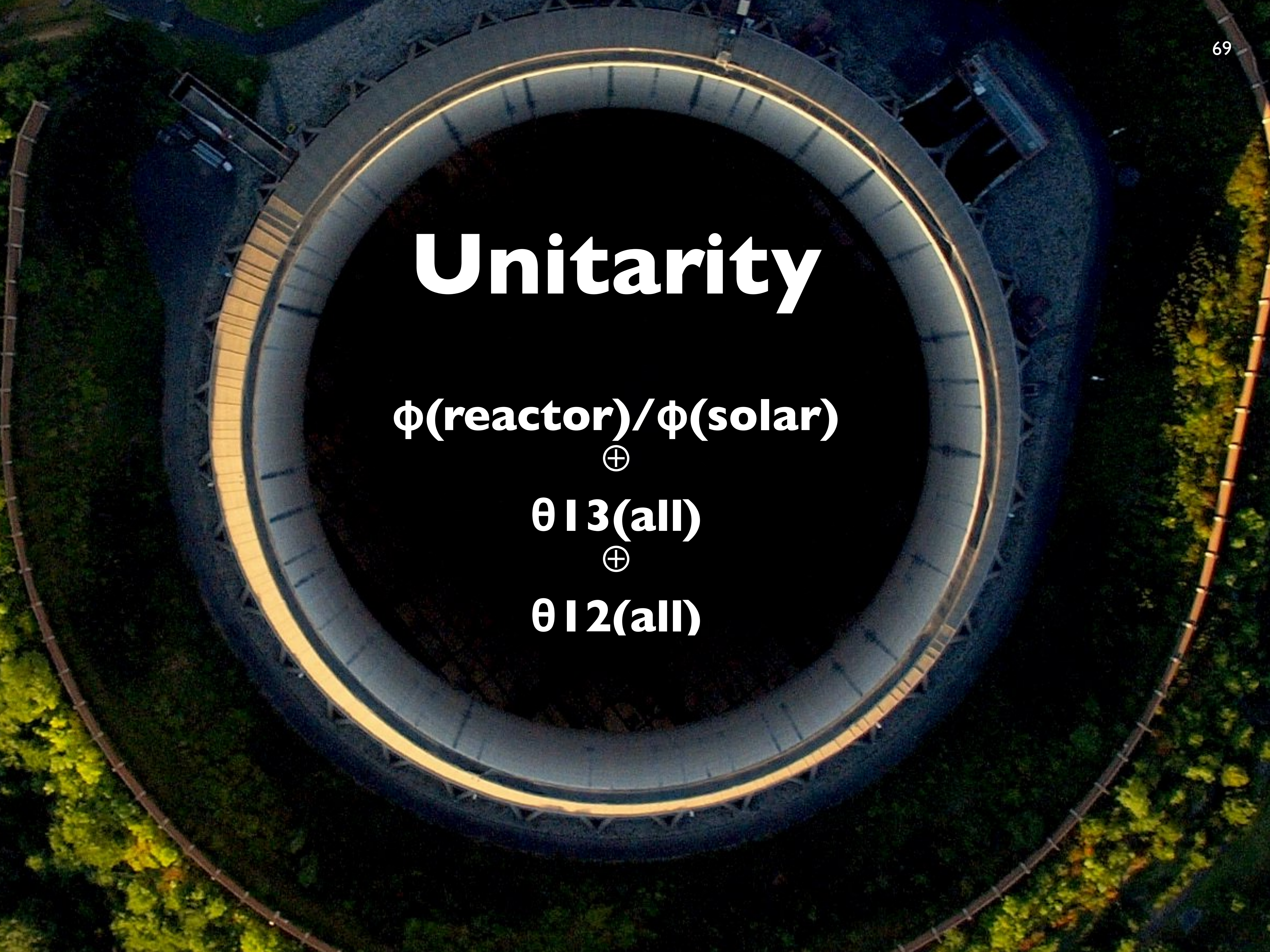
  <u>DUNE</u>(Appearance)
  [≥5σ — *matter effects*]
  vs
  <u>JUNO</u> and DUNE⊕HK(disappearance)
  [≥5σ — *vacuum oscillations*]

discrepancies may lead to discoveries!

JUNO+NOvA+T2K



JUNO and HK⊕DUNE (Disappearance)



Unitarity

ϕ(reactor)/ϕ(solar)

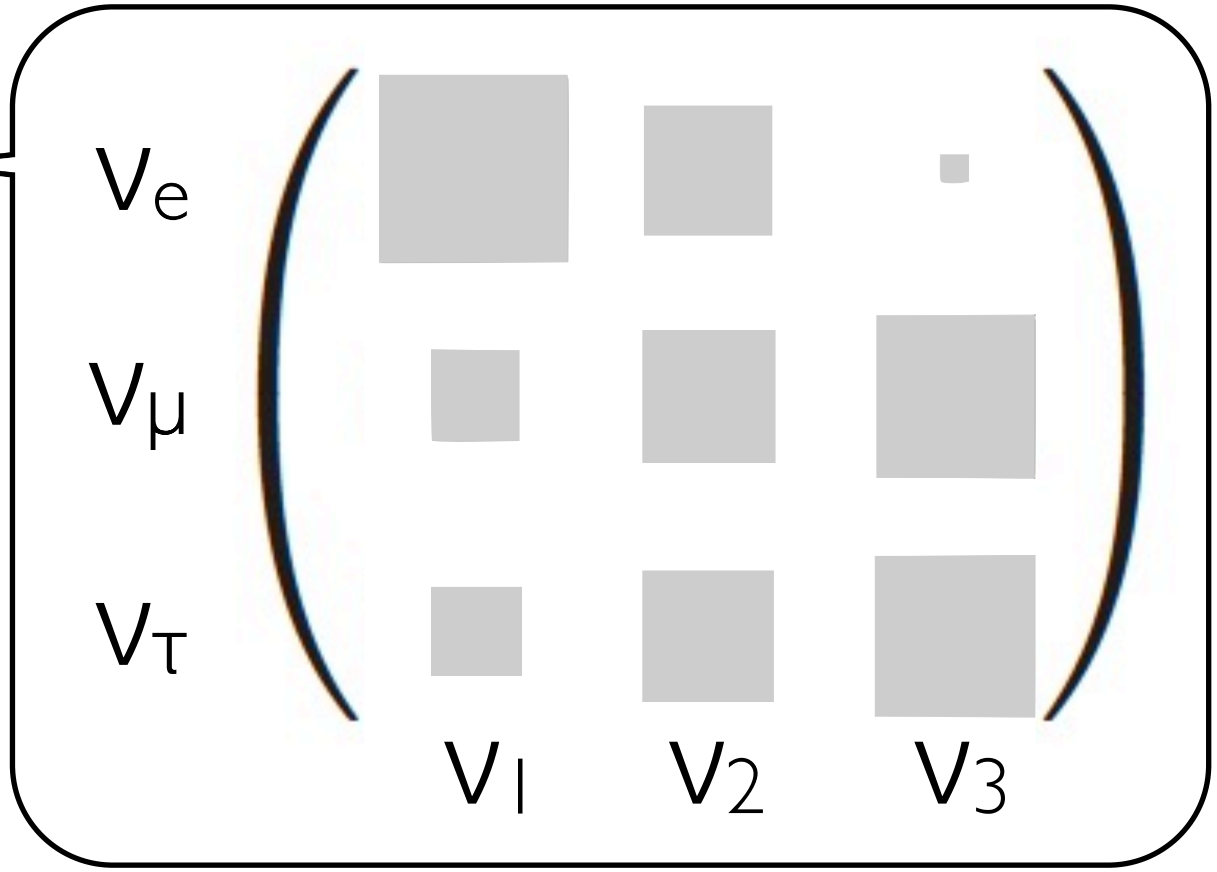
⊕

θ13(all)

⊕

θ12(all)

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



consider full matrix structure

(not just composition)

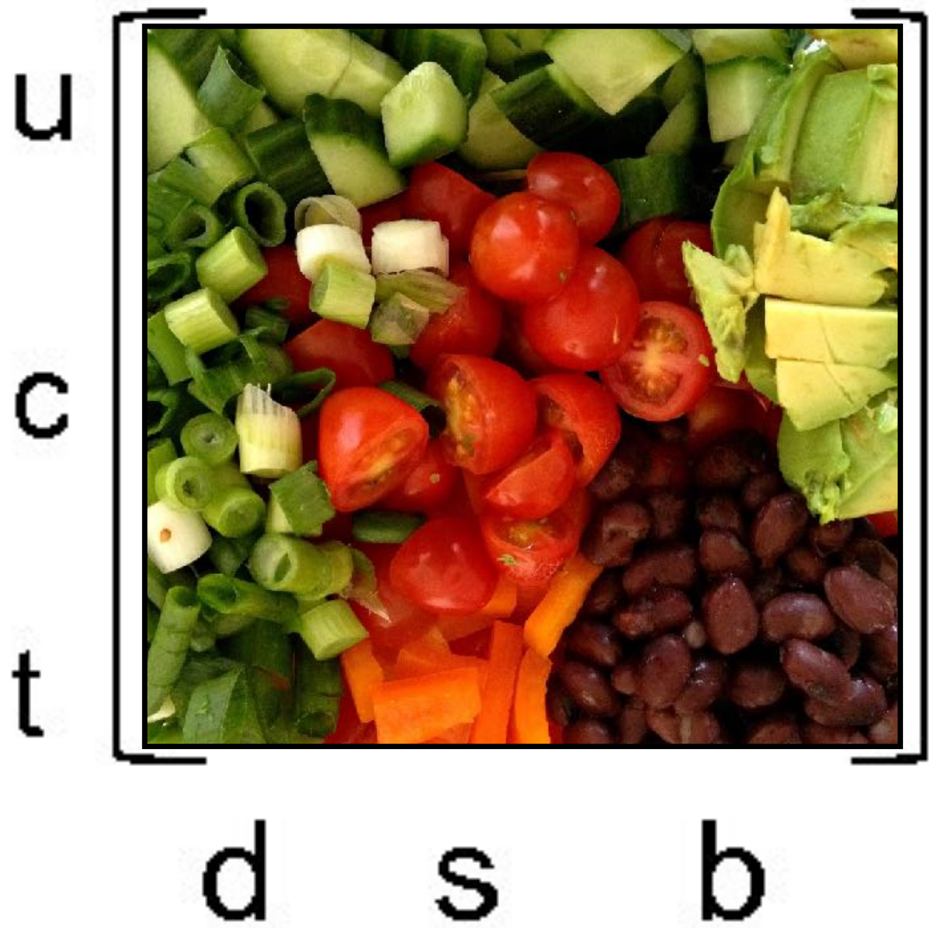
why shape?

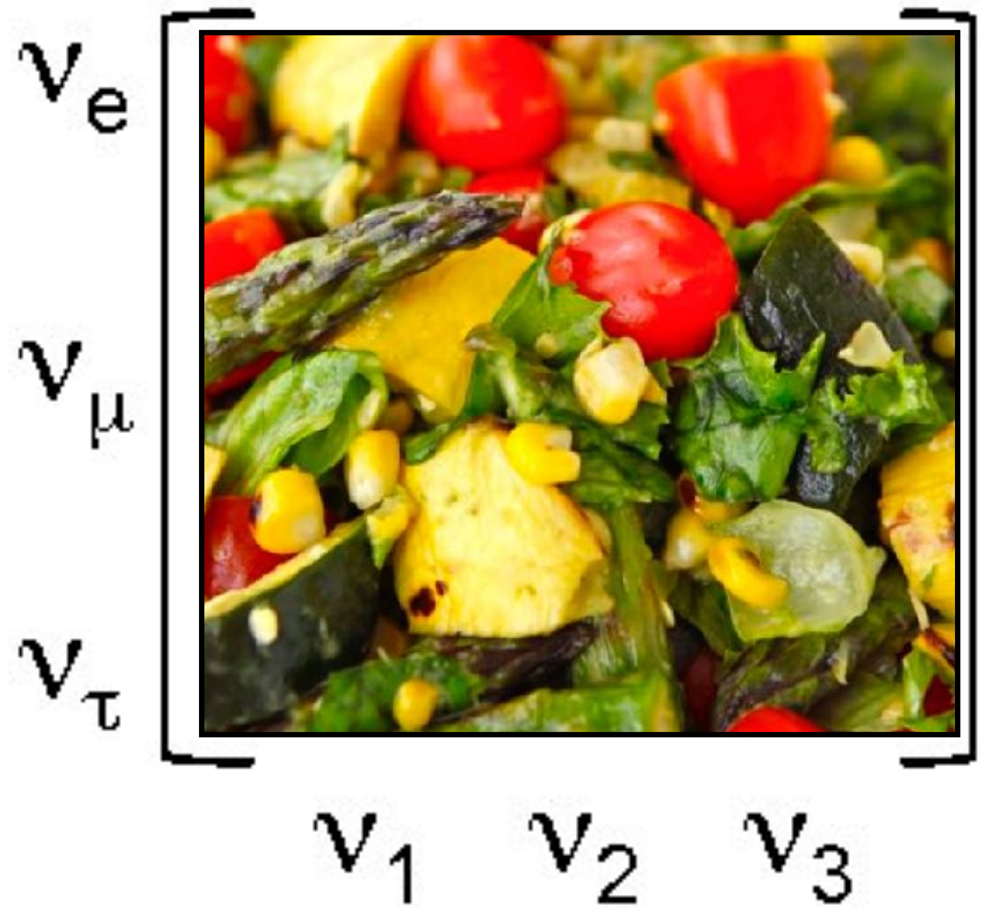
- **large mixing** but a **small one**!
- **largest CP-Violation** (SM)
- **any symmetry behind? [Nature's caprice?]**

U_{3x3} unitary?

[so far assumed]

CKM vs PMNS…





elegance
(symmetry)

stravaganzza
(anarchy?)

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

unitarity is behind all our definitions…

UNITARITY

IF 3 neutrino standard states

[in agreement with quark's **3 families**]

$\Longrightarrow$ **2 mass difference: Δm^2 & δm^2**

$\Longrightarrow$ **3 independent mixing angles: θ_{12},θ_{23},θ_{13}**

$\Longrightarrow$ **1 (Dirac) CP-Violating phase: δ_{CP}**

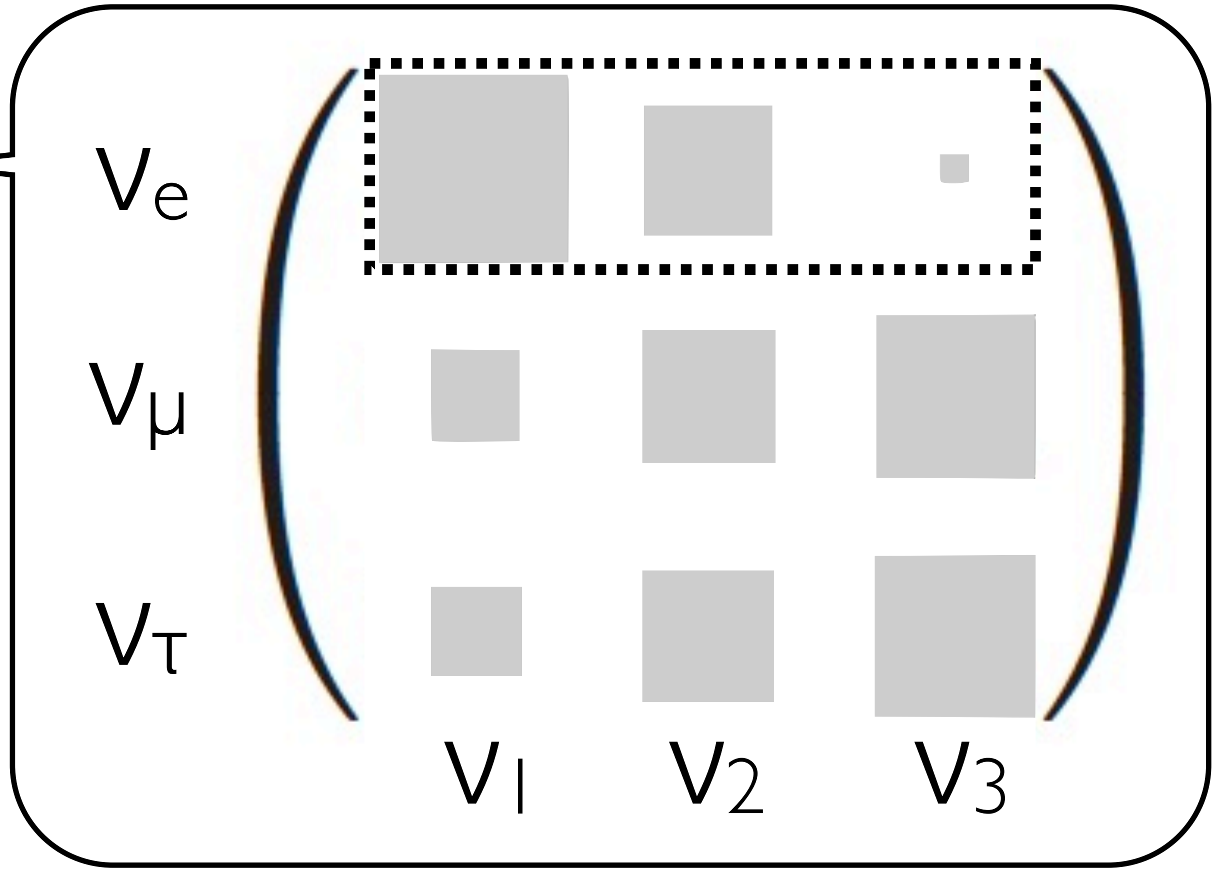
[*i.e. a 3x3 unitarity matrix may be complex*]

if 4 families **3x3 *effective approximation***

UNITARITY testing for new families + more!!

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"

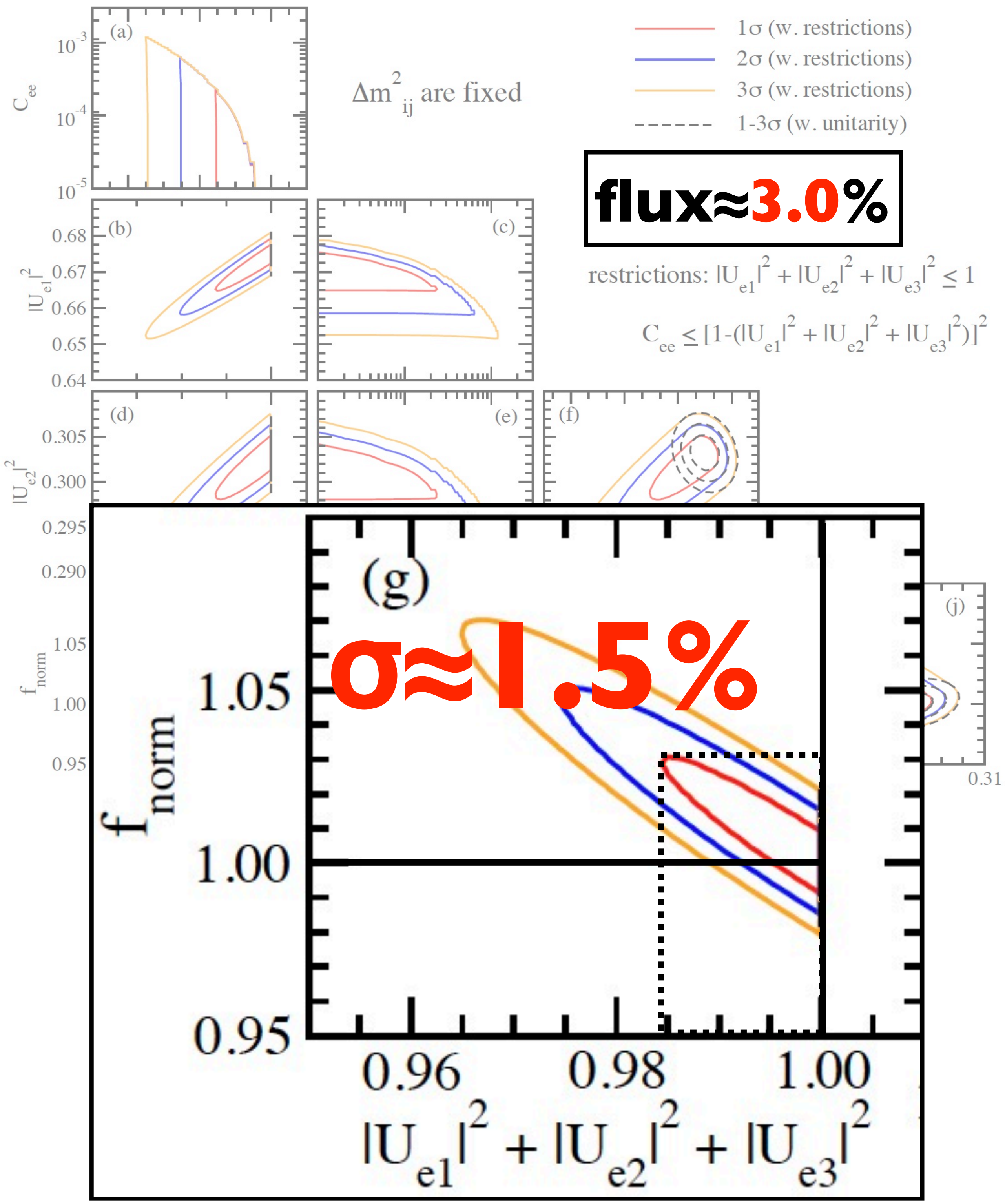
$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$$

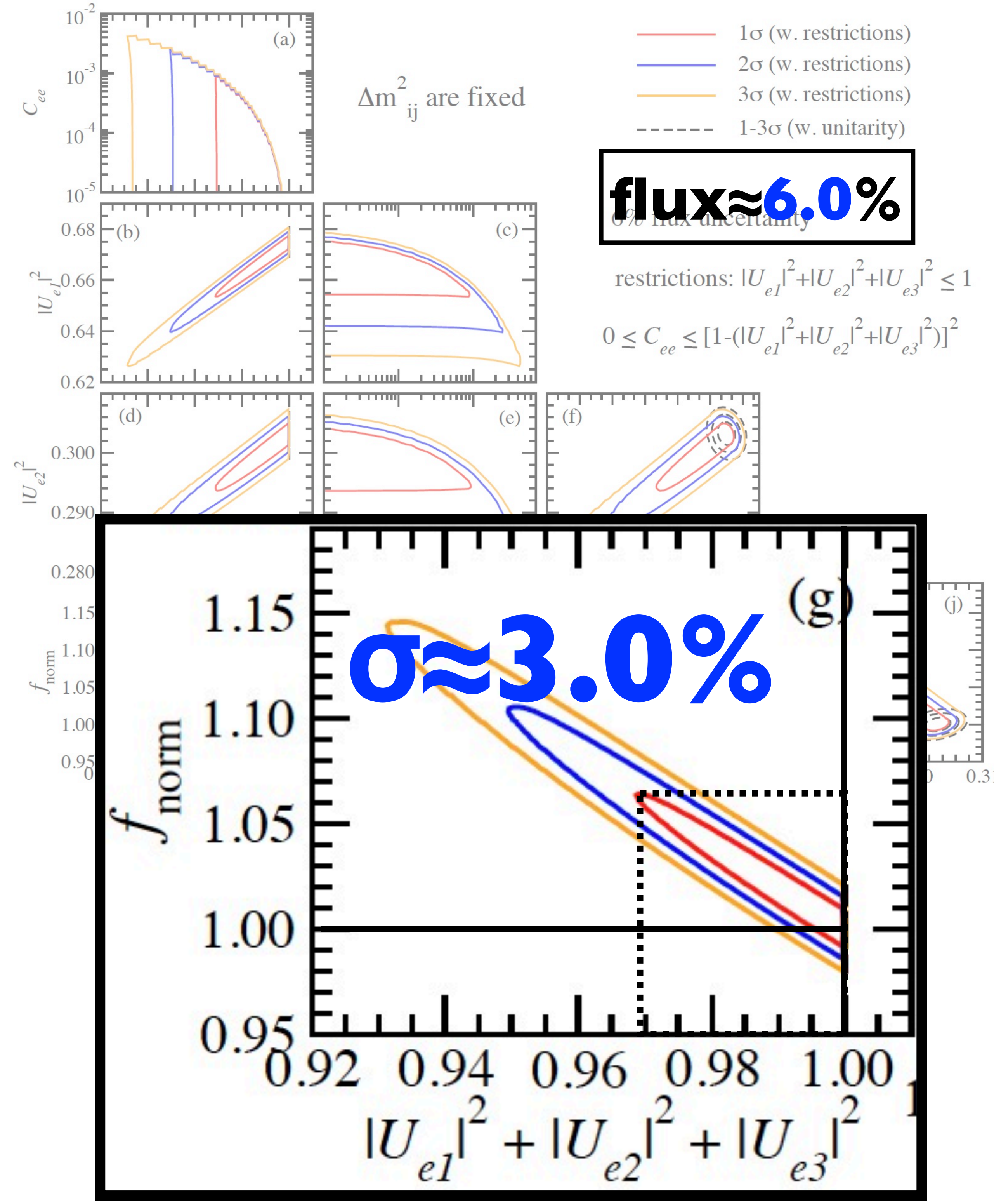
$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$

⇒ **explore "electron top-row"**

only "θ_{12}" and "θ_{13}"

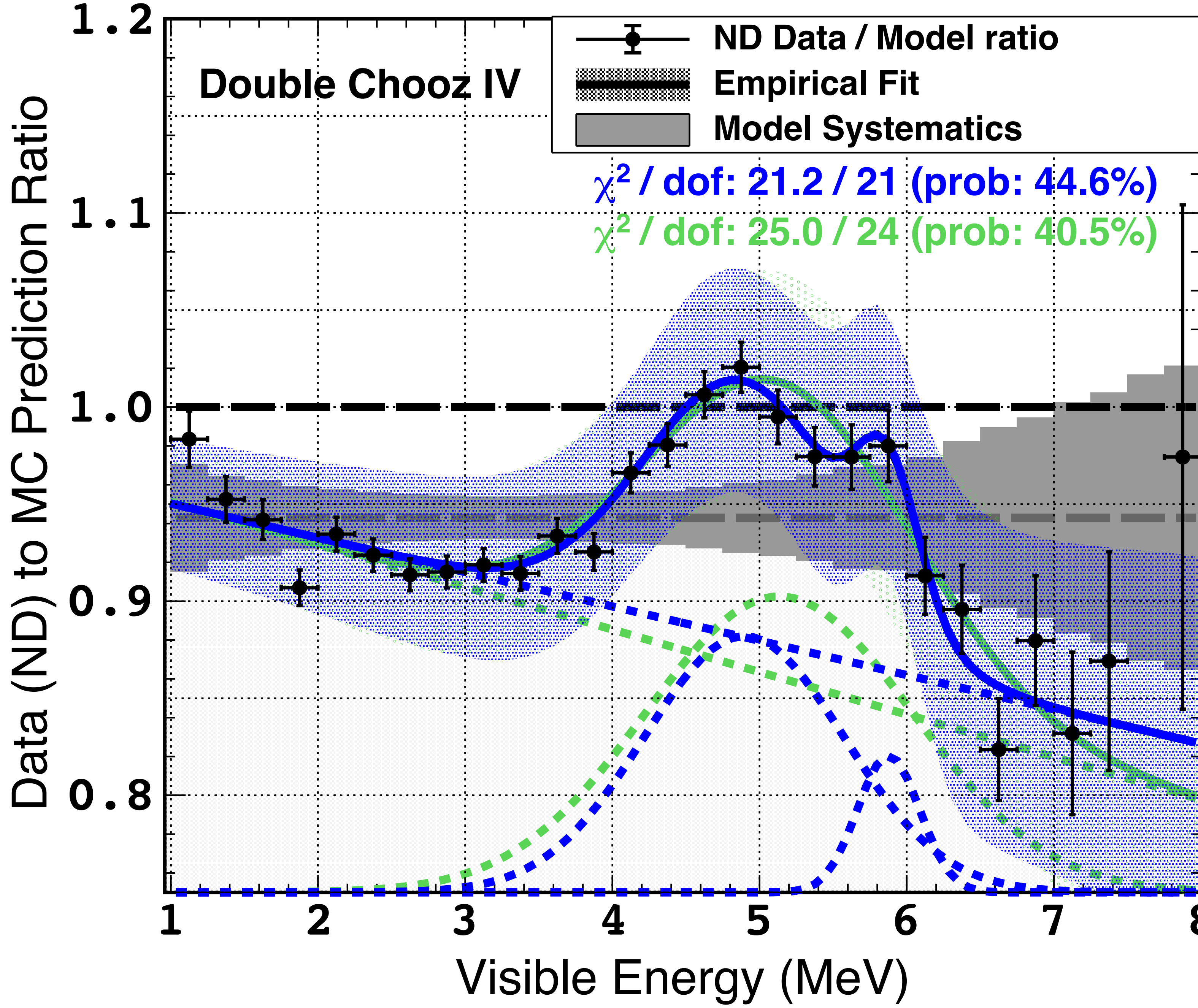
today's (**e-row**) **unitarity** knowledge…





unitary explorations limited by absolute flux uncertainty

reactor flux uncertainty…



Φ(reactor) [exp] best precision (~0.9%)

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

prediction fails to match both rate & shape!

[not just rate]

Shape Uncertainty

~2.2%→6.0%?

[**surely <10%**]

nature physics

ARTICLE

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


neutrino (ν)…
neutrino last modification of the Standard Model… **more discoveries?**


SuperChooZ?

rationale...

- high precision SM's neutrino oscillation

$\Longrightarrow$ synergise with JUNO & HK$\oplus$DUNE

- neutrinos as probe BSM$\longrightarrow$ discoveries?

$\Longrightarrow$ beyond today's paradigm?

status on neutrino oscillation knowledge…

SuperChooz

SuperChooz **BSM discovery?**

	today				**≥2030**	
	best knowledge		global	foreseen	dominant	source
θ_{12}	3,0 %	SK⊕SNO	2,3 %	≤0.5%	JUNO⊕**SC**	reactor⊕solar
θ_{23}	5,0 %	NOvA+T2K	2,0 %	≲1.0%?	DUNE⊕HK [**SC**]	beam (octant)
[illegible]	[illegible]	[illegible]	1,5 %	**≤0.5%**	[illegible]	[illegible]
CP	**violation?**	T2K+NOvA	~3/2π @ ≤2σ	**@5σ?**	DUNE⊕HK [**SC**]	beam driven
CPT	**violation?**	—	—	**<1%?**	**SuperChooz**	reactor⊕solar
Unitarity	**violation?**	—	—	**<1%?**	**SuperChooz**	reactor⊕solar

reactor⊕beam & **solar** again via **SC — SC's atmospherics under study… nice!!**

S U P E R C H O O Z

pathfinder *(i.e. experimental <u>exploration</u>)*

The SuperChooz Pathfinder Exploration

Monday 20 Jun 2022, 11:00 → 12:00 Europe/Paris

https://indico.ijclab.in2p3.fr/event/7663/

100/-1-A900 - Auditorium Joliot Curie (IJCLab)

Videoconference — PHE Seminars — Join

11:00 → 12:00 **The SuperChooz Pathfinder Exploration** ¶ — 1h

A new possible flagship neutrino experiment in Europe opens by exploiting a unique opportunity that has long been hidden in the Chooz nuclear reactor site — Europe's historical and most powerful reactor neutrino science site. The "SuperChooz" project benefits by existence of 2 caverns, formerly hosting the Chooz-A nuclear reactor complex, built in the 60's, that are becoming vacant upon its dismantling completion. The caverns hold a total volume of up to 50 000m^3, thus directly comparable to the size of SuperKamiokande. Its potential use for fundamental science purposes is under active discussion with EDF, thus starting the "pathfinder" exploration era. The SuperChooz caverns combined with the existing ~1km baseline to two of the most powerful N4 Chooz PWR nuclear reactors make this site a unique asset to Europe and specially France. Experimentally, the challenge is the poor overburden (order 100m underground). However, the novel LiquidO technology, born as a byproduct of Double Chooz experiment in the same site, heralds the potential for unprecedented active background rejection of up to two orders of magnitude, thus providing feasibility potential ground for a hypothetical SuperChooz. In this seminar, the rationale of the scientific programme of the hypothetical SuperChooz experiment will be highlighted for the first time. The project is aimed to address some of the most fundamental symmetries (studies under completion) behind the Standard Model, including a design that may open for key synergies that may boost the sensitivities of other neutrino flagship experiments such as DUNE (US), JUNO (China) and HyperKamiokande (Japan).

Speaker: Dr Anatael CABRERA (IJCLab/LNCA - IN2P3/CNRS)

IJCLab⊕Subatech teams — Octobre 2020

CNRS/IN2P3 direction — March 2022

EDF⊕CNRS exploring…

the remaining challenges…

(my view — likely biassed somewhat)

- **improve absolute knowledge precision** (ex. flux cancels by multi-detector)→**discoveries?**
- intrinsic limitations (no appearance, etc)→ **empower synergies with accelerators**, **solar**, etc.

- **$\theta_{12} \oplus \delta m^2$ precision:** is likely hard to improve (**few per mille**) after **JUNO** — world best ≤1year of data
- **$\theta_{13} \oplus \Delta m^2$ precision:** still improve for **θ_{13}** — nobody knows how to!! [→**SuperChooz?**]
  - **θ_{13}** is one of the most intriguing parameter of the PMNS (tiny term among many large terms)
    ⟹ **pointing to a feature(s) or symmetry? certainly this is BSM territory…**
  - understand meaning of **structure of the PMNS** (i.e. large mixing) — very different from CKM

challenge remains on BACKGROUND control

? **JUNO**

goal: **S/BG ≥100 with minimal overburden** **LiquidO?**