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

SUPERCHOOZ

pathfinder

first pre-release

Seminar @ IJCLab / Université Paris-Saclay

June 2022 — Orsay, France

Anatael Cabrera

CNRS-IN2P3 / IJCLab / Université Paris-Saclay

Orsay, France

IJCLab Irène Joliot-Curie

cnrs

université PARIS-SACLAY

FACULTÉ DES SCIENCES D'ORSAY

Université de Paris

European Innovation Council

~50 years of neutrino oscillations…

huge experimental/theory effort

[discovery⊕establishment ⇔ Nobel 2015]

what next?

(an opinion)

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)

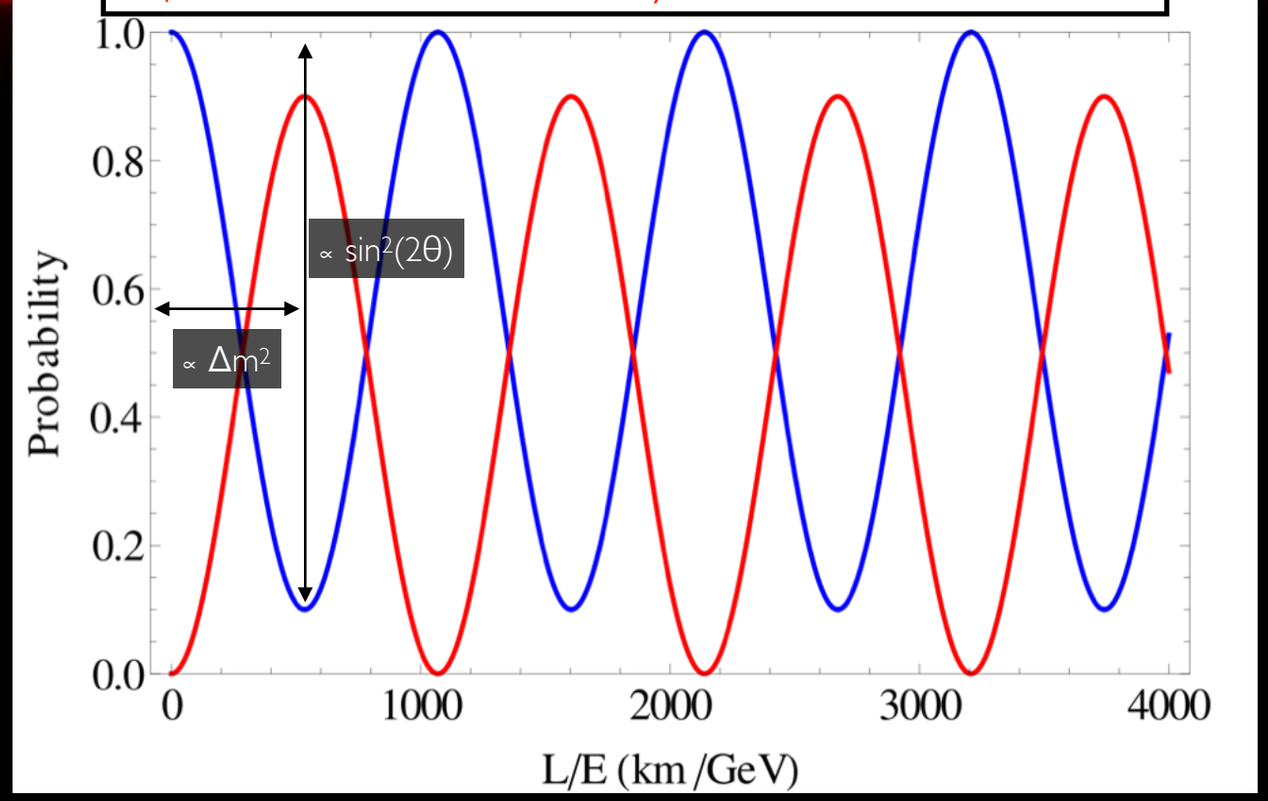
UPMNS matrix (à la CKM)

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

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

the simplest manifestation

$P_{\alpha\alpha}$: Survival Probability — most evidence so far
$P_{\alpha\beta}$: Oscillation Probability — CP-violation



status on neutrino oscillation knowledge…

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

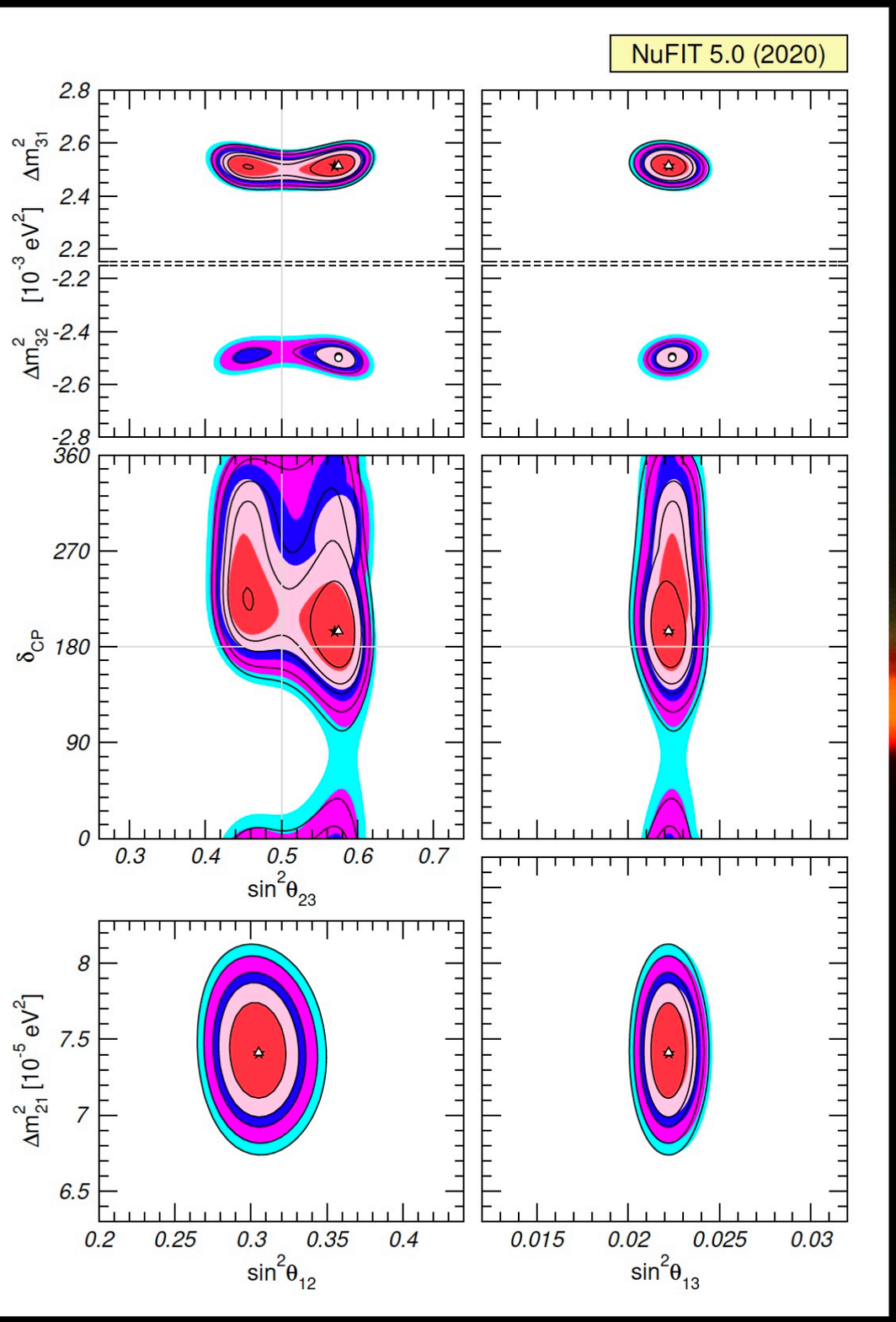
no conclusive sign of any extension so far!!
(inconsistencies vs uncertainties)

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
$+\delta m^2$	2,5 %	KamLAND	2,3 %	≲1.0%	JUNO	reactor
$\lvert\Delta m^2\rvert$	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 & Δm^2 measurements)



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}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$

		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}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

no flagship neutrino in Europe?

is this enough?

European contributions in all experiments — including technology (LAr, etc)

2 accelerator experiments→ **$\delta \oplus MO$ & $\theta_{23} \oplus \theta_{13} \oplus \Delta m^2$ & redundancy**

&

1 reactor experiment→ **MO & $\theta_{12} \oplus \delta m^2$ & $\theta_{13} \oplus \Delta m^2$ & no cross-check!!**

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*]

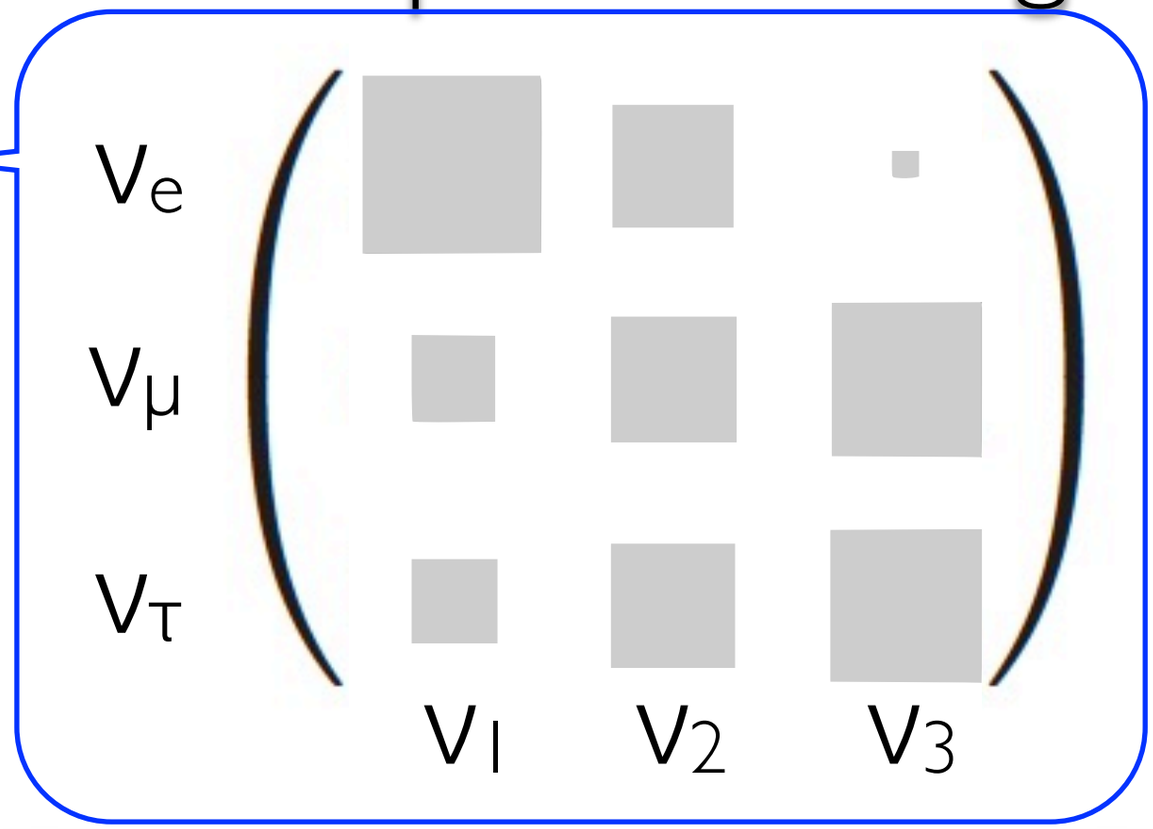
Mass Squared Differences (**2**): **δm^2** (i.e. Δm^2_{12})
Δm^2 (i.e. Δm^2_{13} or Δm^2_{23})

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

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

SM's leptonic mixing sector (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 full matrix structure

(not just composition)

why shape?

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

U_{3x3} unitary?

[assumed!!, not demonstrated]

structure-wise CKM vs PMNS…

stravaganzza
(anarchy?)

elegance
(symmetry)

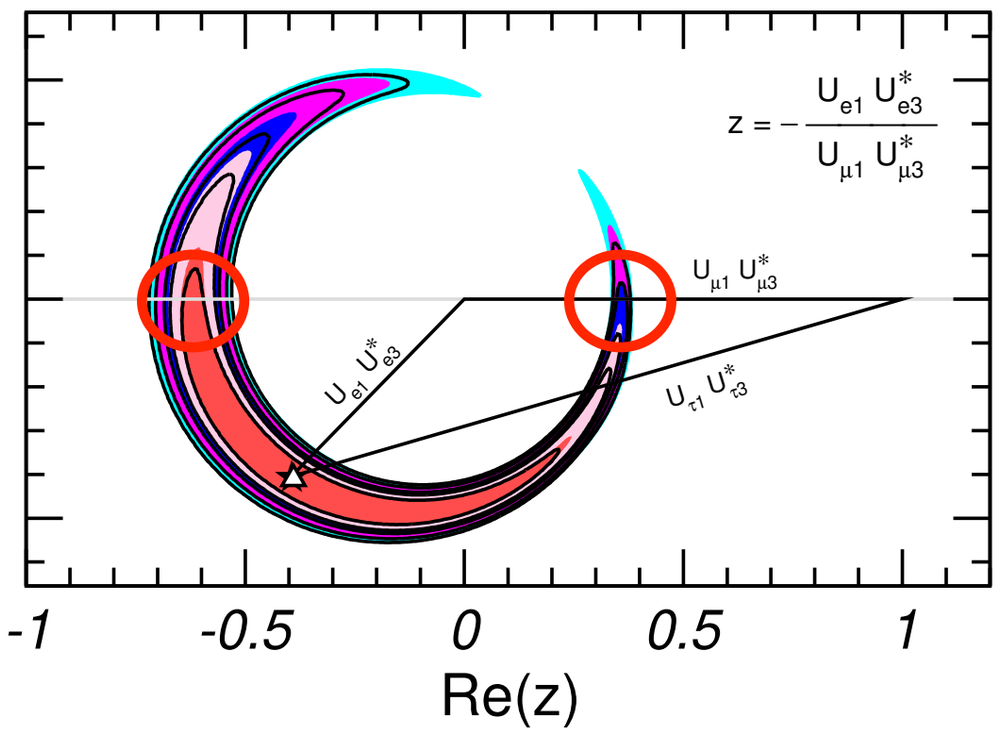
A. De Gouvea, H. Murayama, hep-ph/0301050; PLB, 2015.

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

PMNS

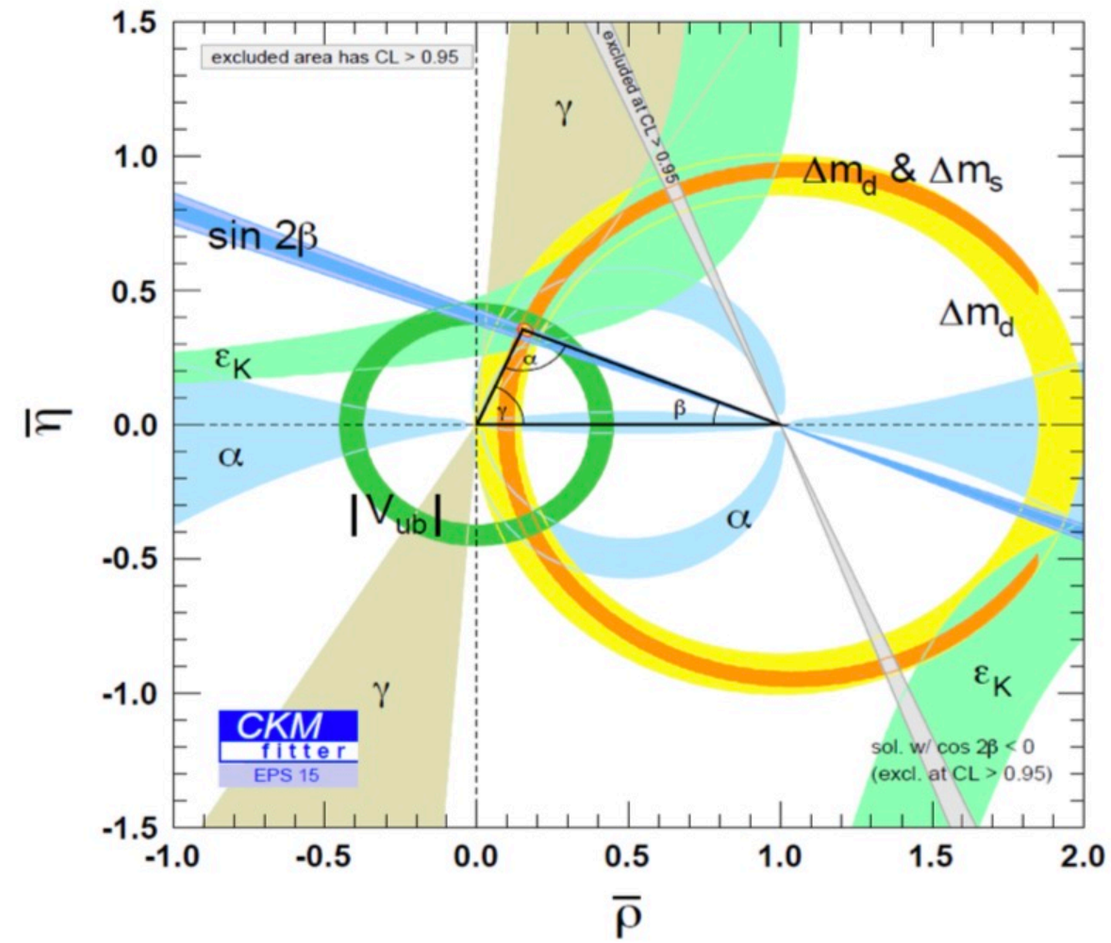
NO

NuFIT 4.0 (2018)



J(PMNS)≈3.33±0.06x10^{-2}

CKM

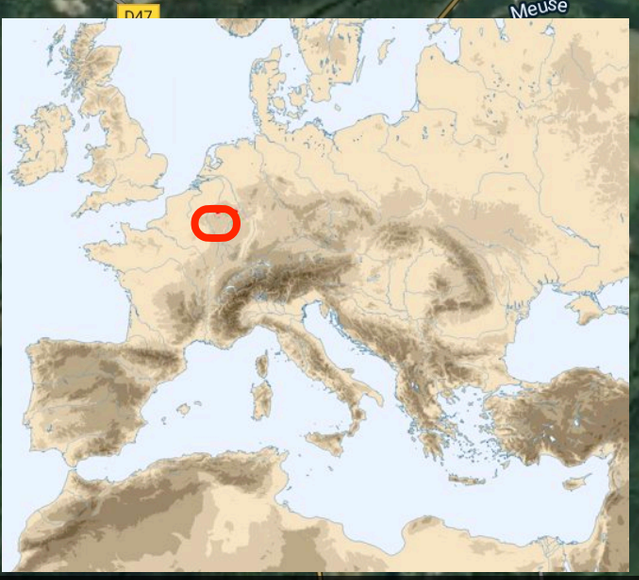


J(CKM)≈3.18±0.15x10^{-5}

PMNS triangle (→ CP violation)…


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

somewhere in the middle of Europe, there is Chooz…



les montagnes des Ardennes (France - Belgique)

maybe Chooz?

Chooz *is tiny cute little village in the Ardennes*

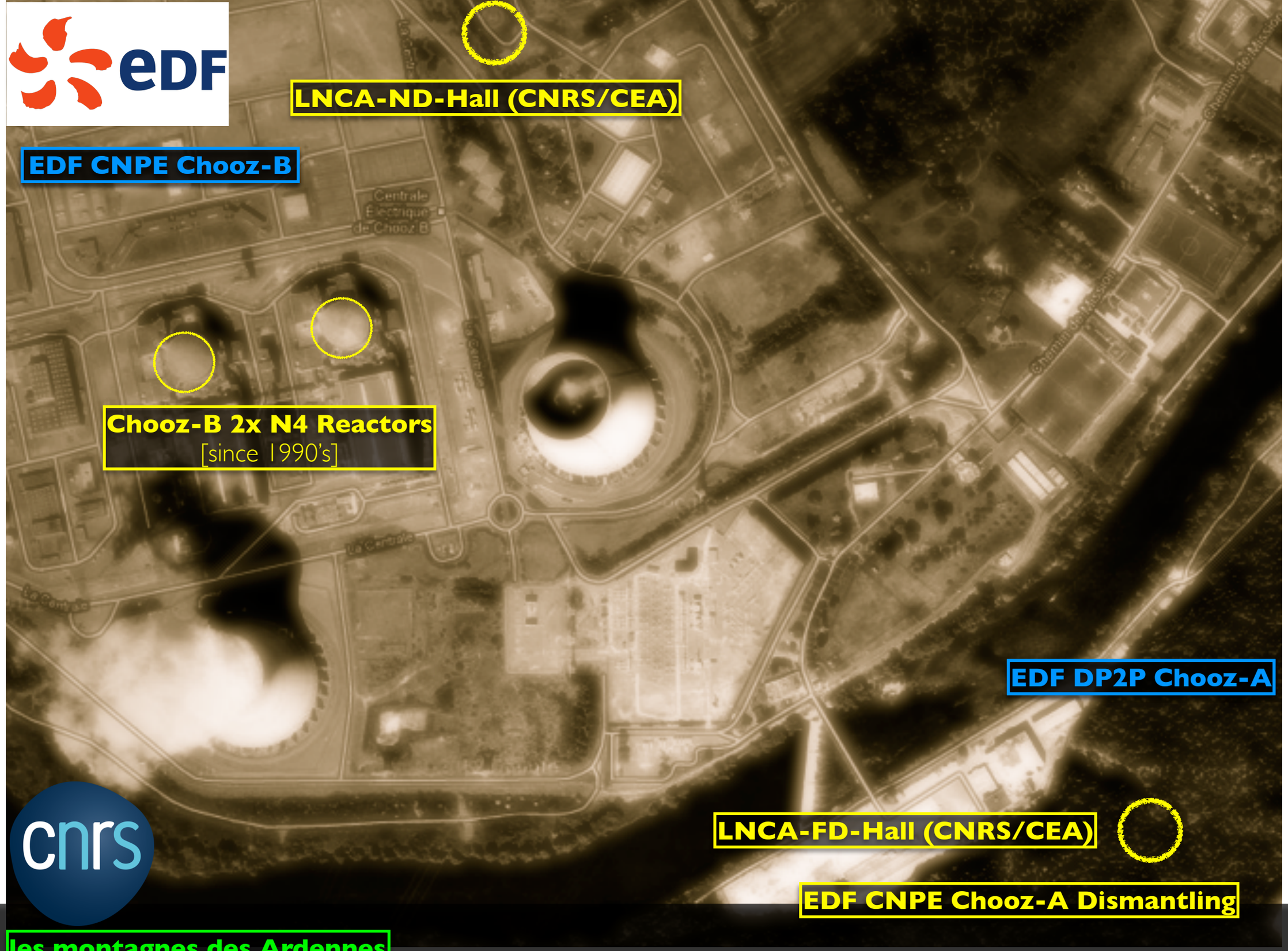
Chooz = super-powerful reactor(s) ⊕ overburden

CNPE Chooz-B… (up to ~2050)

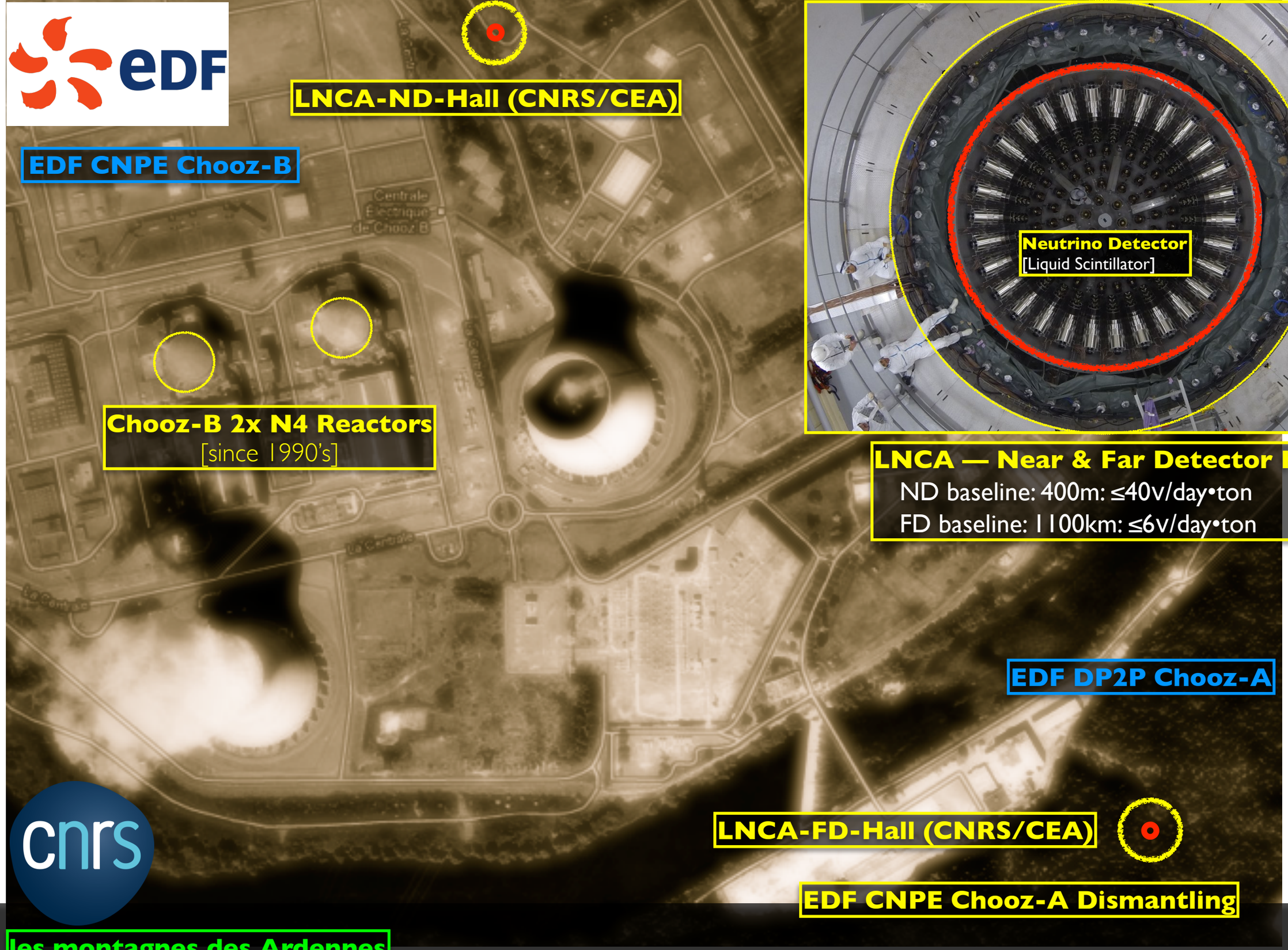
Chooz-B = 2x N4 Reactors: 8.4GW(thermal)→ ~10^{21}ν/s

the reactor (source)…

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

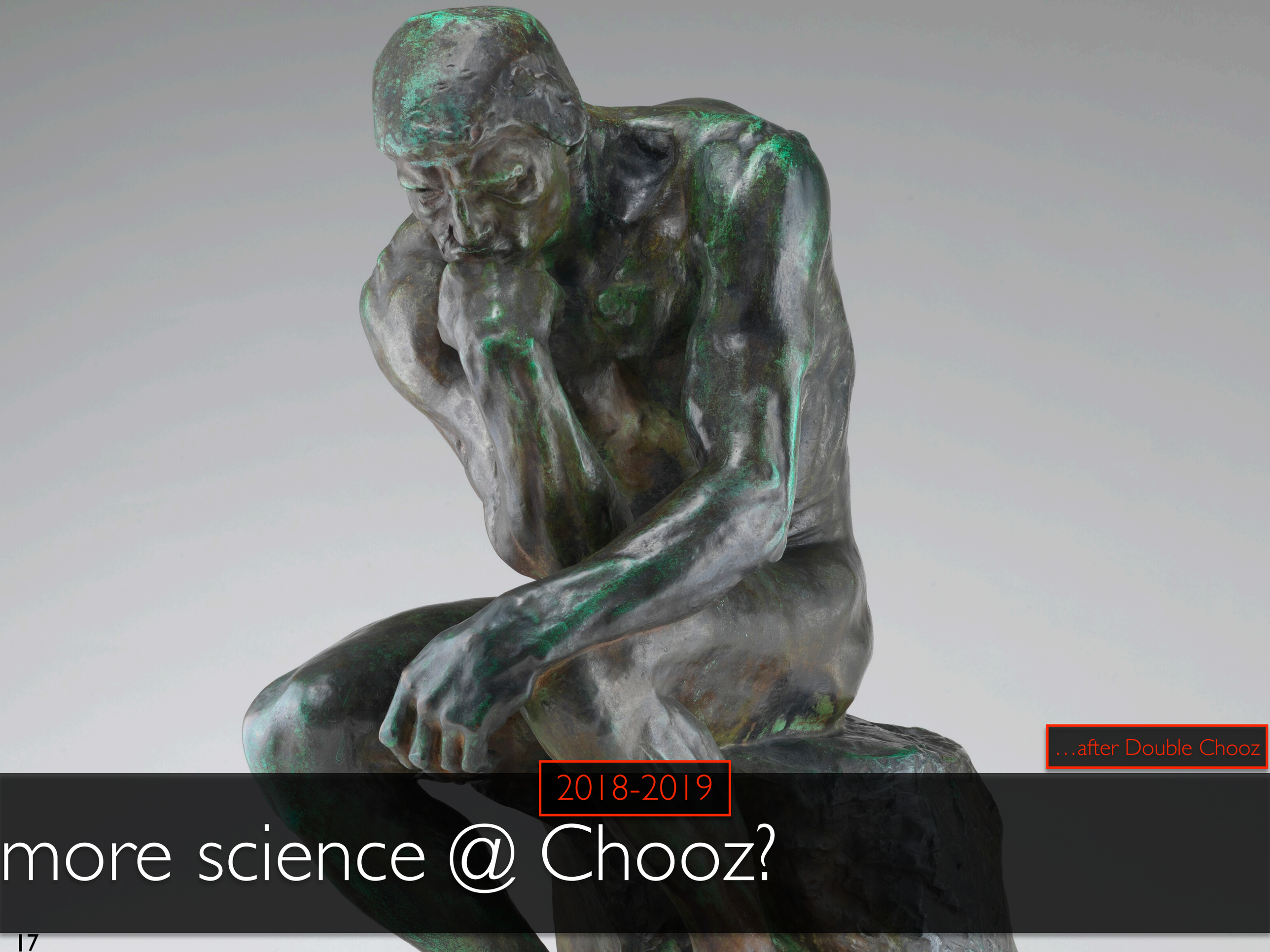


Europe's best reactor neutrino site…



Double Chooz' site (well known)…

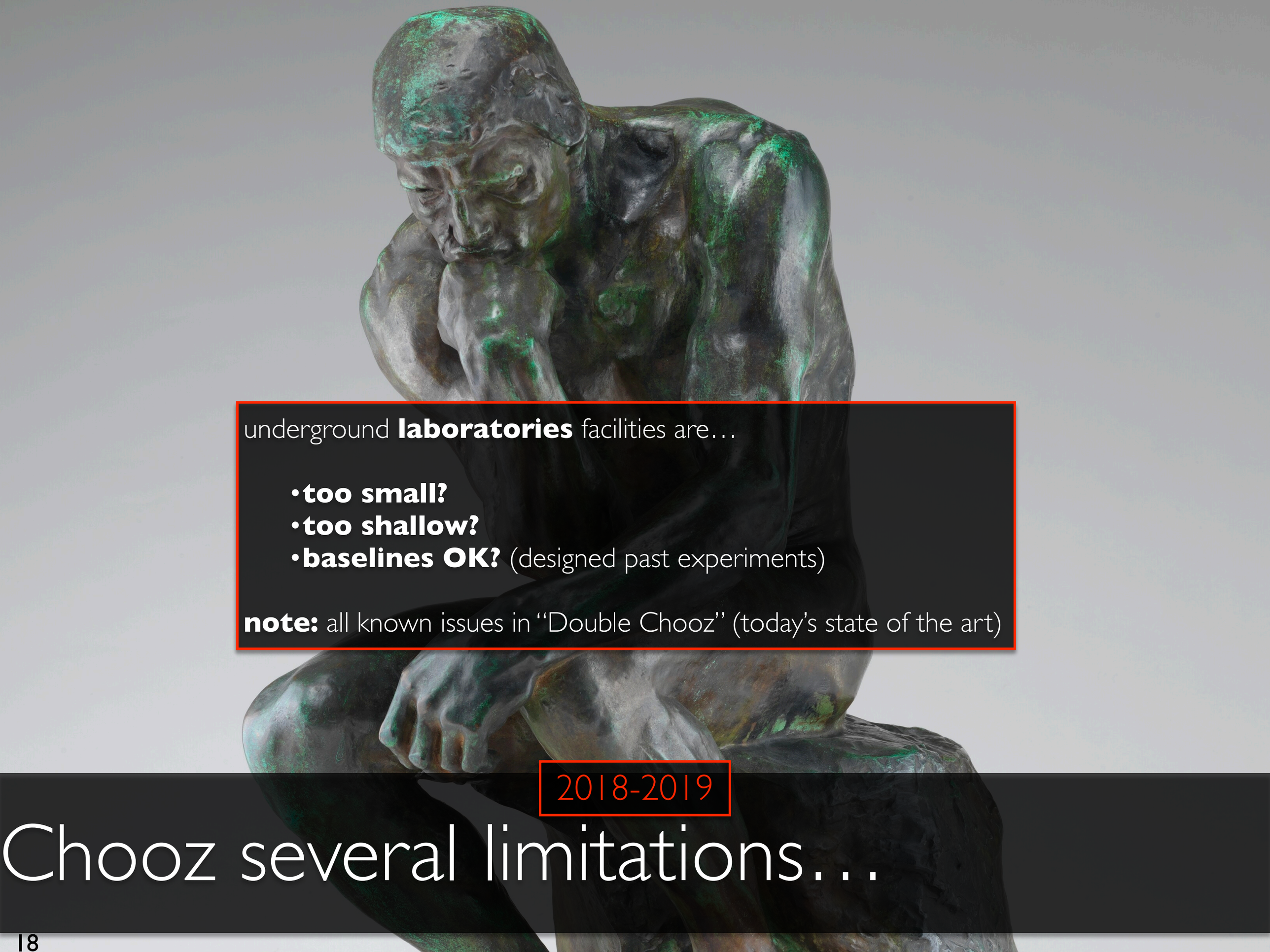
Hervé de Kerret's vision since CHOOZ' experiment



…after Double Chooz

2018-2019

more science @ Chooz?



underground **laboratories** facilities are…

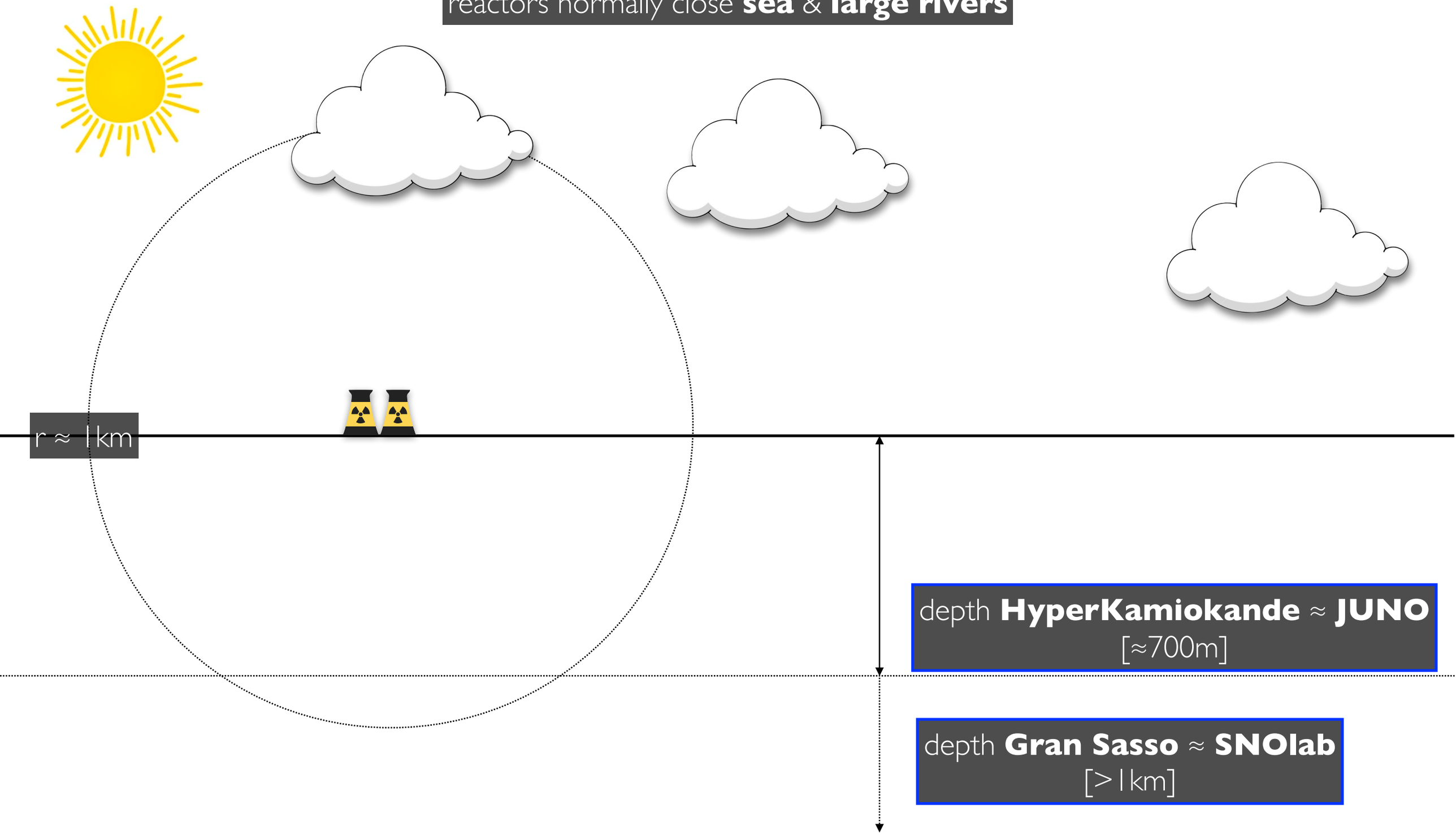
- **too small?**
- **too shallow?**
- **baselines OK?** (designed past experiments)

note: all known issues in "Double Chooz" (today's state of the art)

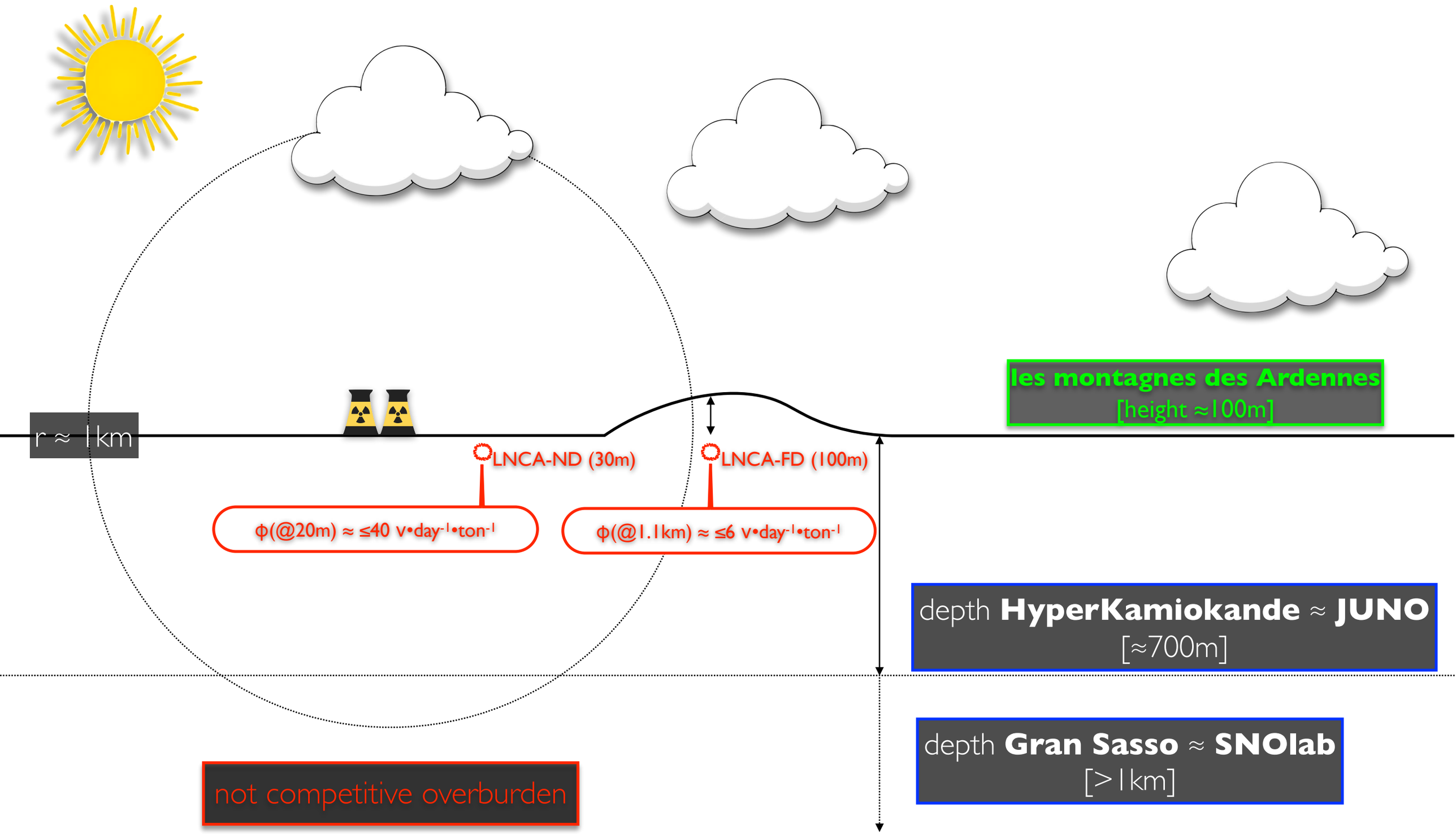
2018-2019

Chooz several limitations…

reactors normally close **sea** & **large rivers**



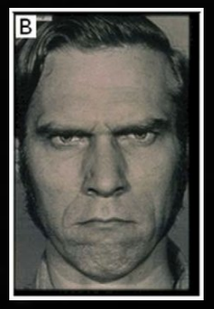
reactor underground challenge…



reactor underground challenge…


civil-construction near a reactor?
lesson: don’t…!

physics at Chooz: finished?



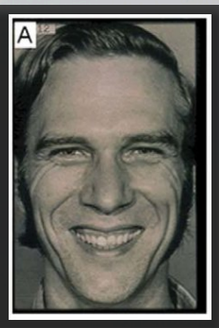
new underground laboratories exploration…

- too small & bad baseline? → **new laboratories!**
- too shallow? → **new technology!**
- new structure at Chooz:

LNCA (DC: CNRS/CEA) → LNCA (CNRS)
[*A.Cabrera*; 2014-2021] [*J-F Le Du*; ≥2022]

2018-2019

science @ Chooz: **yes!**




new era of cooperation between…
eDF
cnrs
how?

an underground secret…

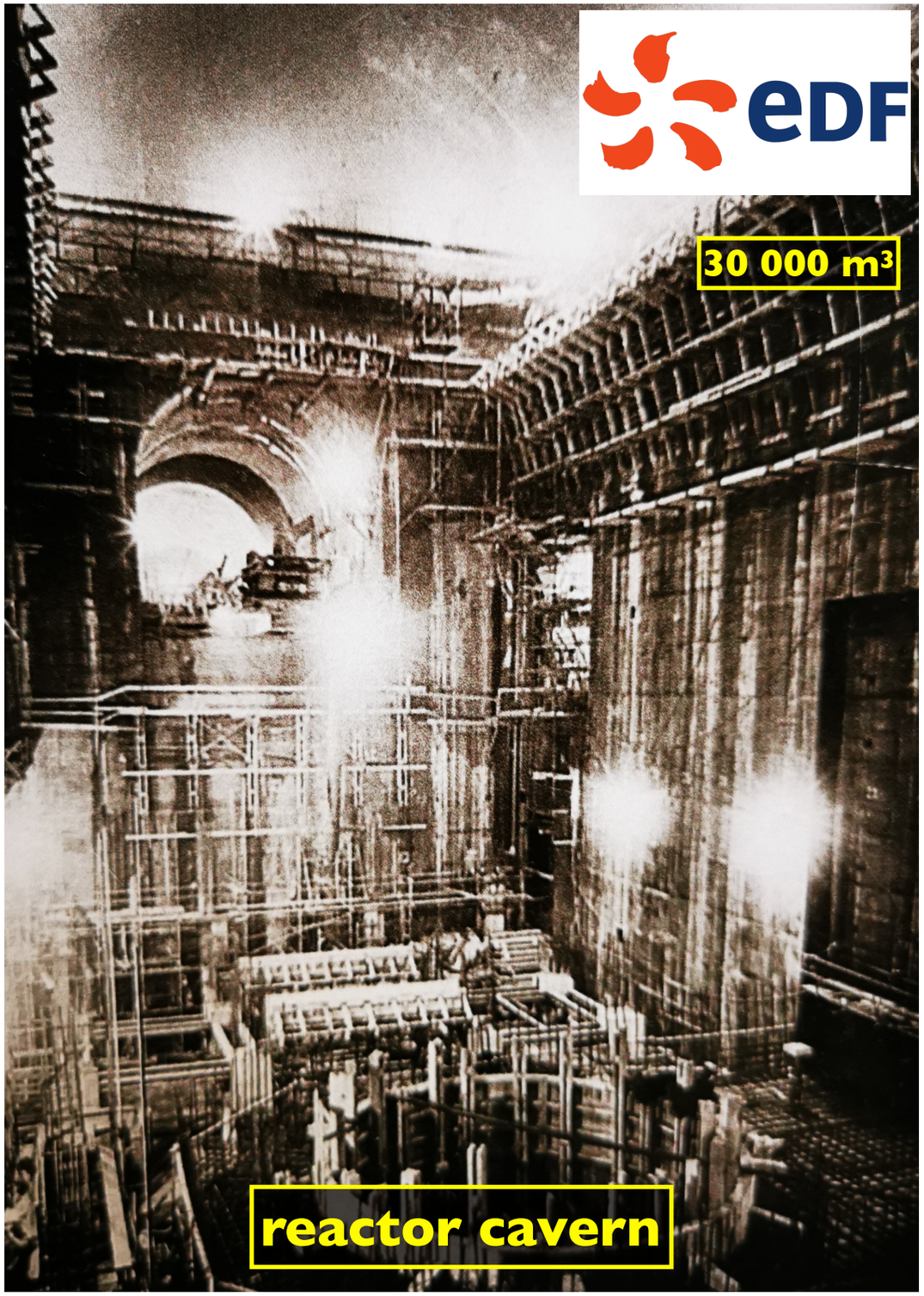
Chooz-A former nuclear reactor

Super-Kamiokande (50kton)

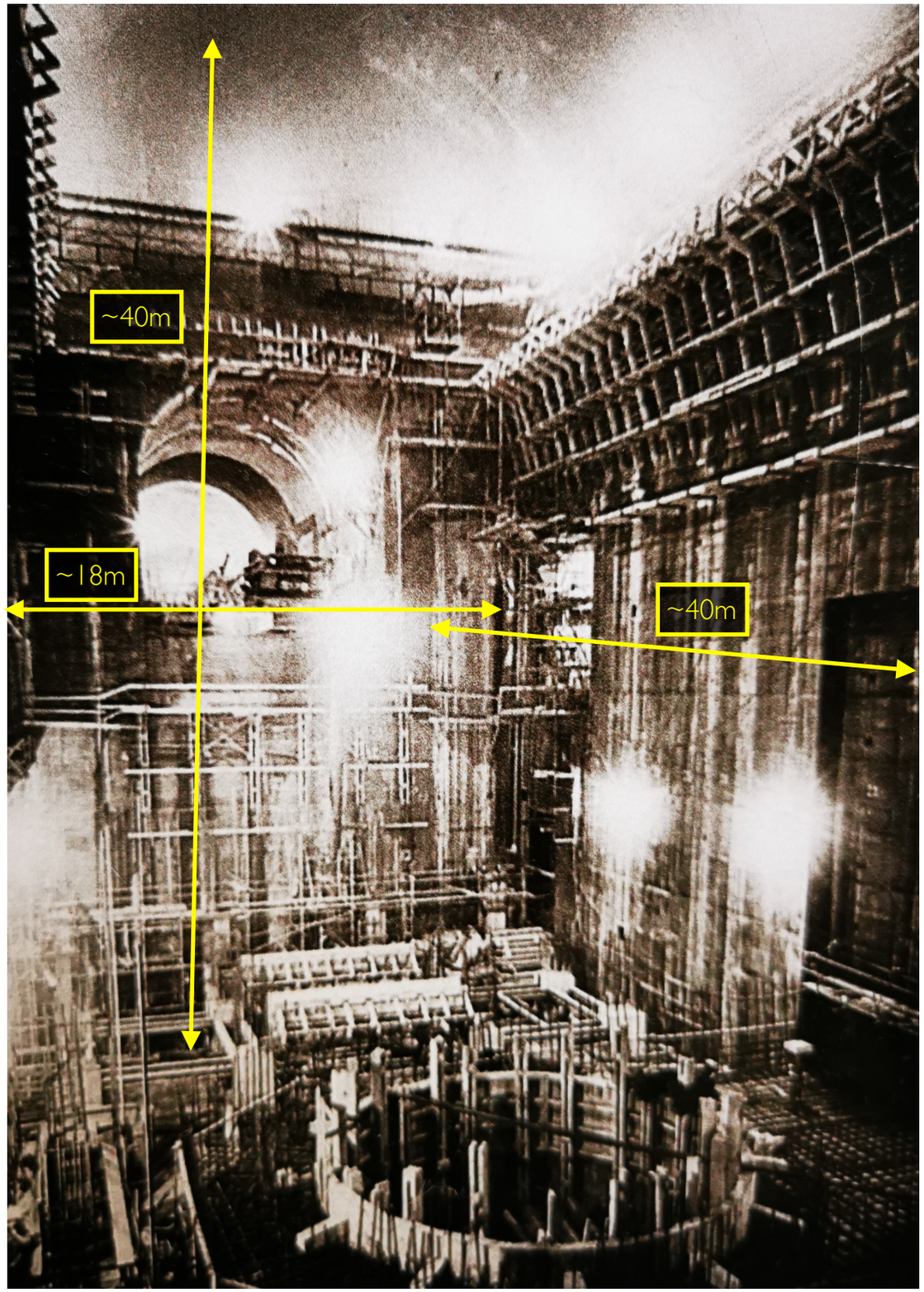
Super-KamiokaNDE @ Japan
(Nobel prize 2015)

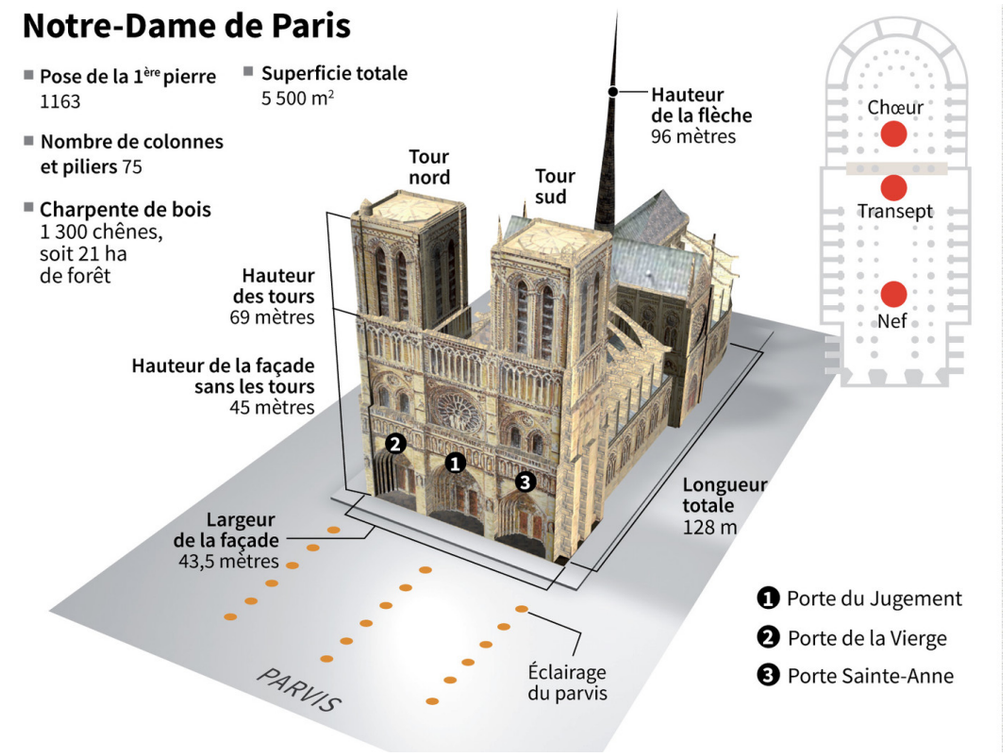
recycling Chooz-A for science?

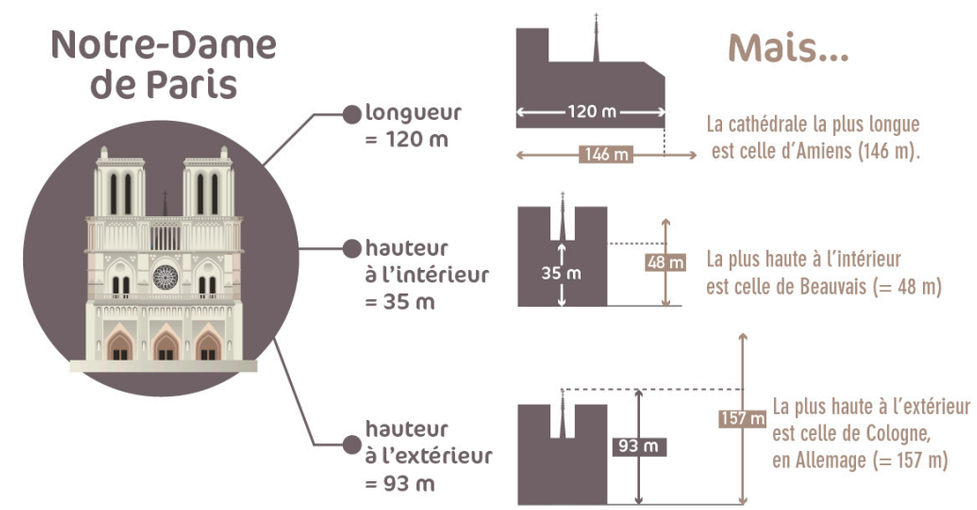
two huge caverns already built of the size of **Super-Kamiokande** just next to **Chooz reactors**!
(unique site in France / Europe / World?)



construction caverns [1962-1967]







Notre Dame de Chooz?

SuperChooz cavern since the 60's…

historical opportunity!! one of the largest underground laboratories in Europe — free?

Super Choo

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

SUPERCHOOZ

pathfinder

IJCLab⊕Subatech teams — Octobre 2020

CNRS/IN2P3 direction — March 2022

EDF⊕CNRS exploring…

SUPERCHOOZ

pathfinder

3 main challenges…

- **new laboratories**
- ***new detector technology***
- ***new physics program***

⟹ **must demonstrate ALL are feasible at once by ≤2028**

IJCLab leading the way…

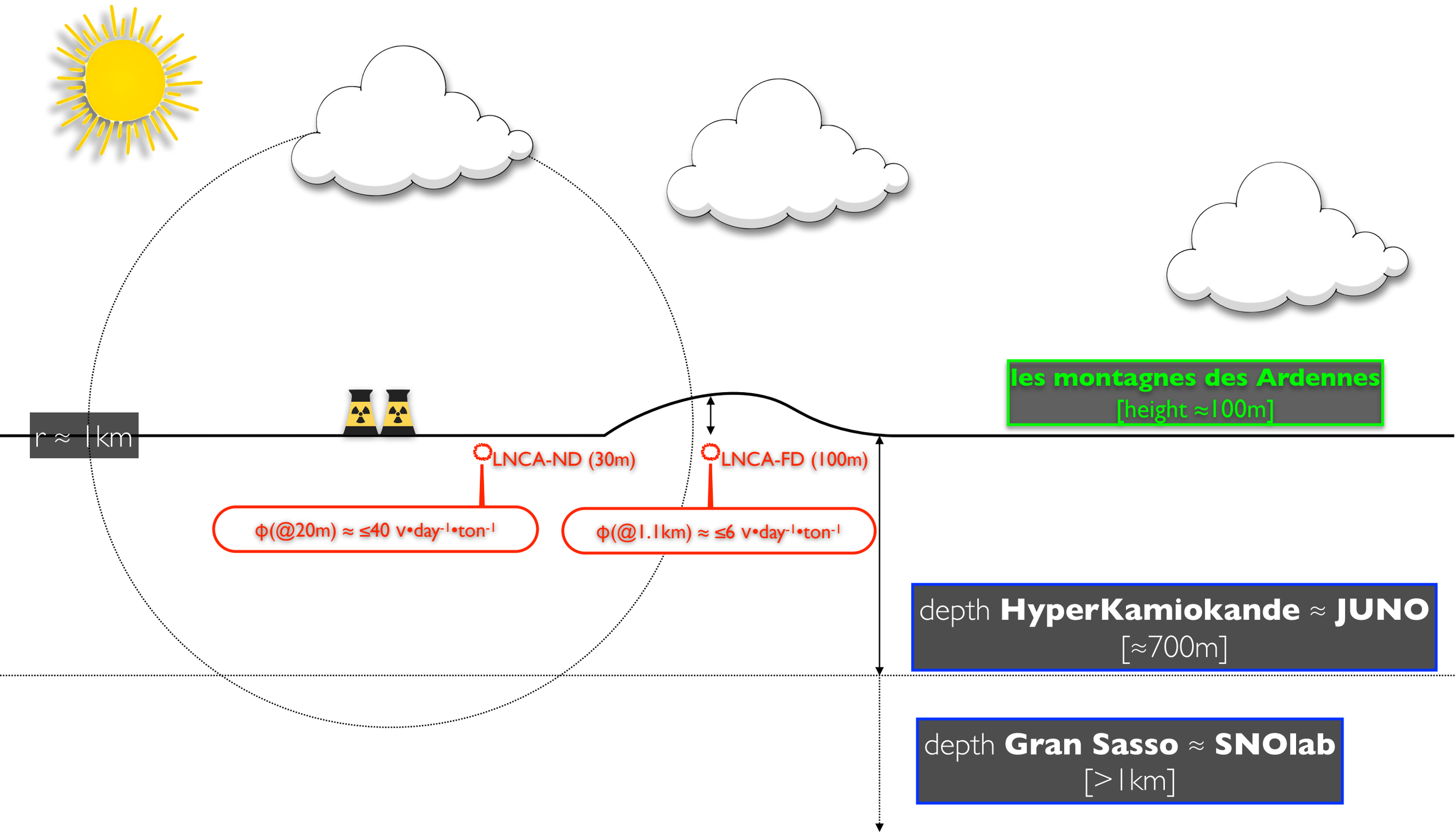
Super Choo Z ?

if exploration was successful → experiment >2030…?

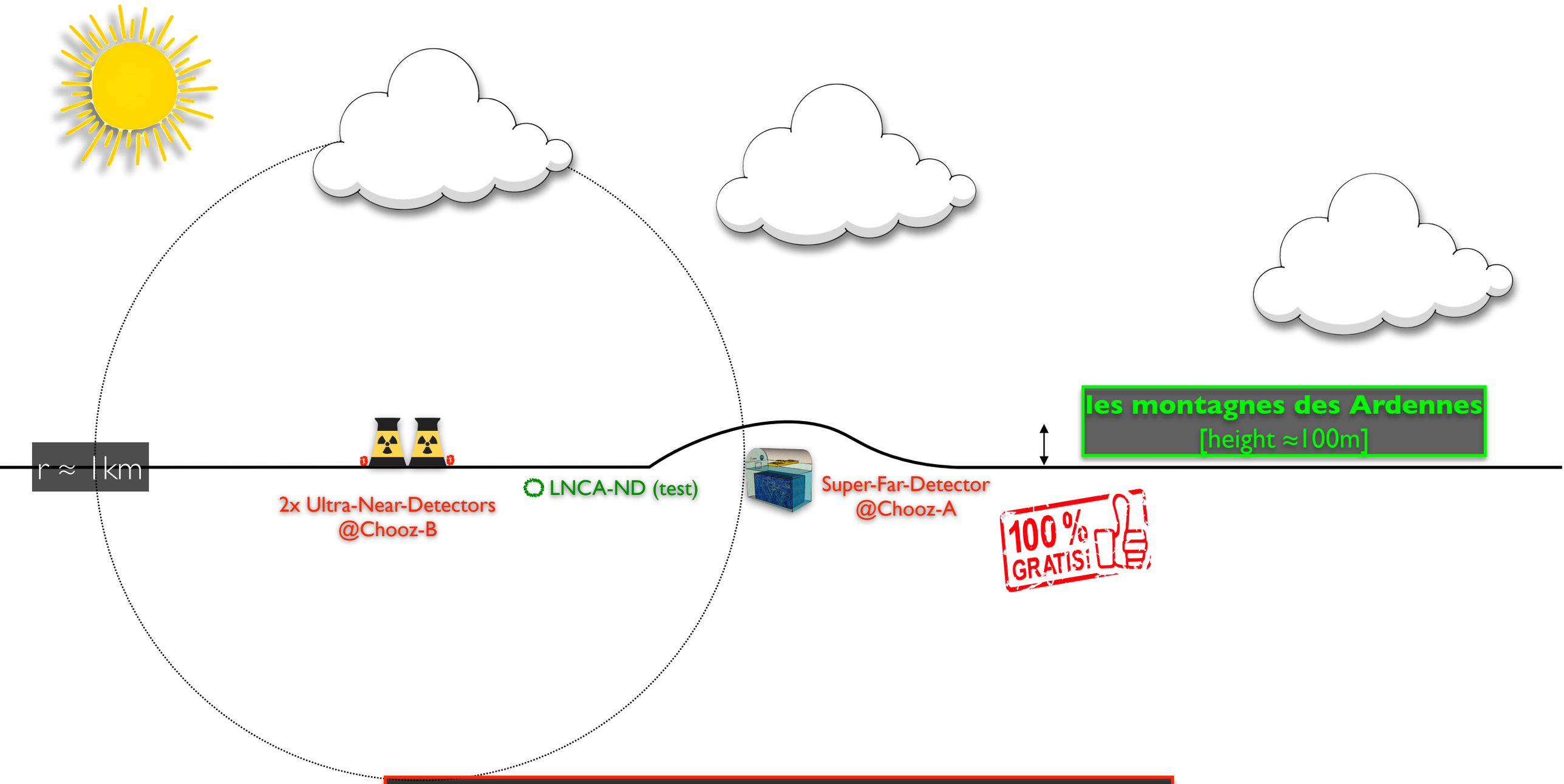
SUPERCHOOZ

pathfinder

experimental configuration



Double Chooz config…



extremely low overburden→ **new technology needed**
(impossible with today's technology)

SuperChooz config…

Europe's best reactor ν site…

SUPERCHOOZ

pathfinder

challenge I: **new detector technology**
(goal: major background reduction)

today's version of similar technology…

extremely low overburden → **new technology needed**
(several experimental requirements impossible with today's technology)

CTF @ Gran Sasso
(Borexino R&D)

by the **LiquidO** consortium…

L I Q U I D

the needed new technology…

LiquidO Consortium*

J. dos Anjos[a], L. Asquith[r], J.L. Beney[q], T.J.C. Bezerra[r], M. Bongrand[q], C. Bourgeois[fα], D. Brasse[g], D. Breton[fα], M. Briere[fα], J. Busto[b], A. Cabrera[†fα], A. Cadiou[q], E. Calvo[c], H. Carduner[q], V. Chaumat[fα], E. Chauveau[h], M. Chen[n], P. Chimenti[e], F. Dal Corso[kα], A. Dahmane[g], J.-F. Le Du[fα], S. Dusini[kα], A. Earle[r], C. Frigerio-Martins[e], J. Galán[s], J.A. García[s], R. Gazzini[fα], A. Gibson-Foster[r], D. Giovagnoli[g], P. Govoni[jα,jβ], M. Grassi[kβ], W.C. Griffith[r], F. Haddad[q], J. Hartnell[r], A. Hourlier[g], G. Hull[fα], I.G. Irastorza[s], L. Koch[iα], P. Laniéce[fα,fβ], C. Lefebvre[n], F. Lefevre[q], P. Loaiza[fα,fβ], G. Luzón[s], J. Maalmi[fα], F. Mantovani[dα,dβ], C. Marquet[h], M. Martínez[s], L. Ménard[fα,fβ], D. Navas-Nicolás[fα], H. Nunokawa[m], M. Obolensky[fα,fβ], J.P. Ochoa-Ricoux[o], C. Palomares[c], P. Pillot[q], J.C.C. Porter[r], M. S. Pravikoff[h], M. Roche[h], B. Roskovec[l], M.L. Sarsa[s], S. Schoppmann[iβ], A. Serafini[kα,kβ], W. Shorrock[r], L. Simard[fα], M. Sisti[jα], D. Stocco[q], V. Strati[dα,dβ], J.-S. Stutzmann[q], F. Suekane[‡p], M.-A. Verdier[fα,fβ], A. Verdugo[c], B. Viaud[q], A. Weber[iα], and F. Yermia[q]

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L I Q U I D O

invention/conception 2012-2013 — since 2016 consortium (~20 institutes & 10 countries)

our first publication…

nature communications physics

Article | Open Access | Published: 21 December 2021

Neutrino physics with an opaque detector

LiquidO Consortium

Communications Physics **4**, Article number: 273 (2021) | Cite this article

Abstract

In 1956 Reines & Cowan discovered the neutrino using a liquid scintillator detector. The neutrinos interacted with the scintillator, producing light that propagated across transparent volumes to surrounding photo-sensors. This approach has remained one of the most widespread and successful neutrino detection technologies used since. This article introduces a concept 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 optical fibres. This technique, called LiquidO, can provide high-resolution imaging to enable efficient identification of individual particles event-by-event. A natural affinity for adding dopants at high concentrations is provided by the use of an opaque medium. With these and other capabilities, the potential of our detector concept to unlock opportunities in neutrino physics is presented here, alongside the results of the first experimental validation.

proof-of-concept: *simulation* & data [**μ-LiquidO**]

physics potential — appetiser

www.nature.com/articles/s42005-021-00763-5

latest results: a few weeks ago

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

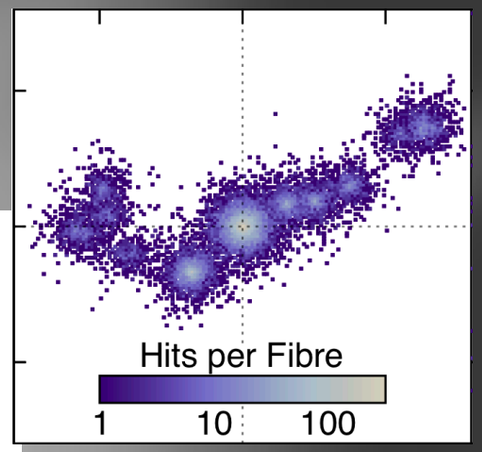
major release with the **latest experimental results** @ **Neutrino 2022** conference (June 2022)

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

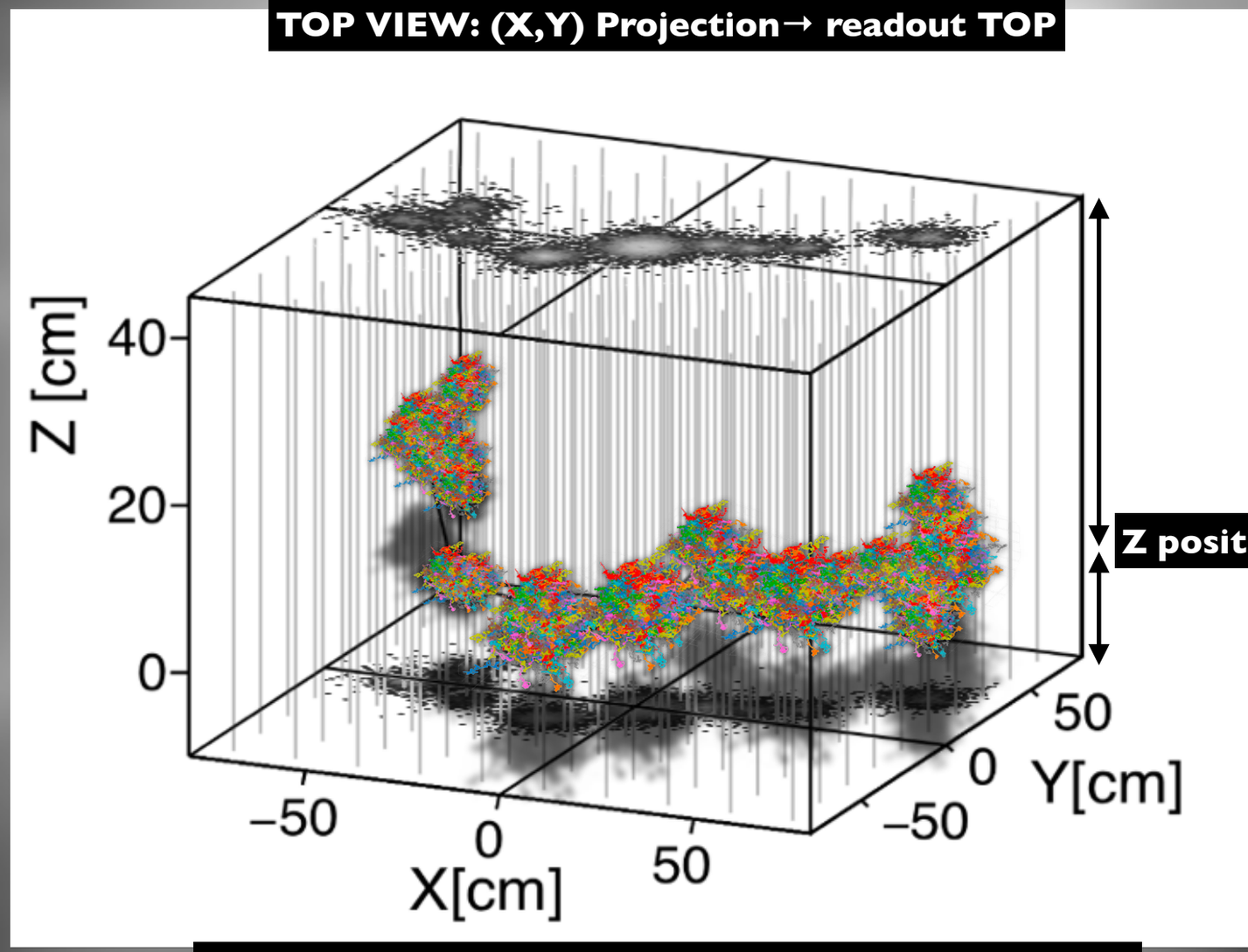
stochastic light confinement

Topology (X,Y) direct & native (PID)→ possible **sub-mm vertex precision**

Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

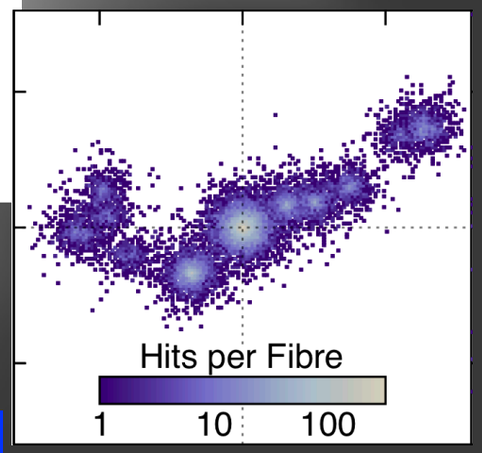


TOP VIEW: (X,Y) Projection→ readout TOP



Z position using: Δt (time difference)

BTTOM VIEW: (X,Y) Projection→ readout BOTTOM



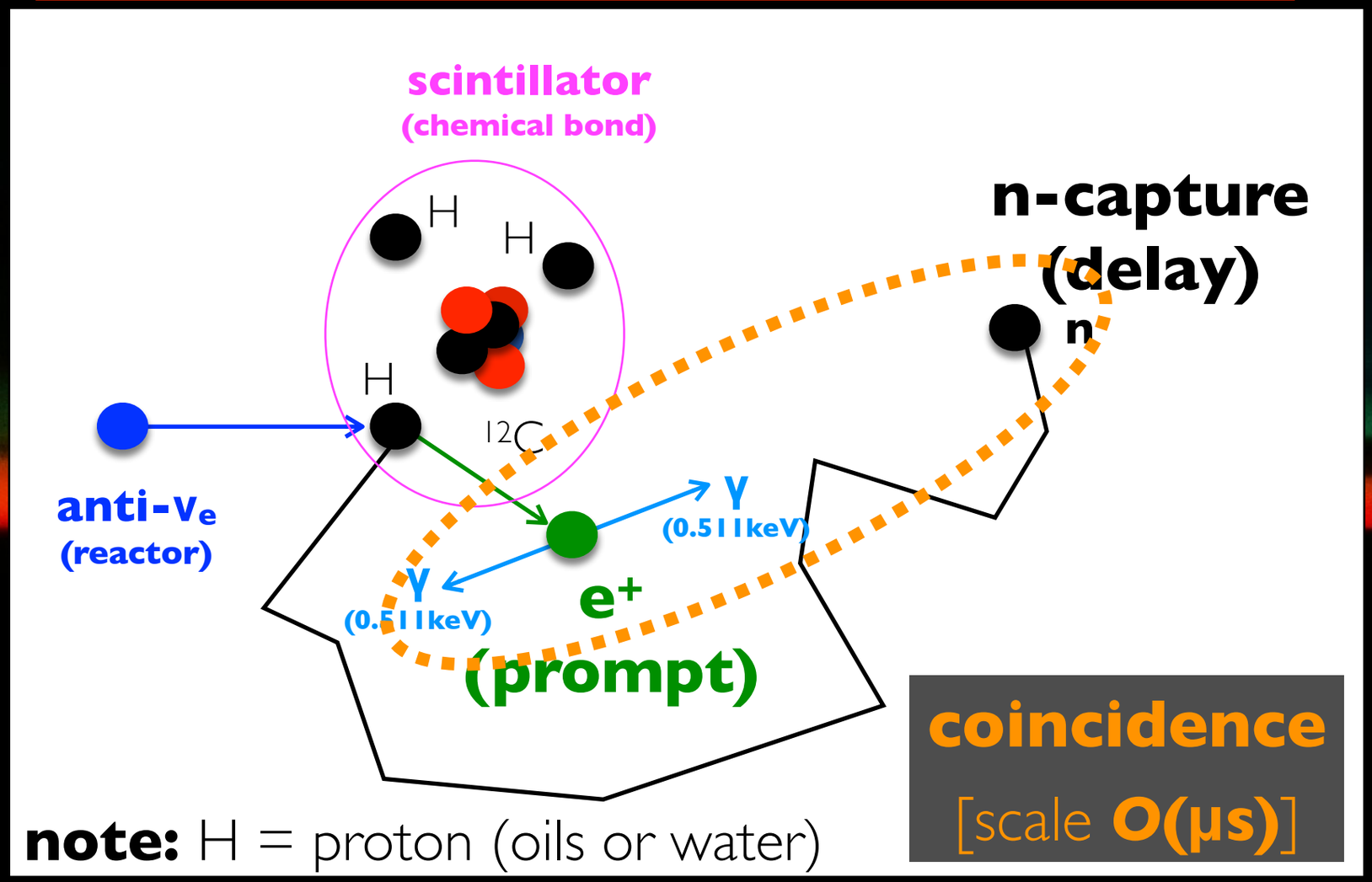
LiquidO can have up 3 orthogonal fibre lattice orientations (3D)

ν discovery pioneers (1950's)…

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n

cross-section known to ~0.2% [↔lifetime of neutron]

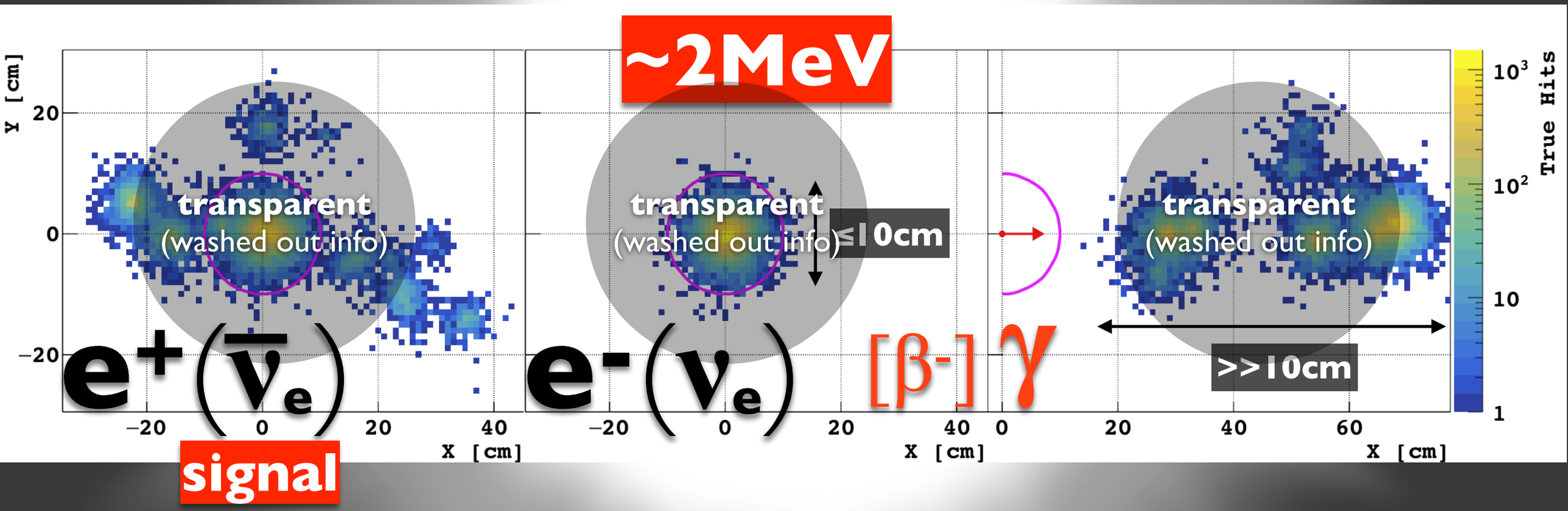


generally, **no e+ PID**

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

unprecedented PID@MeV…

potential: reduce overburden/shielding

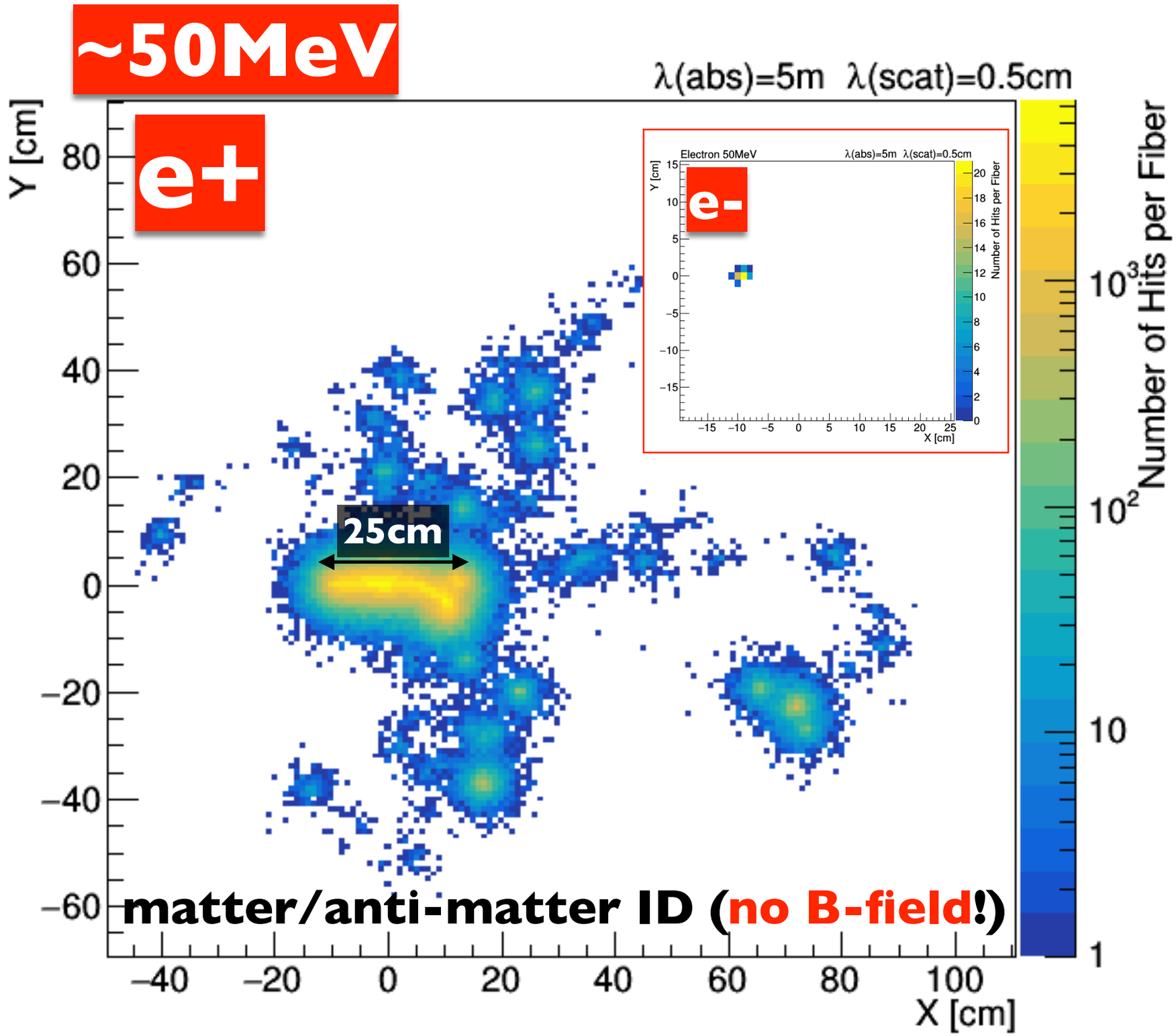


opacity→ (native) self-segmentation

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

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

multi-MeV improves (more light too)…

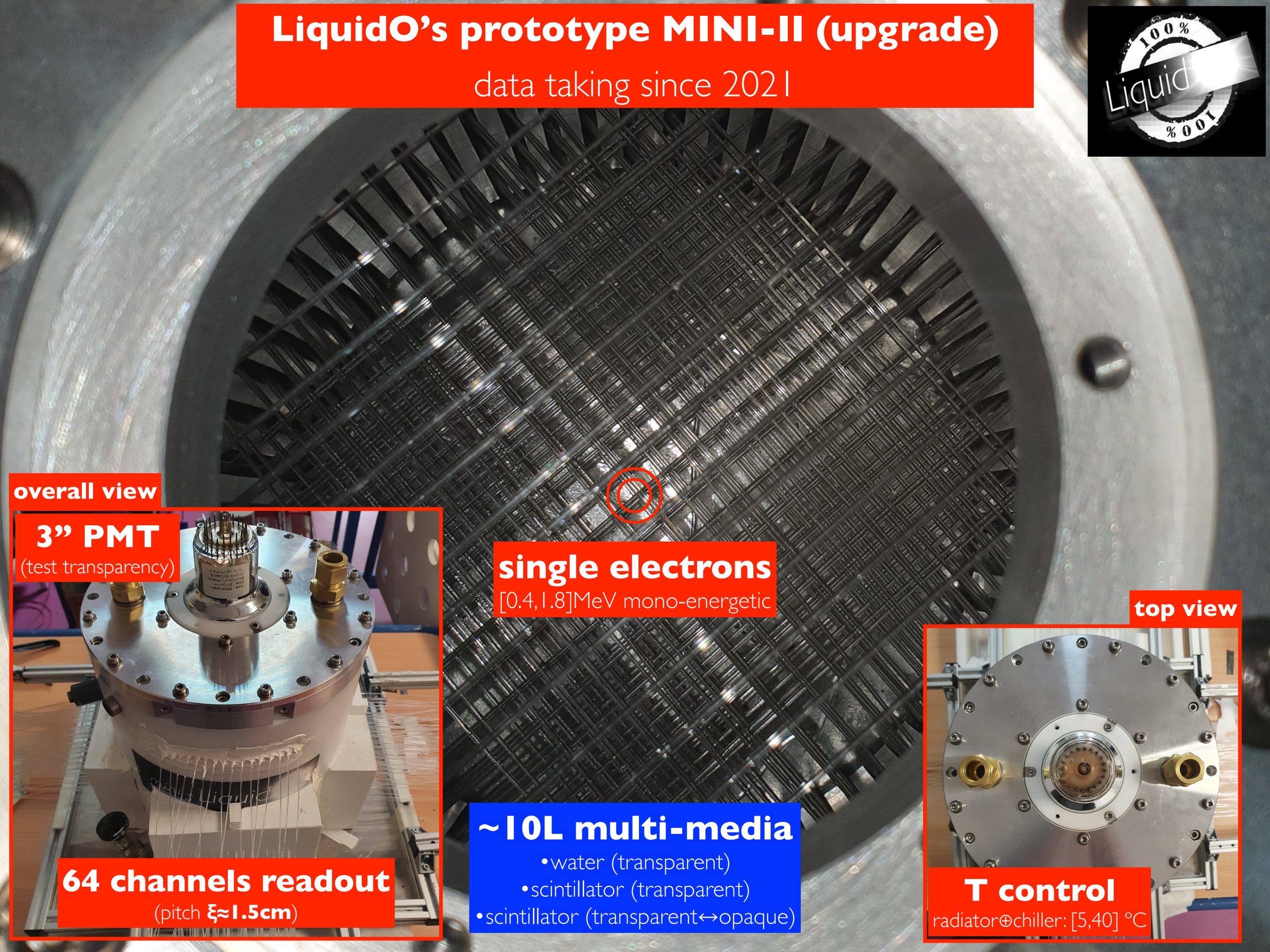


- **powerful PID**
- **energy flow**
- **tracking** (mm)
  →cosmogenic BG tagging
- **directionality**
- **dE/dx** (range)

~10MeV: Michel-e± (μ-decay**), supernovae (**remnant, core-collapse**), low energy atmospherics, etc**

LiquidO's prototype MINI-II (upgrade)

data taking since 2021



topology's PID (no timing)…

Neutrino physics with an opaque detector

LiquidO Consortium

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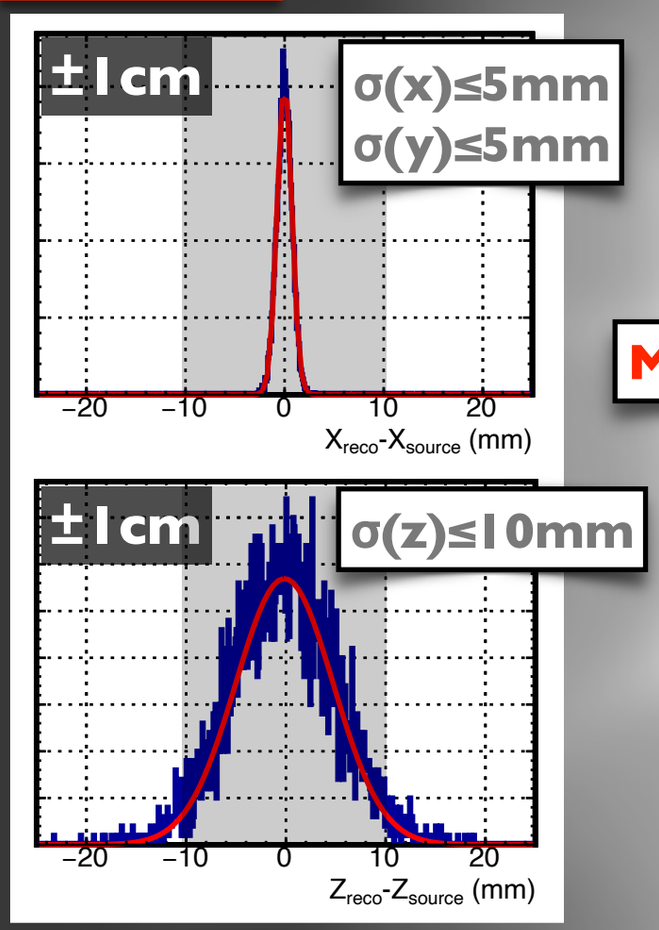
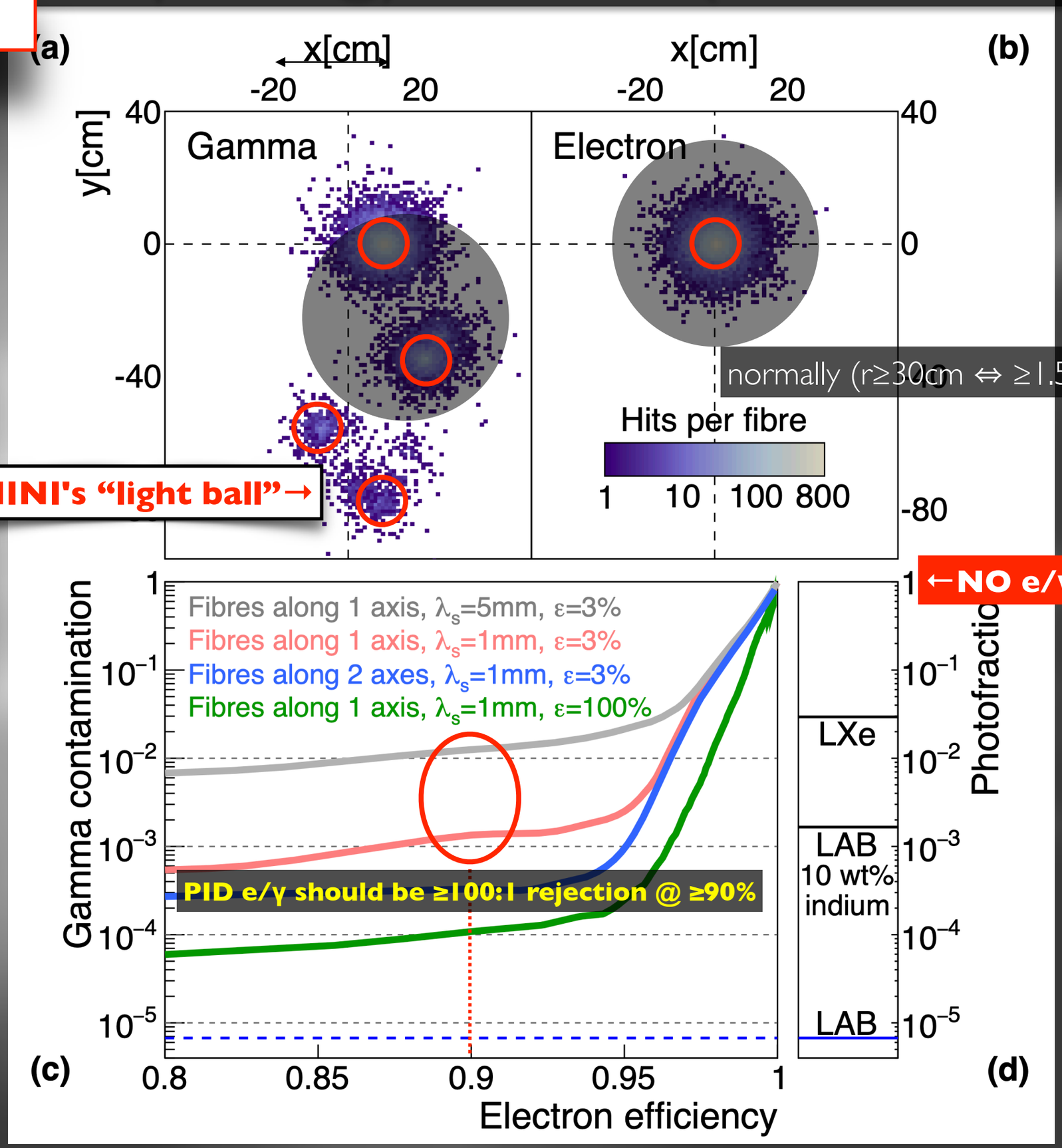
~0.5MeV

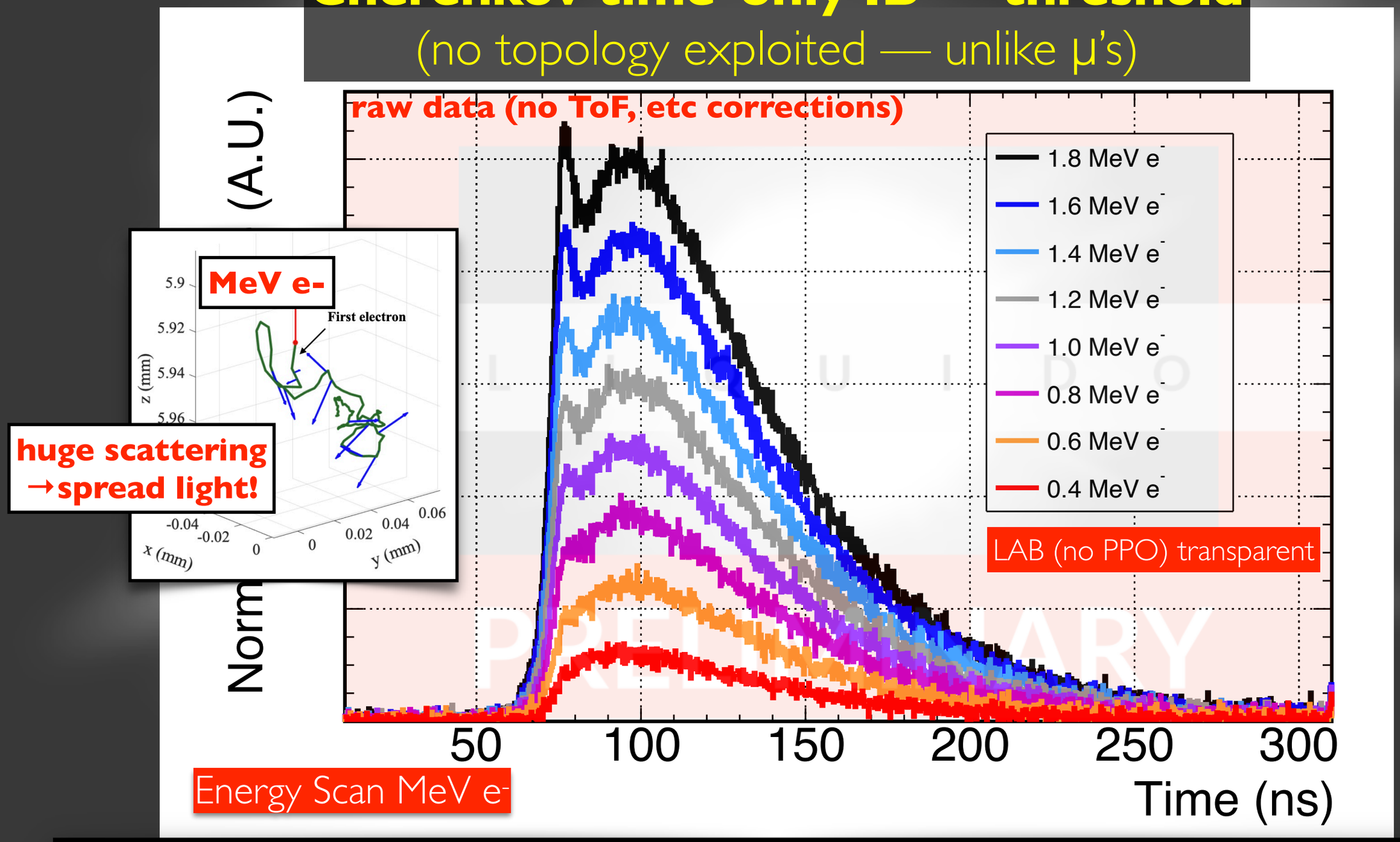




Cherenkov / Scintillation ID…

Cherenkov time-only ID — threshold

(no topology exploited — unlike μ's)



LiquidO's timing potential — under quantification & optimisation

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

SUPERCHOOZ

pathfinder

challenge II: **new laboratories**

- 2x ultra-near-detectors
- 1x super-far-detector

Europe's best reactor ν site…

C L O U D

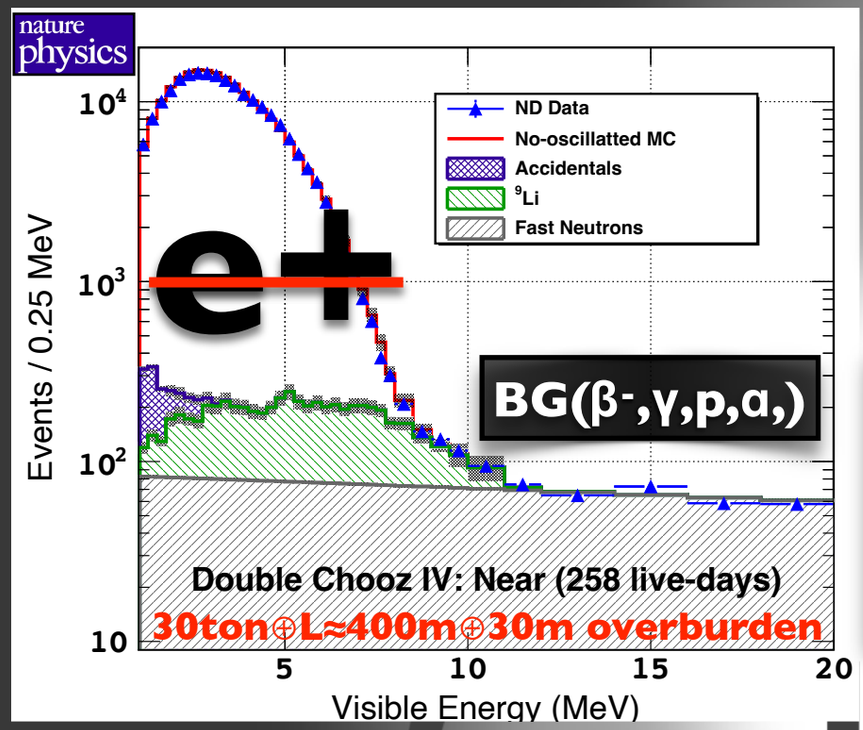
European Innovation Council

UK Research and Innovation

first LiquidO-based experiment…

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

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

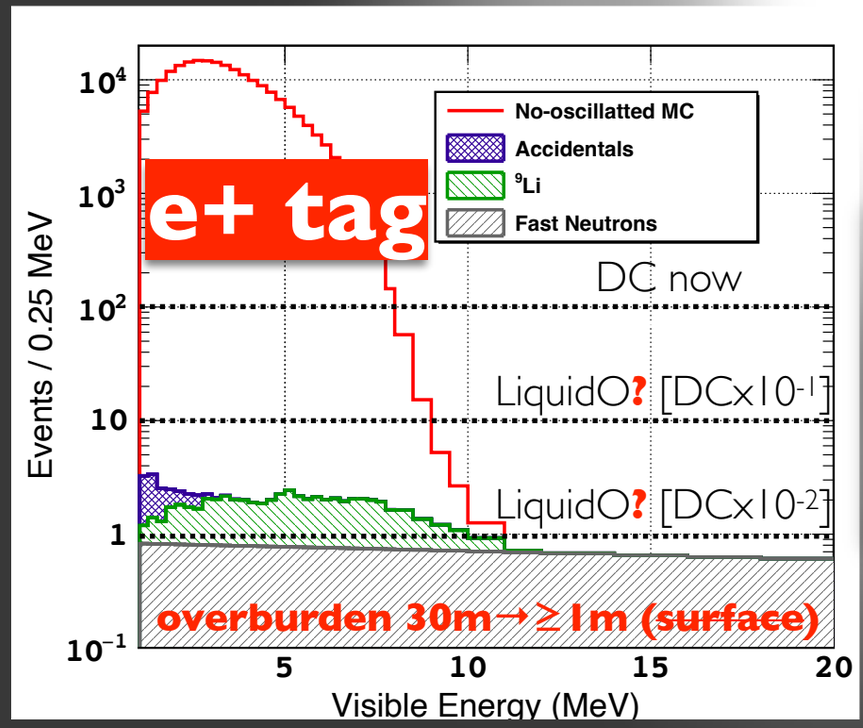
DC-ND:

Signal ≈ 816 ν/day

BG(β⁻,α,γ,p) ≈ 39 day⁻¹ (*"some per day"*)

S/BG≈21

C L O U D



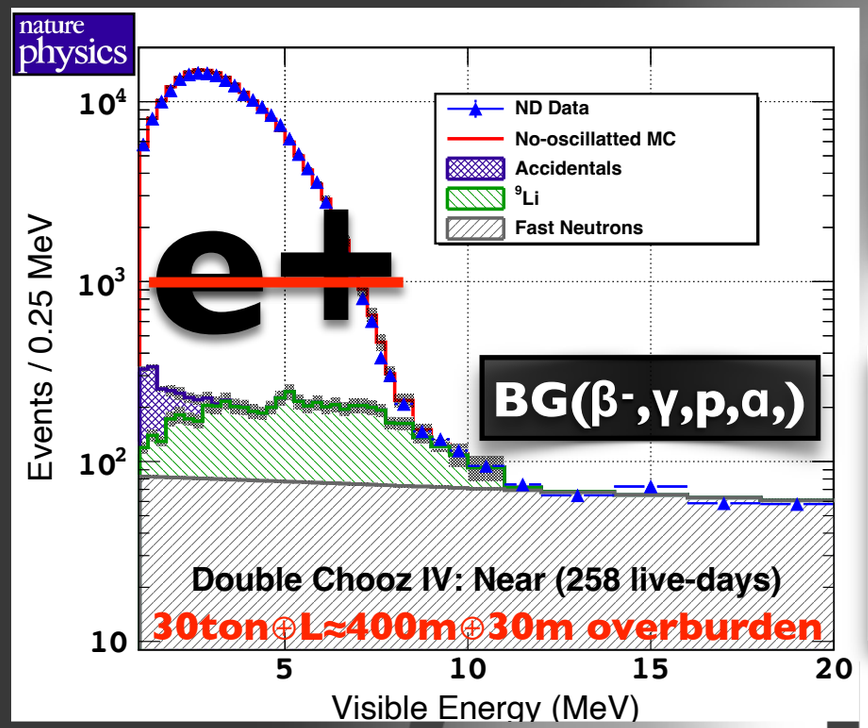
CLOUD:

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

BG(DC) ≈ **≥10x** BG(LiquidO)

S/BG ≈100? same config [demo]

CLOUD @ LNCA...



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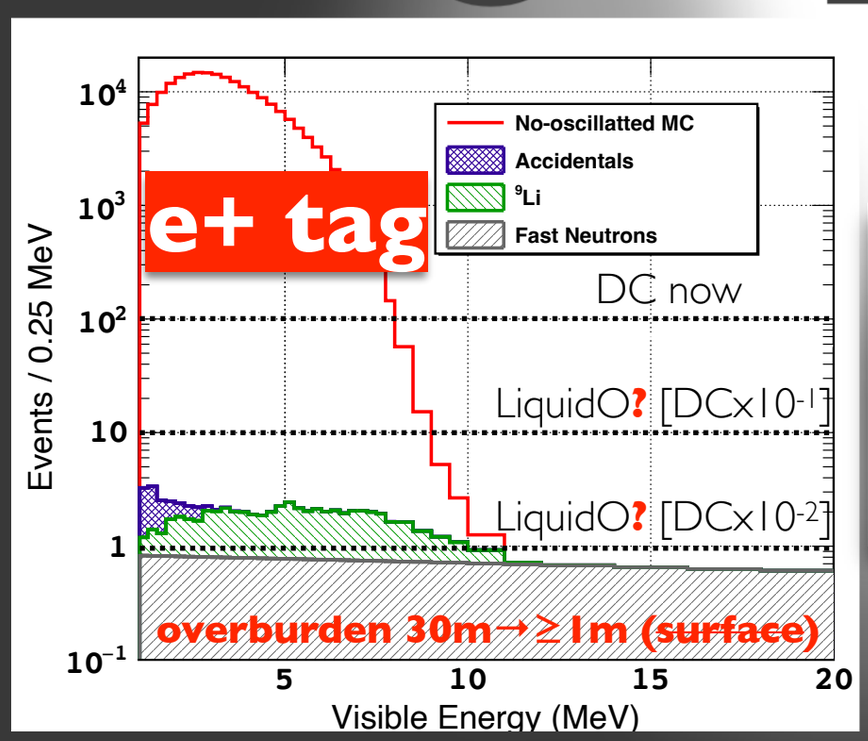

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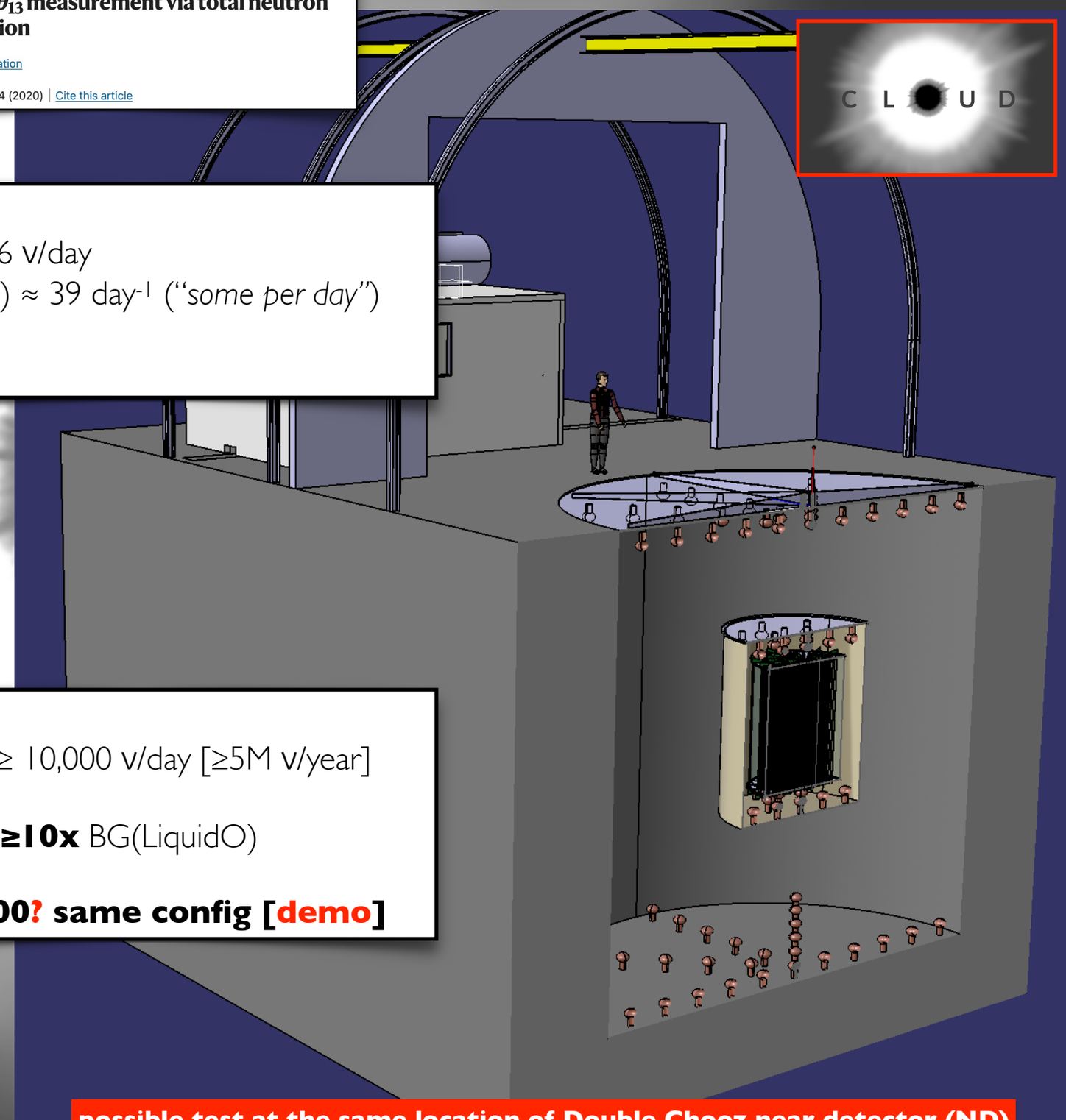
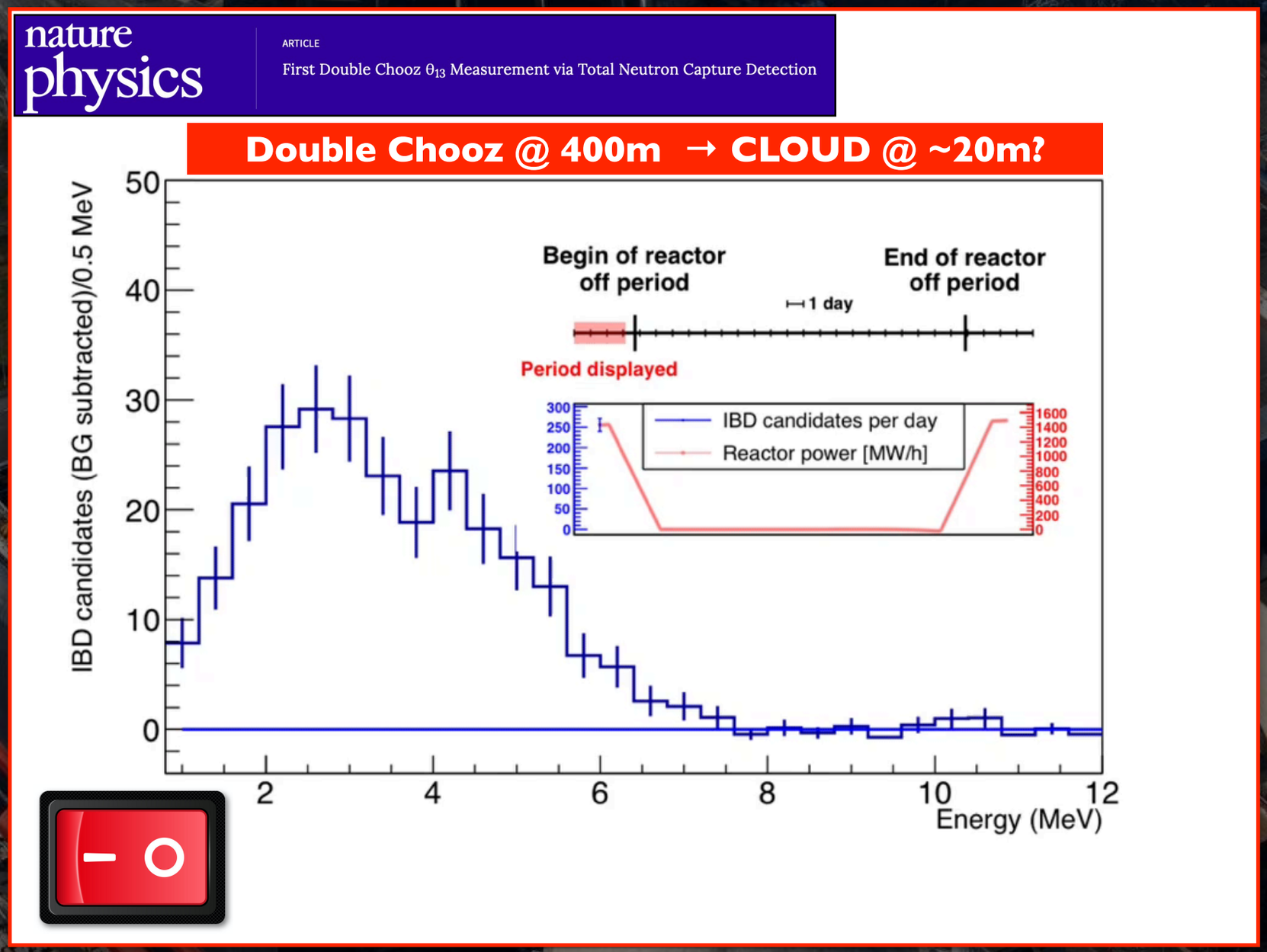
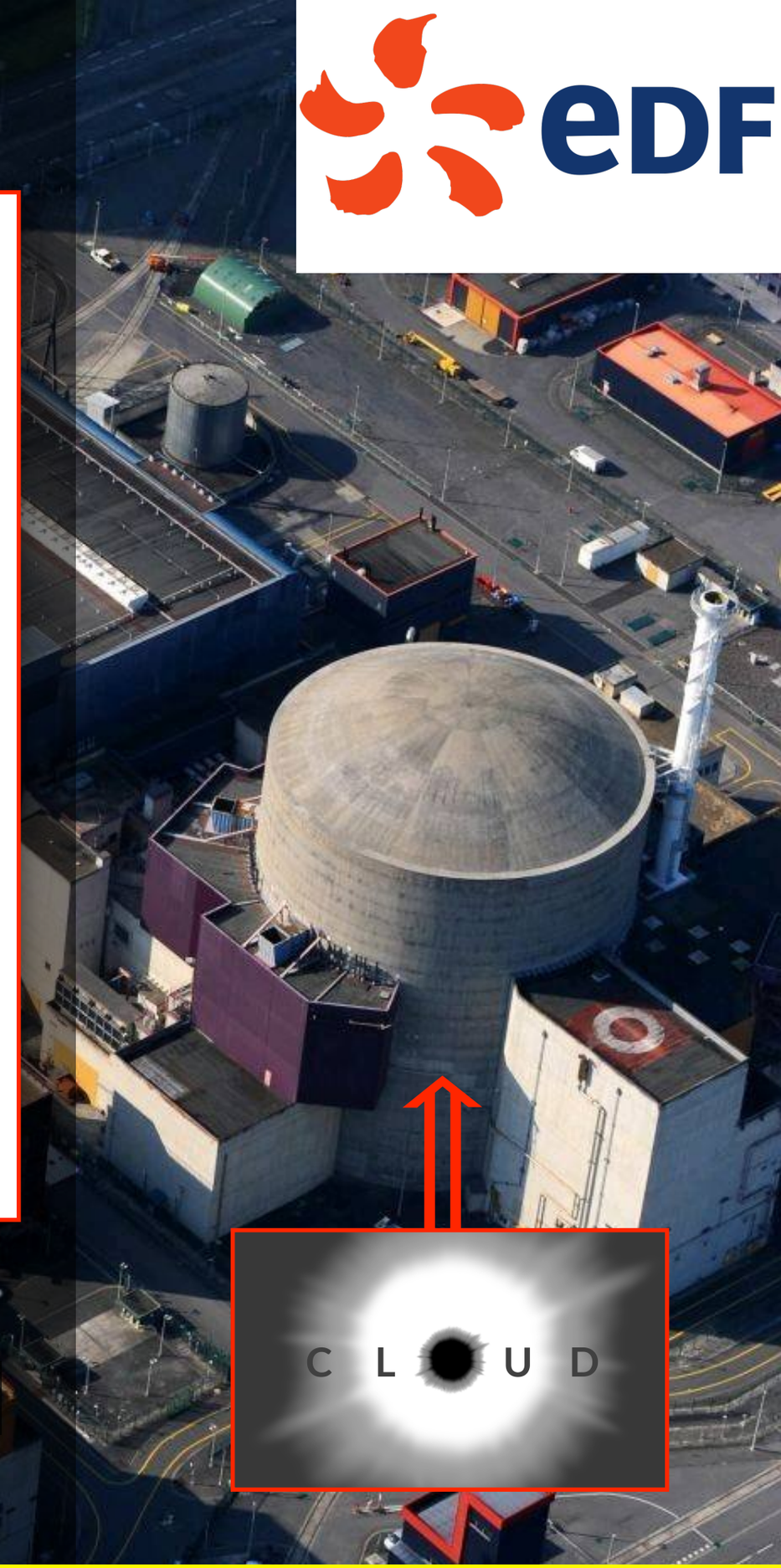


possible test at the same location of Double Chooz near detector (ND)
(well known signal & backgrounds)

ultra-near @ Chooz…





Potential: "background-less" reactor-ν detection?

a new era of science @ Chooz — Europe's most powerful reactor neutrino underground laboratory

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)

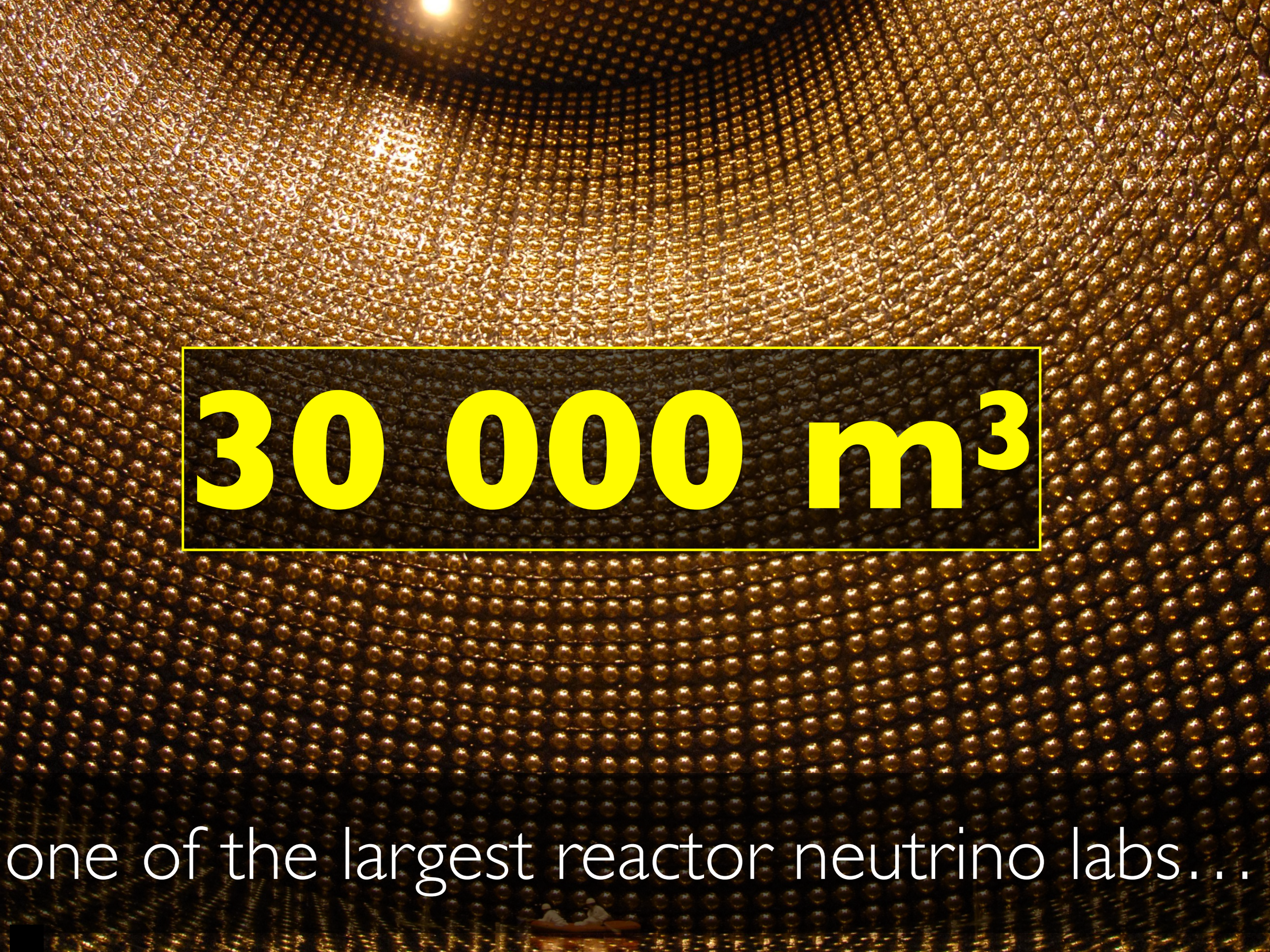
- **EDF** (France) — **first time in neutrinos!**
- **CIEMAT** (Spain)
- **IJCLab**/Université Paris-Saclay (France)
- **J-G Universität Mainz** (Germany)
- **Subatech**/Nantes Université (France)
- **Sussex University** (UK)

—

- **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)

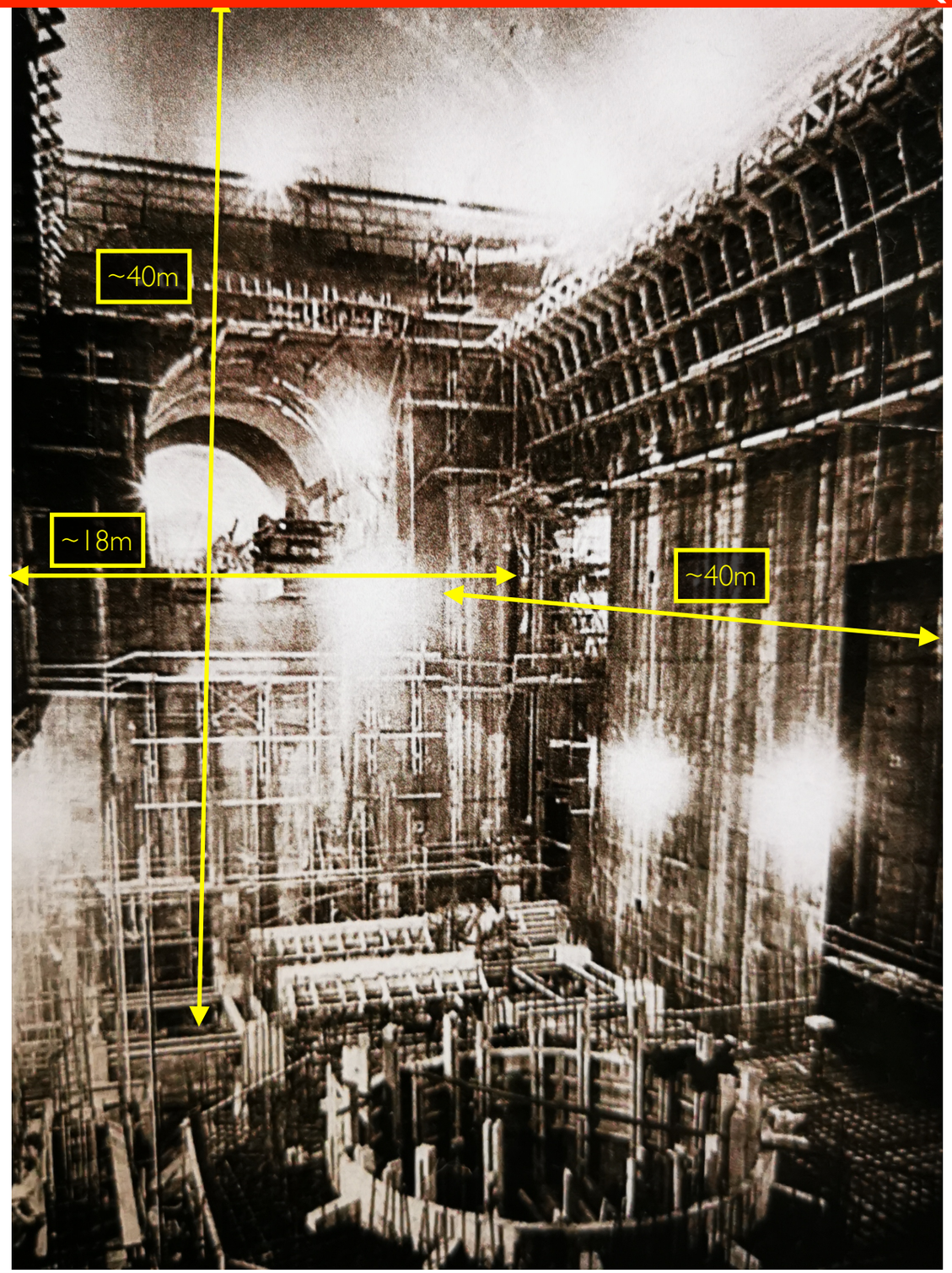
CLOUD collaboration (EDF⊕13 institutions over 10 countries)

Europe's best reactor ν site…

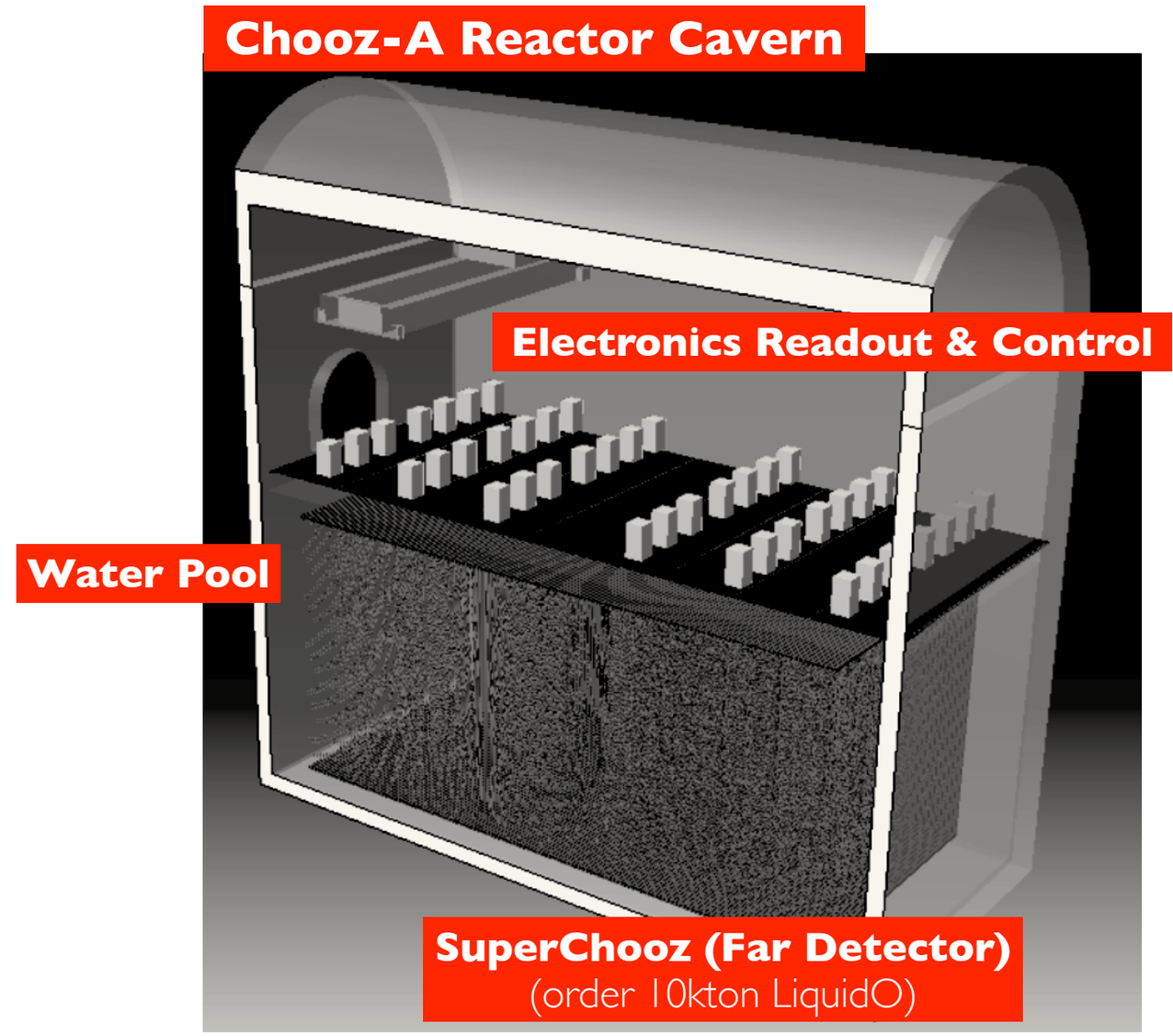


one of the largest reactor neutrino labs…

Chooz-A Reactor Cavern (≤100m underground & 30,000 m³)



- preliminary **analysis: all OK!** (size, access, etc)
- **EDF⊕CNRS** run **full engineering feasibility studies**
  - → new laboratory construction — mainly a water pool
  - → studies for extra constraints for Chooz-A dismantling, etc



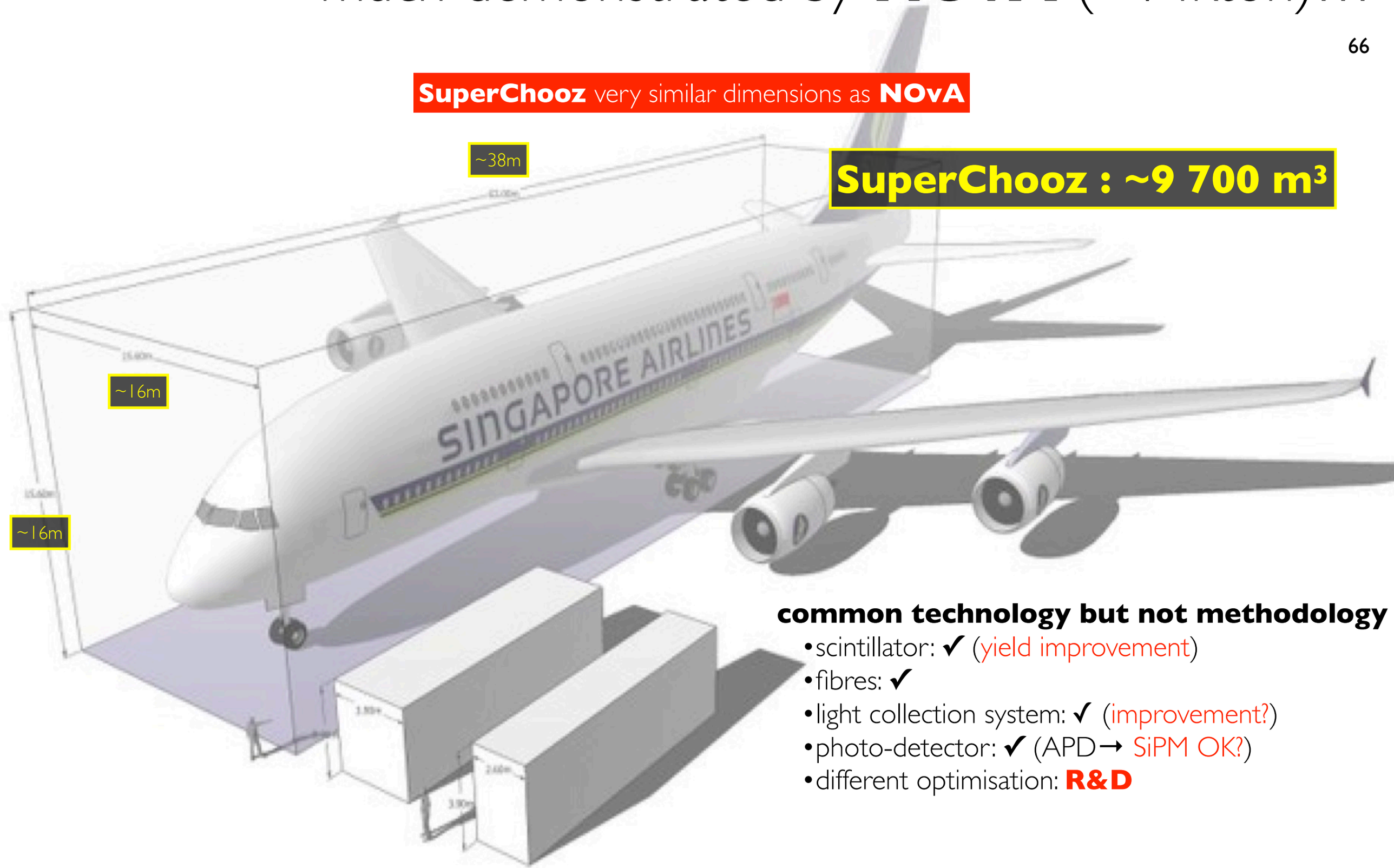
super far-detector design…

L I Q U I D

can we make BIG?

much demonstrated by **NOvA** (~14kton)…

SuperChooz very similar dimensions as **NOvA**



SuperChooz : ~9 700 m³

common technology but not methodology

- scintillator: ✓ (yield improvement)
- fibres: ✓
- light collection system: ✓ (improvement?)
- photo-detector: ✓ (APD→ SiPM OK?)
- different optimisation: **R&D**

GeV OK!! But **~1MeV physics @ 10kton?**

(**R&D**)

SUPERCHOOZ

pathfinder

challenge III: **new flagship experiment physics programme**

rationale...

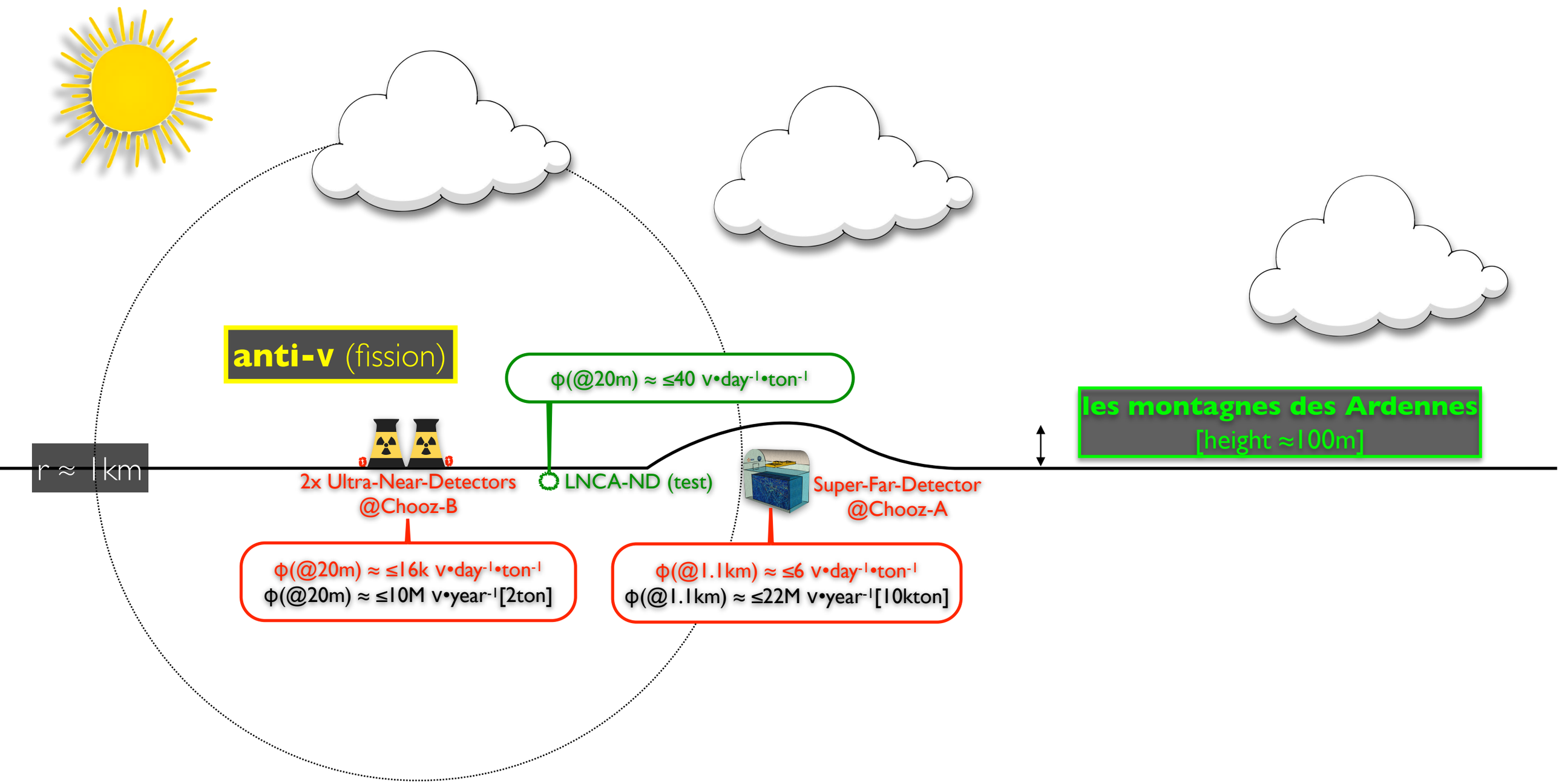
- high precision SM's neutrino oscillation
  $\Longrightarrow$ <u>synergise</u> with JUNO & HK $\oplus$ DUNE

- neutrinos as probe BSM $\longrightarrow$ discoveries?
  $\Longrightarrow$ beyond today's paradigm?

today's menu...

- θ_{13} & $|\Delta m^2|$ — high precision SM
- θ_{12} & δm^2 — high precision SM
- new families/interactions test(s) [BSM]
- CPT violation — SM coherence? [BSM]
- unitarity violation — SM completeness?
  $\Longrightarrow$ neutrino & anti-neutrino [BSM]
- proton decay search: multi-channel! [BSM]
- supernovae: core-collapse & remnant (both)

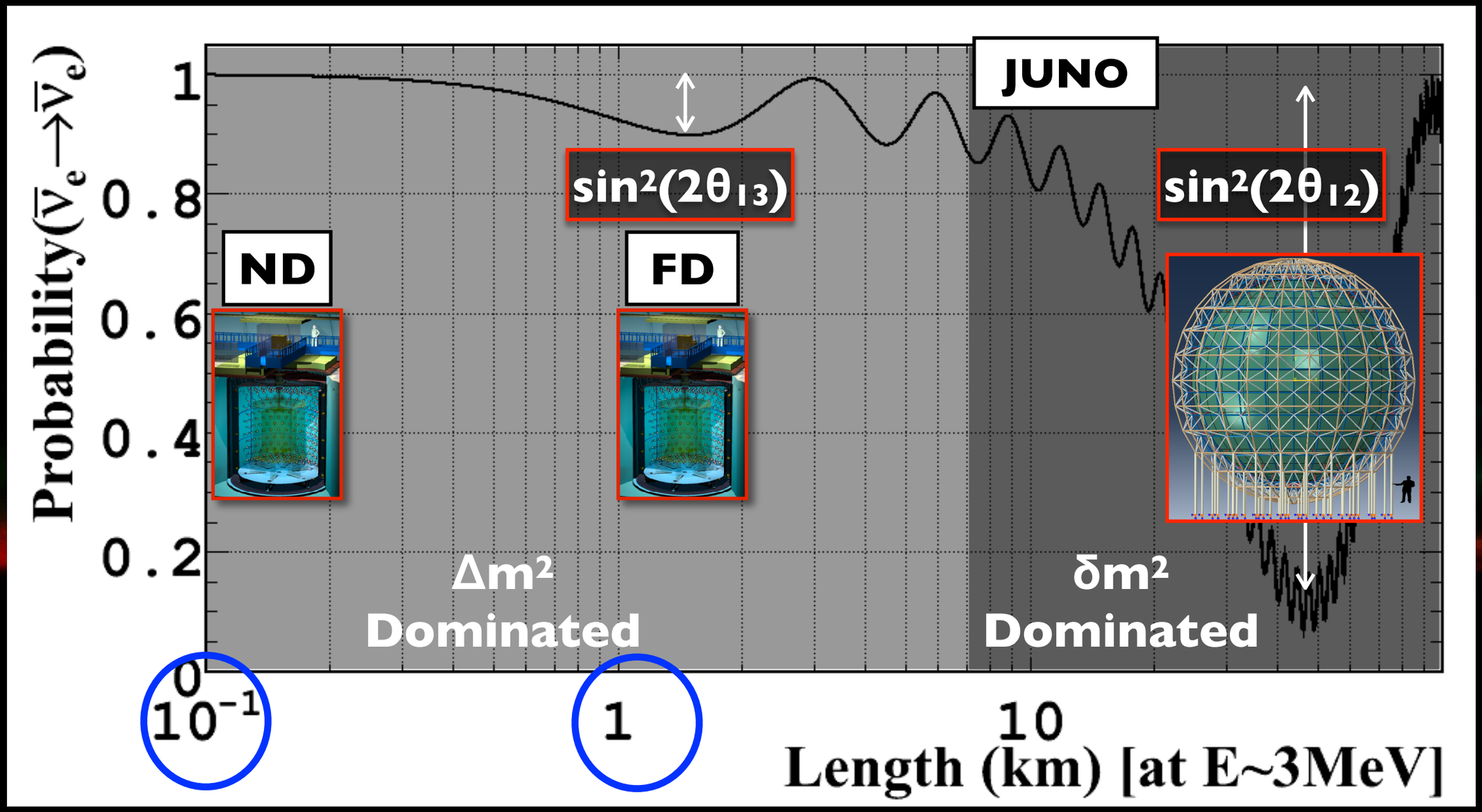
physics I: reactor neutrinos...



reactor underground challenge…

Europe's best reactor ν site…

experimental setup…



- **reactor:** extreme source of neutrino (commercial→1GW≈2x10^{20}/s) — no running cost.
- **3 measurement regimes:** depending on baseline (L):
  - [UND] **zero-baseline** (L→~0km): **ϕ(reactor)** — and/or **new physics?**
  - [SFD] **short-baseline** (L→~1km): **θ13⊕Δm²** [multi-detector: ~~**ϕ(reactor)**~~]
  - [JUNO] ~~**long baseline** (L→≳50km): **θ12⊕δm²** and **θ13⊕Δm²**, if enough resolution~~

NO!

(till now)

θ_{13}

improvable?

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: ~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 (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 to improve at all?

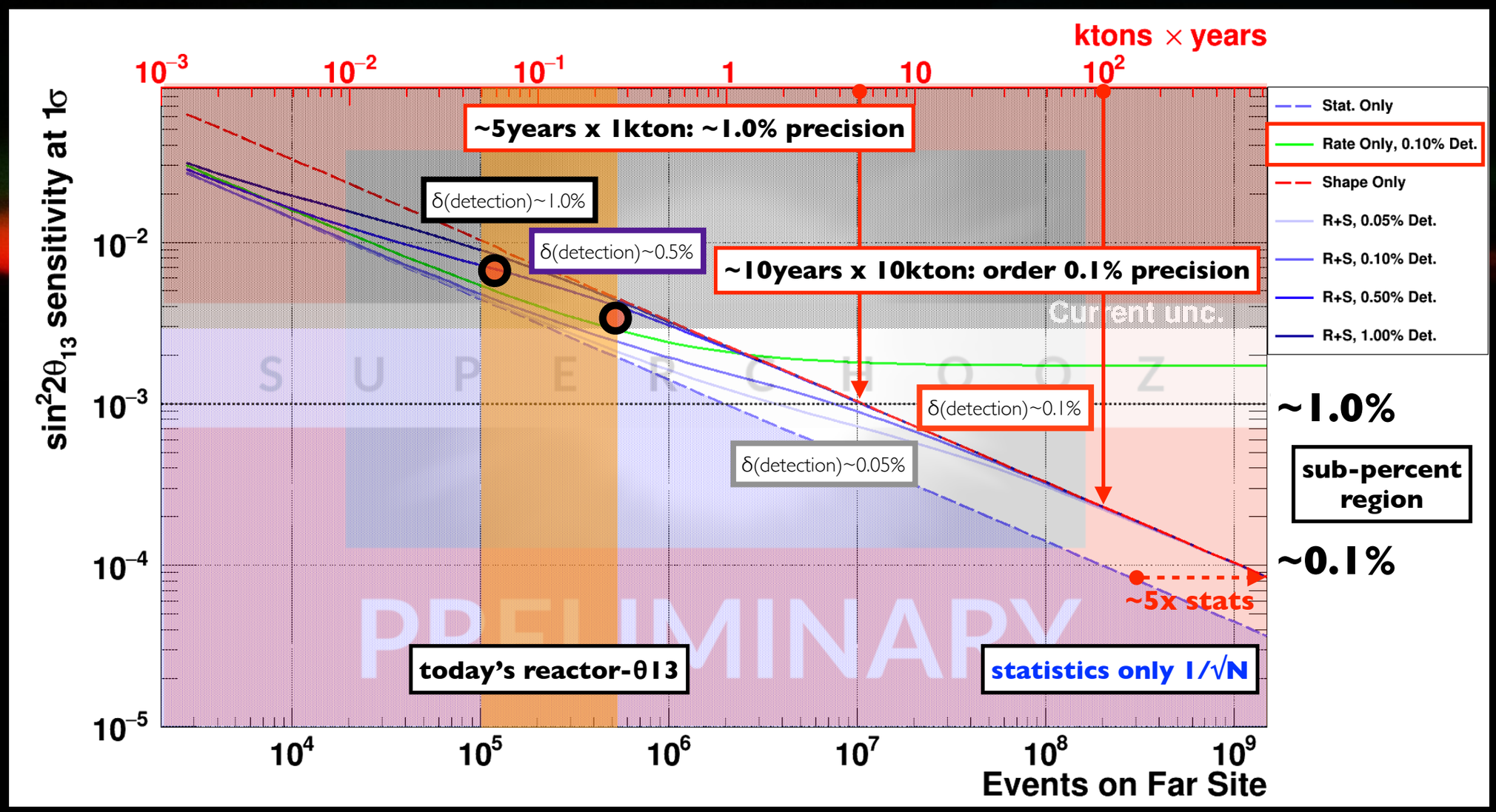
review reactor θ13 sensitivity evolution…

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

- **statistics: ≥10^7 (far) [≳20x today]**
- **detection systematics (~today: ~0.1%)**
- **energy control (≤0.5% precision — today)**

⇒ 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]

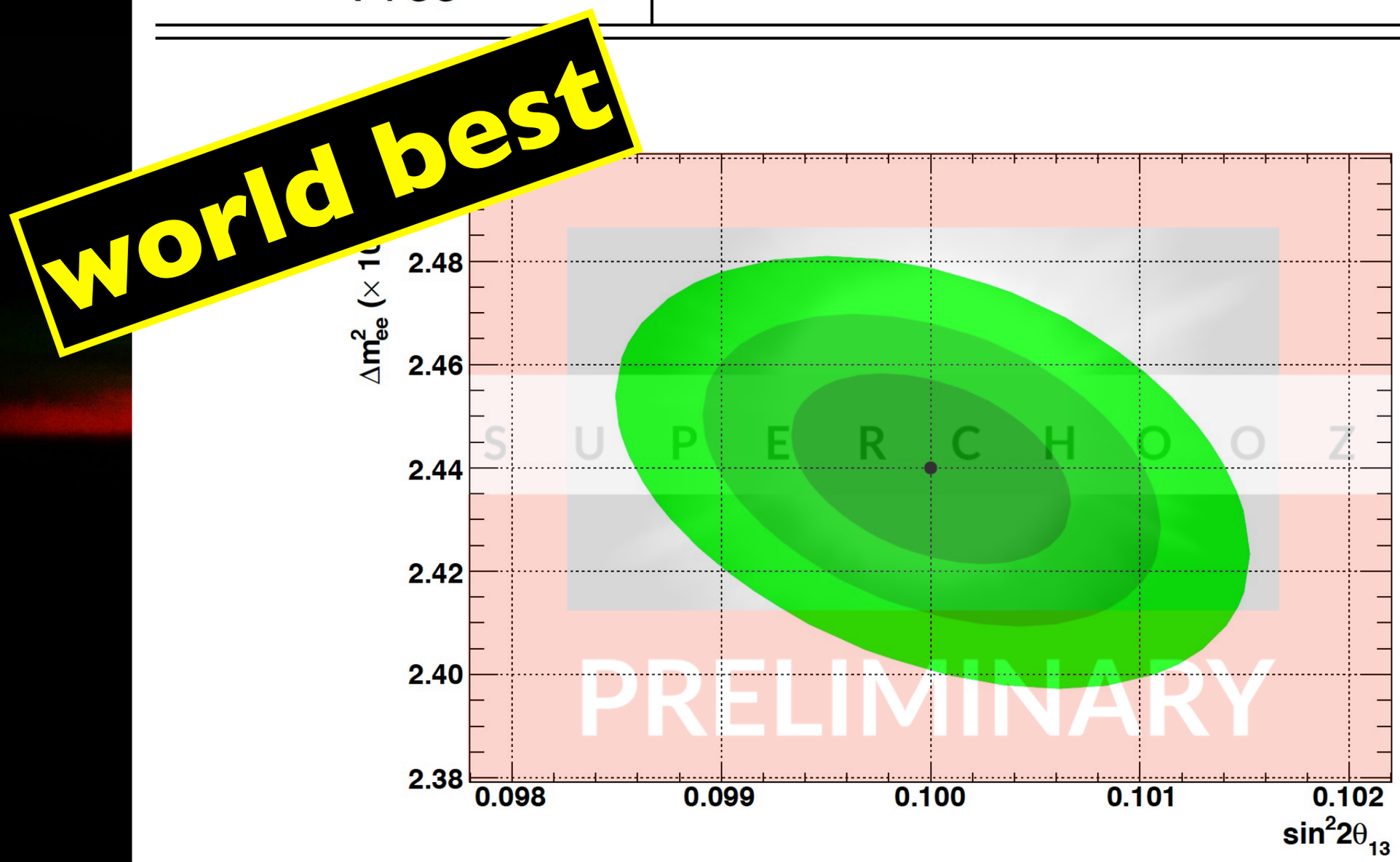


translator: 1 kton implies ~2x10^6 IBD/year→ **~4 IBD/min** [~50x today]

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

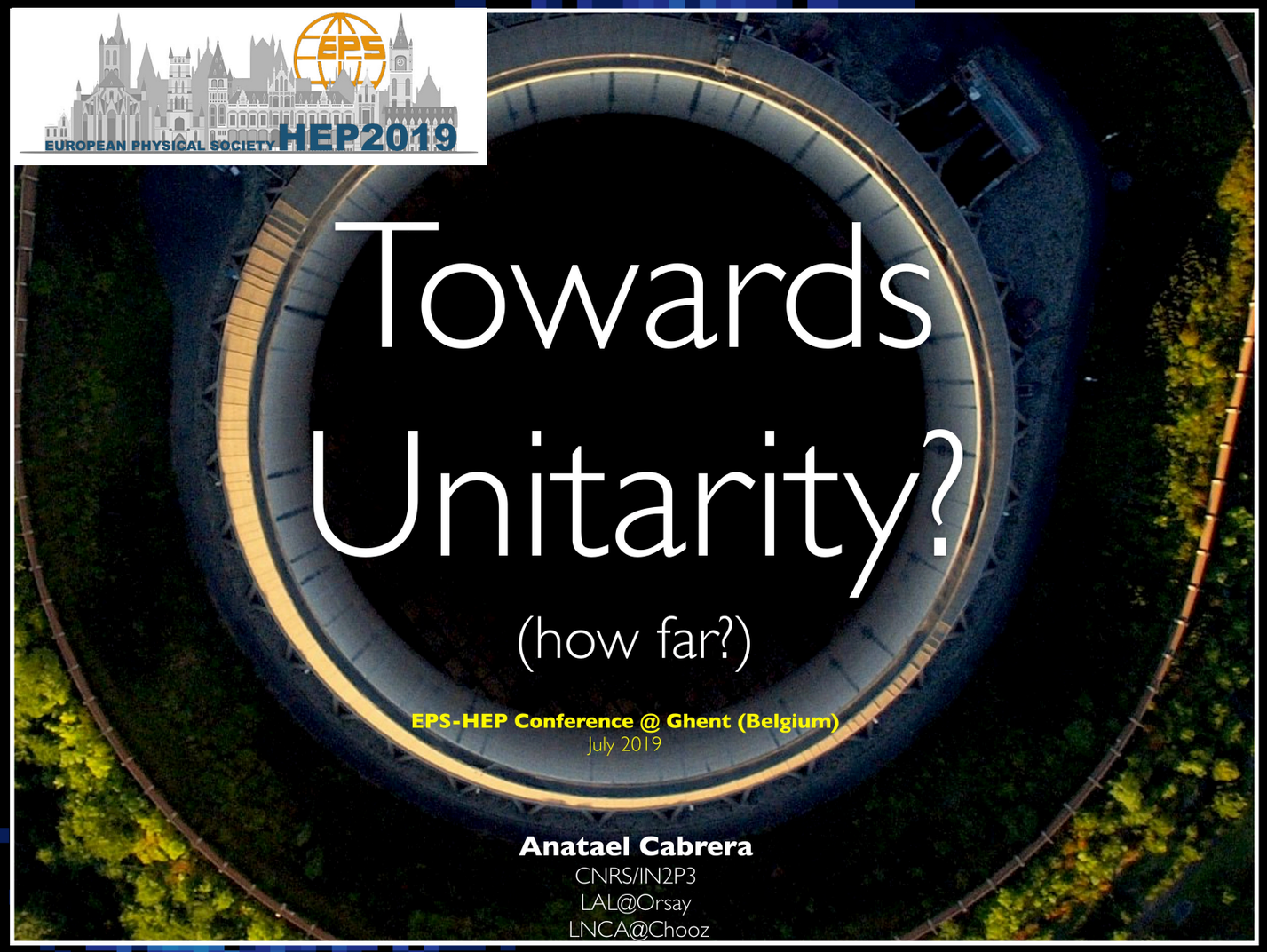
overall θ13⊕Δm²(ee) sensitivity…

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



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

leptonic sector unitarity with LiquidO?



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

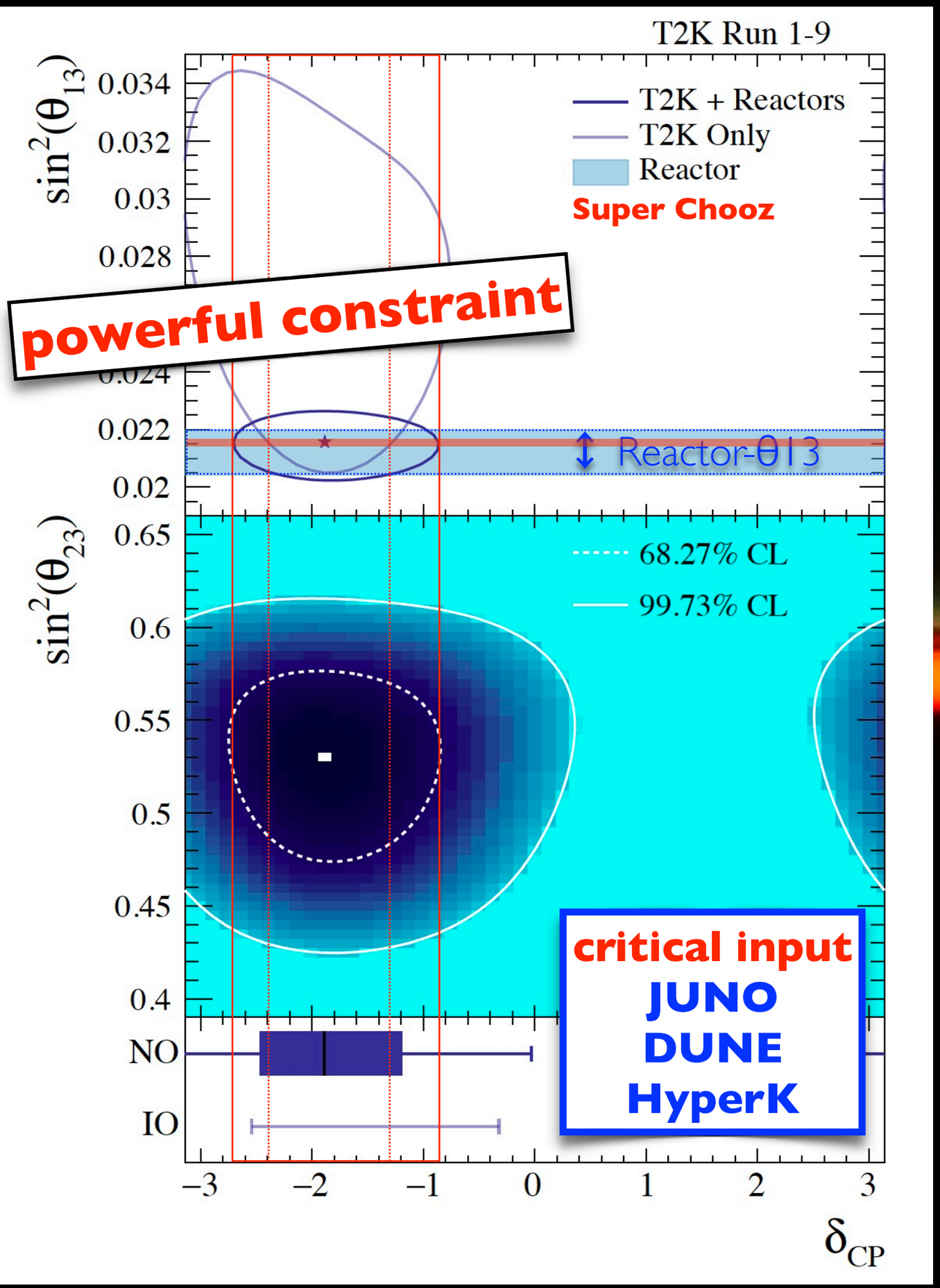
why θ_{13} & $|\Delta m^2|$?

- world most precise θ_{13}!! [~10x better]
- CP violation — synergy HK & DUNE
- Mass ordering — key input for JUNO
- PMNS' shape: the smallest term?
- measure θ_{23}? — synergy HK & DUNE

  $\Longrightarrow$ resolve the "octact" [unknown!]

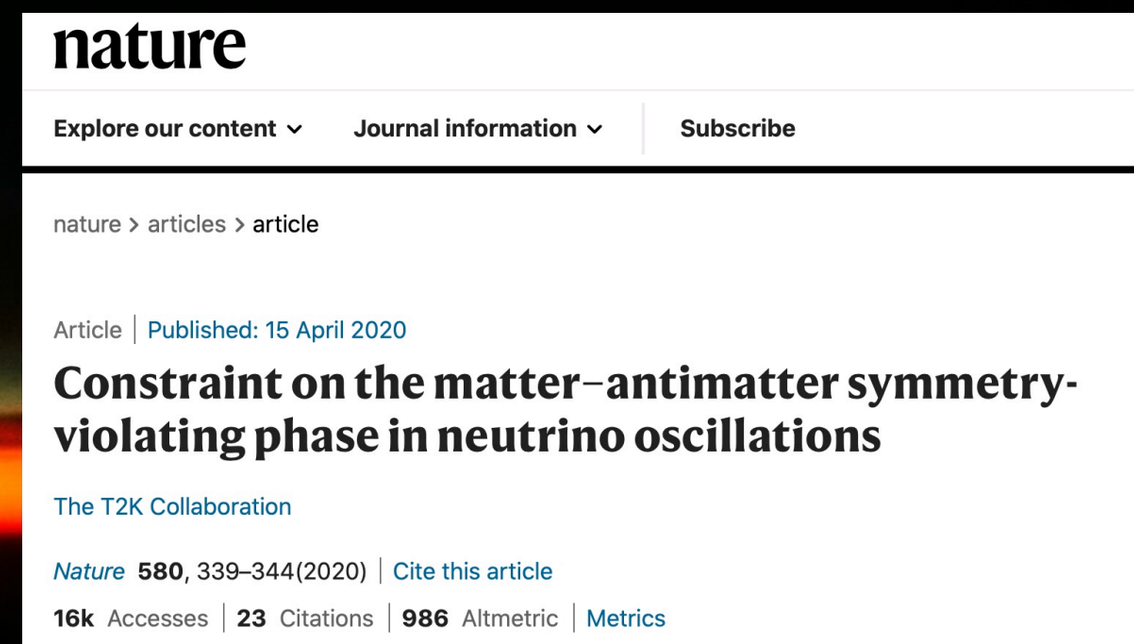
  $\Longrightarrow$ PMNS' shape: the largest term!
- unique cross-check JUNO's Δm^2 info?

measure CP-violation…



CPV phase vs θ13

[constrained by reactor]



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Article | Published: 15 April 2020

Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations

The T2K Collaboration

Nature **580**, 339–344(2020) | Cite this article

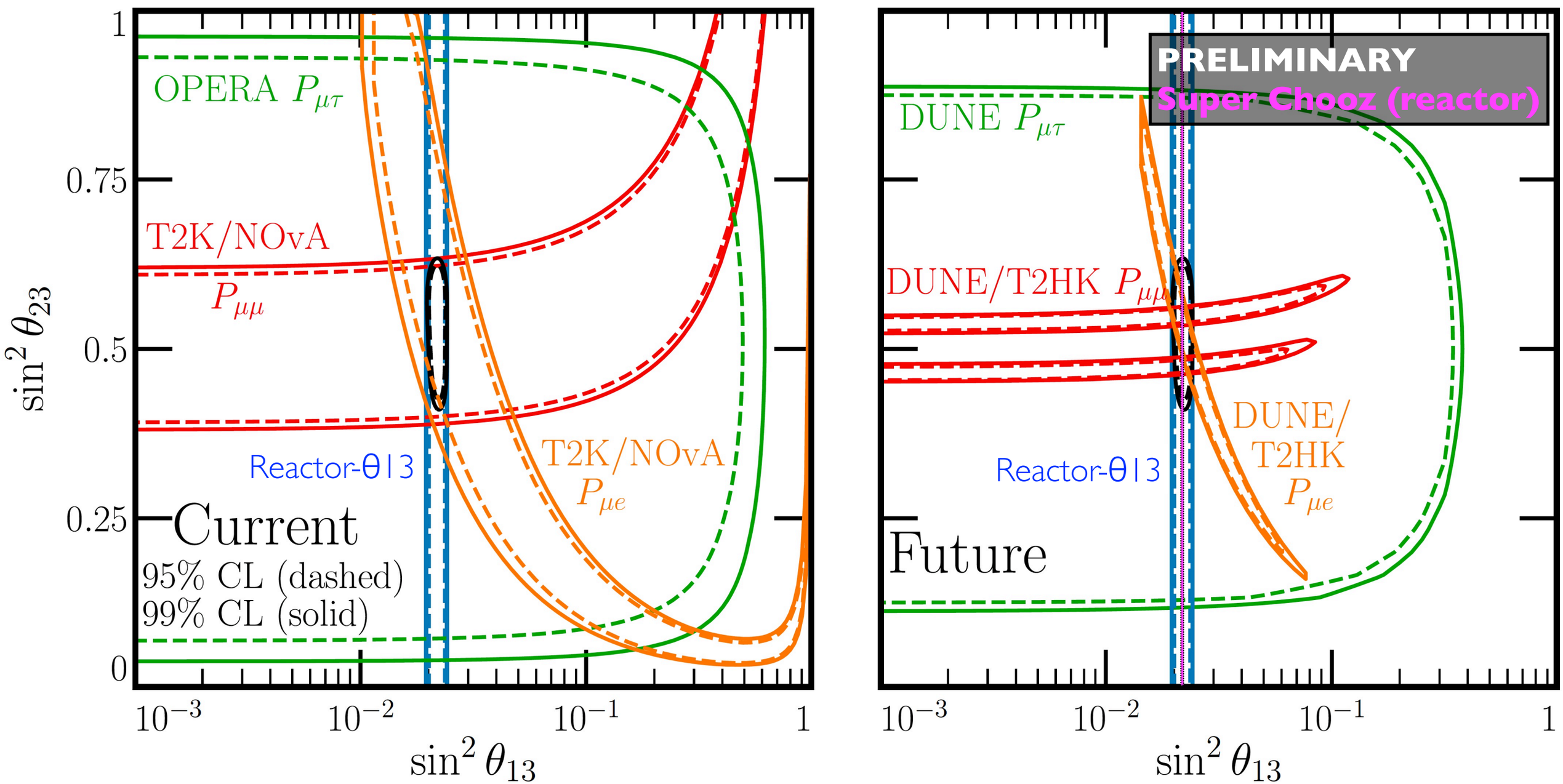
16k Accesses | **23** Citations | **986** Altmetric | Metrics

CPV phase vs θ23

[octant ambiguity]

Super Chooz potential under investigation…

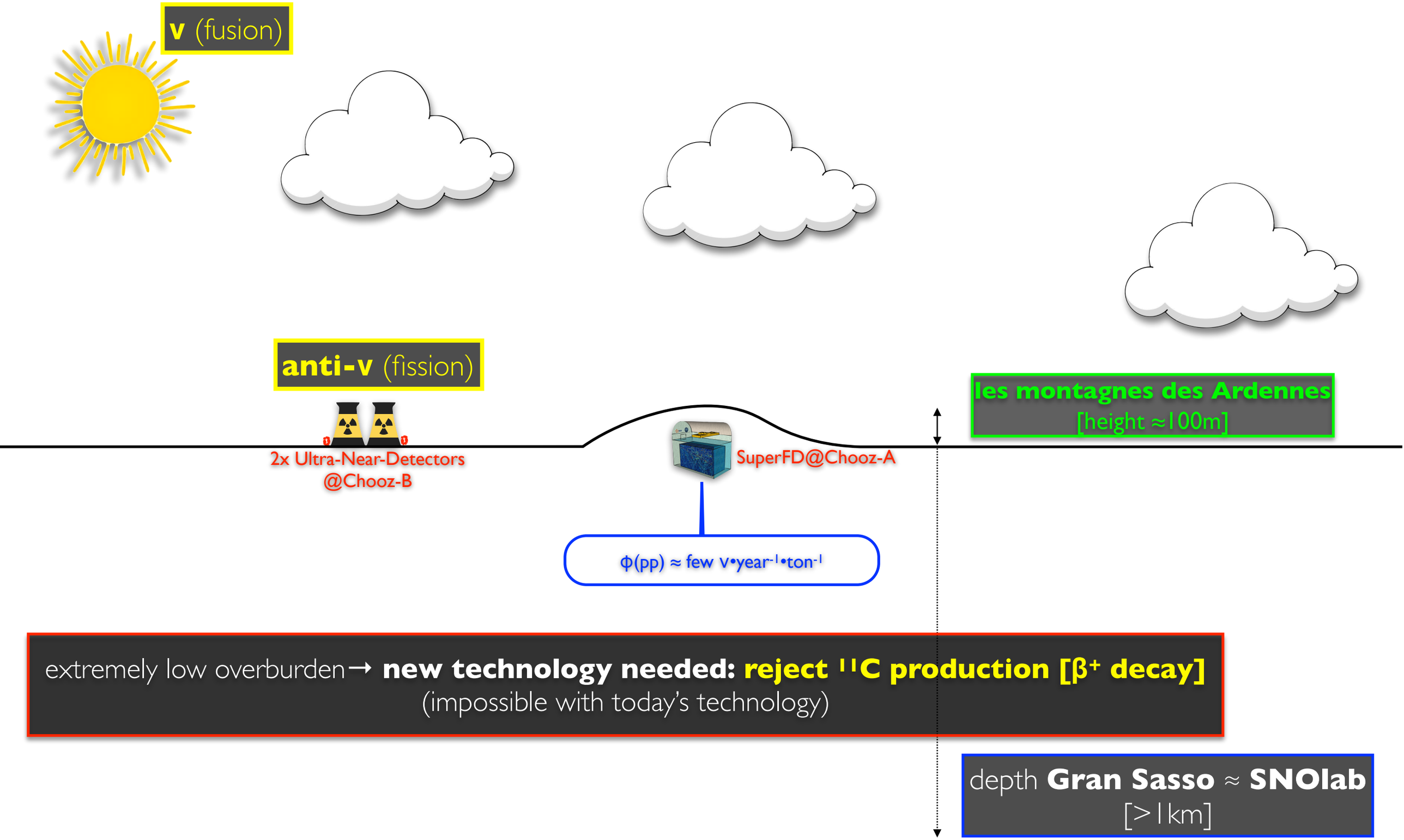
Plot: hacked version from original in ***Ellis, Kelly & Weishi-Li at* arXiv:2008.01088**



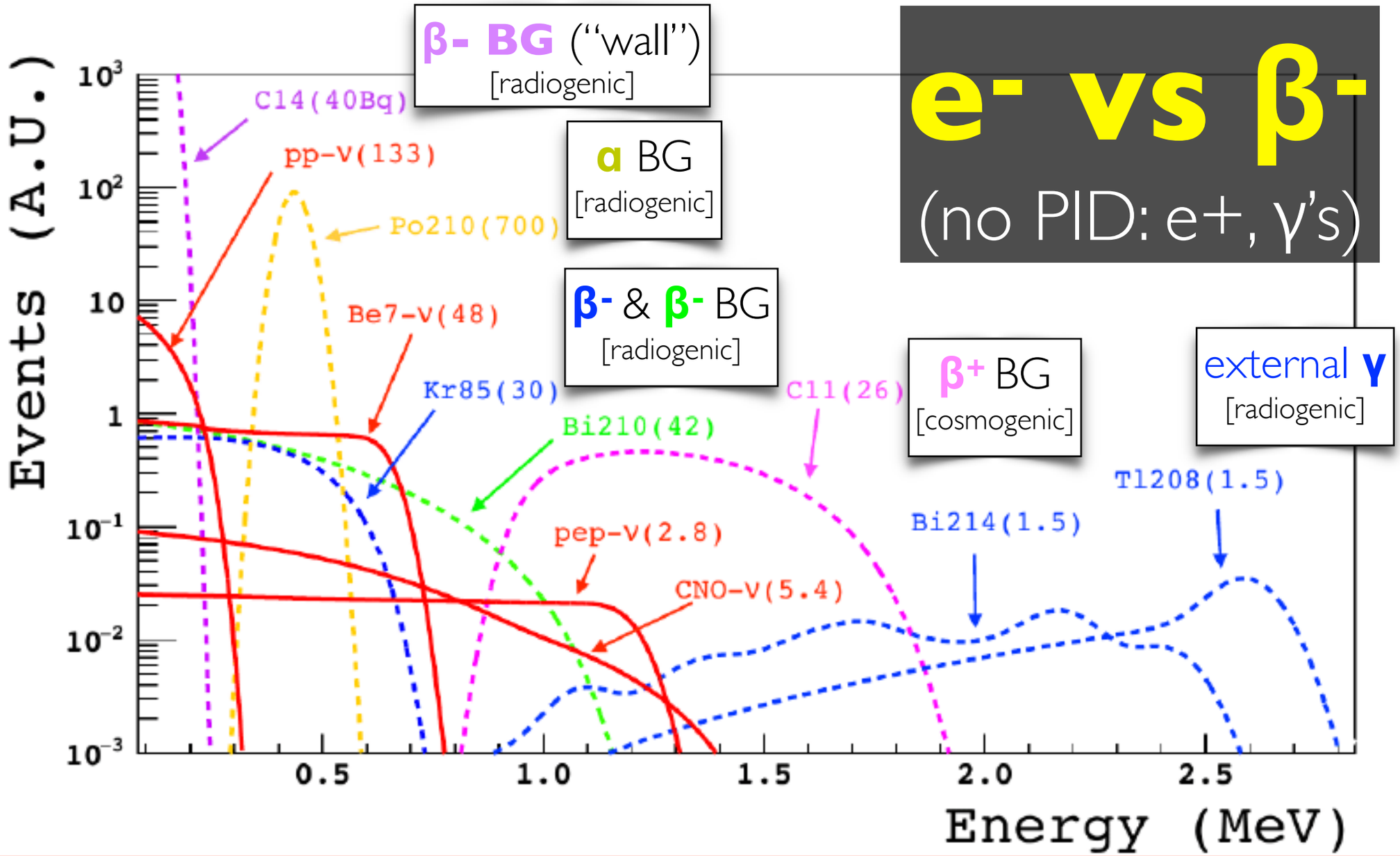
synergy: SC θ13 may help to resolve the "θ23 octant" ambiguity
(HK and DUNE) measured the combined effect of θ13⊕θ23 (harder to disentangle)

Super Chooz: the smallest but powerful…

physics II: solar neutrinos



reactor underground challenge…

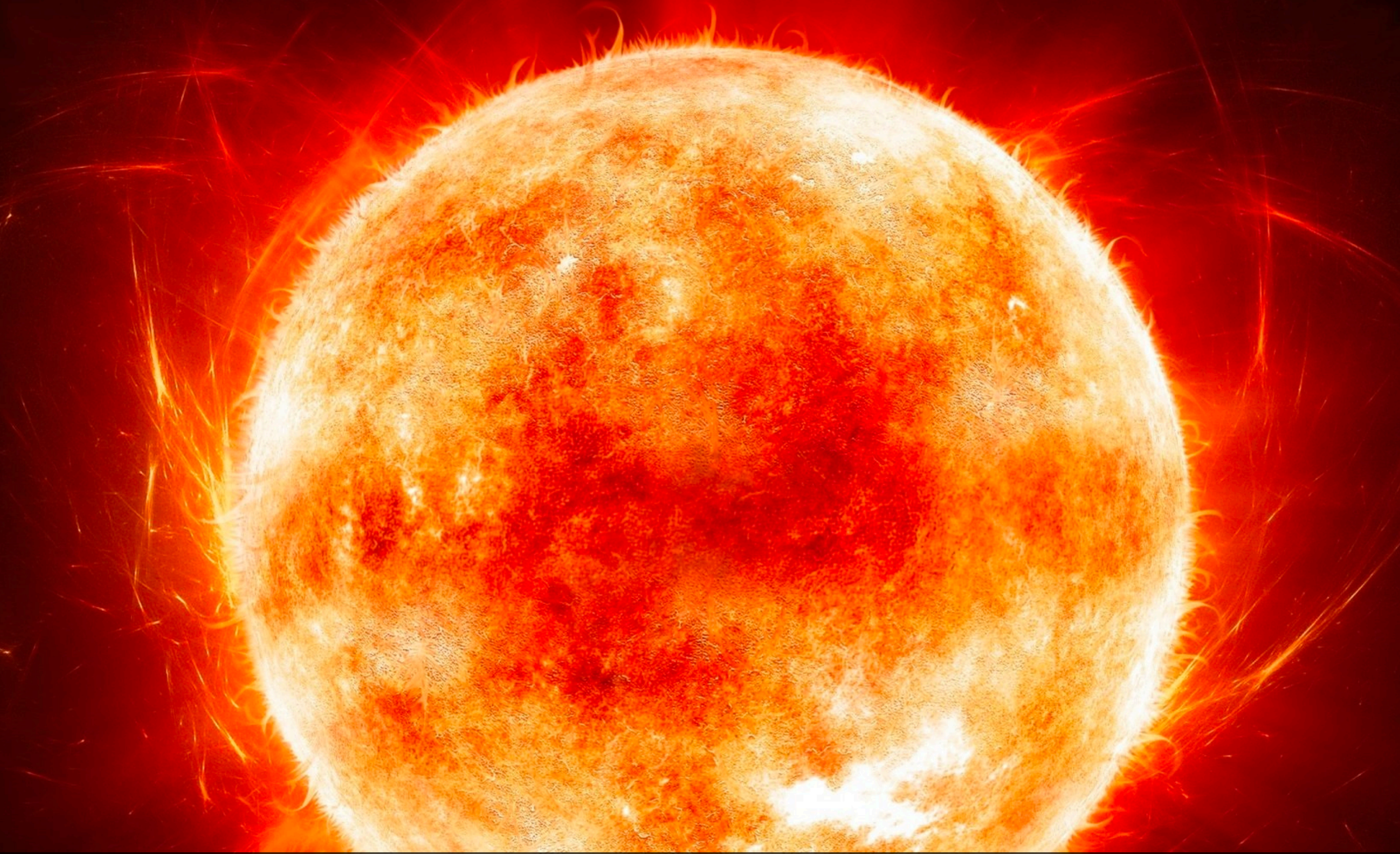


Borexino, JUNO, SNO, SNO+, SuperKamiokande, etc [future: THEIA]

all that, IF you controlled purity ≤1e-18 g/g U/Th
[extreme radio-purity & deep underground→hard and expensive]

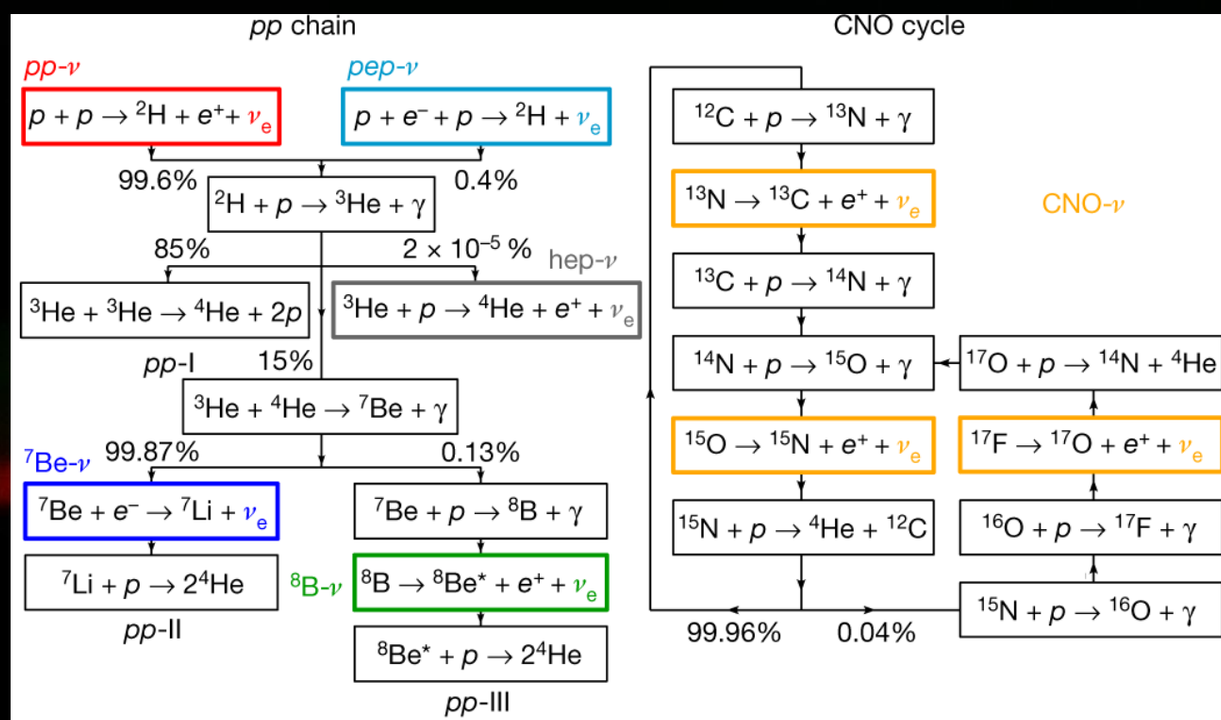
today's challenge…

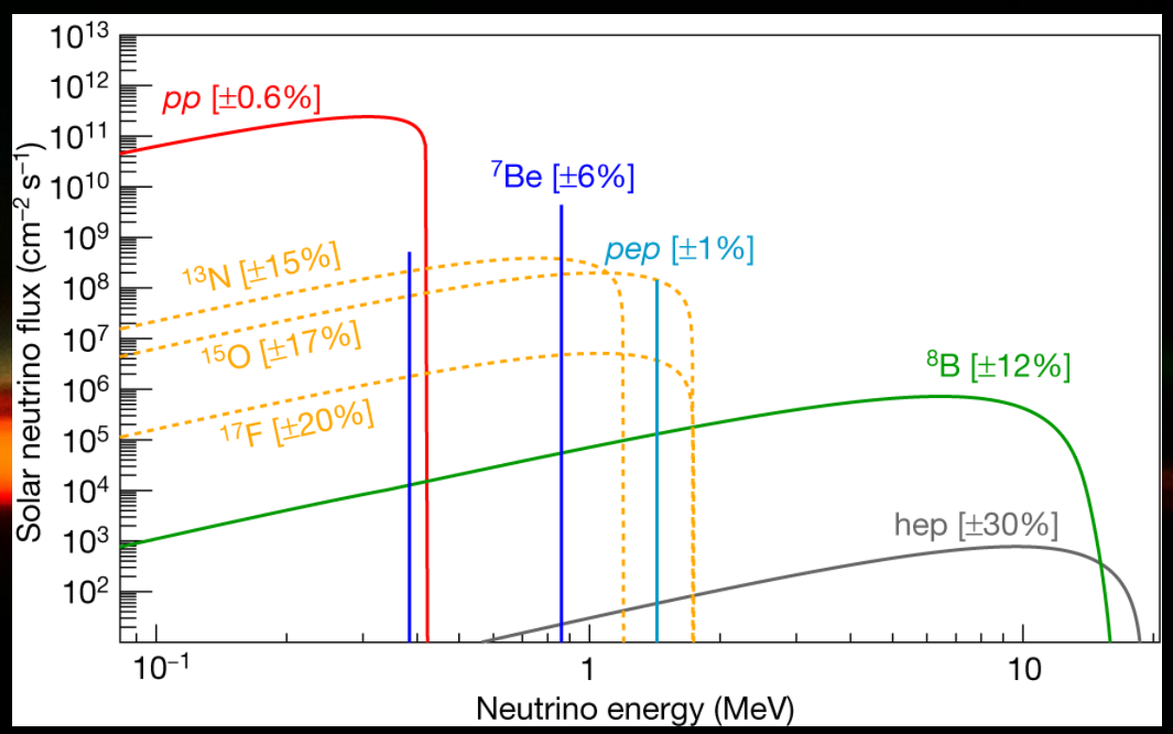
neutrino elastic scattering: <u>too hard</u>...



solar ν physics: progress stalled?

neutrino: inner-most Sun's sight…





2 main reactions…

- **pp chain** (dominant in Sun still)
- **CNO cycle** (older stars dominant)

spectral precision of the "Solar-SM"

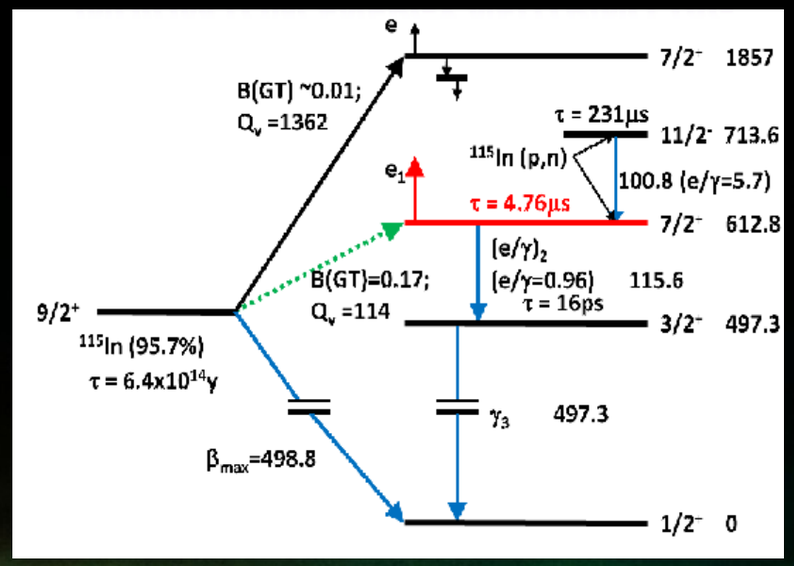
- **extreme ≤% precision**
- **beyond today's knowledge with neutrino?**

solar's **Indium** coincidence…

^{115}In + ν(e) → e- + ^{115}Sn* [CC]

coincidence: **^{115}Sn*** → **β-** or **γ** (E=116keV)
γ (E=497keV)

E(threshold): 114keV [→up to **pp neutrinos**]



Neutrino physics with an opaque detector

LiquidO Consortium

Communications Physics **4**, Article number: 273 (2021) | Cite this article

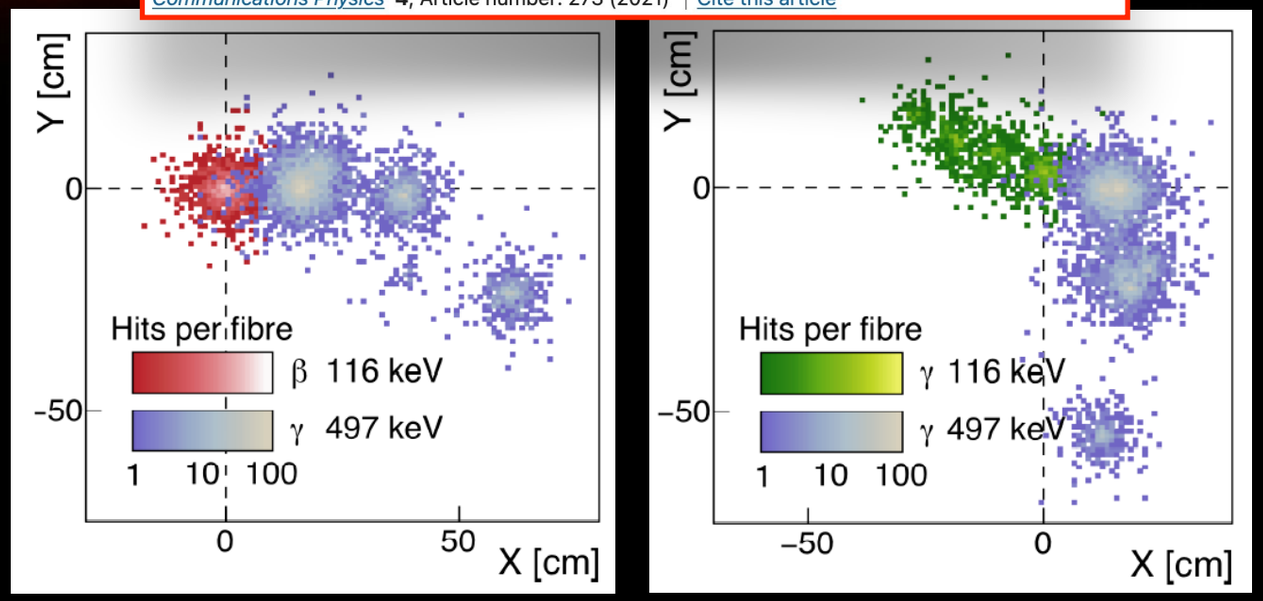
3D coincidence (like IBD) @ 90% efficiency

- time-based rejection: ~10^{-5}
- position-based rejection: ~10^{-6} (vertex: few mm)
- energy-delay rejection: ≤10^{-2} (≥100PE/MeV)

Bremsstrahlung: worsen selection (**understudy**)

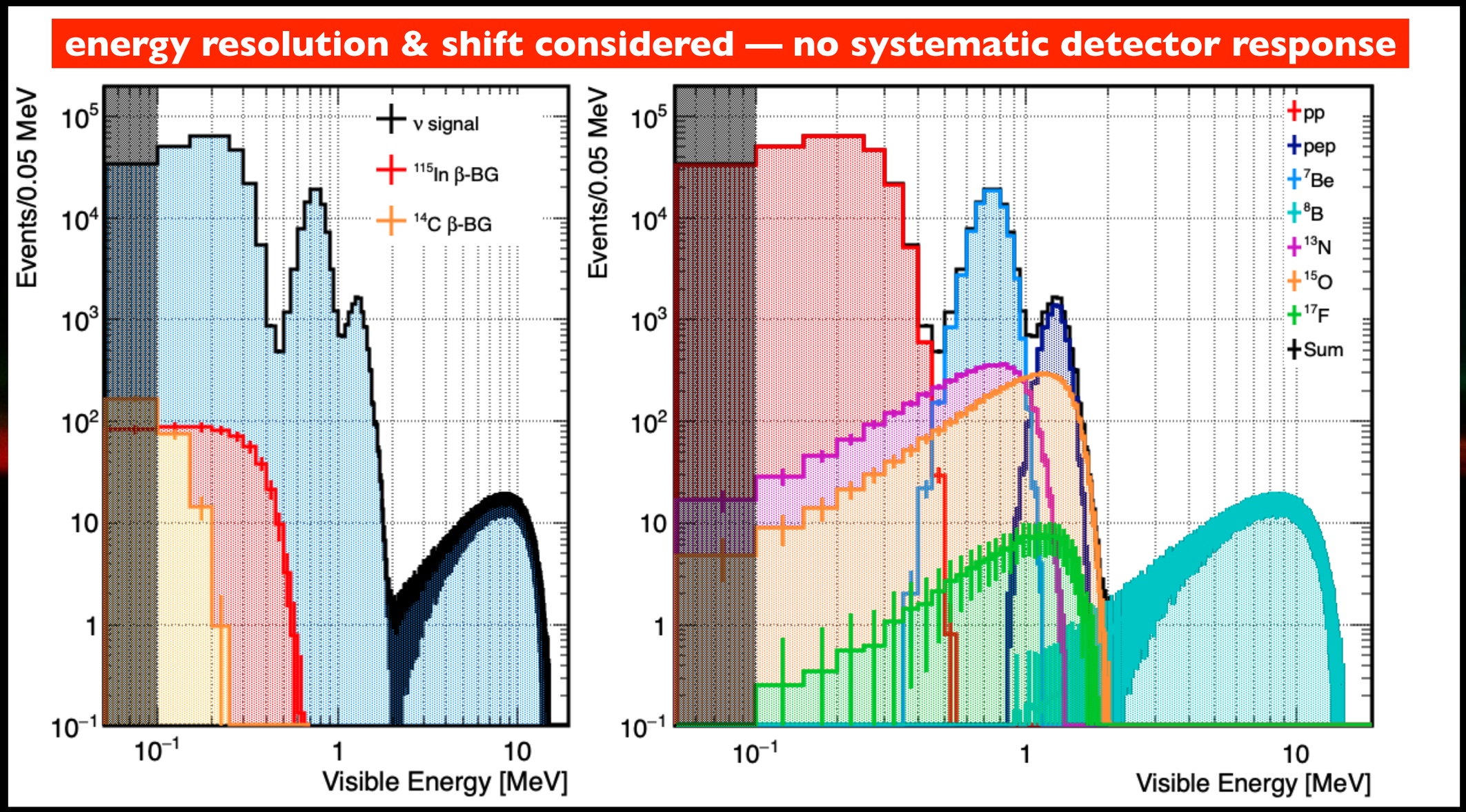
Loading **In** in scintillator studied for long — 10% OK!!

Signal to BG ≥10! ≤0.5MeV [past: **LENS R&D ~3**]



⟹ essentially **background-less solar-neutrino detection** (radio-purity only ~10^{-15}g/g)

solar spectra extraction…



Signal to BG ≥10x
(BG only ≤0.5MeV)

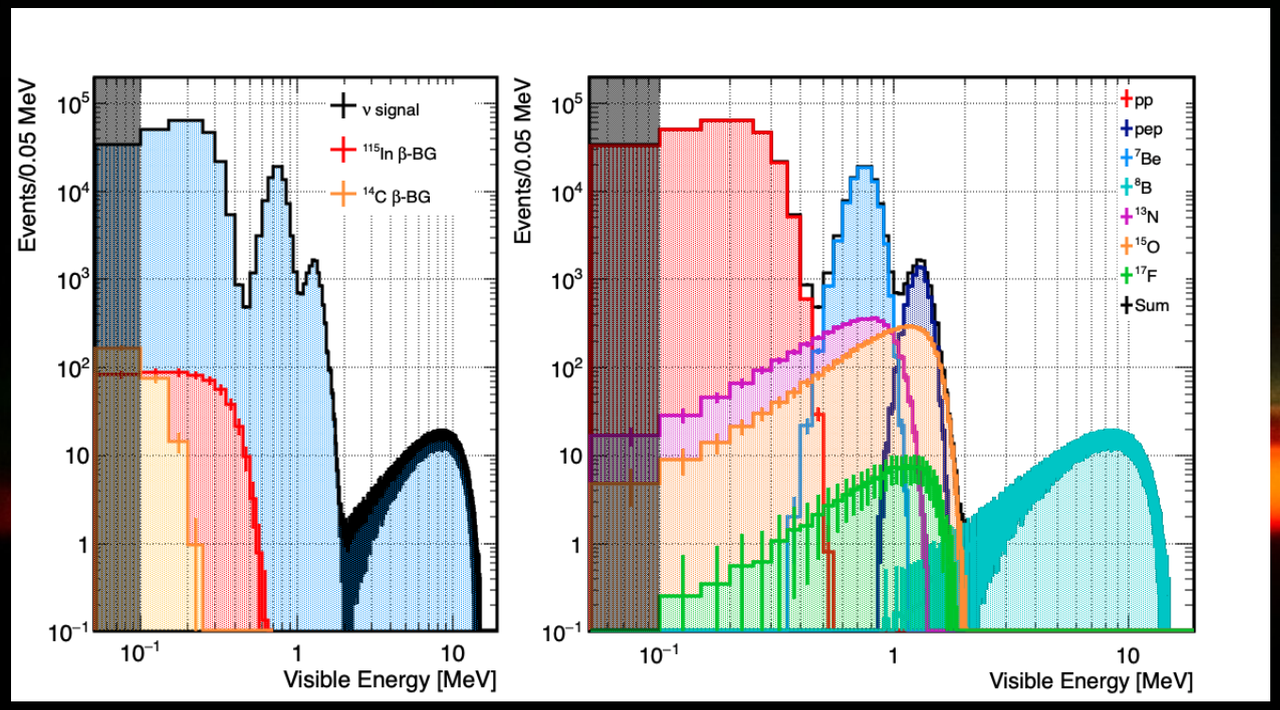
[**missing Bremsstralung**]

Full Spectral Information:

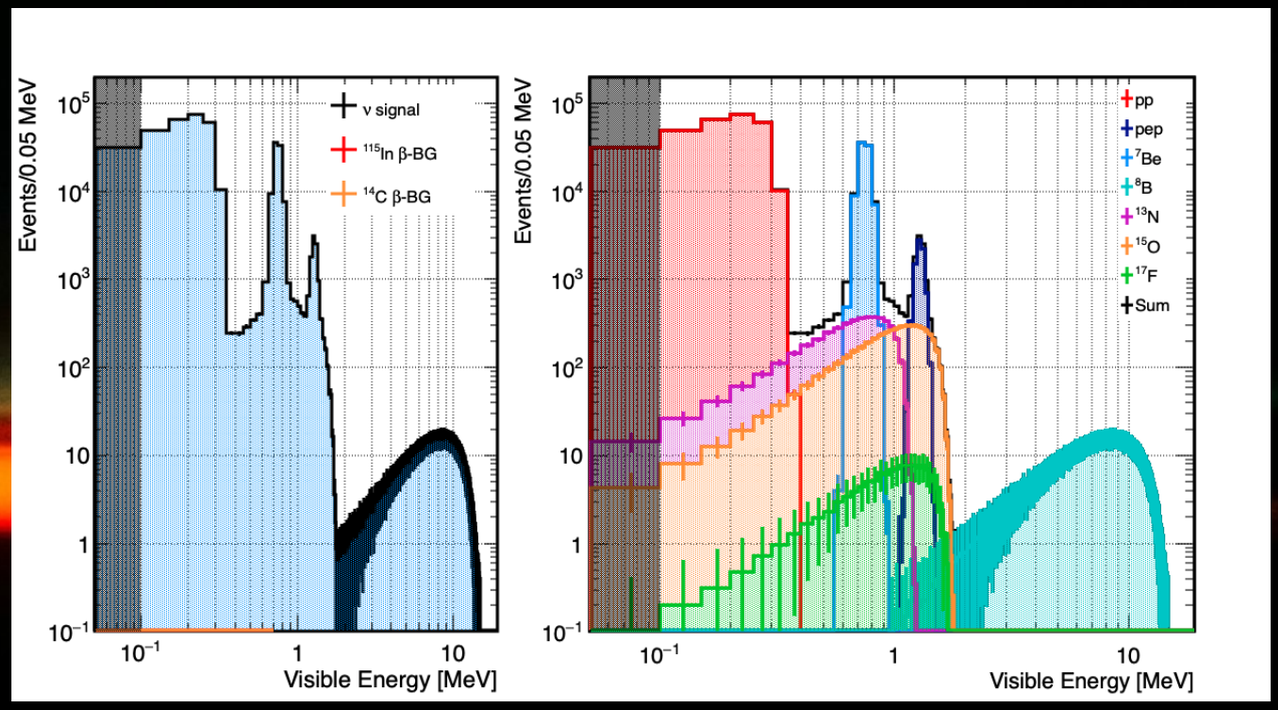
- Neutrino Energy (CC interaction)
- High Statistics: **10%** (In loading) x **10 years**
- Light level: **≥100PE/MeV** (thershold: 0.1MeV)

solar spectra knowledge…

higher light levels expected — 100PE/MeV considered as most pessimistic scenario



light yield 100PE/MeV
(pessimistic)

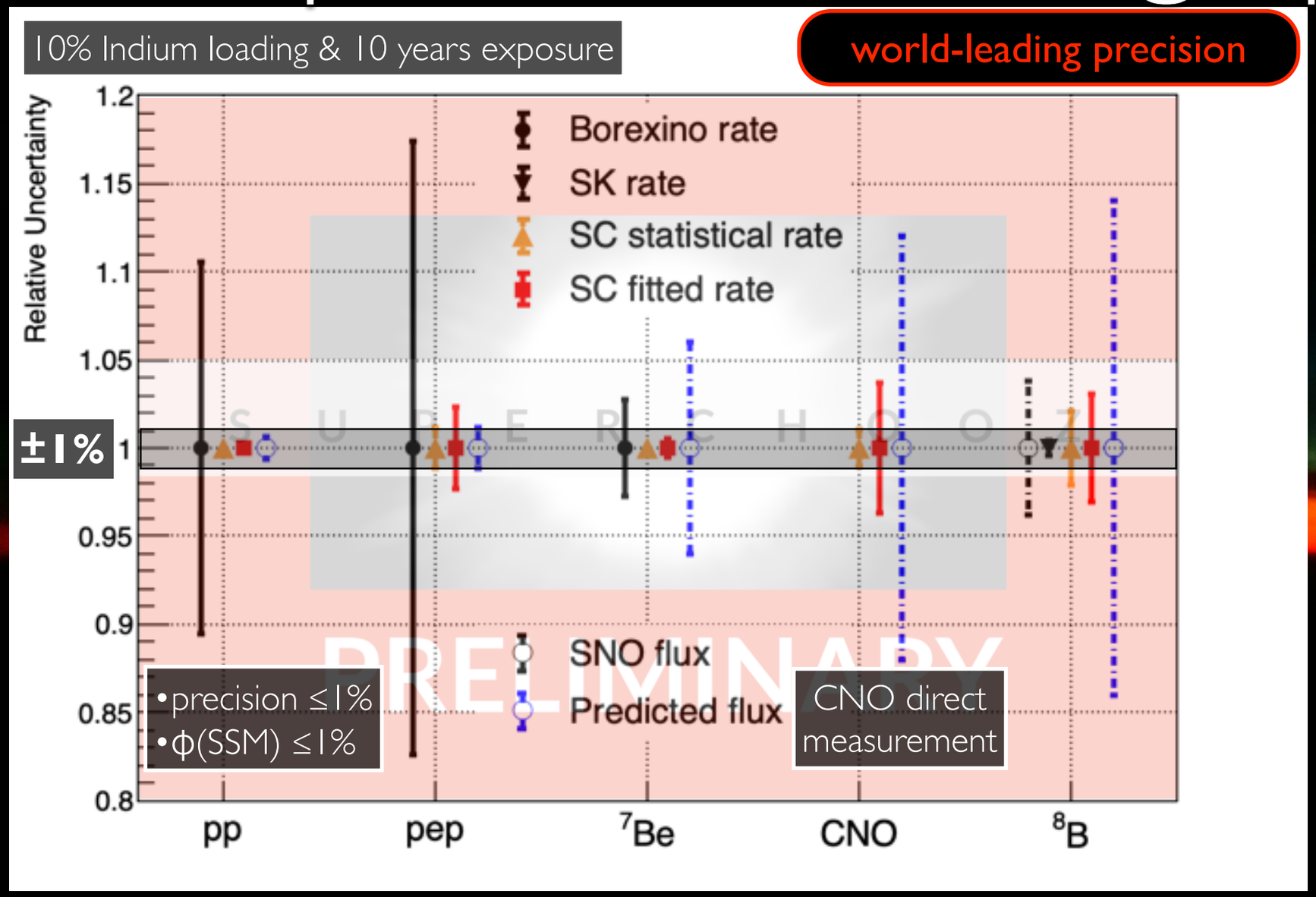


light yield 500PE/MeV
(too optimistic?)

higher light yield optimisation (>100PE/MeV) — scintillator R&D

- better selection: <u>even higher Signal-to-BG</u> — even pp may go "BG-less"?
- better spectral resolution → better <u>CNO direct sensitivity</u> (else under pp⊕^{7}Be⊕pep)

solar spectra knowledge potential…



potential: all spectra measurement precisions better than SSM predictions (HZ vs LZ)

Event Rates (10% load)
- **pp: ~250,000** [0.2%]
- **pep: ~7,700** [1.1%]
- **^{7}Be: ~85,000** [0.3%]
- **CNO: ~9,700** [<2%]
- **^{8}B: ~2,200** — good by SK!
- **hep: ~4** — unlikely

Prediction:
- **SSM HZ & LZ**
- **SNO-NC** for **ϕ(^{8}B)**

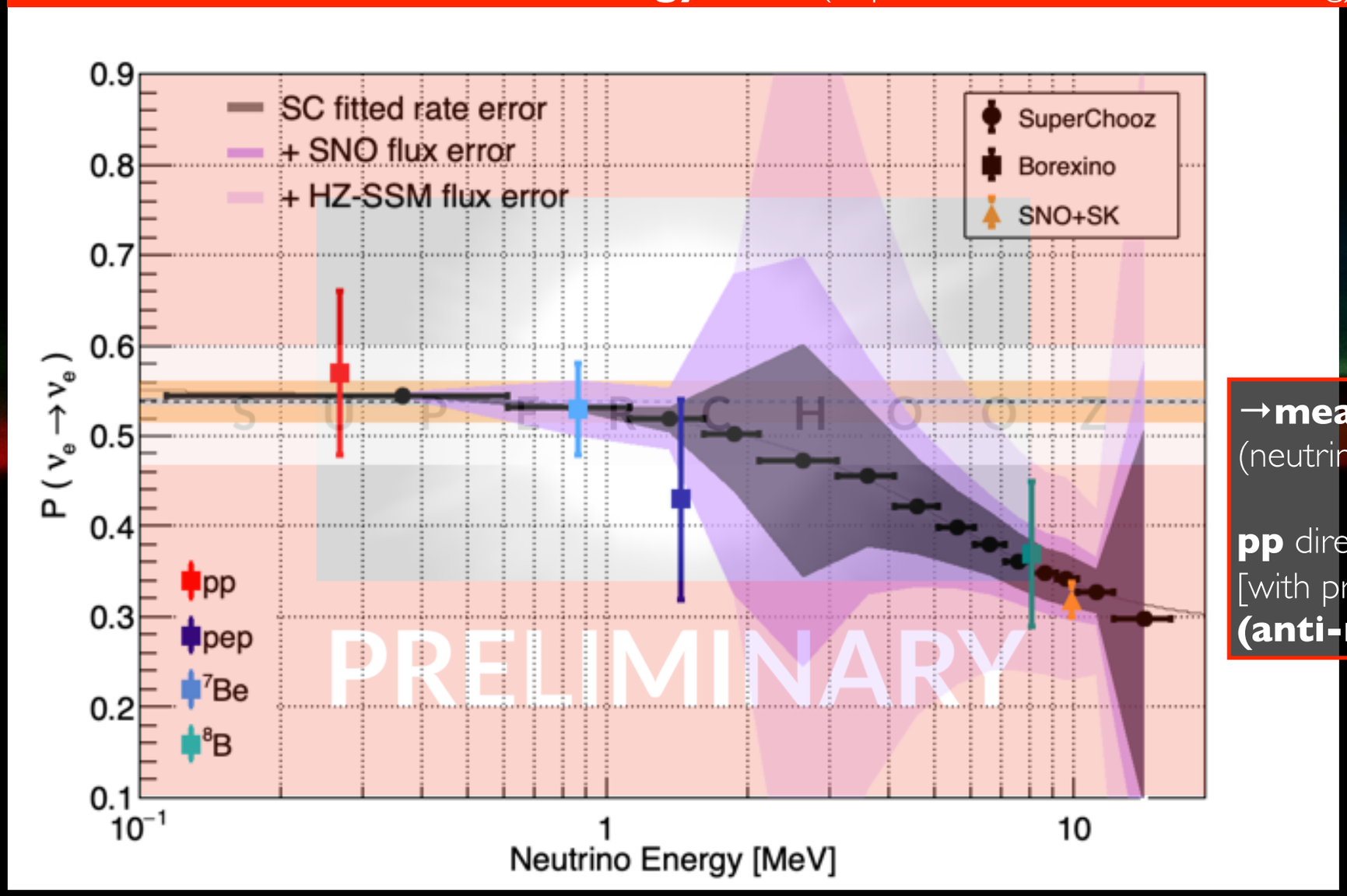
note: σ(In) ≤ σ(ESS)

low systematics (fiducial volume, efficiency, energy, In-fraction, etc) → **under final evaluation**

ISSUE: exclusive In cross-section knowledge? Possible ~1%? [a la Ga]

solar oscillation transition…

In-interaction: neutrino energy scan (impossible for elastics scattering)



→measure θ12 & δm²!
(neutrino)

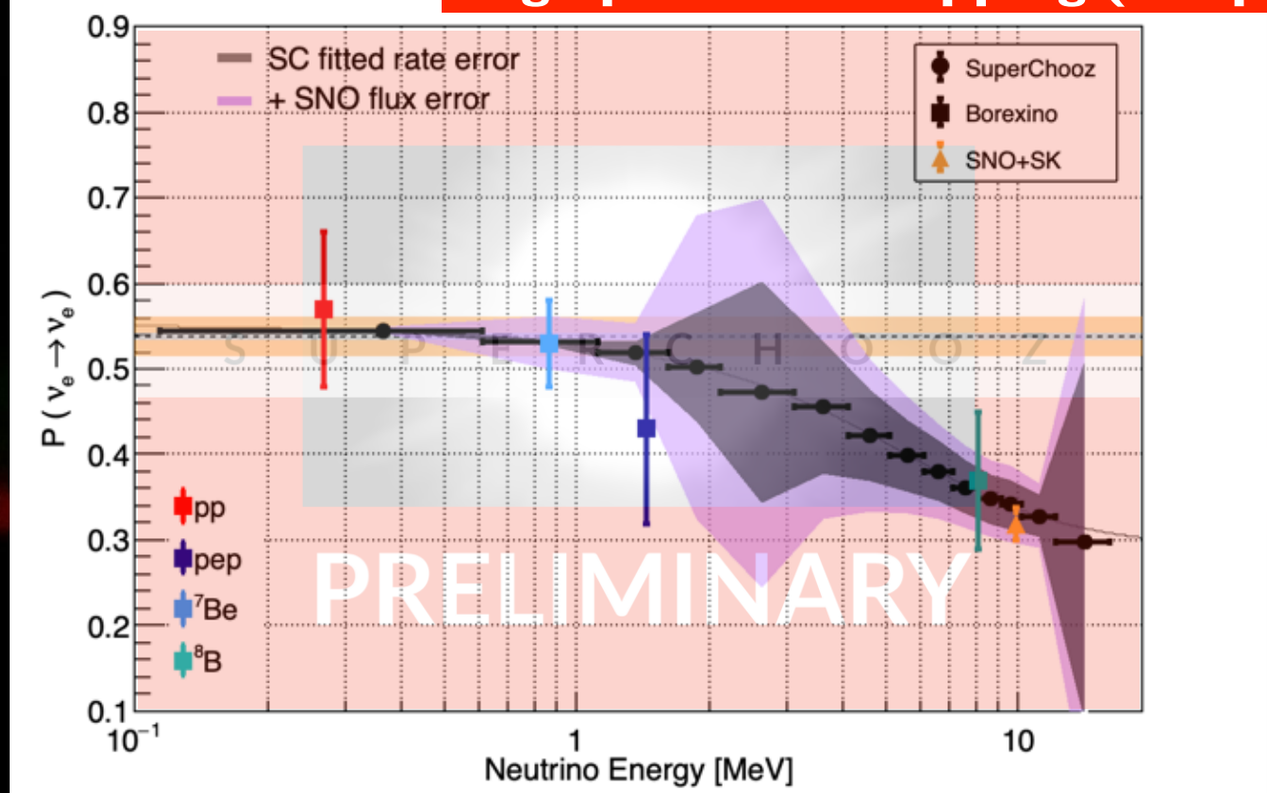
pp direct comparison with JUNO
[with precision ≤0.5%]
(anti-neutrino)

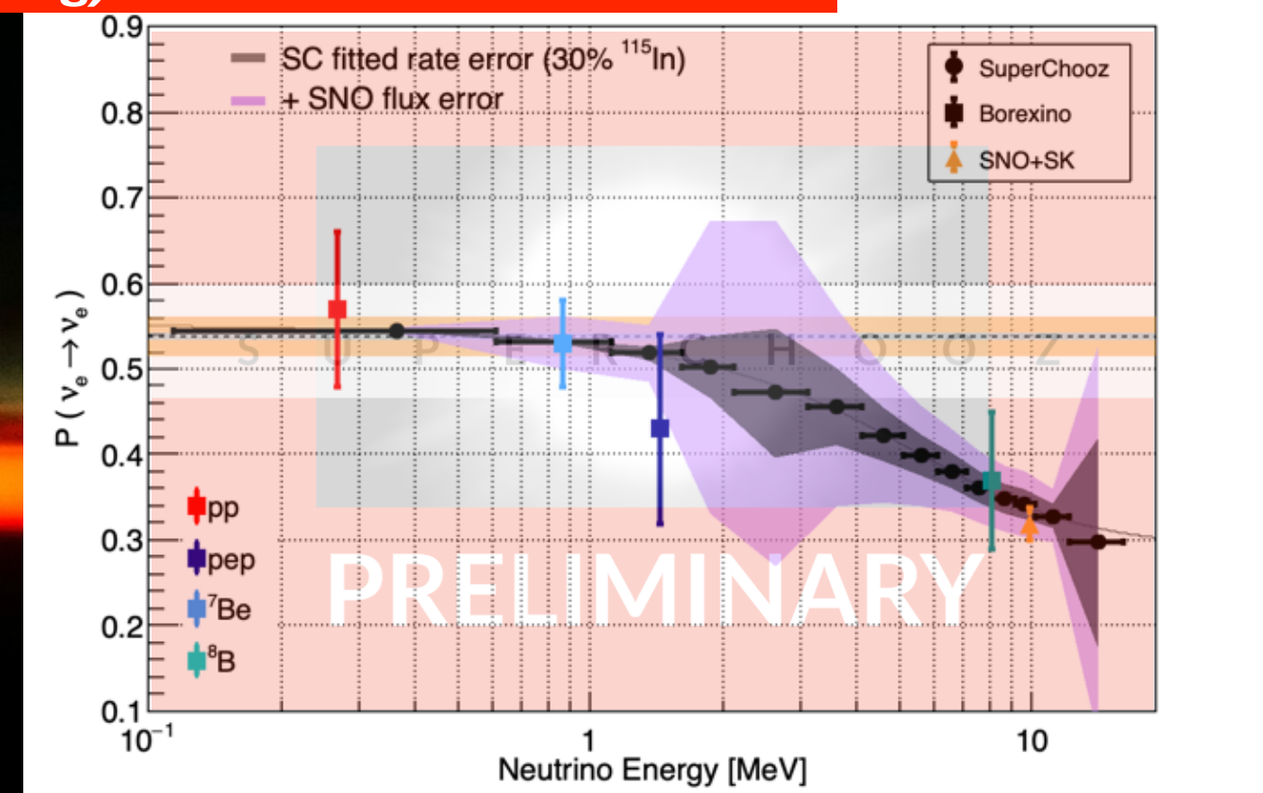
solar neutrinos: longest baseline neutrino with few % precision→ new physics?

use ϕ(SNO-NC) for ^{8}B control [1.5,10] MeV — ultimate limitation?

improving transition precision…

high precision mapping (~~sampling~~) of the "MSW" transition?





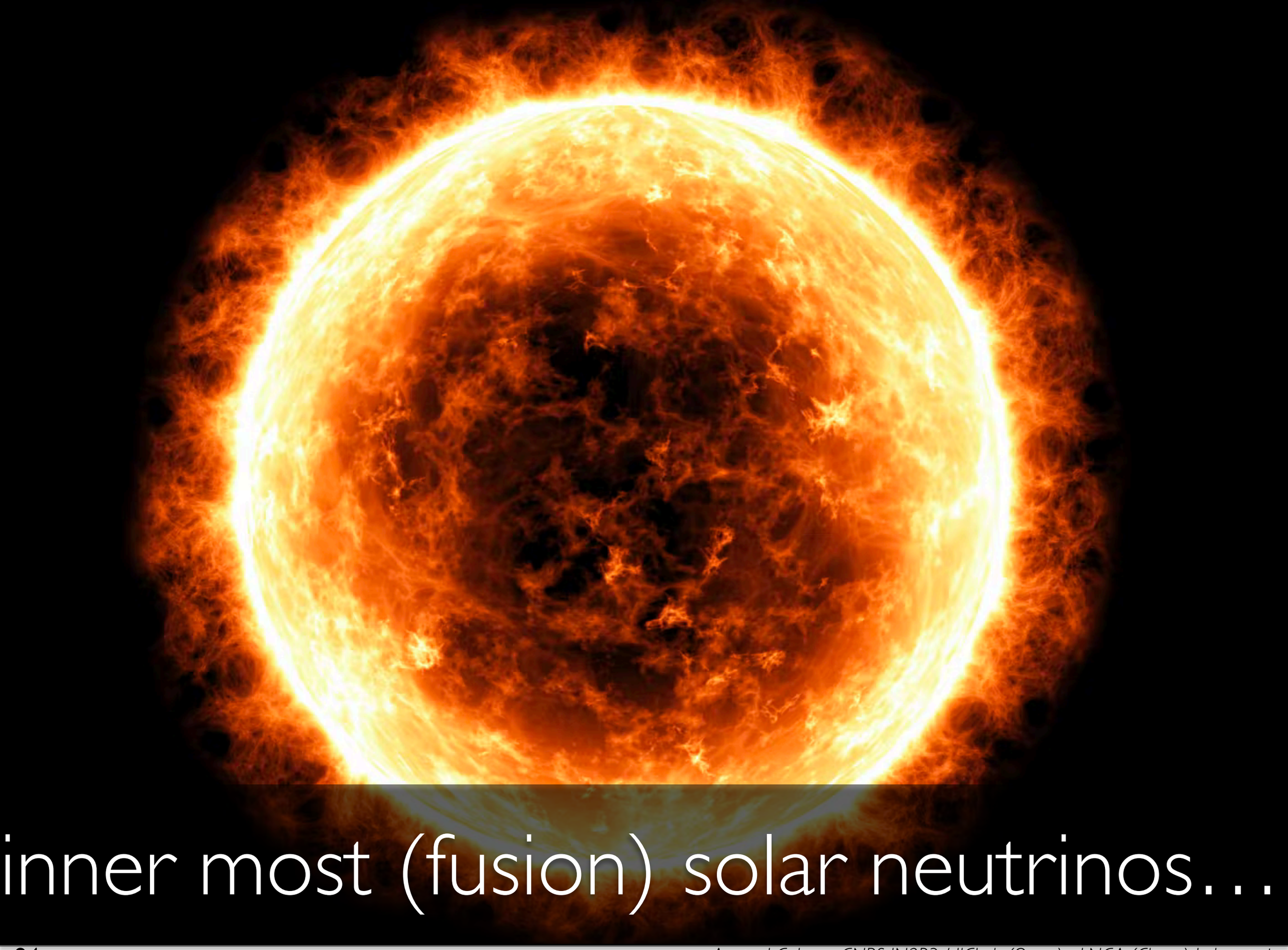
Indium loading: 10% [→LENS]

(light yield 100PE/MeV)

Indium loading: 30% [→R&D]

(light yield 100PE/MeV)

using **SNO-NC: $\phi(^8B)$ [≤5%]** instead of **SMM prediction [12%]**



inner most (fusion) solar neutrinos…

why solar neutrino's θ_{12} & δm^2 ?

- world most precise neutrino θ_{12}! [δm^2?]
- compare to anti-neutrino θ_{12} (JUNO)

$\Longrightarrow$ unique cross-check of JUNO

- first map (~~sample~~) MSW shape (few %)

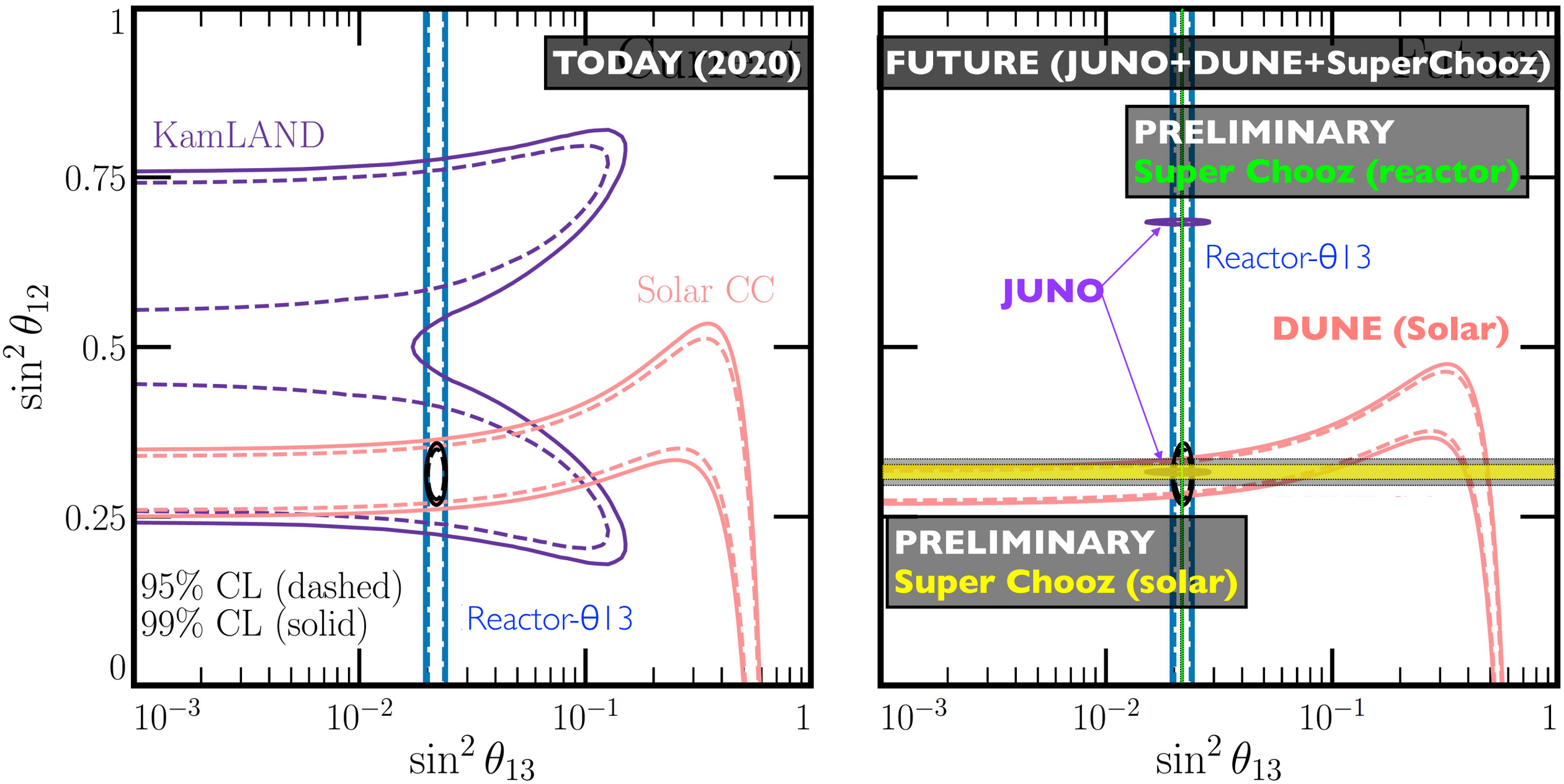
$\Longrightarrow$ new interactions? [BSM]

- cross-check of JUNO's δm^2

physics III: reactor⊕solar inputs...

Super Chooz potential under investigation…

Plot: hacked version from original in ***Ellis, Kelly & Weishi-Li at* arXiv:2008.01088**



Super Chooz: the smallest but powerful…

combining solar $\oplus$ reactor info

- compare to JUNO's anti-neutrino θ_{12}

$\Longrightarrow$ direct CPT violation (BSM) discovery potential

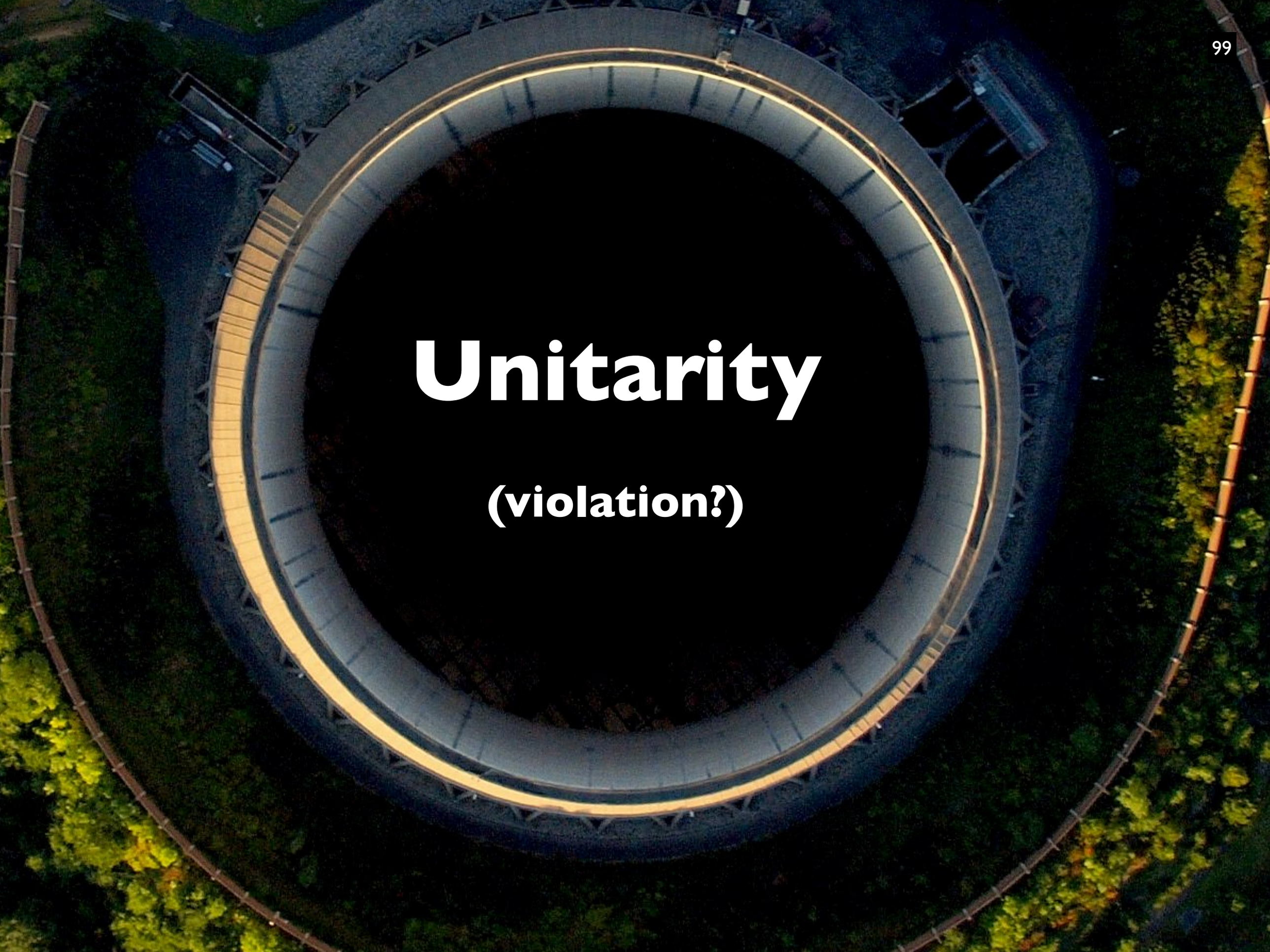
- pp for unitarity violation (BSM)

$\Longrightarrow$ flux known to ~0.6% discovery potential

- improve reactor flux <1%?

$\Longrightarrow$ prove unitarity violation (BSM)

discovery potential



Unitarity

(violation?)

unitarity is behind all our definitions…

UNITARITY implies…

- **IF 3 neutrino standard states — non-standard cases?**

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

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

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

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

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

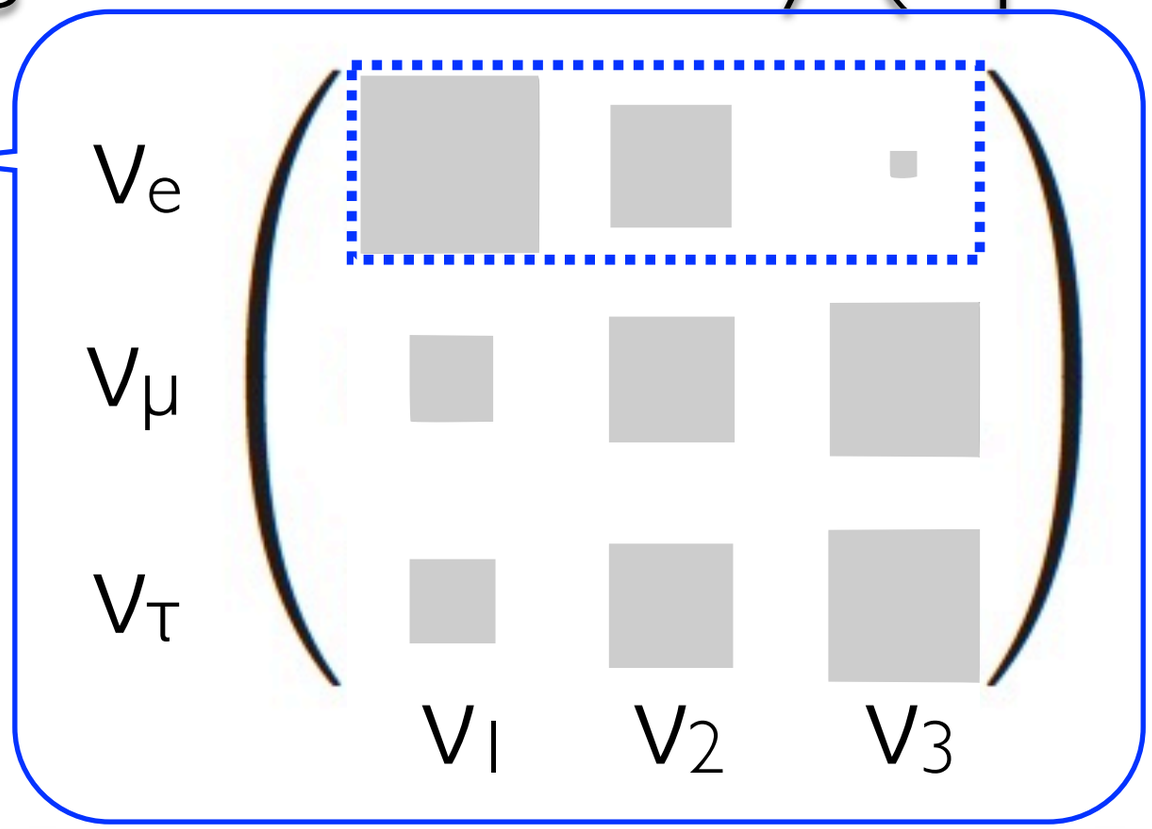
if 4 families, expect more Δm^2's, θ's or δ_{CP}'s → **3x3 *effective approximation***

testing **UNITARITY** → **testing for new families + more!!**

(regardless of kinematics)

testing PMNS Unitarity (lepton universality)…

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



⇒ **best precision?**

⇒ **good precision**

⇒ **poorest precision**

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

⇒ **many equations!!**
[**norm** & **triangle-closure**]

since no CPV (yet) ⇒ test Unitarity <u>norm</u> of "each row"

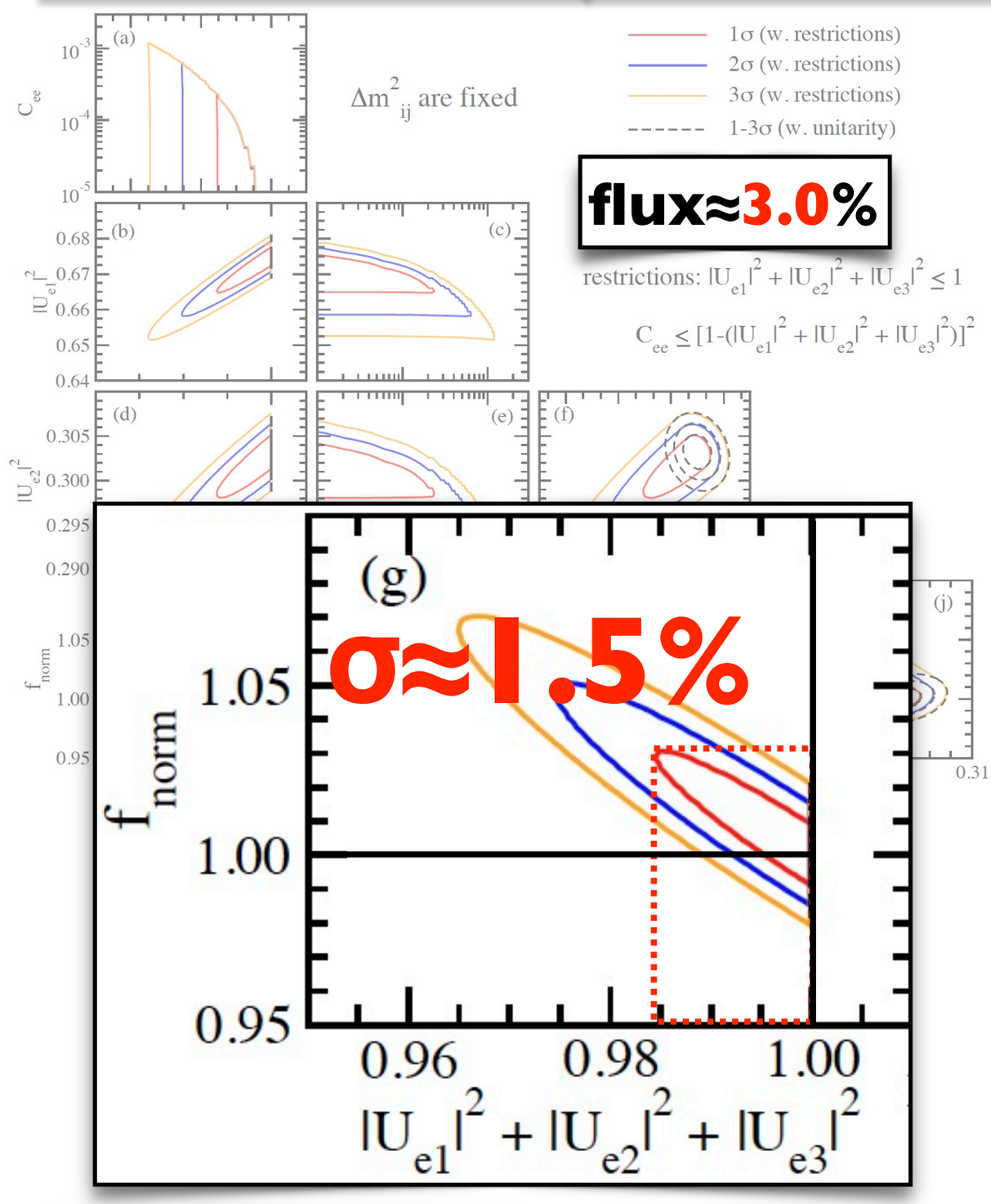
$$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$$

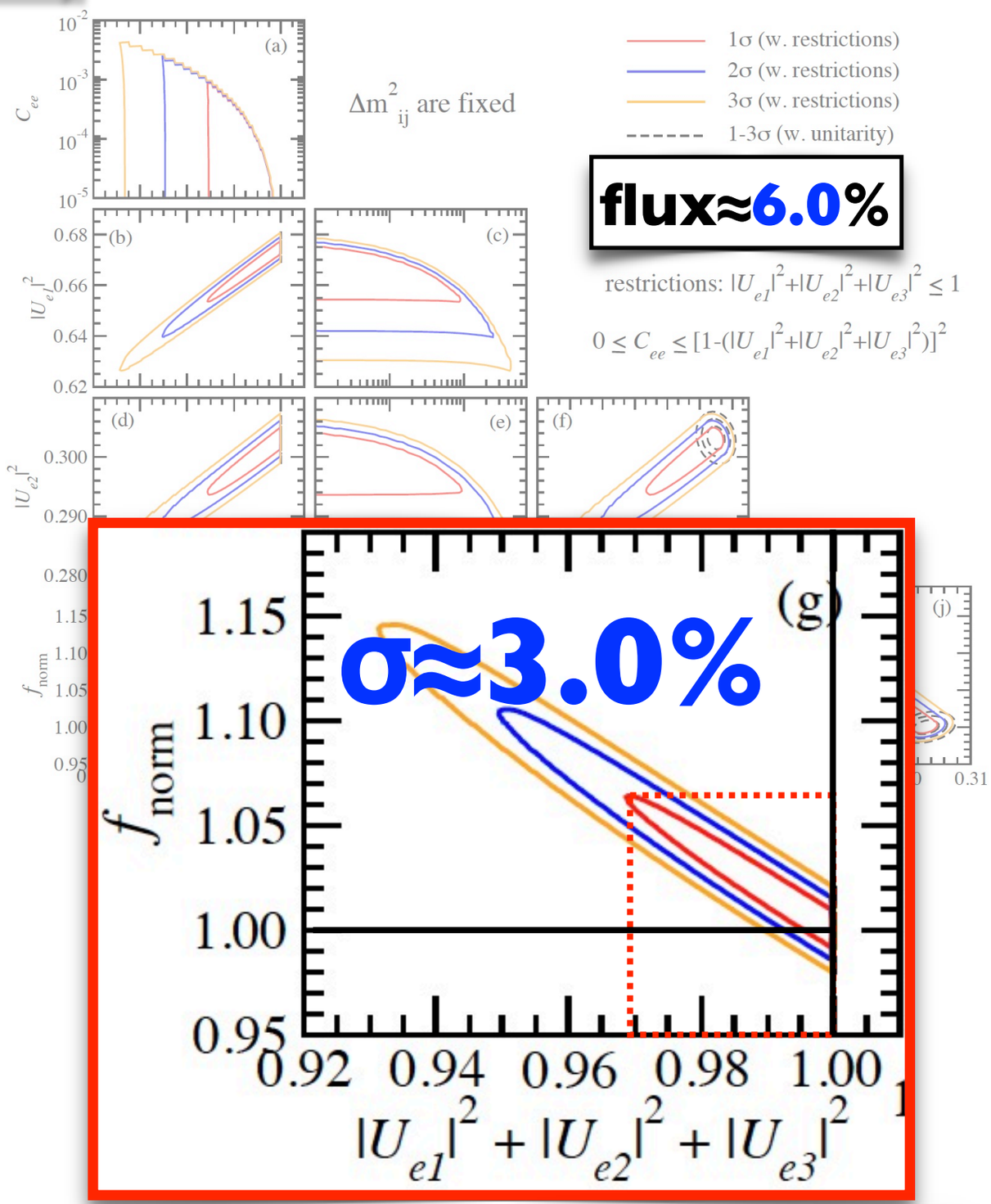
$$|U_{e1}|^2 + |U_{e2}|^2 + |U_{e3}|^2 = 1$$ ⇒ **explore "electron top-row"**

a priori only "θ_{12}" and "θ_{13}"…

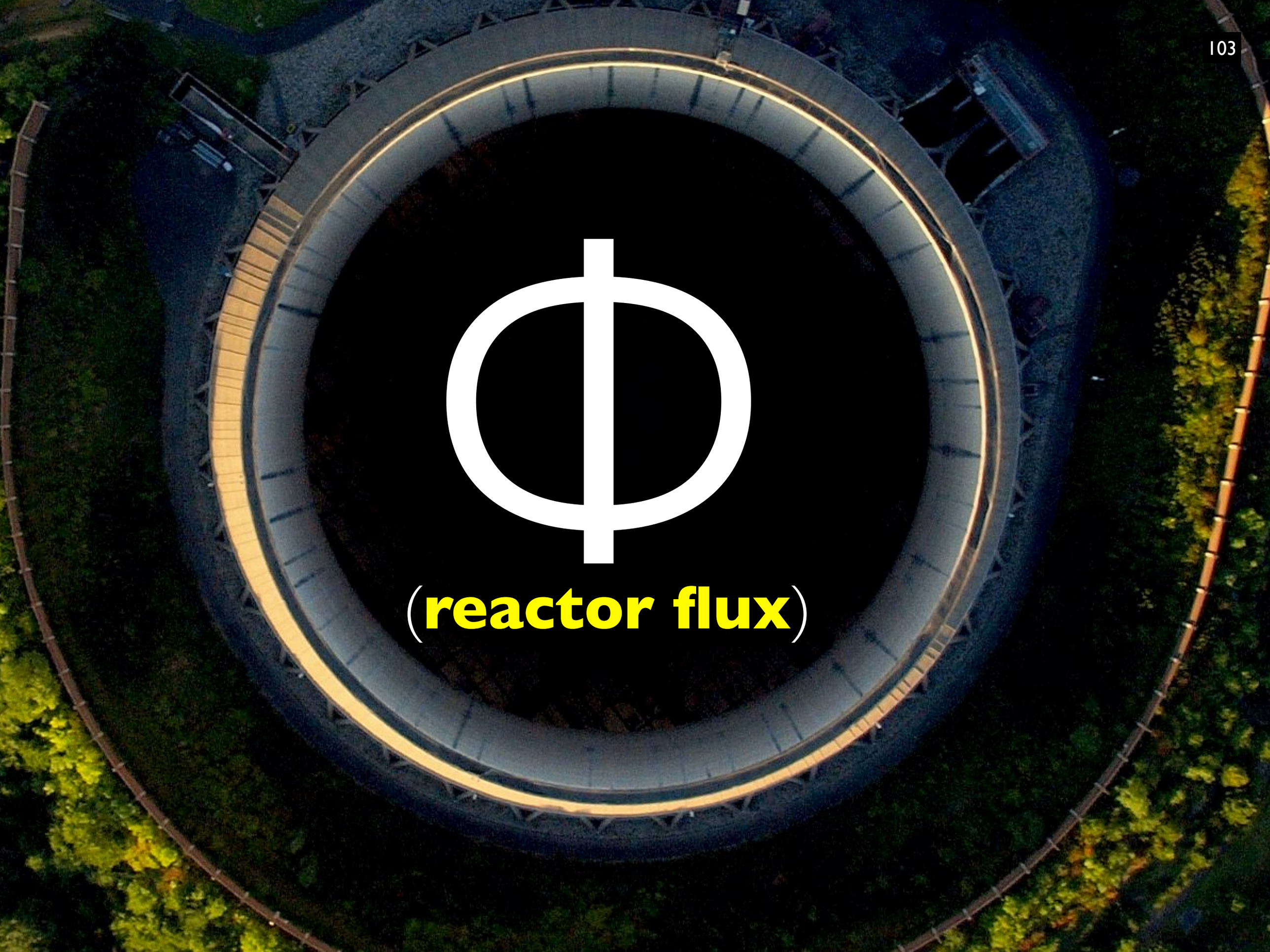
today's (**e-row**) **unitarity** knowledge…

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





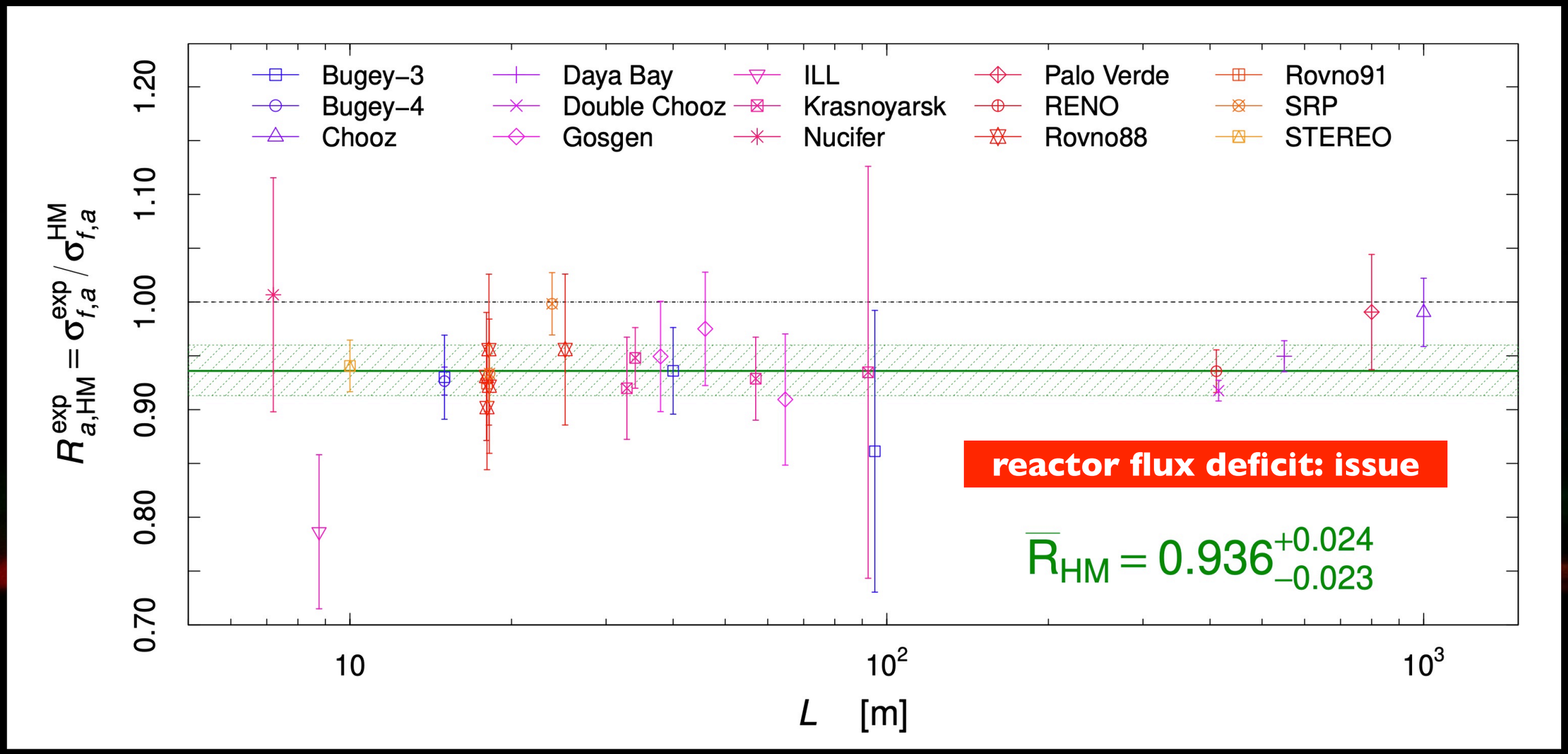
unitary explorations limited by absolute flux uncertainty



Φ

(**reactor flux**)

reactor flux discrepancy…



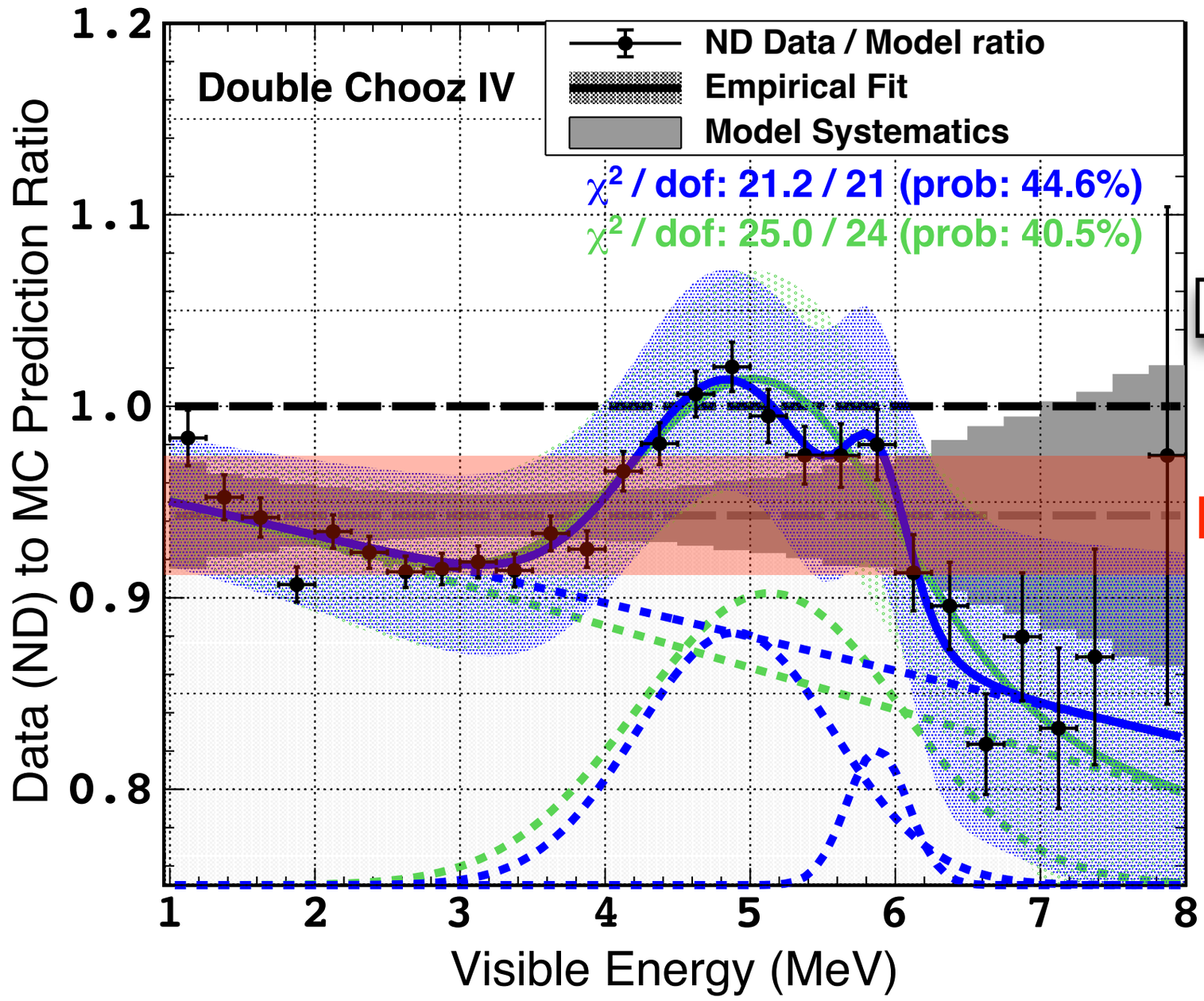
generally excellent agreement <u>among all experiments</u>

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

now ≤7.0% mismatch between ILL-prediction and data

reactor flux uncertainty…

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



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]

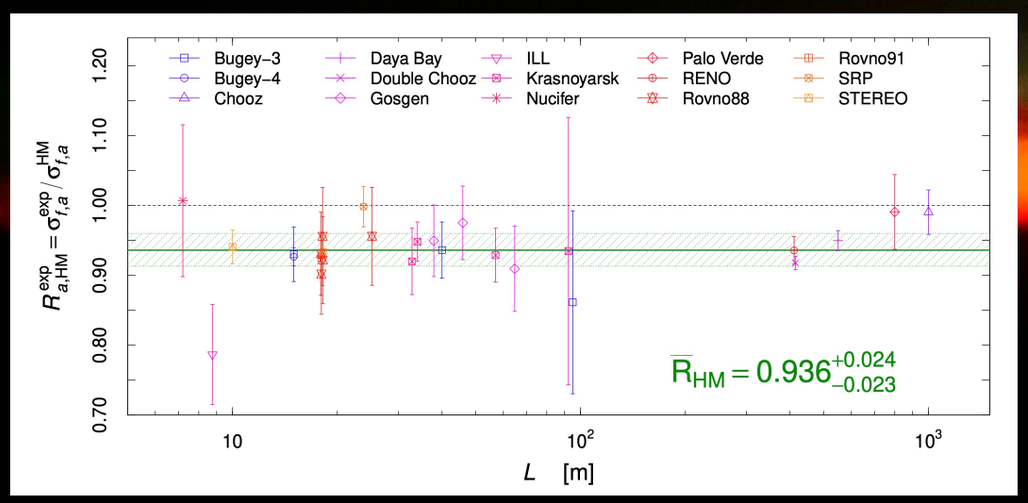
Shape Uncertainty
~2.2%→6.0%?
[**surely <10%**]

nature physics

ARTICLE

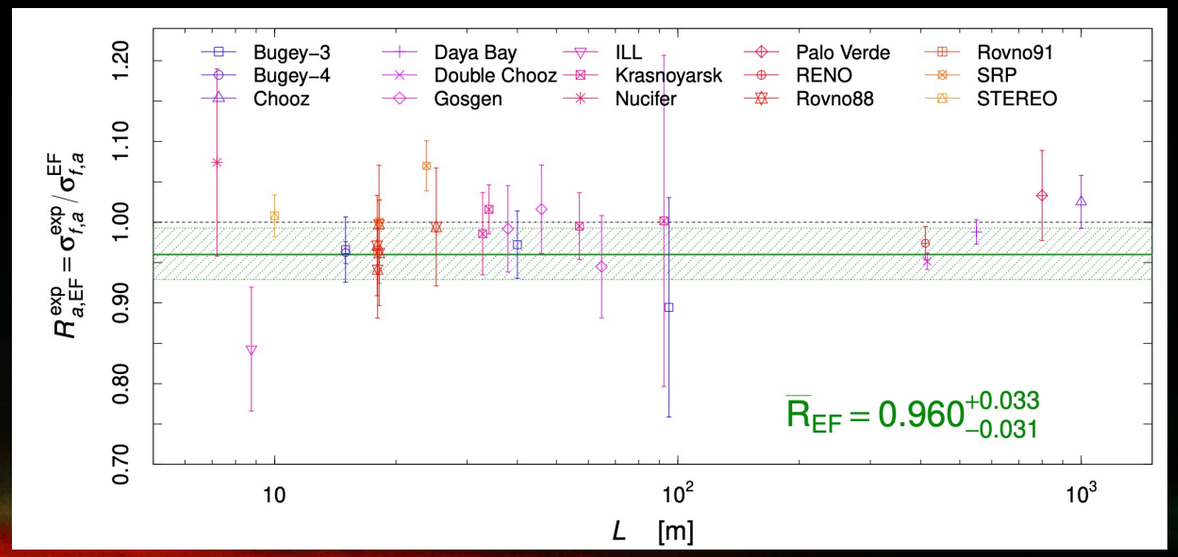
First Double Chooz θ_{13} Measurement via Total Neutron Capture Detection

≥2020 improvements…

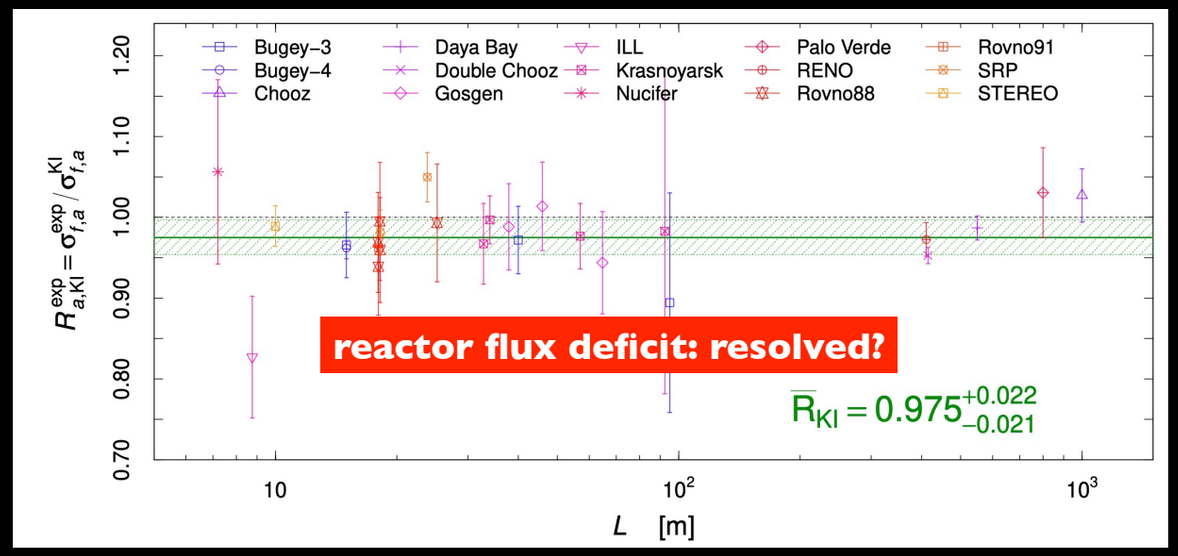


≥2011 → large difference: ≤7%

more data to tune/test the prediction?



≥2020 ab initio estimation
→uncertainties fully understood?



≥2020 conversion (ILL-data based) estimation

status on neutrino oscillation knowledge…

SuperChooz was will improve the ***SM picture*** (3 families) [synergy]

SuperChooz geared to explore the ***SM***'s consistency/completeness→ **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)
θ_{13}	1,8 %	DYB+DC+RENO	1,5 %	**≤0.5%**	**SuperChooz (SC)**	reactor
$+\delta m^2$	2,5 %	KamLAND	2,3 %	<0.5%	JUNO⊕**SC?**	reactor⊕solar
$\lvert\Delta m^2\rvert$	3,0 %	T2K+NOvA & DYB	1,3 %	<0.5%	JUNO⊕DUNE⊕HK⊕**SC**	reactor⊕beam
Mass Ordering	**unknown**	SK et al	NMO @ ≤3σ	@5σ	JUNO⊕DUNE⊕HK (NOvA⊕T2K)	reactor⊕beam
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

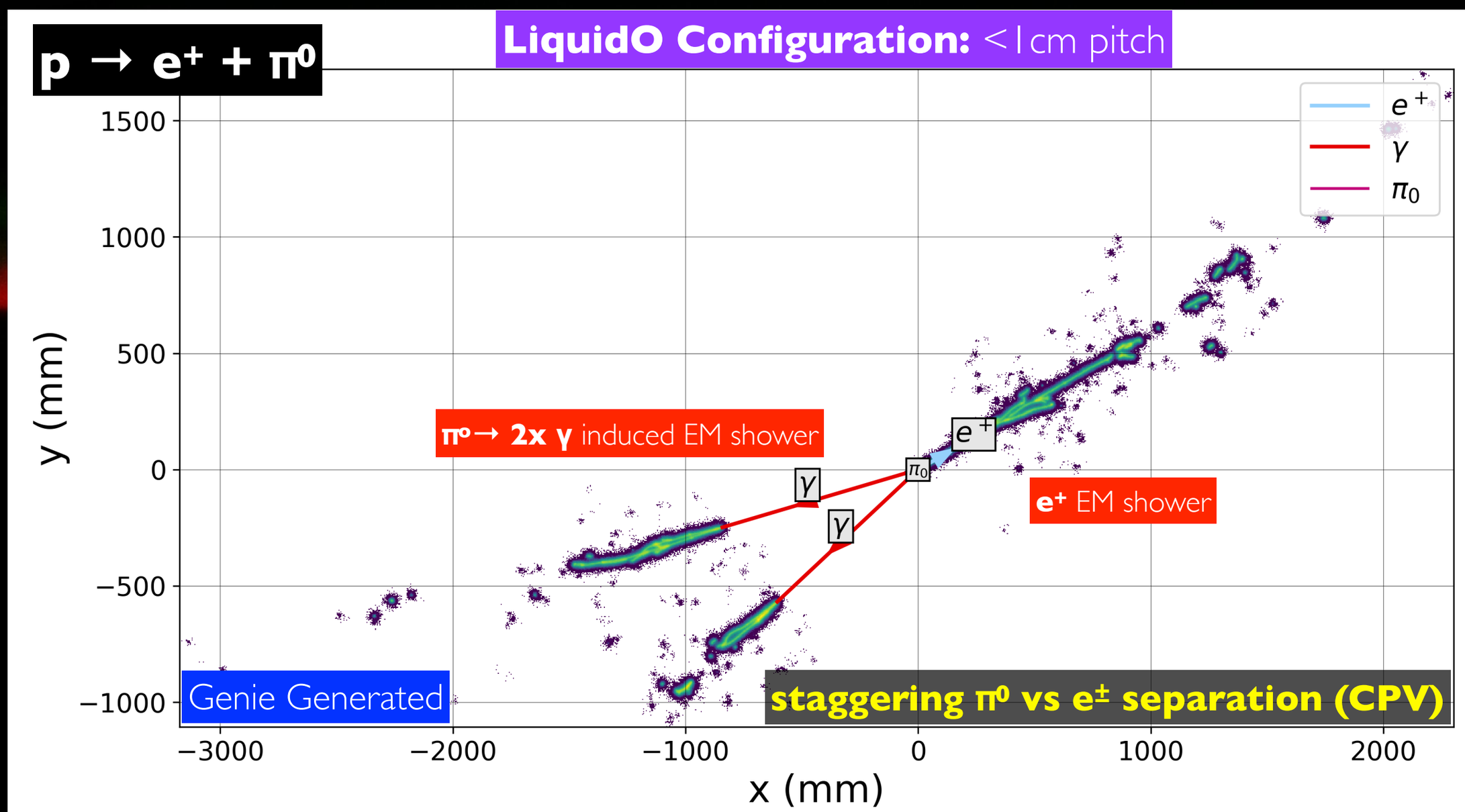
reactor⊕beam & **solar** again via **SC — SC's atmospherics under study… nice!!**

physics IV: other channels...

discovery channels too…

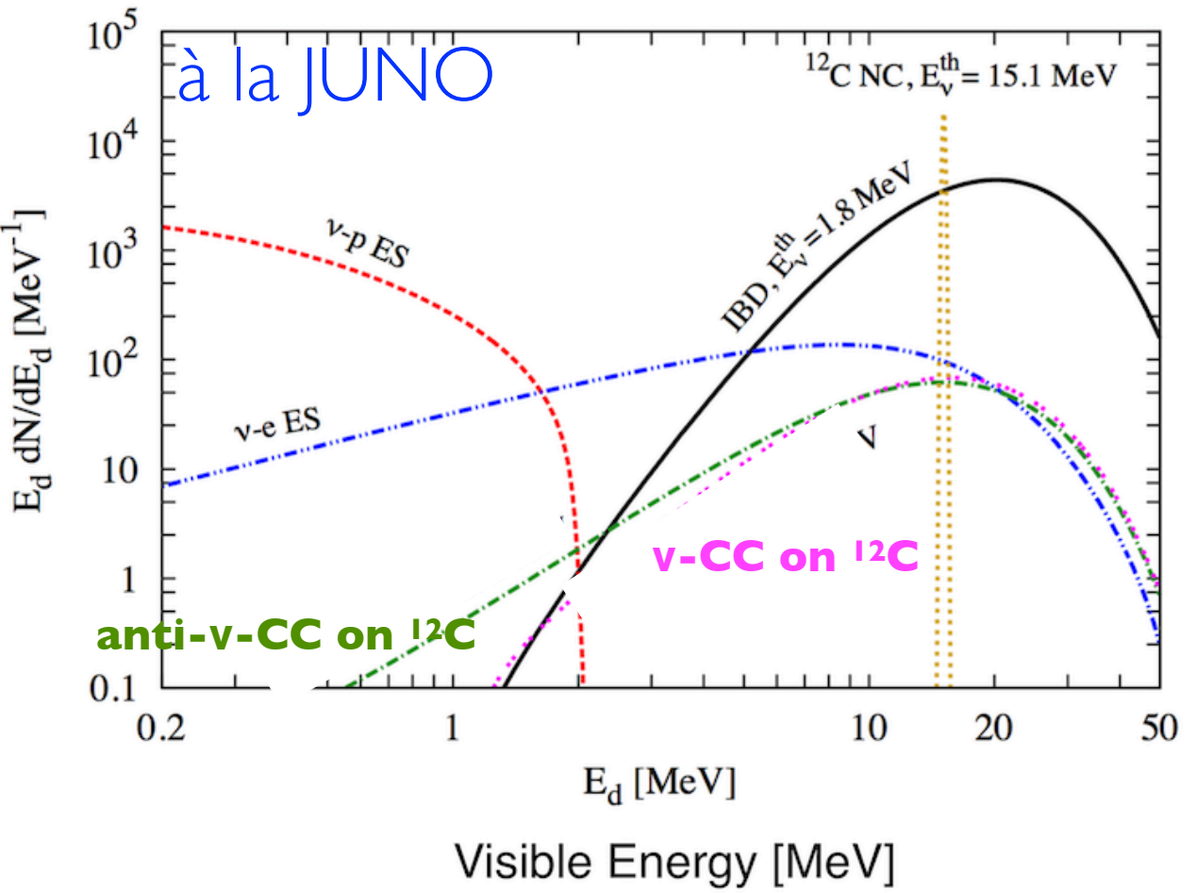
m(proton)**~1 GeV**

free-H per unit of mass:
water: ~10%
scintillator: up to 20%

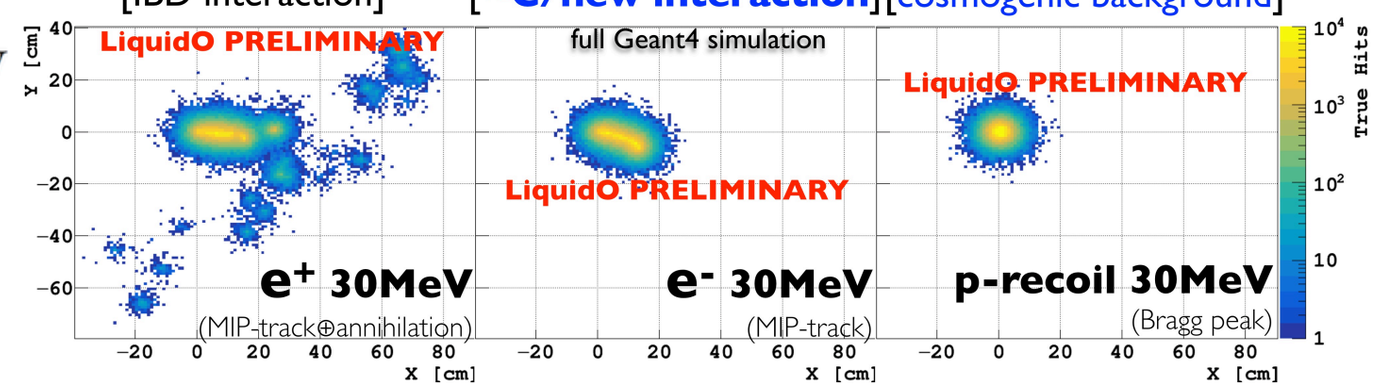


Supernova at 10 kParsec

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



measure **all neutrino types CC, ES & NC** (absolute flux)



main channels(*)...

IBD*	**ν CC (In)***	**ES(p)**
$\bar{\nu}$ CC (^{12}C)	**ES(e)**	**ES(e)** [low energy]
	ν CC (^{12}C)	
↓	↓	↓
core-collapse relic	**core-collapse relic? (hard)**	**core-collapse ~~relic~~**
	(also) **ν NC (^{12}C)***	**fast-neutron (BG)**

supernovae @ SuperChooz...

neutrinos back to Europe?

historical opportunity for Europe's neutrino science (fundamental & innovation)…

S U P E R C H O O Z

pathfinder *(i.e. experimental exploration)*

ICHEP 2022
BOLOGNA

ICHEP 2022 6
XLI 13 07 2022
International Conference
on High Energy Physics
Bologna (Italy)

https://agenda.infn.it/event/28874/contributions/169613/

anatael@in2p3.fr

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

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

S U P E R C H O O Z

pathfinder

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

SuperChooz⊕LiquidO a **new framework for new physics** opportunities — in Europe? [≥2019]

- **SuperChooz**: a possible new neutrino flagship experiment in Europe ["Pathfinder": exploration starting…]
  - **new laboratory** under consideration: studies EDF⊕CNRS — **EDF within neutrino science**
  - new technology: **LiquidO** — performance **proving readiness** **(→results @ Nu2022 conference)**
  - **CLOUD / AM-OTech** (innovation): first demonstrator experiment→ **fundamental physics programme** [synergy with **JUNO** & **HK+DUNE**]→ **several publication in preparation**