tightly linked to **LiquidO**, **AntiMatter-OTech/CLOUD**, and **SuperChooz** team, specially **EDF**

SUPERCHOOZ

European Innovation Council

Seminar @ Università di Padova et INFN-Padova
30 October 2023 — Padova, Italia

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

IJCLab Irène Joliot-Curie
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cnrs
EDF

~50 years of neutrino oscillations…

huge experimental/theory effort

[discovery⊕establishment ⇔ Nobel 2015]

ingredients for **neutrino oscillations**…

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

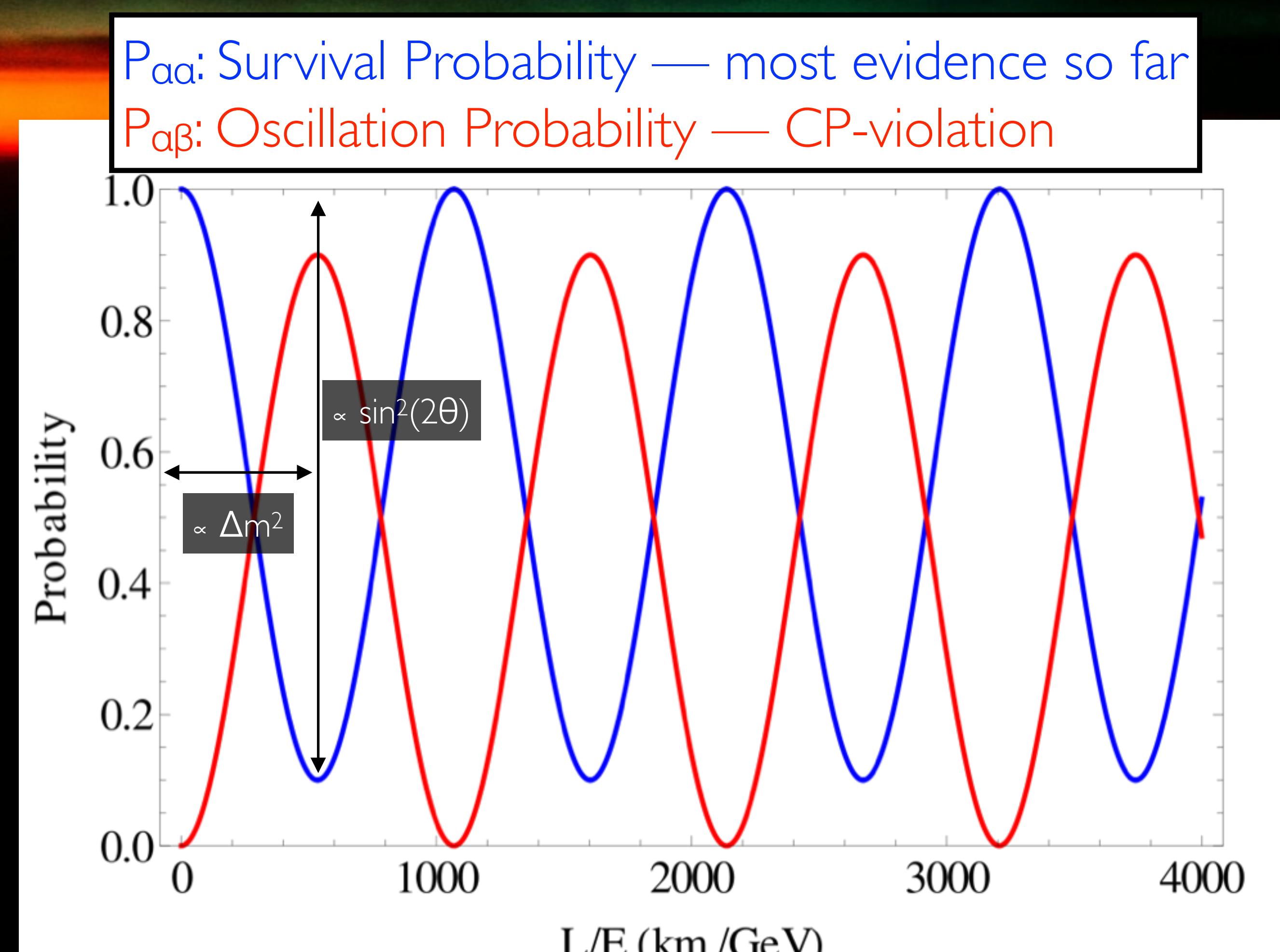
quantum interference (macroscopic)

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



status on neutrino oscillation knowledge…

Standard Model(3 families)
[leptons & quarks]
&
PMNS$_{3x3}$(**θ_{12},θ_{23},θ_{13}**)
&
±Δm² (**±Δm²$_{23}$**) & **+δm²** (**±Δm²$_{12}$**)

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

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

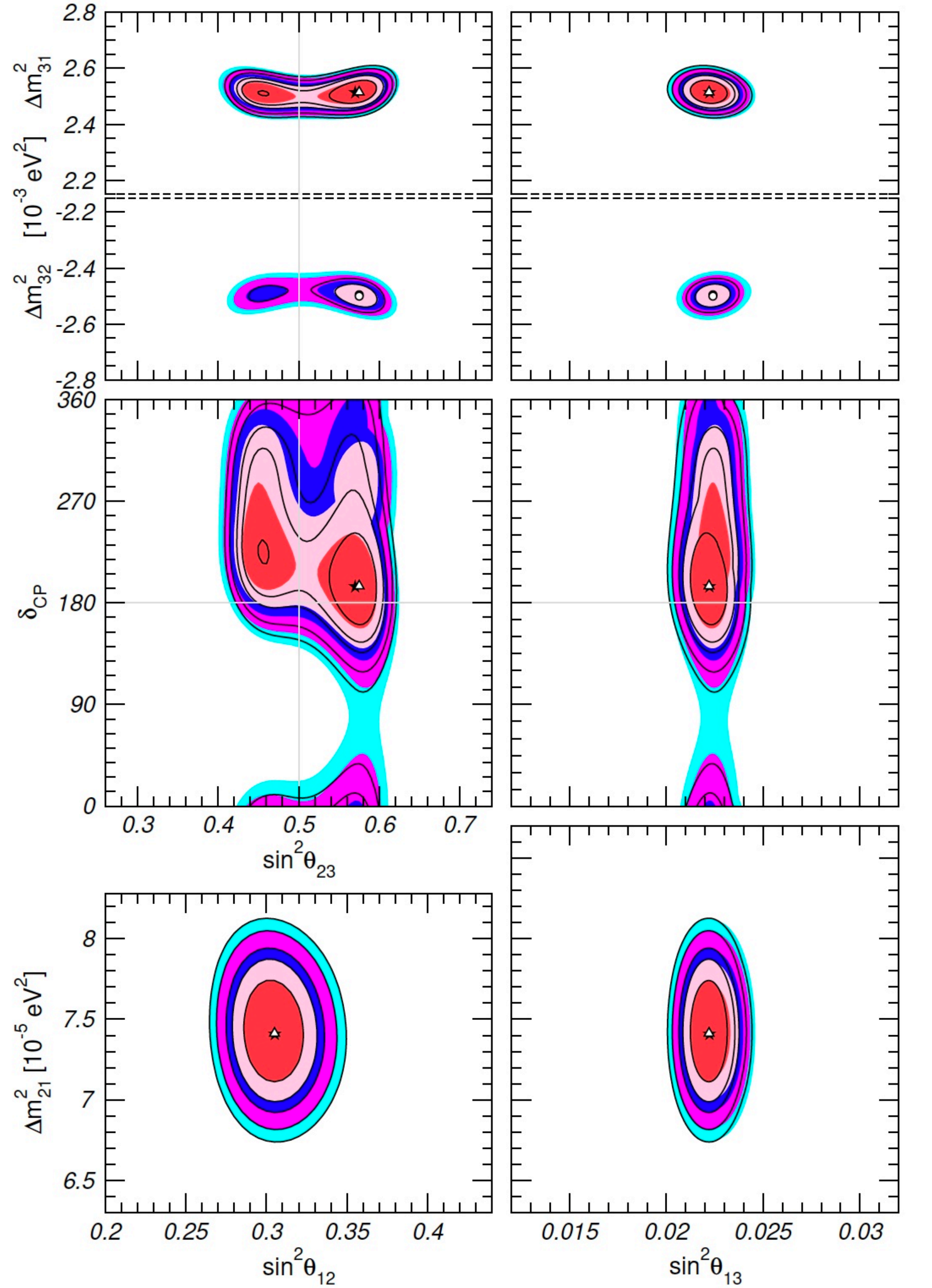
	today			≥2030		
	best knowledge		global	foreseen	dominant	source
θ_{12}	3.0 %	SK⊕SNO	2.3 %	<1.0%	JUNO	reactor
θ_{23}	5.0 %	NOνA+T2K	2.0 %	≲1.0%	DUNE⊕HK	beam (octant)
θ_{13}	1.8 %	DYB+DC+RENO	**1.5 %**	**1.5 %**	DC⊕DYB⊕RENO	reactor
+δm²	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
|Δm²|	3.0 %	T2K+NOνA & DYB	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)

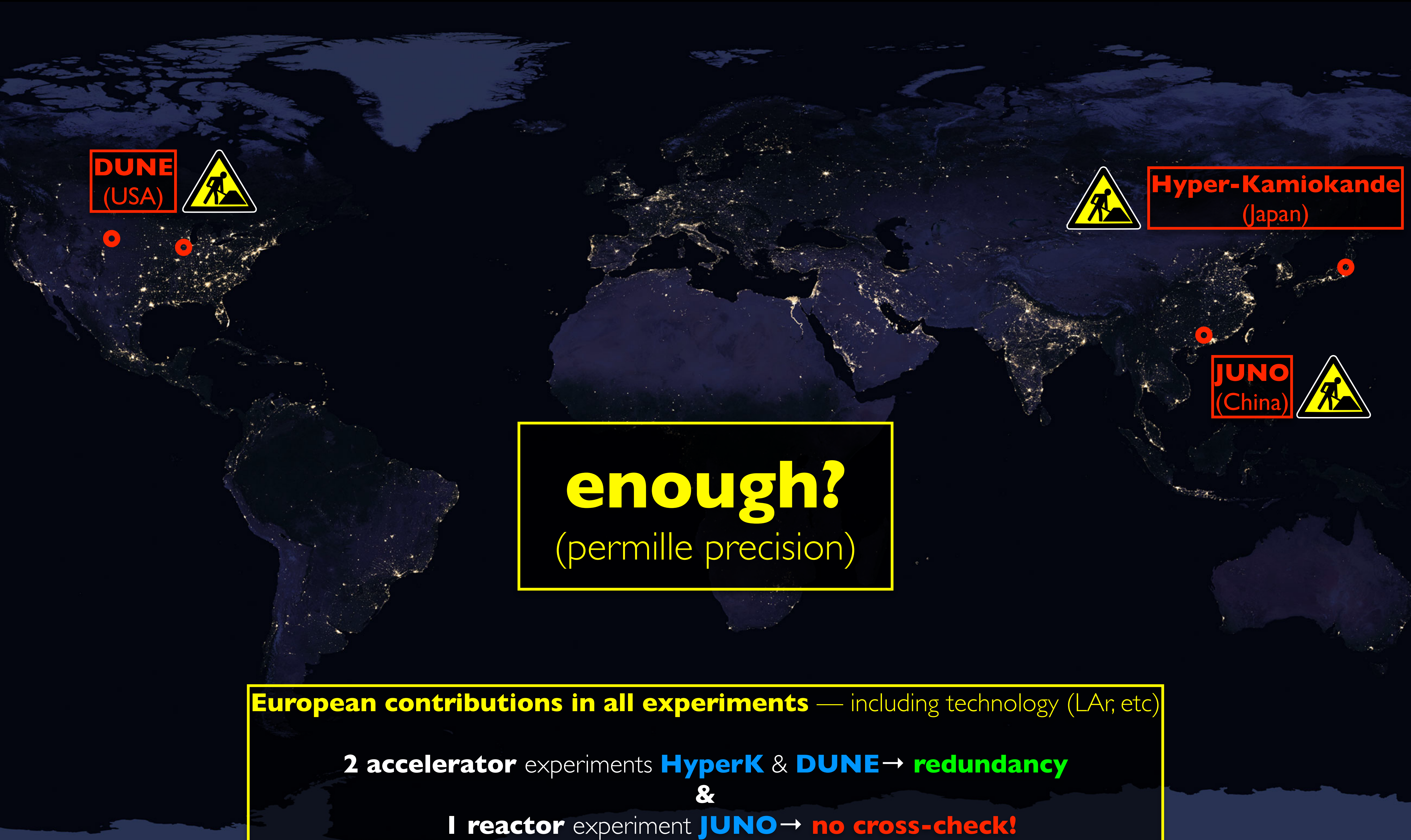


NuFIT 5.0 (2020)

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

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

new **flagship** ν experiments…



enough?
(permille precision)

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

2 accelerator experiments **HyperK** & **DUNE** → **redundancy**
&
1 reactor experiment **JUNO** → **no cross-check!**

neutrinos oscillation : standard picture (SM)

[today's signal = tomorrow's background]

neutrinos to probe BSM ⟶ discoveries?

beyond today's paradigm!

SuperChooz rationale…

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!** [tight cosmology constraints]

SuperChooz?

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] — unknown [*SM*]
- CP-violation parameter (**1**): **δ?** — unknown [*SM*]

JUNO / HyperK / DUNE / SuperChooz?

Mass Squared Differences (**2**): **δm²** (i.e. Δm^2_{12})
Δm² (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*]

JUNO⊕DUNE et al

many

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

ββ

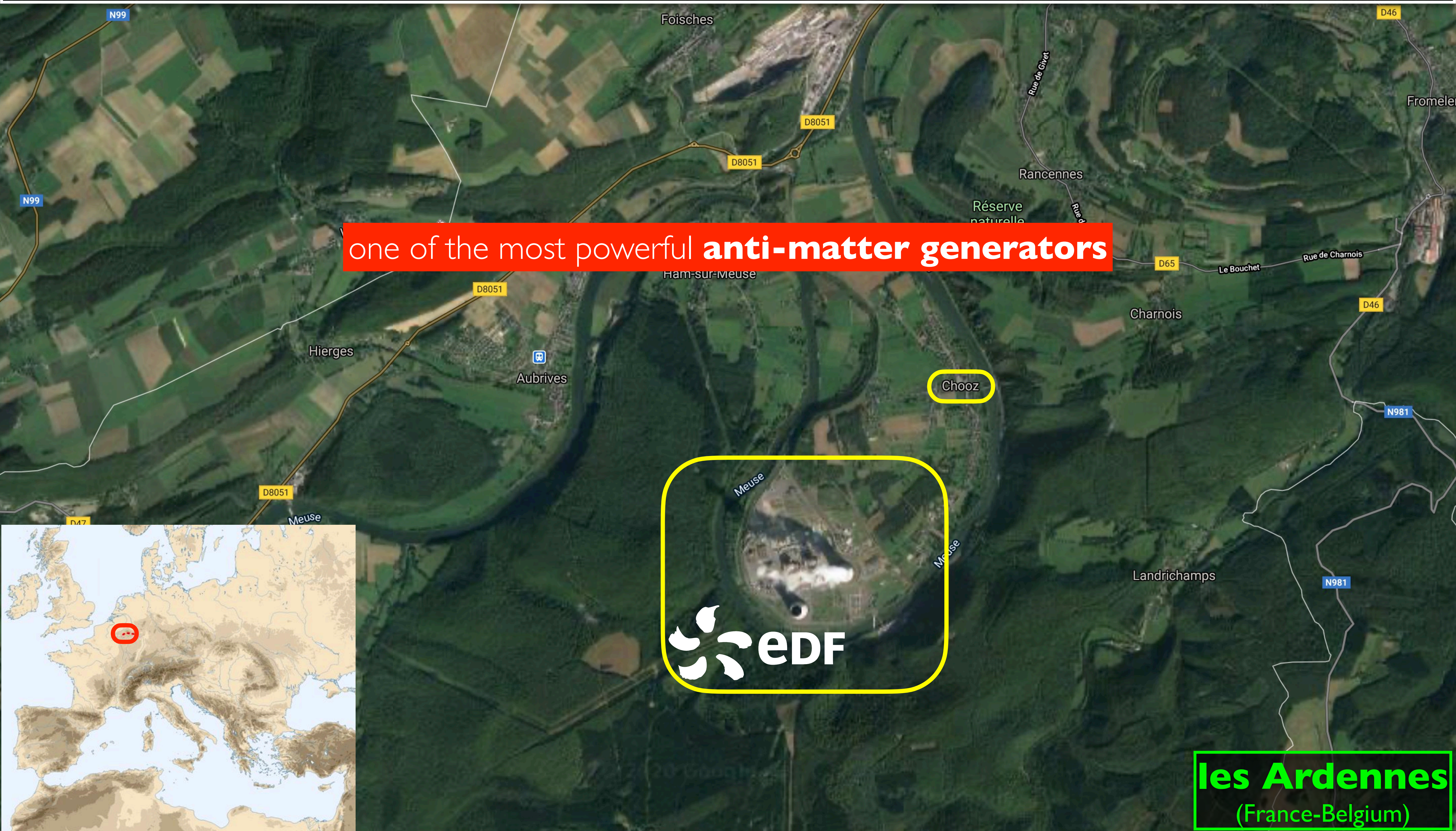
Neutrino Nature: **Majorana?** — discovery!

neutrino unique in Standard Model… **more discoveries?**

SUPERCHOOZ

the new opportunity…

in the **middle of central Europe** (between France-Belgium): **Chooz** [meeting point with Germany, Luxembourg, Netherlands]



Europe's most powerful reactor site…

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

civil-construction near a reactor?

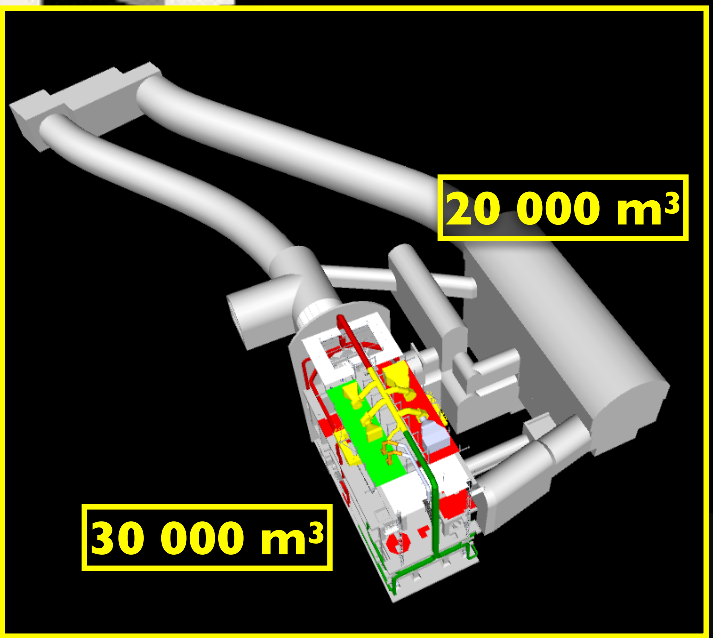
upon **DoubleChooz** underground **laboratories limitations**…

- **too small!**
- **too shallow!** (to today's technology capability)

lesson: don't…!

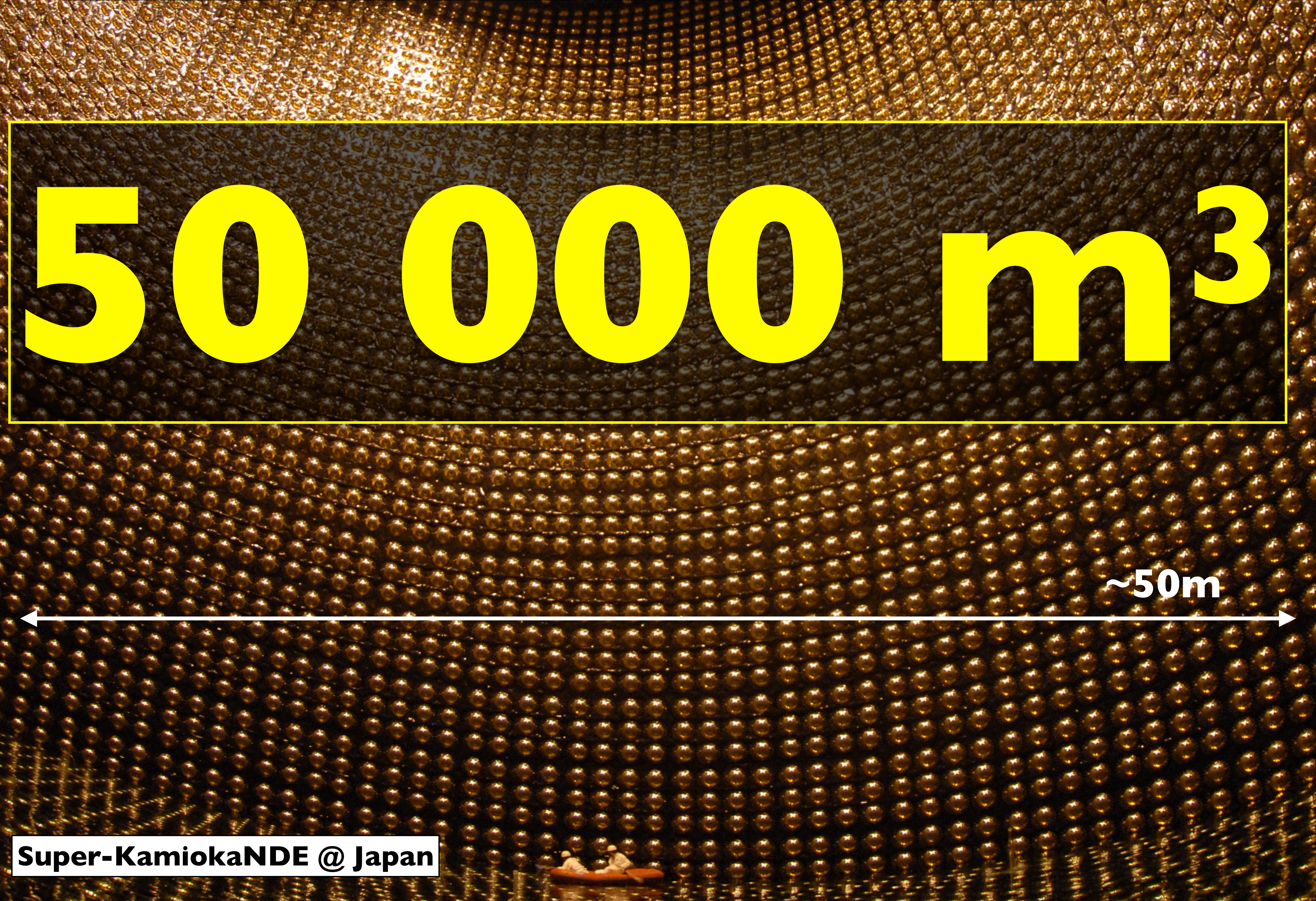
physics at Chooz: **future?**

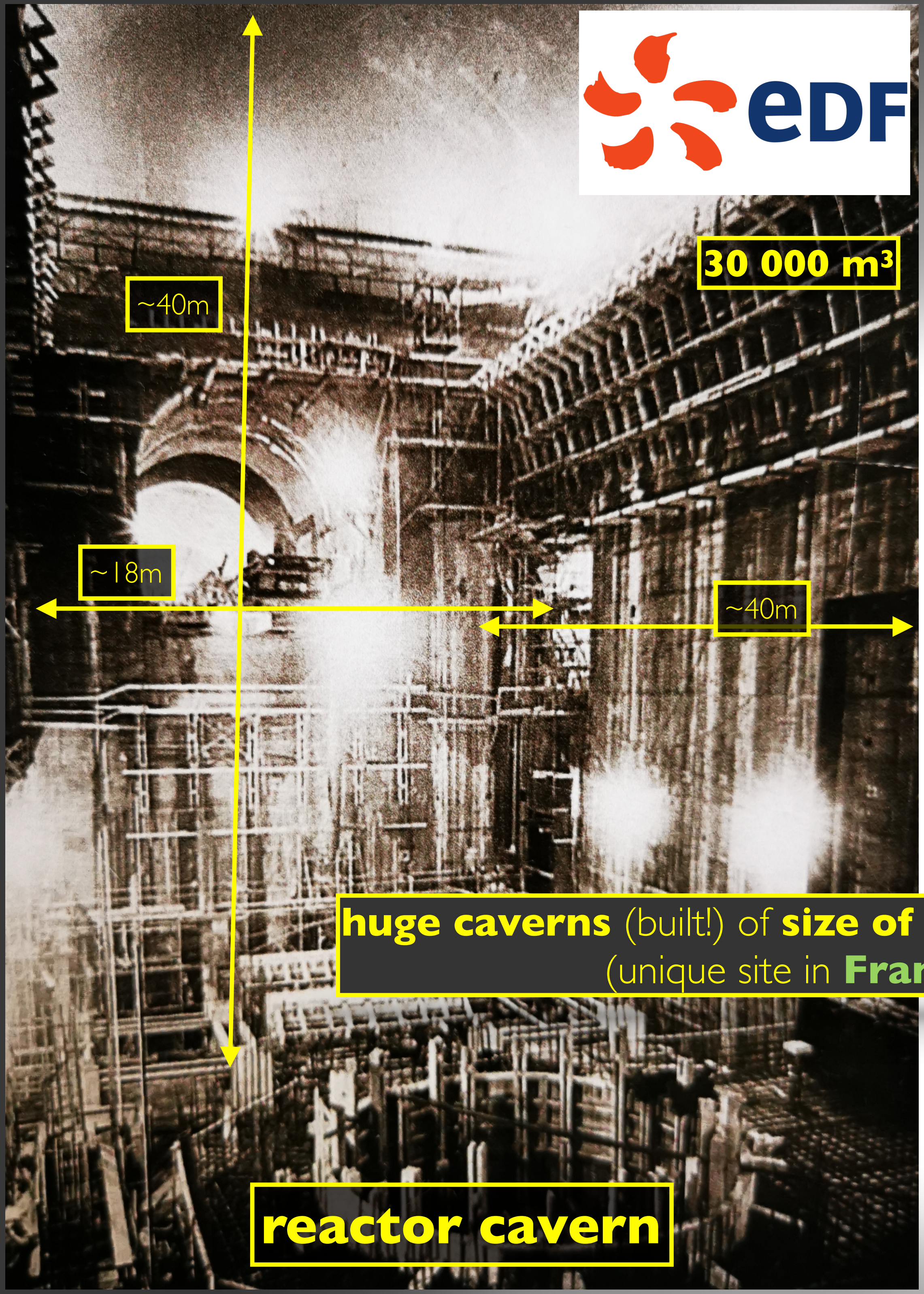
an underground **unknown**…



Chooz-A for science?

Super-Kamiokande (50kton)





huge caverns (built!) of **size of Super-Kamiokande** next to **Chooz reactors!**
(unique site in **France-Belgium** / **Europe** / **World**)

construction caverns [1962-1967]

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

SuperChooz cavern is built (60's)...

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

IJCLab⊕Subatech teams — Octobre 2020

CNRS/IN2P3 direction — March 2022

EDF⊕CNRS exploring (2018)...

(despite COVID)

SUPERCHOOZ

experimental scenario…

SuperChooz Signature September 2022 — CNRS-EDF

SuperChooz Pathfinder starts…

SuperChooz
@Superchooz

We are delighted to announce that the #SuperChooz agreement between @EDFofficiel and @CNRS directions was signed on the 7th Sept 2022 (twitter.com/IN2P3_CNRS/sta...), thus officially starting the so-called “SuperChooz Pathfinder” exploration era.

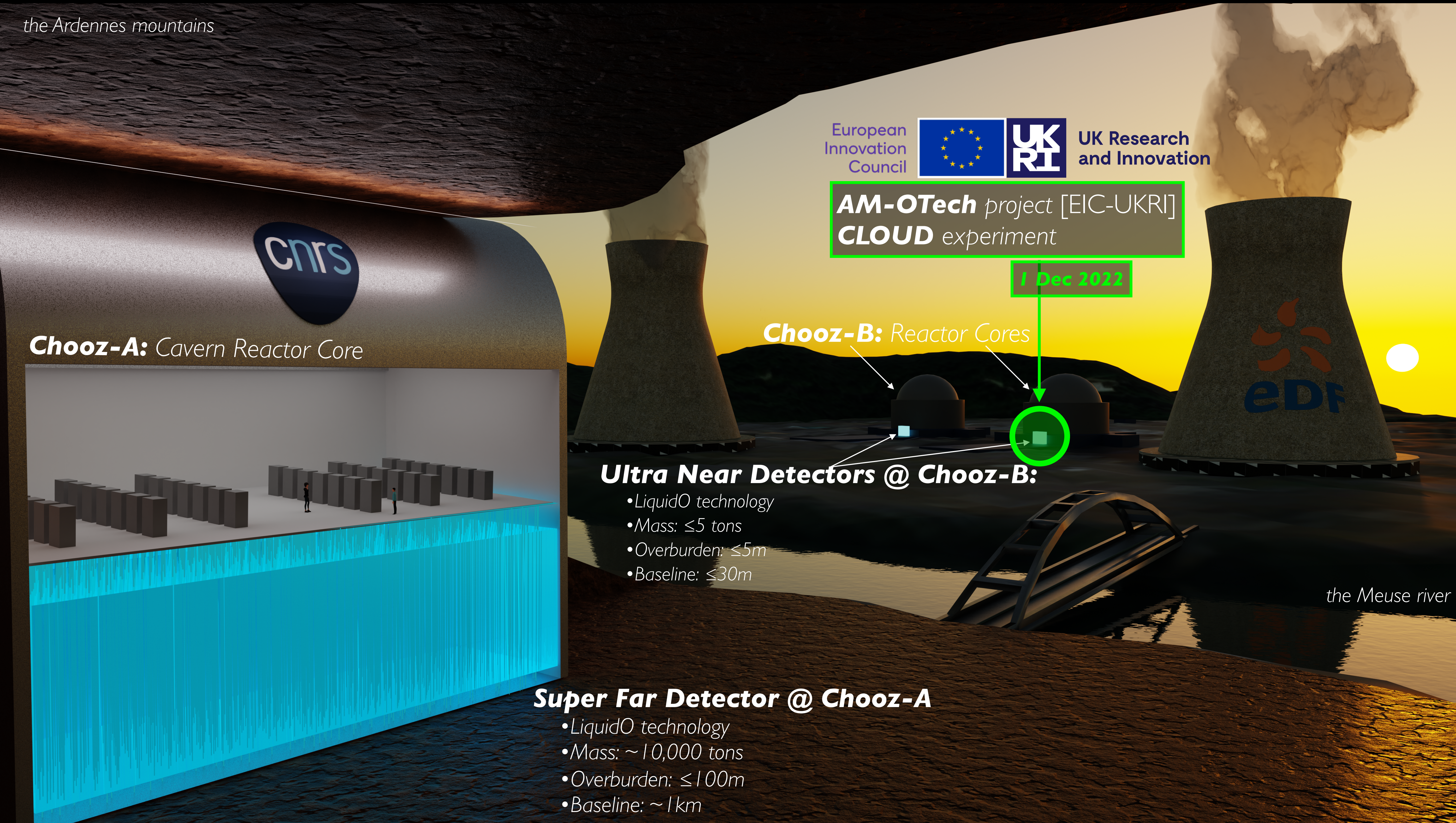
SUPERCHOOZ

pathfinder [2022-2028]

edf cnrs

exploration is now official...

SuperChooz experimental setup…



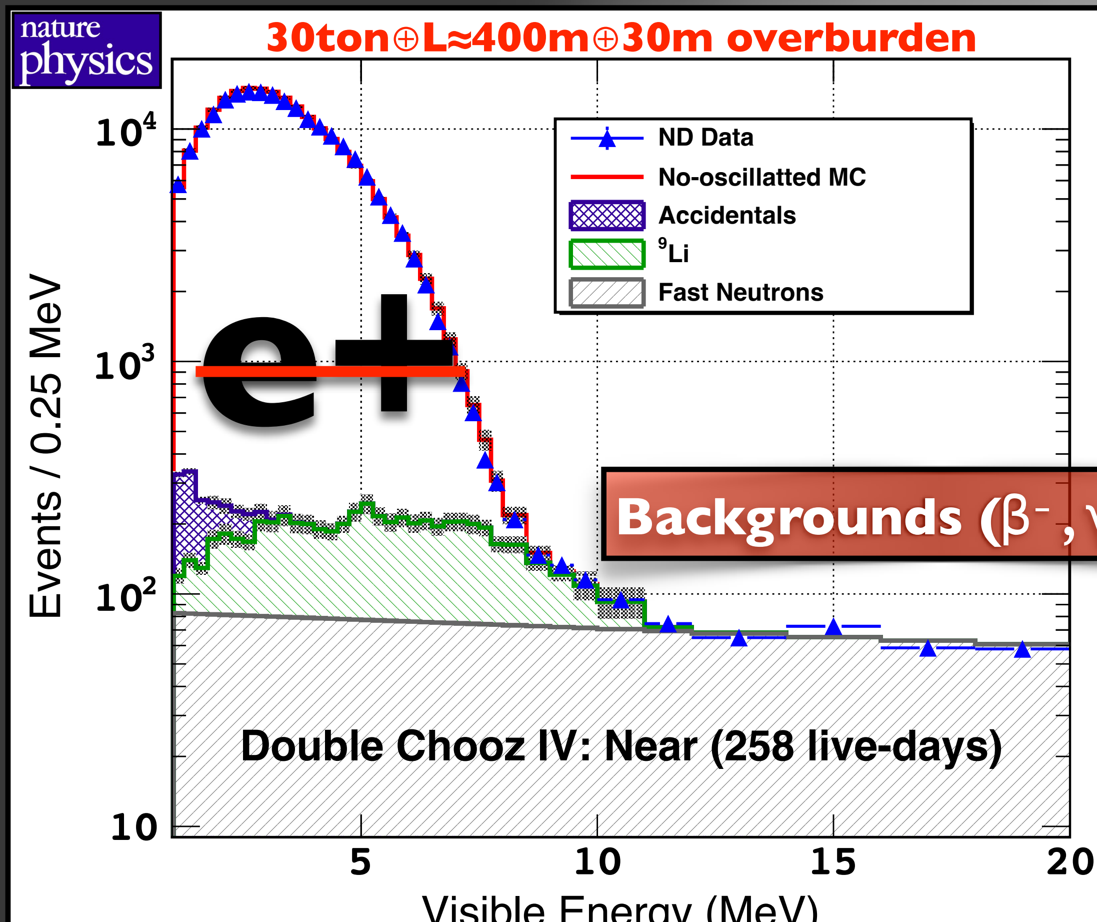
SuperChooz → new laboratory facilities — beyond the existing LNCA (key support!)

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

S U P E R C H O O Z

experimental demonstration(s)

experimental demonstration I



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

- **no Gd** needed a priori — simpler
- extreme precision **single/multi-detector(s)**
  ⟹simpler detectors (avoid multi-volumes)
- control of **all systematics at per mille**
- **geometrical full flux cancellation systematic**
  ⟹**fewer reactors sites** is better!
- exquisite **energy control absolute/relative**
- Chooz site **full background knowledge**

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

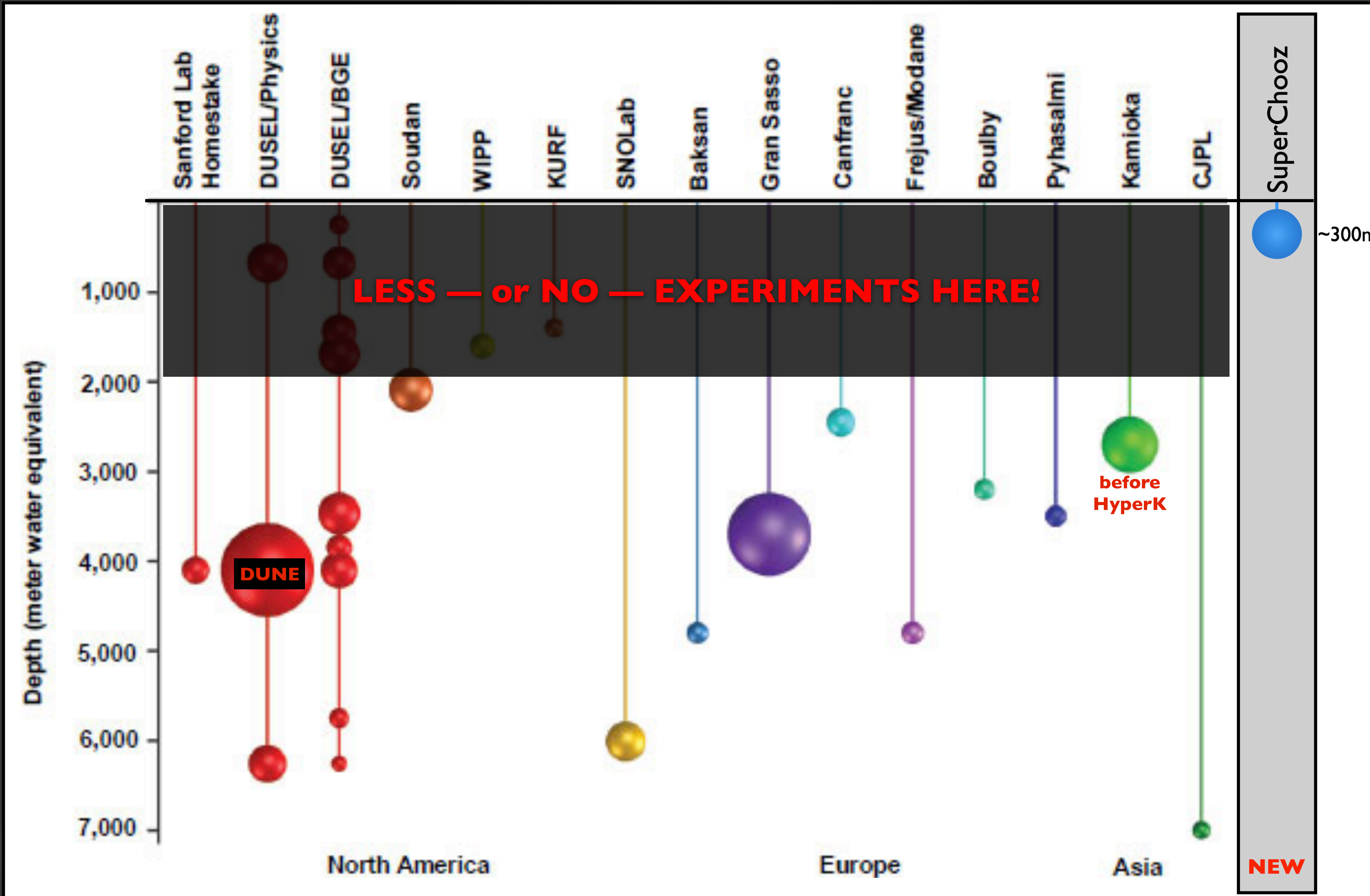
Signal/BG ≈ 21→30 within IBD region [0.5,9.0]MeV

systematics can be controlled: ~0.1% (each)
[flux, background, detection]

energy control: ≲0.5%

enough?

DoubleChooz data & expertise…



ISSUE!!! overburden <100m rock (or <300 mwe)

world underground volume…

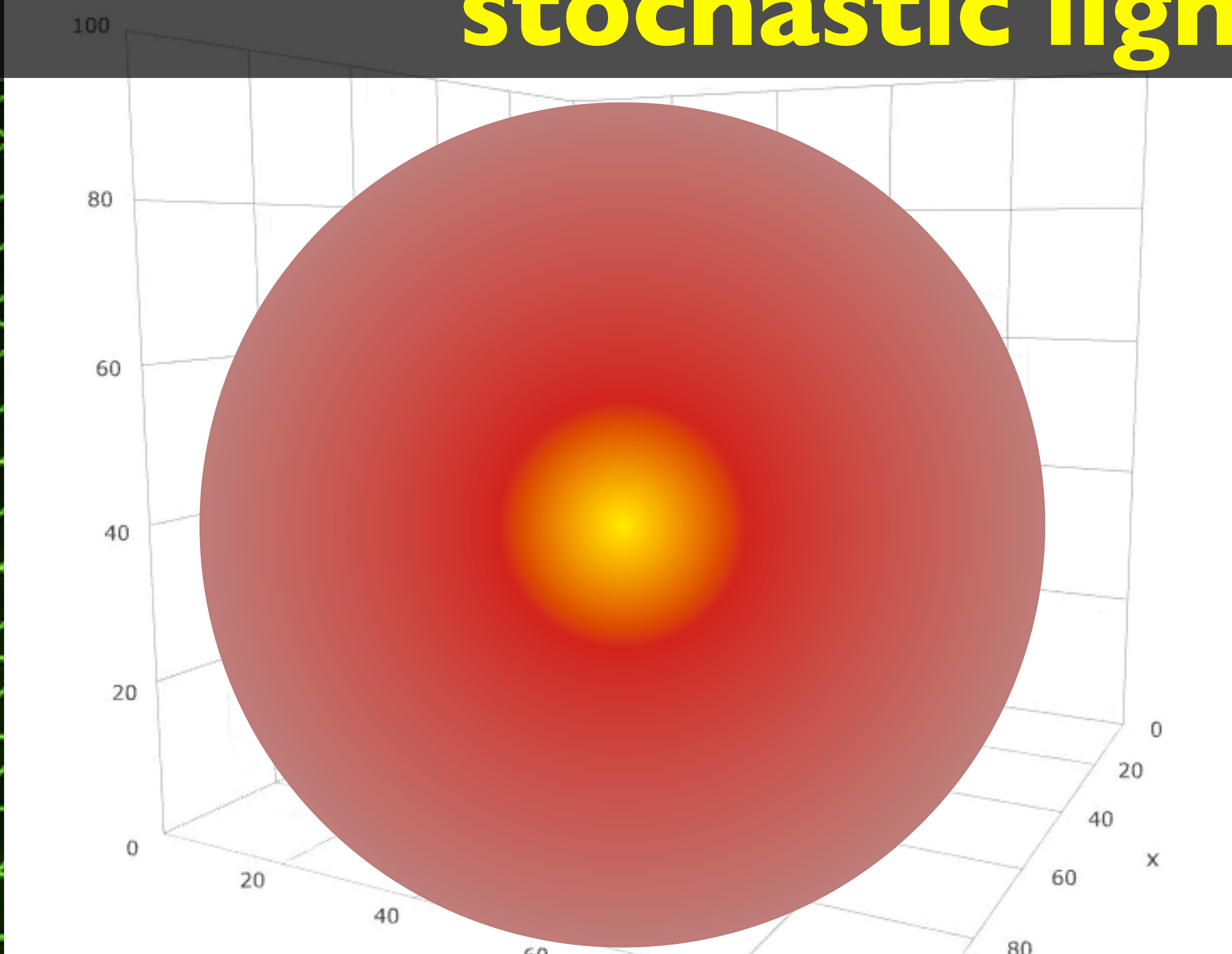
enough underground?

experimental demonstration II

L I Q U I D

new technology — the breakthrough

stochastic light confinement



LiqudiO→ photon's "random walk" (self-confinement)

- **scattering→random walk→light ball** [order 1cm]
  - scattering <u>mean-free-path order 1mm</u>: x10^{-4} smaller than usual

- **lossless (elastic) light scattering:**
  - **Mie scattering:** achromatic & tiny losses ["cloudy" touch]
  - **Rayleigh scattering:** chromatic & lossless
  - **Internal Reflection** (Snell's law lossless)

  warning: <u>avoid reflection</u> (losses @ order ~1%/reflection)

LiquidO ⇔ unique stochastic light confinement

⟹ **must NOT be transparent!!**

Transparency
λ(scattering)≥**10m**

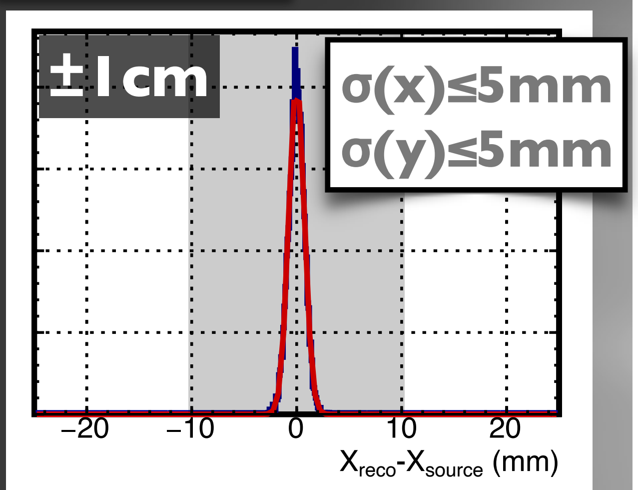
Rayleigh & Mie Scattering
λ(scattering)≤**1cm**

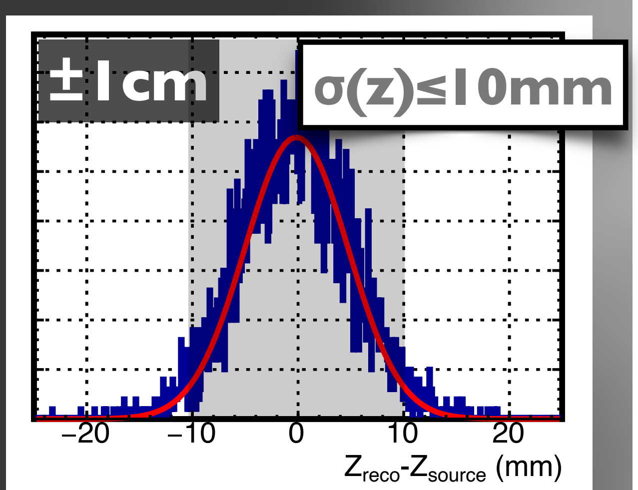
inducing light to a point (lossless)…

LiquidO ↔ stochastic light confinement

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

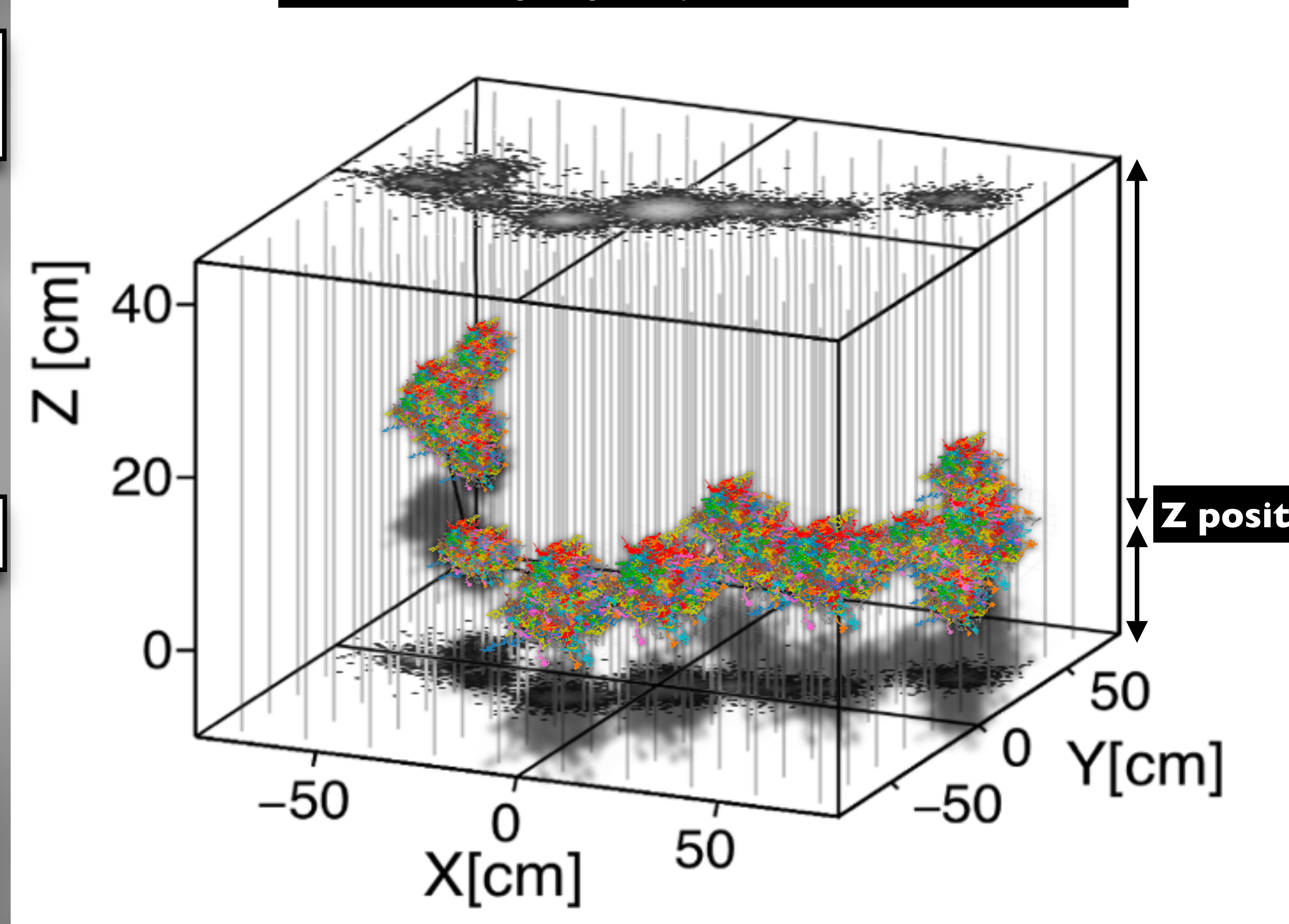
~1.0MeV





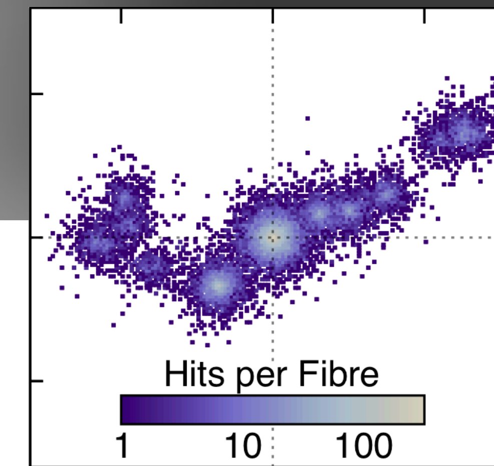
Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

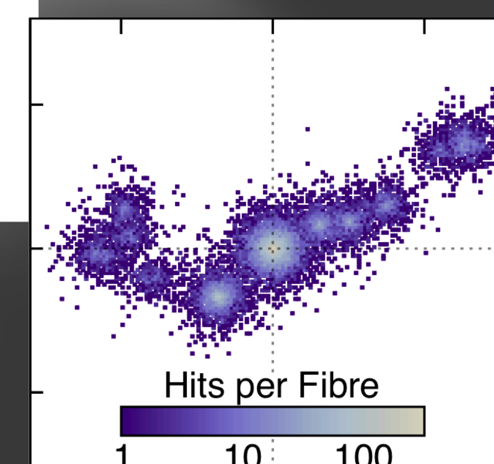
TOP VIEW: (X,Y) Projection→ direct readout



Z position: Δt (time difference)

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



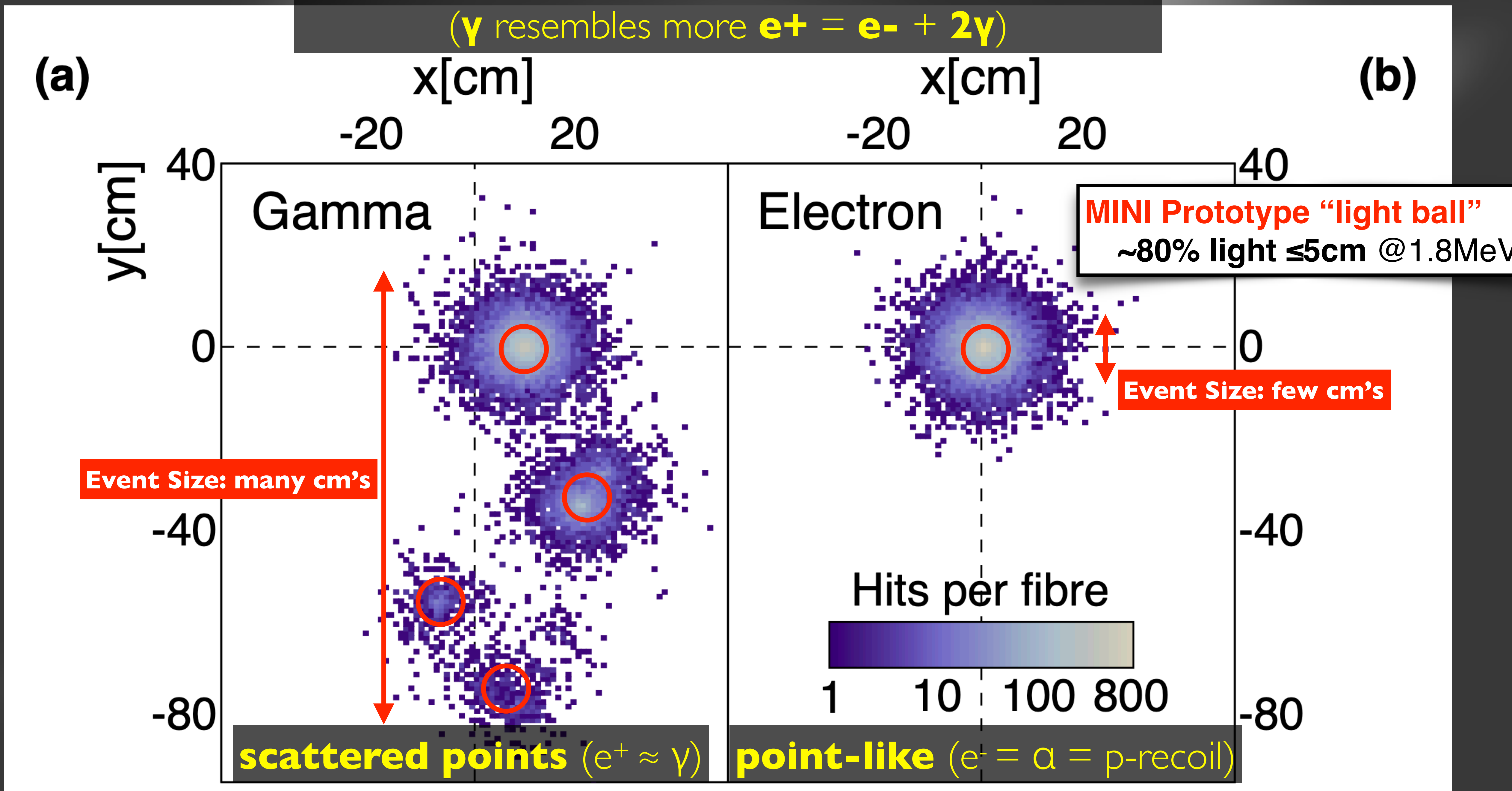


LiquidO can have up 3 orthogonal fibre lattice orientations (3D)

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

topology's PID (no timing)…

PID e/γ should be ≥100:1 rejection @ ≥90%
(**γ** resembles more **e+** = **e-** + **2γ**)



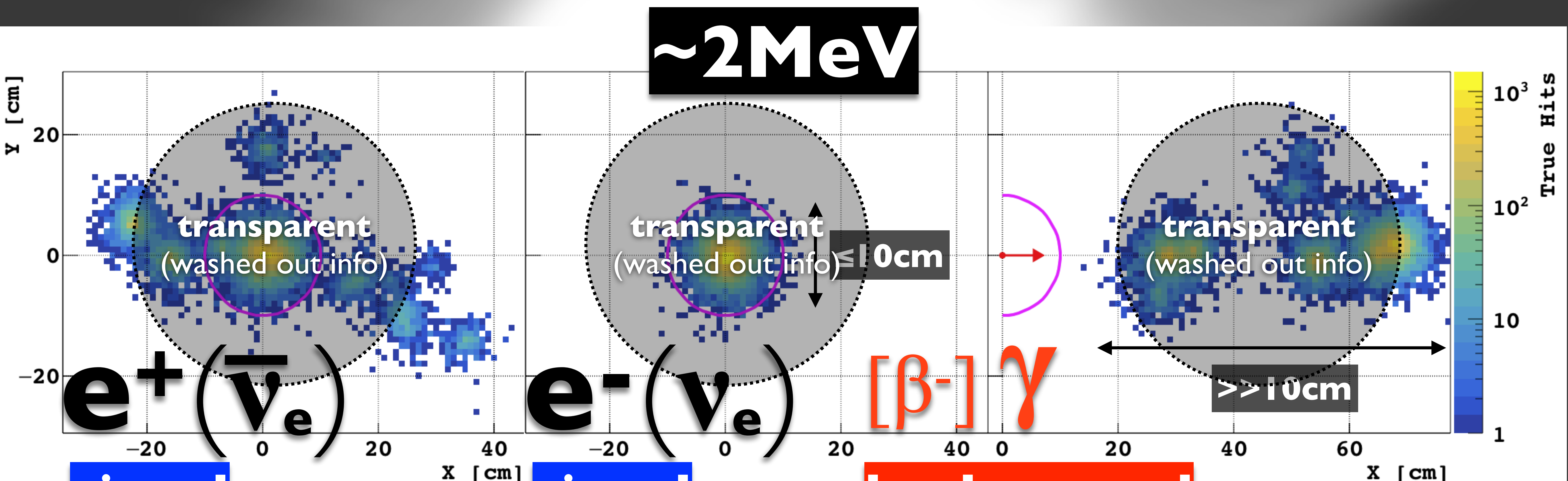
Neutrino physics with an opaque detector

LiquidO Consortium

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

unprecedented PID@MeV…

potential: reduce overburden/shielding

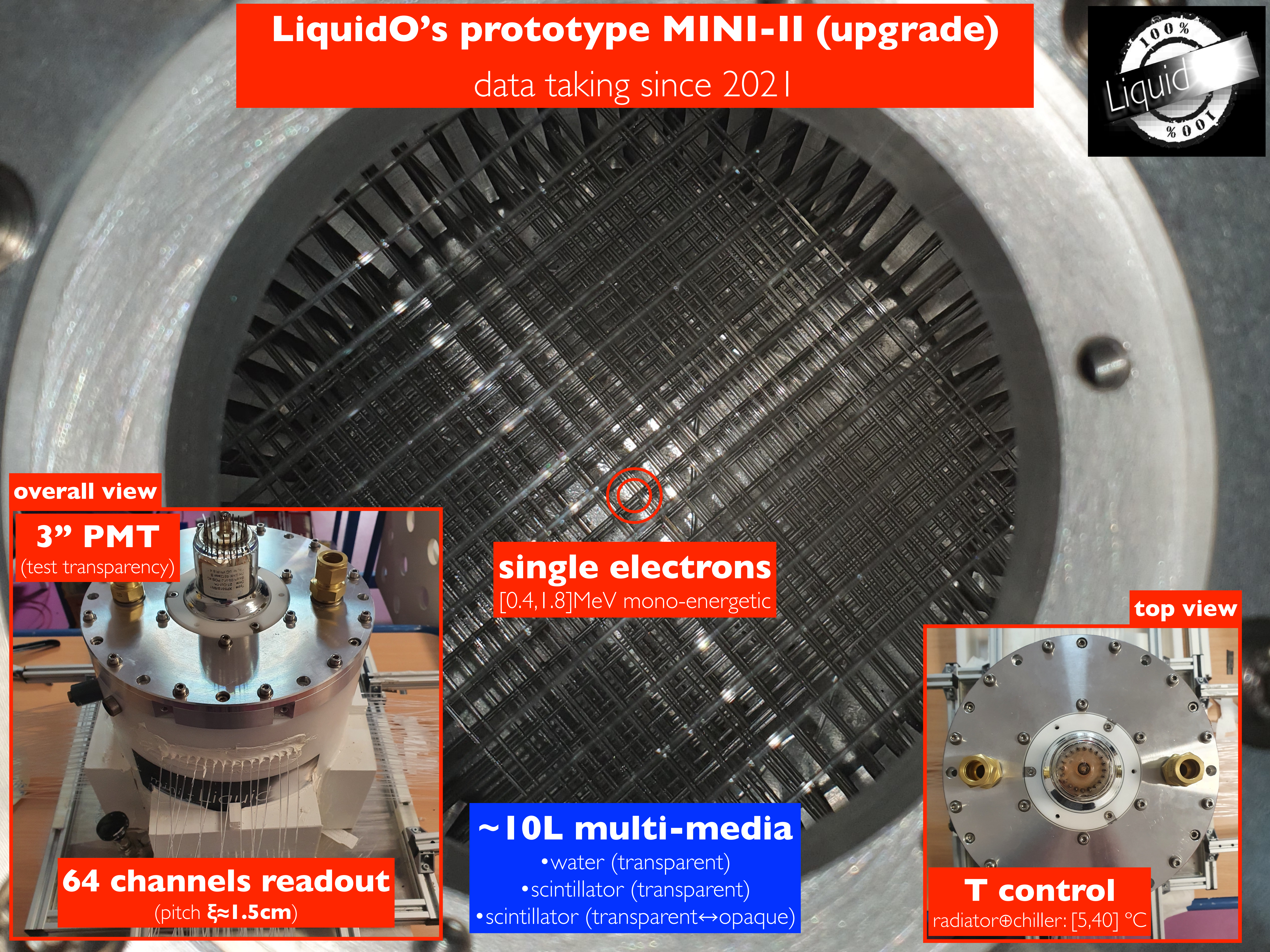


signal **signal** **background**

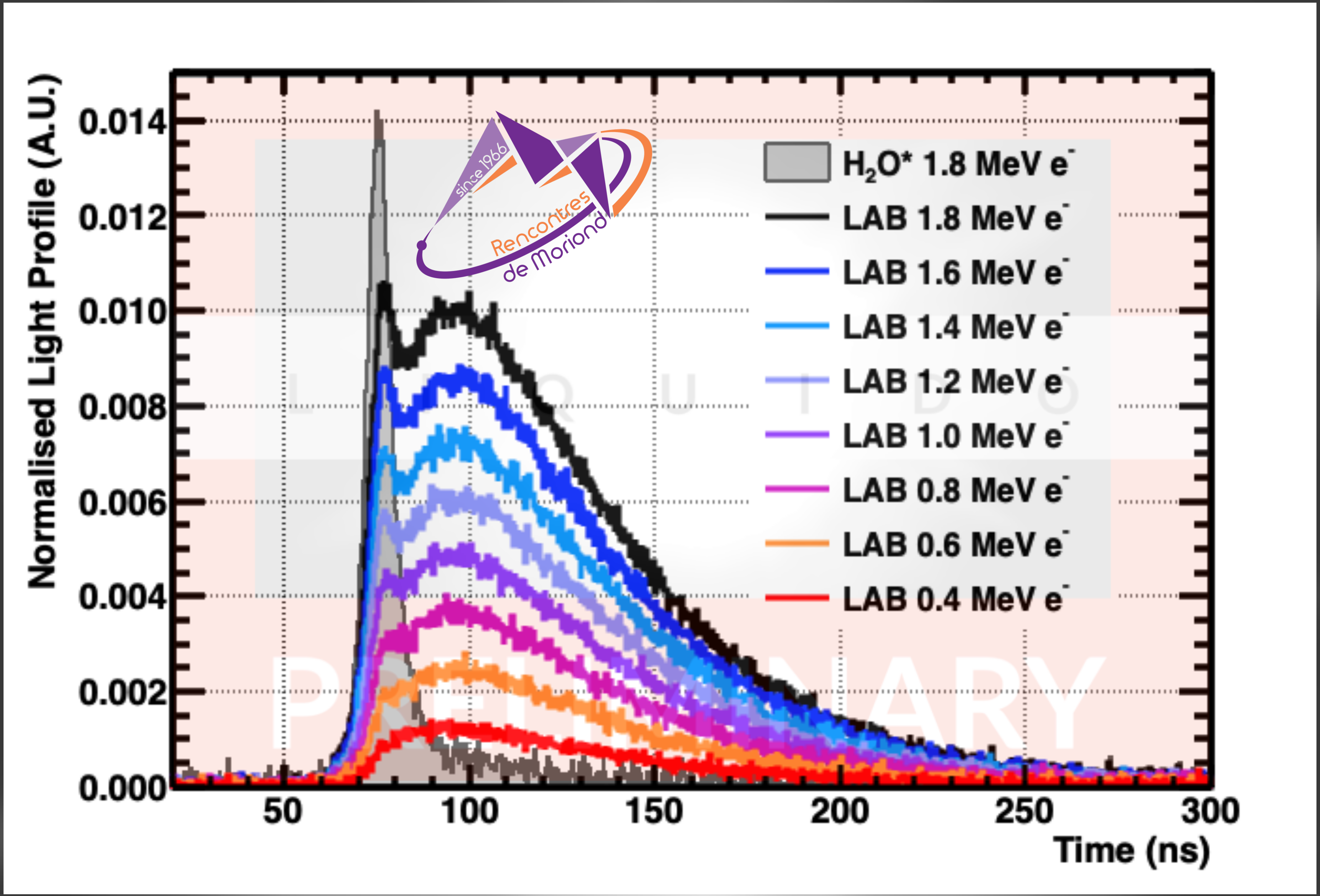
opacity→ (native) self-segmentation

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

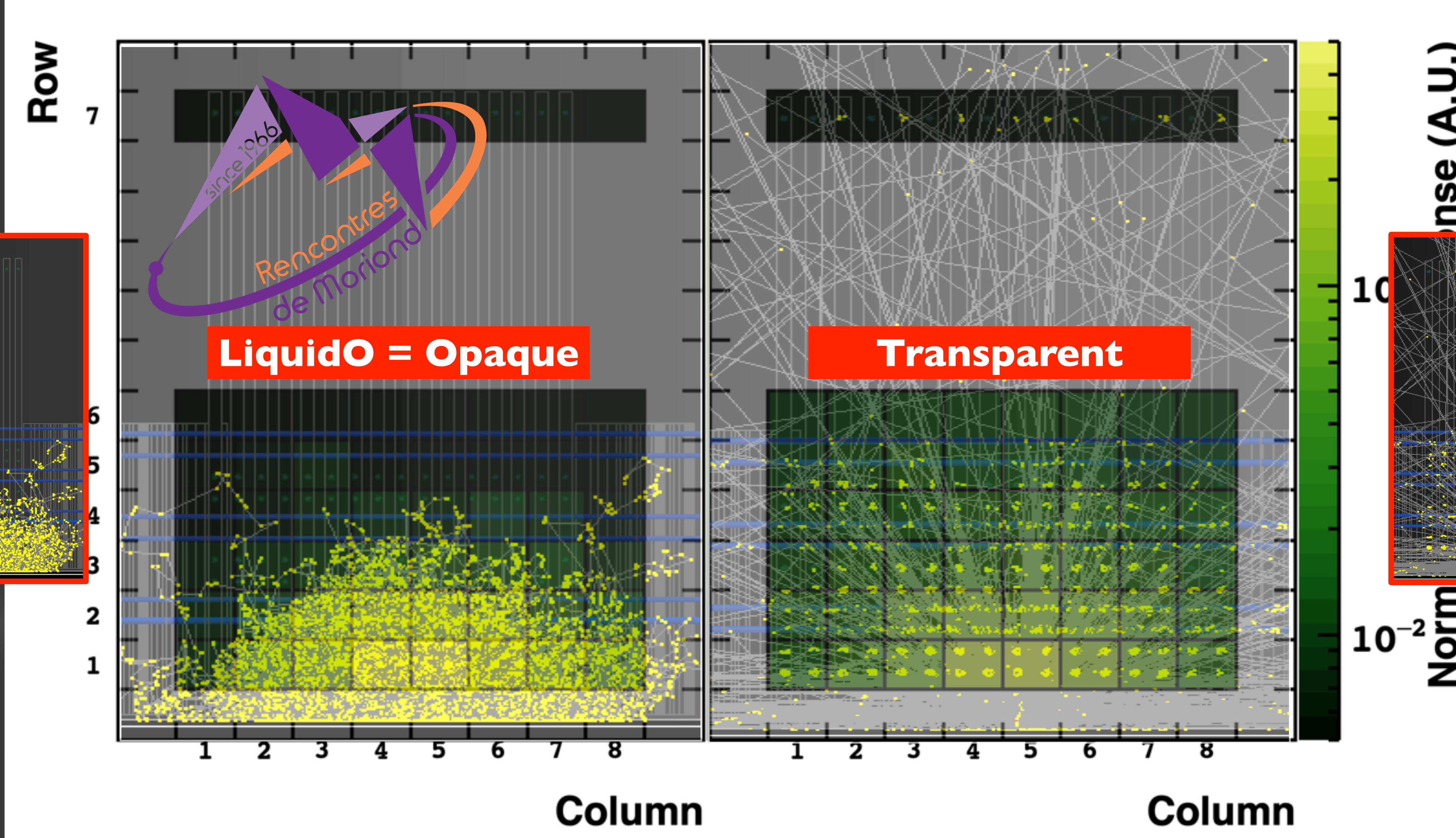
~1MeV: reactor, geoneutrino, solar, ββ-decay, etc

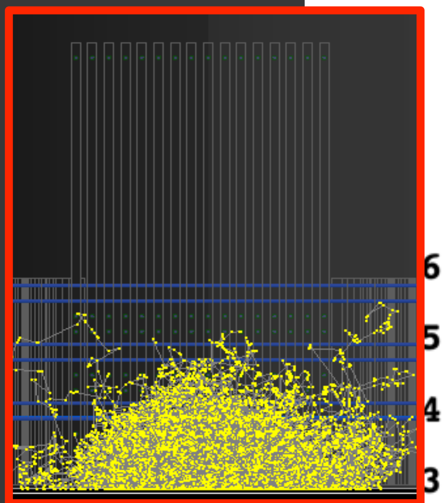


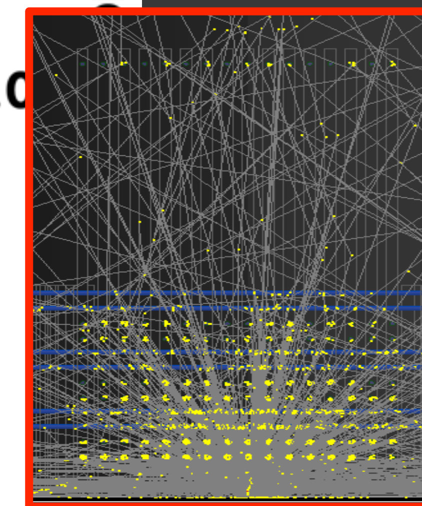
LiquidO's prototype MINI-II (upgrade)
data taking since 2021
overall view
3" PMT
(test transparency)
single electrons
[0.4,1.8]MeV mono-energetic
top view
~10L multi-media
•water (transparent)
•scintillator (transparent)
•scintillator (transparent↔opaque)
64 channels readout
(pitch ξ≈1.5cm)
T control
radiator⊕chiller: [5,40] °C



ANY light detection: Cherenkov / Scintillation / anything!
(ensure the opaque medium is granted)



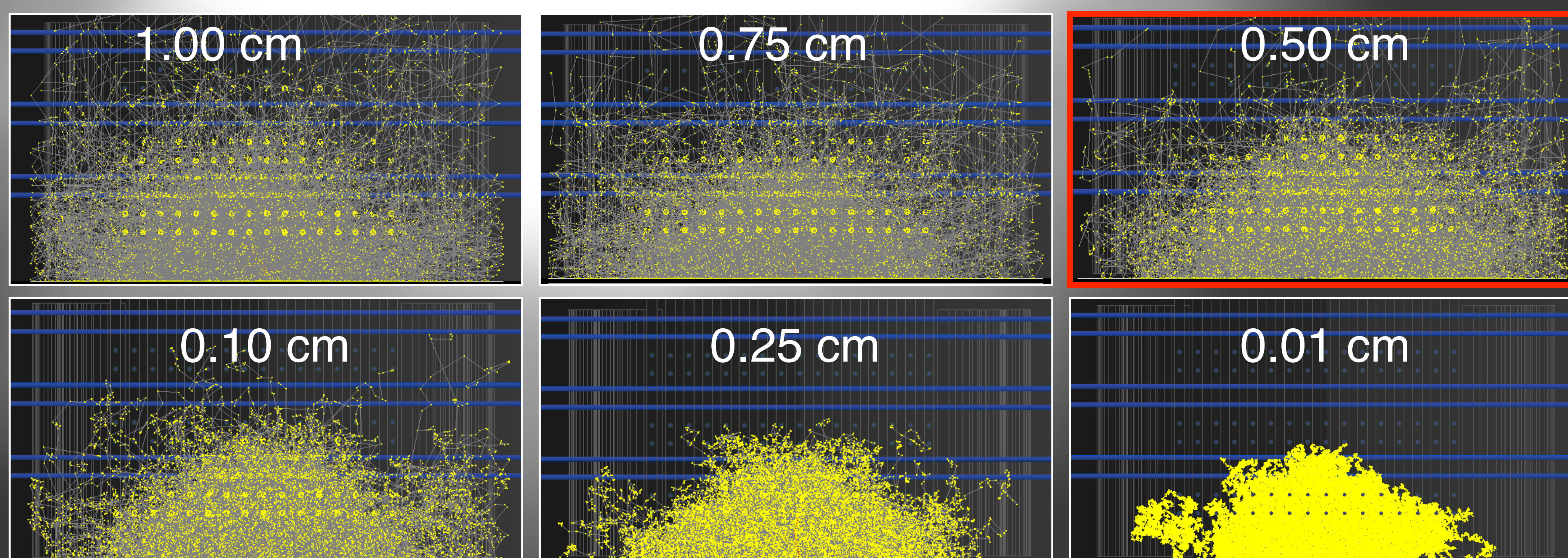




Geant4 Simulation (under tuning)

"light ball" size:

- scattering: λ_s
- # fibres
- absorption?



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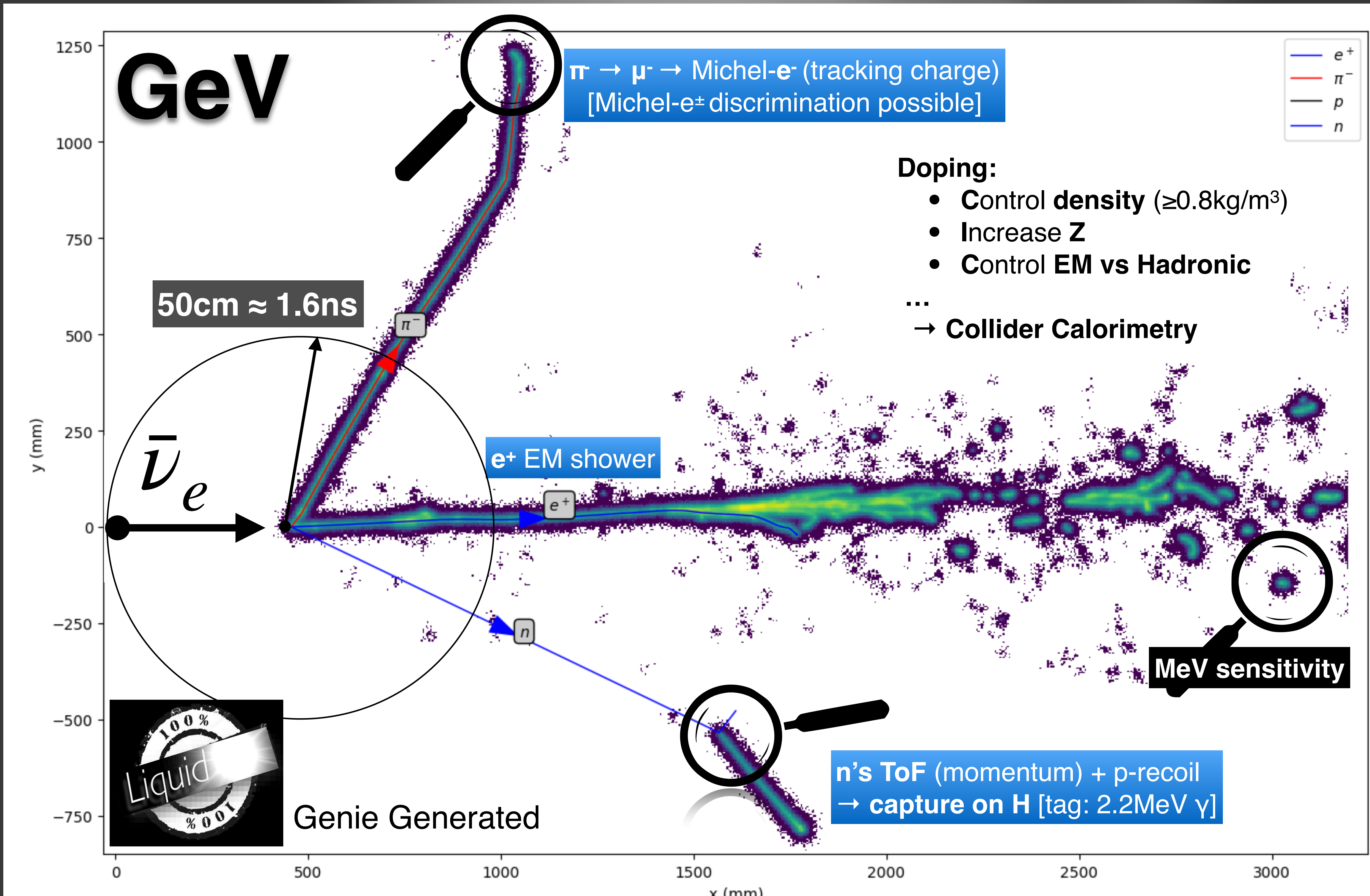
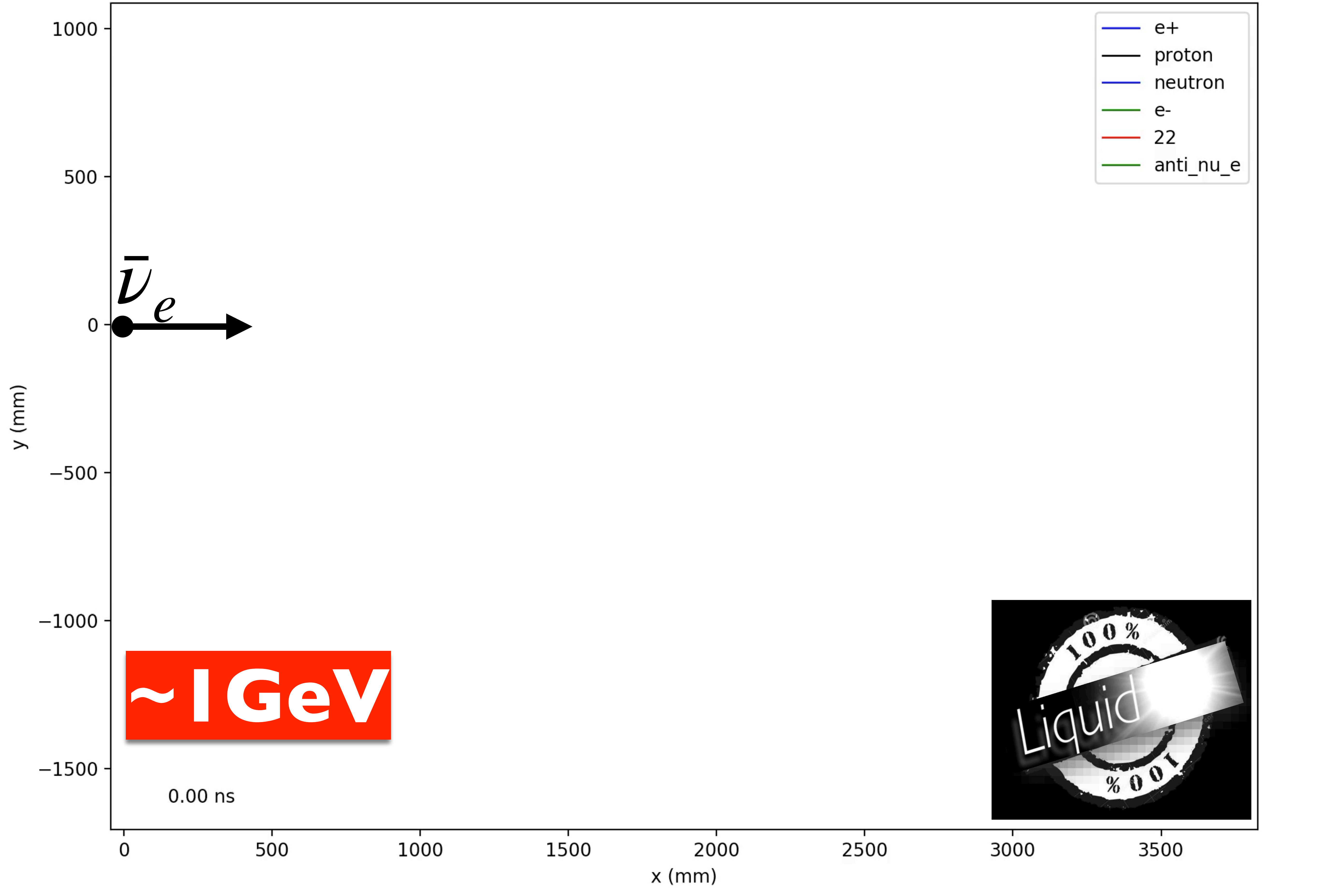


Stochastic calorimetry order 0.1% [~10⁵ PE/GeV] — excellent control of non-stochastic

≥100MeV: accelerator, atmospheric, p-decay, etc

energy flow: EM evolution of energy in time



LiquidO's quintessence…

LiquidO: light/opacity→stochastic light confinement

any source (Cherenkov / scintillation / **any light**)

any media (liquid / solid / (impractical?) gas?)

doping: a powerful (optional) "byproduct"

new technology: **opaque scintillation…**

↑ see Michi's & Christian's previous talks

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First Release at CERN July 2019 (detector seminar)

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

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

5131 Accesses | **9** Citations | **23** Altmetric | Metrics

COVID delayed

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.

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

Neutrino 2022
(June 2022)

FNAL Seminar 2023
(May 2023)

publication under preparation

LiquidO Official WEB: https://liquido.ijclab.in2p3.fr/

invention/conception in 2012 & consortium since 2016 (~94 scientists, 26 institutes & 11 countries)

LiquidO Consortium$^{(a-z)*}$

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Spokespersons:

- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- F. Suekane — Tohoku University / RCNS (Japan)

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

Contact: LiquidO-Contact-L@in2p3.fr

experimental demonstration III

a priori no showstopper

SuperChooz : ~9 700 m³

some **common technology** but **not methodology**

- scintillator: ✓ (improvement)
- fibres ✓ (improvement)
- ~~segmentation~~ ✗ (simplification, cheaper, less BG)
- light collection: ✓ (improvement expected)
- photo-detector: ✓ (simplicaition with SiPM)
- MeV optimisation→**Scaling R&D [≥2024]**

SuperChooz (~10kton) similar dimensions as **NOvA (~14kton)** & one module of **DUNE (~10kton)**

effectively **SuperChooz's pilot** project
(independent project though)

European Innovation Council

UK Research and Innovation

project: "**AntiMatter-OTech**"

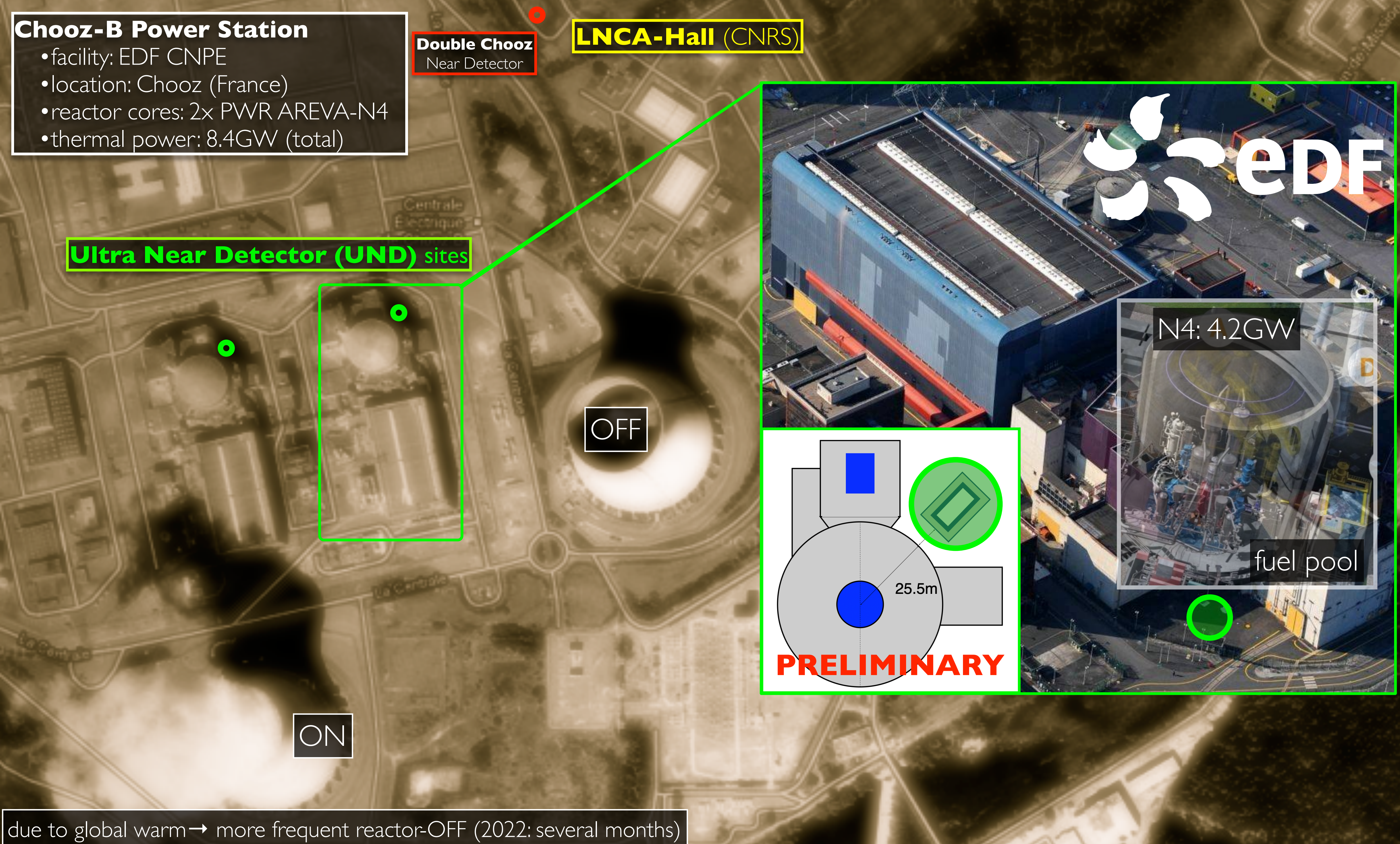
first LiquidO-based experiment...

CLOUD = "**C**hooz **L**iquid**O** **U**ltranear **D**etector"

“Neutrino Telescope” conference — **October 2023**

https://zenodo.org/records/10049846

first ever release **last week**...



CLOUD = "**C**hooz **L**iquid**O** **U**ltranear **D**etector"

Europe's best reactor-ν site…

Double Chooz
Far Detector

our collaboration…

European Innovation Council

UK Research and Innovation

CLOUD International collaboration

- **EDF** (France) — **first time in neutrino science**
- **Brookhaven National Laboratory** (USA)
- **Charles University** (Czechia)
- **CIEMAT** (Spain)
- **IJCLab** / Université Paris-Saclay (France)
- **Imperial College London** (UK)
- **INFN-Padova** (Italy)
- **Instituto Superior Técnico** (Portugal)
- **Johannes Gutenberg Universität Mainz** (Germany)
- **Pennsylvania State University** (USA)
- **Pontifícia Universidade Católica do Rio de Janeiro** (Brazil)
- **Queen's University** (Canada)
- **Subatech** / **Nantes Université** (France)
- **Tohoku University** / **RCNS** (Japan)
- **Universidad de Zaragoza** (Spain)
- **Universidade Estadual de Londrina** (Brazil)
- **University of California Irvine** (USA)
- **University of Michigan** (USA)
- **University of Sussex** (UK)

$\Longrightarrow$ **19 institutions in 11 countries**

Spokespersons:

- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

IB Chair:

- M. Chen — Queen's University (Canada)

Webs:

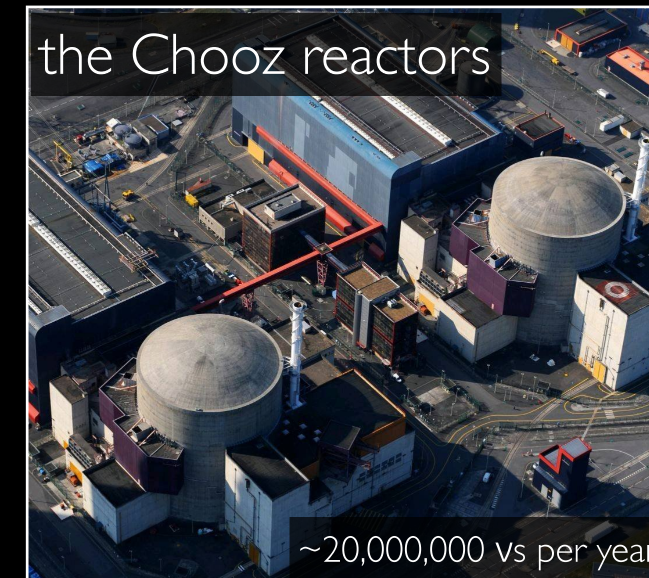
https://antimatter-otech.ijclab.in2p3.fr/ [AMOTech]
https://liquido.ijclab.in2p3.fr/nucloud [via LiquidO]

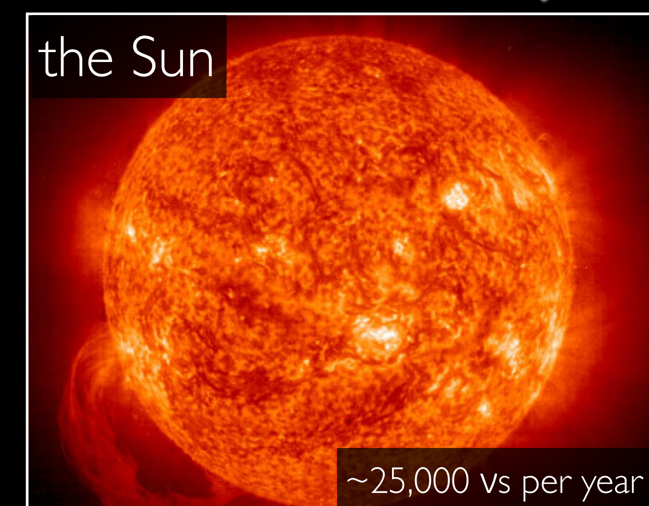
SUPERCHOOZ

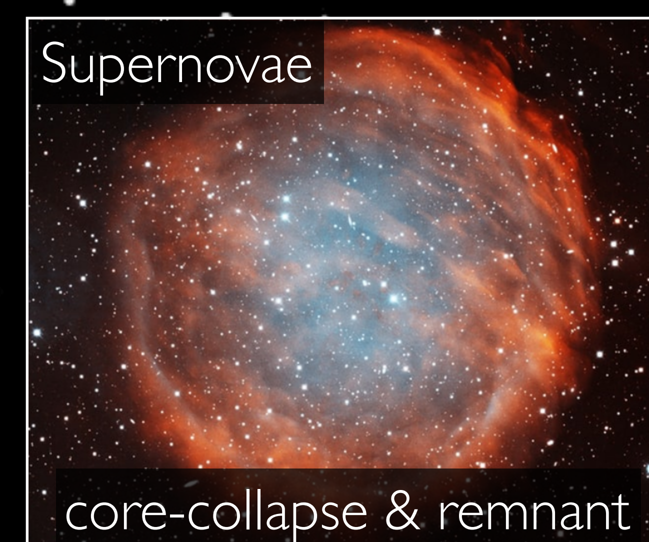
scientific programme…(so far)

neutrino sources…

large **SuperChooz** detector→ **vast physics programme!**







…also **atmospherics**!!

geoneutrino? huge irreducible background by reactor neutrinos!!

SuperChooz rates…

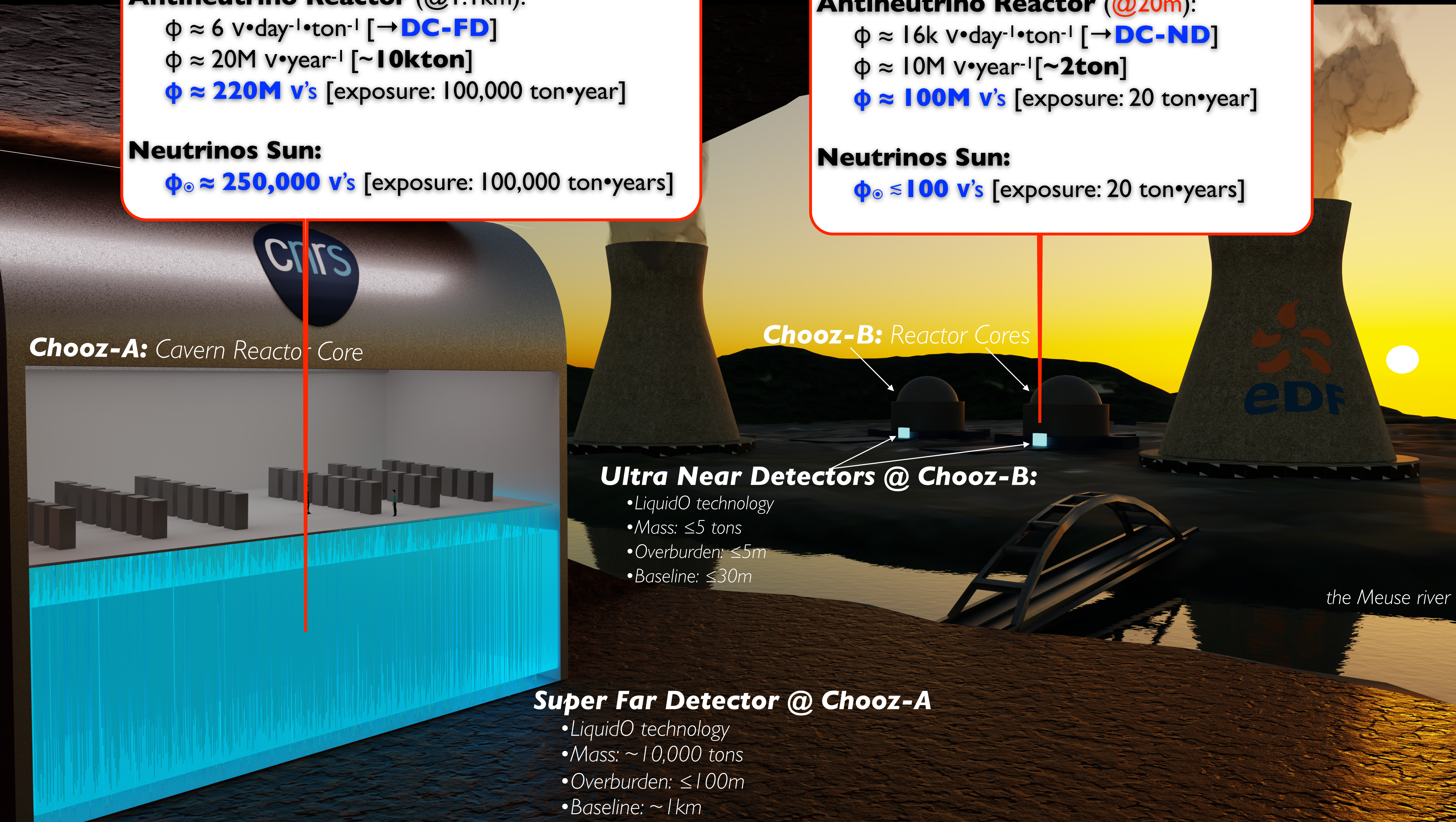
10 years exposure

Antineutrino Reactor (@1.1km):
- $\phi \approx 6$ ν•day^{-1}•ton^{-1} [→**DC-FD**]
- $\phi \approx 20$M ν•year^{-1} [~**10kton**]
- **$\phi \approx$ 220M ν's** [exposure: 100,000 ton•year]

Neutrinos Sun:
- **$\phi_{\odot} \approx$ 250,000 ν's** [exposure: 100,000 ton•years]

Antineutrino Reactor (@20m):
- $\phi \approx 16$k ν•day^{-1}•ton^{-1} [→**DC-ND**]
- $\phi \approx 10$M ν•year^{-1}[~**2ton**]
- **$\phi \approx$ 100M ν's** [exposure: 20 ton•year]

Neutrinos Sun:
- **$\phi_{\odot} \lesssim$ 100 ν's** [exposure: 20 ton•years]



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

detection: all about coincidences…

the power of coincidences

low energy (≤3MeV) neutrinos interactions benefit by interactions leading to coincidences

Reines et al 1956

(neutrino discovery)

CC: $\bar{\nu}_e + p \rightarrow e^+ + n$

($\tau \approx 220\mu s$ for only H⊕C)

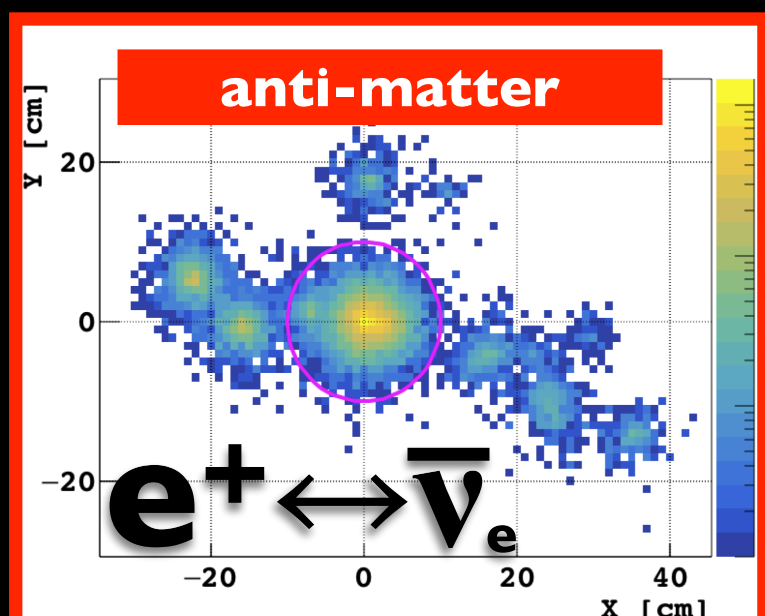
Raghavan et al 1977

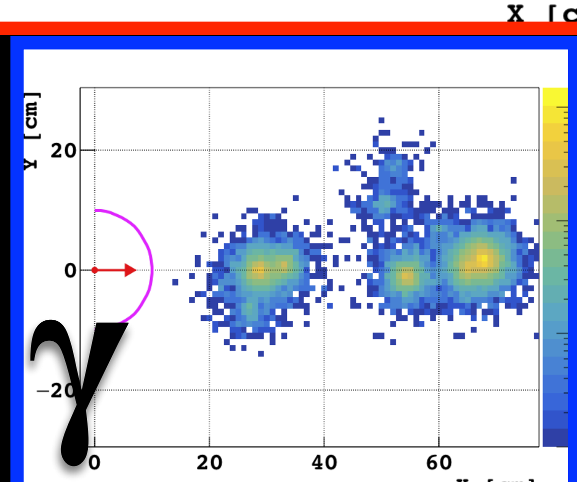
(pp solar neutrino — unobserved)

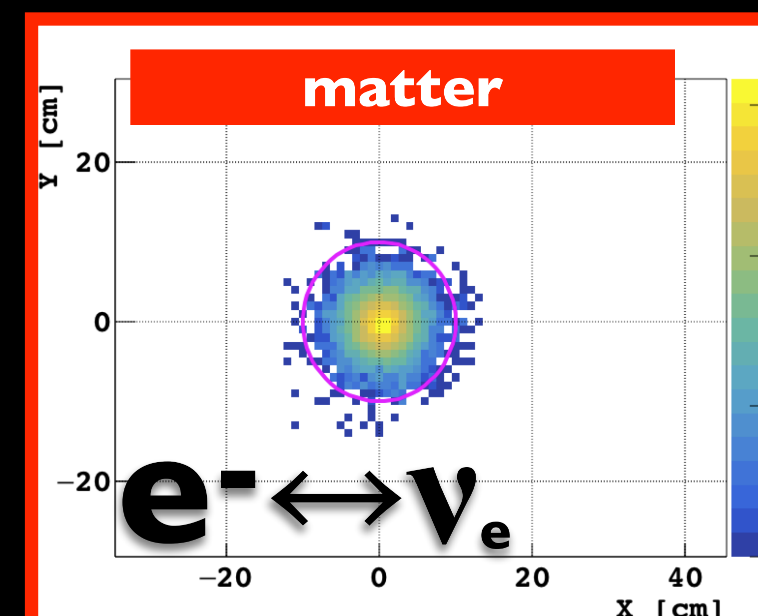
CC: $\nu_e + {}^{115}In \rightarrow e^- + \gamma + \gamma/e^-$

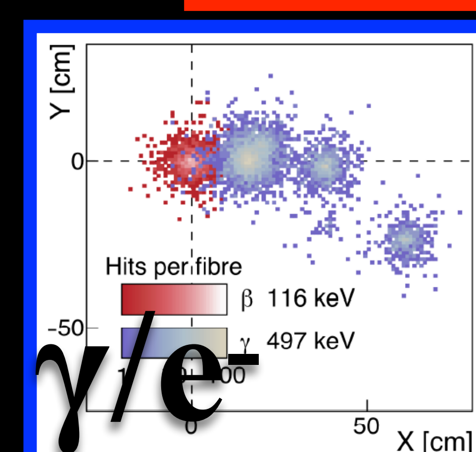
($\tau \approx 4.7\mu s$ decay of **Sn***)

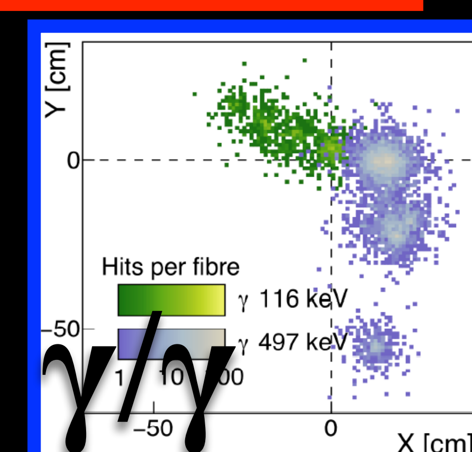
major **R&D** by **LENS** *et al* [many years]











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

S U P E R C H O O Z

preliminary physics programme…

rationale...

- high precision SM's neutrino oscillation

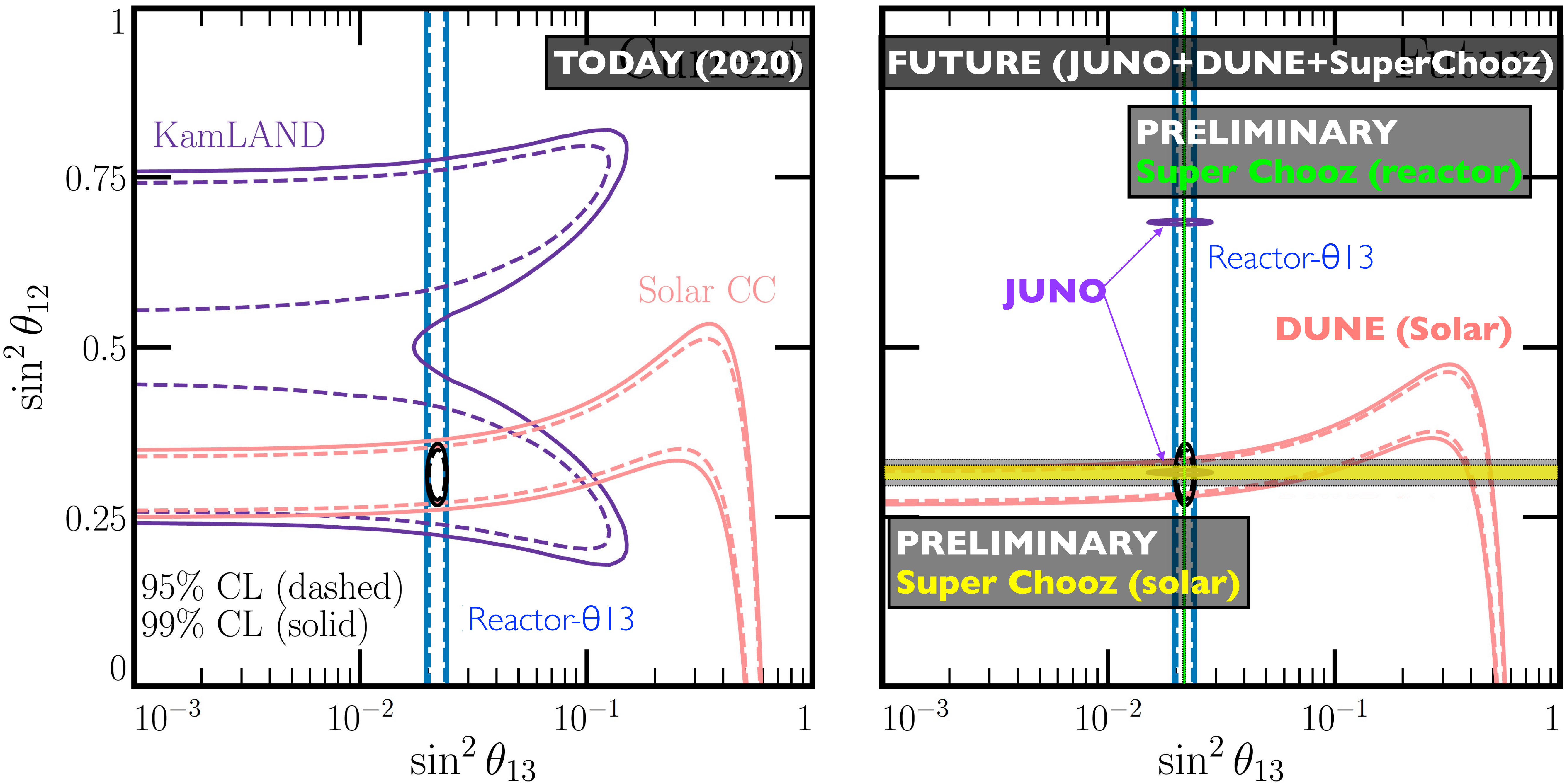
$\Longrightarrow$ synergise with JUNO & HK$\oplus$DUNE

- neutrinos probing BSM$\longrightarrow$ discoveries?

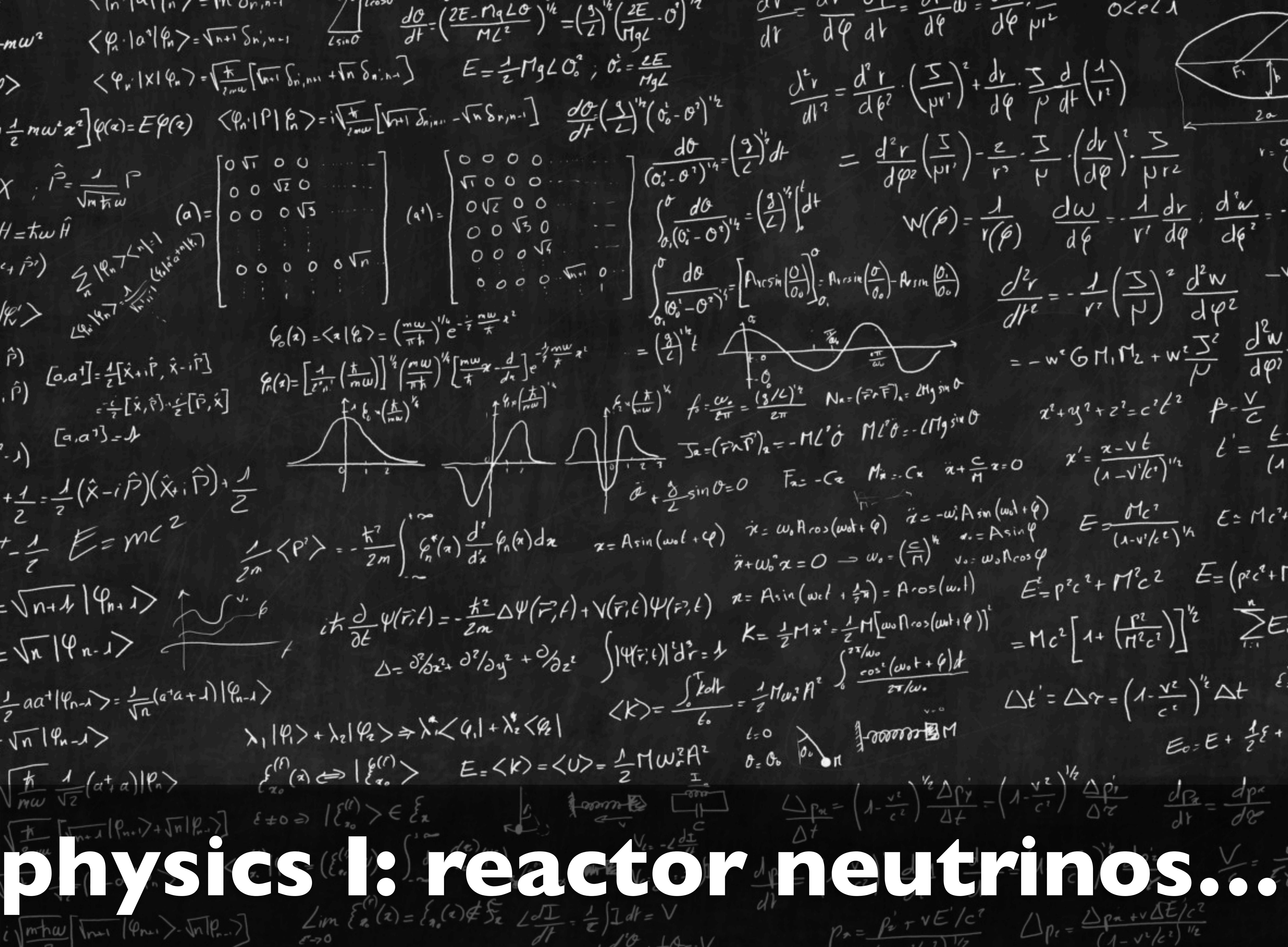
$\Longrightarrow$ beyond today's paradigm?

Super Chooz potential under investigation…

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

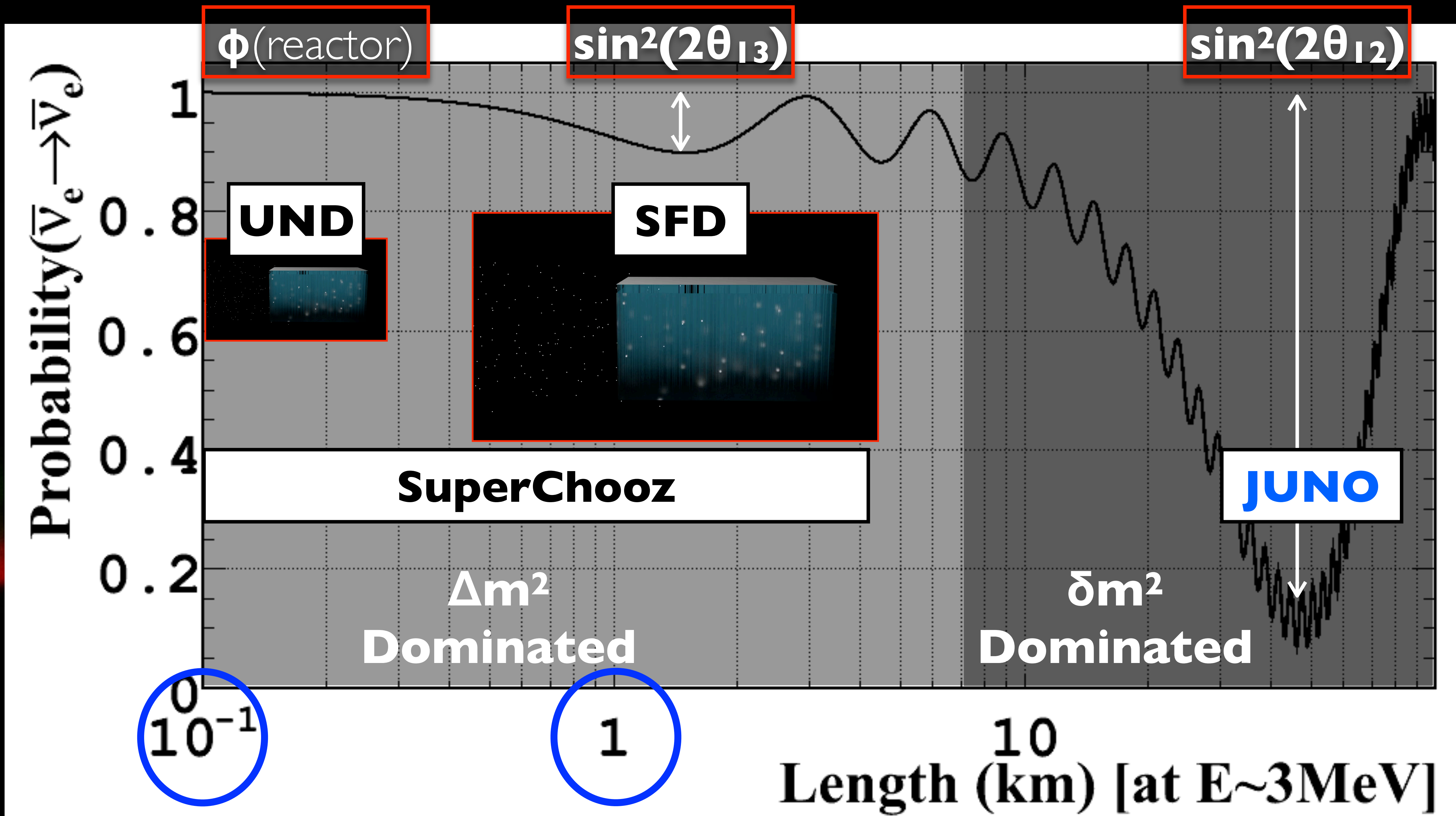


Super Chooz: the smallest but powerful…



physics I: reactor neutrinos…

experimental setup…



- **reactor:** extreme source of neutrino (commercial→1GW≈2×10^{20}/s) — no running cost.
- **3 measurement regimes:** depending on baseline (L):
  - [**UND**] **zero-baseline** (L→~0km): **φ(reactor)** — and **new physics: Unitarity violation?**
  - [**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?

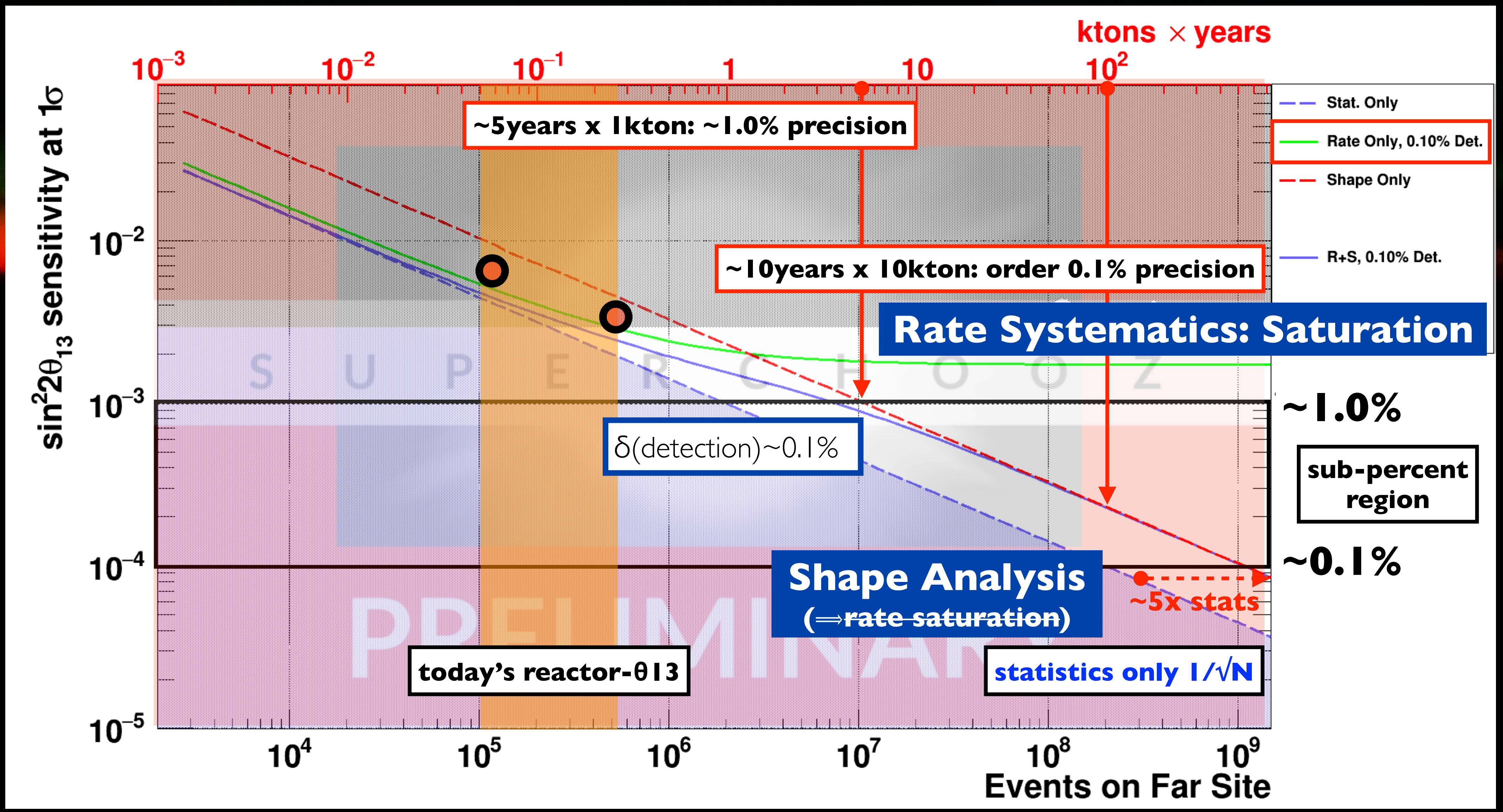
review reactor θ13 sensitivity evolution…

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)**

⇒ systematics flux (→UND) & BG (→LiquidO) cancellation

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



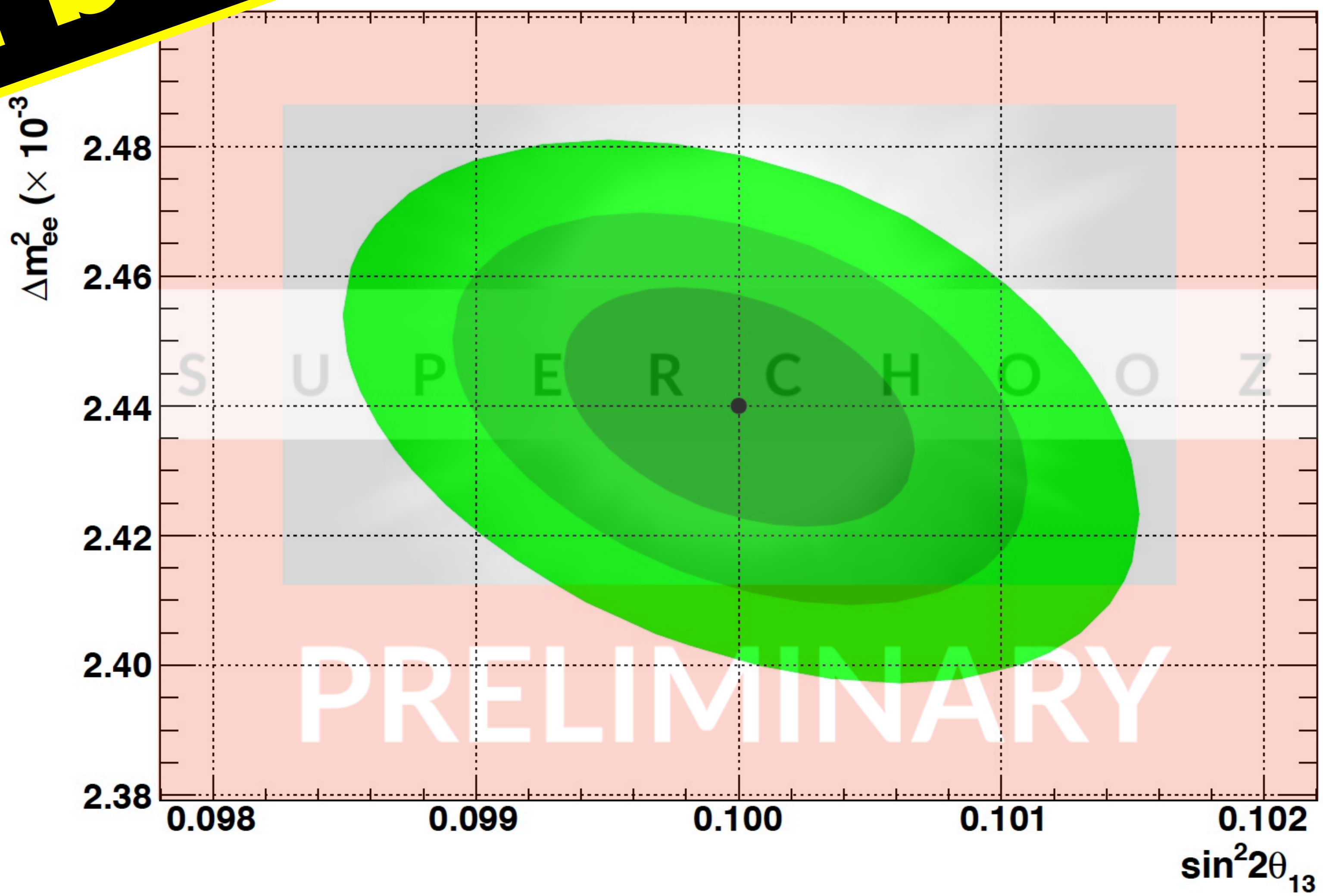
translator: 1 kton implies ~2x10^6 IBD/year→ **~4 IBD/min** [~50x today]

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% Free	≤0.5%	≤0.5%
	≥3x	≥6x

world best

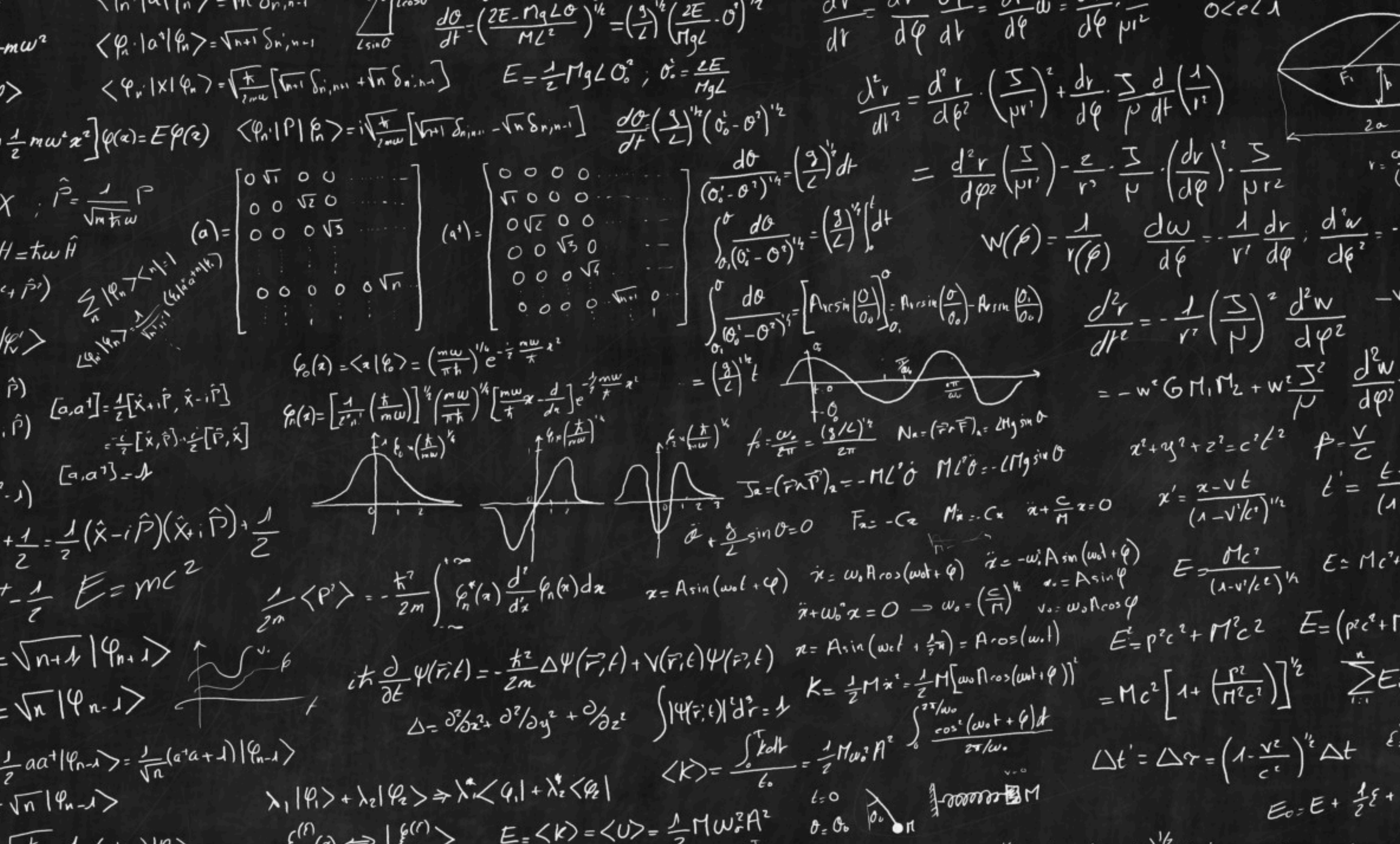


[first time] sub-percent measurement of θ13⊕Δm²(ee)

why θ_{13} & $|\Delta m^2|$? (reactor)

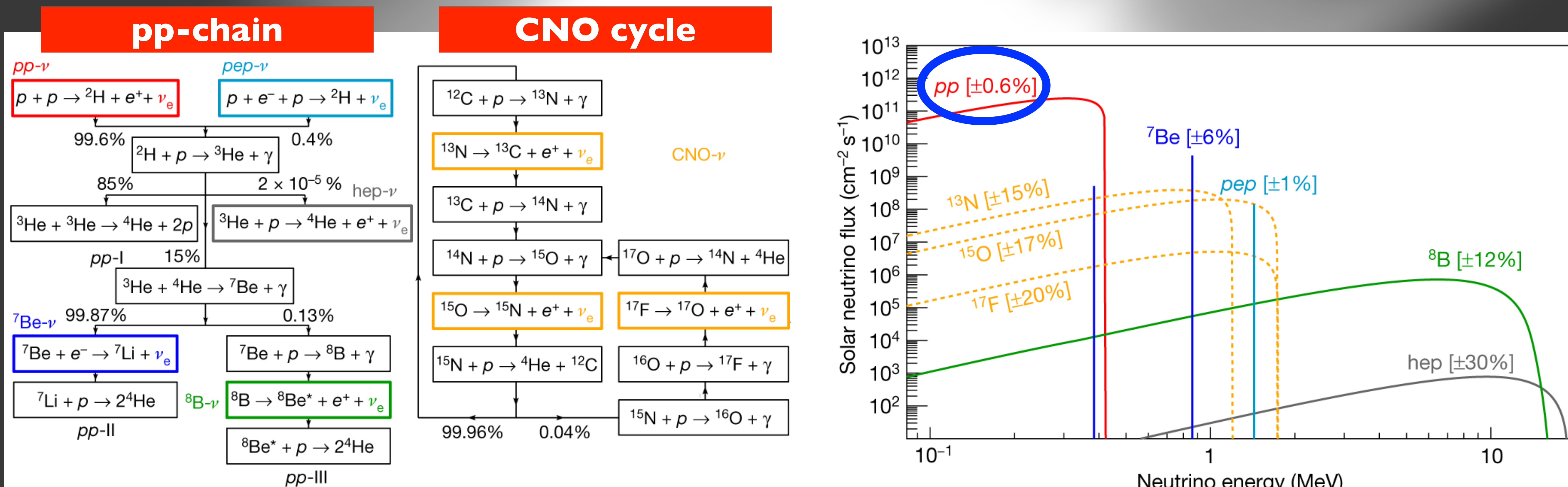
- world most precise θ_{13}!! [permille precision]
  - (unique) cross-check JUNO's Δm^2
- PMNS' shape: the smallest term
- synergies: extra precision on
  - Hyperk$\oplus$DUNE's CP violation
    - (simultaneously) resolve octant-θ_{23}?
    - PMNS' shape: the largest term!
  - JUNO's Mass Ordering (oscillation)

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



physics II: solar neutrinos

Sun's inner-most insight…



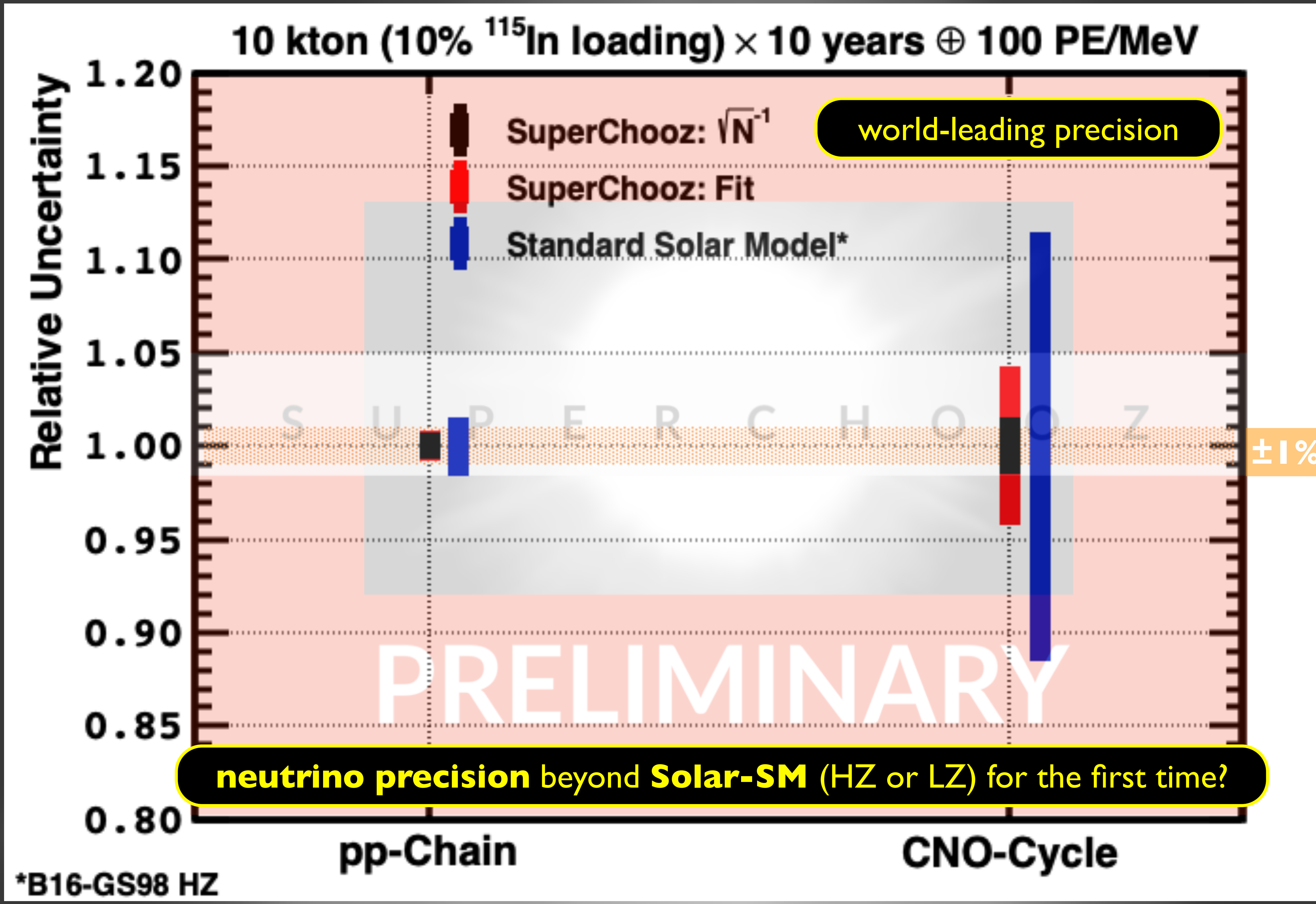
2 main reactions…

- **pp Chain** (dominant in Sun, still)
- **CNO Cycle** (most stars dominant)

spectral precision "Solar-SM" (SSM)

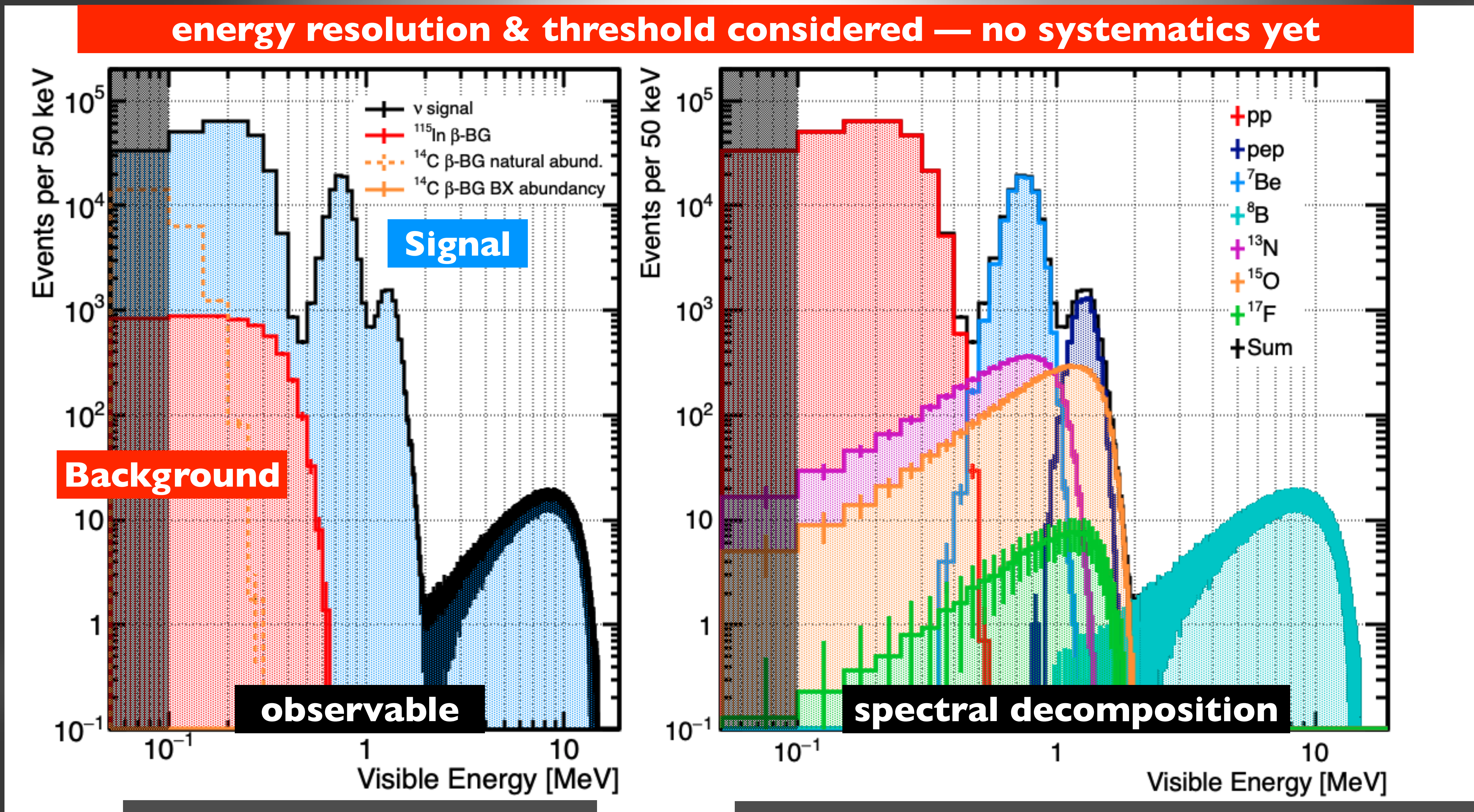
- **SuperChooz** up to sub-% precision on everything
- probe **beyond-SSM** & **beyond-SM**?

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



highest precision solar physics…

solar spectra extraction…



Signal to BG ≥10x

Background-less ≥0.5MeV
[LENS *et al.*]

Full Spectral Information:

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

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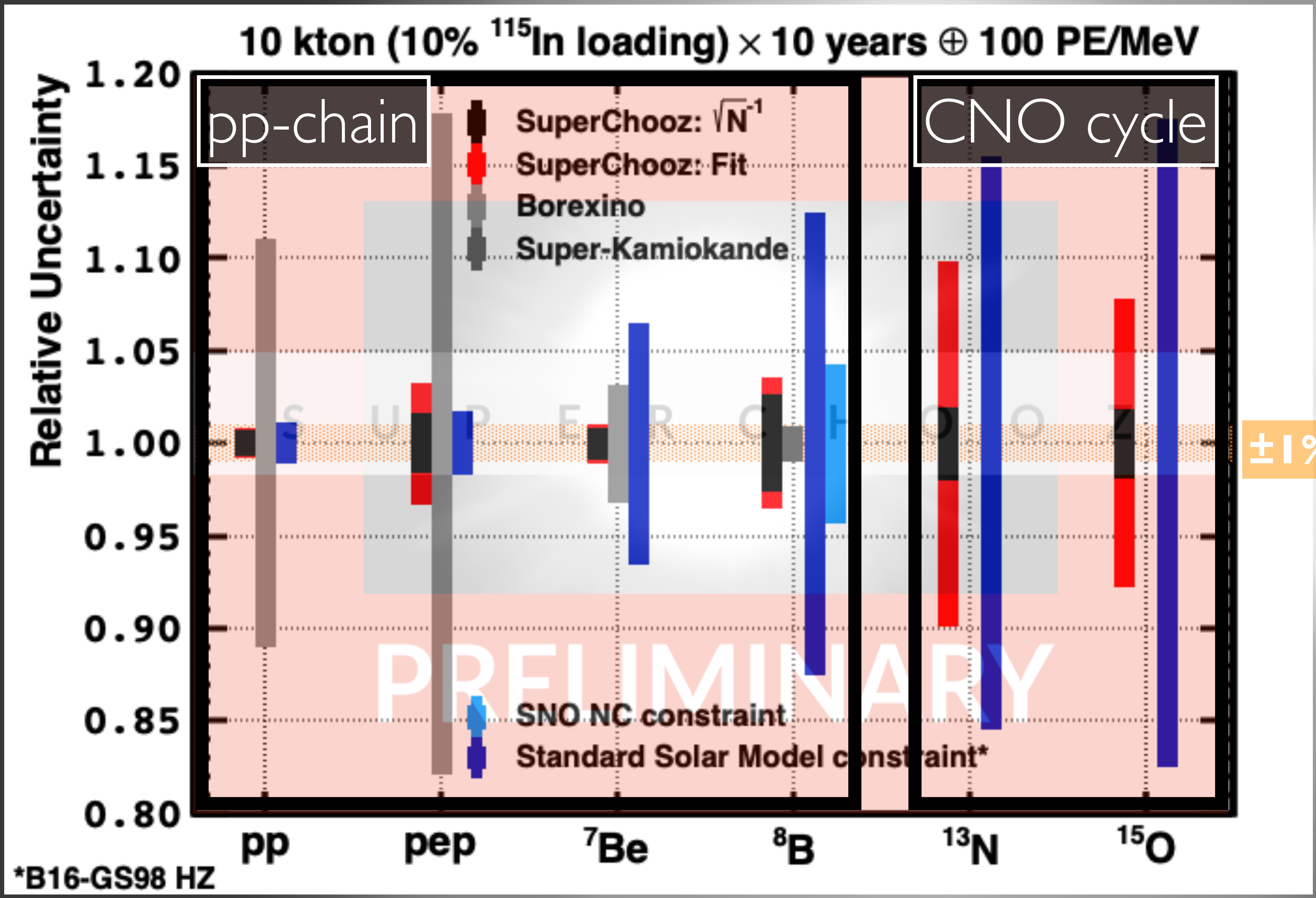
ultimate solar spectra knowledge?



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

→**30%** loading**? ~3x stats?**

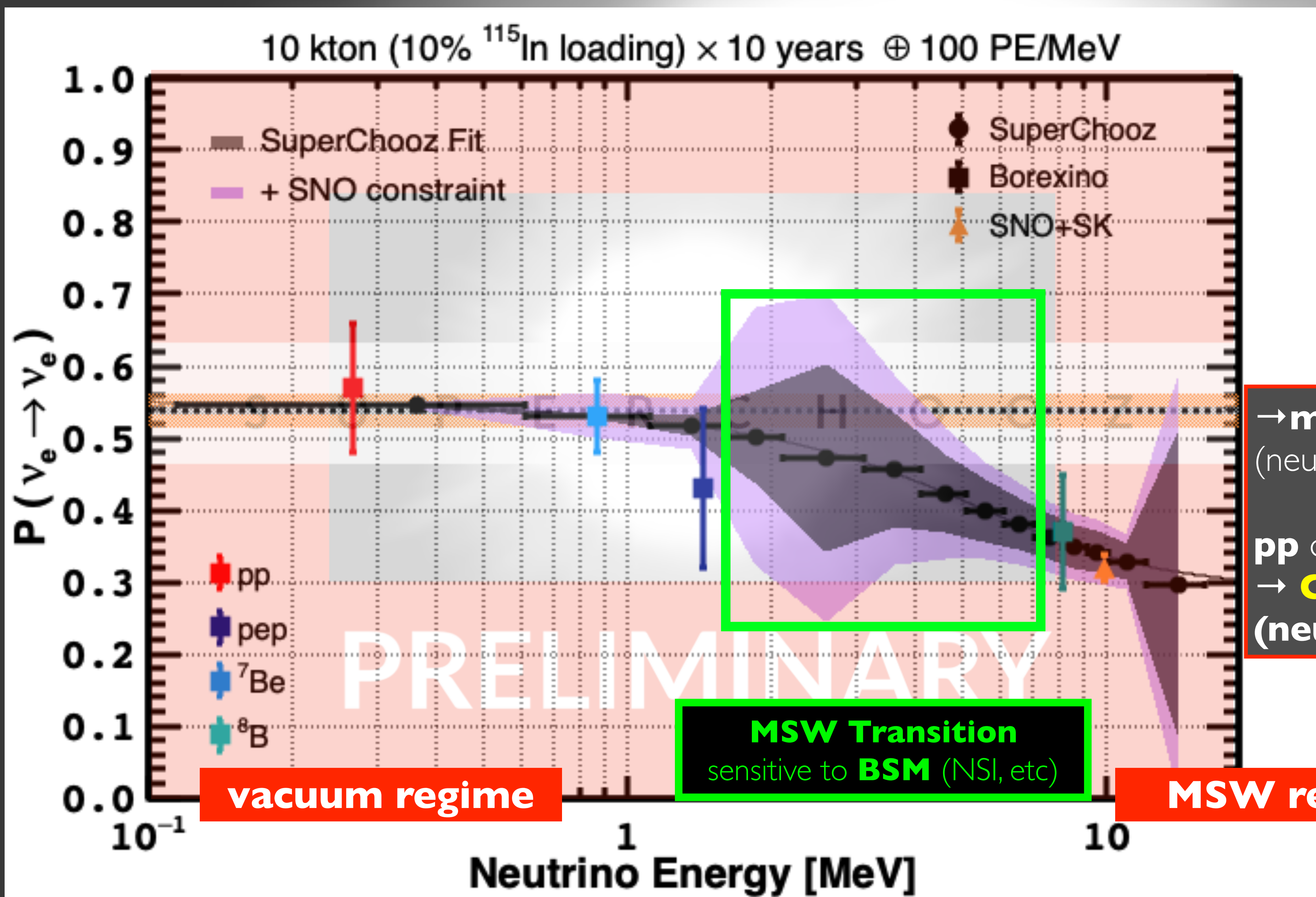
Flux Information:
- •**SSM prediction**
- •**SNO-NC** for **ϕ(^{8}B)**

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

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

neutrino oscillation transition…

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



today's precision on θ12

→measure θ12 & δm²
(neutrino)

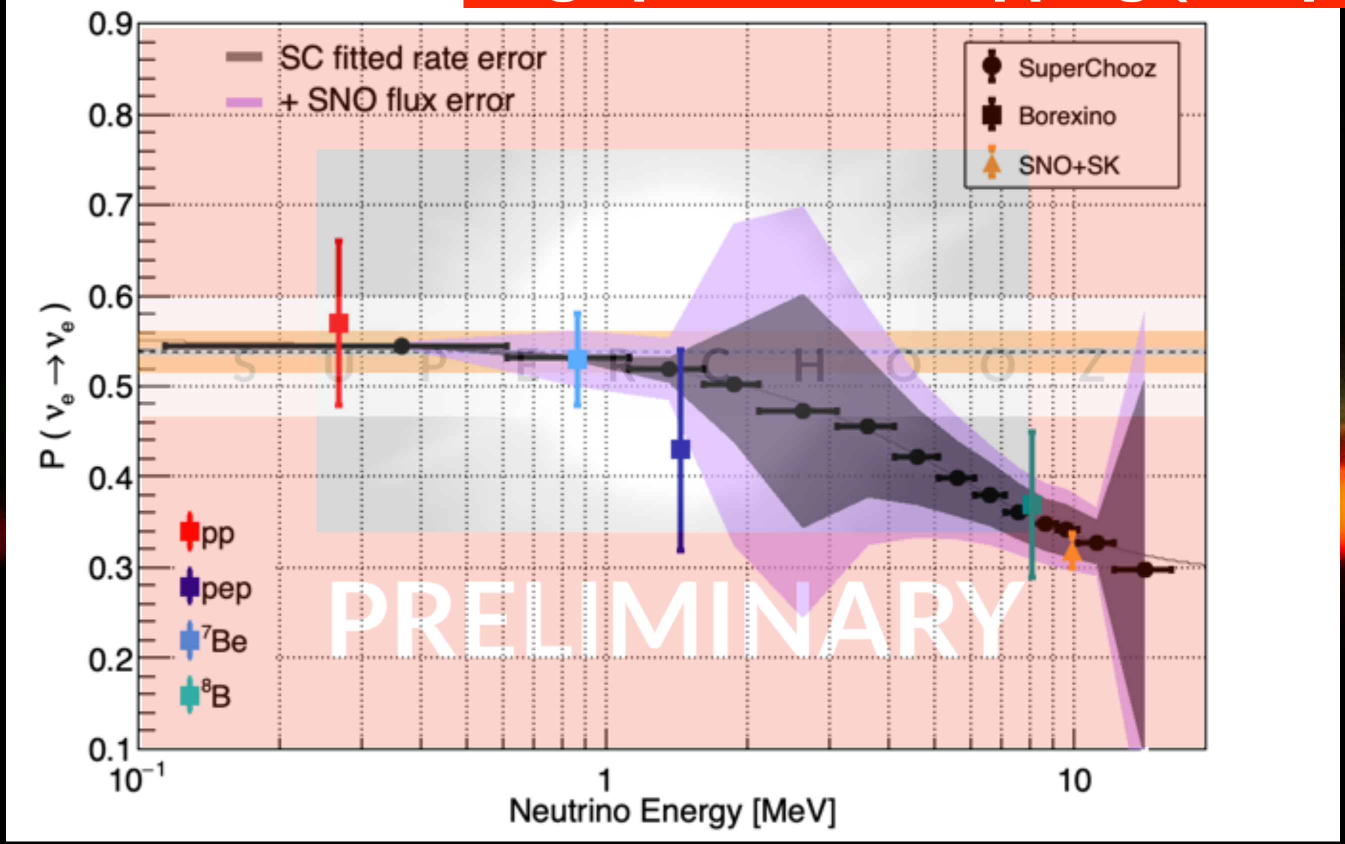
pp direct comparison with **JUNO**[≤0.5%]
→ **CPT violation?**
(neutrino vs anti-neutrino)

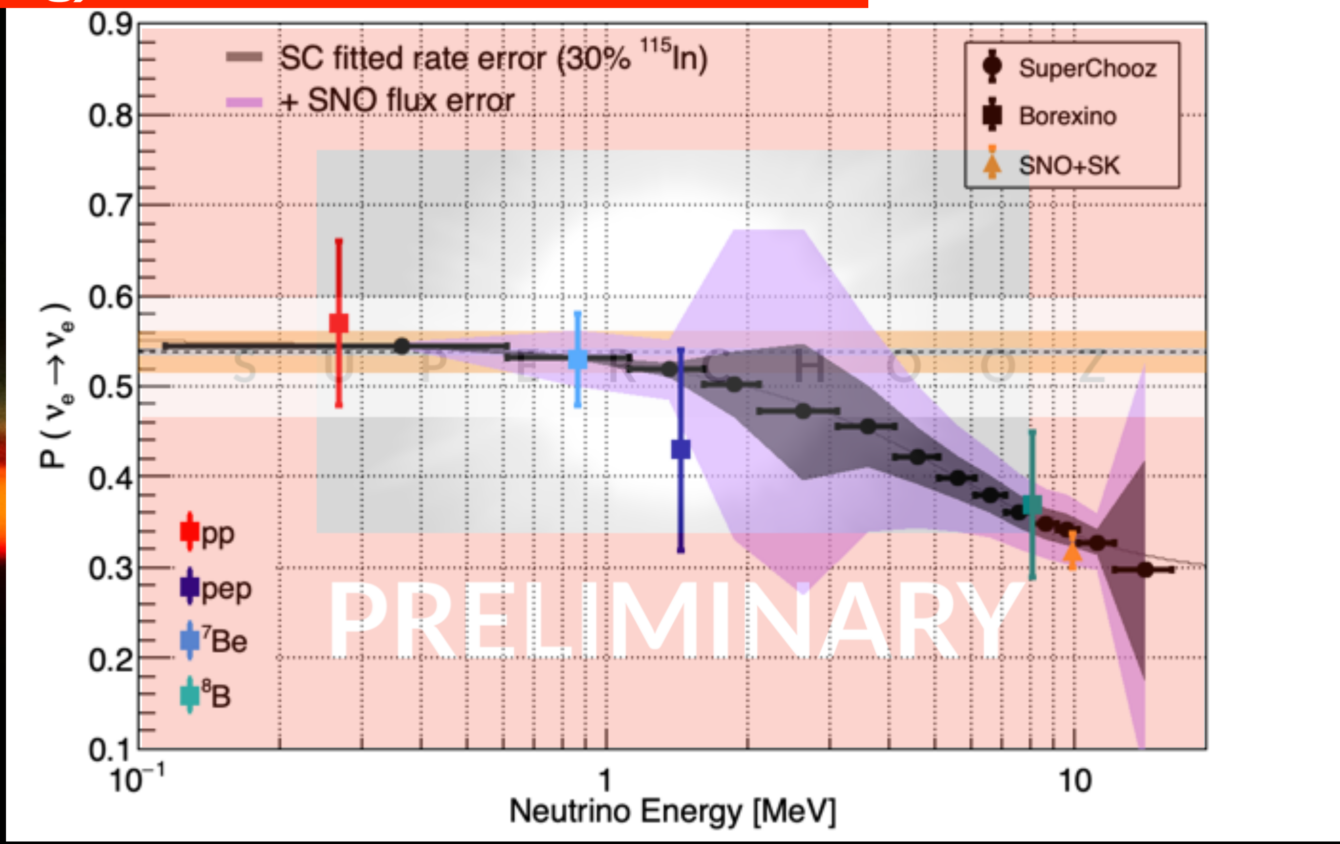
solar neutrinos: longest baseline neutrino with few % precision→ new physics?

use ϕ(SNO-NC) for ⁸B 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: ϕ(^{8}B) [≤5%]** instead of **SMM prediction [12%]**

Sun's neutrino knowledge

- direct probing innermost structure
- precision beyond Solar-SM (all)— first time!
  [^{8}B driven by **HK⊕JUNO⊕DUNE**]

neutrino solar astrophysics!

new phenomenology manifest **effective symmetry violation**

neutrino oscillation:

- **effective lepton# violation** — new physics: **mixing**
- **effective unitarity violation** — new physics: **disappearance**

physics III: fundamental symmetries

beyond-SM neutrino oscillations (L_i)

CP Violation? [SM ⟶ foreseen in CKM and PMNS]

- (indirectly) HyperK⊕DUNE knowledge on θ_{13}

⟶ extra precision on θ_{23} ? [backup]

Unitarity Violation? [BSM]

discovery potential

- @UND: reactor absolute flux (up to 0.5%?) — CLOUD
- @SFD: solar-pp absolute flux (up to 0.6%?)

CPT Violation? [BSM]

discovery potential

- θ_{12} by both SuperChooz⊕JUNO — difference?

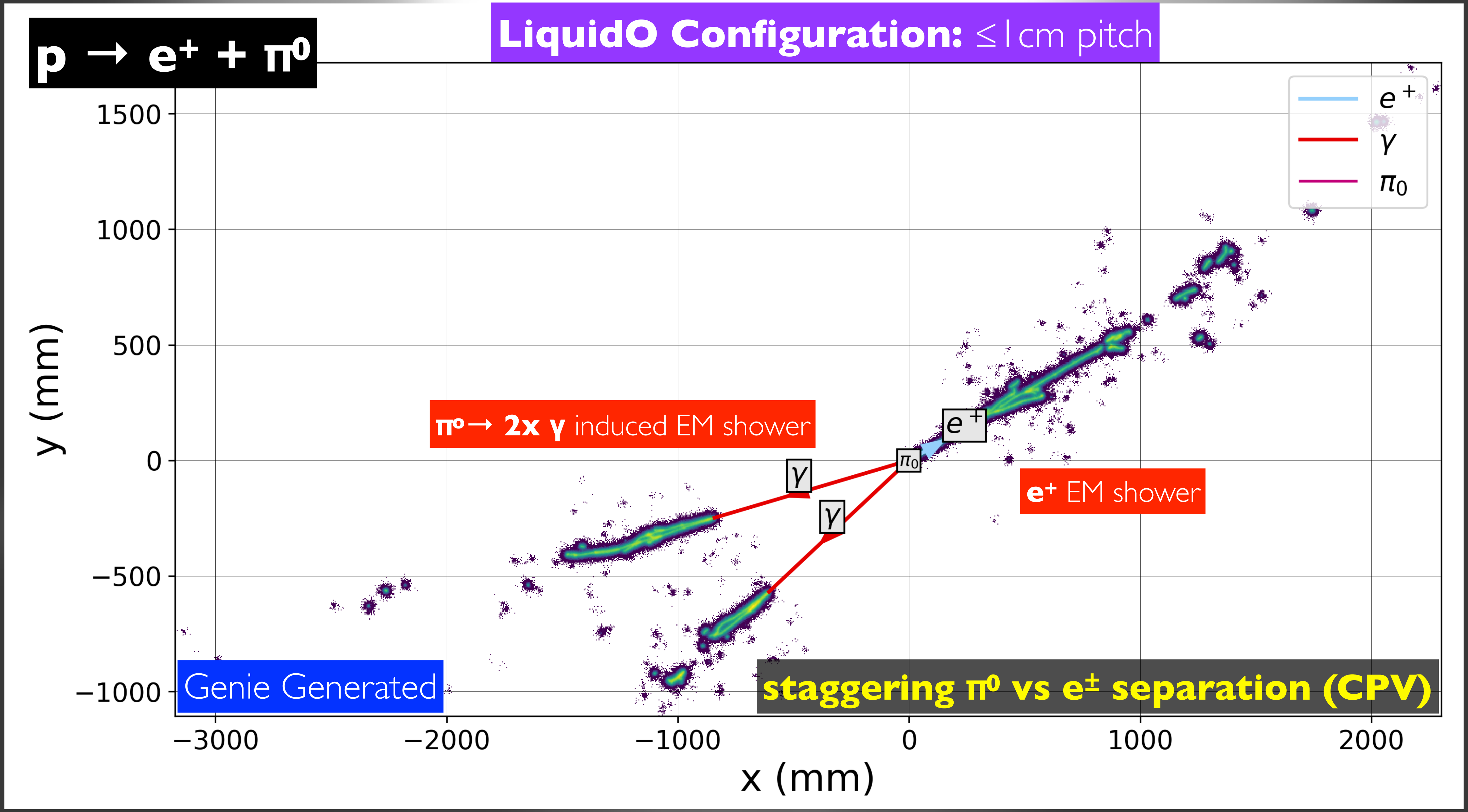
Baryon# Violation? proton-decay [multi-mode]

discovery potential

discovery channels too…

m(proton)**~1GeV**

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



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

SUPERCHOOZ

main conclusions…

status on neutrino oscillation knowledge…

SuperChooz is designed cover the full ***SM picture*** (3 families) [synergy]

SuperChooz explore the ***SM***'s consistency/completeness→ **BSM discovery?**

SuperChooz = SC

	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%**	**SC**	reactor
$+\delta m^2$	2.5 %	KamLAND	2.3 %	<0.5%	JUNO⊕**SC**	reactor⊕solar
$\|\Delta m^2\|$	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	reactor⊕beam
CP	**violation?**	T2K+NOvA	3/2π @ ≤2σ	**@5σ?**	DUNE⊕HK [**SC**]	beam driven
CPT	**violation?**	—	—	**<1%?**	**SC**	reactor⊕solar
Unitarity	**violation?**	—	—	**<1%?**	**SC**	reactor⊕solar
Baryon#	**violation?**	—	—		JUNO⊕DUNE⊕HK⊕**SC**	

reactor⊕solar main channels of **SC**, but low energy **atmospherics under study…**

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

neutrinos back to Europe?

(high precision)

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

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

thanks to **EDF** teams & support,
LiquidO consortia,
AM-OTech consortia,
CLOUD collaboration,
and **SuperChooz** team.

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

SUPERCHOOZ

new **flagship neutrino physics** project in based **Europe** [>2030]**?**
(once **JUNO⊕HyperK⊕DUNE** are **running**)

new detector [**LiquidO**] ⊕ **new site** [Chooz-A] ⊕ **new physics?**

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

anatael@in2p3.fr

HEP-European Physics Society
(July 2019 @ Ghent Belgium)

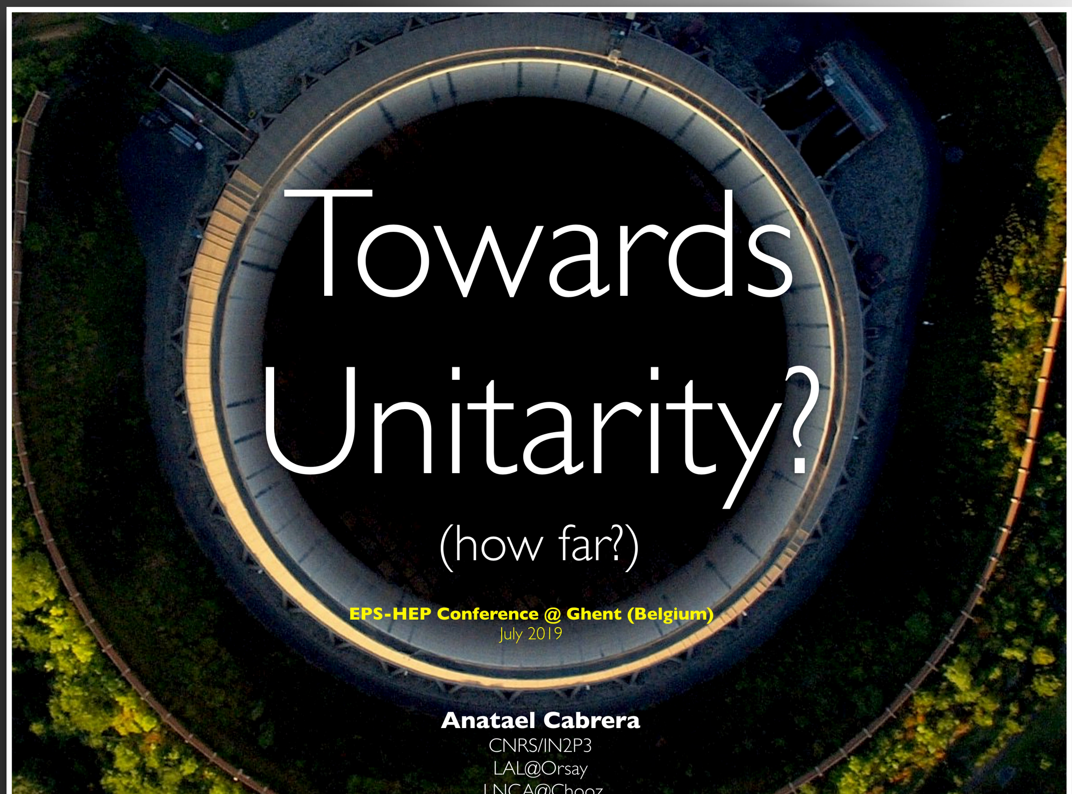
EP Seminar

The SuperChooz Experiment: Unveiling the Opportunity

by Dr Anatael CABRERA (IJCLab - IN2P3/CNRS)

Tuesday 29 Nov 2022, 11:00 → 12:00 Europe/Zurich

222/R-001 (CERN)



https://indico.cern.ch/event/1215214/

https://indico.cern.ch/event/577856/contributions/3421609/

https://zenodo.org/record/7504162

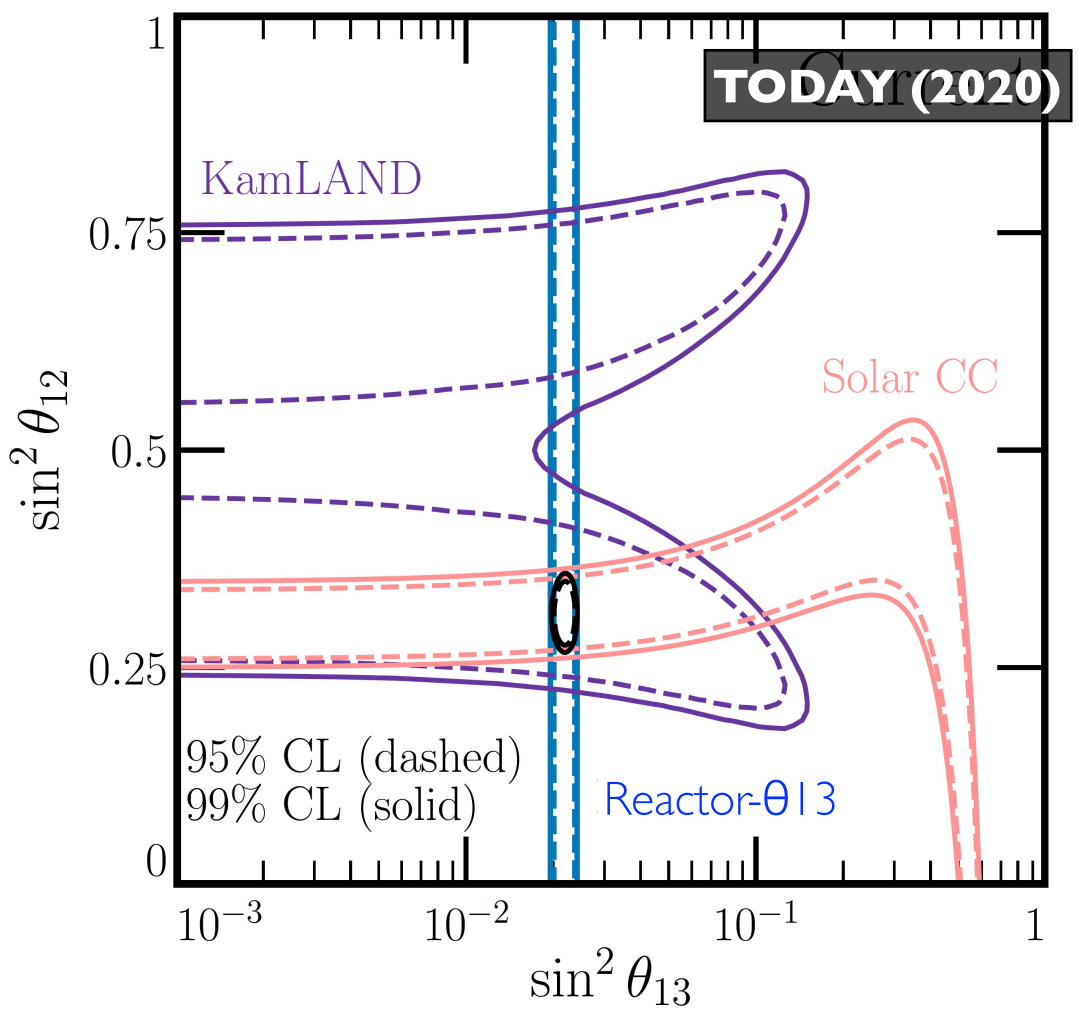
https://liquido.ijclab.in2p3.fr/

exploring since 2018...

backup slides…

Super Chooz potential under investigation…

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

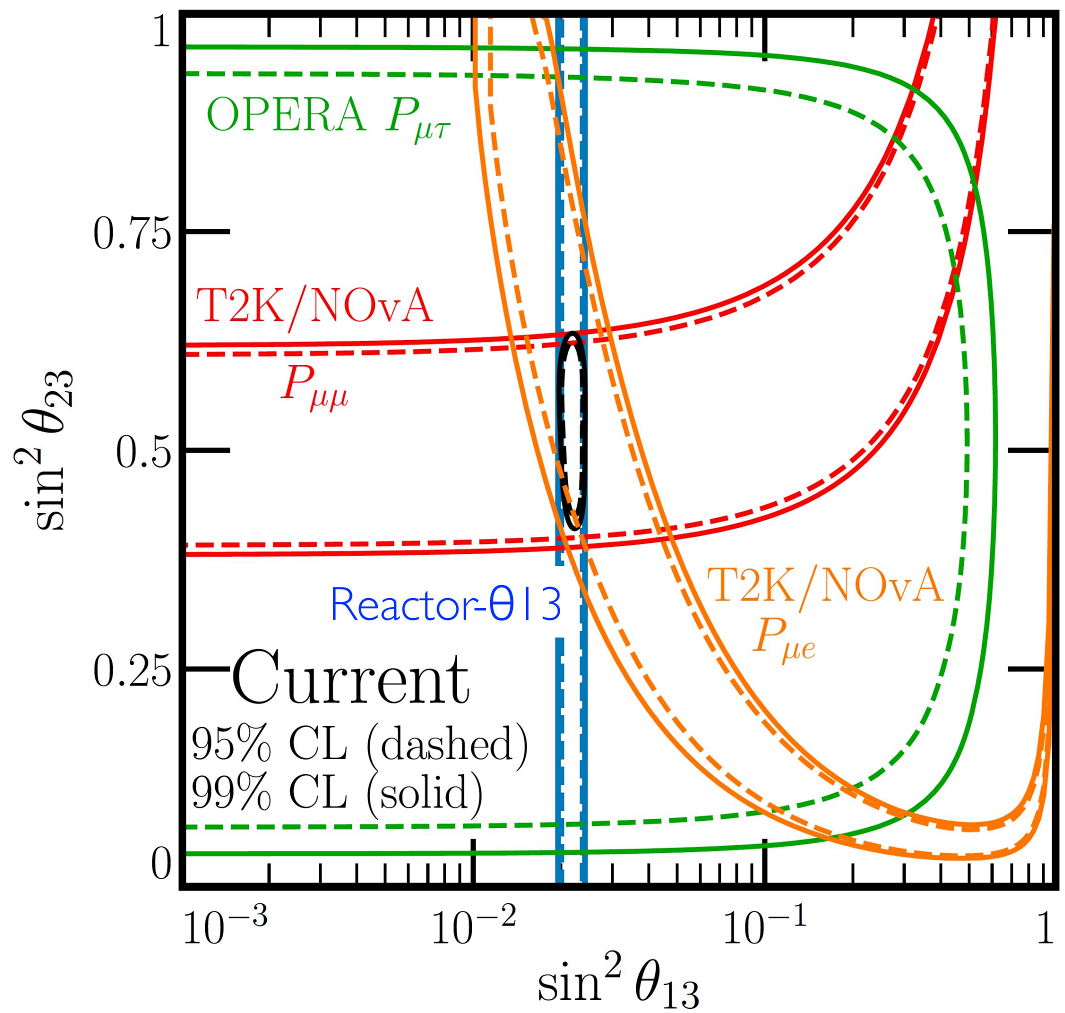


z)

Super Chooz: the smallest but powerful…

Super Chooz potential under investigation…

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



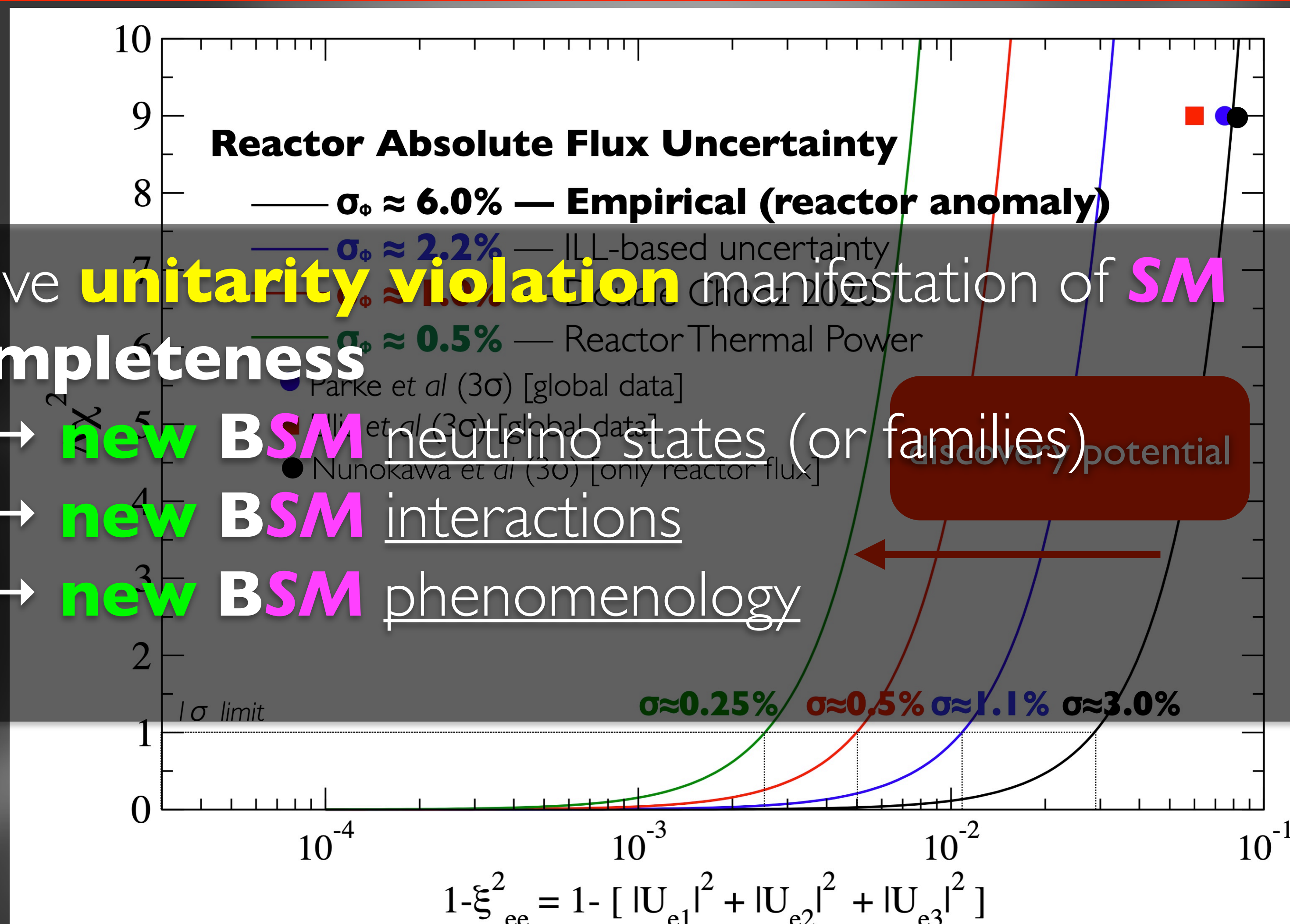
synergy: SC θ13 may help to resolve the "θ23 octant" ambiguity

(HK and DUNE) measured the combined effect of θ13⊕θ23 (harder to disentangle)

Super Chooz: the smallest but powerful…

must improve the reactor flux understanding → discovery potential

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



effective **unitarity violation** manifestation of ***SM*** **incompleteness**

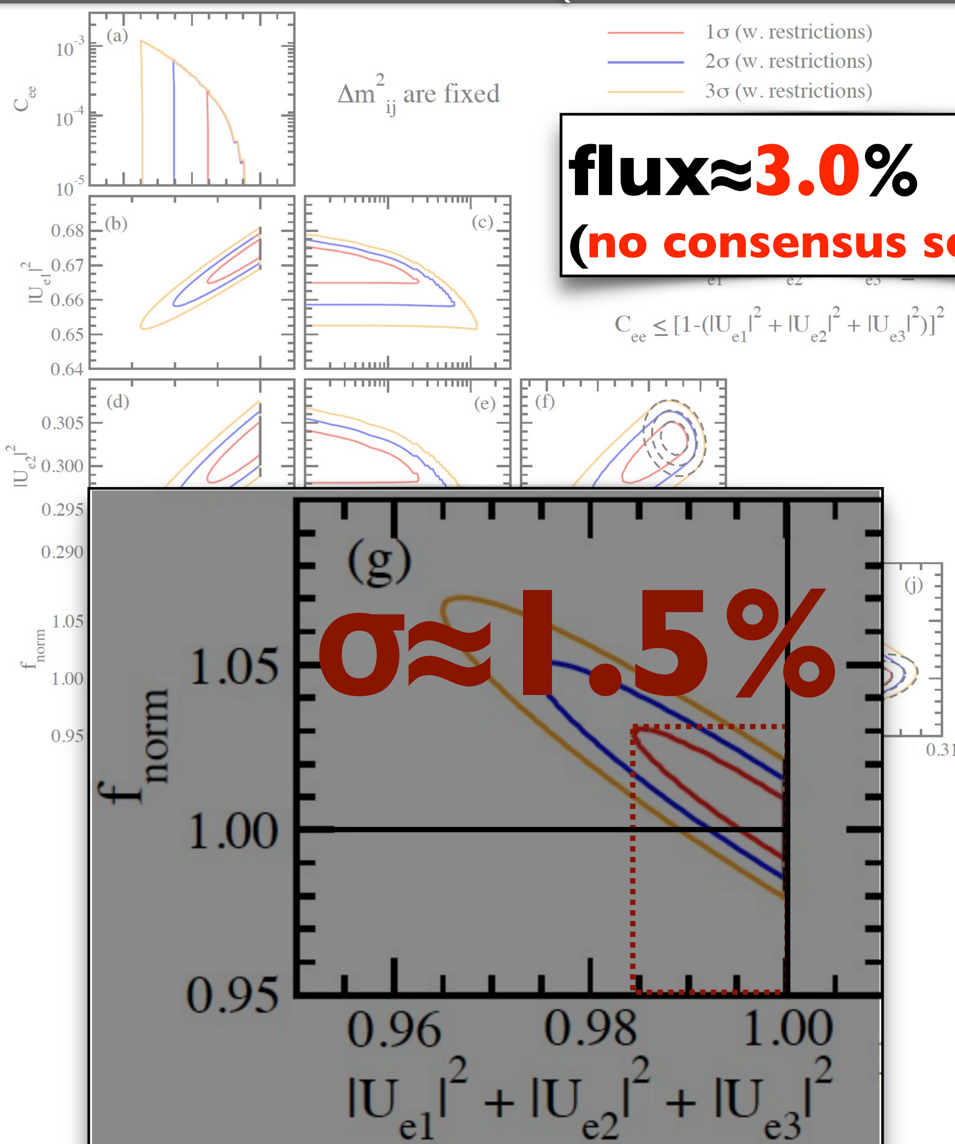
- → **new** **B*SM*** neutrino states (or families)
- → **new** **B*SM*** interactions
- → **new** **B*SM*** phenomenology

Unitarity exploration

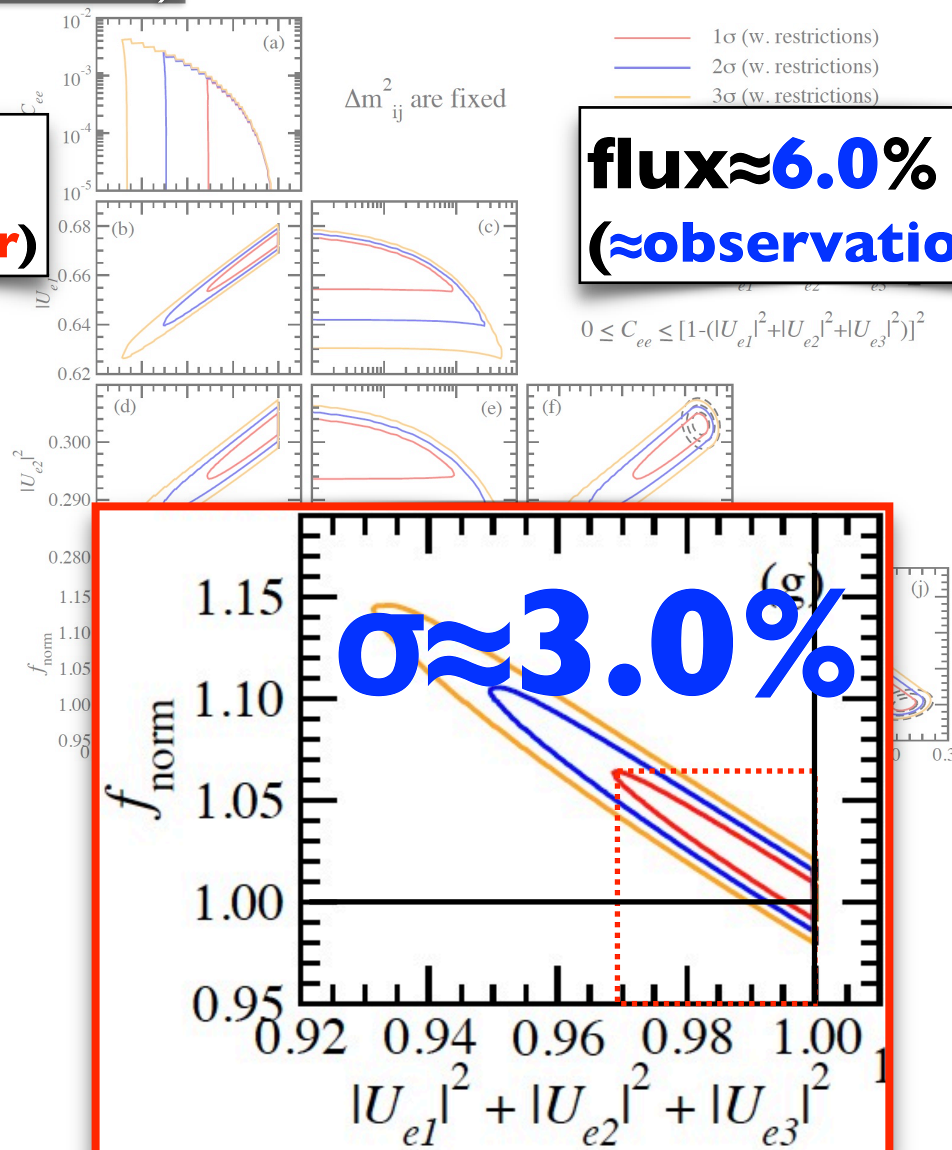
Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

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

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



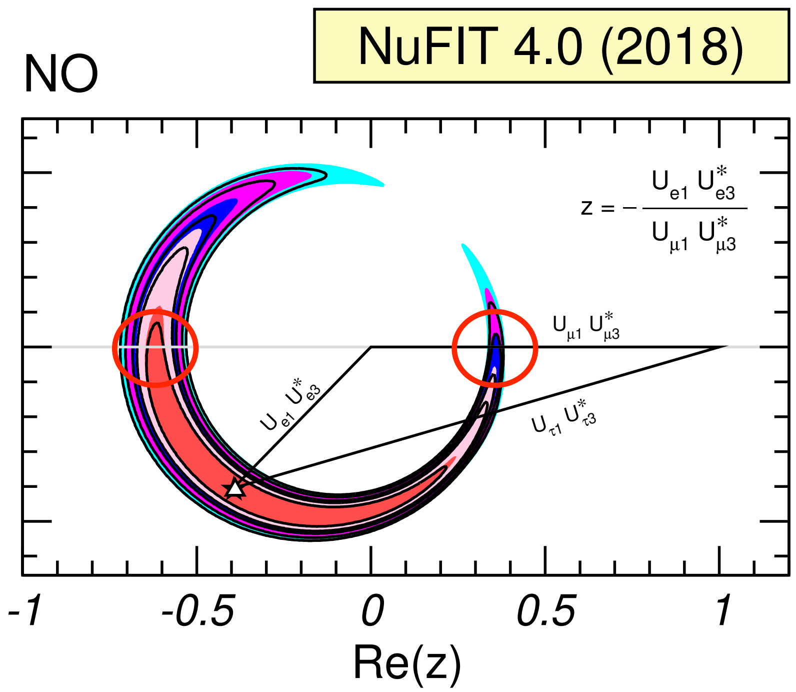
flux≈3.0%
(no consensus so far)



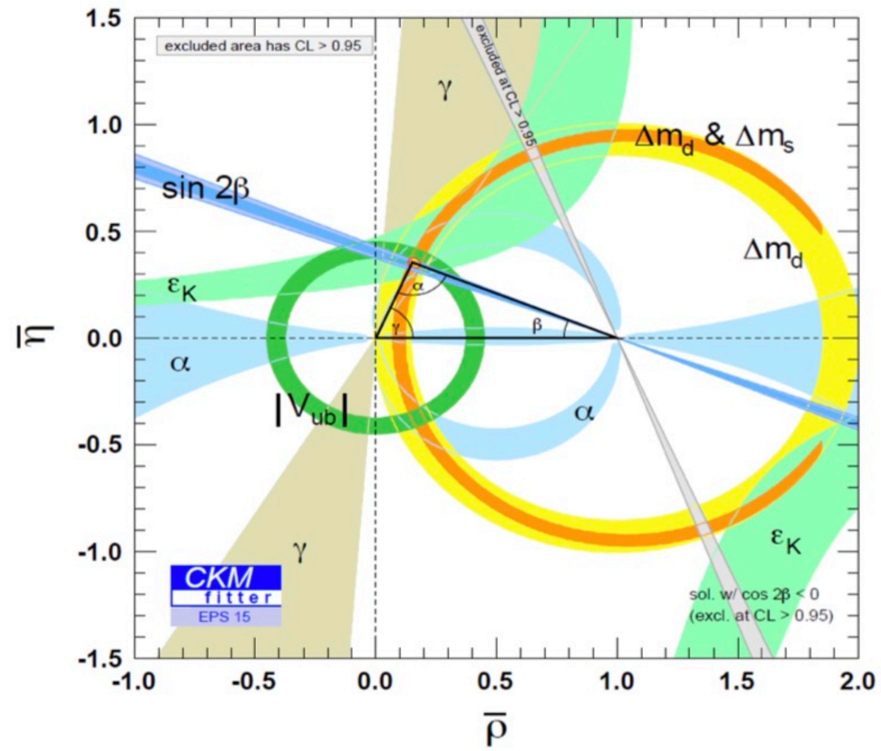
flux≈6.0%
(≈observations)

unitary explorations limited by absolute flux uncertainty

PMNS



CKM

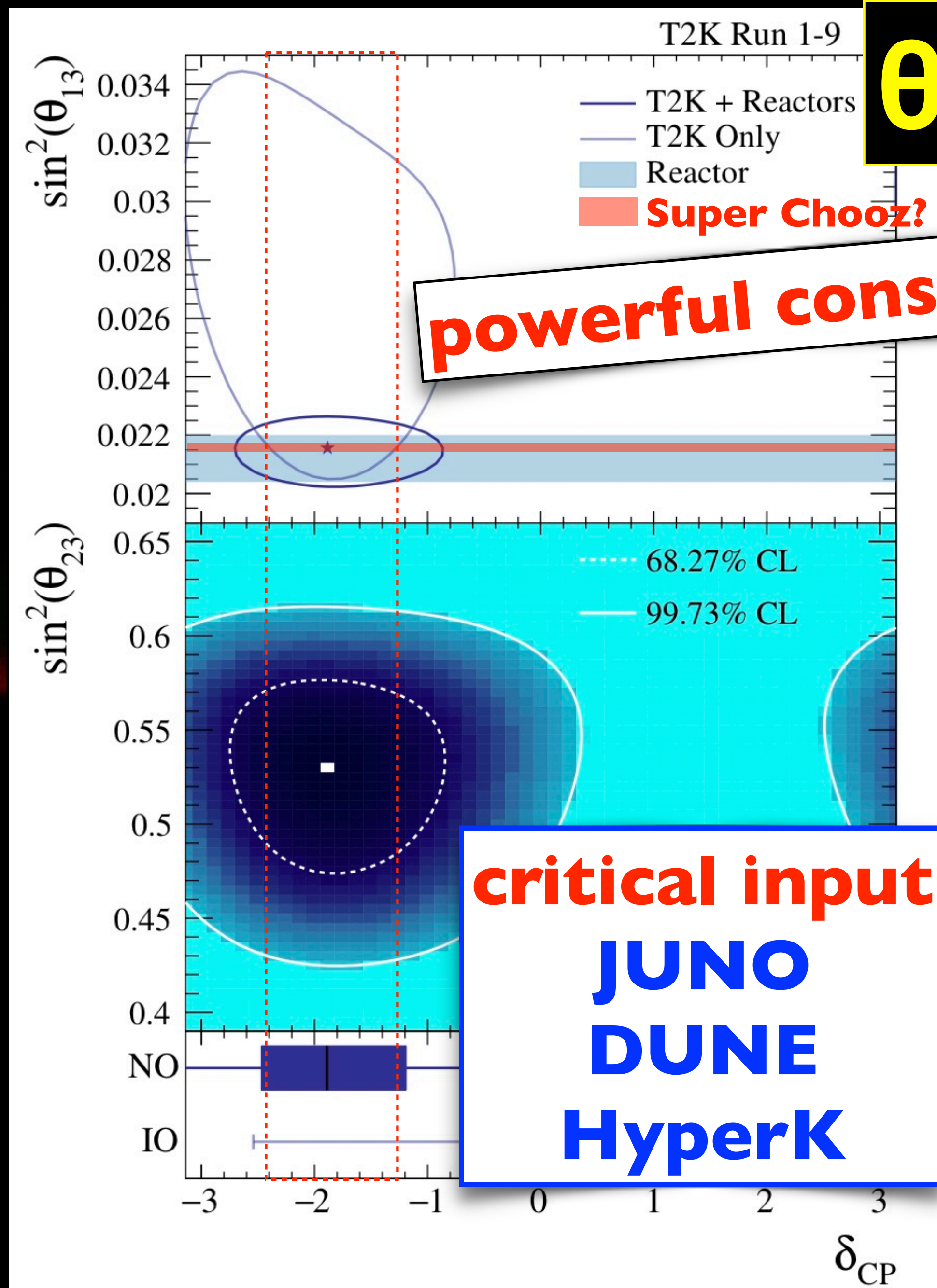


J(PMNS)≈3.33±0.06x10 **J(CKM)≈3.18±0.15x10^{-5}**

PMNS triangle→CP

T2K⊕reactor best knowledge CP-Violation…

θ13 implications

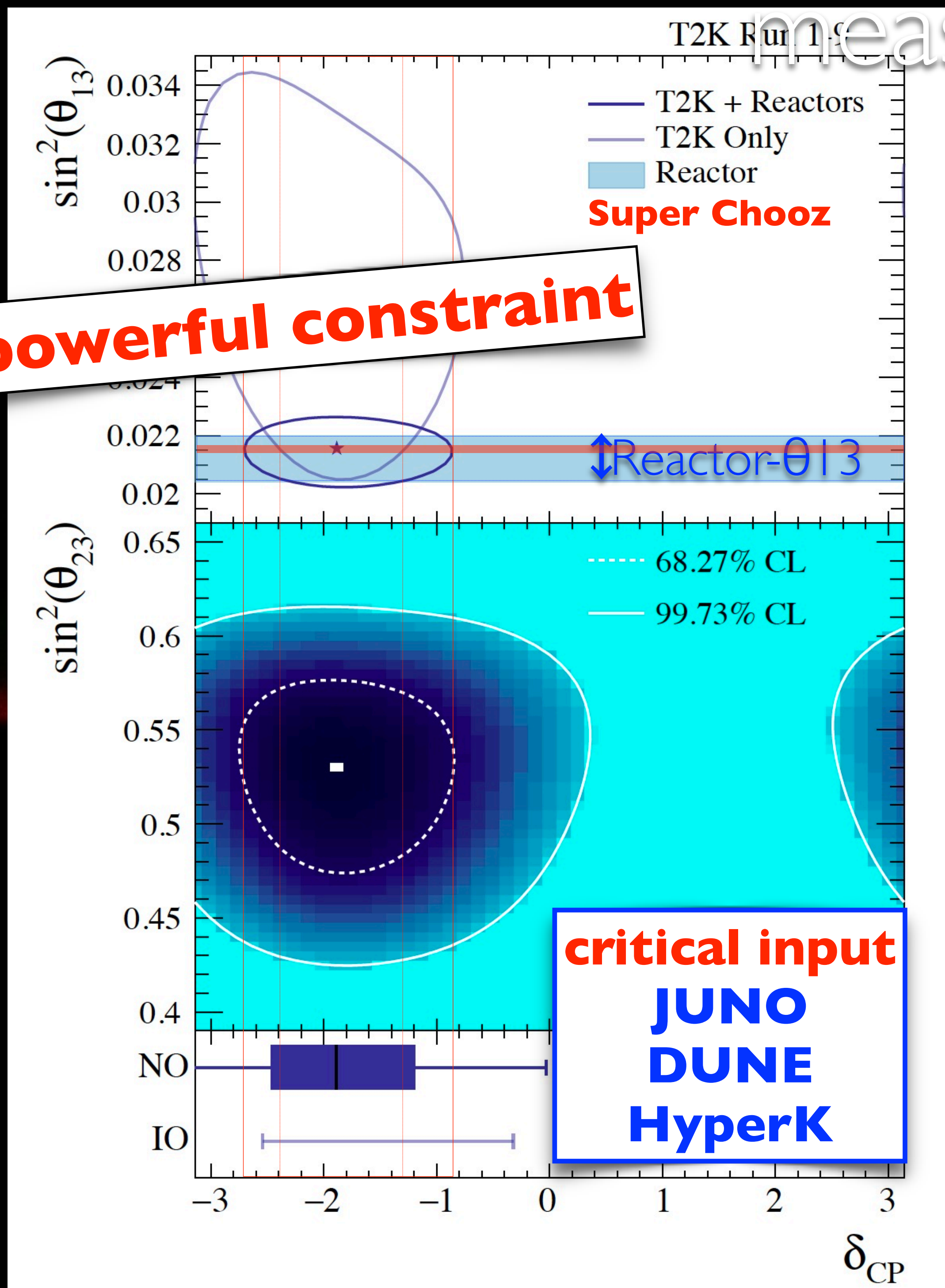


CPV phase vs θ13
[constrained by reactor]

CPV phase vs θ23
[octant ambiguity]

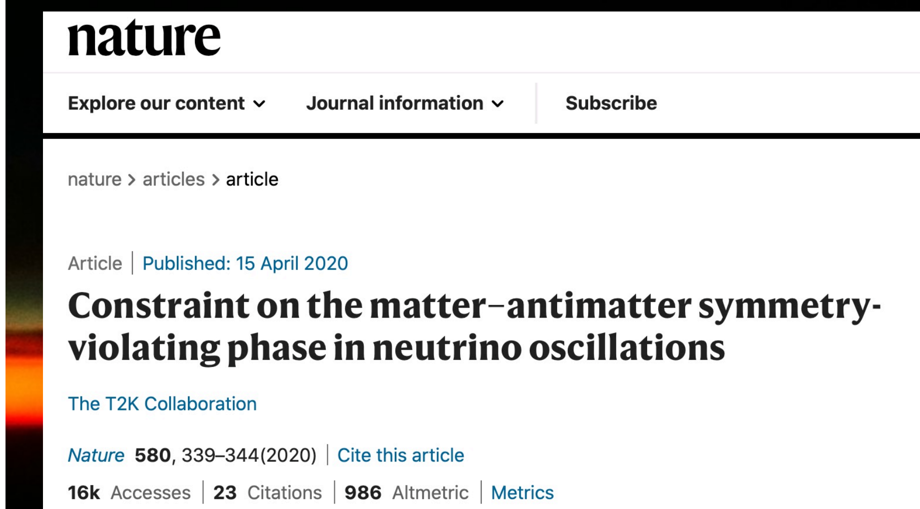
CPV phase vs (Atmospheric) Mass Ordering
[T2K blinded]

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]

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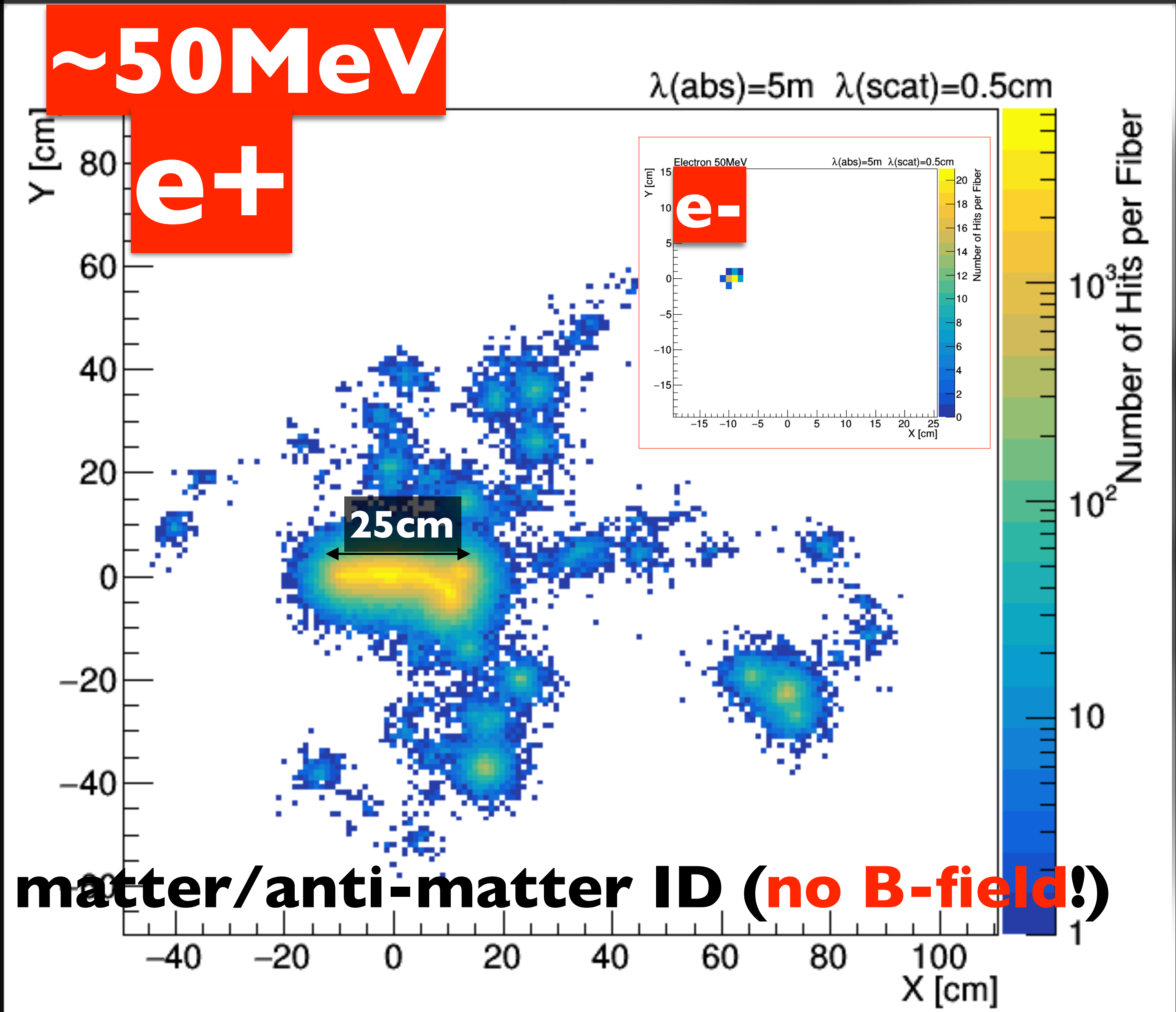
multi-MeV improves (more light too)…



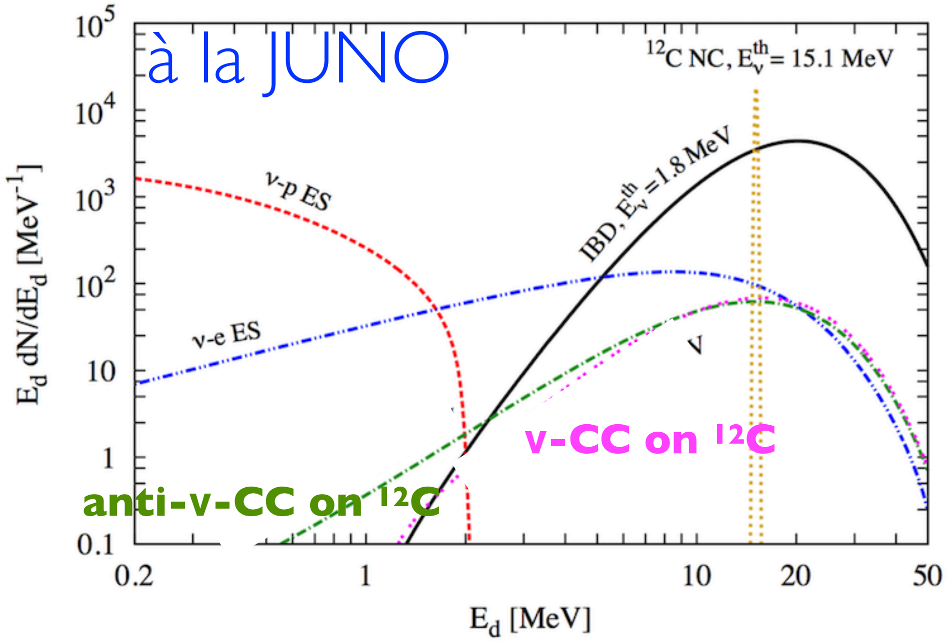
matter/anti-matter ID (no B-field!)

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

~10MeV: supernovae (remnant, core-collapse**), atmospherics, etc**

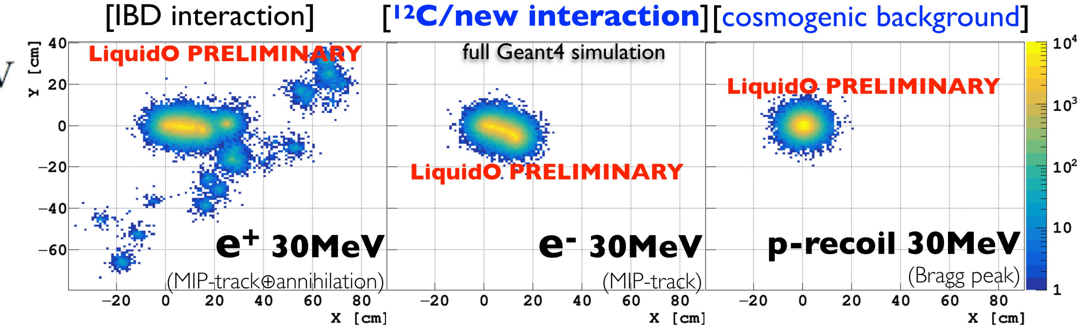
Supernova at 10 kParsec

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



Visible Energy [MeV]

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



main channels(*)...

IBD*
ν̄ CC (^{12}C)
↓
core-collapse
relic

ν CC (In)*
ES(e)
ν CC (^{12}C)
↓
core-collapse
relic? (hard)

ES(p)
ES(e) [low energy]
↓
core-collapse
~~**relic**~~

fast-neutron (BG)

measure **all neutrino types CC, ES & NC** (absolute flux) (also) **ν NC (^{12}C)***

supernovae @

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

experimental demonstration III

a priori no showstopper

SuperChooz : ~9 700 m³

some **common technology** but **not methodology**

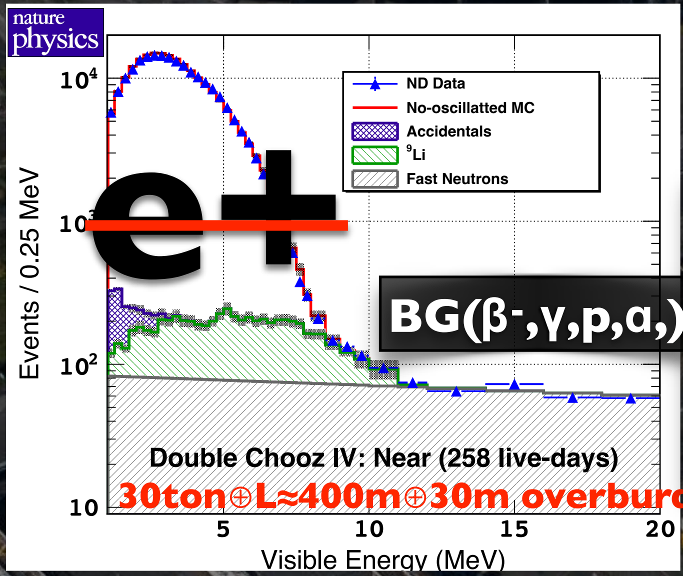
- scintillator: ✓ (improvement)
- fibres ✓ (improvement)
- ~~segmentation~~ ✗ (simplification, cheaper, less BG)
- light collection: ✓ (improvement expected)
- photo-detector: ✓ (simplicaition with SiPM)
- MeV optimisation→**Scaling R&D [≥2024]**

SuperChooz (~10kton) similar dimensions as **NOvA (~14kton)** & one module of **DUNE (~10kton)**

LNCA)

ultranear @ Chooz…

nature physics



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

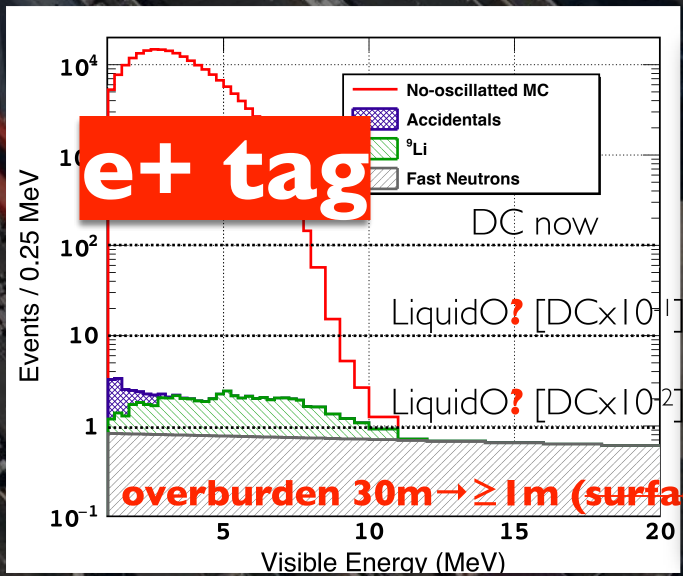
DC-ND:

Signal ≈ 816 ν/day

BG(β-,α,γ,p) ≈ 39 day^{-1} ("*some per day*")

S/BG≈21

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



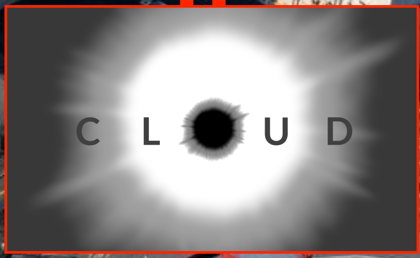
CLOUD:

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

BG(DC) ≈ **≥10x** BG(LiquidO)

S/BG ≥100? same config [demo]

⟹**BG-less reactor-ν?** (some *per year*?)



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

the power of coincidences

low energy (≲3MeV) neutrinos interactions benefit by interactions leading to coincidences

Reines et al 1956

(neutrino discovery)

CC: $\bar{\nu}_e + p \rightarrow e^+ + n$

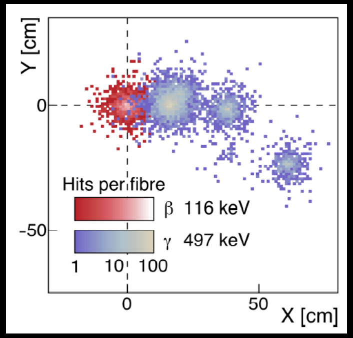
Raghavan et al 1977

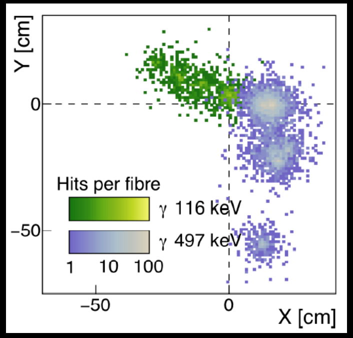
(pp solar neutrino — unobserved)

CC:

major **R&D** by **LENS** *et al* [many years]

	CC antineutrino	CC neutrino
	native [H atoms]	loaded @ **≥10% *indium***
threshold	≥1.8 MeV	≥114 keV
δ(σ)	~0.2% [↔neutron lifetime]	order 1.0%**?** [a la Ga]
prompt /	**e+** / **γ**(2.2MeV) [H-n capture]	**e-** / **γ**(0.5MeV) ⊕ **β-**/
LiquidO's PID	prompt (**e+**)	both prompt & delayed
Δt (1D)	**~220μs**	**~4.7μs**
Δr (3D)	**≲1m** (DC) / **≲0.5?m** (LiquidO)	**few cm's**
ΔE (1D)	around **2.2MeV**	around **0.6MeV**
Rejection (4D)	**~1e5?** (**LiquidO**) **~1e4** (DC)	**≳1e12?** (**LiquidO**)
Signal/BG	**≳100?** (**LiquidO**) [DC: ~20]	**≳10?** (**LiquidO**) [LENS:





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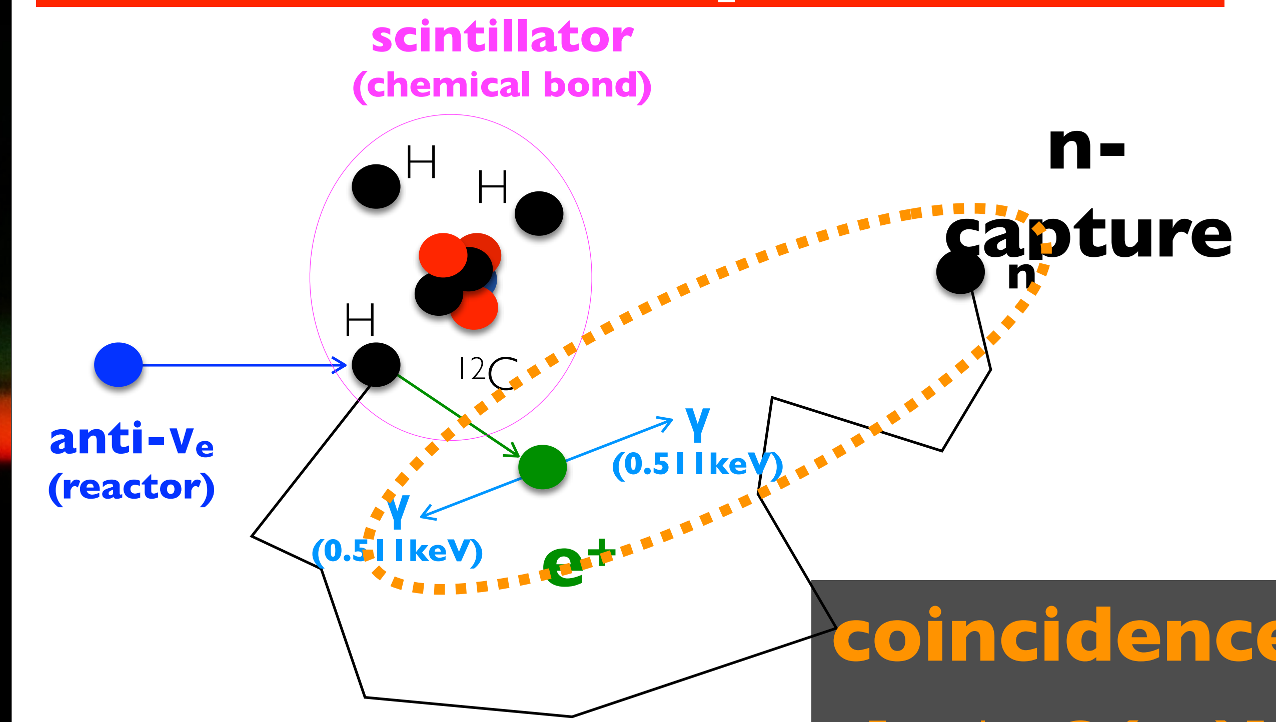
ν discovery pioneers

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n

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



coincidence

[scale **O(μs)**]

note: H = proton (oils or

generally, **no e+ PID**

→ **γ** ≈ **e^-** ≈ **e^+** ≈ α ≈ **p-recoil**

(fast-n)

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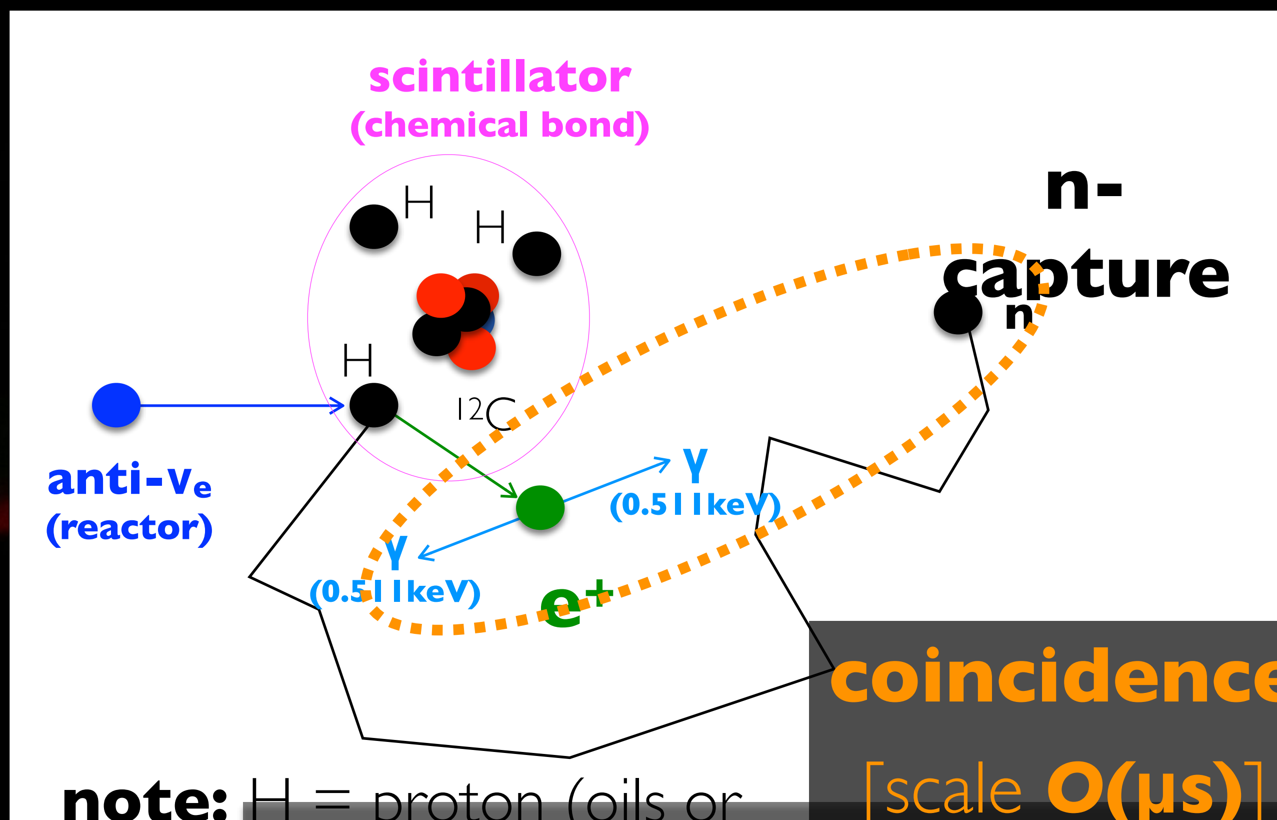
inverse-β decay (IBD) interaction…

IBD detection

IBD: anti-ν_e + p → e^+ + n

art…



coincidence

[scale **O(μs)**]

n-H (**native**)
n-C (**native oil**)
n-O? (**native water**)
n-Cd (non-native)
n-Li (non-native)
n-Gd (non-native)
^{3}He (non-native)

no e+ PID implies

γ ≈ e^- ≈ e^+ ≈ α ≈ p-recoil

(fast-n)

how to catch the n?

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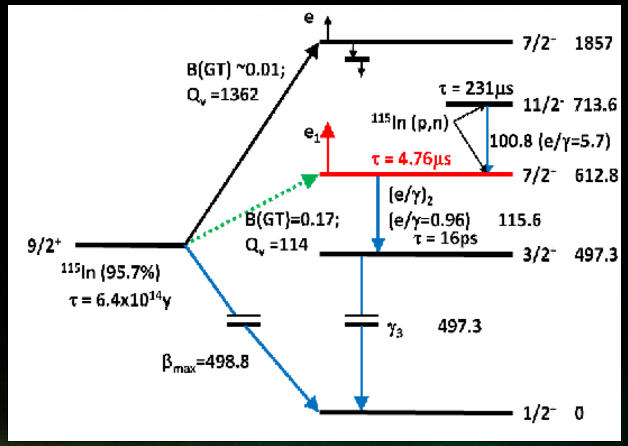
solar's **Indium**

^{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**]

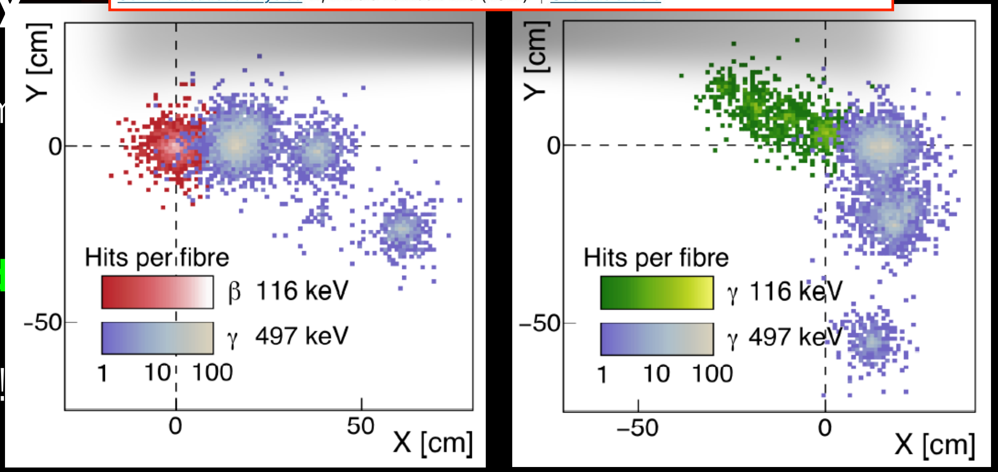


Neutrino physics with an opaque detector

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)

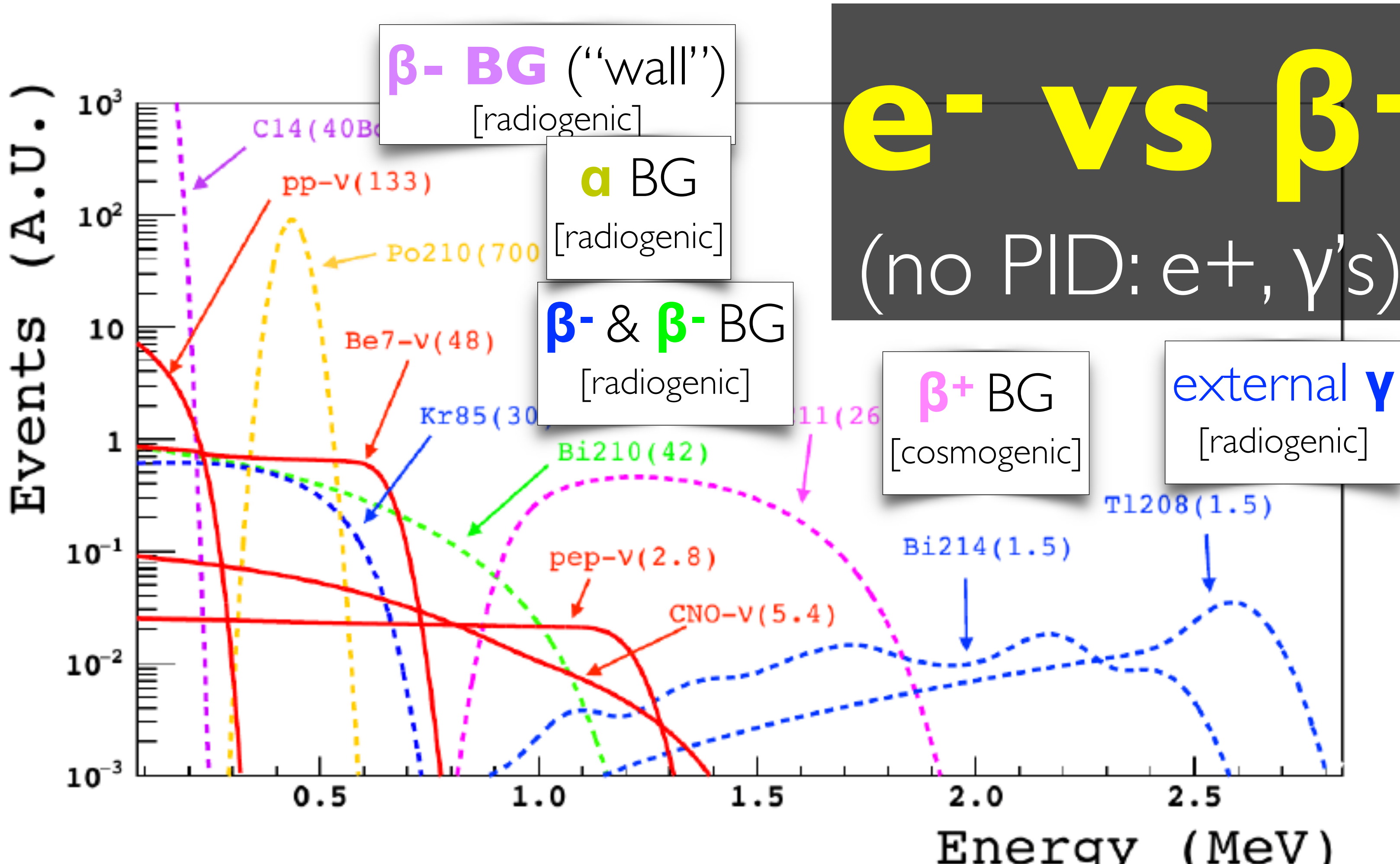


Bremsstrahlung: worsen selection (**understud**

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)



e- vs β-

(no PID: e+, γ's)

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…

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-	
statistics	few %	~0.1%	—	—	~100/day @
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/
detectio	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?

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flux handled by the power of geometry…

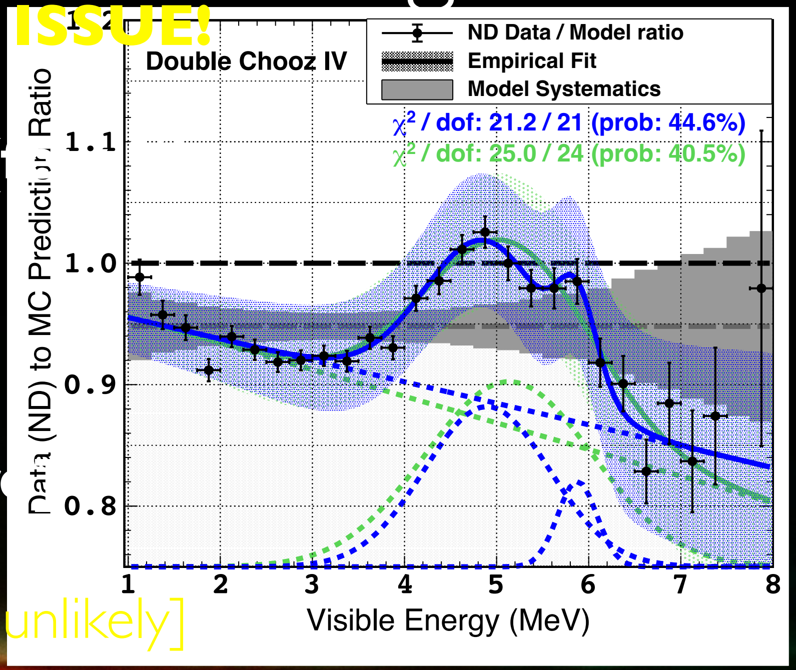
today's knowledge converges: BIG ISSUE!

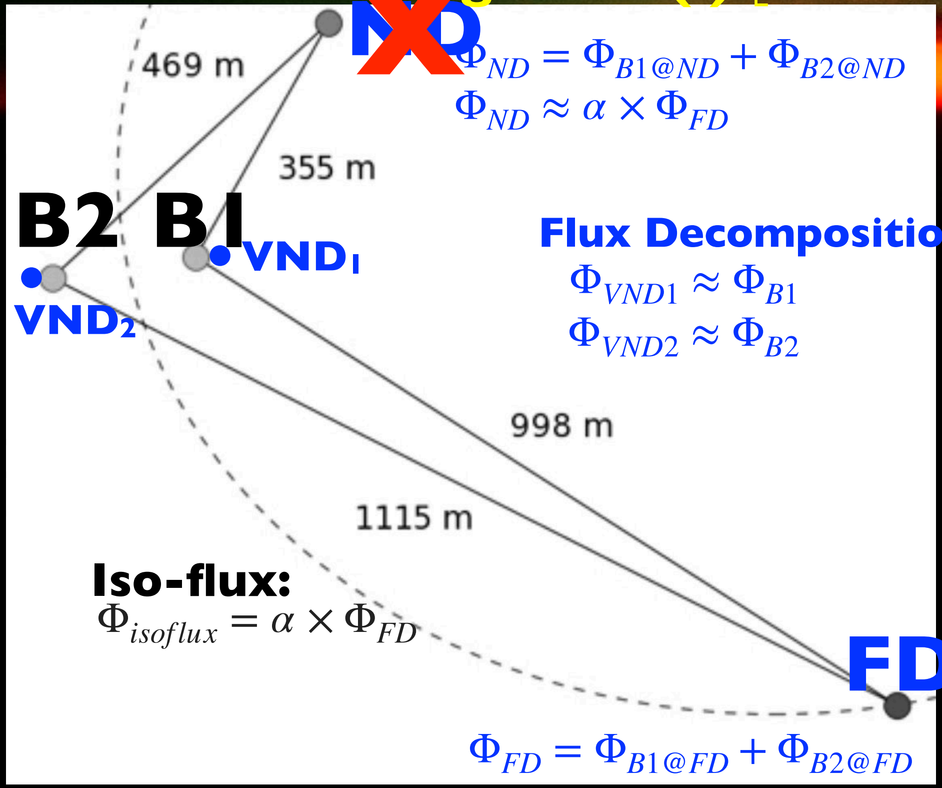
reactor prediction is inaccurate (t

[unsurprisingly more complex than we thought]

- **rate off by ≲10% [deficit]**
- **shape off by up to ≲15% [structur**

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



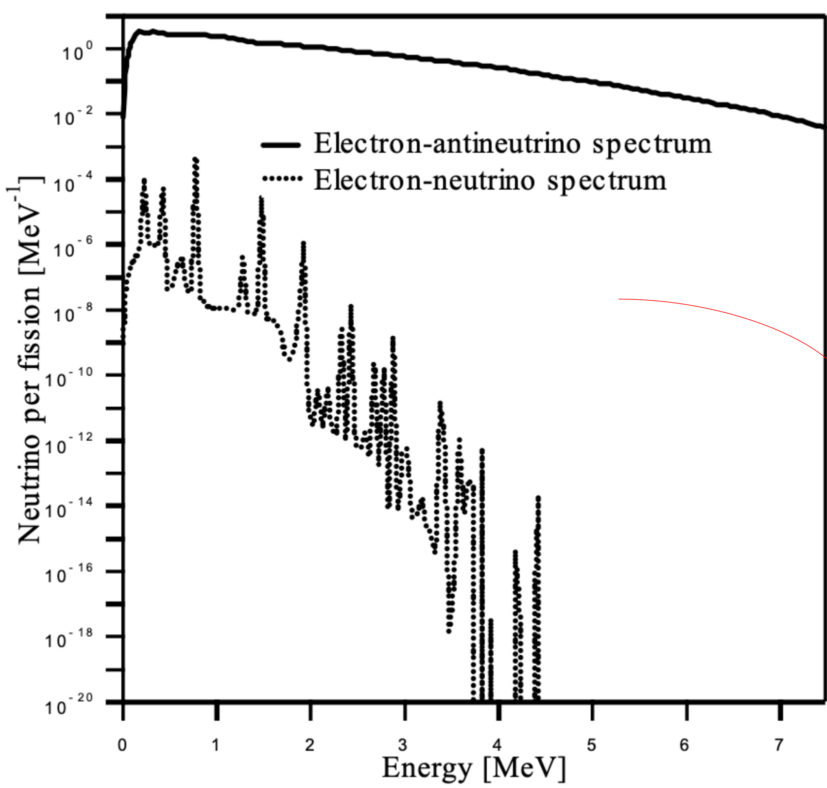


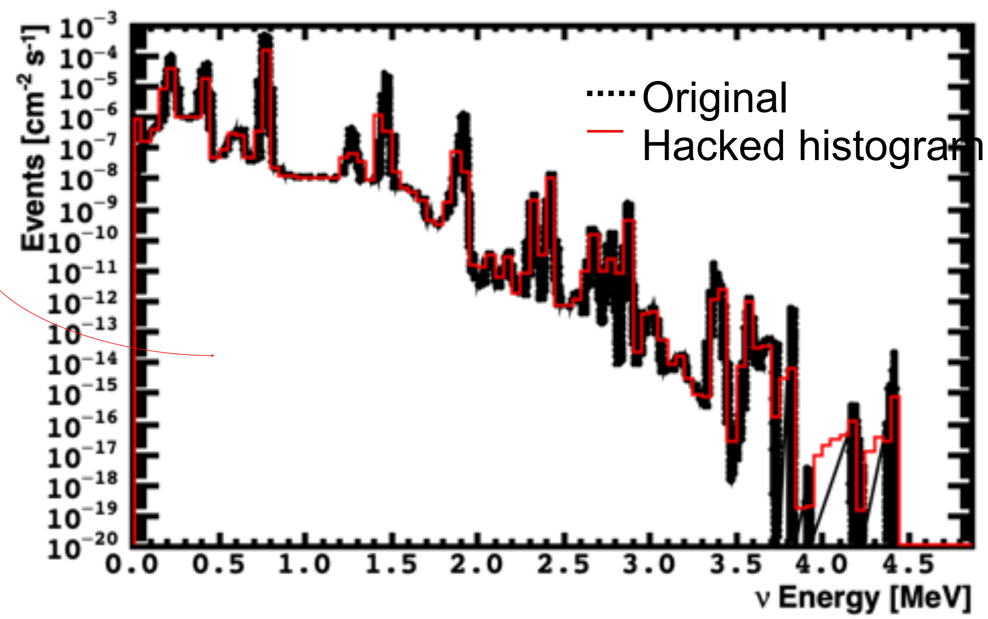
monitor rate+shape cancels (perfect?)

- **conventional ND: not good enough!**
  - →degeneracy flux & θ13 (also far & small)
  - →slight offset to iso-flux⇒ unacceptable
- **flux decomposition (L≲40m): perfect!**
  - →very near detector (**VND**) per reactor
  - →huge statistics:
    1ton @ 20m: 8.2k IBD/day [FD: ≲2.2k IBD/day]
  - →no civil construction [→reactor space?]

- Number of reactor-intrinsic ν_e in AMoTech-^{115}In (5 tons InLS (10% ^{115}In), 25 m)

$$N^{exp}_{\nu_e}(t) = \frac{\epsilon N_{In}}{4\pi} \frac{\phi_{\nu_e}(t)}{L^2} \sigma_{In}$$

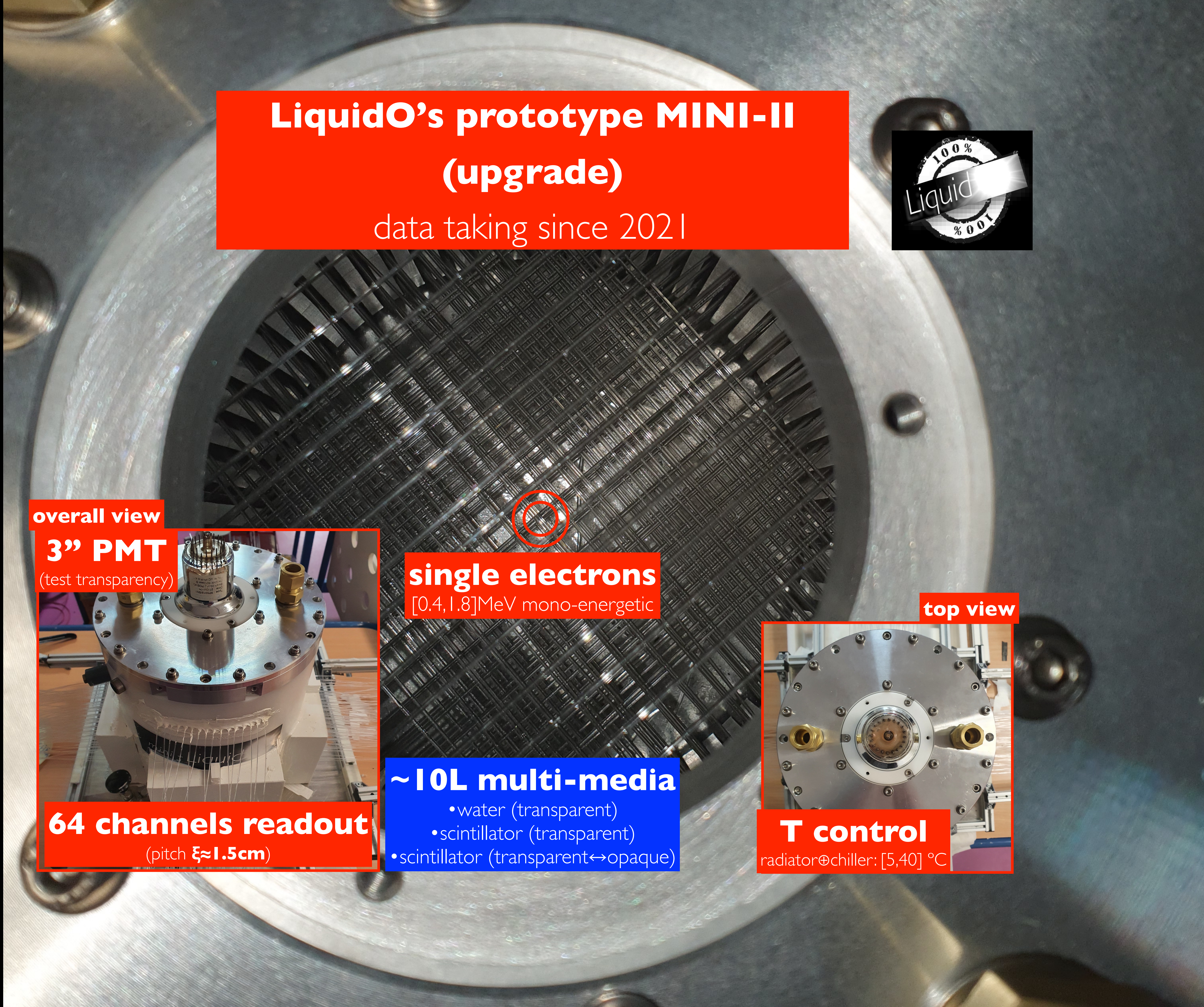




"The neutrino flux is lower by about five orders of magnitudes than that of antineutrinos"

$\phi_{\nu_e}(t) \sim 10^{16}\ \nu_e/s$

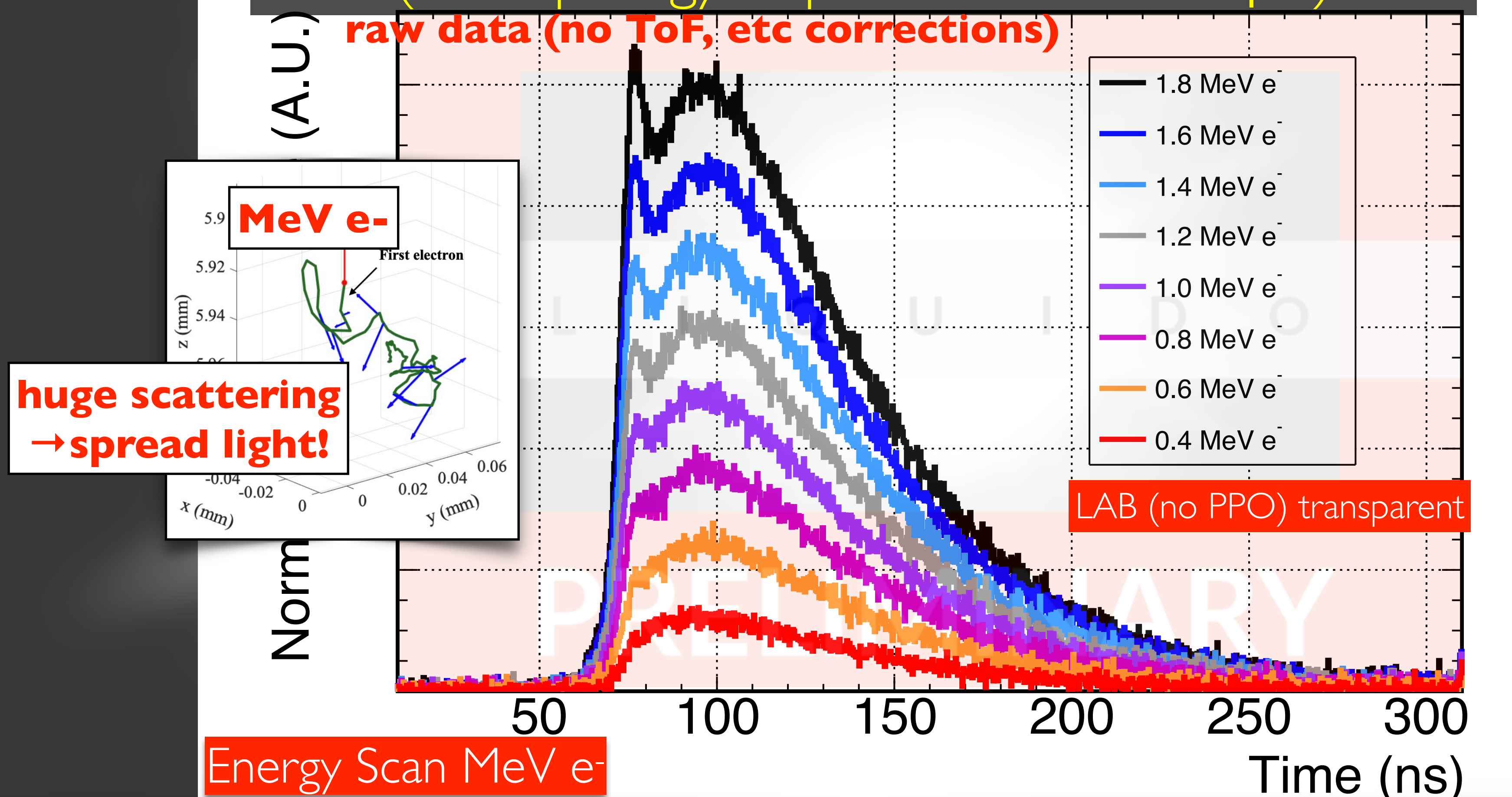
T. Nishimura et al., AIP Conference Proceedings **769**, 1702 (2005); https://doi.org/10.1063/1.1945337


LiquidO's prototype MINI-II
(upgrade)
data taking since 2021
overall view
3" PMT
(test transparency)
64 channels readout
(pitch ξ≈1.5cm)
single electrons
[0.4,1.8]MeV mono-energetic
~10L multi-media
•water (transparent)
•scintillator (transparent)
•scintillator (transparent↔opaque)
top view
T control
radiator⊕chiller: [5,40] °C

Cherenkov / Scintillation

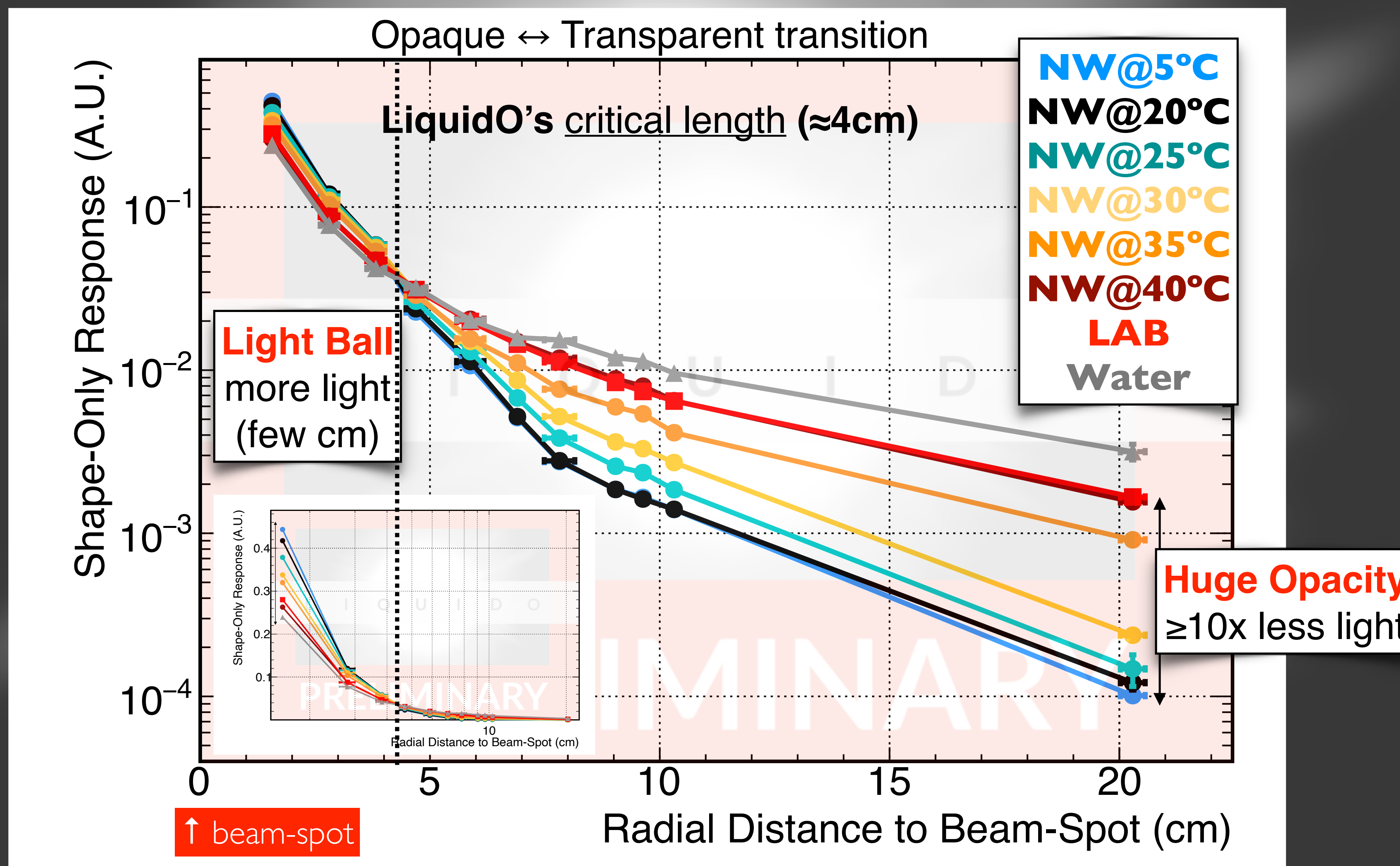
Cherenkov time-only ID — threshold

(no topology exploited — unlike μ's)



LiquidO's timing potential — under quantification & optimisation

opacity metamorphosis…



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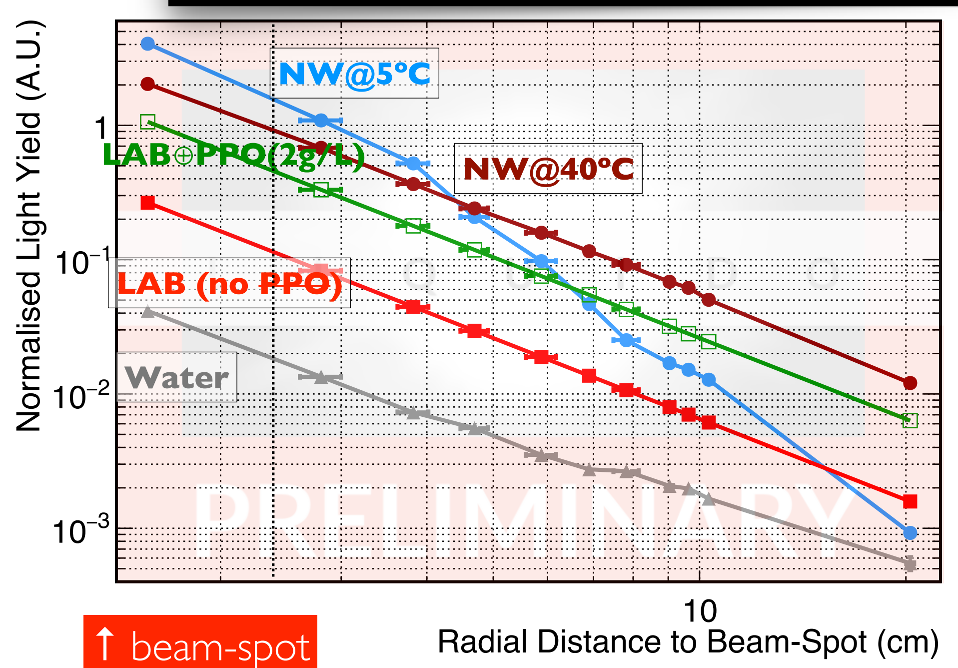
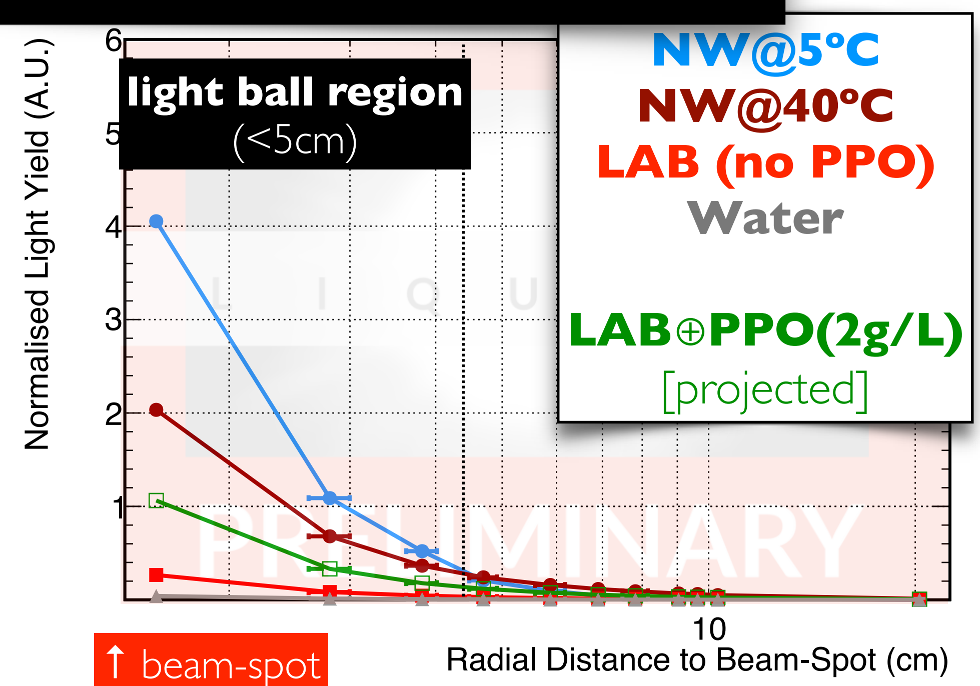
light yield

LiquidO: ~80% light collected within 5 cm's



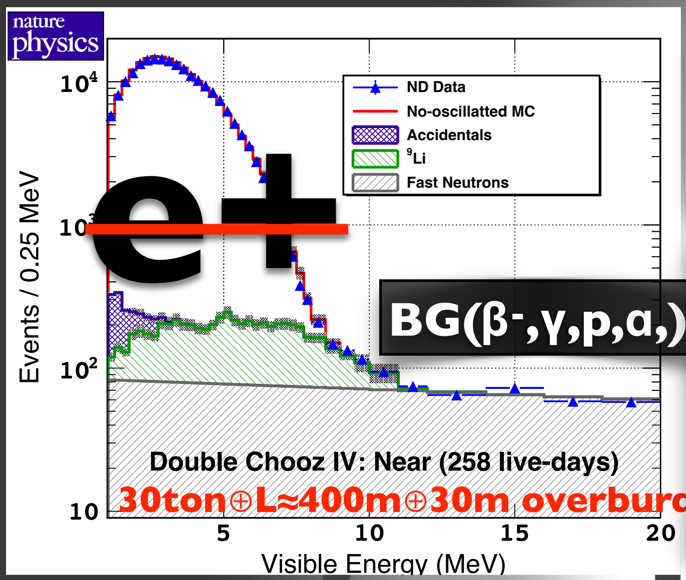


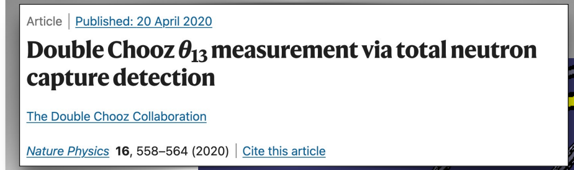
brightest while light falls by almost 4 orders of magnitude in 20cm

effective detected light yield >120PE/MeV [@ SiPM]

≥250PE/MeV — **optimisation** (ongoing engineering)

CLOUD @ LNCA…




Article | Published: 20 April 2020

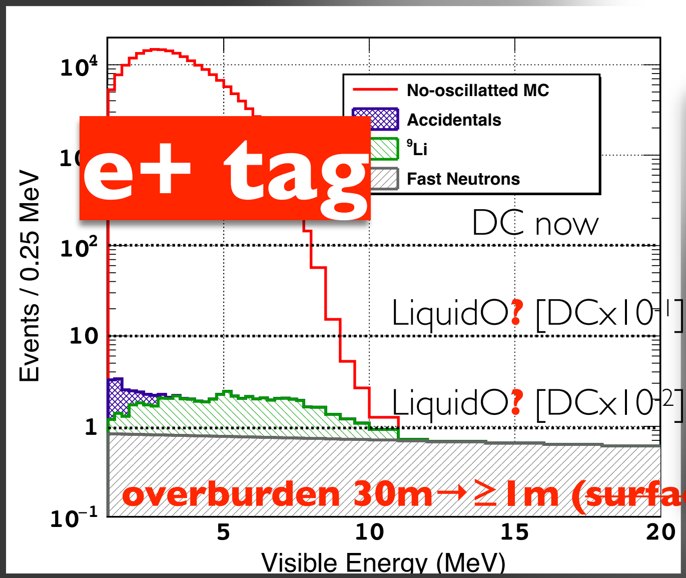
Double Chooz θ_{13} measurement via total neutron capture detection

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*”)

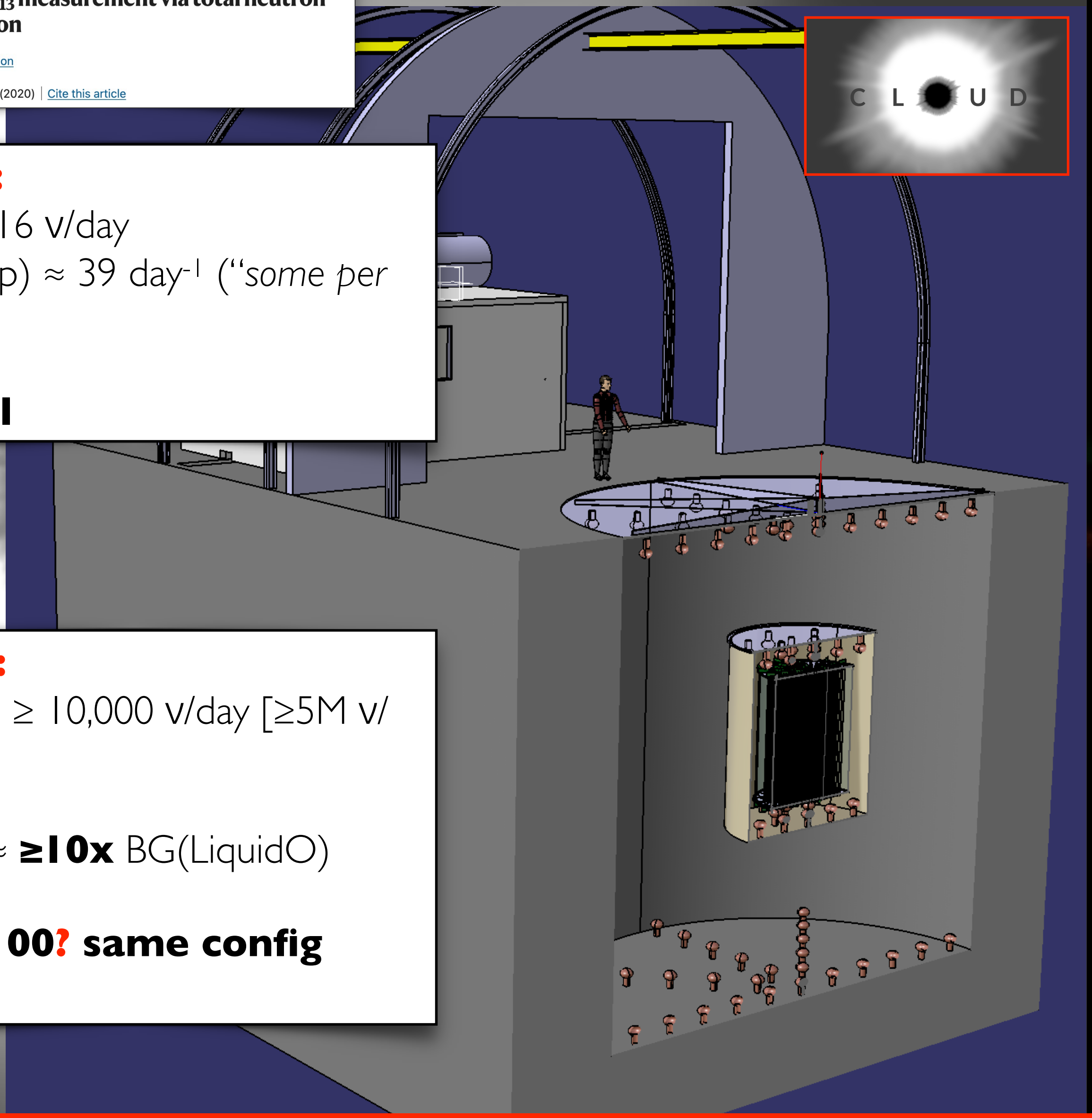
S/BG≈21



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

BG(DC) ≈ **≥10x** BG(LiquidO)

S/BG ≥100? same config [demo]



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

topology's PID (no timing)…

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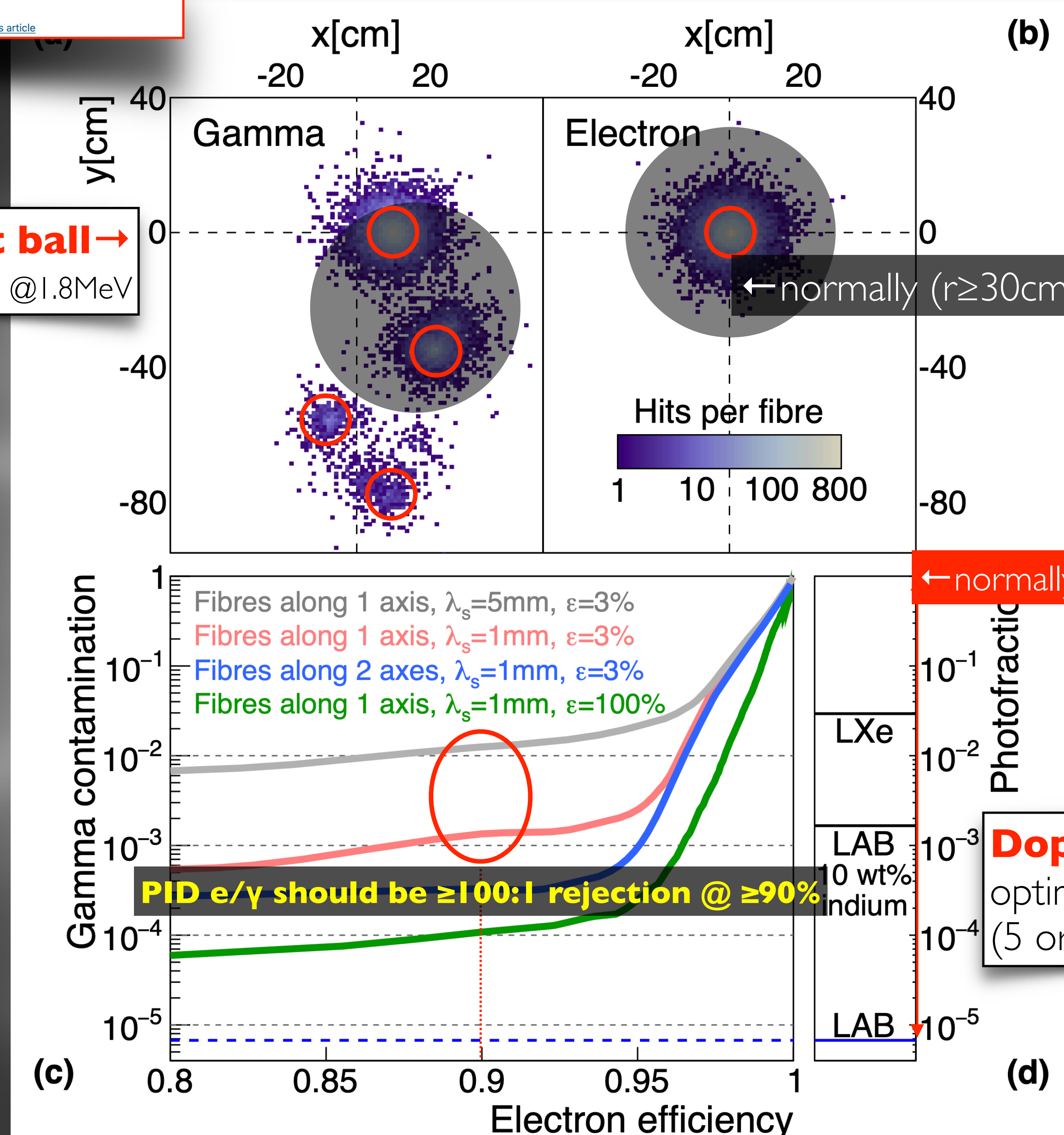
MINI's light ball→
~80% light within ≈4cm (radius) @1.8MeV

←normally (r≥30cm ⇔ ≥1.5ns for σ^{PMT})

←normally here: **NO e/γ PID**

PID e/γ should be ≥100:1 rejection @ ≥90%

Doping Impact
optimisation **PID vs doping**
(5 orders of magnitude)



topology's PID (no timing)…

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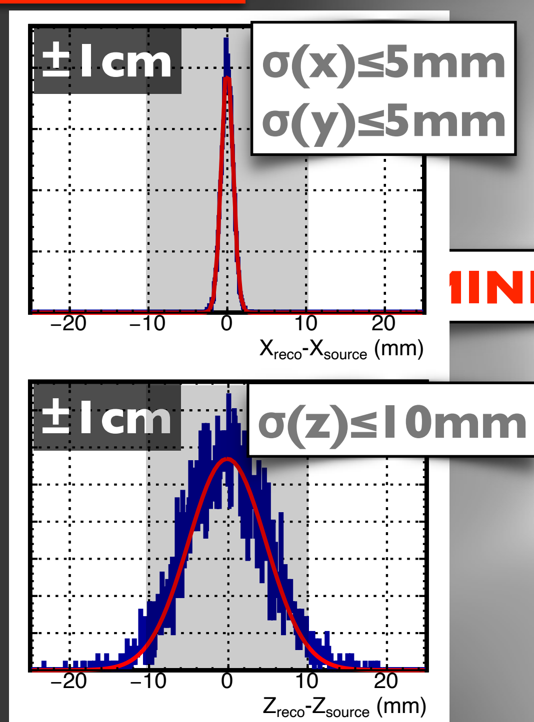
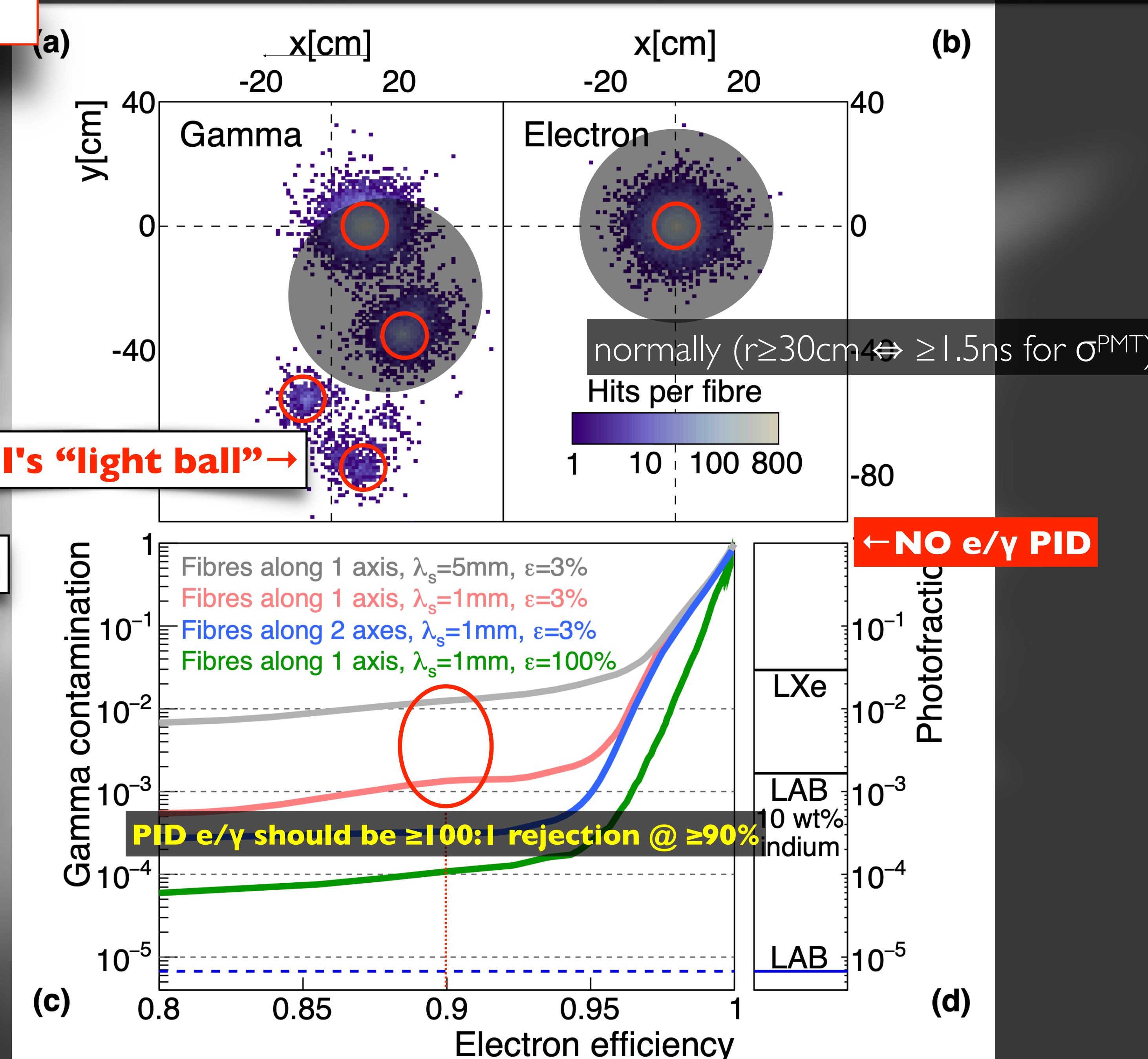
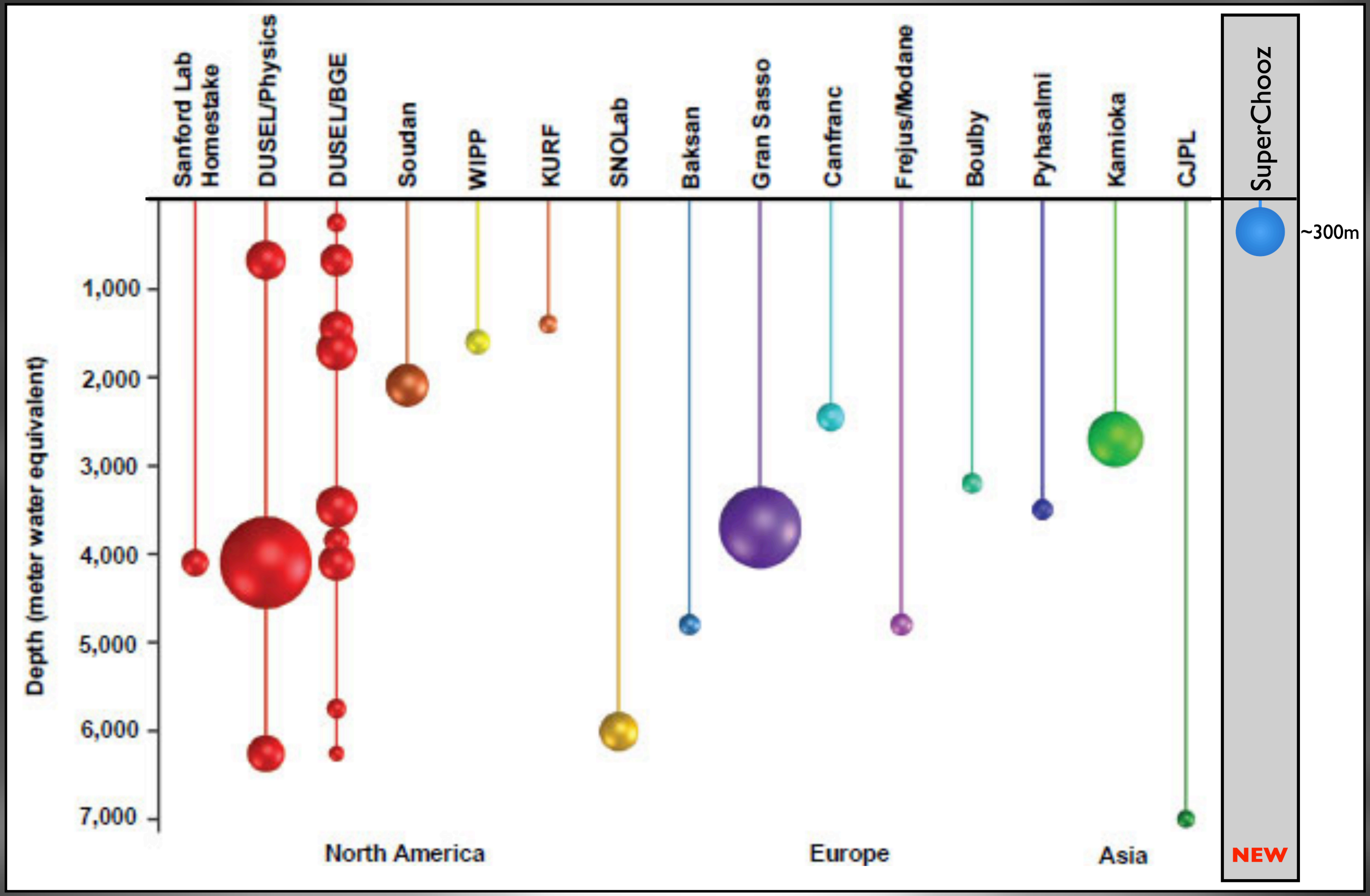
~0.5MeV







SuperChooz underground