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C L O U D

experiment's first release (almost)

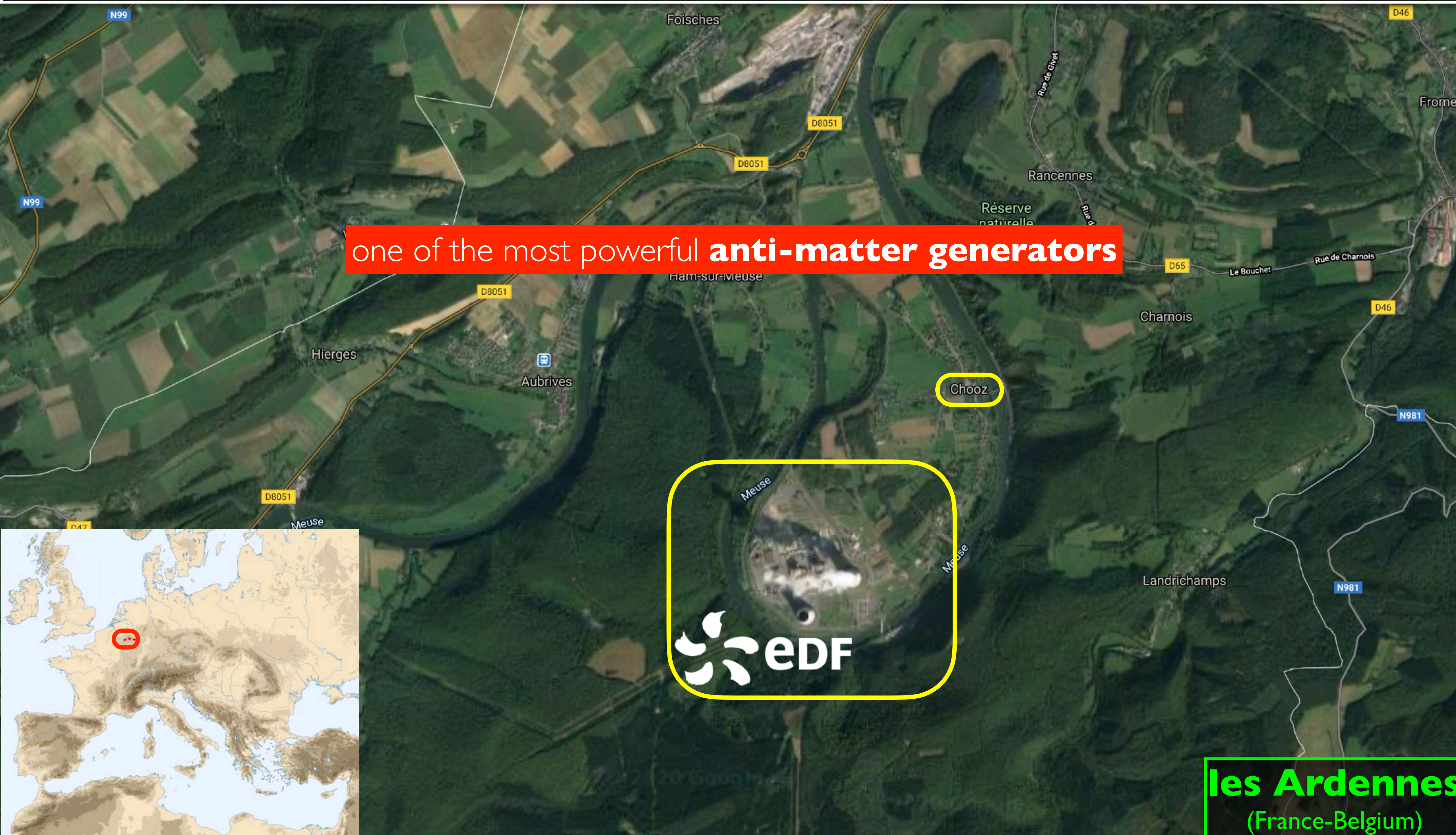
HEP Seminar @ IJCLab
6 November 2023 — Orsay (France)

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

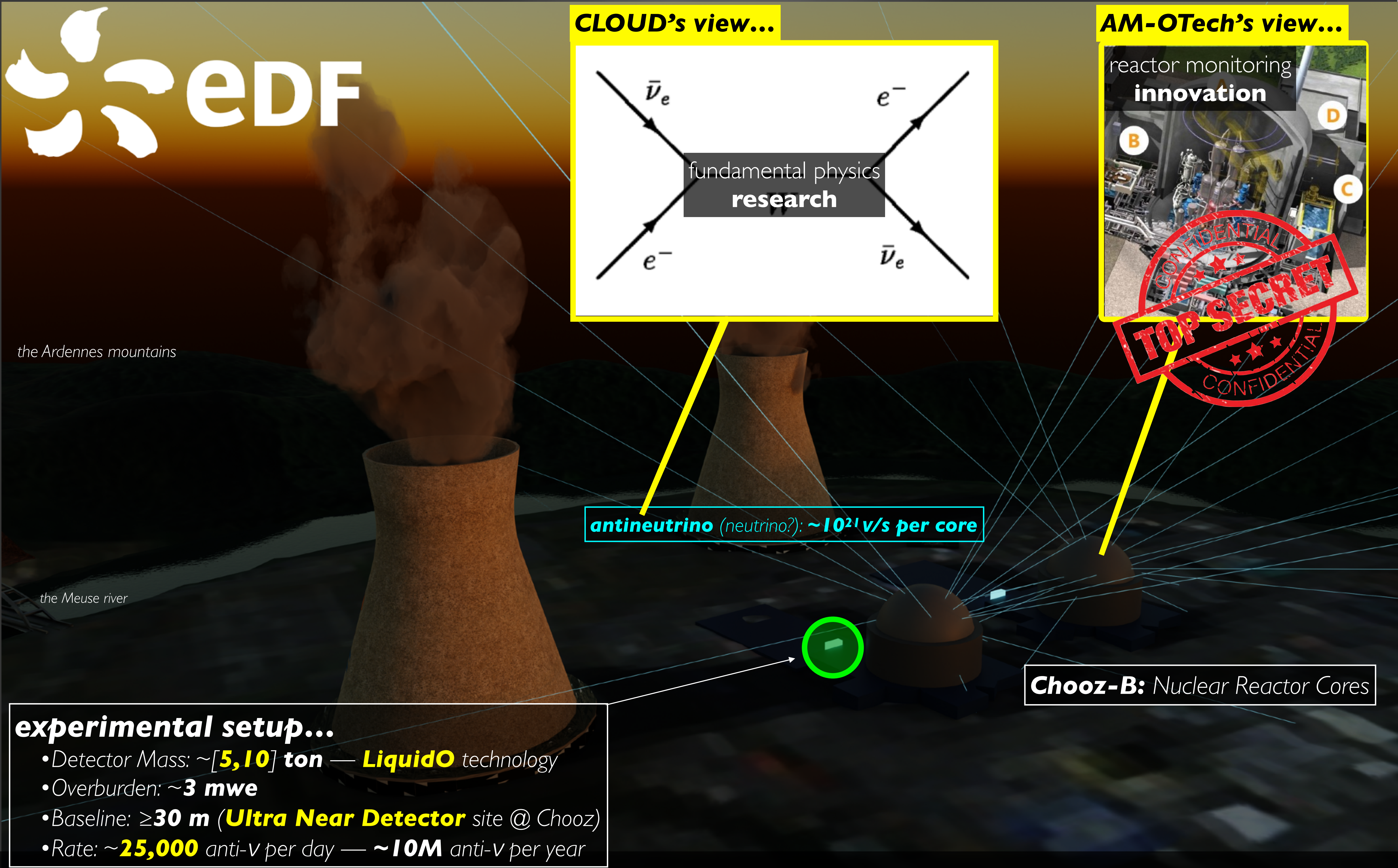
(co)spokesperson:
- DoubleChooz
- LiquidO
- CLOUD — AM-OTech (EIC)
- SuperChooz Pathfinder

IJCLab Irène Joliot-Curie

cnrs · université PARIS-SACLAY · FACULTÉ DES SCIENCES D'ORSAY · Université de Paris in the **middle of central Europe** (between France-Belgium): **Chooz** [meeting point with Germany, Luxembourg, Netherlands]



Europe's most powerful reactor site…



experimental setup...

- Detector Mass: ~[**5,10**] **ton** — **LiquidO** technology
- Overburden: ~**3 mwe**
- Baseline: ≥**30 m** (**Ultra Near Detector** site @ Chooz)
- Rate: ~**25,000** anti-ν per day — **~10M** anti-ν per year

CLOUD vs AntiMatter-OTech...

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

The origin of this idea: L.A. Mikaelyan – Neutrino '77 conference, Baksan

3. I want to talk about the development of the new technique of the remote reactor diagnostics by the neutrino radiation. Due to the novelty of the problem the consideration naturally will be incomplete and limited by two questions only:

- determination of the reactor power production and in prospect
- determination of the dynamics of the fissing isotopes burning-out and accumulation (mainly ^{235}U and ^{239}Pu).

The principle promises of the proposed technique seem to be the remote analysis and fixing the plutonium accumulation immediately in the place of its production. This technique (if developed successfully) will be sufficiently important from the point of view of the control on the leakage of fissing materials and on the non-proliferation of nuclear weapons, and also for the economics of nuclear fuel recycling. More detail consideration of these problems on this conference seems to be irrelevant.

neutrino in the **nuclear** industry?

today, **most experiments** bypass (whenever possible) the **absolute flux knowledge** — complex!

relative knowledge (ex. multi-detector, etc.) well suited to **extract "known model" parameters**

CLOUD

today's "known model": **standard neutrino oscillations**

status on neutrino oscillation knowledge…

Standard Model(3 families)
[leptons & quarks]
&
PMNS$_{3x3}$(θ_{12},θ_{23},θ_{13})
&
±Δm² (±Δm^2_{23}) & **+δm²** (±Δm^2_{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 %	NOvA+T2K	2.0 %	≲1.0%	DUNE⊕HK	beam (octant)
θ_{13}	1.8 %	DYB+DC+RENO	**1.5 %**	**1.5 %**	DC⊕DYB⊕RENO	reactor
+δm²	2.5 %	KamLAND	2.3 %	≲1.0%	JUNO	reactor
|Δm²|	3.0 %	T2K+NOvA & DYB	1.3 %	≲1.0%	JUNO⊕DUNE⊕HK	reactor & beam
Mass Ordering	**unknown**	SK et al	NO @ **~3σ**	@5σ	JUNO⊕DUNE⊕HK	reactor⊕beam
CPV	**unknown**	T2K	3/2π @ **≲2σ**	**@5σ?**	DUNE⊕HK⊕ALL	reactor⊕beam

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

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

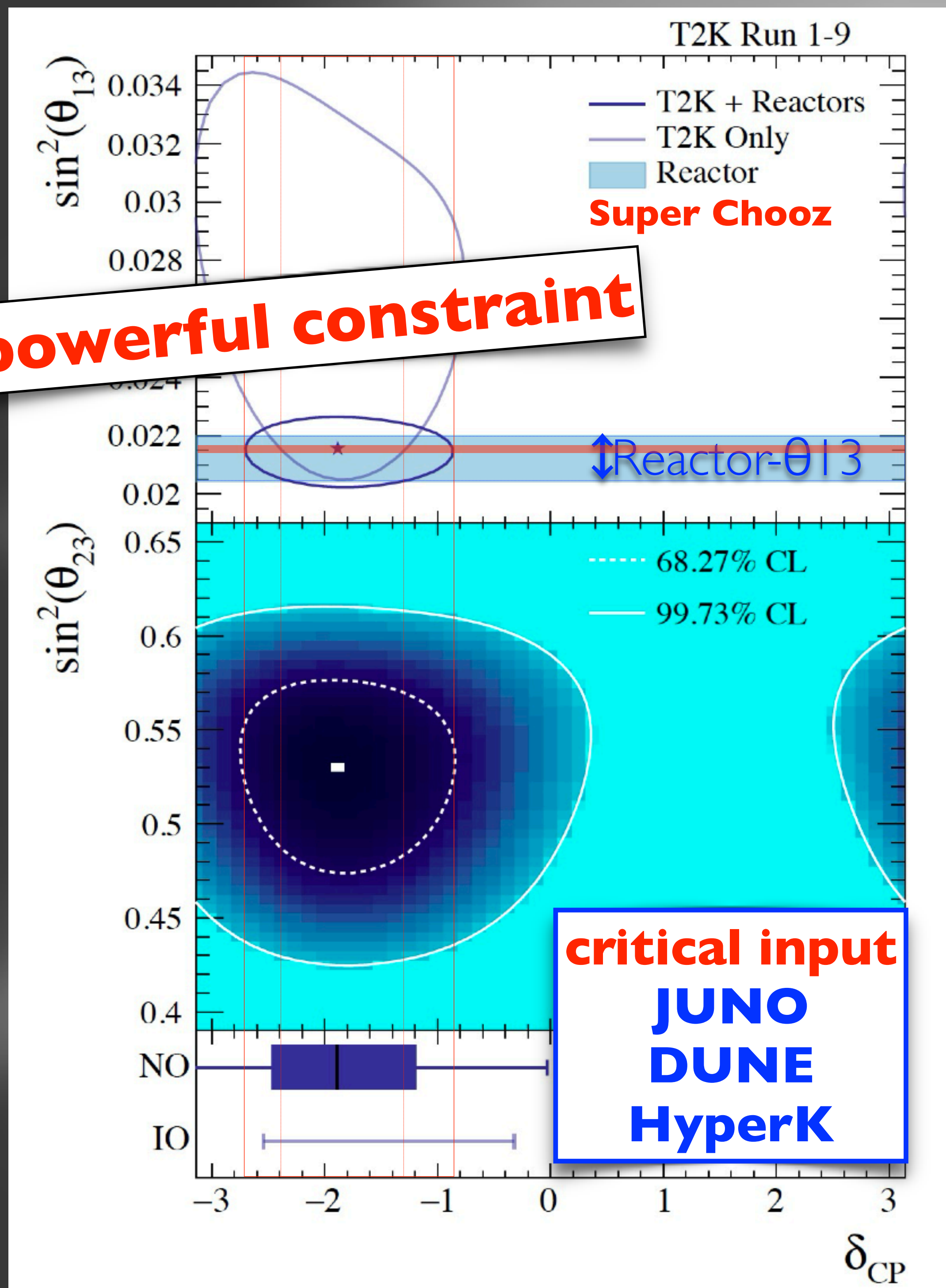
ORCA⊕PINGU⊕IceCube complementary for Mass Ordering & Δm² measurements

reactors drive much of ***SM***'s knowledge…

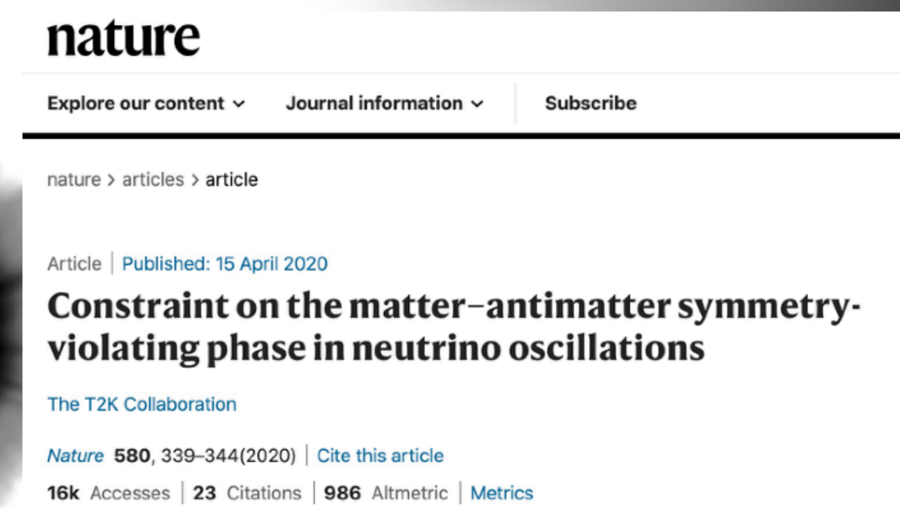
standard neutrino oscillations (θ_{12}, θ_{13}, θ_{23}, $+\delta m^2$, $\pm\Delta m^2$, δ_{CP}) — if **PMNS unitary**

our ability to measure **θ_{23}-octant** and **δ_{CP}** (so far) needs the input from reactor neutrinos!

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]

flagship-ν experiments…

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

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

today, **most experiments** bypass (whenever possible) the **absolute flux knowledge** — complex!

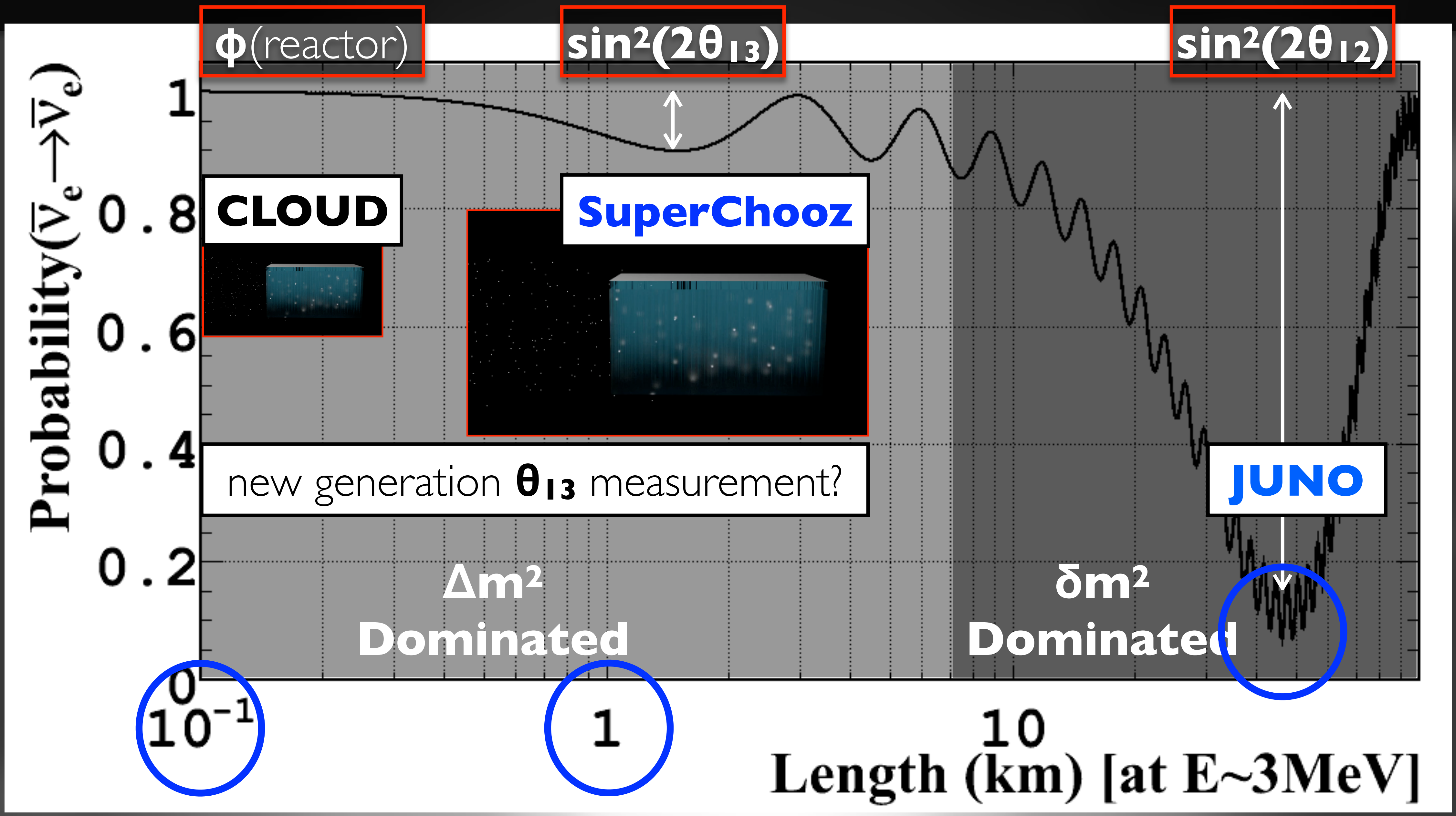
relative knowledge (ex. multi-detector, etc.) well suited to **extract "known model" parameters**

CLOUD

confront ***absolute flux knowledge*** *for* ***new neutrino physics*** *via "flux bias explorations"*

- ***extreme signal*** *(to BG) rates — unprecedented*
- *must: the* ***best-known cross-section****(s) today (≤1%)*
- ***extreme energy control*** *(≤1%)— avoid spectral distortions (→flux biases)*
- ***much redundancy*** *— as much as Nature kindly allows…*

baseline: experimental regime...



- **reactor:** extreme source of neutrino (commercial→1GW≈2x10²⁰/s) — no running cost.
- **3 measurement regimes:** depending on baseline (L):
  - **zero-baseline** (L→~0km; **CLOUD**): **φ(reactor)** — or **new physics?**
  - **short-baseline** (L→~1km; **SuperChooz**): **$\theta_{13}\oplus|\Delta m^2|$** [multi-detector: ~~**φ(reactor)**~~]
  - **long baseline** (L→≳50km; **JUNO**): **$\theta_{12}\oplus\delta m^2$** and (if enough resolution) **$\pm\Delta m^2$**

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]

Mass Hierarchy (*MH*): **the absolute neutrino mass?**
[→why neutrinos so much lighter than charged-leptons?]

PMNS matrix (3x3; *a la CKM*): ***U***, *assumed* ***unitarity*** (→***violation?***)
- mixing parameters (**3**): **θ_{13}**, **θ_{12}**, **θ_{23}** (octant?) — derived ***J*** [Jarlskog invariant]
- CP-violation parameter (**1**): **δ?**

Mass Squared Differences (**2**): **|δm²|** (i.e. Δm^2_{12})
|Δm²| (i.e. Δm^2_{13} or Δm^2_{23})

Mass Ordering (*MO*):
+δm² (solar data — observed!)
±?Δm² → the lightest neutrino ν(1) or ν(3)?

Neutrino Nature: **Majorana?**

several experiments

CLOUD
SuperChooz?

JUNO
HyperK
DUNE
SuperChooz?

ββ decay
other ways?

discovery!

discovery!

unknown [SM]

discovery!

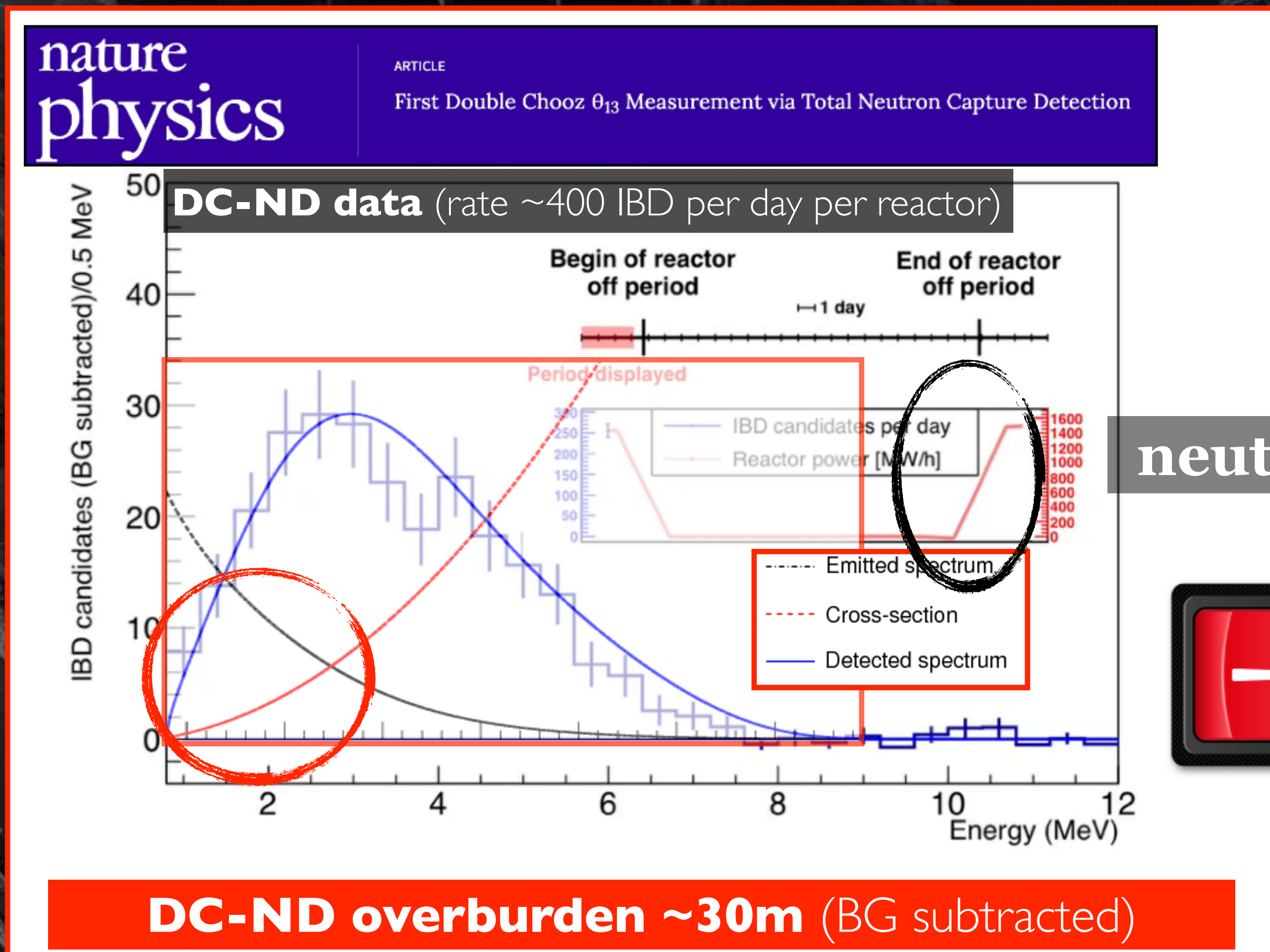
on the shoulders of giants…

breakthroughs with reactor antineutrinos…

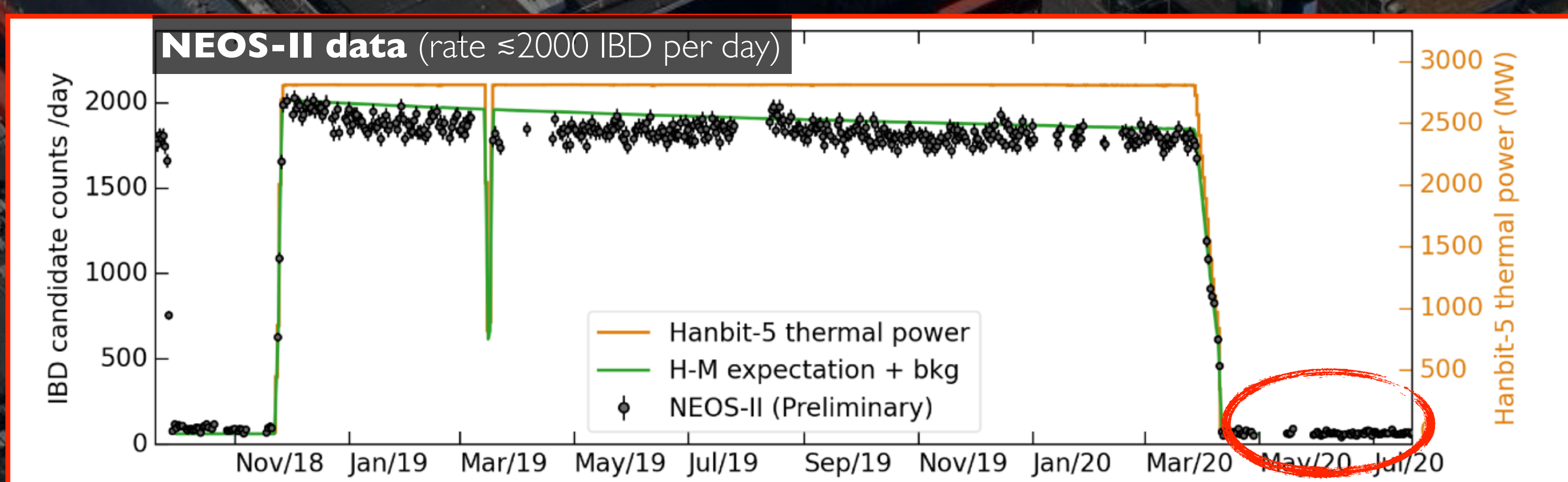
- [**1950s**; L≈10m] **electron-(anti)neutrino discovery** by **Poltergeist** [Nobel Prize 1995]
- [**1980s**; L≈10m] **Bugey3** (shape) & **Bugey4** (rate): reactor flux understood ≤3%? [**ILL** data: **prediction**]
- [**1990s**; L≈1km] **Chooz** & **Palo Verde** absence of oscillation Δm^2 — **limit in θ13**
  - corroborated **Kamiokande's dominant oscillation $\nu_\mu \rightarrow \nu_\tau$** [Nobel Prize 2015]
- [**2000s**; L≈180km] **KamLAND favoured solar "LMA"** — complementary **SNO** [Nobel Prize 2015]
- [**2010s**; L≈1km] **Daya Bay**, **Double Chooz**, **RENO**: observed **predicted θ13**⟹ ***SM*** consolidation!
  - **Double Chooz sub-team:** rate deficit issue→new physics vs prediction? [**prediction bias**]
  - **Double Chooz (all now)**: **spectral distortion** — contradicting **Bugey3** [**cause?**]
- [**2020s**; L≈50km] **JUNO** will measure **θ_{12}, $|\delta m^2|$, $|\Delta m^2|$** to ≤1% — first "bi-oscillation energy spectrum"
  - **mass ordering** (≥5σ) need **synergy** with accelerator experiments [**backup**]
- [**≥2030s**; L≈1km] **SuperChooz** will measure **θ_{13}-$|\Delta m^2|$** & **θ_{12}-$|\delta m^2|$** to ≤1% — & **more**!!

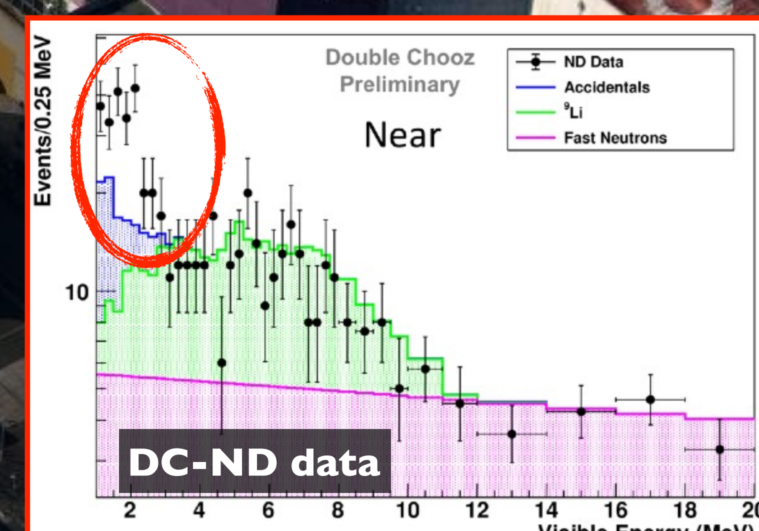
reactors leading much of **world's neutrino knowledge**⟹ **NO new physics** (so far)

reactor neutrinos…



neutrino rate ≈ reactor thermal power

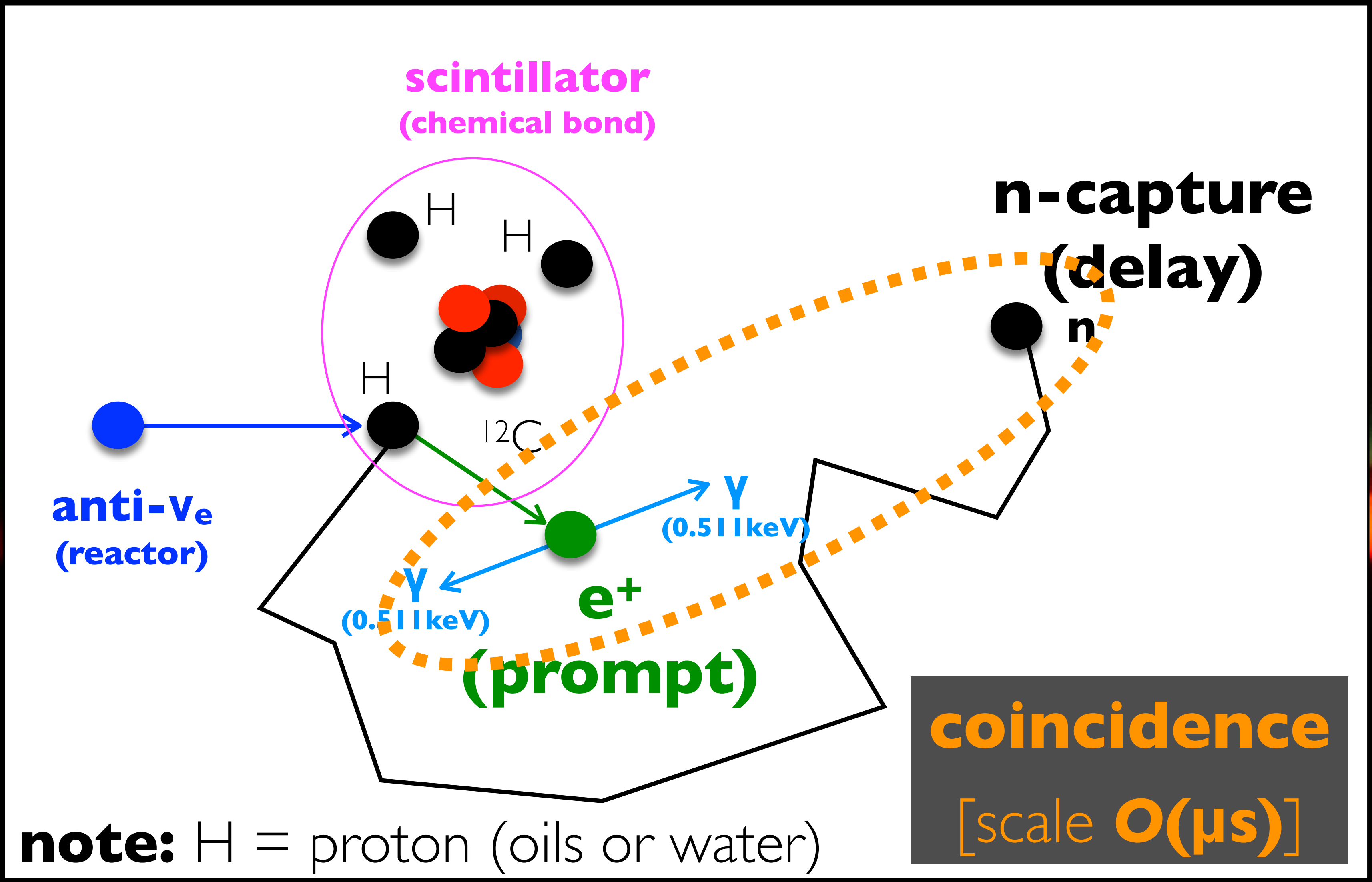




E(ν) controlled up to **≤0.5% accuracy/precision** via the **E(e+)** — demonstrated by **DC⊕DYB**

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n



IBD detection art…

- **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)

how to catch the n?

no e+ PID implies

$\gamma \approx e^- \approx e^+ \approx \alpha \approx$ **p-recoil (fast-n)**

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)

today's reactor neutrino methodology…

the most powerful source on Earth

- **interaction: IBD@p** [inverse-beta-decay on proton]
  - **σ(IBC@p):** CC, high and known to **~0.2%** (→ neutron lifetime) with threshold **≥1.8MeV** (→ **|m_{proton} - $m_{neutron}$|**)
  - no other interactions — few attempts to "**electron elastic scattering**" (past)
- **flux: ~10^{20} antineutrino per second per GW**(thermal) — almost as high as Avogadro's number (~6.0 x 10^{23})
  - **experimental precision ≤1%** [world's precision by Double Chooz]
  - **prediction precision [2~6]%** [**ILL**-based ⊕ approximations ⊕ bias correction by Kopeikin et al.]
    - **URGENT: new accurate reactor predictions** — how to **ensure reliable precision**?
- **signal** (**IBD@p**) features (typically **underground**):
  - **reactor modulation** (up to 100%): rate(ON) / rate(OFF) ≈ 100 [residual flux during rate(OFF)]
    - high-precision **spectral reactor-OFF information** [DoubleChooz]
  - **Signal-to-BG** order **10** (GW reactors — commercial) [≥10x loss with research reactors]
    - BG dominated by **cosmogenic**→ **irreducible** [unless **e+ ID** was possible]
      - **e+ ID** via ortho-positronium [Borexino, Double Chooz] — impractical for reactor physics
    - **monolithic & hermetic detectors** — segmentation limited gain & risk radiogenic-BG issues

reactor neutrinos **experimental methodology largely similar** for the last **~70 years** (Reines et al.)

powerful framework so far, but **good enough for discoveries ≥2025?**

C L O U D

WARNING: from now we should talk about **neutrinos** and **antineutrino**…

reactor (anti)neutrino **future**…(?)

future: discoveries?

background: *standard neutrino oscillation (PMNS)*

neutrino⊕weak-interaction remains **bizarre** (Majorana, etc)…

- new neutrino **phenomenology**? [ex. mixing and masses]
- new neutrino **interactions**?
- new neutrino **states**? [assume: "3+1 sterile" is largely ruled out]

the future reactor neutrino…

- **interaction:** go beyond the **IBD@p** (antineutrino-**CC**)
  - **precise ES@e** [*elastic scattering on electrons*]: **CC⊕NC** & θ_W **@1MeV** (renormalisation running)
    - combined with **IBC@p**⟹ isolate **NC-only** component? [à la SNO]
  - **reactor neutrinos** (β+/EC at the reactor)? [→ the **"missing MeV neutrino source"?**]
  - **IBD@X <1.8MeV:** geoneutrino ^{40}K & (non-intrusive) direct reactor-fuel monitoring (pool, etc.)
- **flux:** measure **all known** & **unknown(s)** possible emissions [**discovery potential**]
  - **ϕ(anti-ν_e;CC):** ultimate precision **~0.5%**$_{\text{thermal-power}}$⟹ **unitarity violation?** — **new physics?**
    - **novel reactor predictions methodology?** probe & demonstrate accuracy
  - **ϕ(ν_e;CC):** first observation ever (**surprises?**) & complementary to ϕ(anti-ν_e;CC) prediction
  - **ϕ(ν_x;NC): NC validation** ↔ agreement to **CC?** [a la SNO] — **new physics?**
- **signal** features:
  - (**IBD@p**) **S-to-BG ≥100** (GW reactors)⟹ address also low power reactors — **the future?**
    - empowered **coincidences & PID**; namely **topology e+ ID** (but not only)
  - other improvements elsewhere — if **ES@e**⟹ radiopurity, etc.
- **neutrino-based innovation?** → exploring in **AntiMatter-OTech** [**CONFIDENTIAL**]

worthy challenges⟹ major breakthrough(s) ahead (≥**2025**) & probing **discovery potential**

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

the experiment…

our collaboration…

European Innovation Council

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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**

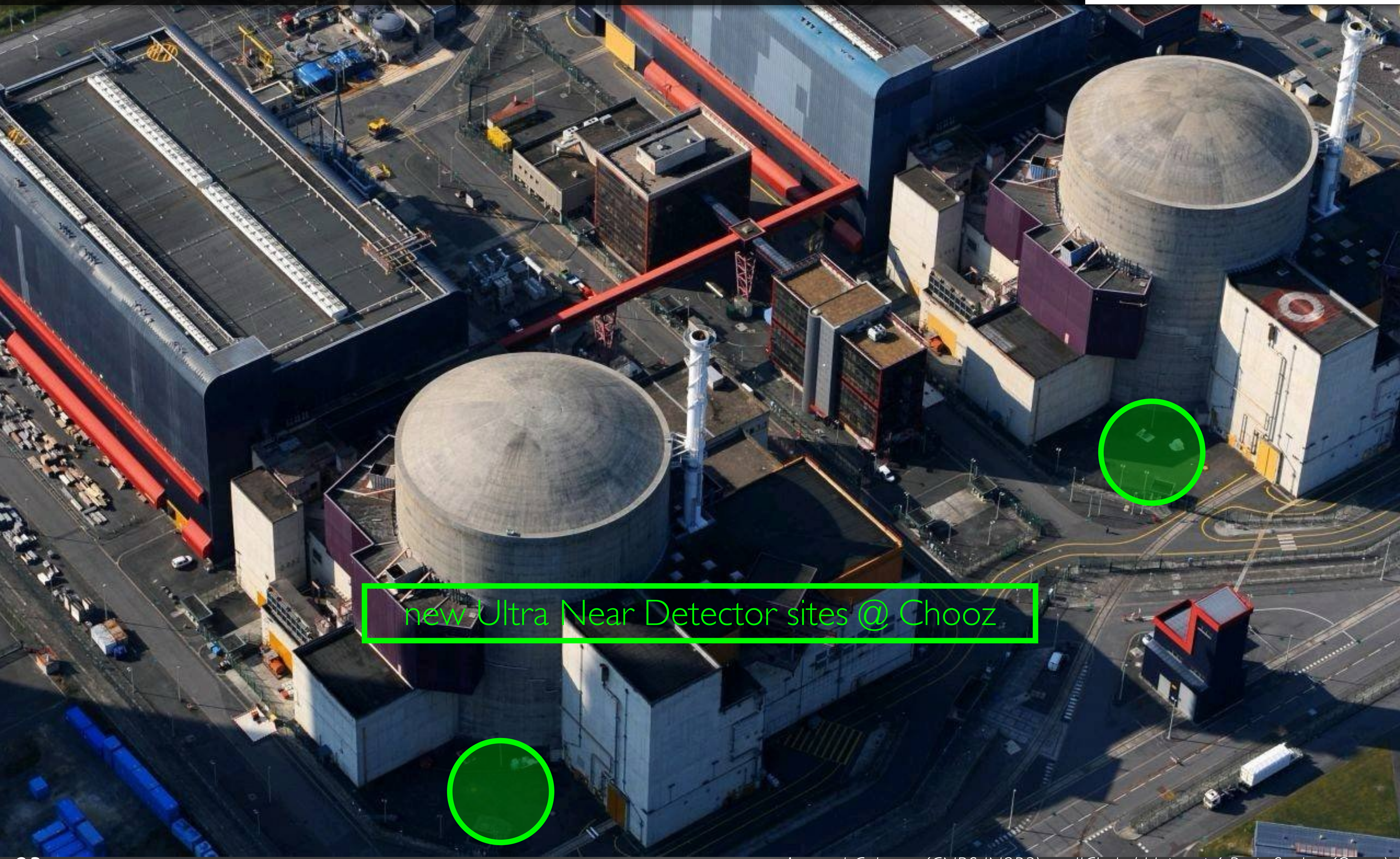
Spokespersons:
- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

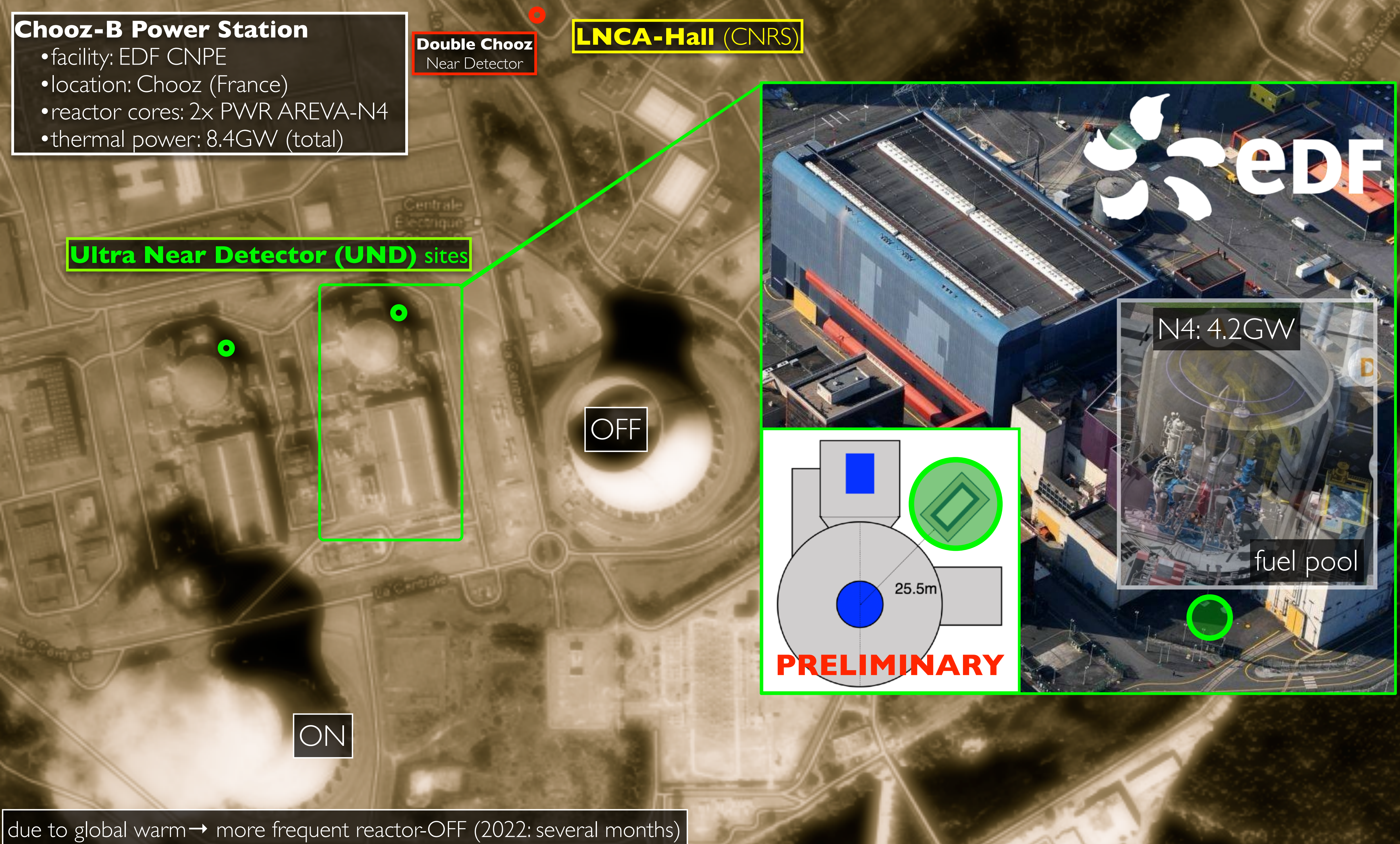
IB Chair:
- M. Chen — Queen's University (Canada)

Webs:

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

Chooz nuclear reactor…





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

Double Chooz
Far Detector

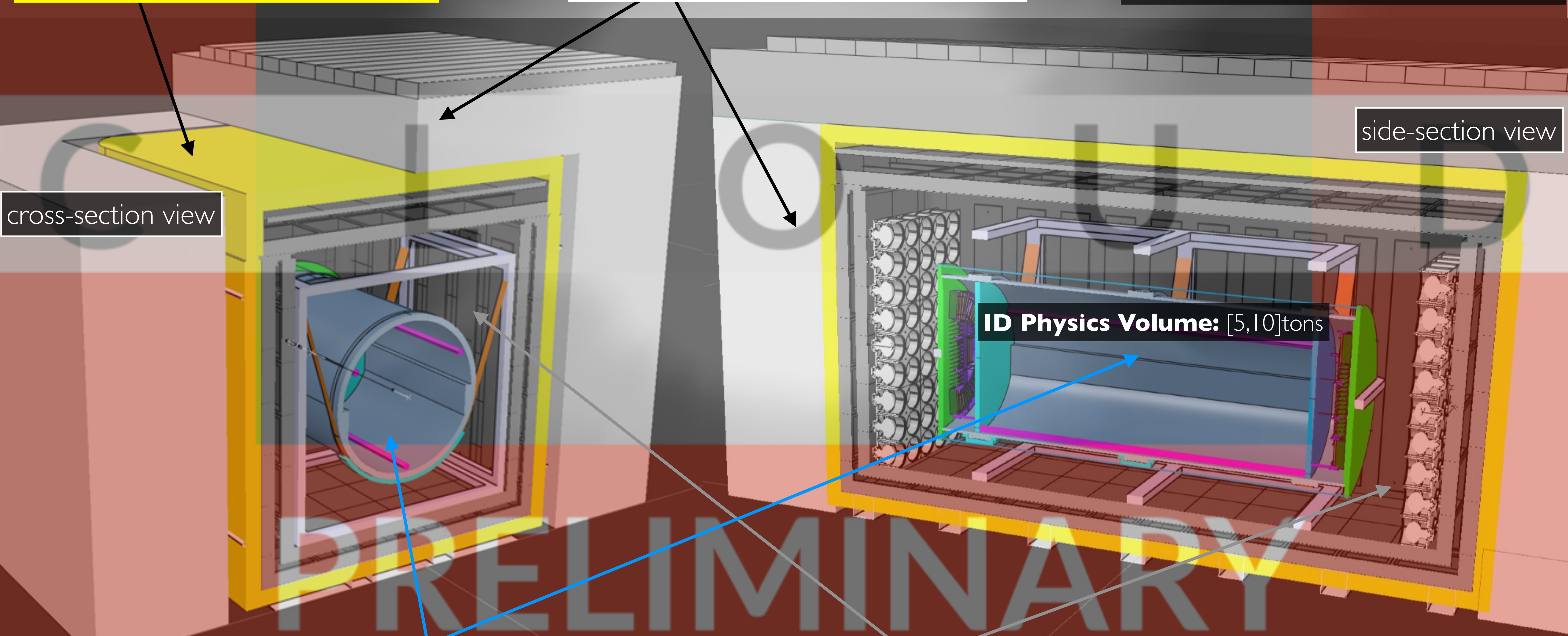
Europe's best reactor-ν site…

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

Water Pool [20,40]cm thick
- 4π shield & neutron moderator
- controllable thermal-bath

IGLOO [~3mwe]
- concrete **bunker** (with boron?)
- DC's iron steel shield (15cm thick)

Redundant "surface neutron" layers…
- **IGLOO** (absorption) — passive
- **Water** (moderator⊕absorption) — passive
- **Armour** (veto⊕moderator⊕absorption) — **OD**
- **Tracker** (PID⊕moderator) — **ID**



LiquidO-Tracker (or inner-detector) [**≤10tons fiducial**]
- <u>opaque scintillator</u> — new formulation(s) [more on this soon]
- **~10,000 fibres⊕SiPM** readout channels (GHz waveforms)
- designed light level: **≥200pe/MeV**

ARMOUR (or outer-detector) [**~0.5m thickness**]
- <u>transparent scintillator</u> (LAB⊕PPO⊕Bis-MSB)
- **≤180 DC-PMT**s & highly reflecting walls
- designed light yield **≥400pe/MeV**

CLOUD detector…

experimental setup…
- *Detector Mass: ~[**5,10**] **ton** — **LiquidO** technology*
- *Overburden: ~**3 mwe***
- *Baseline: ≥**30 m** (**Ultra Near Detector** site @ Chooz)*
- *Rate: ~**25,000** anti-ν per day — **~10M** anti-ν per year*

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CLOUD is powered by…

L I Q U I D

novel imaging detector

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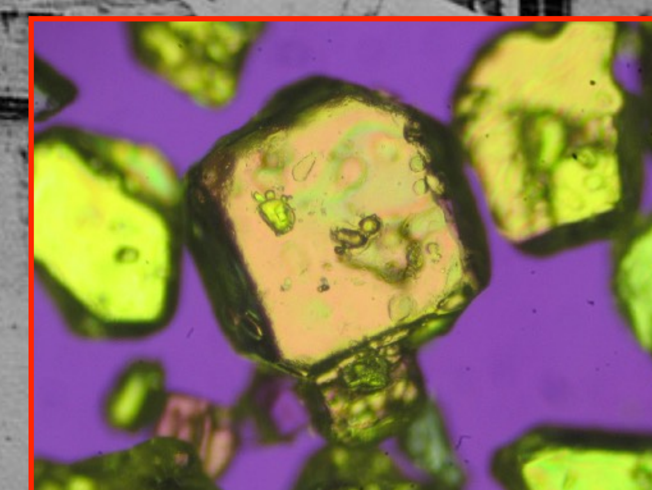
the art of building images (2D)…

placing **point**(s) [confined information] in **space** [2D]



each energy deposition…

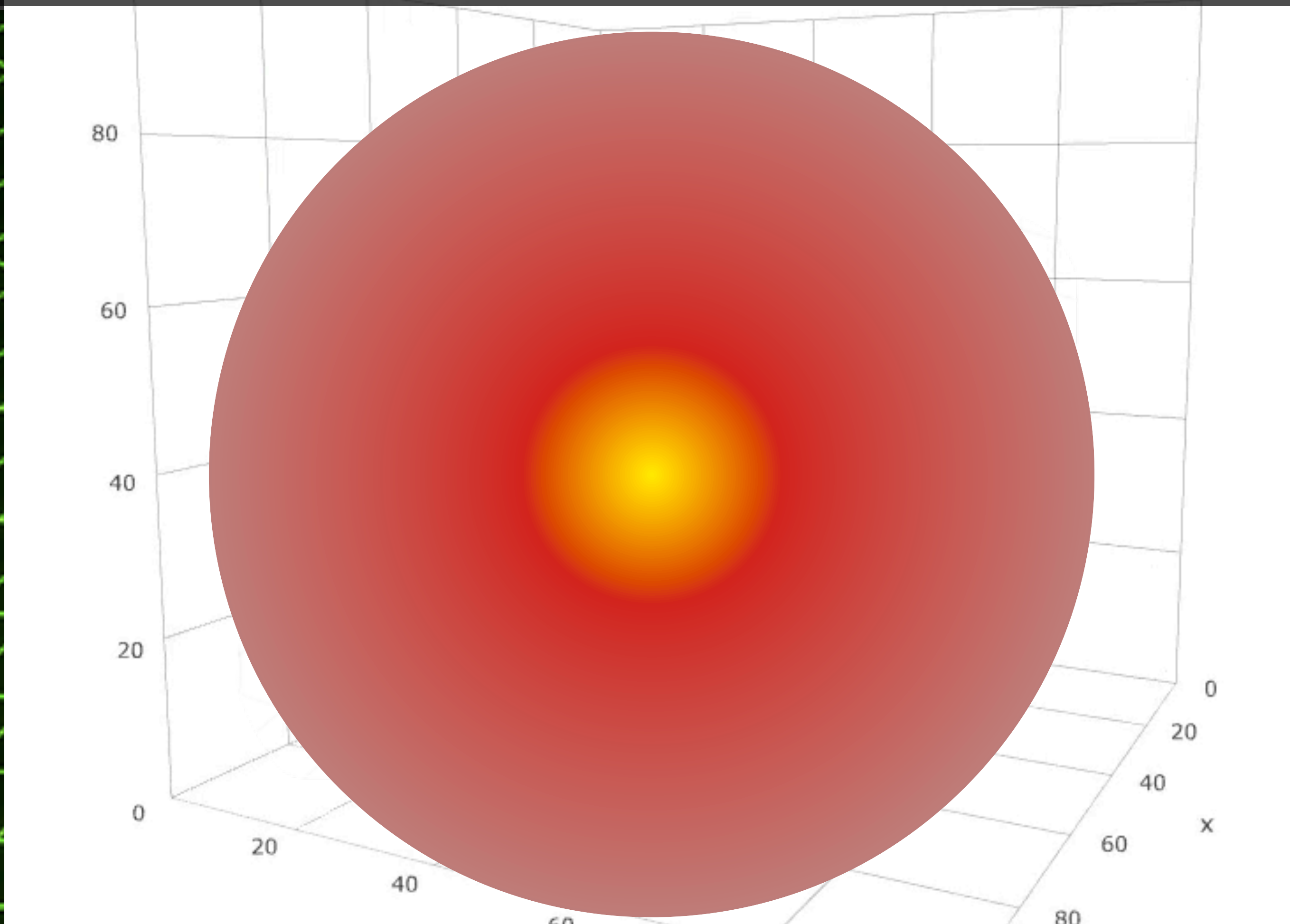
- **points 3D**(x,y,z) & **energy 1D**(E)
  $\Longrightarrow$ **lines** (i.e. point-sequence)

- **time 1D**(t) — <u>optional</u> (generally available)

“energy-flow” → energy-points ordered in **time**

(dynamic) **imaging** building-blocks…

stochastic light confinement

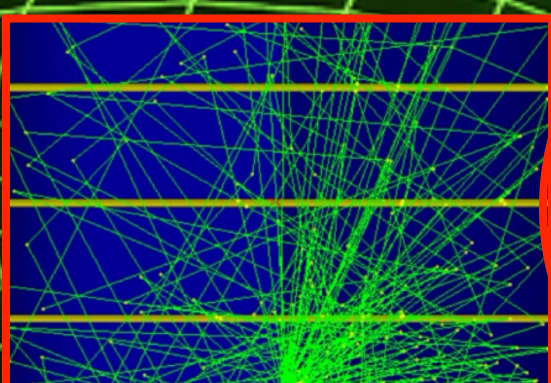


LiqudiO→ photon's "random walk" (self-confinement)

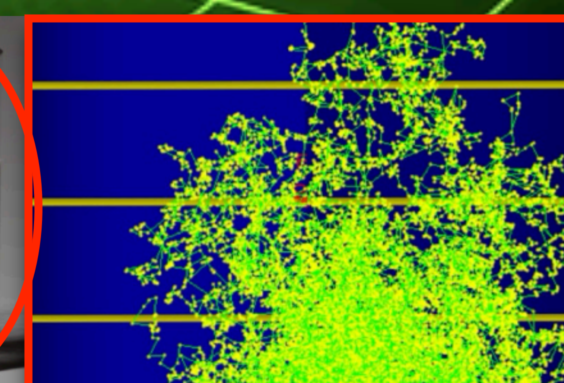
- **scattering→random walk→light ball** [order 1cm]
  - scattering <u>mean-free-path order 1mm</u>: x10^{-4} smaller than usual
- **lossless (elastic) light scattering:**
  - **Mie scattering:** achromatic & tiny losses ["cloudy" touch]
  - **Rayleigh scattering:** chromatic & lossless
  - **Internal 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



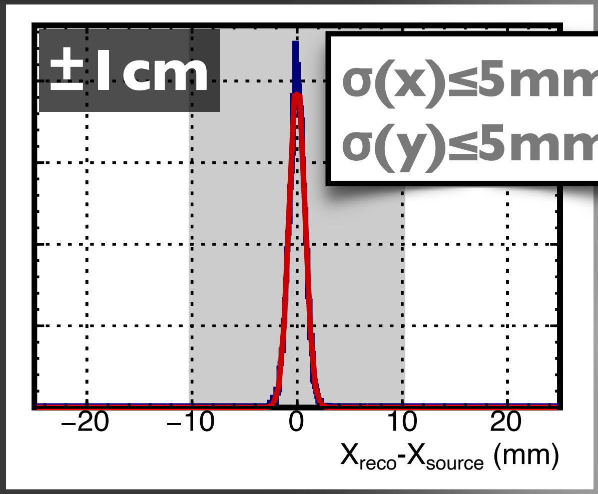
Rayleigh & Mie Scattering
λ(scattering)≤1cm

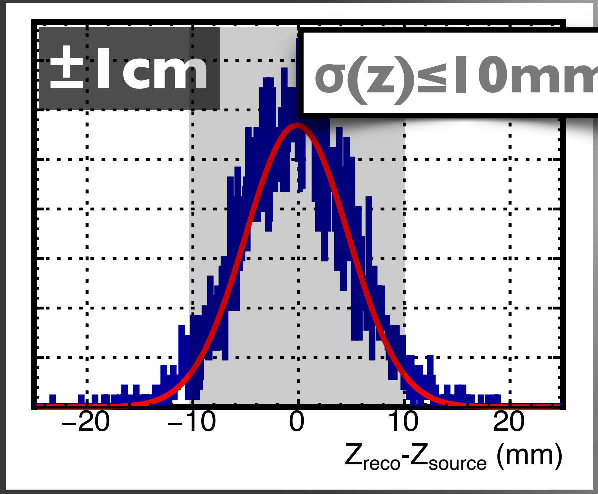
inducing light to a point (lossless)...

LiquidO ↔ stochastic light confinement

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

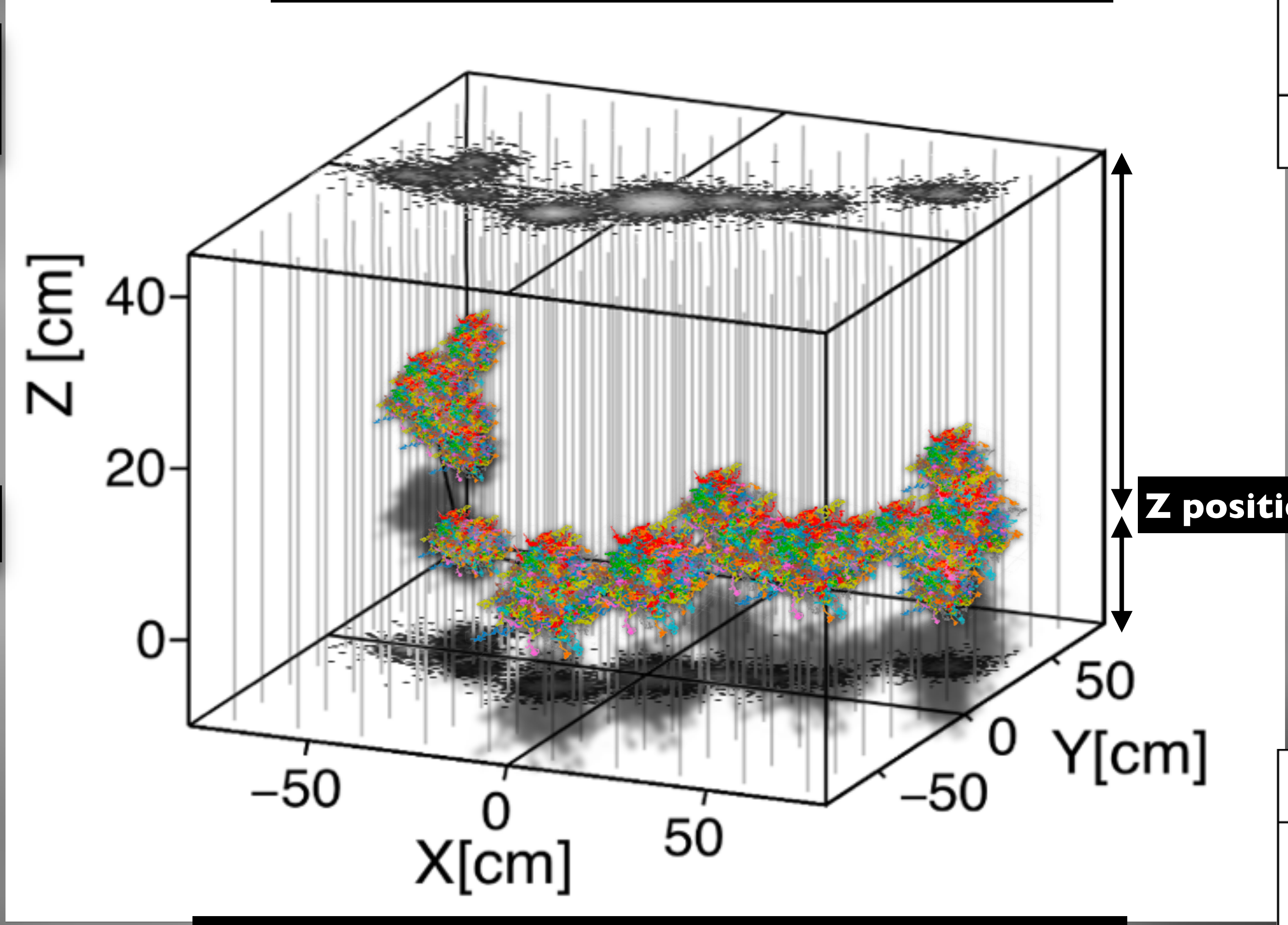
~1.0MeV





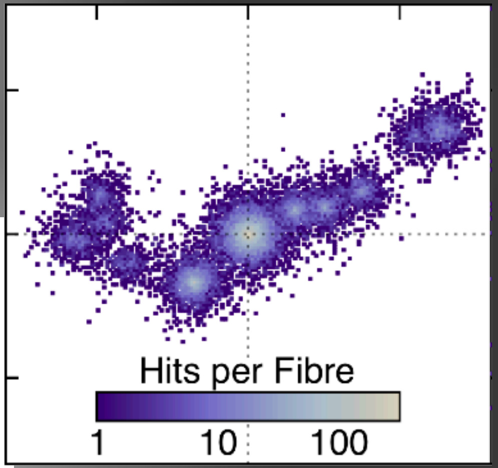
Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

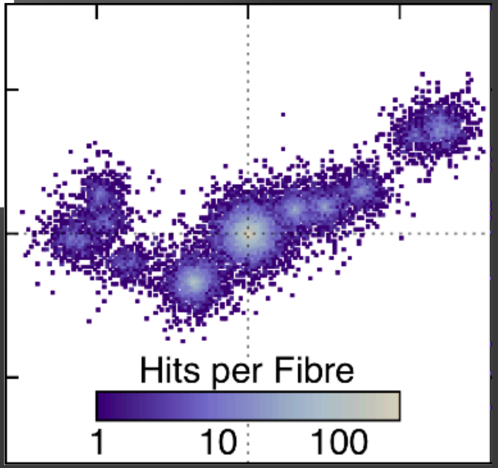
TOP VIEW: (X,Y) Projection→ direct readout



Z position: Δt (time difference)

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





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

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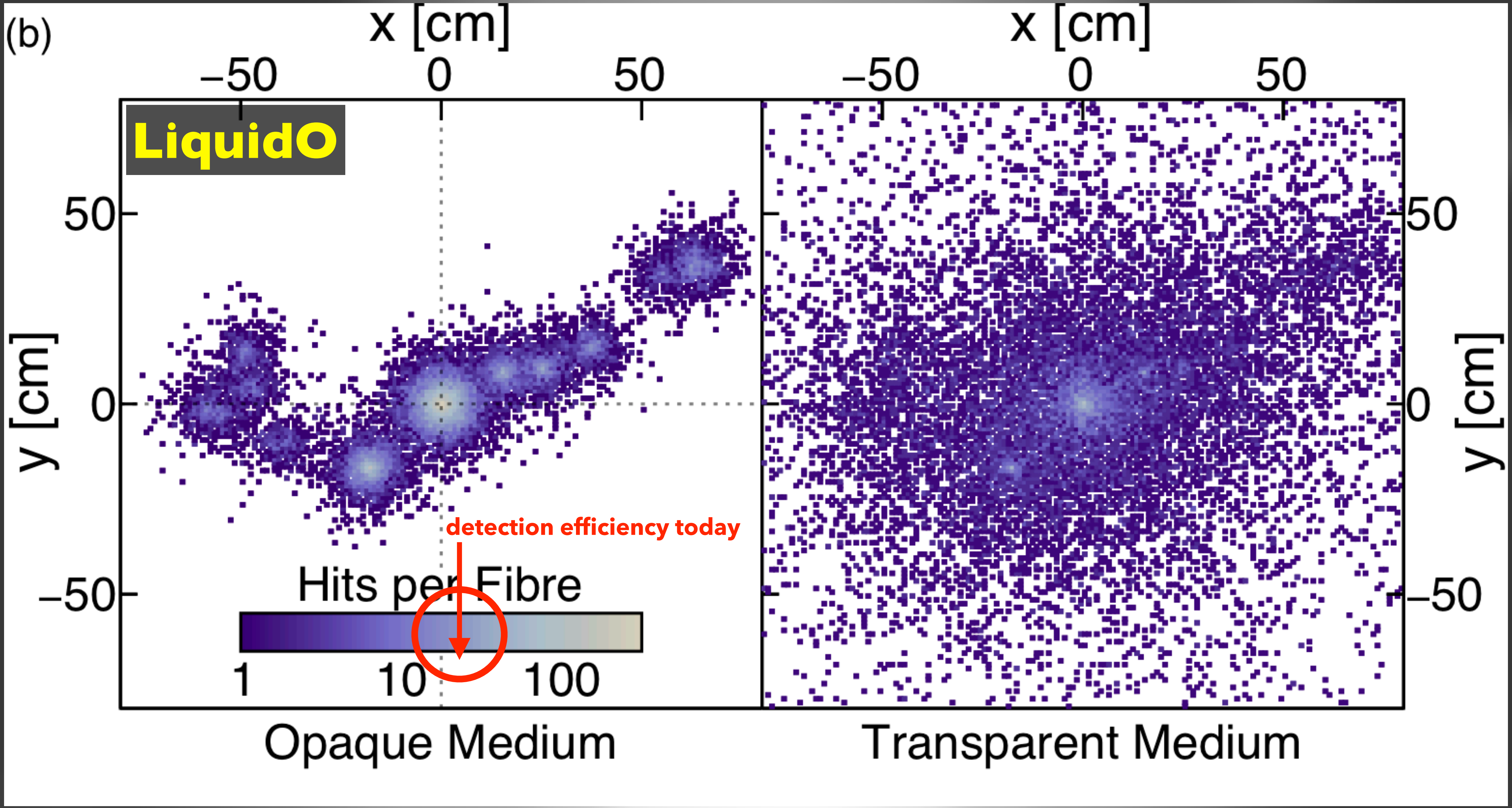
assume conventional liquid scintillators's yield ~10,000 γ/MeV

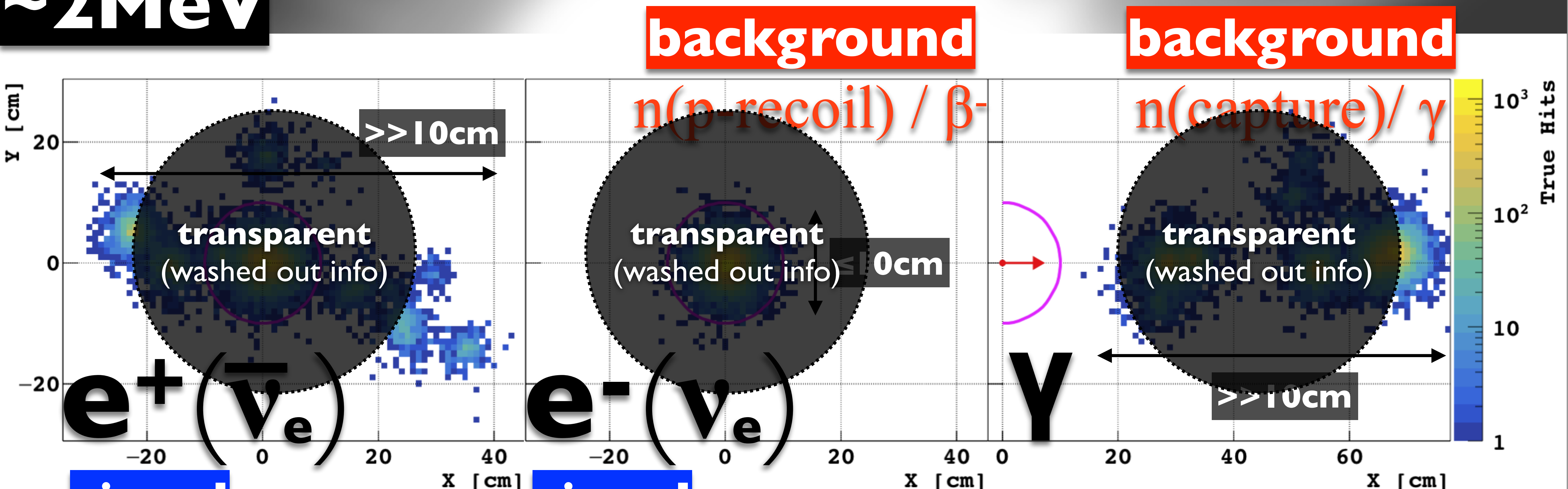


opacity implies neat images…

unprecedented MeV imaging…

reduce overburden/shielding

~2MeV



signal **signal**

LiquidO: stochastic confinement (NO segmentation)

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

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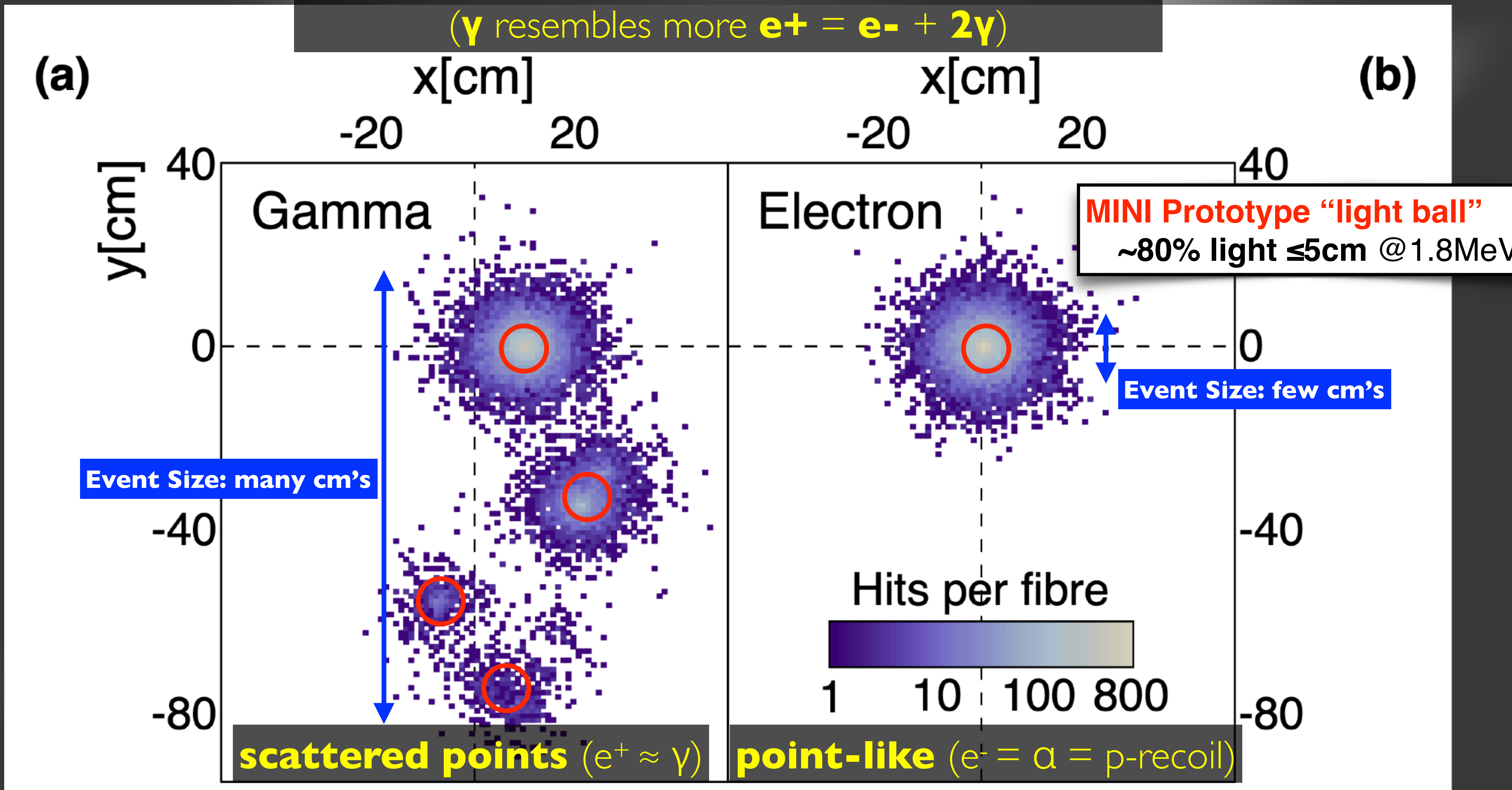
topology's PID (no timing)…

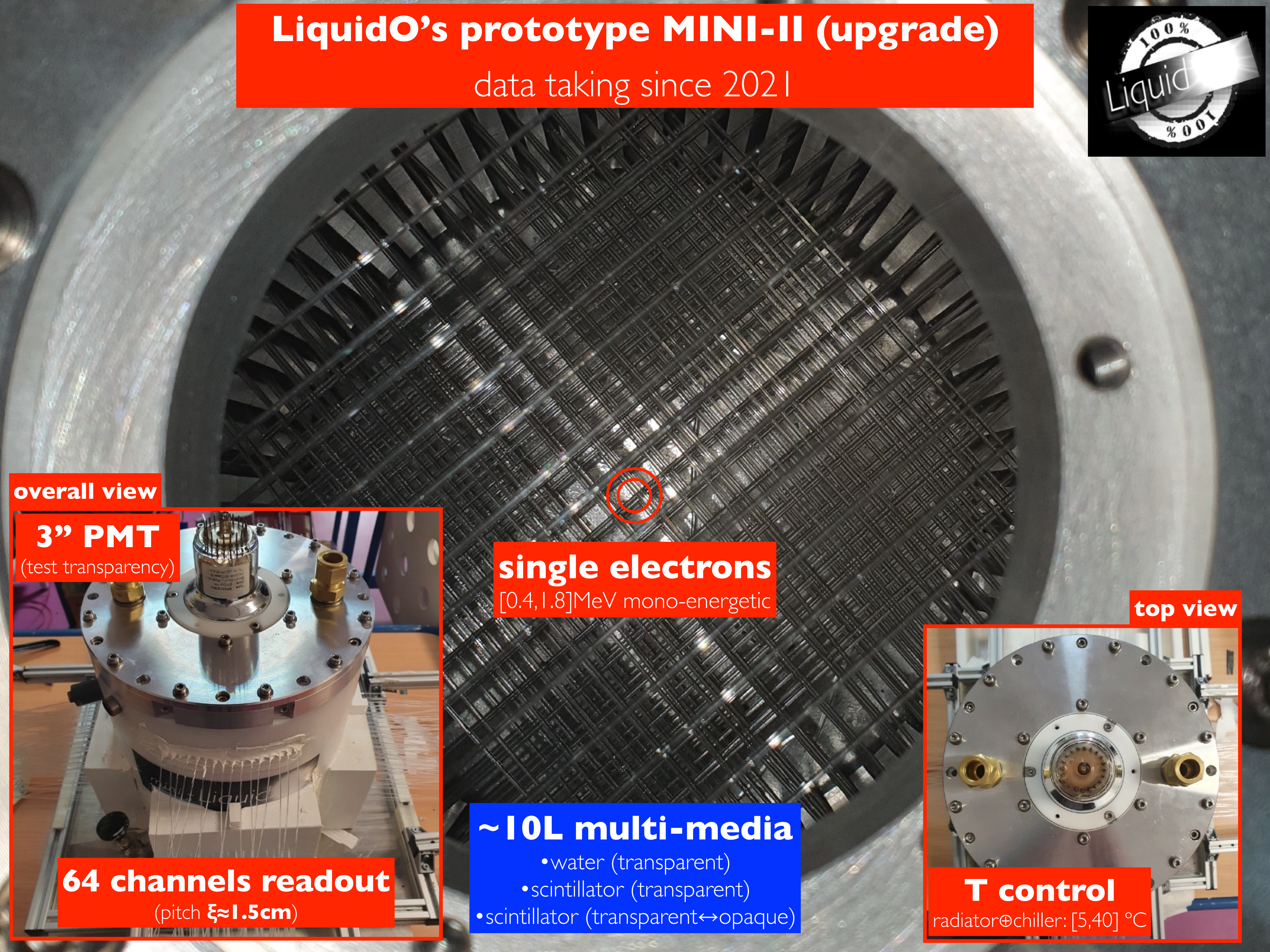
PID e/γ should be ≥100:1 rejection @ ≥90%
(**γ** resembles more **e+** = **e-** + **2γ**)

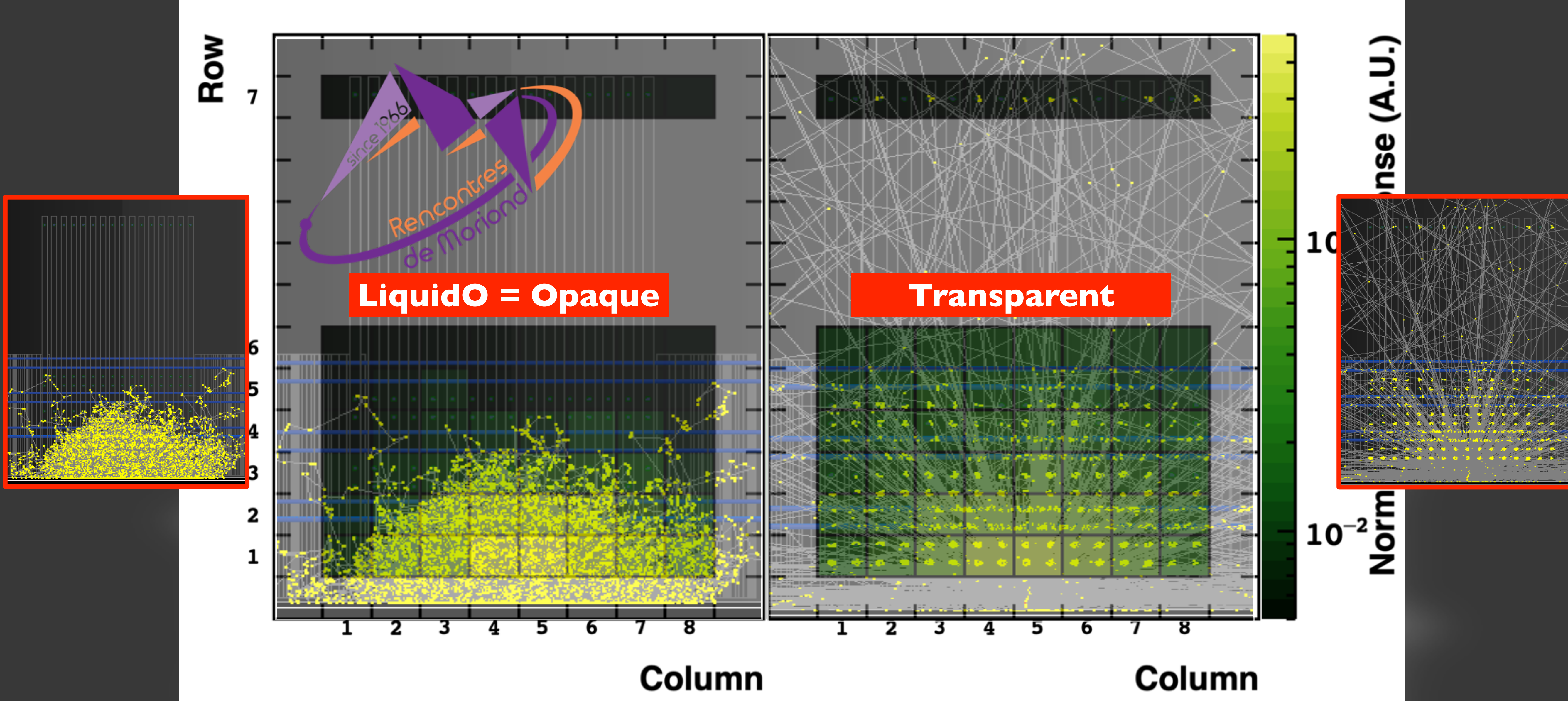


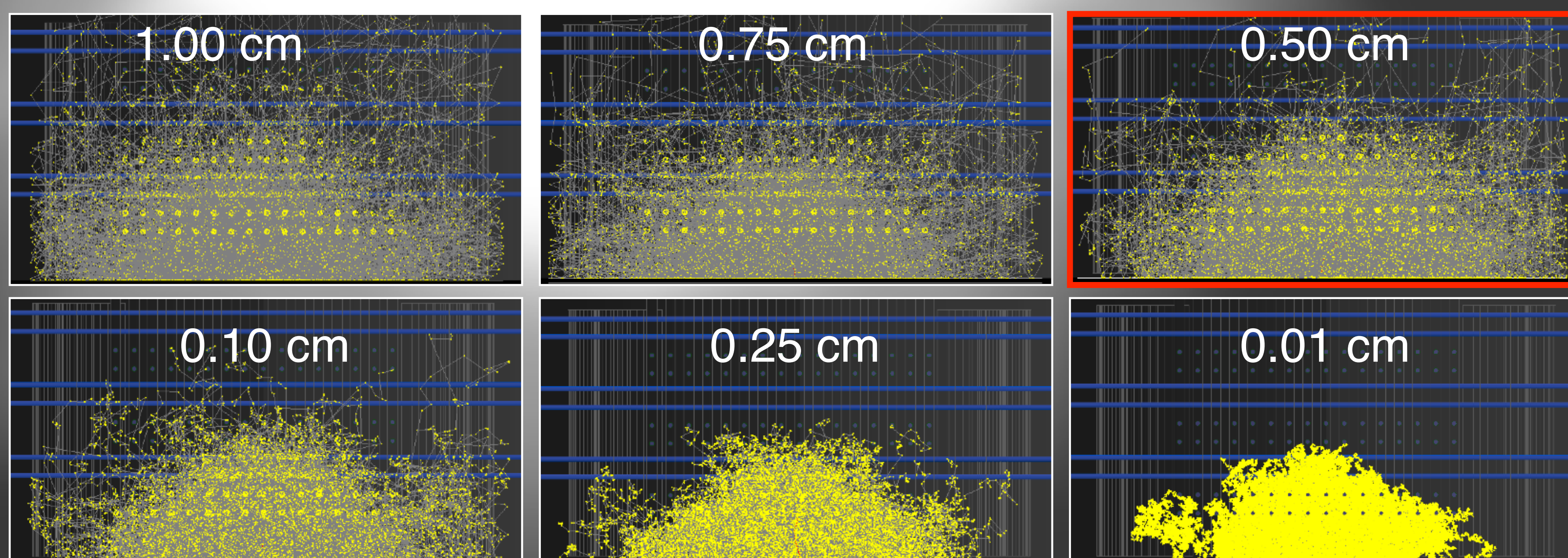
Neutrino physics with an opaque detector

LiquidO Consortium

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


LiquidO's prototype MINI-II (upgrade)
data taking since 2021
Liquid
100%
single electrons
[0.4,1.8]MeV mono-energetic
overall view
3" PMT
(test transparency)
64 channels readout
(pitch ξ≈1.5cm)
~10L multi-media
•water (transparent)
•scintillator (transparent)
•scintillator (transparent↔opaque)
top view
T control
radiator⊕chiller: [5,40] °C

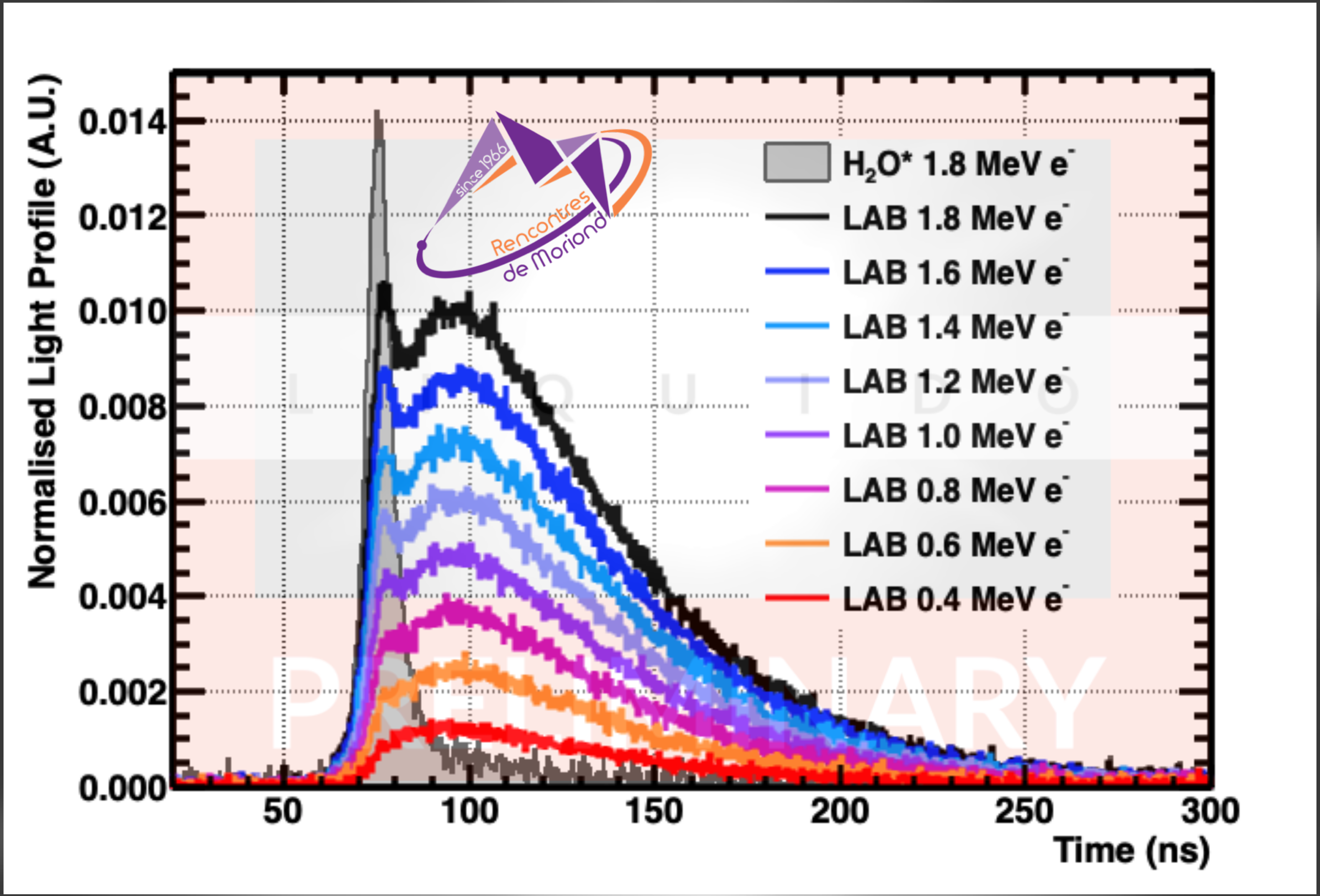




Geant4 Simulation (under tuning)

“light ball” size:

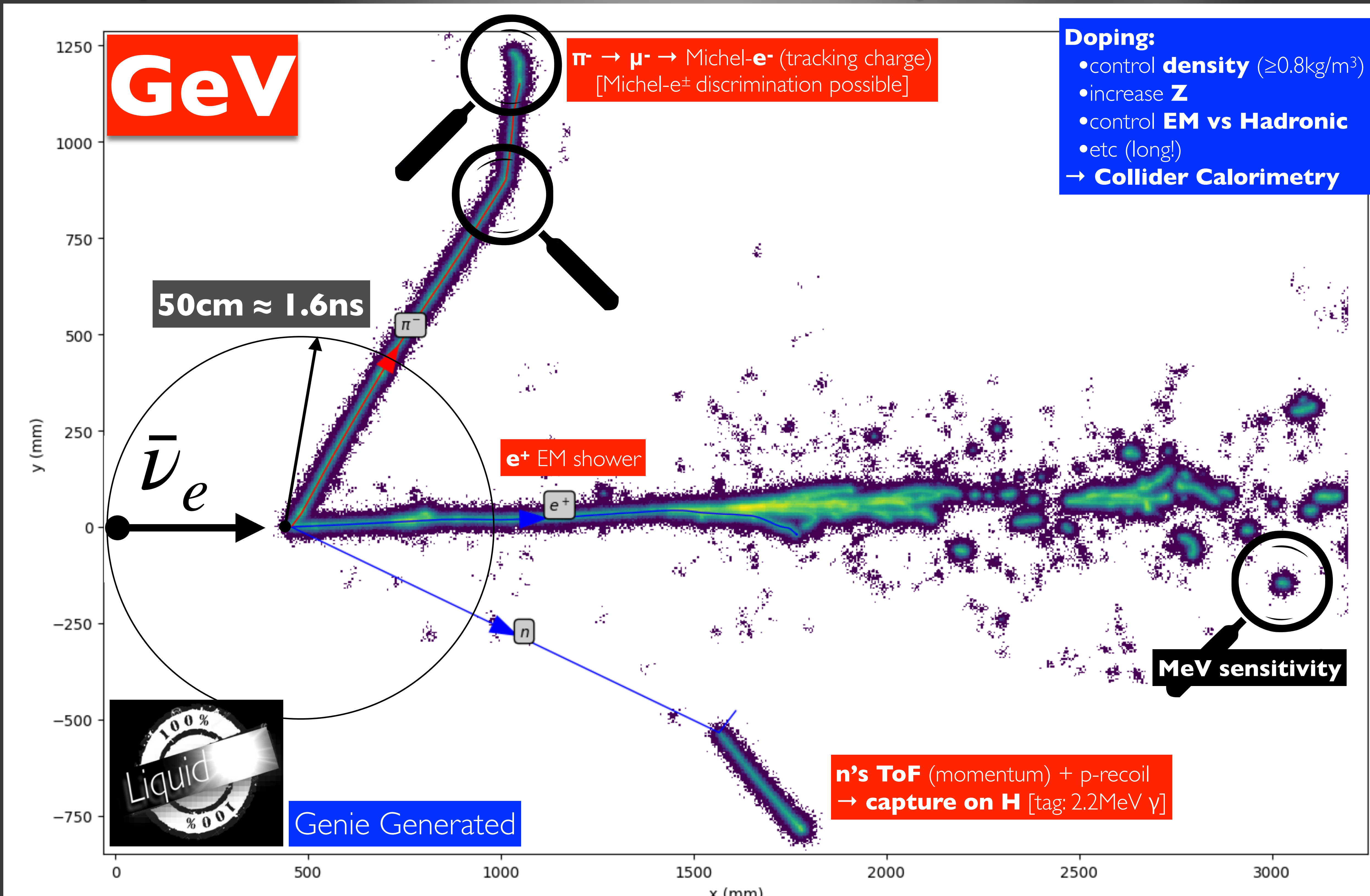
- scattering: λ_s
- \# fibres
- absorption?



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

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

complex GeV with LiquidO…



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

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

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

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

Abstract

COVID delayed

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)

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

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

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- F. Suekane — Tohoku University / RCNS (Japan)

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Contact: LiquidO-Contact-L@in2p3.fr

Chooz (most powerful reactor) ⊕ **UND** (≥30m baseline) ⊕ **LiquidO** (BG rejection)
[**EDF** within the team — unprecedented]

C L O U D

I - II - III

a probe to the future?

CLOUD's sequence…

the power of coincidences

being at **the right "place** & **time** & **energy** & **PID" — huge rejection(s)**

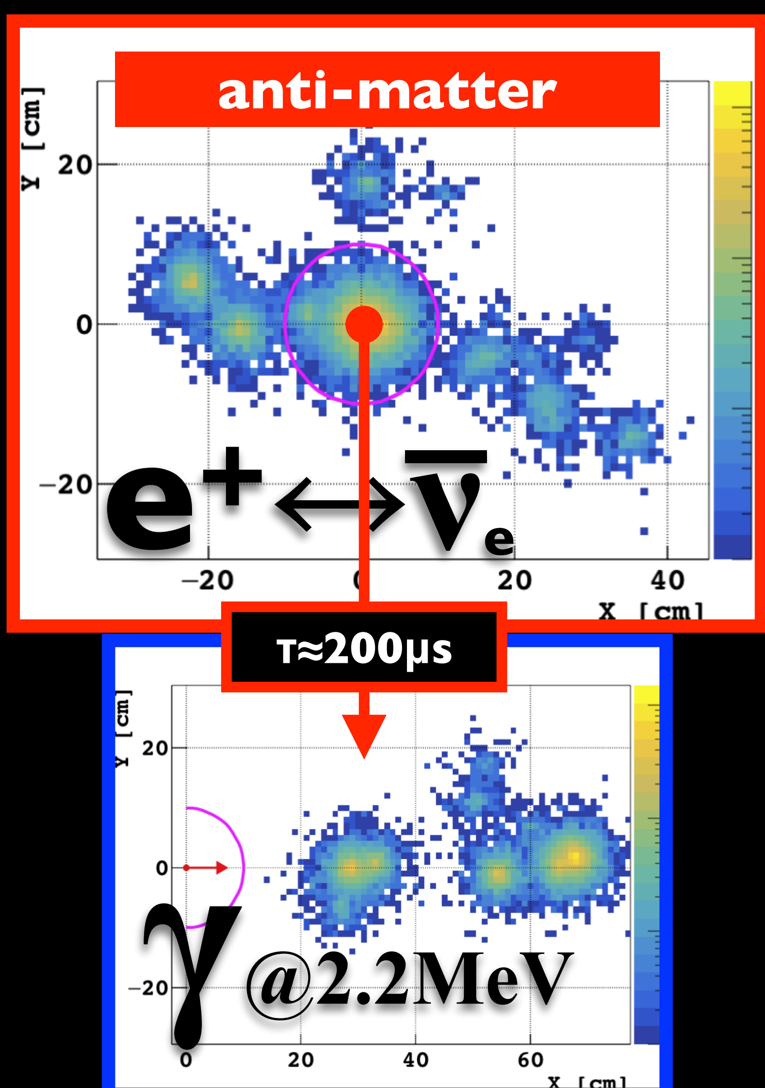
Reines et al '50s

(neutrino discovery)

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

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

(anti)neutrino **discovery** [τ_n & $\Delta m_{p\sim n}$]



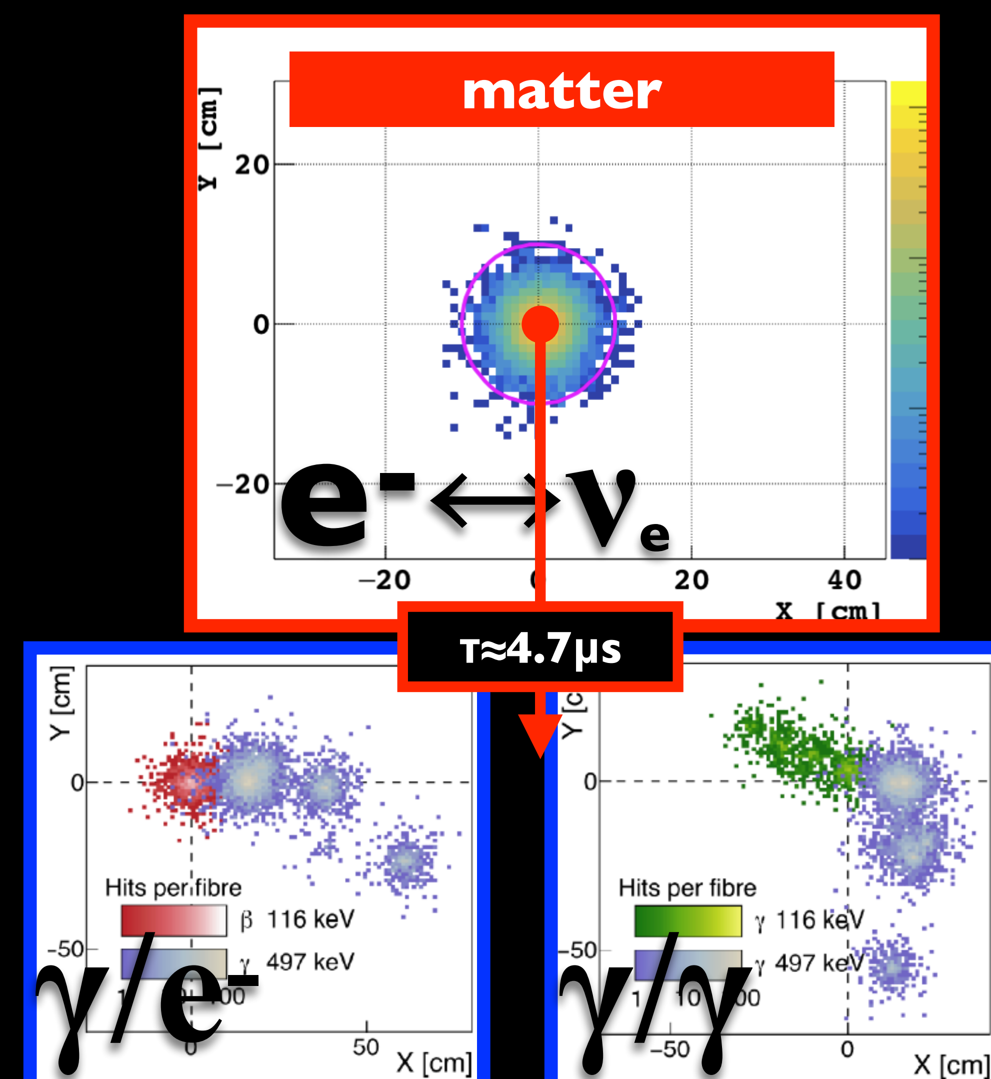
Raghavan et al '70s

(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** [~2 decades] by **LENS** *et al.*



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

the power of coincidences

being at **the right “place & time & energy & PID” — huge rejection(s)**

Reines et al ‘50s

(neutrino discovery)

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

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

(anti)neutrino **discovery** [τn &

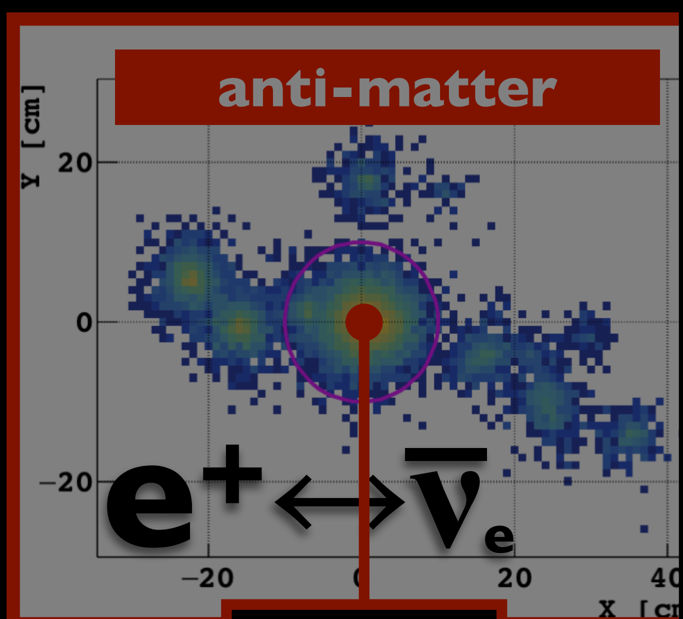
Raghavan et al ‘70s

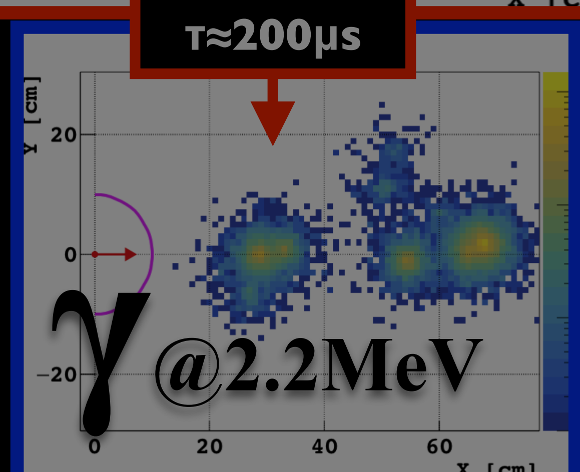
(pp solar neutrino — unobserved)

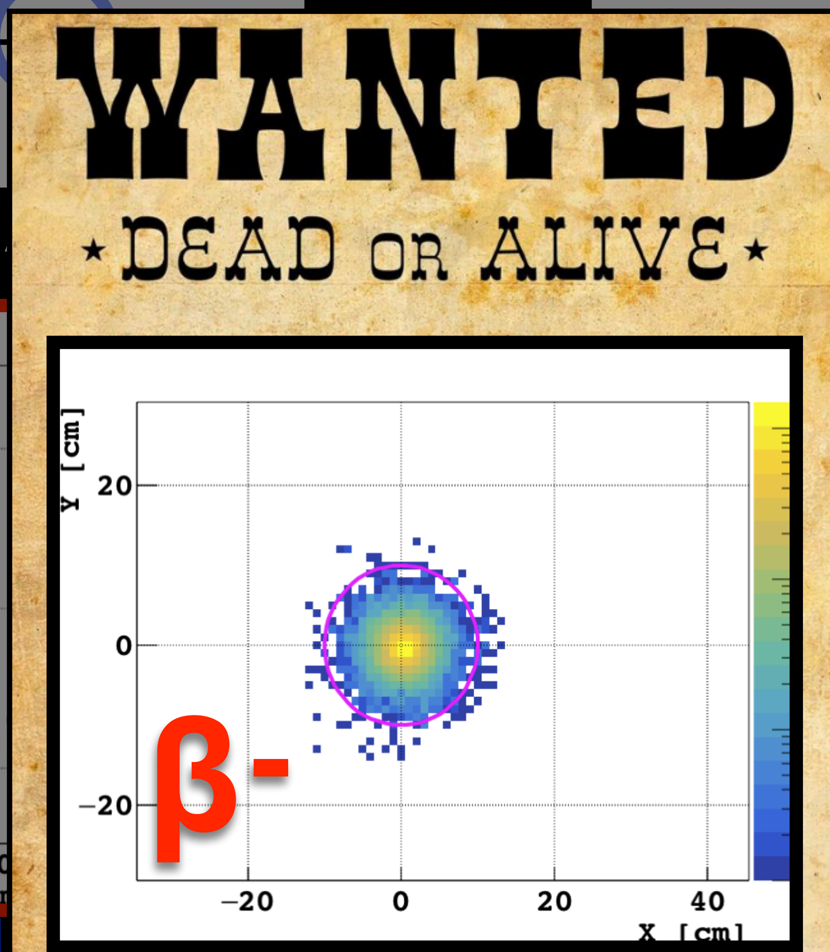
$_e + {}^{115}In \rightarrow e^- + \gamma + \gamma/e^-$

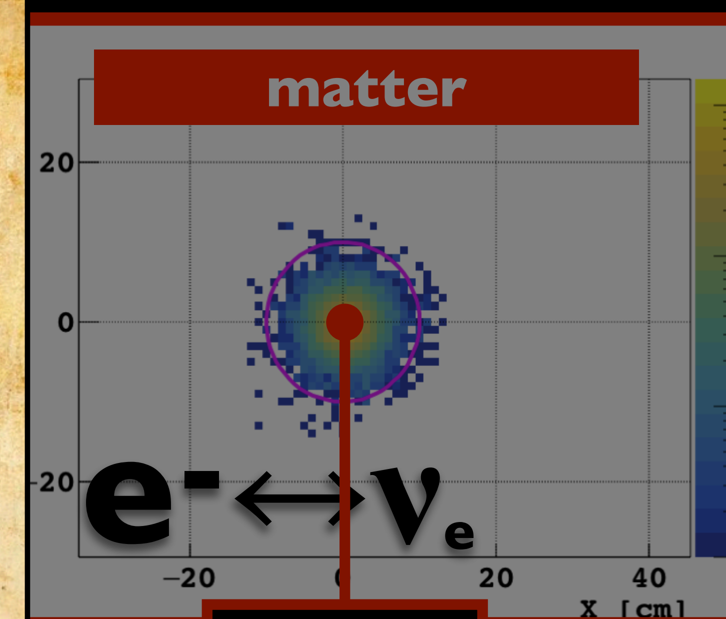
($\tau \approx 4.7\mu s$ decay of **Sn***)

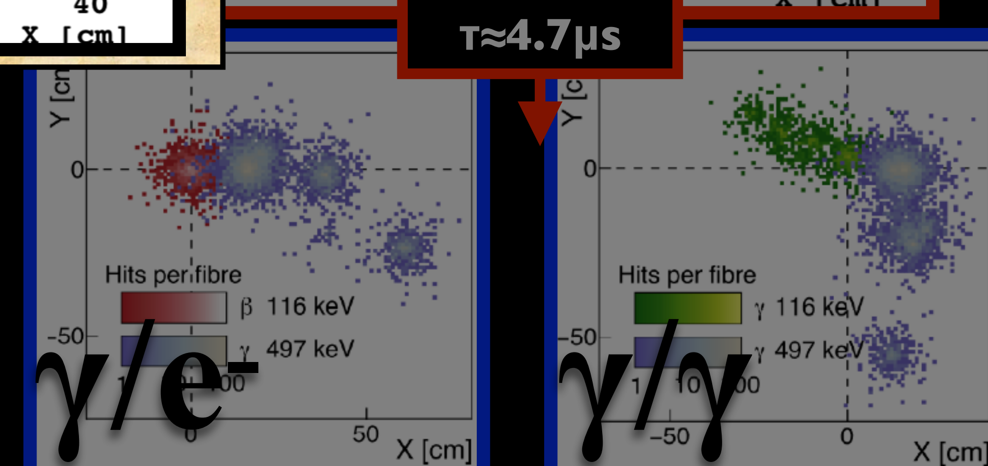
R&D [~2 decades] by **LENS** *et al.*











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

the power of coincidences

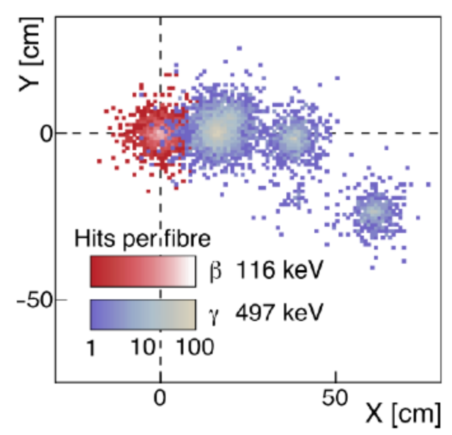
low energy (≲3MeV) neutrinos interactions benefit by interactions leading to coincidences

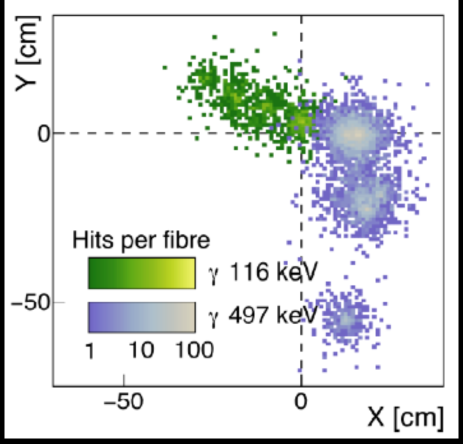
Reines et al 1956
(neutrino discovery)
CC: $\bar{\nu}_e + p \rightarrow e^+ + n$
($\tau \approx 220\mu s$ for only H⊕C)

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]

	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 / delayed	**e⁺** / **γ**(2.2MeV) [H-n capture]	**e⁻** / **γ**(0.5MeV) ⊕ **β⁻/γ**(0.1MeV)
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: ~3]





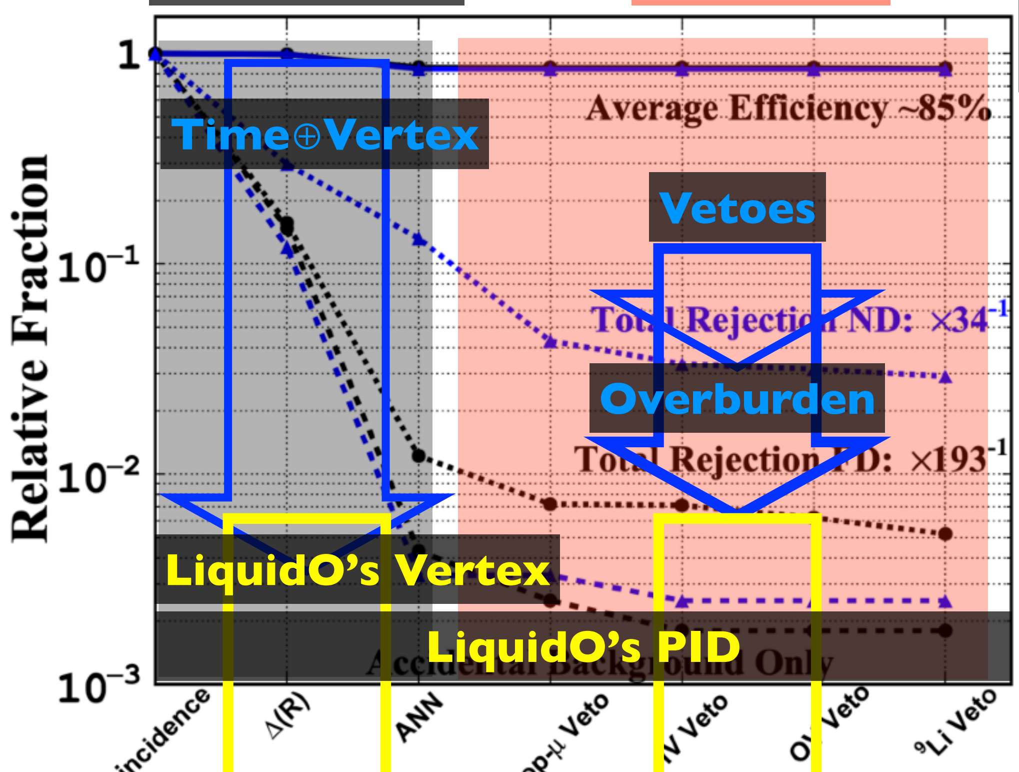
Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

active BG rejection and control…

- detection using **coincidence-signal** (ex. **IBD@p**)⟹ prompt-delayed correlations
  - **combinatory (uncorrelated) BG(s): 5D-coincidence** (Δt⊕Δr⊕ΔE) — **LiquidO's** mm-vertex
  - **cosmogenic (correlated) BG(s): particle-ID** — **LiquidO's** imaging **[impossible so far]**
- **active rejection**→ rejected-BG as **data-driven BG input** (high accuracy physics extraction)
  - **radiogenic control:** in-situ radiogenic BG model tuning (radiopurity control order ≤10^{-14}g/g)

at right **place⊕time⊕energy⊕PID — many orders of magnitude**

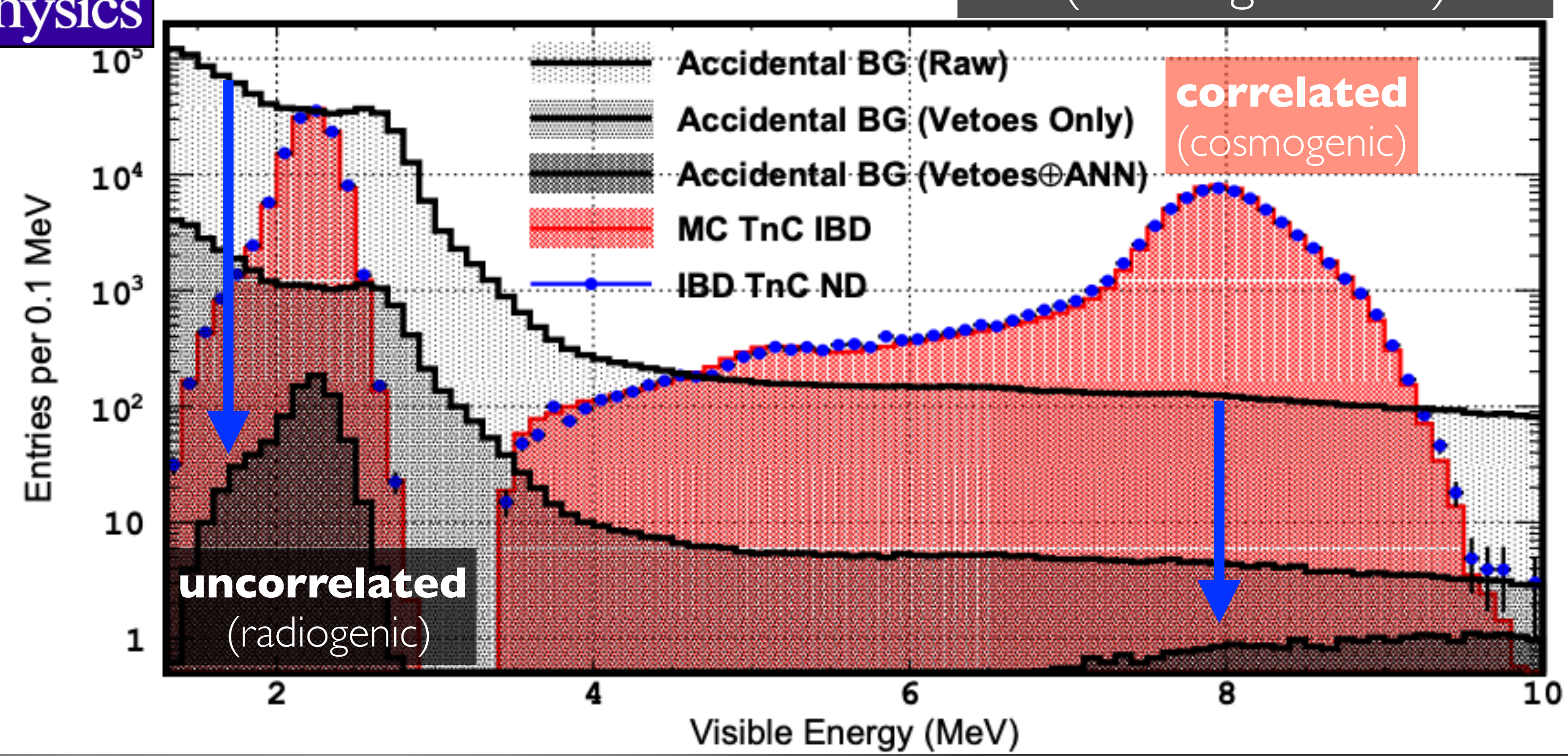
uncorrelated (radiogenic) | **correlated** (cosmogenic)



extra ~10^{-2} rejection? | extra ~10^{-2} rejection?

nature physics

DC: no need for Gd? (cosmogenic BG)



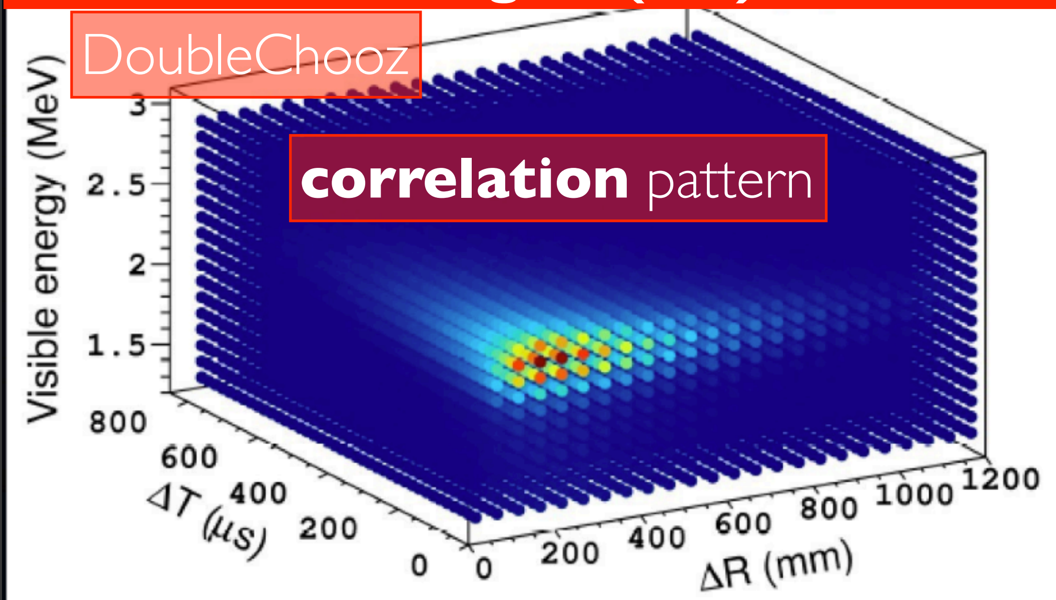
easier to lower **combinatory-BG** (~3 orders of magnitude) than **cosmogenic-BG** (~1 order of magnitude)

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

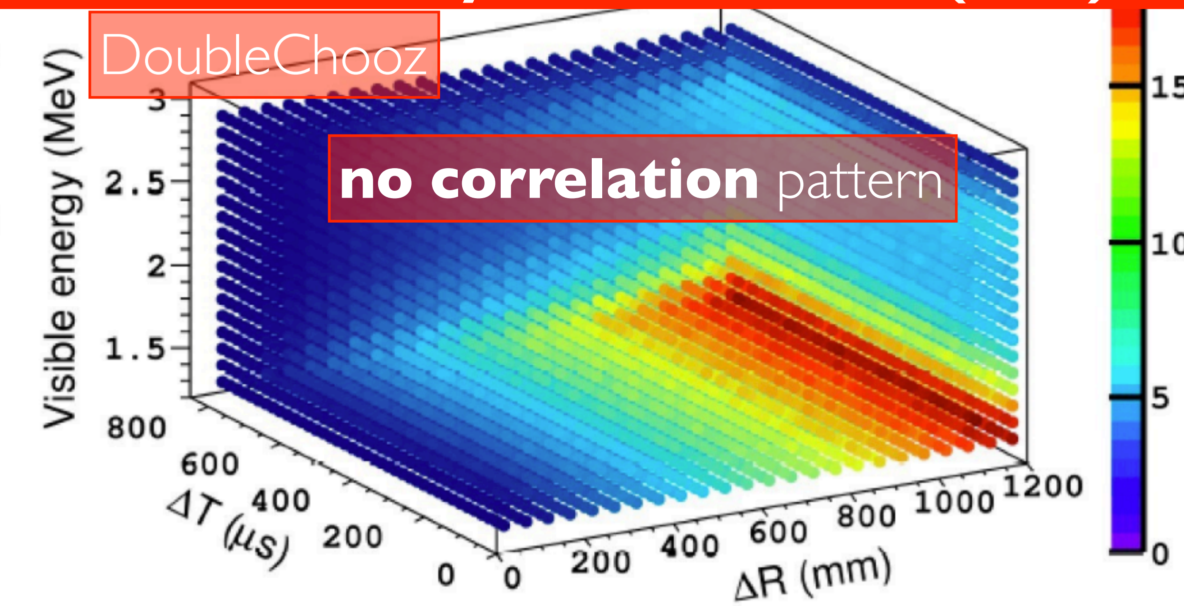
"combinatory" background…

at ~1MeV **backgrounds** due to **radiogenic** (radio-purity only **~10^{-15}g/g**) & **cosmogenic**

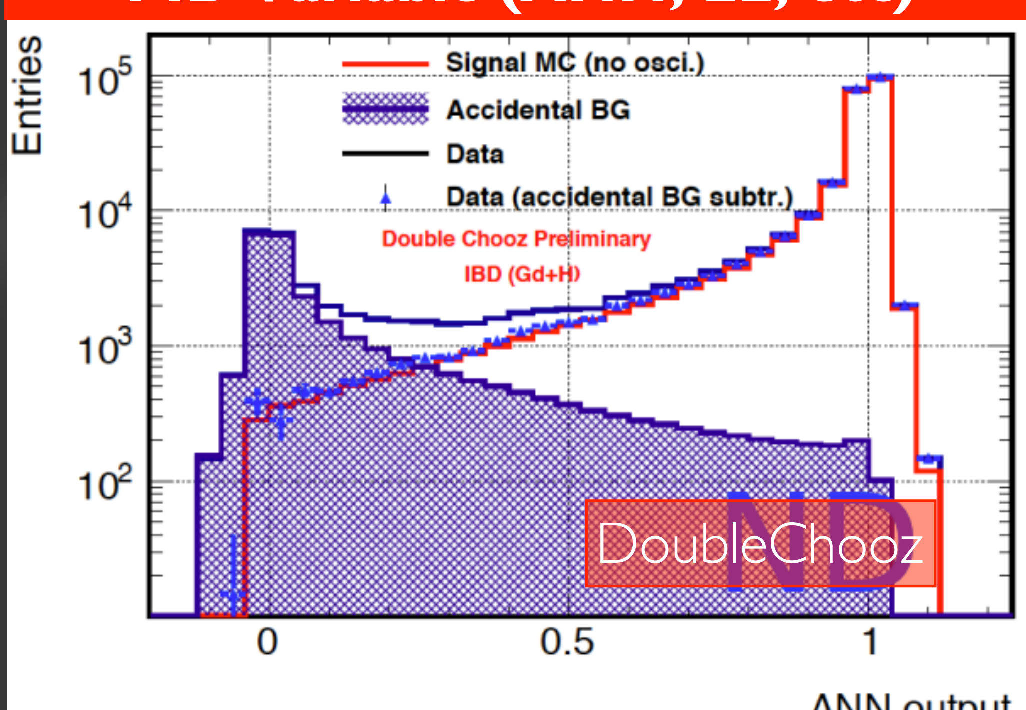
Signal (MC)



Combinatory/Accidental BG (data)



PID Variable (ANN, LL, etc)



LiquidO's vertex precision sub-cm — major

CC antineutrino (reactor)

- **sub-dominant BG** — enough shielding (easy)
- **dominant: correlated cosmogenic**

CC neutrino (solar)

- **dominant BG: β- decay of ^{115}In**

[^{14}C is lower: oil from underground petrol]

C L I U D

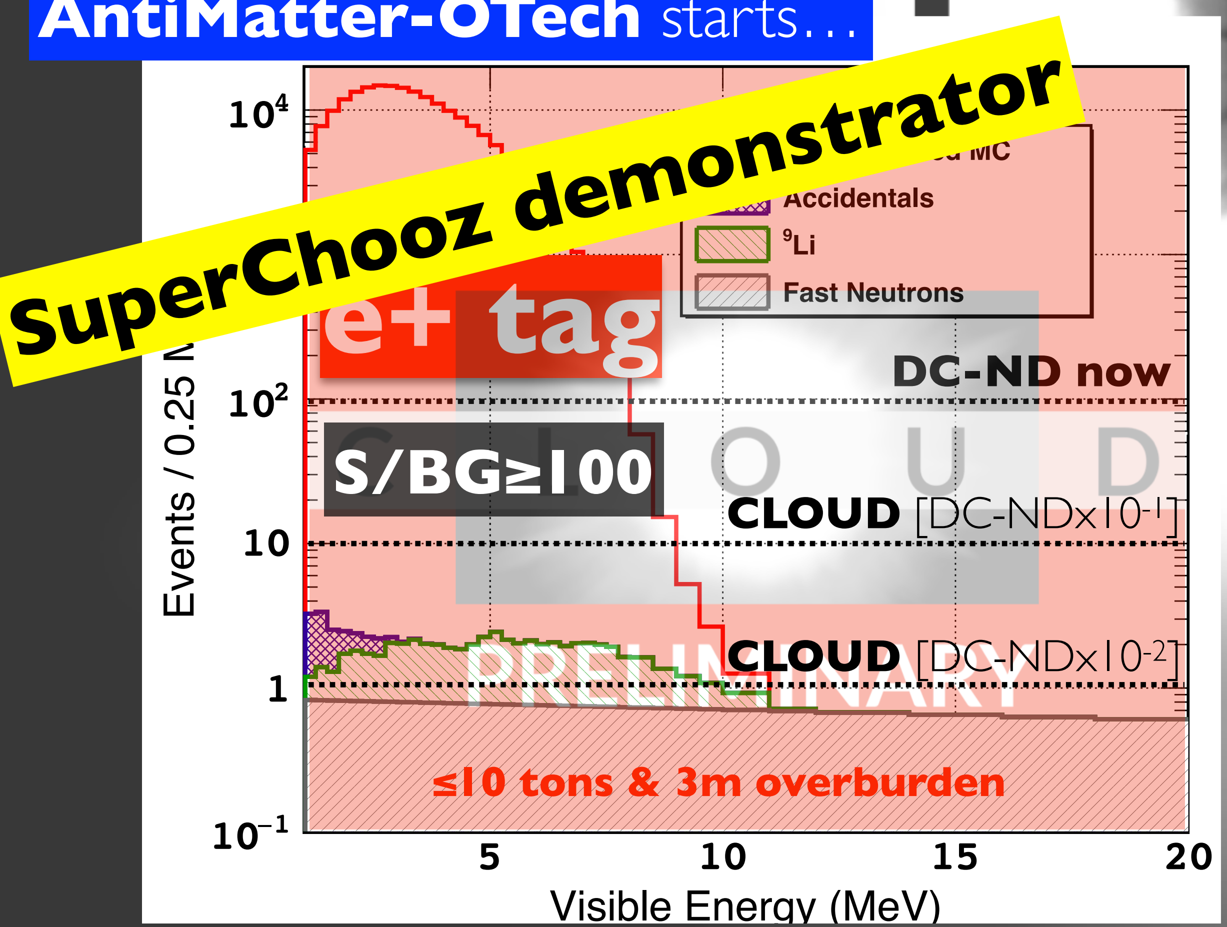
AntiMatter-OTech — synergy
SuperChooz's antineutrino golden channel **demonstration** — byproduct

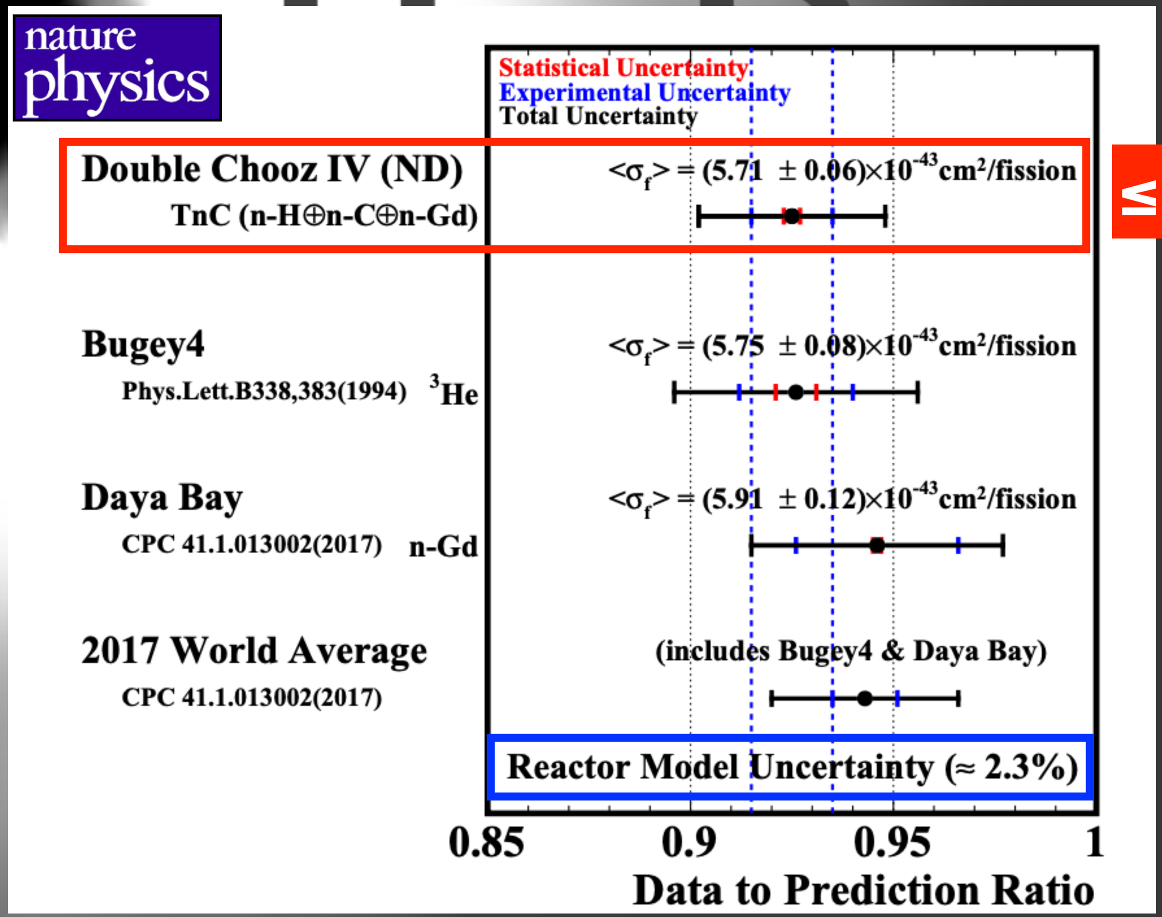
antineutrino CC & NC? (~~doping~~)…

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

- **IBD@p** (anti-ν CC): **≥10,000** interaction per day for **10tons ID** [**≥3M** interactions per year]
  - **LiquidO** reach a **background-less** regime — improve **≥3x** today's BG control (ex. DC-ND)
  - **Signal(ON)-to-BG ≥100** — unprecedented high precision reactor characterisation
    - dominant **~0.5(thermal power) uncertainty** & accurate **U/Pu composition**
  - **Signal(OFF)-to-BG ≥1** — unprecedented **reactor-fuel monitoring**
    - accurate monitoring of **transitions OFF-ON-OFF** — some interesting physics
  - **unique test-bench data for accurate prediction** — validate uncertainties, too?

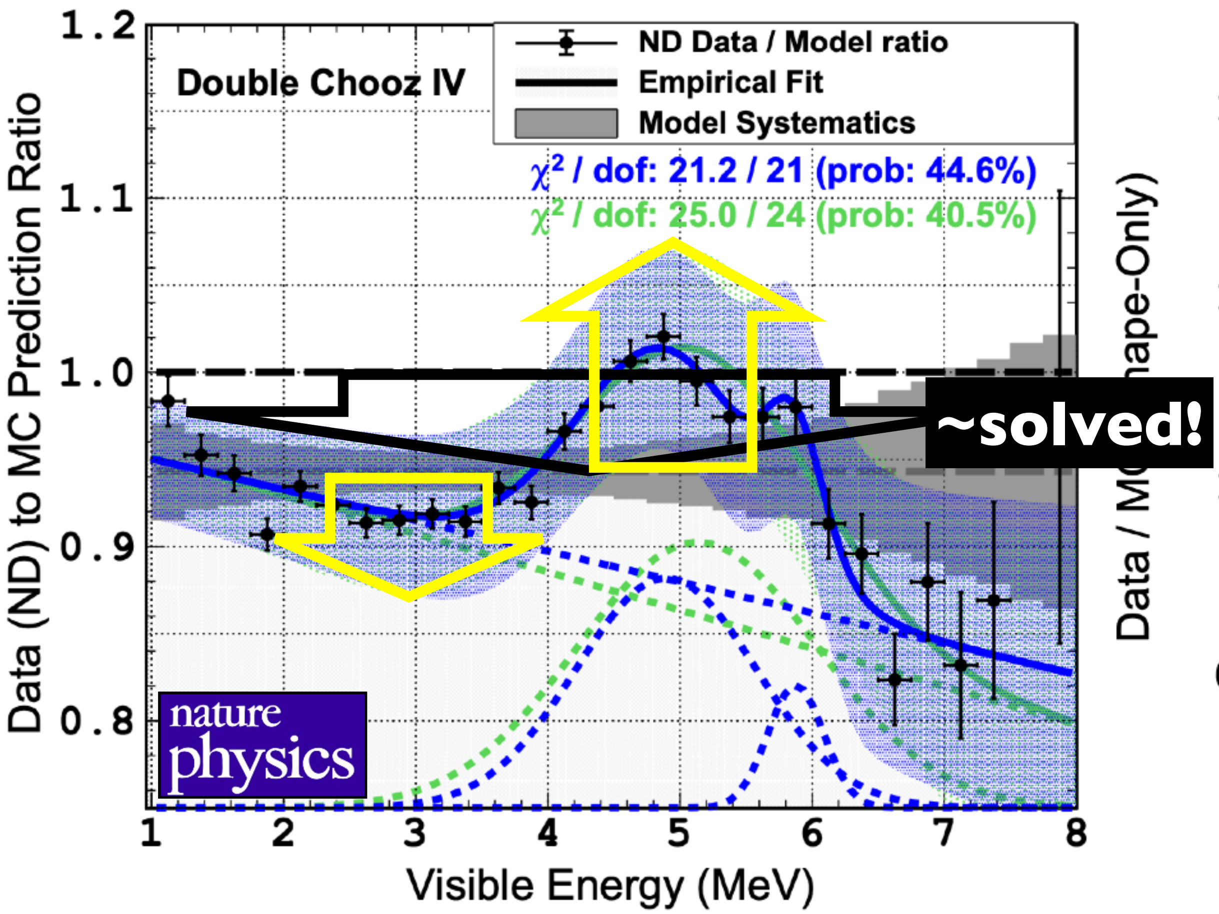
AntiMatter-OTech starts…

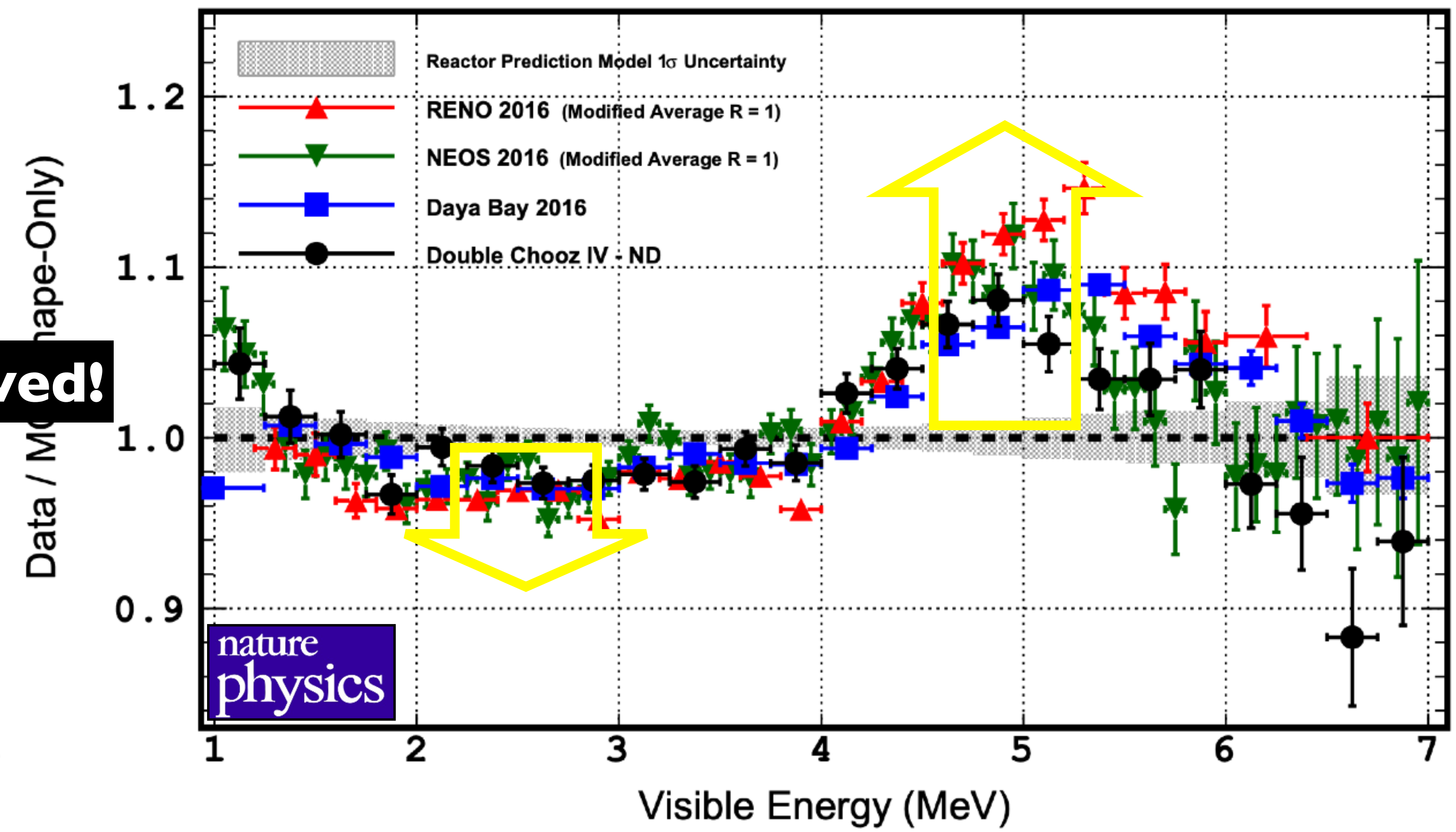




CLOUD precision ≥0.6%⟹ Unitarity Violation? (if predictions are improved)!

all experiments consistent — except Bugey3?!





ABSOLUTE FLUX: the future of reactor-antineutrino physics

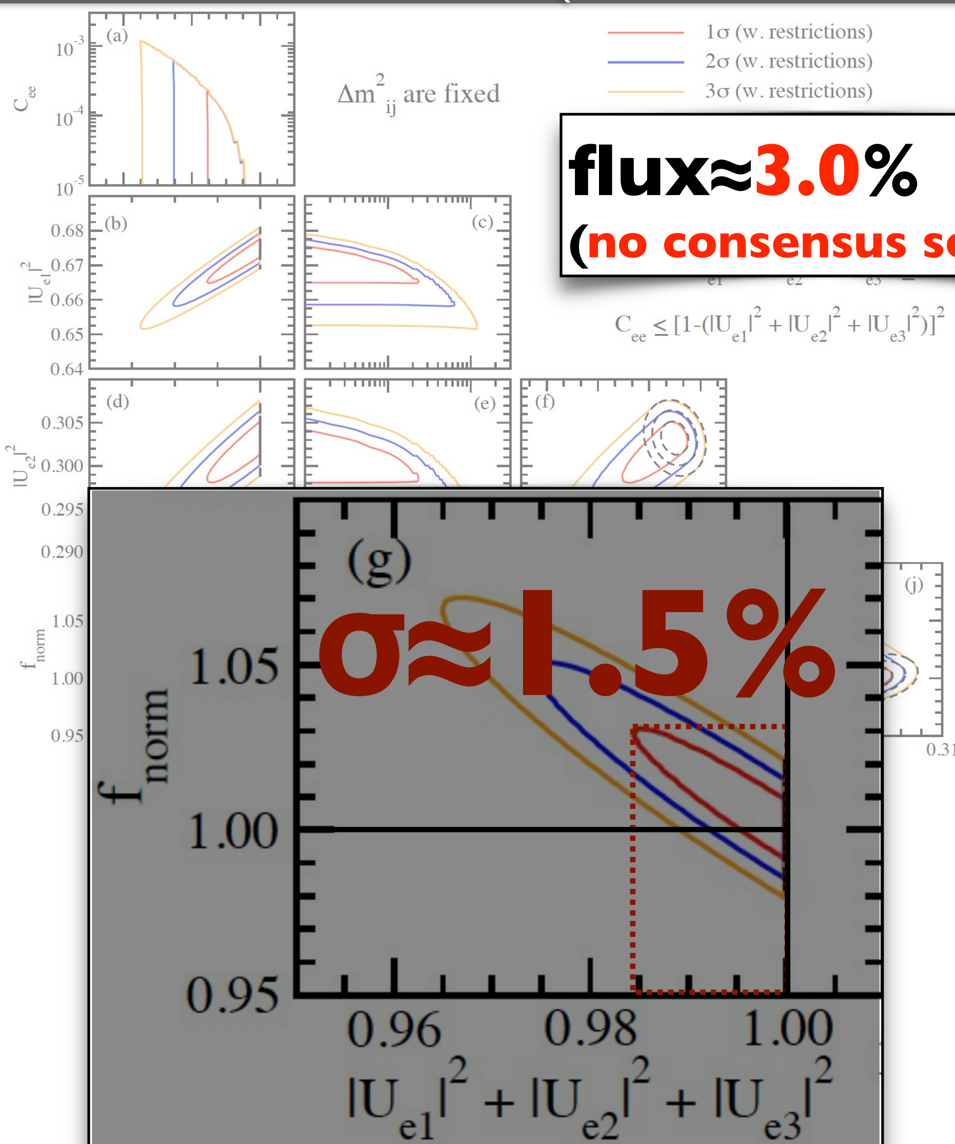
we must solve this "mess" ⟹ the reward **possible new physics!**

(if so, prediction should not use neutrino input⟹**no** new physics)

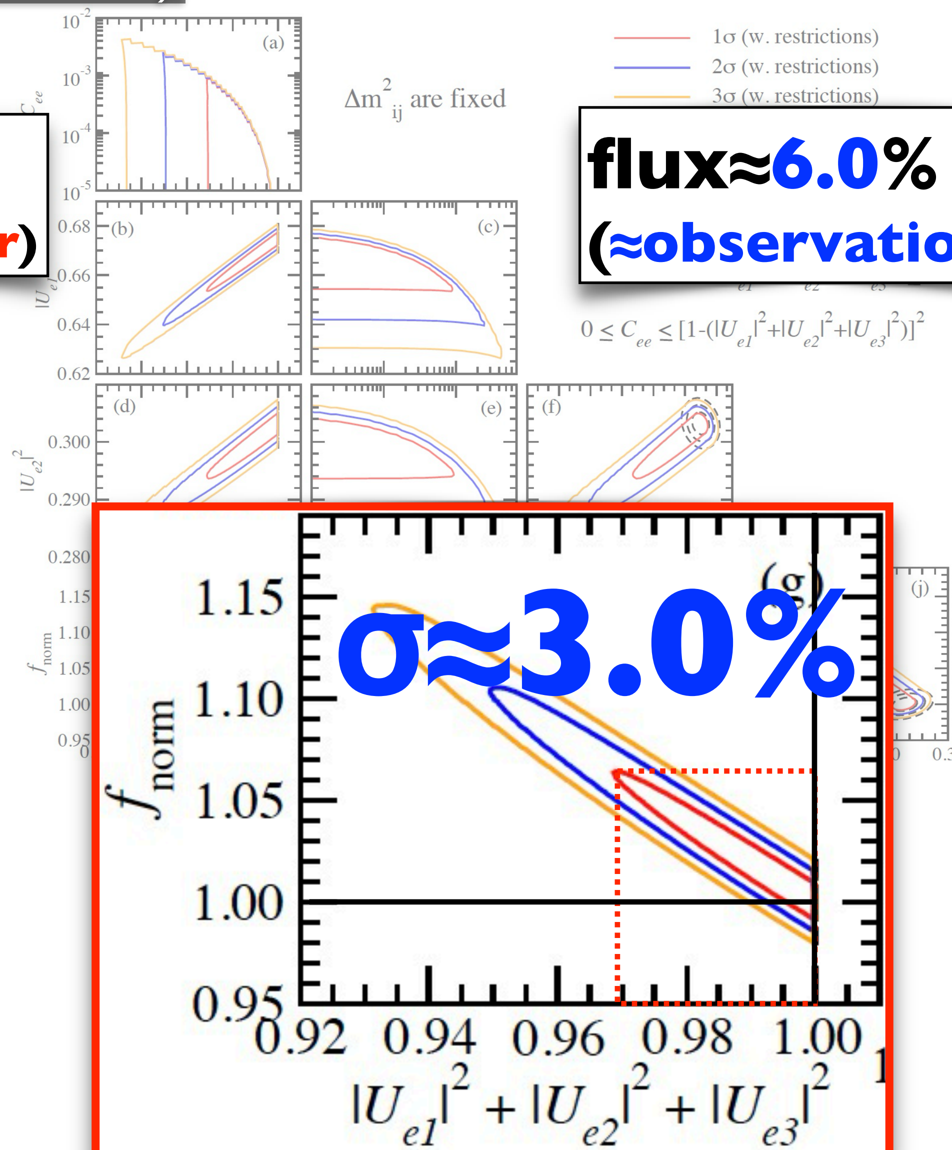
must understand flux ≤1%...

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

if **unitarity** (must for the "definition" of any mixing-angle θ_{ij}) is **only controlled to ≥3%** (today)

C L O U D

how to ensure the **correctness** of **any θ_{ij} permille precision measurement**?

[ex. **JUNO's $\delta(\theta_{12})\leq0.5\%$**]

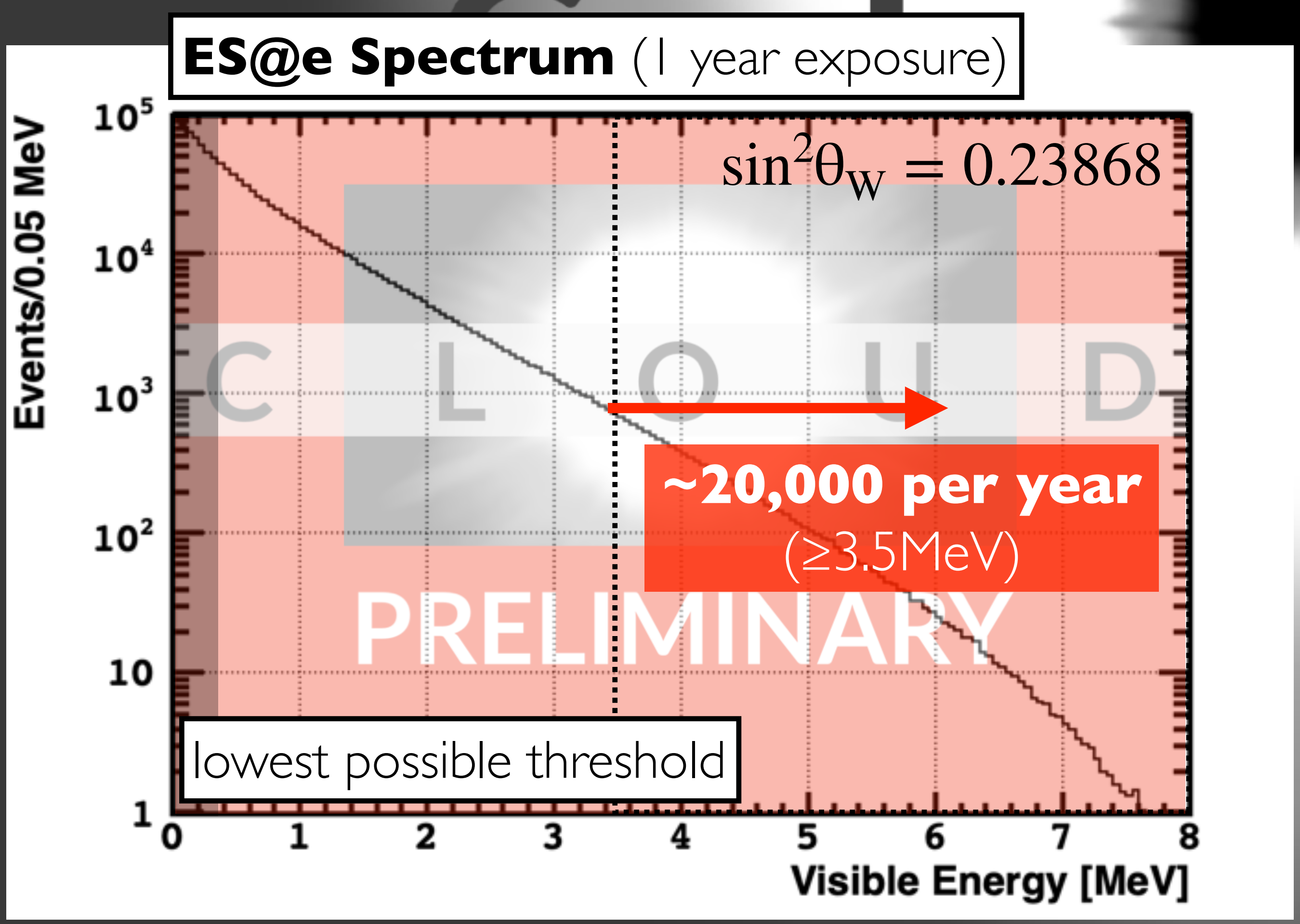
CLOUD's fundamental question…

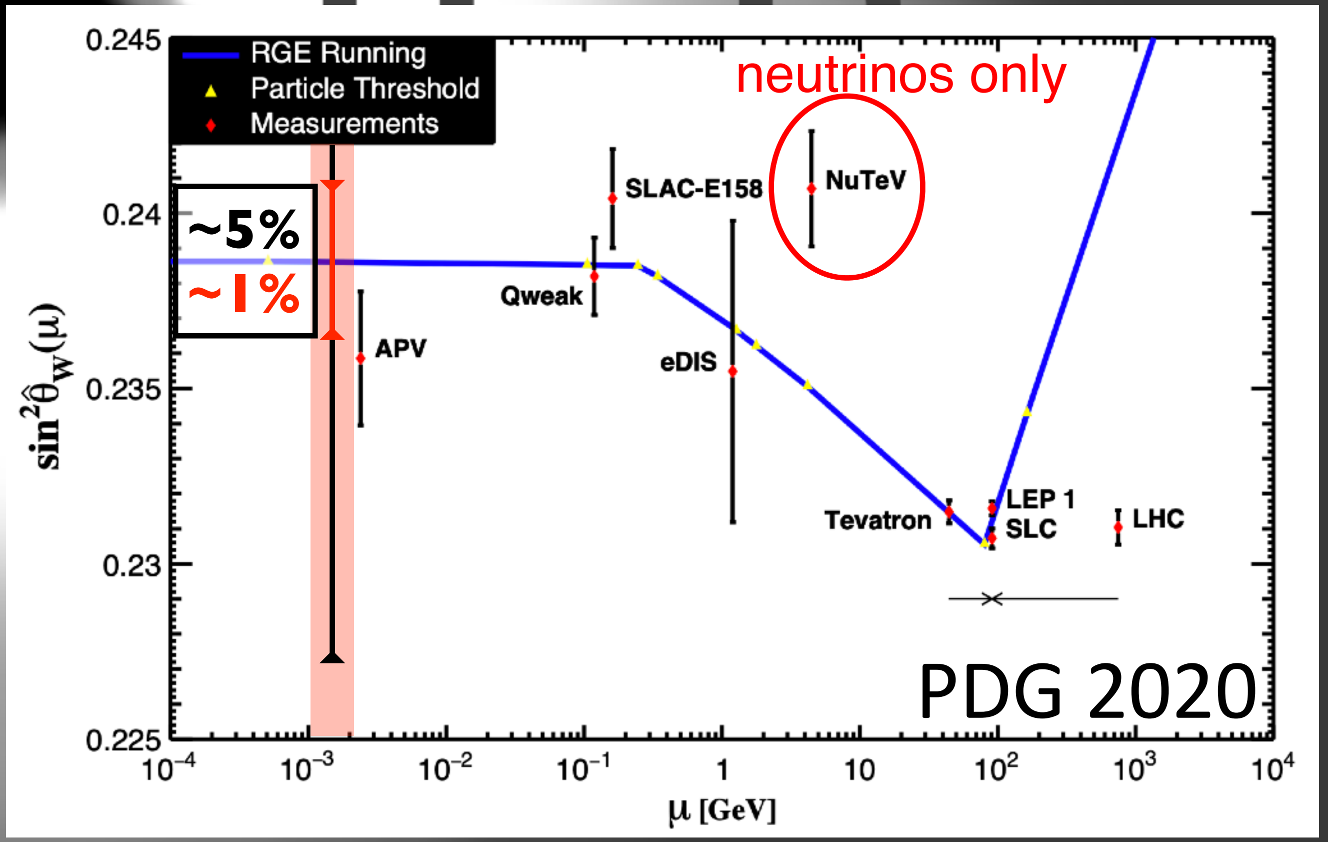
C L O U D

accuracy implies **redundancy**…

CLOUD-I physics programme: **ES@e**…

- **eES** (anti-ν CC⊕NC): **≲5,000** interactions per day for **10tons ID** [≲**2M** interactions per year]
  - interference CC & NC — different for neutrino (easier) and antineutrino (harder)
  - measure θ_W and the **NC flux** component: **absolute flux Z-coupled** (~~neutrino oscillation~~)
  - PDG-2022's $\sin^2\theta_W \approx$ **[0.231,0.239]** — the **running** due to SM's renormalisation
- **major challenge**: **LiquidO isolate "e-like" PID** and exploit **high-rate reactor modulation**
  - likely strong **fiducial volume** & **higher energies** — reduce detected rate drastically
  - **≲10% precision** (≥5σ observation) tolerates much BG but **≲1%**⟹ **S/BG≥2(!!) impossible?**





R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

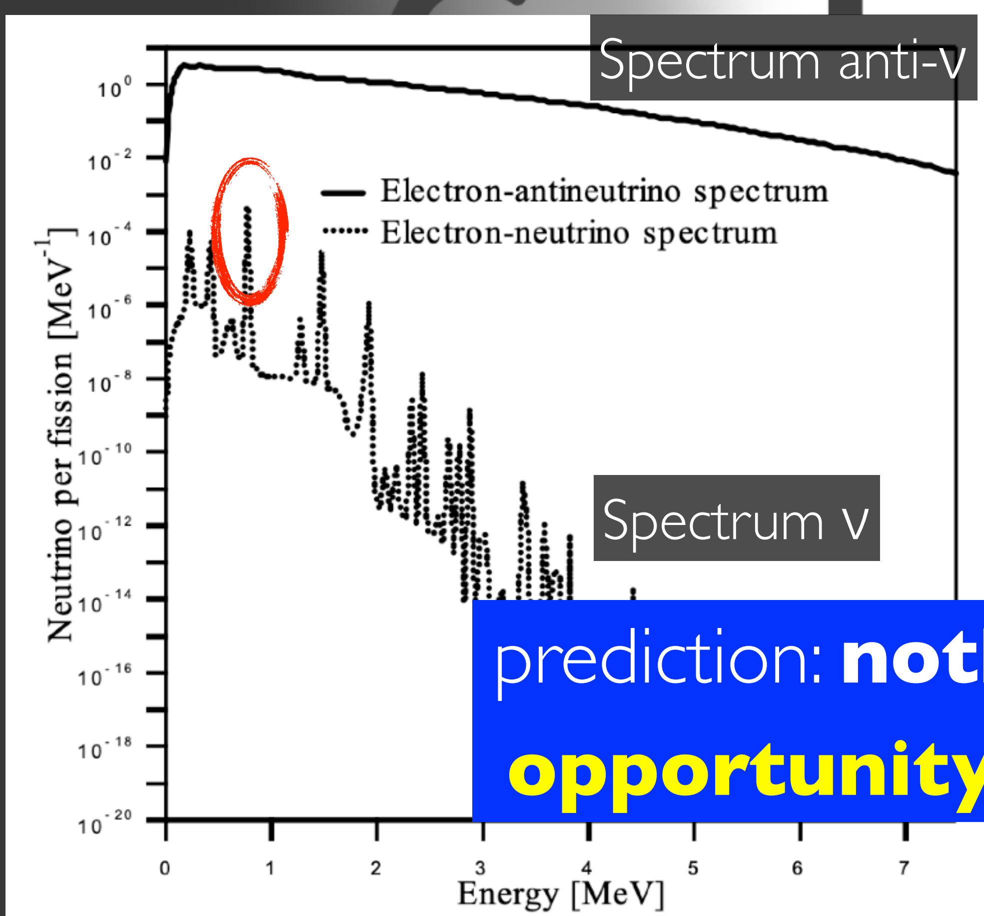
SuperChooz's neutrino golden channel **demonstration** — byproduct

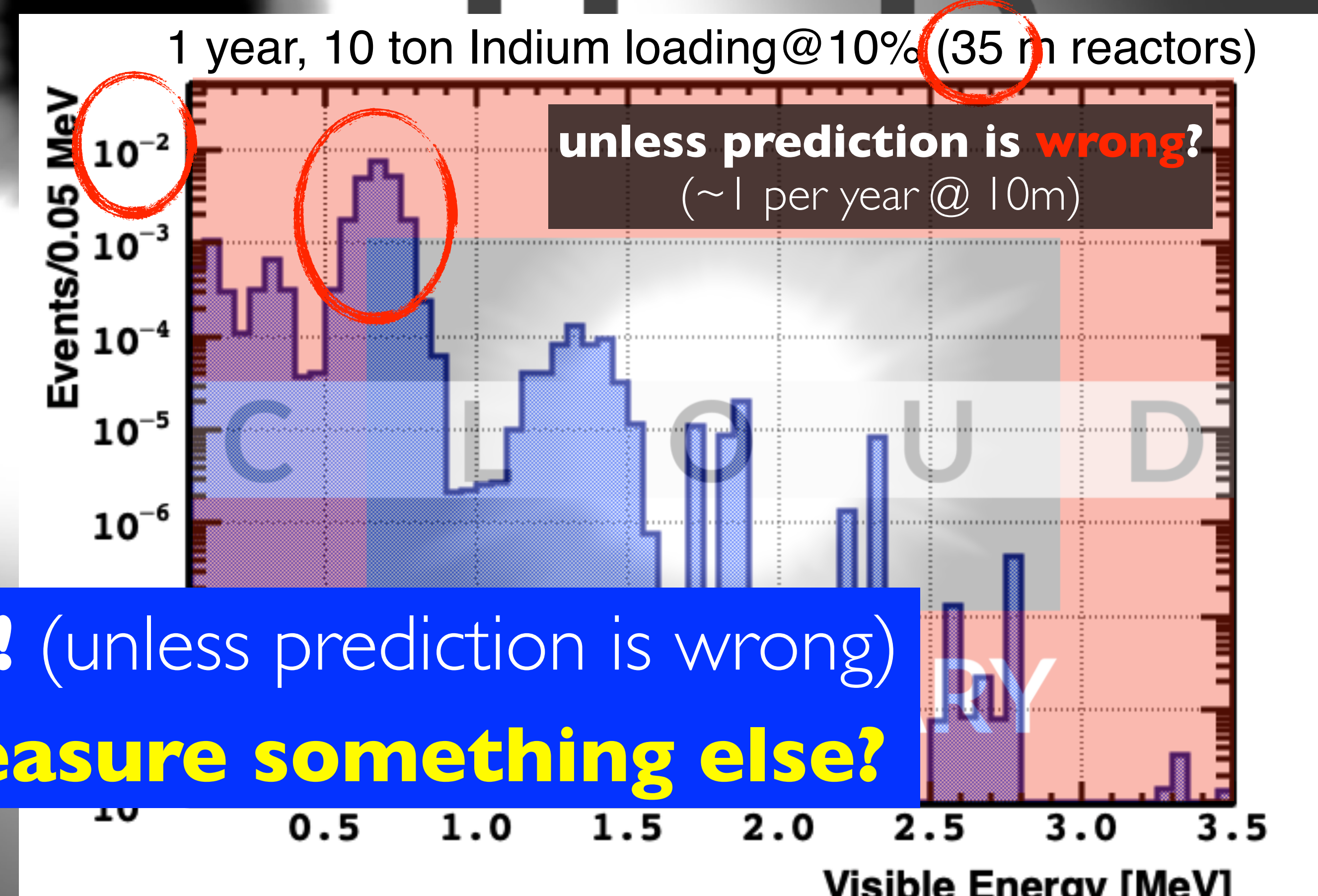
neutrino CC (doping)…

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

CLOUD-II physics programme: **neutrino**…

- loading **indium** on the detector — **unique strong coincidence ≥114keV** (“solar-pp” in mind)
  - low threshold ⊕ high natural-abundance ⊕ high-ish cross-section ⊕ BG-killer (coincidence)
  - CC interaction: ν_e + ^{115}In → **e-** + ^{115}Sn* [τ:4.8μs decay: **γ/e**(116keV) + **γ**(496keV)]
  - reactor neutrino **modulate with the reactor power** — no ambiguity whatsoever
- detecting **neutrinos close to a reactor**? **possible?**
  - **reactor neutrinos** (from β+/EC): **rate(ν) ≈ 10^{-5} rate(anti-ν)** — prediction (both correlated)
  - could **reactors be the missing MeV neutrino source?** [otherwise impractical]





prediction: **nothing!** (unless prediction is wrong)

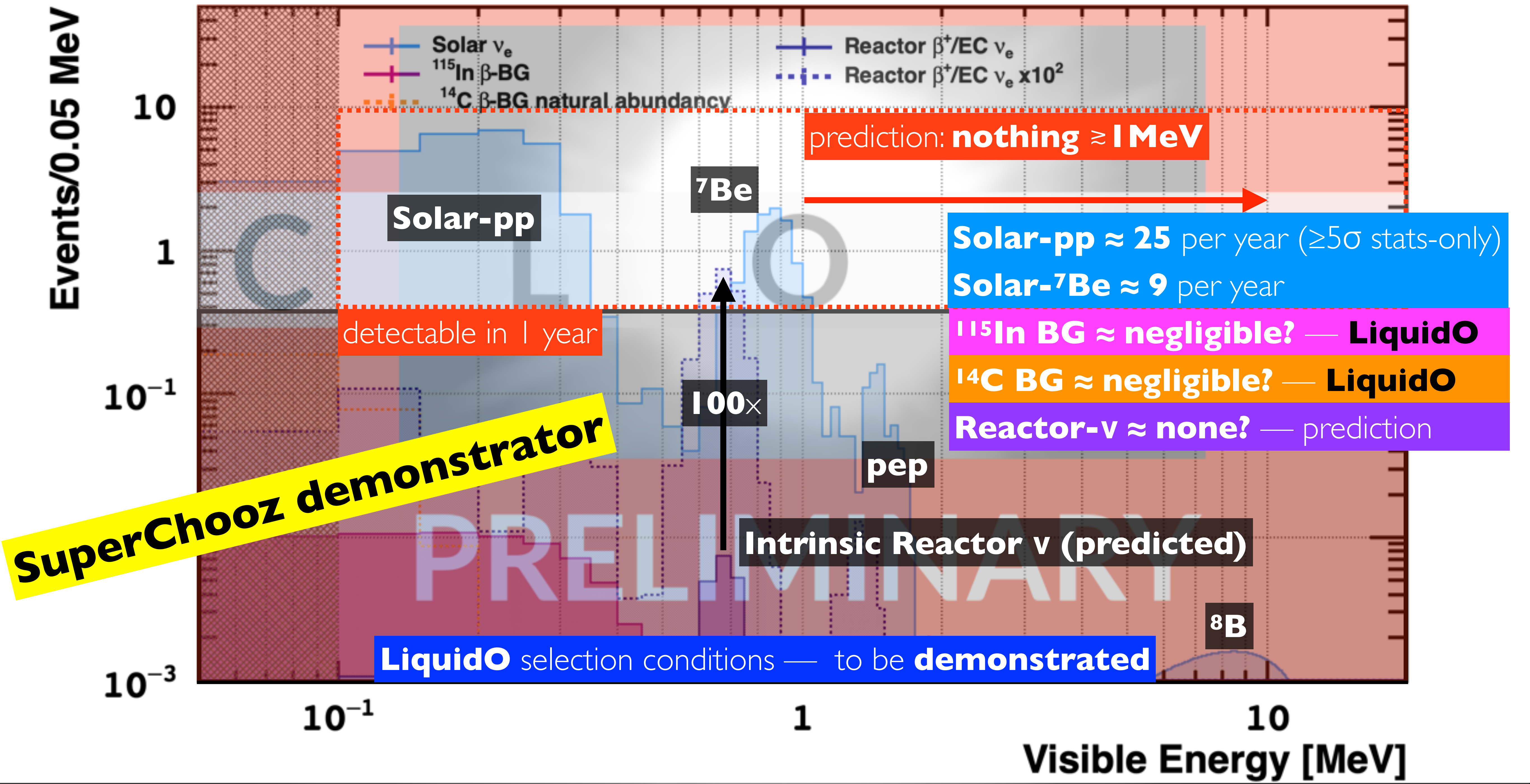
opportunity: measure something else?

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

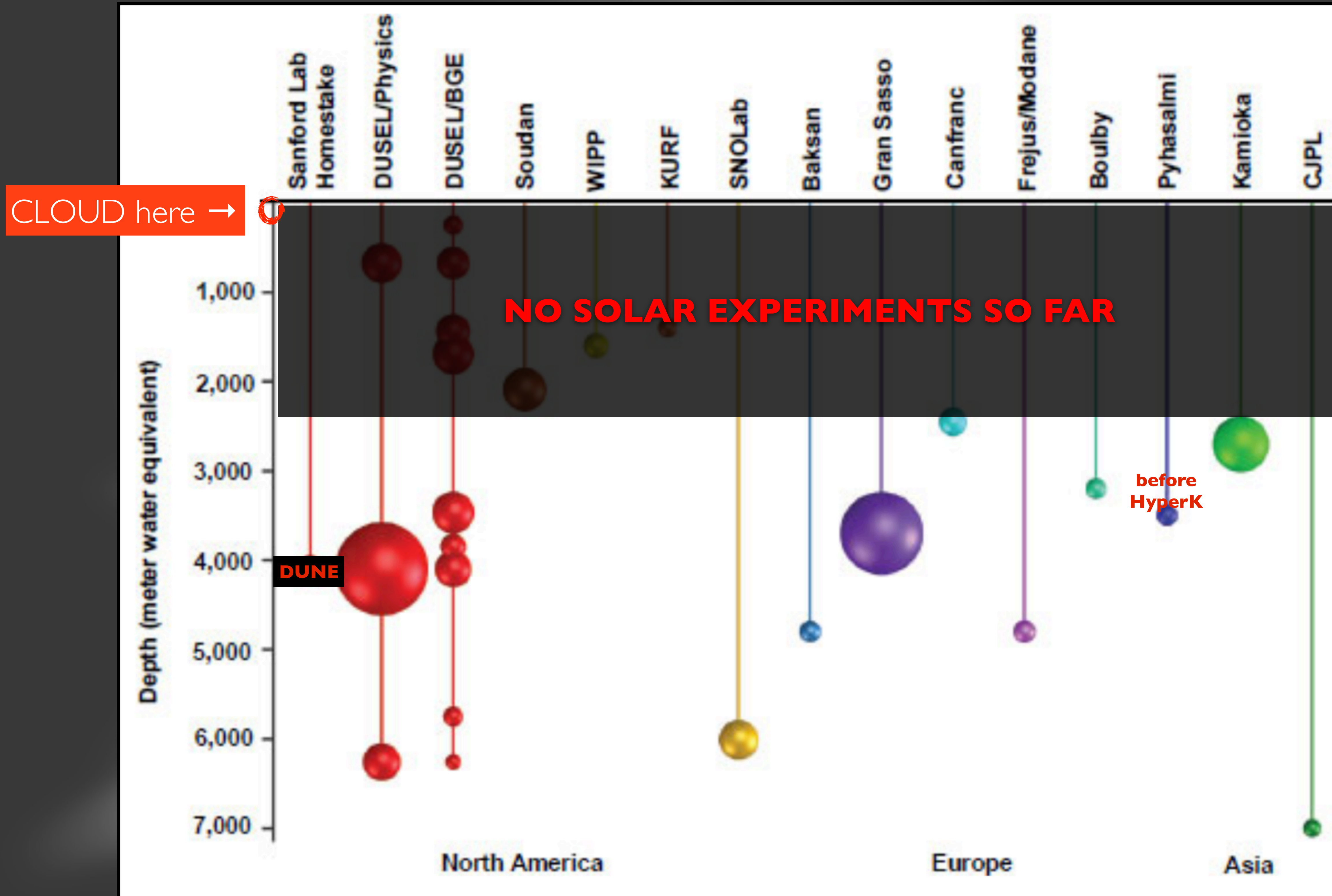
the big picture of neutrinos @CLOUD…

assuming the **LENS "BG model"** — valid at **overburden ~3m?** (to be demonstrated)

1 year, 10 ton Indium loading@10% (35 m reactors)



detection **solar-pp neutrinos** on a **10ton** detector **almost on surface** right **next a nuclear reactor?**



ISSUE!!! overburden almost at surface ⟹ first time ever?

solar-ν detection on surface…?

R&D for **low energy reactor-fuel monitoring** & **geoneutrino ^{40}K discovery** — demonstration

new antineutrino CC (doping)...

just released! the inspiration…

arXiv:2308.04154

Probing Earth's Missing Potassium using the Unique Antimatter Signature of Geoneutrinos

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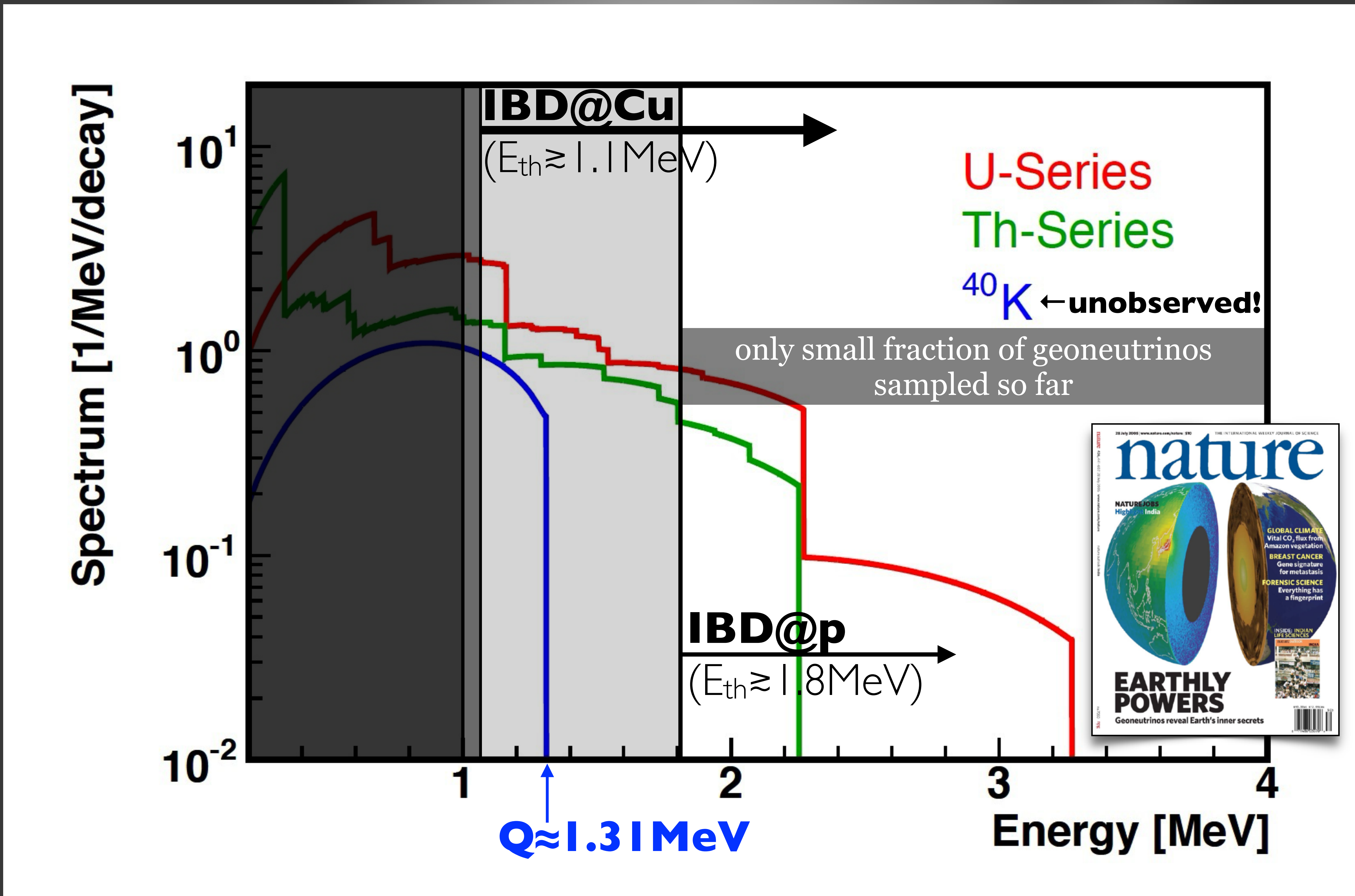
(LiquidO Consortium)

^{40}K geoneutrino new methodology→ good enough for discovery?

^{40}K geoneutrino ("holy grail") via IBD@Cu?



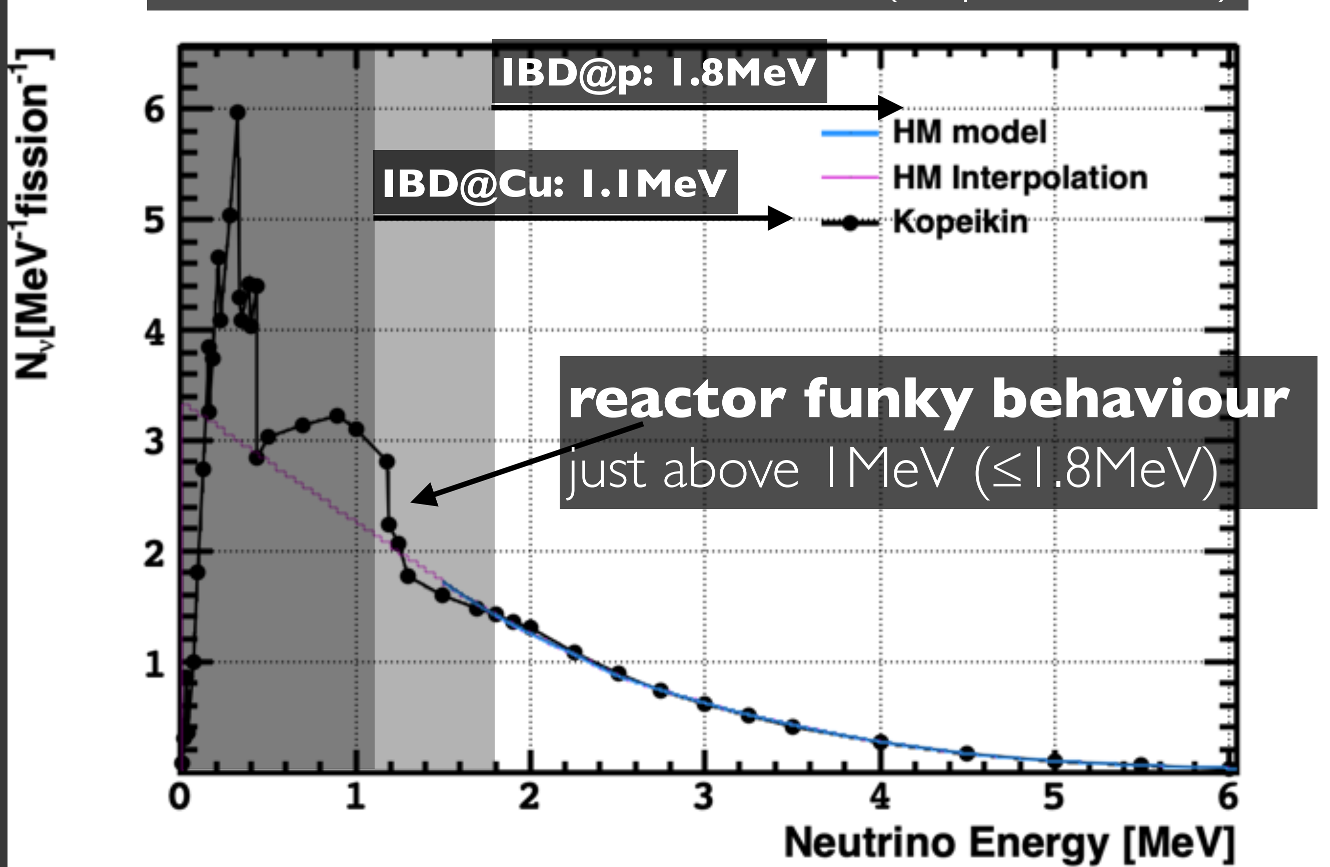
Anatael Cabrera (CNRS-IN2P3) — IJCLab / Université Paris-Saclay (Orsay)

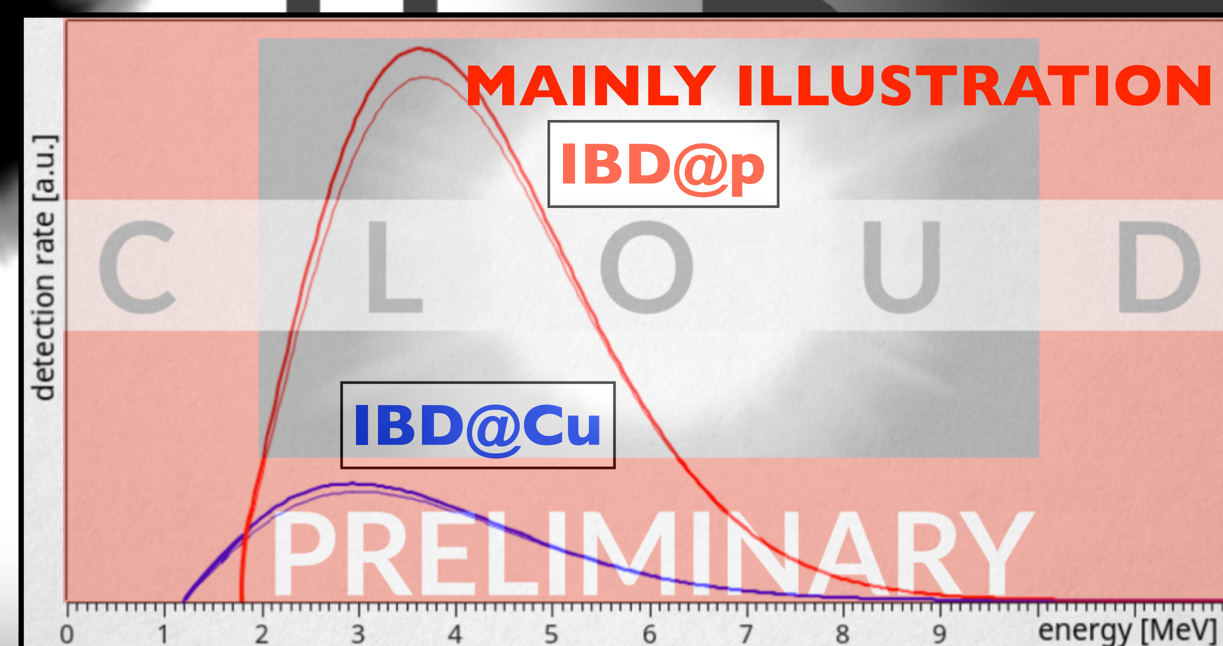
CLOUD-III physics programme…

Probing Earth's Missing Potassium using the Unique Antimatter Signature of Geoneutrinos

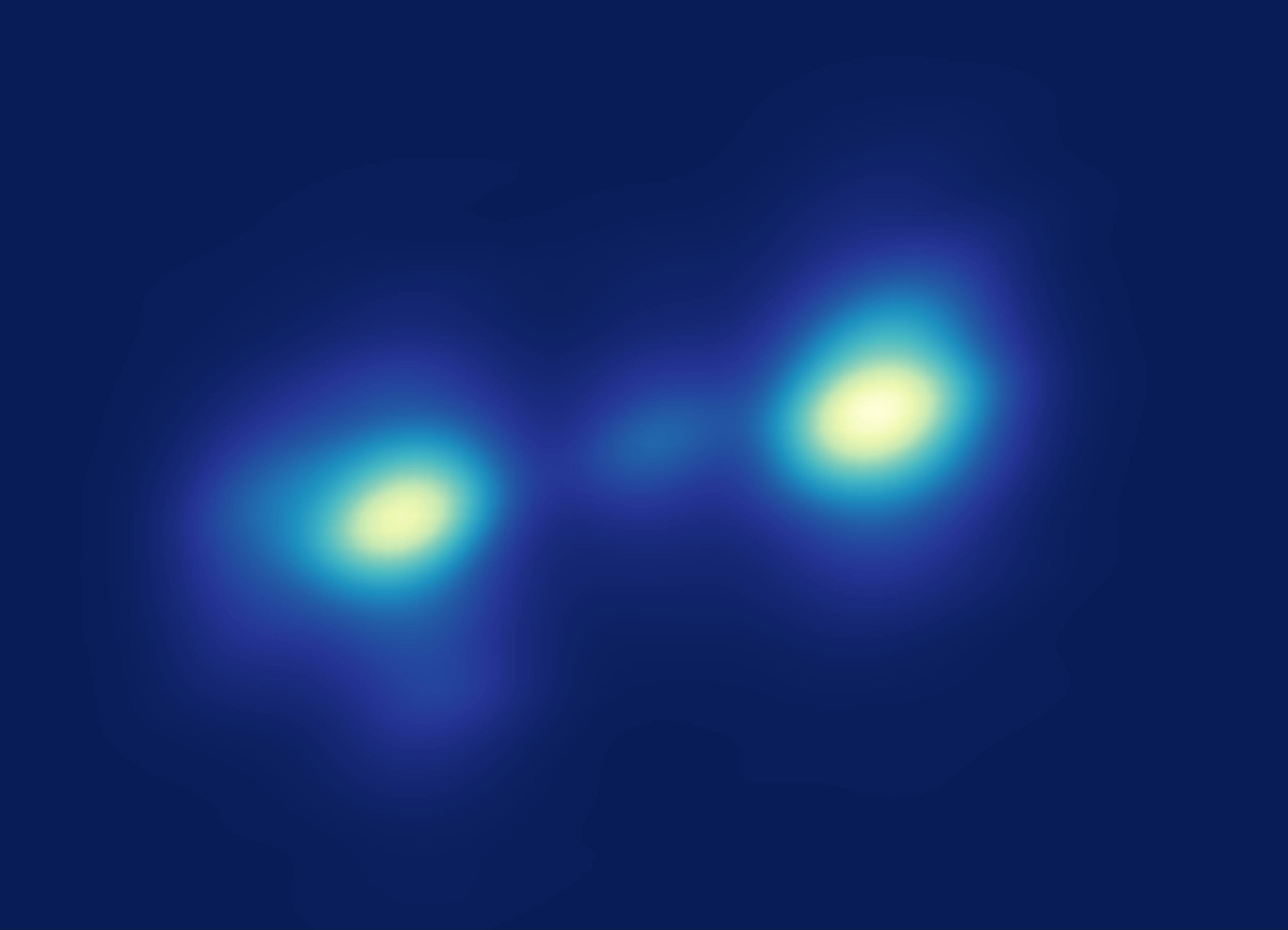
- **unique IBD-like** interaction on **Cu** [E(threshold): **~1.176 MeV**]— **unique in the Universe**
  - low threshold ⊕ high natural-abundance ⊕ high-ish cross-section ⊕ BG-resilience**?** (even coincidence?)
  - CC interaction: **anti-ν_e** + **^{63}Cu** → **e+** + ^{63}Ni + [if ^{63}Ni was excited: **γ**(87keV; τ≈1.67μs)]
- **possible applications:** reactor as **team-beam (demo)**
  - direct **reactor-fuel monitoring**? — remote **fuel-storage monitoring**?
  - **^{40}K geoneutrino exploration?** (discovery?) — extremely challenging

Reactor Flux Prediction (Kopeikin *et al.*)





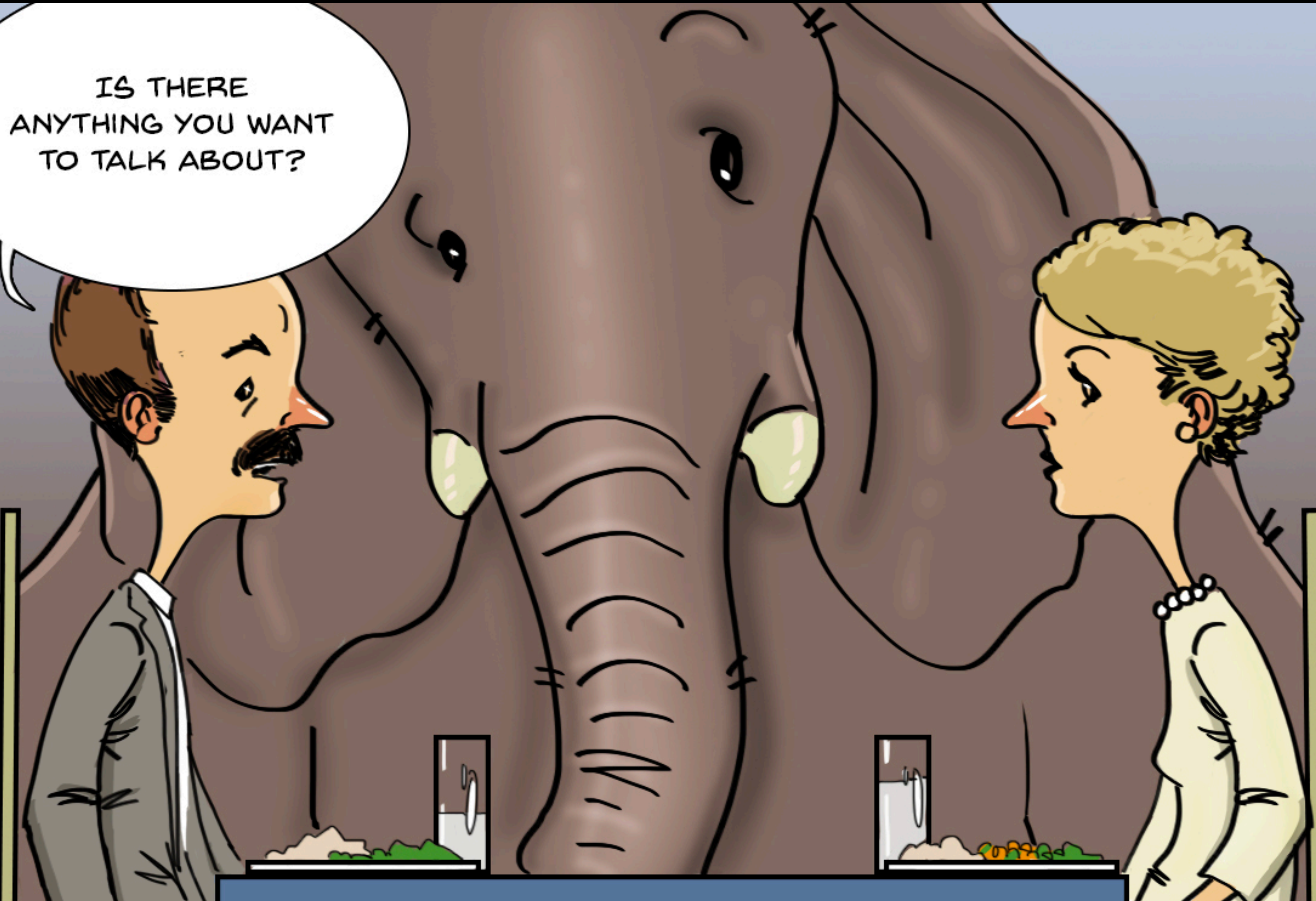
IBD@Cu: net increase of events — to be demonstrated
- **detection feasibility**
- **cross-section** measurement — relative to IBD@p
- branching-ratio for **Cu* (tagging)** versus Cu



e+ PID: mainly an annihilation pattern (i.e. negligible kinetic energy) — **the same as in LPET!**

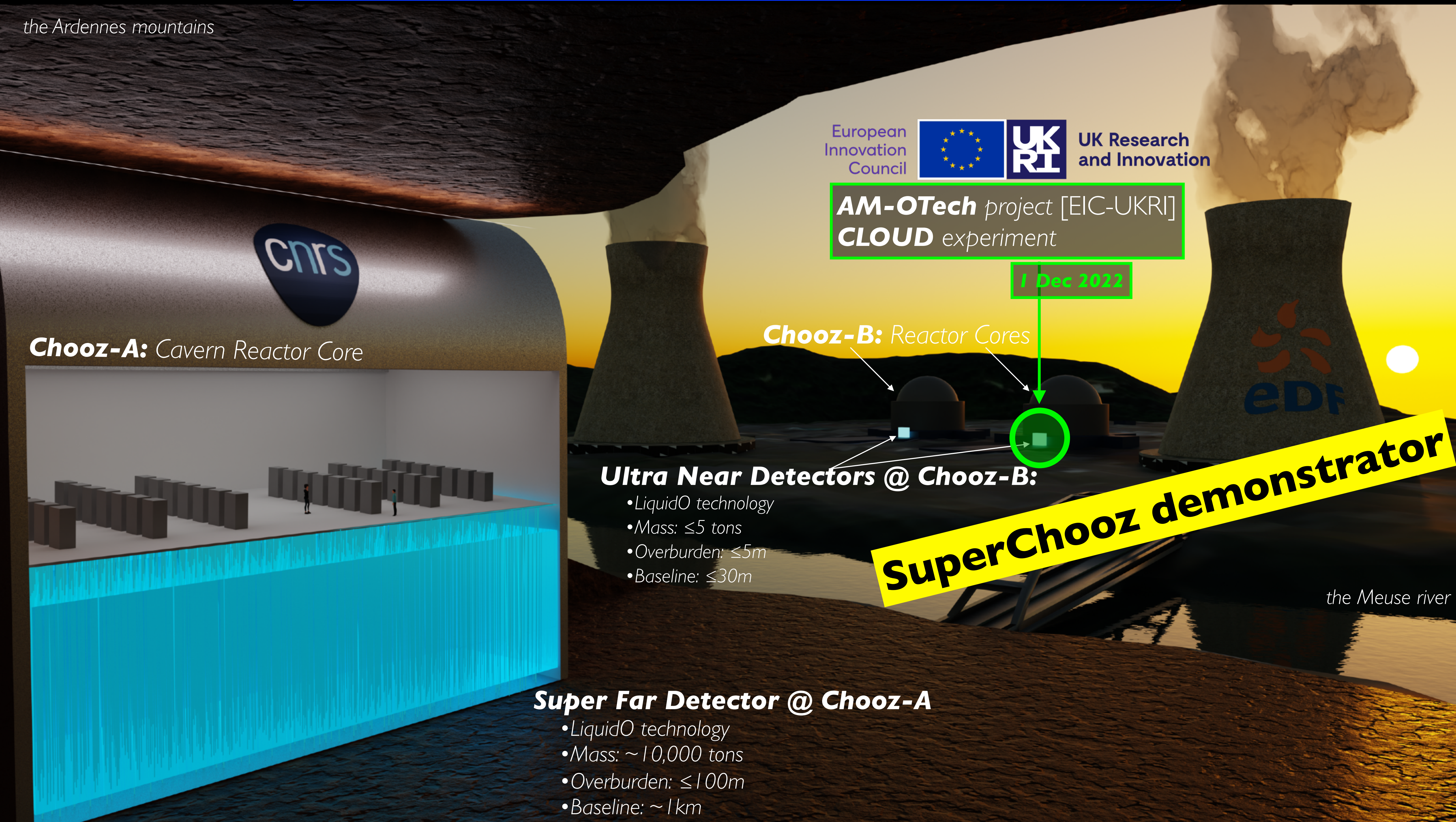
CLOUD

a long story short…


IS THERE ANYTHING YOU WANT TO TALK ABOUT?

SuperChooz exploration…

flagship neutrino oscillation experiment in Europe?



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

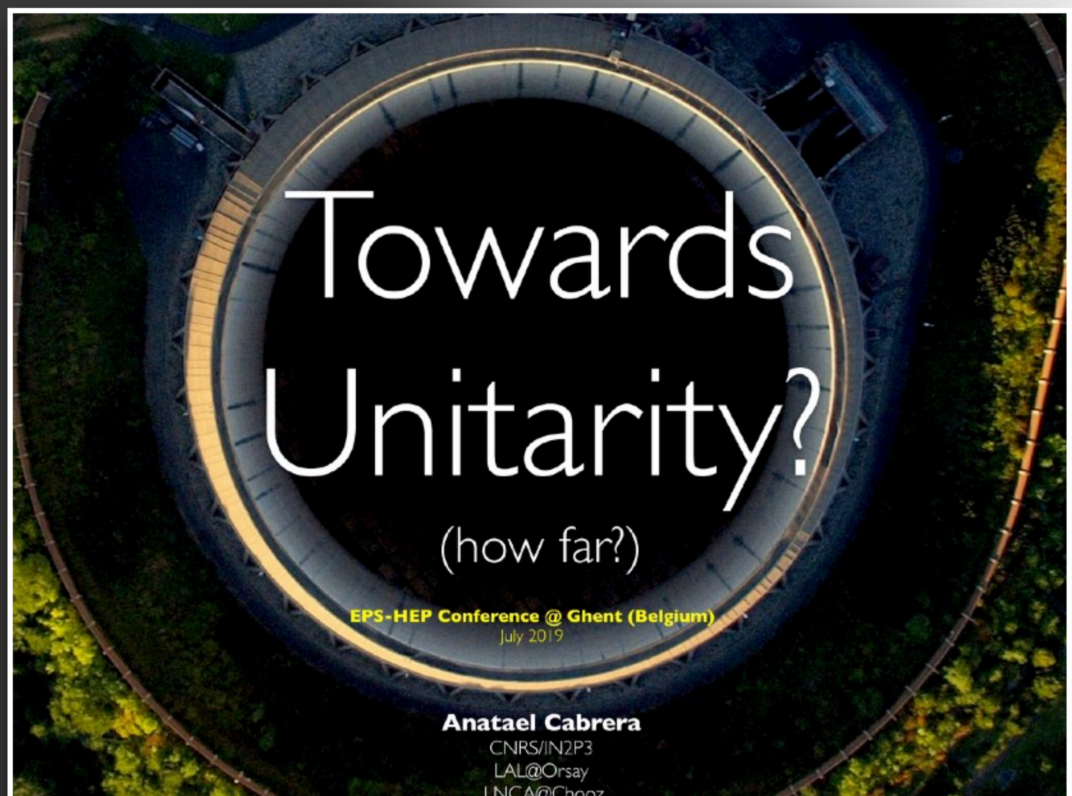
EP Seminar

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/577856/contributions/3421609/

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

https://zenodo.org/record/7504162

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

exploring since 2018…

- **CLOUD** demonstrator for **LiquidO's (anti)neutrino detection capabilities** — **a revolution?**
  - byproduct to **new reactor monitoring capability**? [a dream since '70s]
- **CLOUD-I:** approved & funded **[AM-OTech]** **plan: data by 2025**
  - **most precise absolute CC-antineutrino flux** — **new physics?**
  - possible **first NC-(anti)neutrino flux** — **new physics?**

SuperChooz demonstrator

- **CLOUD-II:** under feasibility study (→new **indium**-loaded opaque scintillator)
  - (first) **absolute CC-neutrino flux reactor** — **new physics?**
  - **measure solar-pp (≥5σ)** in a tiny detector almost on the surface?⟹ **a major breakthrough**
    - [backup]⟹ explore **new physics?**

SuperChooz demonstrator

- **CLOUD-III:** under feasibility study (→new **copper**-loaded opaque scintillator)
  - probe **reactor flux at low energies?** — **surprises?** [first time ever below 1.8MeV]
  - demonstration for **^{40}K detection methodology** — **a discovery one day?**

a vaster future of reactor (anti)neutrinos ahead?

conclusions…

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

our collaboration…

European Innovation Council

UK Research and Innovation

C L O U D

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]