European Innovation Council

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C L O U D

experiment's first release

"Neutrino Telescopes" Conference
25 October 2023 — Venezia (Italia)

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

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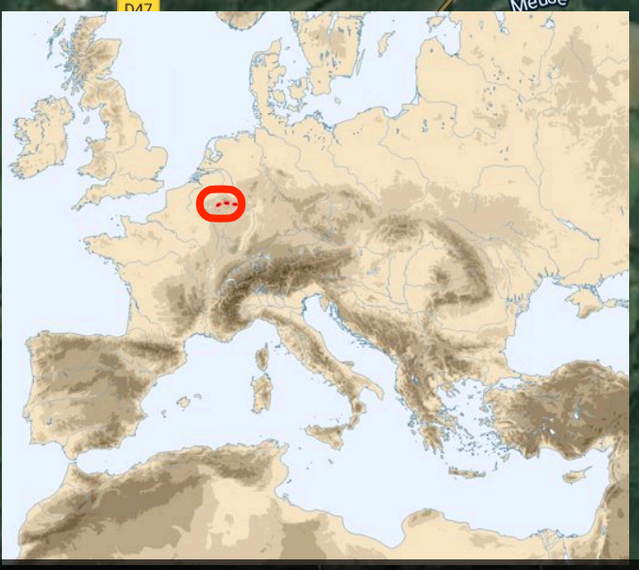
cnrs université PARIS-SACLAY FACULTÉ DES SCIENCES D'ORSAY
Université de Paris

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

one of the most powerful **anti-matter generators**



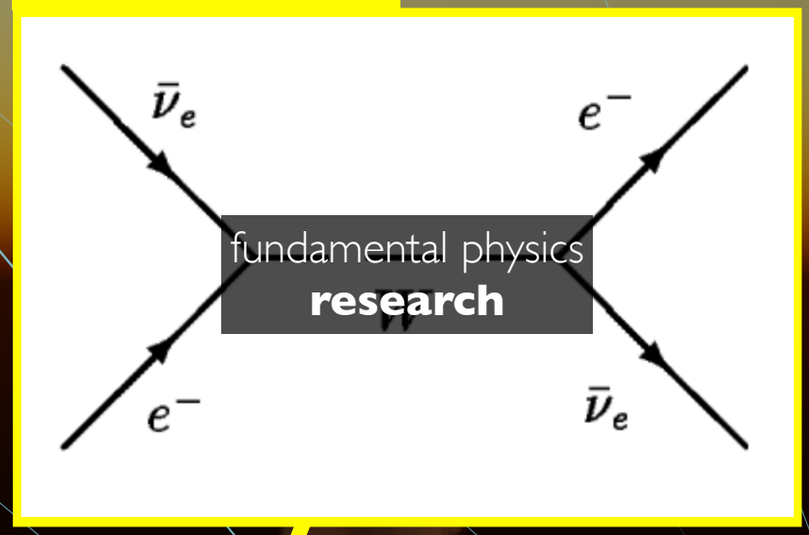
Europe's most powerful reactor site…

3rd generation of reactor neutrino experiments @ Chooz

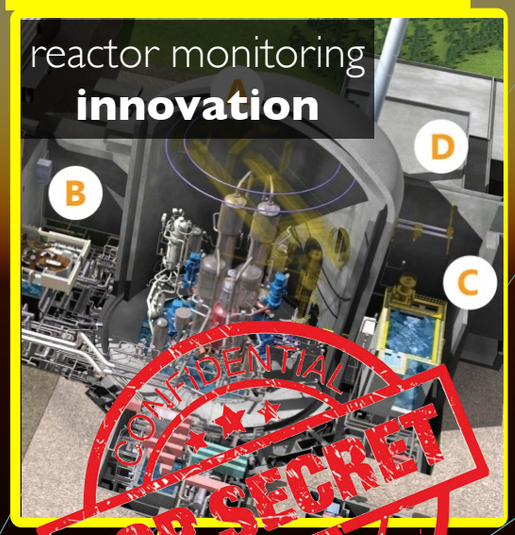
les Ardennes
(France-Belgium)

CLOUD vs AntiMatter-OTech…

CLOUD's view…



AM-OTech's view…



antineutrino *(neutrino?):* ***~10²¹ ν/s per core***

Chooz-B: *Nuclear Reactor Cores*

the Ardennes mountains

the Meuse river

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*

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

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

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…*

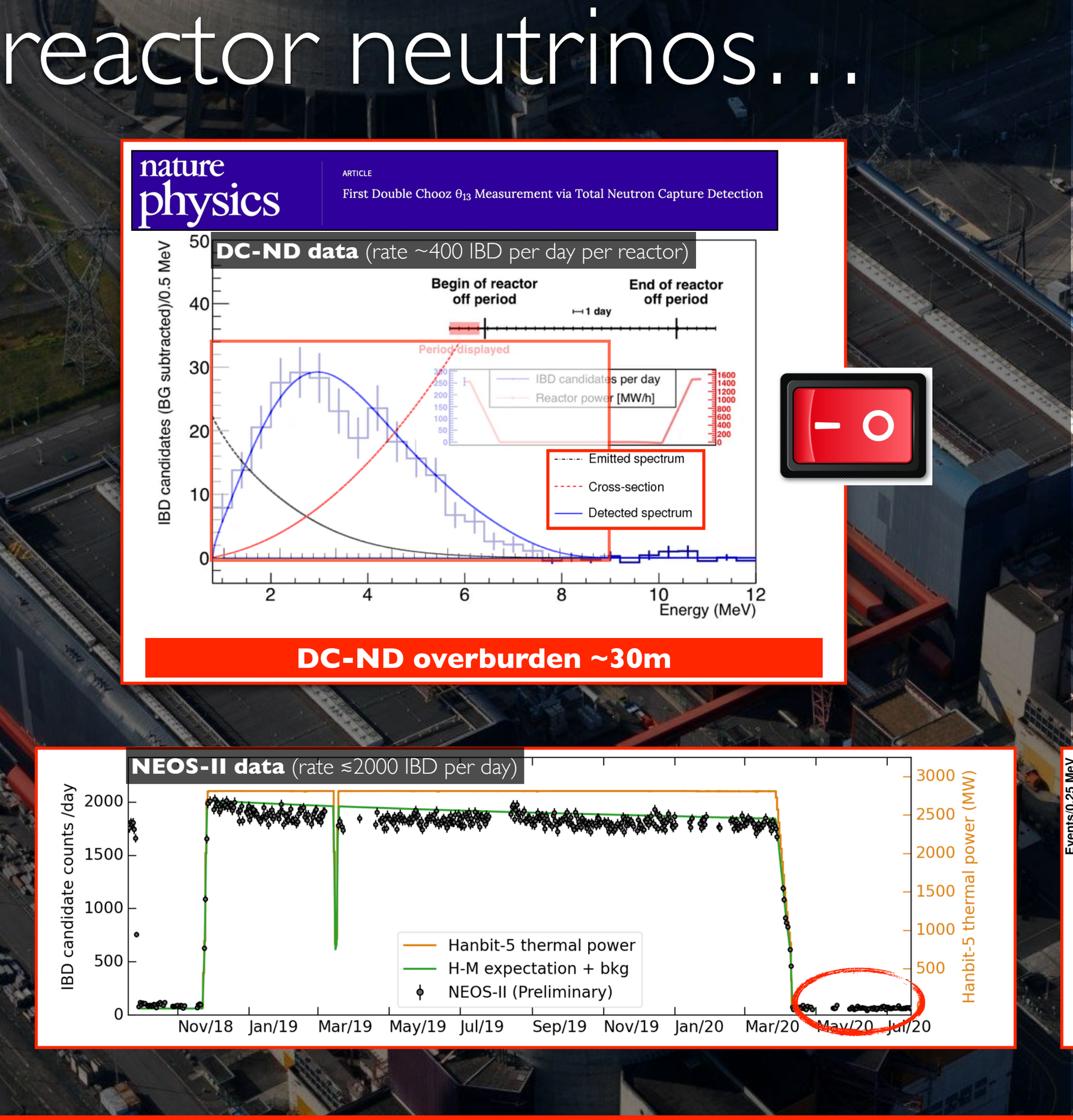
on the shoulders of giants…

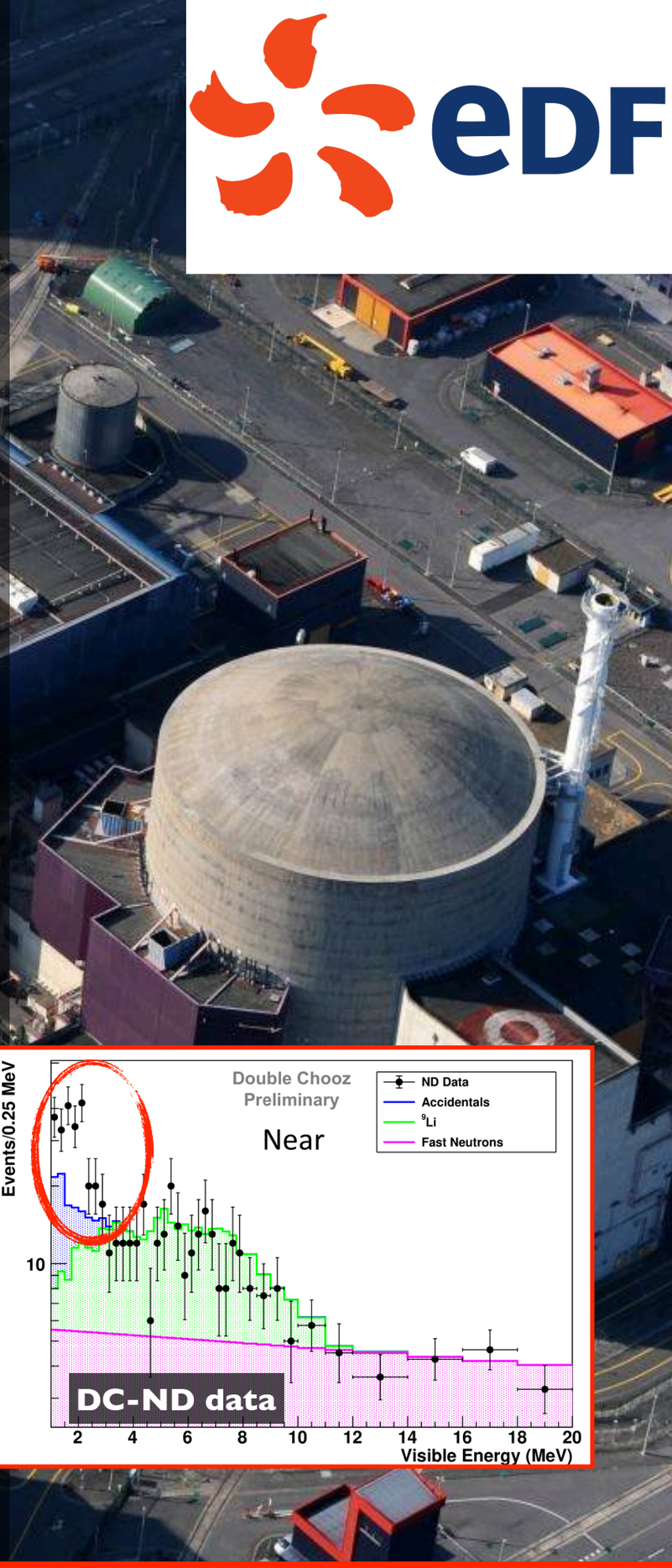
breakthroughs with reactor antineutrinos…

- [**1950s**; L≈10m] **electron-antineutrino 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**
  - corroborate **Kamiokande's oscillation $\nu_\mu \rightarrow \nu_T$ dominant transition** [Nobel Prize 2015]
- [**2000s**; L≈180km] **KamLAND favoured solar "LMA"** — **SNO** complementary [Nobel Prize 2015]
- [**2010s**; L≈1km] **Daya Bay**, **Double Chooz**, **RENO**: observe **predicted θ13** ⟹ consolidation!!
  - **Double Chooz sub-team:** rate prediction bias→new physics vs prediction? [biased prediction]
  - **Double Chooz *et al.***: **spectral distortion** — contradiction to **Bugey3** [what's wrong?]
- [**2020s**; L≈50km] **JUNO** will measure **θ12**, **$|\delta m^2|$**, **$|\Delta m^2|$** to ≤1% — first "bi-oscillation energy spectrum"
  - **mass ordering** (≥5σ) need **synergy** with accelerator experiments [**backup**]
- [≥**2030s**; L≈1km] **SuperChooz** will measure **θ13-$|\Delta m^2|$** & **θ12-$|\delta m^2|$** to ≤1% — exploring more!

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

reactor neutrinos…





nature physics

ARTICLE

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

DC-ND overburden ~30m

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

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**
  - no other interactions — few attempts to "**electron elastic scattering**" (past)

- **flux: ~10^{20} antineutrino per second per GW**(thermal)
  - **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 [a la 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?**

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

reactor (anti)neutrino future…(?)

future: discoveries?

today's BG: *standard neutrino oscillation*

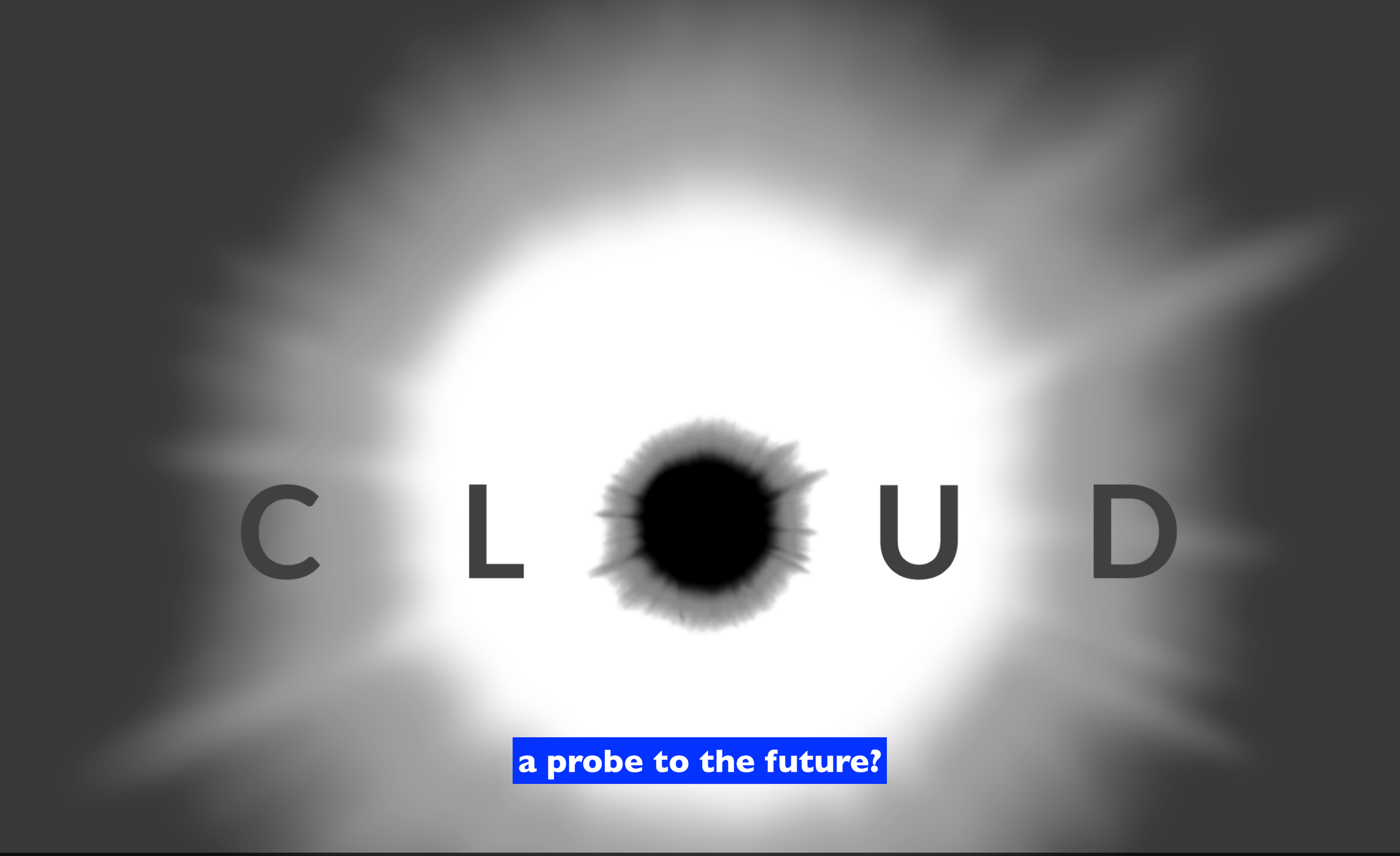
neutrino⊕weak-interaction remains **bizarre** (Majorana, etc)…

- 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 (especially for **ES@e**) — radiopurity, etc.
- **neutrino-based innovation?** → exploring in **AntiMatter-OTech** [**CONFIDENTIAL**]

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



the experiment…

Chooz-B Power Station
- facility: EDF CNPE
- location: Chooz (France)
- reactor cores: 2x PWR AREVA-N4
- thermal power: 8.4GW (total)

Double Chooz
Near Detector

LNCA-Hall (CNRS)

Ultra Near Detector (UND) sites

OFF

ON

due to global warm→ more frequent reactor-OFF (2022: several months)

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

Europe's best reactor-ν site…

Double Chooz
Far Detector

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**

cross-section view

side-section view

ID Physics Volume: [5,10]tons

LiquidO-Tracker (or inner-detector) [**≤10tons fiducial**]
- opaque scintillator — 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**]
- transparent scintillator (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*

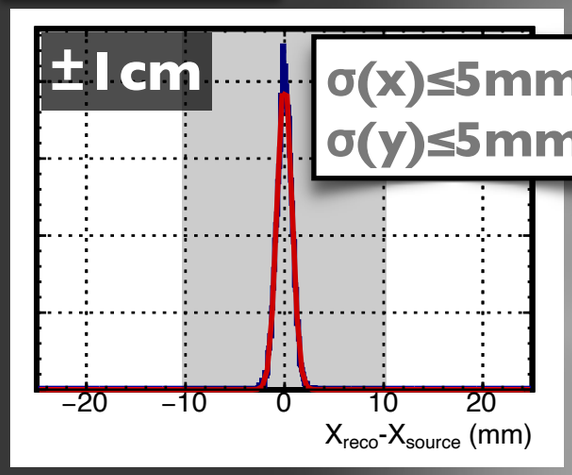
CLOUD is powered by...

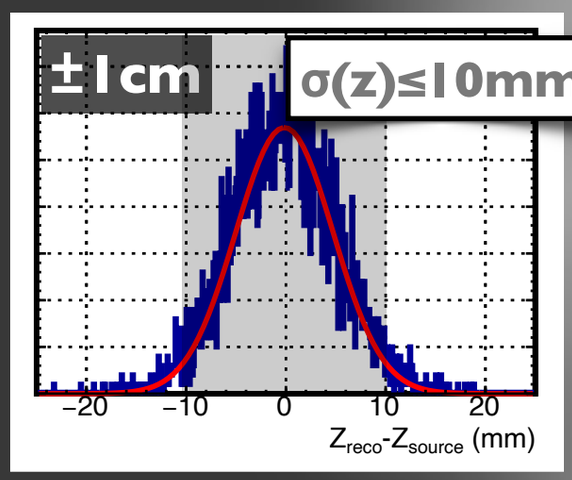
L I Q U I D

LiquidO ↔ stochastic light confinement

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

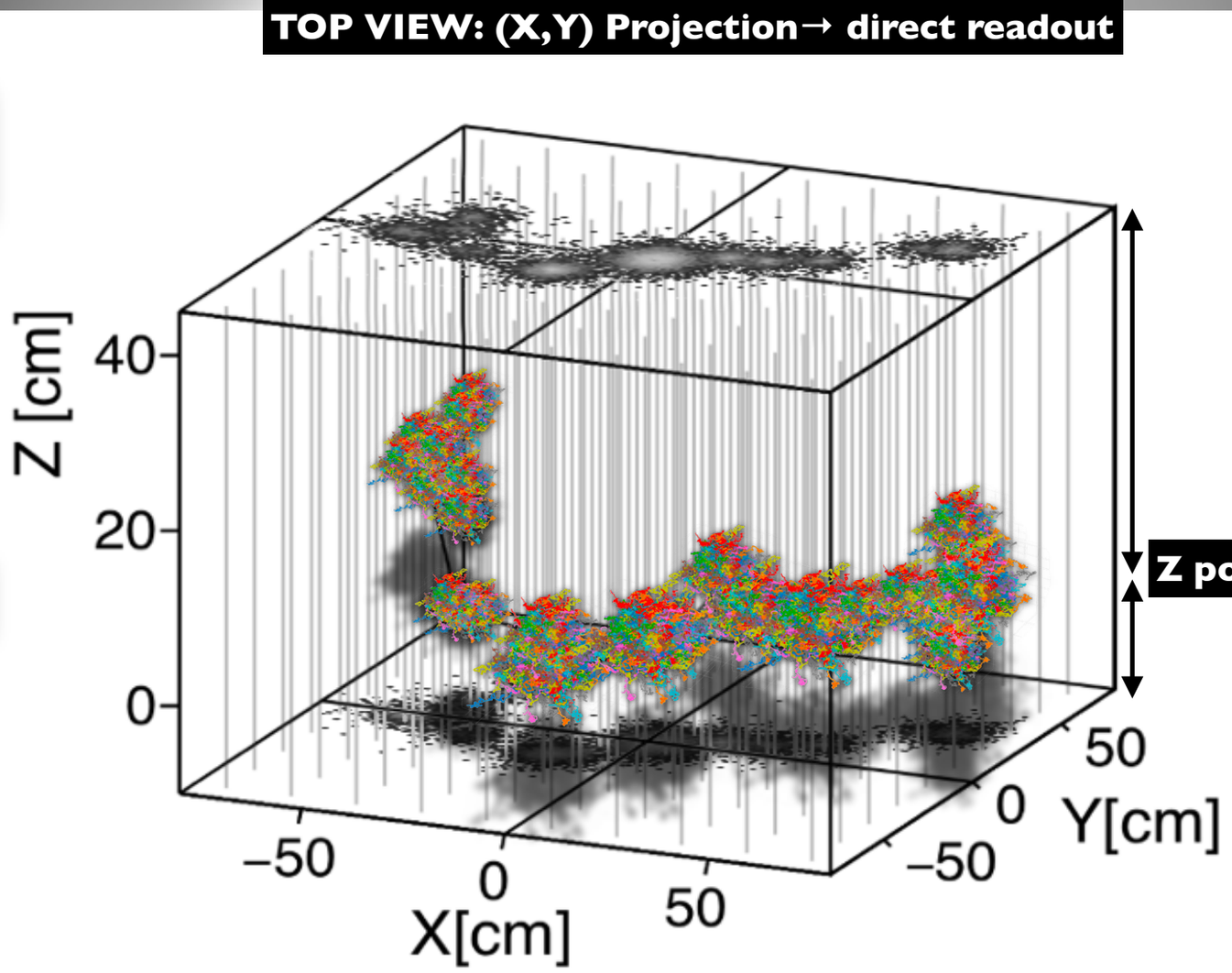
~1.0MeV



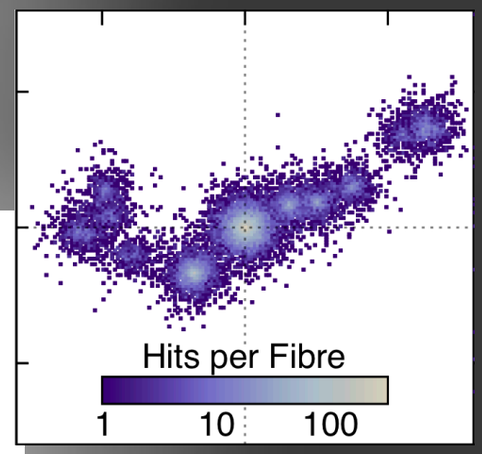


Vanilla LiquidO: 1D lattice (fibres along Z-axis only)

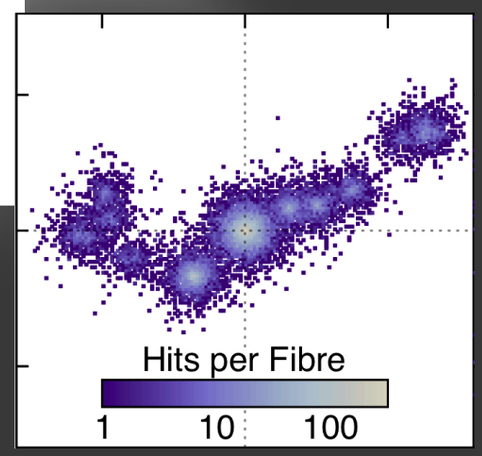
TOP VIEW: (X,Y) Projection→ direct readout



Z position: Δt (time difference)

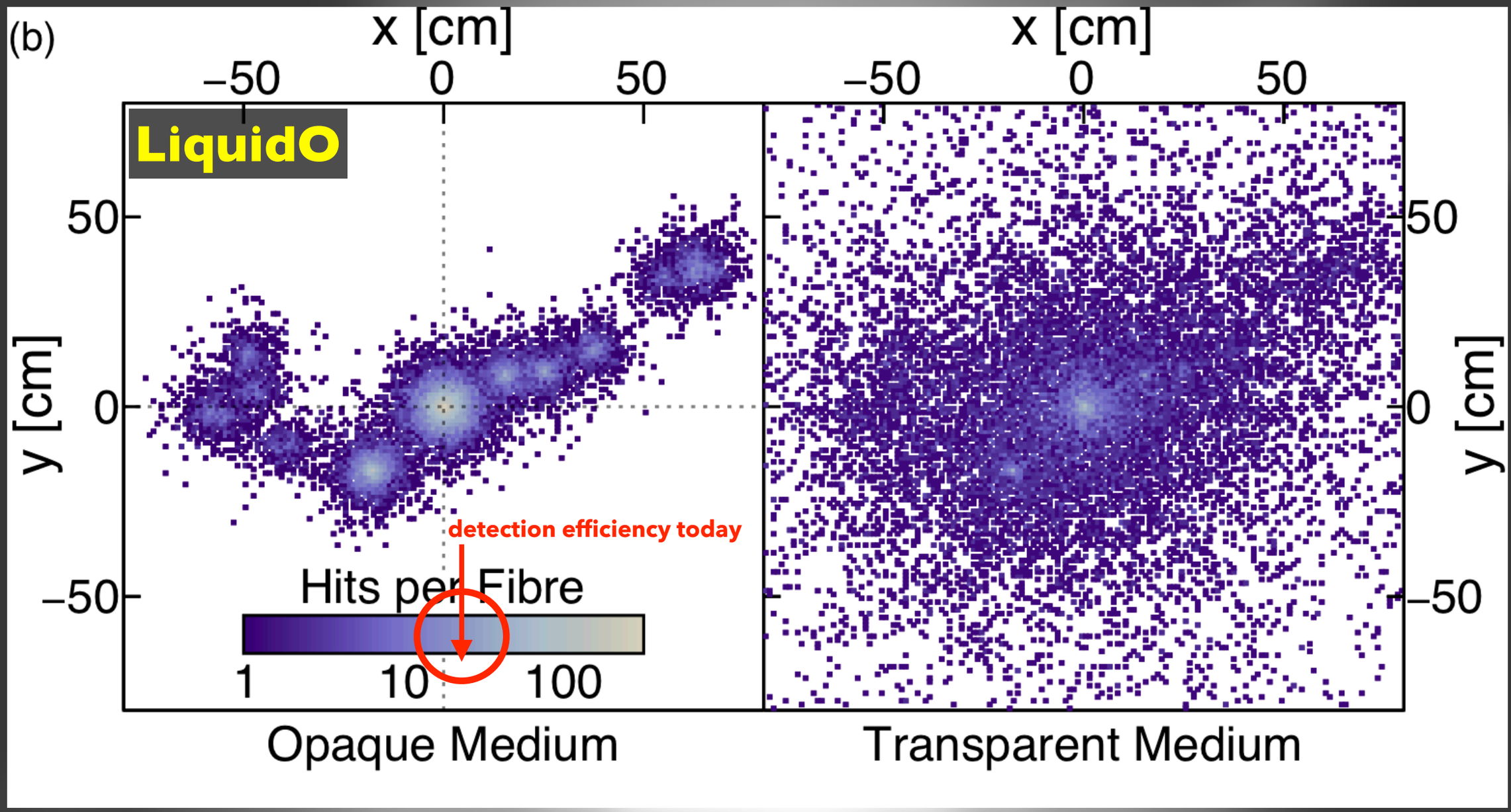


BOTTOM VIEW: (X,Y) Projection→ direct readout



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

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

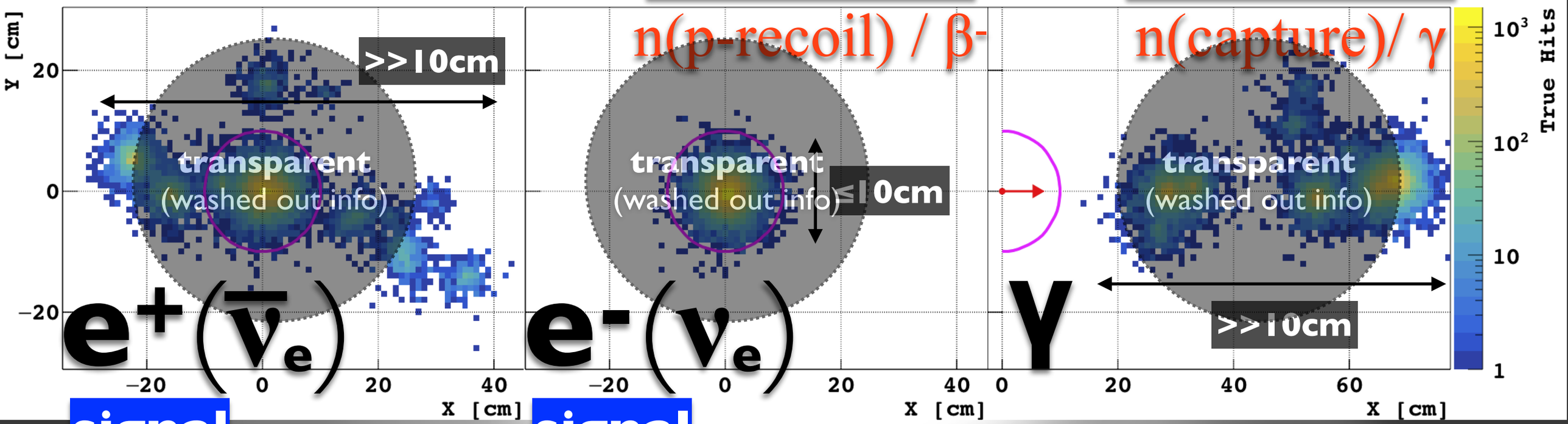


opacity implies neat images…

unprecedented MeV imaging…

reduce overburden/shielding

~2MeV



LiquidO: stochastic confinement (NO segmentation)

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

topology's PID (no timing)…

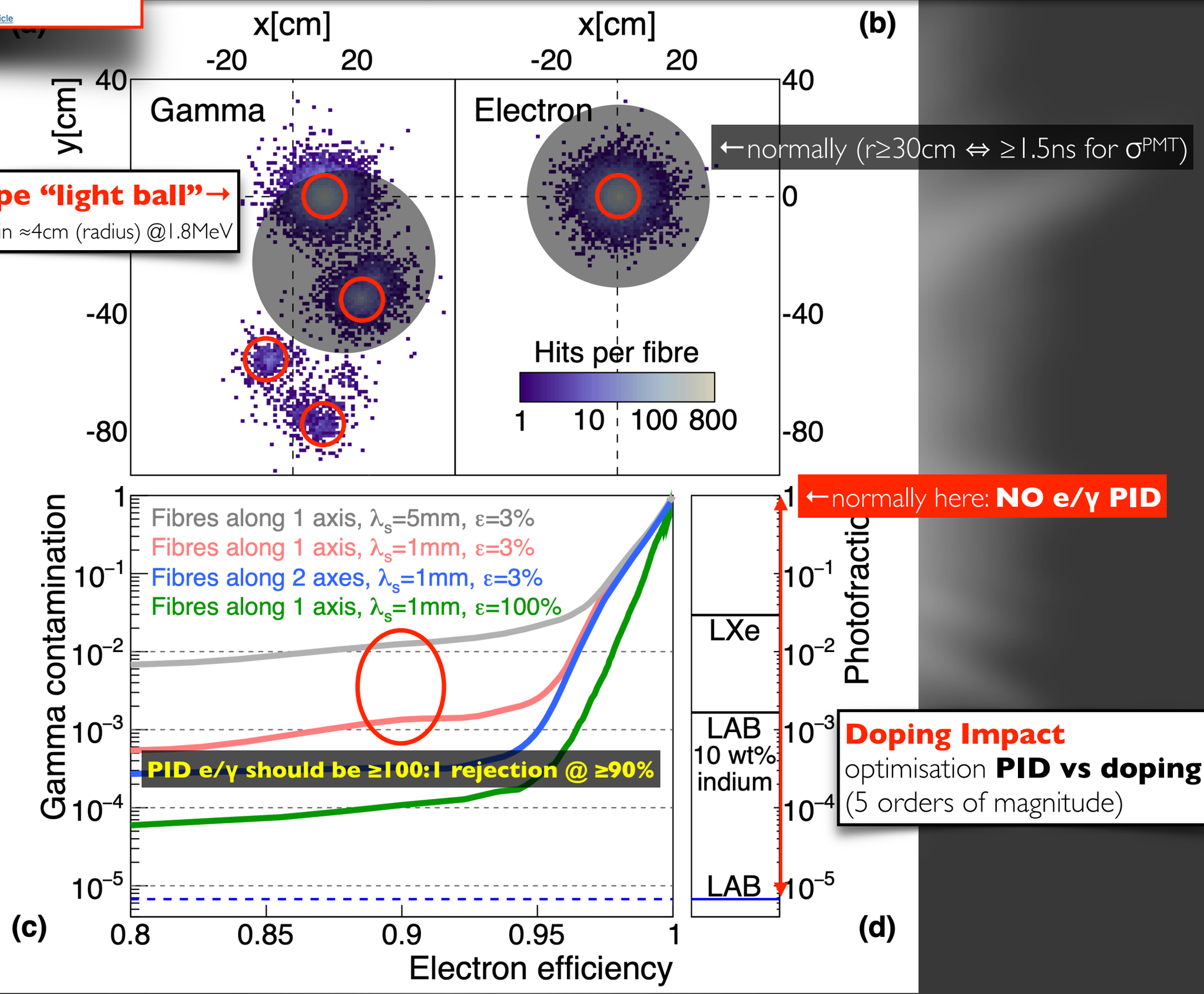
Neutrino physics with an opaque detector

LiquidO Consortium

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

LiquidO prototype "light ball"→

~80% light within ≈4cm (radius) @1.8MeV



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

←normally here: **NO e/γ PID**

Doping Impact

optimisation **PID vs doping**

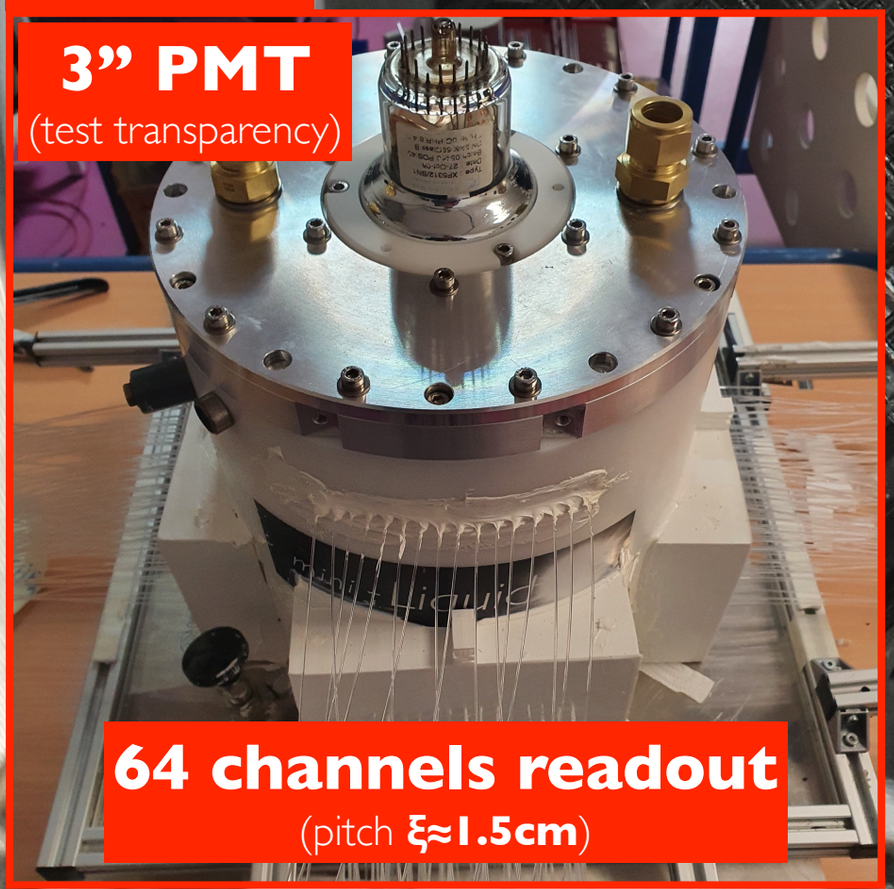
(5 orders of magnitude)

LiquidO's prototype MINI-II (upgrade)

data taking since 2021

overall view

3" PMT
(test transparency)

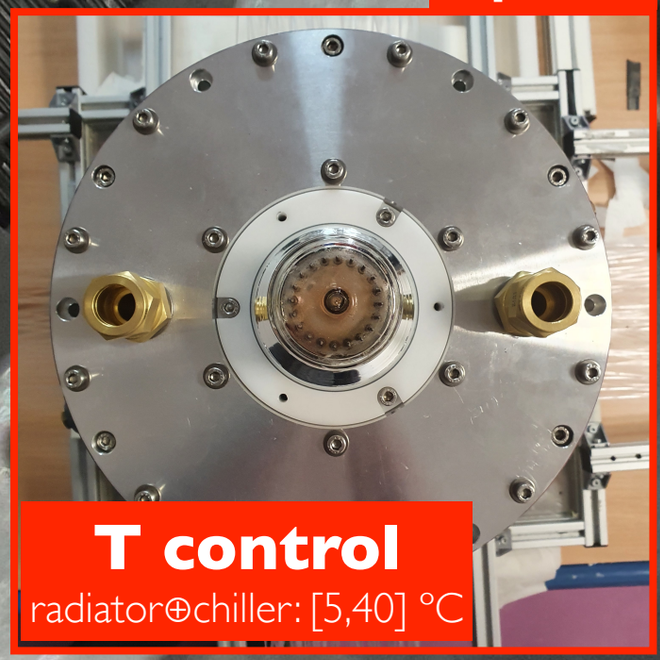


64 channels readout
(pitch **ξ≈1.5cm**)

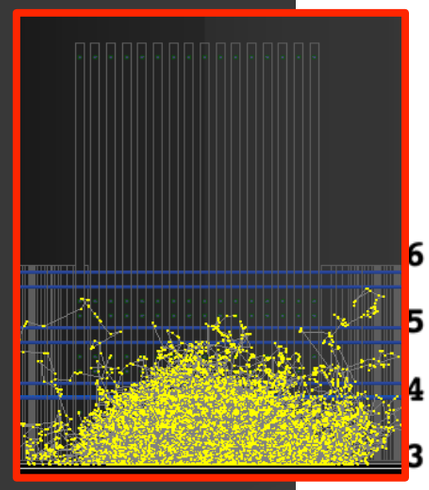
single electrons
[0.4,1.8]MeV mono-energetic

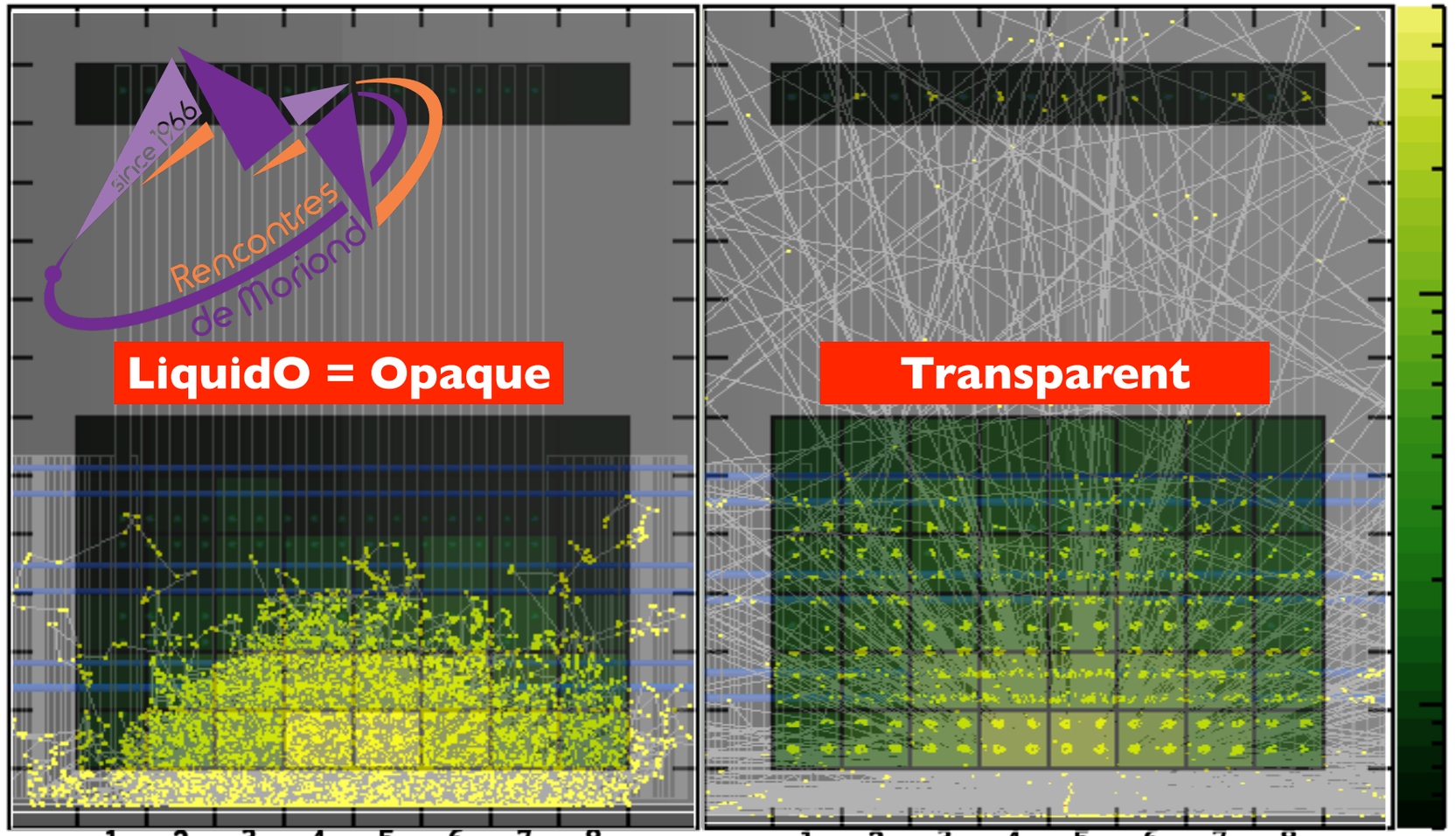
~10L multi-media
- water (transparent)
- scintillator (transparent)
- scintillator (transparent↔opaque)

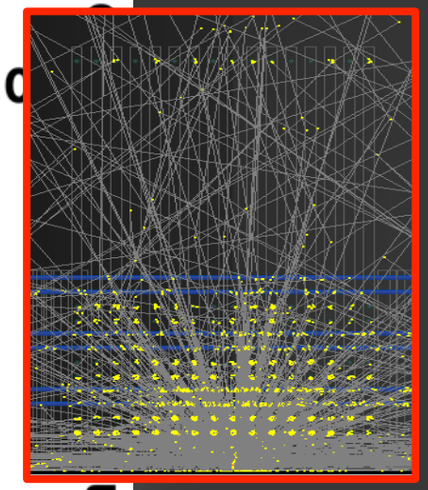
top view



T control
radiator⊕chiller: [5,40] °C



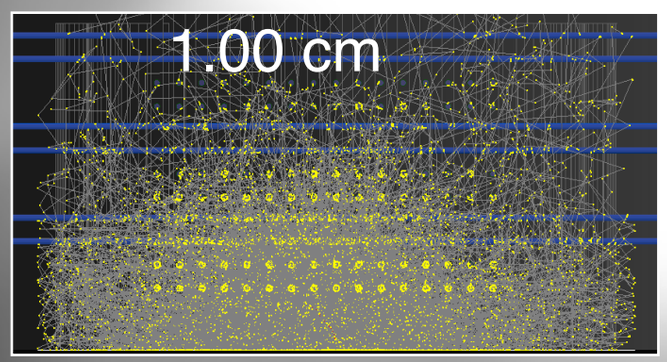


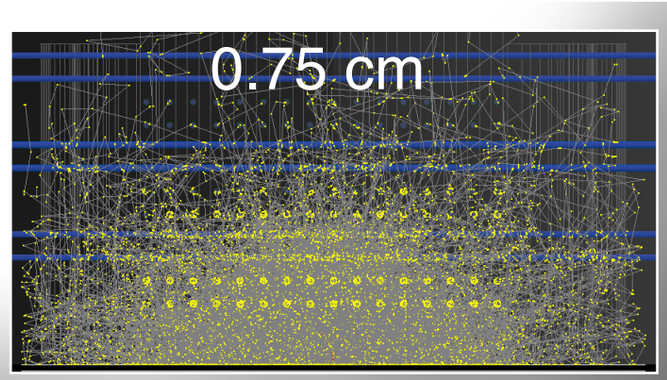


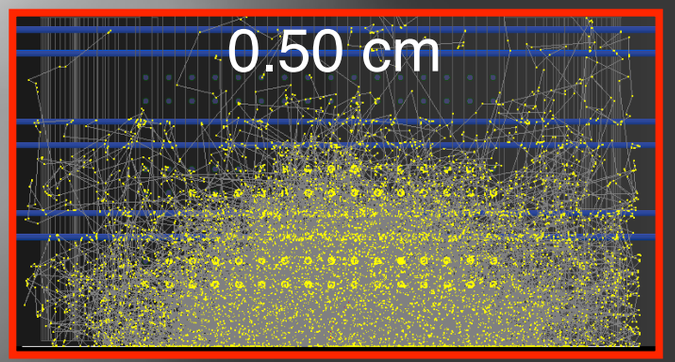
Geant4 Simulation (under tuning)

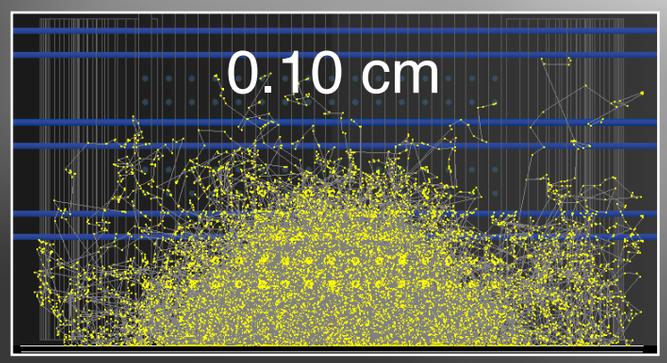
"light ball" size:

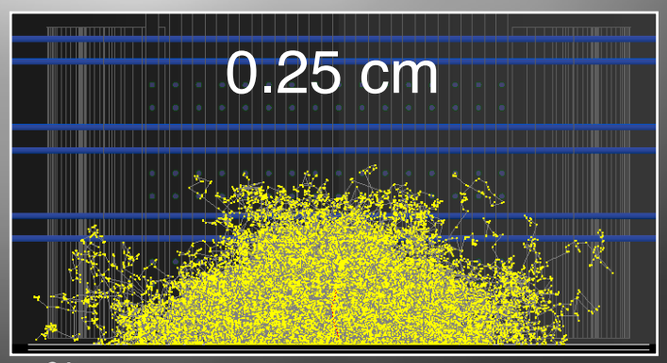
- scattering: λ_s
- # fibres
- absorption?

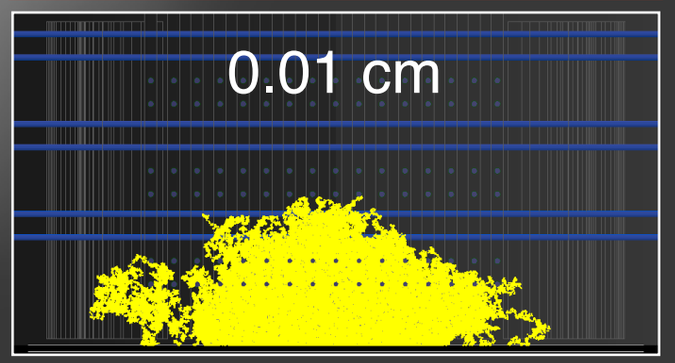


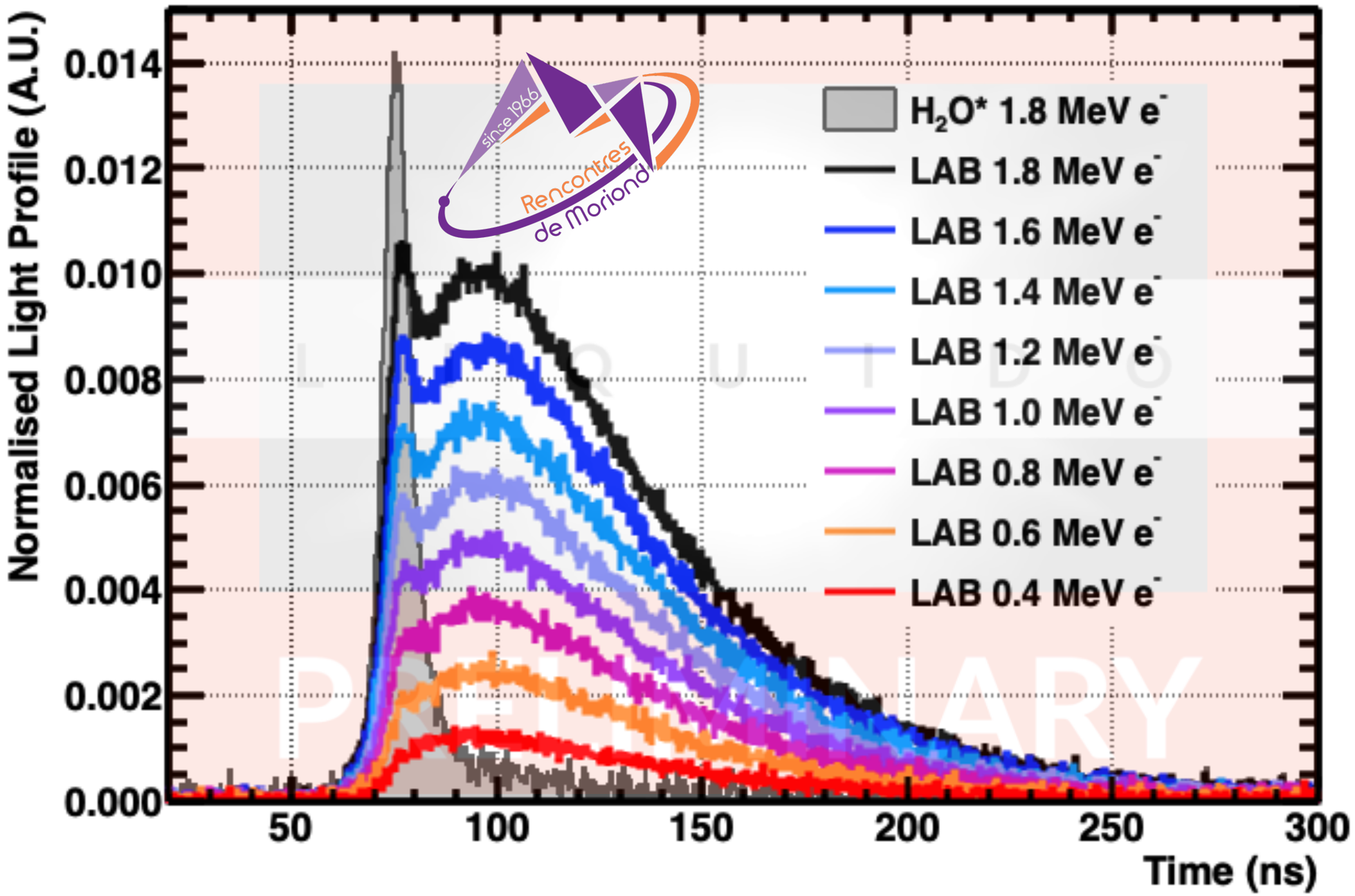












ANY light detection: Cherenkov / Scintillation / anything!
(ensure the opaque medium is granted)

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

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

C L O U D

I - II - III

CLOUD's sequence…

the power of coincidences

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

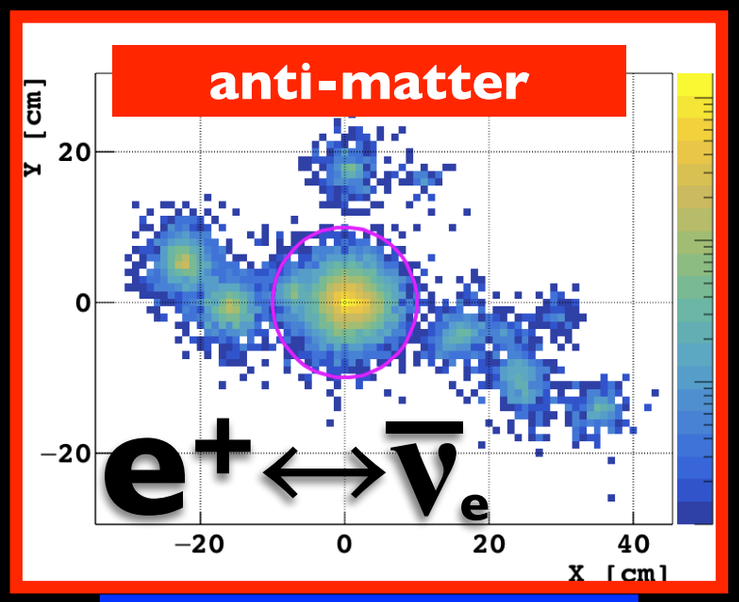
Reines et al '50s

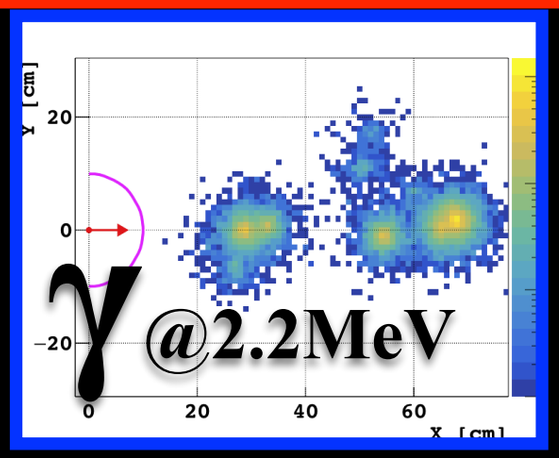
(neutrino discovery)

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

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

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





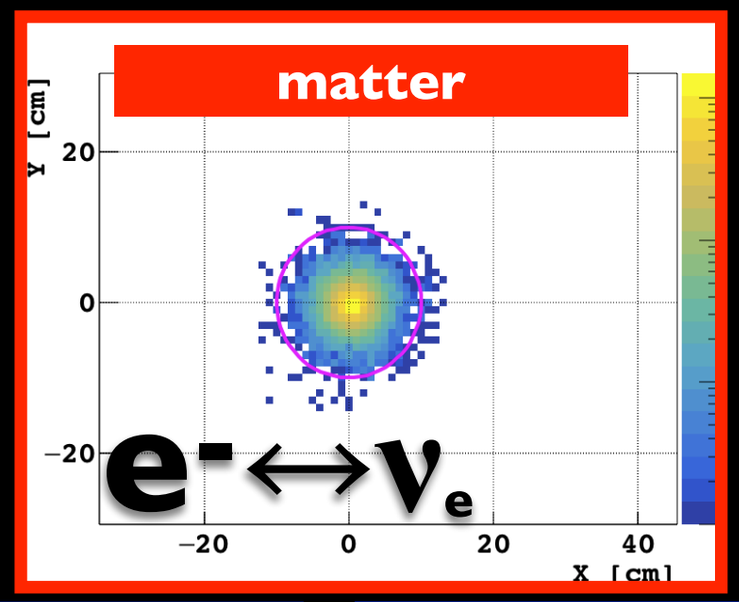
Raghavan et al '70s

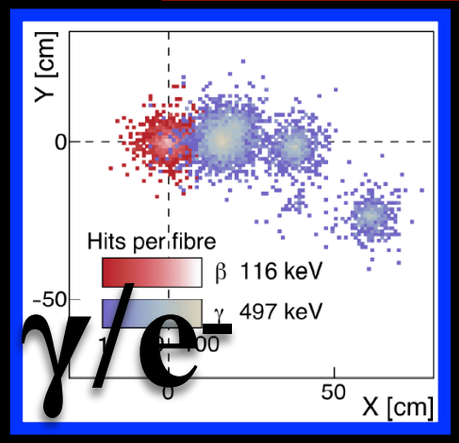
(pp solar neutrino — unobserved)

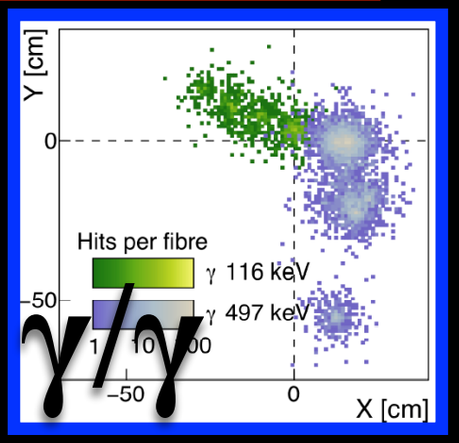
CC: $\nu_e + {}^{115}In \rightarrow e^- + \gamma + \gamma/e^-$

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

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





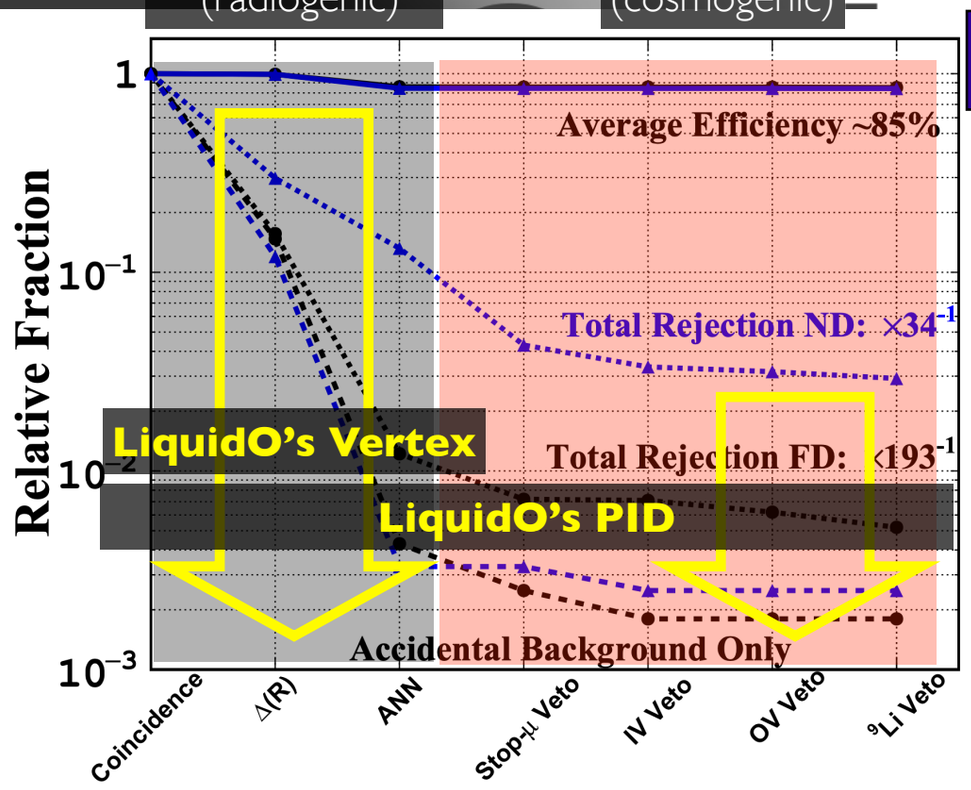


active BG rejection and control…

- 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)

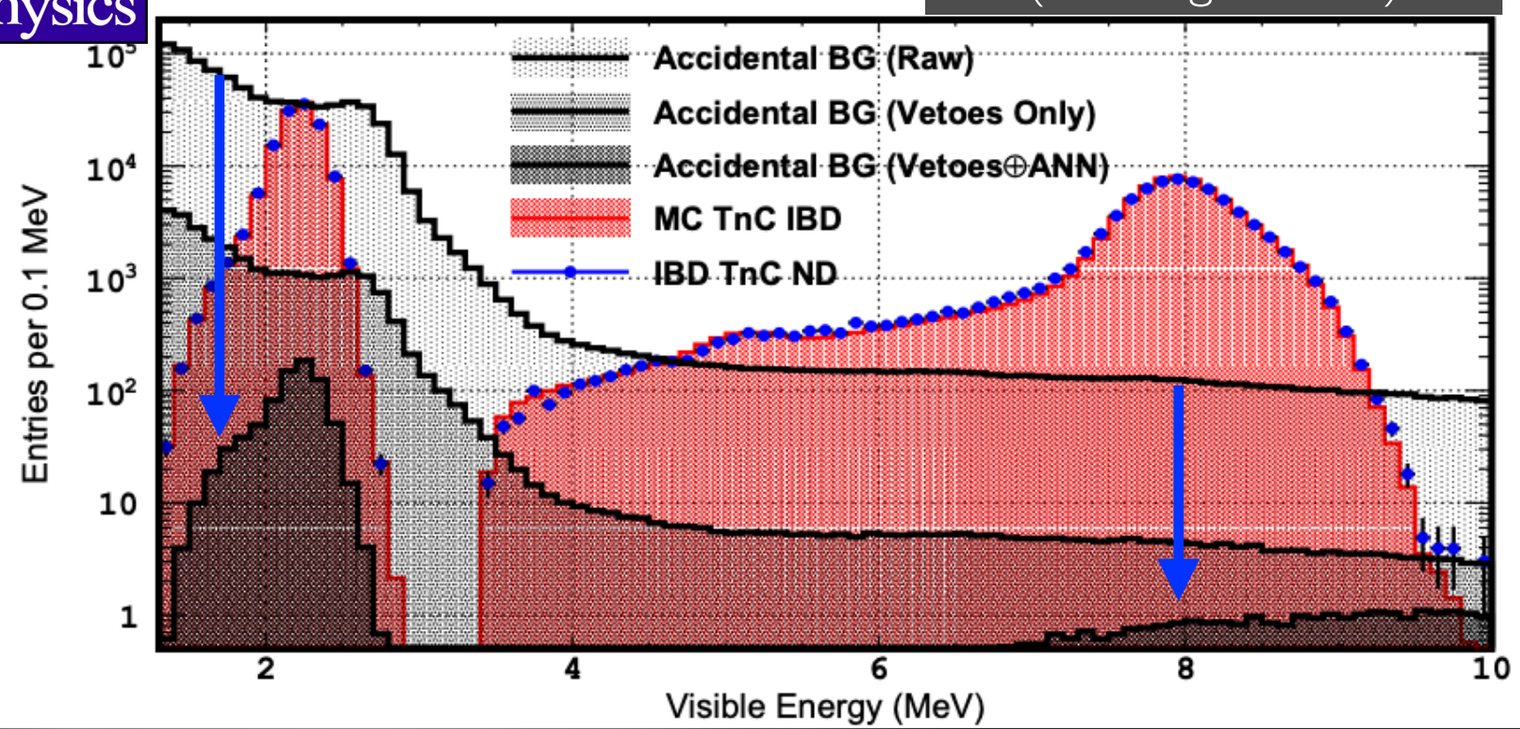
at right **place⊕time⊕energy⊕PID — many orders of magnitude**

uncorrelated (radiogenic) — **correlated** (cosmogenic)



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)

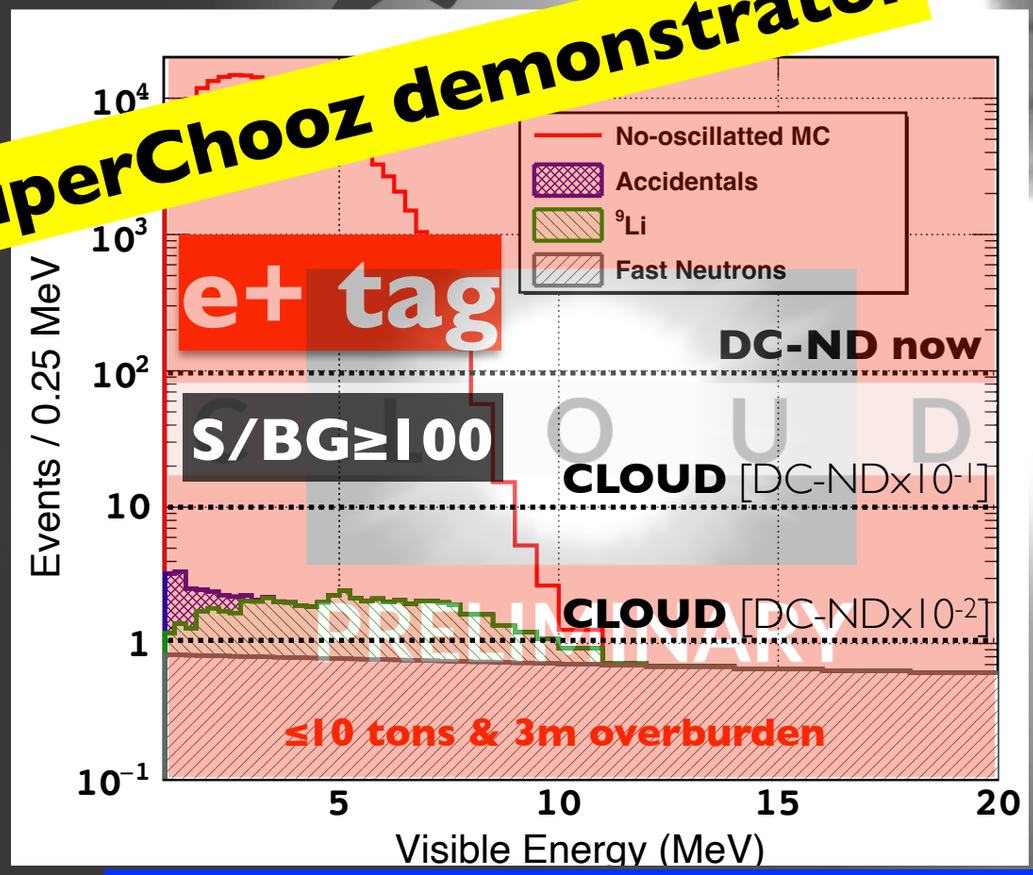
AntiMatter-OTech — synergy
SuperChooz's antineutrino golden channel **demonstration** — byproduct

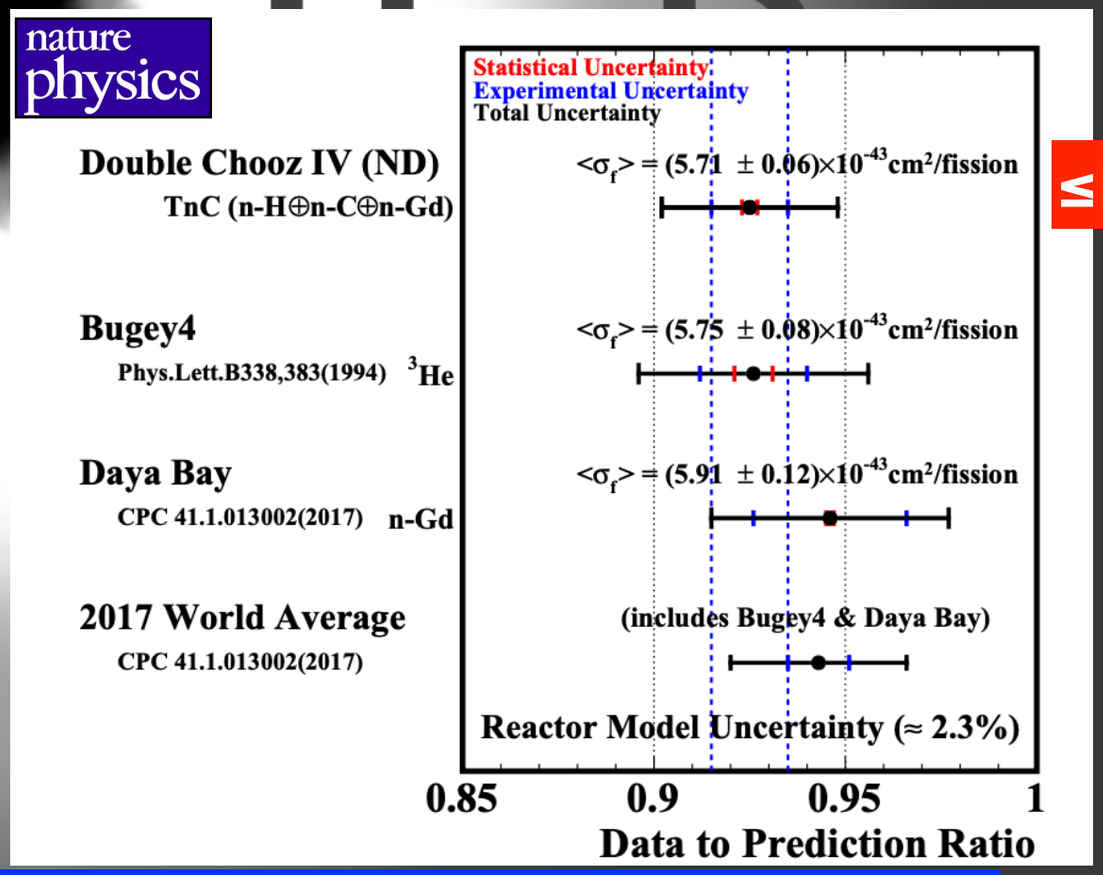
antineutrino CC & NC? (~~doping~~)...

CLOUD-I physics programme: **IBD@p**…

- **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?

SuperChooz demonstrator

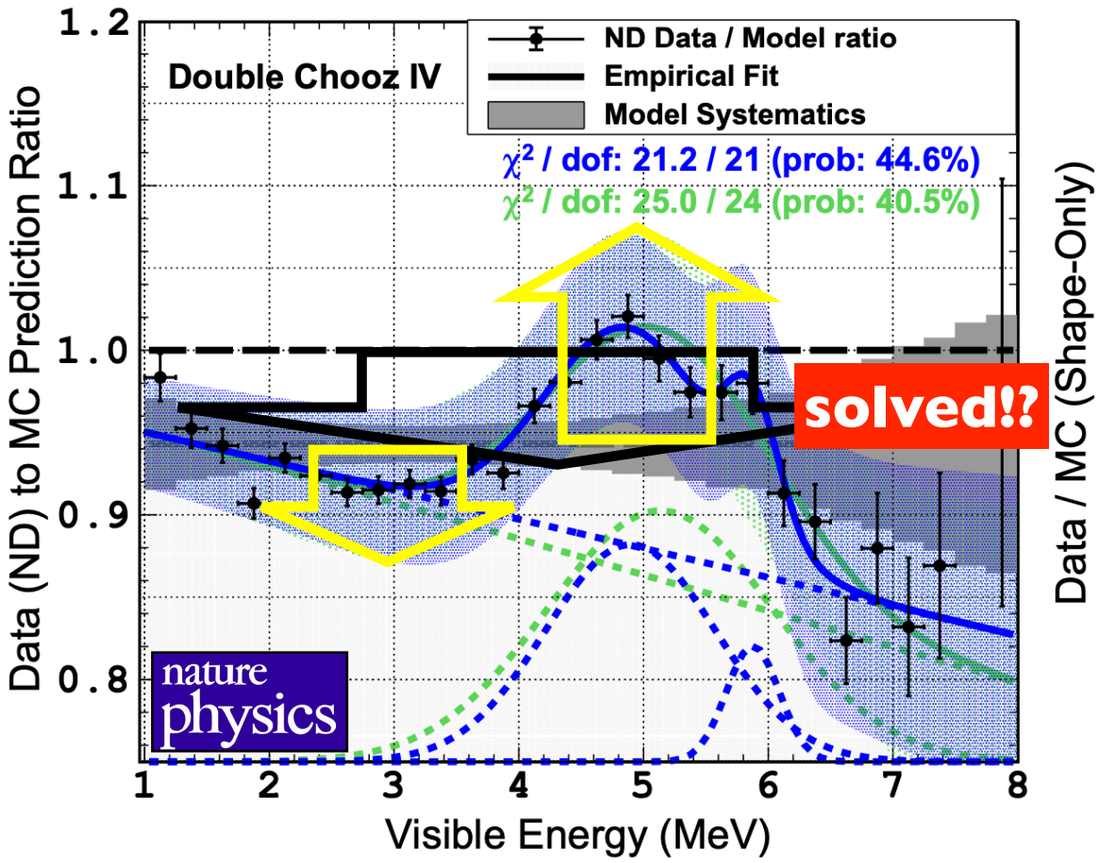


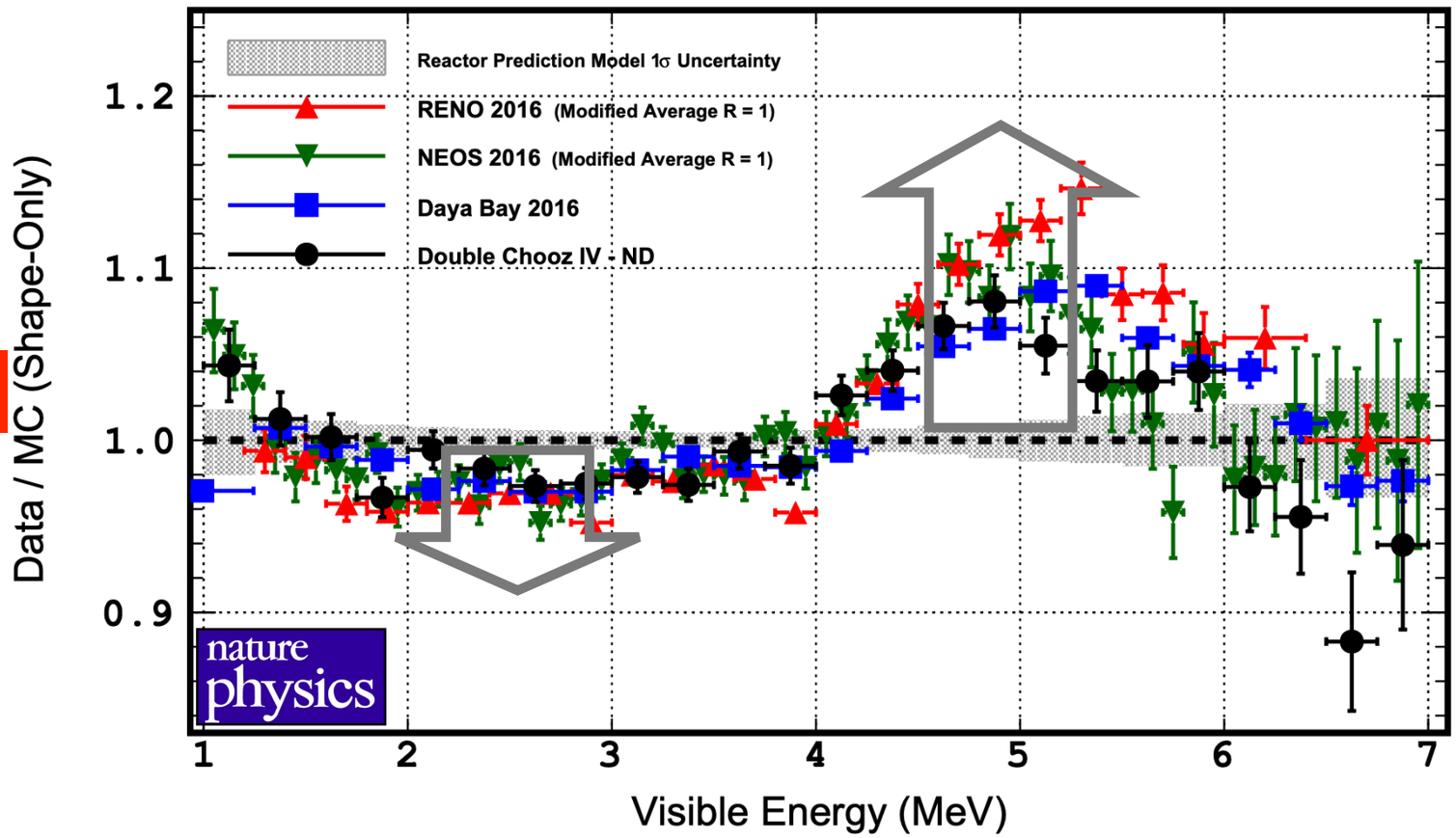


≤1%

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

all experiments consistent — except **Bugey3?!**





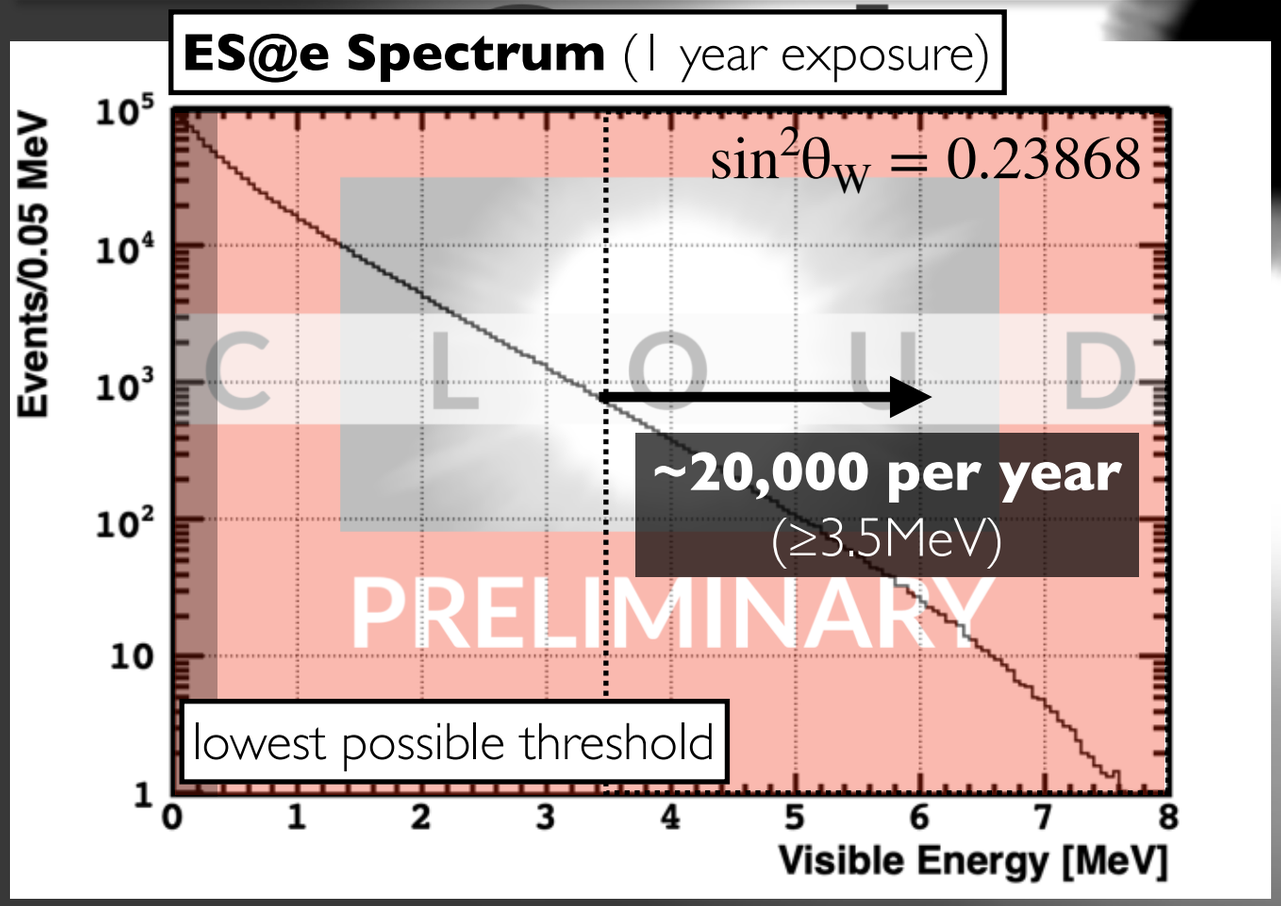
ABSOLUTE FLUX: the future of reactor-antineutrino physics

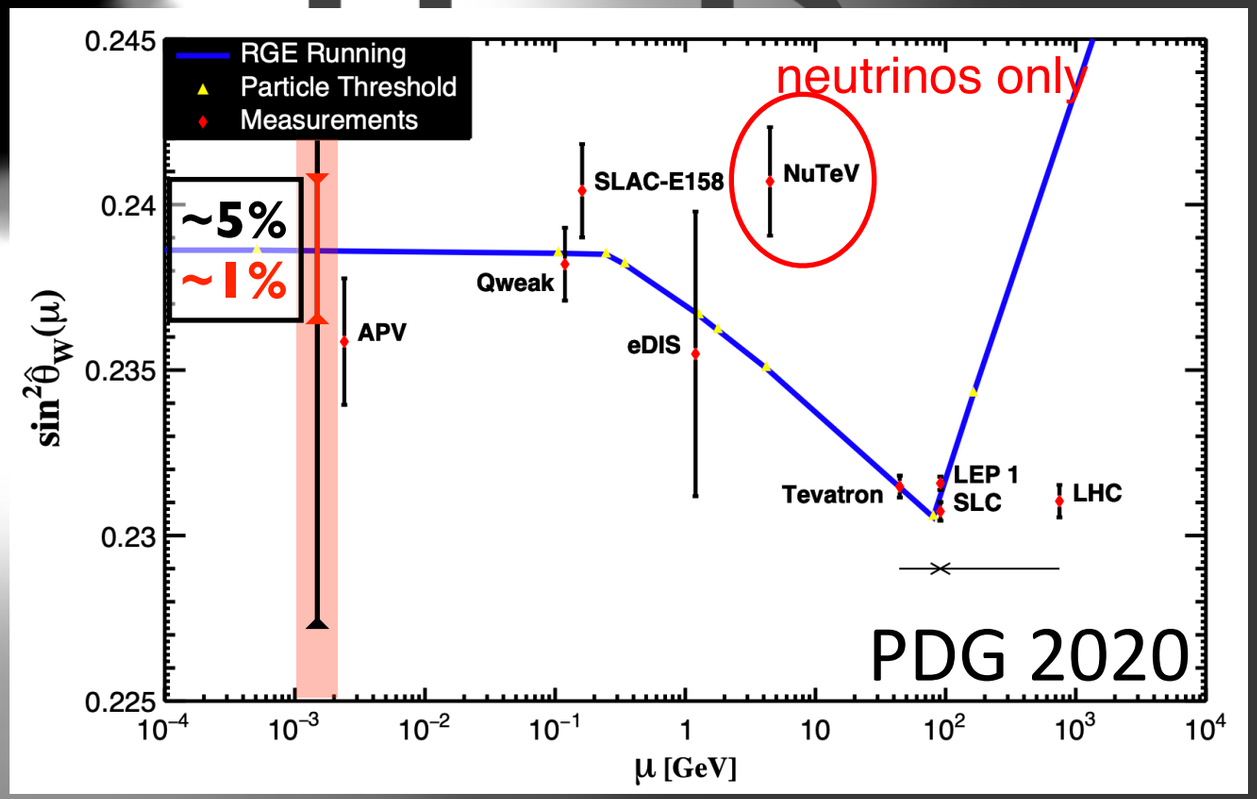
we must solve this "mess" ⟹ the reward **possible new physics!**
(if so, prediction should not use neutrino input⟹**no** new physics)

must understand flux ≤1%...

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 or use to **decompose the NC flux** component
  - PDG-2022's $\sin^2\theta_w$ **= [0.231??,0.23868]** — 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?**





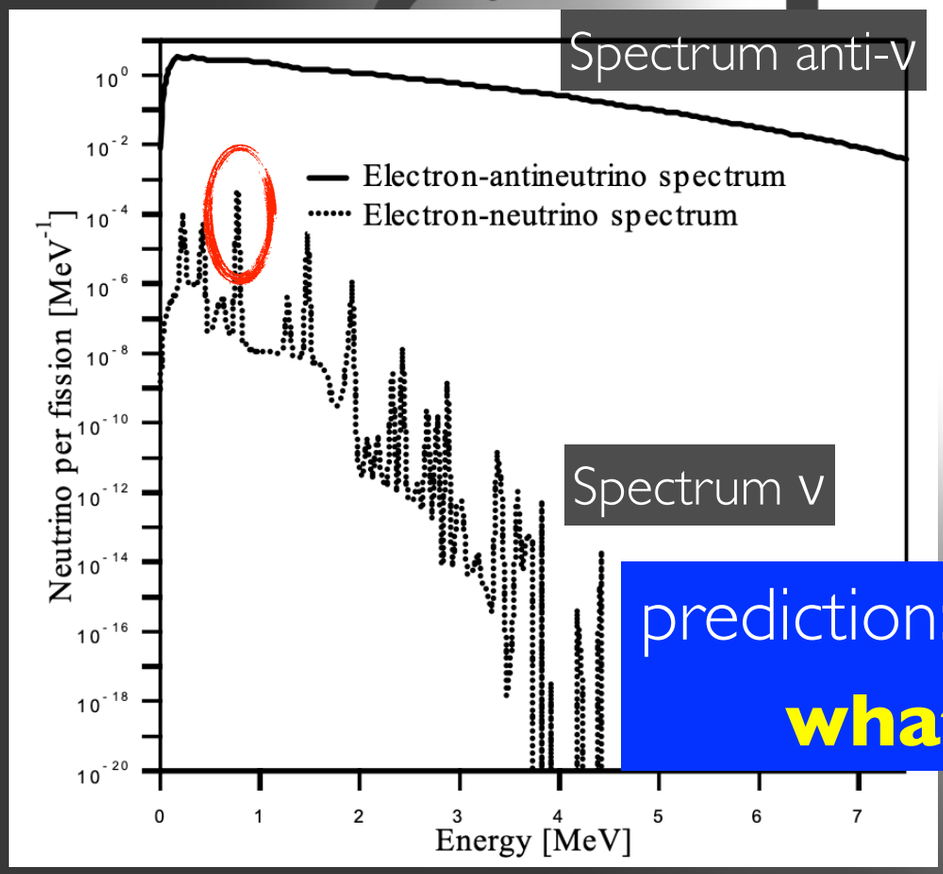
R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

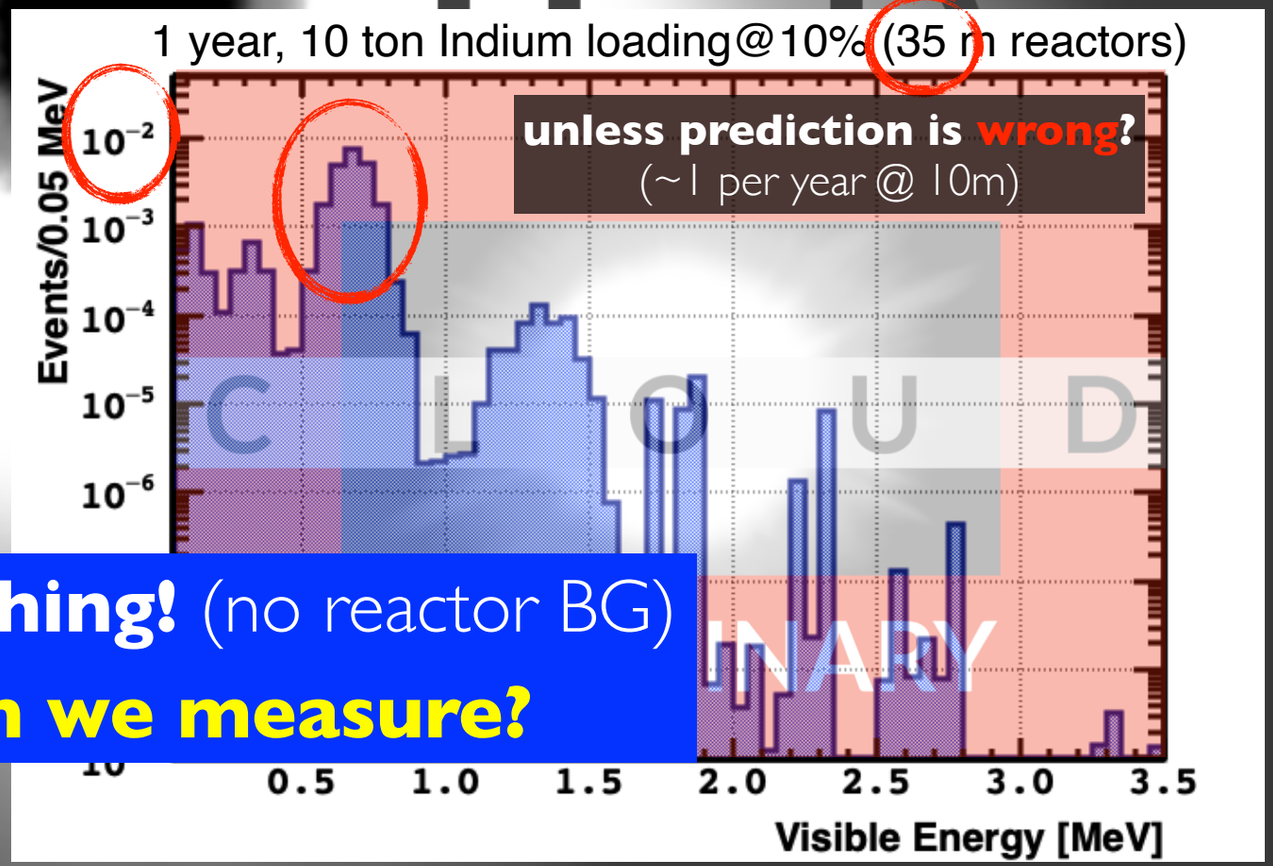
SuperChooz's neutrino golden channel **demonstration** — byproduct

neutrino CC (doping)…

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
- why to detector neutrinos close to a reactor?
  - **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]





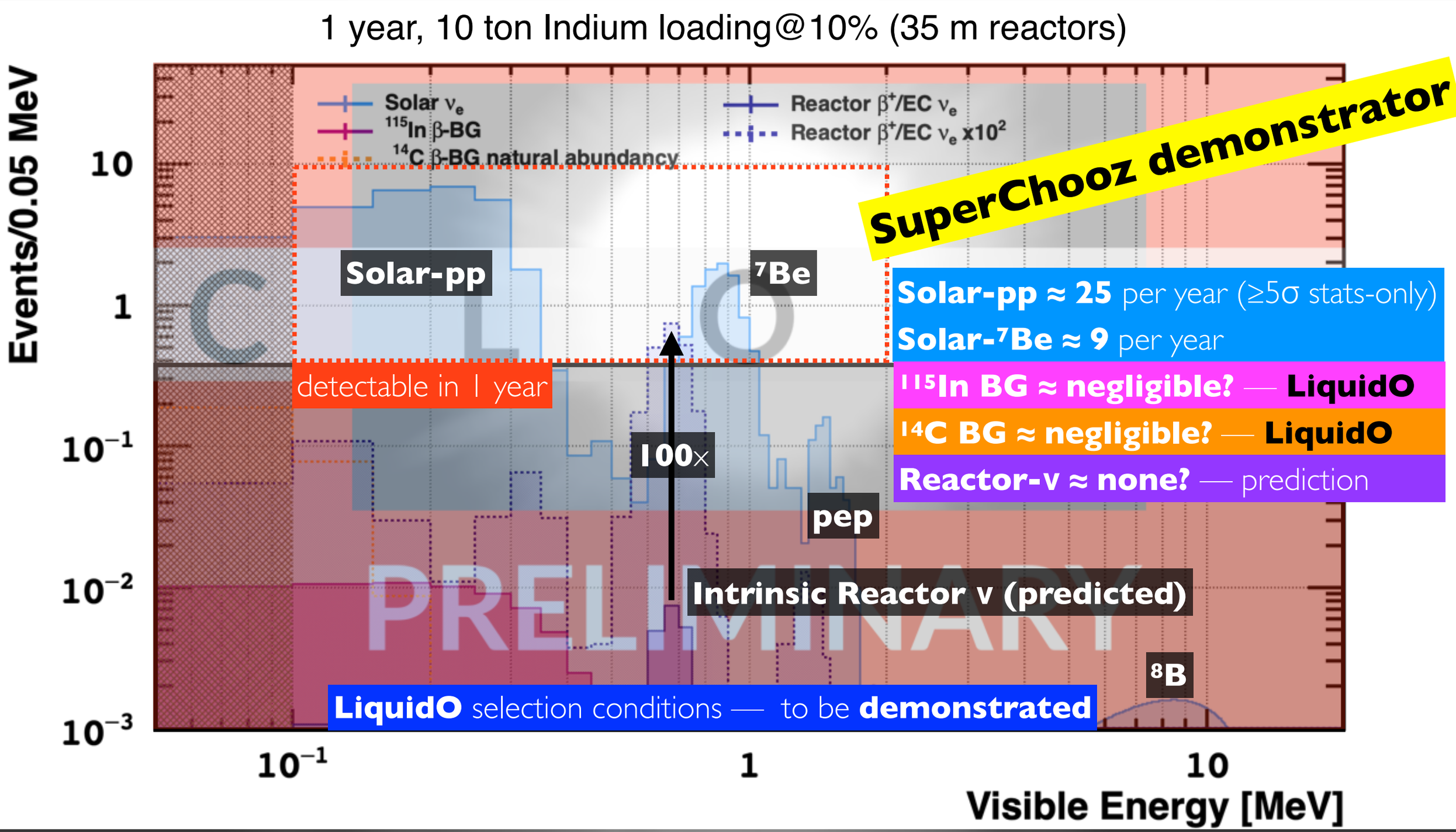
prediction: **nothing!** (no reactor BG)

what can we measure?

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)



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

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)

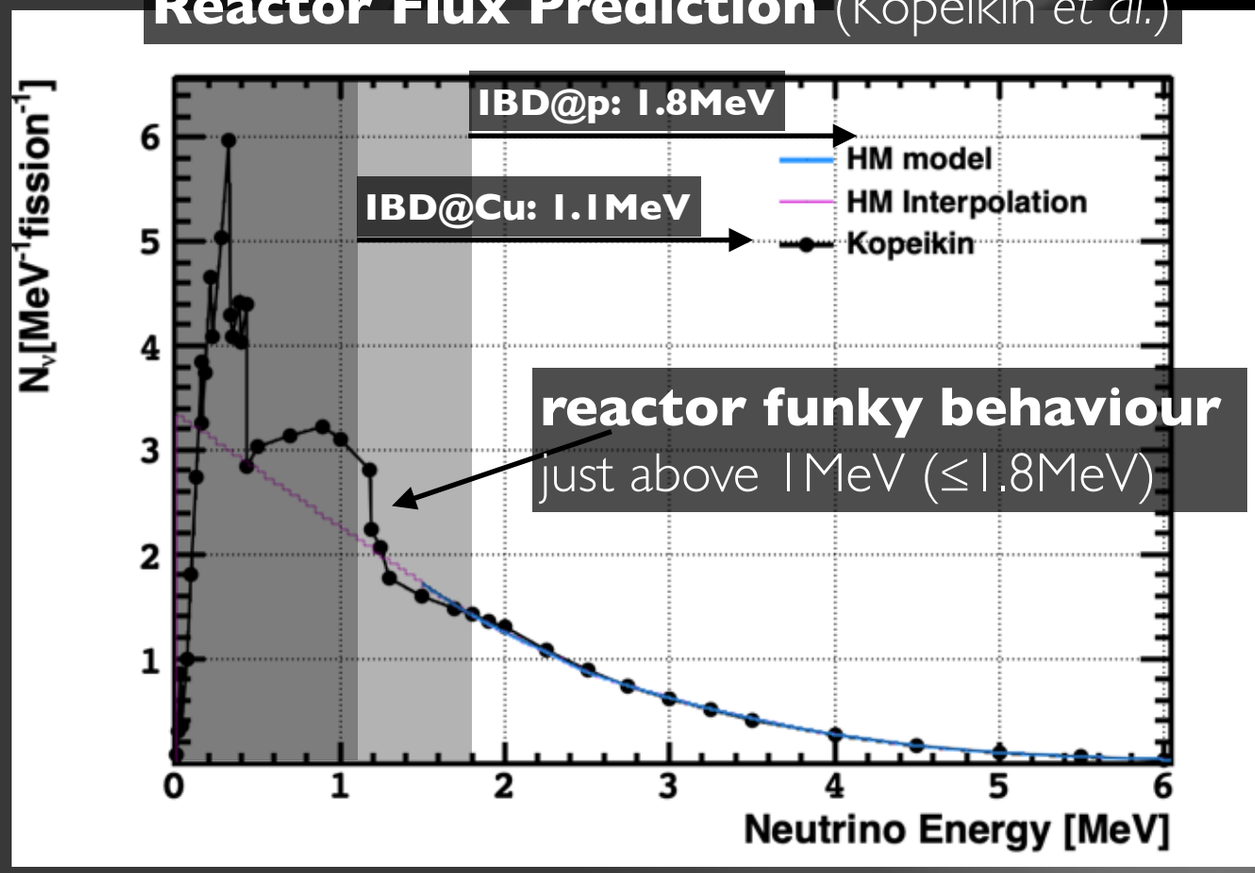
^{40}K geoneutrino new methodology → good enough for discovery?

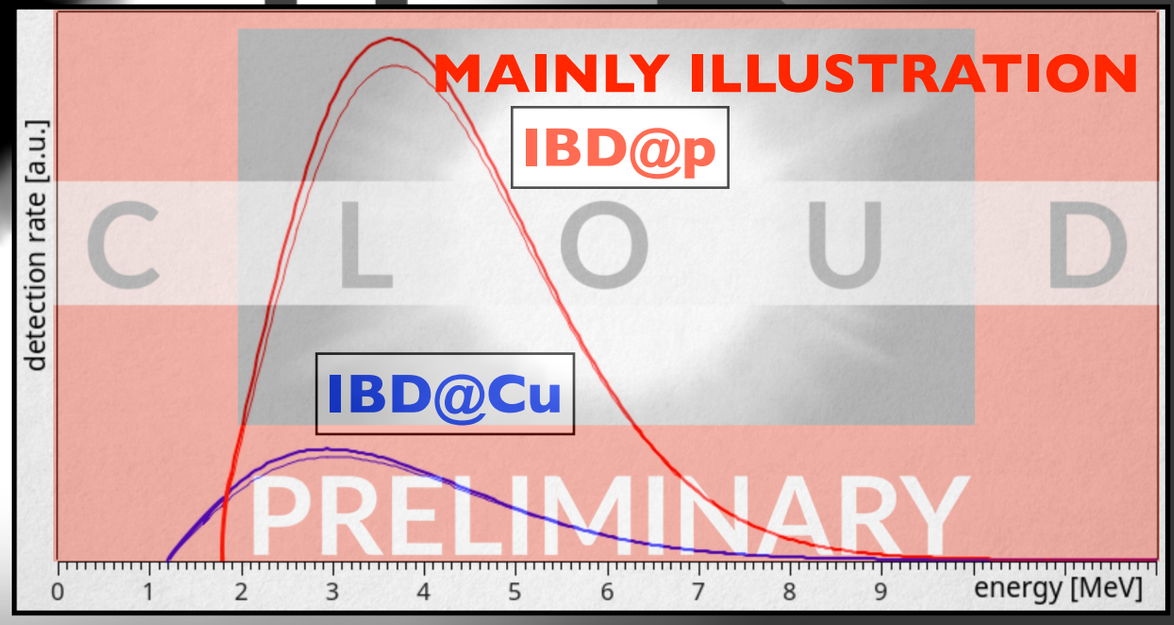
CLOUD-III physics programme…

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:**
  - **direct reactor-fuel monitoring?** — fuel-storage systems?
  - **^{40}K geoneutrino exploration** (discovery) — extremely challenging

Reactor Flux Prediction (Kopeikin *et al.*)





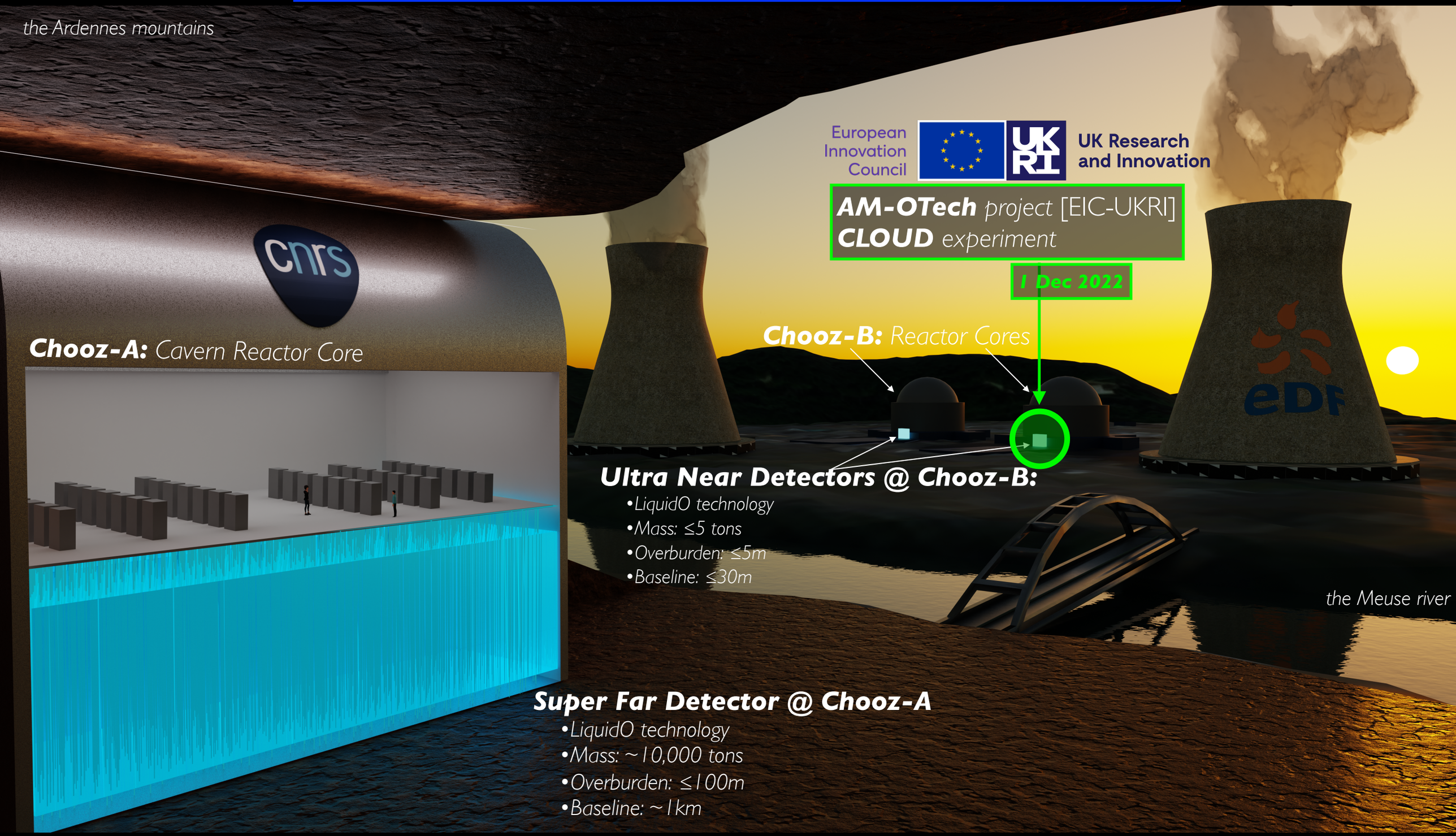
IBC@Cu: net increase of events — to be demonstrated
- **detection feasibility**
- **cross-section** measurement — relative to IBD@p
- branching-ratio for **Cu* (tagging)** versus Cu

note: geoneutrino slide in **backup**

a long story short…

SuperChooz exploration…

flagship neutrino oscillation experiment in Europe?



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

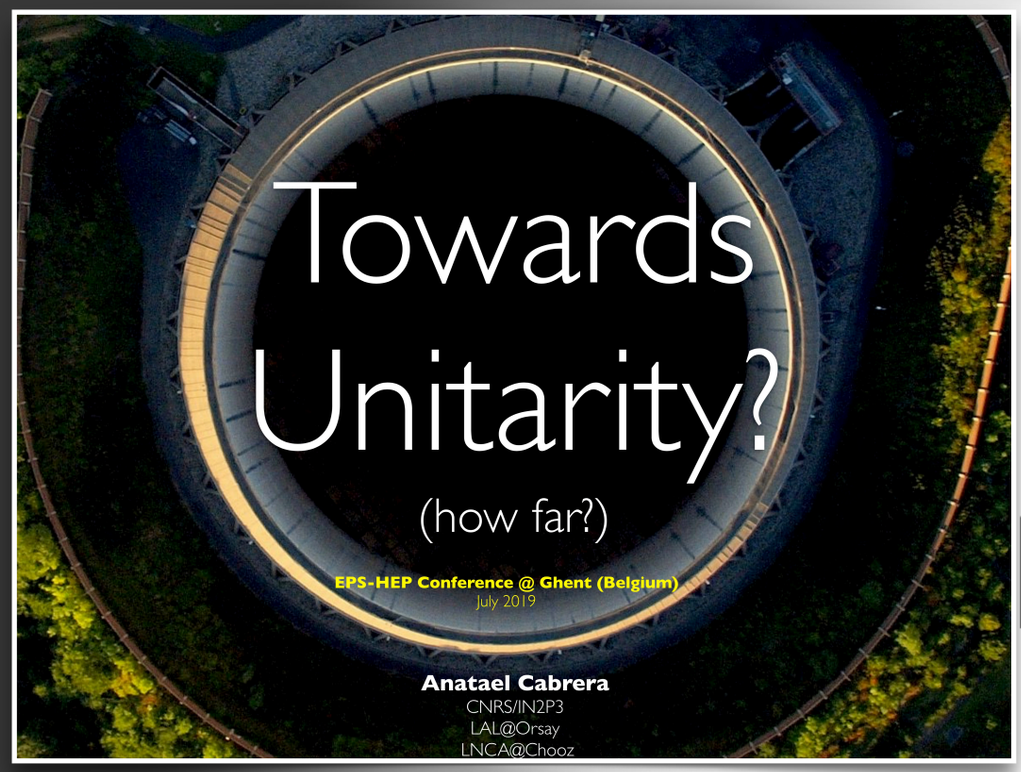
EP Seminar

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/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?**
- **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?**
- **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?**

an even vaster future of reactor (anti)neutrinos ahead?

conclusions...

SuperChooz demonstrator

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)

⟹ **19 institutions in 11 countries**

Spokespersons:
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- 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]