thanks to the **LiquidO consortium**…

L I Q U I D O

Detection and Imaging in Opaque Media

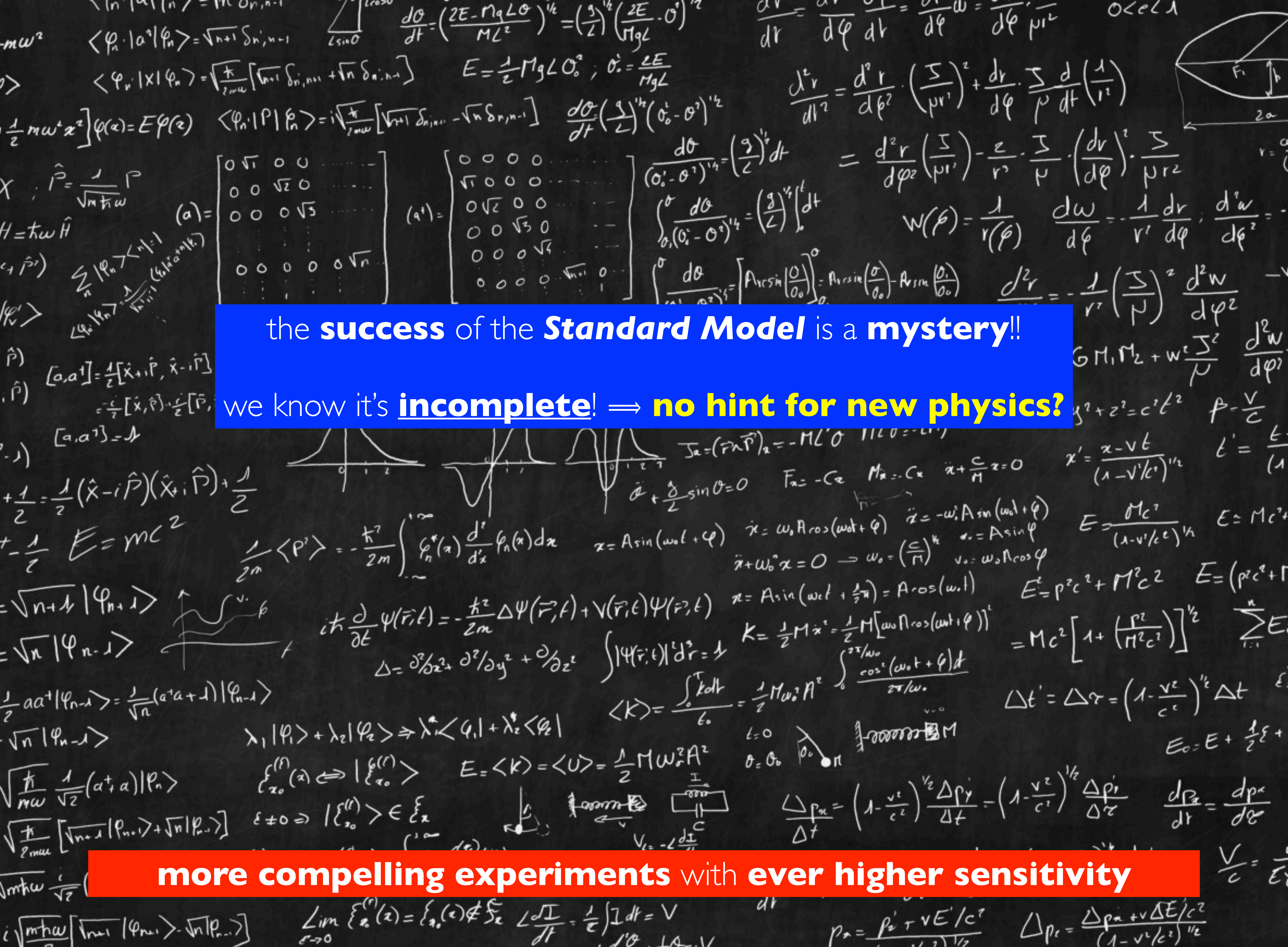
Seminar @ LIP / Lisbon University
7th October 2024 — Lisboa, Portugal

European Innovation Council

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

L I Q U I D O

why LiquidO?



the **success** of the ***Standard Model*** is a **mystery**!!

we know it's **<u>incomplete</u>**! ⟹ **no hint for new physics?**

more compelling experiments with **ever higher sensitivity**

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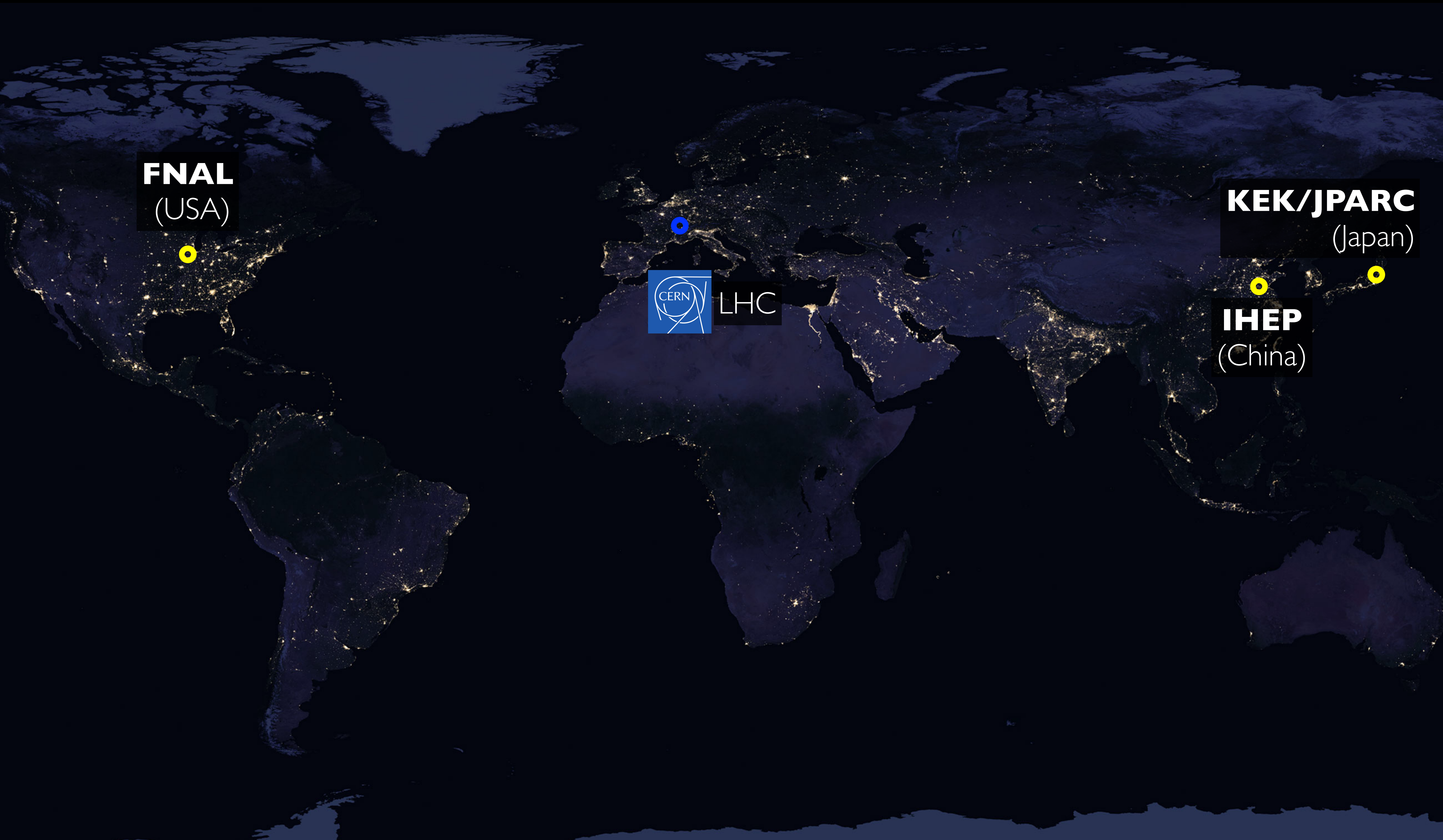
HEP landscape leaning neutrino...?



caveat: only the most prominent facilities are considered — not a complete list.

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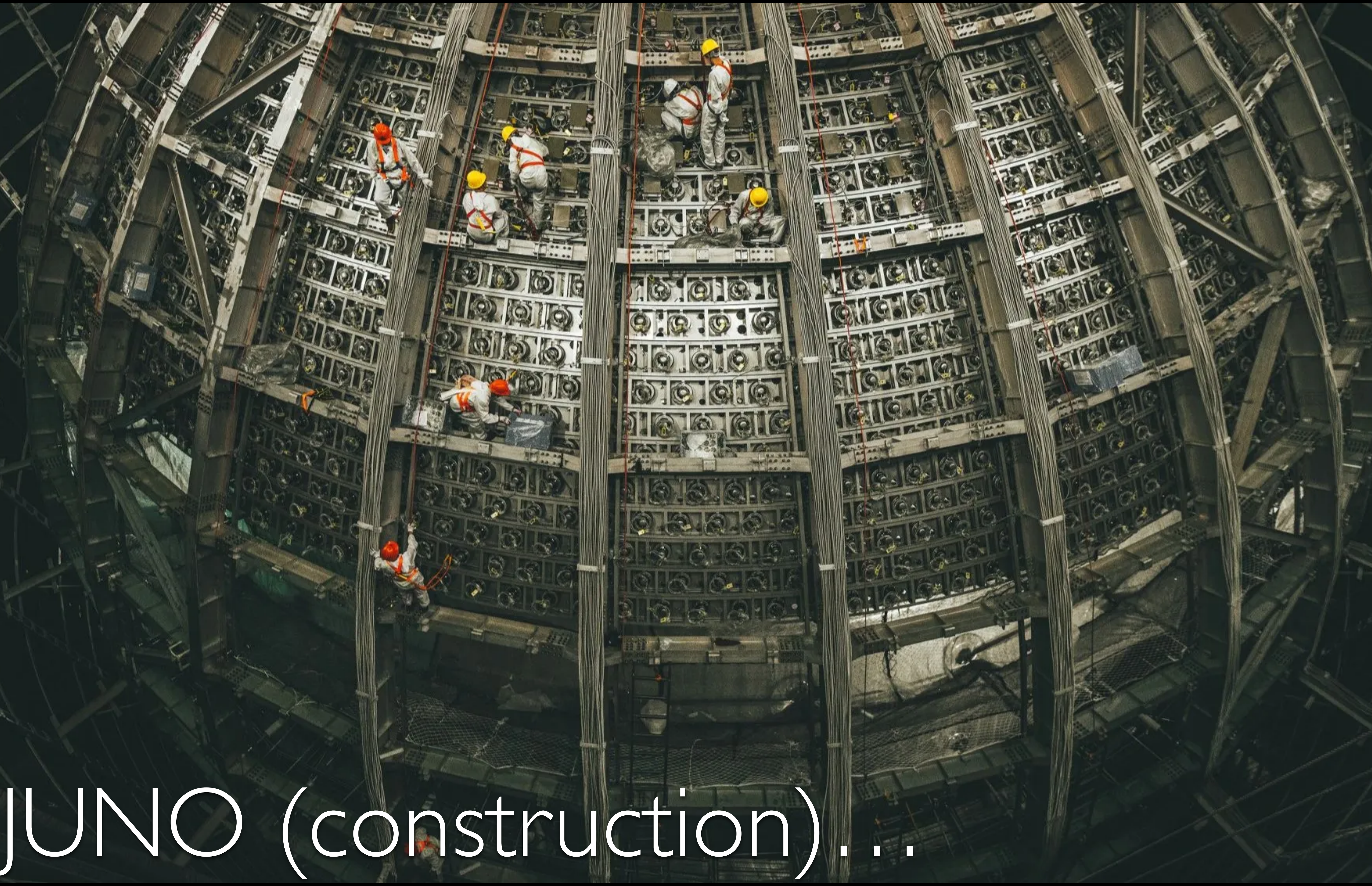
flagship-ν experiments…

several fundamental questions
(understanding the Universe)

the largest underground excavations in humankind…



JUNO (construction)…

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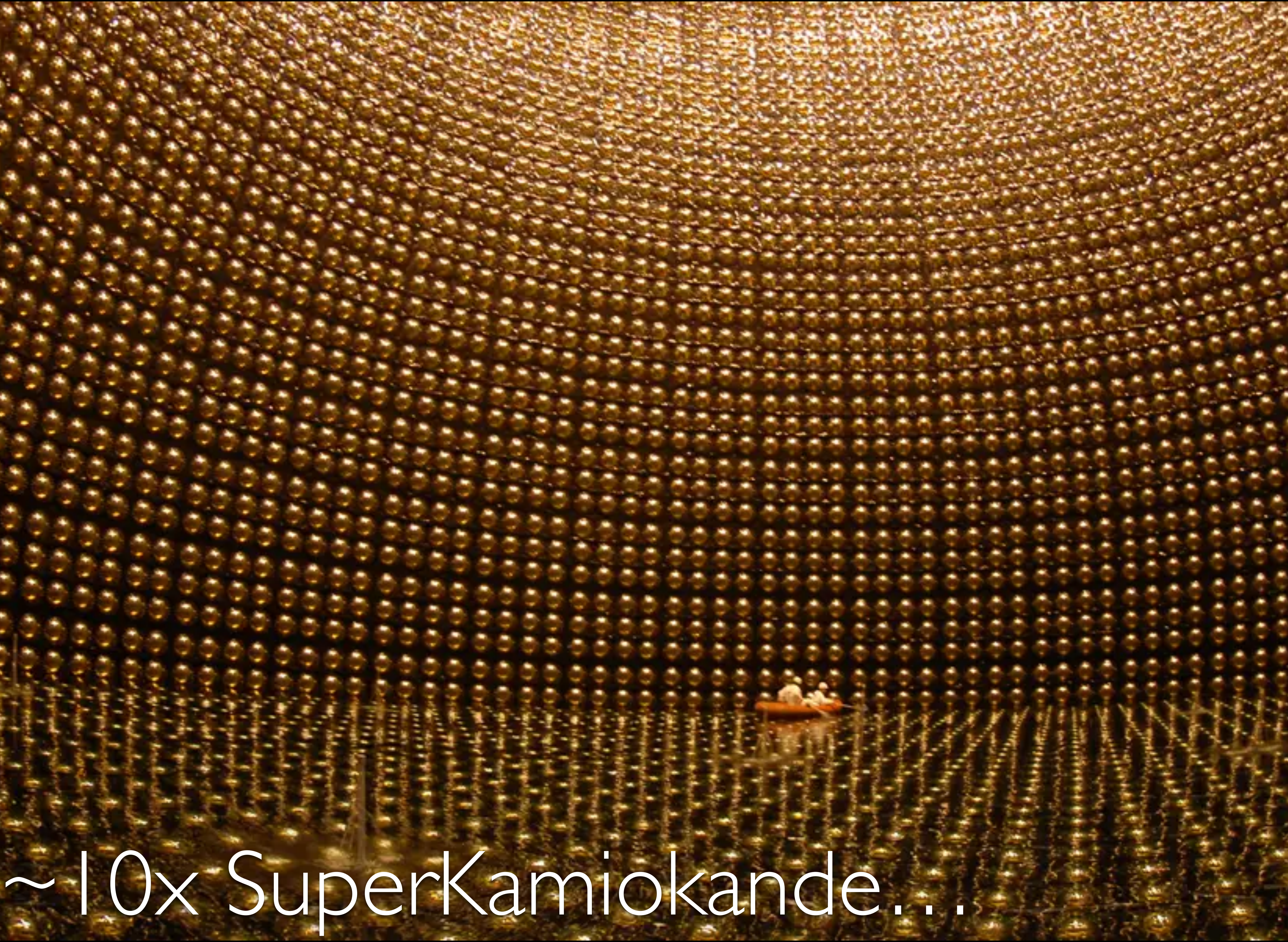
DUNE @ SURF (construction)

FNAL goes "*neutrino capital*"...

HyperKamiokande (construction)


~10x SuperKamiokande…

neutrino science's limitations...

- **reactors** — background⊕technology **limited**!
- **solar** — background⊕technology **limited**!
- **atmospheric** — background⊕technology **limited**!
- **supernovae collapse** — background⊕technology **limited**!
- **accelerator** — source **limited**! (soon systematic → technology)

L I Q U I D O

- **geoneutrino** (discovered) — background⊕technology **limited**!
- **ββ decay?** — background⊕technology **limited**!
- **proton decay?** — background⊕technology **limited**!

many mysteries in **SM → huge tech-limitation!**

why new technology is needed?

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reduce (eliminate) need overburden?

future: powerful-large **detectors on the surface?** — cosmogenic backgrounds

today's liquids technology: transparent. . .

must shield/overburden→ new technology needed

CTF @ Gran Sasso
(Borexino R&D)

what's LiquidO?

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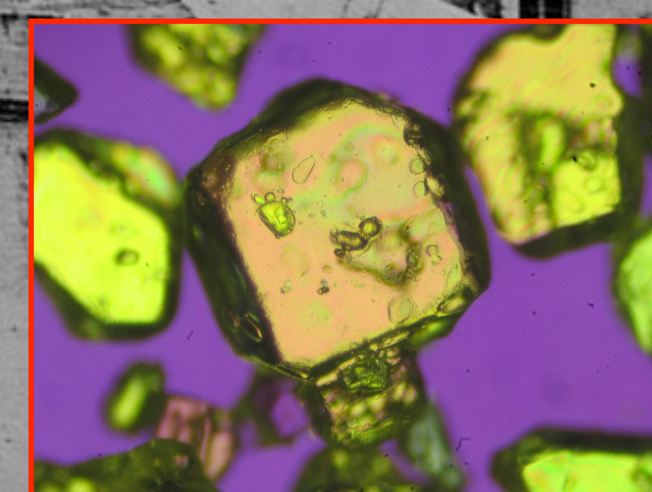
the art of building images (2D)…

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



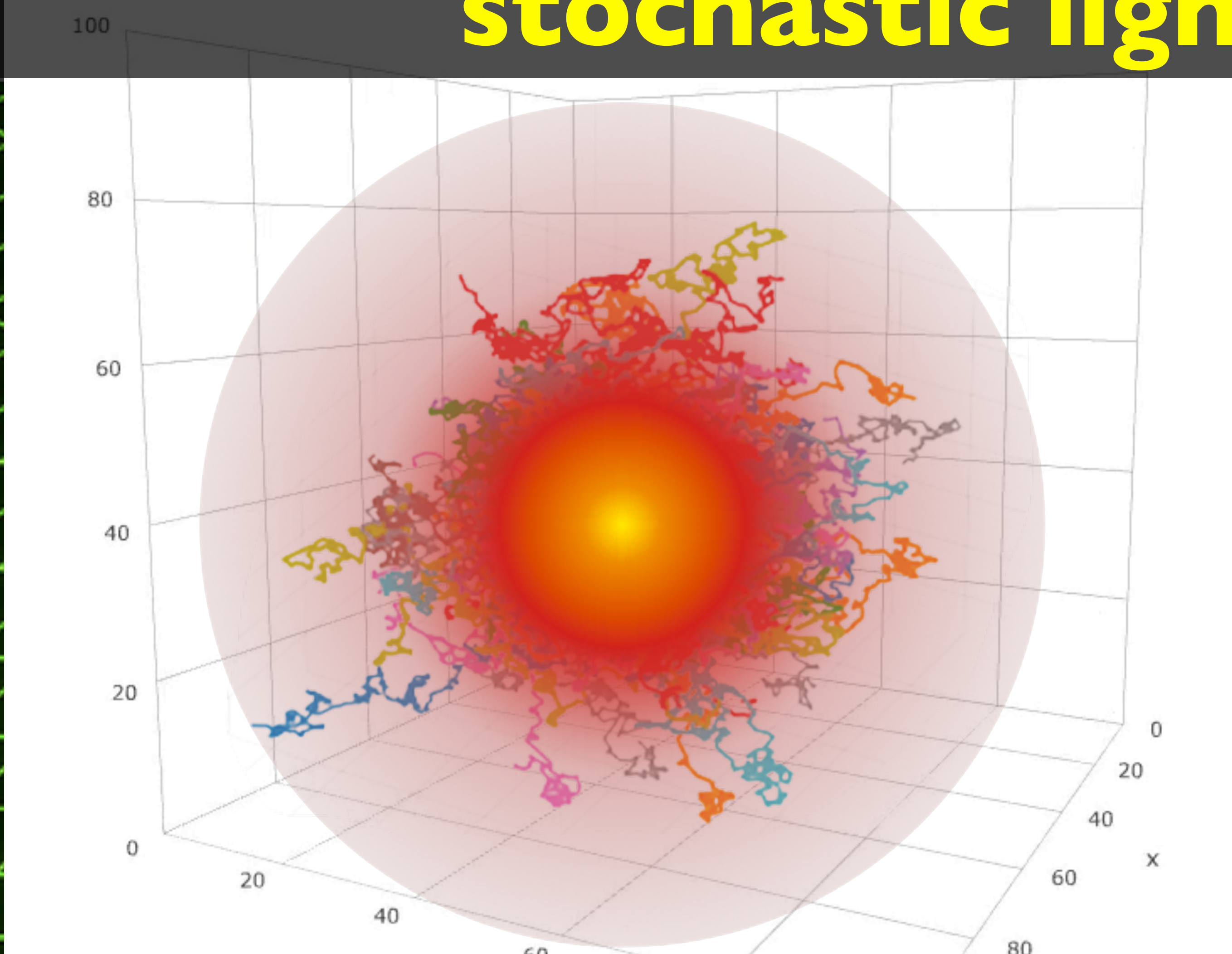
each energy deposition…

- **points 3D**(x,y,z) & **energy 1D**(E)
  ⟹ **lines** (i.e. point-sequence)
- **time 1D**(t) — optional (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!!**

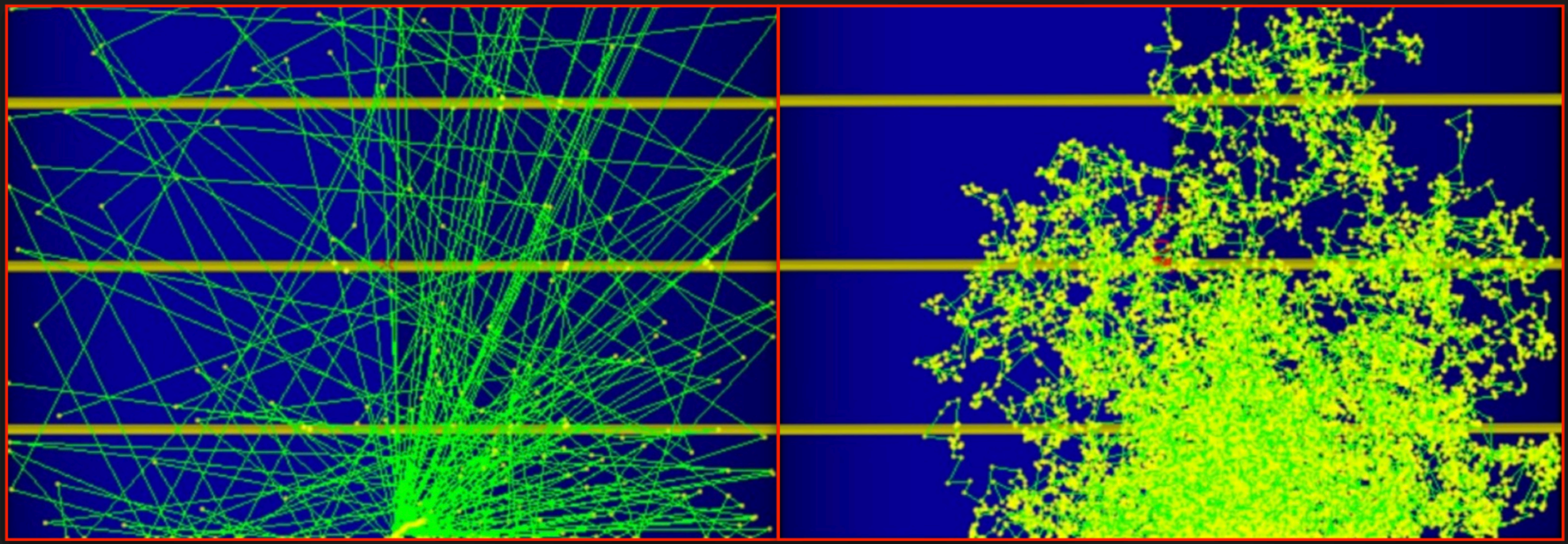
Transparency
λ(scattering)**≥10m**

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

inducing light to a point (lossless)…

IMAGE WORTH MORE THAN WORDS…

Mie & Rayleigh scattering (elastic = lossless)



NO Scattering in Medium: each photon ≈ "ray"
(scatter only off surfaces, etc)

Scattering in Medium: each photon ≈ "whirlpool"
(scatter also on surfaces, etc)

SEGMENTATION: use reflectivity to confine light
(a good (98%) reflector loses ~90% of the light after ~100 reflections)

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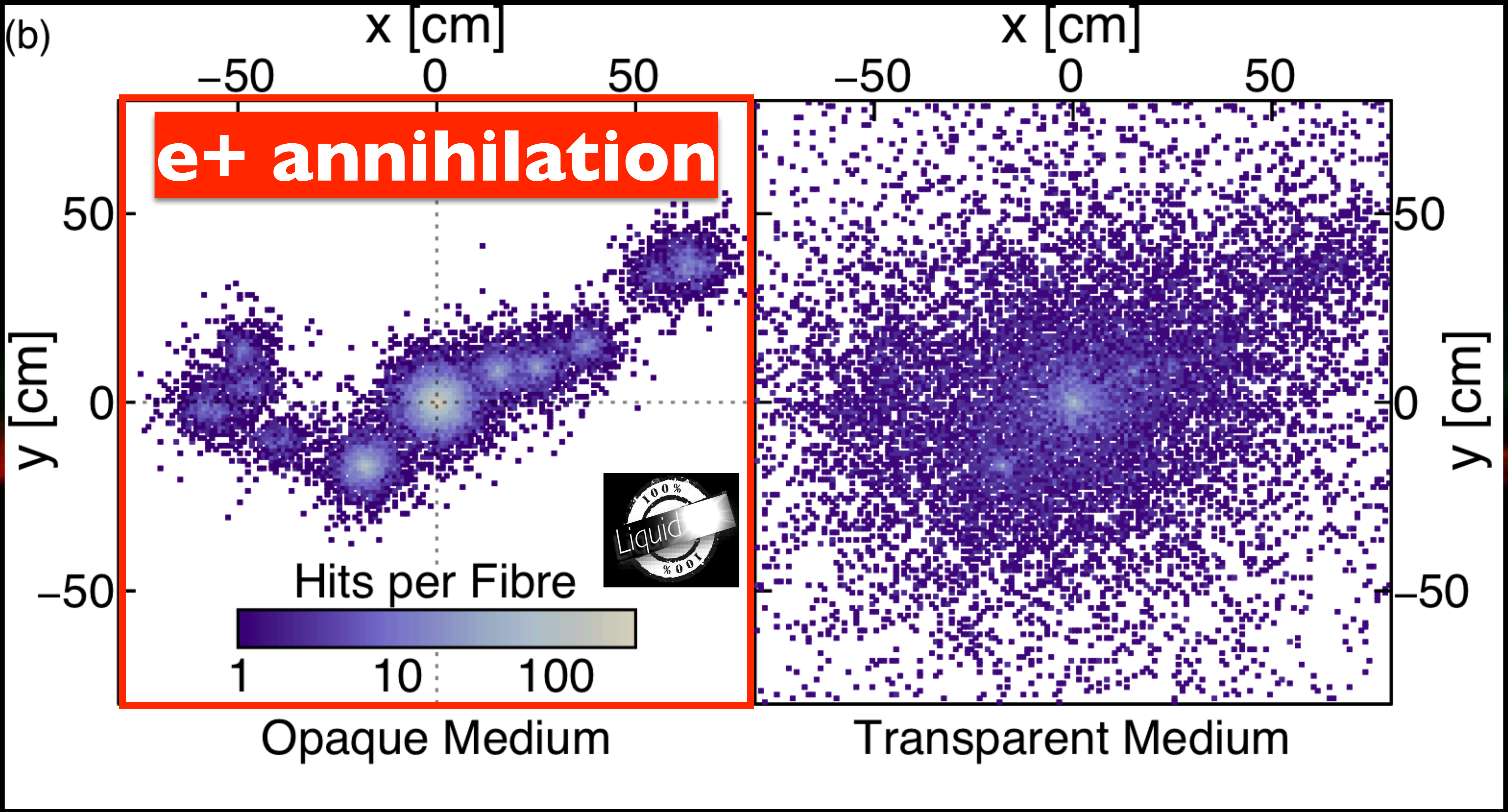
LiquidO: sub-nuclear MeV imaging…



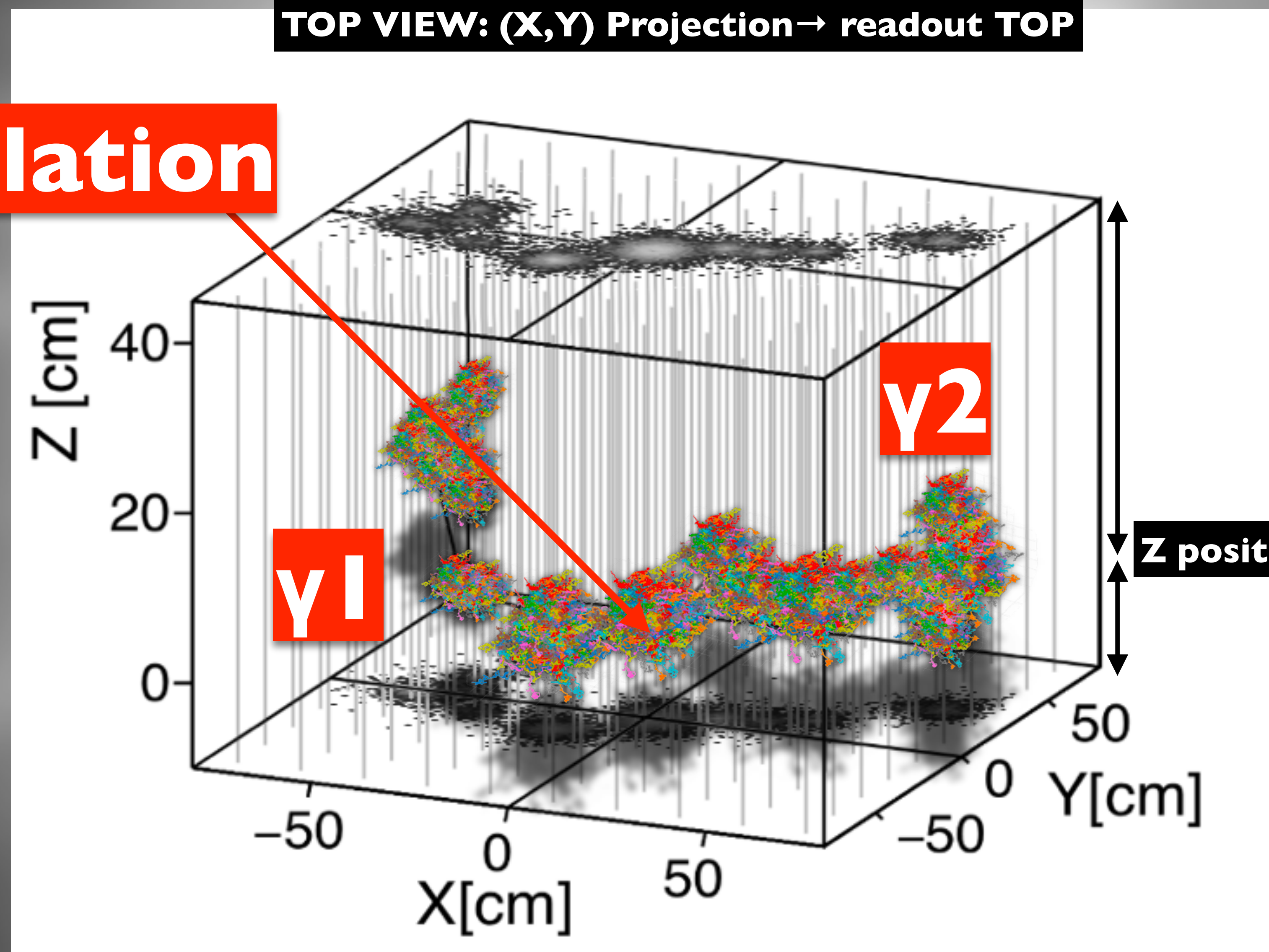
opaque medium→stochastic light confinement

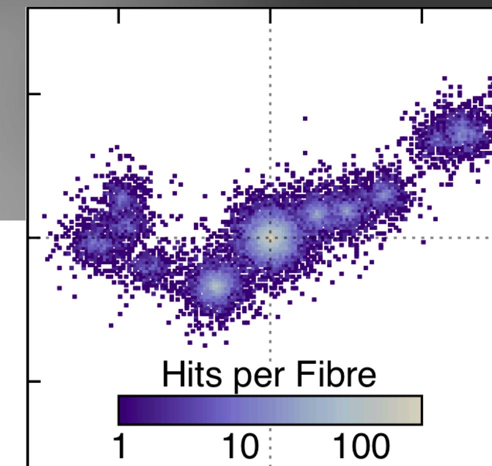
(**self-segmentation**)

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

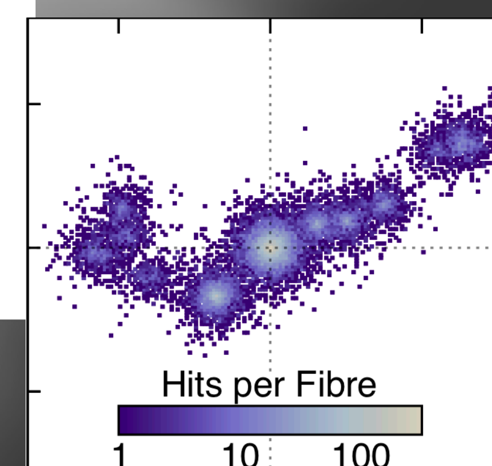
Simplest LiquidO: 1D lattice (fibres along Z-axis only) — **axial configuration**

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





Z position using: Δt (time difference)



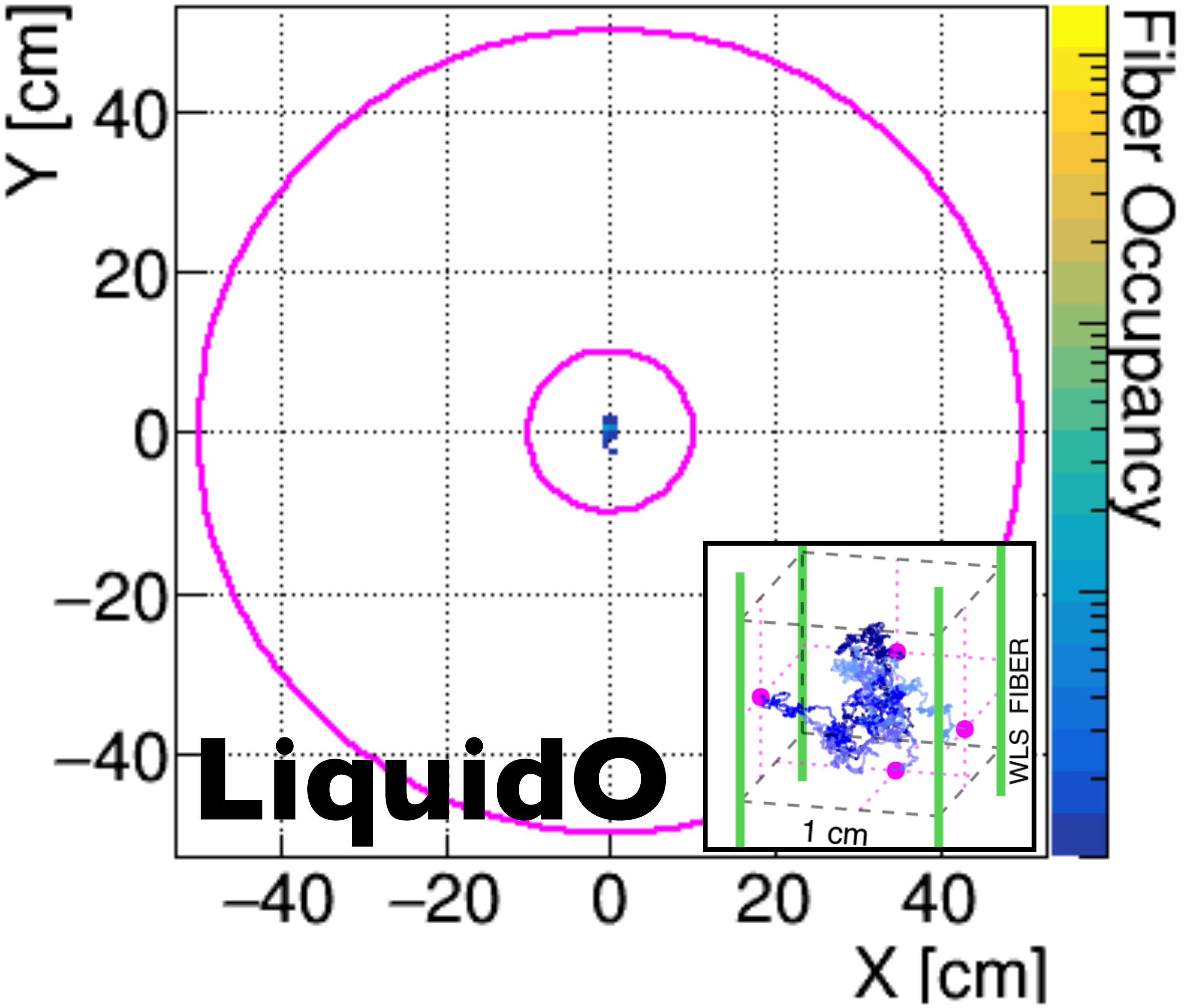
BOTTOM VIEW: (X,Y) Projection→ readout BOTTOM

opaque medium→stochastic light confinement (self-segmentation)

LiquidO vs "traditional LS" (example: e+)

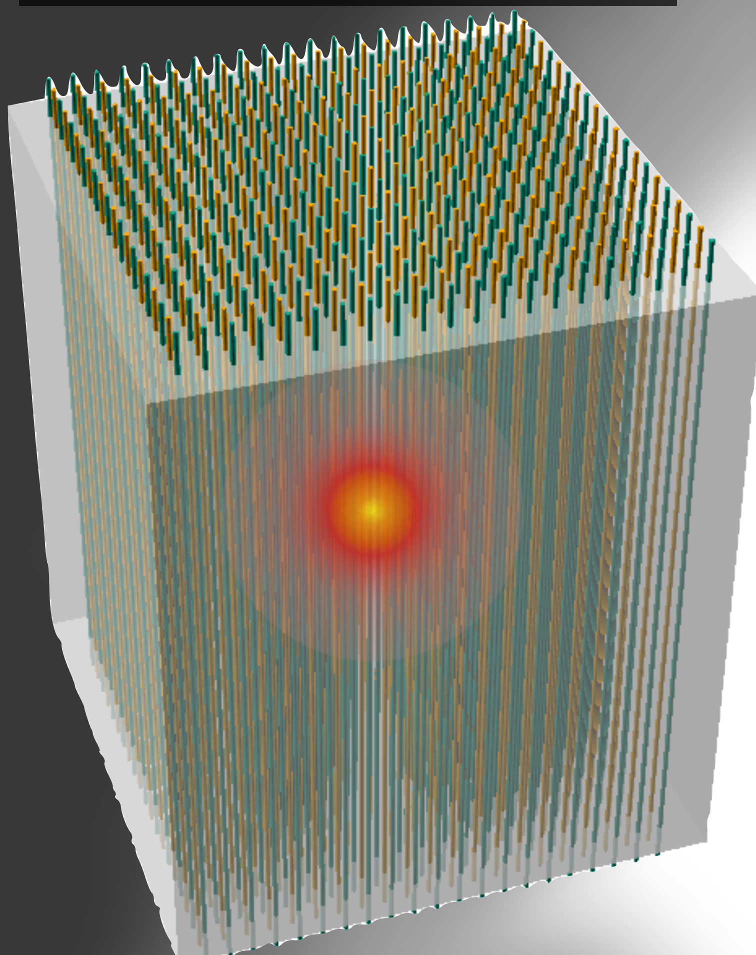
e+ @ 1MeV

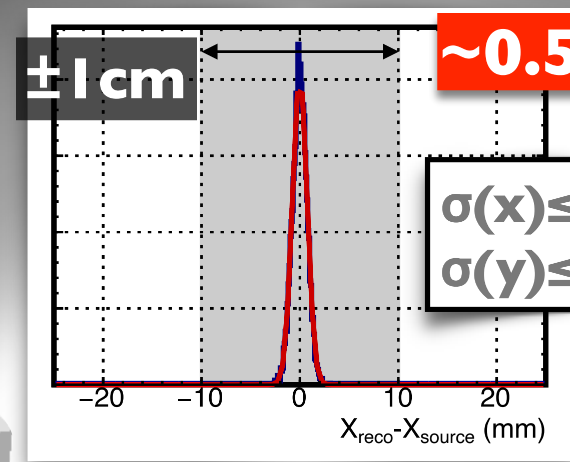
e+ @ 1MeV



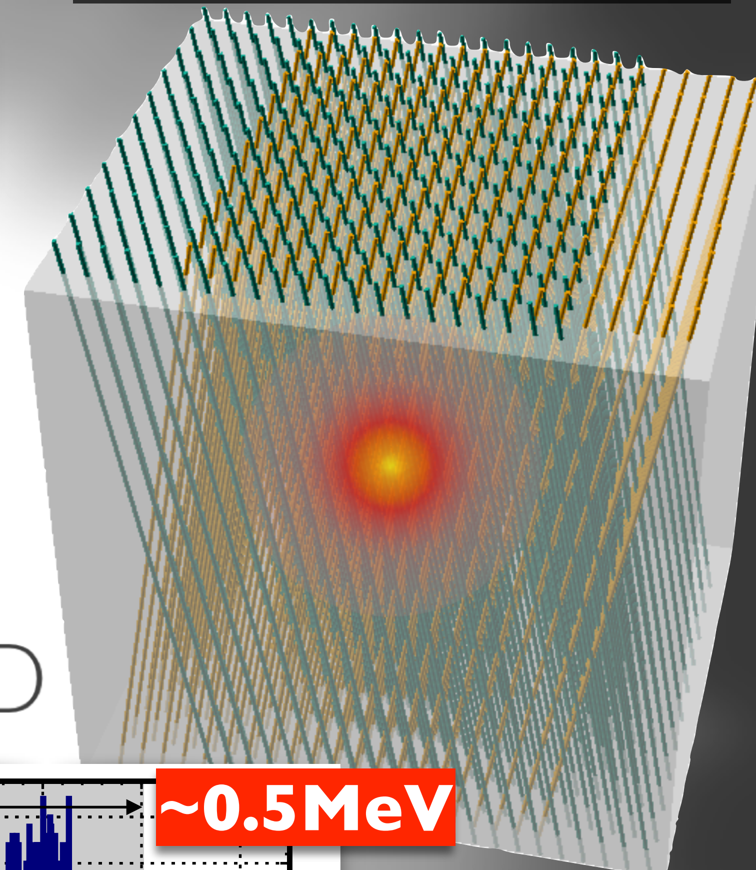
novel LiquidO engineering…

LiquidO axial-fibres
"parallel"

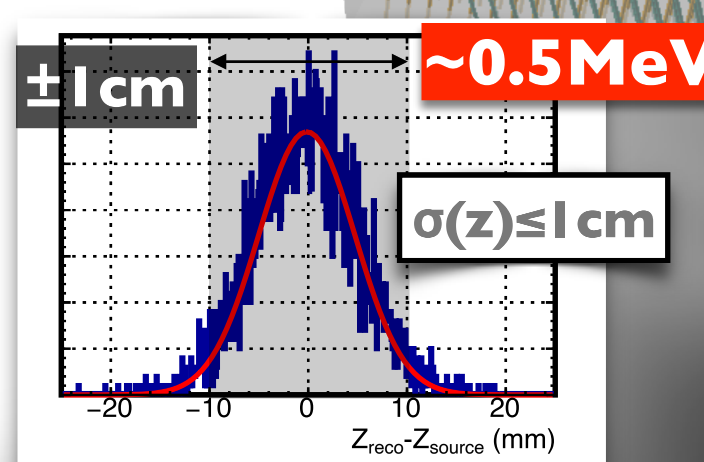




LiquidO axial-fibres
"crossed"



I Q U I D



1x Axis(Z) — low cost & simplicity
- (X,Y): topology→ **mm resolution** (robust)
- Z: **timing**→ **few cm resolution** →**some fragility:** light yield, rise-time, etc

2x Axes — complexity & cost…
- (X,Y,Z): topology→ **mm resolution** (robust)
- (X,Y,Z): timing→ cheap-readout / over-constrained

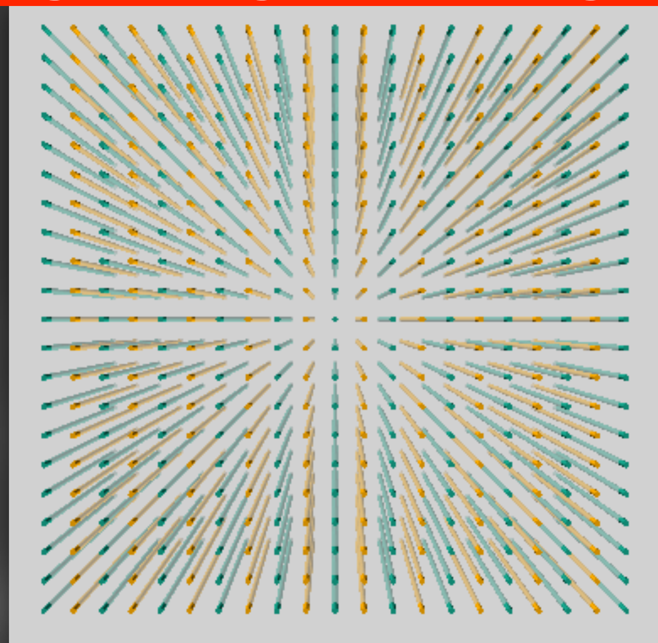
3x Axes — useless?

"1x" Axis(twisted-Z @ ≤10º**) — development**
- (X,Y): topology→ **mm resolution** (robust)
- Z: topology→ **≤1cm resolution** (robust)
- (X,Y,Z): timing→ over-constrain & **energy-flow**

more Axes: necessary?

main technological ingredients…

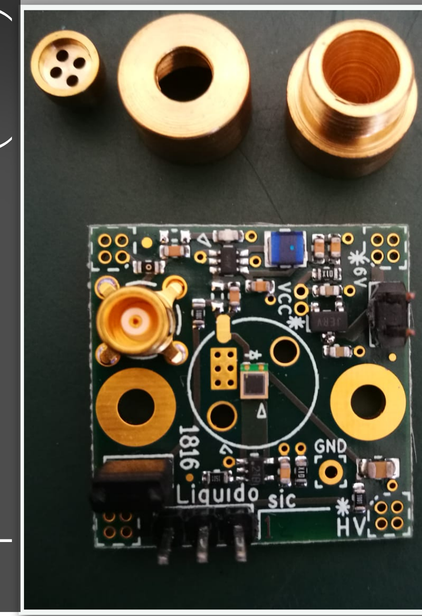
full engineering for "floating fibres"



⊕

sub-100ps custom front-end & digitisation

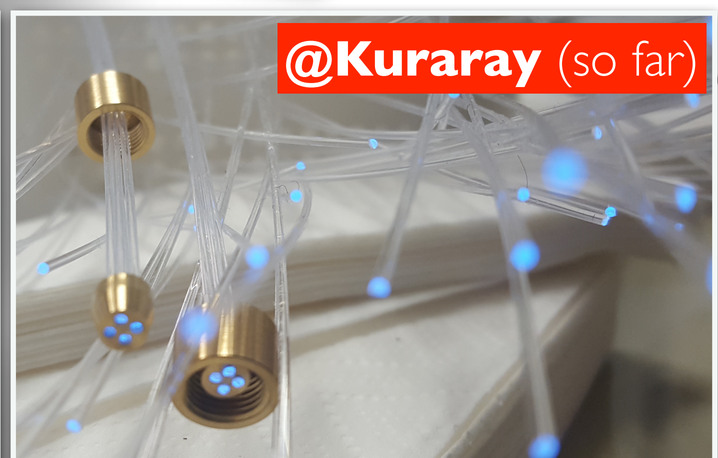
LiquidO Front-End (SiPM)



SiPM @Hamamatsu S13 (so far)

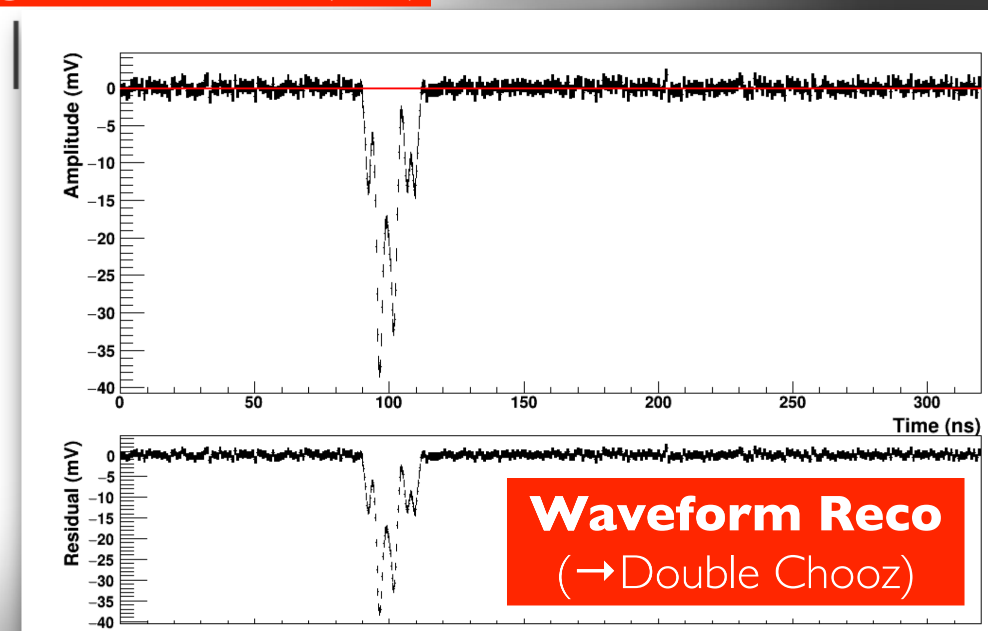
⊕ **Waveform Digitisers**
(FADC or Analogue-Memories)

new media developments…



@Kuraray (so far)

new scintillation & fibres technologies
(Cherenkov / scintillation / etc)



Waveform Reco
(→Double Chooz)

fast readout ⊕ reconstruction
(potential resolution ≤100ps)

new framework for light detection→ several new ideas…

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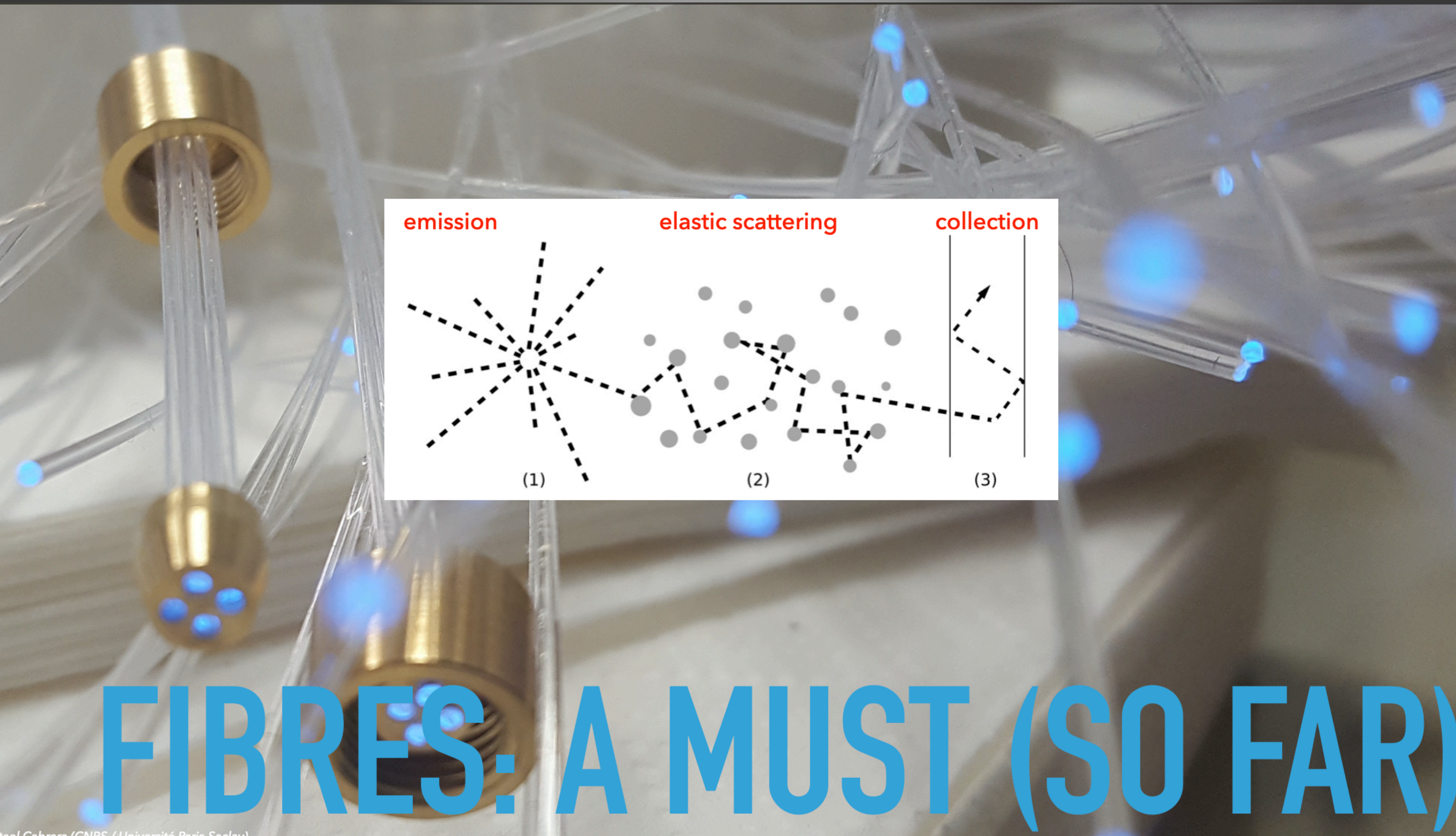
FIBRES: A MUST (SO FAR)



wave-shifting or scintillating fibres — clear fibres are **≈useless**

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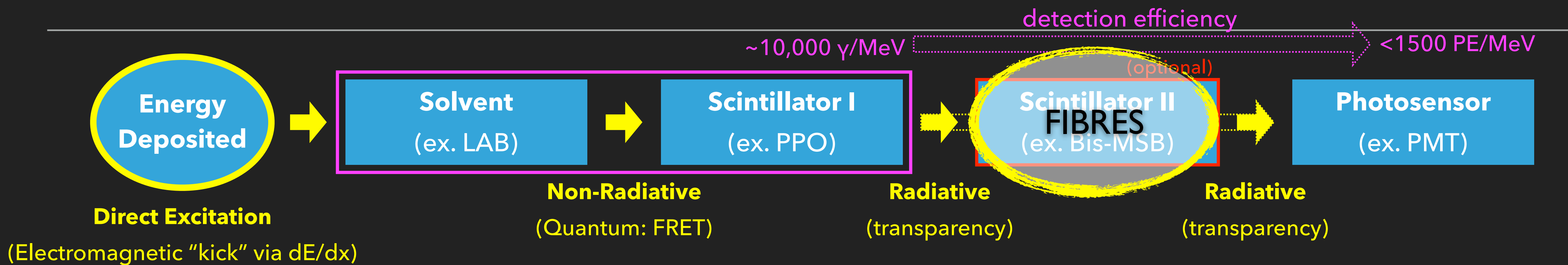
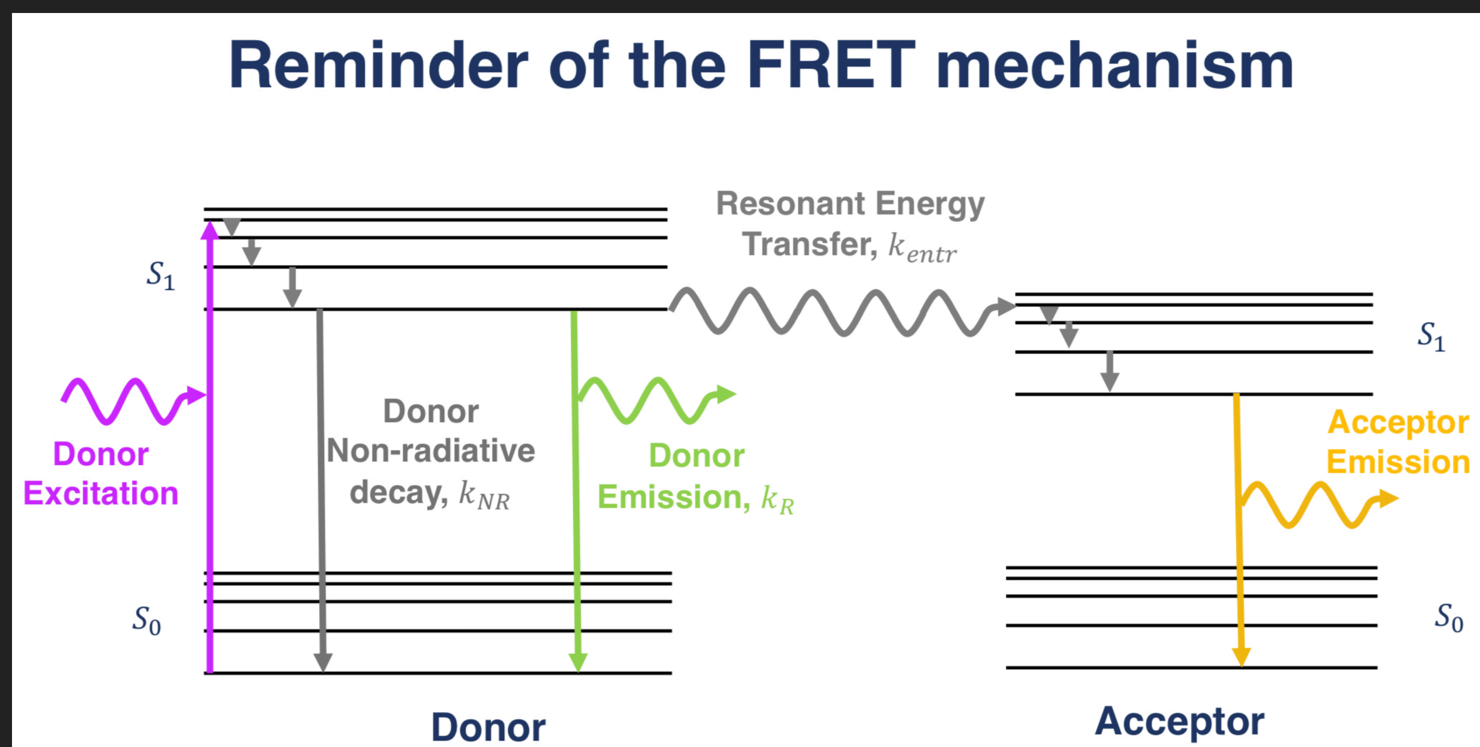
REMINDER ABOUT “TRADITIONAL” LIQUID SCINTILLATORS…





Upon excitation (dE/dx ⊕ complex chain), mainly **radiative de-excitation via SINGLETs** & much less **radiative de-excitation via TRIPLETs**

[TRIPLETS de-excitation is slower⟹ suffers from “competition” with other non-radiative mechanisms]

dE/dx (particle dependently) can change the relative SINGLET to TRIPLET ratio and overall light yield (Birk’s constant)

⟹ **Pulse Shape Discrimination**

FIRST "MICRO-CRYSTAL" PROOF-OF-PRINCIPLE — FRANCE CIRCA 2018

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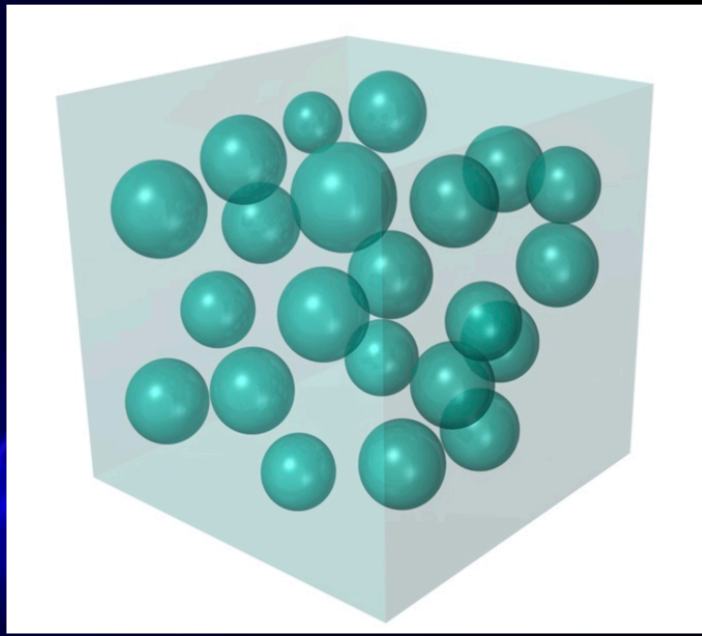
pulverised inorganic μ-Crystals in a liquid system (scintillating or not) to maximise light output

note: possible quantum energy transfer under active R&D



pioneering **opaque scintillation** — a byproduct of **LiquidO**


FIRST "NOWASH" SYSTEM (PROTOTYPING) — GERMANY CIRCA 2018
arXiv:1908.03334
Anatael Cabrera (CNRS / Université Paris-Saclay)

EMULSIONS: A NATURAL SOLUTION

- MILK*-like: water-based solution with unmixed μ-droplets of oil (i.e. scintillator⊕scattering) – used in "traditional **WbLS**"

- MAYONNAISE-like: oil-based solution (i.e. scintillator**) with unmixed μ-droplets of water (i.e. scattering): **NEW formulation!**

both schemes benefit (very similar) exploit **micelles** for μ-level scattering: Mie & Raleigh scattering → **LiquidO**

***milk**'s extreme "whiteness" (due to Mie scattering), only needs a few % of fat content.

**the more scintillator, the higher the light yield – water does not scintillate.

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TODAY: OPACIFYING TRANSPARENT SCINTILLATORS — DEVELOPMENTS

	Basis	Opacity Dopant	Intuitive	Where? (likely incomplete)
"NOWaSH" (arXiv:1908.03334)	LAB/DIN/etc PPO	wax (pioneered for LiquidO)	candle/yoghurt like (→solidification)	Germany
"Emulsion" (WbLS like: 2014)	LAB/DIN/etc PPO	water (a la WbLS)	mayonnaise like	US/Canada
"μ-Crystal" (arXiv:1807.00628)	LAB/DIN/etc PPO?	crystal-scintillators (more light?)	powdery gel	France/Germany
"nano-Crystal" (not sure, sorry)	???	quantum-dots, nano stuff (?)	never seen	US/UK/Germany
new ideas!! (cagy efforts)	various options (confidential)		confidential	several (France, Canada, Portugal, UK, Germany, US, etc)

please email me, if you are missing – sorry!

LIQUIDO: FRAMEWORK FOR COOPERATION SO FAR

GROWING FIELD — EXCITING RESULTS SOON!

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TOMORROW? NOVEL NATIVE OPAQUE SCINTILLATOR — MORE LIGHT?

European Innovation Council

UK Research and Innovation

AntiMatter Tech

France, Germany, Portugal, Spain, UK with tight links to Canada

(tight work with the **CLOUD collaboration:** 20 institutions, 11 countries)

EIC just approved **extra ~1M€** [LiquidO specialised technology]

- new (opaque) scintillator formulation [→photo-chemistry]
- new (transparent) wave-shifting/scintillating fibres [→industry]
- technological solutions beyond LiquidO only scope

kuraray

https://antimatter-otech.ijclab.in2p3.fr/

≳0.1MeV

topology	physics	LiquidO Information	
point	unresolved (≲few cm)	**point-like**	sub-mm possible (primitive)
track	points-like sequence	**track-like**	sub-mm possible (enhanced)
point's ⊕ track's	complex event	combination ⊕ **timing**	reconstruction (energy⊕x,y,z⊕t)

input 5D→ energy-flow, kinematics$(\bar{p})$, **PID**, etc (derived)

imaging & outcome (upon reco)...

LiquidO Consortium*

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L I Q U I D O

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

beyond native capability…?

scintillator ✓ (Borexino et al)

($\leq 10^{-14}$g/g *U/Th*)

⊕

fibres ✓ (R&D)

($\approx 10^{-12}$g/g *U/Th*)

⊕

~~**segmentation**~~

⊕

photo-detector ✓ (SiPM→**no PMT**)

(maximisal distance: end of the fibres)

⊕

doping with anything?

(physics dependent)


doping stability via solidification…
(beyond chemical stability)

L I Q U I D O

heavy detector doping potential…

why going beyond native composition?

organic scintillator = H + ^{12}C + ^{12}C(~1%) [+ impurities]

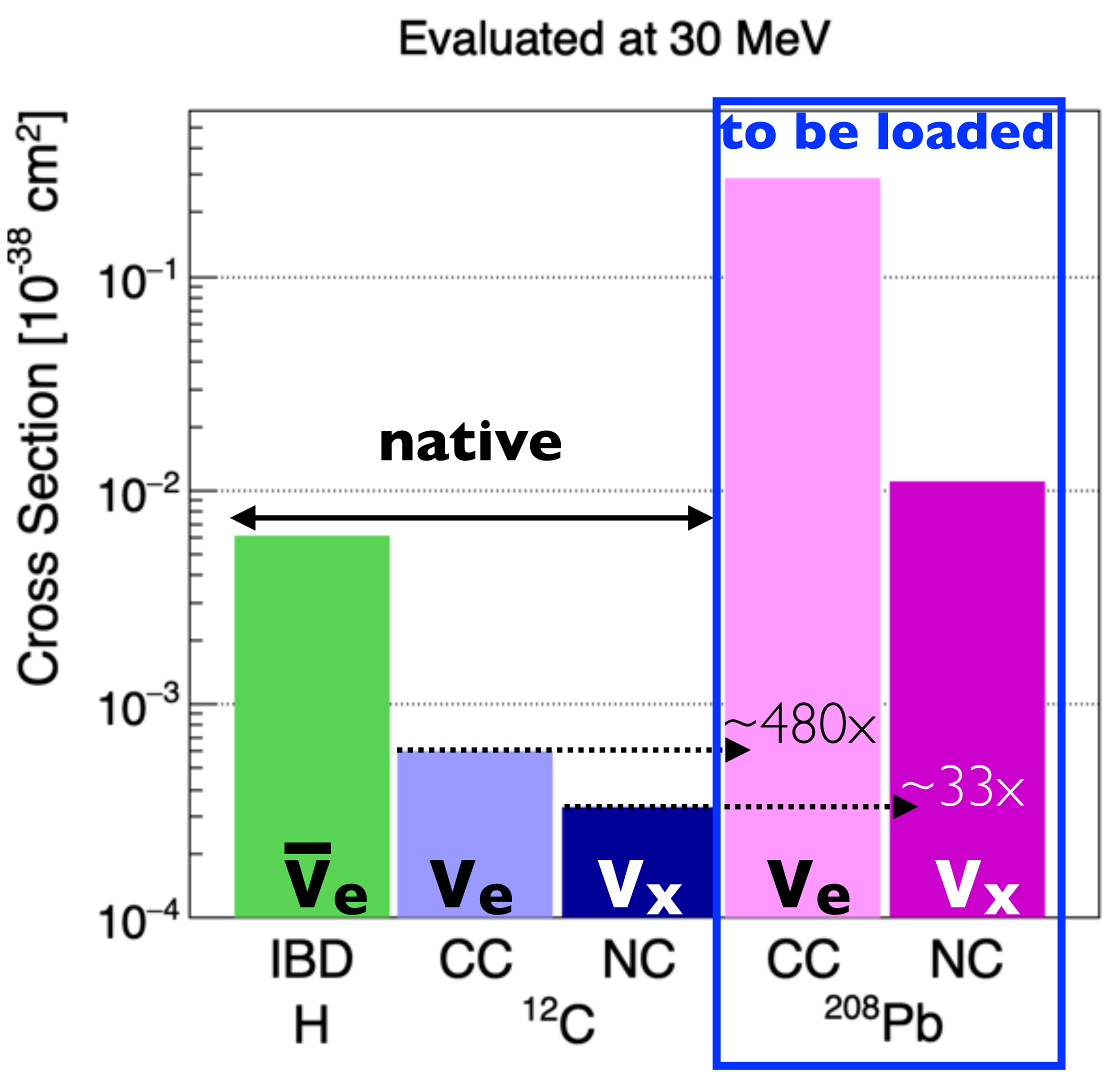
detection efficiency enhancement

neutrino interaction(s) enhancement

rare decay source enhancement

Cd loading
[Reines et al]

Gd/Li loading
[typical in reactors]



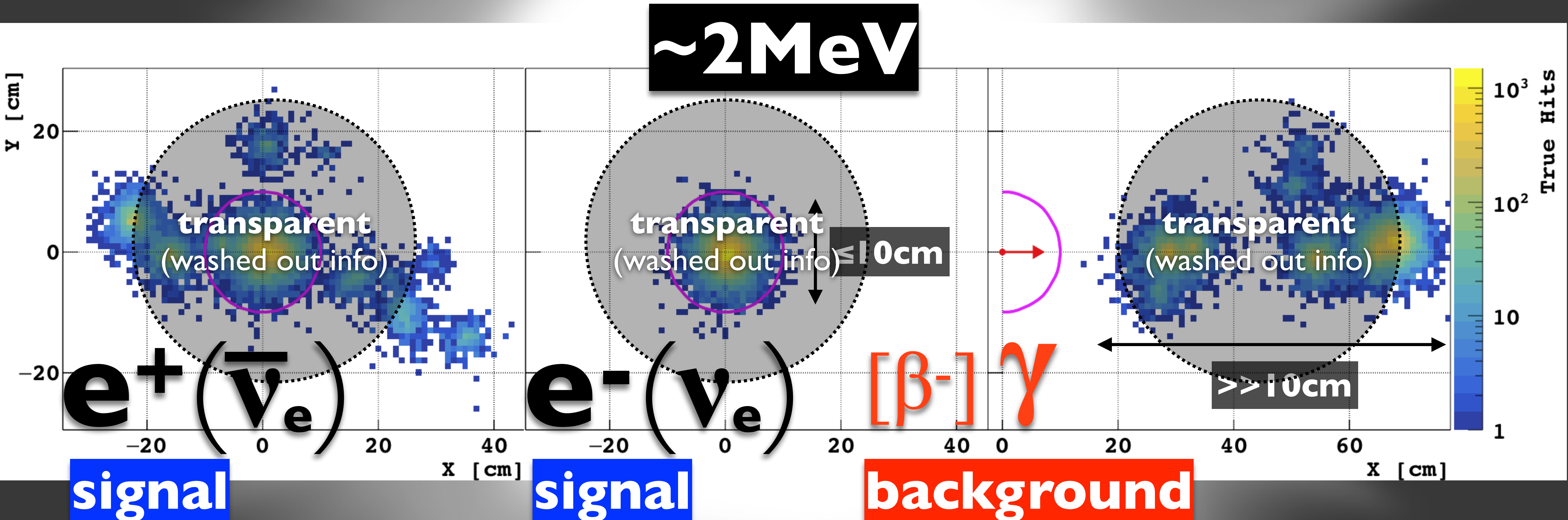
ββ decay
^{136}Xe [KamLAND-Zen]
^{130}Te [SNO+]

≥1 tons ββ?

physics appetiser… (simulation)

unprecedented PID@MeV…

potential: reduce overburden/shielding

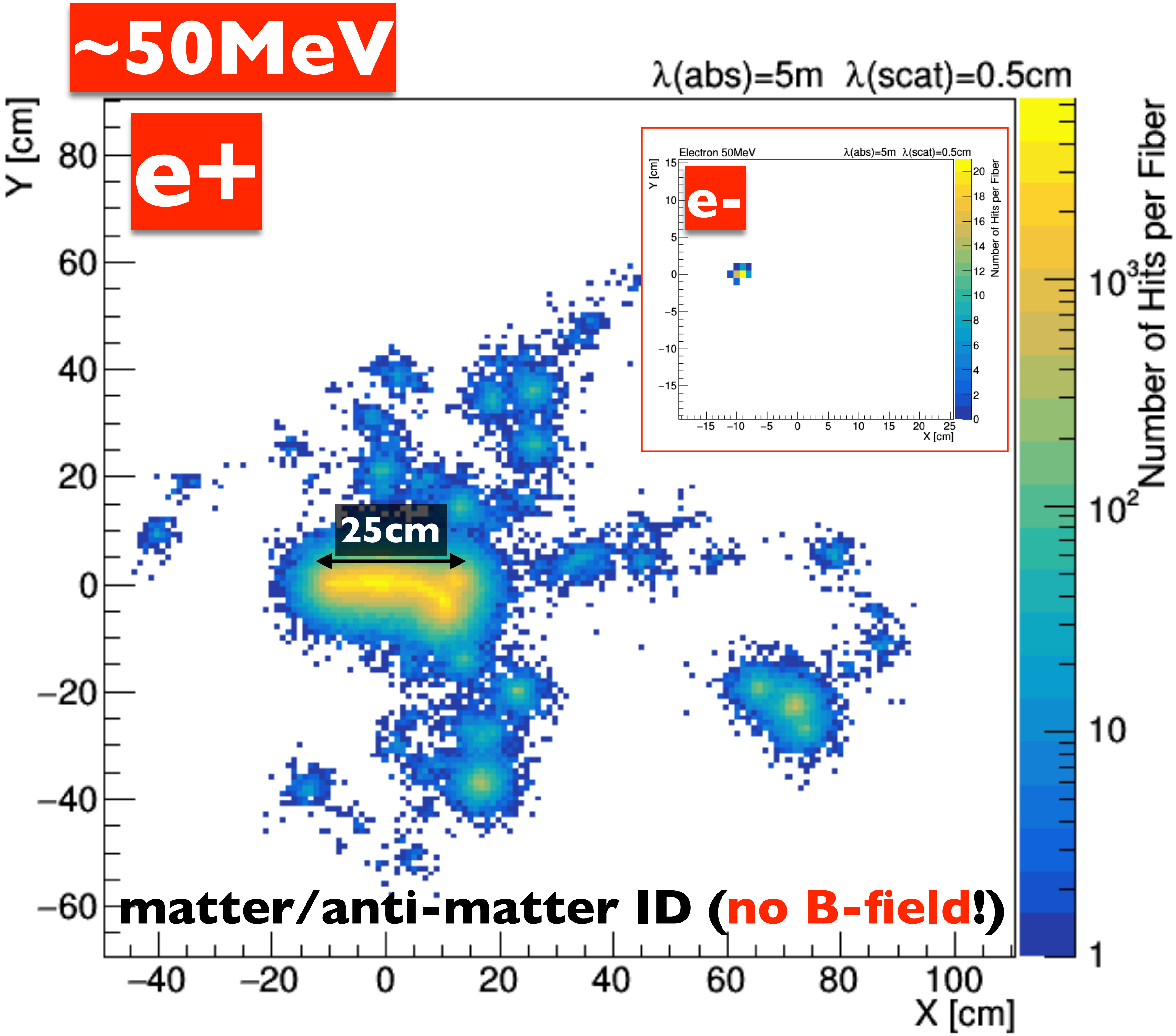


opacity→ (native) self-segmentation

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

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

multi-MeV improves (more light too)…



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

~10MeV: D@R (μ,π,K)**, supernovae** (remnant, core-collapse)**, atmospherics, Michel-e±** (μ-decay)**, etc**

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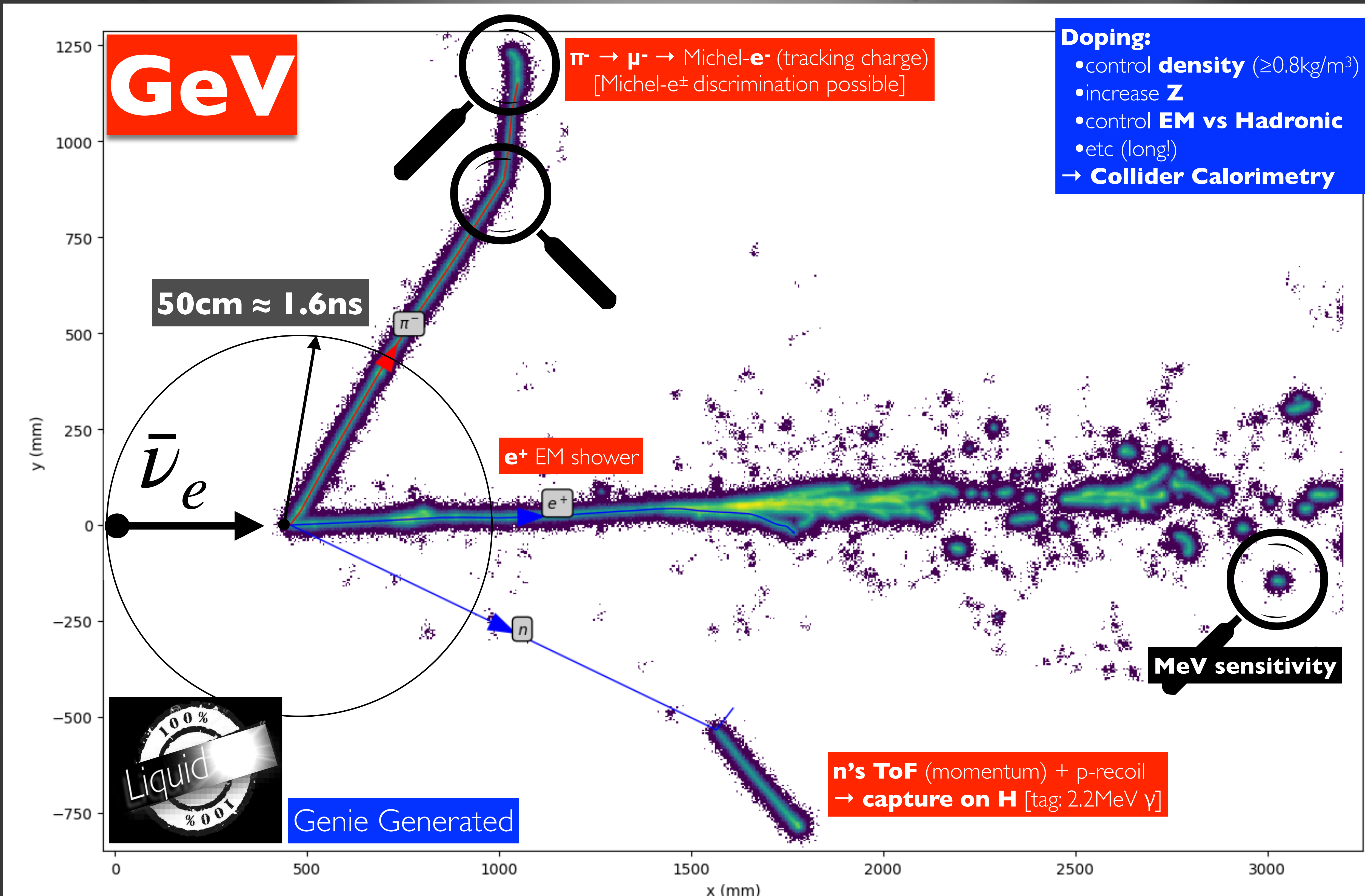
complex GeV with LiquidO…



Stochastic calorimetry order 0.1% [~10^5 PE/GeV] — excellent control of non-stochastic

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

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energy flow: EM evolution of energy in time

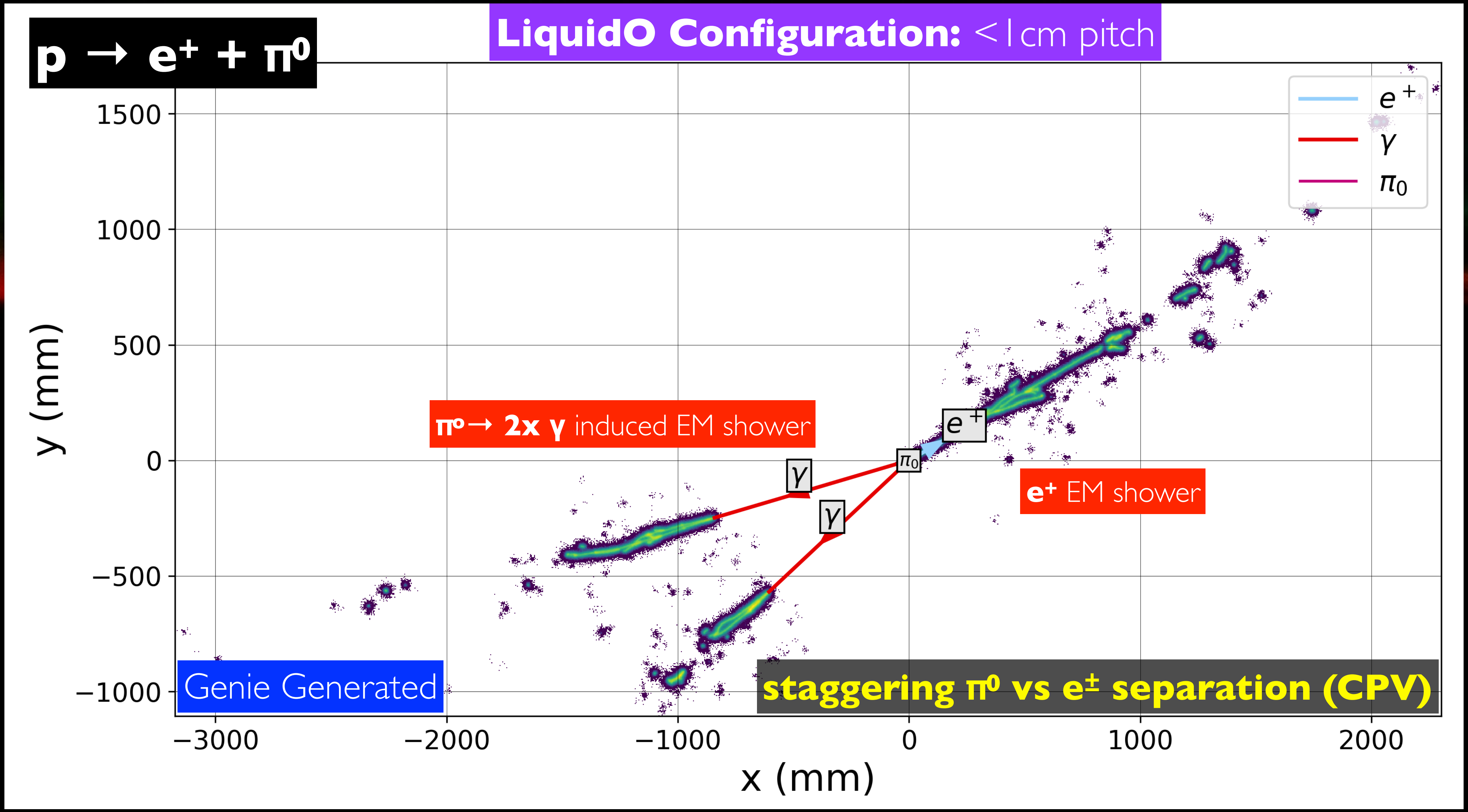
~1GeV

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

discovery channels too…

m(proton)**~1GeV**

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



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

L I Q U I D O

experimental demonstration (data)

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

the first demonstration ≤2020…

nature
communications physics

nature › communications physics › articles › article

Article | Open Access | Published: 21 December 2021

Neutrino physics with an opaque detector

LiquidO Consortium

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

Abstract

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

In the top 25% of all research outputs scored by Altmetric

High Attention Score compared to outputs of the same age (92nd percentile)

High Attention Score compared to outputs of the same age and source (88th percentile)

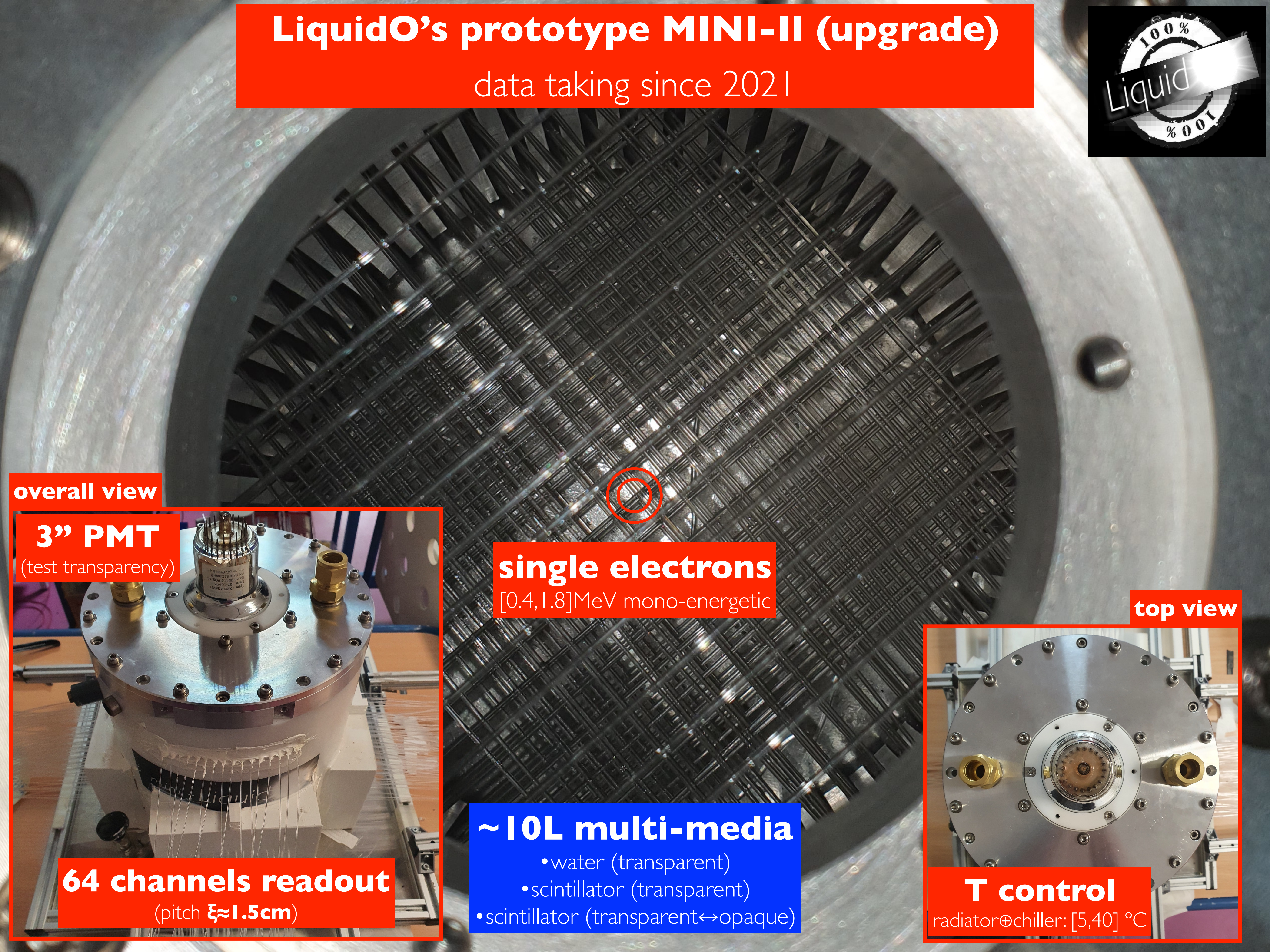
proof-of-concept: *simulation* & data [**μ-LiquidO** prototype]

neutrino physics potential — appetiser

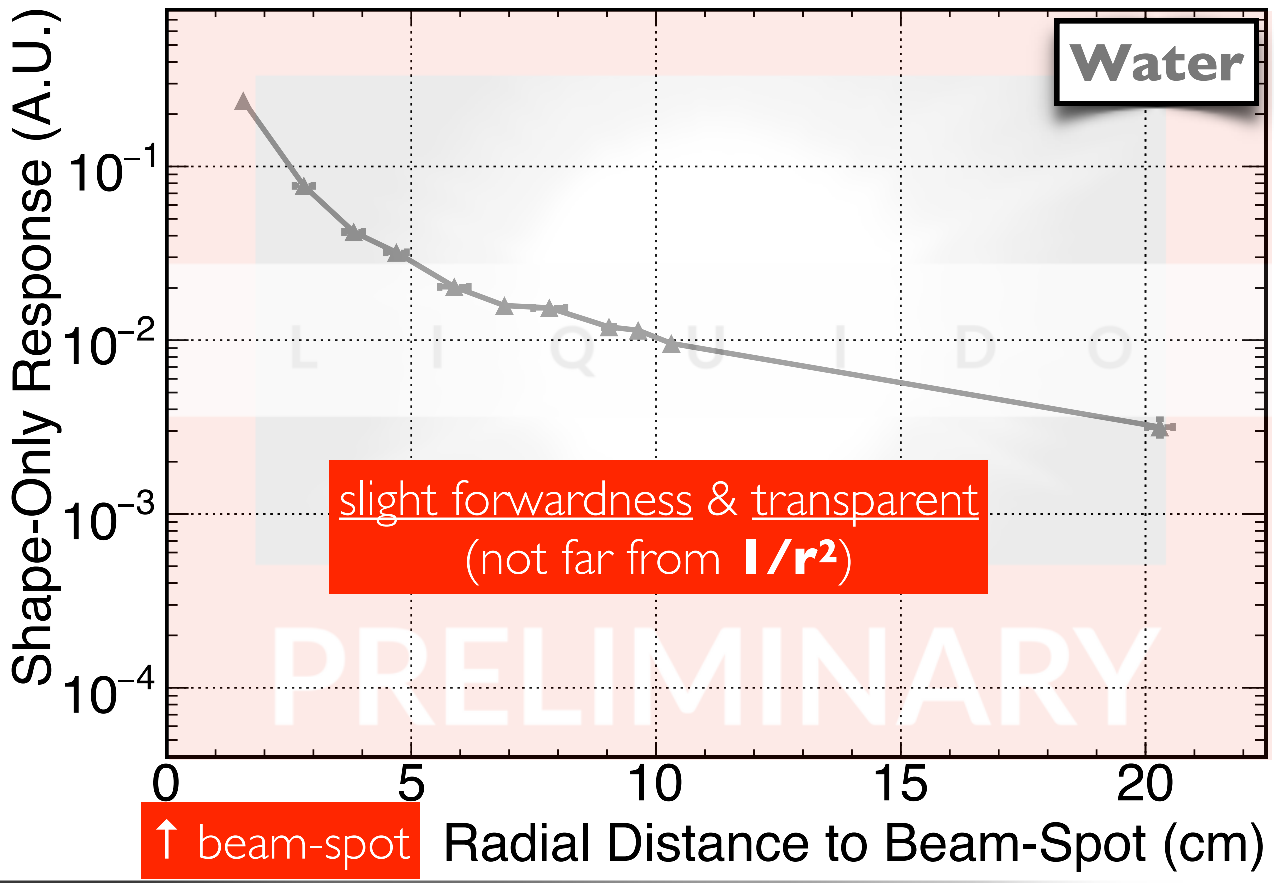
www.nature.com/articles/s42005-021-00763-5

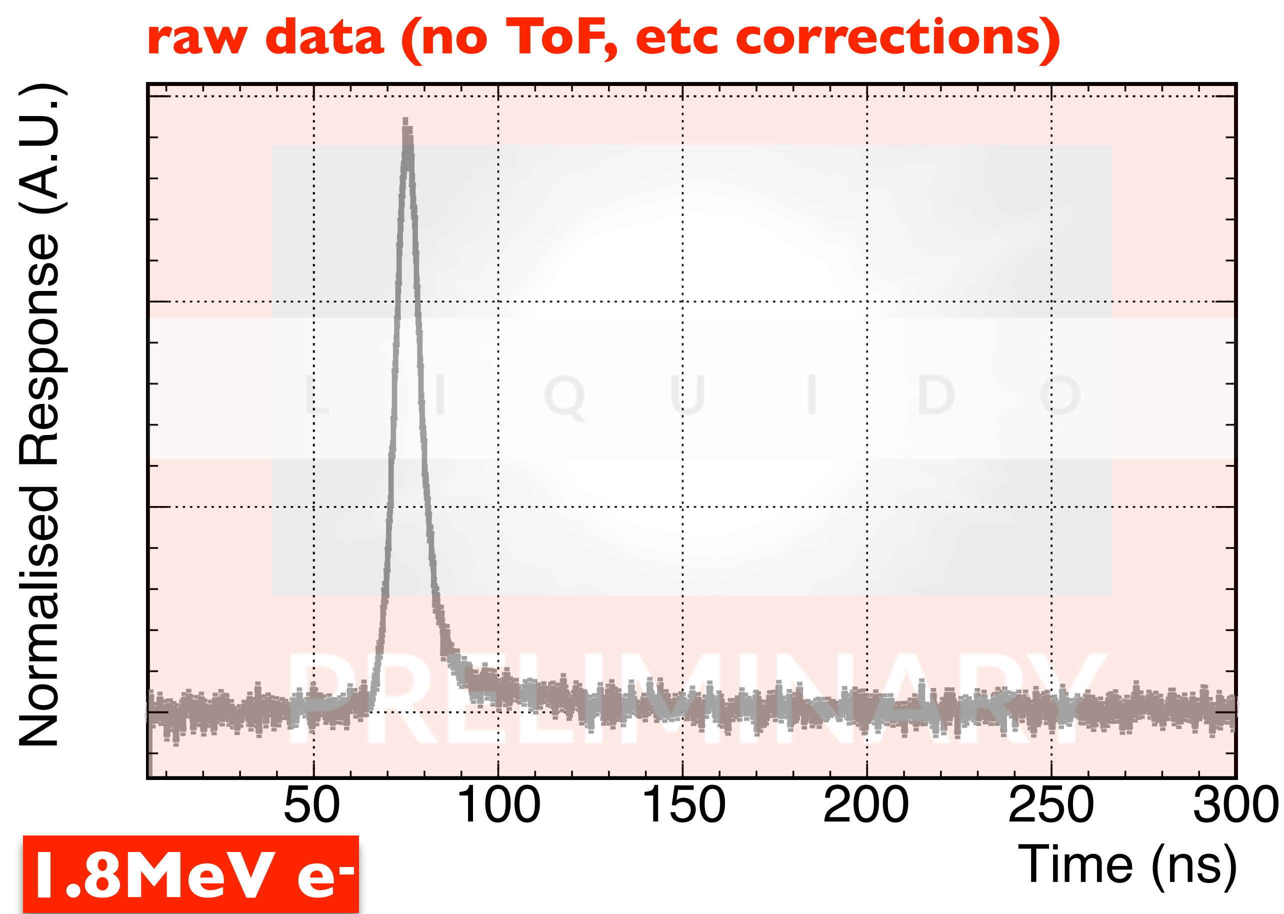
LiquidO's prototype MINI-II (upgrade)

data taking since 2021



Water: single e- Cherenkov only

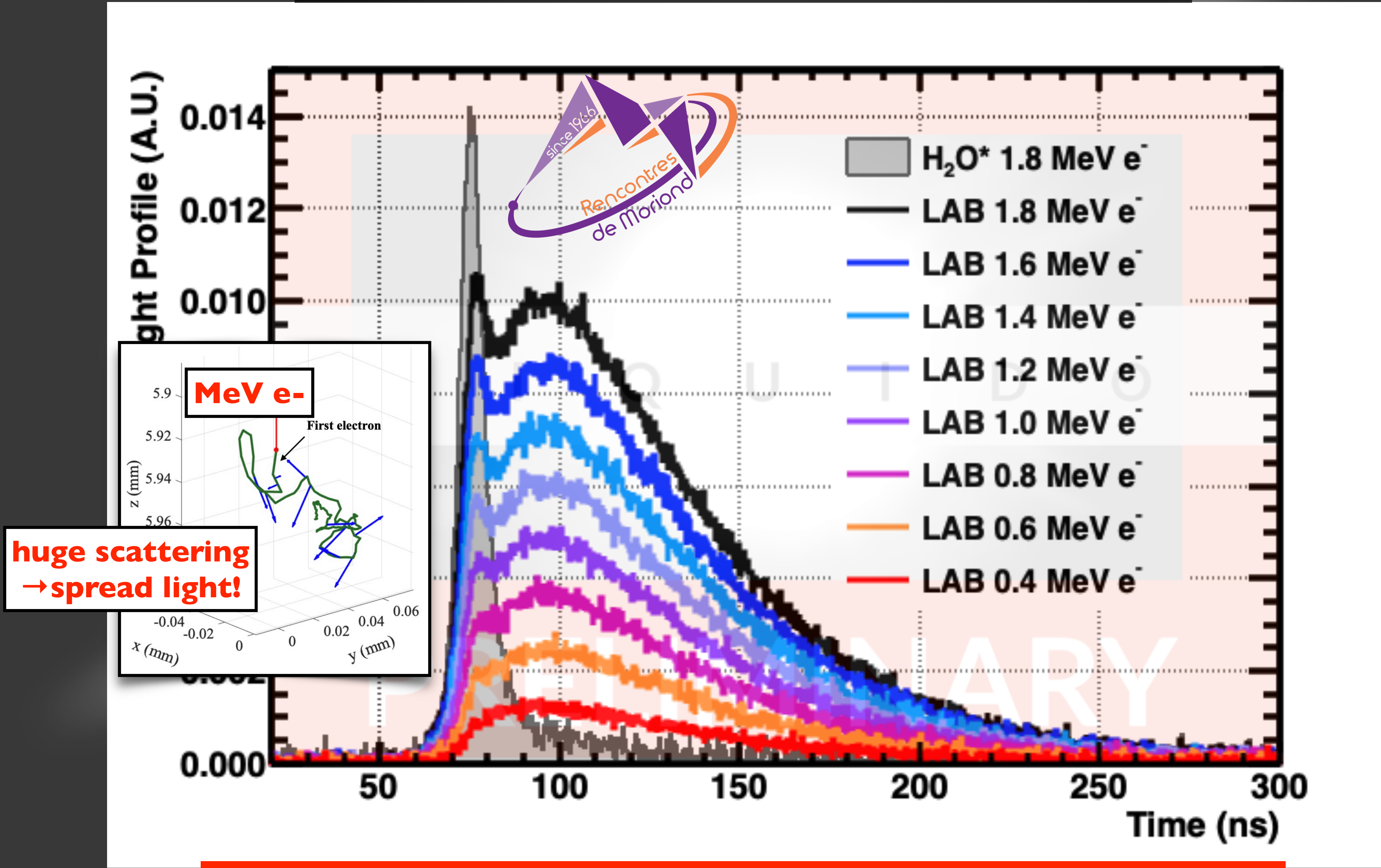




little light: Cherenkov only & transparent (LiquidO's lowest acceptance)

→validate detector's integral timing readout — dominated by fibre's excitation?

Cherenkov time-only ID — threshold
(no topology exploited — unlike μ's)



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

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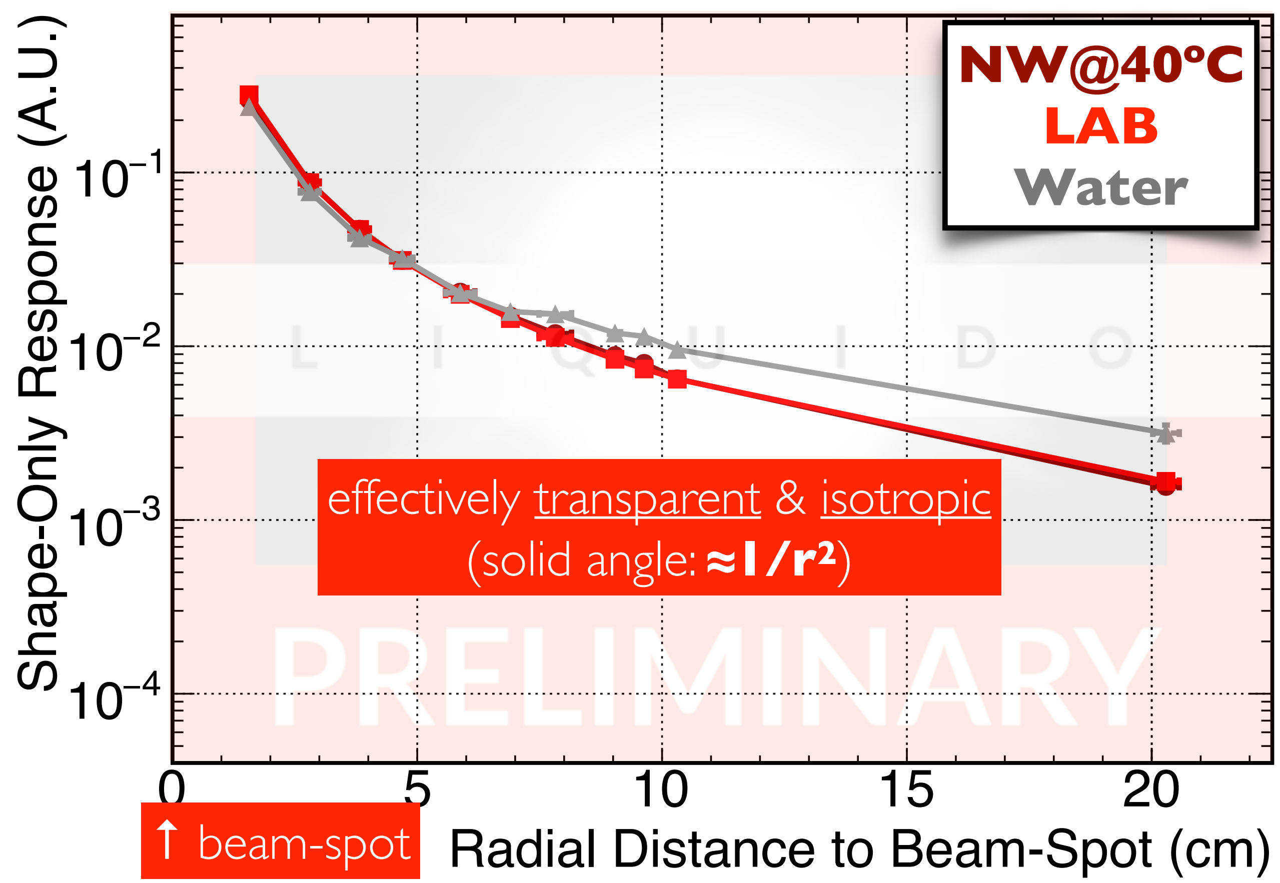
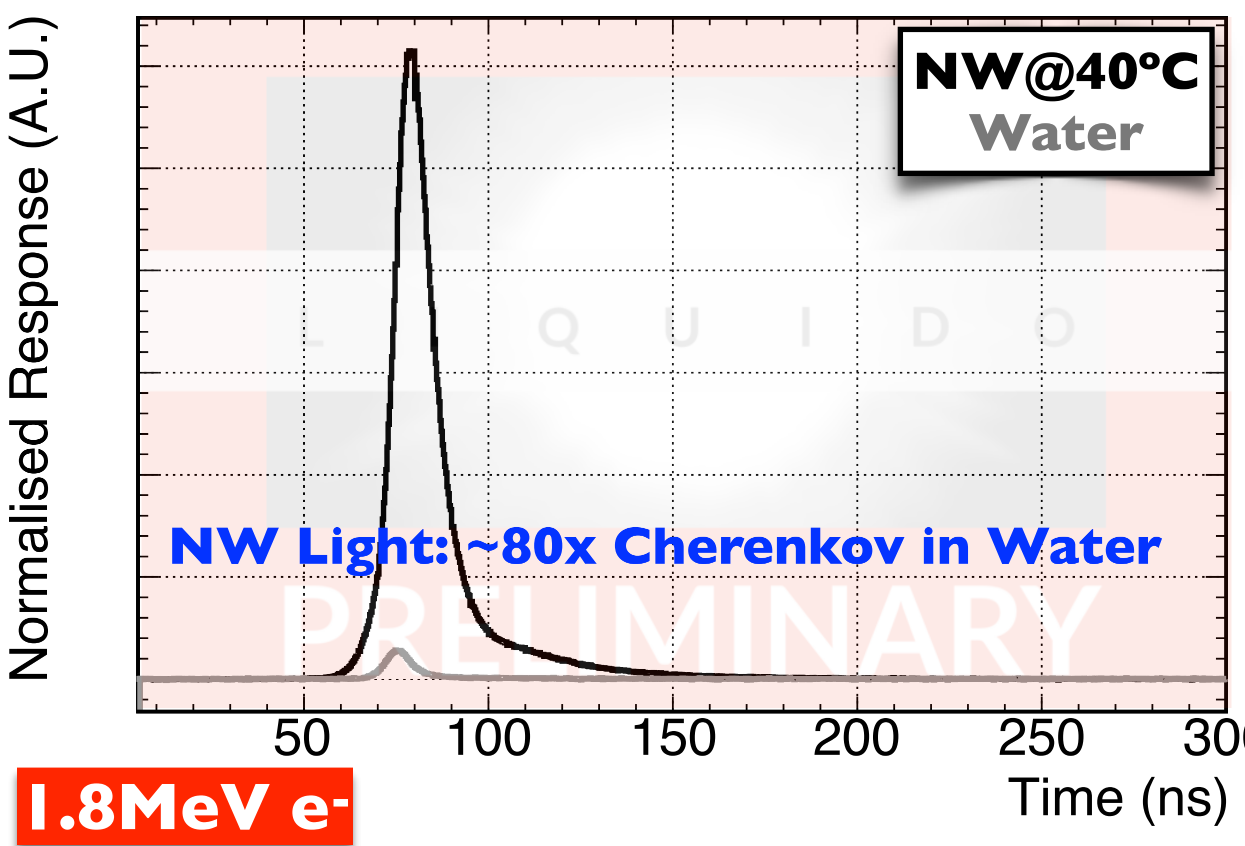
NW@40°: Scintillation⊕~~Cherenkov~~

“NW” = NoWaSH scintillator



raw data (no ToF, etc corrections)



“transparent” — effectively like LAB or Water

more light? scattering enhances fibre’s collection → **translucent** regime

Cherenkov reduced by paraffine? — under investigation

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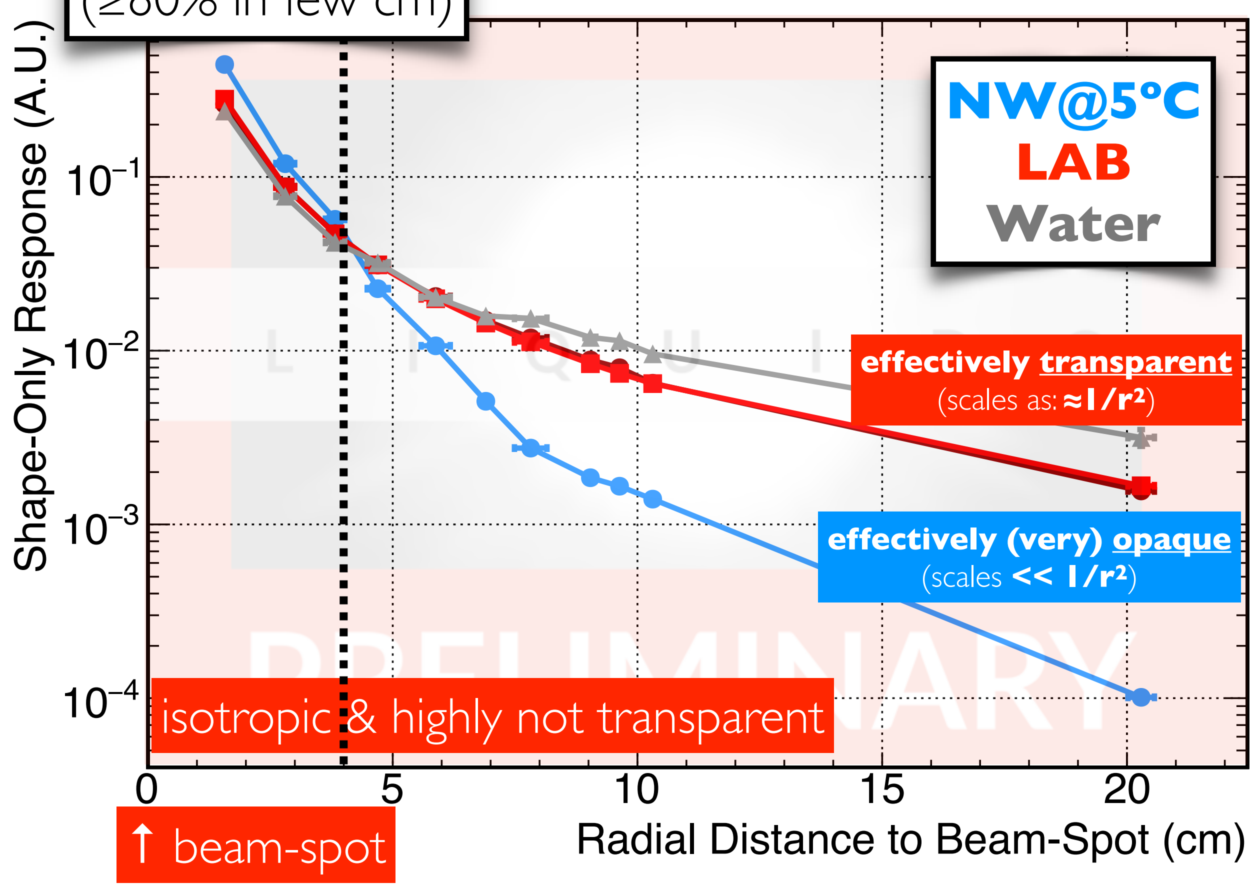
“NW” = NoWaSH opaque scintillator (our prototype scintillator)

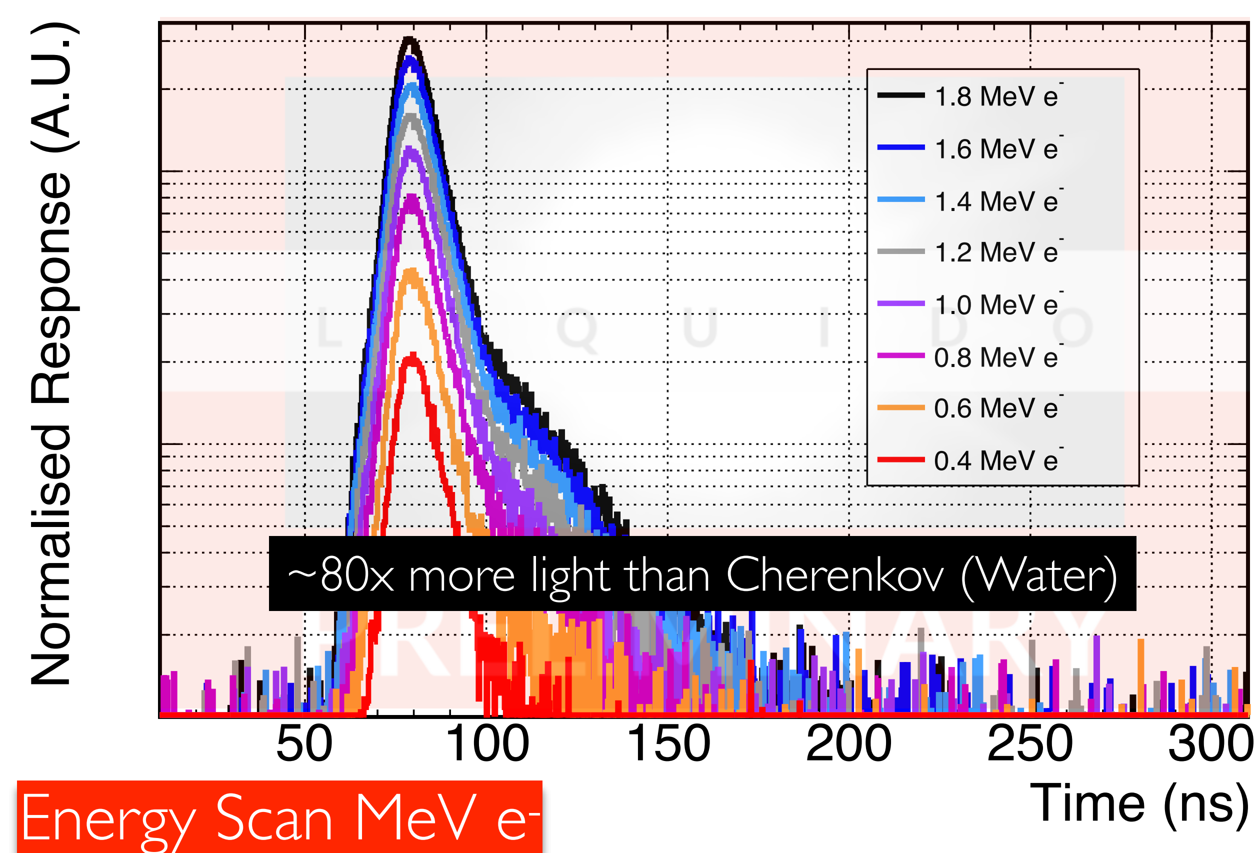
LiquidO (Opaque Scintillation)

Light Ball
more light
(≥80% in few cm)

light falls by almost 4 orders of magnitude in 20cm — very opaque indeed



raw data (no ToF, etc corrections)



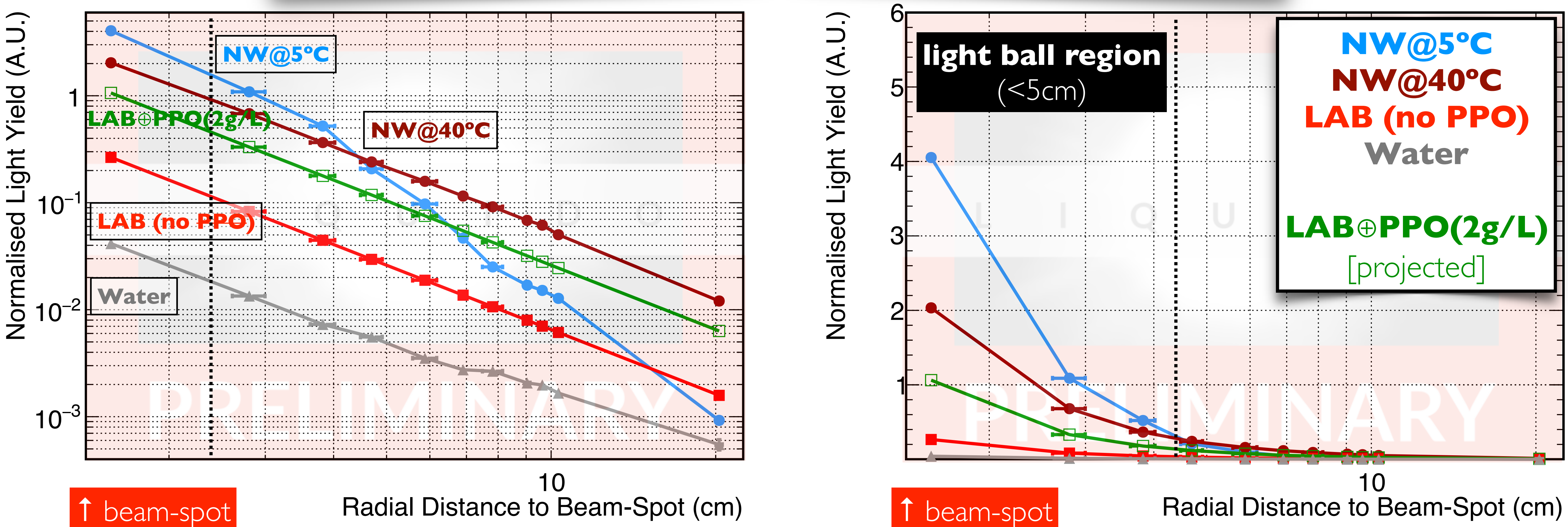
more light thanks to LiquidO’s aggressive scattering…

- faster collection & better light containment
- formation **topology**→ **stochastic light confinement** →LiquidO

self-segmentation→lossless light scattering [data→**negligible losses?**]

light yield exploration…

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)

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light-opacity duality…

LiquidO’s Duality: lightness & darkness coexist

“one is cause/consequence of the other”

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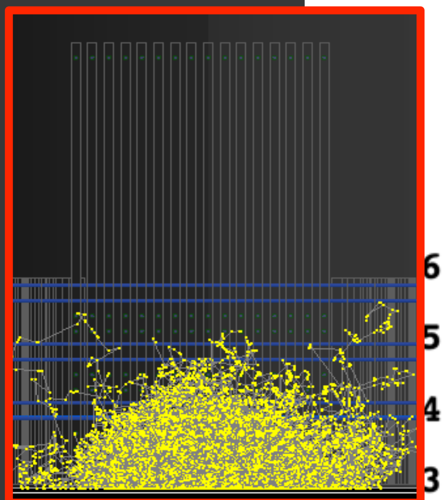
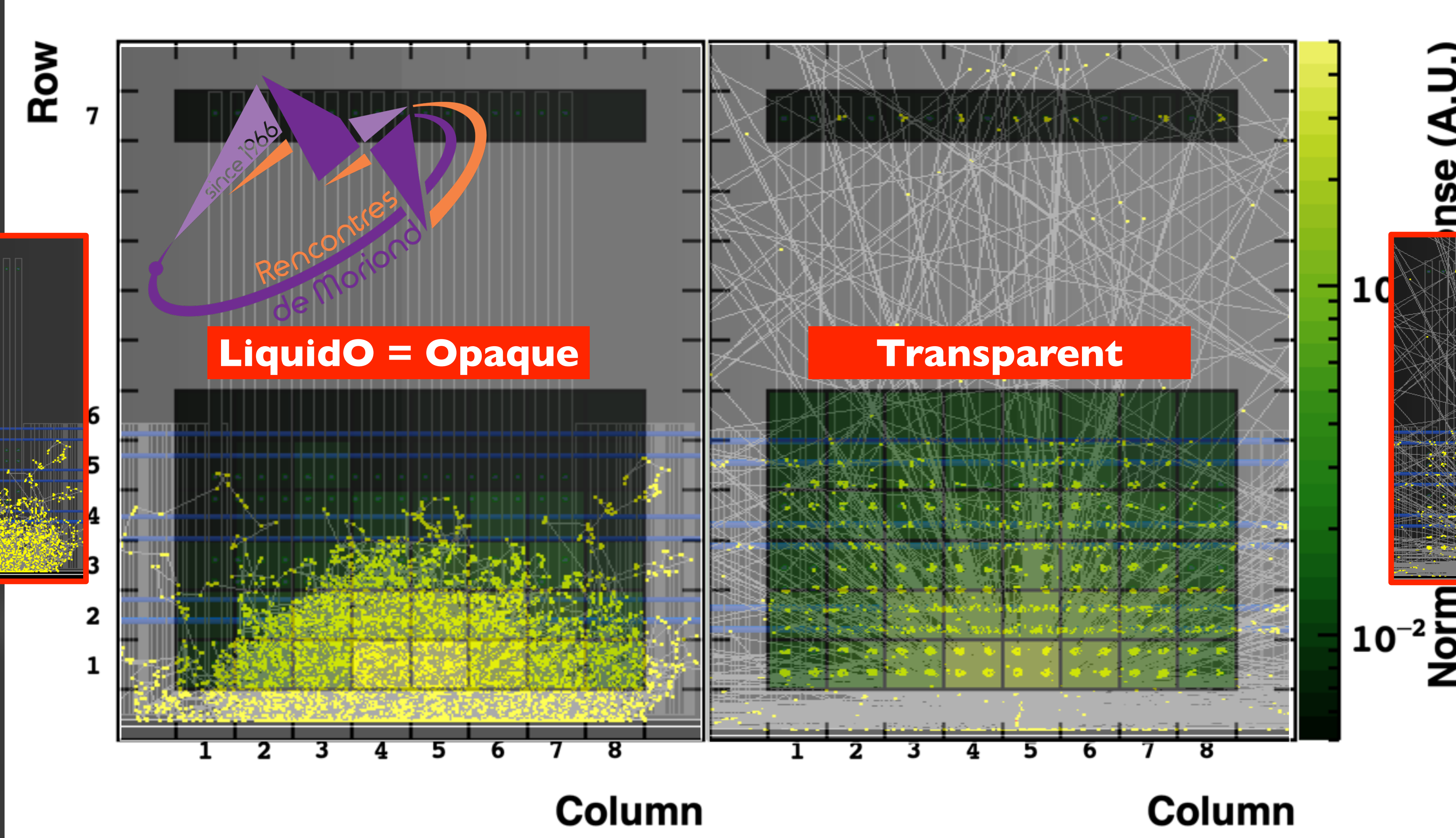
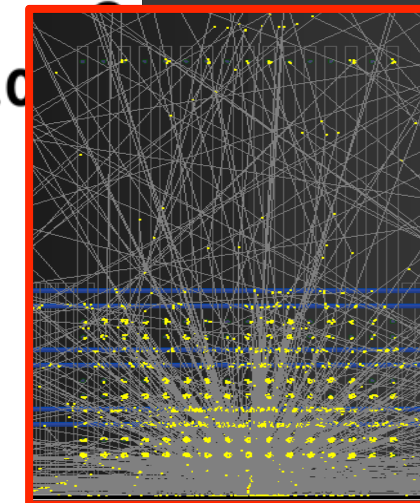
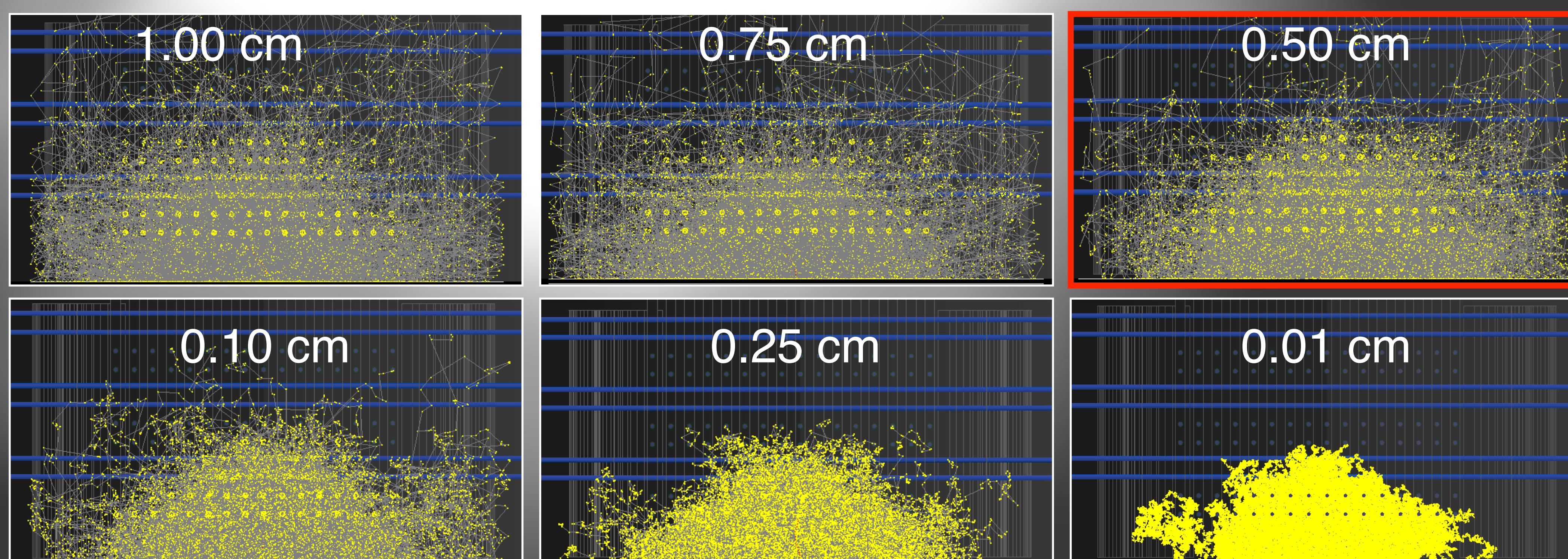





Geant4 Simulation (under tuning)

"light ball" size:

- scattering: λ_s
- # fibres
- absorption?



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…**

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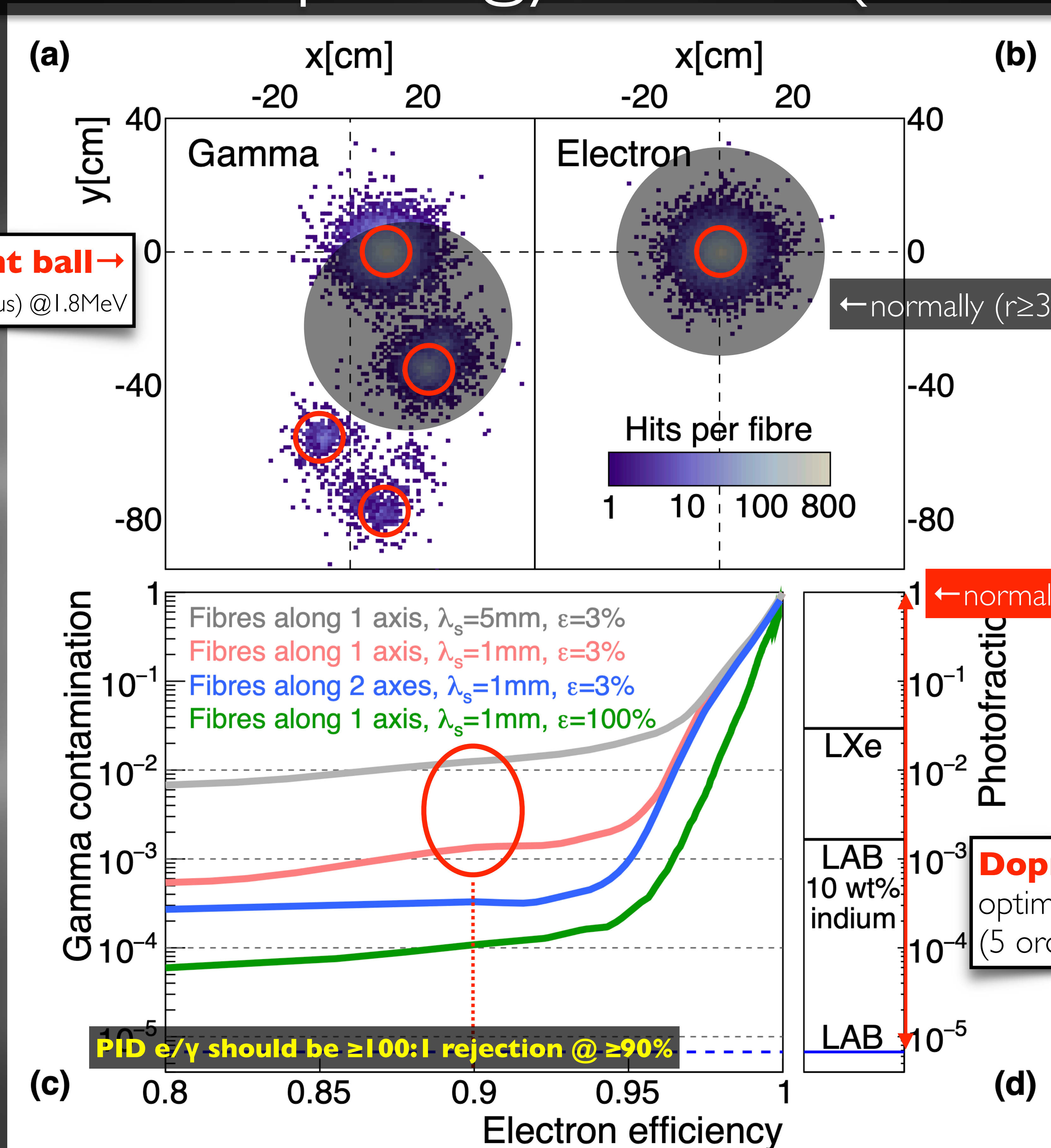
topology's PID (no timing)…



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

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

←normally here: **NO e/γ PID**

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

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

LiquidO: light detector with **opaque** medium

[*stochastic light confinement*→**imaging**⊕topology & **PID**]

⇓

LiquidO (5D primitive imaging info**)**

L I Q U I D O

light-based **"TPC"** (highest duty-cycle)

⊕

uniform calorimeter (scintillation)

⊕

Time-of-Flight (4π acceptance)

⊕

imaging (PID, energy-flow, magnetisable, etc)

⊕

doping (variable composition/density & more physics)

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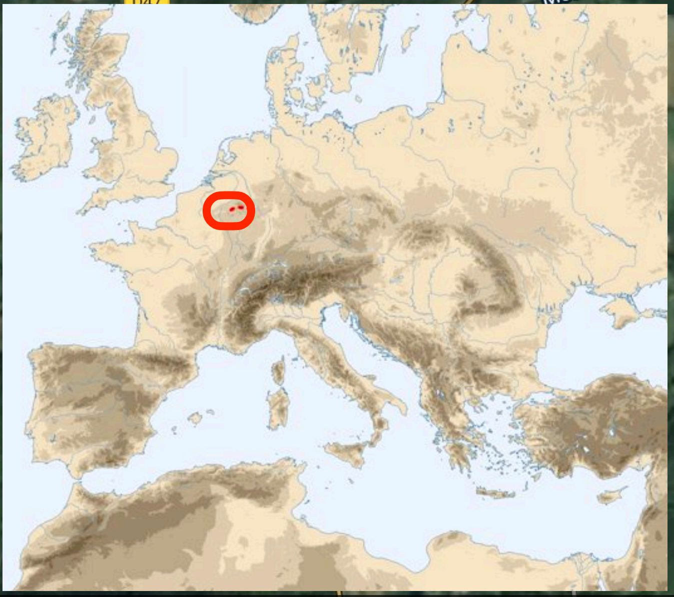
physics?

LIQUID

somewhere in the middle of Europe, there is Chooz…



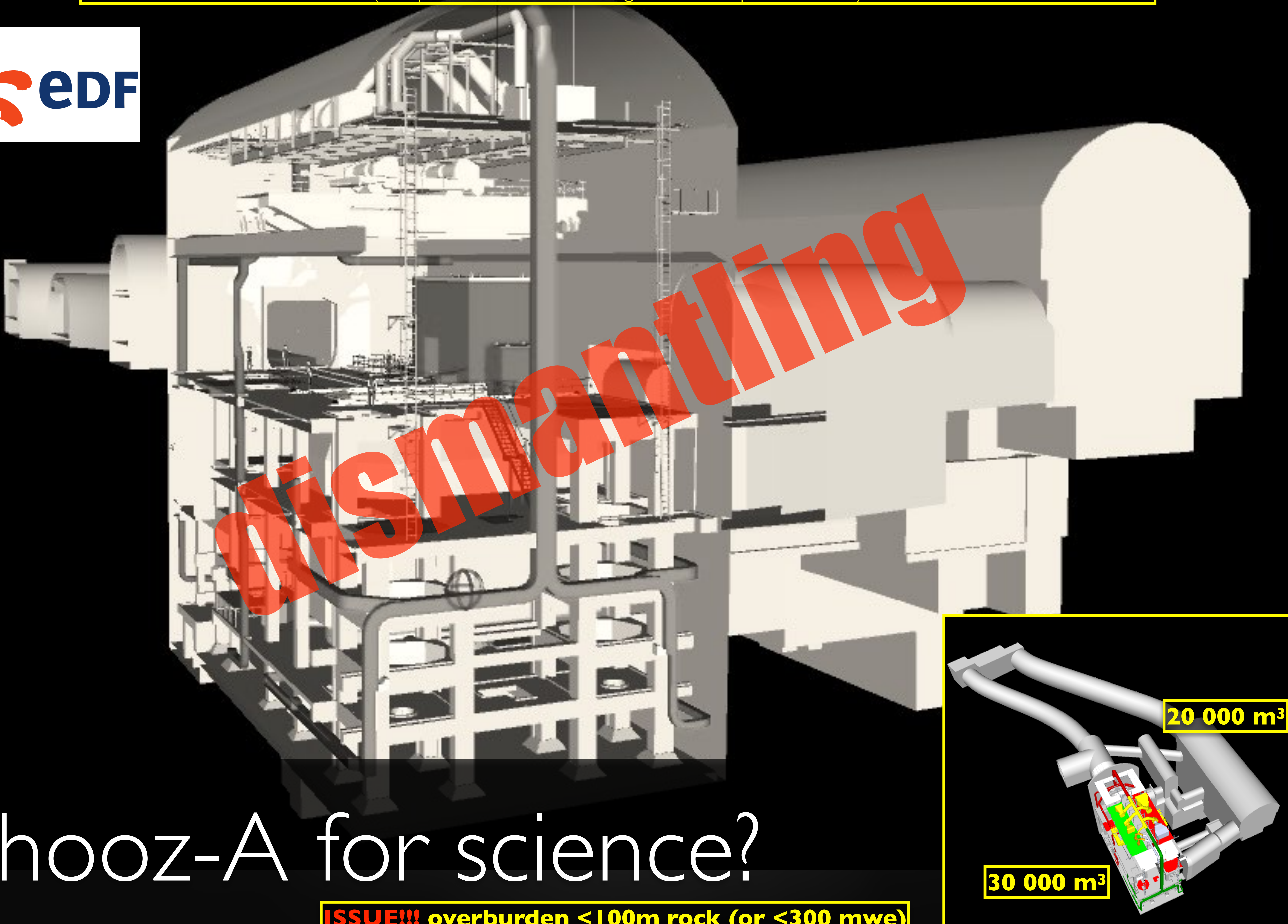
les Ardennes
(France-Belgique)

maybe Chooz?

Chooz *is tiny cute little village in the Ardennes*

Chooz = powerful reactor(s) ⊕ overburden

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



Chooz-A for science?

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

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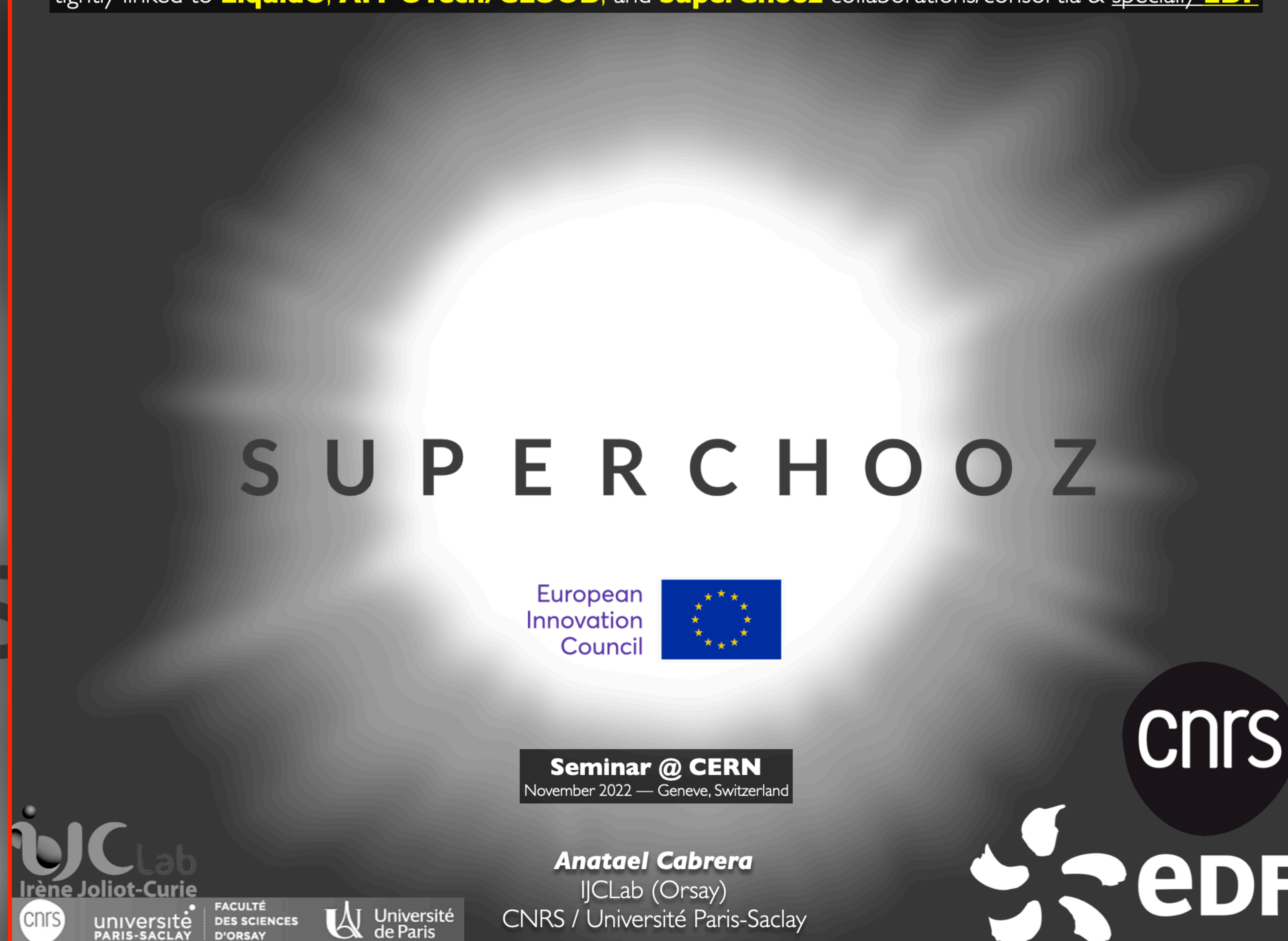
CERN EP-Seminar 2022 https://indico.cern.ch/event/1215214/

tightly linked to **LiquidO**, **AM-OTech/CLOUD**, and **SuperChooz** collaborations/consortia & specially **EDF**



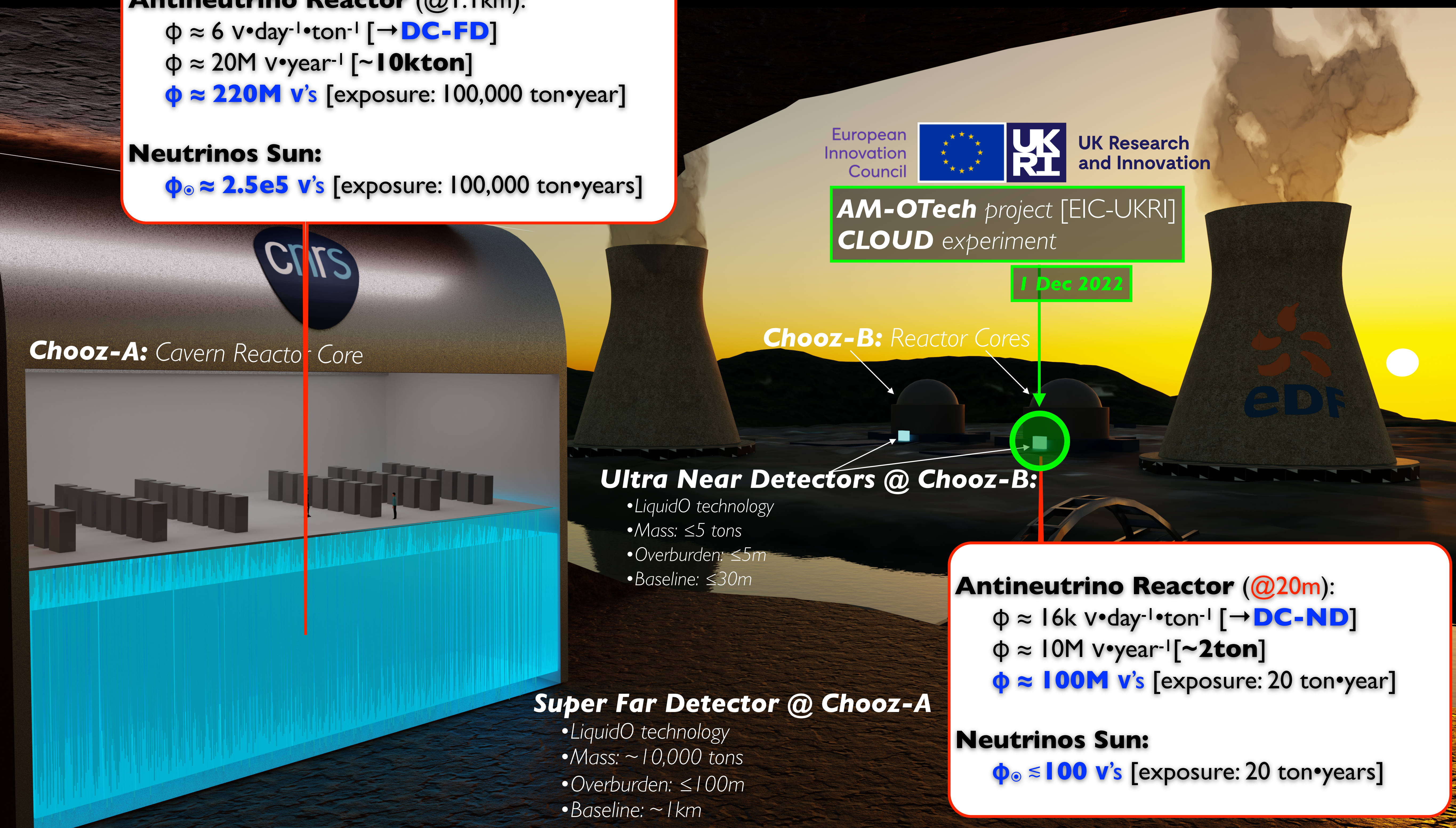
DOI 10.5281/zenodo.7504162 https://zenodo.org/record/7504162

SuperChooz just released…

SuperChooz experimental site…

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

Neutrinos Sun:
- **$\phi_\odot \approx$ 2.5e5 ν's** [exposure: 100,000 ton•years]



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

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

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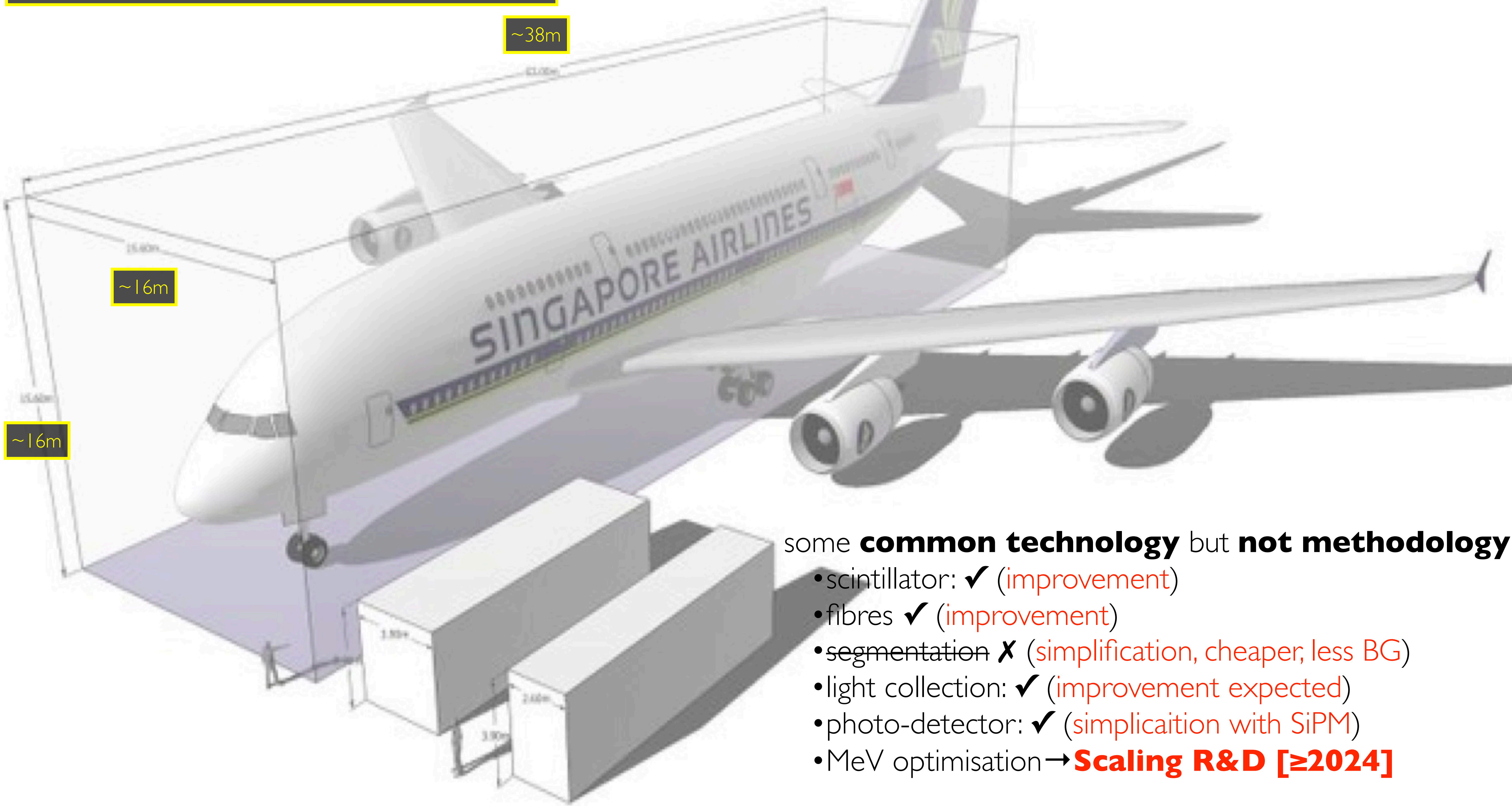
neutrinos in Europe?

powerful synergies JUNO⊕HyperK⊕DUNE — after all running!

experimental demonstration...

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)**

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:

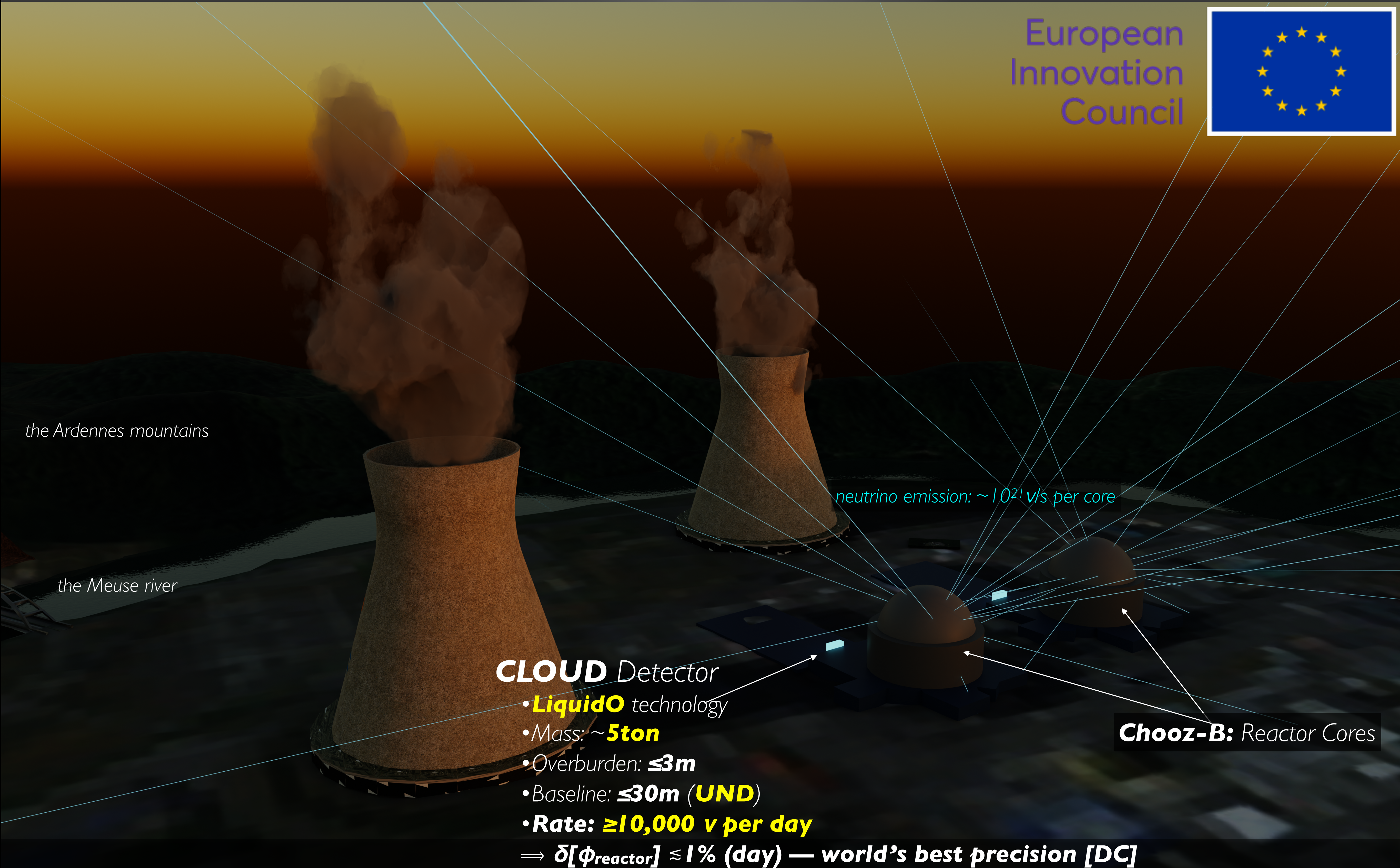
- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

IB Chair:

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

Webs:

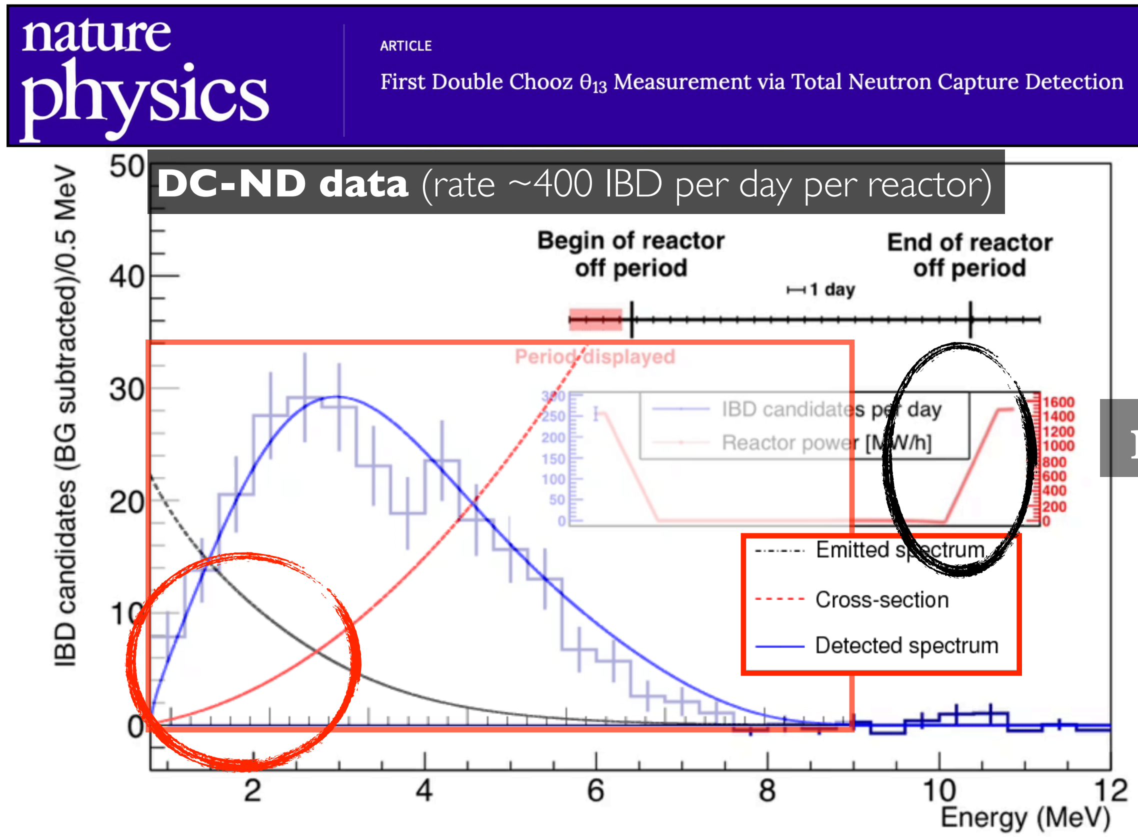
https://antimatter-otech.ijclab.in2p3.fr/ [AMOTech]
https://liquido.ijclab.in2p3.fr/nucloud [via LiquidO]



experimental setup…

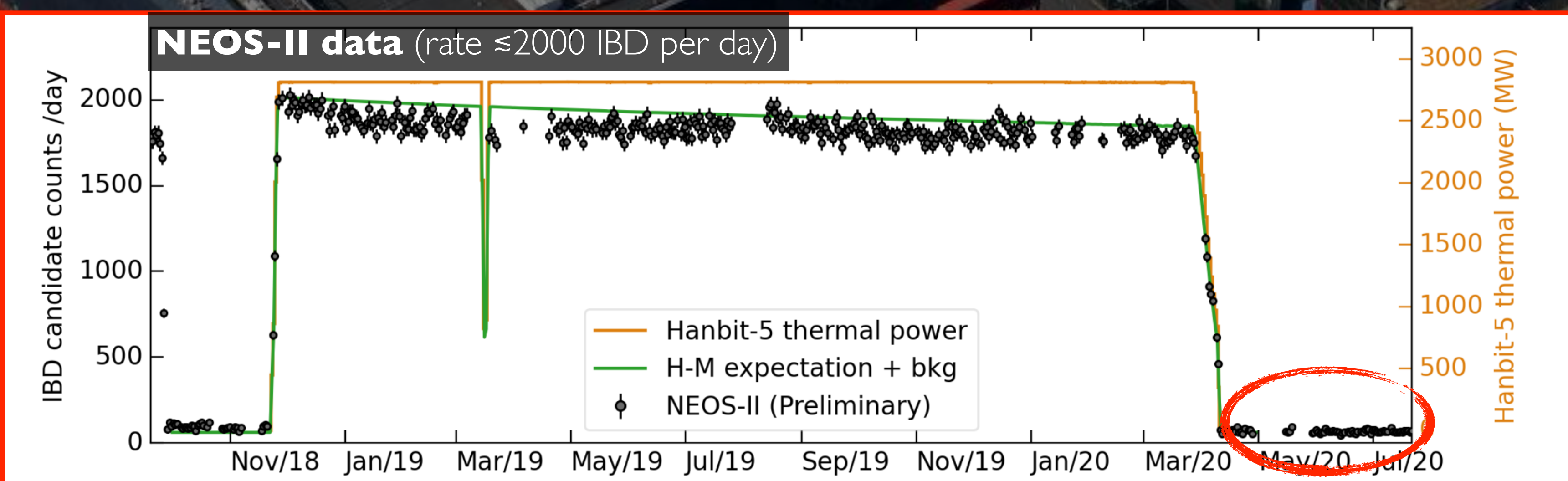

Chooz-B Power Station
•facility: EDF CNPE
•location: Chooz (France)
•reactor cores: 2x PWR AREVA-N4
•thermal power: 8.4GW (total)
Double Chooz
Near Detector
LNCA-Hall (CNRS)
Ultra Near Detector (UND) sites
Centrale Electrique
OFF
ON
N4: 4.2GW
fuel pool
25.5m
PRELIMINARY
Double Chooz
Far Detector

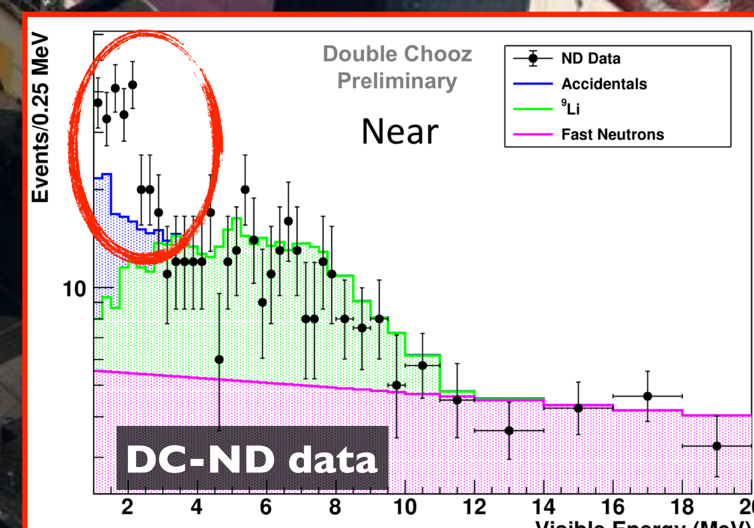
reactor neutrinos…



DC-ND overburden ~30m (BG subtracted)

neutrino rate ≈ reactor thermal power





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

C L U D

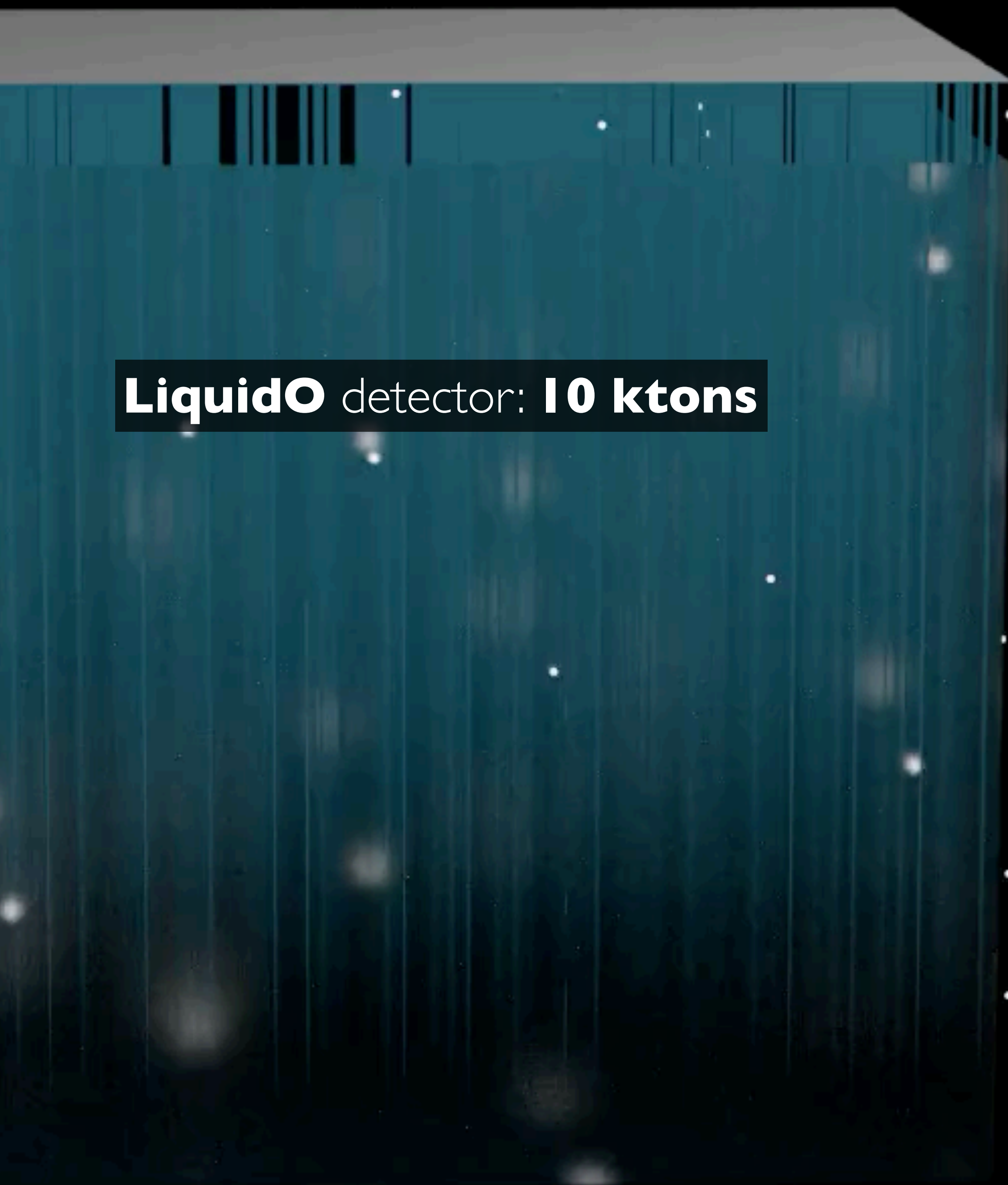
European Innovation Council

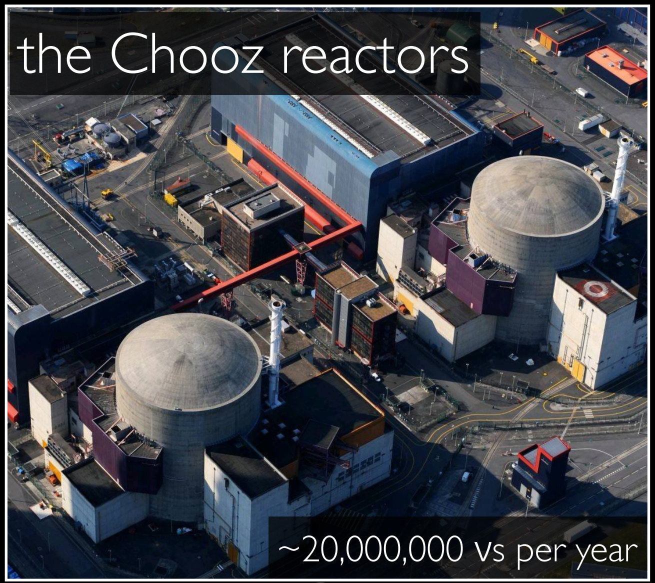
UK Research and Innovation

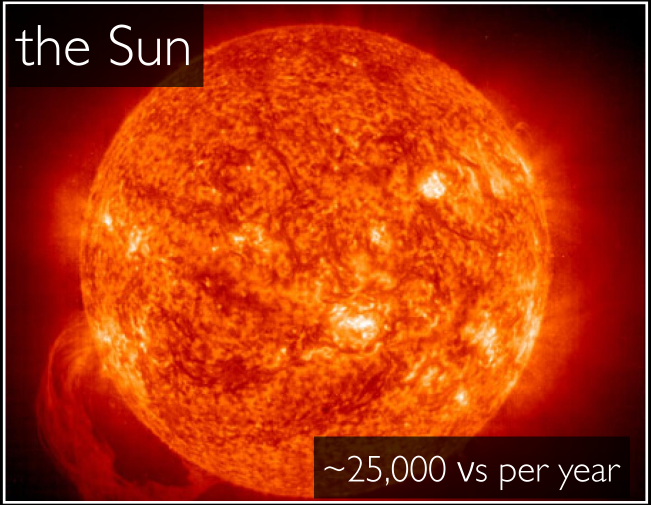
funded & preparing construction…

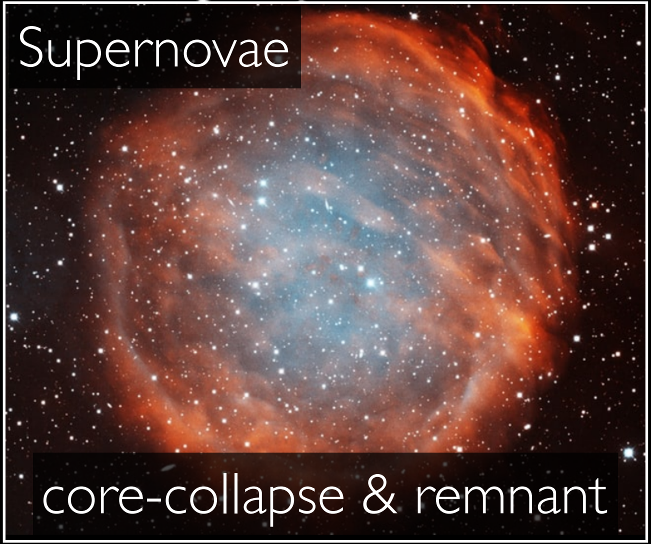
neutrino sources…

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









…also **atmospherics**!!

geoneutrino? yes, but huge irreducible background by reactor neutrinos!!

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

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REGISTRATION OPEN UNTIL OCT 25: ***Register***

Preliminary agenda now avaliable

You can check it **here**

The abstract submission closed on Oct 6th

DUNE Module of Opportunity Open Workshop

The DUNE experiment consists of four 17 kton liquid-argon far detector modules in separate cryostats. The technology choices for the first two modules have been established and are being implemented as part of the experiment's Phase I. The third and fourth modules will complete the DUNE Far Detector. These modules provide opportunity for further development of liquid-argon or alternate detector technologies in support of the DUNE physics goals.

The DUNE Collaboration invites the broader particle physics community to participate in this OPEN WORKSHOP (DUNE collaboration membership not required) to explore options for expanded physics opportunities and novel detector technologies for these "modules of opportunity" that will be part of DUNE's Phase II. The meeting will address how to improve the DUNE's primary physics program and how to broaden the physics scope of the experiment. The meeting will cover all major aspects of liquid argon TPC technology, including proposals for improvements in tracking, photon detection, electronics, high voltage, electronics and data-acquisition, considering improvements in detector integration, installation and background reduction. New detector concepts that can satisfy and expand the DUNE physics goals are also encouraged.

This is the second edition of this workshop series. The first edition was held at BNL (USA) in November 2019: https://www.bnl.gov/dmo2019/

This Workshop is sponsored by:

IFIC Institut de Física Corpuscular — CSIC Consejo Superior de Investigaciones Científicas — Universitat de València — Facultad de Física — Departamento de Física Atómica, Molecular y Nuclear

Gobierno de España, Ministerio de Ciencia e Innovación — Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas — cfp CIEMAT física de partículas

possible support to DUNE?

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anatael@in2p3.fr

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

L I Q U I D O

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

LiquidO — performance **proved**→ **optimisation!! (**first experiments **funded→imminent construction)**

- **how far? bring neutrino detection to the surface**… ?
    - **robust & rich detection framework** — **sub-atomic topology imaging** (PID) / **mm vertex** / **doping**, etc
    - **R&D** (still)**: enhance & specialise performance** — ex. **new opaque scintillators!**
- **CLOUD/AntiMatter-OTech**: fundamental science physics programme [**publication soon**]→ **SuperChooz** one day**?**