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Energéticas, Medioambientales
y Tecnológicas

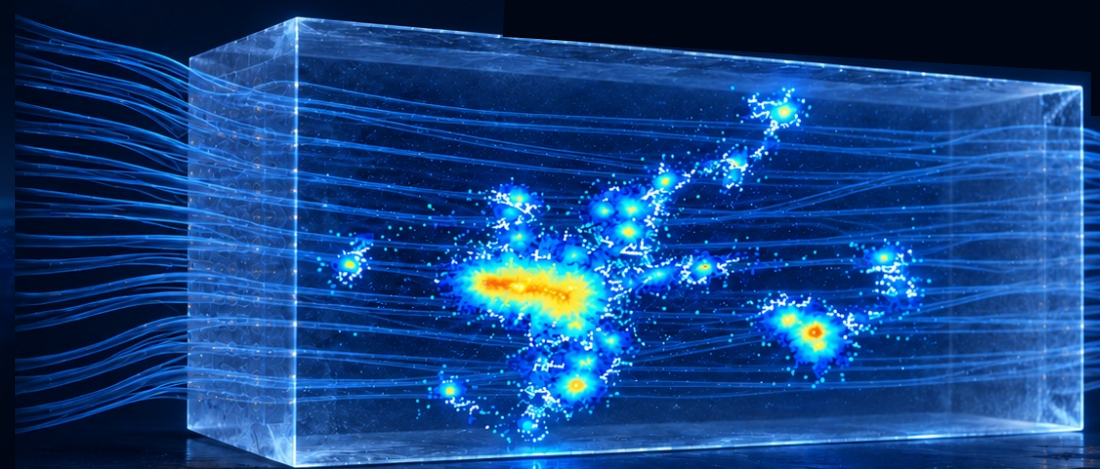
Liquid

Event Reconstruction in Opaque Scintillators

Diana Navas Nicolás

On behalf of the LiquidO Collaboration

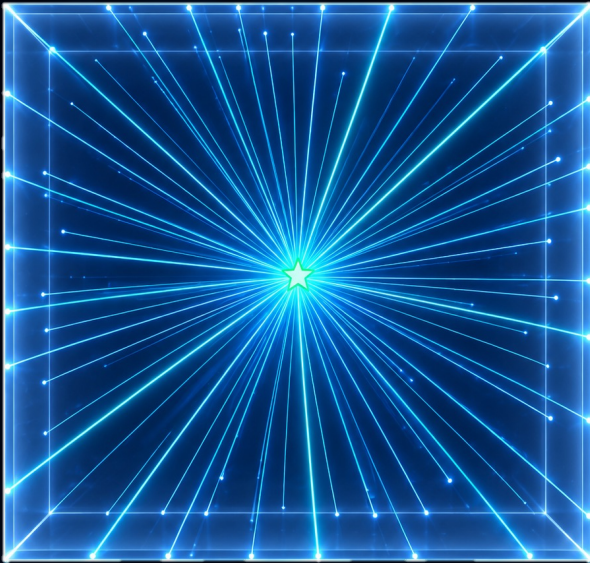
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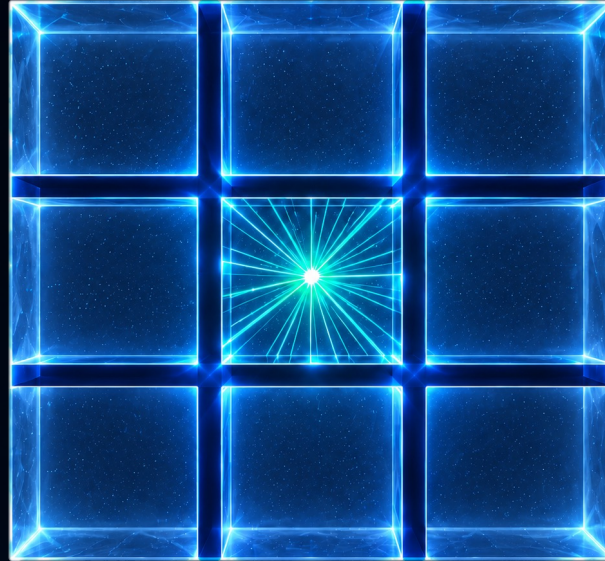
LiquidO: from transparent to opaque media

Transparent

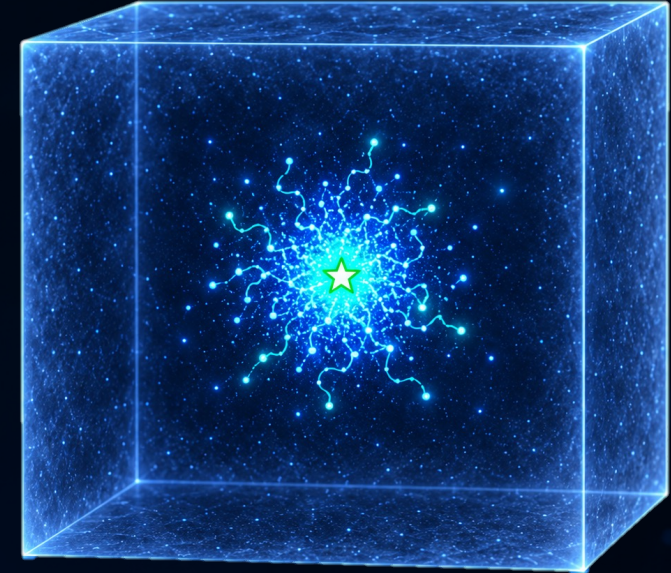
Single volume



Segmented



Opaque



- Light propagates over long distances
- Excellent calorimetry
- Limited local topology

- Spatial information through segmentation
- Increased detector complexity
- Inactive boundaries

- Strong stochastic scattering
- Local light confinement
- Self-segmented detector
- Topological information preserved

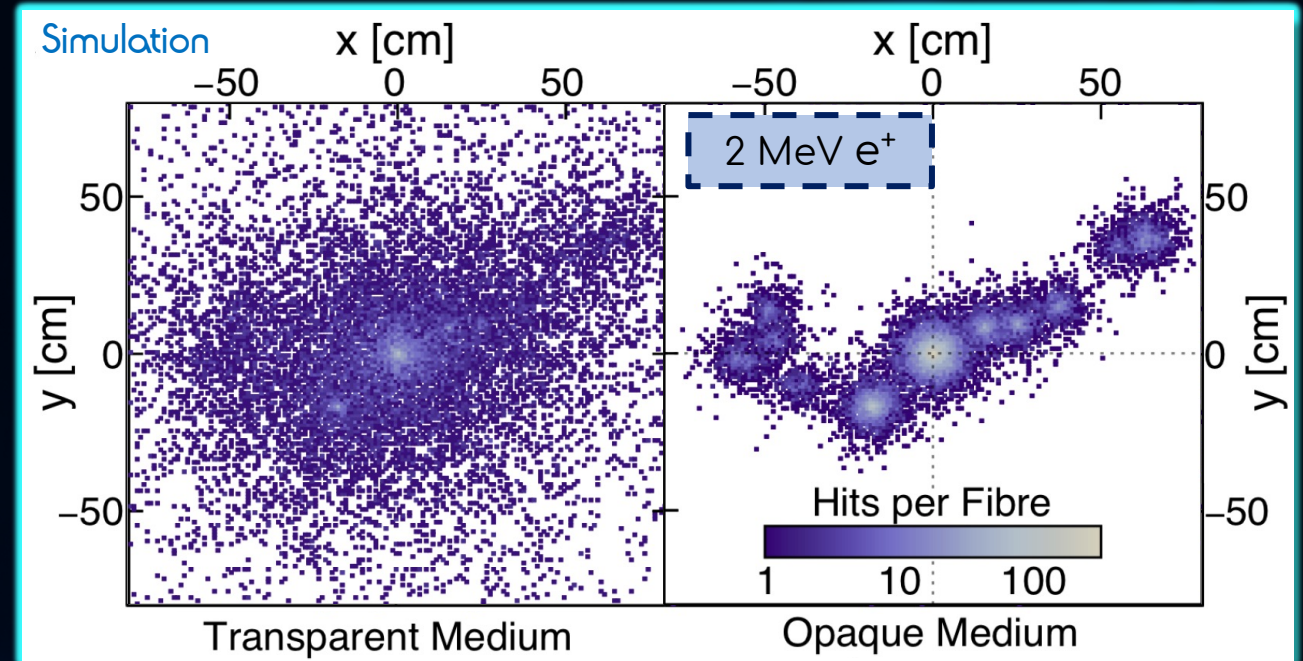
The LiquidO ingredients

1) Opaque scintillator

- ★ Originally using NoWaSH (NW) [arXiv:1908.03334](https://arxiv.org/abs/1908.03334)
- ★ Linear Alkyl Benzene (~80 wt.%) + PPO (~0.3 wt.%) + Paraffin Wax (~20 wt.%)
- ★ LiquidO R&D extensive field: reduction of the paraffin concentration, water-based opaque scintillator [arXiv:2406.13054](https://arxiv.org/abs/2406.13054), μ Crystal scintillators [arXiv:1807.00628](https://arxiv.org/abs/1807.00628), emulsion...

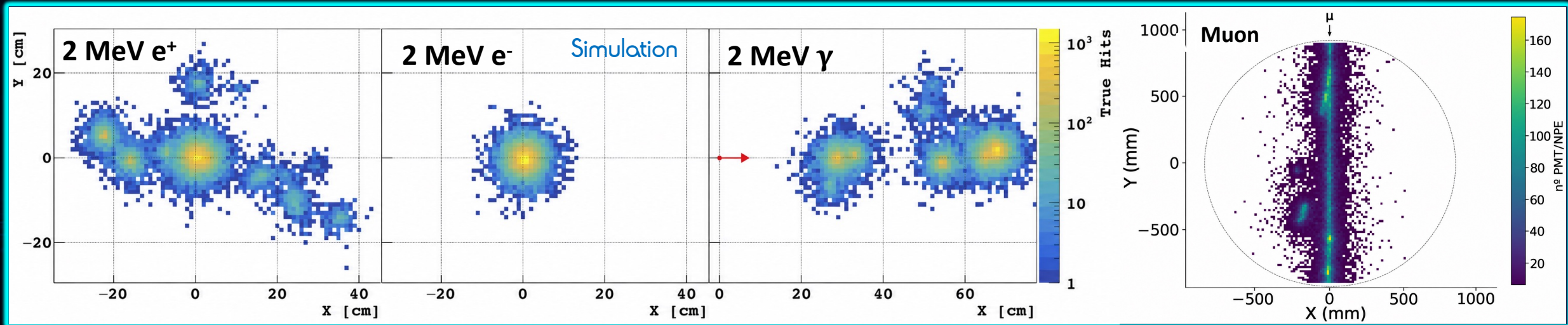
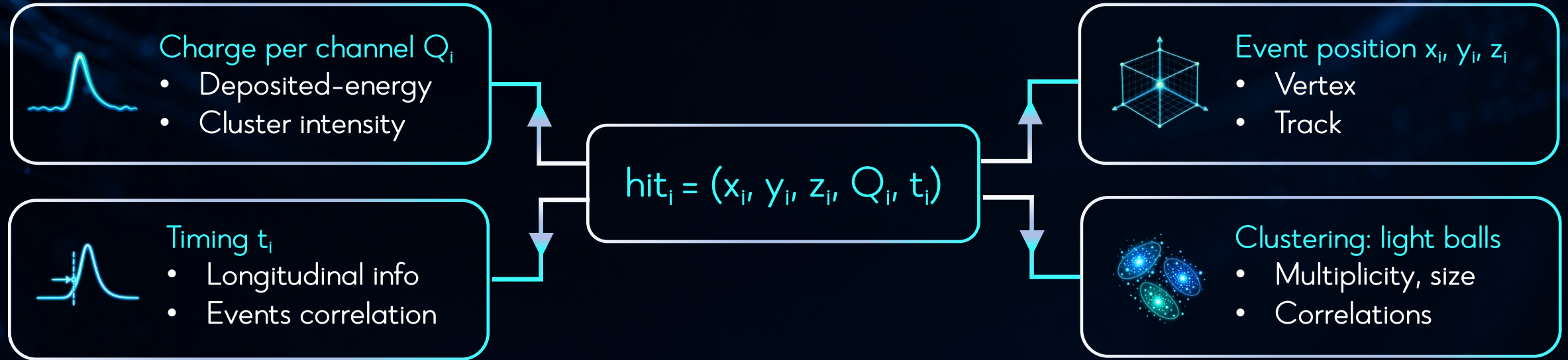
2) Maximal light collection by a dense array of wavelength-shifting (WLS) fibers

3) Fast time resolution (electronics + SiPMs) (~ ns)



- ★ Discrimination of individual e^+ , e^- and γ events @MeV
- ★ Powerful Background Rejection

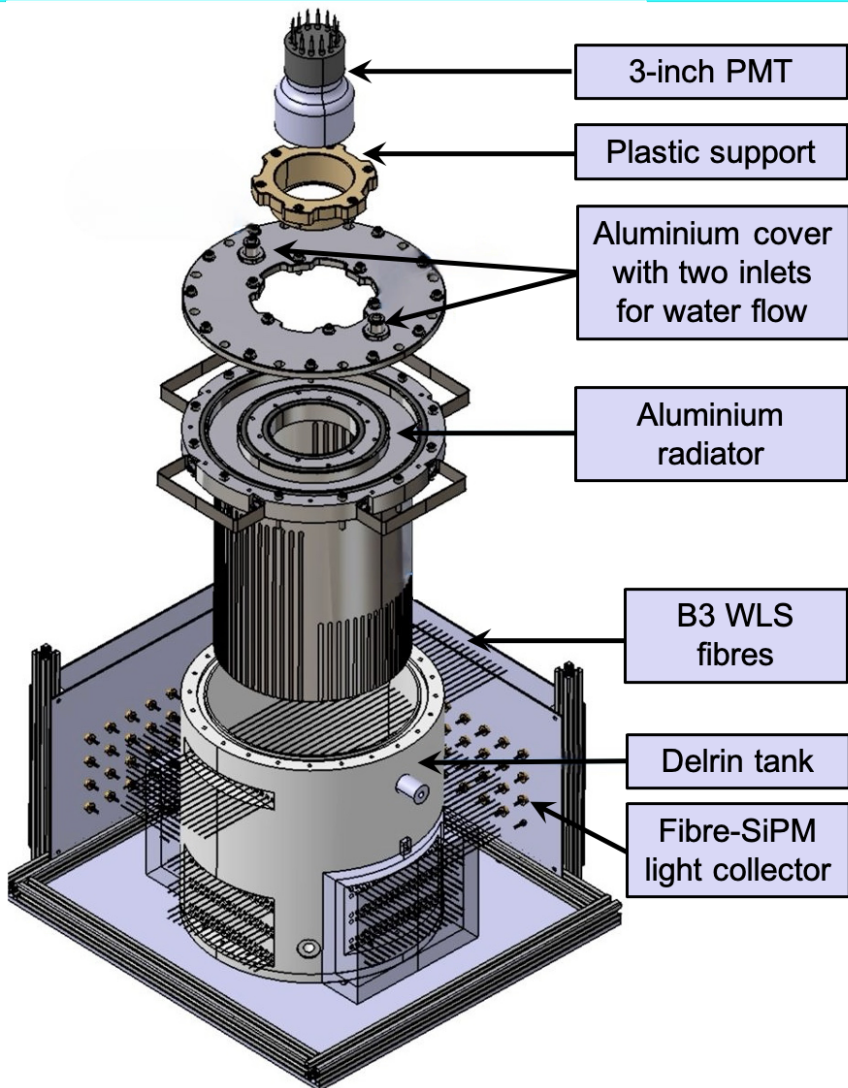
From fibre hits to event information



Rich prototype program: Mini-LiquidO

[arXiv: 2503.02541](https://arxiv.org/abs/2503.02541)

- ★ 10 L detector
- ★ 56 WLS fibres (Kuraray B3), 15 mm pitch
- ★ Single readout with SiPMs (Hamamatsu S13360-1350PE)
- ★ MeV e^- from monoenergetic beam (^{90}Sr -Y) [0.4–1.8 MeV]
- ★ T cycle [5,40] $^\circ\text{C}$ – transparent vs opaque
- ★ Very fast electronics: fast low-power custom preamplifier with sub-ns rise time
- ★ 64-channel WaveCatcher system for waveform digitization (ps time resolution)



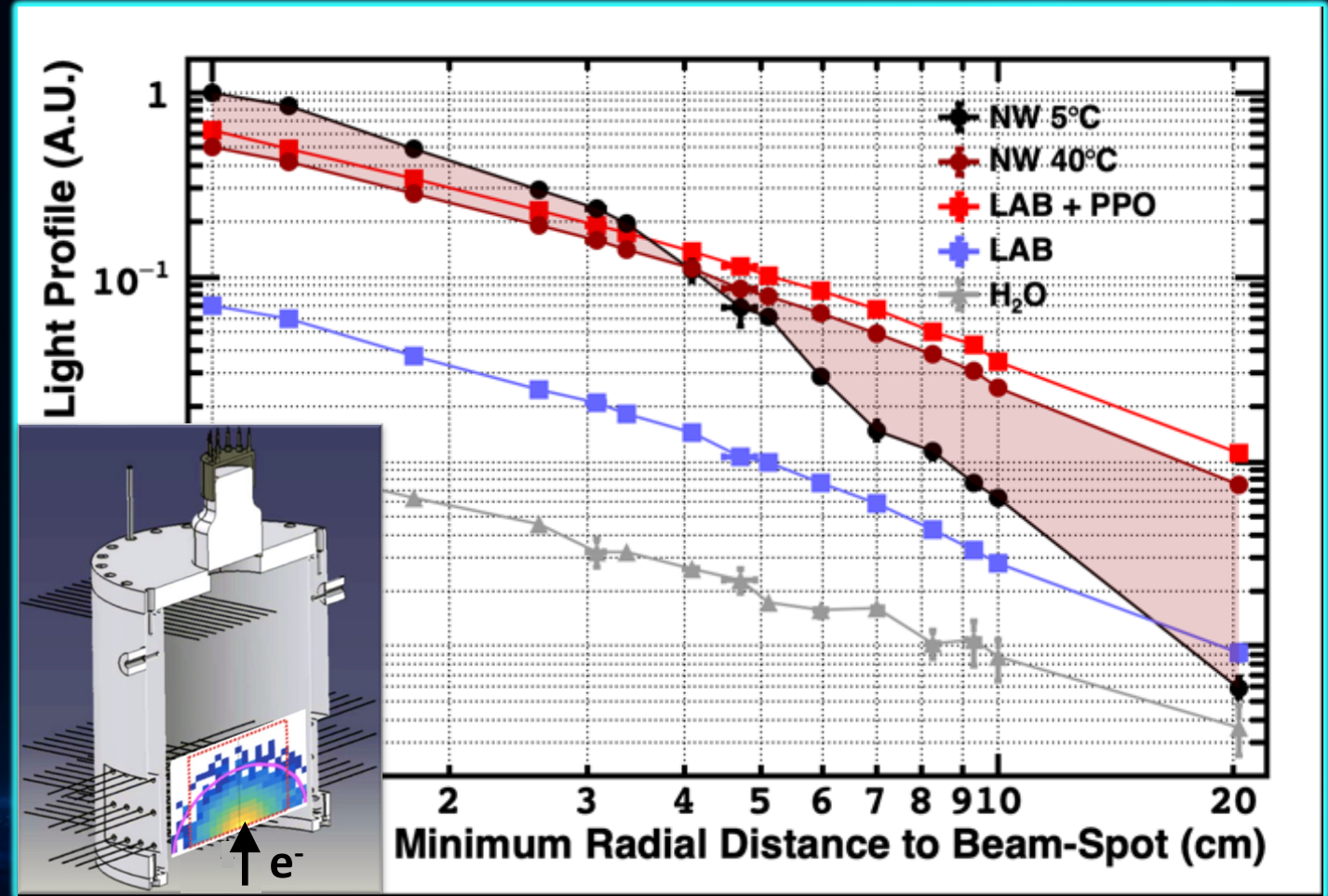
Rich prototype program: Mini-LiquidO

- ★ NW at 40°C - transparent
- ★ NW at 5°C - opaque
- Faster collection and better light confinement in the opaque mode
- $\geq 90\%$ detected light within a few cm
- Light Ball formation at $\sim 4\text{cm}$

Light confinement ✓



Major demonstration of the LiquidO technology



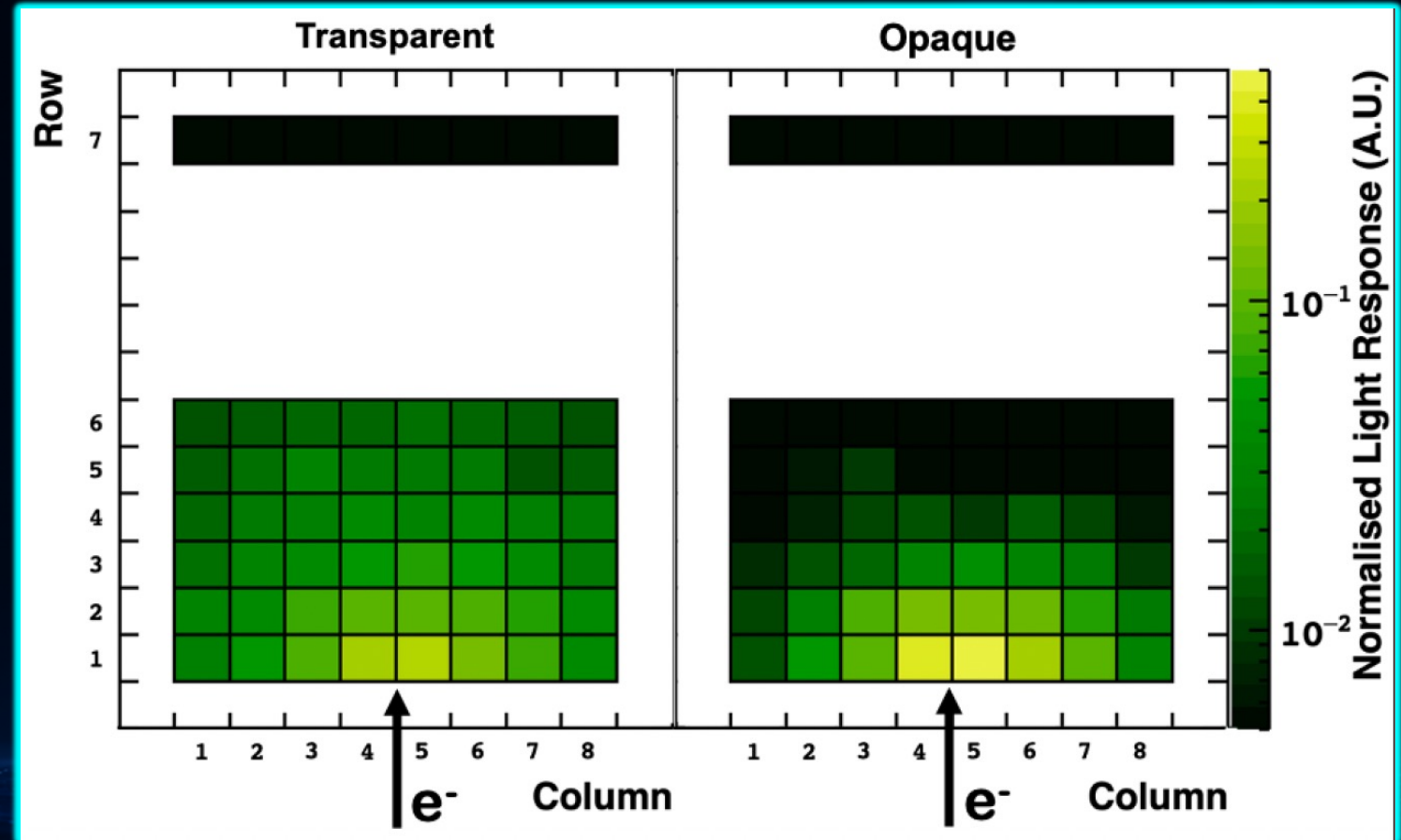
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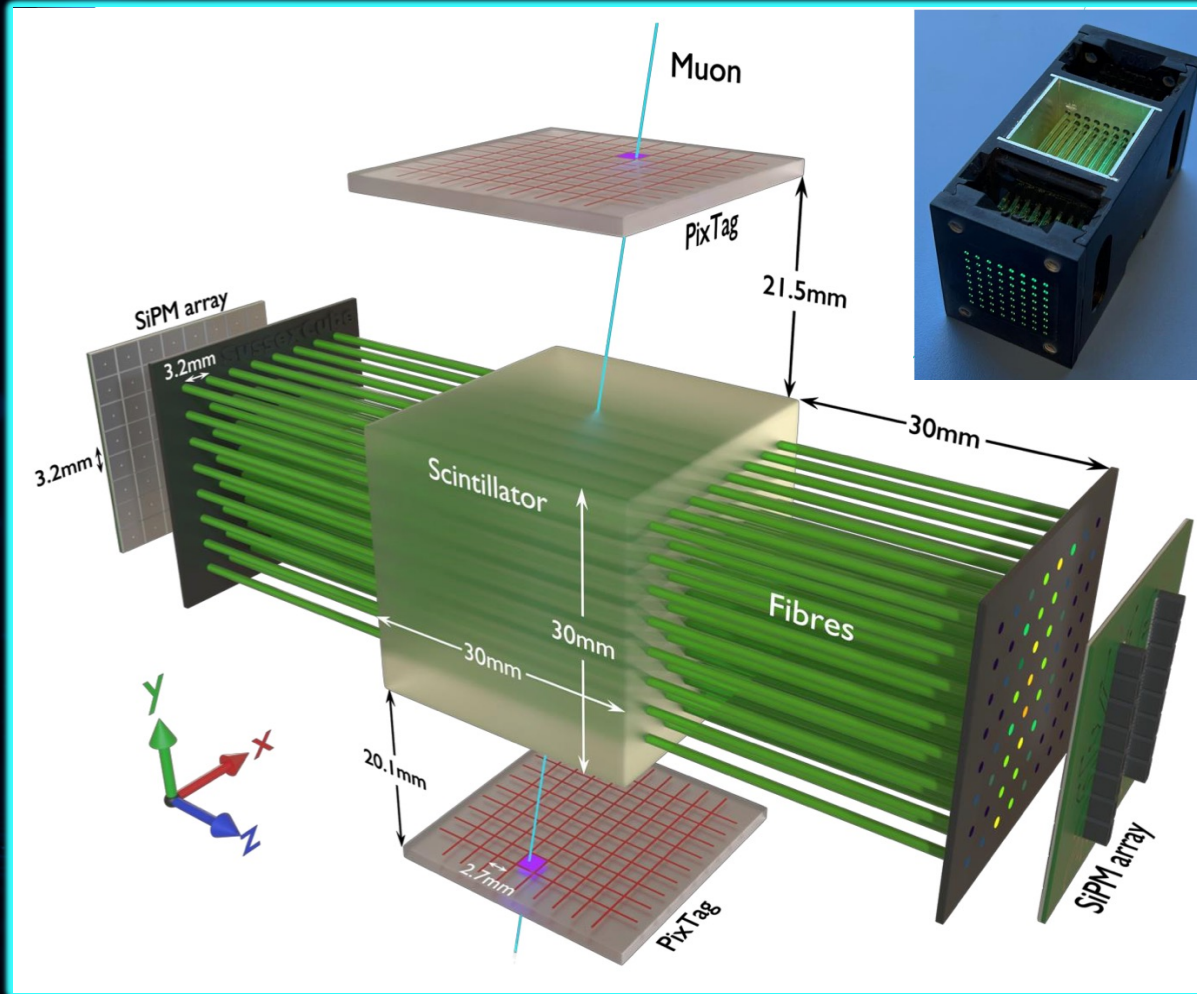


Major demonstration of the LiquidO technology

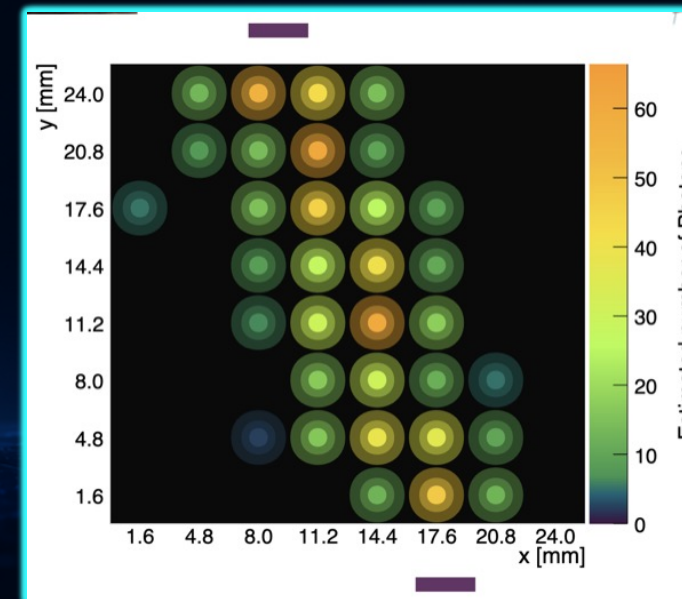


Rich prototype program: Cube

J. Apilluelo *et al* 2026 JINST21 P01010



- ★ $3 \times 3 \times 3 \text{ cm}^3$ cube
- ★ 64 WLS fibres (BCF-91A), 3.2 mm pitch
- ★ Dual-end SiPMs (HPK S13361-3050-AE-08)
- ★ PETsys TOFPET2 ASIC read-out
- ★ Wax (10 w.t.%) opaque scintillator ($\lambda_s \sim 0.5 \text{ mm}$)
- ★ Pixelated muon taggers ($\sim 1\text{k}$ muons)

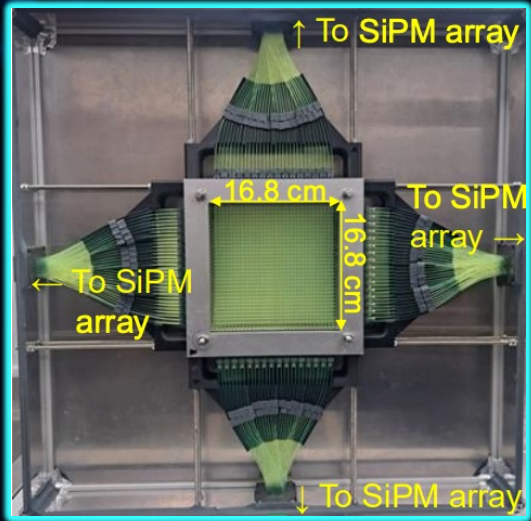


Tracking resolution

- Opaque: 0.45 cm^*
- Transparent: 0.92 cm

* Detector components not optimized

Rich prototype program: Tile

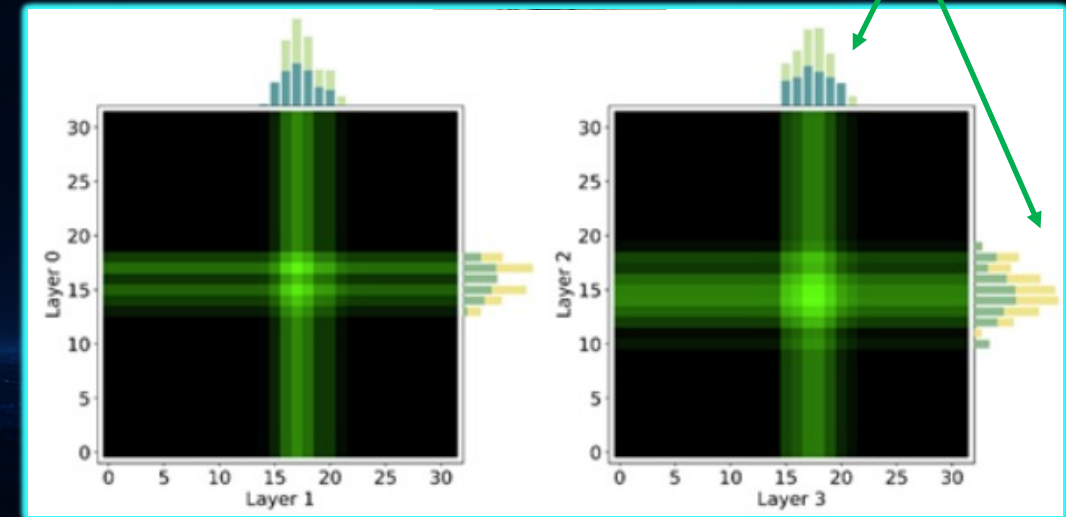
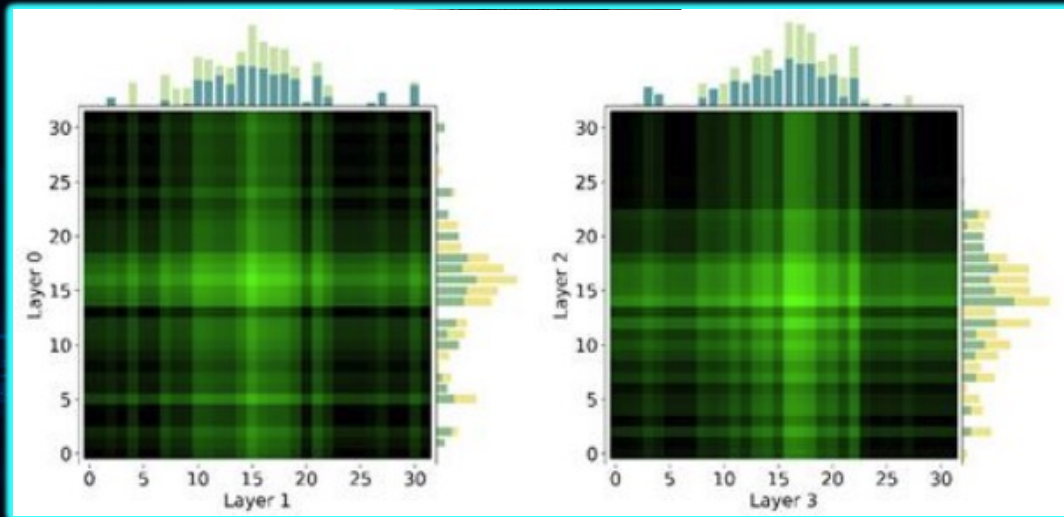


- ★ 2 litres volume
- ★ 256 WLS fibres (BCF-91A), ~5 mm pitch, 4 planes (~7 mm)
- ★ Hamamatsu S13361-3050-AE-08 MPPC arrays. PETsys TOFPET2 ASIC read-out
- ★ Wax (15 w.t.%) opaque scintillator ($\lambda_s \sim 0.5$ mm)
- ★ Muon tracking

Transparent

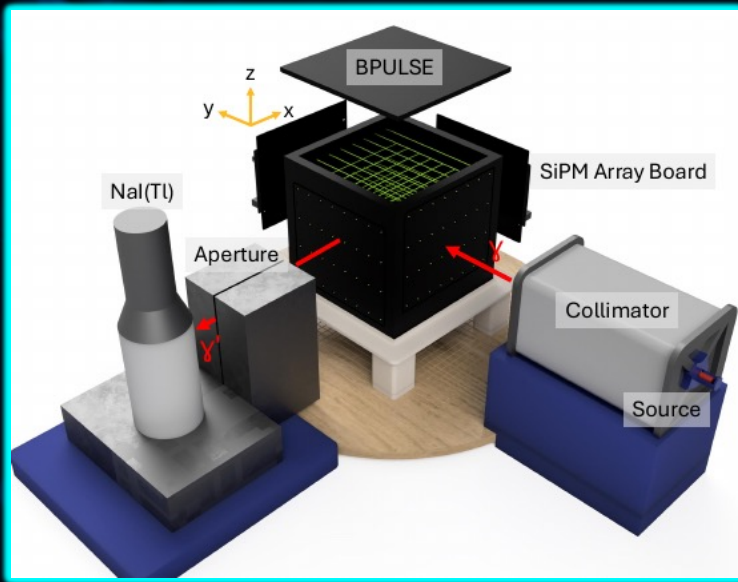
Opaque

Initial results



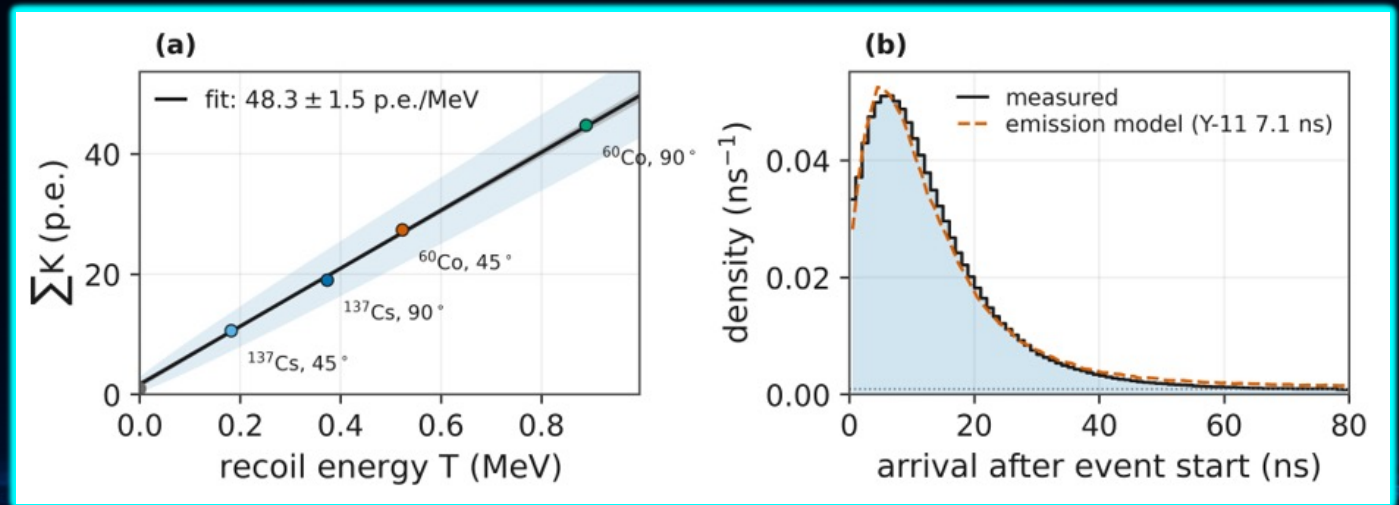
Photons on
fibre per
SiPM side

Rich prototype program: BPULSE



- ★ A NaI tagging detector at 45° or 90° selects Compton electrons of 182, 373, ~520 and ~890 keV
- ★ Light yield 48.3 ± 1.5 p.e./MeV, linear over the range
- ★ Resolution $\sigma/E = 23.4 \pm 0.4$ % at 373 keV, equal to the photon-statistics limit (22.9 %)
- ★ Event vertex reconstructed from the fibre pattern to ~1–2 cm

- ★ 4 L NoWASH opaque scintillator (wax 9w.t.%), 160 mm cube
- ★ 64 WLS orthogonal fibres (Y11), 20 mm pitch. 64 SiPM waveform readout (1 fibre-end)
- ★ External gammas ^{137}Cs (662 keV) and ^{60}Co (1173, 1332 keV) at two fixed angles

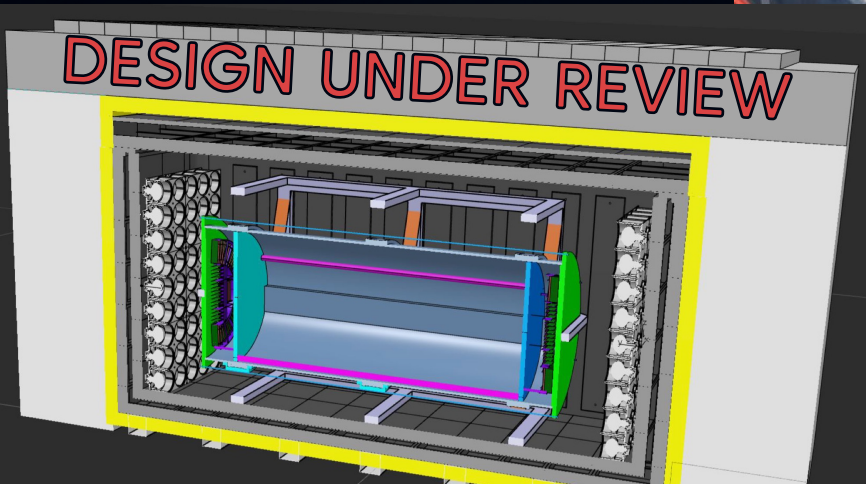


- ★ Two-sided fibre readout ($\times 2$) and 6 mm SiPMs ($\times 1.2$) $\rightarrow$ ~120 p.e./MeV
- ★ Higher-PDE SiPMs and brighter scintillator $\rightarrow$ ~200 p.e./MeV

CLOUD: the first multi-ton LiquidO detector

Chooz LiquidO Ultra-near Detector

- ~ 35 m from reactor core → $\sim 10000 \bar{\nu}_e/\text{day}$
- ★ Operate on surface
- ★ Minimum shielding: detector as compact as possible
 - Goal $S/BG > 100$? → to be demonstrated



5-10 tons LiquidO-Tracker Inner Detector
Opaque scintillator + 10,000 fibres + SiPMs at both ends
~1.8 m diameter, $>200 \text{ PE/MeV}$ design, sub-ns timing

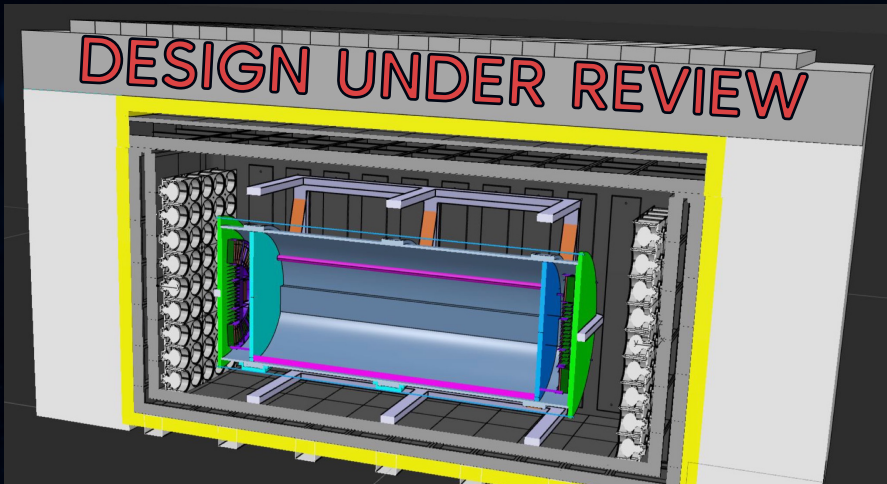


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5-10 tons LiquidO-Tracker Inner Detector

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~1.8 m diameter, >200 PE/MeV design, sub-ns timing



- ★ 2m prototype (~ 200 L)
- ★ 150 WLS fibres
- ★ Initial water-run
- ★ Muon Cerenkov light observed



What must survive when LiquidO scales up?

Locality

$$\lambda_s$$

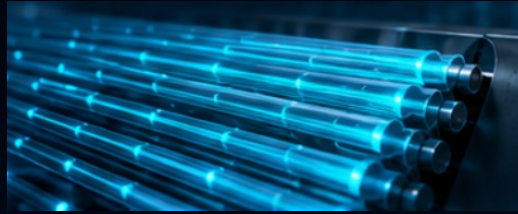
Deposits remain distinguishable



Sampling

$$p_{\text{fibre}}$$

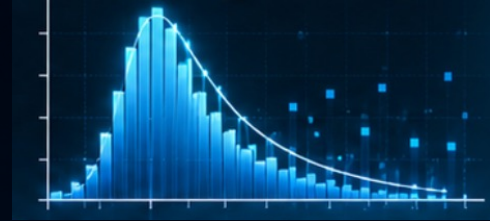
Pitch resolves the relevant topology



Photon statistics

$$LY_{\text{det}}$$

Enough light for topology and timing



Time resolution

$$\sigma_t$$

Preserve longitudinal and temporal information



Scale-level requirements

- Optical response must be known: scintillator scattering and absorption length, fibre attenuation and transport
- Full detector response calibration: channel-to-channel response (charge+timing) and spatial non-uniformities
- Electronic noise under control: Dark noise, crosstalk
- Fast optical simulation → data accuracy

What must LiquidO demonstrate at multi-ton scale?



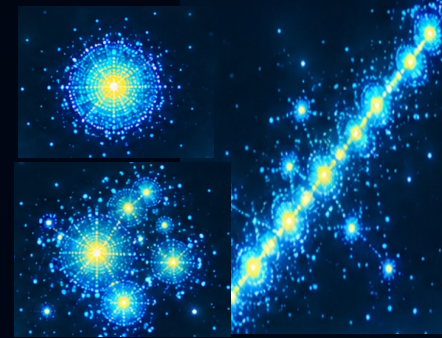
Local information survives

- ✓ Light confinement across full volumen
- ✓ Sufficient light
- ✓ Timing information preserved
- ✓ Response stable with position



Complex topology reconstruction

- ✓ 3D vertex reconstruction
- ✓ Multi-site separation (nearby energy deposits)
- ✓ Cluster multiplicity
- ✓ Extended tracks



Topology becomes PID

- ✓ e^+/e^- discrimination
- ✓ e^+/γ discrimination
- ✓ Muon/cosmogenic events topology
- ✓ Background rejection



Simulation predicts data

- ✓ Optical properties
- ✓ Photon statistics
- ✓ Spatial and temporal response
- ✓ Reconstruction/PID performance

Take home message

LiquidO: stochastic light confinement in a opaque medium
local event topology, high-resolution images and PID

Basic ingredients are experimentally demonstrated
Confinement, localisation, tracking, response mapping

Next step is validation at multiton scale
Several challenges but very promising results

LiquidO is a new way of thinking
about a scintillator detector
We have only just started... your
ideas/contributions welcome!



LiquidO consortium consists of more than 90
scientists in 26 academic institutions (universities
and/or laboratories) in over 11 countries

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

Back-up

Tyle prototype: Michel electrons

- ★ Source: Muon decays ($2.2 \mu\text{s}$ lifetime)
- ★ Electrons emitted isotropically
- ★ MIP track-like events

X = estimation of muon stopping position
→ = Michel electron direction

