Rare event searches with LiquidO technology

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On behalf of the LiquidO consortium

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DUΦ Deep Underground Physics

Some remarks to begin with …

- Neutrinos are rare events in this talk
- This presentation is not focused on other rare events (double beta, proton decay, dark matter …)

- … but its goal is to highlight the possible benefits of the LiquidO technology in the context of Deep Underground Physics, such as the extra handles for the control of cosmogenics

Outline

- What is LiquidO?
- Physics potential
- Experimental validation
- Future prospects and conclusions

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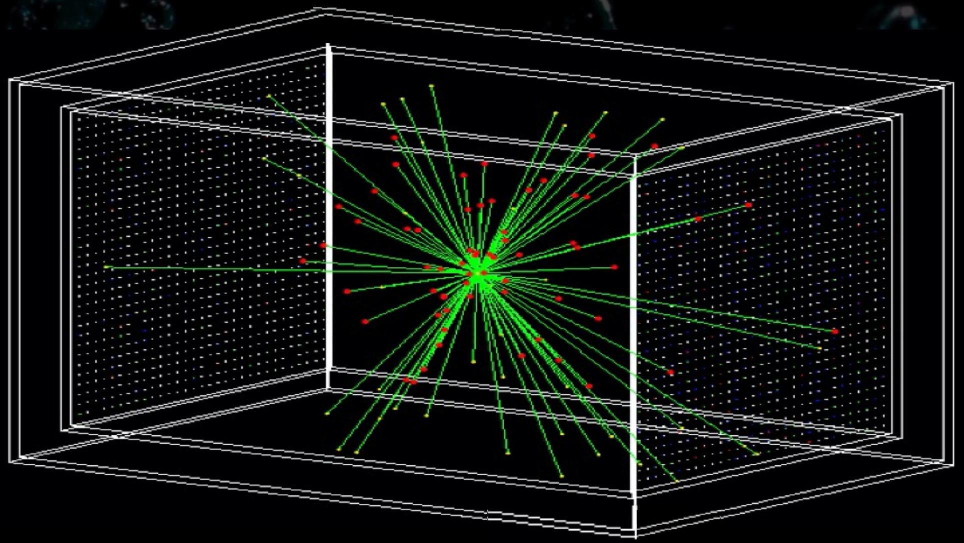
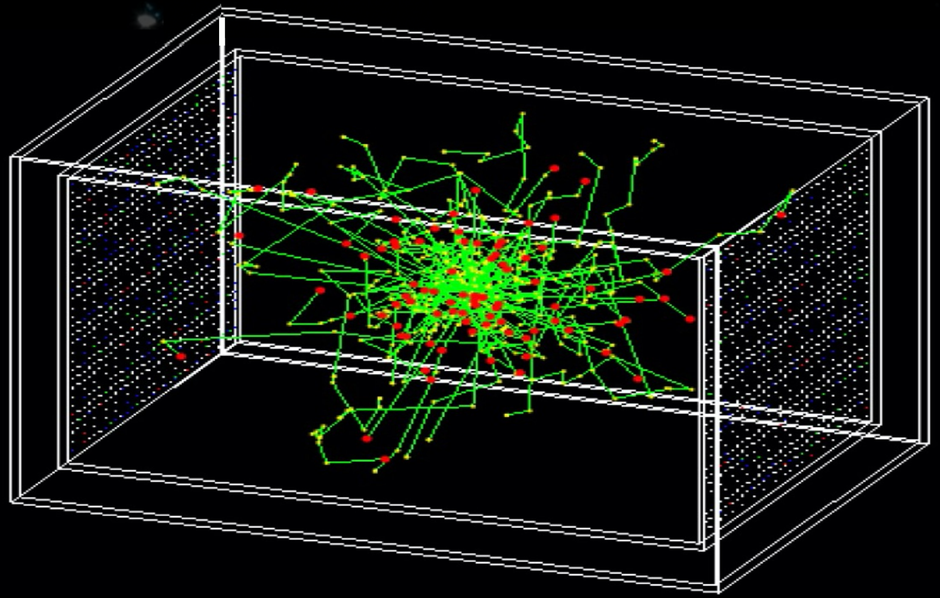
What is LiquidO?

A new Approach

Stochastic light confinement near its creation point by using opaque medium



Transparent: Today's technology
Topology information washed-out

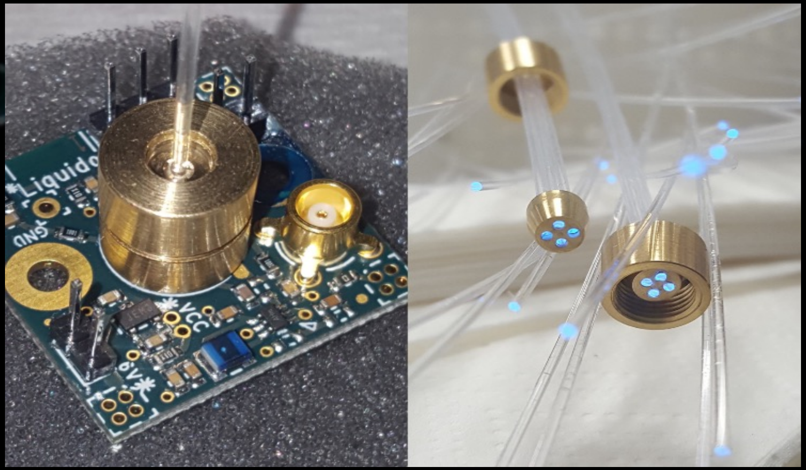


Opaque: LiquidO technology
Light clustering

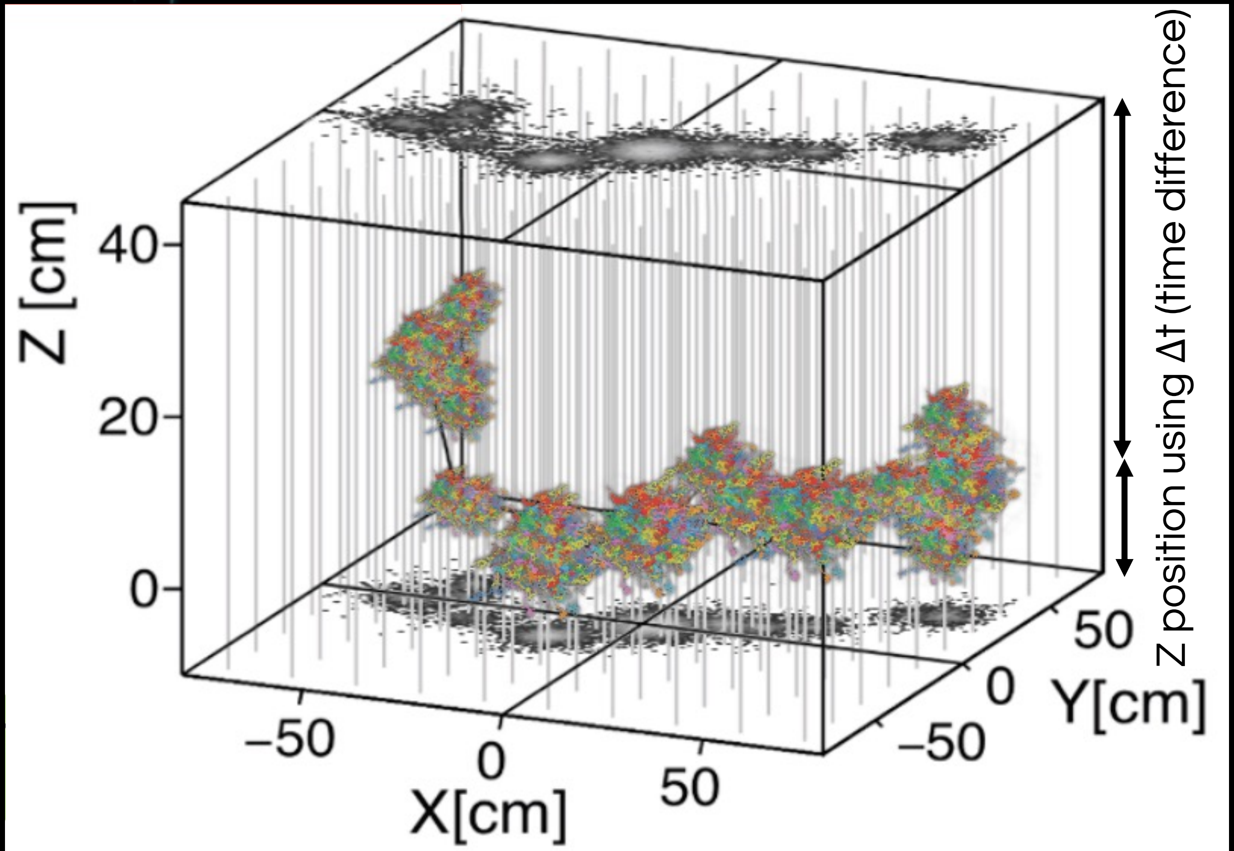
What is LiquidO?

Innovative Detection Technique

- ★ Maximal light collection by a **dense array of fibers** connected to **SiPMs**
- ★ **Low background, high efficiency**
- ★ **Fast time resolution** (< 0.1 ns)
- ★ **Excellent spatial resolution** (≲ 1 mm)



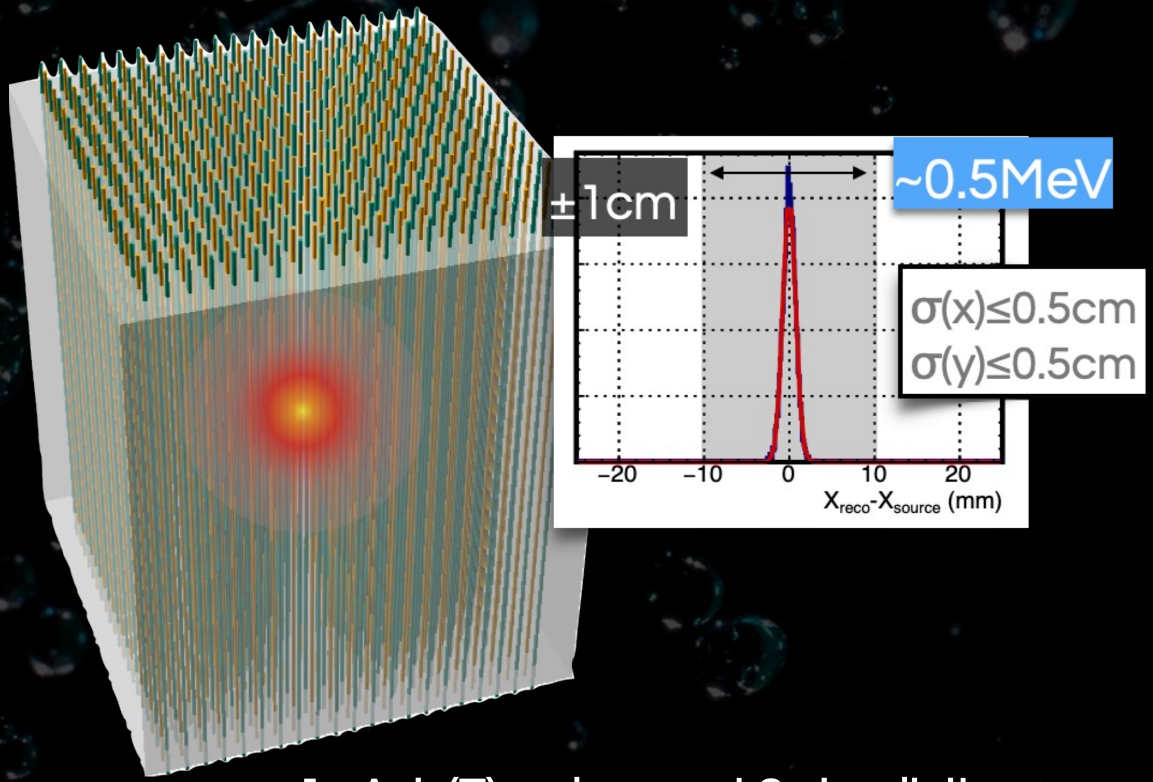
Top view: (x,y) projection

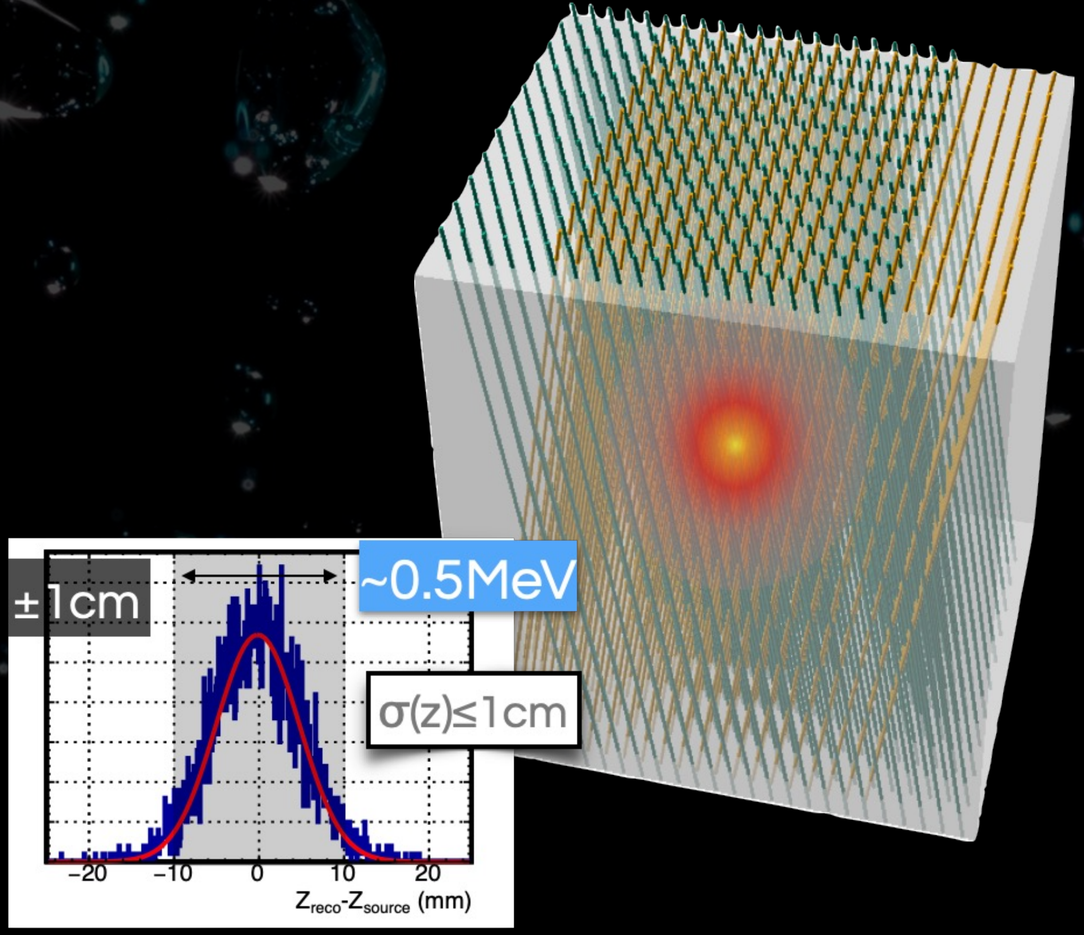


Bottom view: (x,y) projection

What is LiquidO?

Novel engineering solutions



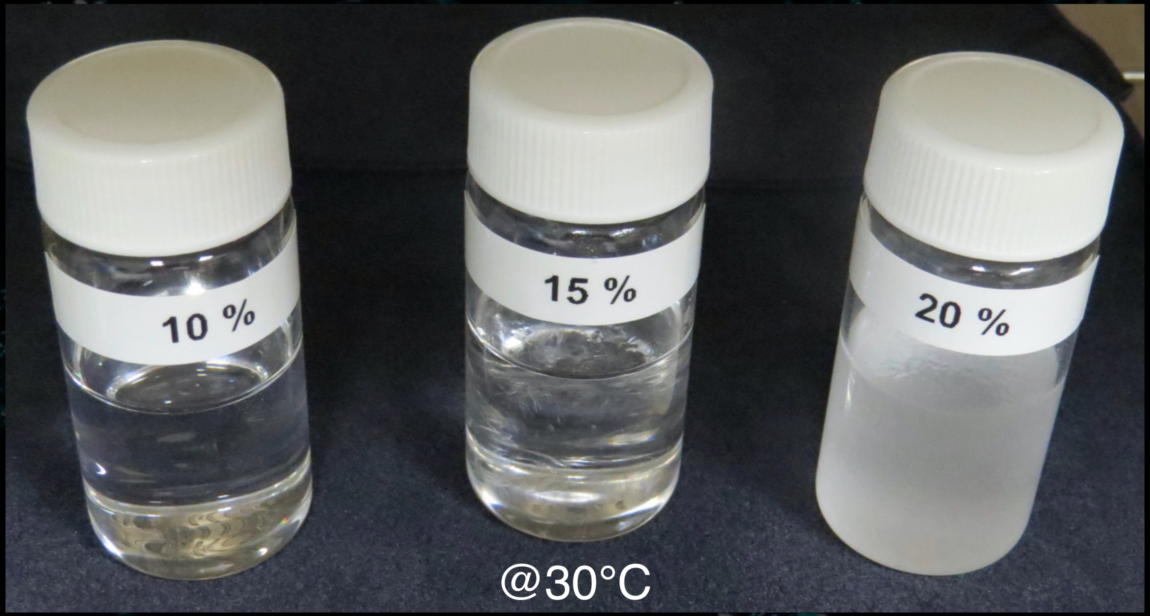


- ★ **1x Axis(Z) — low cost & simplicity**
- ★ (X,Y): topology→ **mm resolution** (robust)
- ★ Z: timing→ **few cm resolution**

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

What is LiquidO?

Opaque Medium



NoWaSH [prototype]

- ★ Opaque Liquid Scintillator
- ★ Linear Alkyl Benzene (~80 wt.%) + Paraffin Wax (~20 wt.%) + PPO (~0.3%)
- ★ Opacity depends on paraffin concentration (changes crystalisation temperature)
- ★ Short scattering length and moderate absorption length

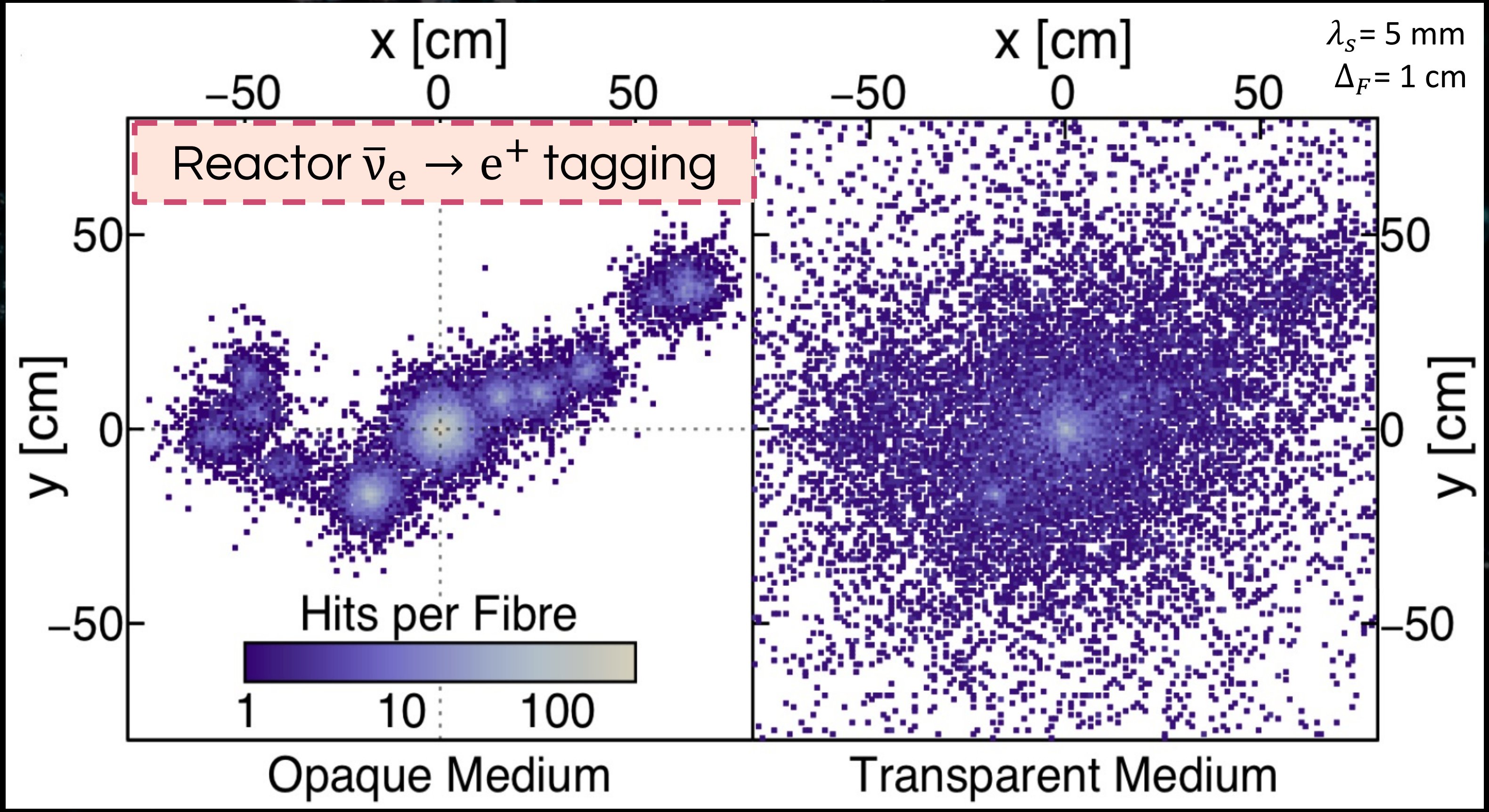
arXiv:1908.03334

LiquidO R&D extensive field: new μCrystal scintillators arXiv:1807.00628, emulsion…

What is LiquidO?

Unprecedented Imaging Capabilities

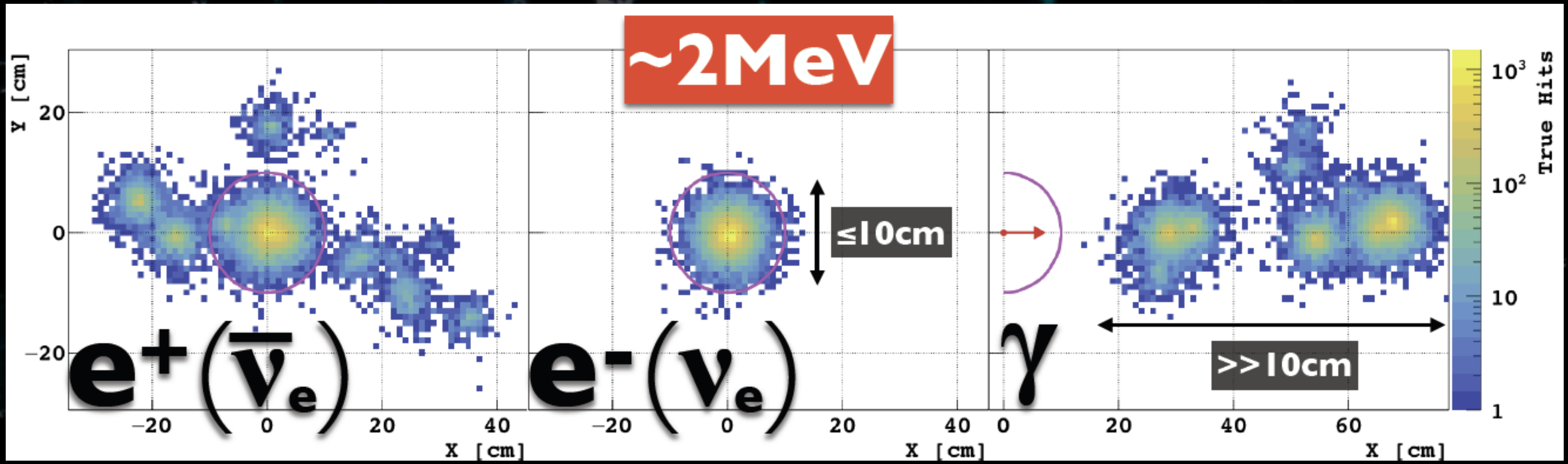
Energy deposition 1 MeV e^+



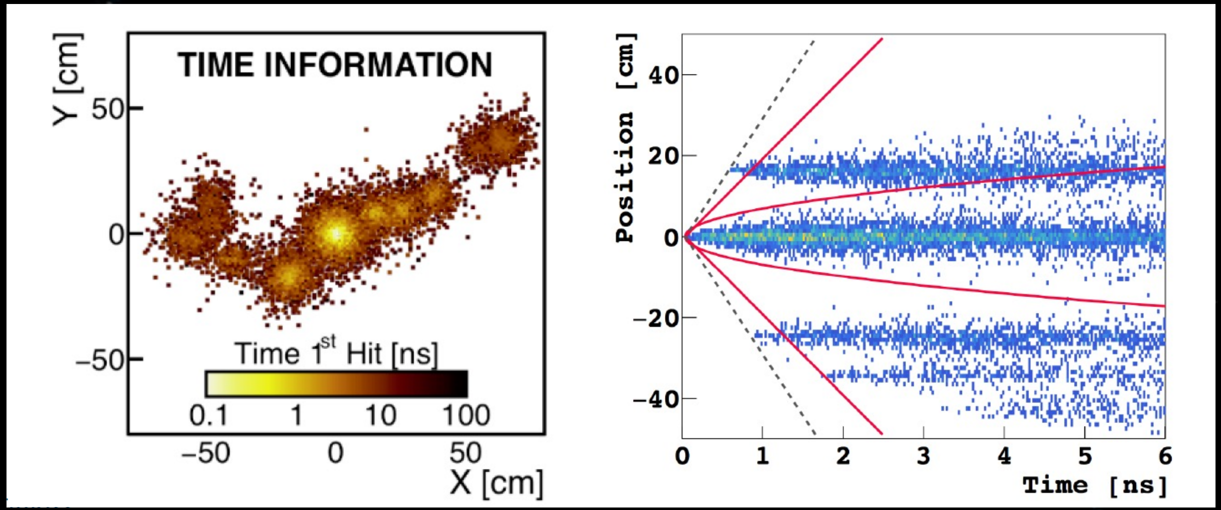
- ★ Particle Identification (PID) is a major challenge in MeV neutrino detection.
- ★ Confinement of light into **sphere around each ionization point**
- ★ **A self-segmented detector!** (no need to introduce dead material for segmentation)
- ★ **Discrimination of individual e^+, e^- and γ events @1MeV**

What is LiquidO?

Unprecedented PID @MeV scale



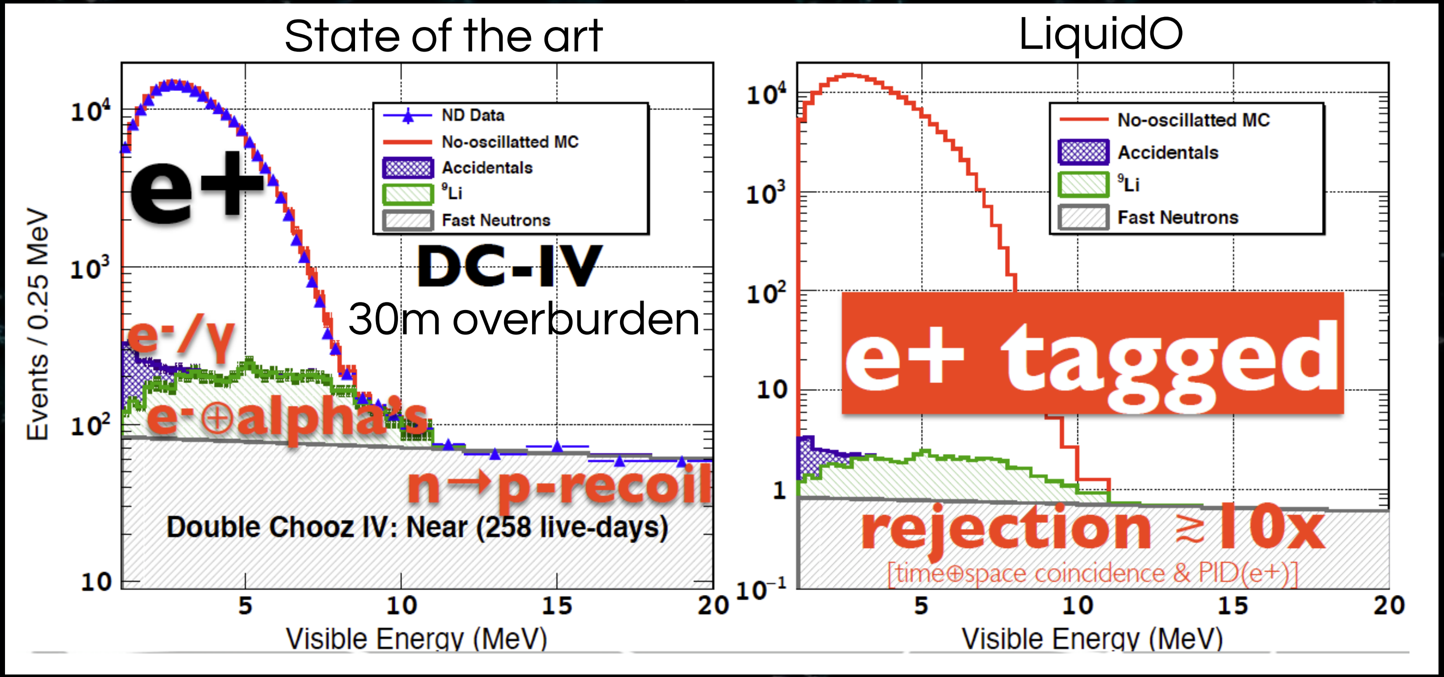
- ★ $\nu_e/\bar{\nu}_e$ separation
- ★ Background (cosmogenic) identification
- ★ No segmentation (less background for MeV physics)



- ★ Topology of deposited energy
- ★ "Energy flow": time pattern for the light to be collected
- ★ Able to achieve e- separation from γ with efficiency > 85% and contamination ~10^{-3} @2MeV

What is LiquidO?

Powerful Background Rejection



Signal : Background ~ 30 : 1
Background: few/day

Signal : Background ≳ 10x30 : 1
Background: few/year

PID + vertex reconstruction

Possibility of Doping

- ★ Relaxing scintillator transparency requirement
- ★ Unparalleled affinity for loading
- ★ Plenty of room to explore unconventional scintillators (e.g. ultra high light-yield)

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Physics potential

Solar neutrinos

Indium loading will allow to perform precise pp solar neutrino physics and beyond

$$\nu_e + {}^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn} + e^-$$ (LENS)

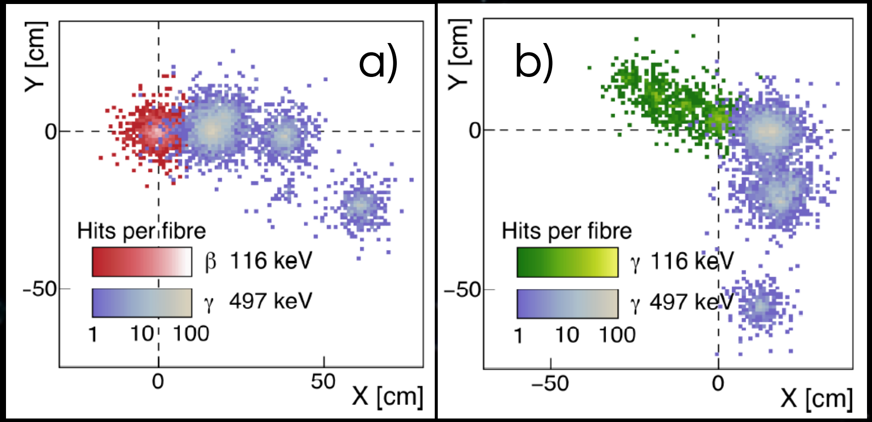
prompt

delay

$\tau = 4{,}76\ \mu s$

e_1^-/γ_1 E = 116 keV (e/γ)=0.96
\+
γ_2 E = 497 keV

Delay

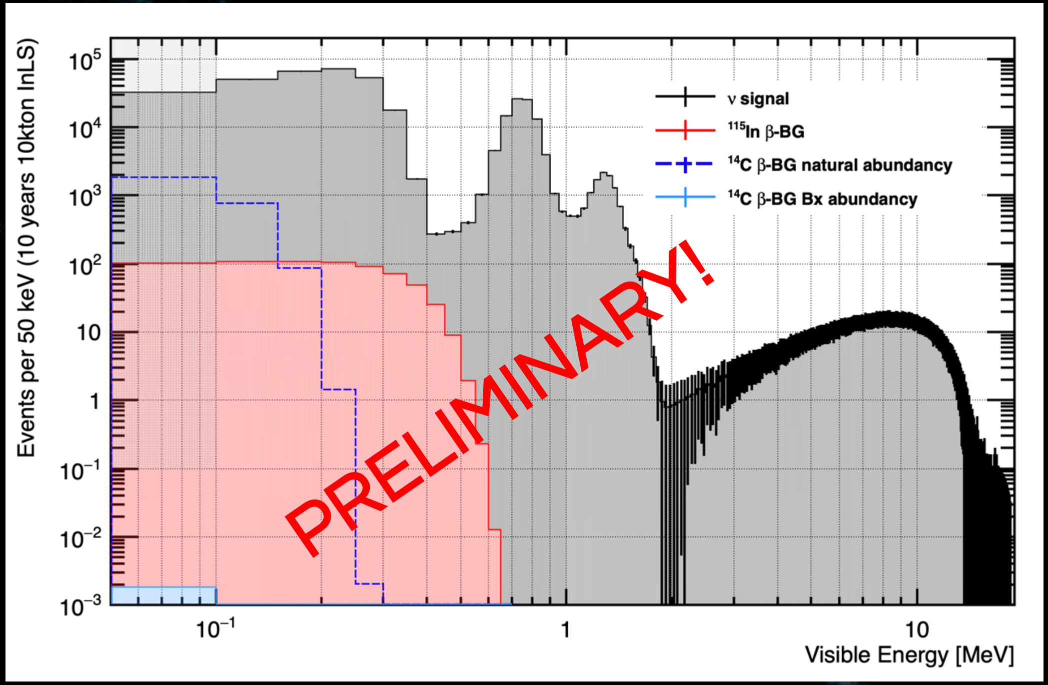


THREE-FOLD COINCIDENCE

BG-less ($\lesssim 10^{-15}$g/g)

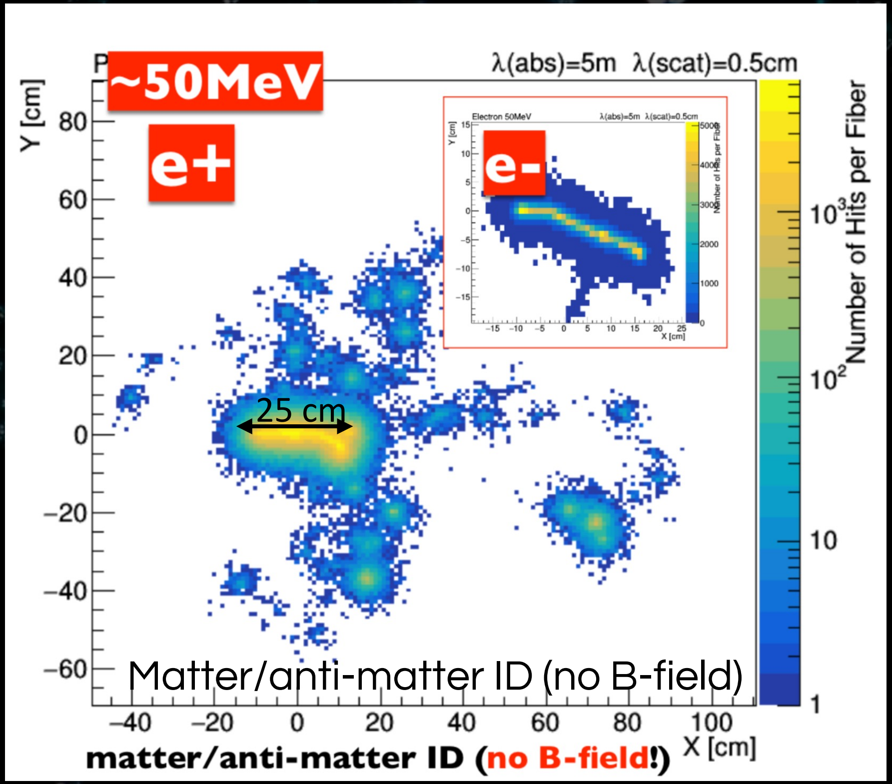
Low threshold = 114 keV (95.5% of pp ν_e)

$\mathbf{E_{vis}} = \mathbf{E_\nu}$ – threshold



Physics potential

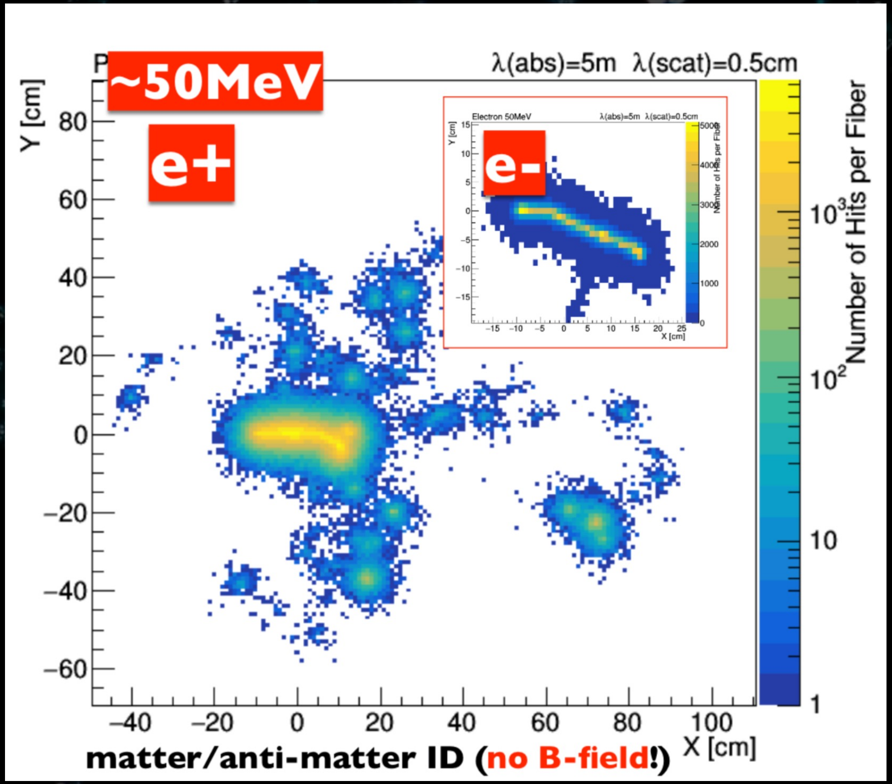
From MeV to MultiMeV



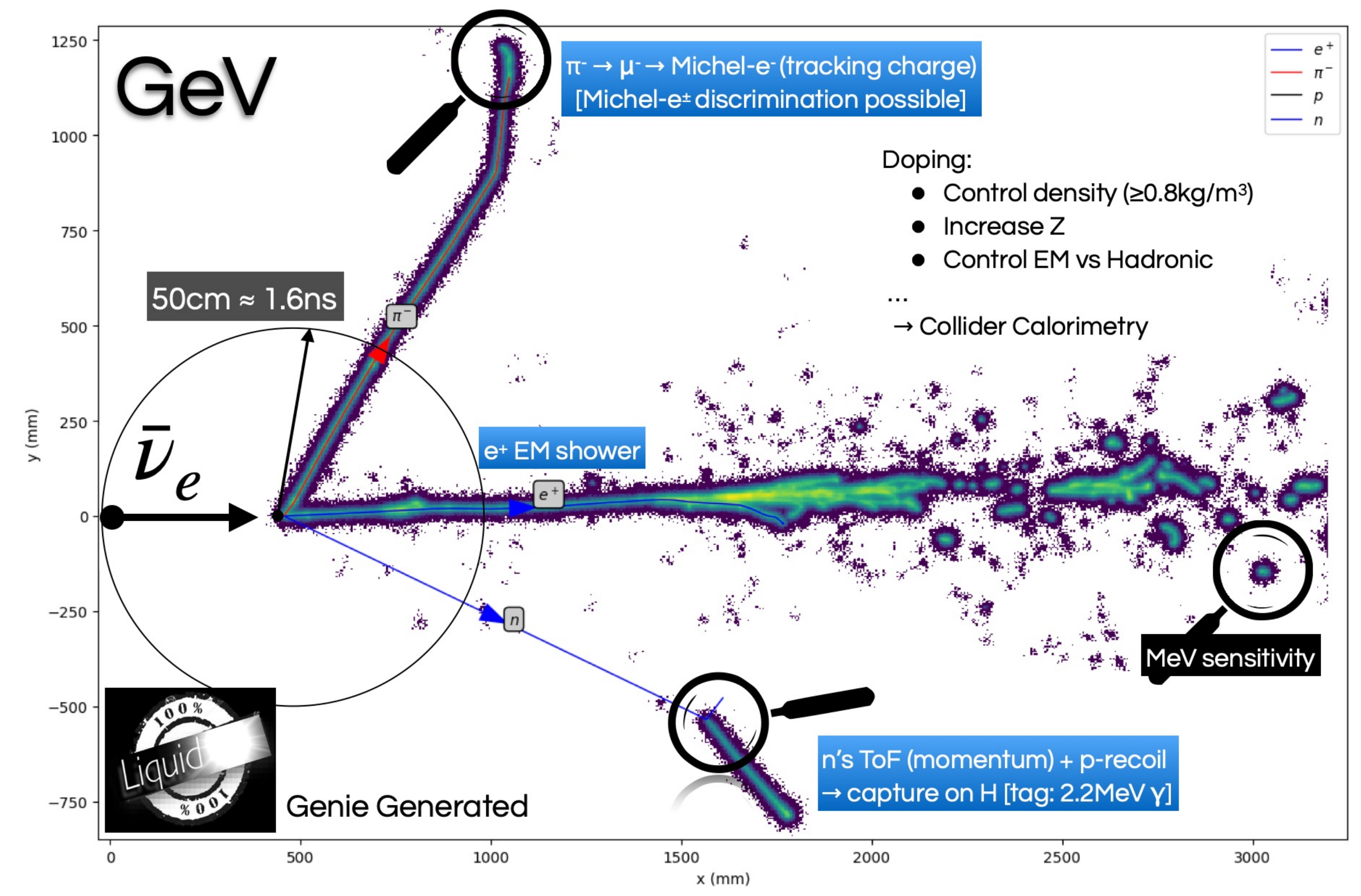
- ★ Powerful PID
- ★ Energy Flow
- ★ Tracking (mm)
- ★ Directionality
- ★ dE/dx (range)

Physics potential

From MeV to MultiMeV

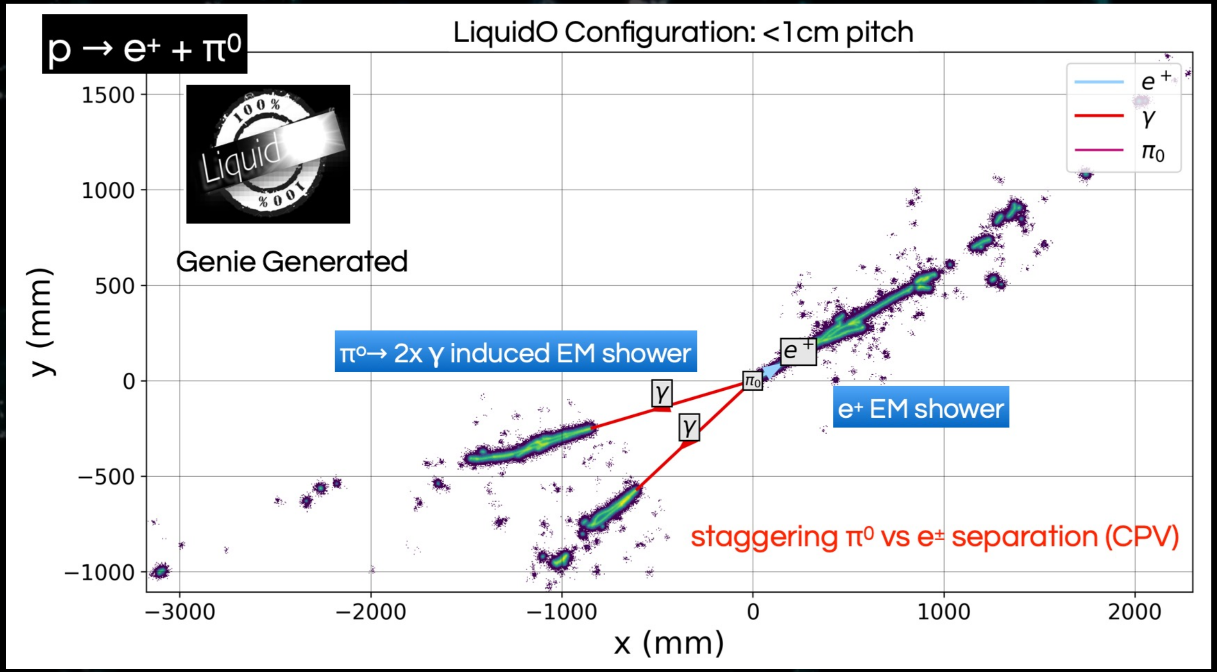


From MultiMeV to GeV



Physics potential

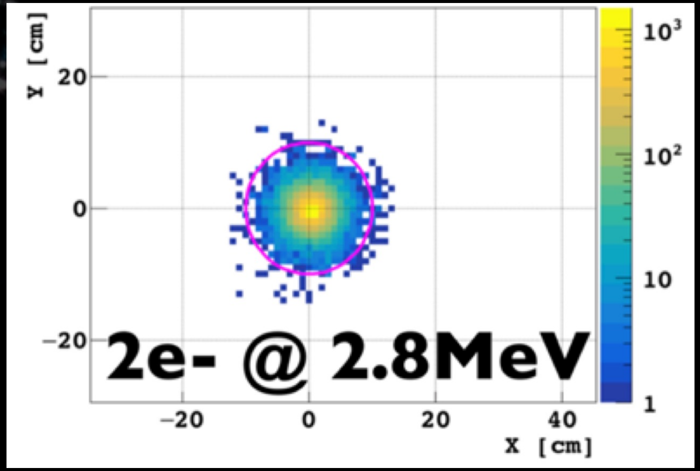
Nucleon Decay



- ★ Largest achievable free protons densitiy (scintillator)
- ★ Very high-efficiency
- ★ Full topological information and sign-ID for some channels through final Michel-e- (magnetize det)

Neutrinoless Double beta decay

- ★ Key advantages: background control and ability to load well beyond current limits
- ★ Looks like a very promising path for reaching deep into the normal ordering region!



Supernova neutrinos, ^{40}K geoneutrinos, Reactor antineutrinos...

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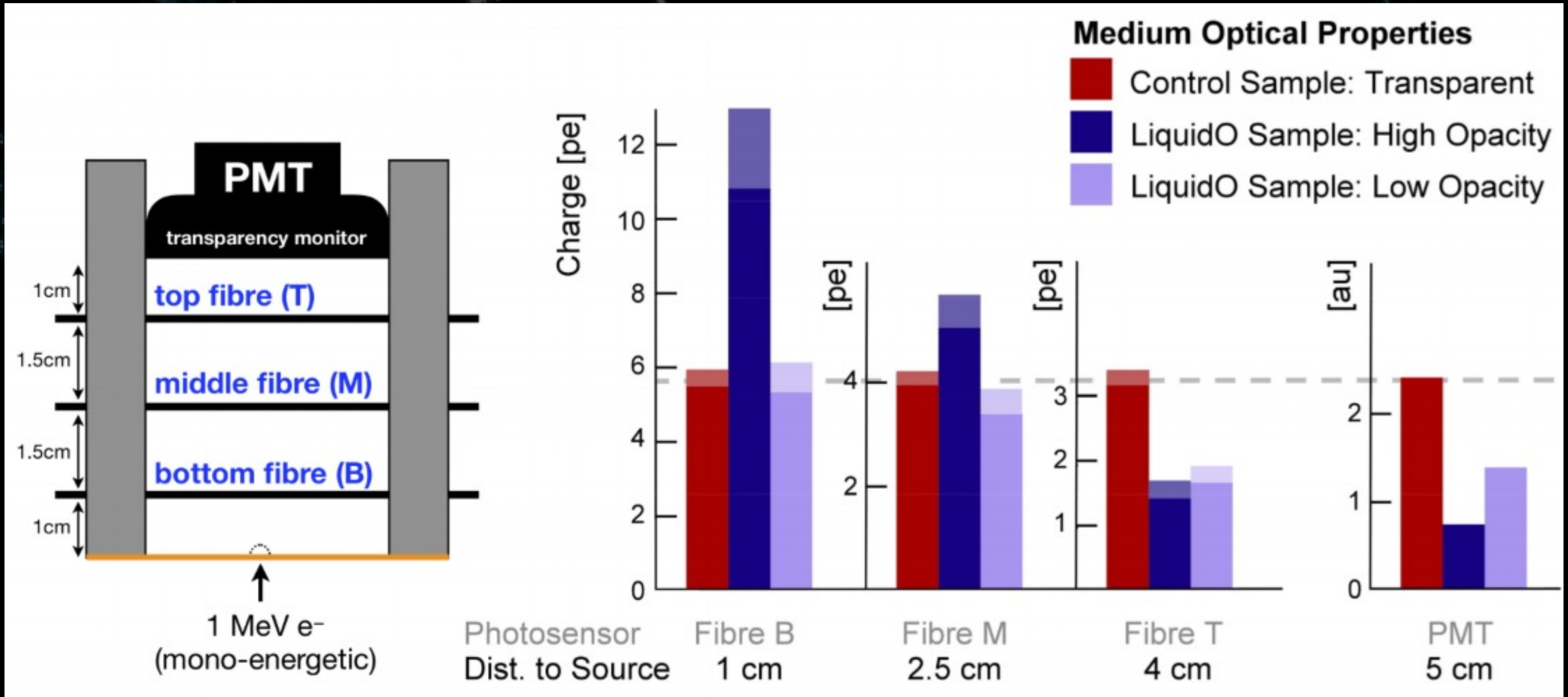
Experimental validation

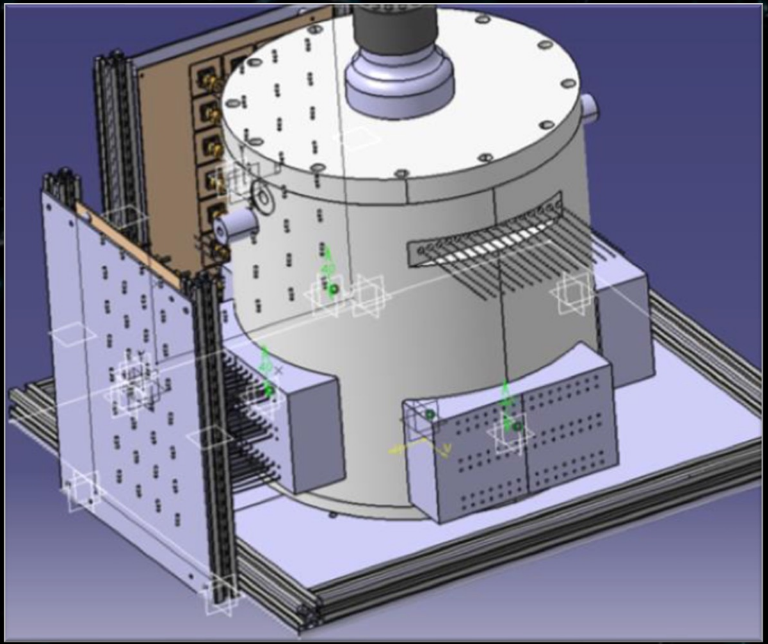
MICRO-LIQUIDO: FIRST EXPERIMENTAL PROOF OF PRINCIPLE

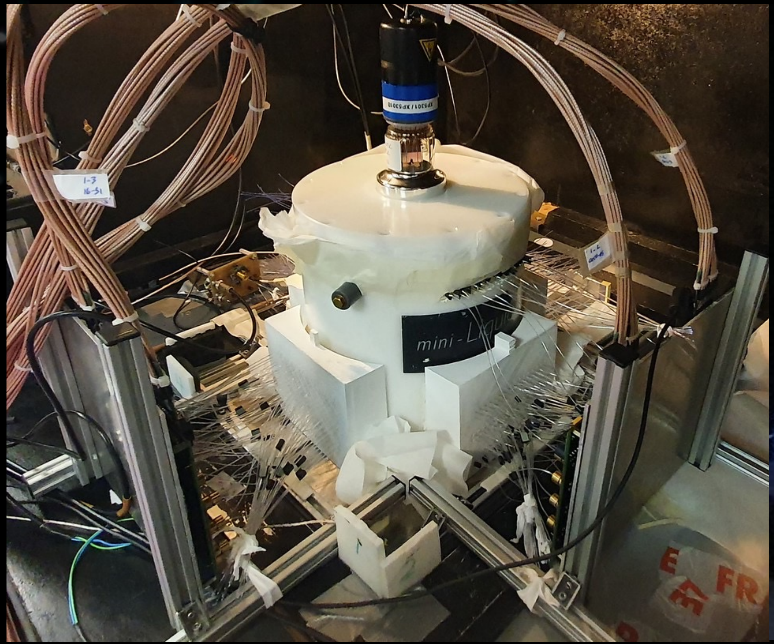


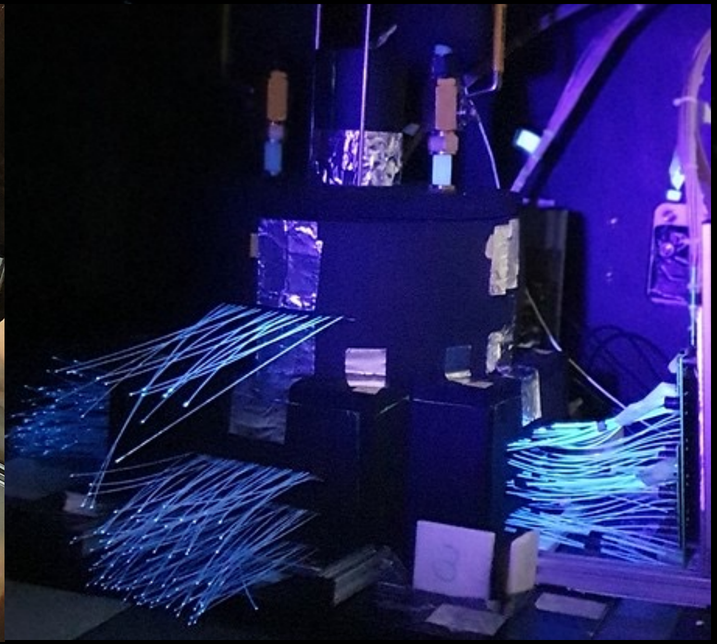
More light collected by the fibres near the light source with the opaque sample!

Experimental validation

Mini-II (upgrade): LiquidO's prototype data taking since 2021



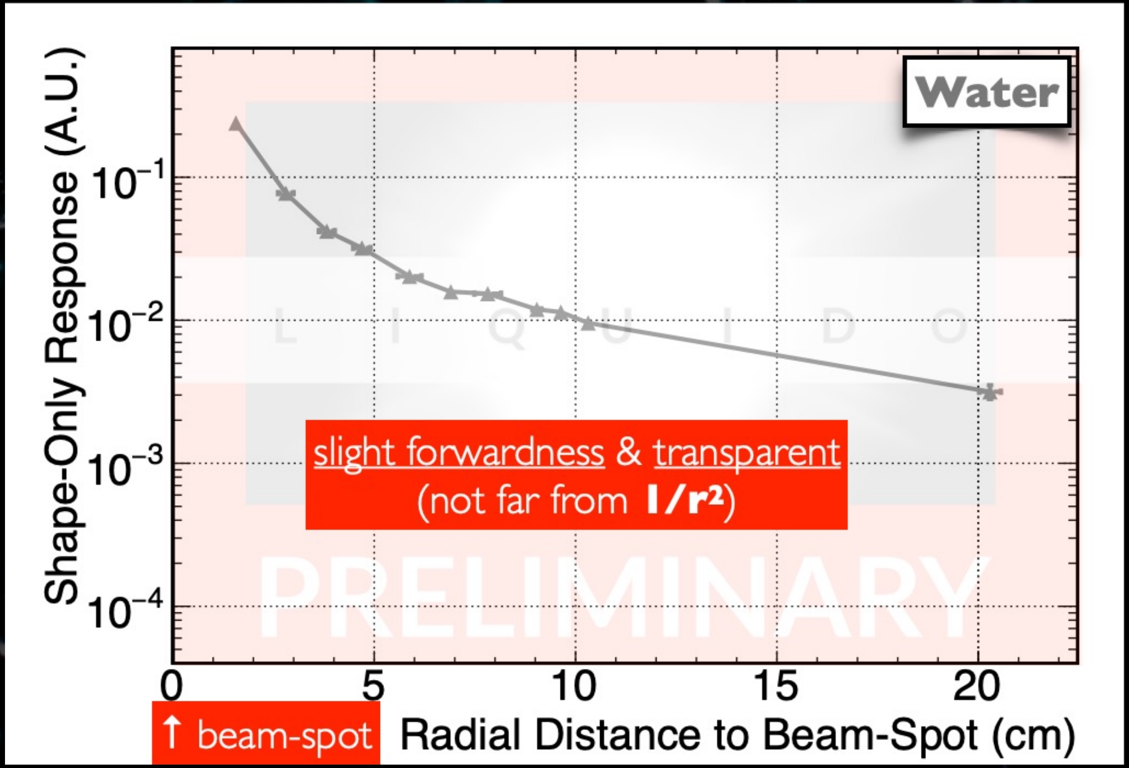


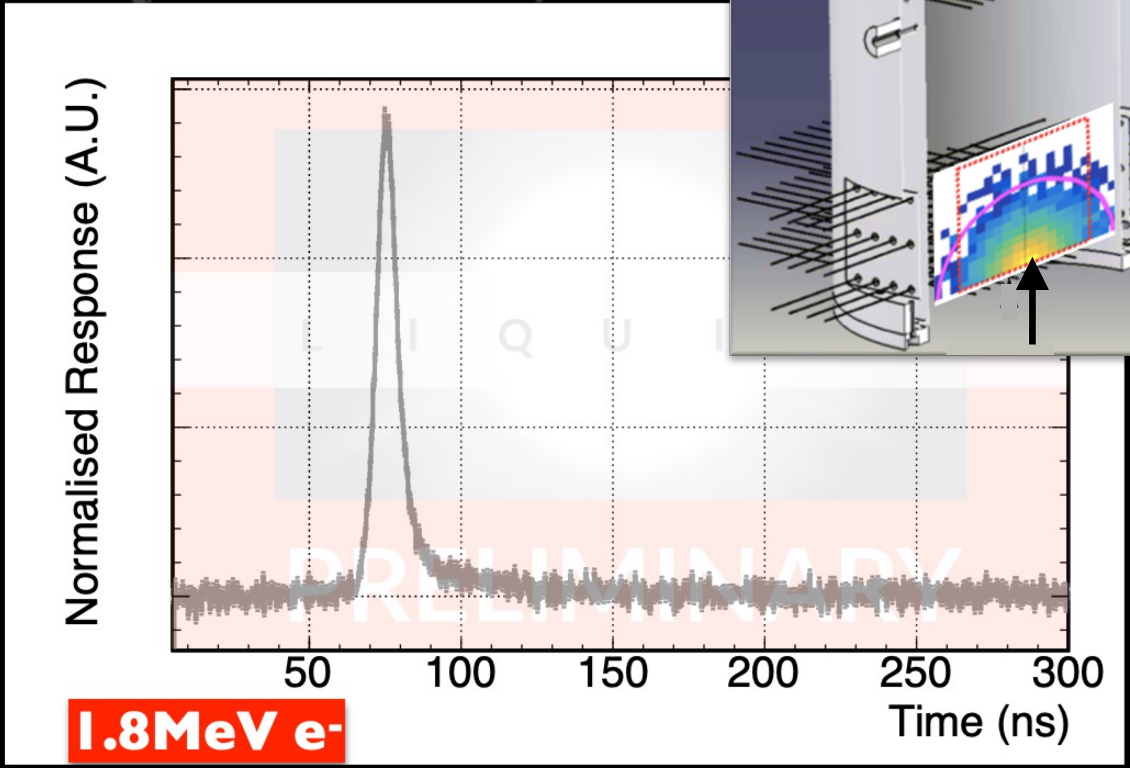


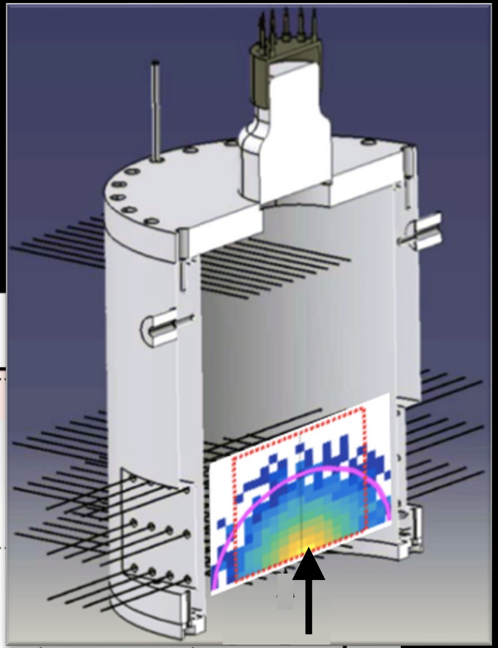
- ~10 L with 64 readout fibres including a 3" PMT
- e- from monoenergetic beam (^{90}Sr) [0.4-1.8 MeV]
- Stochastic light confinement observation
- T cycle [5,40]°C — powerful T control system (Chiller)
- Very fast electronics: fast low-power custom preamplifier with sub-ns rise time
- 64-channel WaveCatcher system for waveform digitization (ps time resolution)

Experimental validation

WATER: SINGLE e⁻ CHERENKOV ONLY





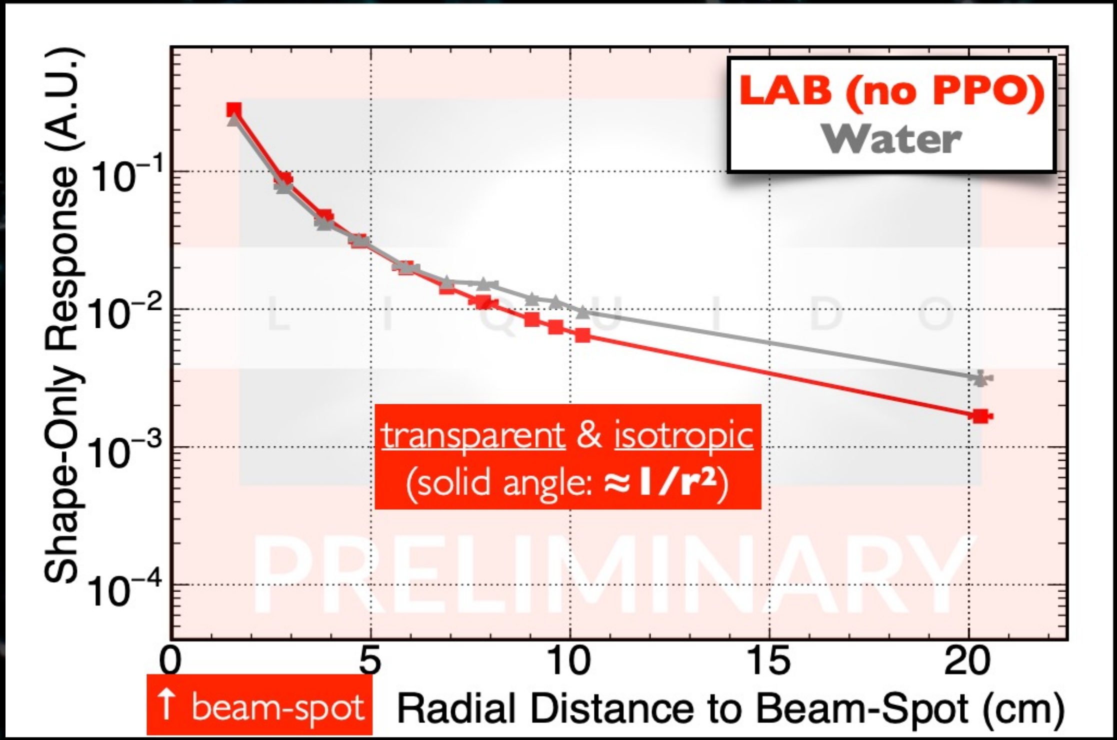


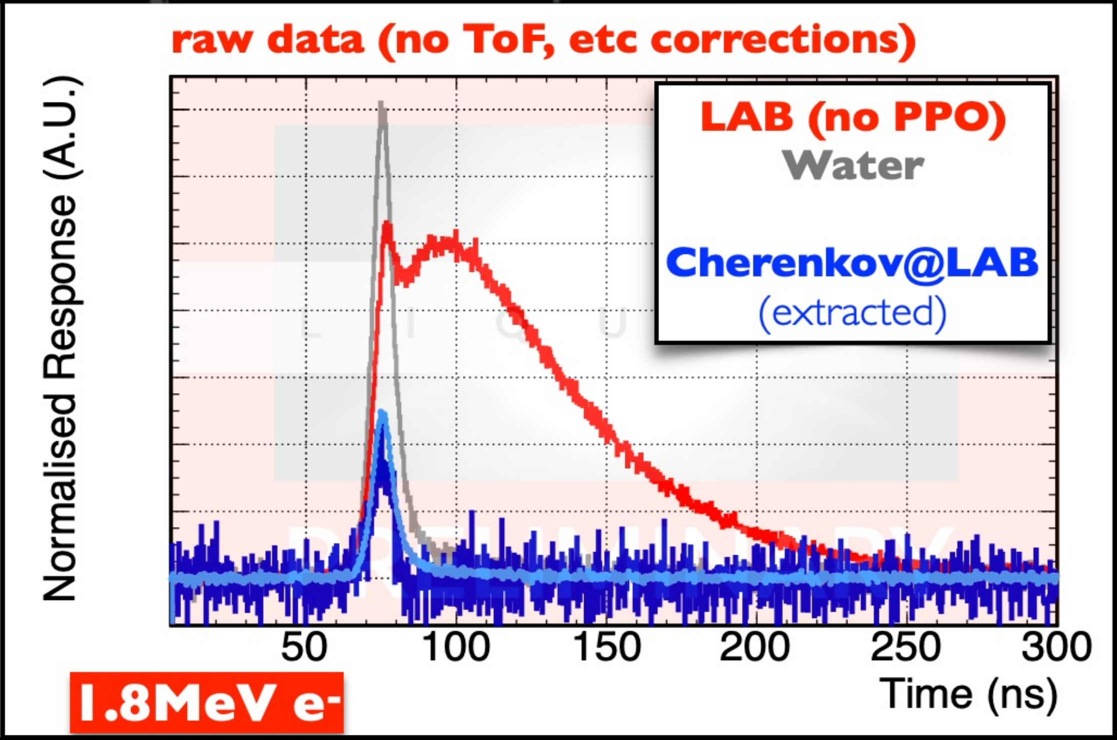
Low amount of light: Cherenkov only & transparent (LiquidO's lowest acceptance)

Validation detector's integral timing readout

Experimental validation

LAB: Cherenkov ⊕ Scintillation



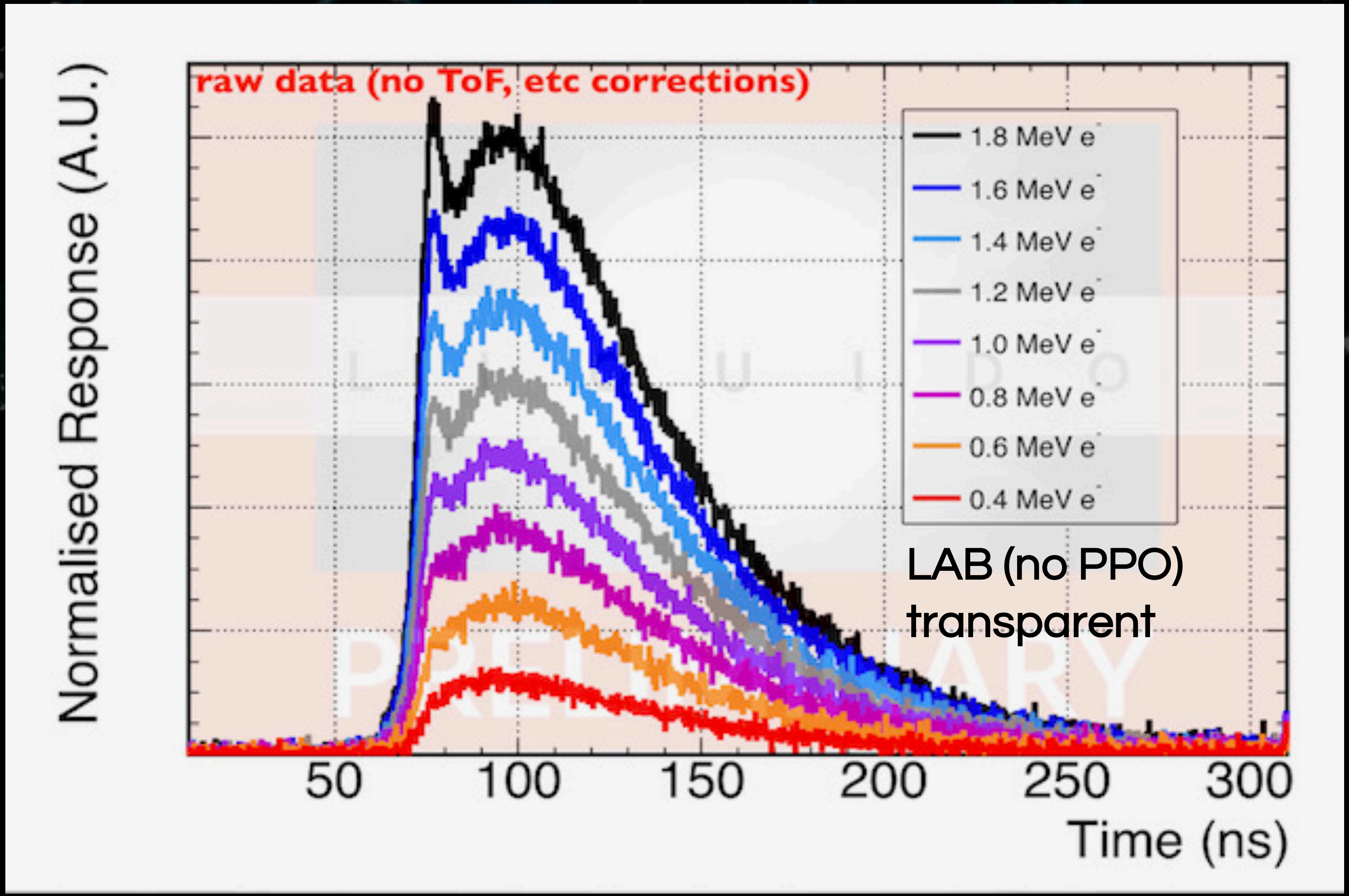


~8.7x more light due to LAB's scintillation [no PPO]

Cherenkov excites the scintillator — loss ≥50% (optimisation)

Experimental validation

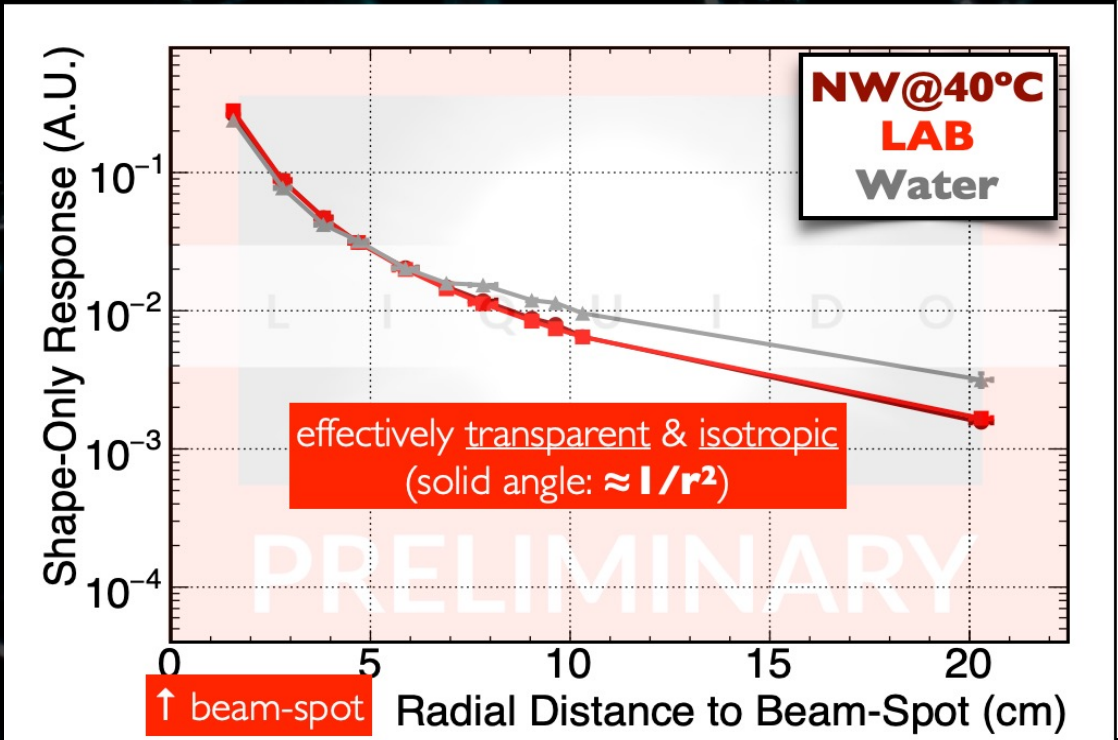
Transparent LS: Cherenkov vs Scintillation

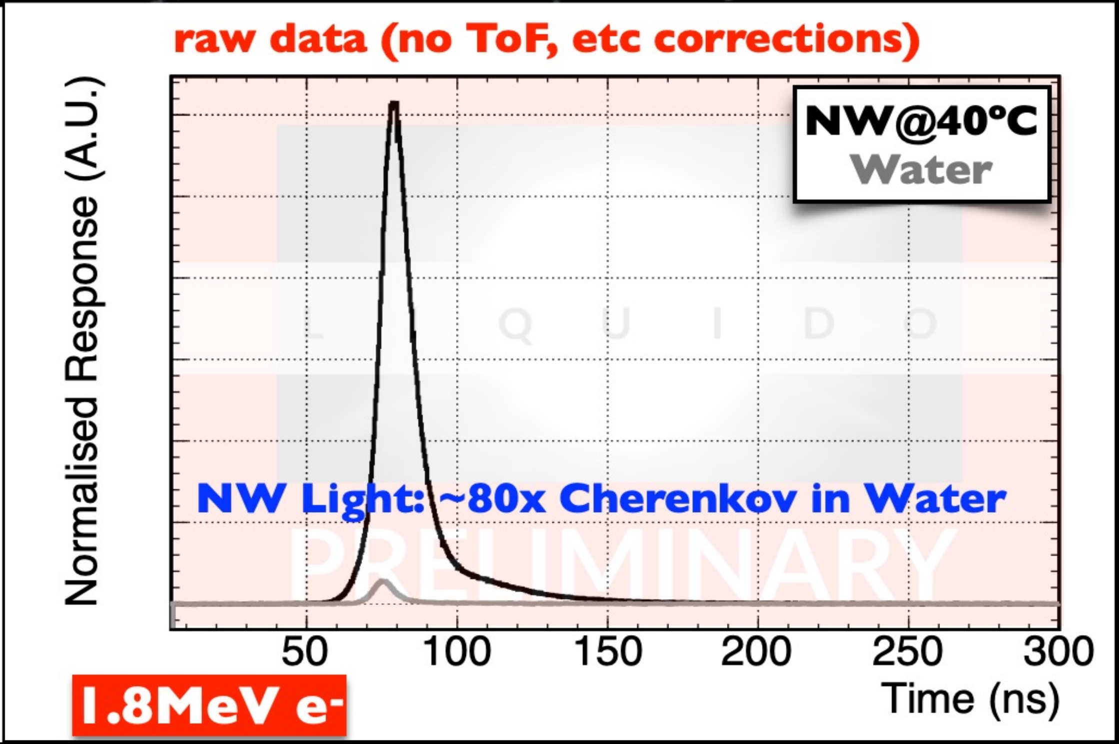


- ★ Transparent liquid scintillator (LS)
- ★ Remarkable separation using only timing
- ★ Cherenkov light production threshold

Experimental validation

NW@40°C: ~~Cherenkov~~ ⊕ Scintillation



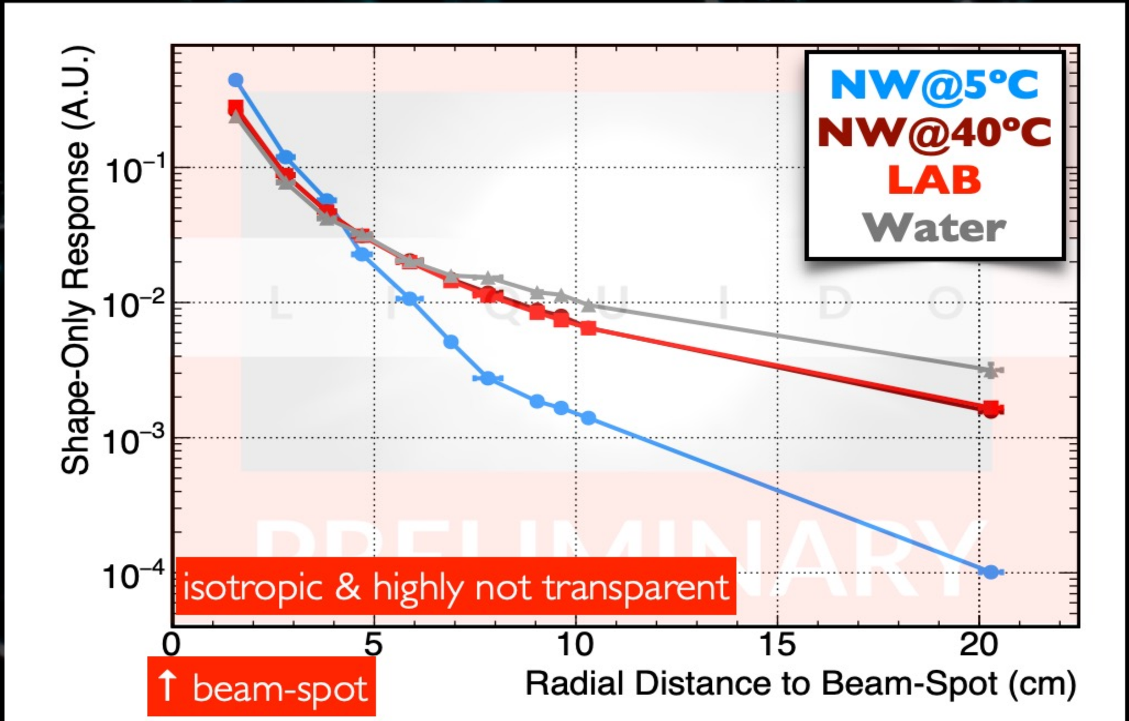


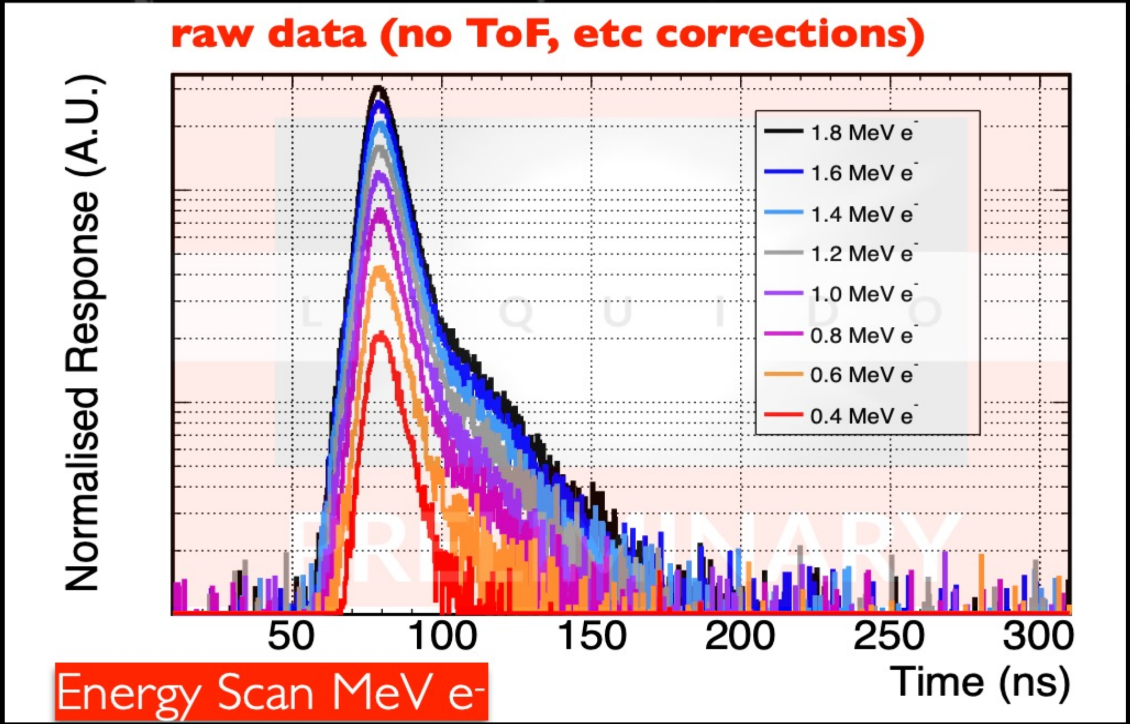
NW at 40℃ "Transparent" — effectively like LAB or Water

Cherenkov reduced by paraffine? — under investigation

Experimental validation

NW@5°C: ~~Cherenkov~~ ⊕ Scintillation





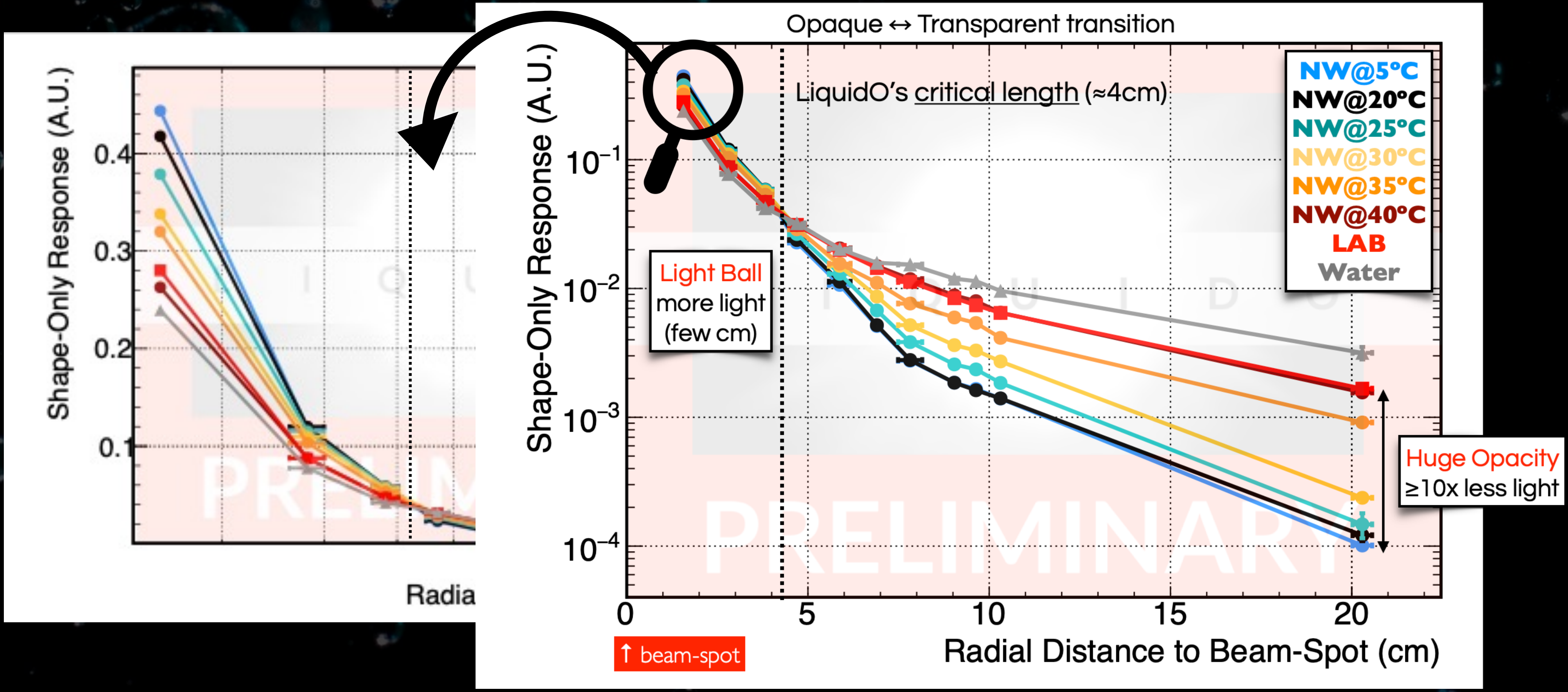
~2x more light due to LiquidO's aggressive scattering

Faster collection and better light containment

Formation topology → stochastic light confinement → LiquidO

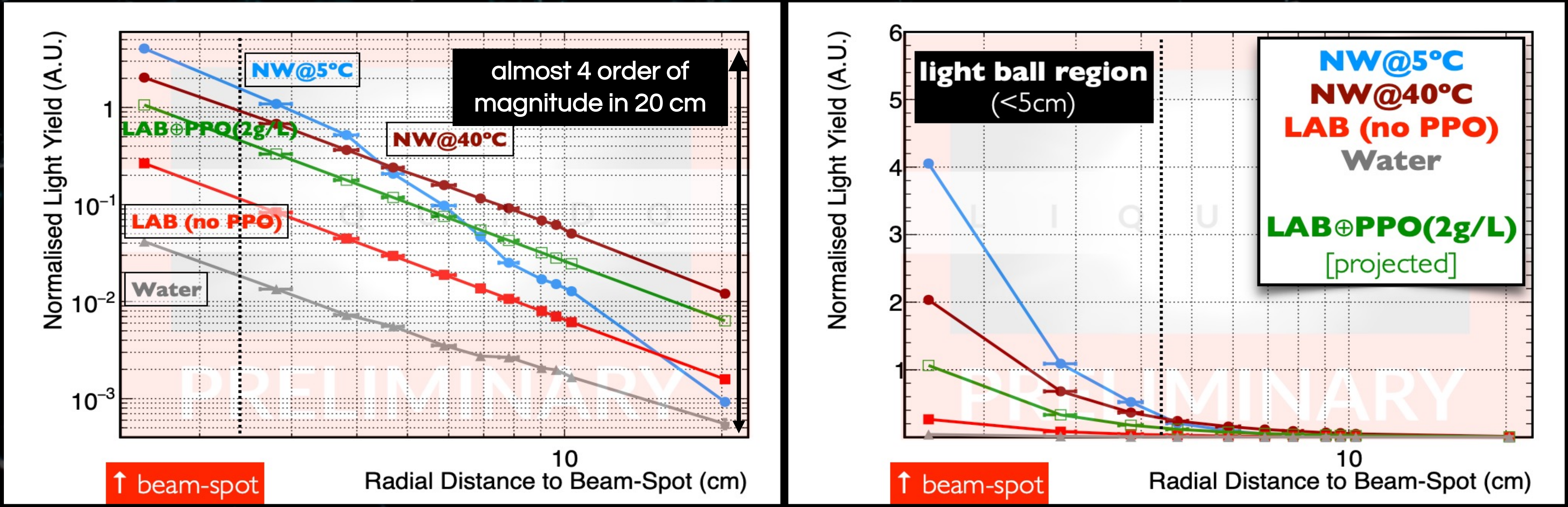
Experimental validation

Opacity demonstration



Experimental validation

Light Yield Exploration



~80% light collected within 5 cm's

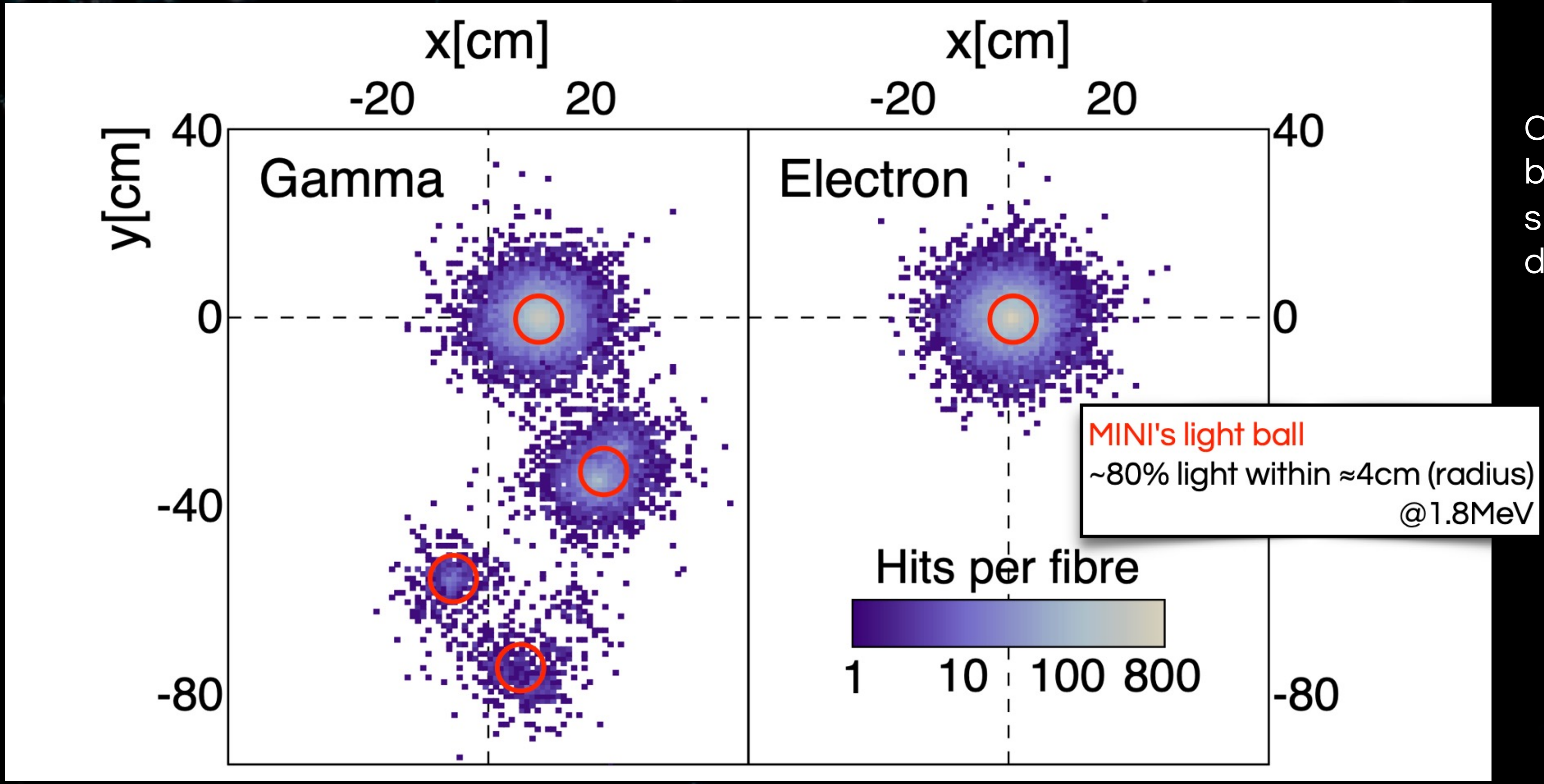
Effective detected light yield >120PE/MeV [@ SiPM]

≥250PE/MeV — optimisation (ongoing engineering)

Experimental validation

Topology PID (no timing)

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



Comparison between simulation and data (red circles)

Outline

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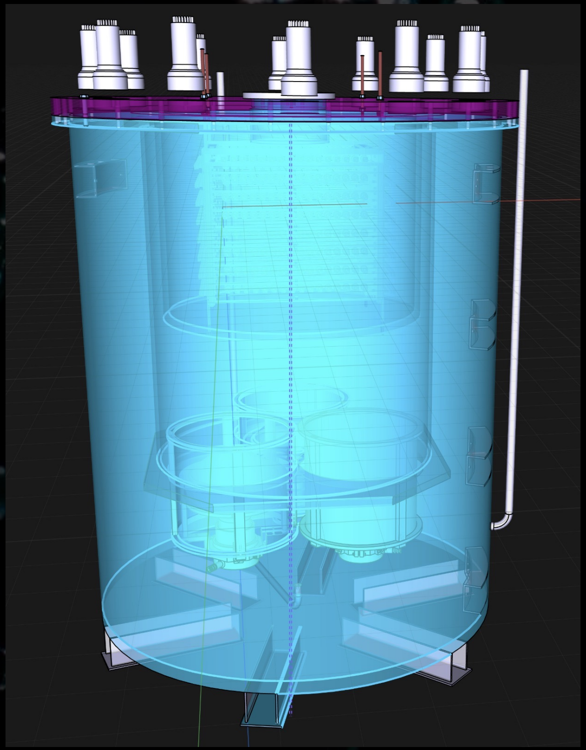
Future prospects

Projects sequence and Timeline

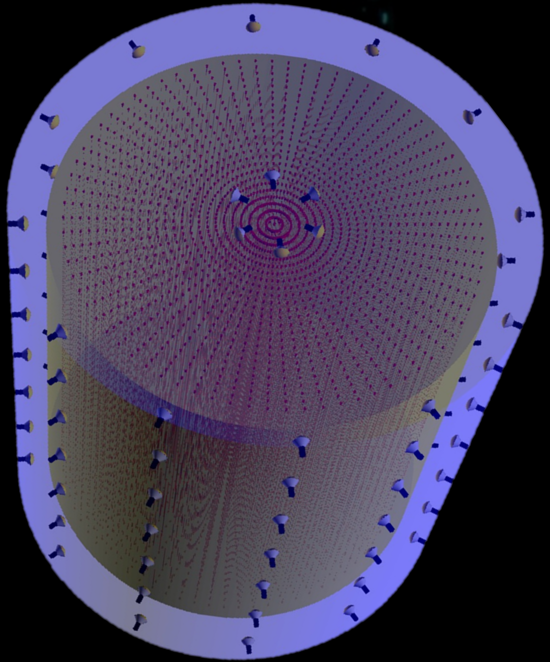
MINI-γ project



~100 kg
2022-2023

νAM-Otech project

Applied & Innovation R&D



~ 5 tons
2022-2027

European Innovation Council

UK Research and Innovation

+ LPET-Otech project
(medical approach)
2022-2024
ANR funded

Future prospects

LiquidO consortium

LiquidO consortium consists of more than 70 scientists in 22 academic institutions (universities and/or laboratories) in over 10 countries

LiquidO@IN2P3:
CPPM, IJCLab, IPHC, LNCA, LP2IB, Subatech (6 laboratories)

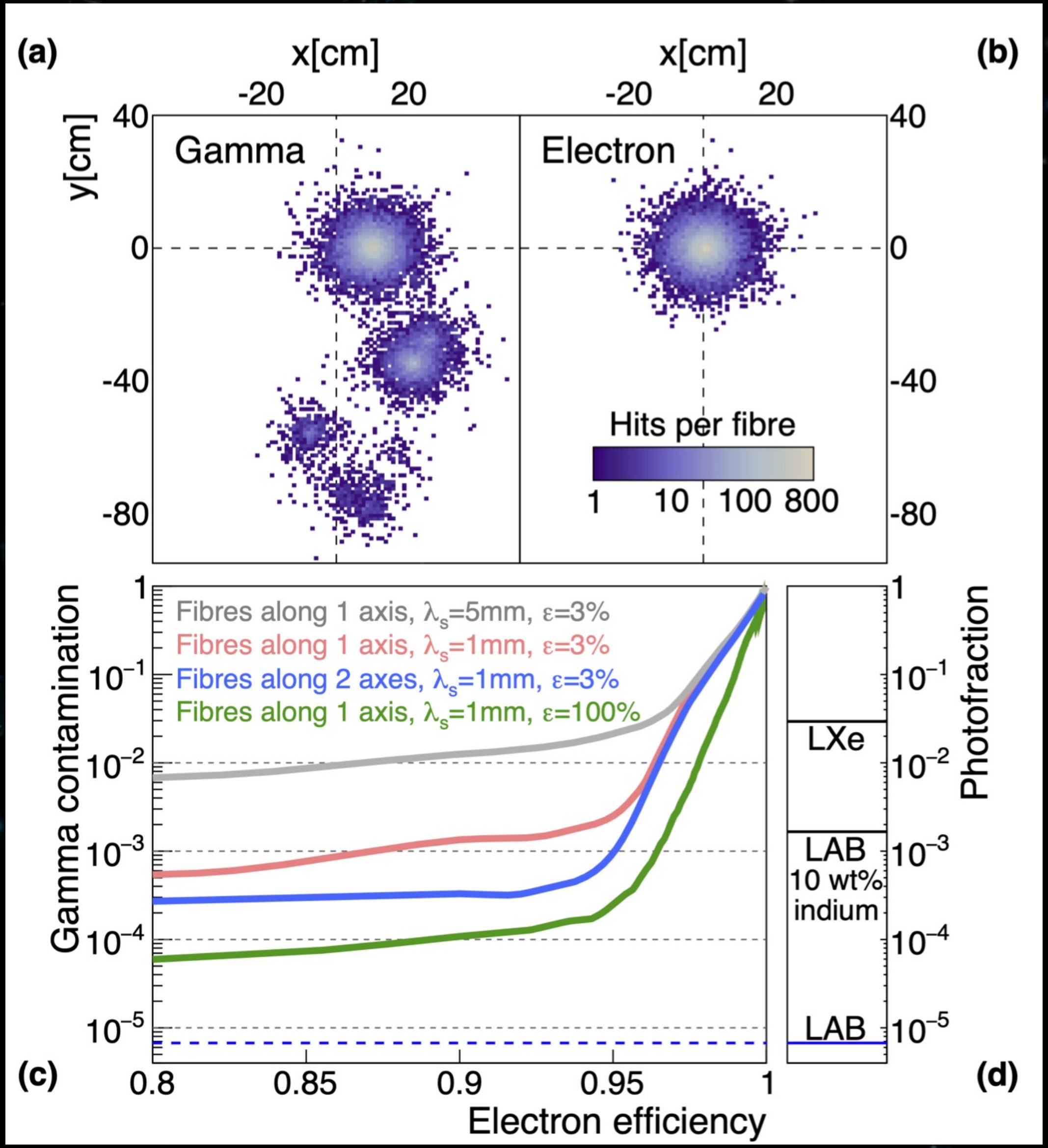
More info
https://liquido.ijclab.in2p3.fr

Conclusions

- LiquidO is a novel detector concept → opaque LS
  - Light confiment close to its creationpoint by a short scattering length
  - Light collection by a dense grid of wavelength shifting fibers + SiPMs
- LiquidO enables highly efficient PID
  - Event-by-event topological discrimination power
  - Powerful background discrimination
- Possibility of loading dopants at high concentrations
- Extensive and exciting physics potential (solar, reactor, SN, geoneutrinos...)
- Experimental validation of light confinement (MINI-II prototype)
- Future projects under development!

Thank you!

Back-up

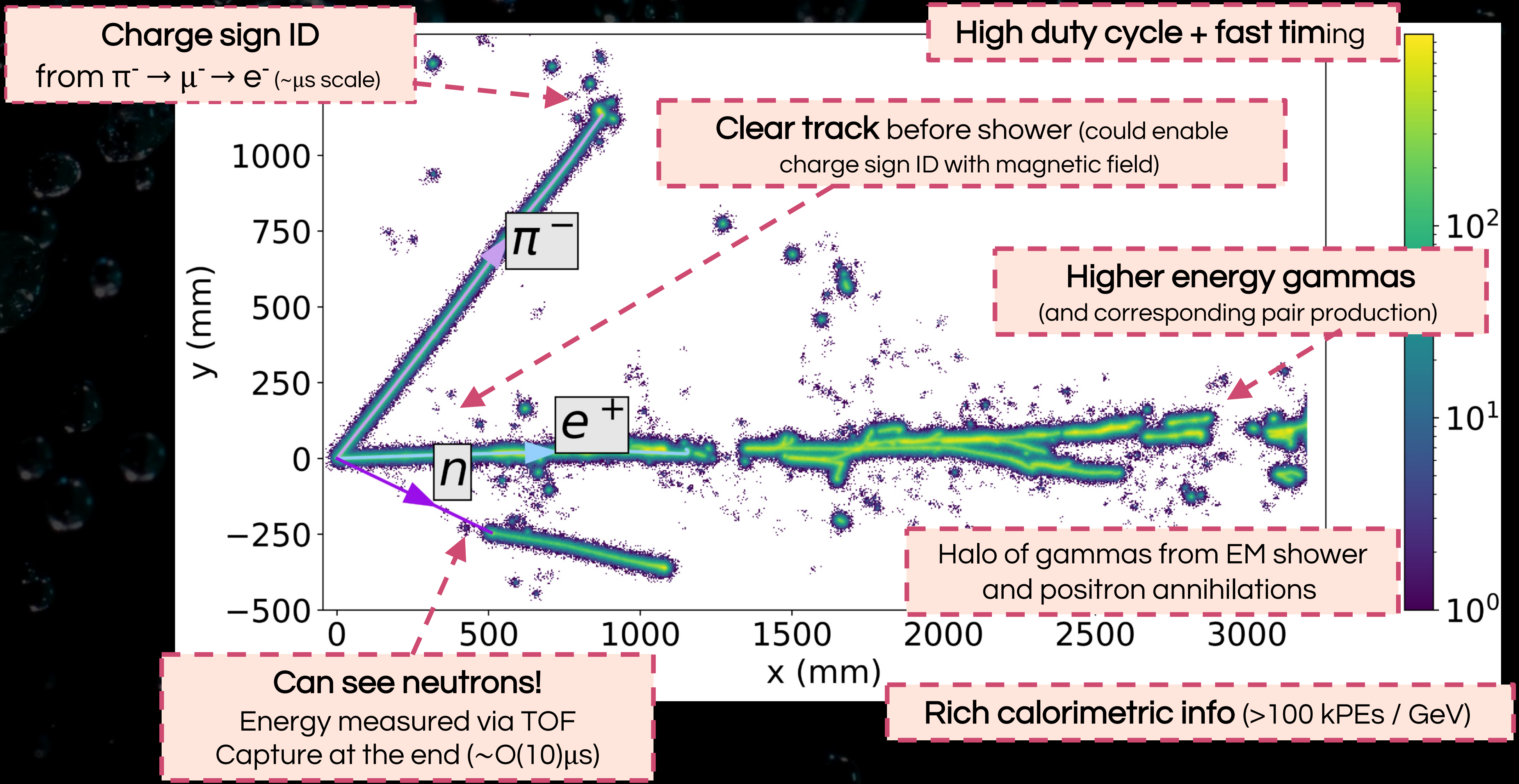


- 1-cm-pitch lattice running along the z-axis
- Probability of misidentifying a γ as an e^- vs. the efficiency of selecting e^-
- mean scattering length λs of either 1 mm or 5 mm
- photon detection efficiency ε of 3% (fibre trapping efficiency (~10%) and SiPM QE (~50%)
- The grey curve shows the probability of misidentifying a 2 MeV γ as an e^- is estimated to be at the 10^{-2} level with an efficiency of 87% for λs=5 mm.

Physics potential

Beam Physics

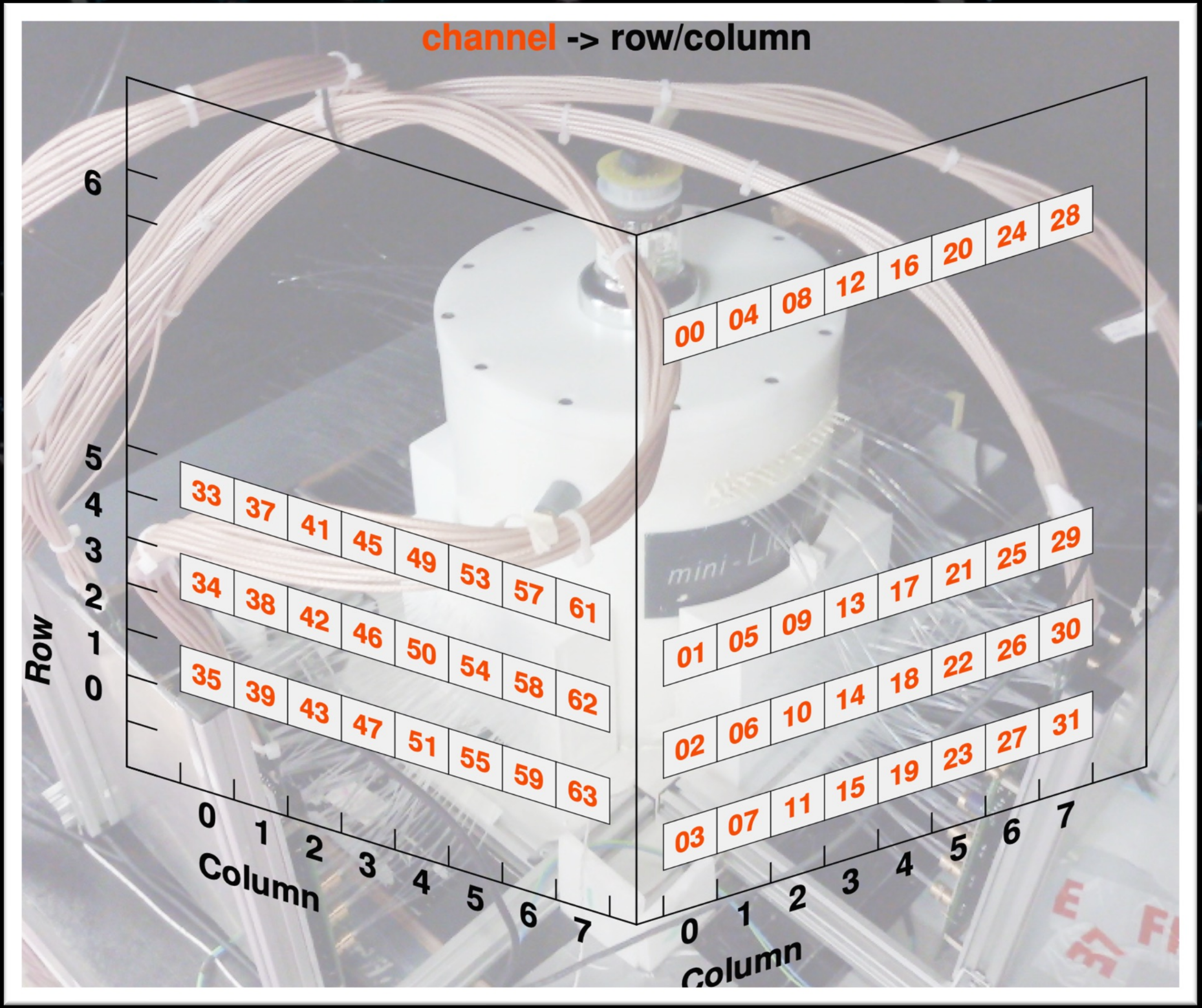
GeV-neutrino interactions



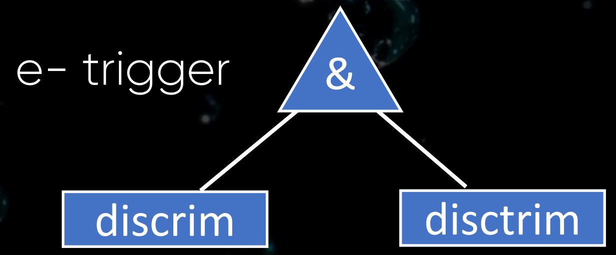
Imaging capabilities comparable to LArTPC
+
Complementary features unique to LiquidO

Experimental validation

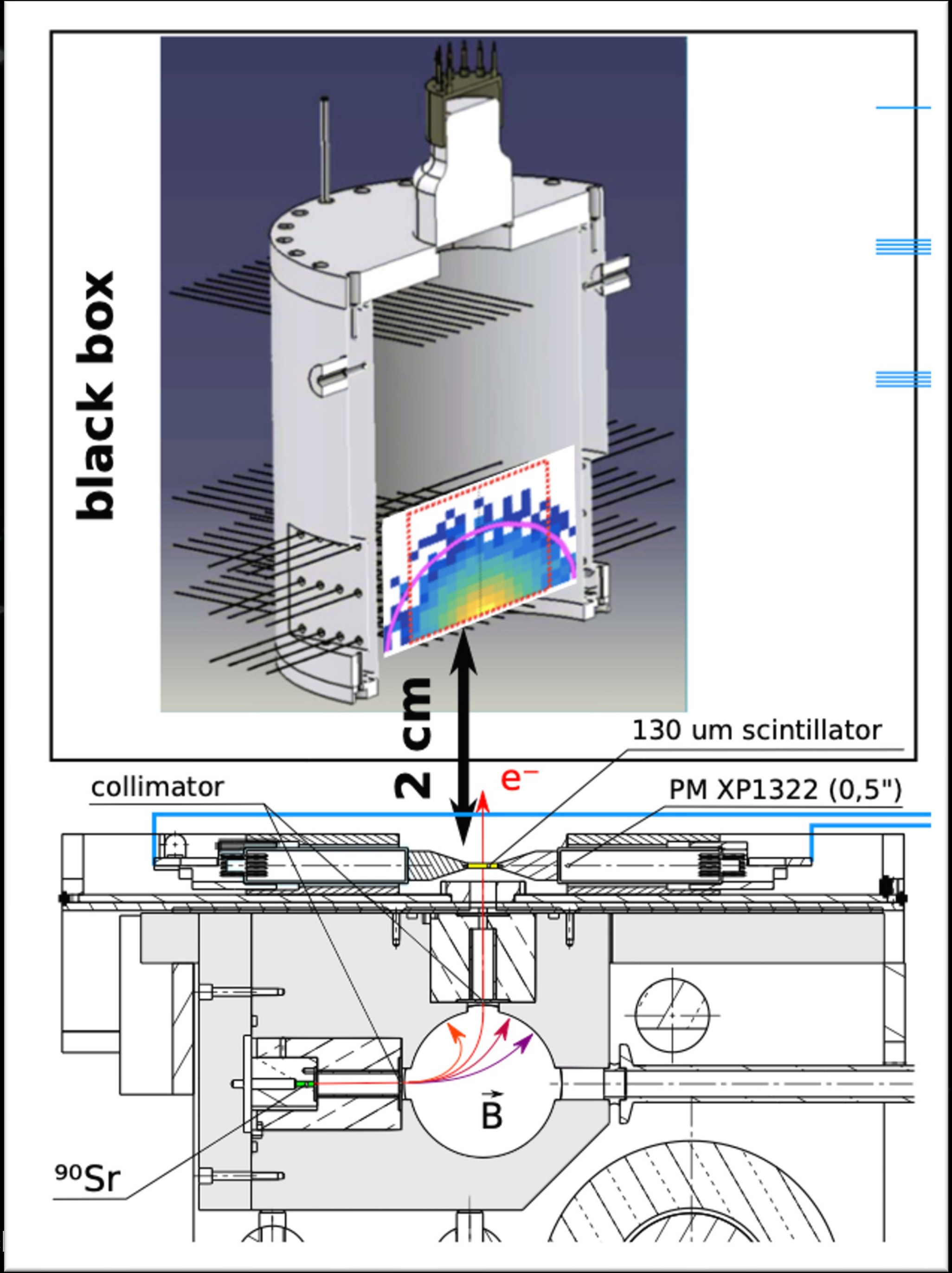
Mini-II Set Up



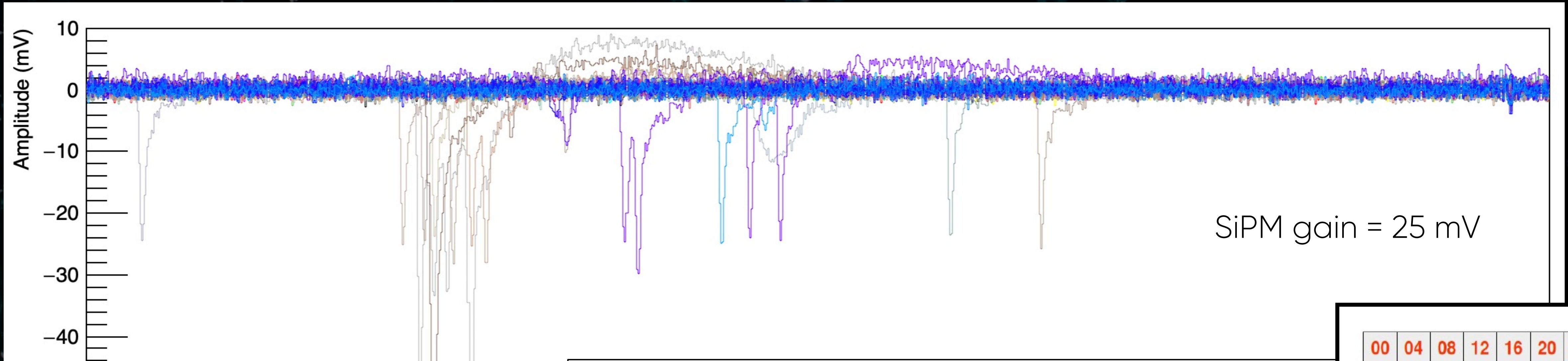
Experimental validation

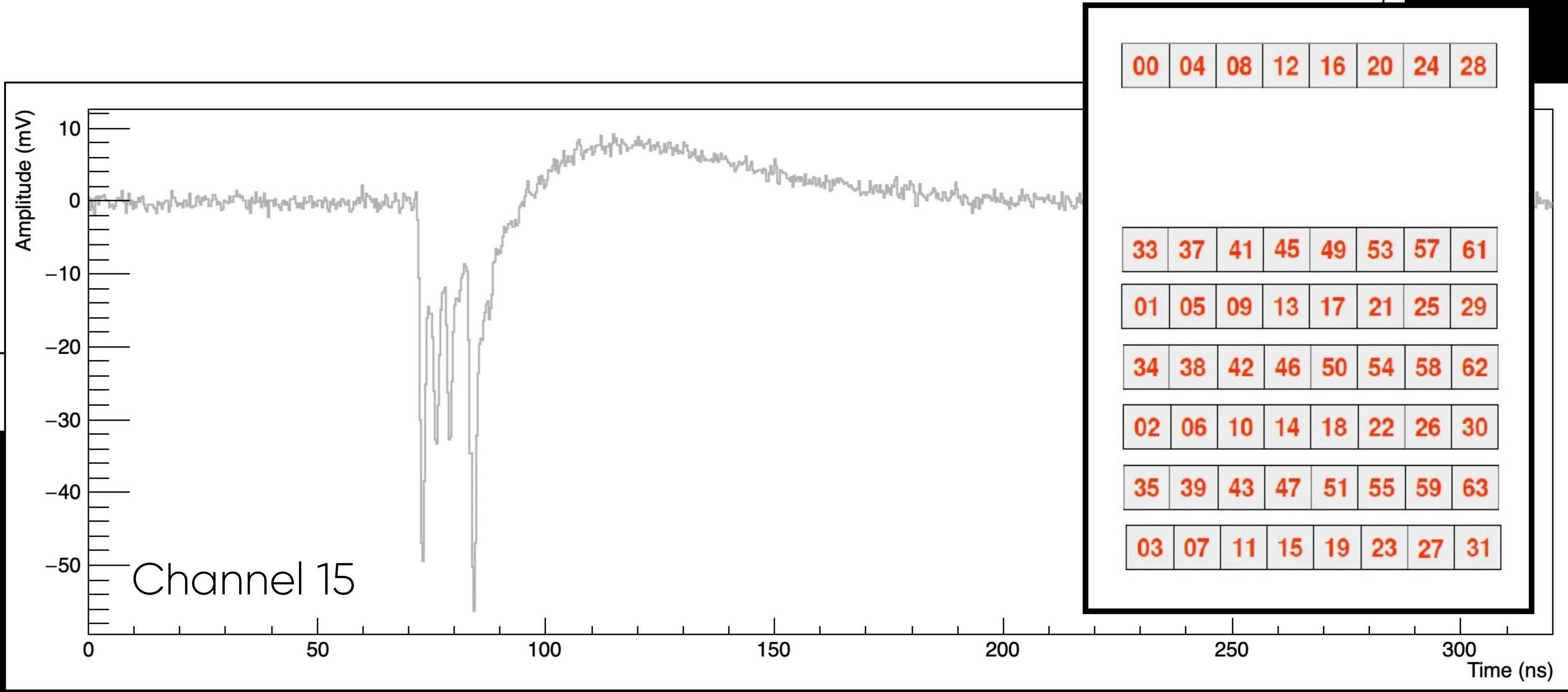


Coincidence between 2 PMT triggers is done directly by wavecatcher



Experimental validation

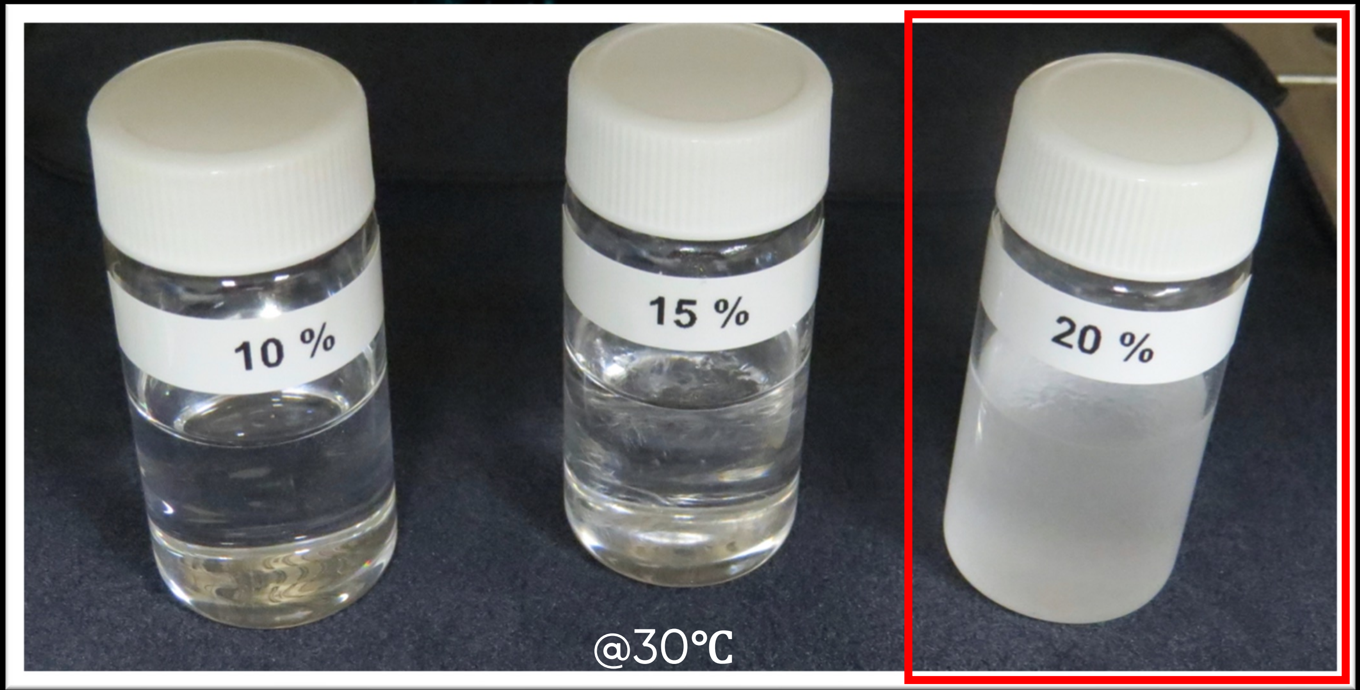




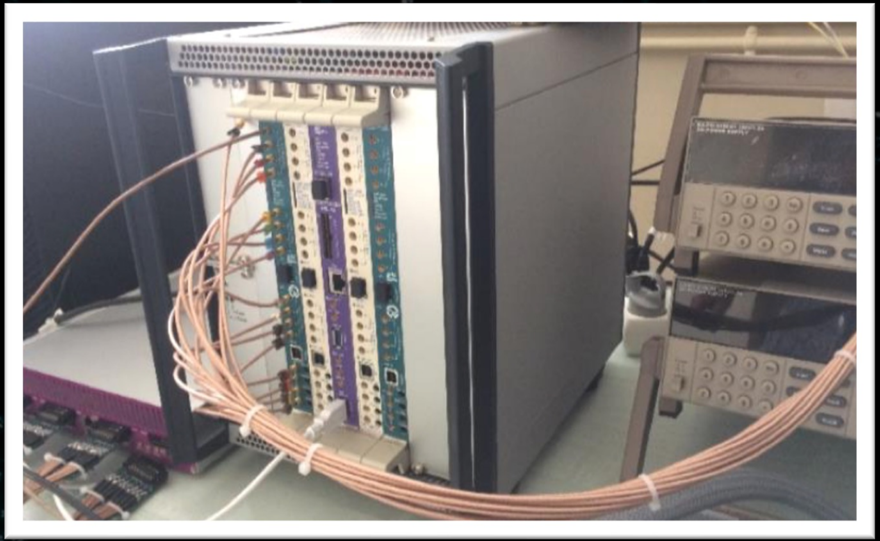
Experimental validation

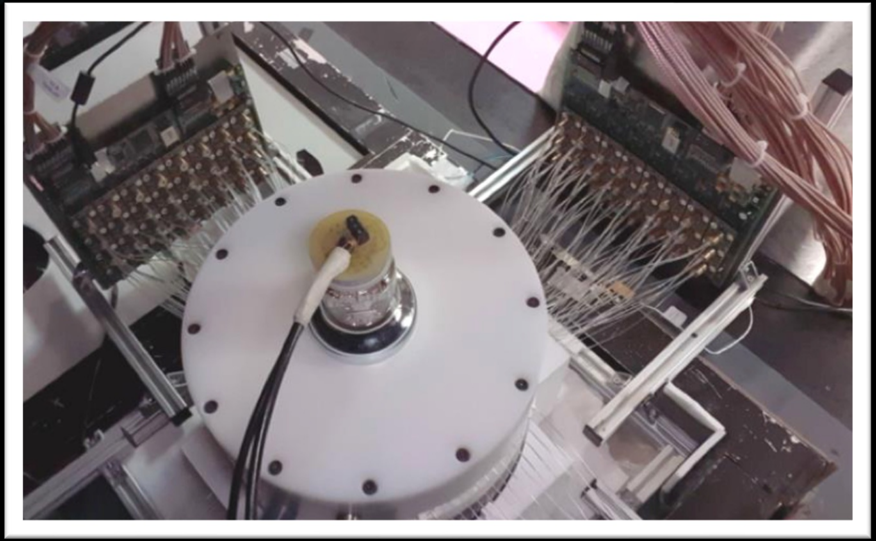
- WATER: Cherenkov (transparent)
- LAB: Scintillator + Cherenkov (transparent)
- NoWASH-0: LAB + PPO
- NoWASH-20: addition of paraffin wax into the LAB scintillator with PPO shifter

  - Scattering lengths in the mm range without significant absorption
  - Light yield losses are small
  - Radiopurity estimates are promising
  - Open the possibility of using techniques for high loadings which were rejected from attenuation length limitations

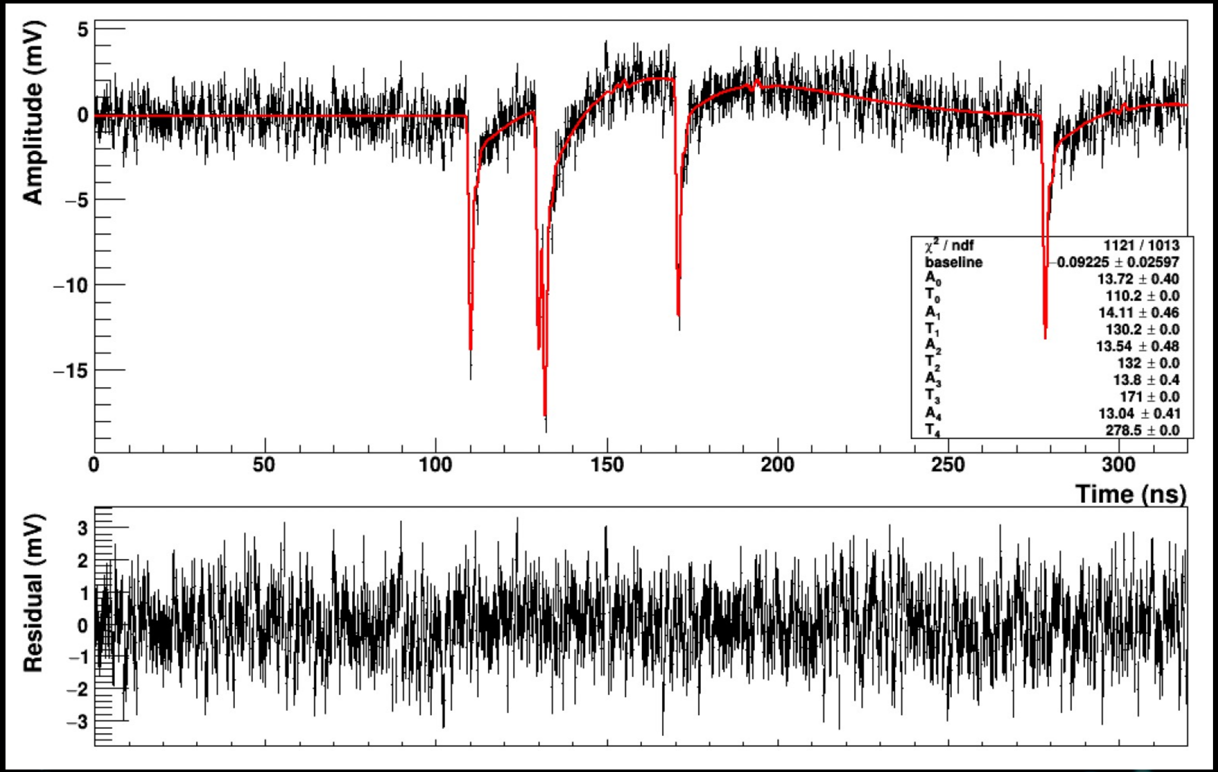


Electronics

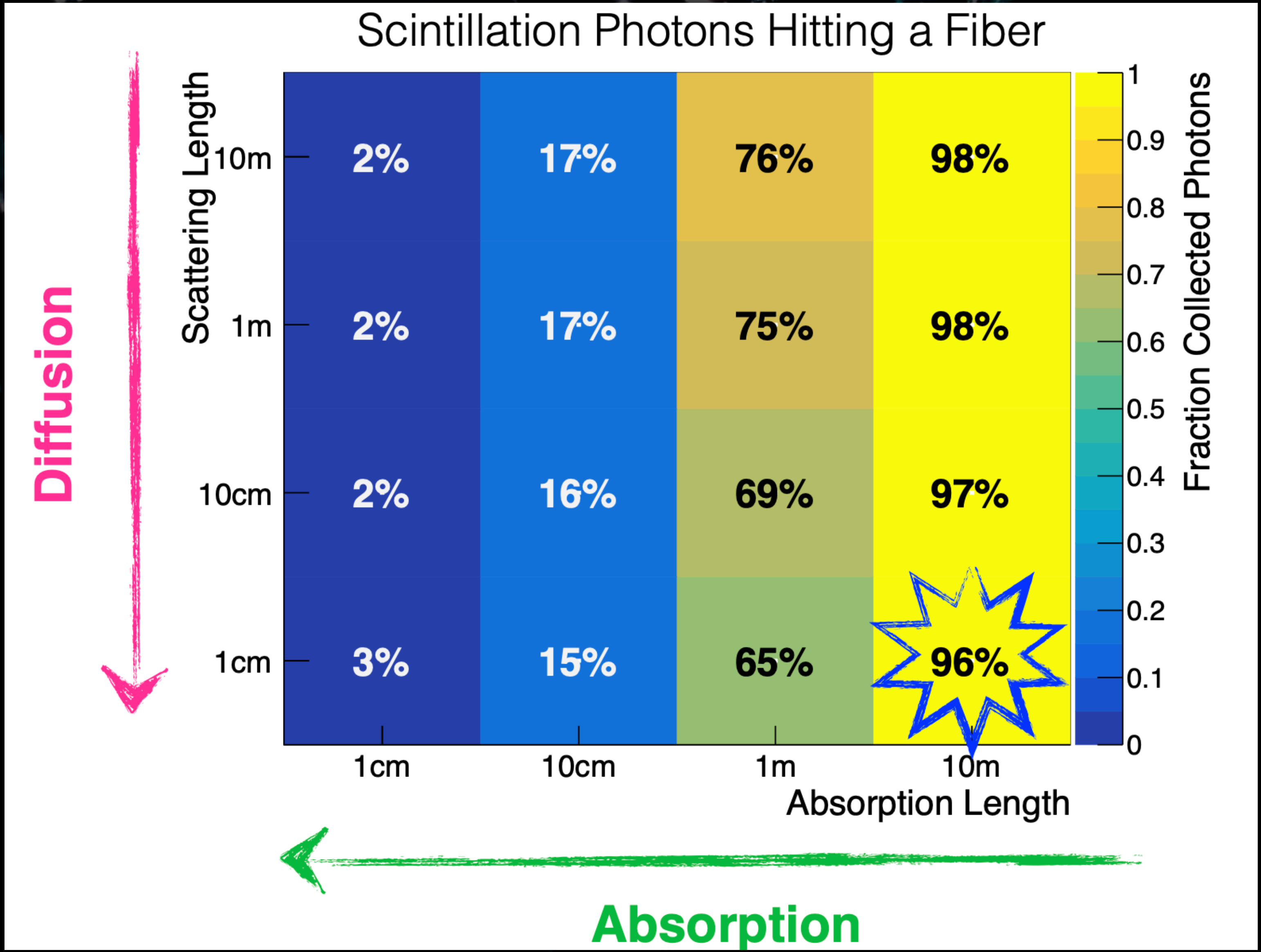




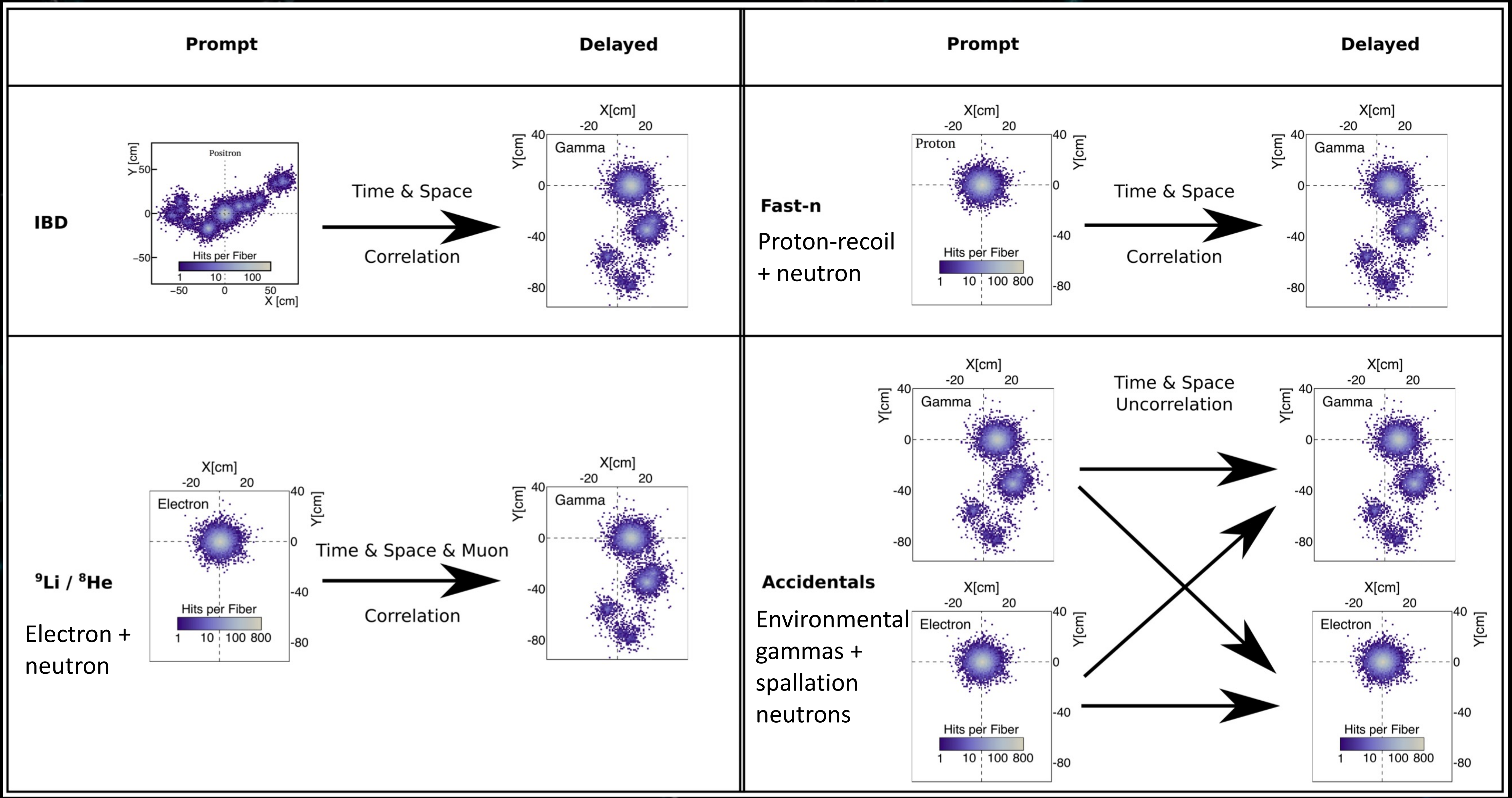
- Analog memory digitiser using SAMLONG chip (CNRS/IJCLab + CEA/IRFU)
- Sampling frequency from 400 MHz to 3.2 GHz
- ADC dynamic range of 2.5 V coded on 12 bits (1 ADC tick = 0.61035 mV)
- Exists in 2, 8 or 16 ch desktop format, and 64 ch mini-crate
- Fast readout: potential resolution ≤100ps



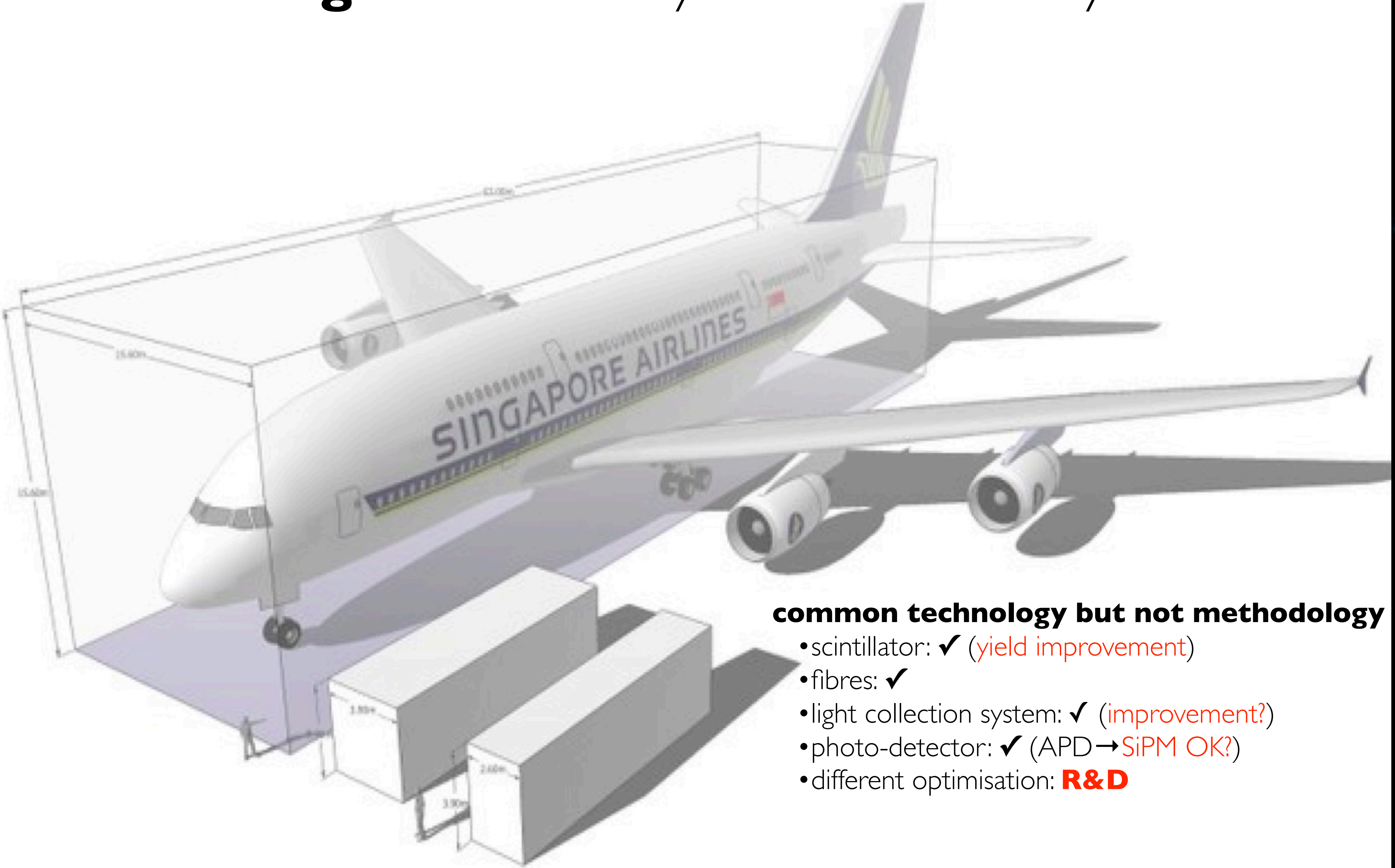
Light collection efficiency



Reactor neutrino background



scaling? much already demonstrated by **NOvA**…



common technology but not methodology

- scintillator: ✓ (yield improvement)
- fibres: ✓
- light collection system: ✓ (improvement?)
- photo-detector: ✓ (APD→SiPM OK?)
- different optimisation: **R&D**

GeV OK!! But **~1MeV physics @ 10kton?**

(**R&D**)

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