LiquidO: Opaque light detection technology

Cloé Girard-Carillo

On behalf of the LiquidO Consortium

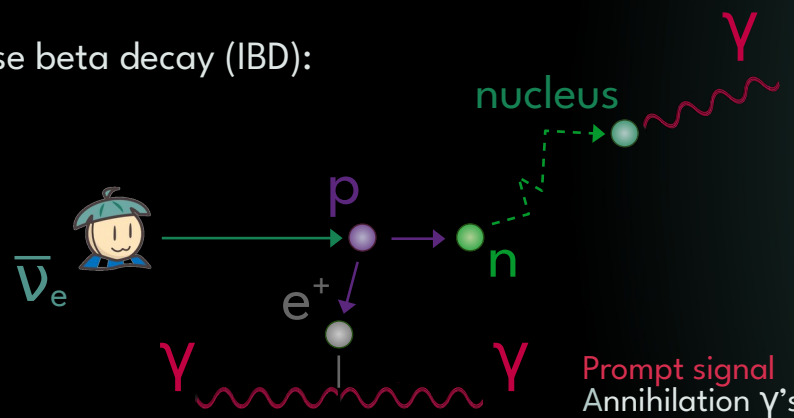
28 August 2023

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TAUP VIENNA 2023

Transparent scintillator detectors

Inverse beta decay (IBD):



Delayed signal
Nuclear capture of n

Prompt signal
Annihilation γ's

First neutrino experimental discovery
Cowan & Reines, reactor experiment

Transparent scintillator detectors

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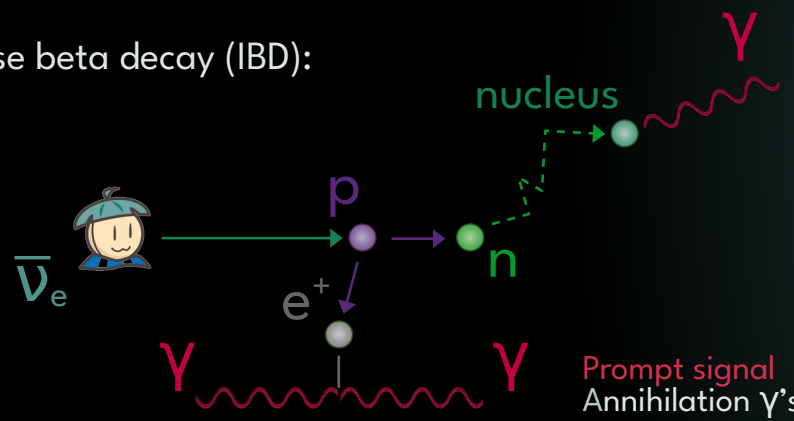

Delayed signal
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First neutrino experimental discovery
Cowan & Reines, reactor experiment

- Electrons from scintillator material are excited, and de-excite with emission of photon
- Light propagates across transparent volume to surrounding photo-sensors (PMTs)

Transparent scintillator detectors

Limitations

- Detector size (today up to 20 kT)
- Doping possibilities
  (for enhanced detection capabilities + bkg rejection + rare processes searches)
- Topological information
  Hard to disciminate individual e+ / e− / γ below 10 MeV

One solution is detector segmentation (a la NOνA) but

- Limited by dead material, radiopurity constraints...
- Hard to achieve the required granularity for MeV scale

First neutrino experimental discovery
Cowan & Reines, reactor experiment

"LiquidO" concept

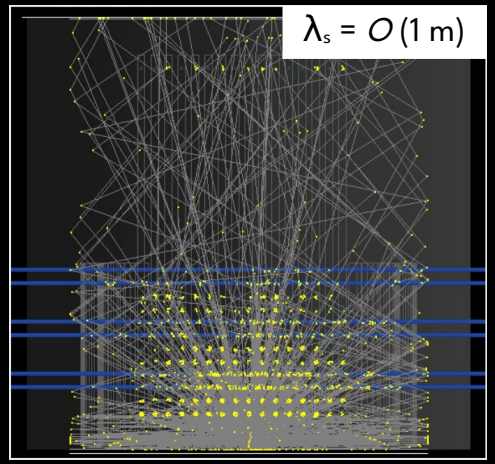
LiquidO: a new detection paradigm

~ meters

Scattering length

Transparency

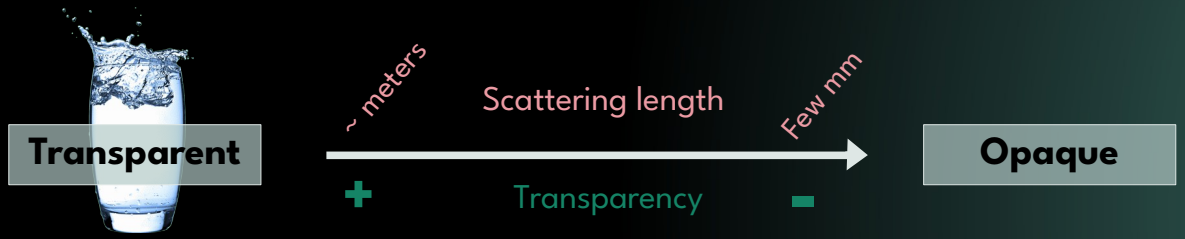
Path of light in liquid scintillator, depending on scattering length / opacity of the medium:



Transparent: current technology

Topology information washed out

LiquidO: a new detection paradigm



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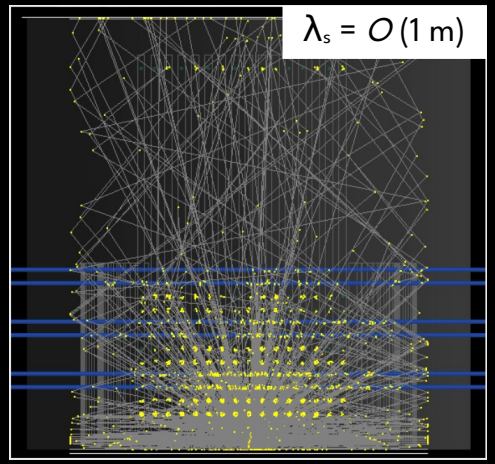

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LiquidO: a new detection paradigm

Transparent

~ meters

Scattering length

Few mm

\+ Transparency −

Opaque

Short absorption length

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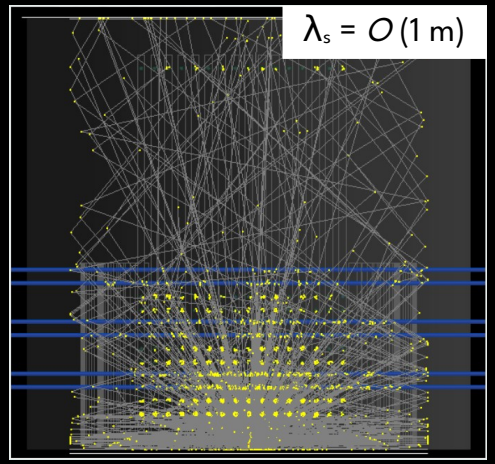

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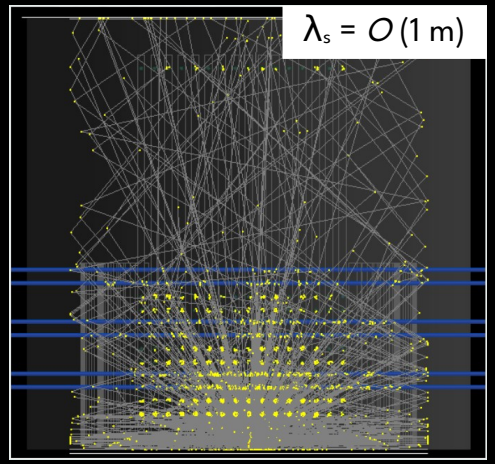

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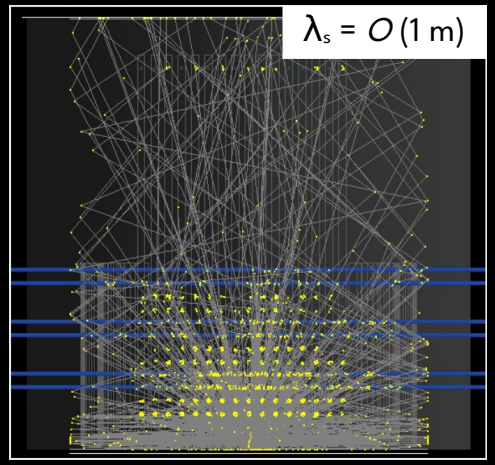

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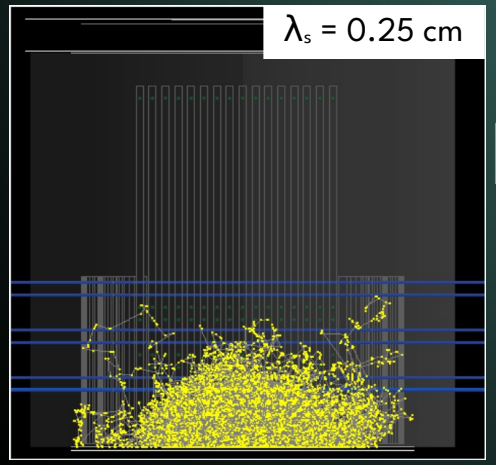
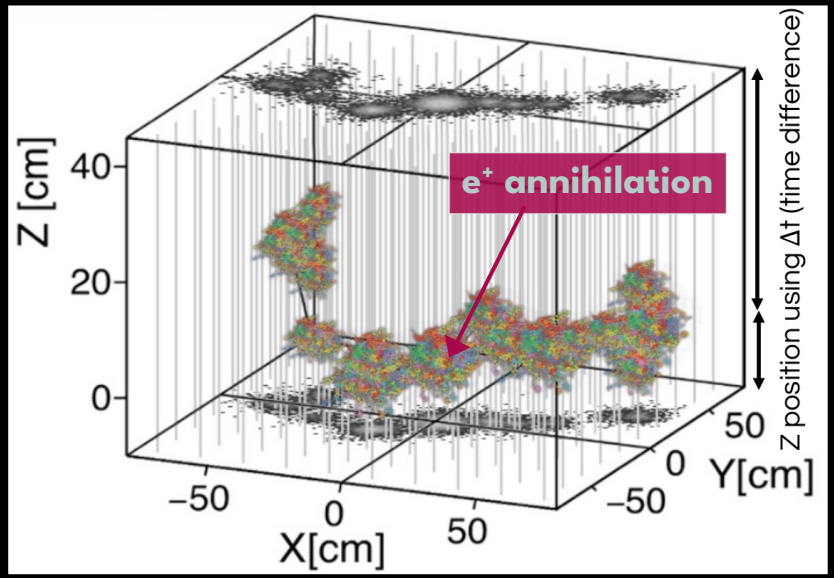


Opaque: LiquidO technology

Random walk

An innovative detection technique

Simulation of light propagation in opaque scintillator (random walk)
e+ of 1 MeV Kinetic Energy



Bottom/top views: (X,Y) projections

- Opaque scintillator
  → Light confinement around each ionisation point
- Dense array of wavelength shifting fibres (WLS)
  → Light collection near interaction point

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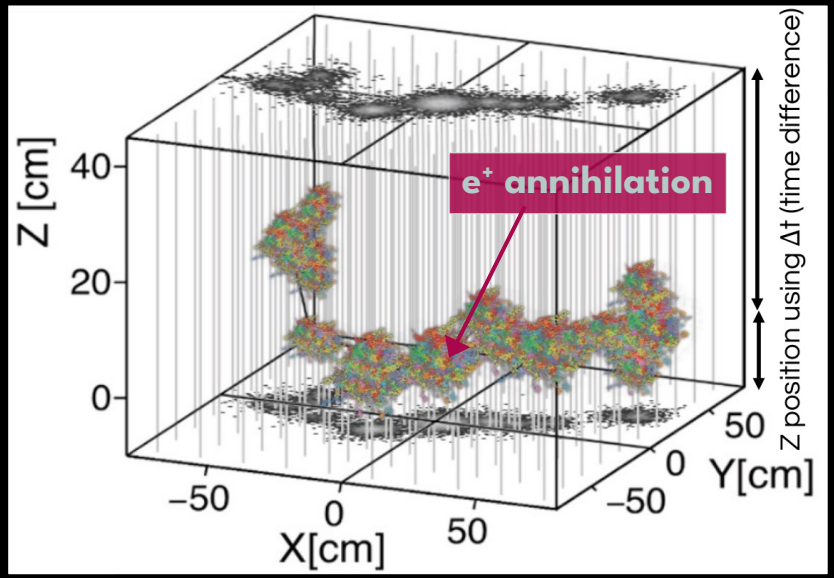

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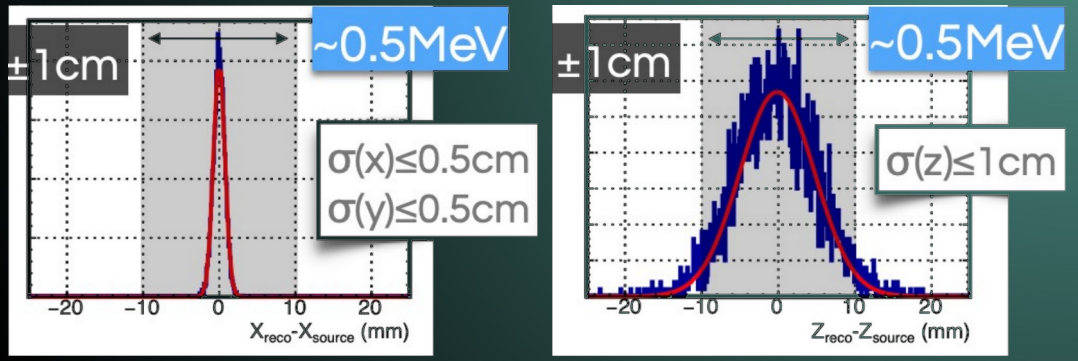


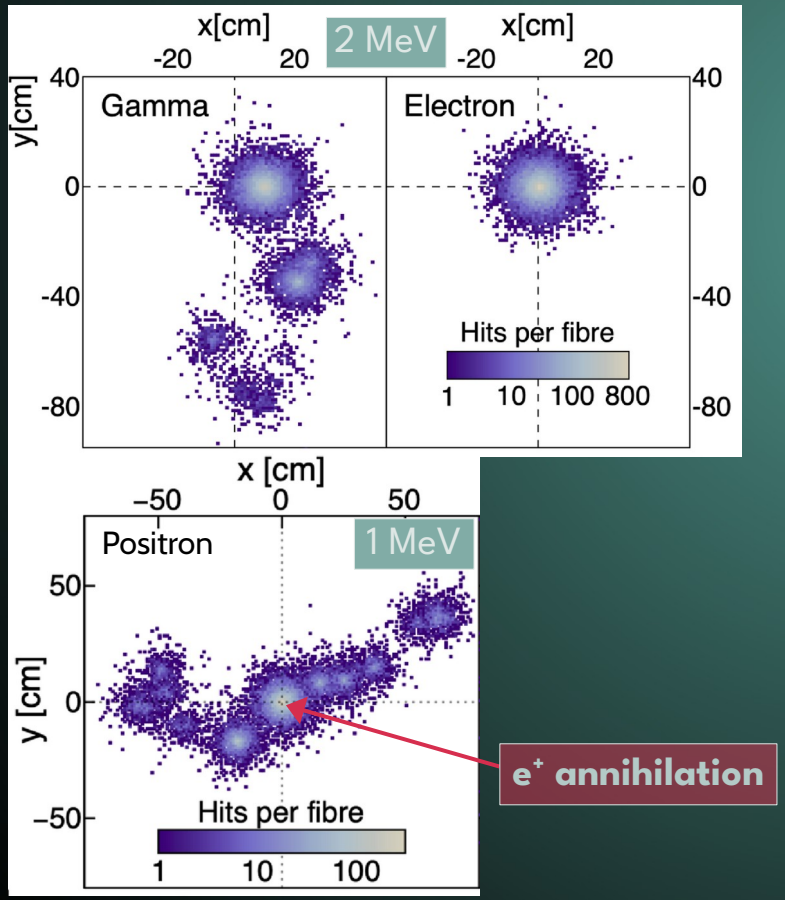
- **High spatial resolution** (≤ 1 cm)
- Fast time resolution (SiPMs < 0.1 ns)

Unprecedent particle identification @ MeV scale

- Particle discrimination

  Individual e+, e- and gamma @ MeV scale
- Powerful background rejection capability
- Self-segmented detector
  → No need to introduce dead material for segmentation

Potential: reduce overburden/shielding

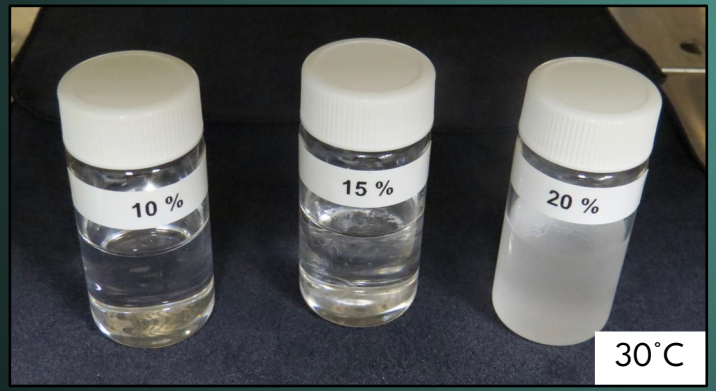


Opaque Liquid Scintillator for prototyping

Organic scintillator:

NoWaSH (New opaque Wax Scintillator, Heidelberg): Gel-like material

Linear Alkyl Benzene (LAB) (~80 wt. %) + Paraffin wax (10-20 wt. %)
+ Wavelength shifter (PPO) (0.3 %)



Novel Opaque Scintillator for Neutrino Detection
C. Buck et al. JINST 14 P11007 (2019)

Advantages:

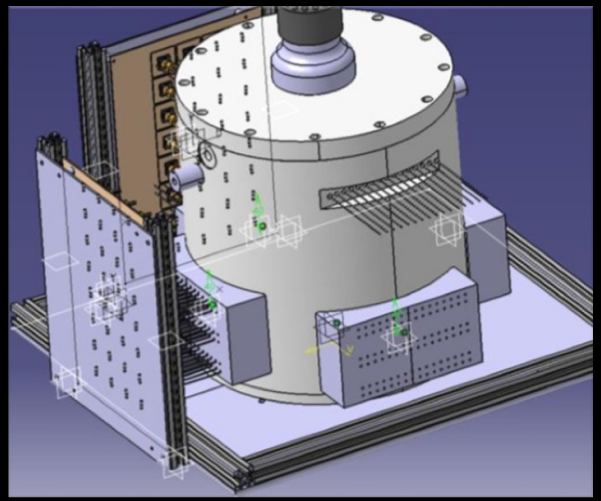
- Short scattering length & moderate absorption length
- Opacity depends on wax concentration / temperature

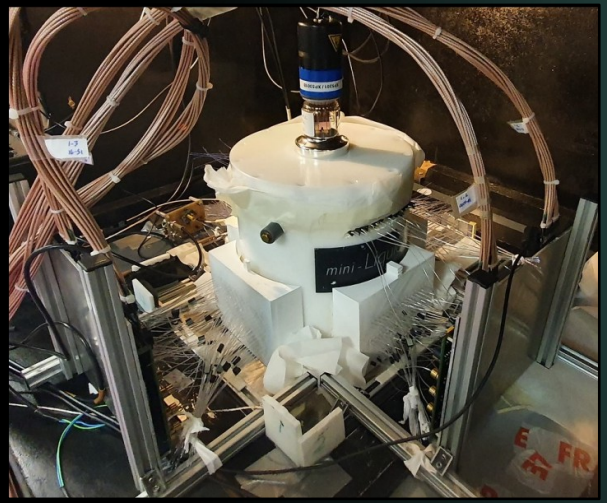
LiquidO extensive R&D in this field: Several new formulations under exploration

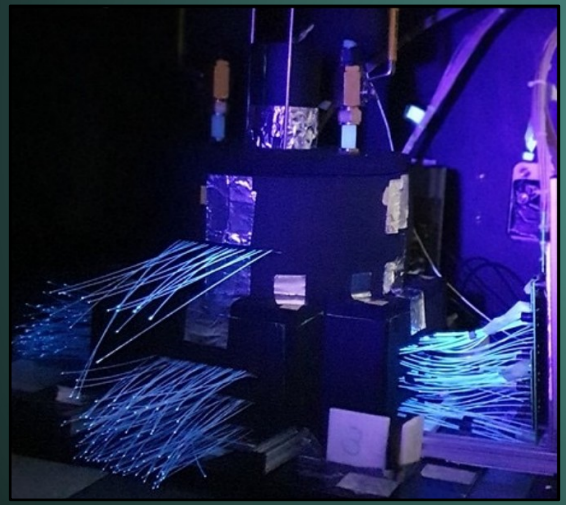
Experimental validation

Mini-LiquidO Prototype: data taking since 2021

Source: e- from monoenergetic beam (^{90}Sr) [0.4-1.8 MeV]
Operated @ LP2i Bordeaux (France)







- ~10 L with 56 readout fibres in 2 orthogonal directions + one 3" PMT
- Opaque Liquid Scintillator: NoWaSH 20 + runs with Water & LAB (+PPO)

- TEMP cycle [5, 40] ˚C — powerful TEMP 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)

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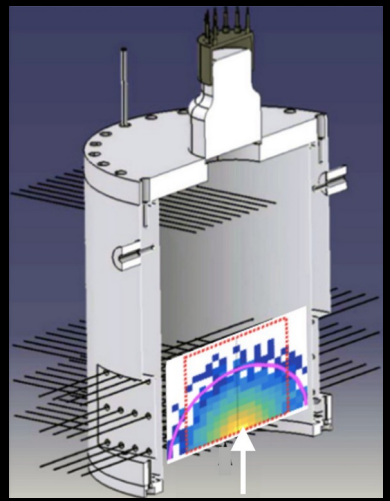

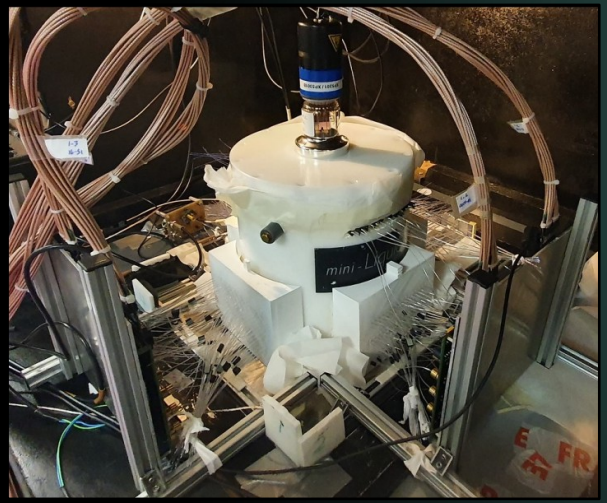

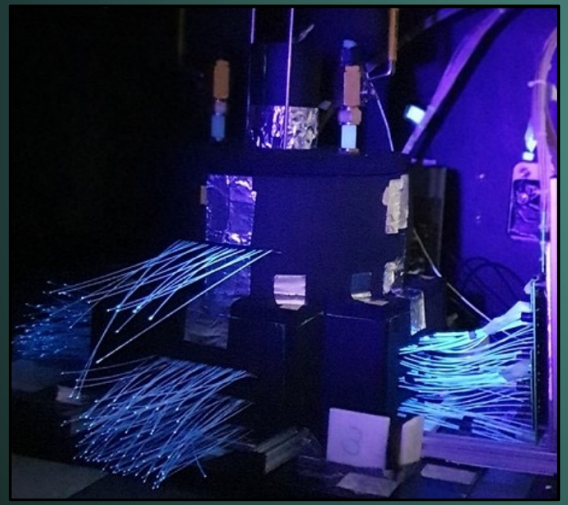

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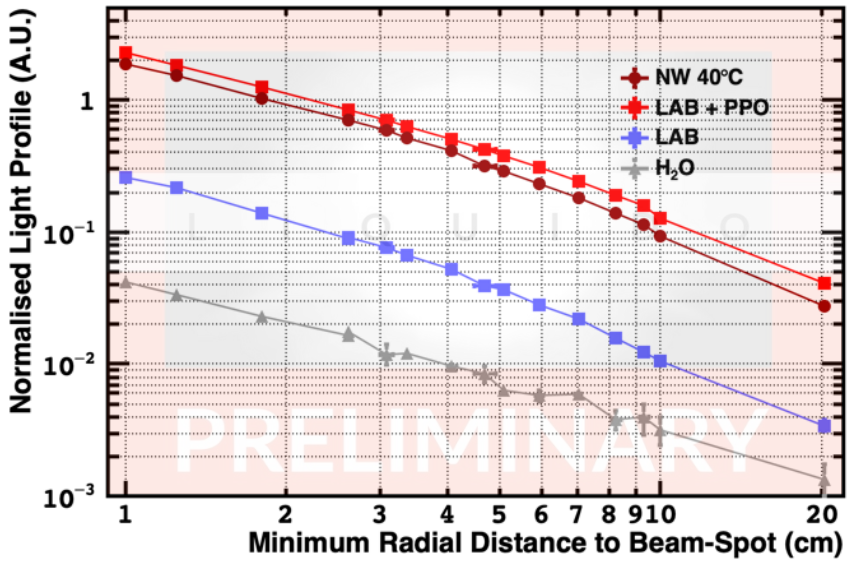
Goal: Observation of light confinement

Experimental validation

Transparent vs Opaque



NW @ 40 °C : almost as transparent as the usual LAB+PPO (less light due to 20 % paraffine)

LAB+PPO (3g/L): amount of light increased

LAB: more light due to scintillation

Water only [Cherenkov]

Experimental validation

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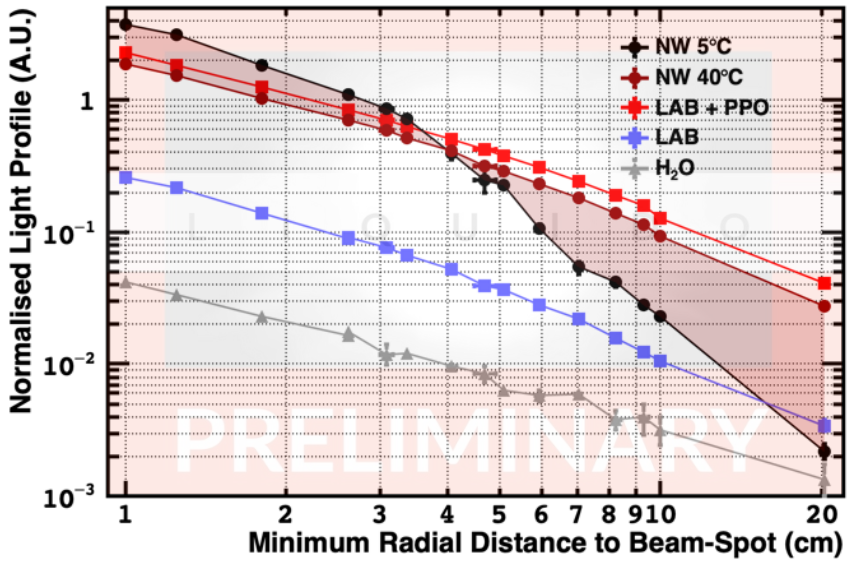

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→ Faster collection and better light confinement in the opaque mode

→ Light Ball formation at ~4 cm

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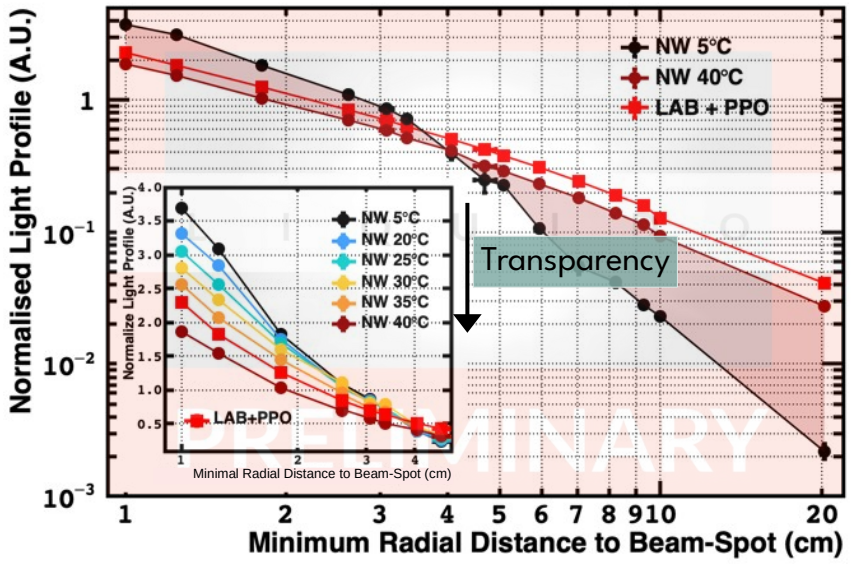

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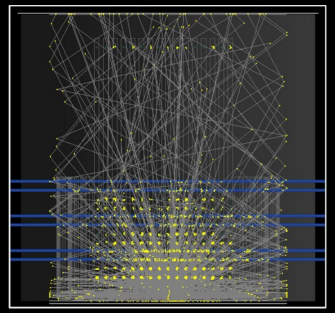
Light confinement is observed

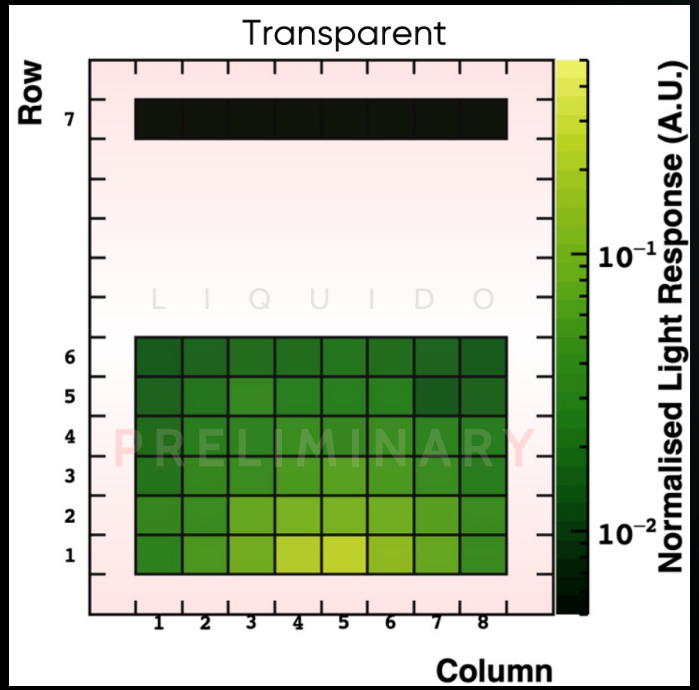
→ Major demonstration of the LiquidO technology

Experimental validation

Transparent vs Opaque

Light confinement demonstration



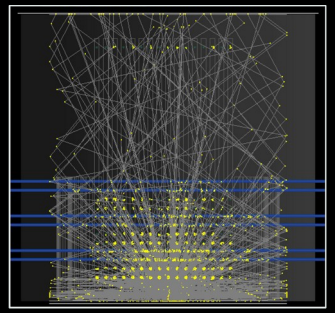


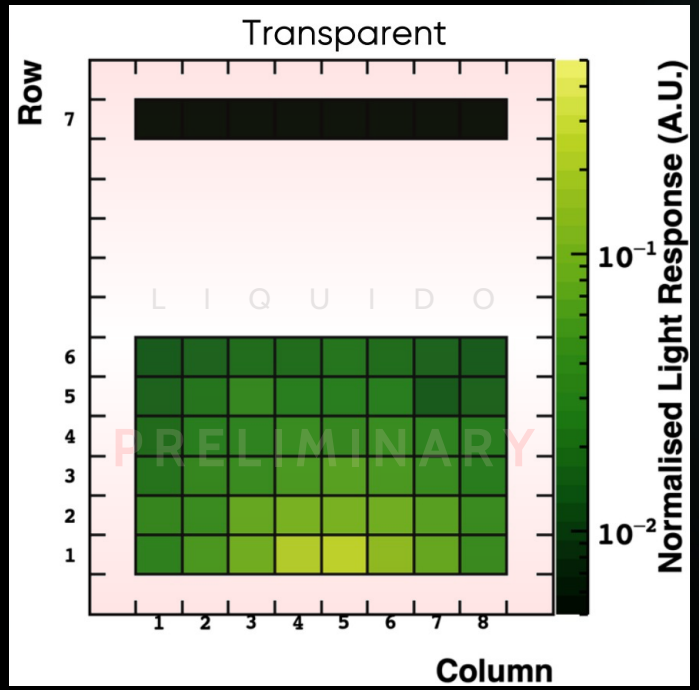
Amount of light collected by each of the 56 fibres of the detector

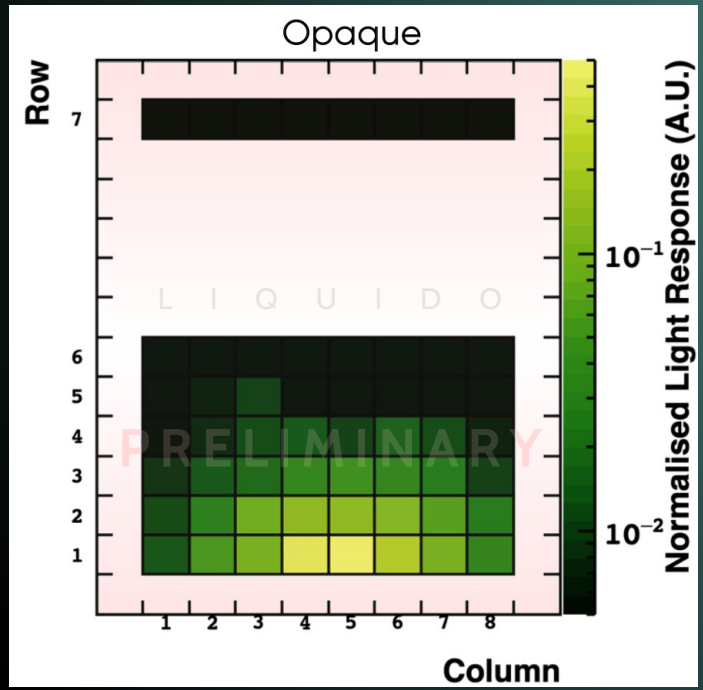
Experimental validation

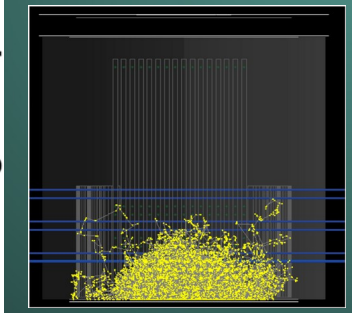
Light confinement demonstration

Transparent vs Opaque









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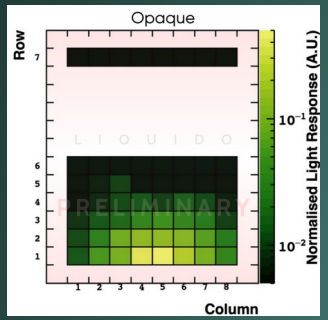
Conclusion



- Innovative new "LiquidO" detector technology → Light confinement
  - Opaque medium + lattice of fibres
  - High-resolution imaging
- Many LiquidO projects now funded and underway: CLOUD experiment (reactor neutrinos), LPET (medical physics)…

More than 94 scientists in 26 academic institutions (universities and/or laboratories) in 11 countries

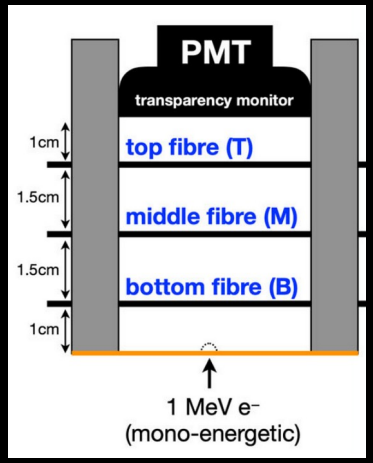
More info:
https://liquido.ijclab.in2p3.fr

Thank you!

Back Up

Micro-LiquidO prototype

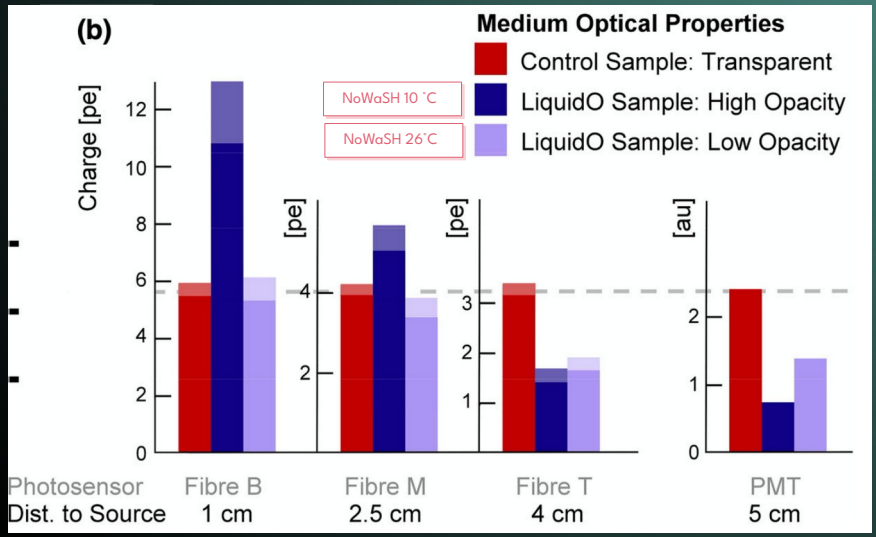
Experimental ligth-confinement proof of principle



> 30 ˚C: Transparent liquid phase
< 15 ˚C: opaque solid phase

Prototype:

- Scintillator: LAB + PPO 2 g/l (+ 10 wt. % wax)
- 3 fibers B3 Kuraray WLS / SiPM readout
- Small LiquidO prototype detector
- 1 MeV e- source

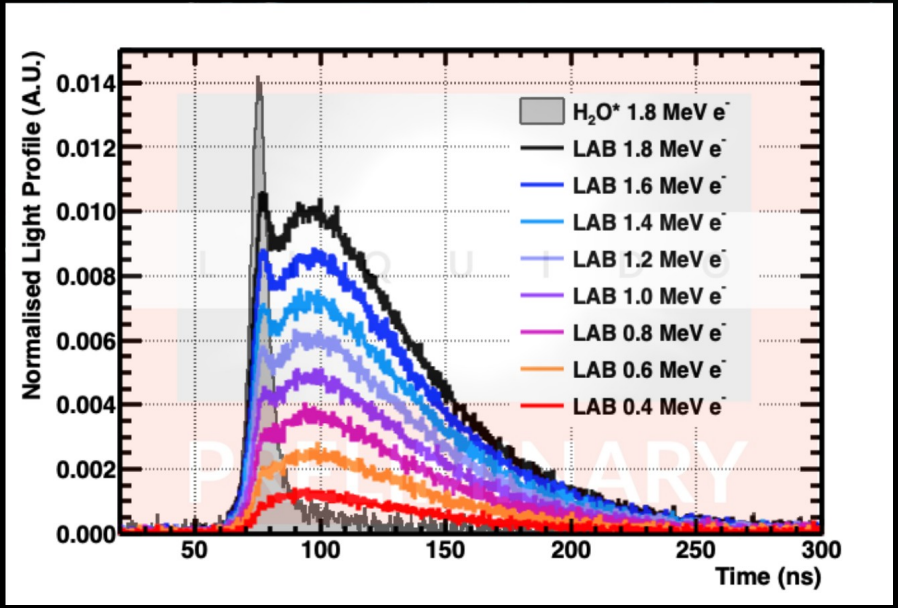


Conclusions:

- Light collected at fibers increases by more than factor of 2 between opaque NoWaSH / transparent LS
- signals further away strongly reduced → local light confinement achieved! (without significant loss of total photoelectron signal)

Mini-LiquidO prototype

Cherenkov vs scintillation light



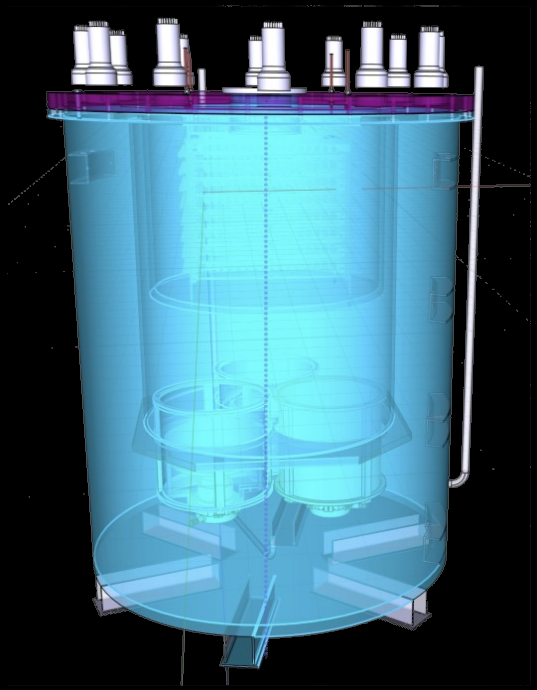
Transparent media regime

- Liquid scintillator: pure LAB without PPO
- Water data allows confirmation of the Cherenkov peak time position
- Remarkable separation using only timing
- Cherenkov light production threshold

Future prospects

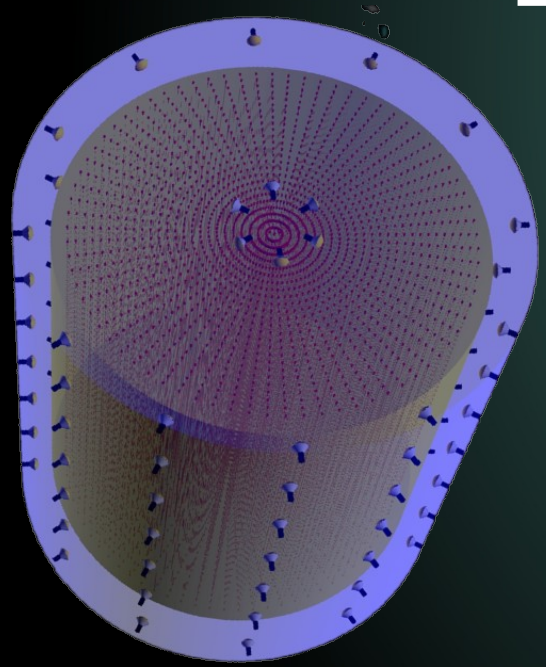
Projects sequence and time-line

Mini-gamma project



~100 kg
2022-2023

AntiMatter-Otech project
Applied & Innovation R&D



~ 5 tons
2022-2027

European Innovation Council

UK Research and Innovation

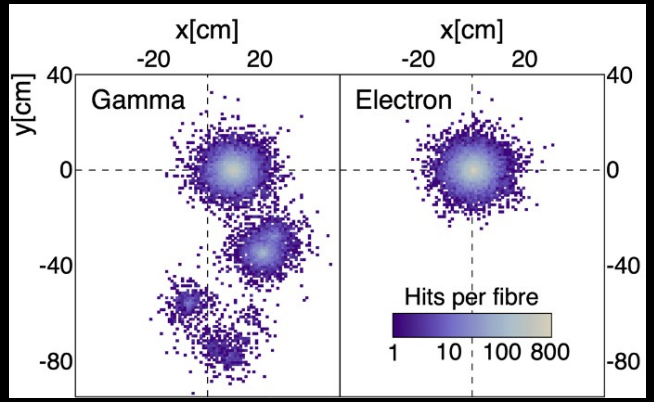
+ LPET-Otech project (medical physics)
2022-2024
ANR funded

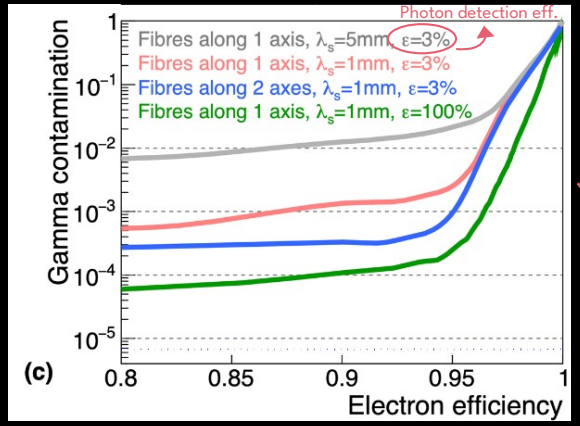
Future prospects

SuperChooz Pathfinder project

Particle identification

LiquidO discrimination power





Discrimination between events:

- MeV-scale e-: **point-like**
- e+ and γ: **spatially dispersed energy depositions**
  - + timing important to discriminate e+ from γ below 3 MeV

γ and e− with 2 MeV KE

- e- deposits all its energy within a cm
- γ Compton scattering tens of cm

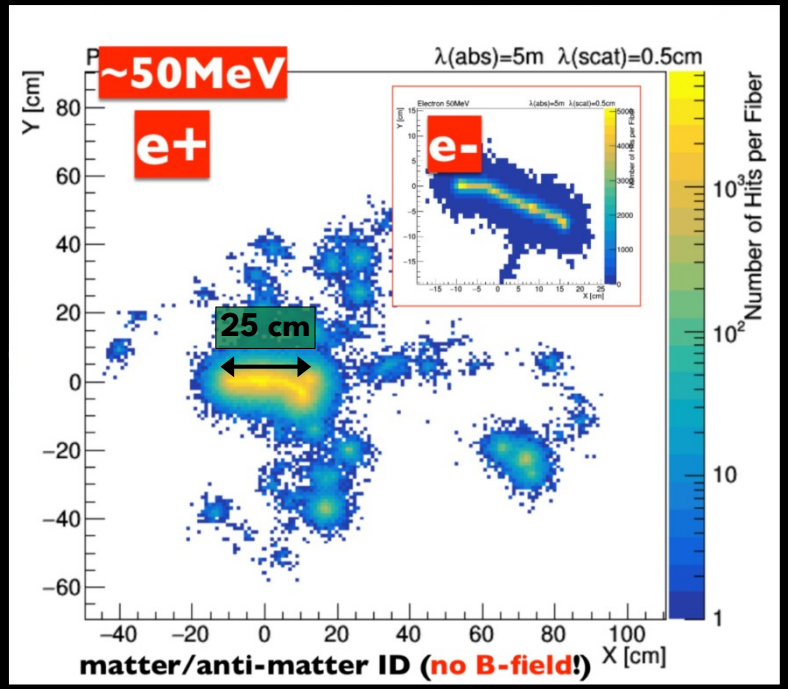
Discrimination power of LiquidO

Probability e- is misidentified by γ v.s. e- selection efficiency

1 cm pitch fibres along z-axis
Conventional light yield

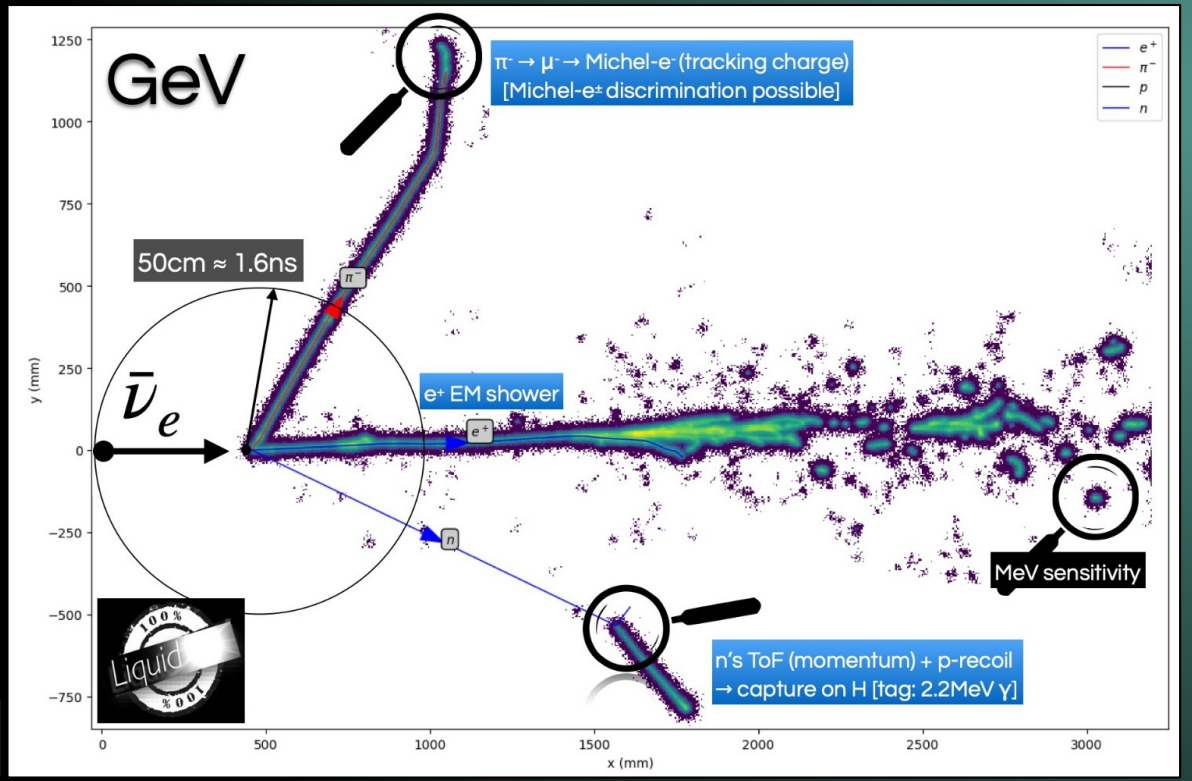
Wide physics potential

From MeV to Multi-MeV



~10MeV: Supernovae, atmospherics, Michel-e± (μ-decay)…

From Multi-MeV to GeV



2 GeV $\bar{\nu}_e$ 4 mm fibre pitch λ_s = 1 mm

Expected capabilities

- Typical organic scintillator light yield: ~10 photons / keV & 5 m absorption length
- Wavelength-shifting fibre (WLS) acceptance ~10% (main loss in detection)
- Small 1 cm pitch lattice detector

  → Number of detected photons ~400 PE/MeV

  → Energy resolution ~5 % / √(E (MeV))

Scaling to larger sizes → PE / MeV will reduce (several-metre attenuation lengths WLS fibres)

→ Work on optimisation of light collection

- Particle identification
- Reduced constraints on the absorption properties compared to transparent liquid scintillator
- Dopants possible (bkg rejection + search for rare processes)
- Background rejection