LiquidO: Neutrino Detection in Opaque Media

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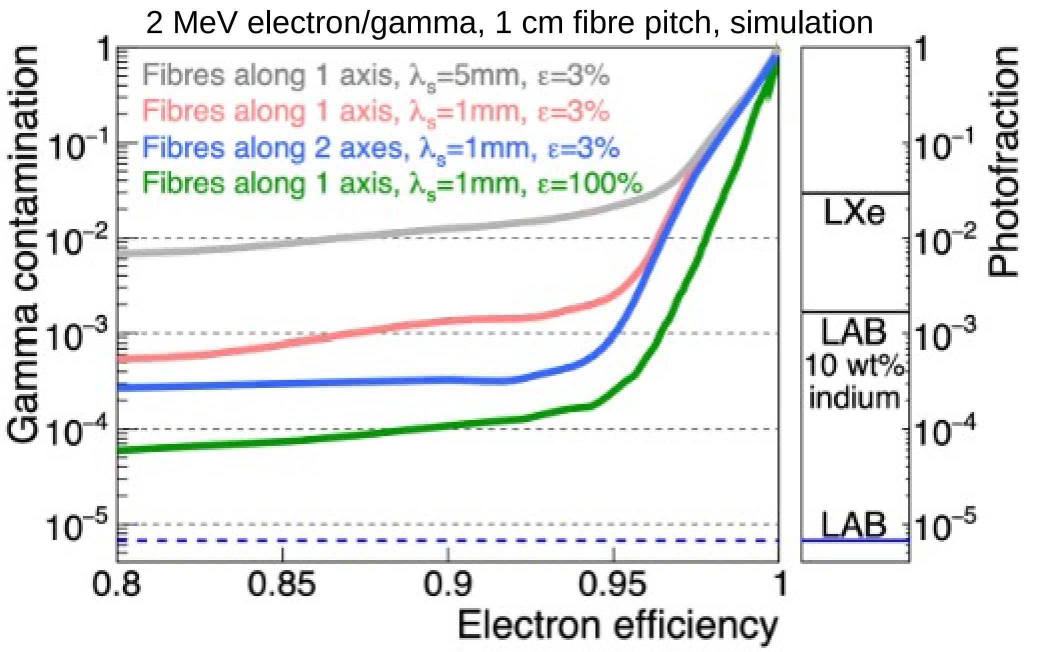
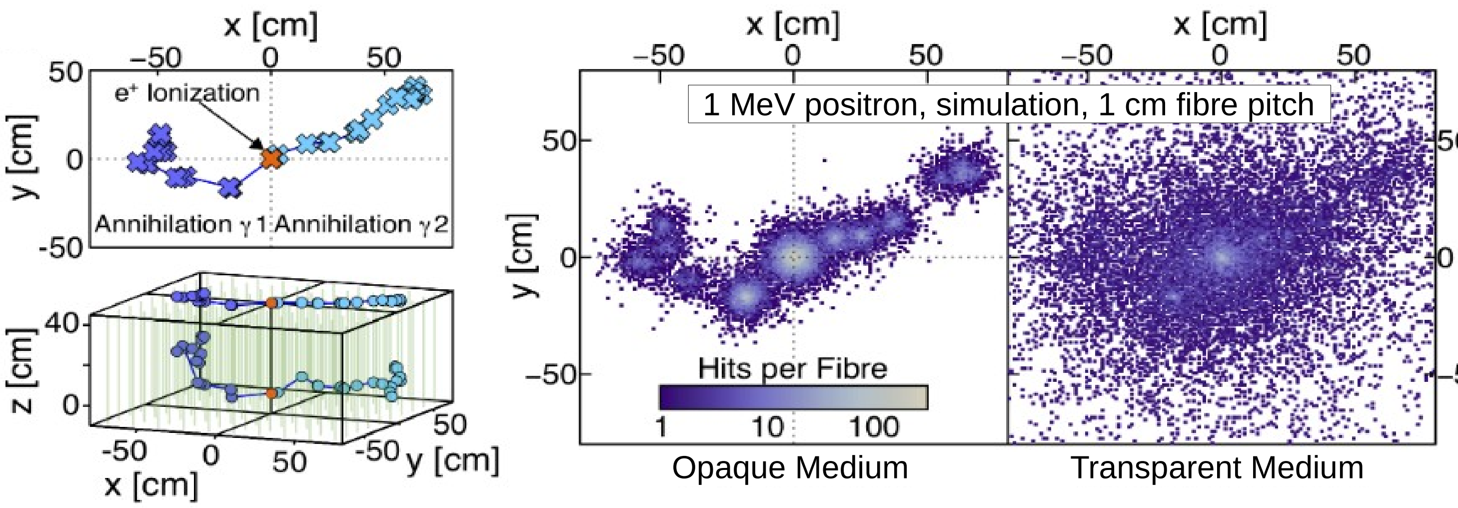
Outline

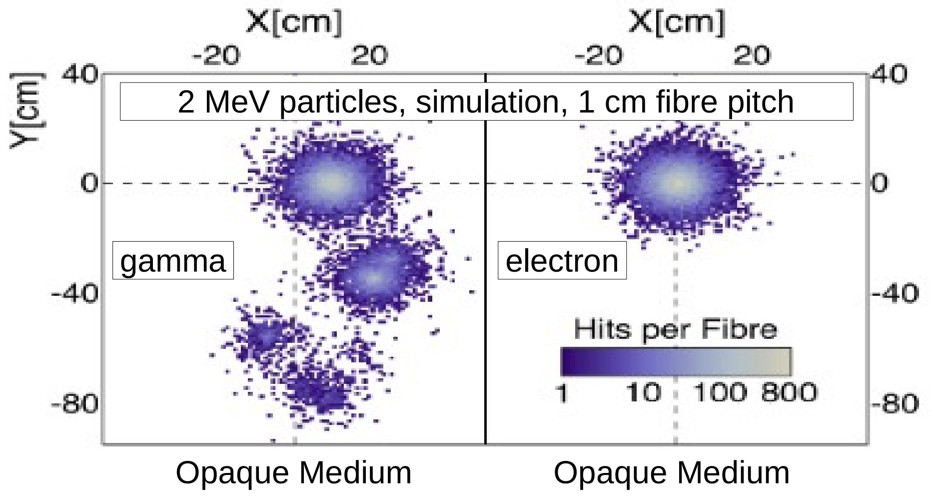
- The Idea behind LiquidO’s Opacity
- Opaque Scintillators
- LiquidO Prototypes
- Derived Projects
- Summary

The Idea behind LiquidO's Opacity

- → Transparent liquid scintillator:
  - → energy depositions converted into scintillation light
  - → topology is washed out when scintillation light propagates
- → Energy depositions happens on smaller scale
  - → opaque medium confines lights to its point of creation
  - → preserve timing information of order 2ns
  - → light-readout via grid of fibres
  - → particle-ID through vertex resolution at cm-scale
  - → e.g. electron/gamma discrimination of 1000/1 possible
  - → http://doi.org/10.1038/s42005-021-00763-5







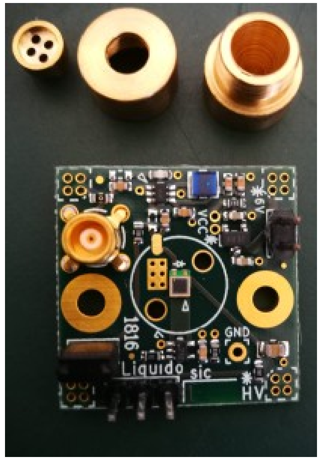
Communication Physics 4, 273 (2021)

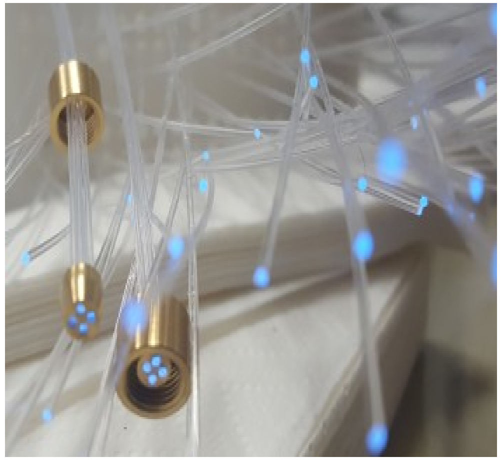
Detector Design

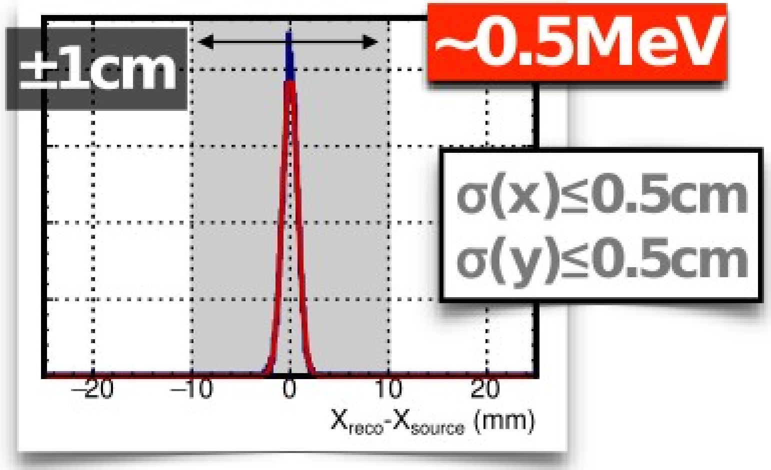
→ instrumented by grid of wavelength-shifting/scintillating fibres

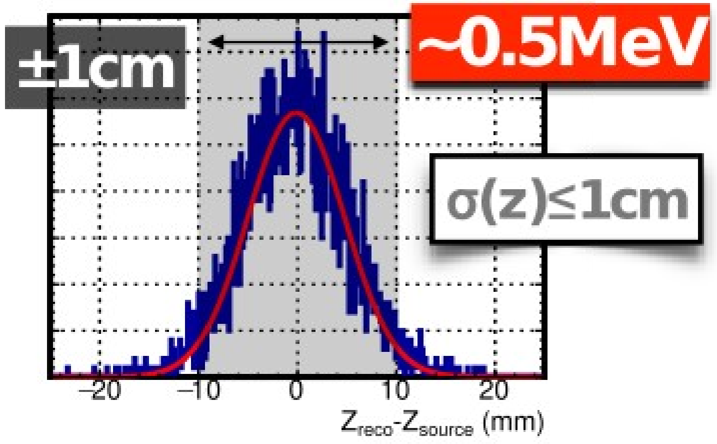
→ good scalability due to uni-directional design

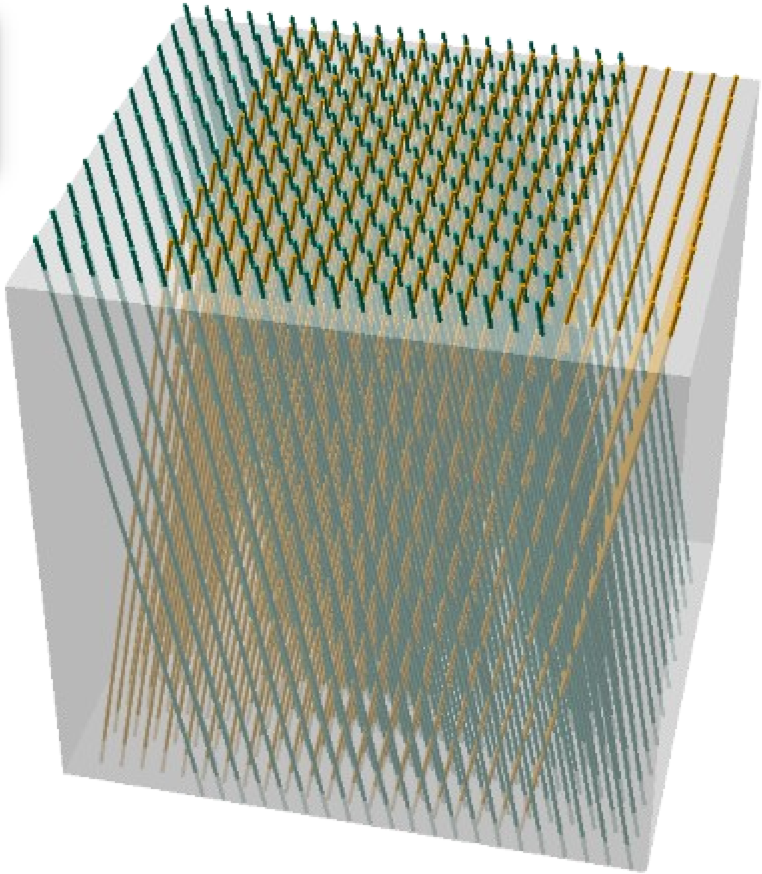
→ z-direction via timing and/or crossing fibres











→ SiPM readout of fibres

→ sub-100ps timing resolution
  → https://doi.org/10.1109/RTC.2014.7097545

→ amount of light: >400 PE/MeV

Potential

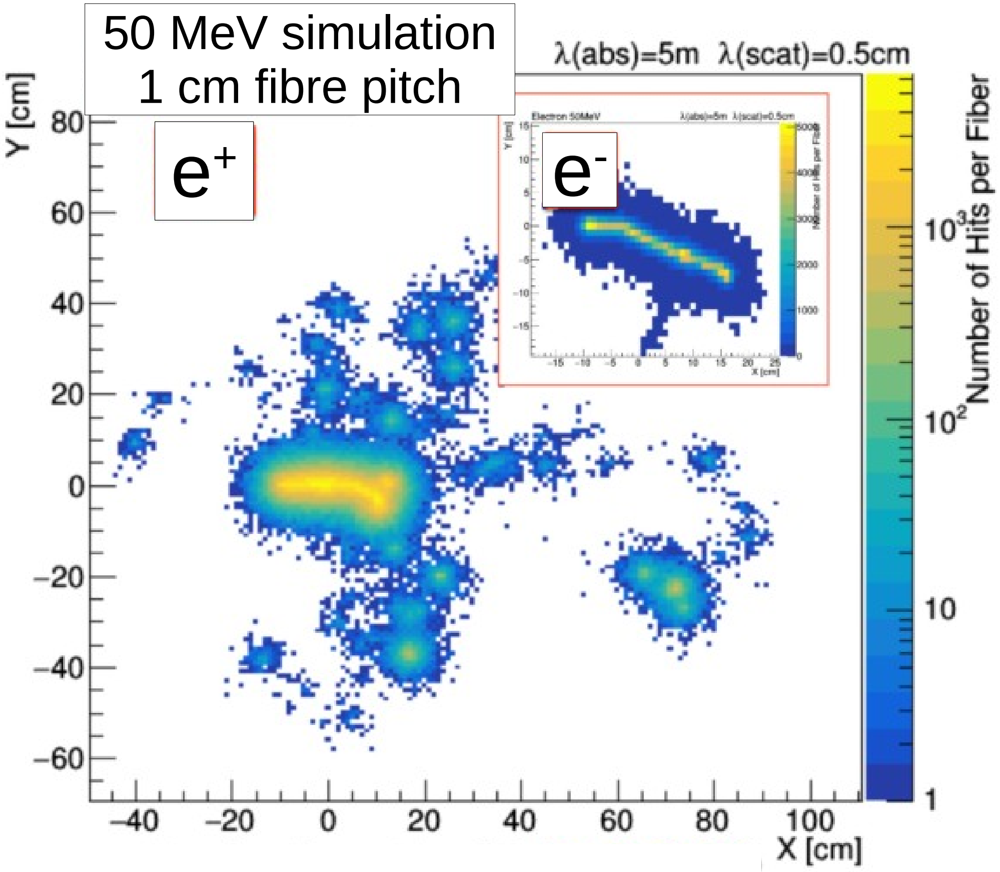
tracking

→ directionality

→ dE/dx

→ particle ID from topology

→ without magnet (large volumes possible)



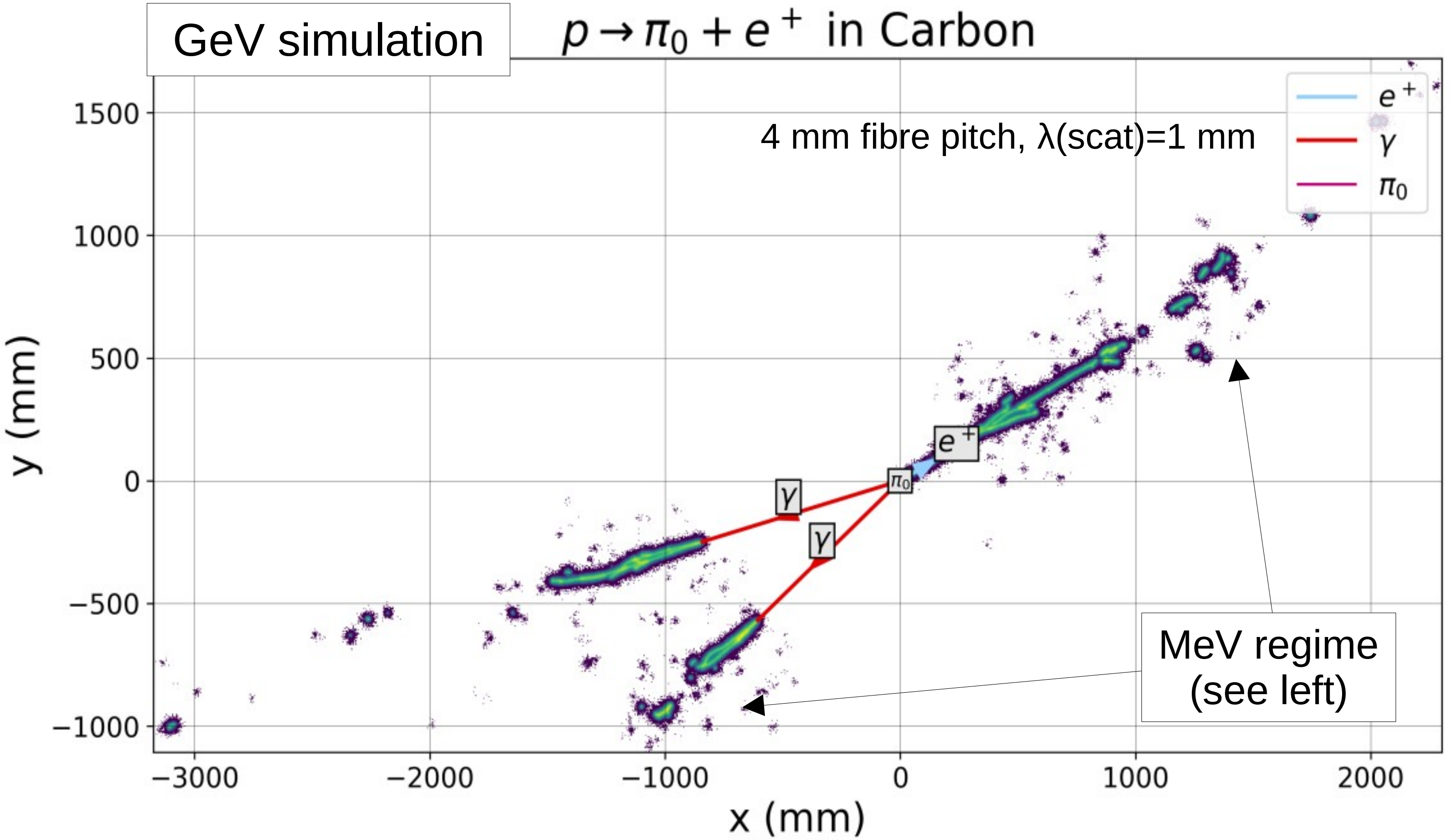
proton decay

→ event tagging trough tracking

→ higher abundance of protons per fiducial mass

→ 10% in water

→ up to 20% in scintillator



https://doi.org/10.5281/zenodo.7504162

Potential

electrical charge via missing annihilation gammas: negative

muon to Michel electron/positron

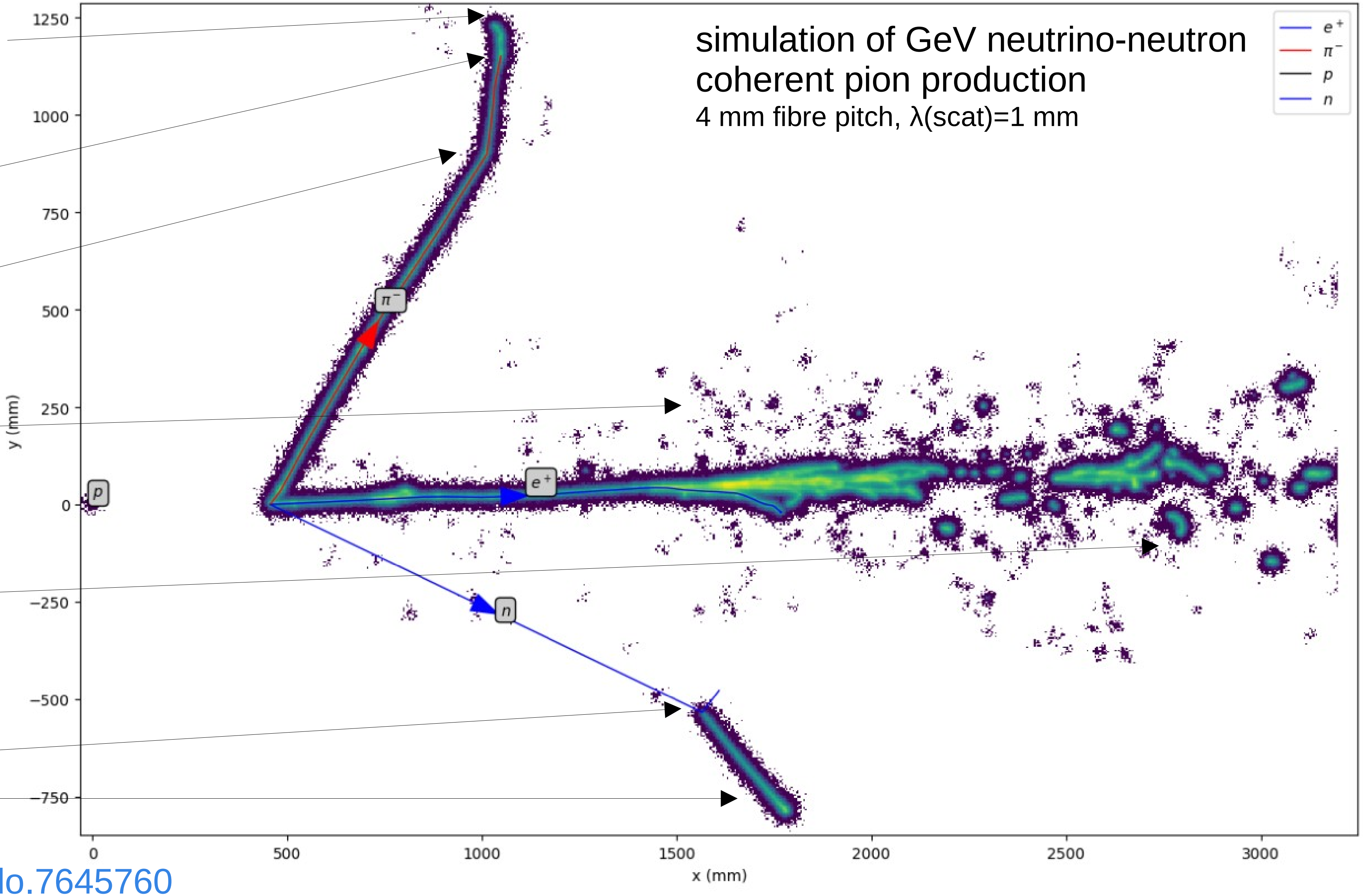
pion to muon

EM-shower

MeV regime

neutron momentum via time of flight and proton recoil

simulation of GeV neutrino-neutron coherent pion production
4 mm fibre pitch, λ(scat)=1 mm



https://doi.org/10.5281/zenodo.7645760

Potential

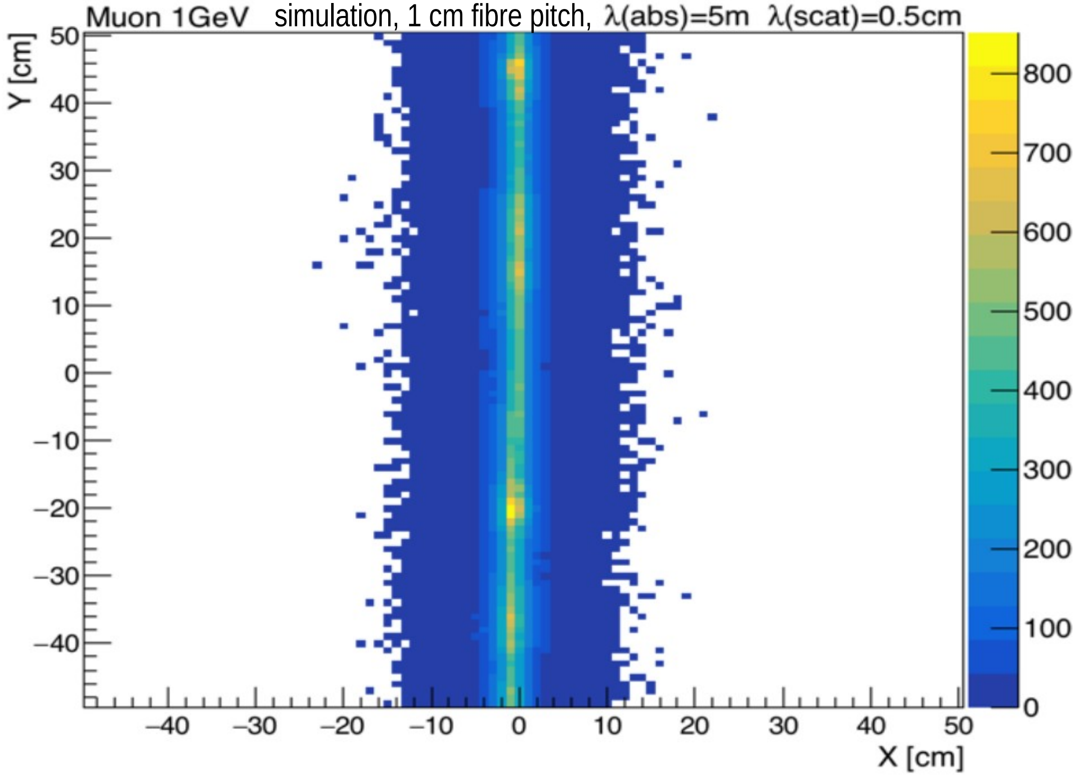
Current projects:

→ reactor physics with AntiMatter-OTech/CLOUD (https://doi.org/10.5281/zenodo.10049846):
  → monitoring, oscillations

→ medical imaging with LPET (https://doi.org/10.5281/zenodo.7556760)
  → positron discrimination for PET-scanners

→ geoneutrinos (http://arxiv.org/abs/2308.04154):
  → metal loading to lower energy threshold
  → access potassium decays

→ muon tracking:
  → improved spatial and angular resolution



Future projects:

→ particle trackers (https://doi.org/10.5281/zenodo.7645760):
  → multiple avenues for particle ID and momentum measurements

→ solar neutrinos (http://doi.org/10.1038/s42005-021-00763-5):
  → indium loaded detector to observe pp-neutrinos
  → particle-ID for tagging of coincidence

→ supernova neutrinos (https://doi.org/10.5281/zenodo.7504162):
  → simultaneous observation of neutrino and anti-neutrino CC via positron and electron tagging

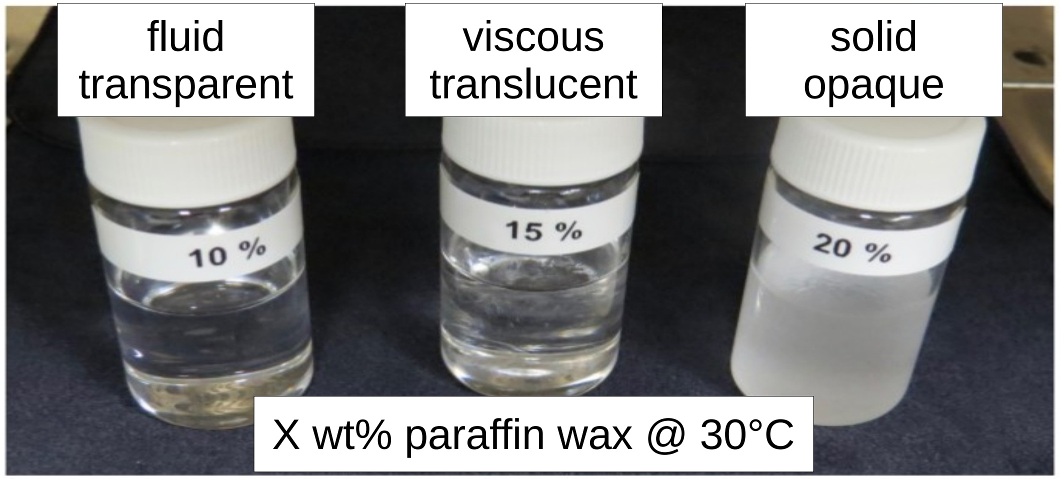
→ search for $0\nu2\beta$ (https://zenodo.org/doi/10.5281/zenodo.7645430 / https://zenodo.org/doi/10.5281/zenodo.7645450):
  → high isotope loading

Scintillators

Opaque Scintillator

- several options
  - liquid scintillator + wax (NoWaSH): http://doi.org/10.1088/1748-0221/14/11/P11007
  - liquid scintillator + water + surfactant (oWbLS): https://doi.org/10.48550/arXiv.2406.13054
  - mirco-crystals: https://doi.org/10.48550/arXiv.1807.00628
- opacity through scattering without absorption (Mie scattering, scattering length of millimetres)
- scattering length tunable via:
  - NoWaSH: wax type / wax concentration / temperature (in some NoWaSH formulations)
  - water+surfactant concentration (oWbLS)
- high metal loading possible
  - relaxed requirement on absorption length
  - proof of principle via boron / TBB in NoWaSH

NoWaSH



C. Buck, B. Gramlich, S. Schoppmann, JINST 14 P11007 (2019)

oWbLS

LiquidO collaboration (J. Apilluelo et al.), arXiv:2406.13054

Prototypes

Micro-LiquidO

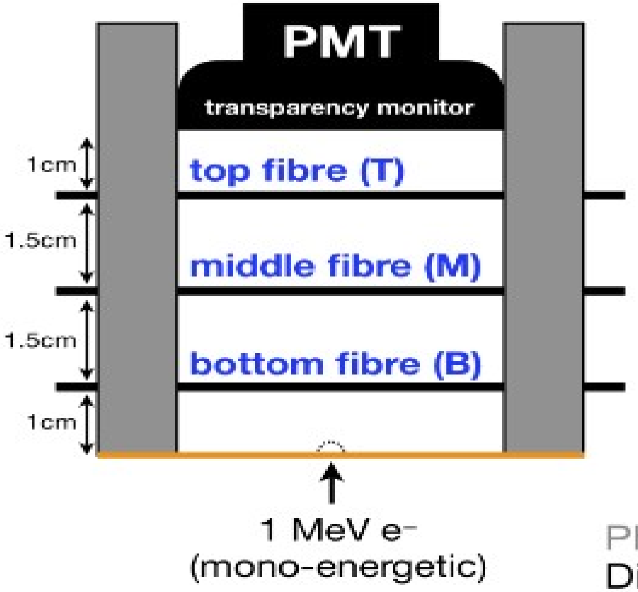
→ 250 ml volume

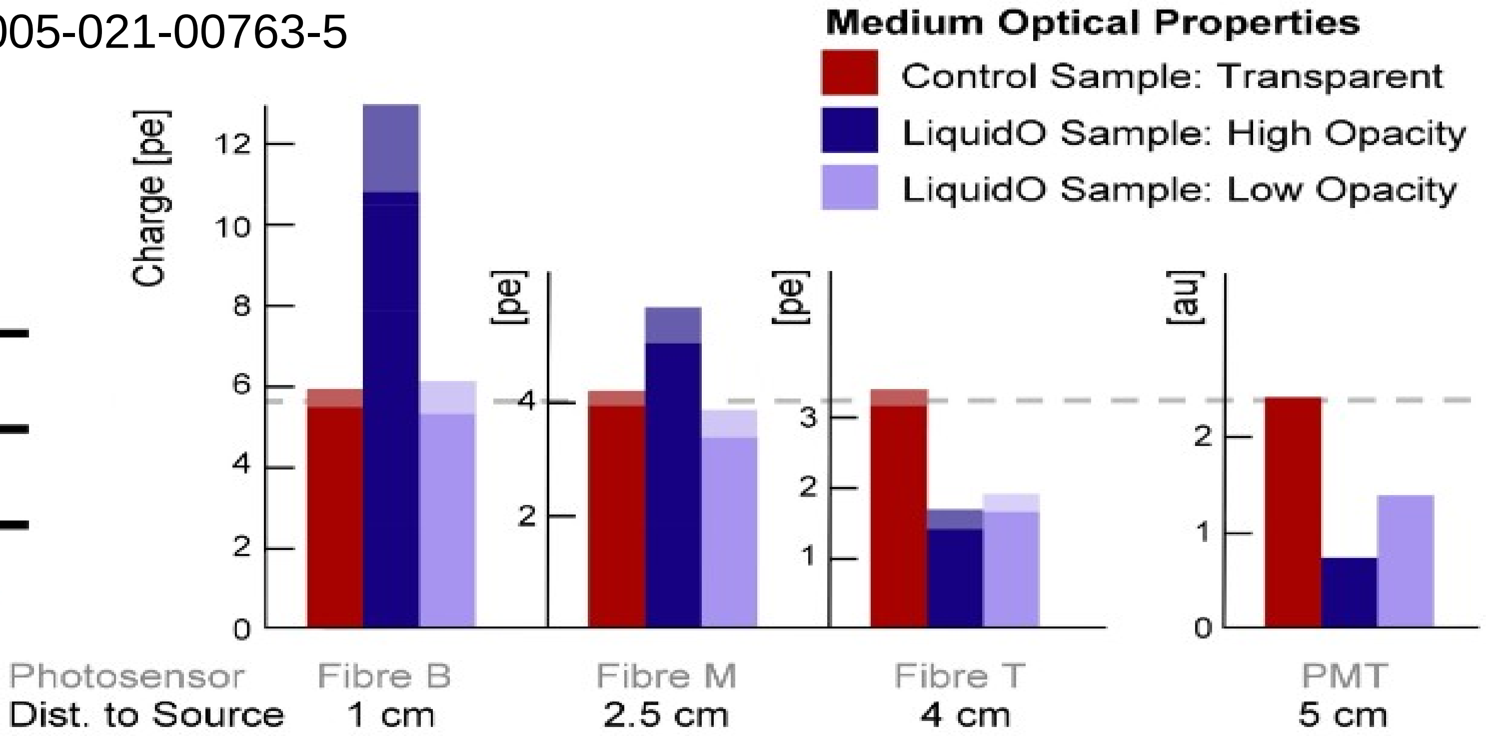
→ goal: proof of principle

→ readout via three fibres and PMT demonstrated in opaque scintillator (NoWaSH)

→ opacity via scattering without absorption confirmed

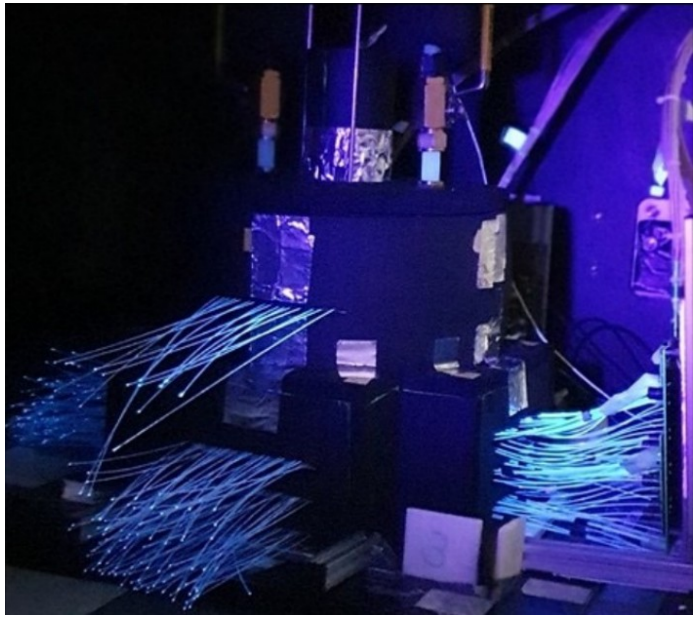
→ http://doi.org/10.1038/s42005-021-00763-5

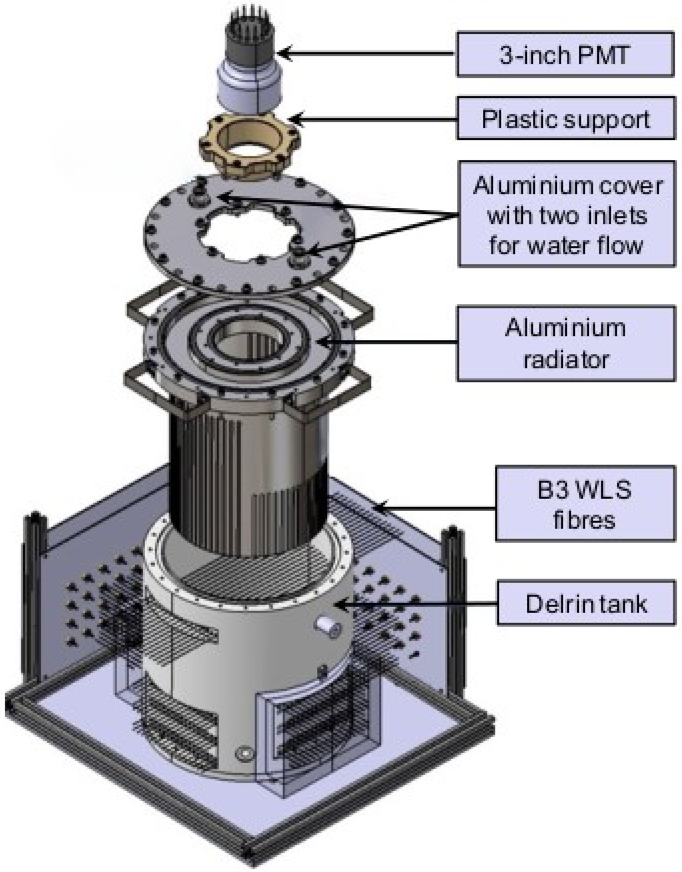


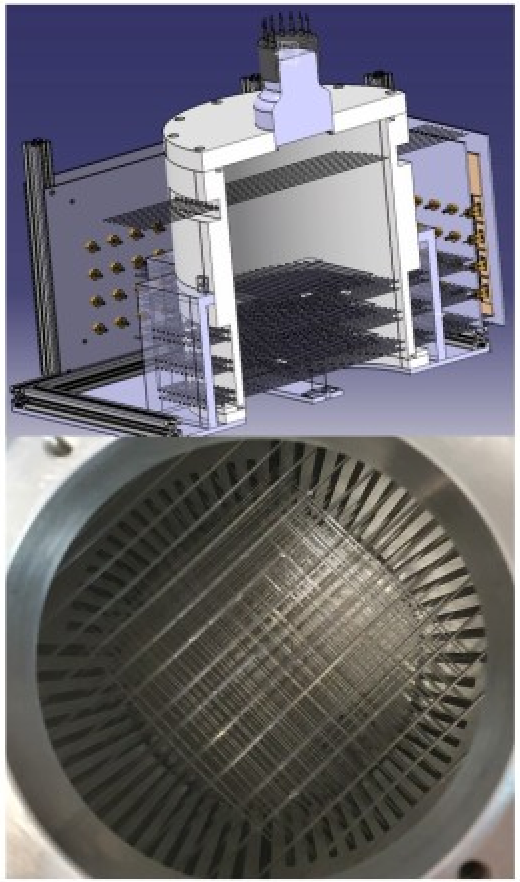


Communication Physics 4, 273 (2021)

Mini-LiquidO







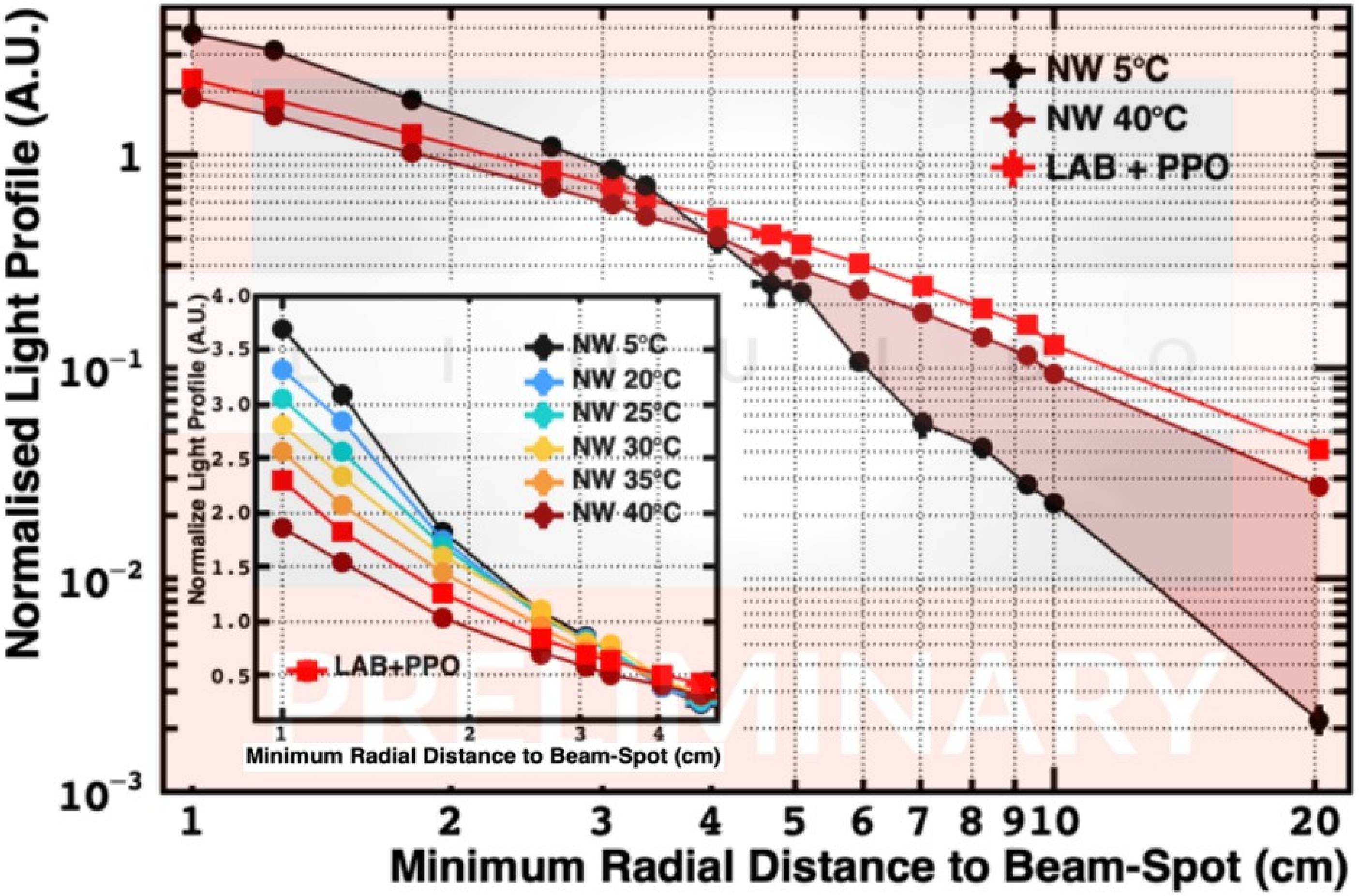
- → 10 litres detector
- → goal: light ball formation and characterisation
- → 56 wavelength-shifting fibres read-out in 2 orthogonal directions
- → narrow-energetic electron beam from ^{90}Sr source tunable between 0.4 and 1.8 MeV
- → operated @ LP2i Bordeaux, France

data taking since 2021 including runs with:

- → wax-based liquid scintillator: NoWaSH-20 in transparent and opaque mode (temperature dependent, 5 to 40°C)
- → transparent scintillator
- → transparent water (non-scintillating)

Temperature dependent opacity of NoWaSH leads to confinement of light compared to transparent reference

90% (80%) [50%] of light confined within 5cm (4cm) [2cm] radius

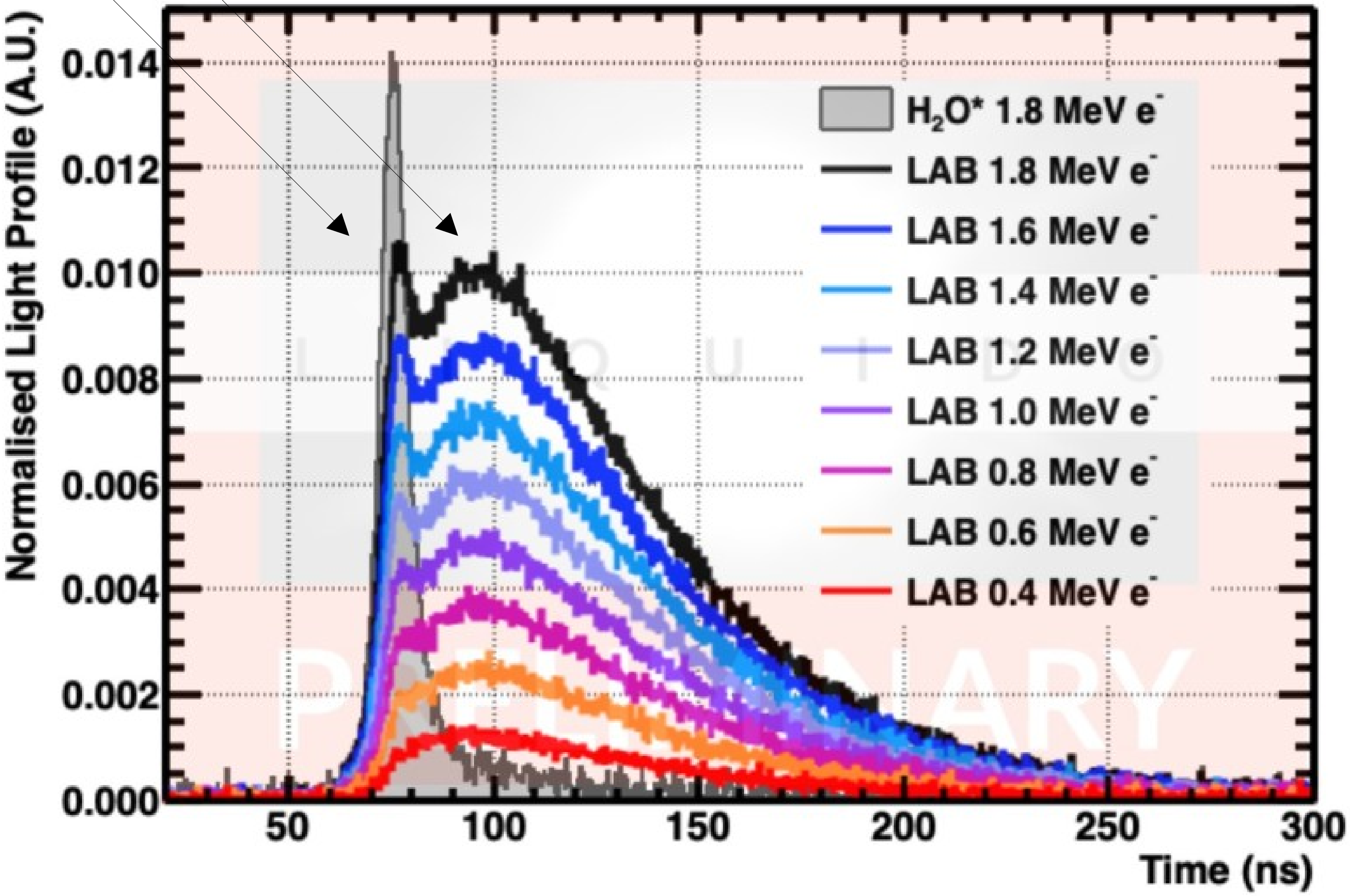


Mini-LiquidO: Pulse Shape

→ Cherenkov and scintillation distinguishable
  → demonstrated with slow transparent scintillator (pure LAB)
→ possibility of multi-variable particle-ID (topology and Cher/scint ratio)
→ fast timing: dominated by fibre

Scintillation photons

Cherenkov photons



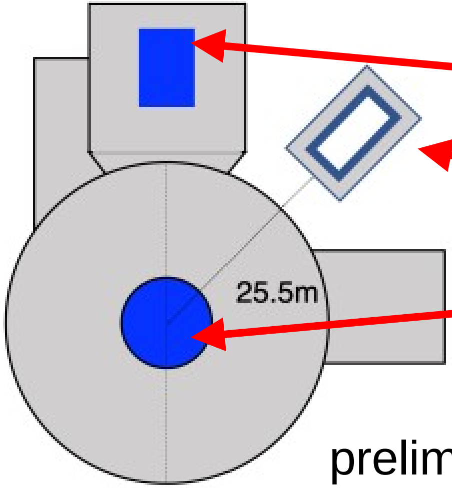
Derived Projects

AntiMatter-OTech/CLOUD

Chooz B nuclear reactor site in France
4.2 GW thermal power (single core)

AntiMatter-OTech (innovation project):
→ reactor monitoring

European Innovation Council
UK Research and Innovation



spent fuel pool
detector
reactor pool

preliminary design

CLOUD (fundamental physics extension to AntiMatter-OTech)
→ phase I: reactor physics
→ phase II: solar neutrinos
→ phase III: geo-neutrinos

Further Derived Projects

Micro-LiquidO
~ 0.25 litre
Proof of principle

↓

Mini-LiquidO
~10 litre
Light ball formation

↓

Mini-Gamma
~100 kg
Demonstration of PID

LPET
full-body PET-scan
Medical imaging

AM-OTech/CLOUD
~8 tonnes
Reactor monitoring

SuperChooz
$\mathcal{O}$(10 kt)
Fundamental Physics (Solar / SN / reactor-nu / nucleon decay / …)

Conclusions

- → LiquidO: opaque detector technology (http://doi.org/10.1038/s42005-021-00763-5)
  - → brought spectrum of applications
  - → improved vertex resolution possible
  - → improved particle identification possible (electron/positron/gammas)
  - → pulse shape discrimination achievable
  - → particle tracking
  - → high metal loading
- → opaque scintillator
  - → millimetre-scale scattering length
  - → similar properties as transparent scintillator basis
  - → several options:
    - → http://doi.org/10.1088/1748-0221/14/11/P11007
    - → https://doi.org/10.48550/arXiv.2406.13054
    - → https://doi.org/10.48550/arXiv.1807.00628
- → current/future derived projects:
  - → AntiMatter-OTech/CLOUD (reactor neutrinos)
    https://doi.org/10.5281/zenodo.10049846
  - → LPET (medical imaging)
    https://doi.org/10.5281/zenodo.7556760
  - → Super Chooz pathfinder (large scale, multi-purpose)
    https://doi.org/10.5281/zenodo.7504162
  - → …

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- → …


Photo: B. Gramlich, MPIK

Candle built from NoWaSH
(opaque wax-based scintillator)

LiquidO Collaboration

~100 members
26 institutes
11 countries

LiquidO-Contact-L@in2p3.fr
https://liquido.ijclab.in2p3.fr

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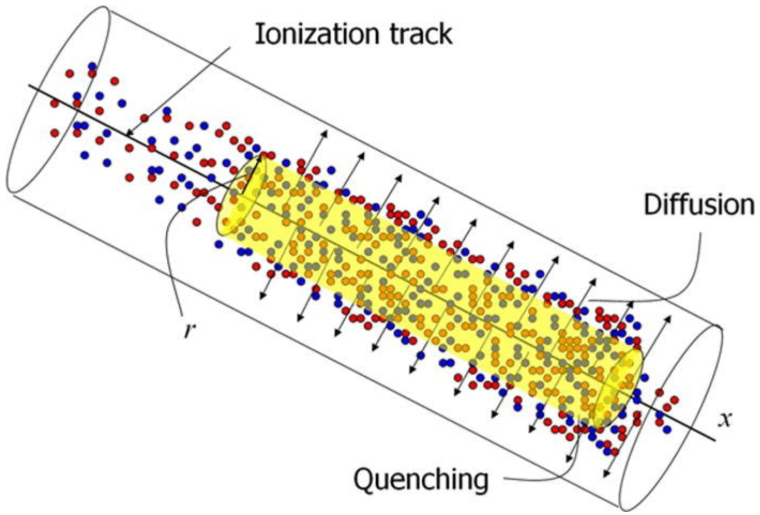
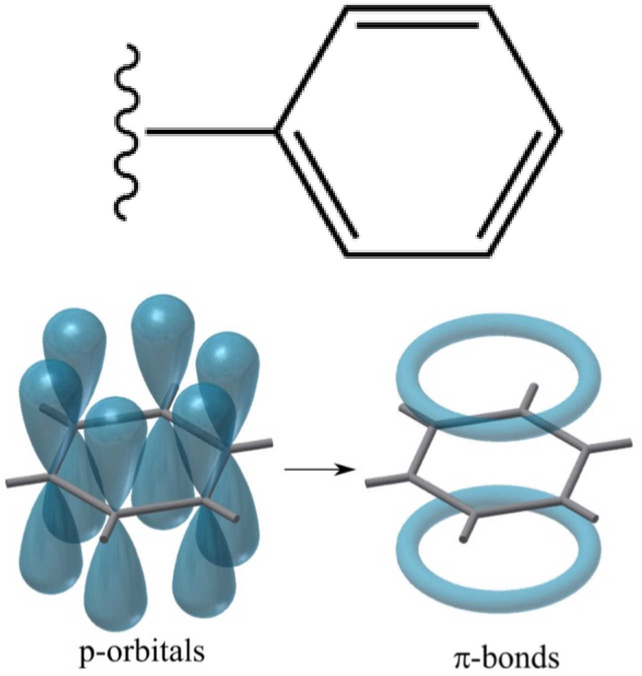
Appendix

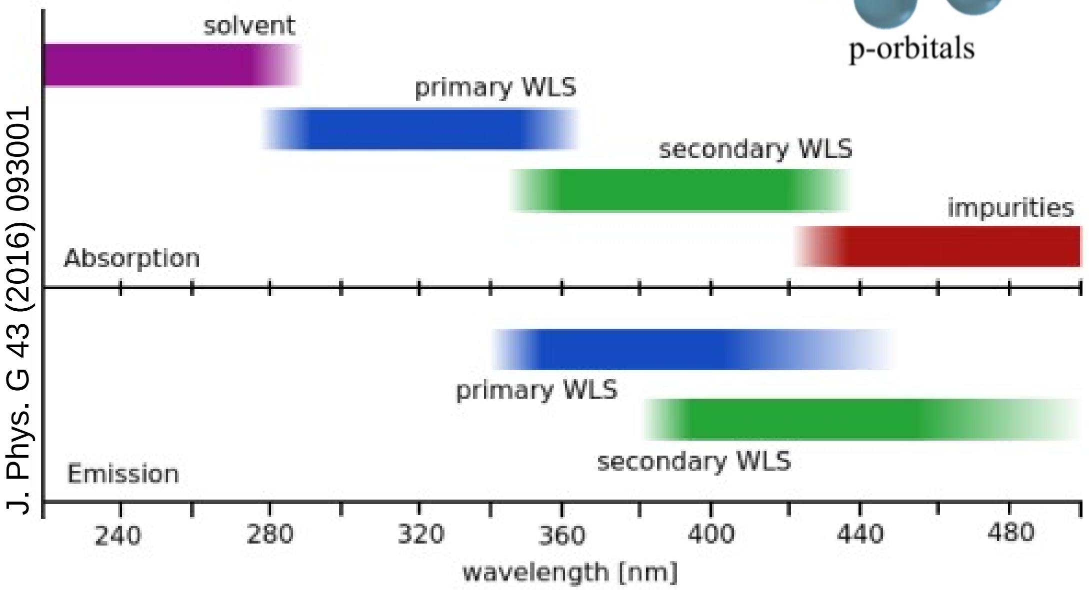
Motivation – Liquid Organic Scintillators

Basic principle:
→ carbon-hydrogen-based molecules
→ conjugated – especially aromatic – molecules
→ scintillation mostly through benzene-like groups
→ shifting of initial UV-light towards blue/green
  → addition of wavelength shifters (WLS)
  → matching with sensitivity of photosensors

Advantages:
→ cost effective (large volumes)
→ high light yield
→ light output (almost) linear to incident energy
→ transparency
→ self-shielding against radiation
→ clean / multiple purification
→ volume flexibility
→ modifiable (blending/loading)
→ …

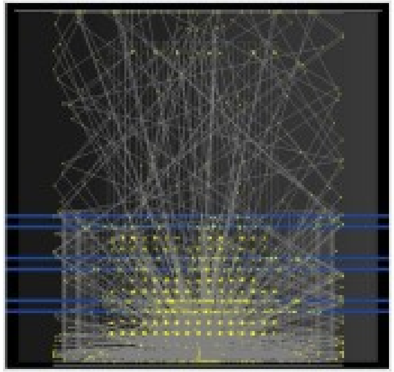




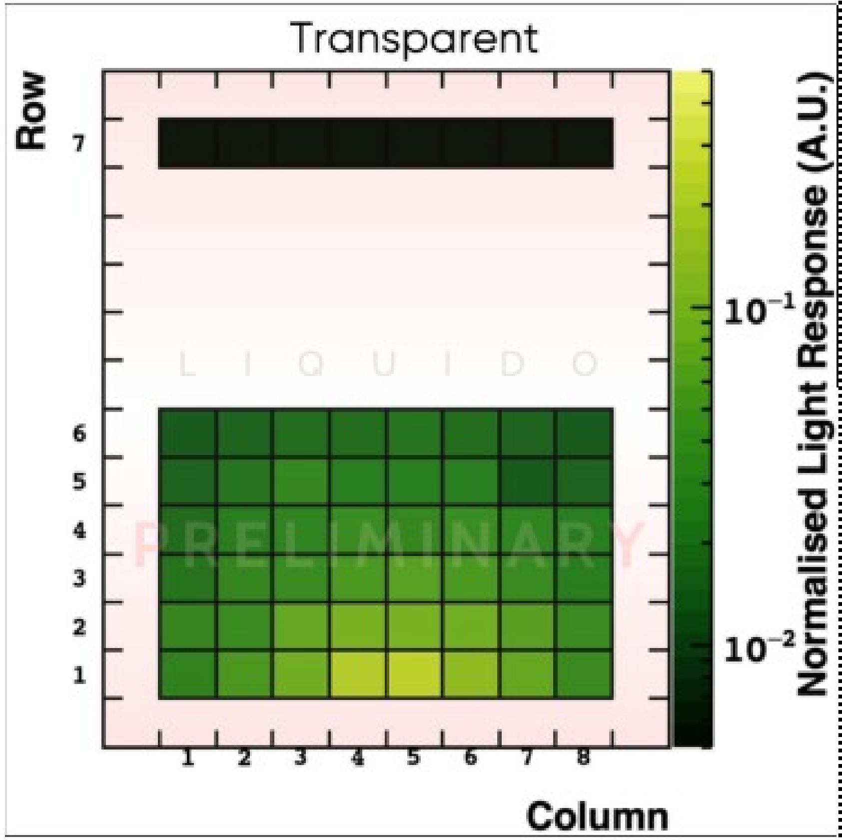


Mini-LiquidO: Light Ball Formation

Amount of light collected by each of the 56 fibres



simulation



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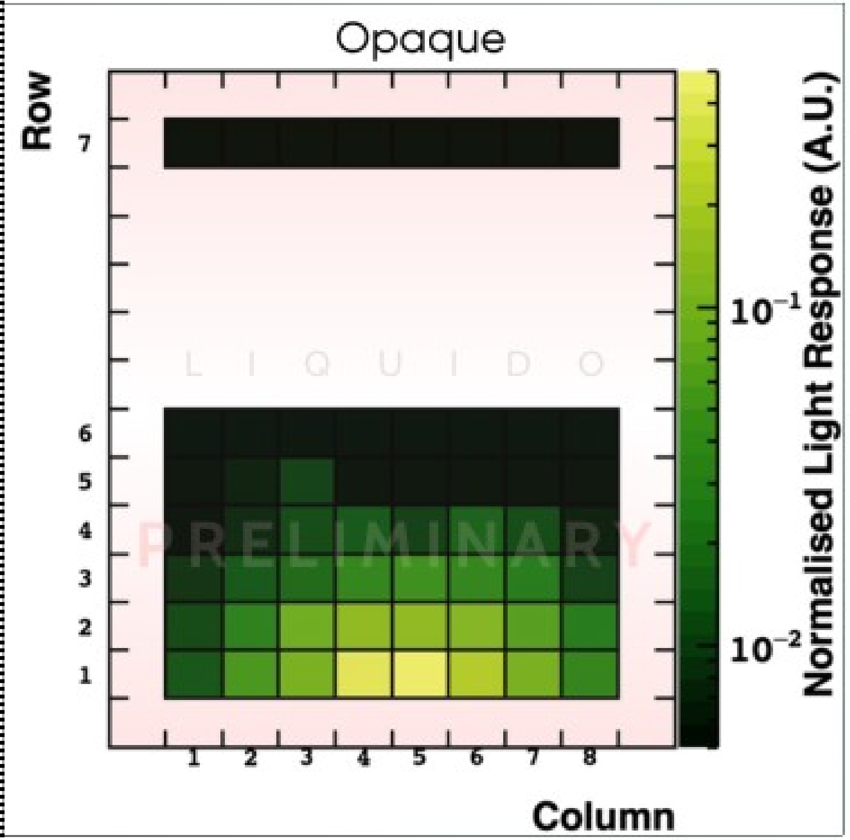

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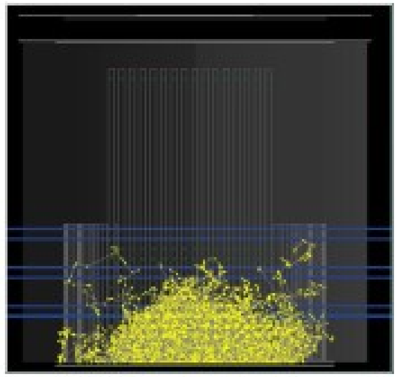
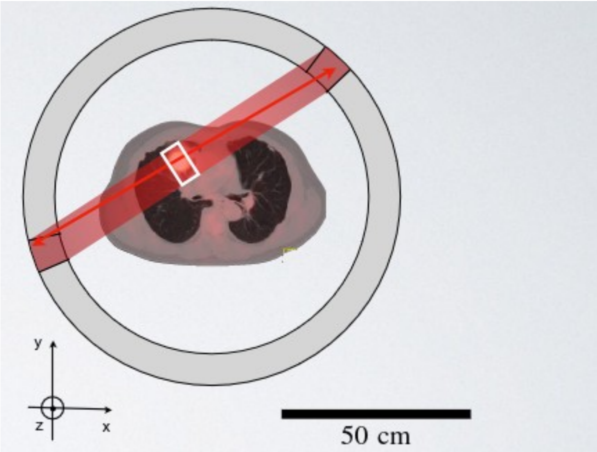


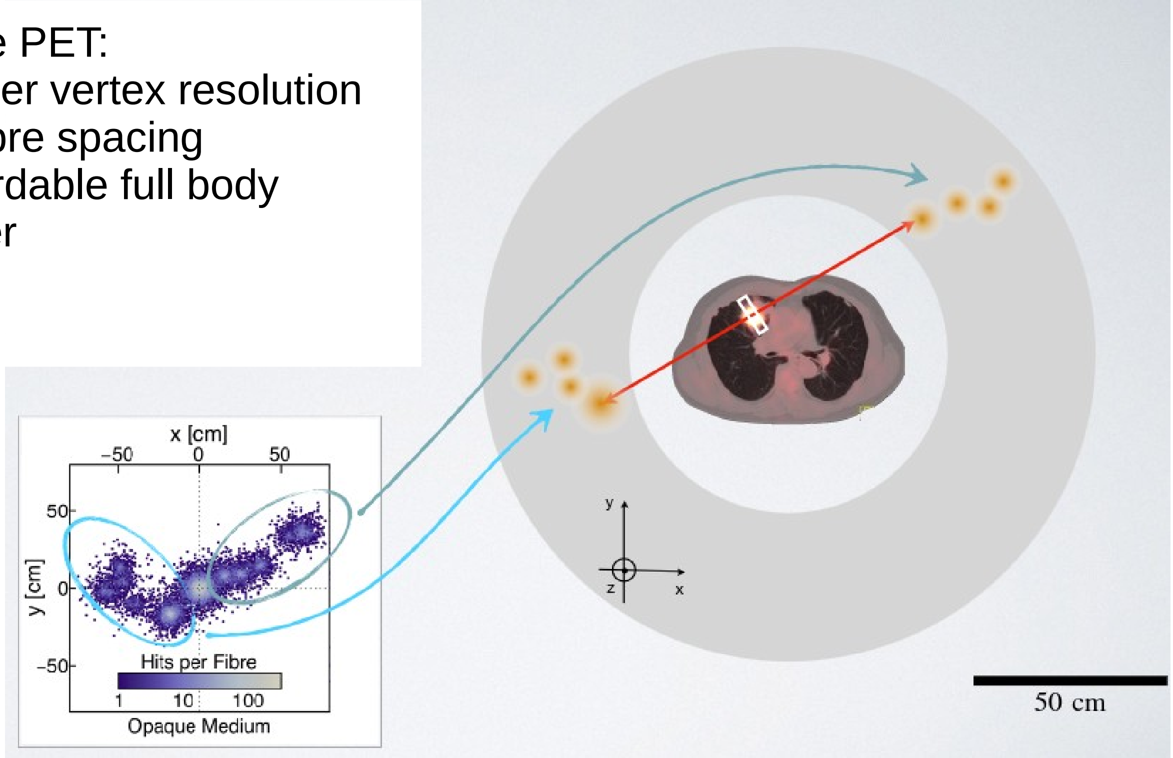
simulation

Positron Emission Tomography

traditional PET:
→ transparent scintillator crystals
→ limited vertex resolution due to crystal size
→ expensive (only ring of crystals)



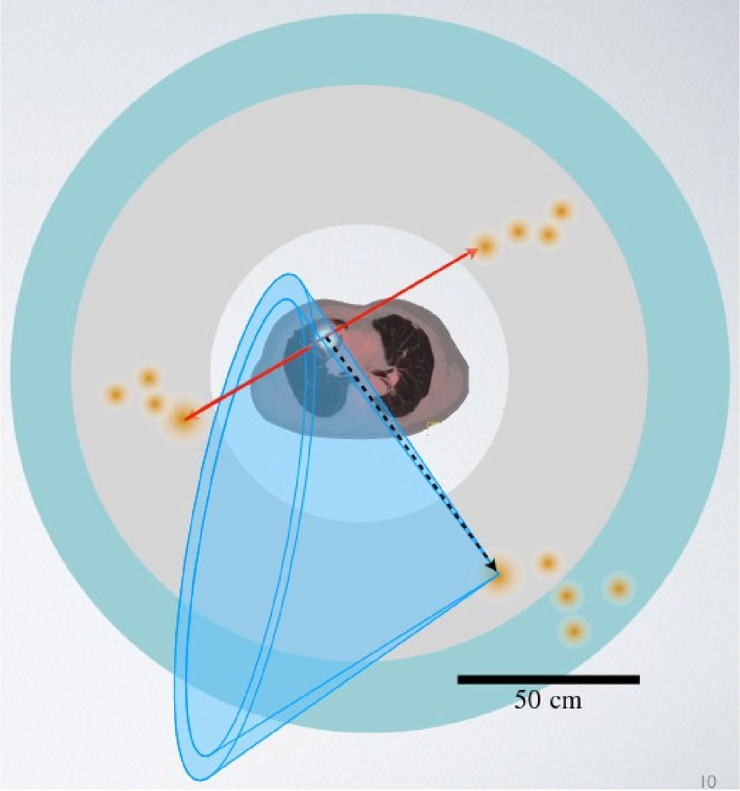
opaque PET:
→ higher vertex resolution from fibre spacing
→ affordable full body scanner



3-gamma imaging:
→ single prompt gamma from ^{44}Sc tracer decay
→ 2 delayed annihilation gammas from positronium decay

→ opaque low-Z material:
  → directionality resolution via Compton-scatters
  → track prompt gamma to origin of delayed gammas

→ novel imaging via material-dependent in vivo lifetime measurement of ortho-positronium



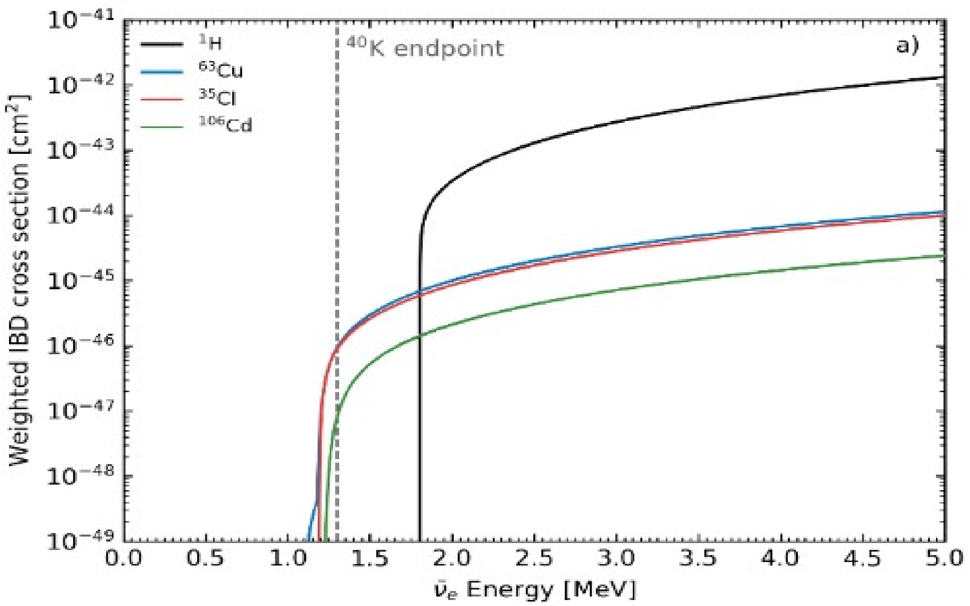
Geoneutrinos from Potassium

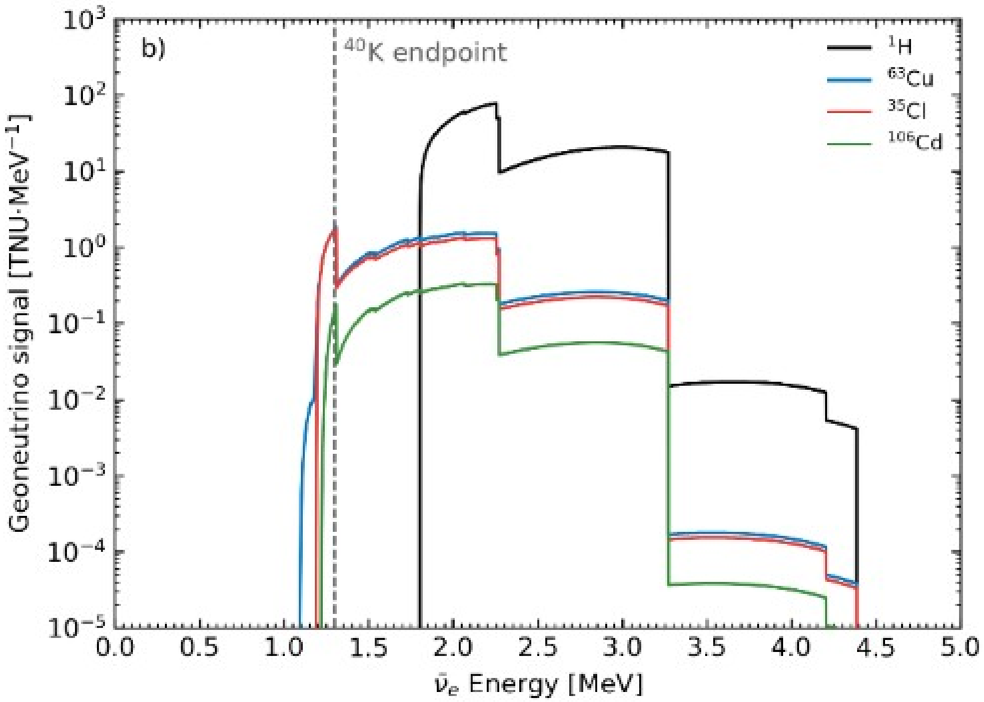
→ detect geoneutrions via inverse beta decay (IBD)

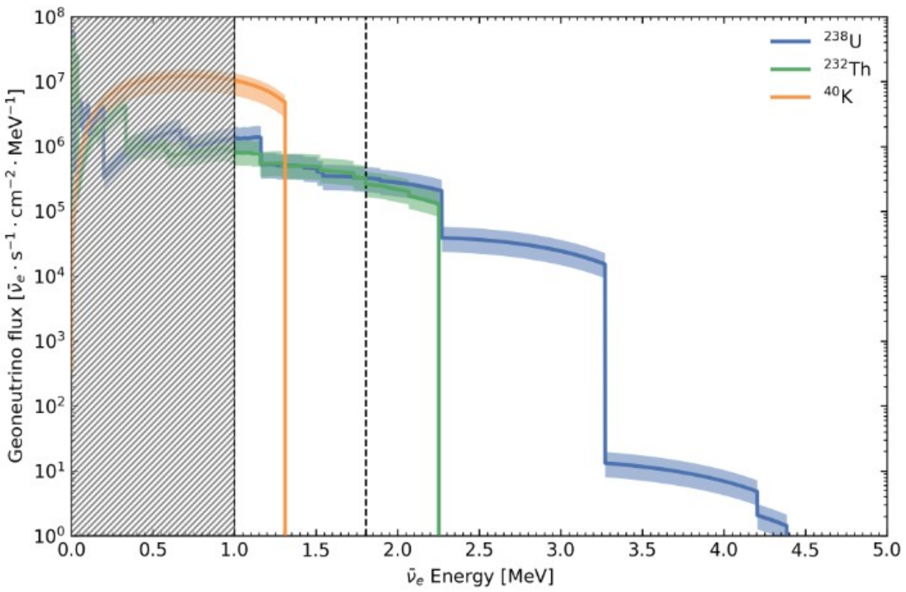
→ load scintillator with isotope to lower energy threshold for IBD, e.g. copper

→ large amounts of metal-loading possible in opaque medium due to relaxed requirement on transparency

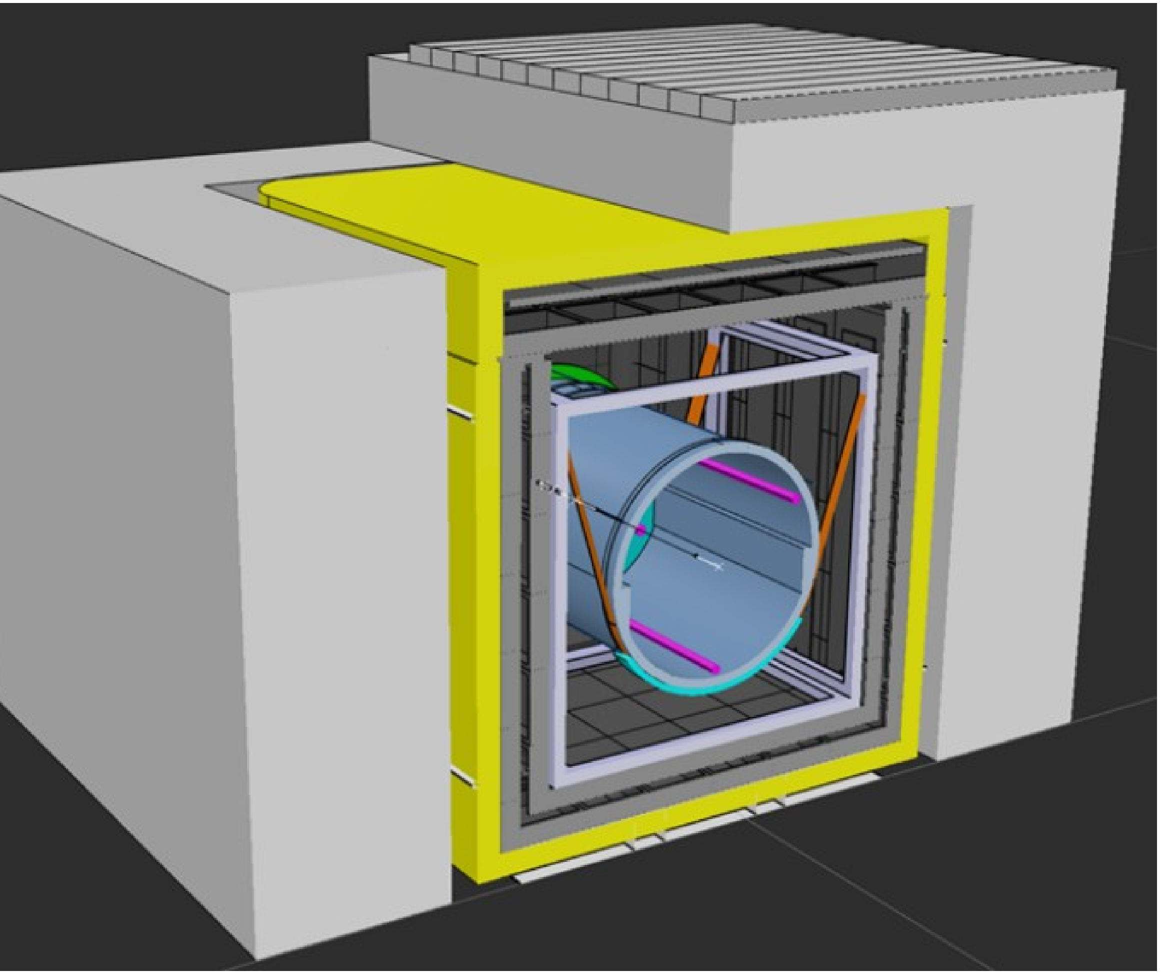
→ arXiv:2308.04154

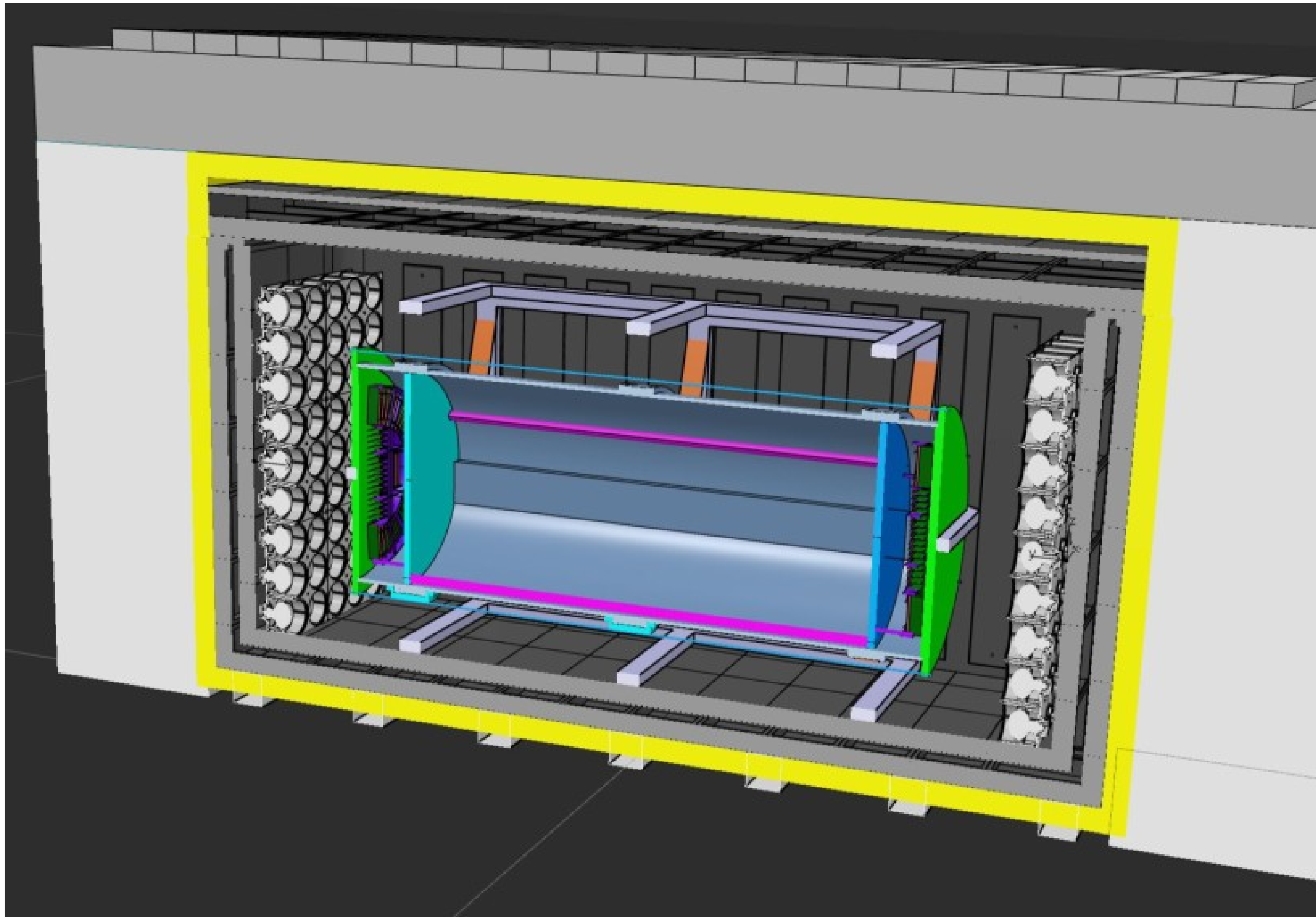






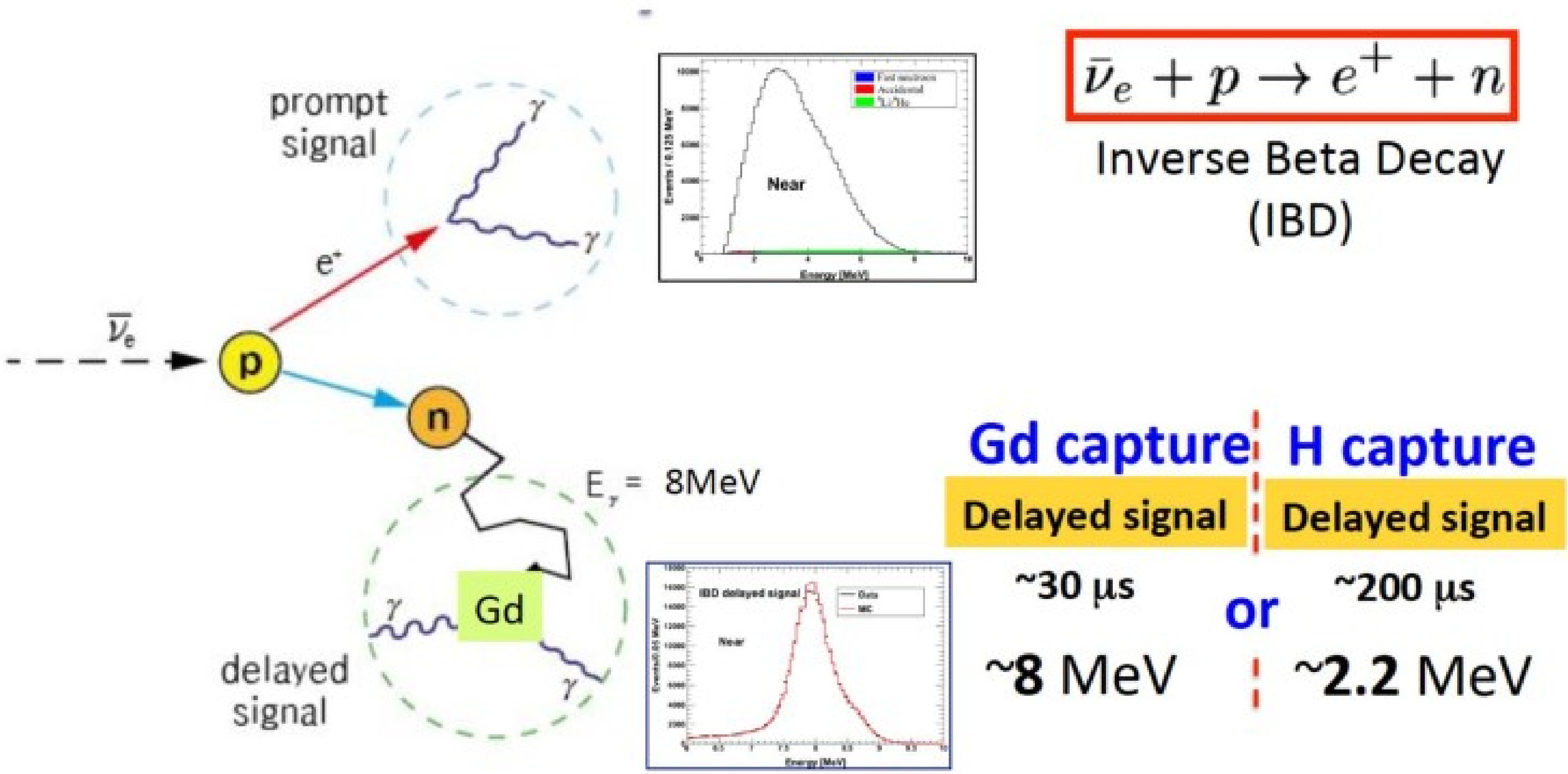
AMOTech/CLOUD





Preliminary design:
Inner detector: ~8 tonnes fiducial opaque scintillator / ~10000 fibres / >200 PE/MeV
Outer detector: transparent scintillator / ~180 PMTs / >400 PE/MeV
Shielding: concrete+iron / ~3 m.w.e.

Neutrino Detection via IBD



- Prompt signal (e^+) : 1 MeV 2γ's + e^+ kinetic energy (E = 1~10 MeV)
- Delayed signal (n) : 8 MeV γ's from neutron's capture by **Gd** in ~30 μs
  or 2.2 MeV " by H in ~200 μs