

Opaque Scintillator

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(he/him/his)

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Physics Opportunities

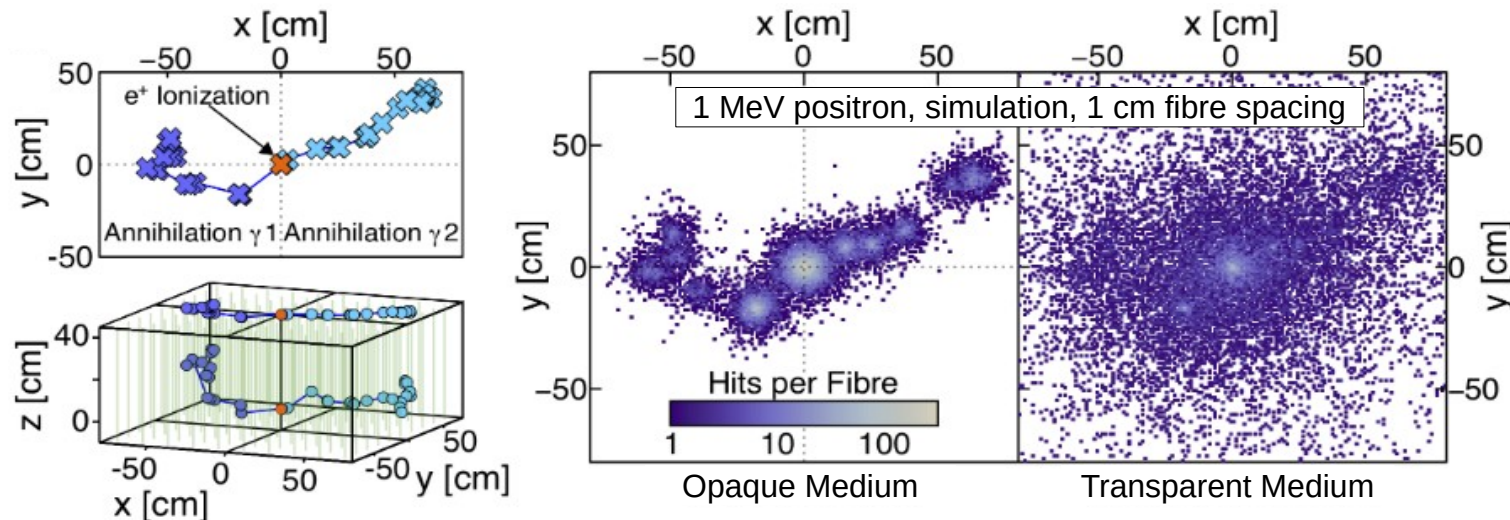
29th October 2024



JOHANNES GUTENBERG
UNIVERSITÄT MAINZ

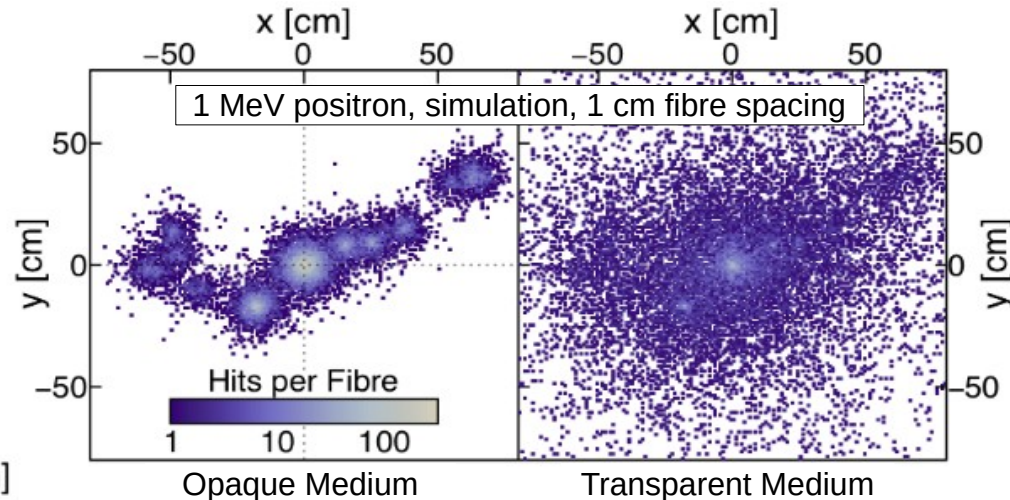
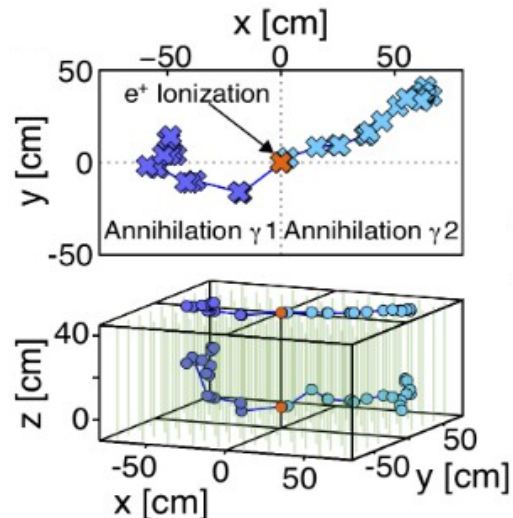
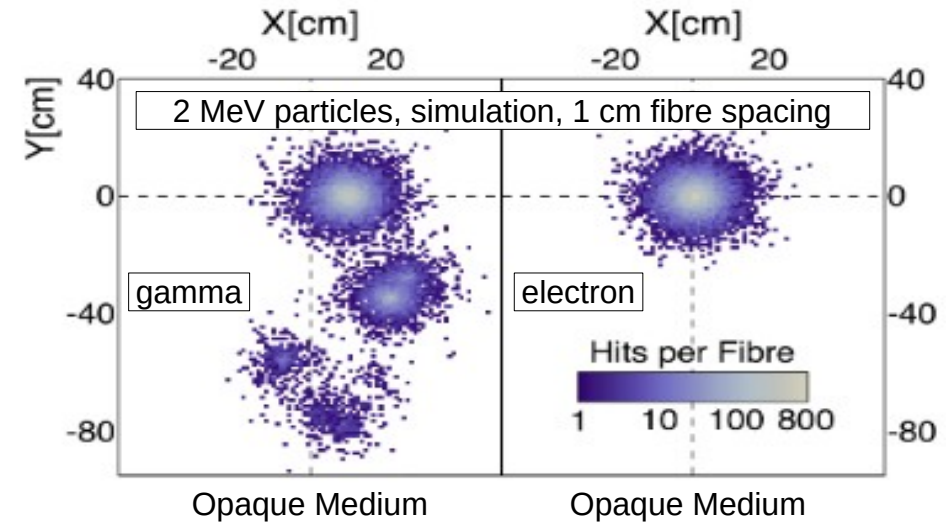


- Transparent scintillator:
 - energy depositions are washed out
- Opaque scintillator:
 - confined light
 - readout via grid of fibres
 - particle-ID through vertex resolution



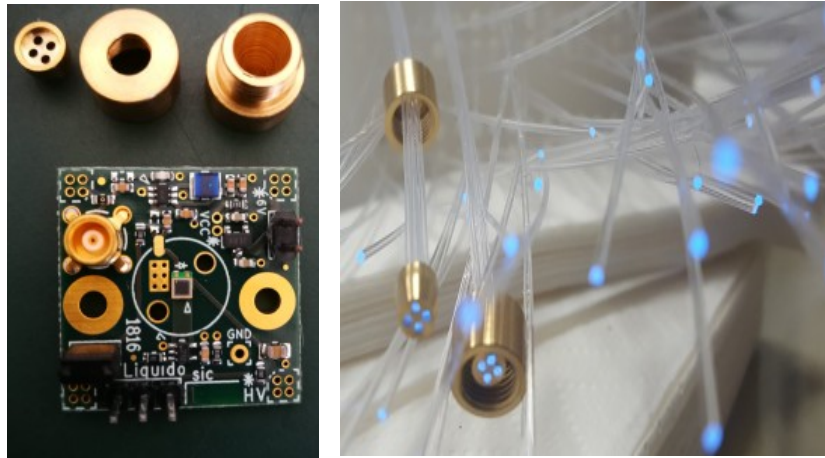
LiquidO collaboration, Communication Physics 4 (2021) 273

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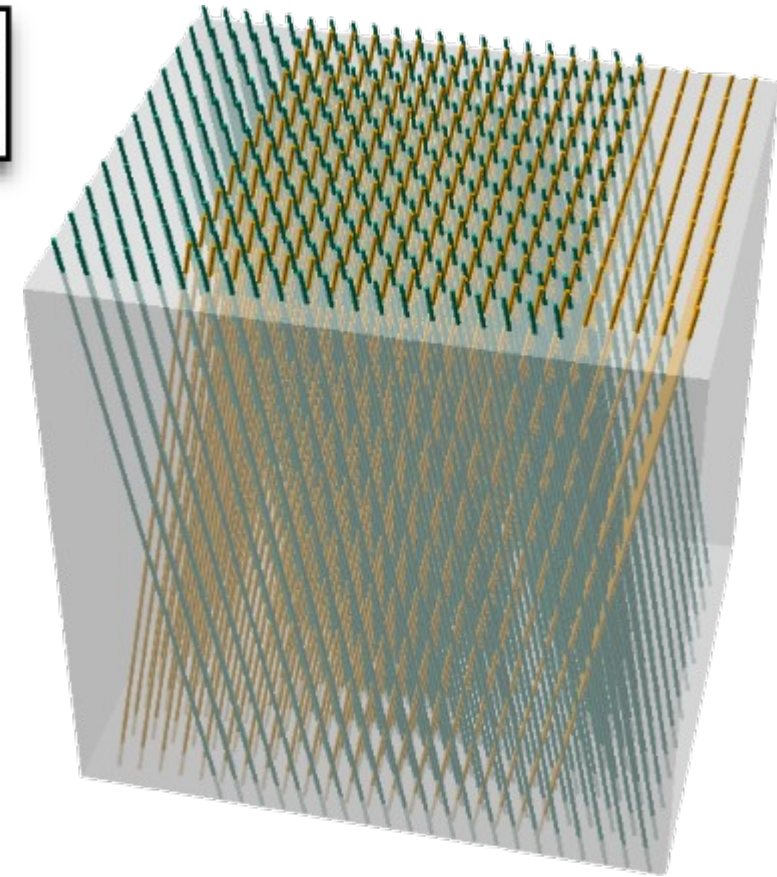
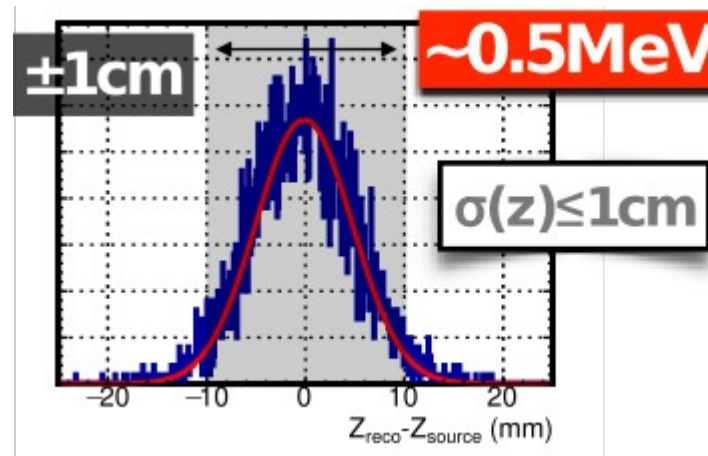
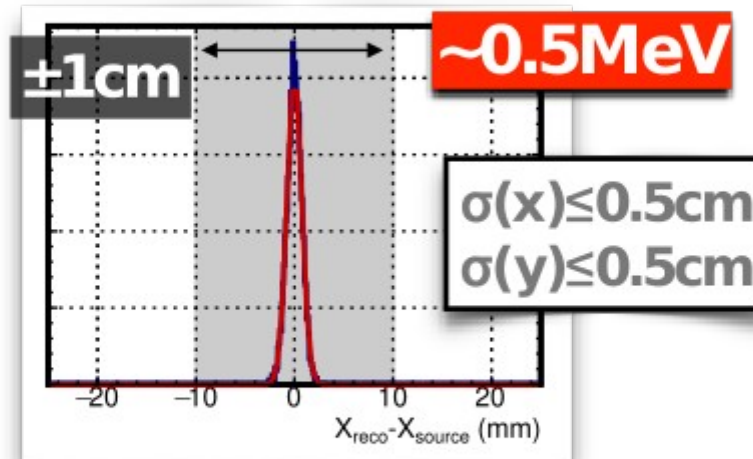


LiquidO collaboration, Communication Physics 4 (2021) 273

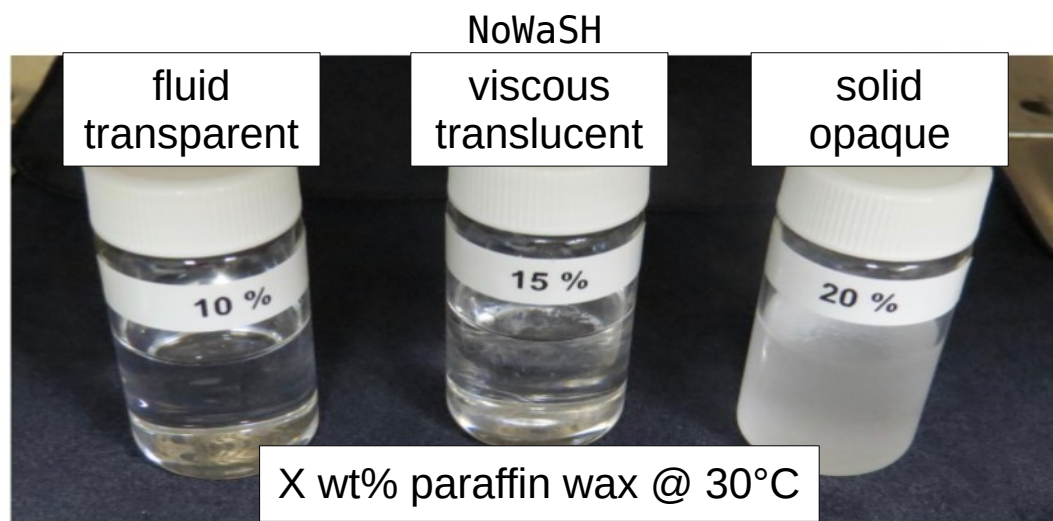
- instrumented by grid of wavelength-shifting/scintillating fibres
- good scalability due to uni-directional design
- z-direction via timing and/or crossing fibres



- SiPM readout of fibres
- sub-100ps timing resolution
 - <https://doi.org/10.1109/RTC.2014.7097545>
- amount of light: >400 PE/MeV



- 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



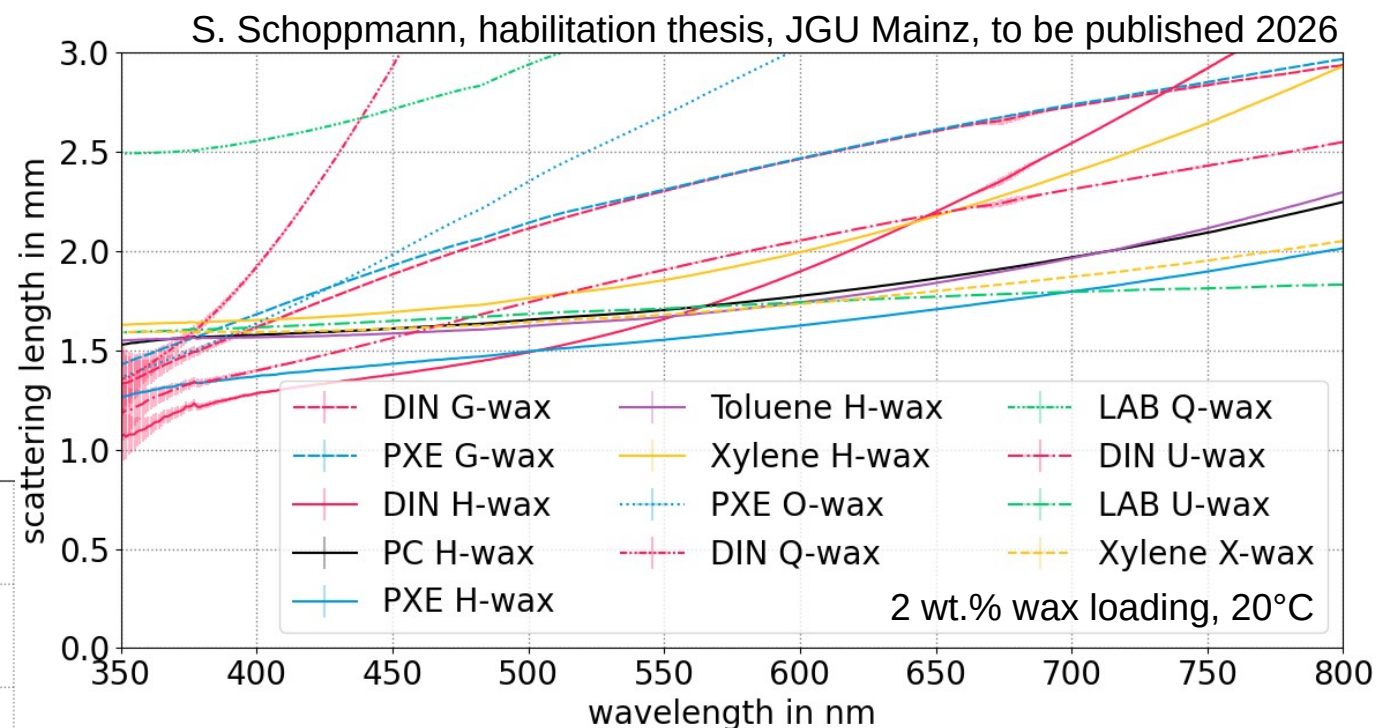
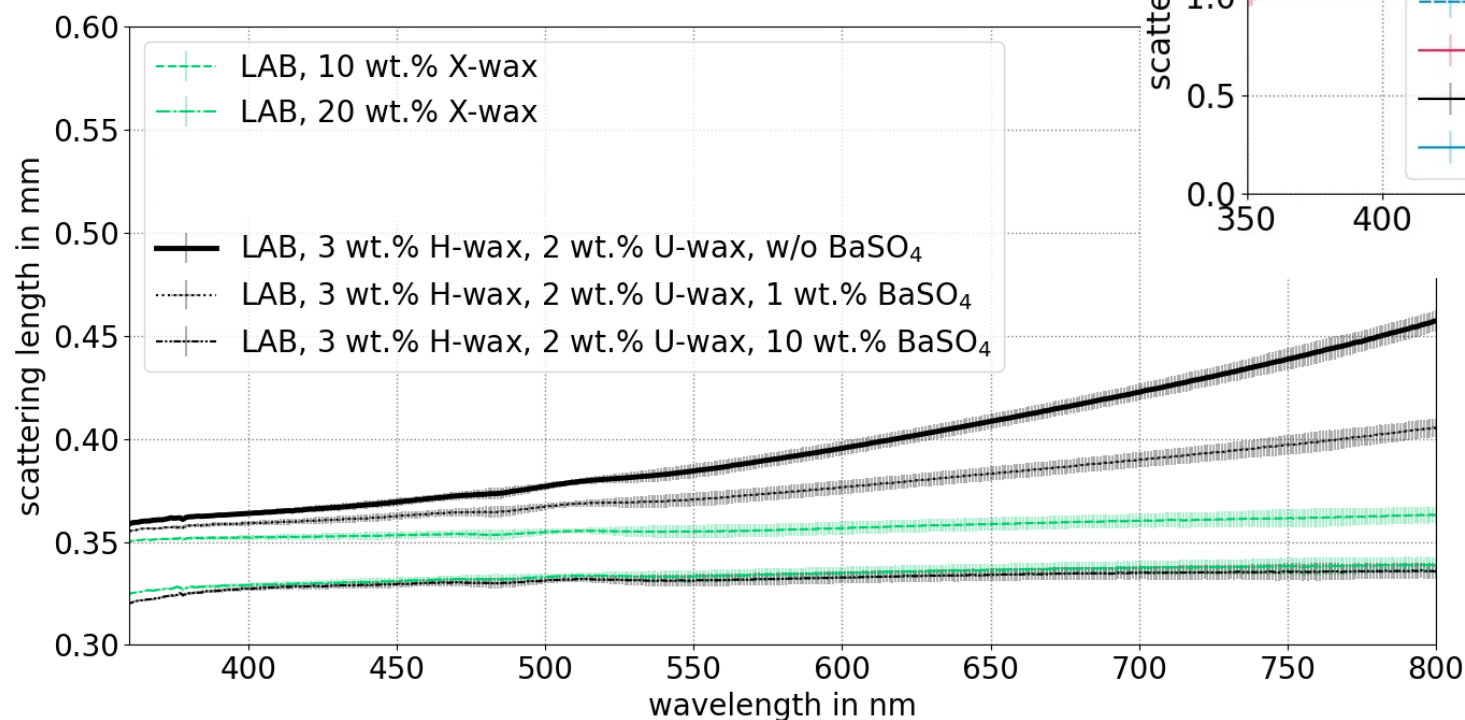
C. Buck, B. Gramlich, S. Schoppmann, JINST 14 P11007 (2019)

oWbLS



Liquid0 collaboration (J. Apilluelo et al.), arXiv:2406.13054

- wax content reduced to ~2 wt.%
- full light yield
- liquid, viscous or solid
- scattering length between 300 μm and 3 mm



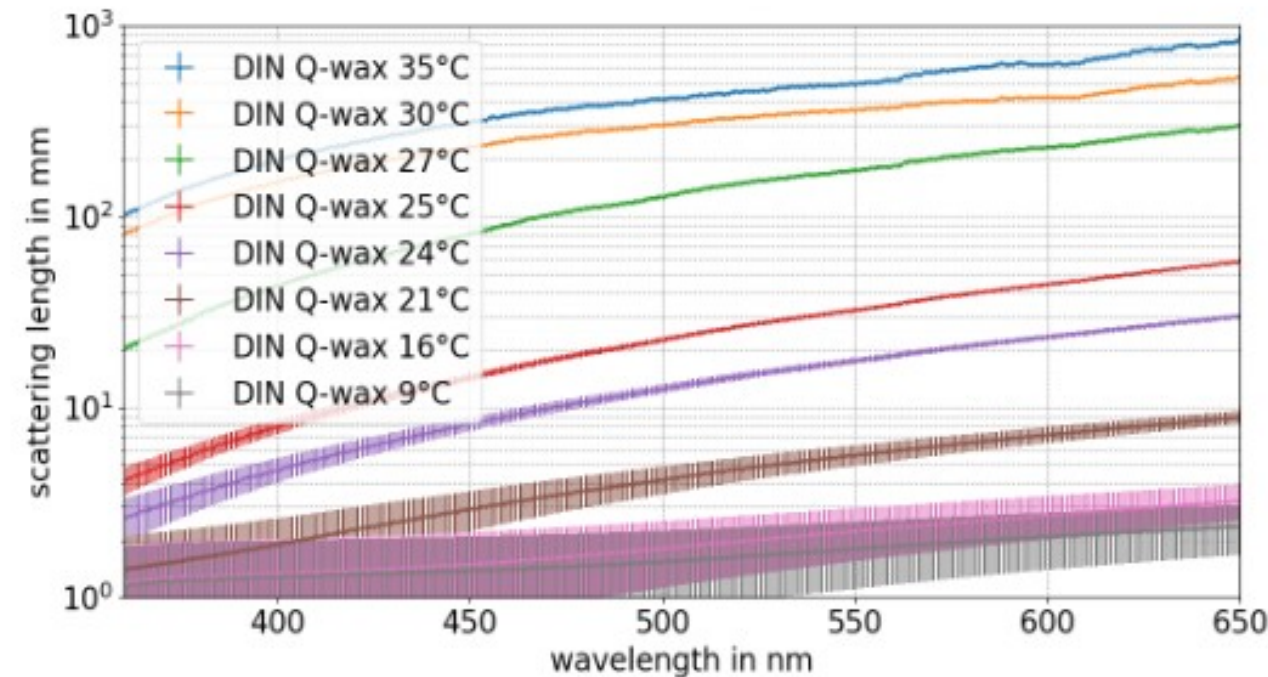
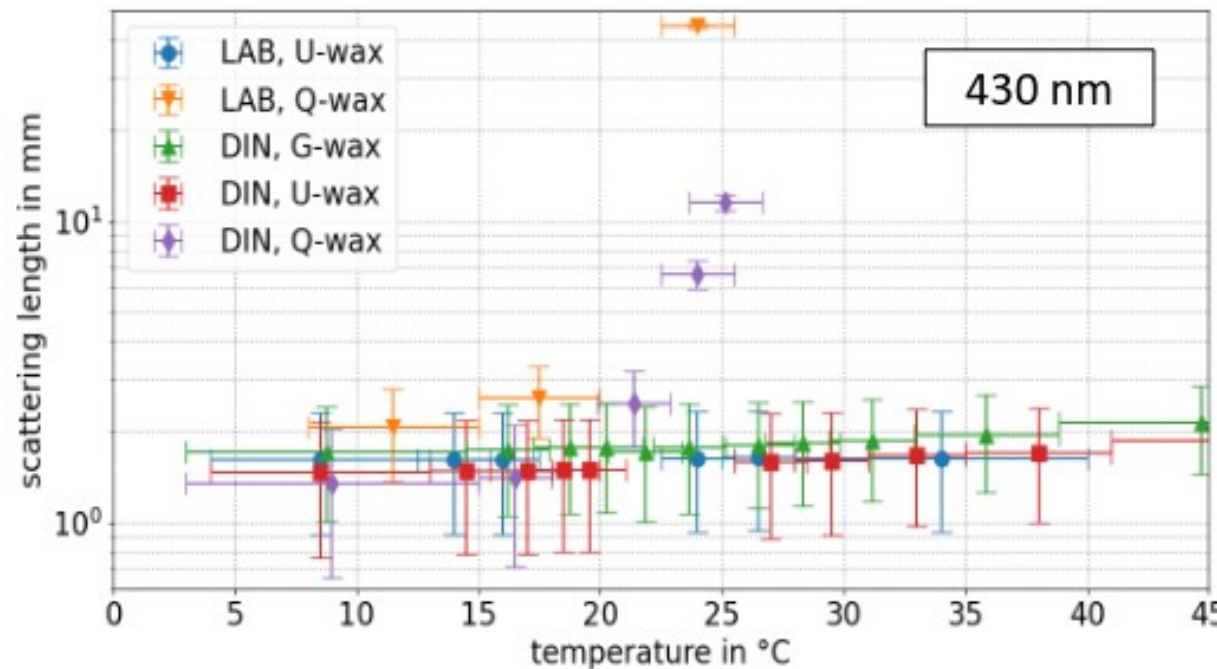
G / O	Polyethylene waxes
H / X	N-N' Ethylene-bis-steramid waxes
Q	Paraffin wax
U	Fischer-Tropsch wax

→ no hazard according to GHS and ADR

→ low radioactivity:

Isotope	U-238	Ra-226	Th-228	Ra-228	Cs-137	Co-60	K-40
Activity [mBq/kg]	< 86.5	< 2.17	< 2.79	< 1.66	< 0.85	< 0.40	< 5.26

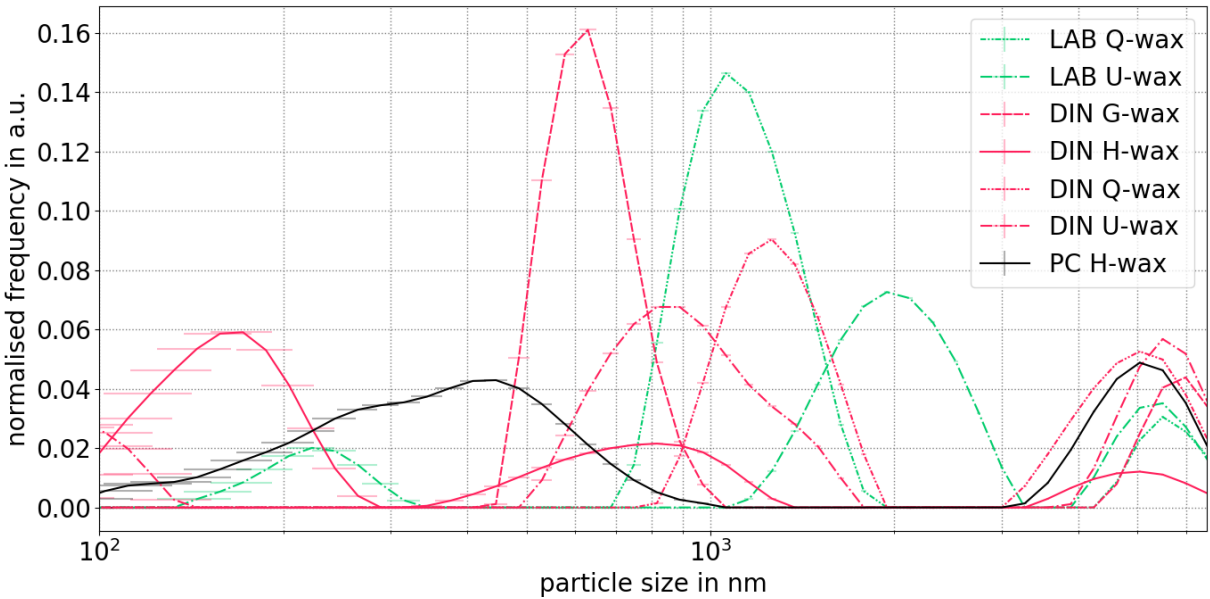
→ temperature dependency:



S. Schoppmann, habilitation thesis, JGU Mainz, to be published 2026

~ 10 wax types tested with 6 solvents

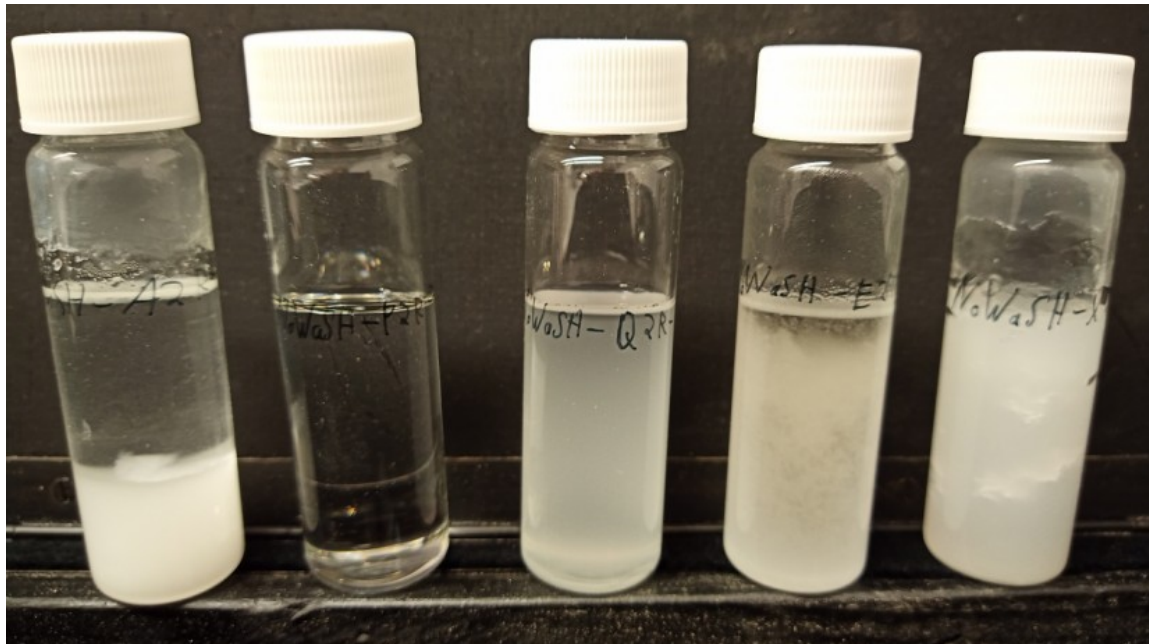
→ stable combinations are broadly / multi-dispersed



images of 1 μm $\times$ 1 μm		solvent					
		LAB	DIN	PXE	PC	Xylene	Toluene
wax	G	-			-	-	-
	H	-					
	O	-	-		-	-	-
	Q			-	-	-	-
	U			-	-	-	-
	X	-	-	-	-		-

Sedimentation Tests

- 1st step
 - small volume test (25ml)
- 2nd step
 - large volume test (1 litre)
 - selected combinations tested for > 1 year

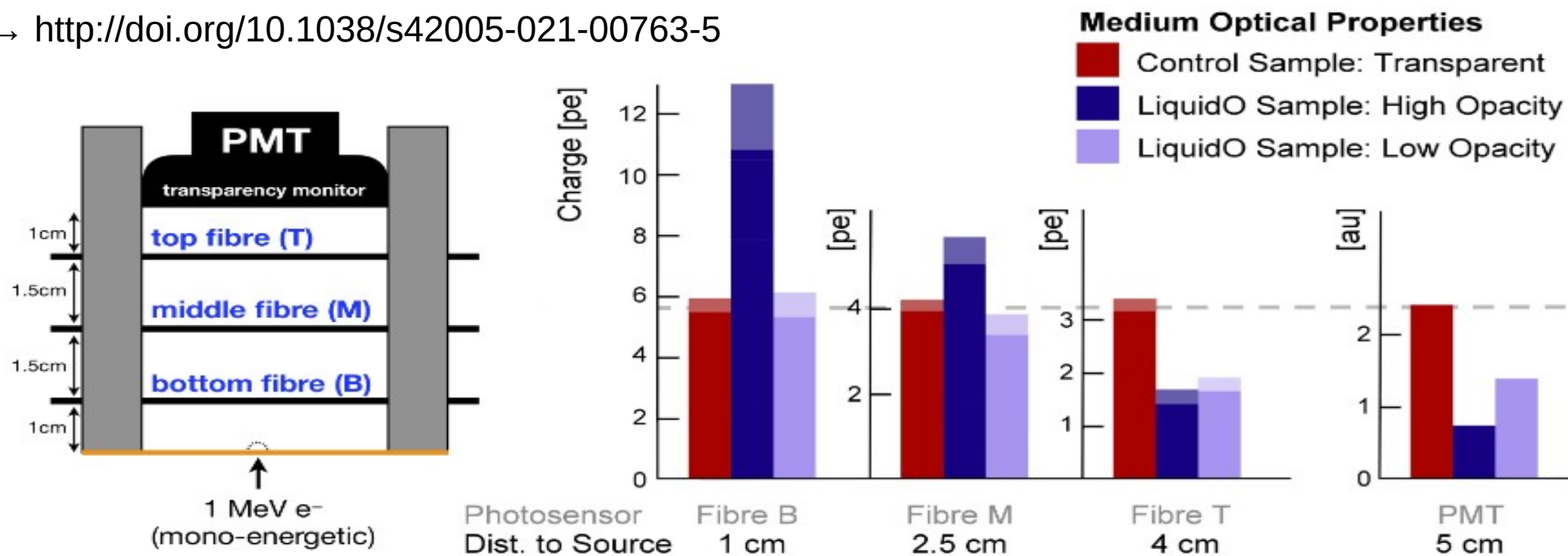


Examples of unstable/unsuitable combinations



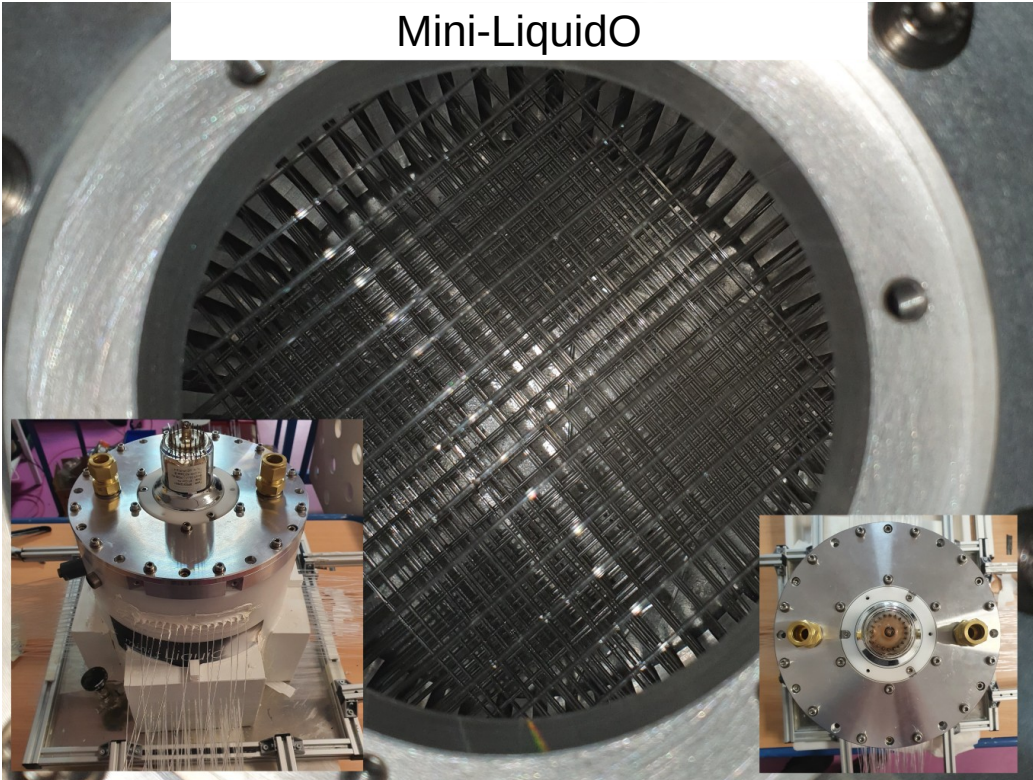
Example of stable combination

- 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>



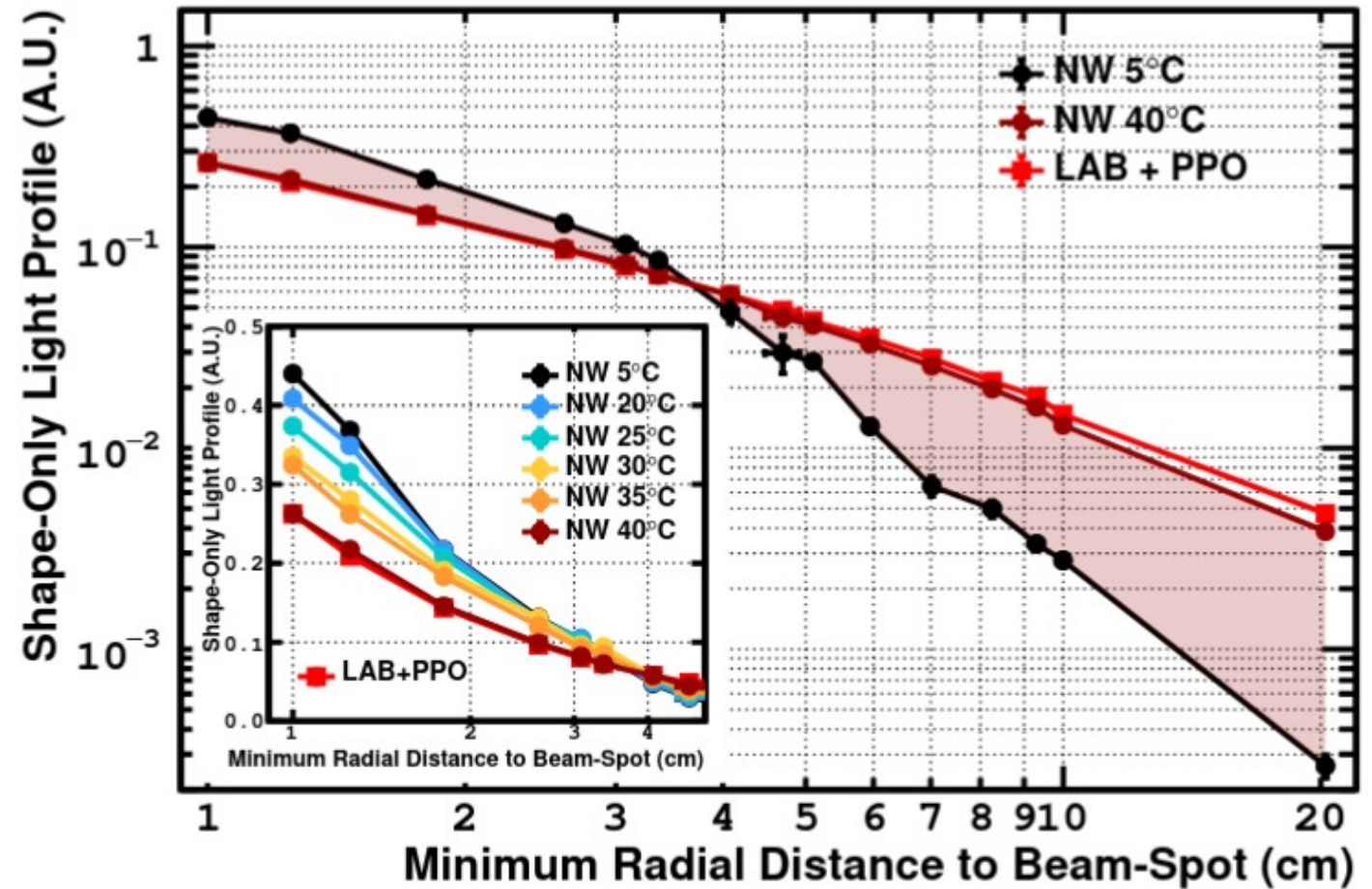
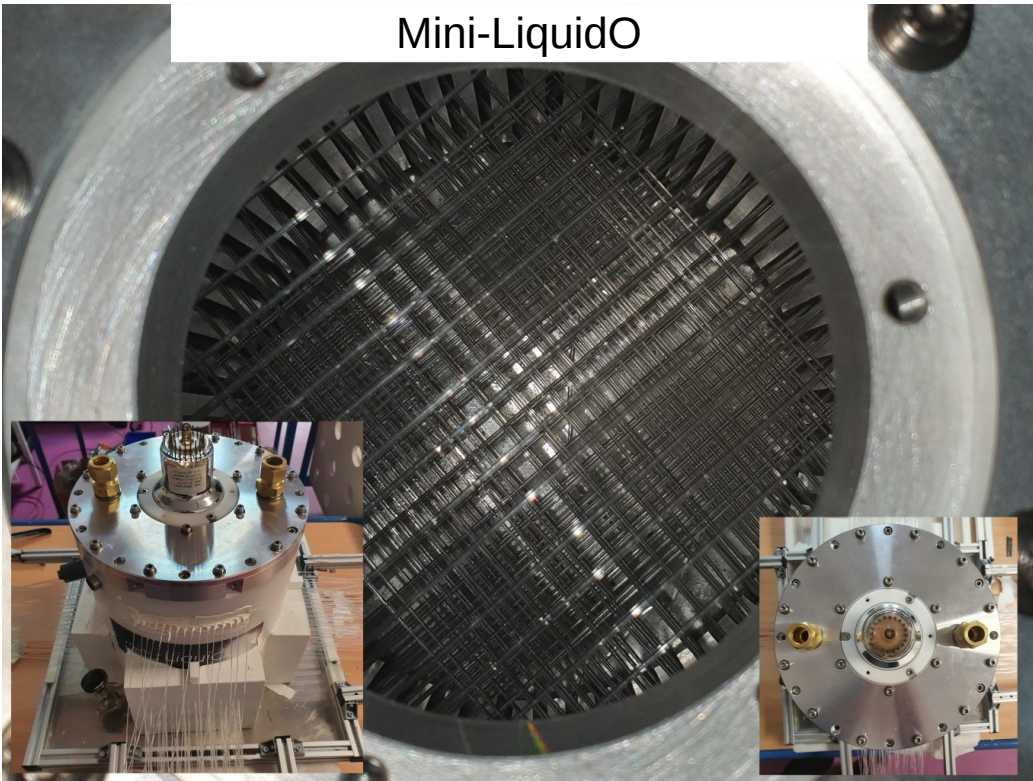
- Mini-LiquidO Prototype
 - 10 litres
 - 64 crossed fibres
 - ~1 MeV electron beam injected
 - temperature dependent opaqueness

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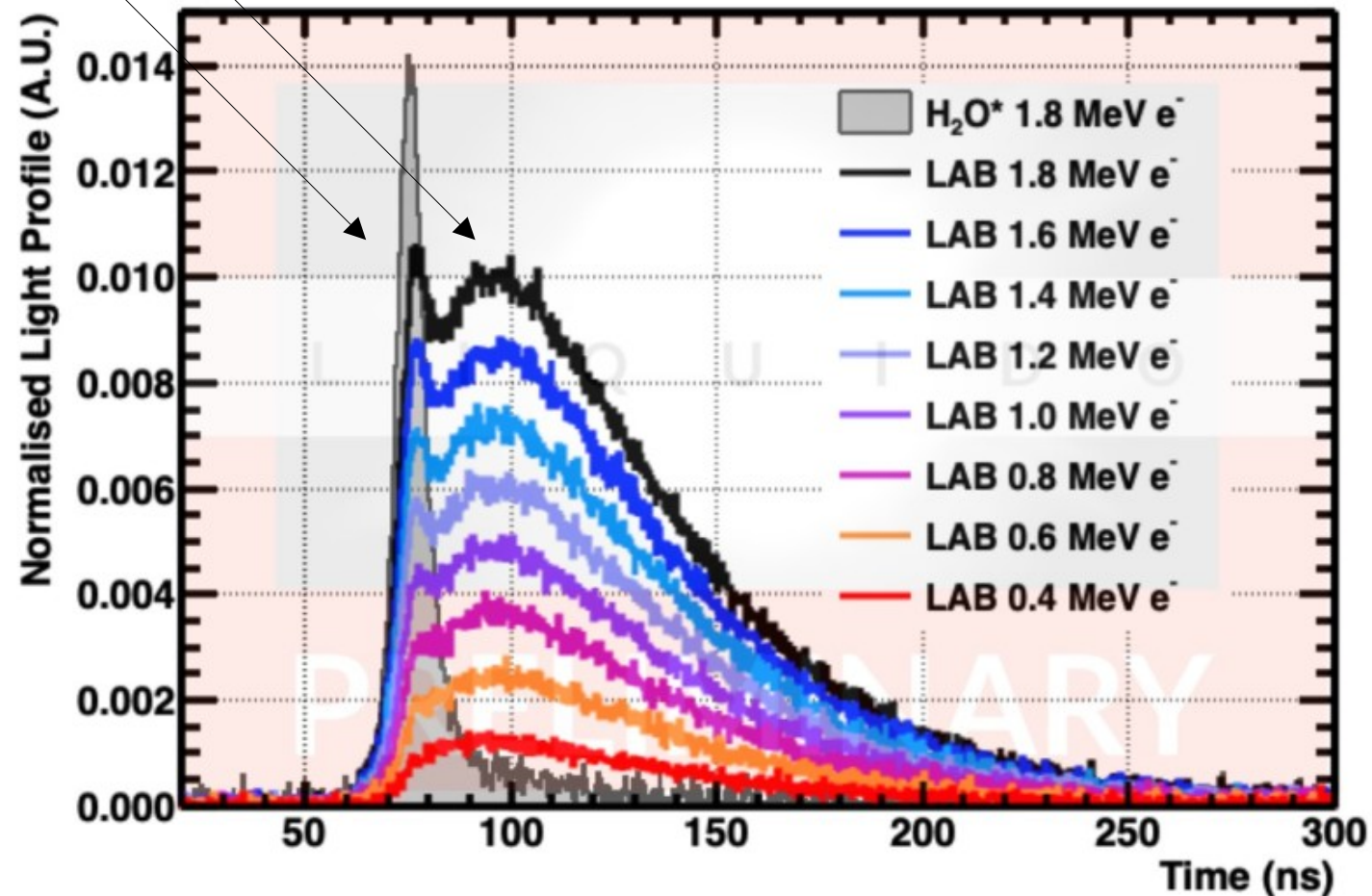


LiquidO collaboration, arXiv:2503.02541

Scintillation photons

Cherenkov photons

- 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



Micro-LiquidO
~ 0.25 litre
Proof of principle



Mini-LiquidO
~10 litre
Light ball formation



BPULSE
~4 litre
Gammas

BNL/NASA
~1 litre
Beams

oMAMI
~25 litre

past
future

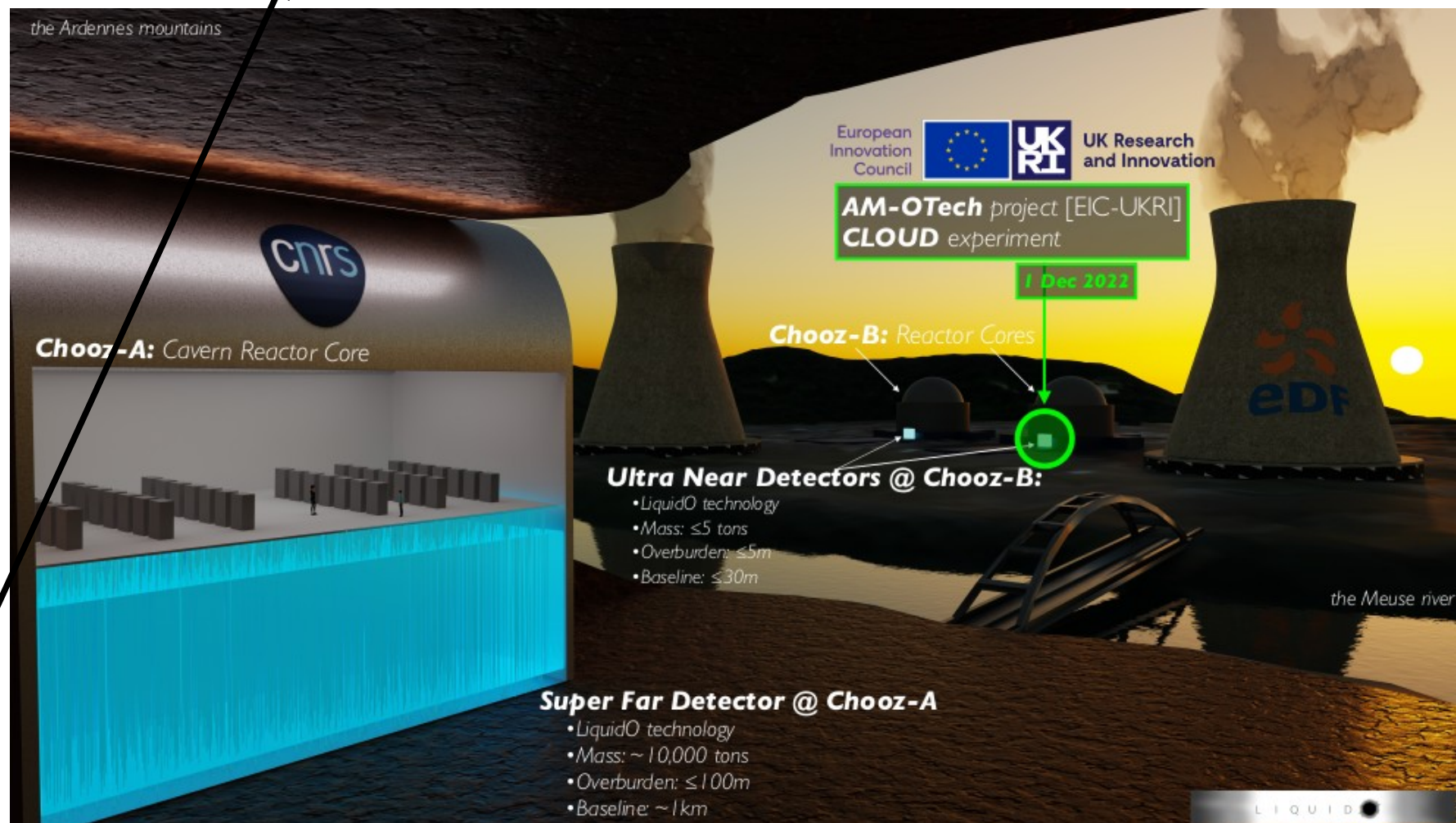


AM-OTech
~8 tonnes
Reactor / geo

CLOUD
~8 tonnes

NuDoubt++
~3 tonnes
double beta

SuperChooz
 $\mathcal{O}(10 \text{ kt})$
Solar / SN / reactor / nucleon decay / ...



Attenuation of light collecting fibres

- currently $\mathcal{O}(1\text{ m})$
- need $\mathcal{O}(10\text{ m})$

Light sensors

- currently $\mathcal{O}(100\text{ channels})$
- need $\mathcal{O}(10^7\text{ channels})$

Stability

- currently shown at $\mathcal{O}(10\text{ litre})$
- need $\mathcal{O}(10^7\text{ litre})$

Deployability

- scintillator mixing, handling, pumping

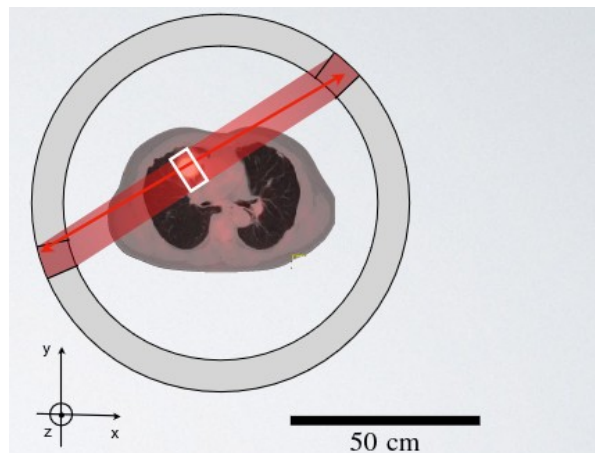
The path forward goes through tonne-scale demonstrators

- Eos, Annie and Brookhaven Demonstrators testbeds for injection of organics in water
- AM-OTech, CLOUD, NuDoubt⁺⁺ testbeds for fibre and light sensor instrumentation $\mathcal{O}(10^4)$ channels

Appendix

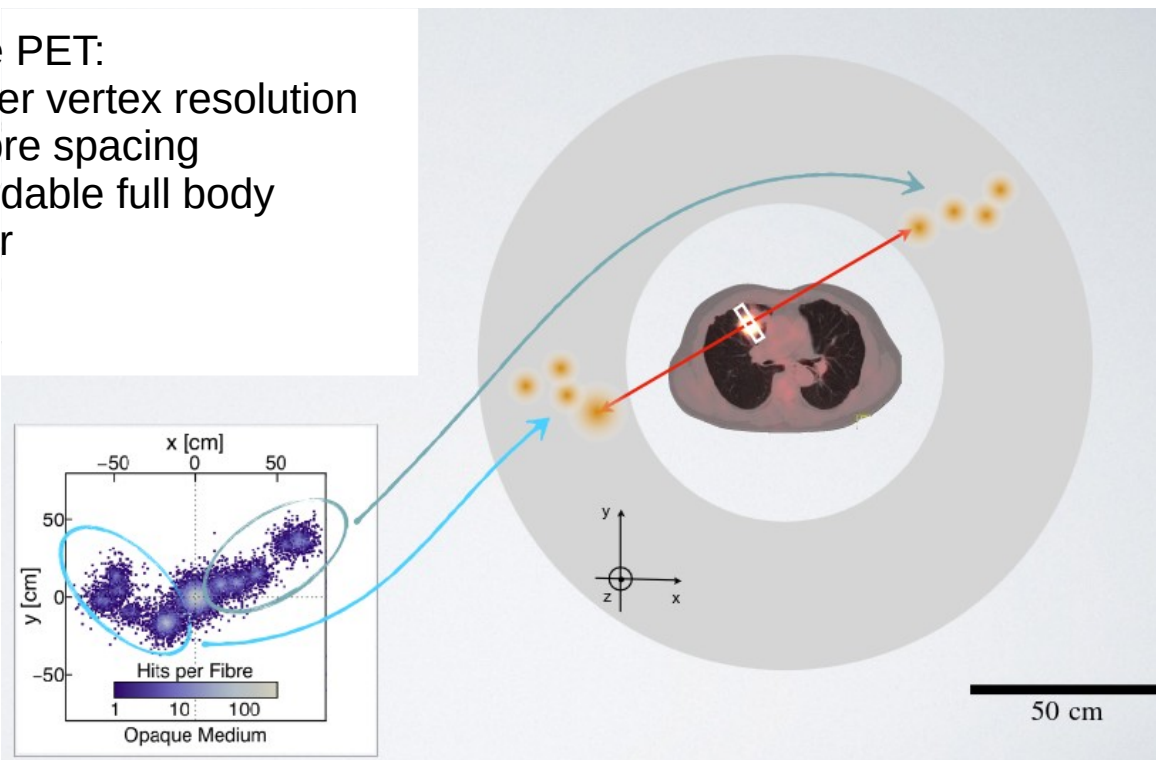
traditional PET:

- transparent scintillator crystals
- limited vertex resolution due to crystal size
- expensive (only ring of crystals)



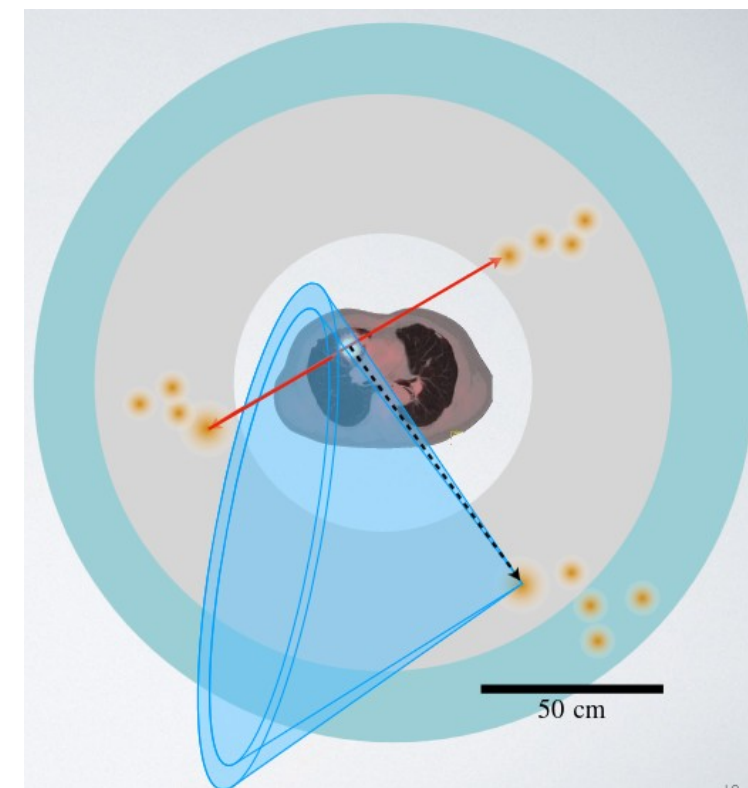
opaque PET:

- higher vertex resolution from fibre spacing
- affordable full body scanner

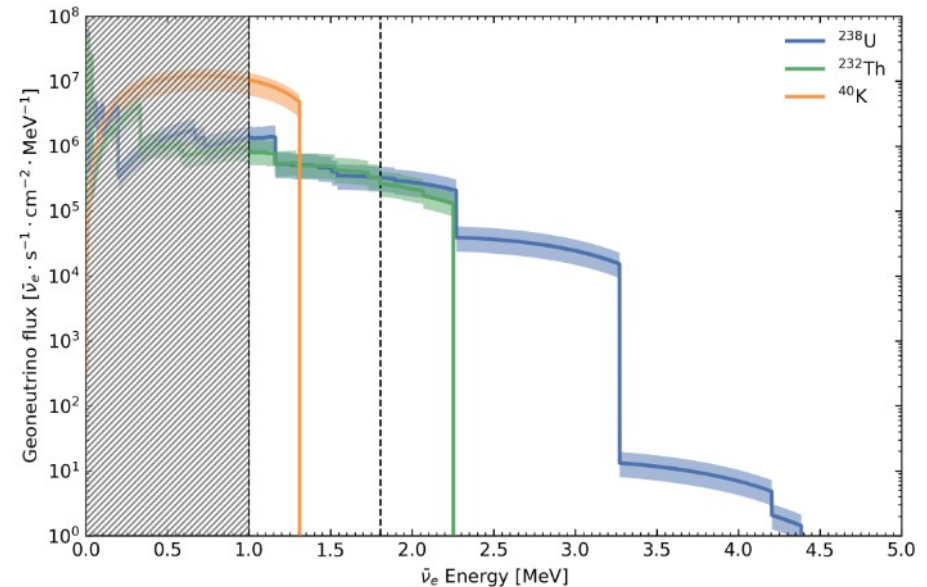
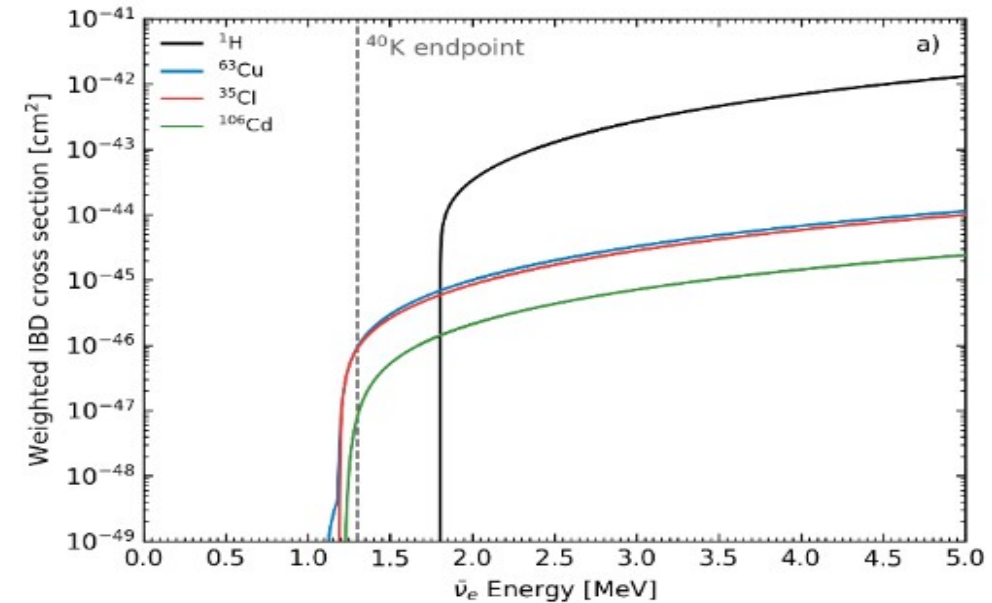
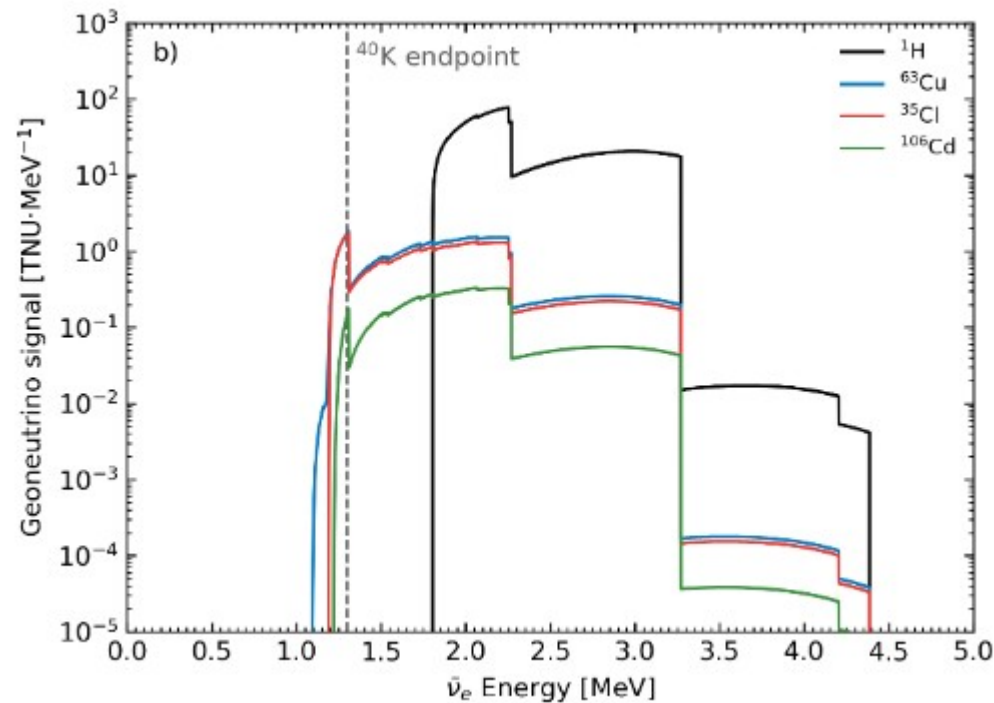


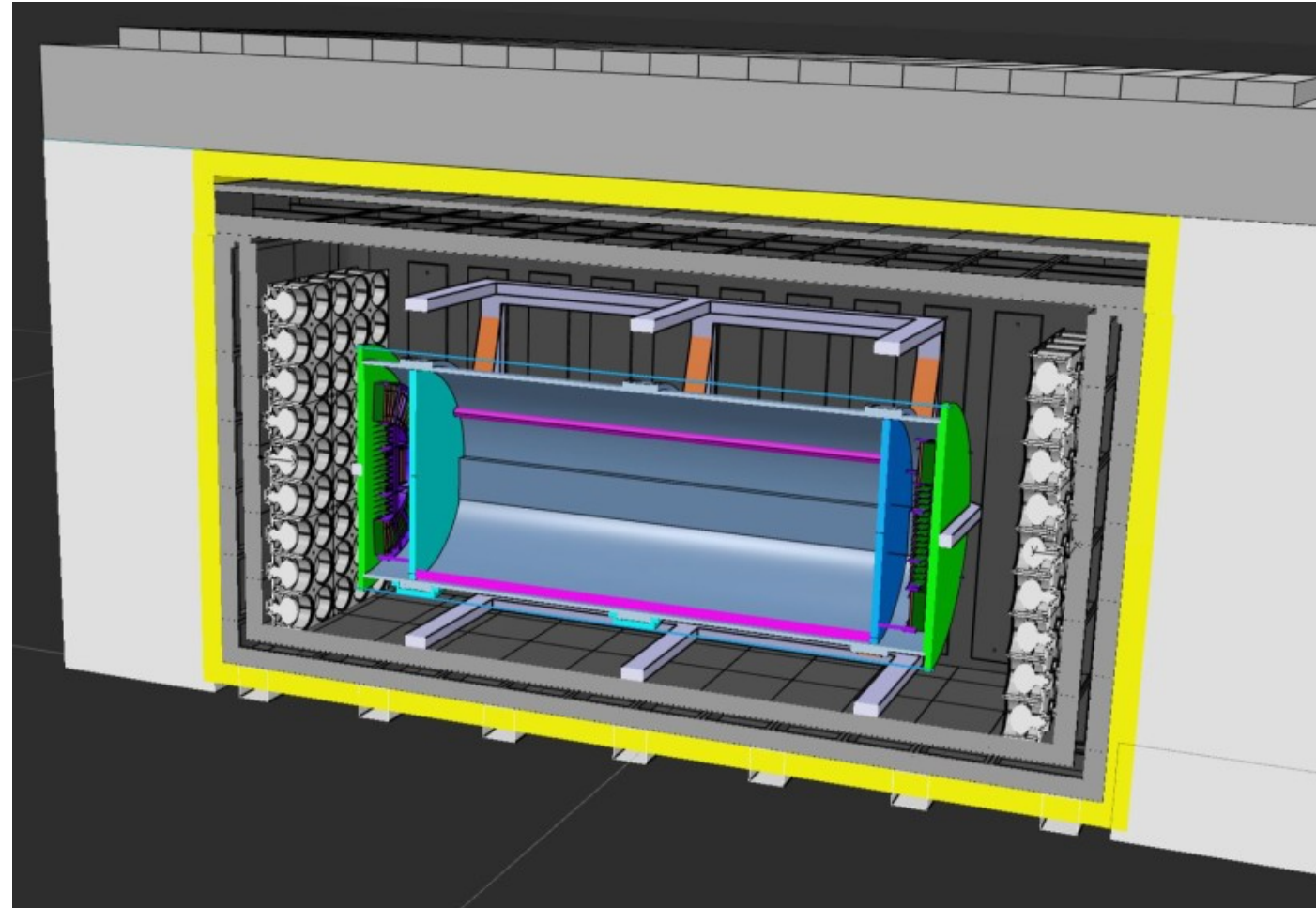
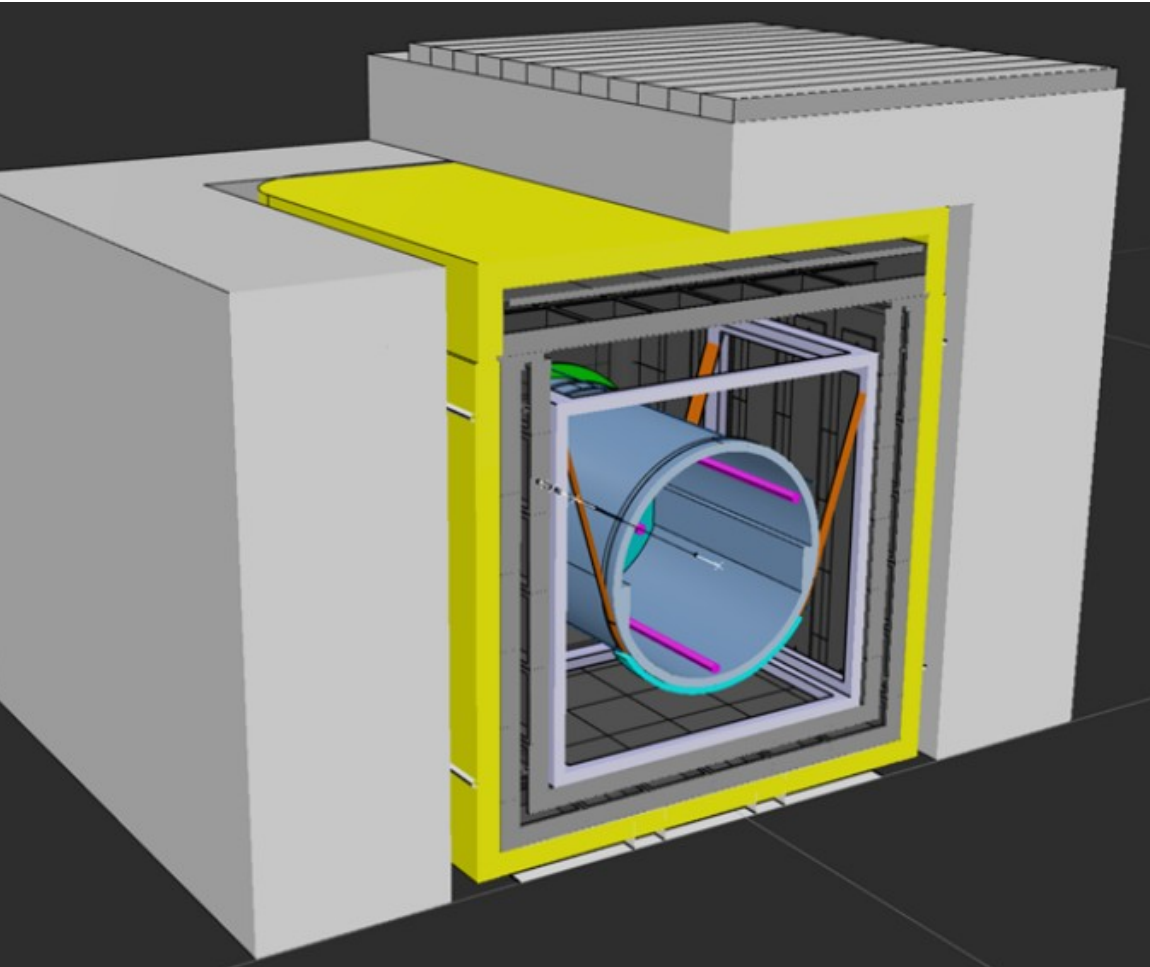
3-gamma imaging:

- 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



- detect geoneutrinos 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



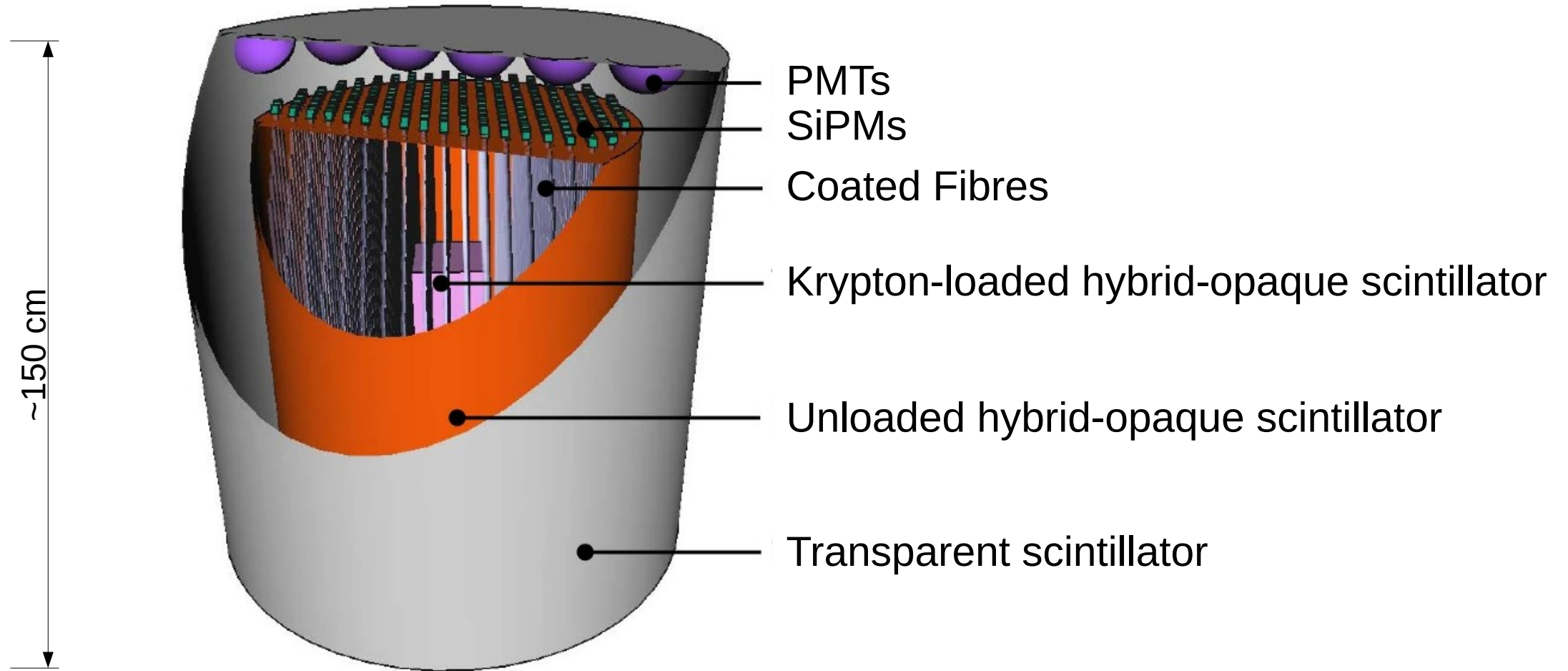


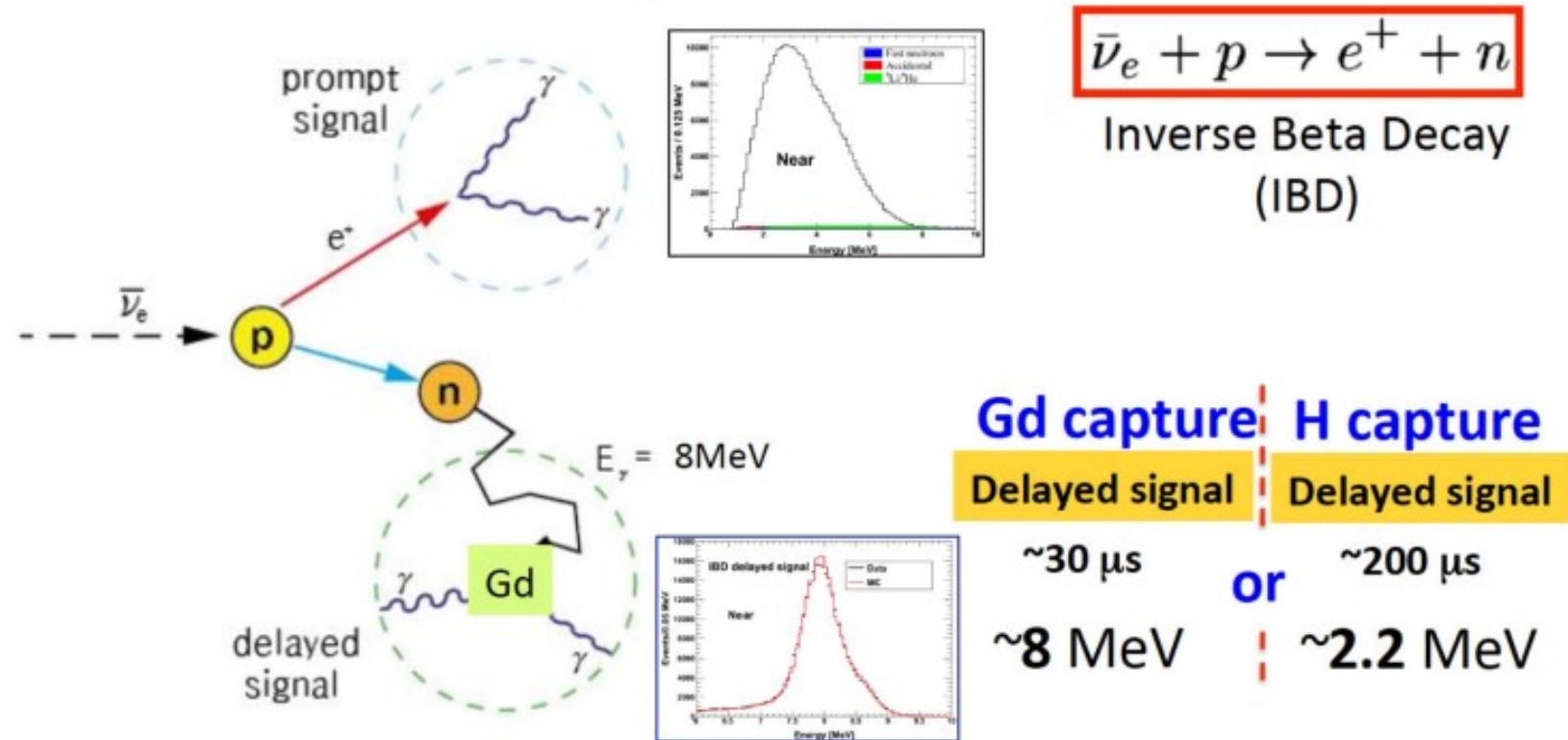
Preliminary design:

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.





- Prompt signal (e^+) : 1 MeV 2γ 's + e^+ kinetic energy ($E = 1\sim 10 \text{ MeV}$)
- Delayed signal (n) : 8 MeV γ 's from neutron's capture by **Gd** in $\sim 30 \mu\text{s}$
or 2.2 MeV **by H** in $\sim 200 \mu\text{s}$