LIQUIDO OPAQUE-SCINTILLATOR DETECTORS FOR HIGH-RESOLUTION MUON IMAGING

N. Tuccori

On behalf of LiquidO Collaboration

Muographers 2026

1st June – Budapest

UNIVERSITY OF SUSSEX

NOVEL LIQUIDO[1] TECHNOLOGY

[1] LiquidO Collaboration, Commun Phys 4, 273 (2021). https://doi.org/10.1038/s42005-021-00763-5

Transparent scintillator → Segmented

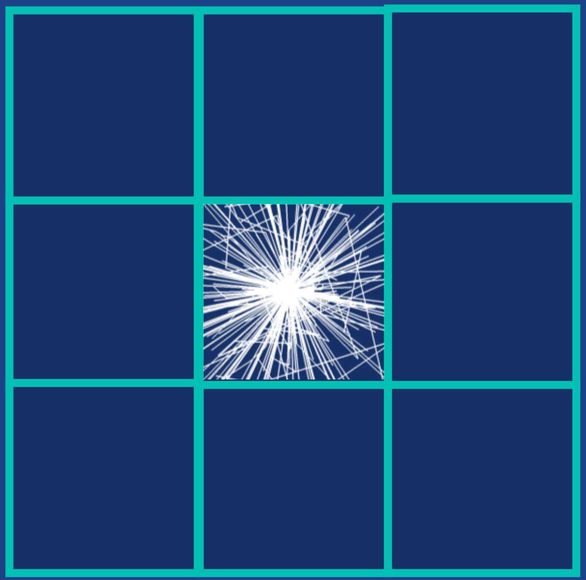
- Long scattering length
- Long absorption length

Segmented

- Long scattering length
- Long absorption length

Opaque scintillator

- Short scattering length
- Long absorption length



NOVEL LIQUIDO[1] TECHNOLOGY

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Opaque scintillator

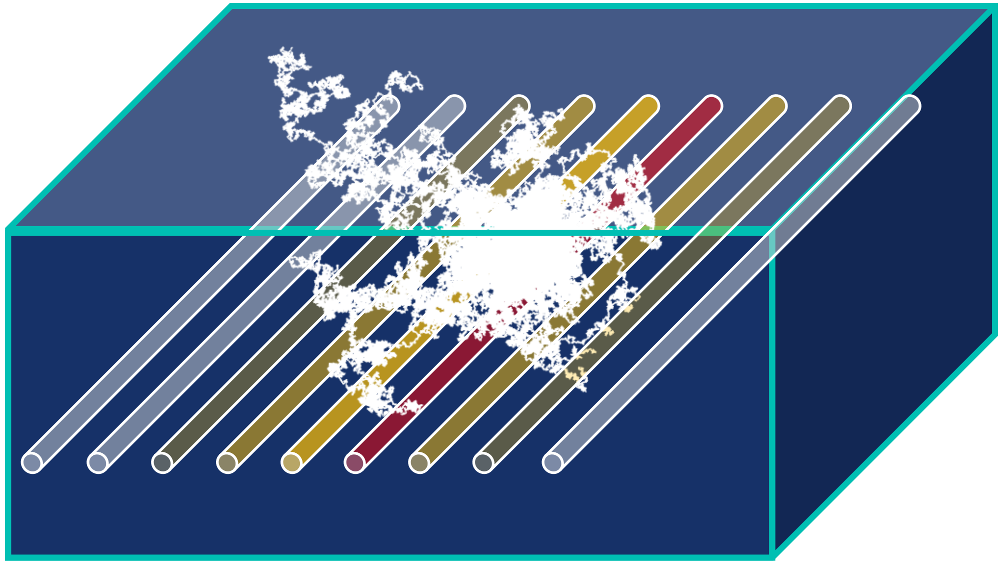
In a scintillator with a short scattering length the light stays near where it is produced

+ Lattice of Wavelength Shifting Fibres

Collect and extract the light from near the point of production using a lattice of wavelength-shifting fibres

= LiquidO!

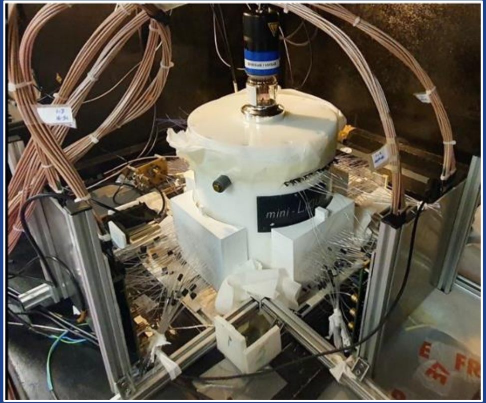
- Self-segmentation of detection volume
- Rich optical and topological information
- high-resolution imaging detectors



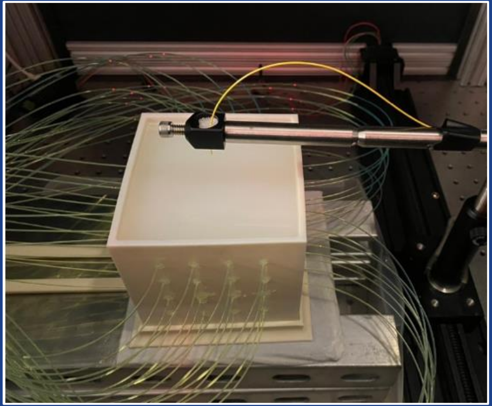
LIQUIDO COLLABORATION

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

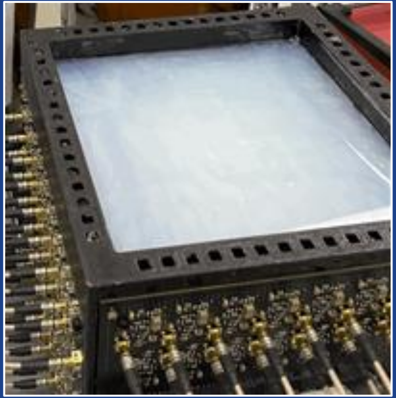
Prototypes



MINI-LiquidO @ LP2i, France
https://doi.org/10.48550/arXiv.2503.02541

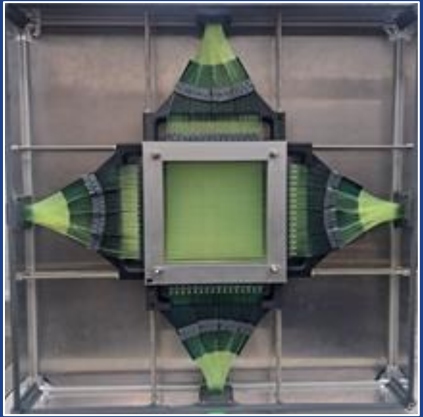


LIME @ Uni. of Michigan, USA
https://doi.org/10.48550/arXiv.2406.13054



BPULSE @ Penn State, USA

Cube

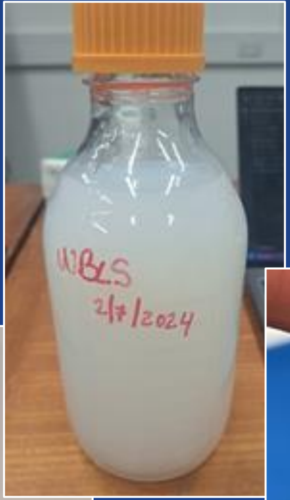


Tile

@ Uni. Of Sussex
https://doi.org/10.1088/1748-0221/21/01/P01010

Opaque scintillator R&D

Water-based Opaque scintillator
@ Brookhaven National Lab., USA



NoWaSH @ JGU Mainz, Germany
https://doi.org/10.48550/arXiv.1908.03334

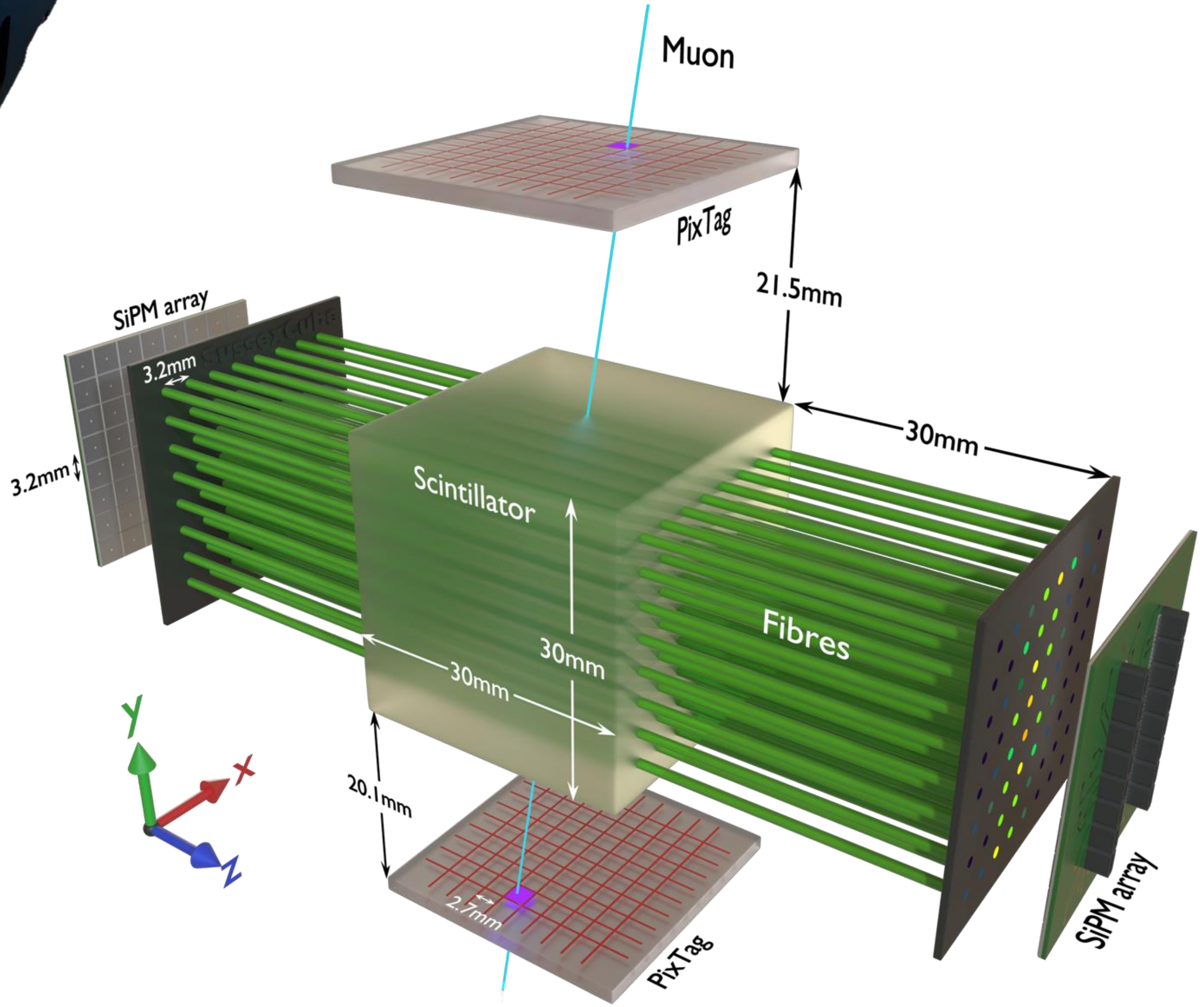
Water-based Opaque scintillator
@ IST, Portugal

SUSSEX CUBE:

64 FIBRES LIQUIDO PROTOTYPE

SUSSEX CUBE LIQUIDO DETECTOR

https://doi.org/10.1088/1748-0221/21/01/P01010

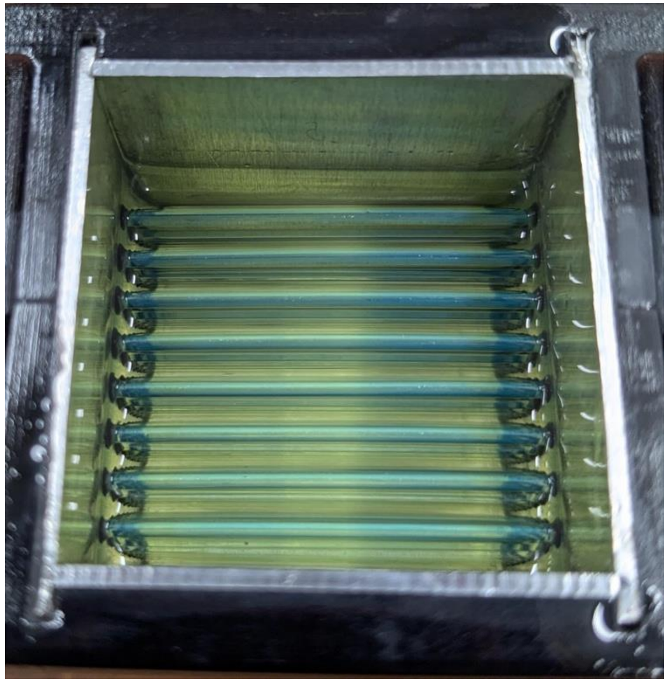


- 3 cm size cube of scintillator
- 64 wavelength-shifting fibres
  - Saint-Gobain BCF-91A
  - 3.2 mm pitch
- Dual-end readout with SiPMs
  - Hamamatsu S13361-3050-AE-08
- Pixelated muon taggers
  - 64 pixels each, SiPMs read-out
- PETsys TOFPET2 ASIC read-out

SUSSEX CUBE LIQUIDO DETECTOR

https://doi.org/10.1088/1748-0221/21/01/P01010

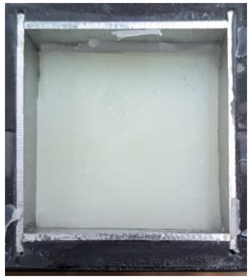
LAB-based
transparent scintillator



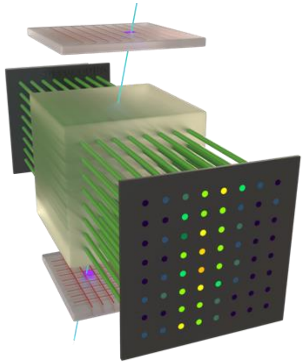
LAB + wax (NoWaSH)
opaque scintillator

C. Buck et al., J. Instrum. 14 (2019) P11007.
https://doi.org/10.48550/arXiv.1908.03334

- Opaque scintillator (NoWaSH)
  - LAB + PPO + POPOP
  - ~ 10% wt wax
  - Scattering length ~ 0.5 mm
- Transparent liquid scintillator
  - LAB + PPO + POPOP
  - Scattering length >> 1 mm
  - Absorption length >> 1 m
  - Light yield 10000 ph/MeV



OPAQUE



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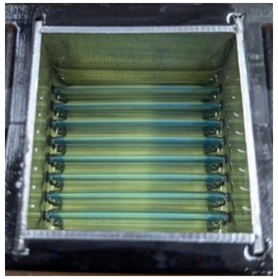
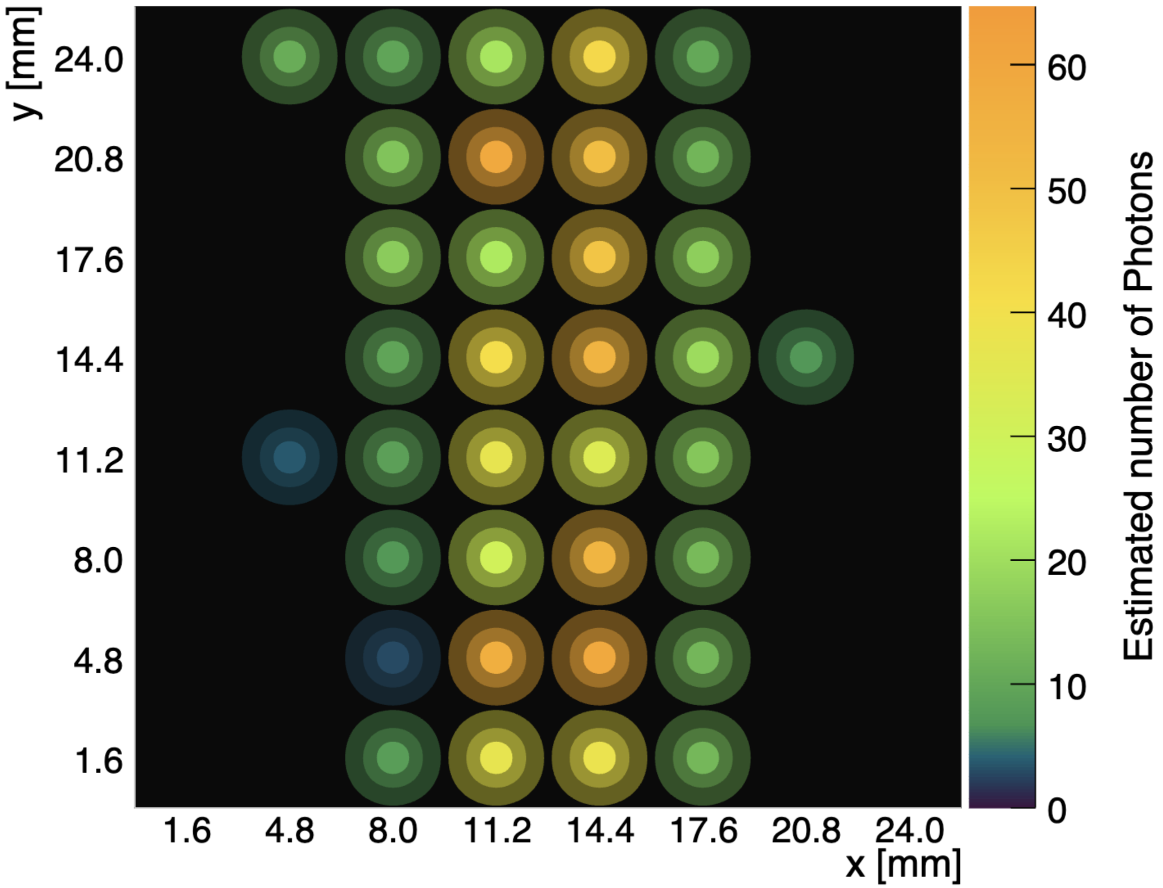
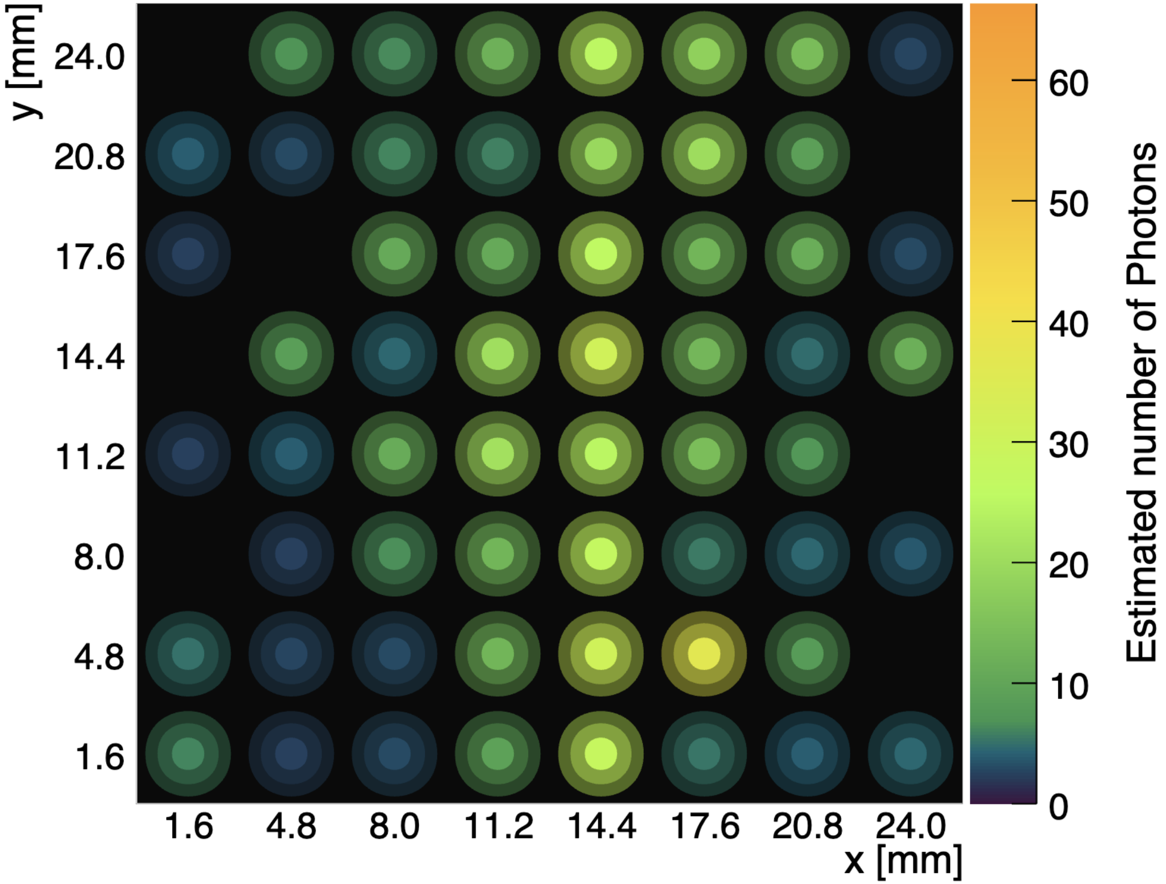
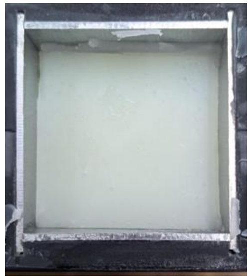
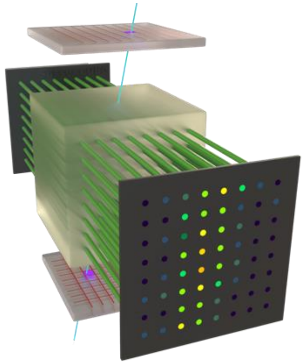




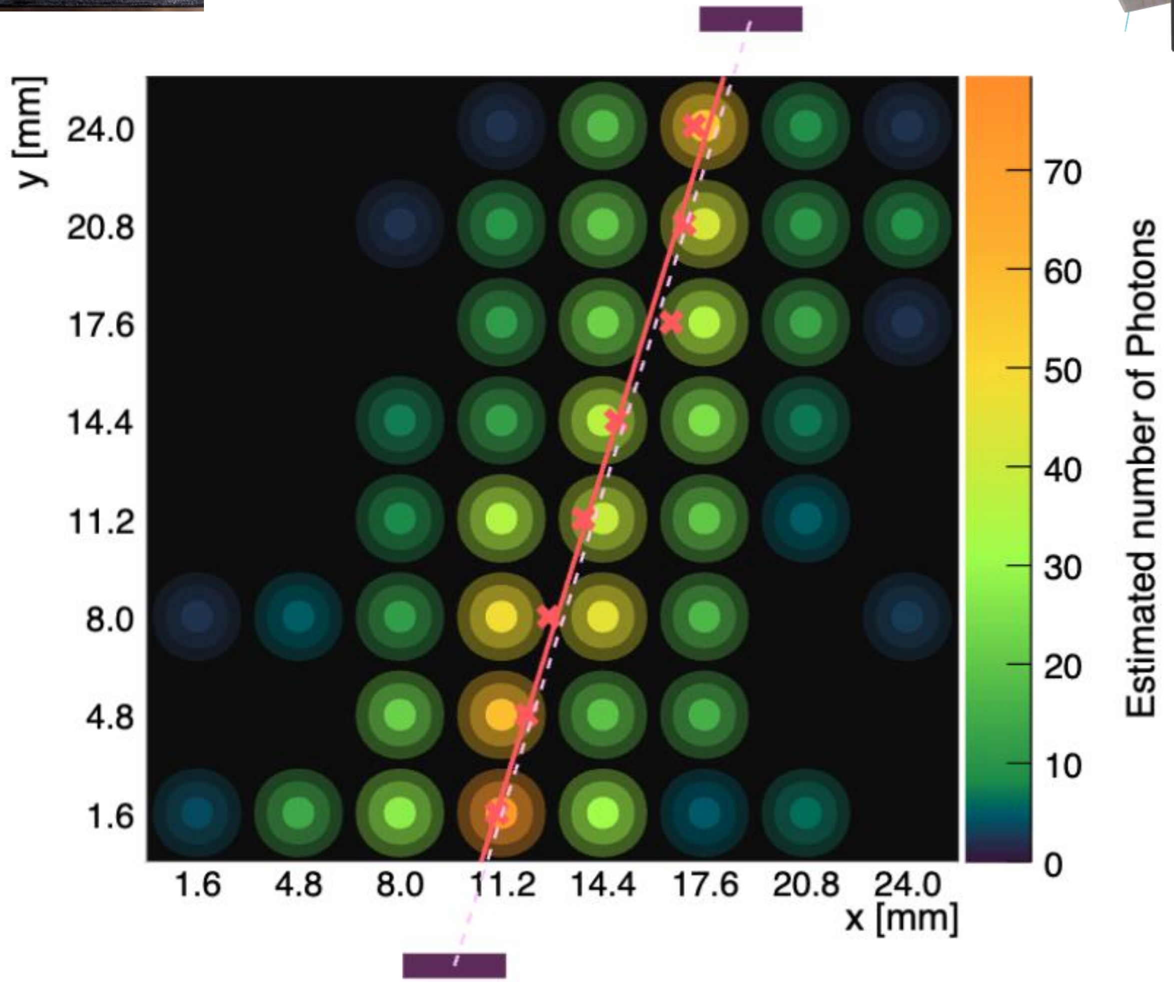


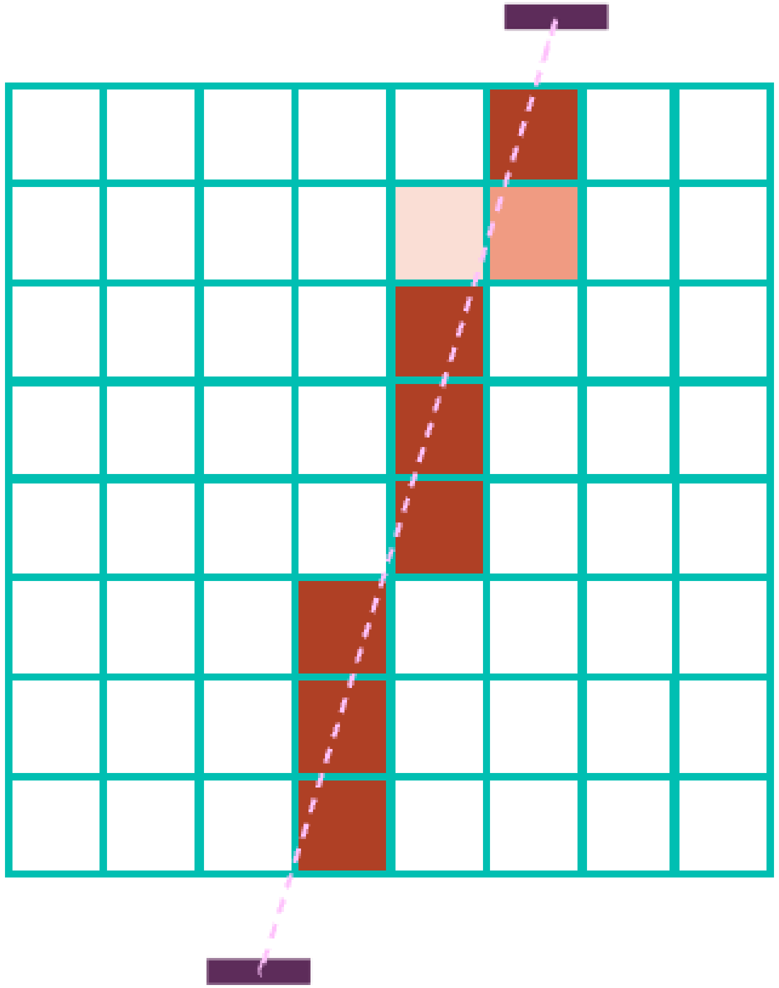


OPAQUE



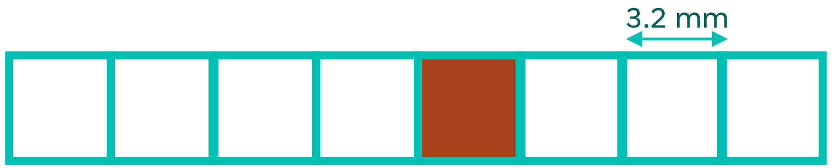
SEGMENTED





SUSSEX CUBE RESULTS

https://doi.org/10.1088/1748-0221/21/01/P01010



Position resolution

450 ± 20 μm

3.2 mm / $\sqrt{12}$ = **920** μm

Twice as precise as a simple scintillator-based segmented detector!

Simulations show we can improve tuning geometry and materials parameters

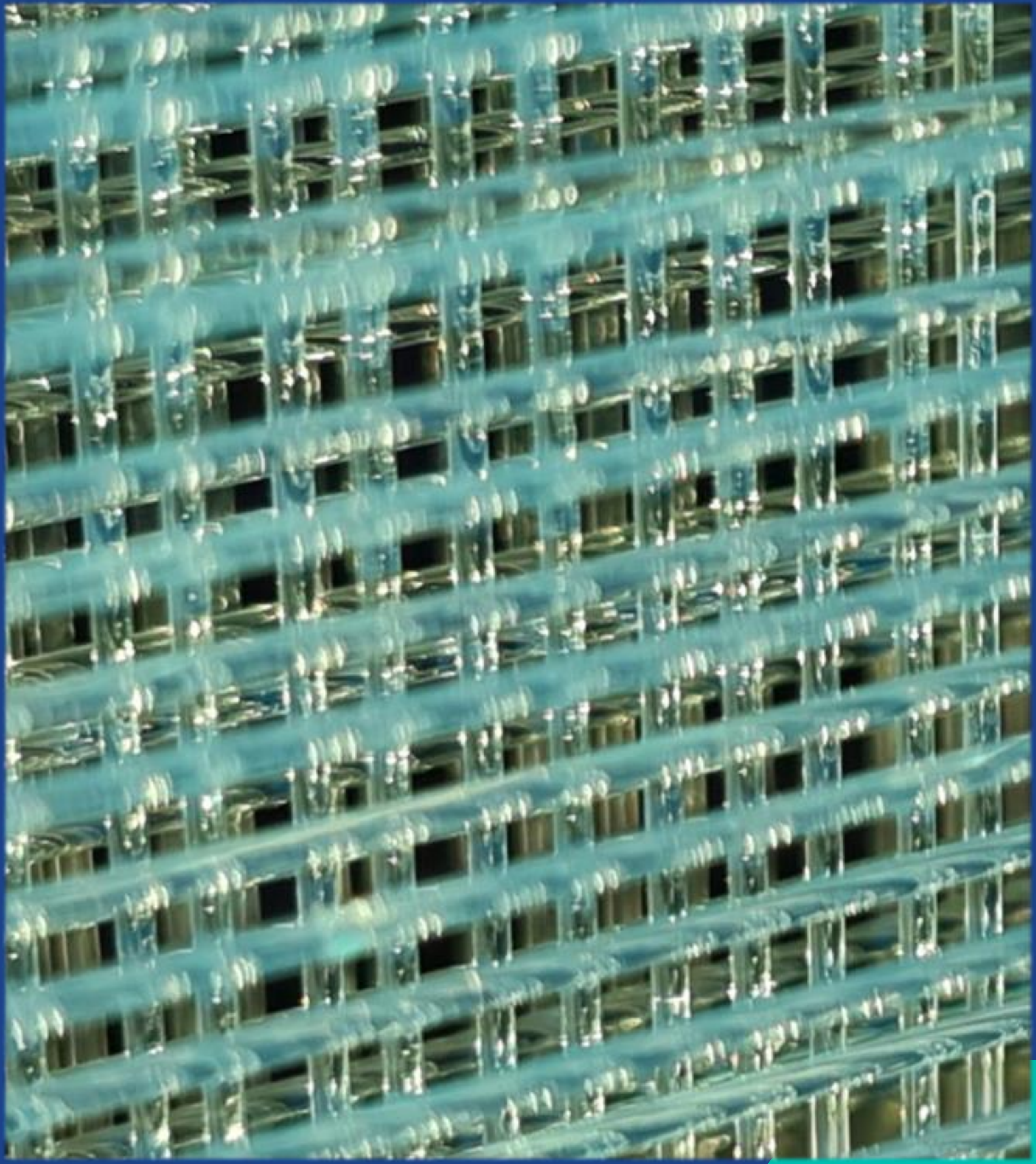
-> 5-10x more precise !

Compared to a simple scintillator-based segmented detector, potential to:

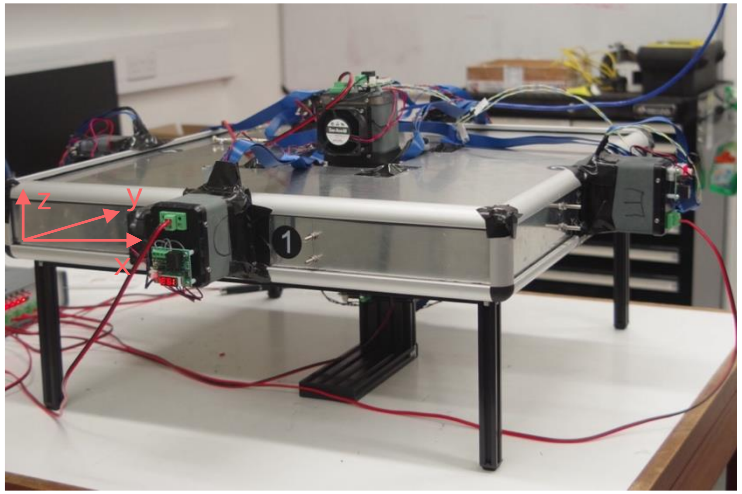
1. make detector 5-10x more precise for a similar cost (same readout channels)
2. Reduce the cost by 5-10x for the same performance

SUSSEX TILE:

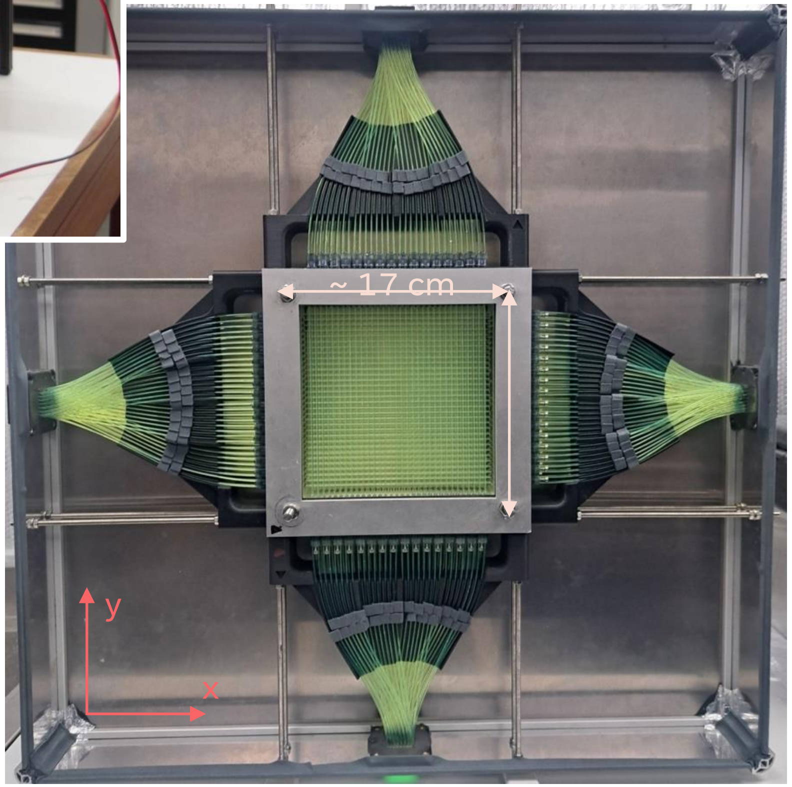
256 FIBRES LIQUIDO PROTOTYPE



SUSSEX TILE LIQUIDO DETECTOR

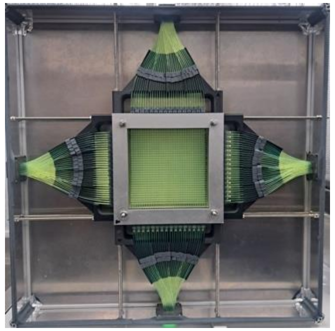


The tile on the bench



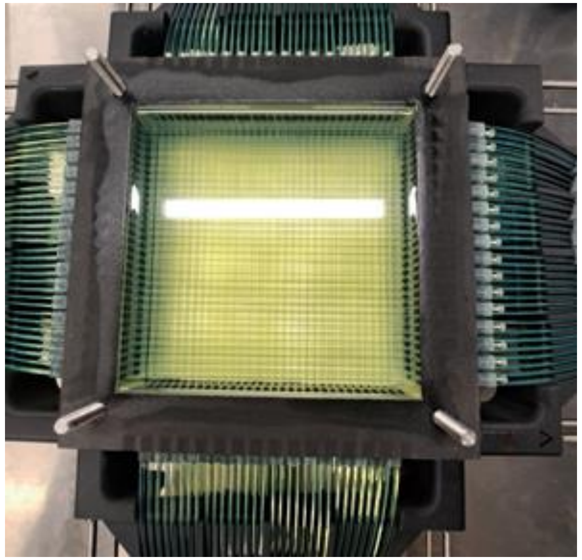
A top-down photo of the prototype open and without scintillator

- ~ 2 L of scintillator volume
- 256 wavelength-shifting fibres
  - Saint-Gobain BCF-91A
  - ~ 5 mm pitch
- 4 logical layers stacked vertically:
  - 2 along X
  - 2 along Y
- Dual-end readout with SiPMs
  - Hamamatsu S13361-3050-AE-08
- PETsys TOFPET2 ASIC read-out

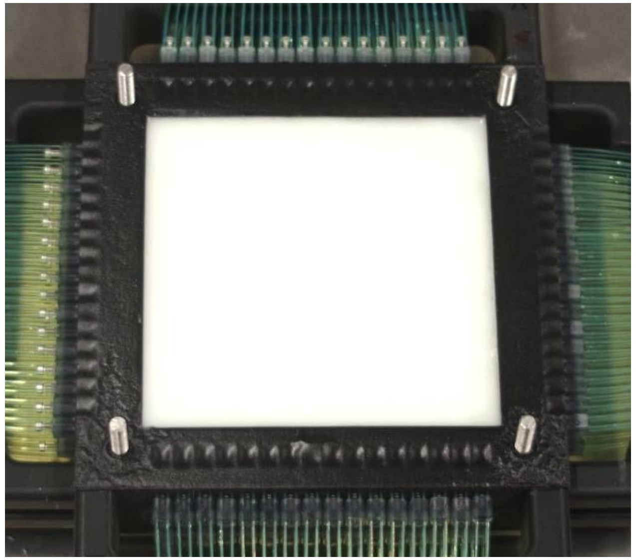


SUSSEX TILE LIQUIDO DETECTOR

LAB-based
transparent scintillator

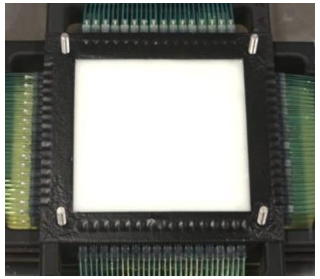


LAB + wax (NoWaSH)
opaque scintillator

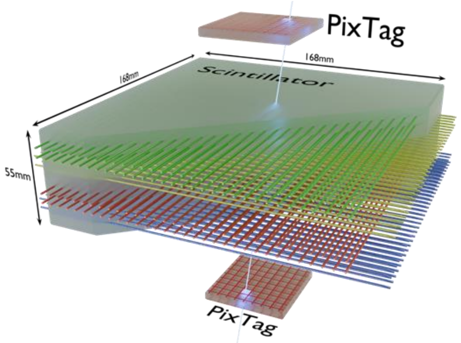


C. Buck et al., J. Instrum. 14 (2019) P11007.
https://doi.org/10.48550/arXiv.1908.03334

- Opaque scintillator (NoWaSH)
  - LAB + PPO + POPOP
  - ~ 10% wt wax
  - Scattering length ~ 0.5 mm
- Transparent liquid scintillator
  - LAB + PPO + POPOP
  - Scattering length >> 1 mm
  - Absorption length >> 1 m
  - Light yield 10000 ph/MeV



OPAQUE



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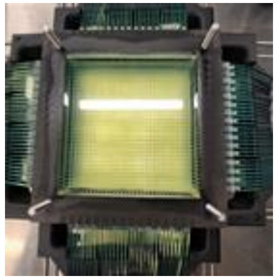

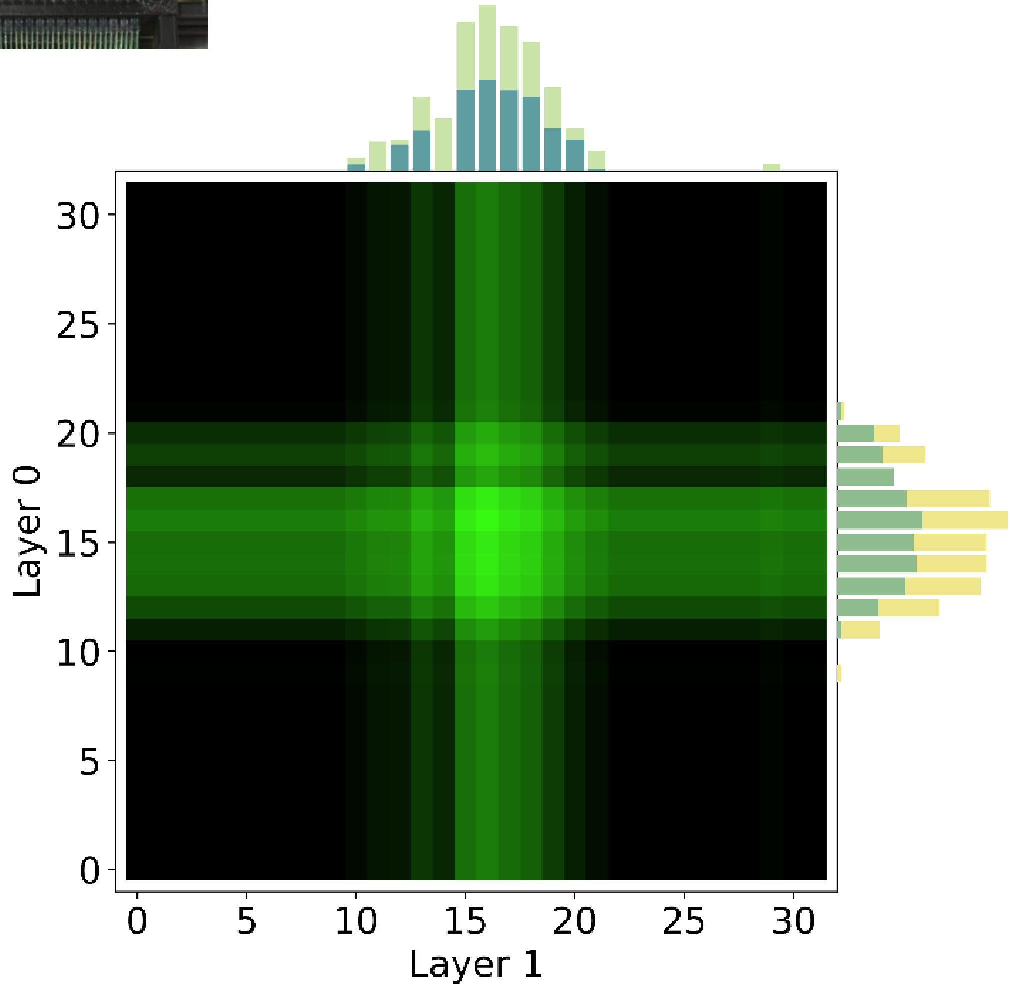

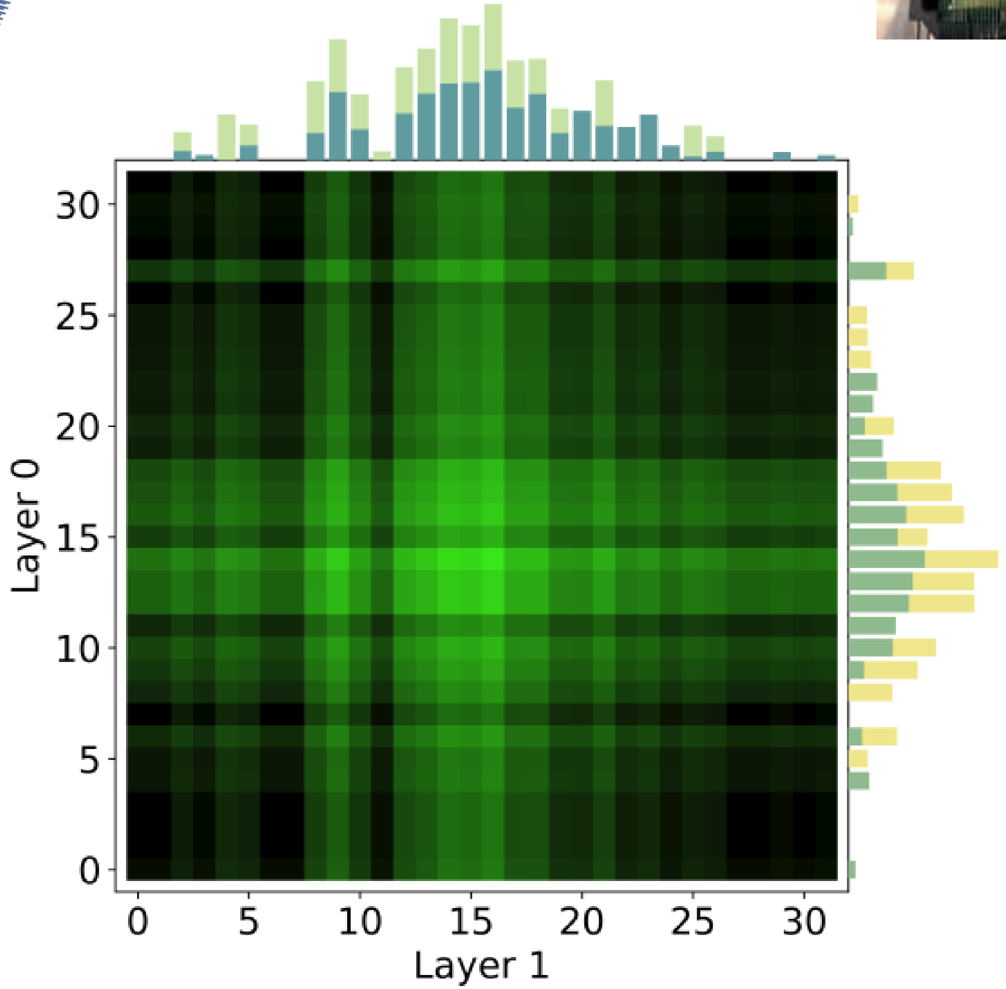

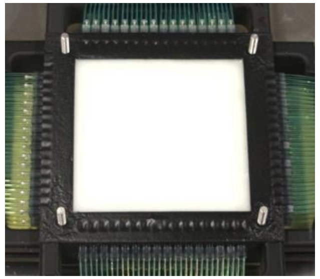

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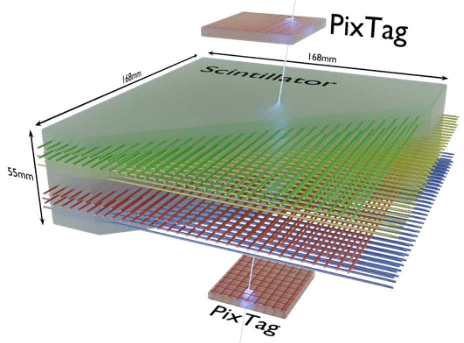

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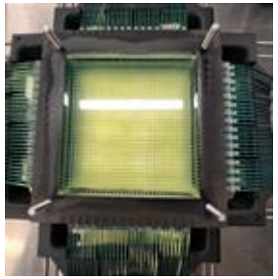
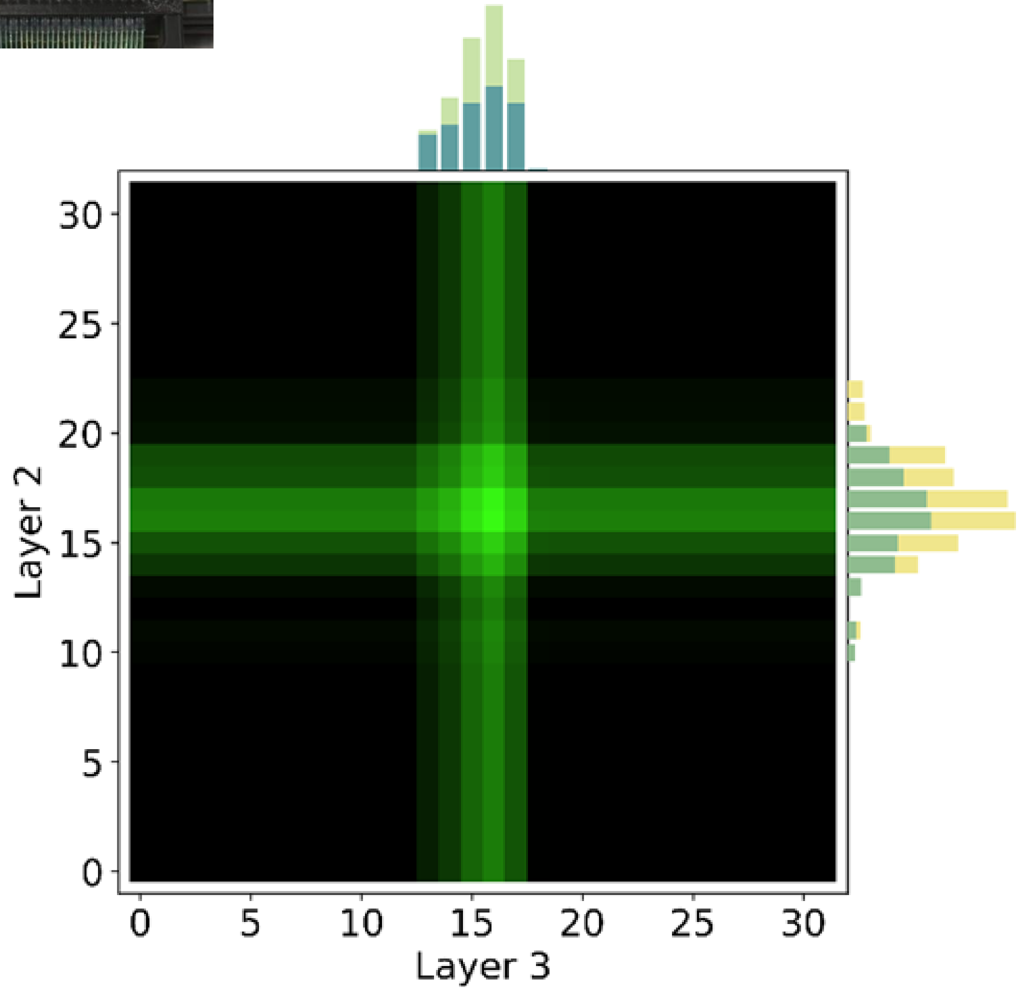
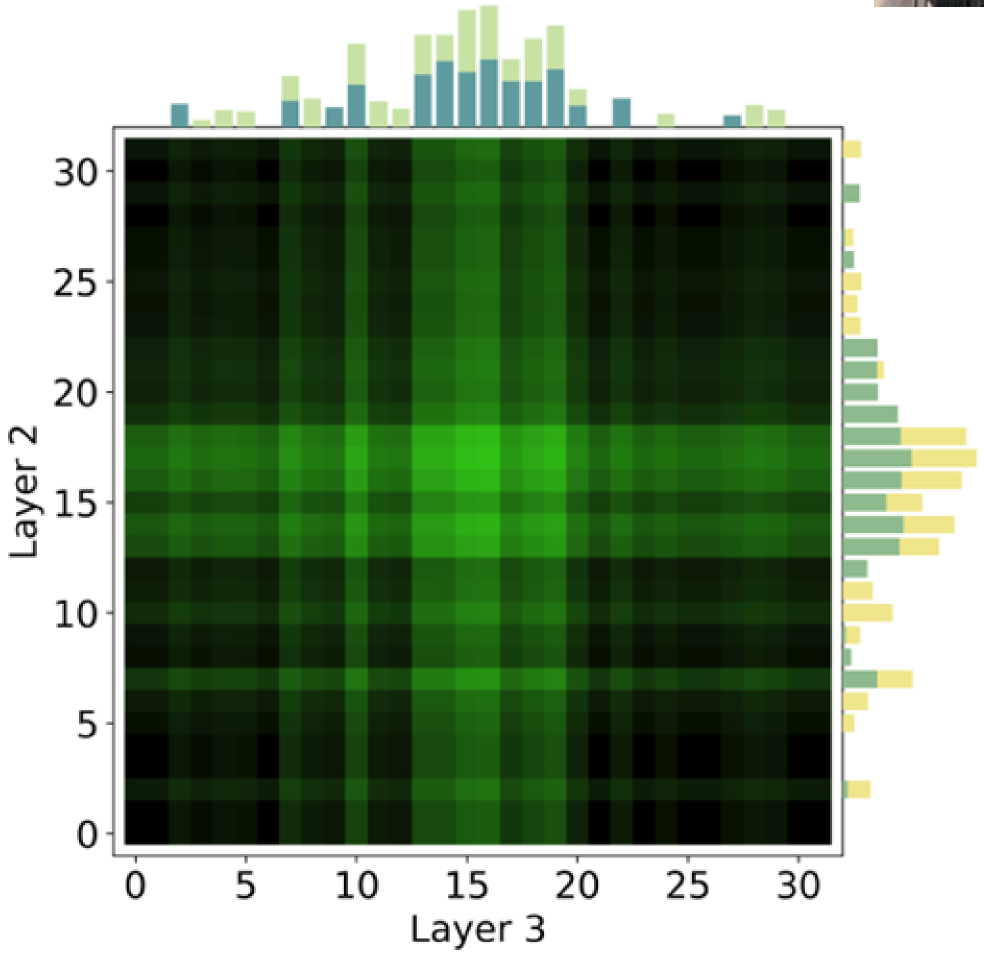
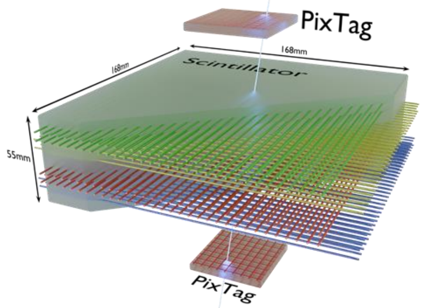




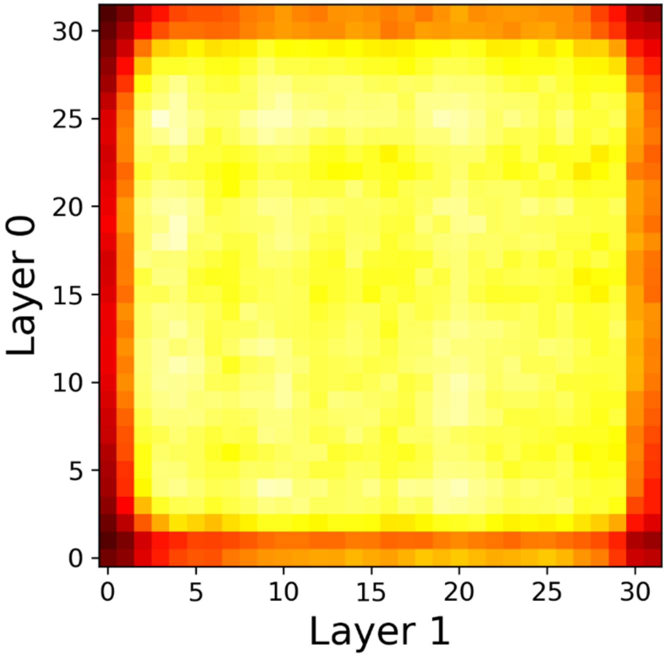


SUSSEX TILE (PRELIMINARY) RESULTS

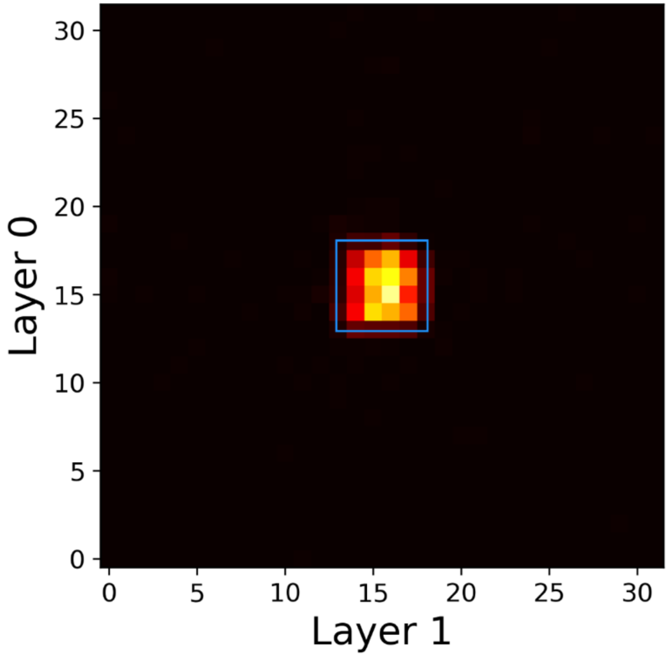


First, qualitative demonstration of position reconstruction

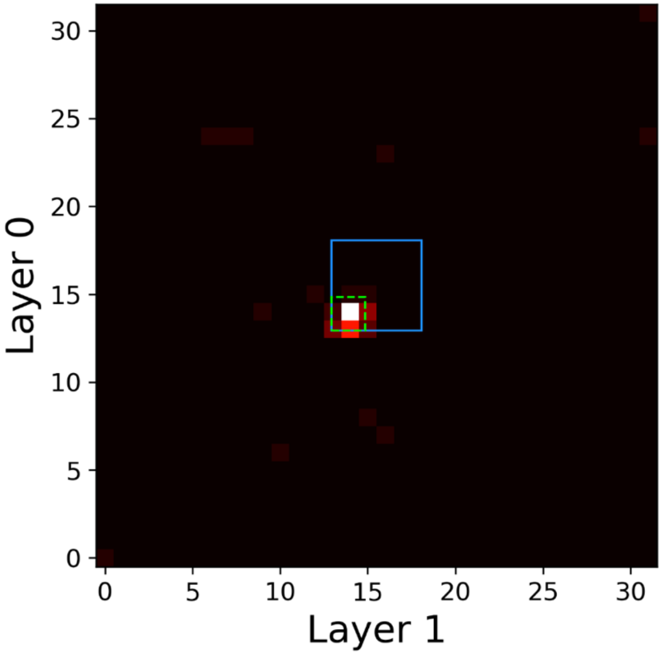
1. all through-going muons (> 10k / hour)



2. muons going through external 3x3 cm^2 taggers

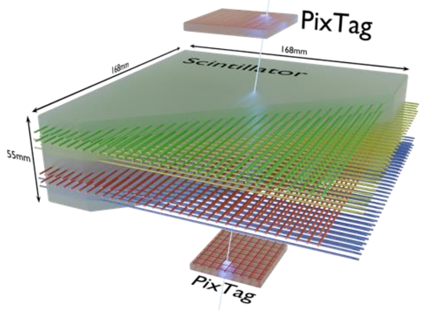


3. muons going through a 9x9 mm^2 area of the taggers



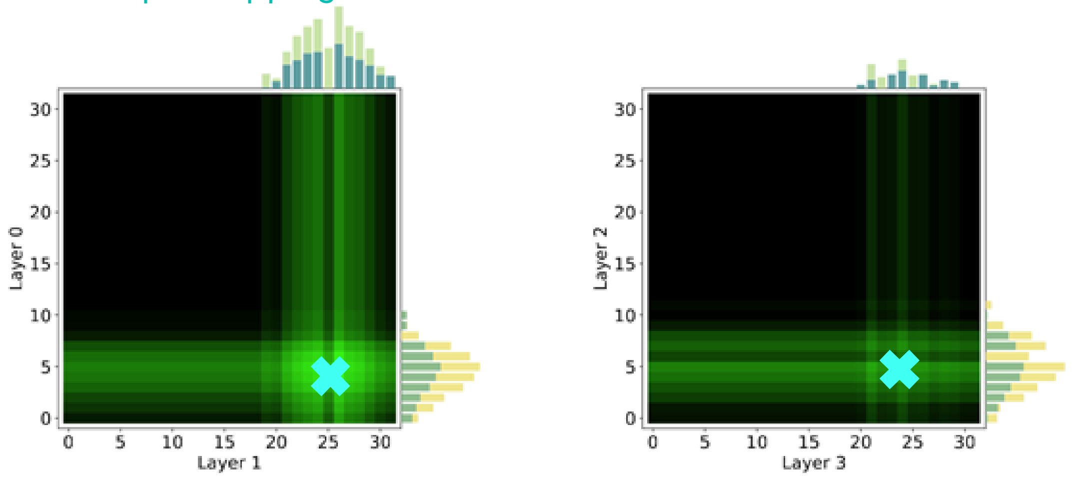
More quantitative results to come!

SUSSEX TILE (PRELIMINARY) RESULTS



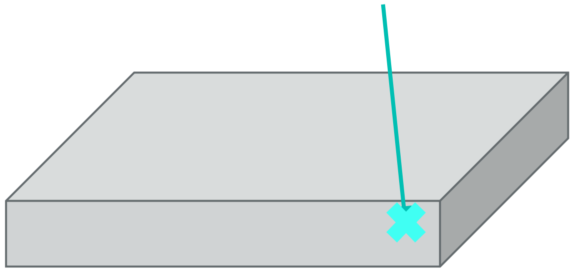
Observation of stopping muons and Michel electrons

Prompt: stopping muon



Top 2 layers of fibres

Bottom 2 layers of fibres



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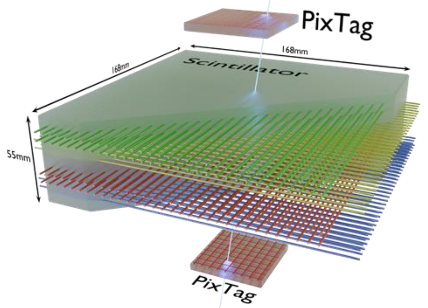

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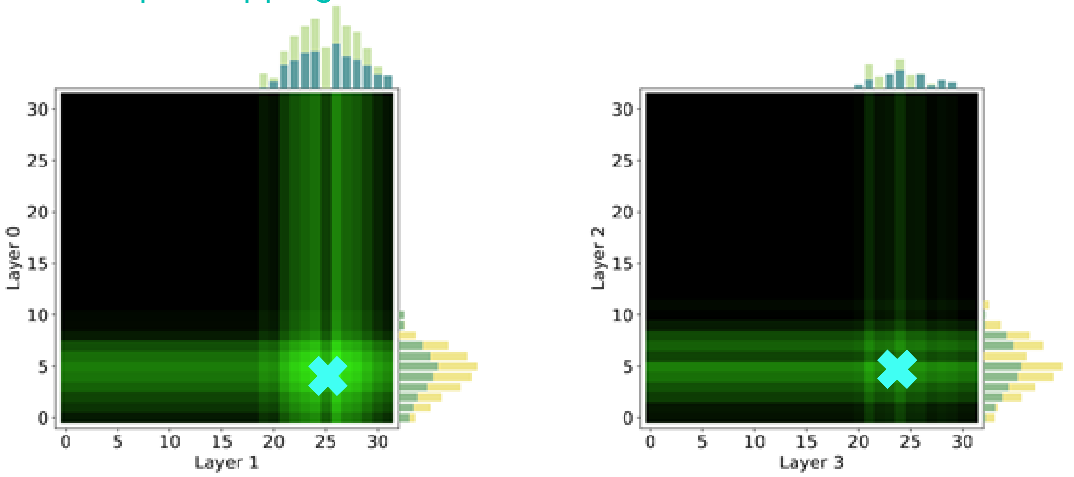
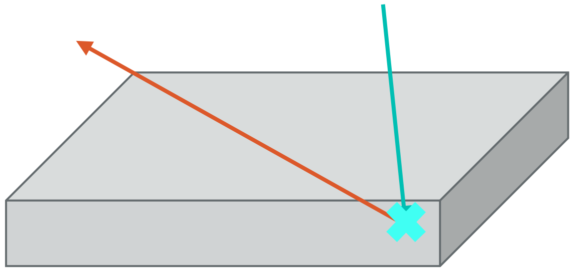


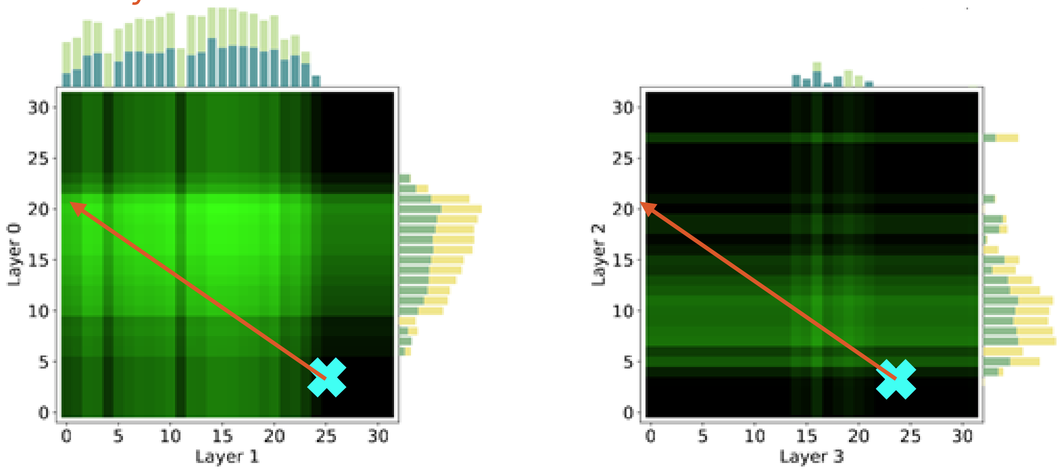
Top 2 layers of fibres

Bottom 2 layers of fibres

0.79 µs later



Delayed: Michel electron



Top 2 layers of fibres

Bottom 2 layers of fibres

- Innovative new LiquidO detector technology
  - Opaque scintillator + lattice of wavelength-shifting fibres
- R&D progressing rapidly
- For applications requiring precise radiation position reconstruction
  - Potential for muon tomography!
- Whole new way of thinking about a scintillator detector
  - We’ve only just started… your ideas/contributions welcome!

UNIVERSITY OF SUSSEX

THANK YOU

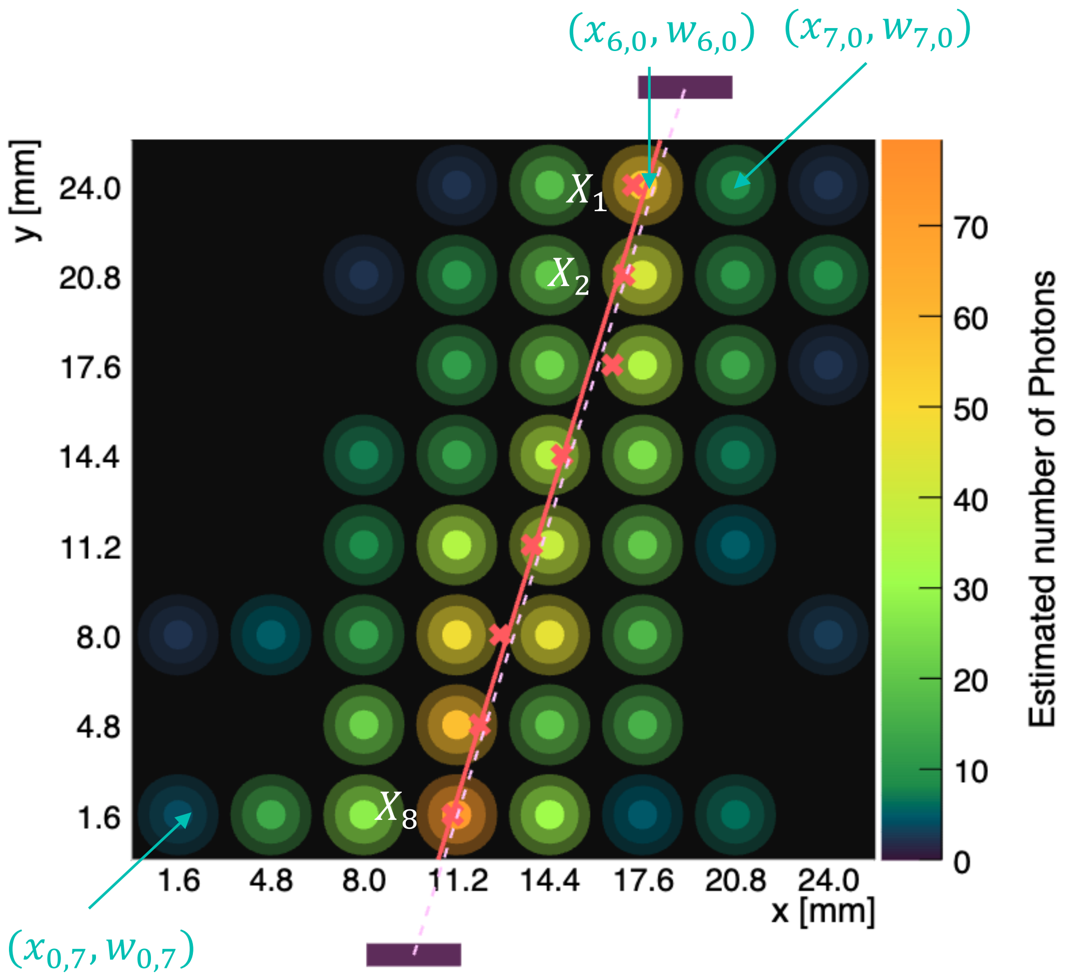
n.tuccori@sussex.ac.uk

European Innovation Council

UK Research and Innovation

BACK-UP

POSITION RESOLUTION: HOW TO



POSITION RESOLUTION

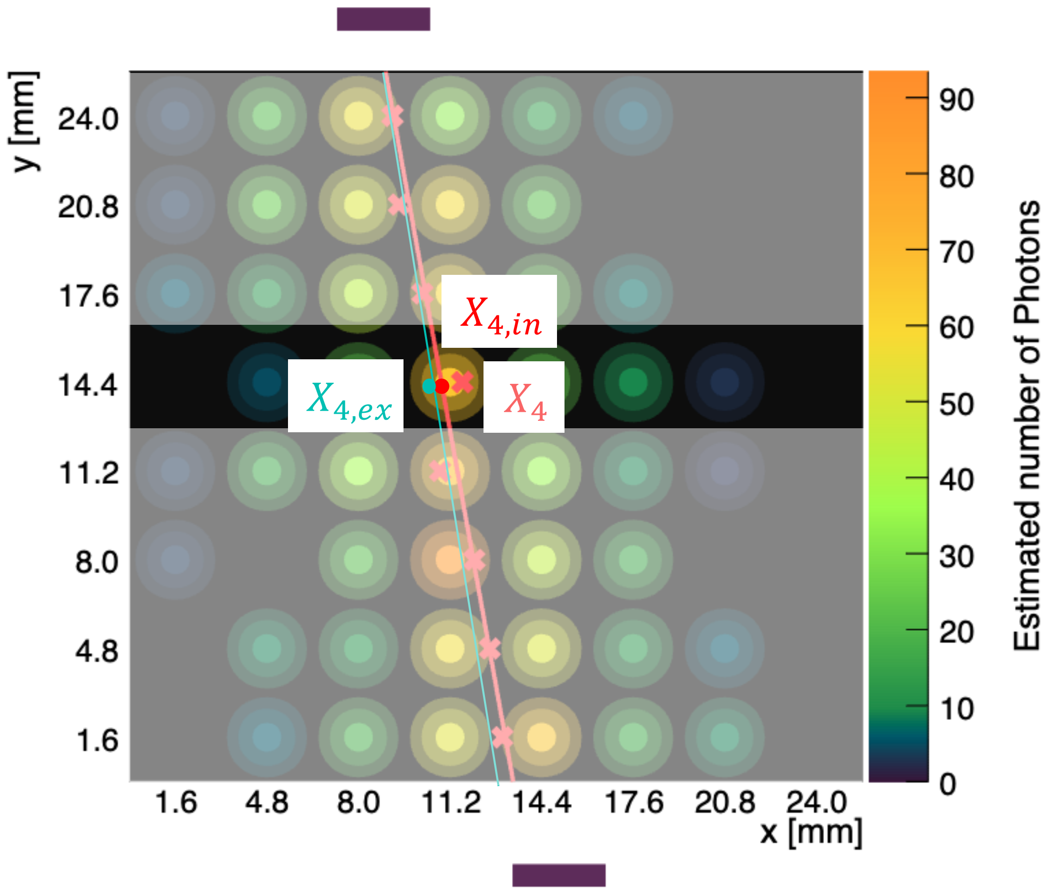
= capability of ONE ROW of LiquidO-detector fibres to reconstruct the position of the traversing particle

RECONSTRUCTED POSITION FOR EACH ROW OF FIBRES

Weighted average X_r of the "measured light" $w_{c,r}$ in each fibre of one row

$$X_r = \frac{\sum_c w_{c,r} * x_{c,r}}{\sum_c w_{c,r}}$$

POSITION RESOLUTION: HOW TO



HOW TO MEASURE THE POSITION RESOLUTION?

Standard data-driven approach used in literature[4,5,6].

1. Track residuals are calculated twice: with the test row reconstructed position excluded ($X_{r,ex}$) and included ($X_{r,in}$) from the track fit.

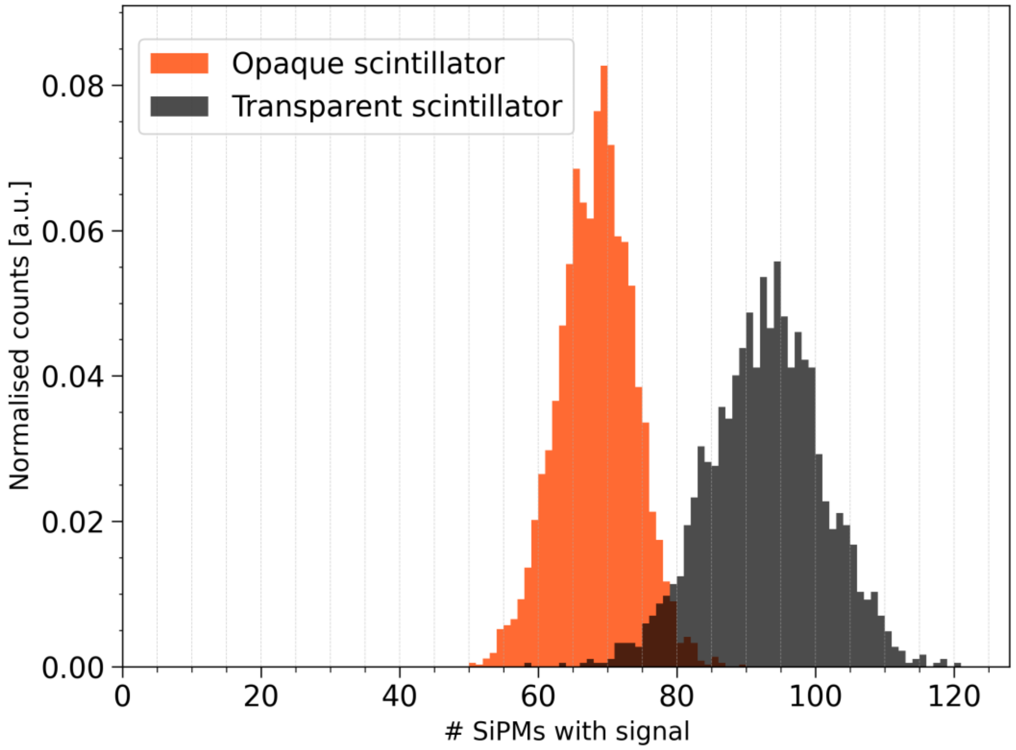
2. This yields two residual distributions: one biased lower (included) and one biased higher (excluded).

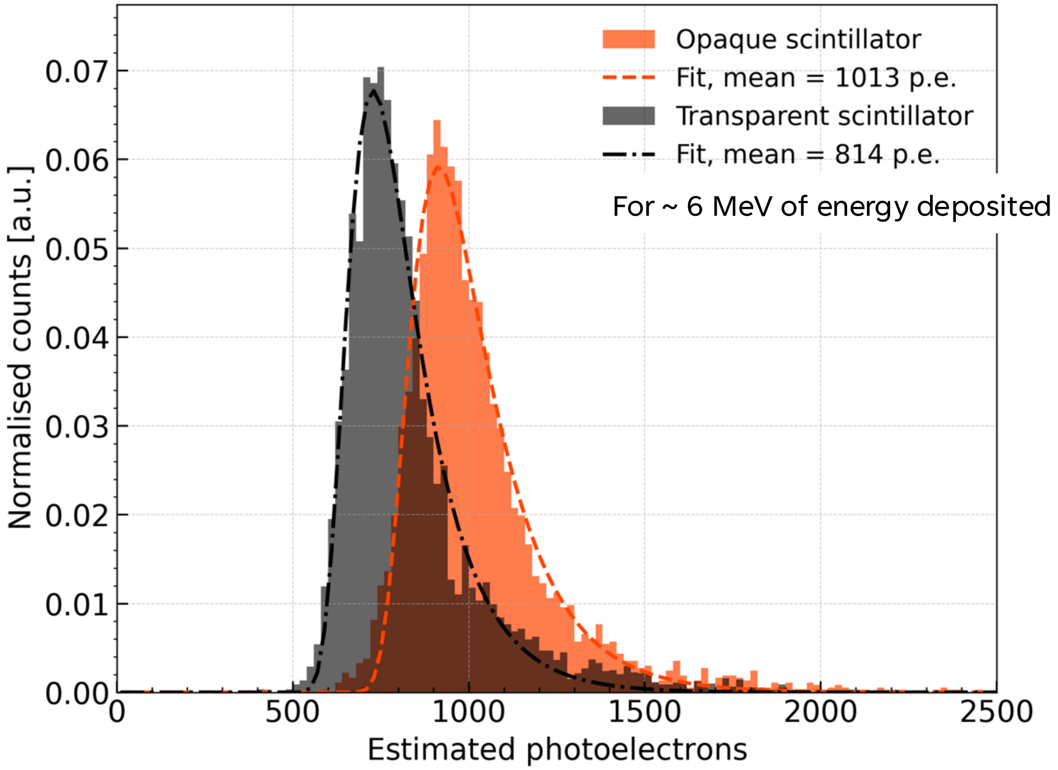
3. The intrinsic resolution is determined by taking the geometric mean of the standard deviation of these two distributions, providing an unbiased estimate.

[4] R.K. Carnegie et al., Nucl. Instrum. Methods A 538 (2005) 372-83. https://doi.org/10.1016/j.nima.2004.08.132
[5] T. Alexopoulos et al., J. Instrum. 9 (2014) P01003. https://doi.org/10.1088/1748-0221/9/01/P01003
[6] V. Anghel et al., Nucl. Instrum. Methods A 798 (2015) 12-23. https://doi.org/10.1016/j.nima.2015.06.054

“LIQUIDO EFFECT” IN THE SUSSEX CUBE

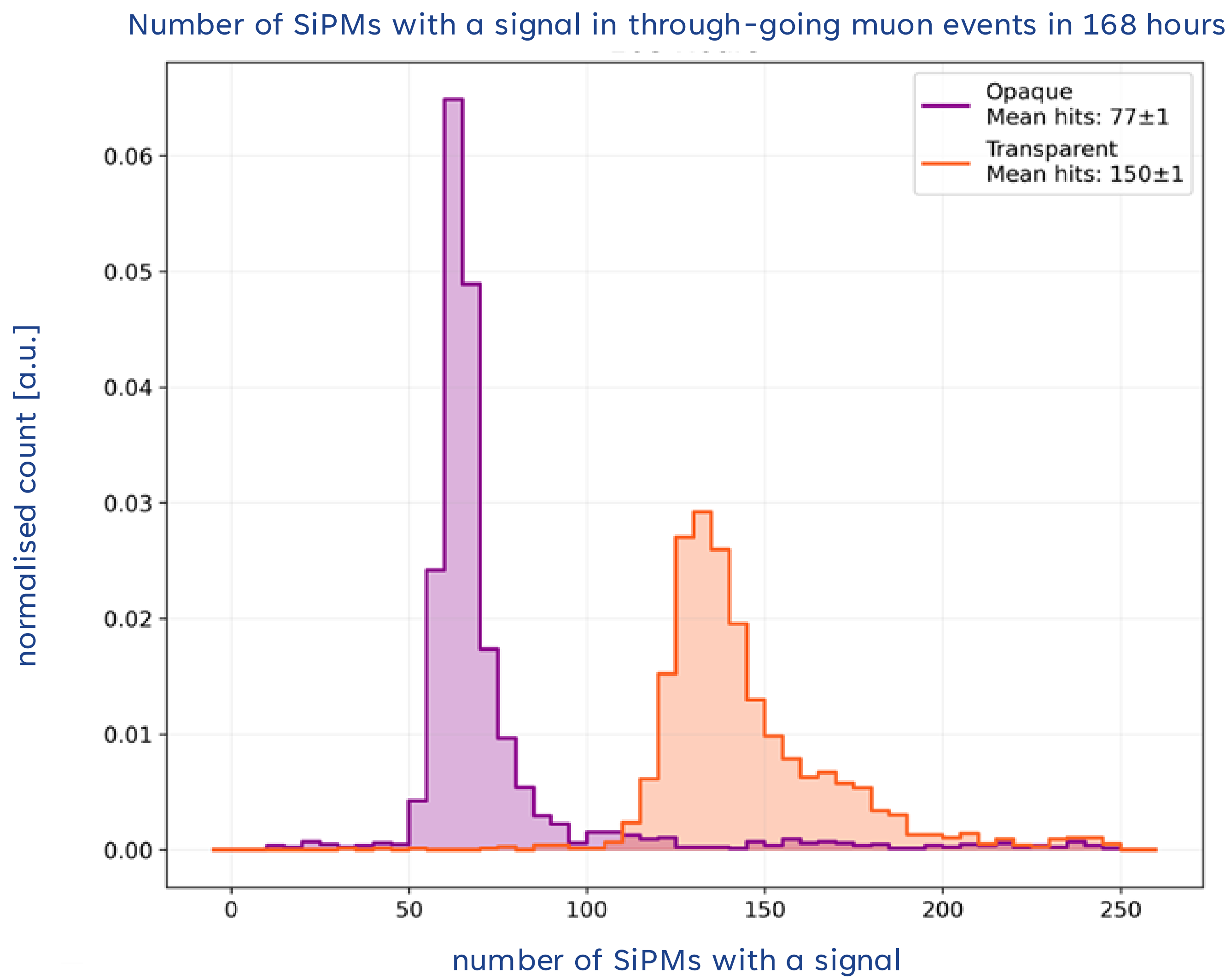
In the opaque case,
Fewer SiPMs have a signal during a muon event
And light collection is enhanced

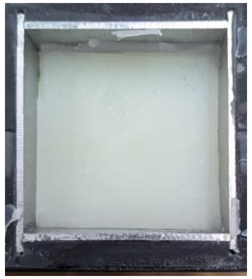




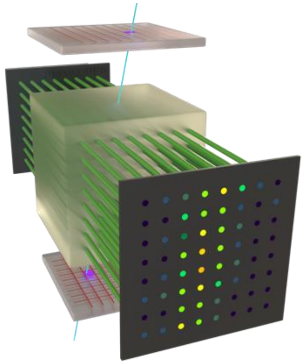
https://doi.org/10.1088/1748-0221/21/01/P01010

“LIQUIDO EFFECT” IN THE SUSSEX TILE

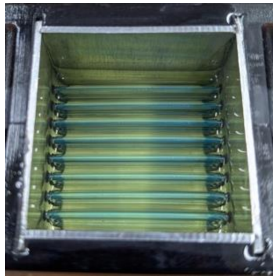


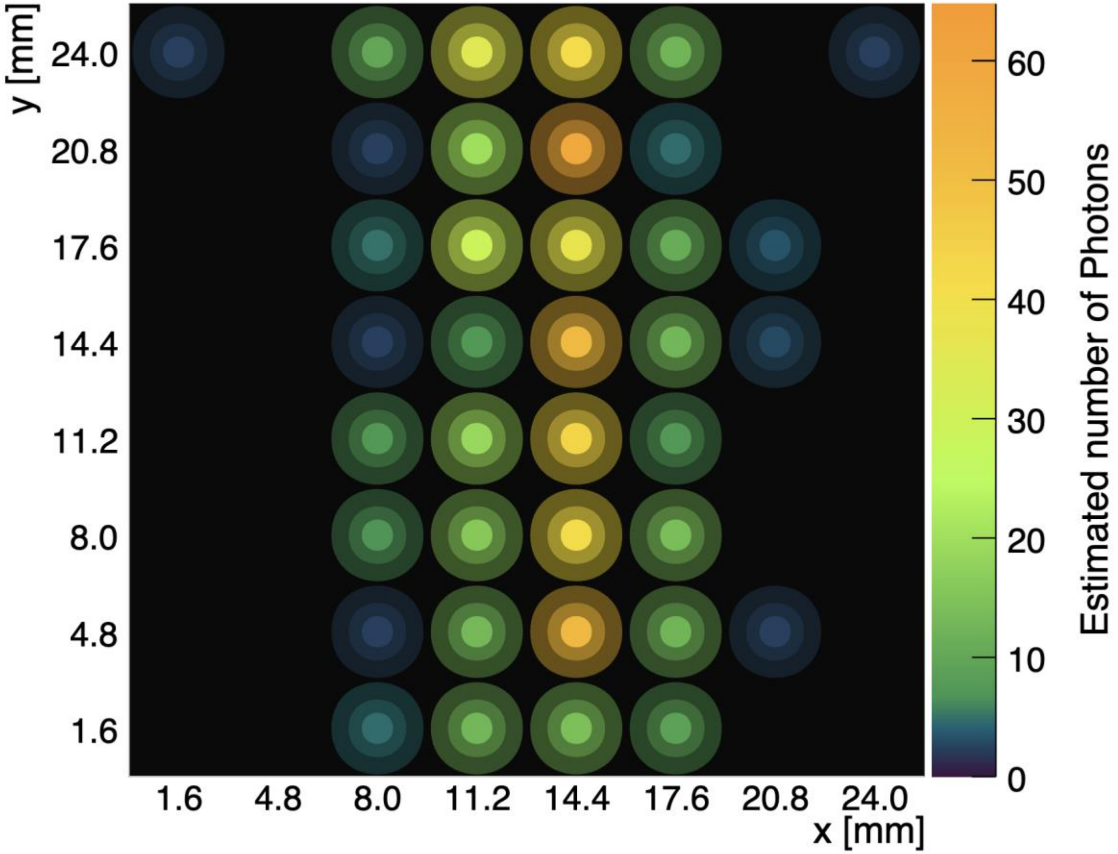


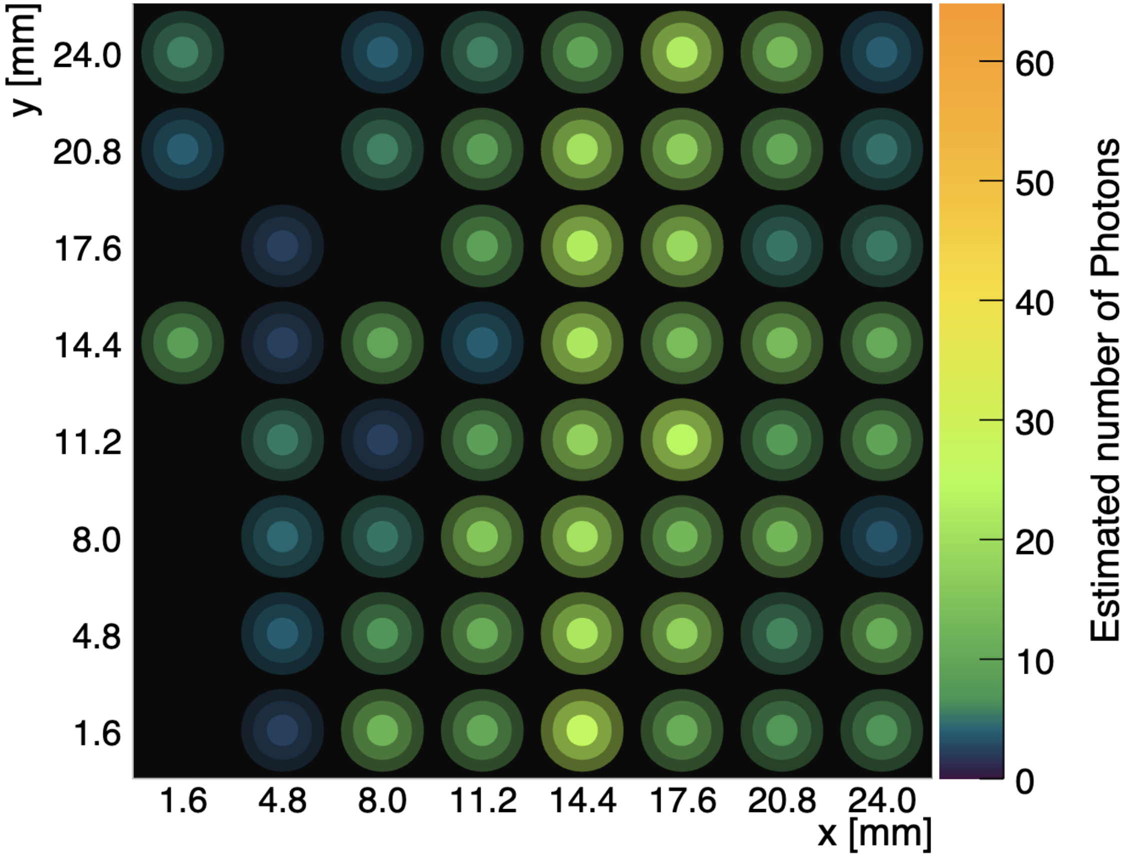
OPAQUE

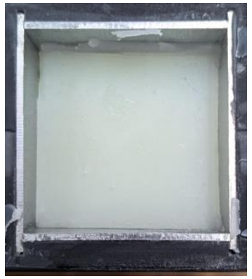


TRANSPARENT

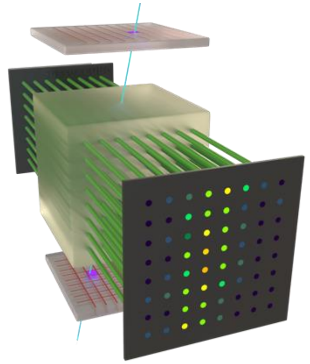




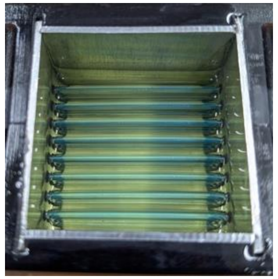




OPAQUE



TRANSPARENT



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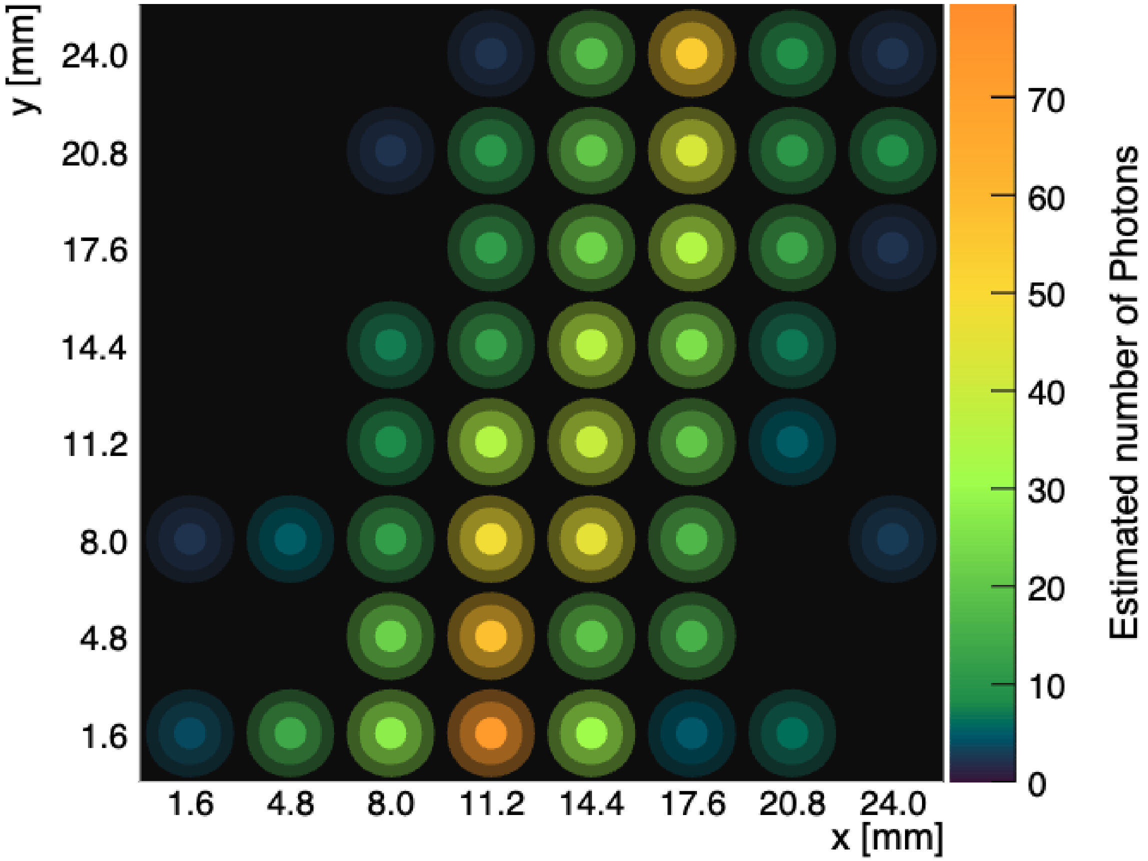

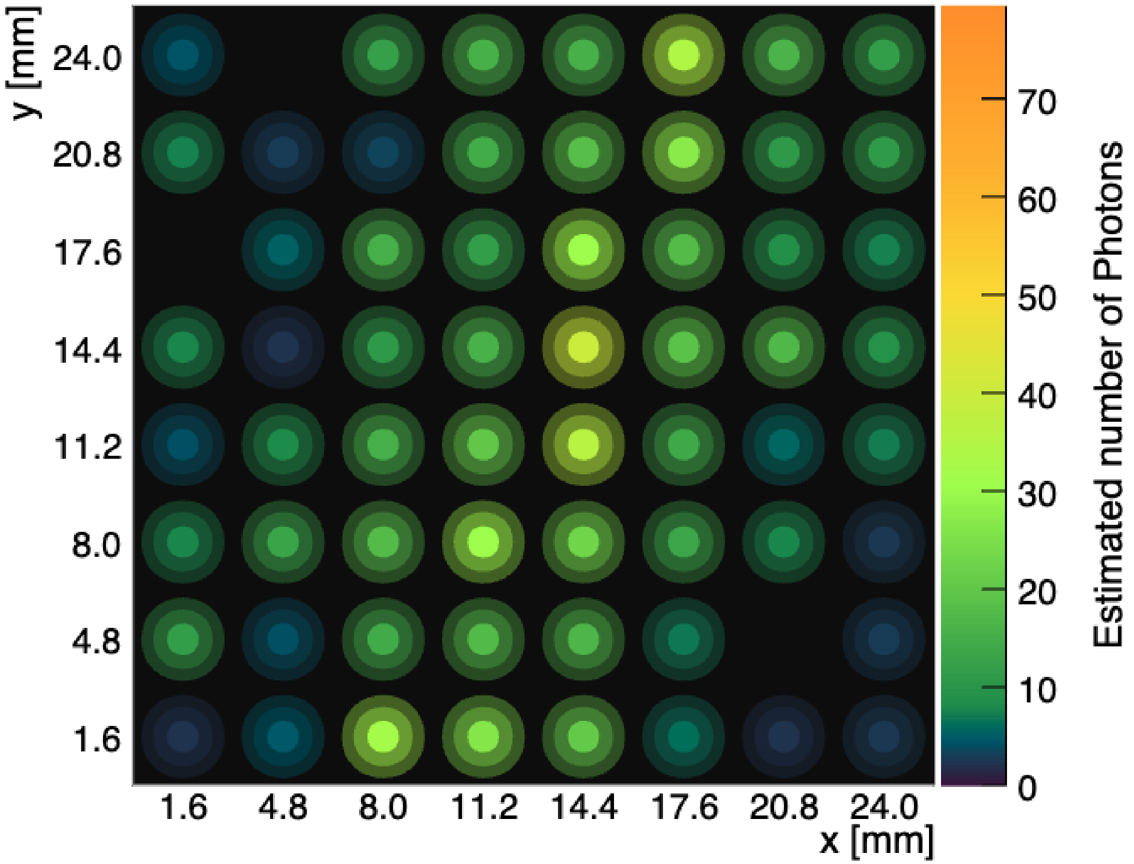

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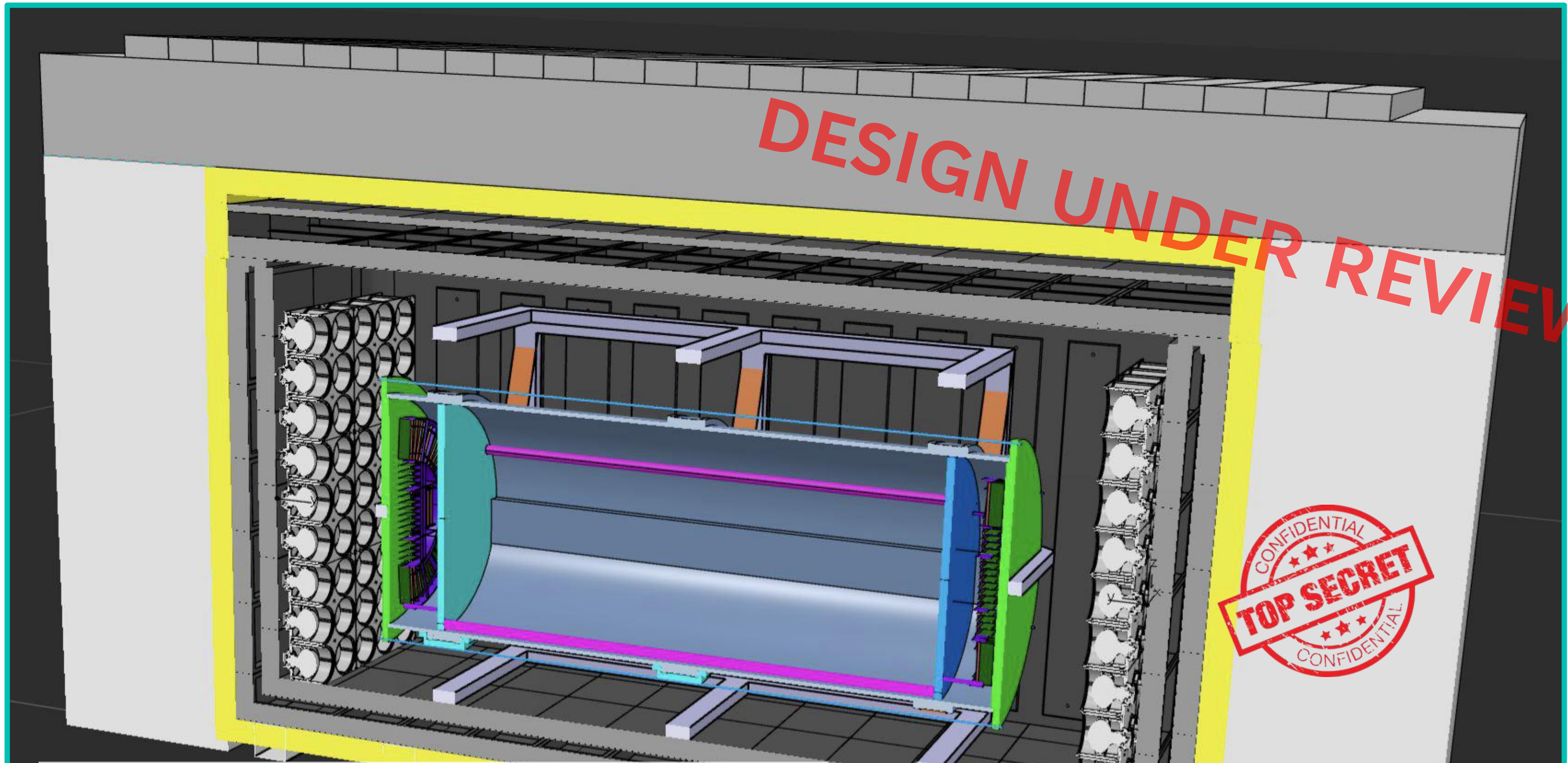
CLOUD: LIQUIDO FOR ANTI-NEUTRINO DETECTION



5-10 tons **LiquidO** Inner Detector
10,000 WLS fibres + SiPMs dual read-out
1.8 m diameter, >200 PE/MeV design

https://antimatter-otech.ijclab.in2p3.fr/