



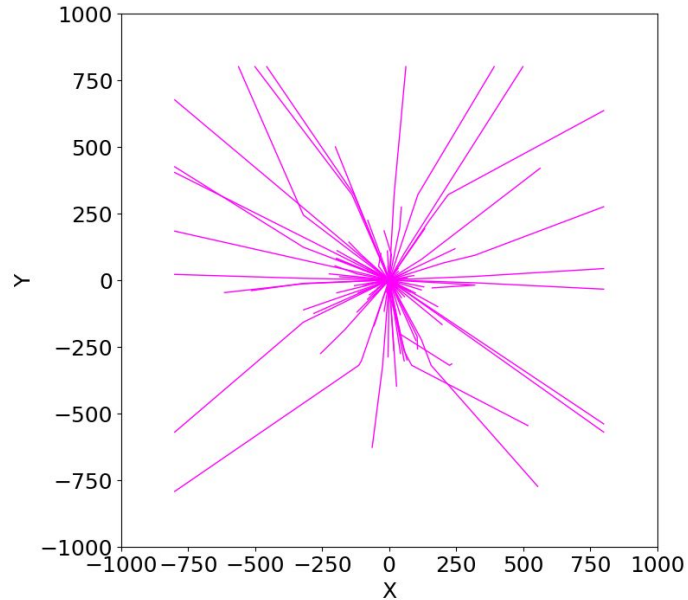
# Muon Tracking in an Opaque Detector

Jessica Lock on behalf of the  
LiquidO Consortium

For the IOP Joint APP and HEPP  
Annual Conference 2025

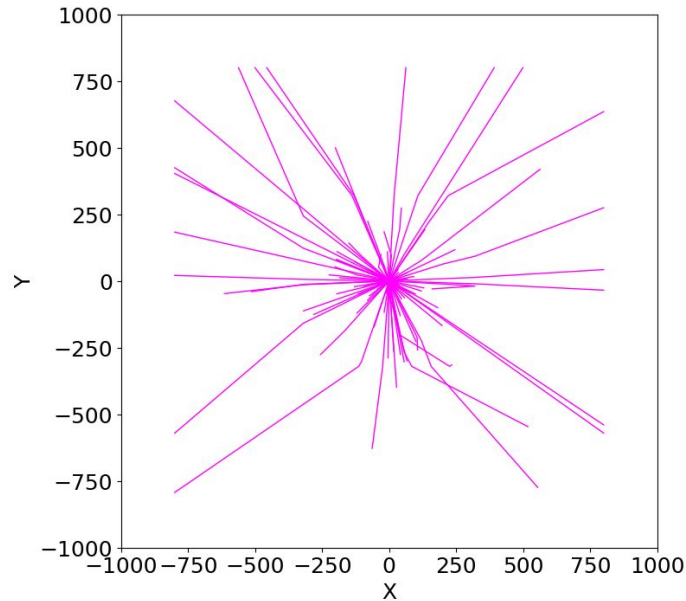
# LiquidO Technology

Light in traditional transparent detectors travels in straight lines to photodetectors.

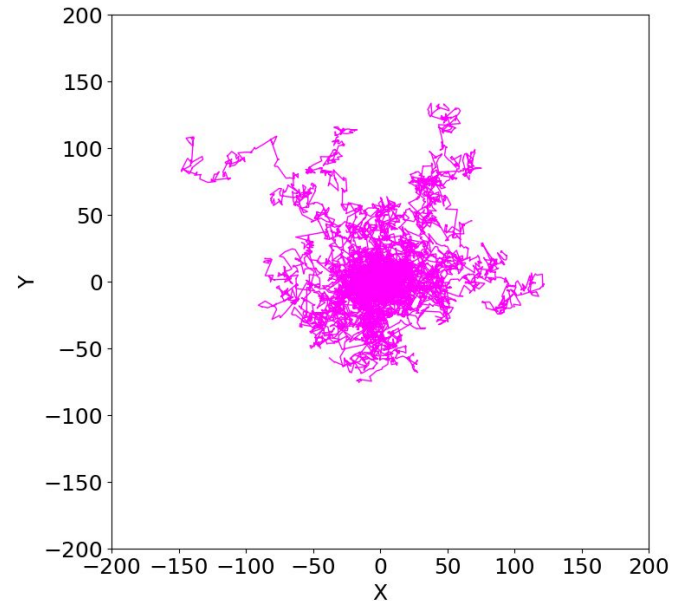


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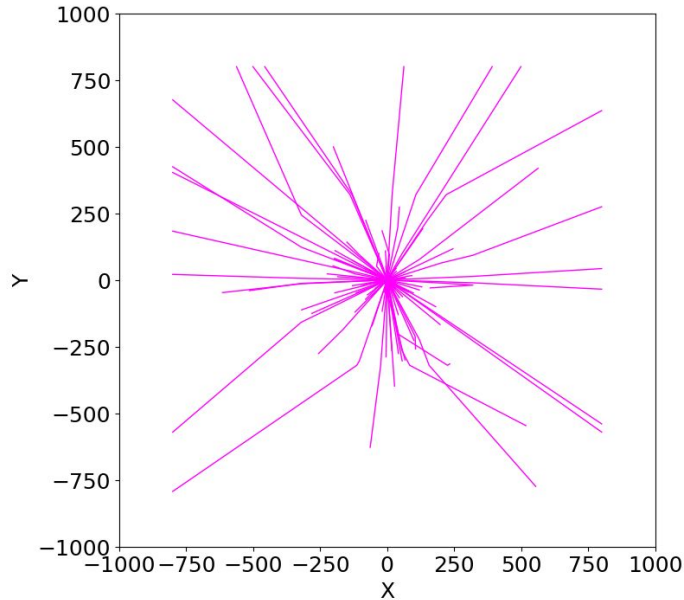


LiquidO detectors use **opacity** to scatter light, which is then picked up by arrays of fibres.



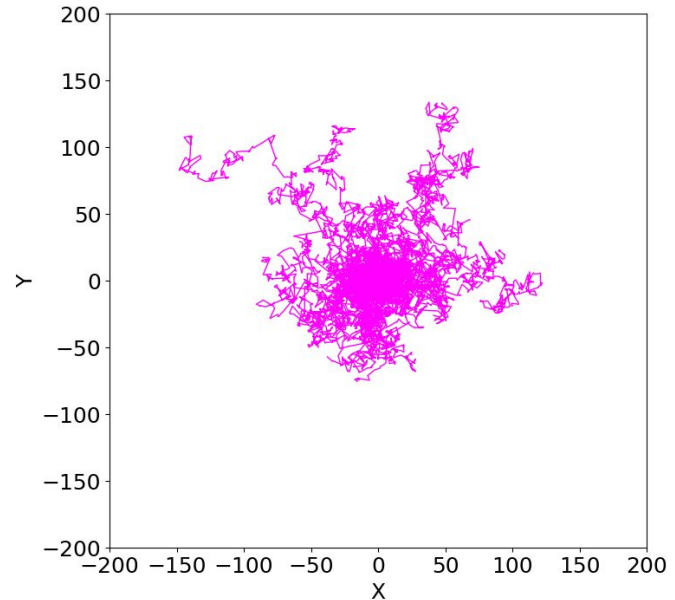
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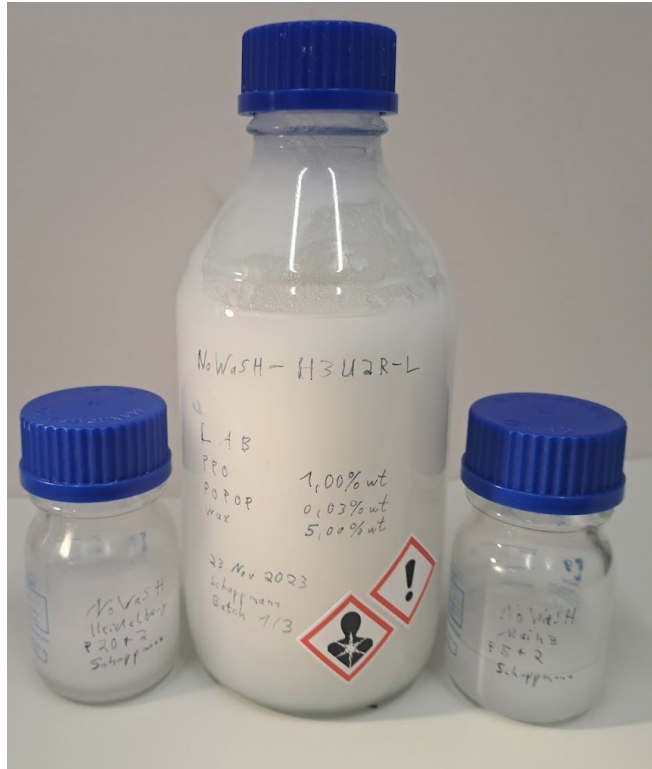


- Short scattering length
- Long absorption length

LiquidO detectors use **opacity** to scatter light, which is then picked up by arrays of fibres.

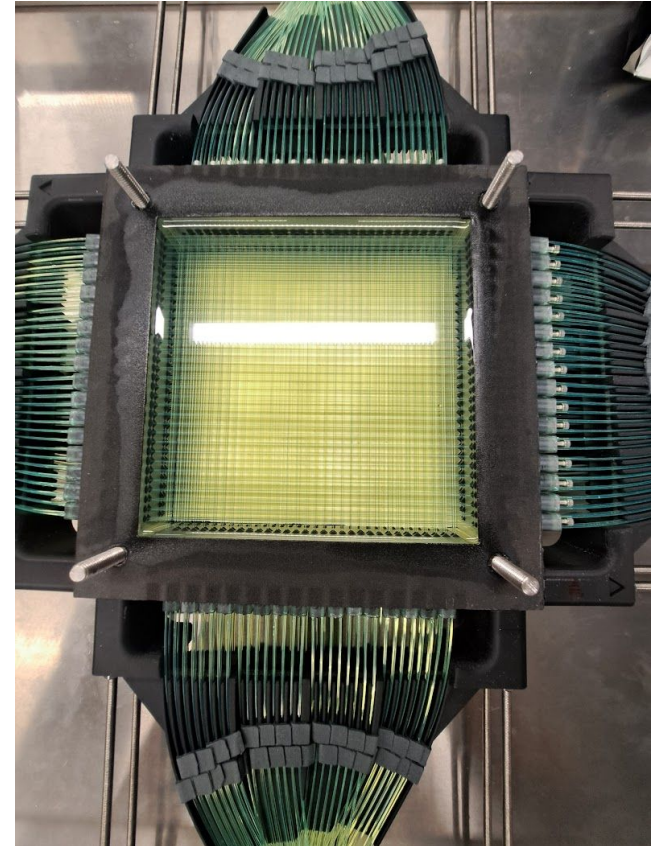


# LiquidO Technology



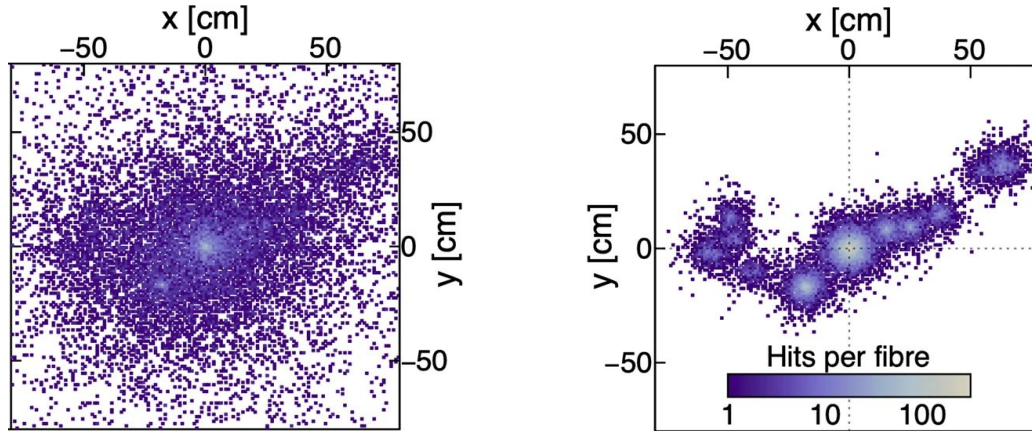
Our prototypes use **opaque scintillator** with **wavelength-shifting fibres**.

Opacity creates a self-segmented detector. The optical fibres collect the produced light.



# LiquidO Technology

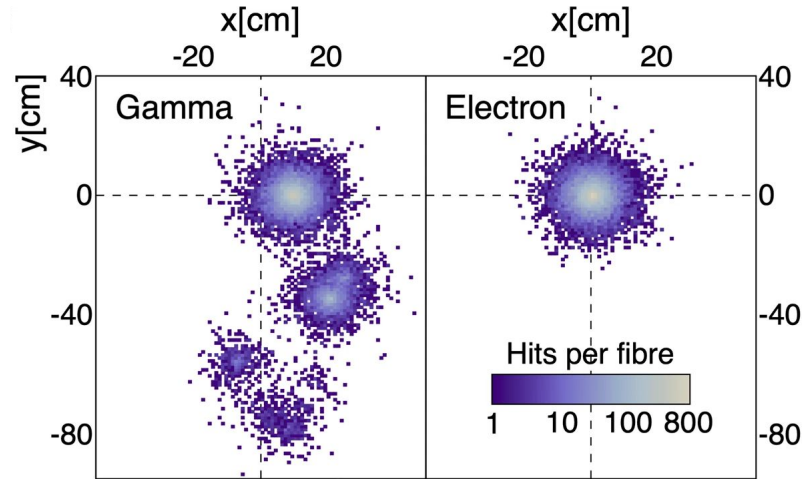
LiquidO has unique particle identification capabilities through the **stochastic confinement of light**.



1 MeV positron annihilation in  
**transparent (left)** and **opaque (right)** scintillator

# LiquidO Technology

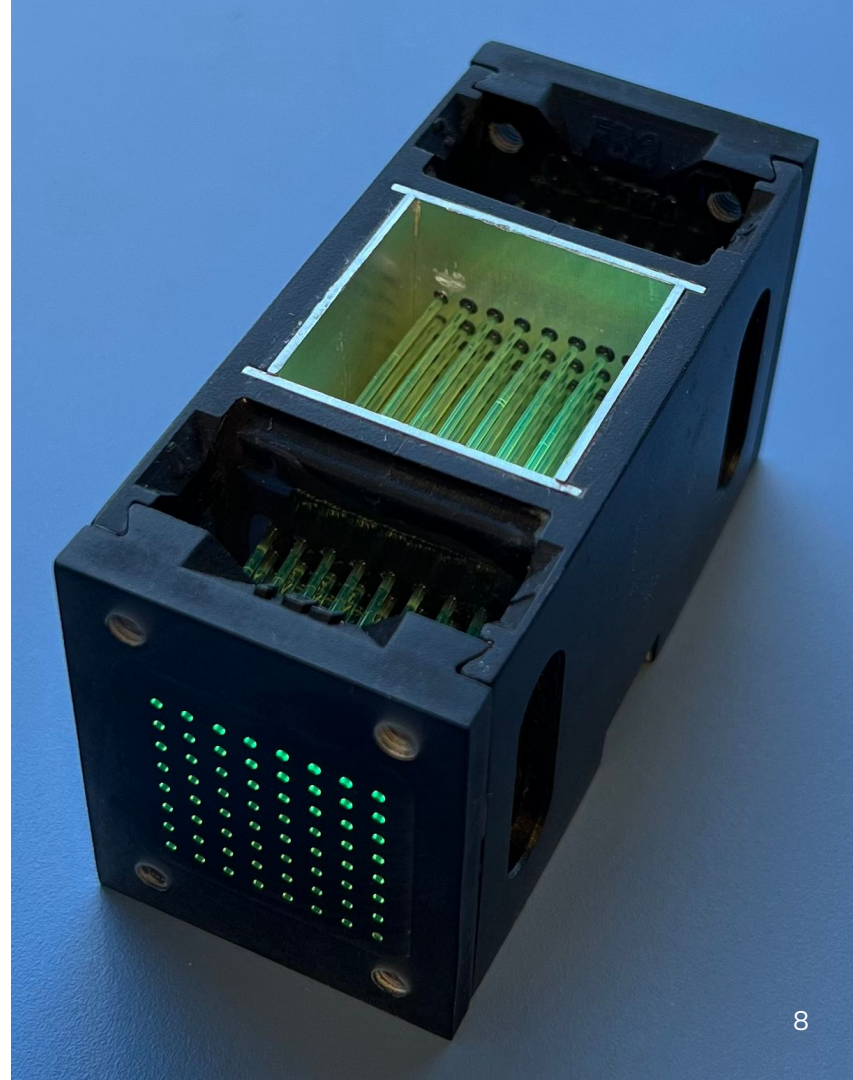
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2 MeV kinetic energy events

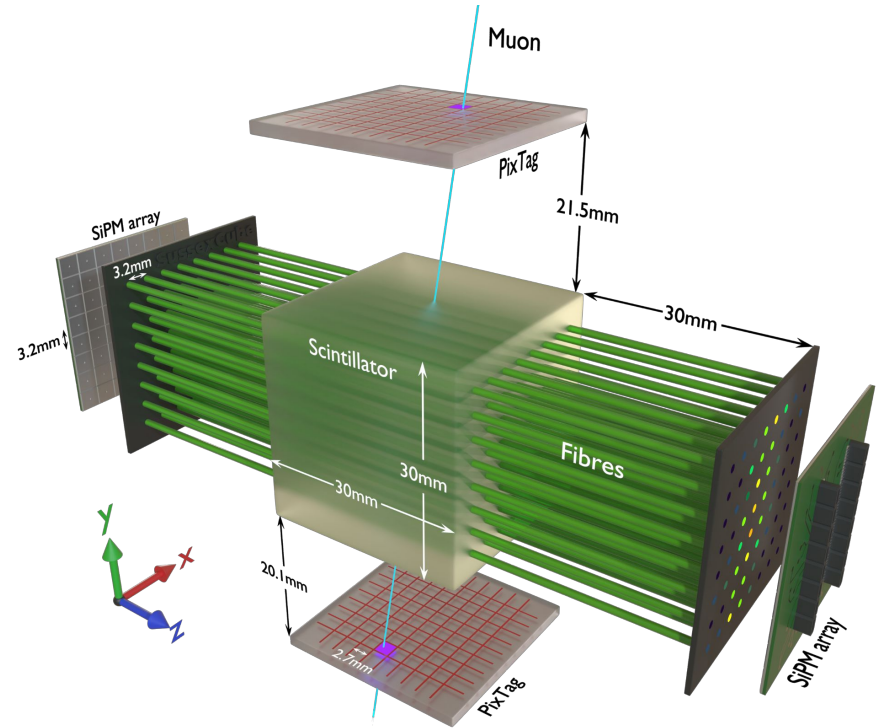
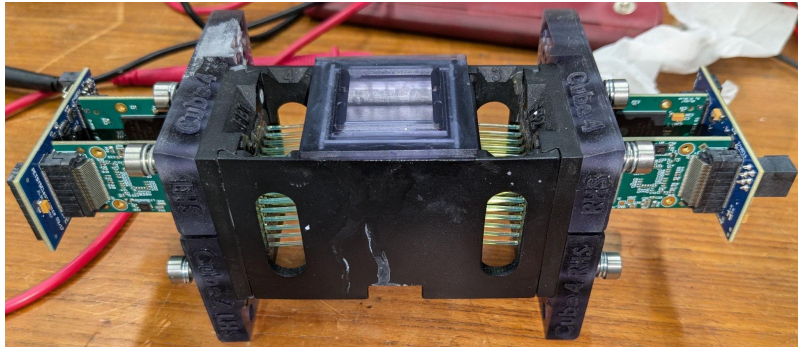
# LiquidO-Cube Prototype

- Small prototype (~25ml)
- 3D-printed resin skeleton
- Aluminium internal reflector plates
- 64 wavelength-shifting St. Gobain BCF-91A fibres with 3.2 mm pitch



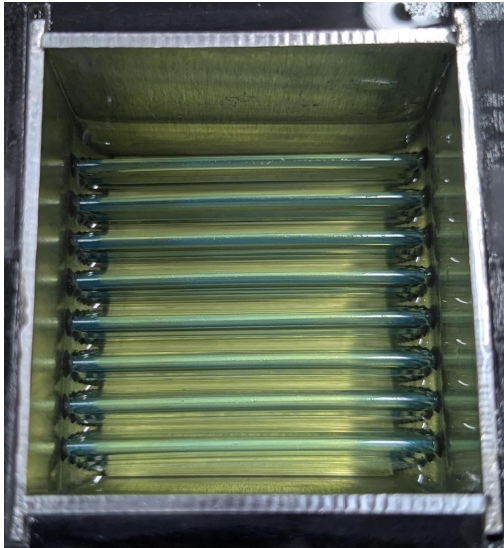
# LiquidO-Cube Prototype

- Dual end readout using 8x8 Hamamatsu S13361-3050-AE-0 SiPM arrays
- PETsys TOFPET2 ASIC read-out
- Pixelated muon taggers (64 pixels, same SiPM readout)

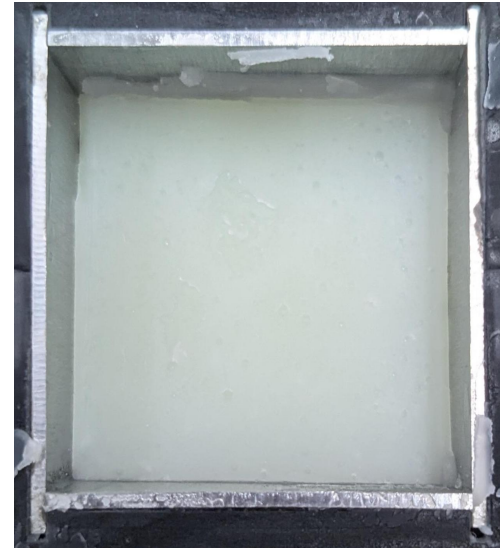


# LiquidO-Cube Scintillator

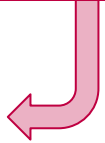
**Transparent**  
LAB + PPO + POPOP



**Opaque (“NoWaSH”)**  
LAB + PPO + POPOP  
+ 15wt.% wax



Scattering length  $\sim 0.4$  mm



# Muons in LiquidO-Cube

Muons create “light cylinders”.

# Muons in LiquidO-Cube

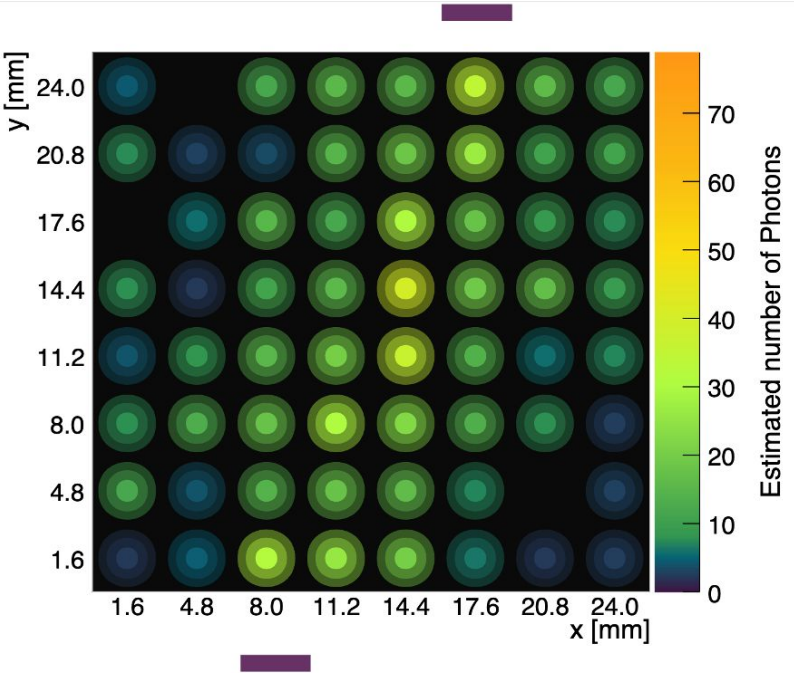
Muons create “light cylinders”.

Pixelated taggers sit above + below to select cosmic muons.

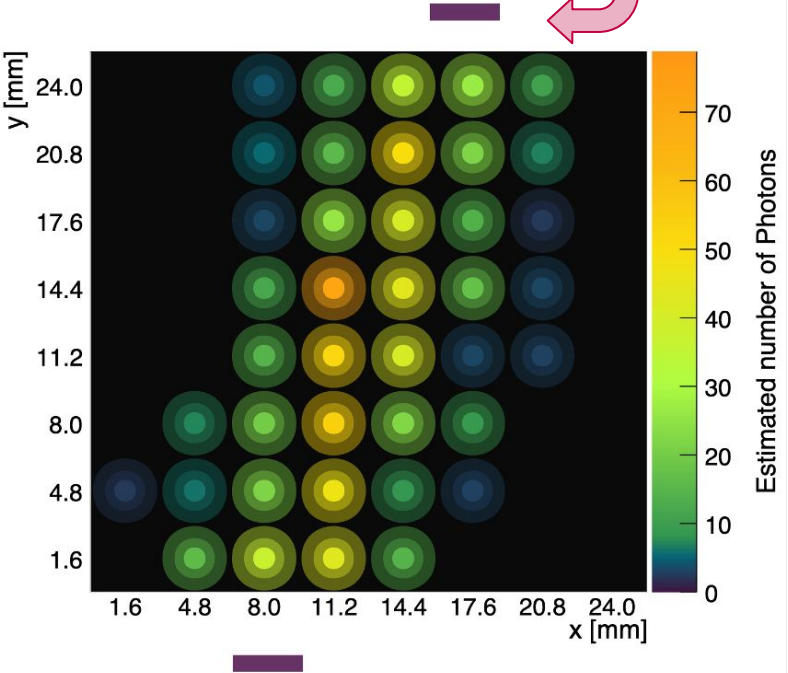
We can compare similar events seen in the cube based on the areas of the taggers the muons trigger.

# Muons in LiquidO-Cube

Transparent Scintillator

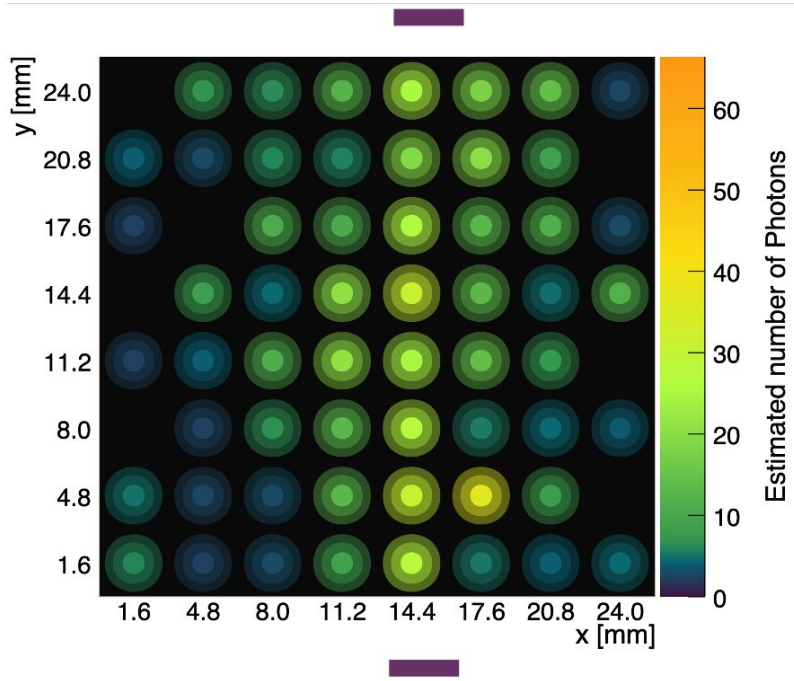


Opaque Scintillator

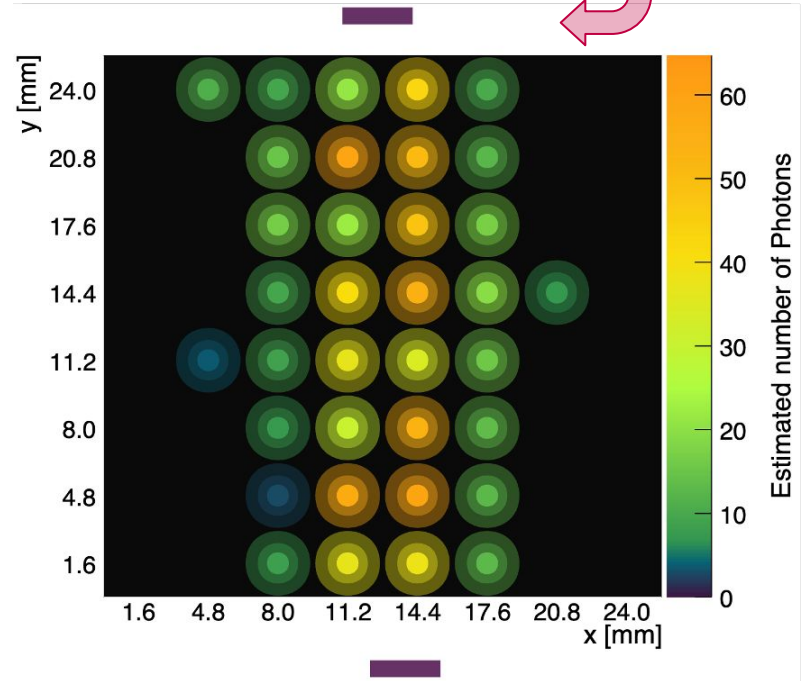


# Muons in LiquidO-Cube

Transparent Scintillator



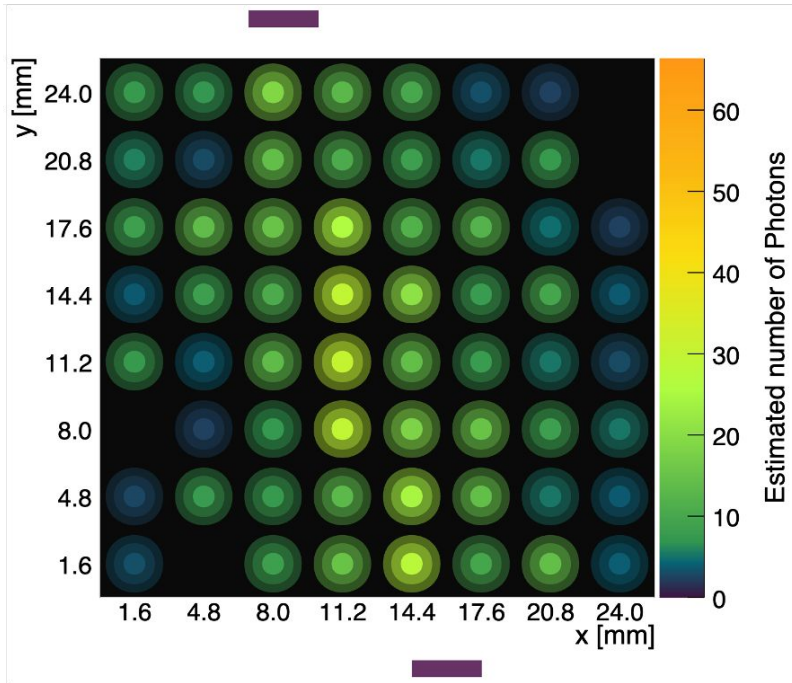
Opaque Scintillator



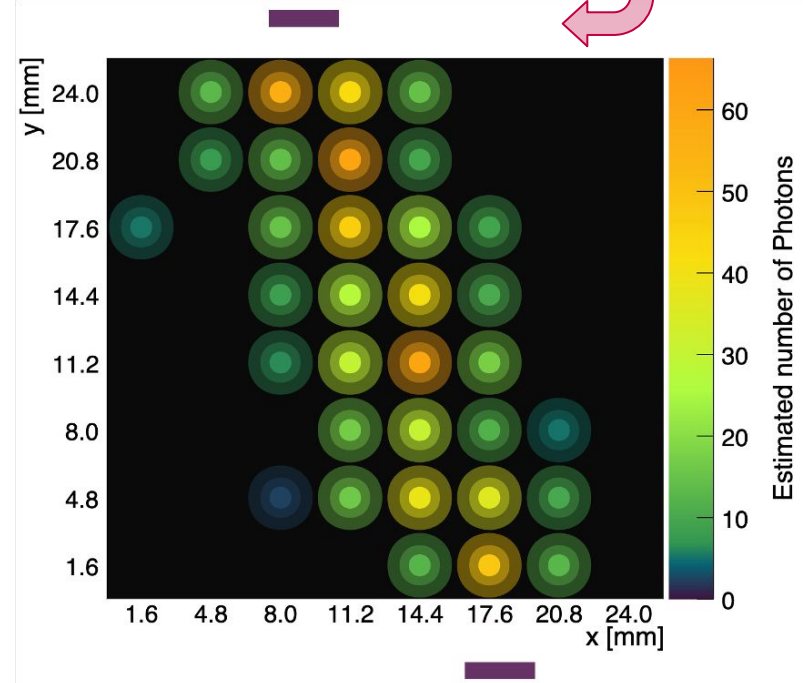
Purple bars represent tagger locations

# Muons in LiquidO-Cube

Transparent Scintillator

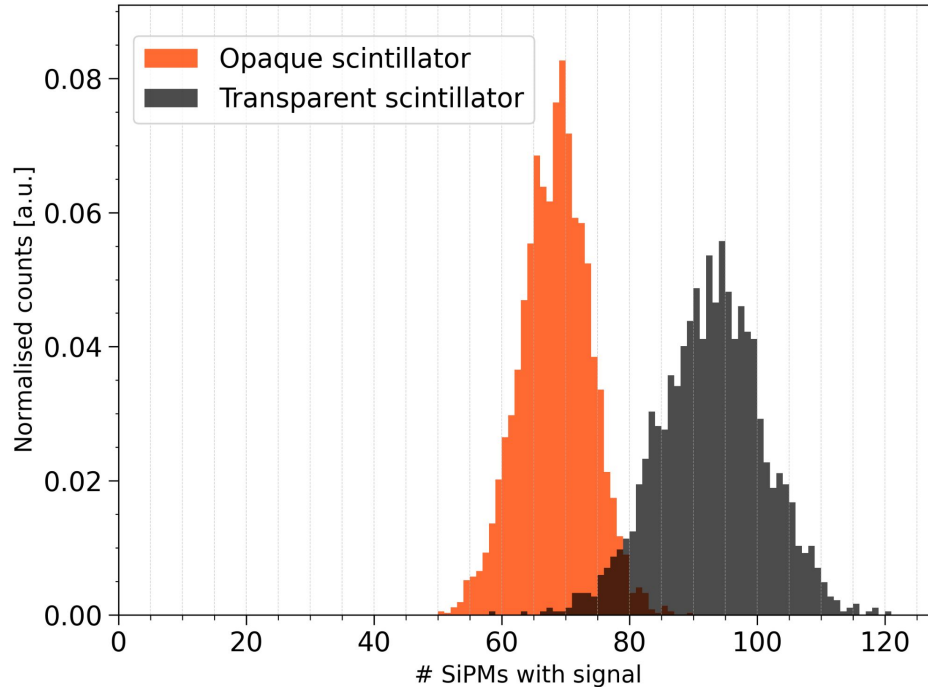


Opaque Scintillator



Purple bars represent  
tagger locations

# Muons in LiquidO-Cube



Tighter confinement of light in the opaque case, as expected.

# Position Resolution

Data-driven, unbiased approach for single row position resolution found in literature.

Position resolution method used by:

1. R.K. Carnegie et al., Nucl. Instrum. Methods A 538 (2005) 372-83.  
<https://doi.org/10.1016/j.nima.2004.08.132>
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	Position Resolution [mm]
Transparent Scintillator	$0.73 \pm 0.03$
Opaque Scintillator (scattering length ~0.4 mm, fibre pitch 3.2 mm)	<b><math>0.45 \pm 0.02</math></b>

With opaque scintillator, the LiquidO-Cube has **~35% better position resolution** than with transparent scintillator.

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Physically Segmented Detector (3.2 mm pitch, rectangular bars)	0.92

With opaque scintillator, the LiquidO-Cube has  **$\sim 35\%$  better position resolution** than with transparent scintillator.

It is **twice as good** as the physically segmented case.

Position resolution method used by:

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# Comparison with State-of-the-Art Muon Imaging

Some of the current state-of-the-art muon imaging detectors use plastic scintillator triangular bars. With a **15 mm pitch**, they achieve **2.5 mm position resolution**.

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Assuming the ratio of position resolution/pitch is constant, for a larger hypothetical LiquidO detector with a 15 mm pitch:

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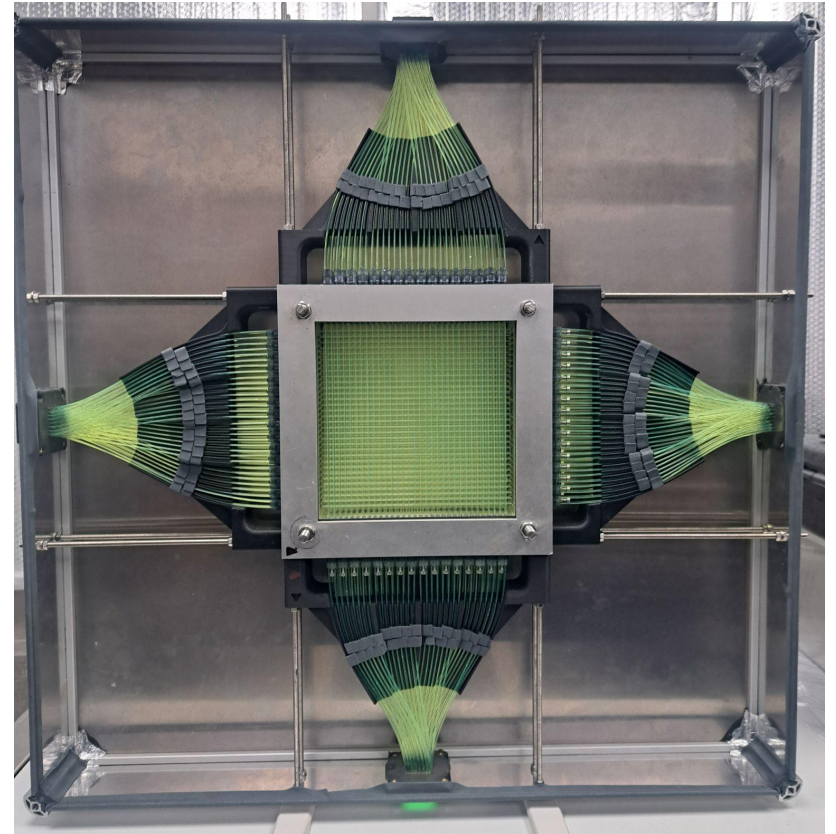
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This is a **broad approximation** to show LiquidO potential, not a claim we have this level of performance!

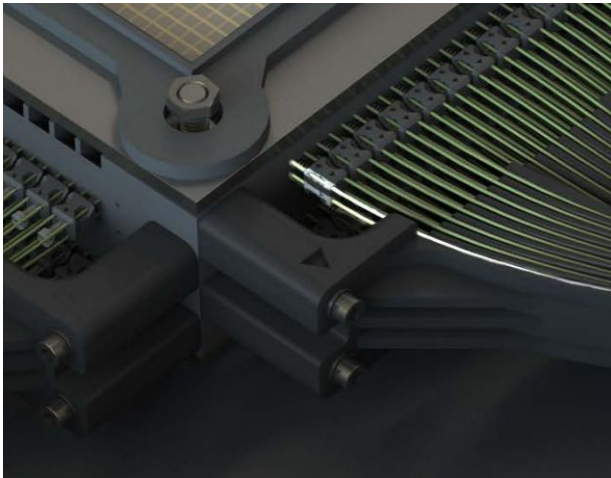
# Prototype Upgrade: Tile

- 3D printed components (internal chamber and fibre guides)
- Same St Gobain BCF-91A fibres as Cube
- Aluminium outer frame
- 168x168x55 mm<sup>3</sup> internal volume

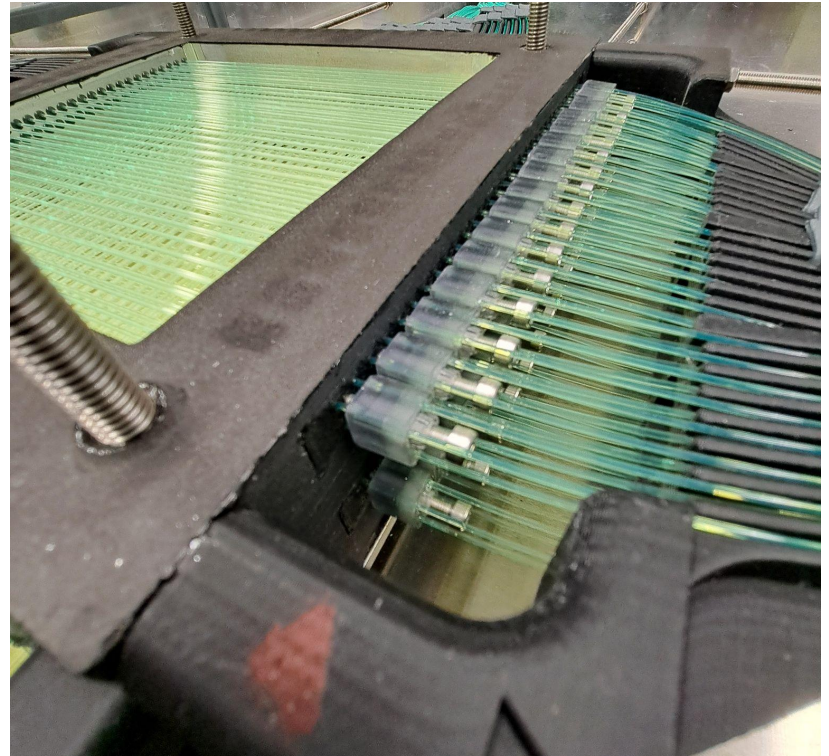


# Prototype Upgrade: Tile

- 8 layers = 4 'real' layers of fibres  
For both x and y, the pairs of layers go to one SiPM to maximise light output
- 256 fibres read out by 256 SiPM channels  
(2 fibres per SiPM, read out both ends)

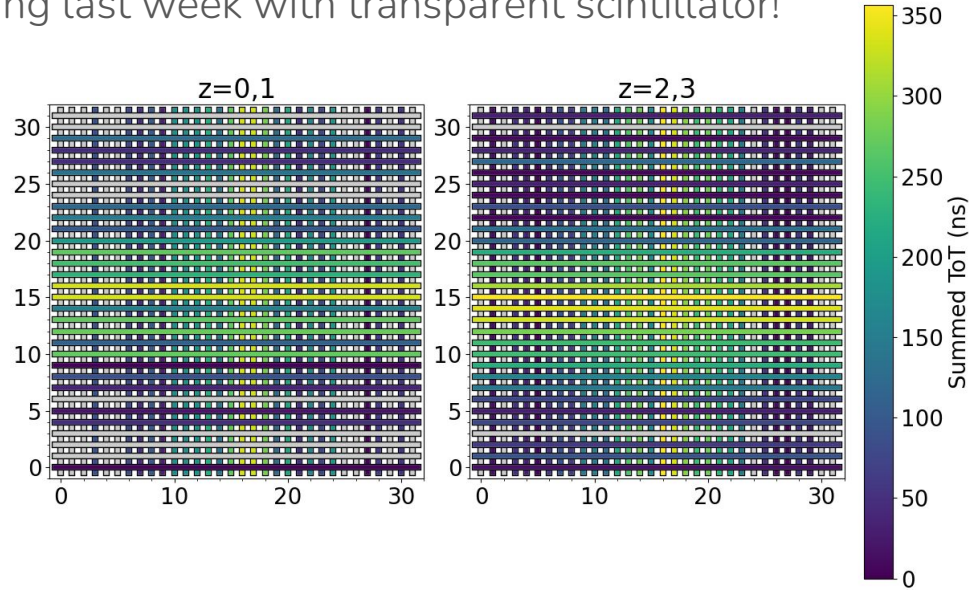


Left: These two fibres go to the same SiPM



# LiquidO-Tile

Just started data taking last week with transparent scintillator!



# LiquidO-Tile

Intended as a proof-of-concept muon imaging with opaque scintillator.

Next steps: fill with opaque scintillator and take some muon data.

# Summary

- LiquidO presents a novel particle detection method using opacity
- Small prototypes demonstrate concept
- Single row resolution competitive with current muon imaging detectors

Thank you

On behalf of the LiquidO Consortium

European  
Innovation  
Council



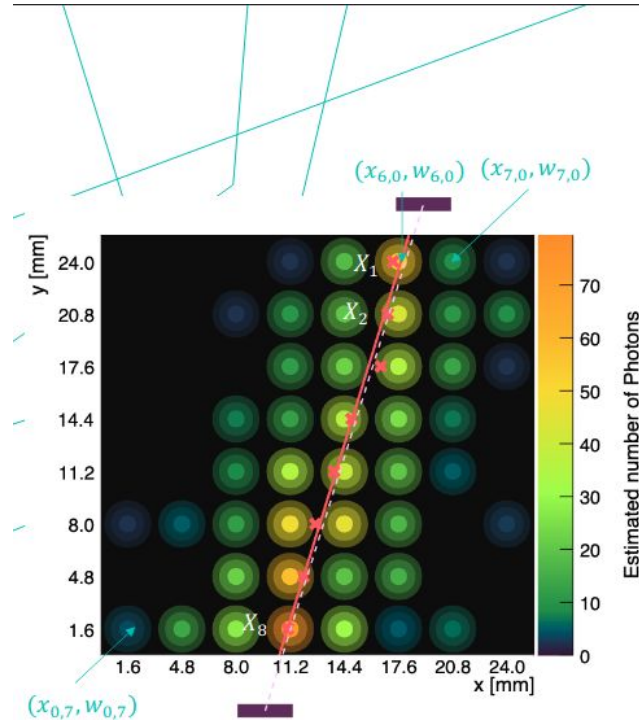
US  
UNIVERSITY  
OF SUSSEX



UK Research  
and Innovation

# Back-Up

# Nico's DRD-2 Talk, Position Resolution



## POSITION RESOLUTION HOW TO

### POSITION RESOLUTION

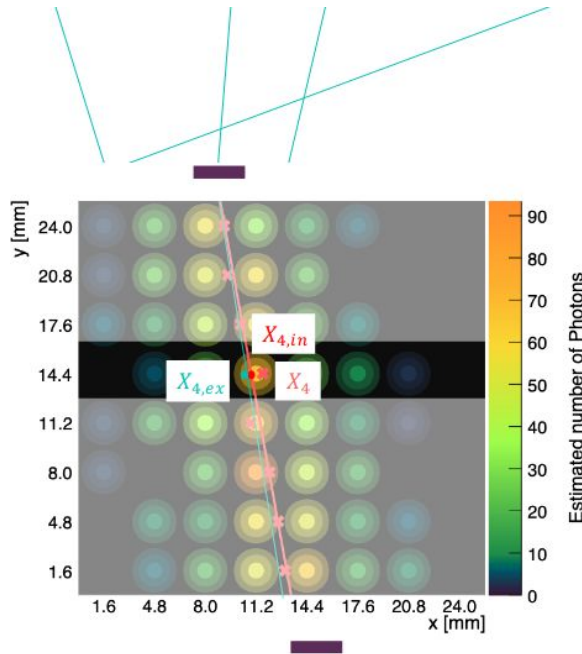
= capability of ONE ROW of LiquidO-detector fibres to reconstruct the position of the traversing particle

### RECONSTRUCTED POSITION FOR EACH ROW OF FIBRES

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

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

# Nico's DRD-2 Talk, Position Resolution



## POSITION RESOLUTION HOW TO

### HOW TO MEASURE THE POSITION RESOLUTION?

Standard data-driven approach used in literature<sup>[4,5,6]</sup>.

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>

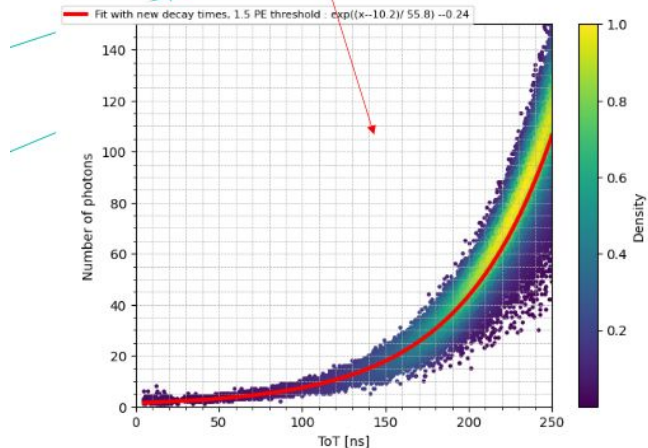
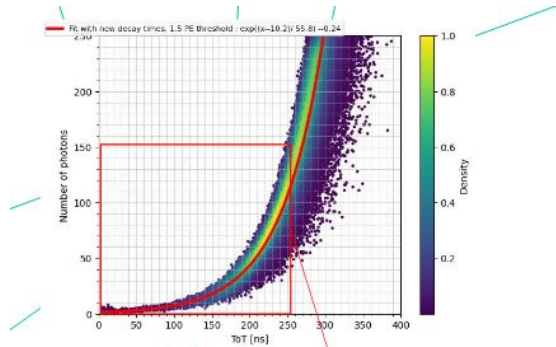
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# Nico's DRD-2 Talk, Physically Segmented Detector



# Nico's DRD-2 Talk, TOT Conversion



## TOT-PE RELATIONSHIP

Steps followed to extract the relationship between the number of photons generating a signal in a SiPM (PE) and ToT

1. Characterise 1 photon pulses used by PETsys to measure the ToT
2. Simulate pulses generated by #PE photons
3. Compute the time-over-threshold
  - Random threshold at 1.3, 1.4, 1.5, 1.6 or 1.7 PE
4. Fit a logarithmic function to the ( #PE, TOT ) points
5. Invert to find the #PE ( ToT ) relationship



