LiquidO Opaque Scintillator Detectors and the Physics Opportunities

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UNIVERSITY OF SUSSEX

Manchester Seminar

29th May 2026

Outline

- Radiation detectors and scintillators
- Novel LiquidO concept
    - Opaque scintillator + Lattice of optical fibres
- High resolution imaging capabilities
- Sussex Cube and Tile LiquidO detectors
- Physics opportunities
    - CLOUD
- Applications

Radiation Detectors

- Make information in the world around us accessible to human perception
- Enable many aspects of our modern lives
  - Photon detectors in our smartphones
  - PET scanners for cancer diagnosis
  - X-ray scanners at the dentist
  - Airport luggage scanners for security
- Tools of discovery
  - Higgs boson, neutrino oscillations
  - Astrophysical objects, e.g. gamma-ray bursts

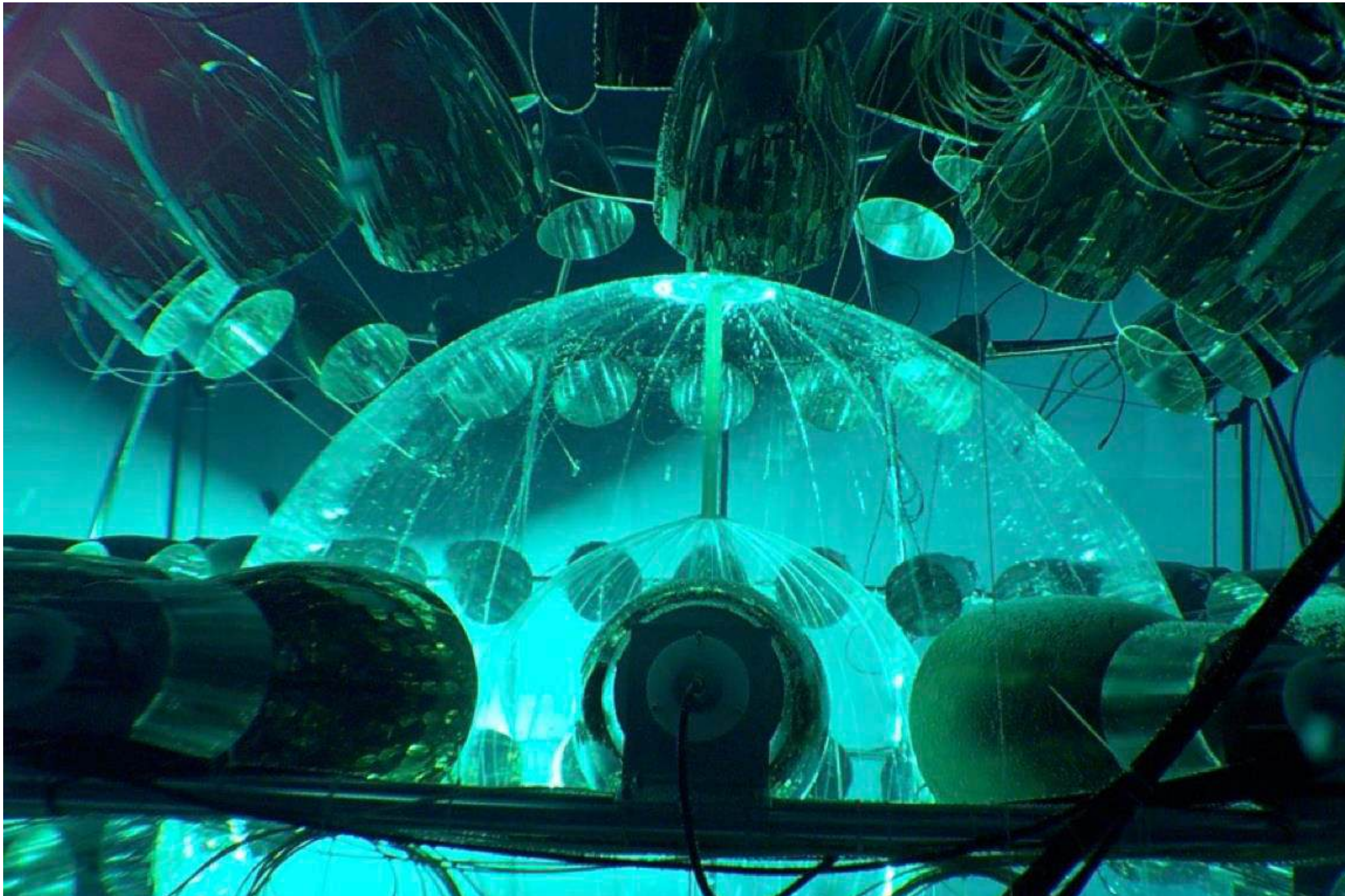
Scintillator Basics

- Charged particles ionise materials
- Recombination leads to photon emission

- Need a material (i.e. a scintillator) that doesn't immediately re-absorb its own light
  - Physical chemistry of molecule energy levels

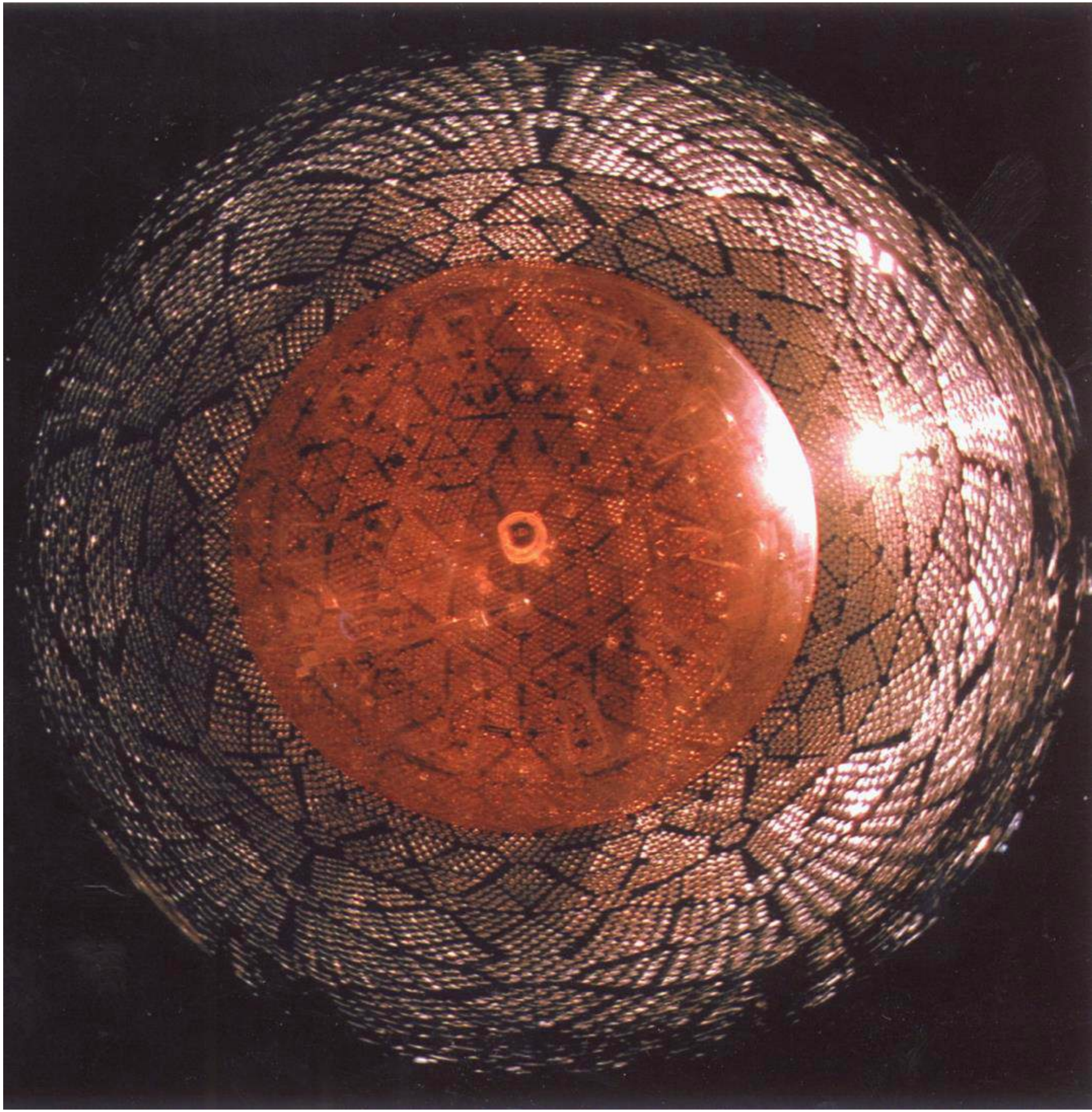
- Can also photoexcite the scintillator molecules

Huge scintillator detectors used for neutrino physics



SNO+

- Central volume filled with transparent scintillator
  - 800 tons
- 10,000 PMT light sensors



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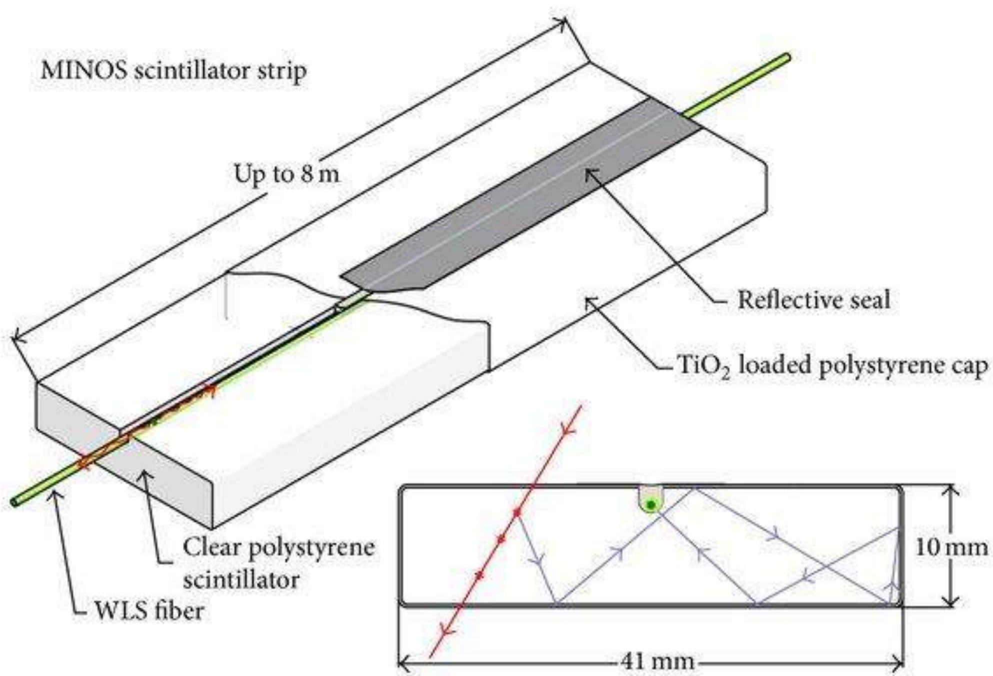
Pros and cons (huge ball scintillator)

- Cost effective way of instrumenting huge masses
  - Often need large mass detectors to get neutrinos to interact
- Good timing resolution (~1 ns)
- Extremely good radiopurity (low contaminants)
- Poor spatial resolution (~10s of cm)

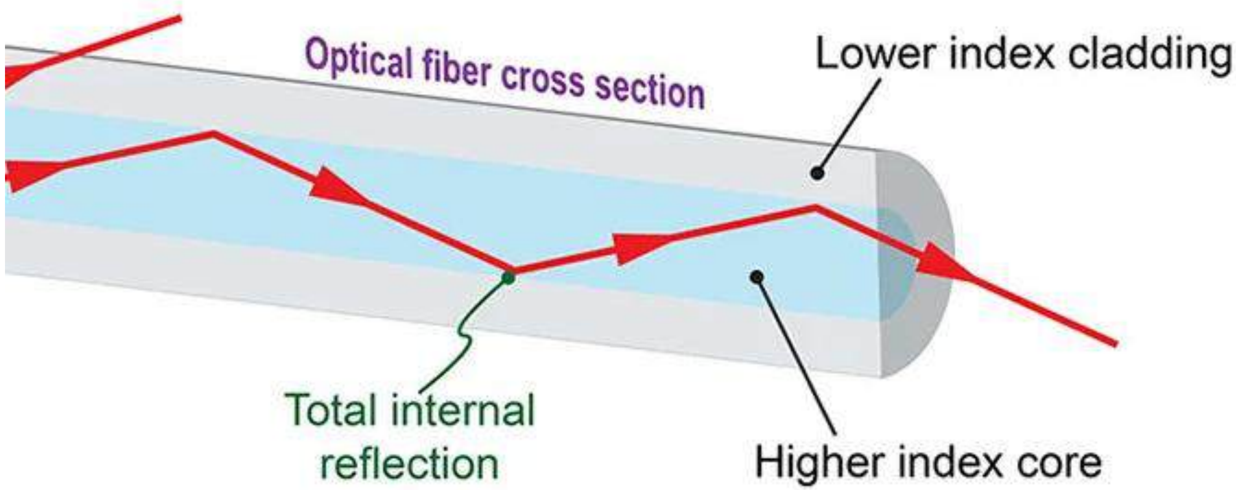
How to get better spatial resolution?

- Traditional approach is to physically segment your transparent scintillator
  - Divide it up into lots of pieces and wrap each piece in a reflective material
    - E.g. titanium dioxide – very good diffuse reflector



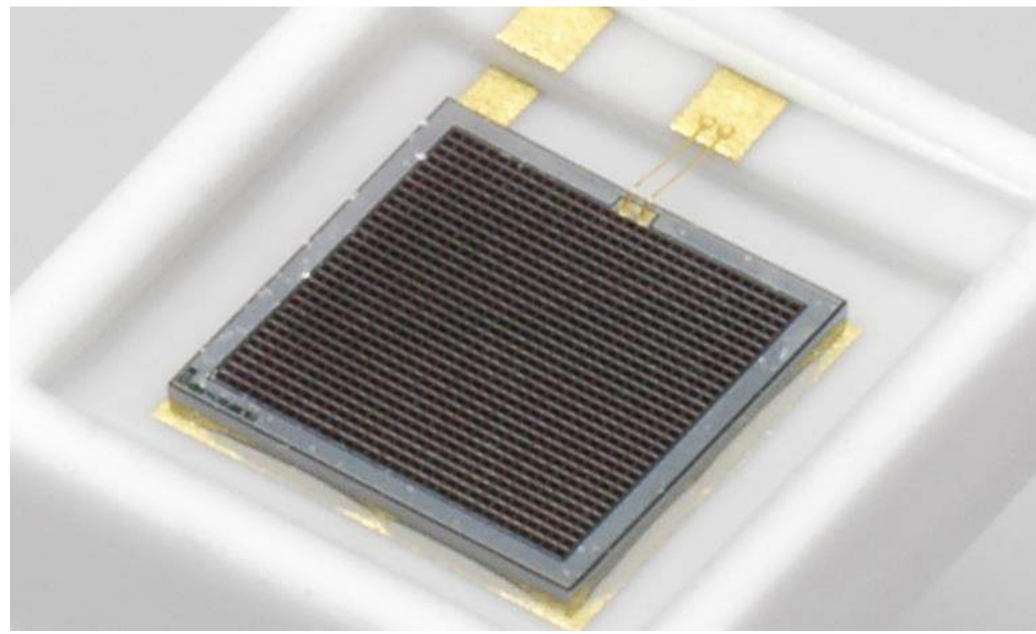
Optical fibres

- Very effective at transporting light over long distances
  - Use to extract light from large detectors
- We use wavelength shifting fibres
  - Absorb and re-emit isotropically
  - Light emitted in the direction along the fibre is trapped
    - Otherwise lost



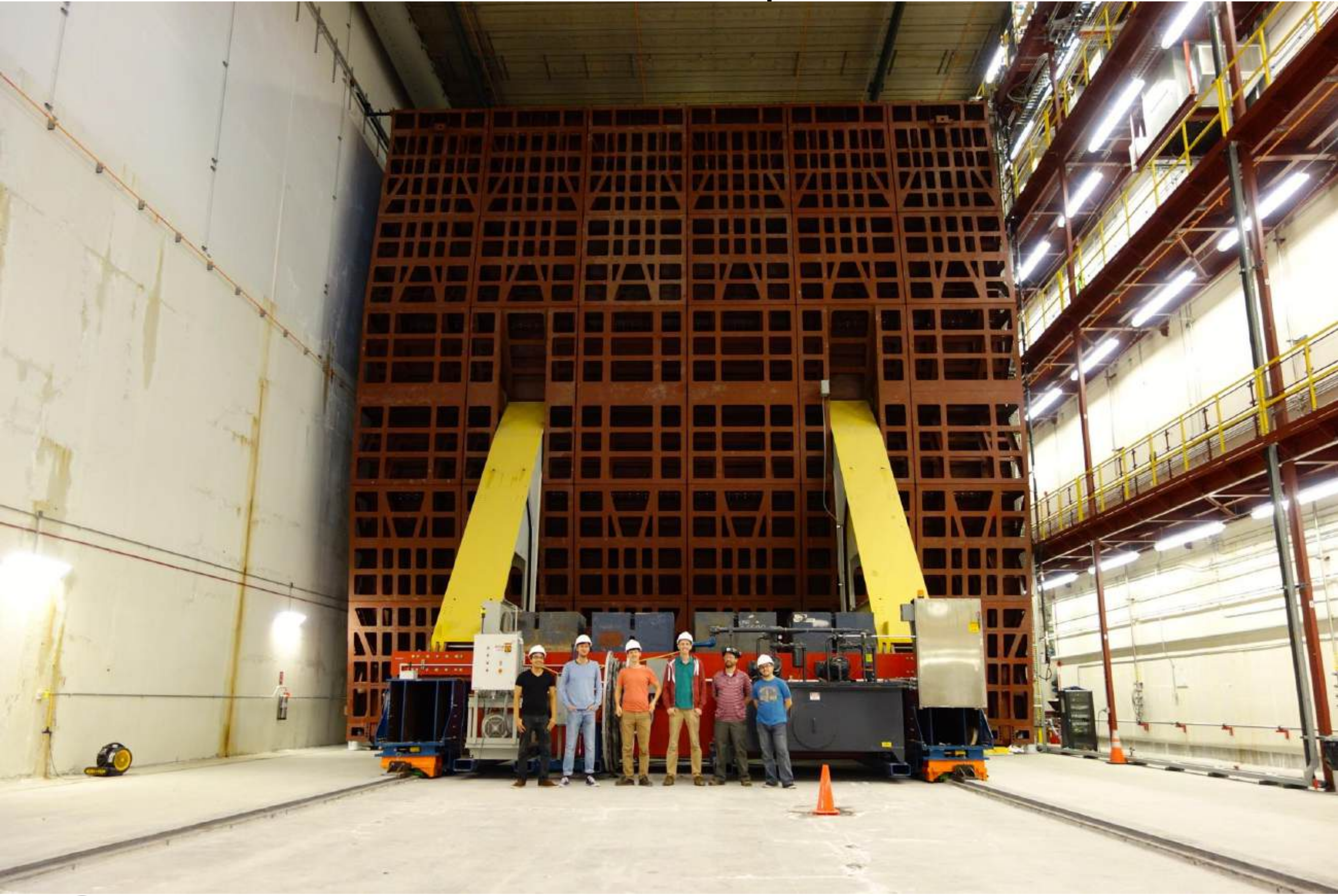
Photon sensors

- Silicon Photomultipliers (SiPMs)
  - Detect single optical photons



What can we do with a segmented detector?

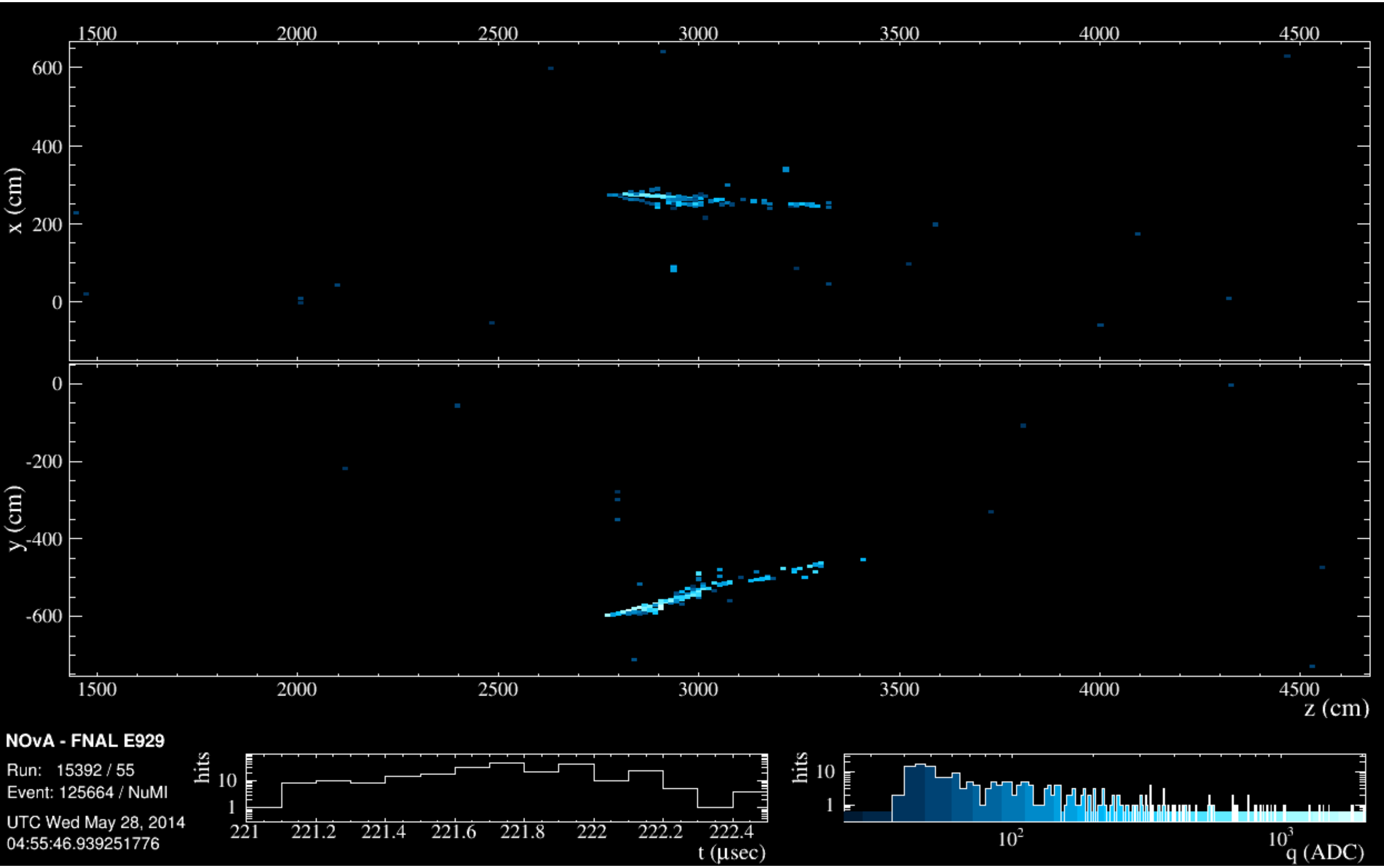
NOvA Neutrino Experiment



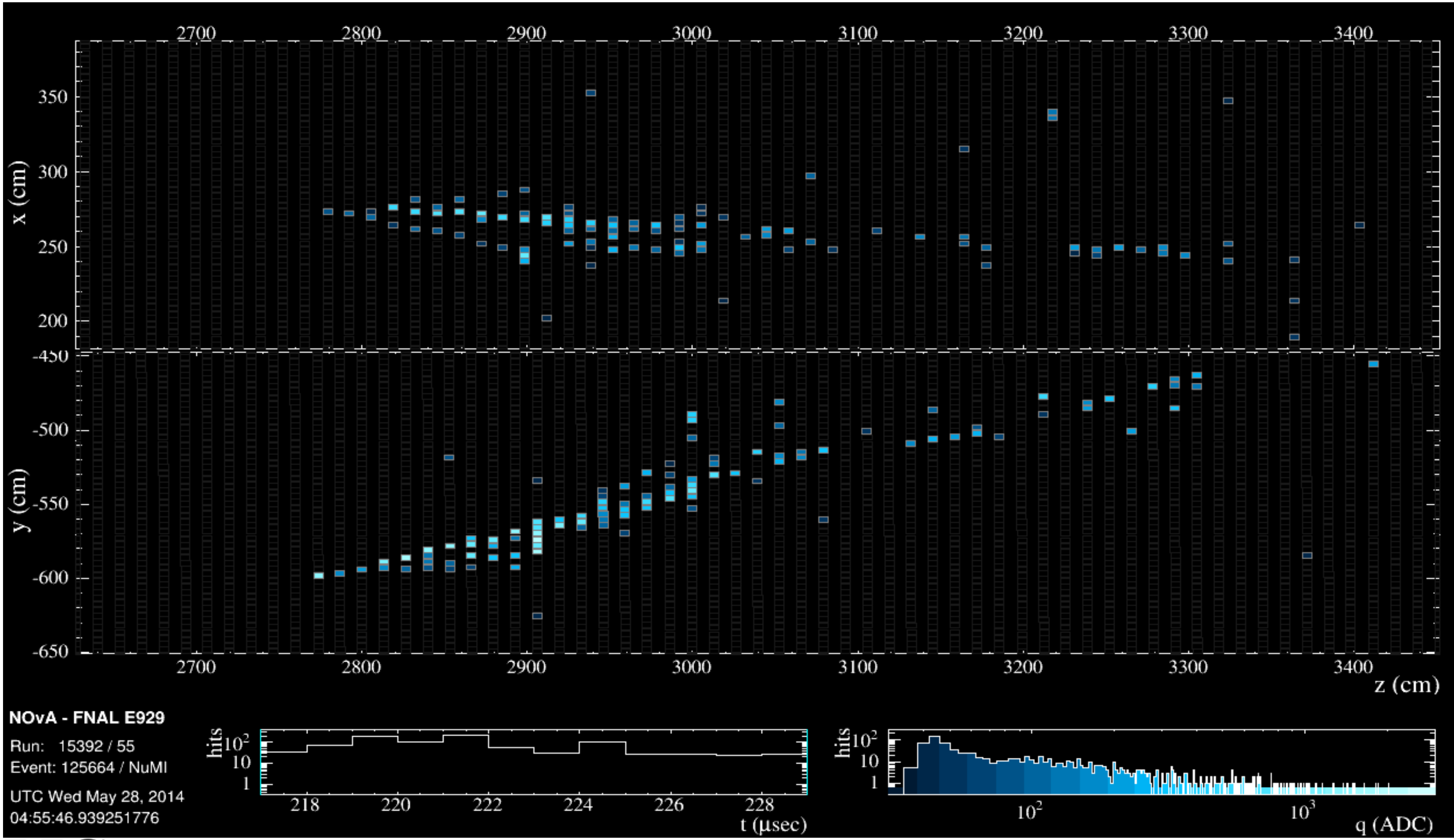
NOvA

- 14,000 tons!
- 15 metre long cells filled with transparent scintillator oil

NOvA Electron Neutrino Event



Pixelated images



Pros and cons (segmentation)

- Get good spatial resolution (cm or mm or even down to ~100 microns)
- Get good timing resolution (1 ns)
- Usually need more sensors
  - expensive
- Have to physically segment
  - complexity/cost to manufacture
  - introduce inactive material
- Hard to collect as many photons
- Hard to get excellent radiopurity

How can we keep the benefits of segmented detectors while mitigating the issues?

L I Q U I D

New “LiquidO” approach

- Make the scintillator opaque (not transparent)
  - i.e. stop the light from streaming away from where it’s produced

- What?!
- Why would you do that?
- How are you going to detect the light?

- Highly counter intuitive approach
  - Probably why no-one thought of it until now!

First Papers

Neutrino Physics with an Opaque Detector

arXiv:1908.02859v1 [physics.ins-det] 7 Aug 2019

August 9, 2019

The discovery of the neutrino by Reines & Cowan in 1956 revolutionised our understanding of the universe at its most fundamental level and provided a new probe with which to explore the cosmos. Furthermore, it laid the groundwork for one of the most successful and widely used neutrino detection technologies to date: the liquid scintillator detector. In these detectors, the light produced by particle interactions propagates across transparent scintillator volumes to surrounding photo-sensors. This article introduces a new approach, called LiquidO, that breaks with the conventional paradigm of transparency by confining and collecting light near its creation point with an opaque scintillator and a dense array of fibres. The principles behind LiquidO's detection technique and the results of the first experimental validation are presented. The LiquidO technique provides high-resolution imaging that enables highly efficient identification of individual particles event-by-event. Additionally, the exploitation of an opaque medium gives LiquidO natural affinity for using dopants at unprecedented levels. With these and other capabilities, LiquidO has the potential to unlock new opportunities in neutrino physics, some of which are discussed here.

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Novel opaque scintillator for neutrino detection

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Abstract: There is rising interest in organic scintillators with low scattering length for future neutrino detectors. Therefore, a new scintillator system was developed based on admixtures of paraffin wax in linear alkyl benzene. The transparency and viscosity of this gel-like material can be tuned by temperature adjustment. Whereas it is a colorless transparent liquid at temperatures around 40°C, it has a milky wax structure below 20°C. The production and properties of such a scintillator as well as its advantages compared to transparent liquids are described.

Keywords: Detector design and construction technologies and materials; Neutrino detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

ArXiv ePrint: 1908.03334

[1]Corresponding author.

2019 JINST 14 P11007

More information about LiquidO can be found in
https://www.nature.com/articles/s42005-021-00763-5
and https://iopscience.iop.org/article/10.1088/1748-0221/14/11/P11007

(See also seminar at CERN: https://indico.cern.ch/event/823865/)

Opacity

- Two ways to make something opaque

Short scattering length ✅

Short absorption length ❌

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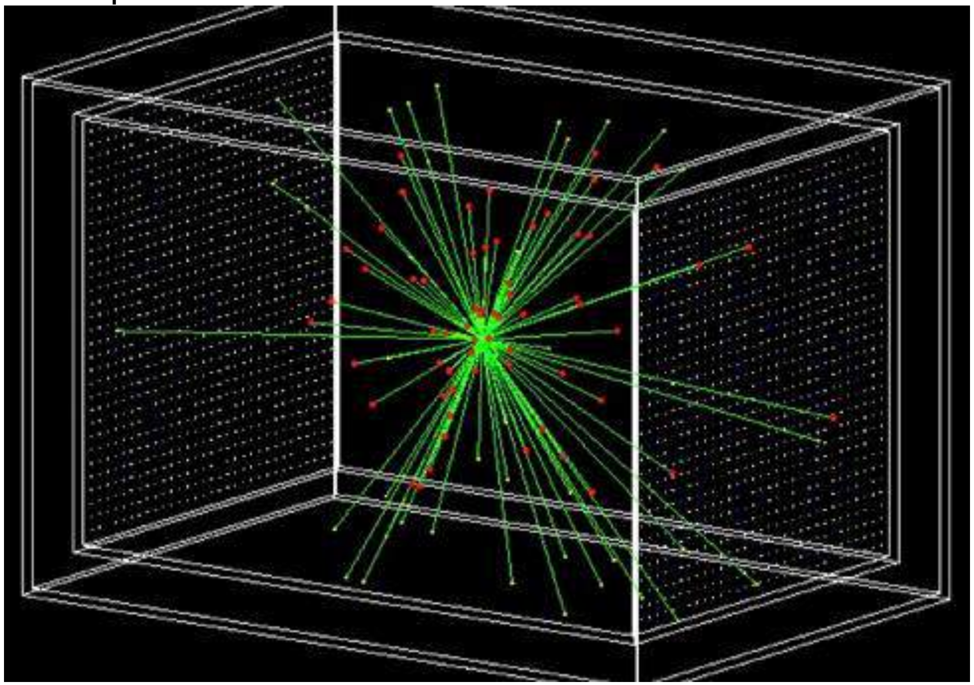
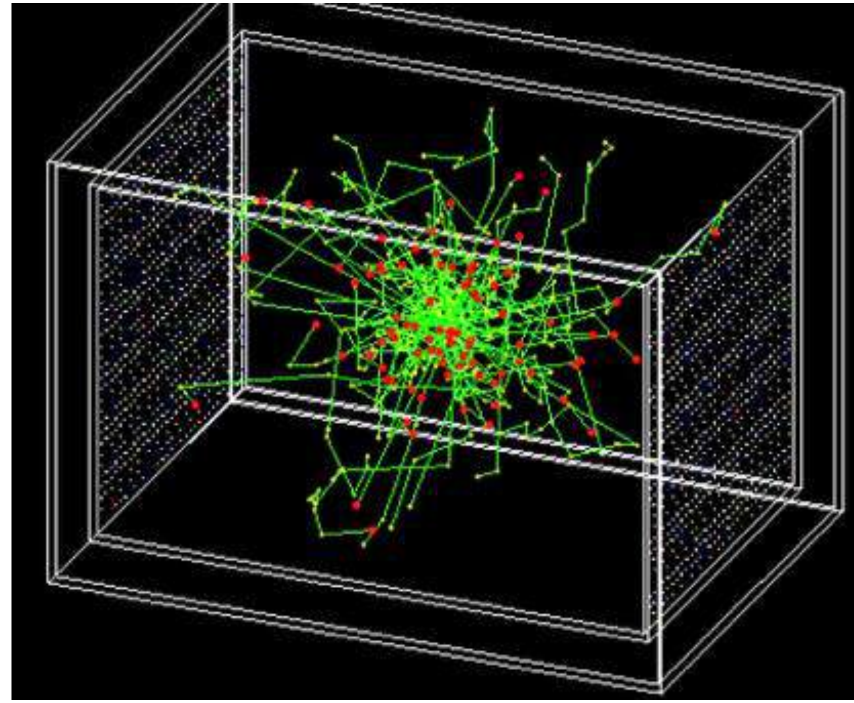
Stochastic confinement of light

Transparent scintillator



Opaque scintillator

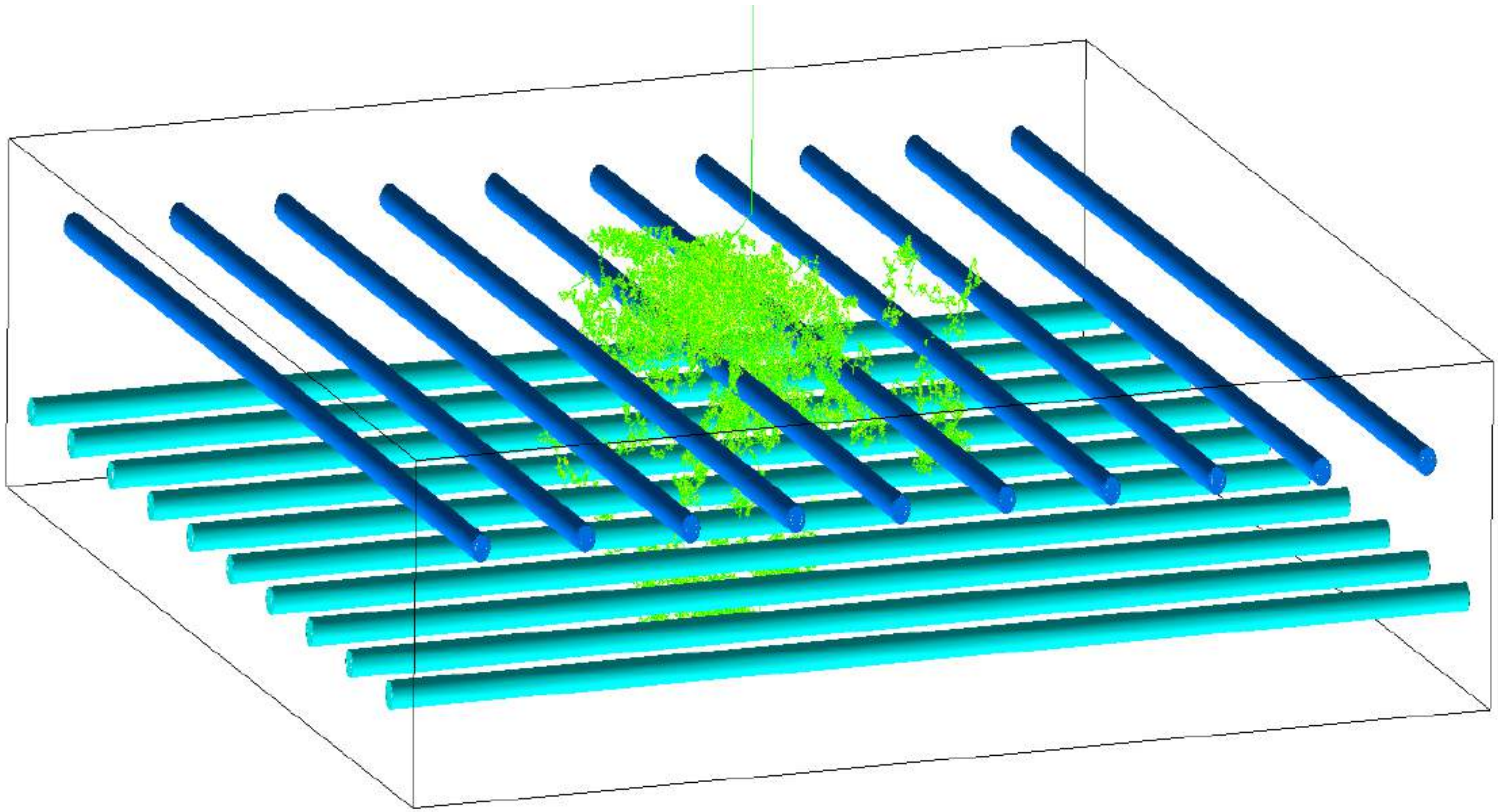


In a scintillator with a short scattering length the light stays near where it is produced

– Each photon undergoes a random walk

So, how do we measure the light?

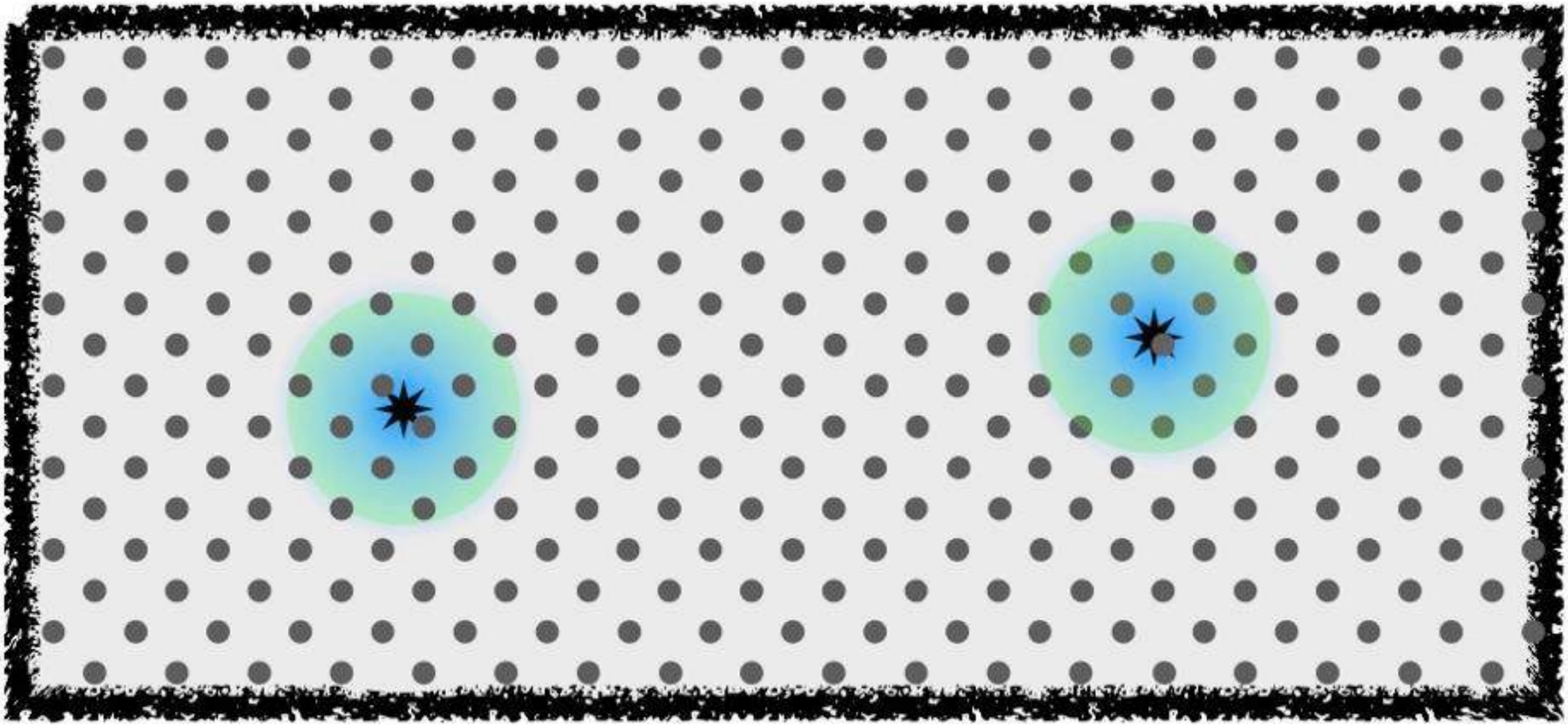
Lattice of Wavelength Shifting Fibres



Collect and extract the light from near the point of production using WLS fibres

LiquidO: Opaque Scintillator + fibres

Confine light locally → freeze information



Side-on or top-down view

Enables a high-resolution imaging detector

(without physical segmentation)

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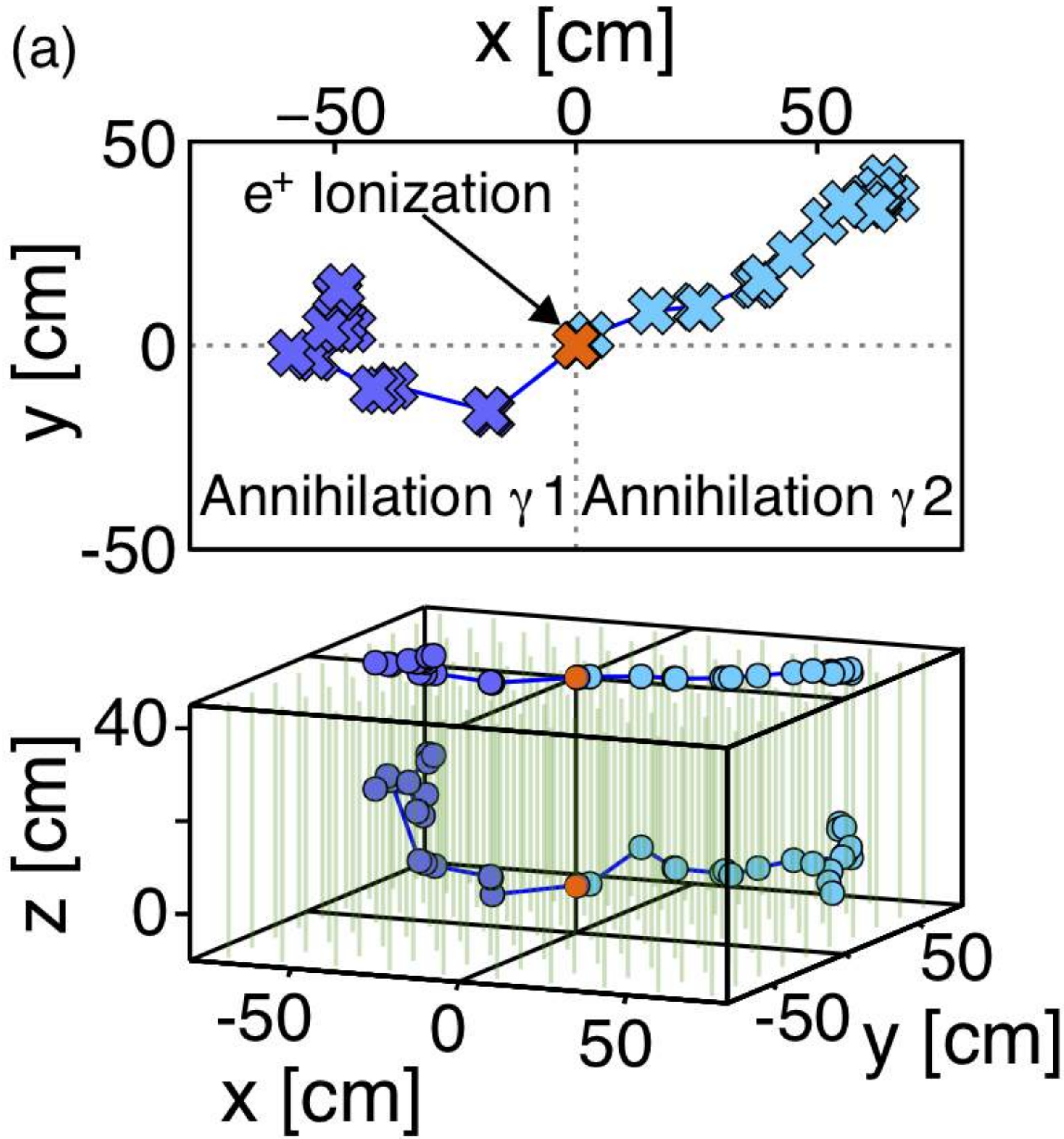
Simple example detector

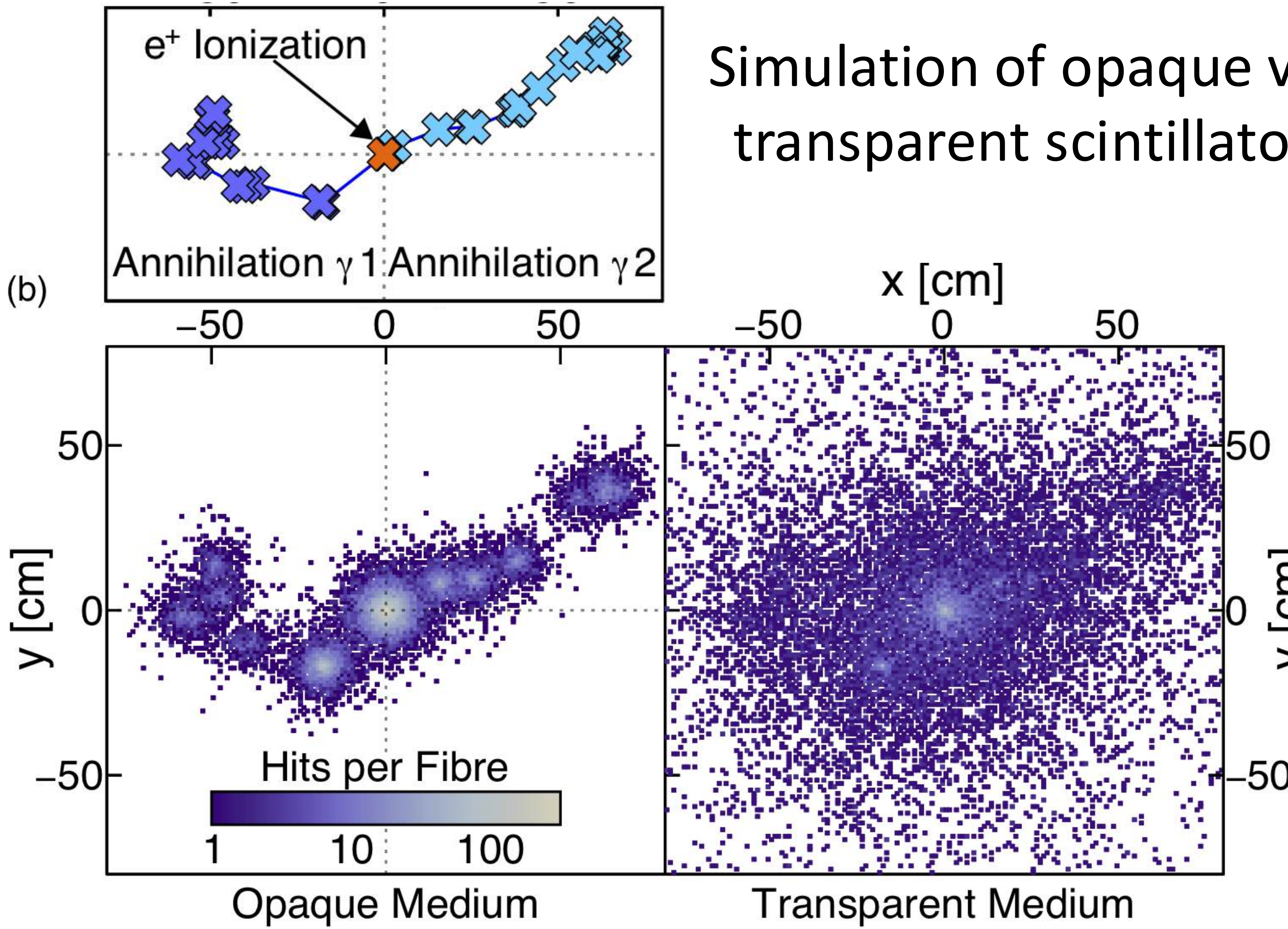
Positron of 1 MeV

Two annihilation gammas

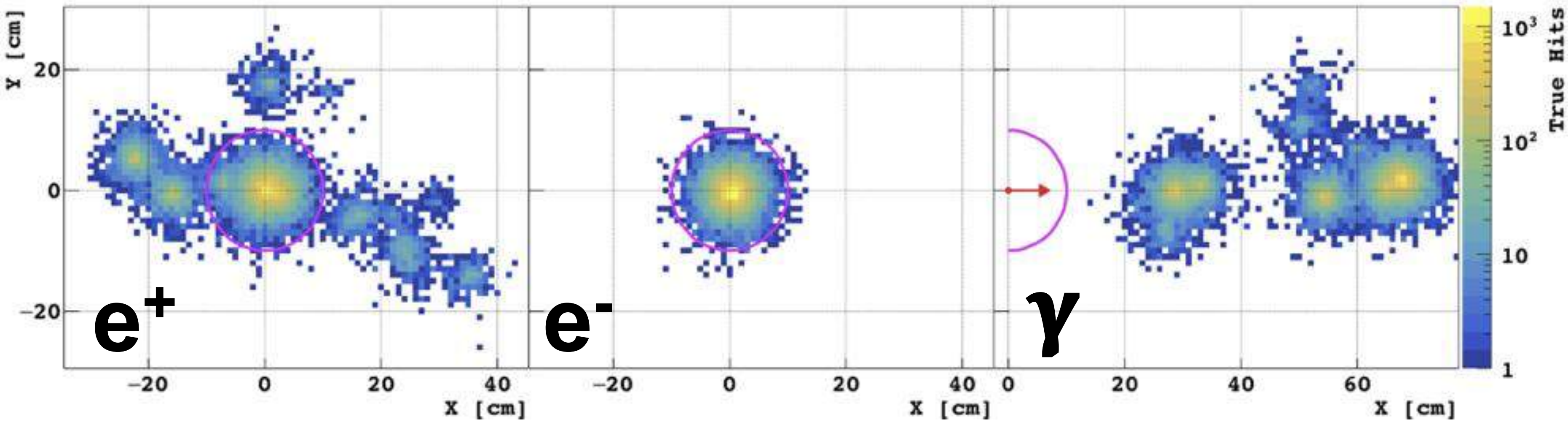
1 cm pitch lattice of fibres, along a single direction



Simulation of opaque vs. transparent scintillator



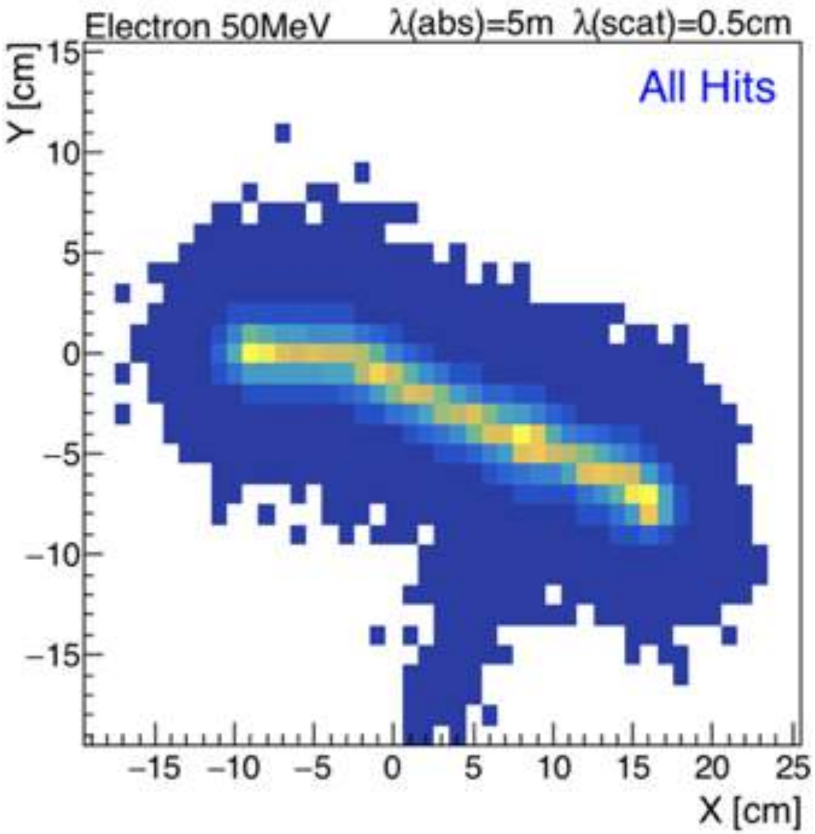
Use high-resolution imaging for particle identification



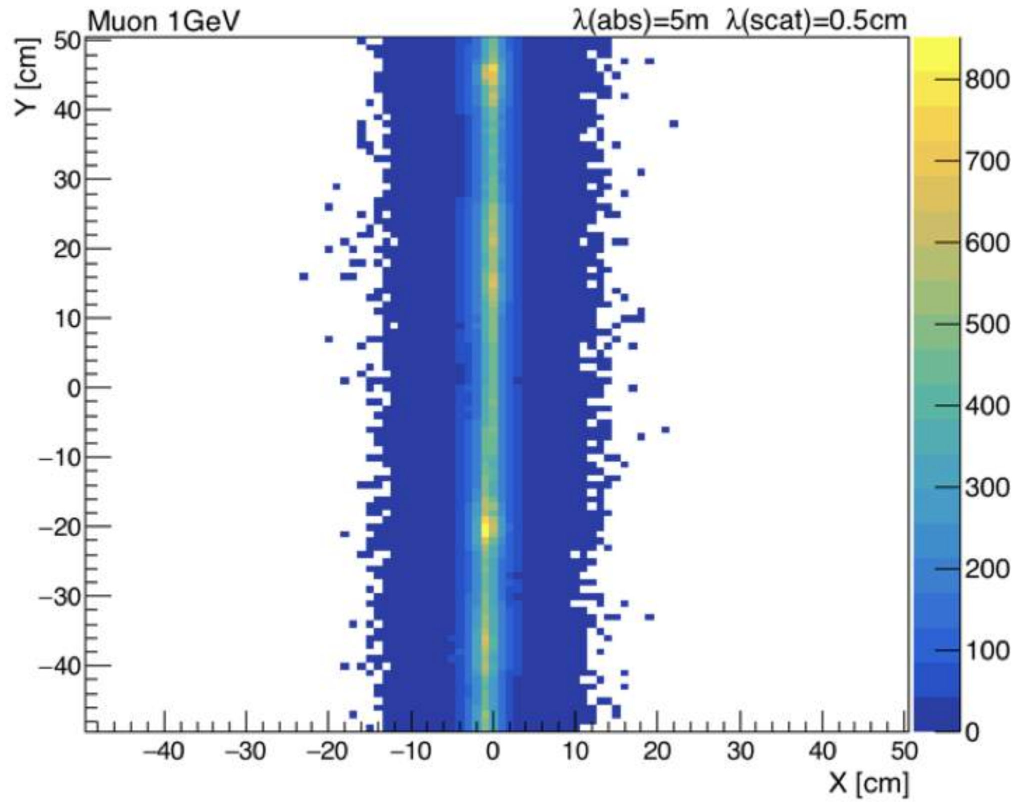
Low energy: 2 MeV

Distinguish positrons from point-like energy depositions (e.g. electrons, protons, alphas) and from gammas

Use high-resolution imaging for particle identification



50 MeV e⁻



1 GeV μ

(through-going)

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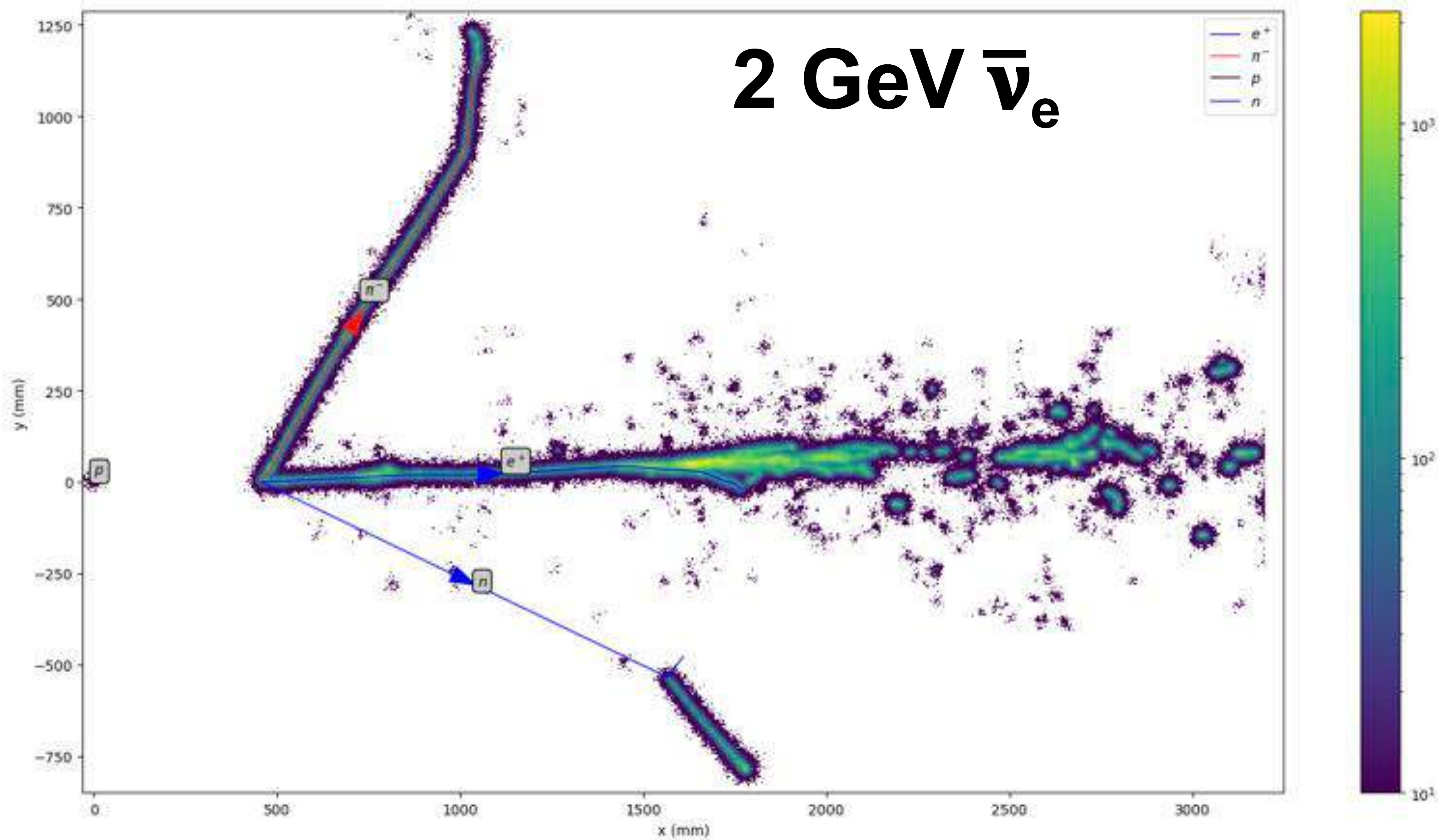
Use high-resolution imaging for particle identification



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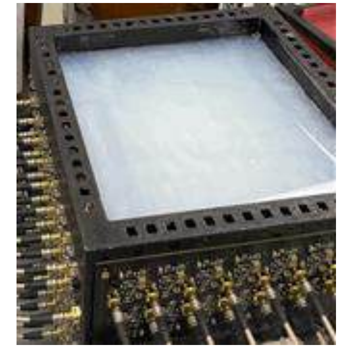
Worldwide LiquidO R&D Effort

Opaque scintillators

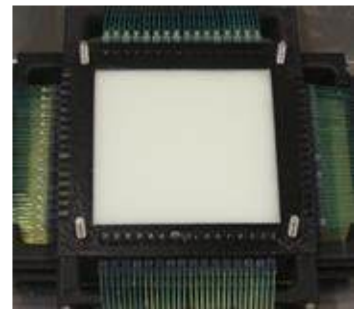
Scintillator R&D:
→ Water-based opaque scintillator
@ IST, Portugal

Scintillator R&D:
↑NoWaSH @ JGU Mainz, Germany
iopscience.iop.org/article/10.1088/1748-0221/14/11/P11007
→ oWbLS @ Brookhaven National Laboratory, USA
doi.org/10.1016/j.nima.2024.170075

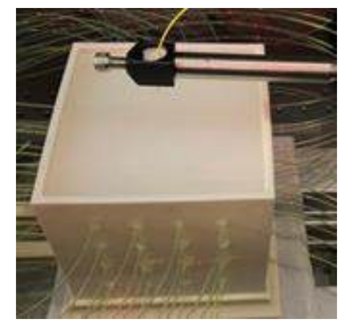
LiquidO detector prototyping



↑BPULSE @ Penn State, USA



↑Tile @ University of Sussex, UK

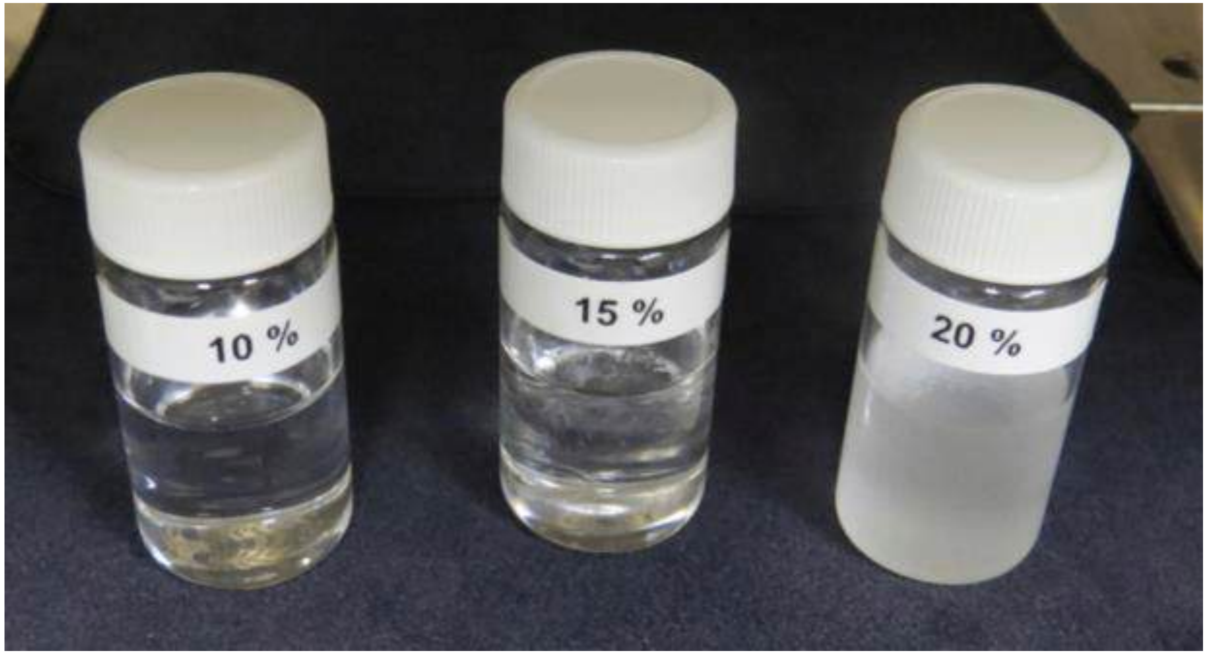


↑LIME @ University of Michigan, USA
doi.org/10.1016/j.nima.2024.170075

↑MINI-LiquidO @ LP2i, France
arxiv.org/abs/2503.02541

← Cube @ University of Sussex, UK
https://iopscience.iop.org/article/10.1088/1748-0221/21/01/P01010

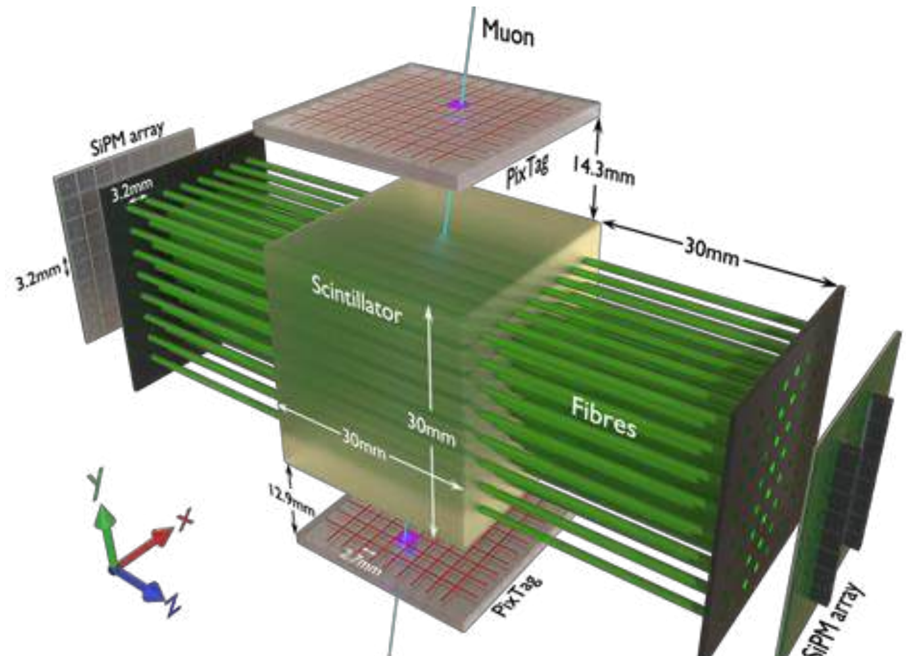
First Opaque Scintillator Mixture



"NoWaSH" = Linear Alkyl Benzene + PPO + Paraffin

Opacity depends on paraffin concentration, which changes crystalisation temperature

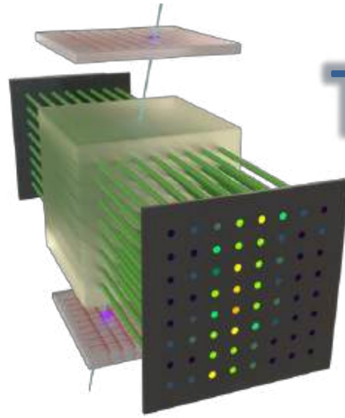
Sussex Cube LiquidO Detector



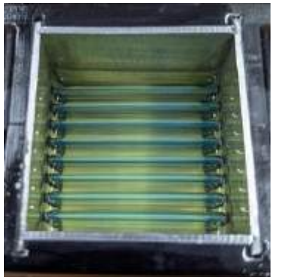
- 3x3x3 cm^3 scintillator volume
- NoWaSH opaque scintillator
- ~0.5 mm scattering length

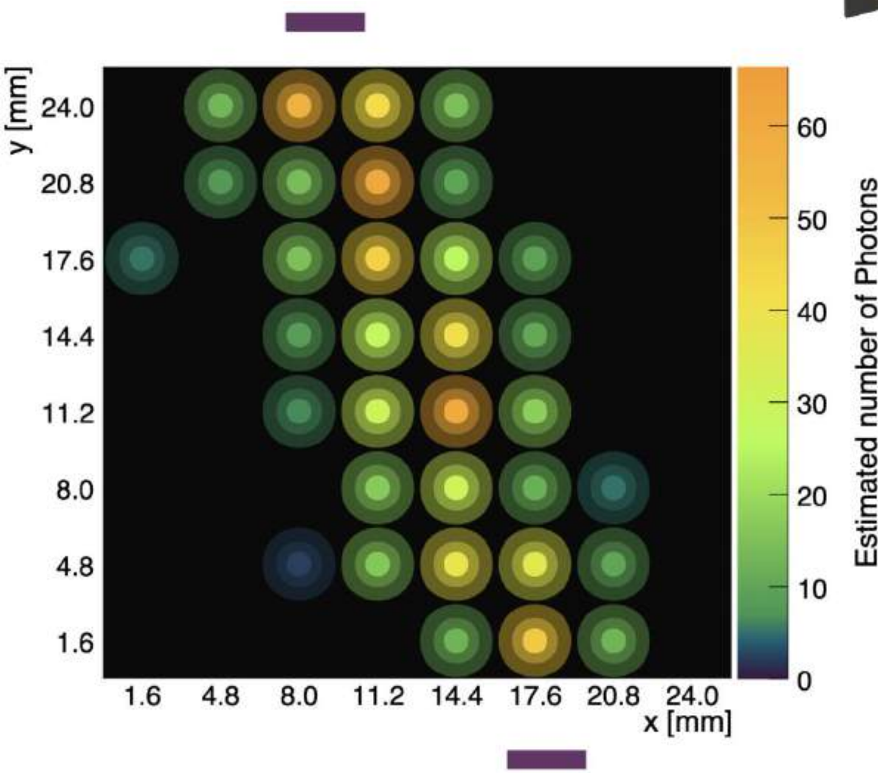
- 64 fibres, 3.2 mm pitch
- SiPM arrays
- PETsys TOFPET2 ASICs

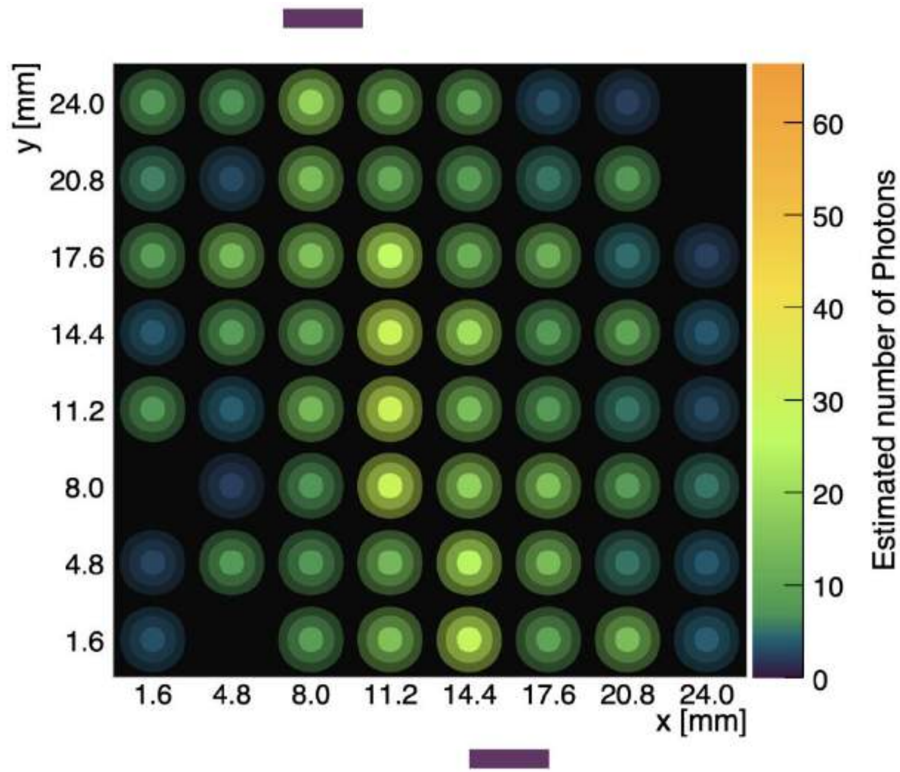
OPAQUE

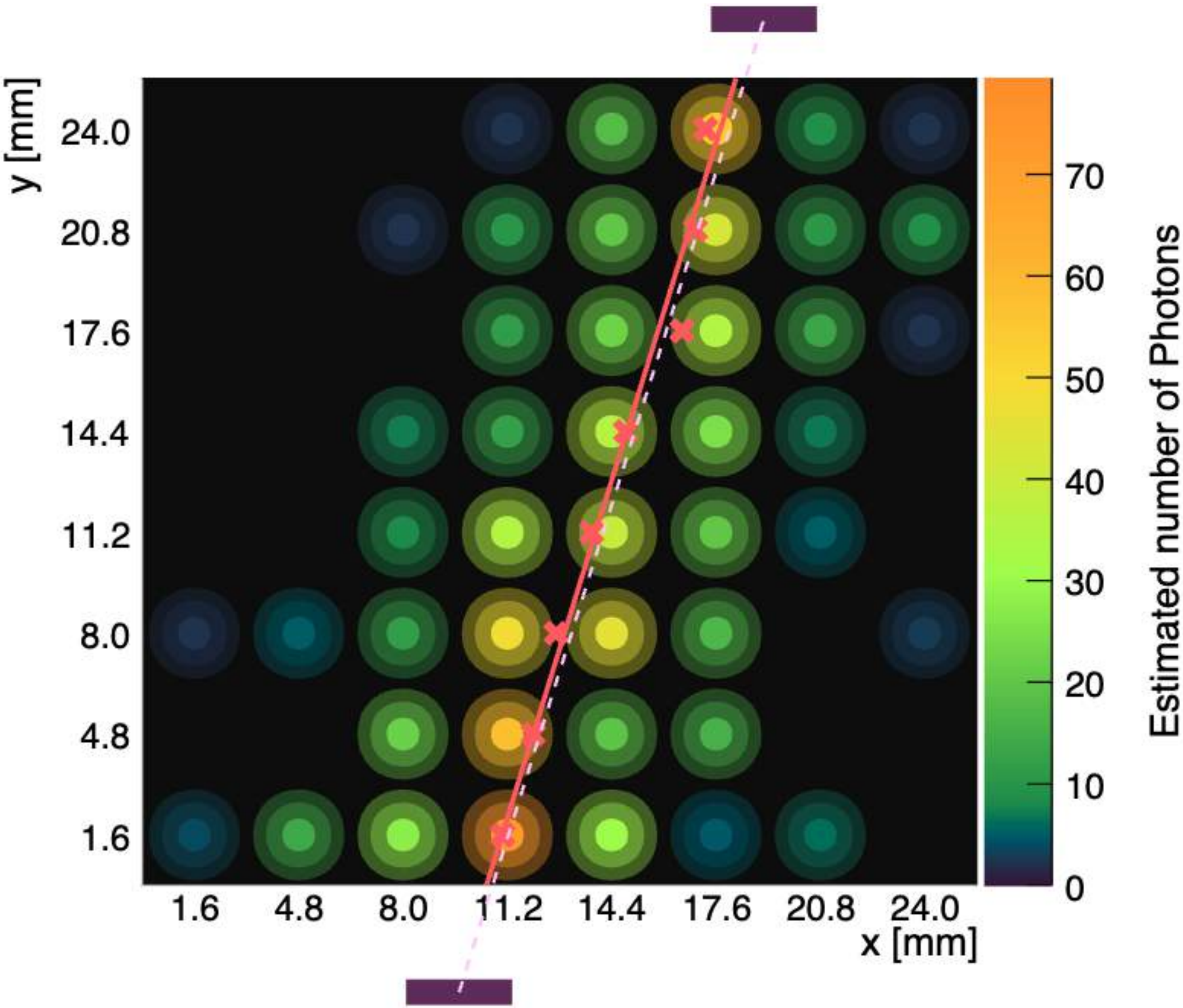


TRANSPARENT



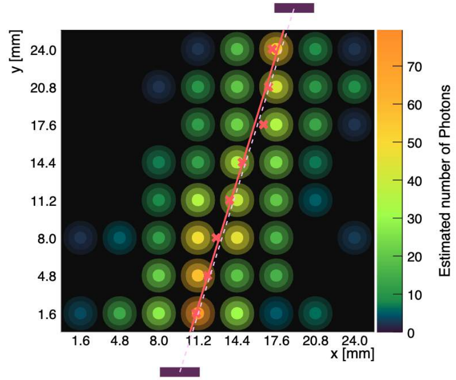






y [mm]
24.0
20.8
17.6
14.4
11.2
8.0
4.8
1.6
1.6
4.8
8.0
11.2
14.4
17.6
20.8
24.0
x [mm]
Estimated number of Photons
70
60
50
40
30
20
10
0

Sussex Cube Results



- Position resolution twice as precise as a simple segmented detector
- Simulations show we can improve
  --> 5-10x more precise

- Can make detectors 5-10x more precise for a similar cost
  – or can reduce the cost by 5-10x for the same performance

	Single row position resolution using cosmic muons [mm]
Cube with opaque scintillator	0.45 ± 0.02
Hypothetical segmented transparent scintillator detector (L =3.2 mm pitch)	$L/\sqrt{12} = 0.92$

World's most precise LiquidO detector ever built

J. Apilluelo et al., Journal of Instrumentation, Volume 21, January 2026

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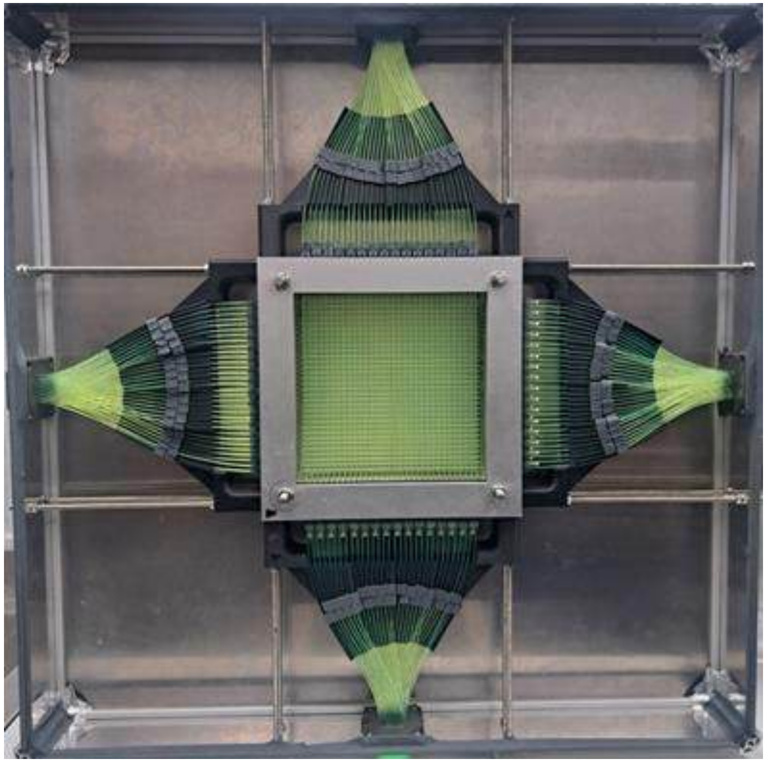
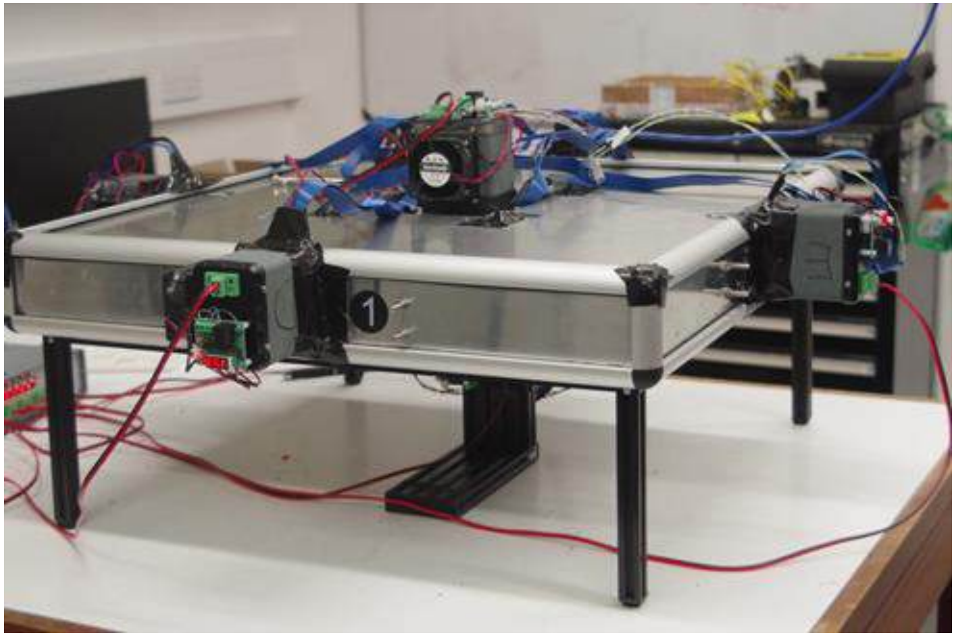
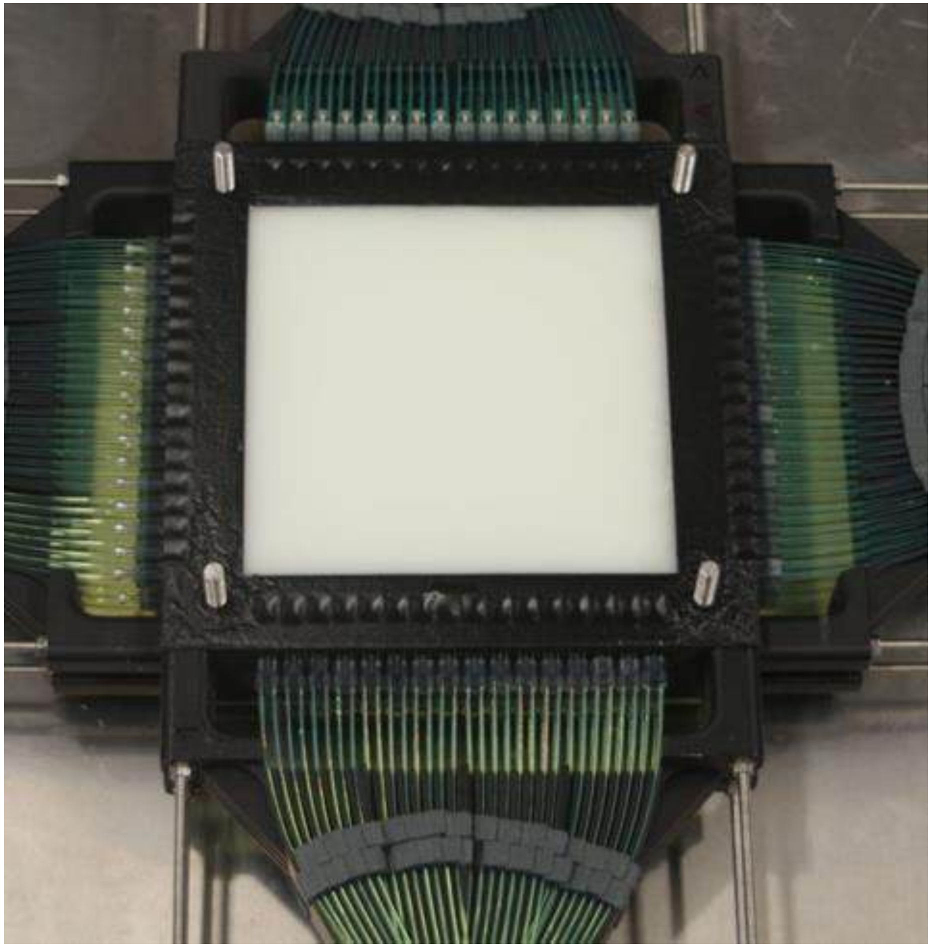
Sussex Tile LiquidO Detector





- 256 Saint Gobain BCF-91A 1 mm wavelength-shifting fibres
- 8 layers of 32 fibres
  - 2 fibre ends readout per channel
  - 4 logical layers: 2X + 2Y directions
- 64 channel Hamamatsu S13361-3050-AE-08 MPPC arrays
- 64 channel PETsys TOFPET2 ASICs

OPAQUE



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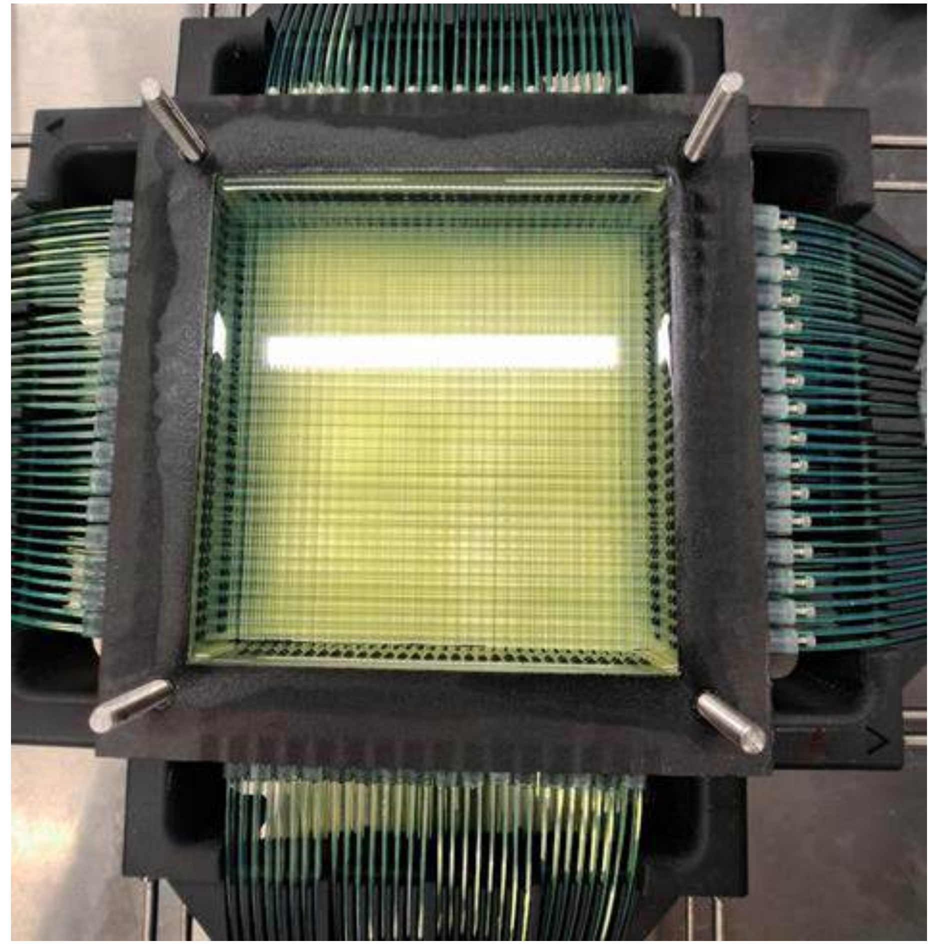
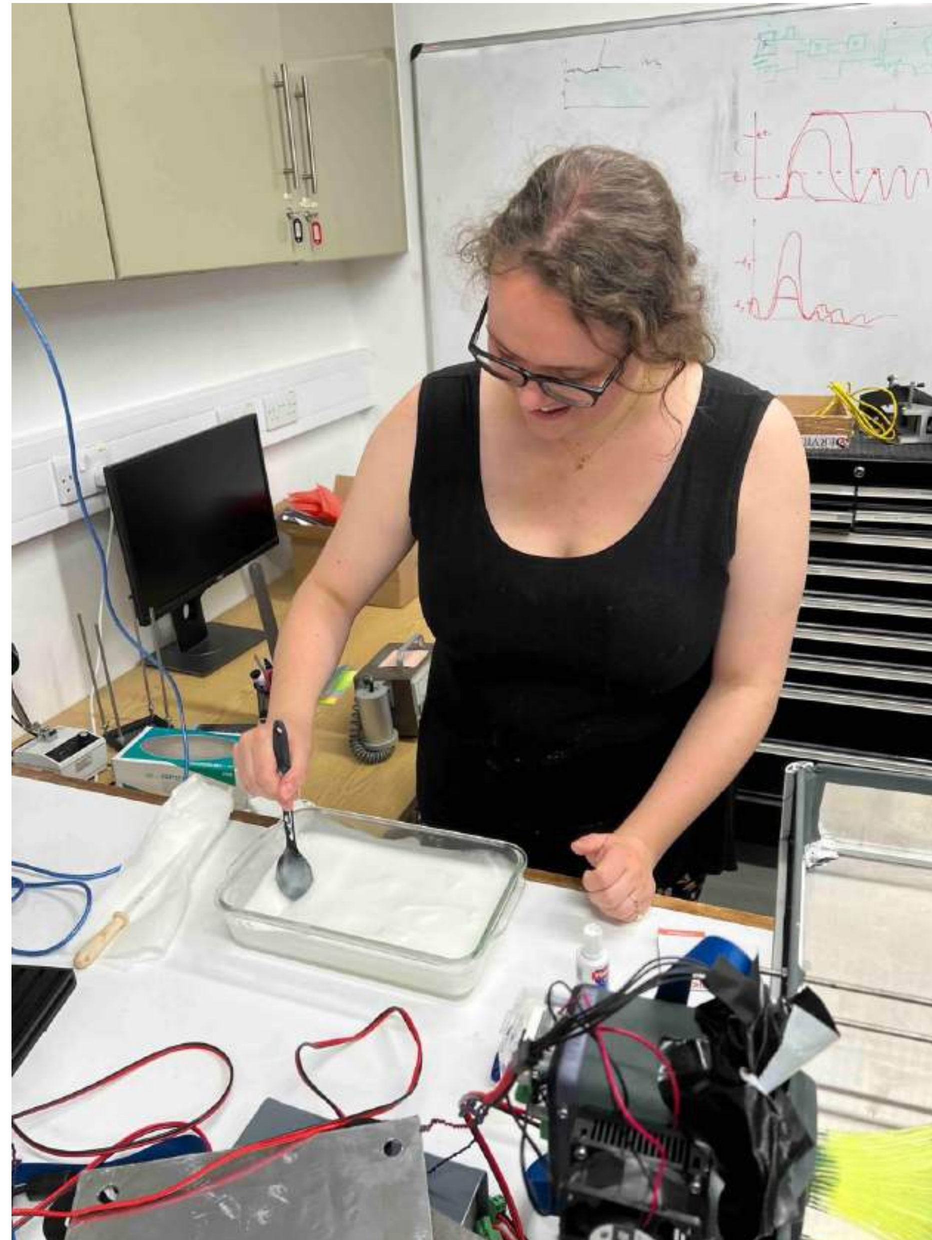


- LAB + PPO (1 w.t.%) + POPOP (0.03 w.t.%) (+ wax at 15 w.t.%)
- ~10k photons/MeV
- ~0.5 mm scattering length

Results

- First results from the Sussex Tile released at November IEEE conference in Japan



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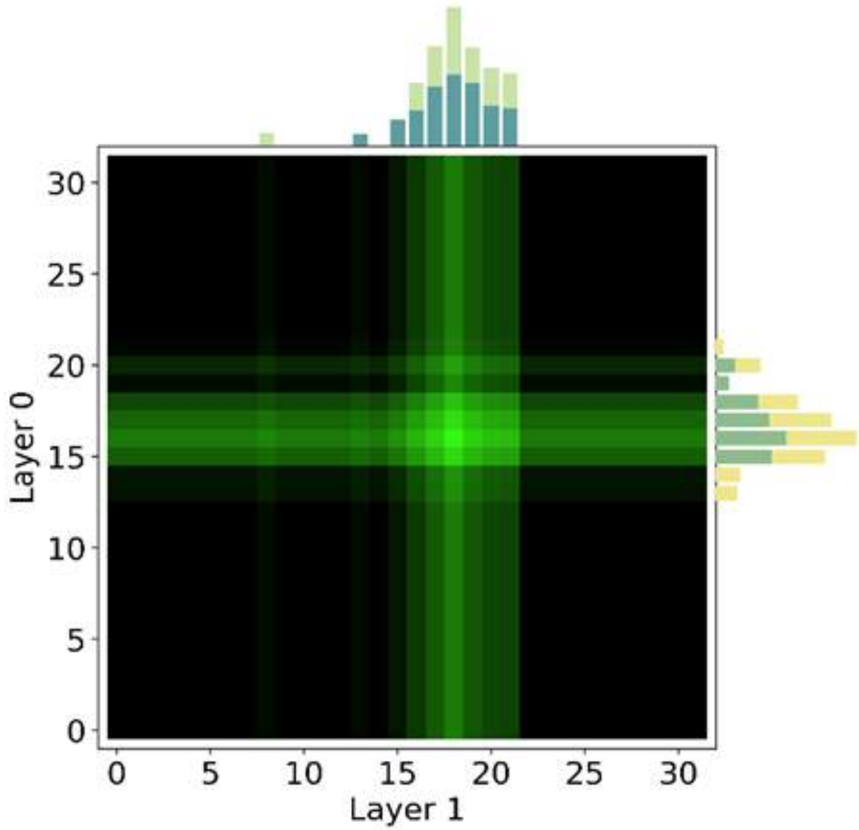

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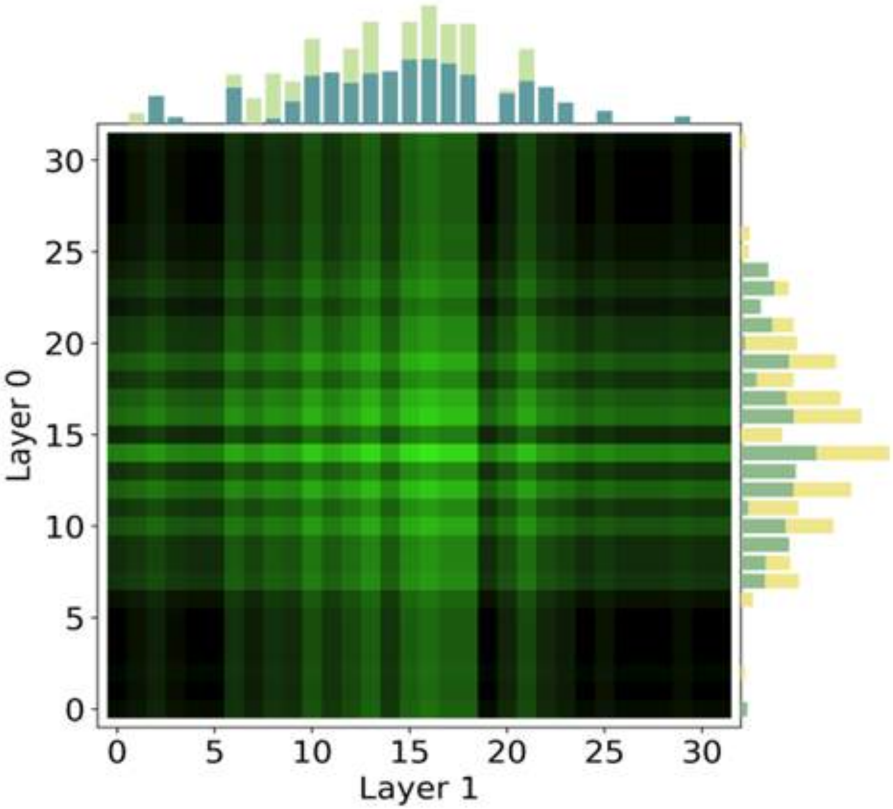
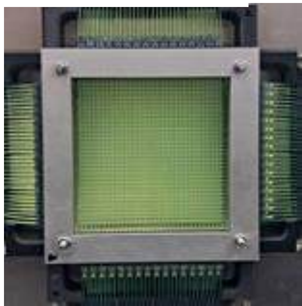
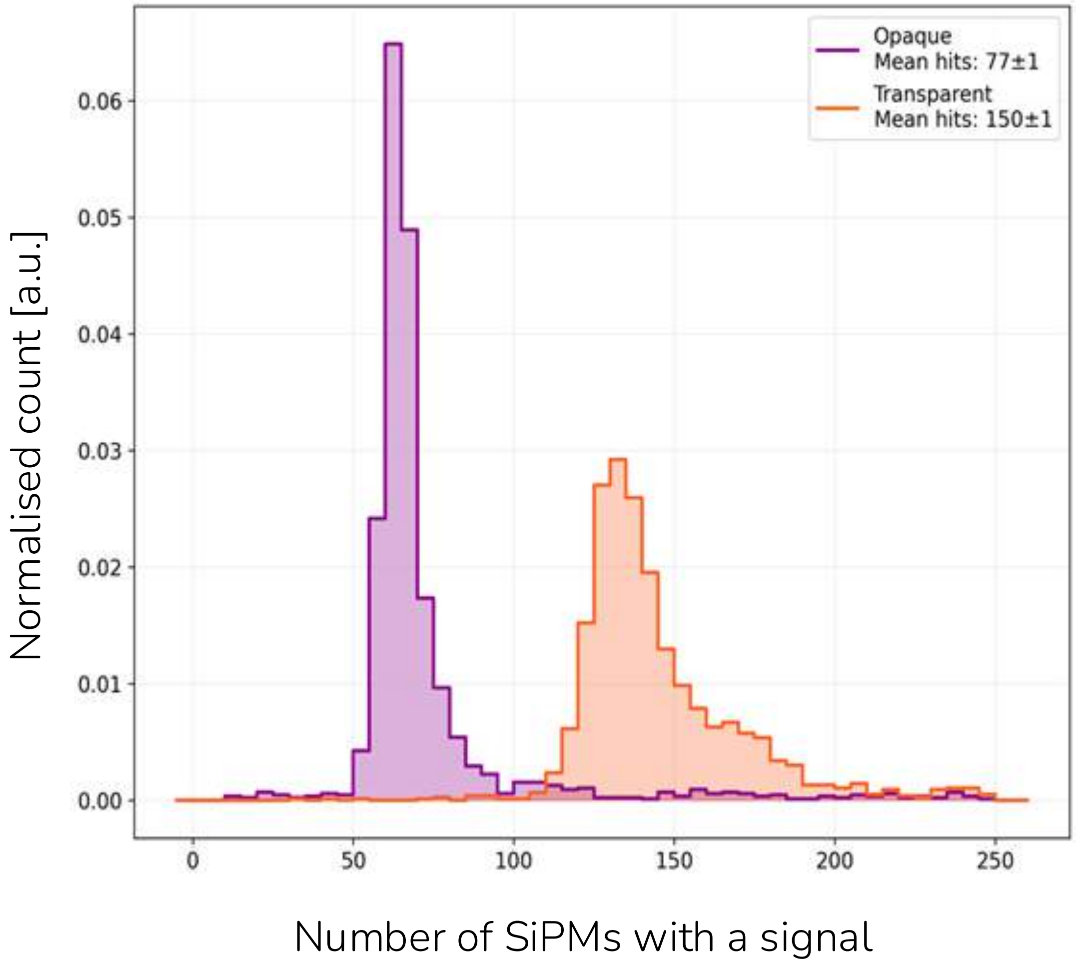


Detect 18,000 cosmic ray muons an hour!



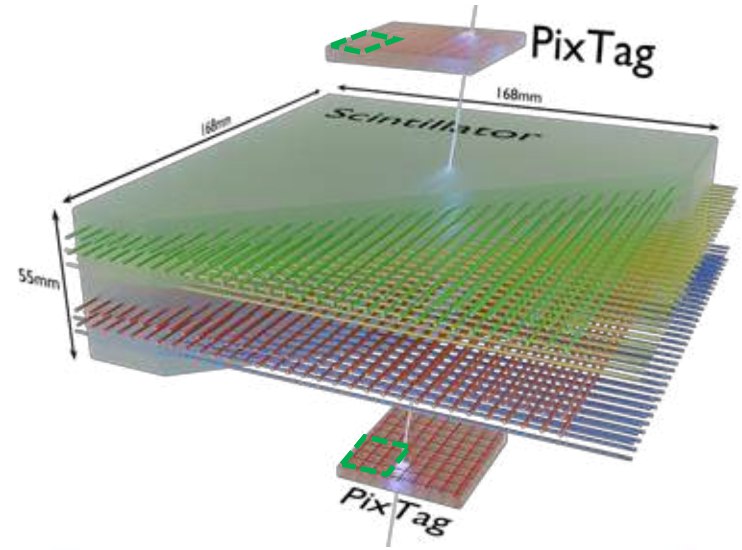
Muon hit distributions

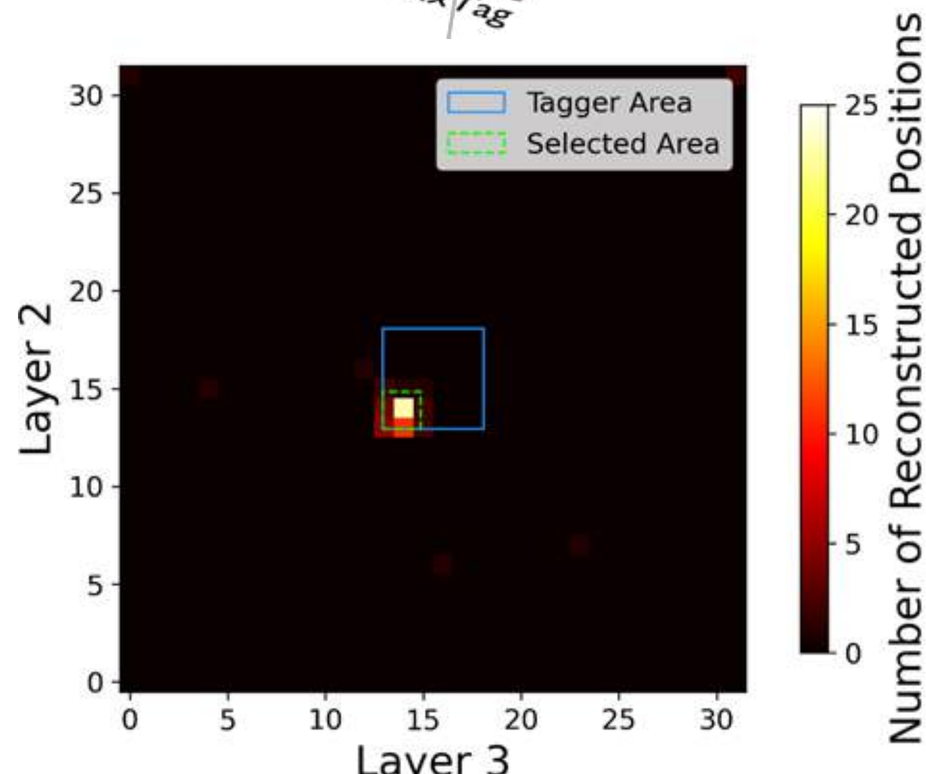
- Many fewer hits in opaque case
- Light is concentrated in fewer channels



Position Resolution

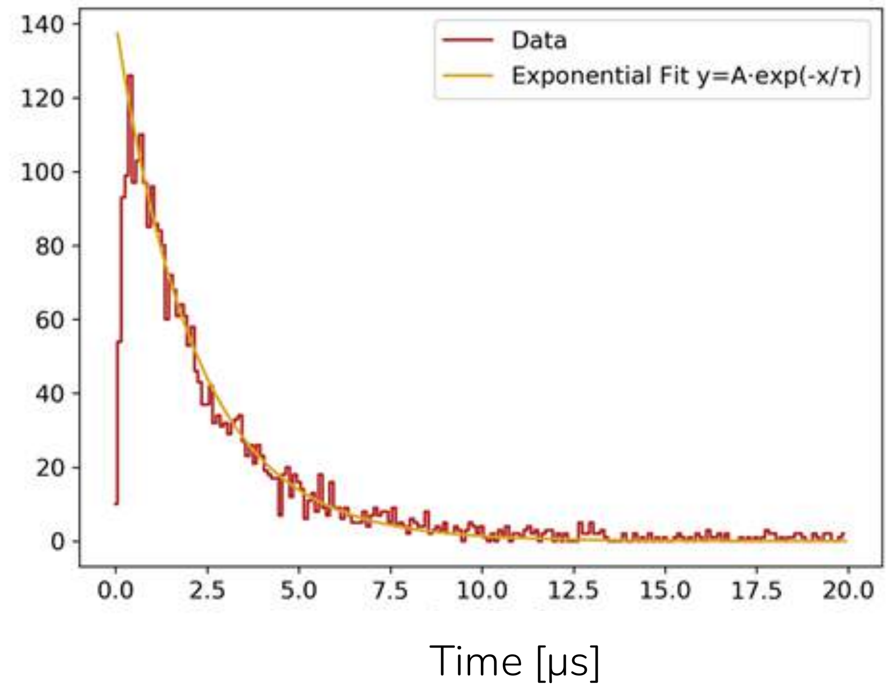
- First, qualitative demonstration
- Selecting on the bottom left 3x3 pixels of the 8x8 taggers
- More quantitative results to come



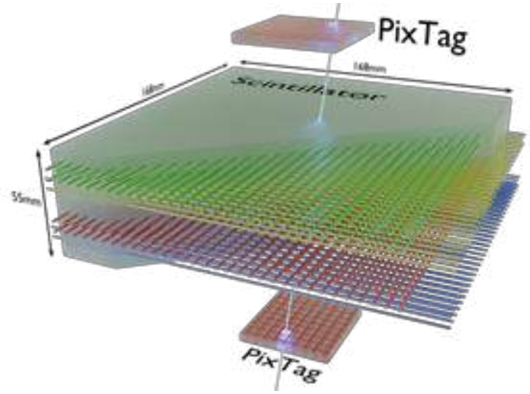


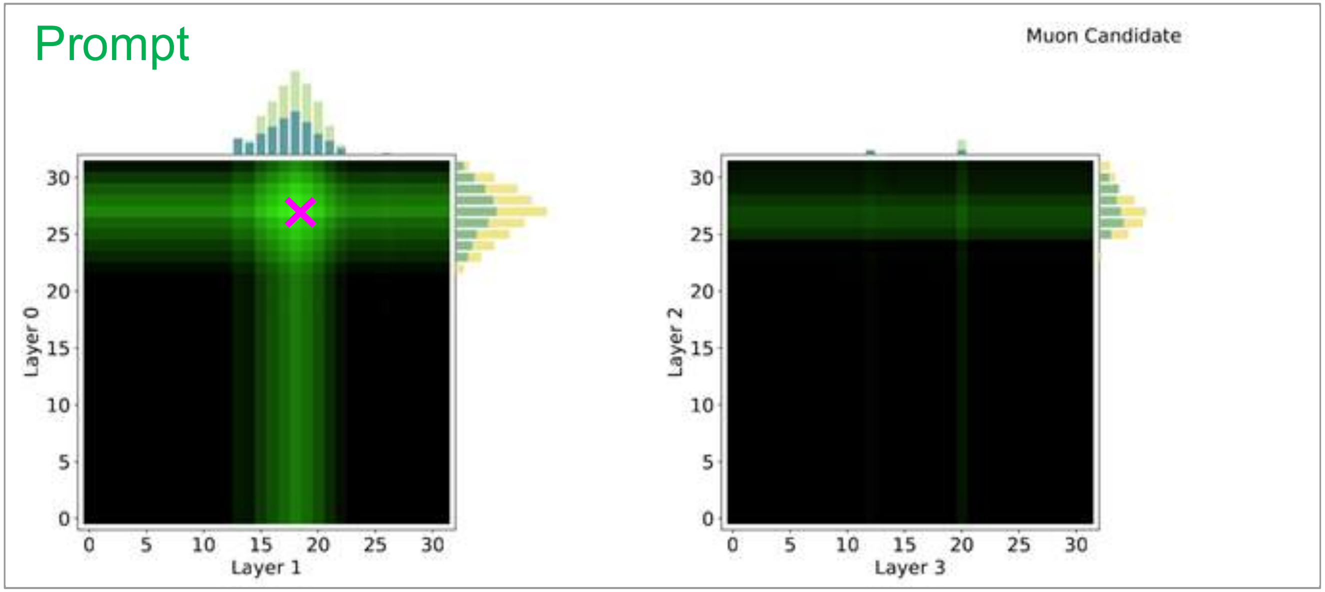
Michel Electrons

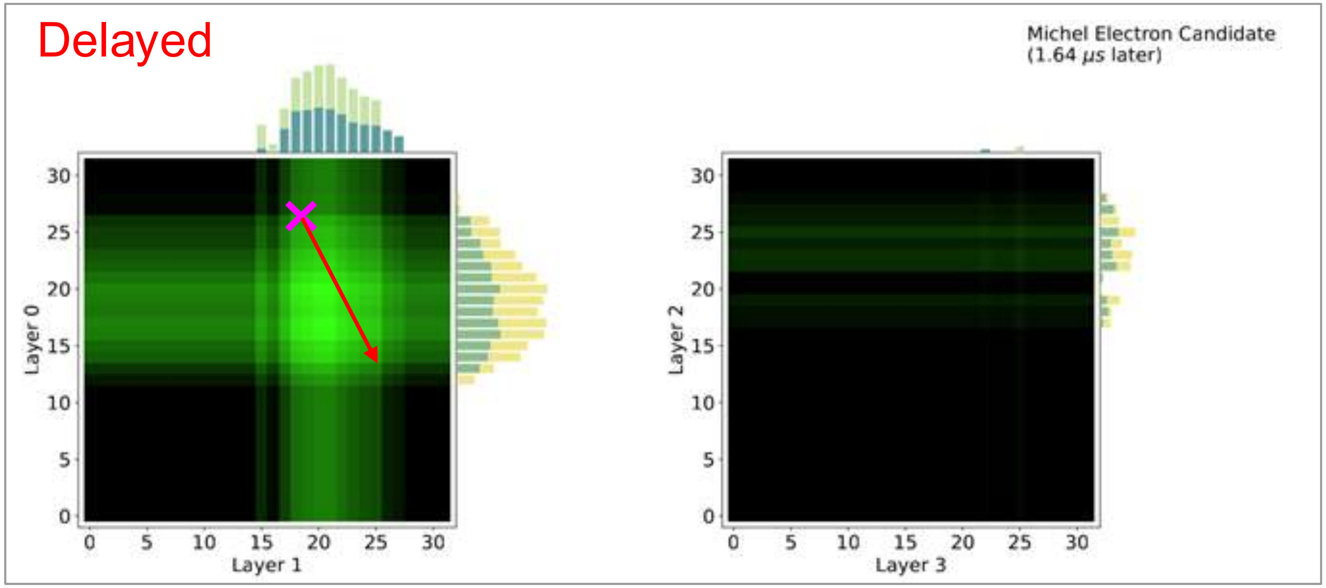
- Classic undergrad lab experiment
  - Look for energetic events in delayed coincidence
- Some cosmic ray muons stop in the detector
  - Decay to an electron (plus 2 neutrinos)
  - Lifetime 2.2 μs
- Sussex Tile results
  - 0.4 to 4.4 μs delayed coincidence
  - 2123 events observed
  - background of 10 expected
- Fit gives τ = (2.16 ± 0.04) μs
- 99.5% purity of Michel electrons estimated



Michel Electron Candidate



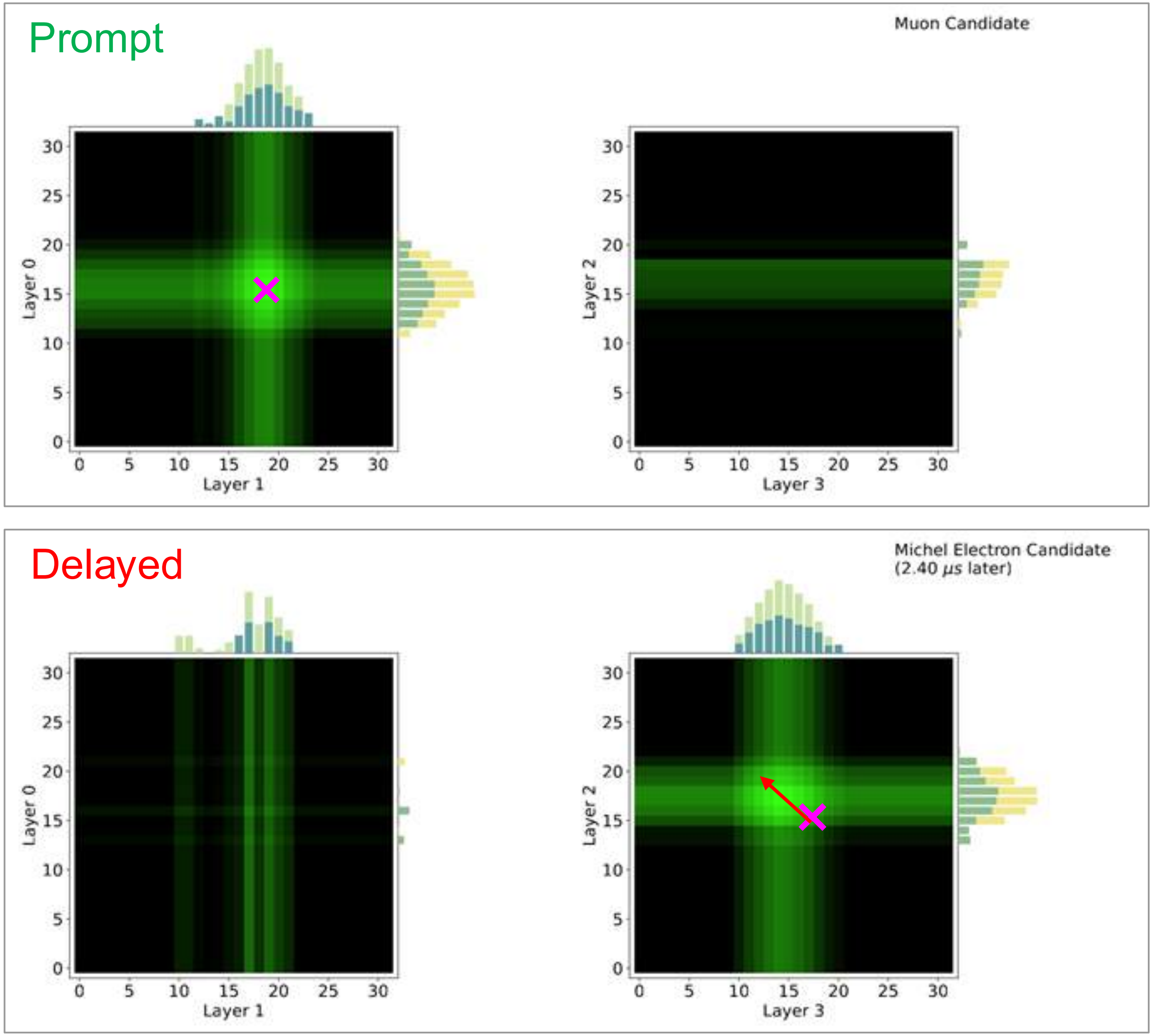


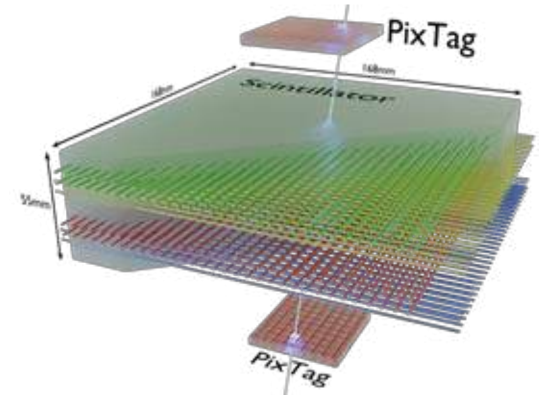


× = estimation of muon stopping position

↑ × = estimate of Michel electron location

Michel Electron Candidate



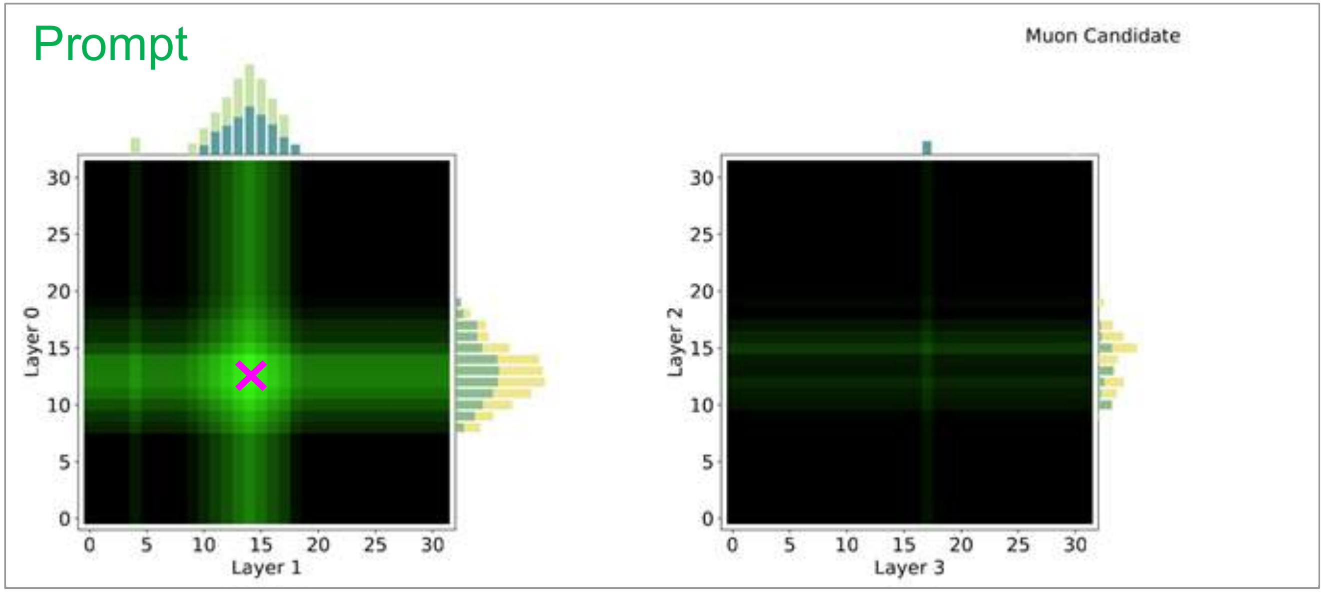


× = estimation of muon stopping position

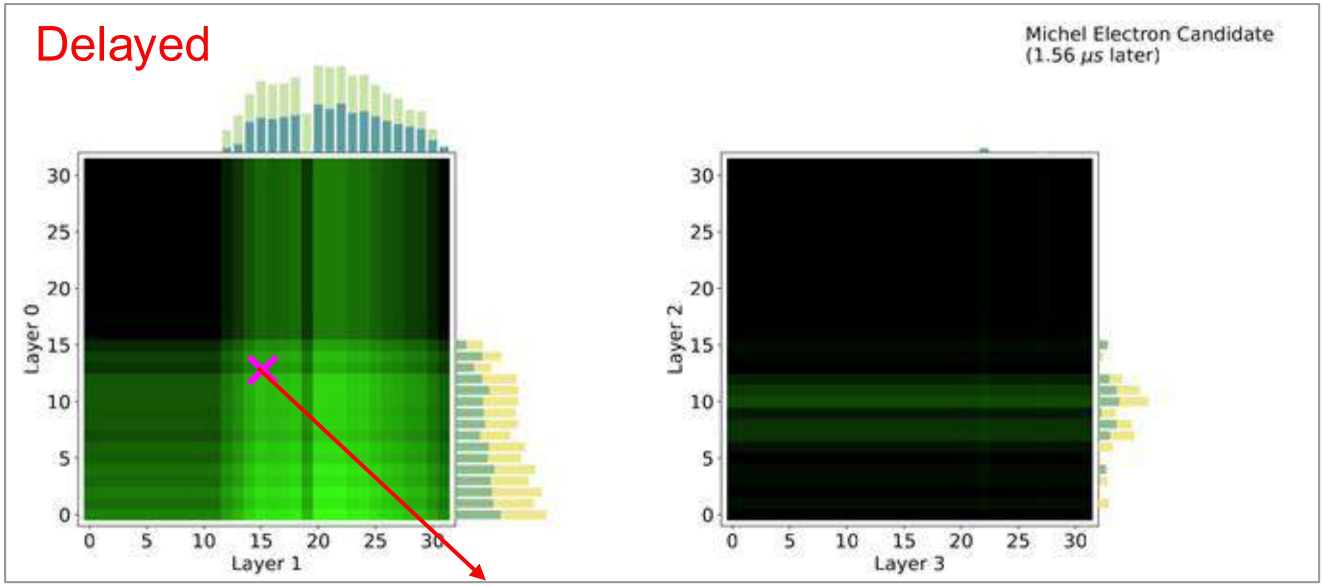
↑ × = estimate of Michel electron location

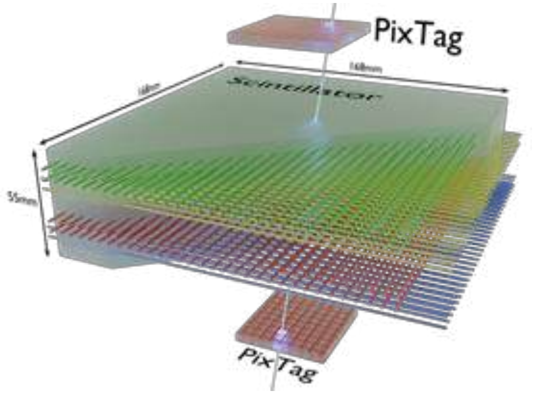
Michel Electron Candidate

Prompt



Delayed





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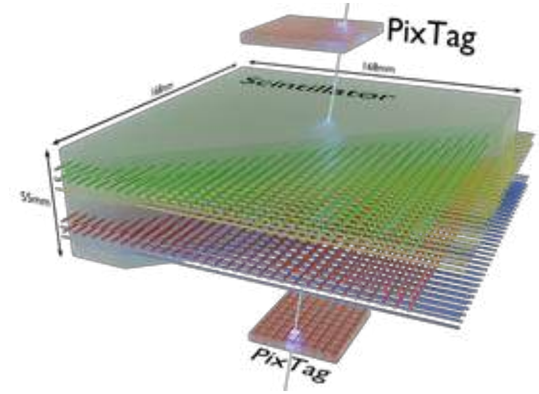
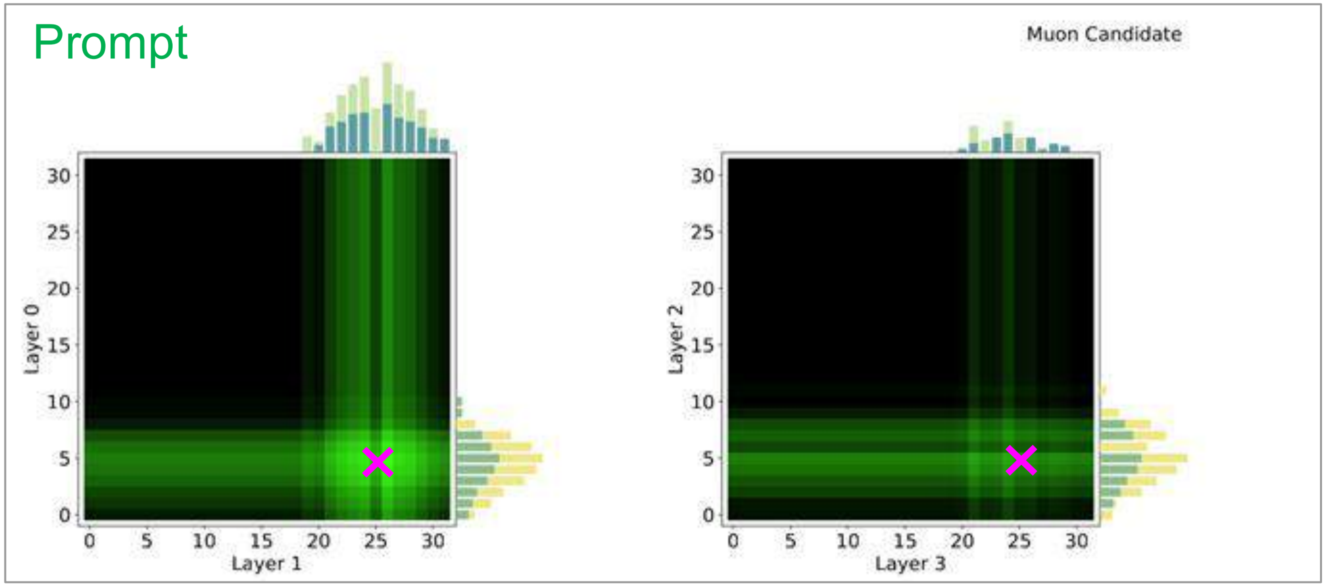
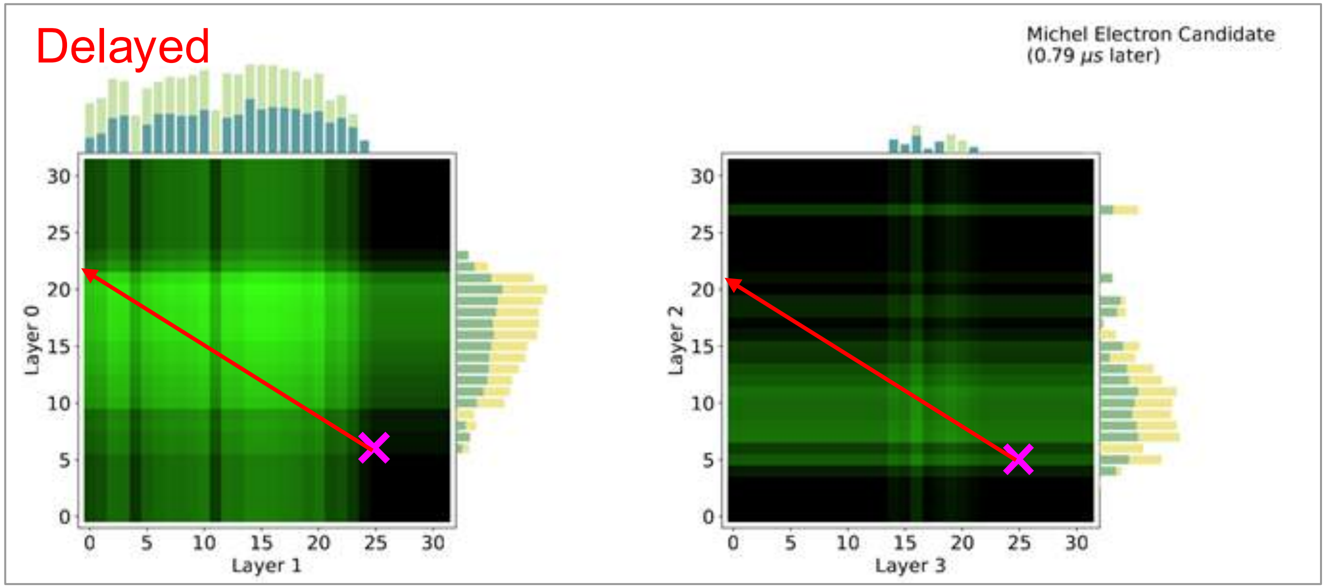
↑ × = estimate of Michel electron location

Michel Electron Candidate







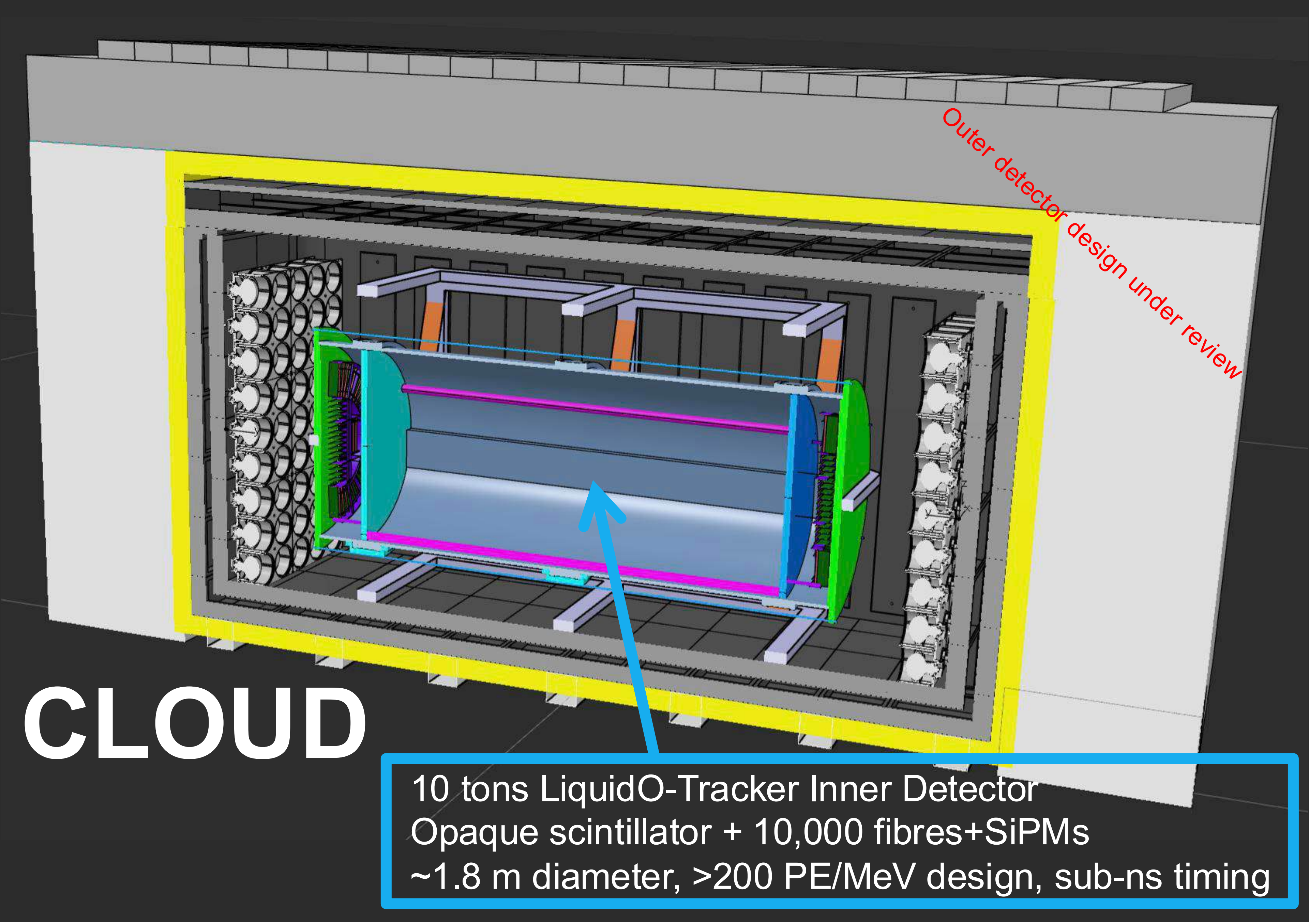
× = estimation of muon stopping position

↑ × = estimate of Michel electron location

Pros and cons (LiquidO)

- Get excellent spatial resolution (predict 5-10x better for same cost)
- Get good timing resolution (1 ns)
- Need 5-10x less sensors than segmented for same performance
  - Sensors are expensive
- Don't have to physically segment
  - Less complexity/cost to manufacture
    - still need a lattice of fibres
  - Don't introduce inactive material
- Collect more photons than segmented
- Can get excellent radiopurity
- Technology is developing rapidly

Next Steps


Outer detector design under review
CLOUD
10 tons LiquidO-Tracker Inner Detector
Opaque scintillator + 10,000 fibres+SiPMs
~1.8 m diameter, >200 PE/MeV design, sub-ns timing

European Innovation Council

UK Research and Innovation

CLOUD

International collaboration

- EDF (France) — first time in neutrino science
- LP2I Bordeaux (France)
- Brookhaven National Laboratory (USA)
- Charles University (Czechia)
- CIEMAT (Spain)
- IJCLab / Université Paris-Saclay (France)
- Imperial College London (UK)
- INFN-Padova (Italy)
- Instituto Superior Técnico (Portugal)
- Johannes Gutenberg Universität Mainz (Germany)
- Pennsylvania State University (USA)
- Pontifícia Universidade Católica do Rio de Janeiro (Brazil)
- Queen's University (Canada)
- Subatech / Nantes Université (France)
- Tohoku University / RCNS (Japan)
- Universidad de Zaragoza (Spain)
- Universidade Estadual de Londrina (Brazil)
- University of California Irvine (USA)
- University of Michigan (USA)
- University of Sussex (UK)
- Rutherford Appleton Laboratory (UK)

⟹ 21 institutions in 11 countries

Spokespersons:

- A. Cabrera — IJCLab / Université Paris-Saclay (France)
- J. Hartnell — Sussex University (UK)

IB Chair:

- M. Chen — Queen's University (Canada)

https://antimatter-otech.ijclab.in2p3.fr/ [AM-OTech]
https://liquido.ijclab.in2p3.fr/nucloud [via LiquidO]

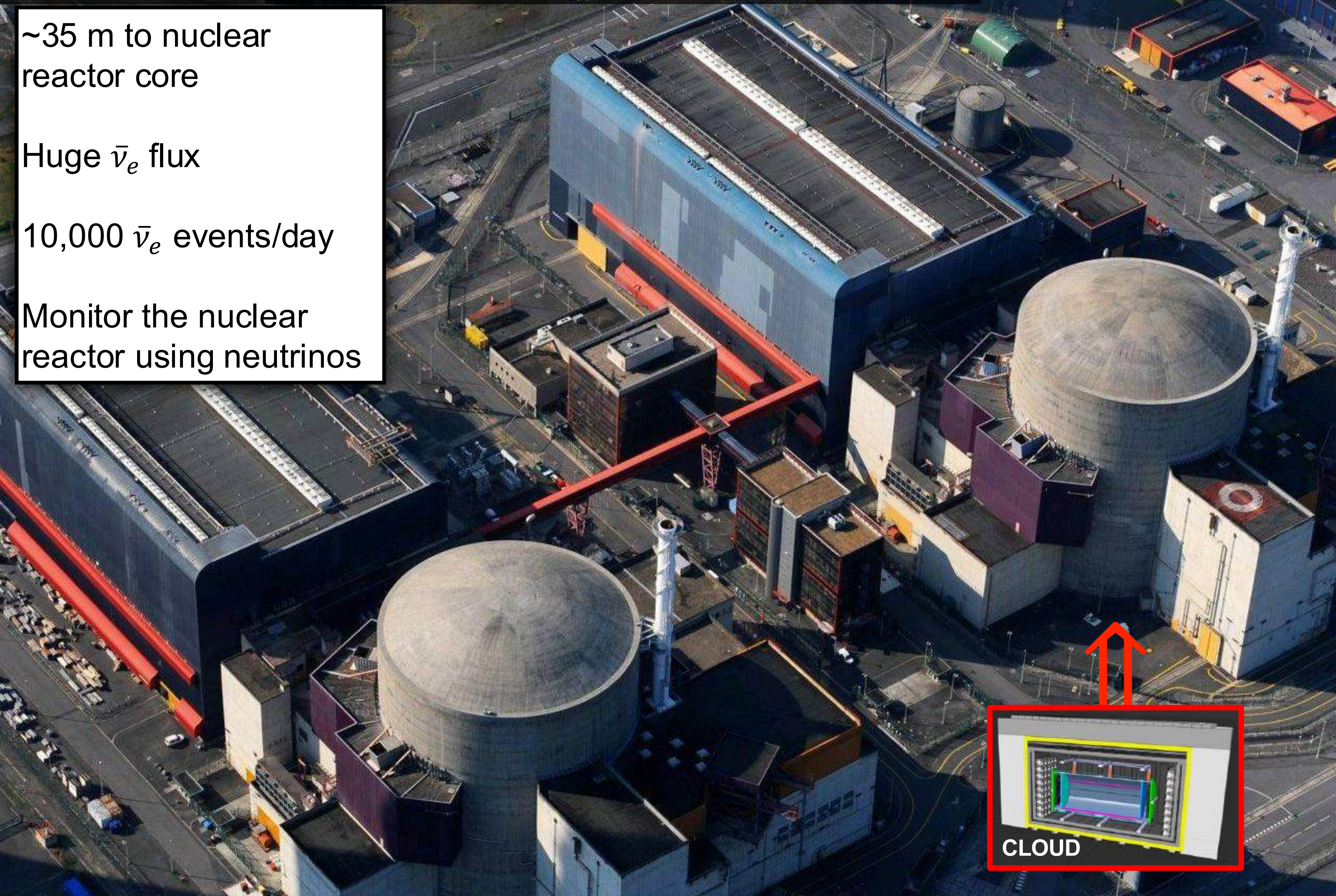
Place by Chooz nuclear reactor

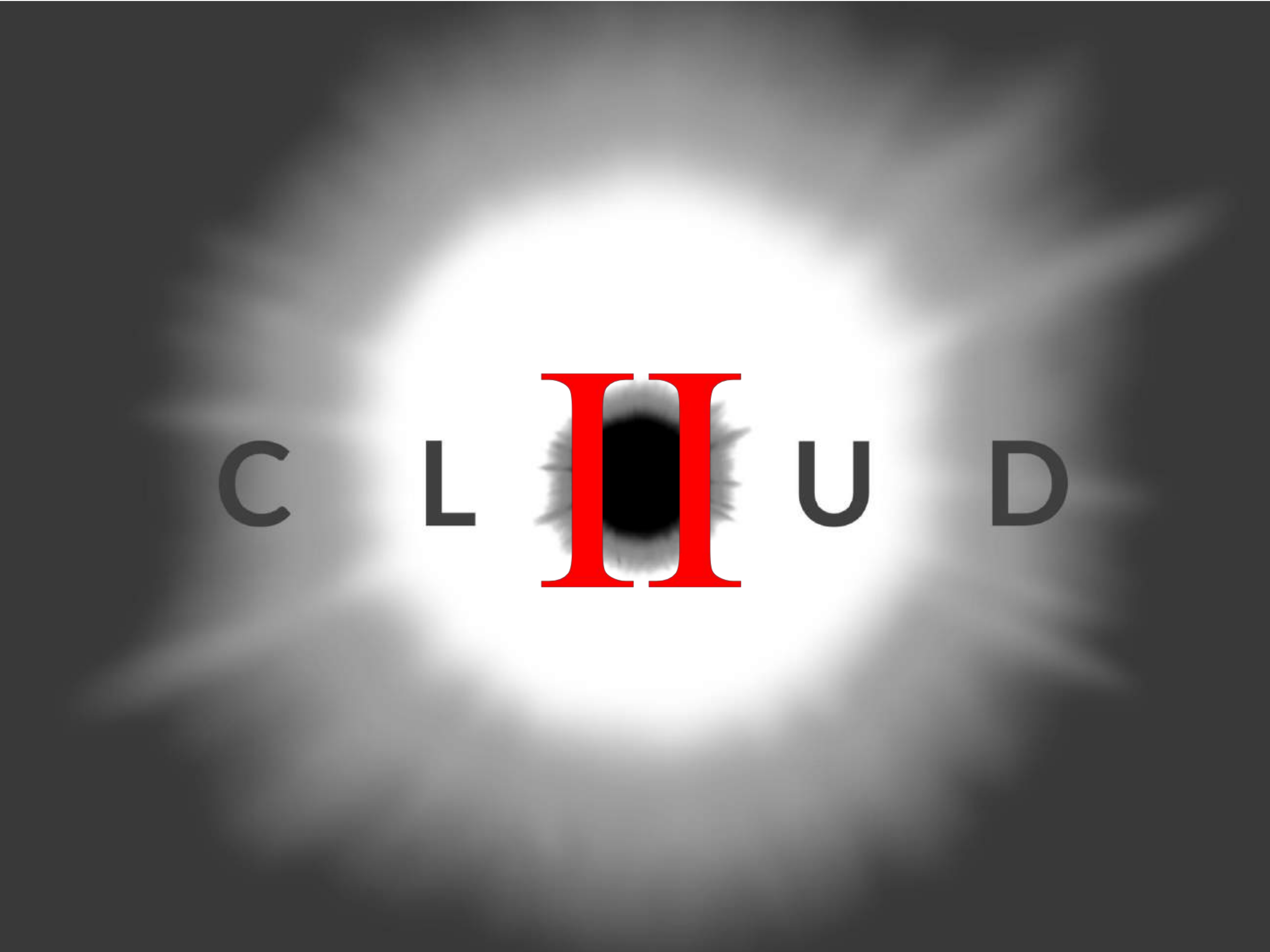
~35 m to nuclear reactor core

Huge $\bar{\nu}_e$ flux

10,000 $\bar{\nu}_e$ events/day

Monitor the nuclear reactor using neutrinos




C L II U D

Indium Loading in Scintillator

- Electron neutrino CC with indium nucleus

$$\nu_e + {}^{115}In \rightarrow e^- + {}^{115}Sn^*$$
$$\hookrightarrow \gamma/e^- \; (116\,keV) + \gamma \; (497\,keV)$$

- Very low threshold (114 keV)
- High natural abundance (96%)
- Fast delayed coincidence ($\tau = 4.8\,\mu s$)
- Signature: multi-fold coincidence
  - Require right particles in right places at right times with right energies…
  - LiquidO precision imaging means
    - can require 1st e^- to be in same cubic cm of the detector as the 2nd e^-
    - can require a nearby gamma-like event has 497 keV in time with 2nd e^-

Why indium?

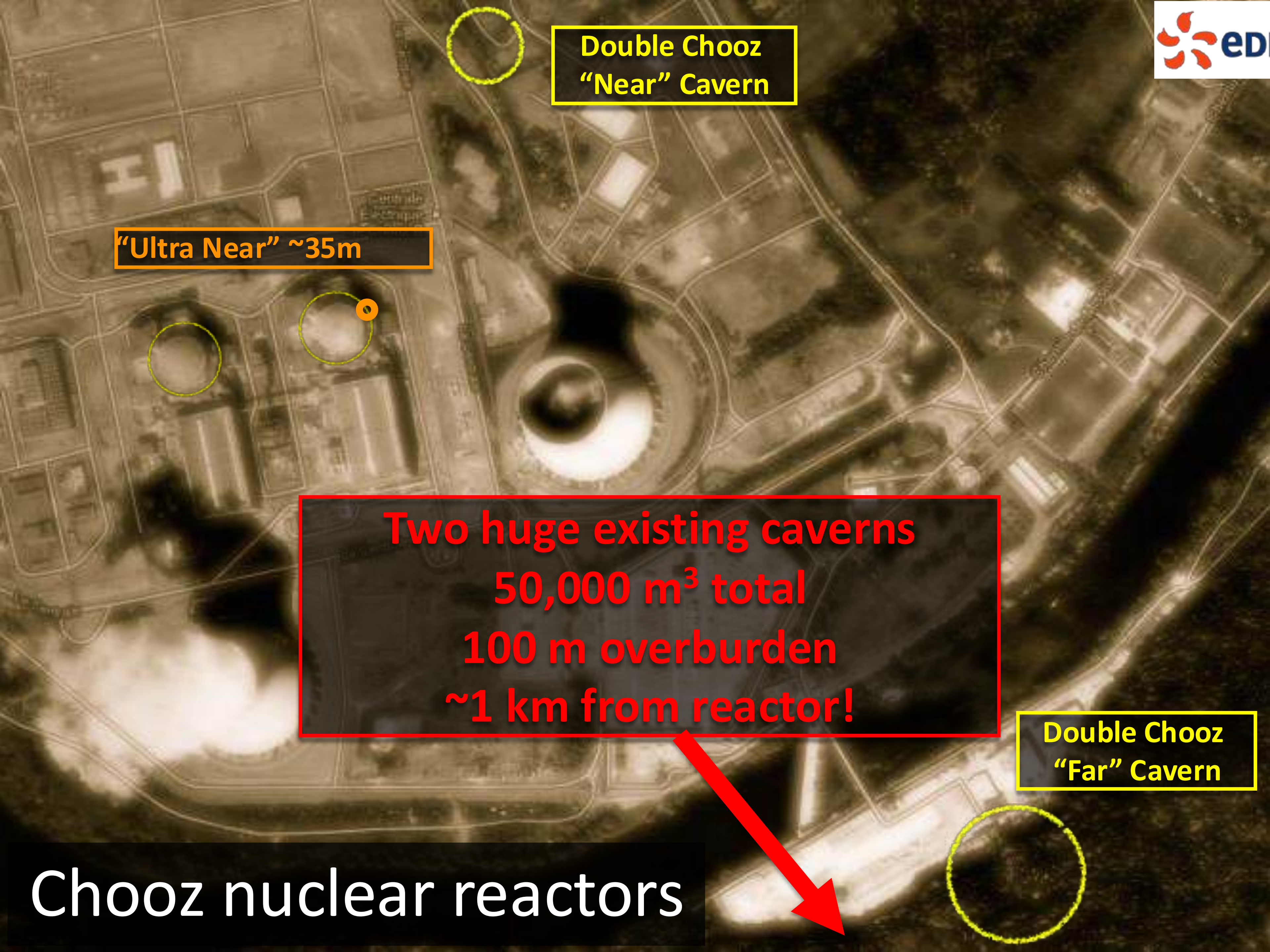
- Opens multiple new physics opportunities
- Historically low energy ν_e detected using elastic scattering (or radiochemical)
  - Successful but limitations
  - Poor event-by-event energy information
  - Requires extreme radiopurity
    - Complex detector construction
    - Deep underground sites
- Indium enables low energy ν_e spectroscopy, potentially on the surface
  - Solve the 5σ neutrino gallium anomaly
    - https://arxiv.org/abs/2507.07397
  - Solar neutrino spectroscopy
  - Search for reactor $\bar{\nu}_e \rightarrow \nu_e$ transitions
- LiquidO detector technology makes indium, a 50 year old idea, experimentally feasible
- CLOUD Phase II is the pilot project

SUPERCHOOZ

CERN Seminar: ***"The SuperChooz Experiment: Unveiling the Opportunity"***

https://indico.cern.ch/event/1215214/

https://zenodo.org/record/7504162


Double Chooz
"Near" Cavern
"Ultra Near" ~35m
Two huge existing caverns
50,000 m³ total
100 m overburden
~1 km from reactor!
Double Chooz
"Far" Cavern
Chooz nuclear reactors

Many other ideas

E.g. GeV neutrino physics

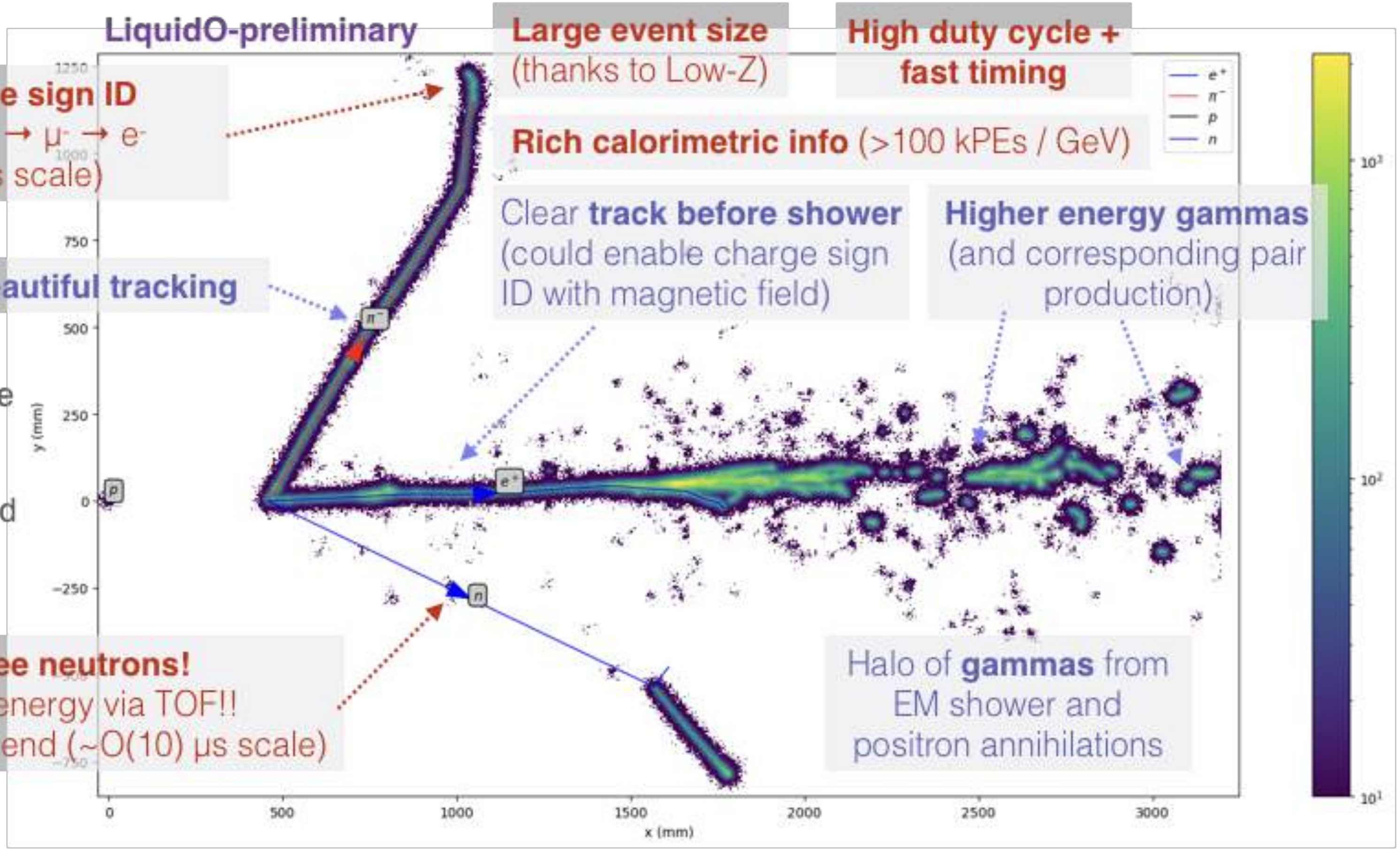
DUNE 4th Far Detector Module?

DUNE Near detector?

HyperK Near detector?

– LiquidO would reveal GeV-neutrino interactions in **extremely powerful** way:

(2 GeV electron antineutrino; 4 mm fibre pitch and 1 mm scattering length; inefficiencies associated with photon detection are accounted for)



Imaging capabilities comparable to those of LArTPC + **Complementary features unique to LiquidO**

Applications

Applications outside particle physics

- LiquidO provides large scale, cost-effective high-resolution imaging detectors
- Muon tomography
  - Huge array of projects currently using segmented detectors
- Gamma ray imaging (Compton camera)
  - LiquidO detector on a satellite for astronomy
    - https://doi.org/10.1016/j.astropartphys.2025.103135
  - Homeland security
  - Medical imaging
    - PET scanners (LPET project)

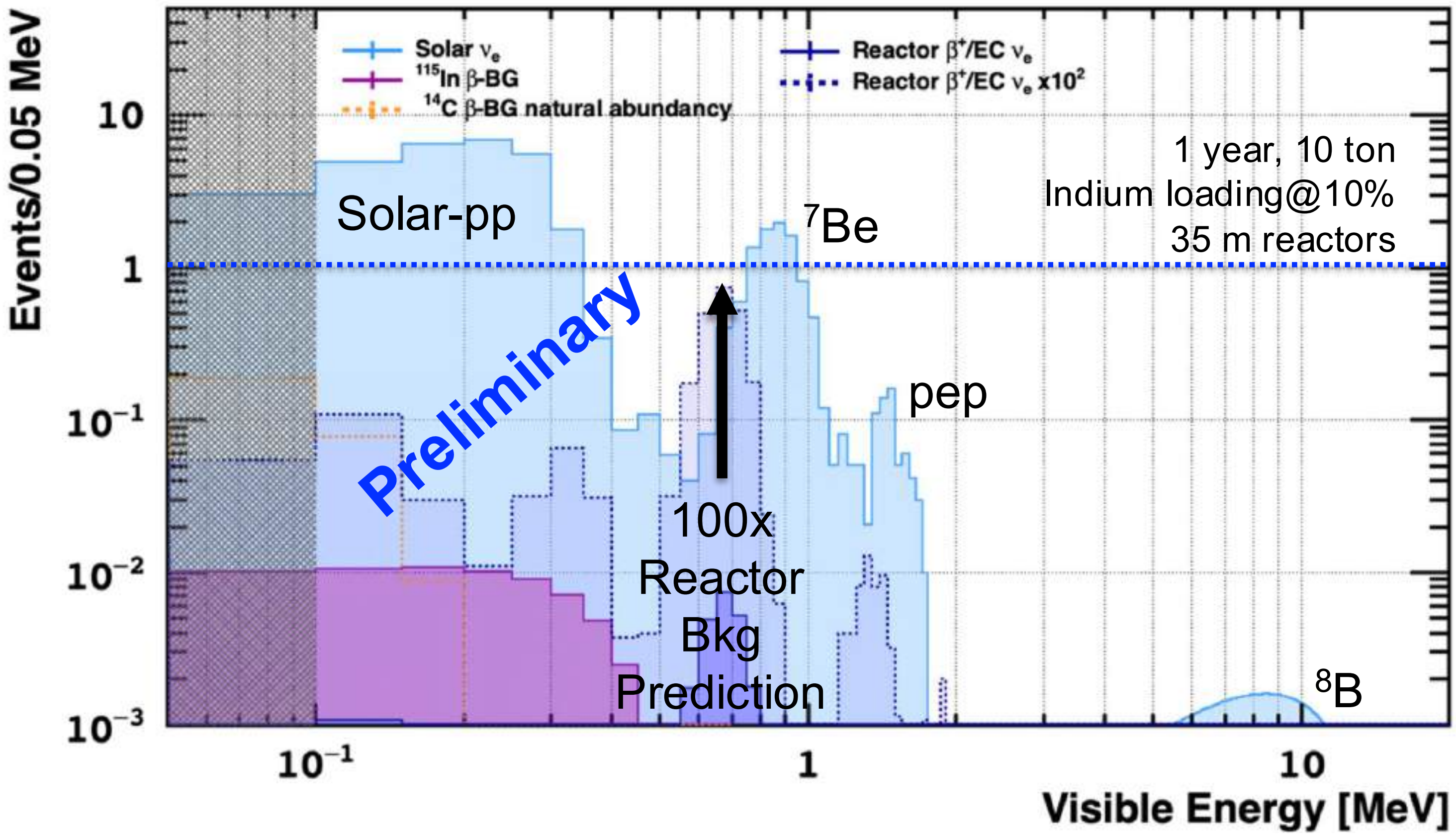
Conclusions

- Innovative new "LiquidO" detector technology
  - Opaque scintillator + lattice of fibres
  - High-resolution imaging and particle identification
  - 5-10x better performance/cost than traditional segmented detectors
- R&D progressing rapidly
- LiquidO opens new opportunities
  - Particle physics
  - Astronomy
  - Muon tomography
  - Gamma ray imaging
- LiquidO is a whole new way of thinking about a scintillator detector
  - we've only just started… your ideas/contributions welcome!

The End

Backup slides

What's the Solar Neutrino Spectrum?



Solar-pp
~25/year

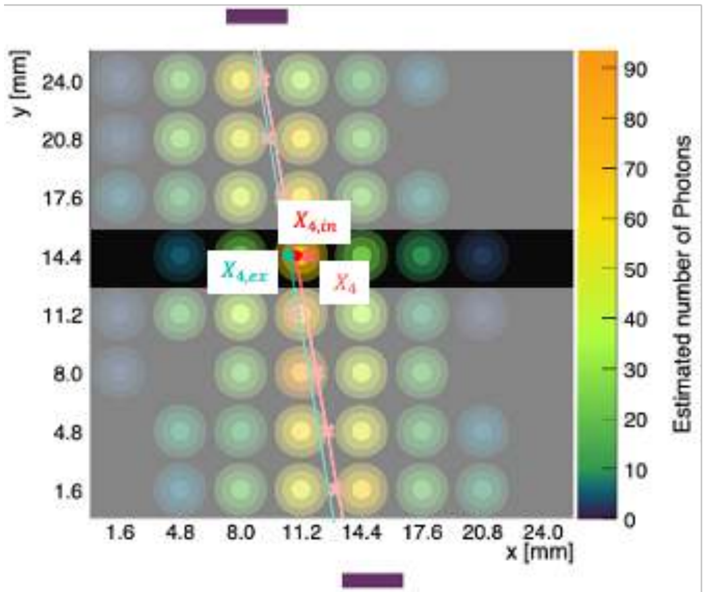
Solar-^{7}Be
~9/year

^{115}In
intrinsic bkg
~negligible
(w/ LiquidO)

^{14}C
~negligible

- Plot uses LENS background model
  - Under feasibility study for CLOUD
- Demonstrator for future SuperChooz expt.

POSITION RESOLUTION HOW TO



HOW TO MEASURE THE POSITION RESOLUTION?

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

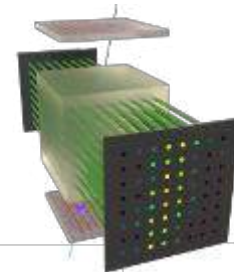
1. Track residuals are calculated twice: with the test row reconstructed position excluded ($X_{r,ex}$) and included ($X_{r,in}$) from the track fit.

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

OPAQUE



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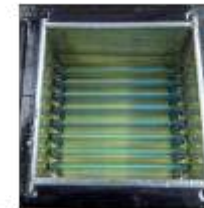

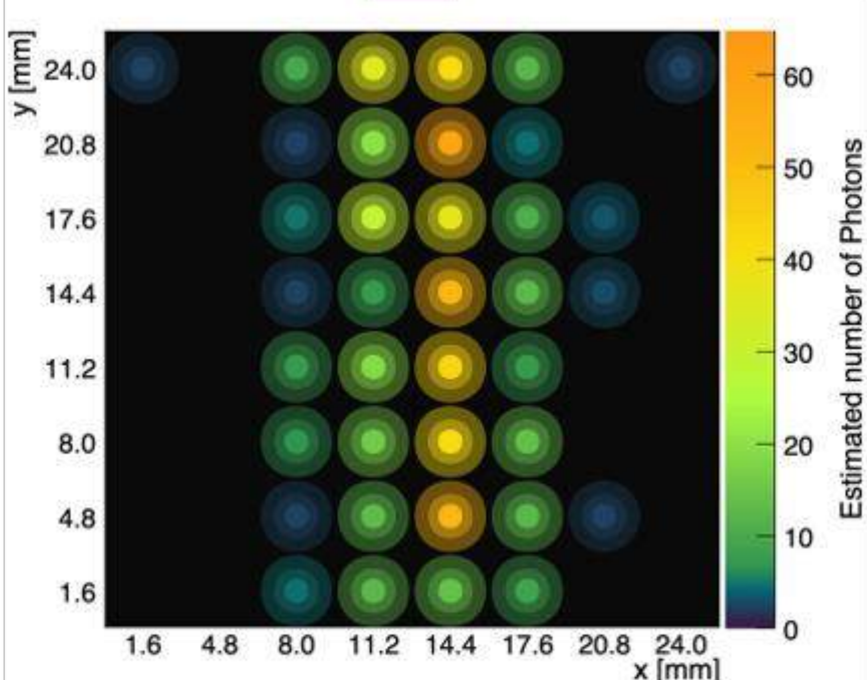

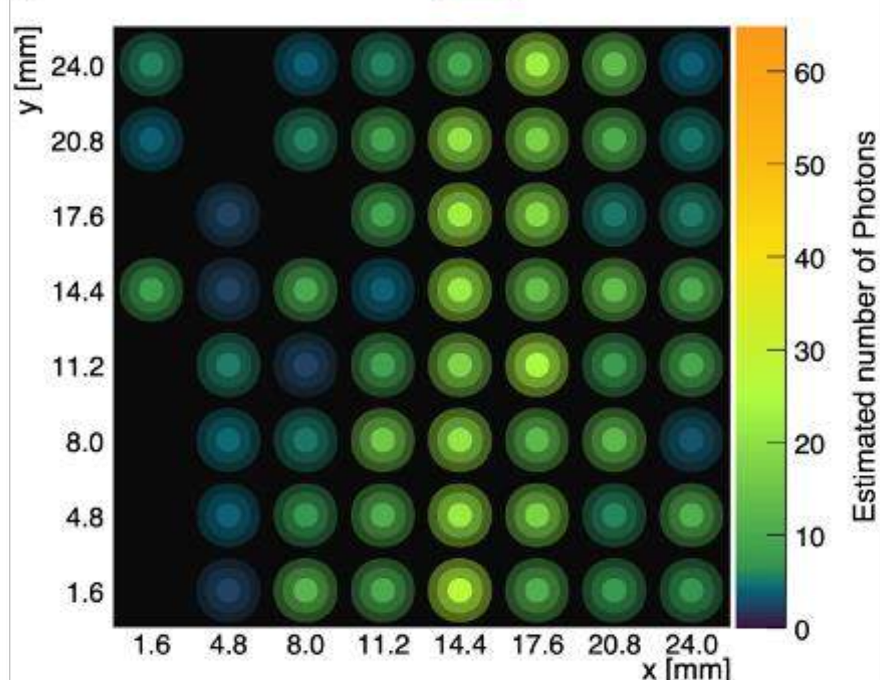

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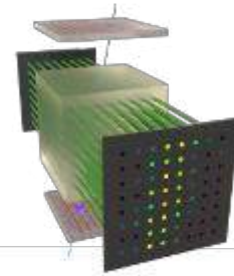

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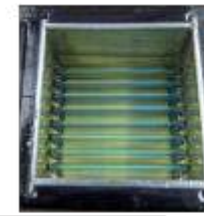

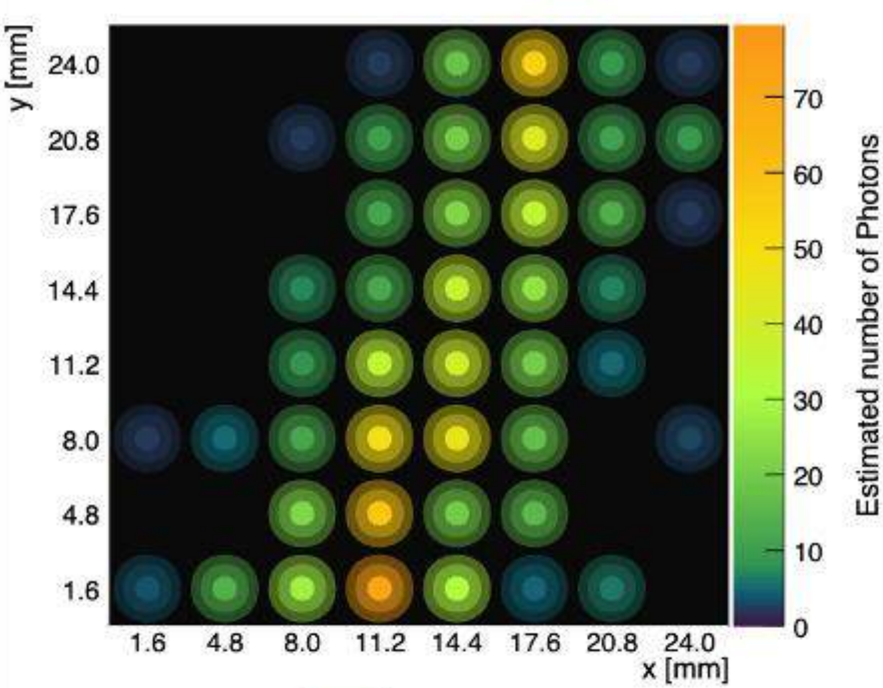

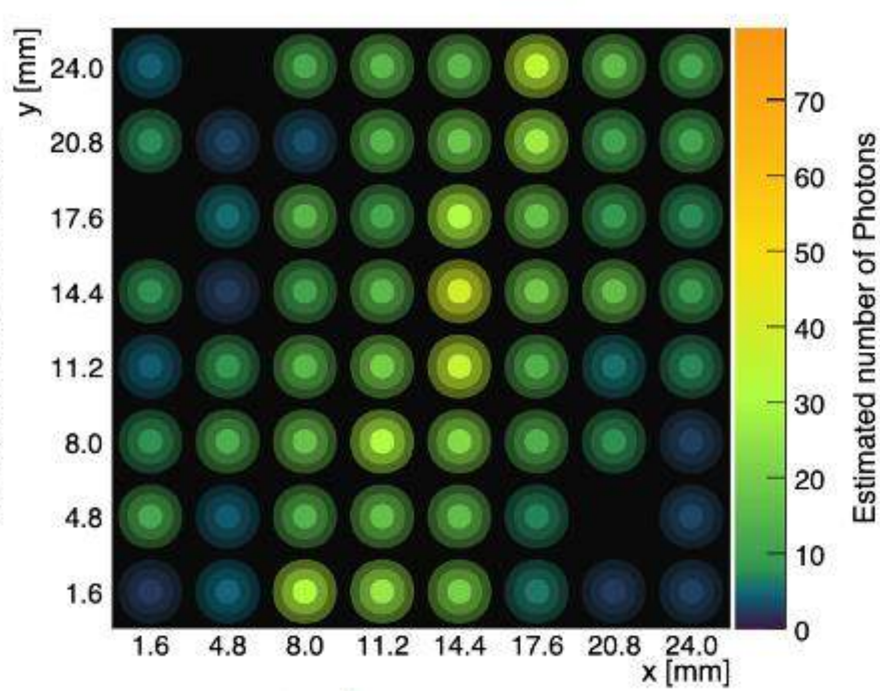

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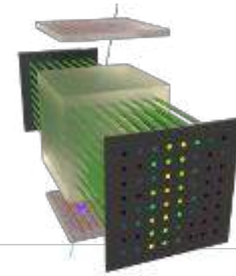

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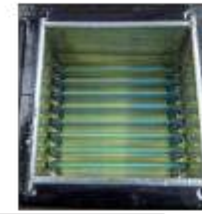

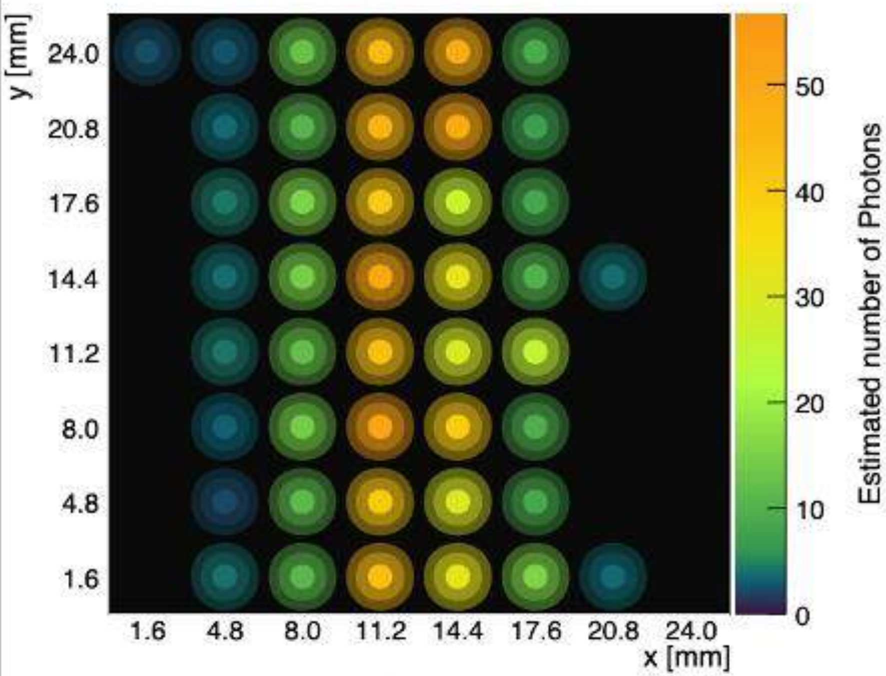

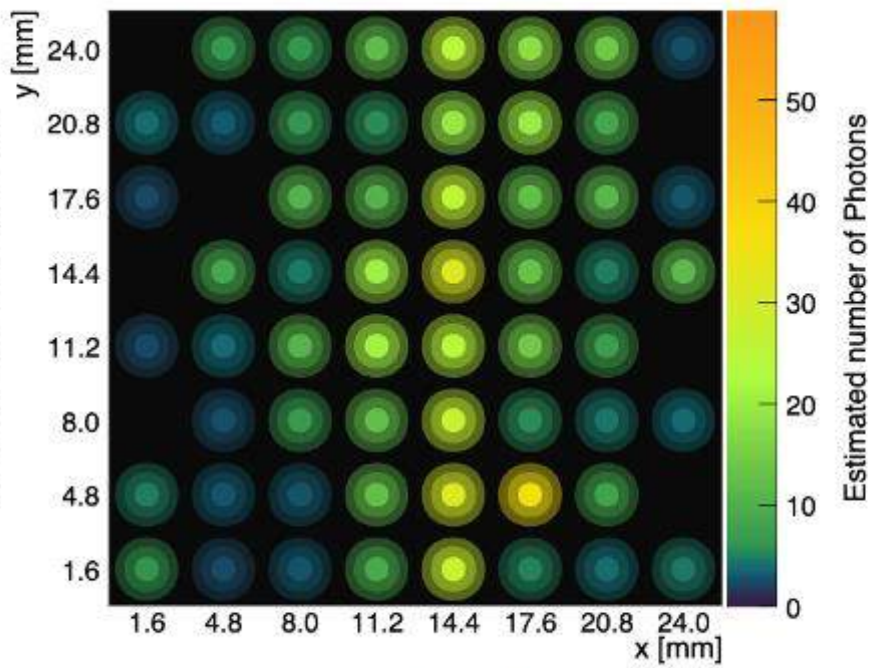

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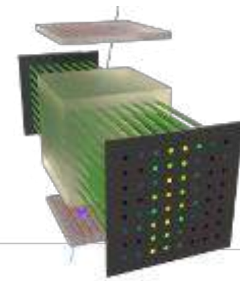

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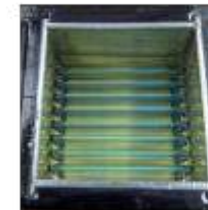
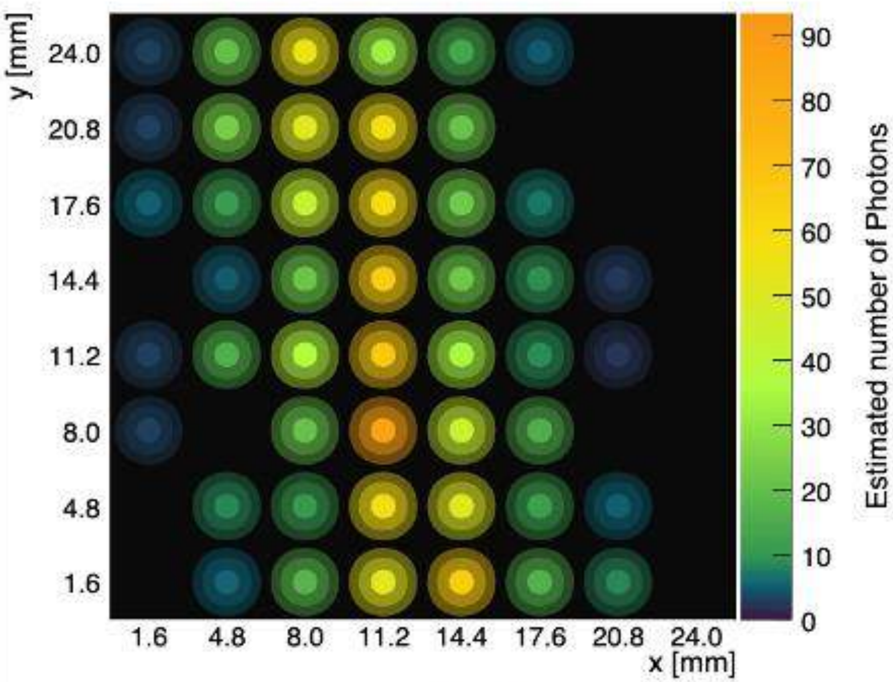
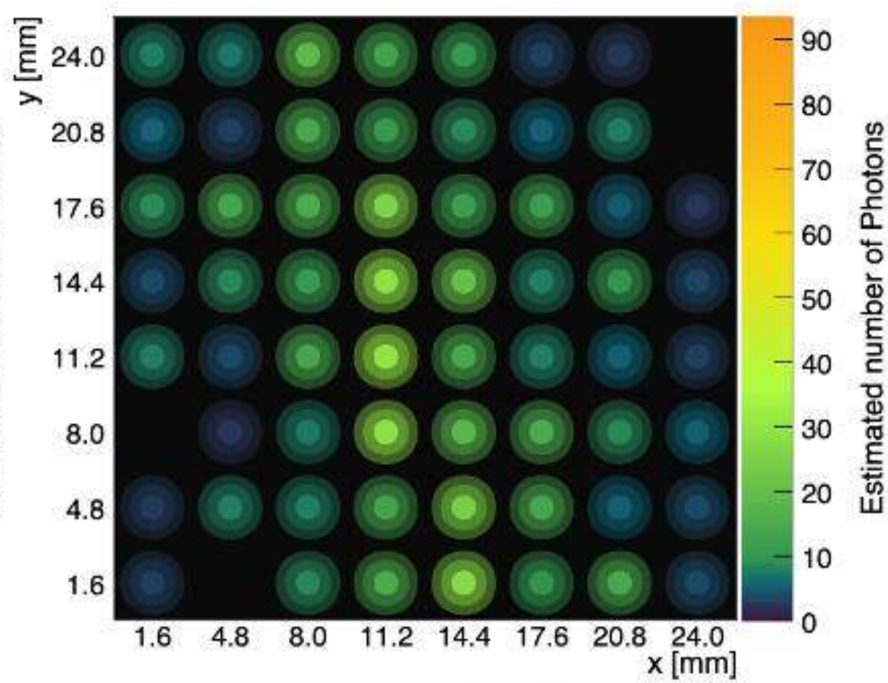
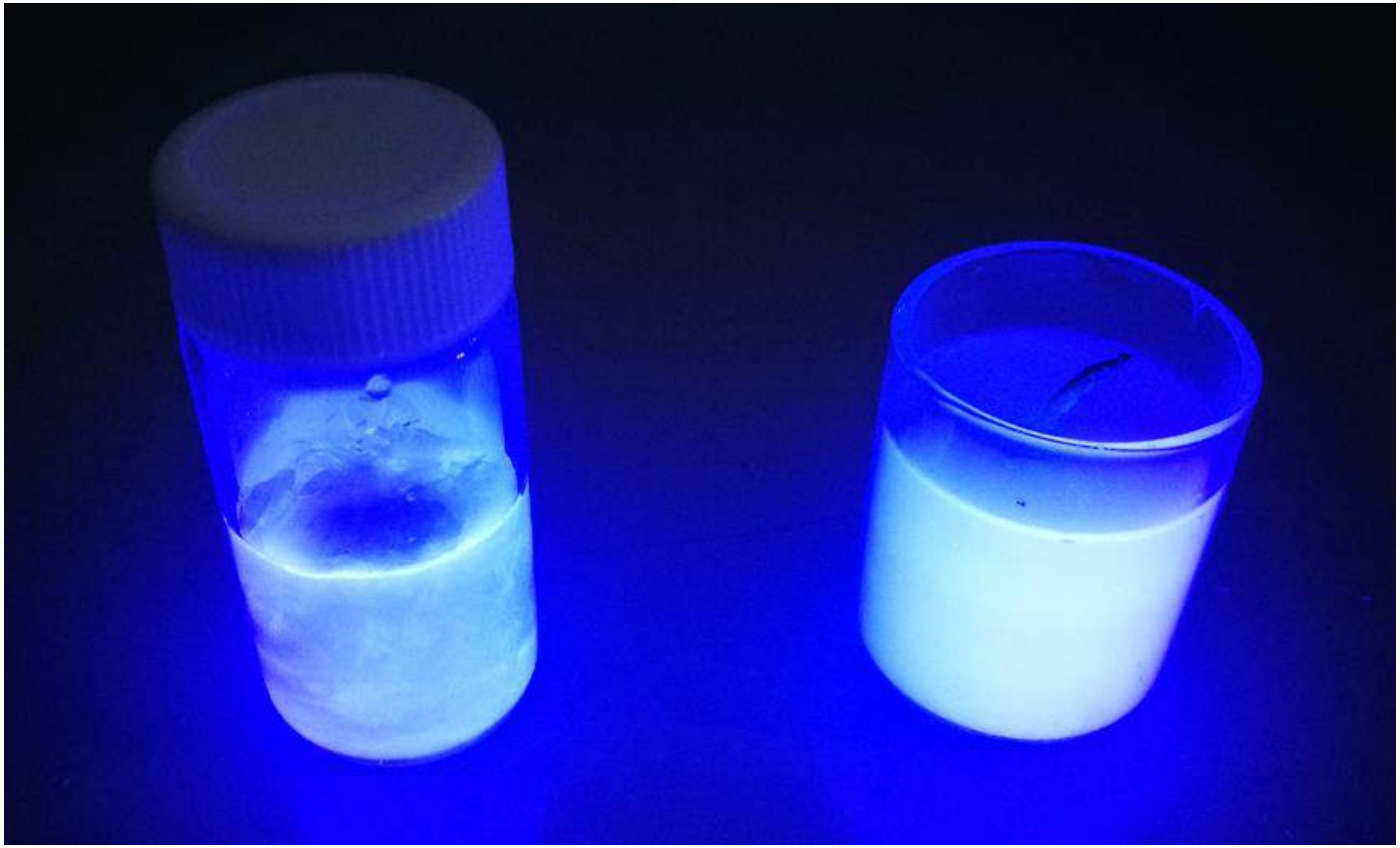






“NoWaSH” Opaque Scintillator



Behaviour similar to candle wax

Transparent liquid when warm (>36 degC)

Opaque solid when cooled (~25 degC)