# “LiquidO”
# An Opaque Detector


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For the LiquidO Proto-collaboration

University of Sussex



Conference on Neutrinos and Nuclear Physics, Cape Town

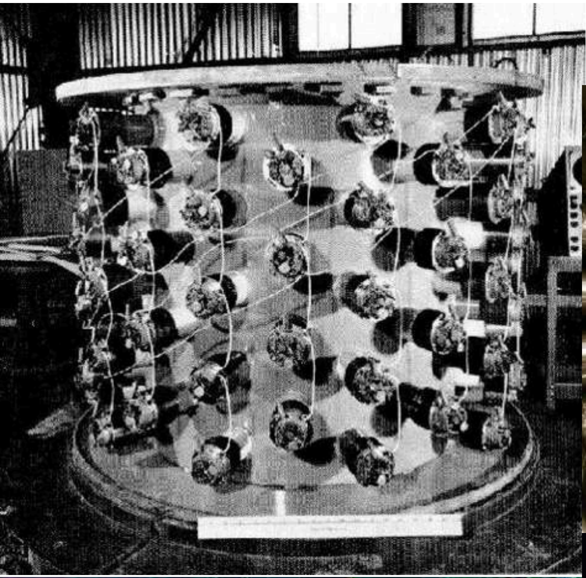
25th February 2020

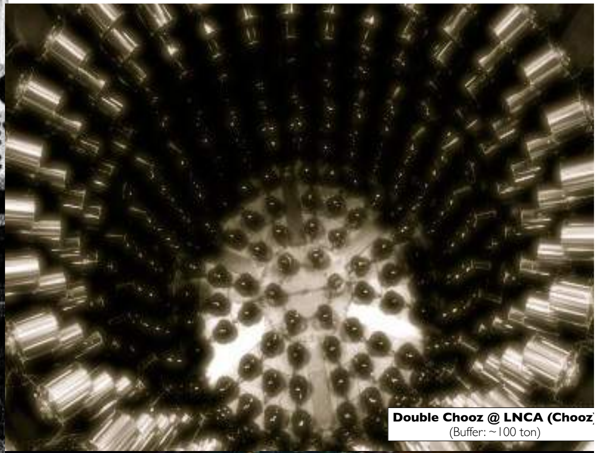
# Outline

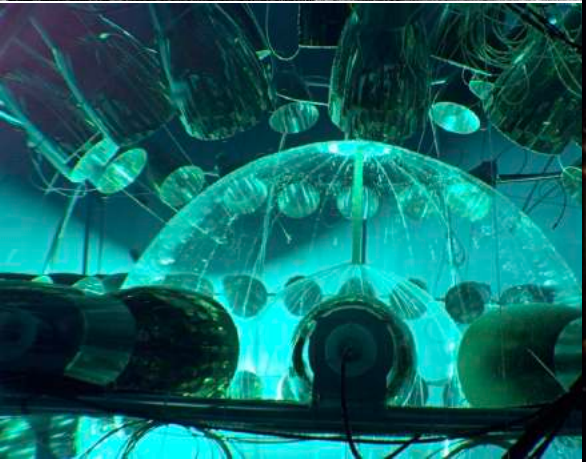
- LiquidO
  - Opaque scintillator
  - Lattice of fibre optic cables
- High resolution imaging capabilities
  - Particle identification (PID)
- First papers
- “NoWaSH” scintillator
- Proof of principle experiment
- Physics with LiquidO

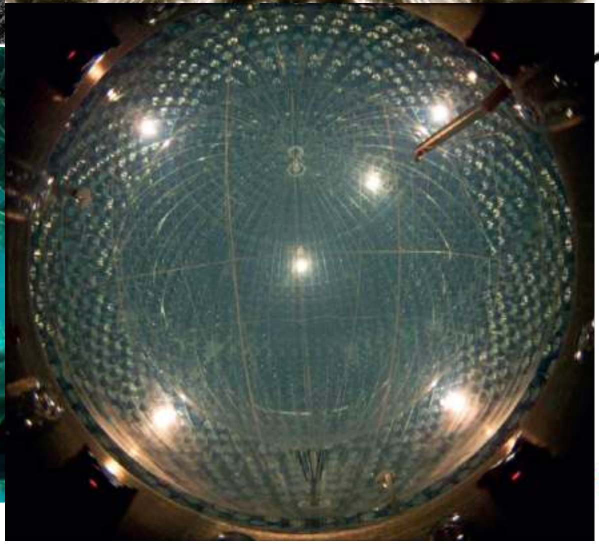
# Transparent scintillator detectors

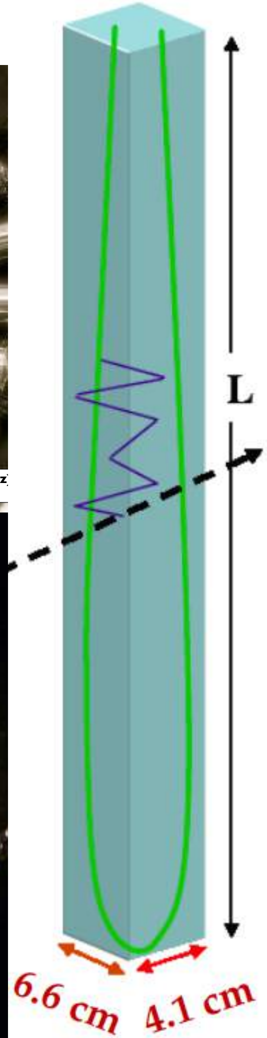
## A workhorse of neutrino physics

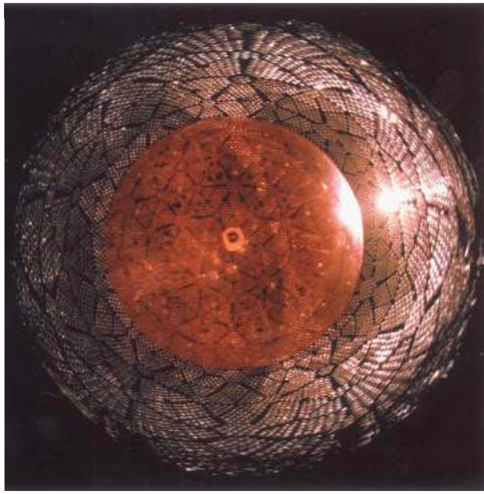








So, why make an opaque detector?

**“LiquidO” concept**

# Opacity

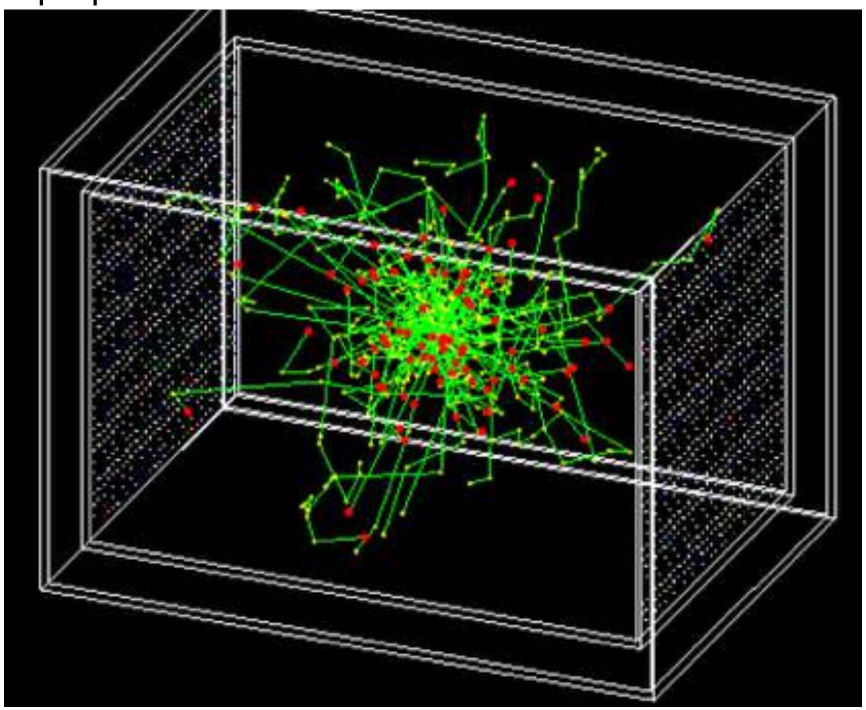
- Two ways to make something opaque
  - – Short scattering length
  - – Short absorption length

# Stochastic confinement of light

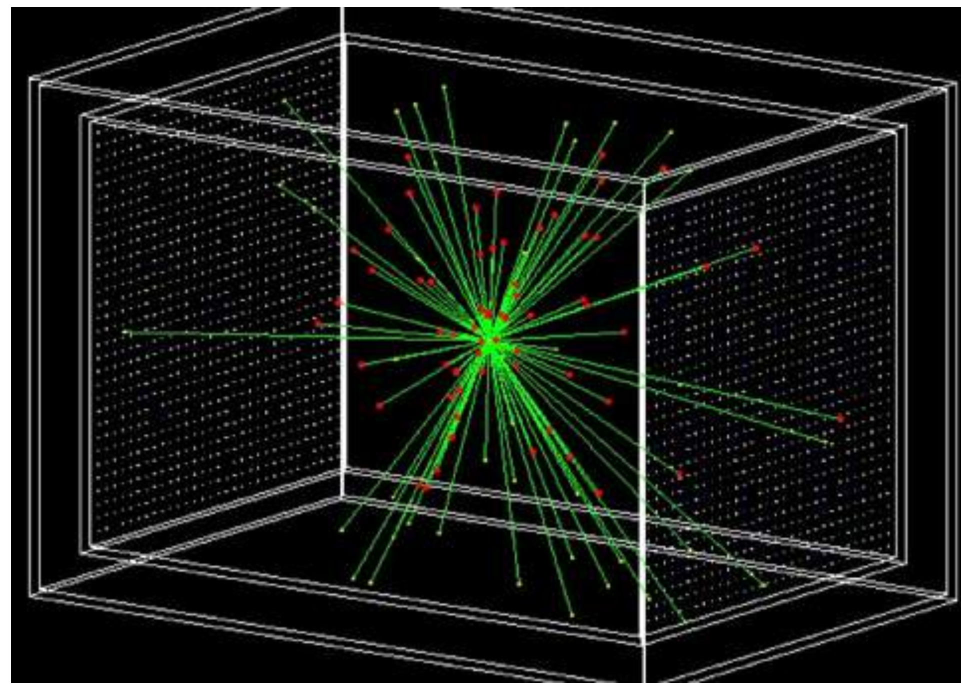
In a scintillator with a short scattering length the light stays near where it is produced

- Each photon undergoes a random walk

Opaque scintillator

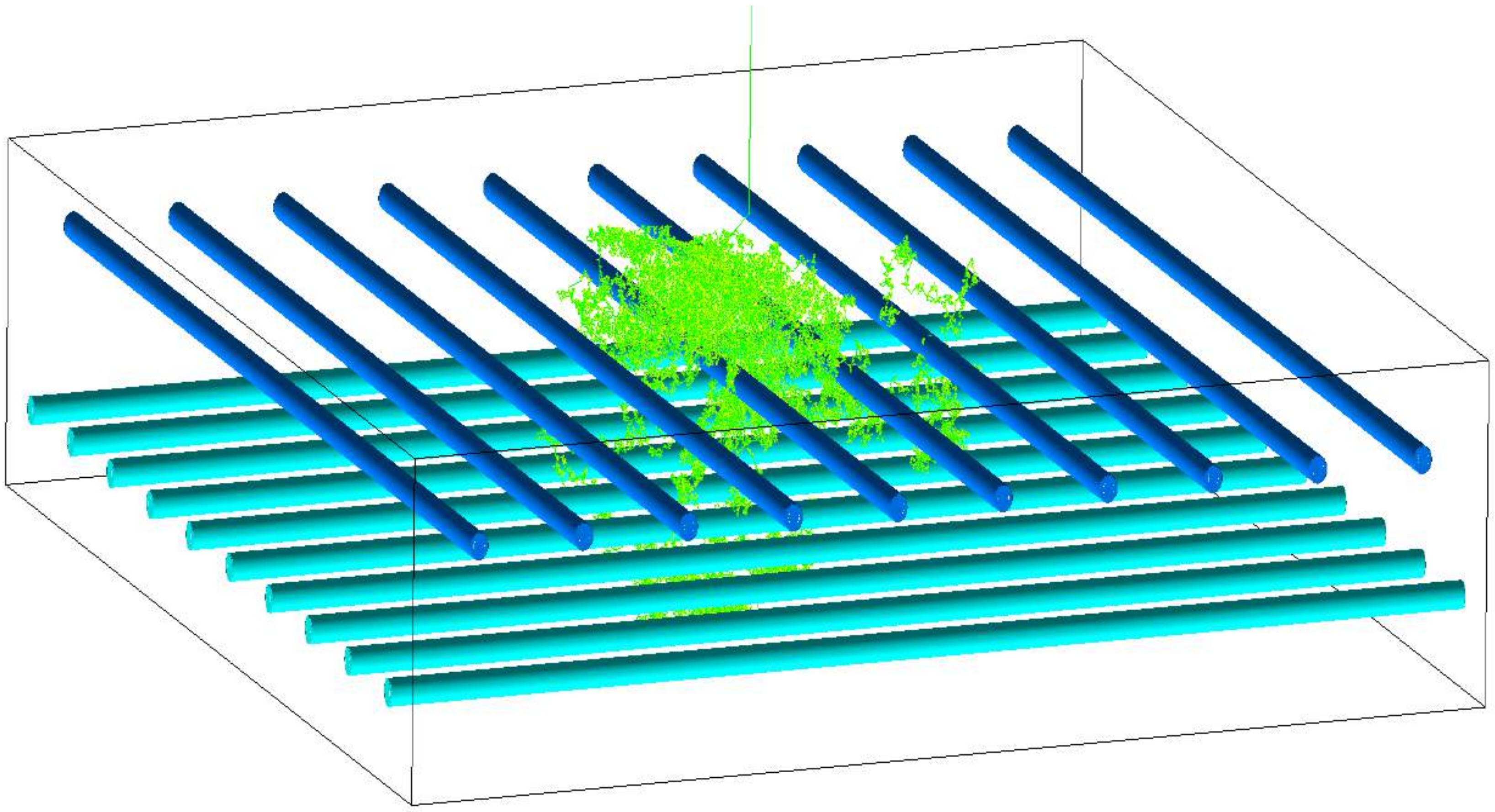


Transparent scintillator



**So, how do we measure the light?**

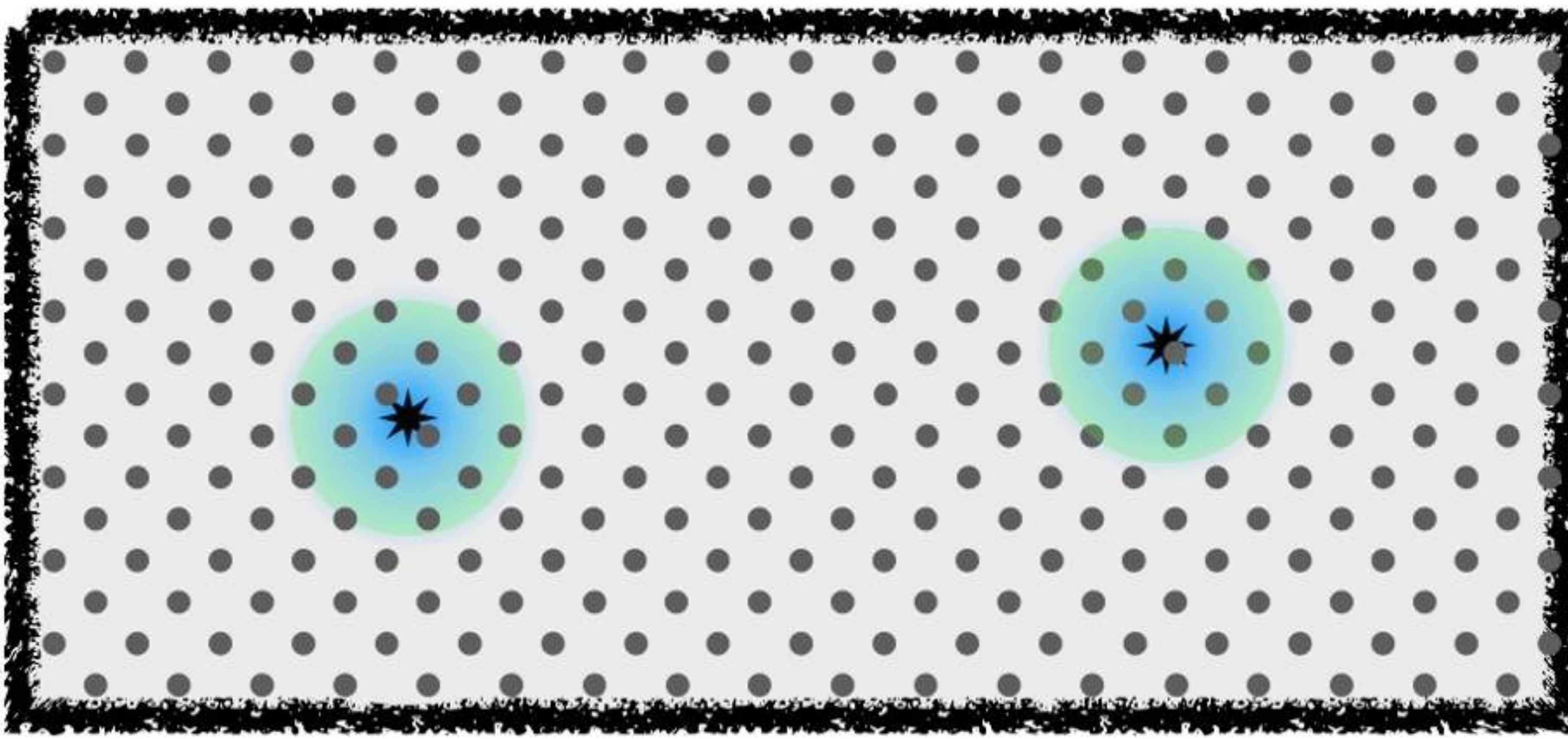
# Lattice of Wavelength Shifting Fibres



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

**Potential for high-resolution imaging detector**

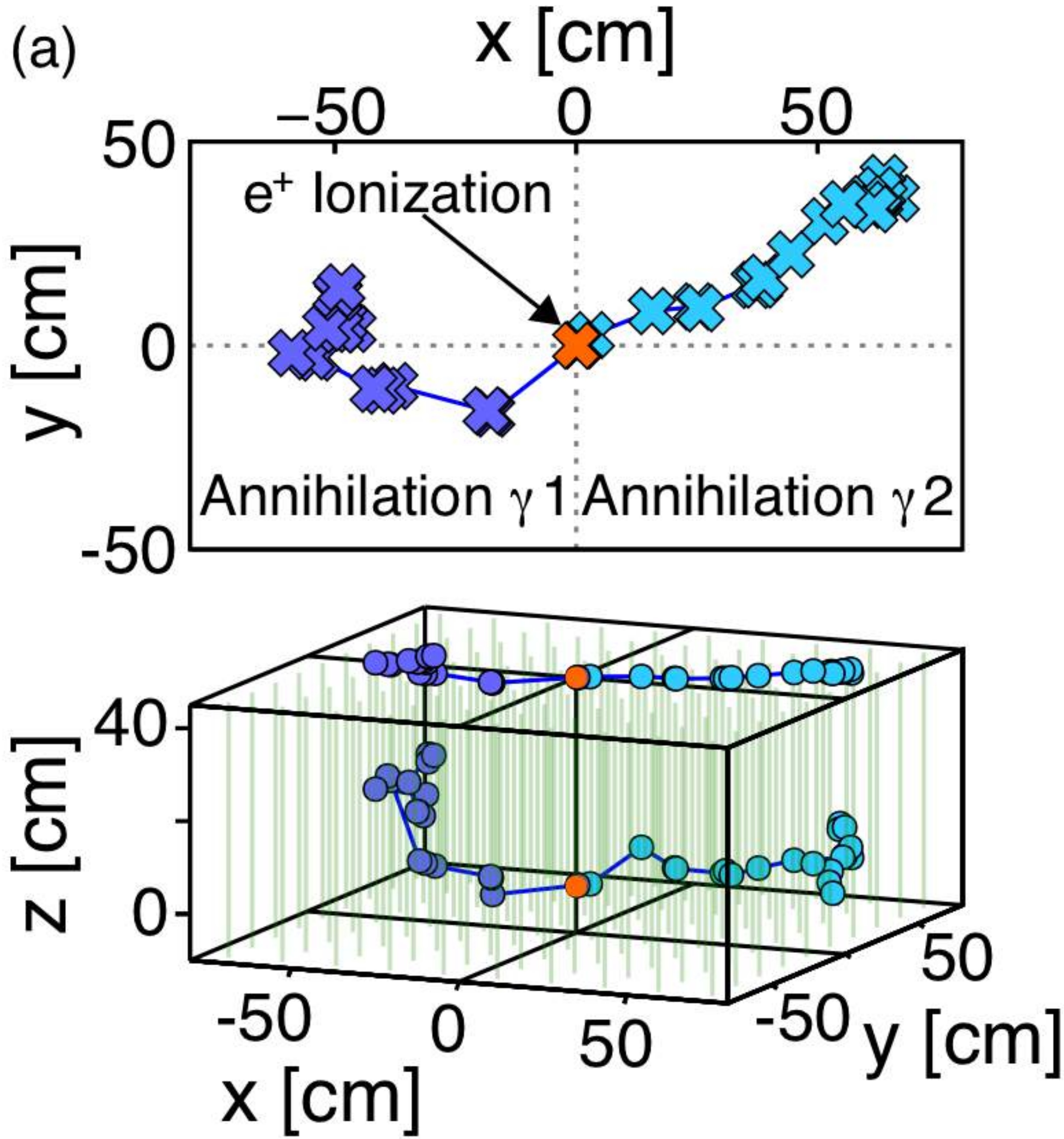
(without manual segmentation)

# Simple example detector

1 cm pitch lattice of fibres, along a single direction

Positron of 1 MeV

Two annihilation gammas

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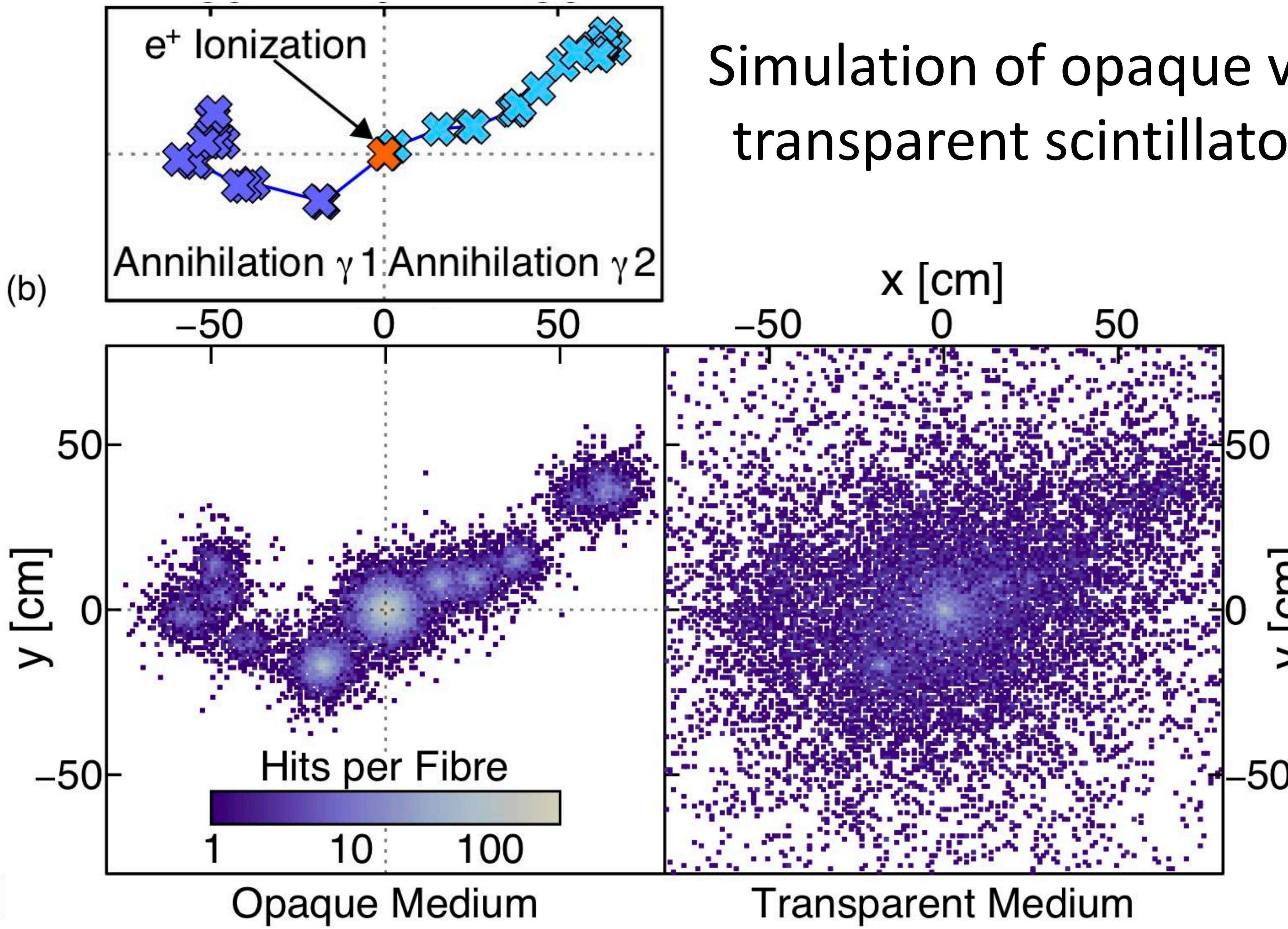
# Simulation of opaque vs. transparent scintillator

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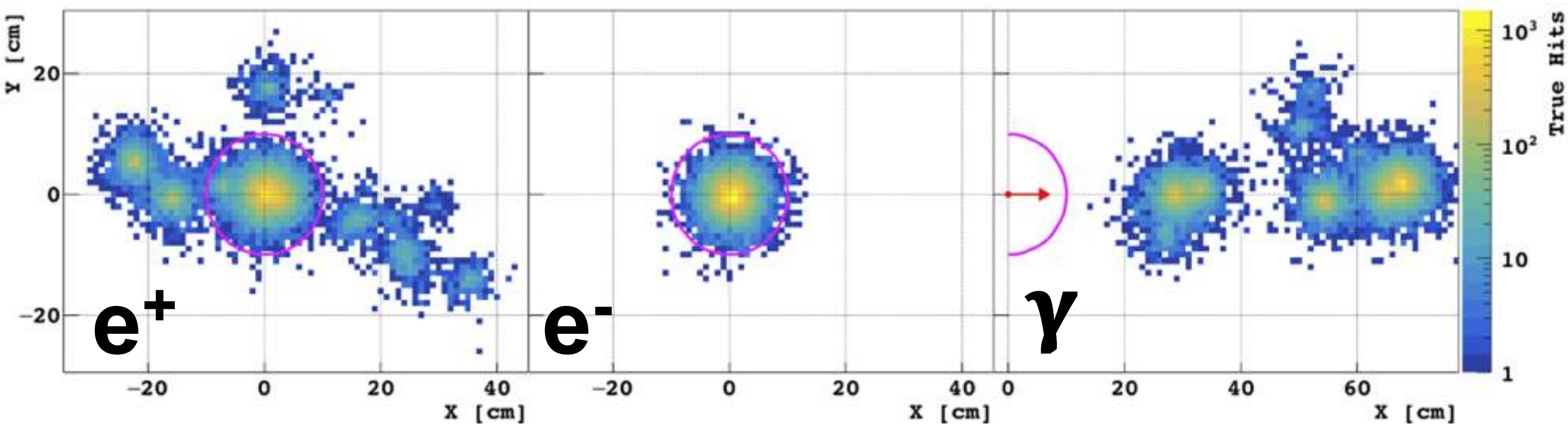
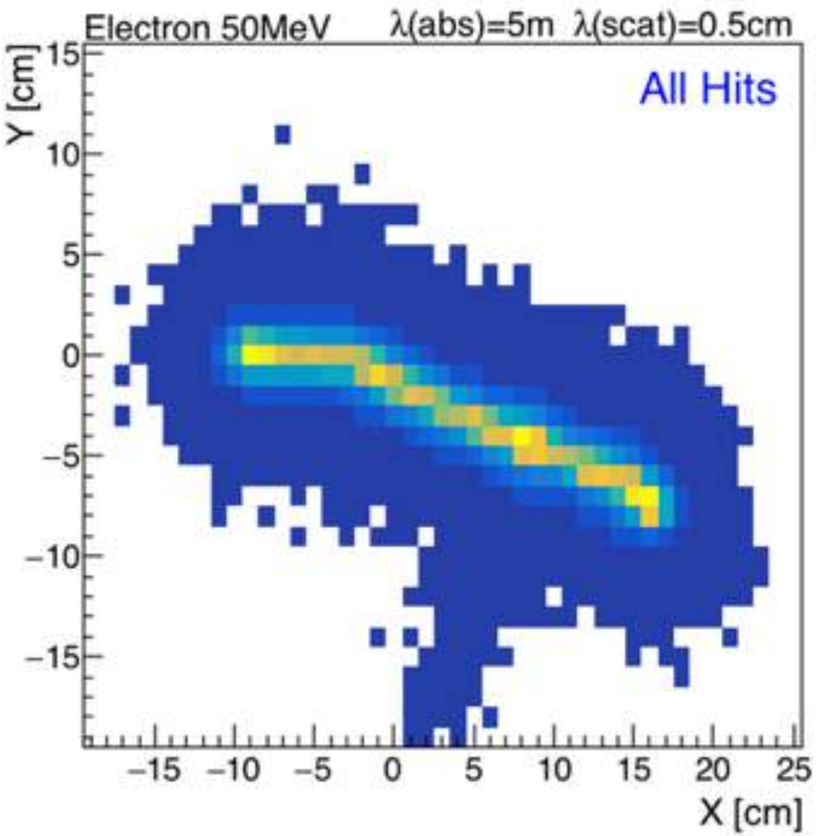
# Use high-resolution imaging for particle identification



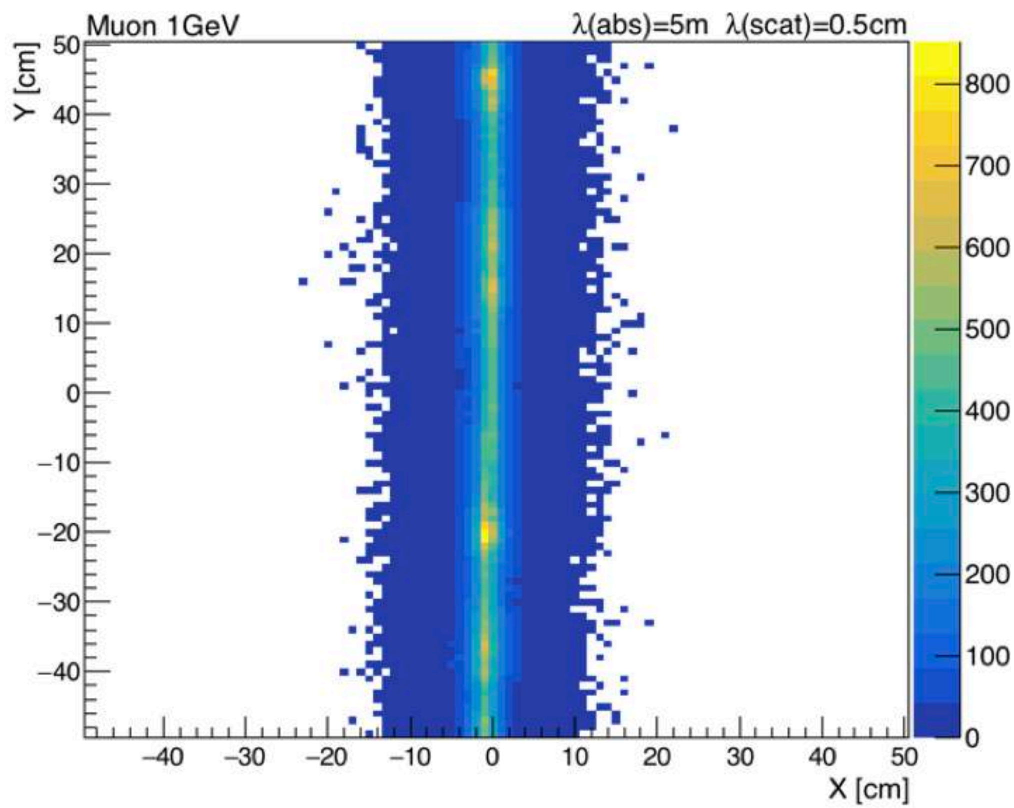

Low energy: 2 MeV

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

# Use high-resolution imaging for particle identification



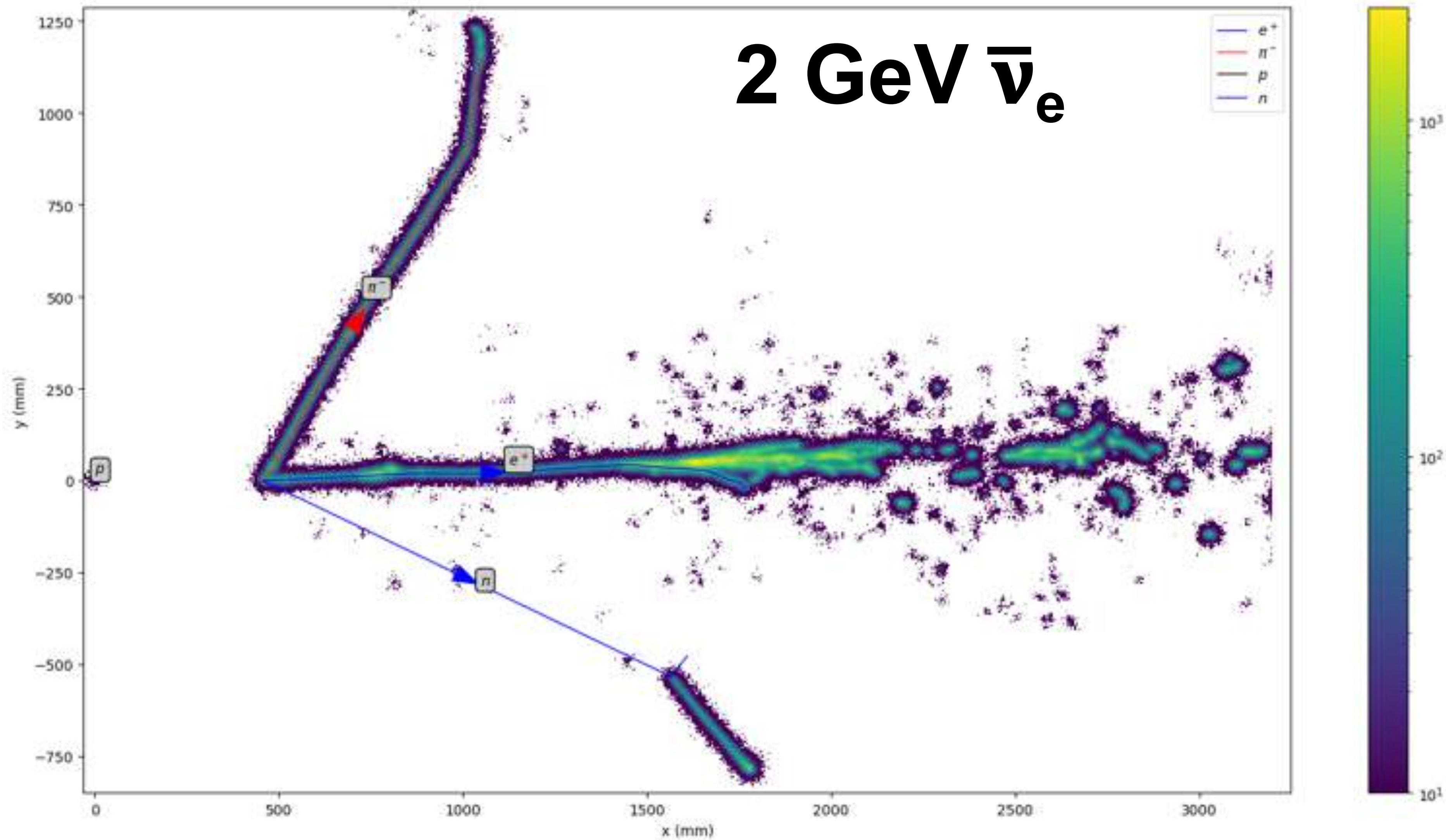

**50 MeV $e^-$**




**1 GeV μ**

**(through-going)**

# Use high-resolution imaging for particle identification



# 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

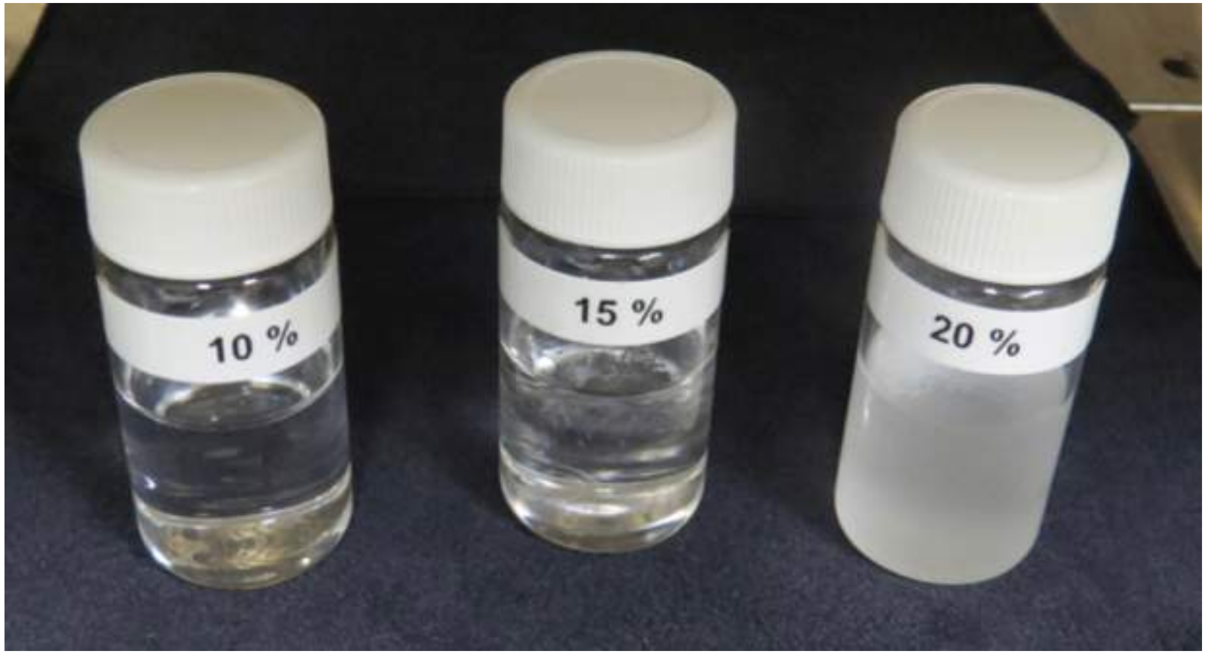
[1]Corresponding author.

2019 JINST 14 P11007

More information about LiquidO can be found in [arXiv:1908:02859](https://arxiv.org/abs/1908.02859) and [arXiv:1908.03334](https://arxiv.org/abs/1908.03334)

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

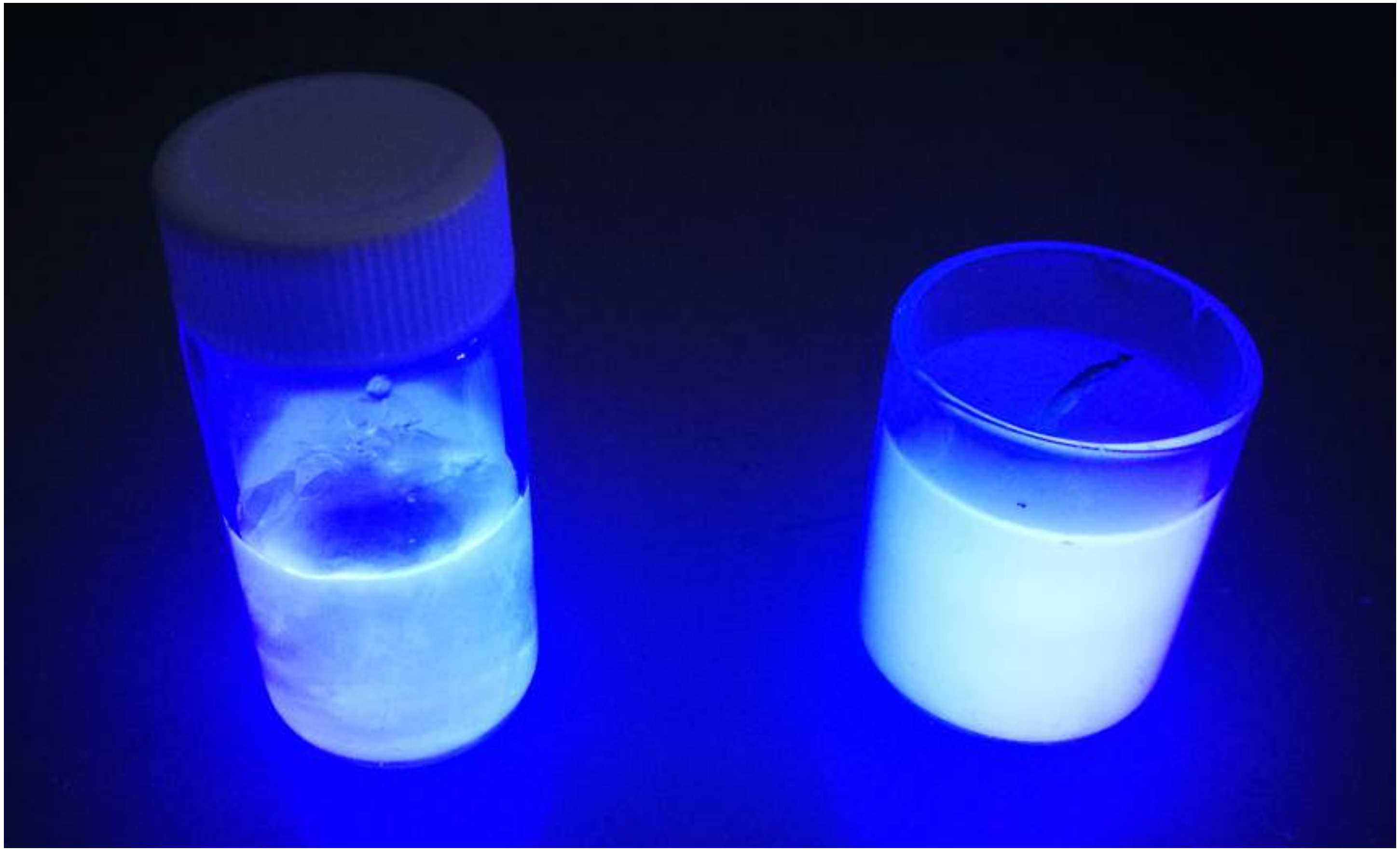
# What is the Scintillator Mixture?




"NoWaSH" = Linear Alkyl Benzene + PPO + Paraffin

Opacity depends on paraffin concentration, which changes crystalisation temperature

# “NoWaSH” Opaque Scintillator

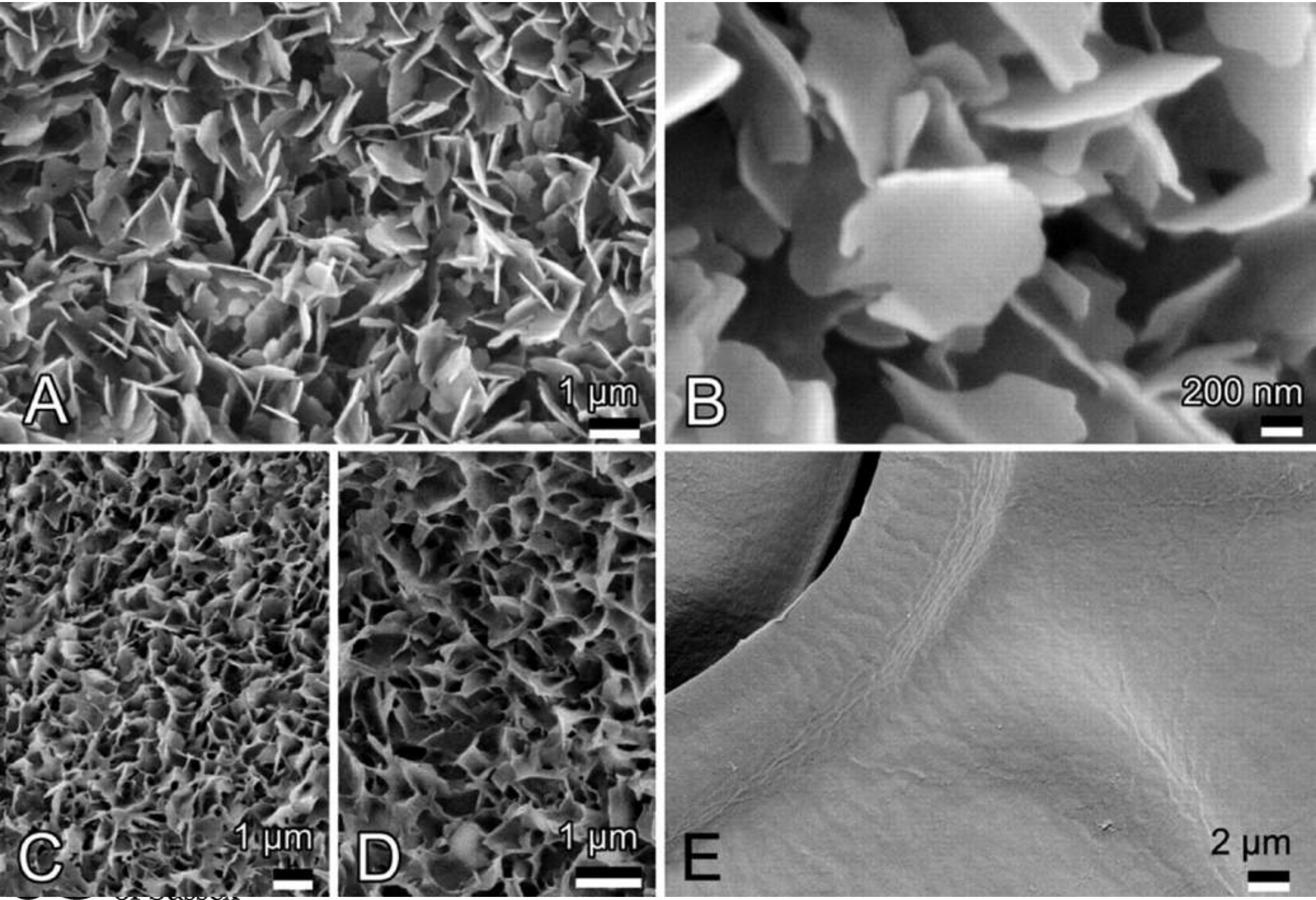


Behaviour similar to candle wax

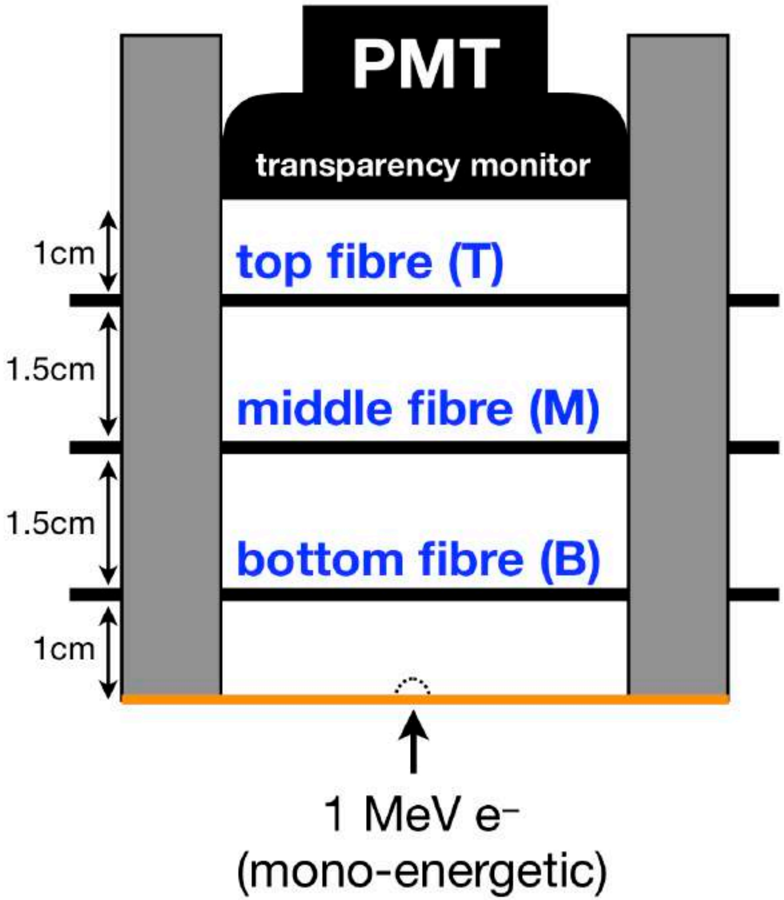
Transparent liquid when warm (>36 degC)

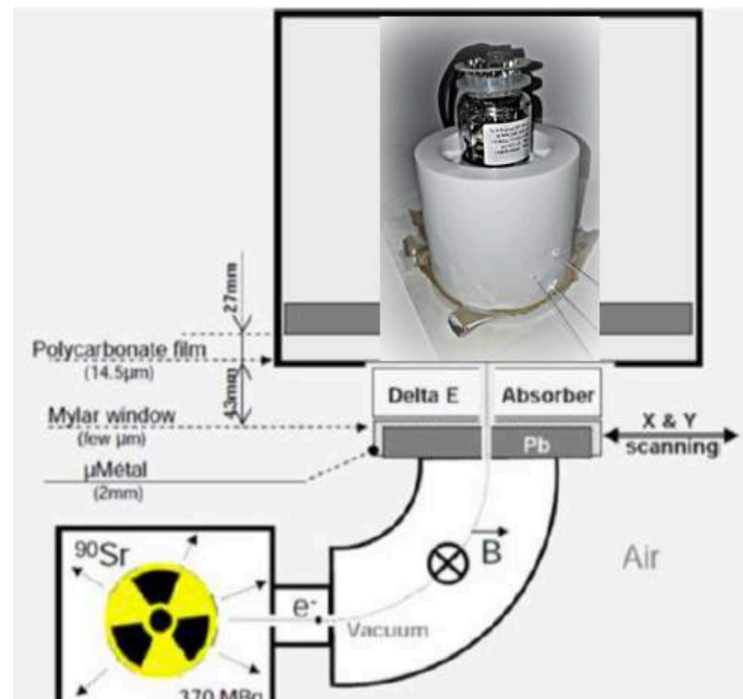
Opaque solid when cooled (~25 degC)

# Wax (random) structure

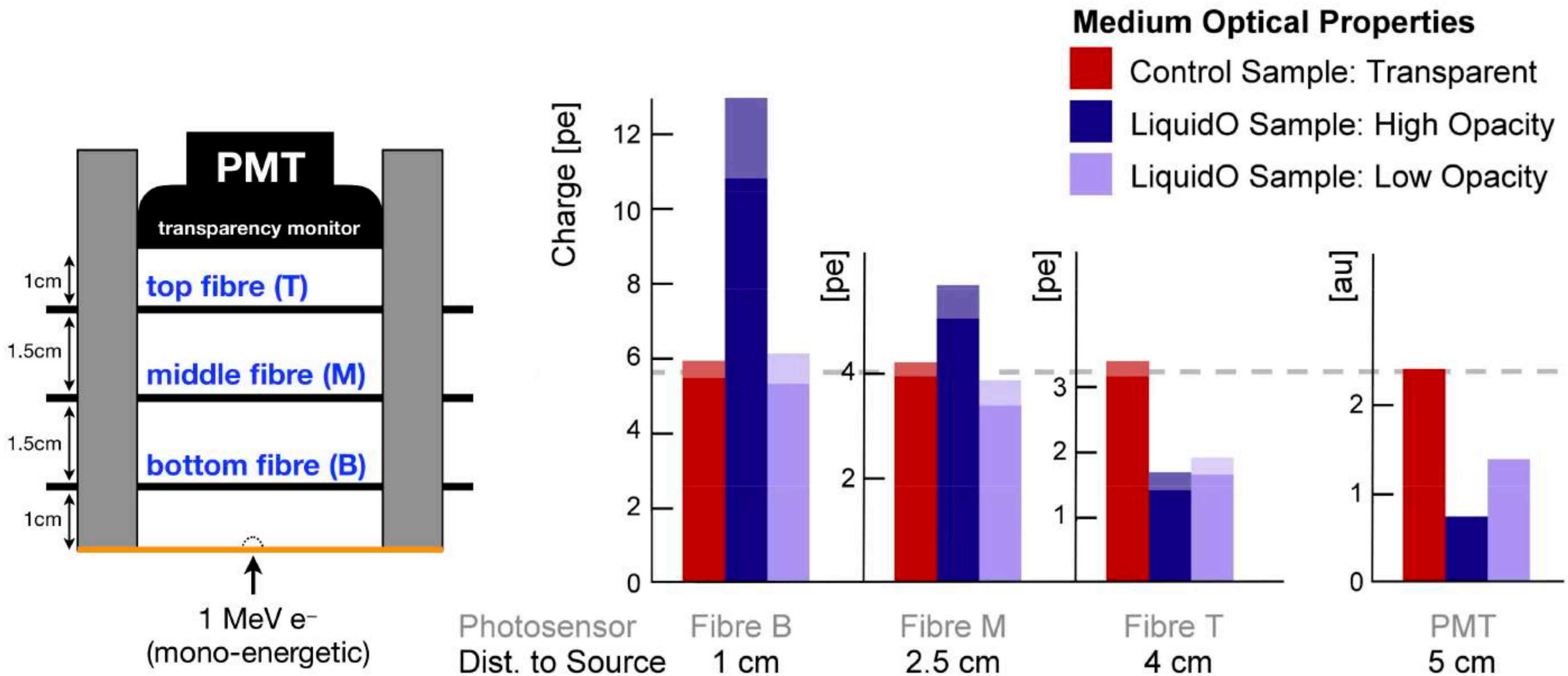


# "micro-LiquidO" Proof of Principle



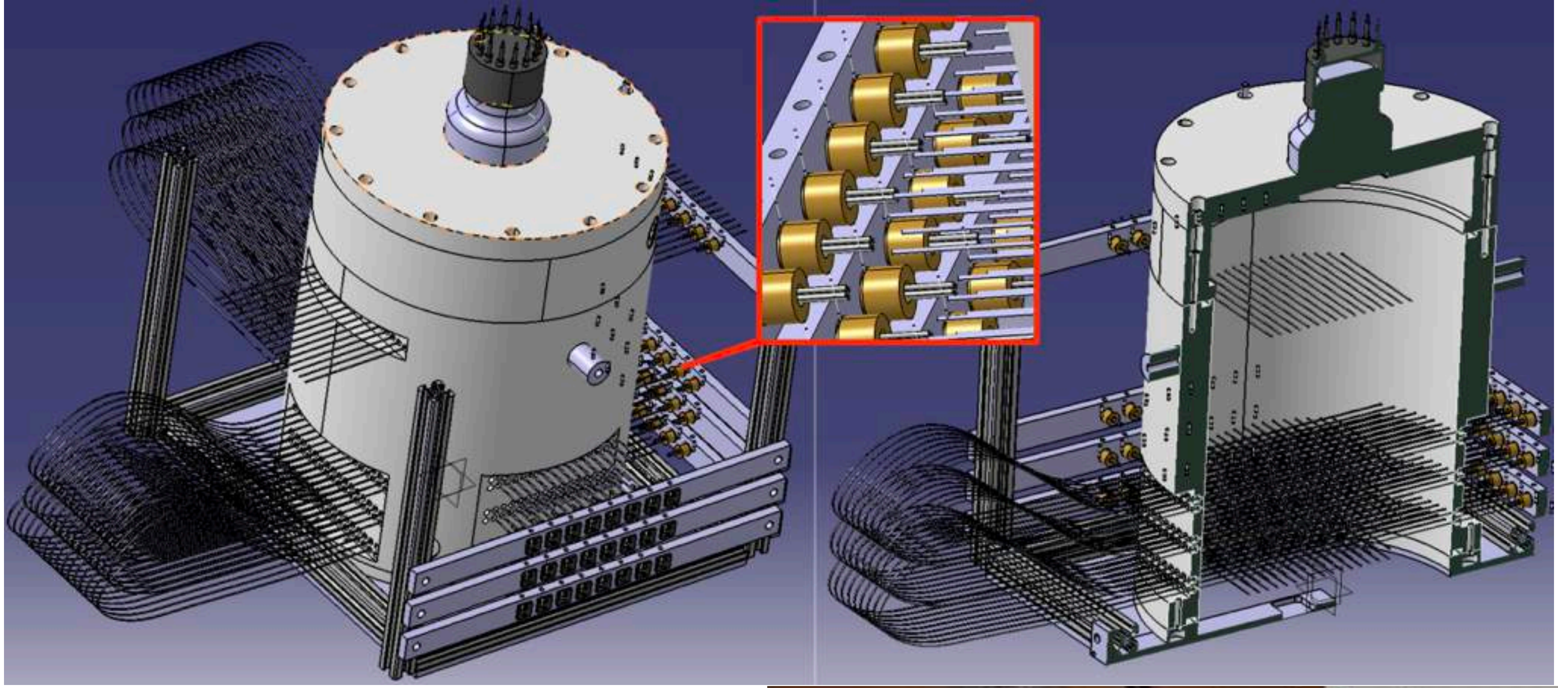
# Proof of Principle




**Three scintillators compared**

The predicted and yet remarkable feature:

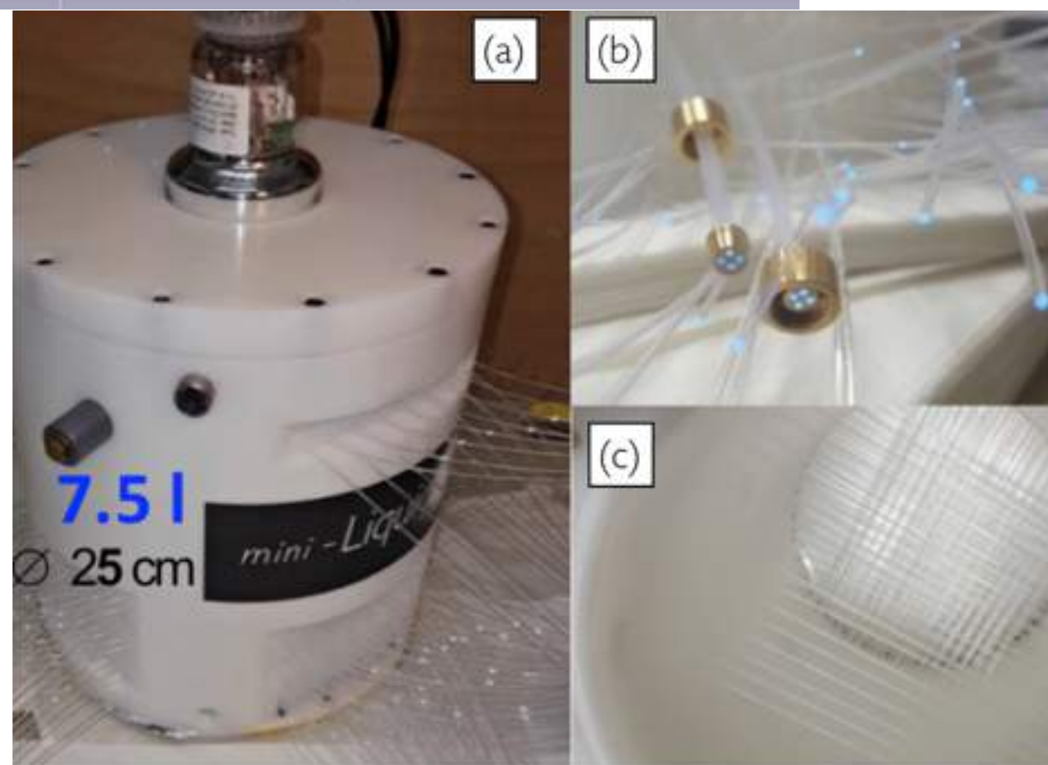
**More** light was collected by the WLS fibres near the light source when the scintillator became opaque



Next step…

“mini-LiquidO”

Data imminent

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# What physics can we do?

- Lots of ideas
  - Not enough time to cover them all
- Multiple papers in preparation
  - Ultra precise $\theta_{13}$ measurement for unitarity test
    - https://indico.cern.ch/event/577856/contributions/3421609/attachments/1878723/3095931/190711-UnitariryLiquidOChooz_EPS-Anatael.pdf
  - $^{40}K$ geo-neutrino measurement
    - https://indico.cern.ch/event/825708/contributions/3550280/attachments/1931708/3199582/Serafini_NGS19.pdf
  - CPv search using pion DAR beam
    - https://arxiv.org/abs/1807.04731
  - CPv search with GeV-scale pion DIF beam
  - and more…

# What physics can we do?


## Motivation

The DUNE experiment consists of four 10kton liquid-argon detector modules in separate cryostats. The technology choices for the first three modules have been described in the recent DUNE TDR. A fourth module will complete the DUNE Far Detector. This module provides opportunity for further development of liquid-argon or alternate technologies in support of the DUNE physics goals.

The DUNE Collaboration invites the broader particle physics community to participate in a workshop to explore opportunities for novel detector technologies for this "module of opportunity". The meeting will cover all major aspects of liquid argon TPC technology, including proposals for improvements in tracking, photon detection, electronics, high voltage, electronics and data-acquisition, considering improvements in detector integration and installation.

New detector concepts that can satisfy and expand the DUNE physics goals are encouraged.

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

**Workshop Dates**
November 12–13, 2019

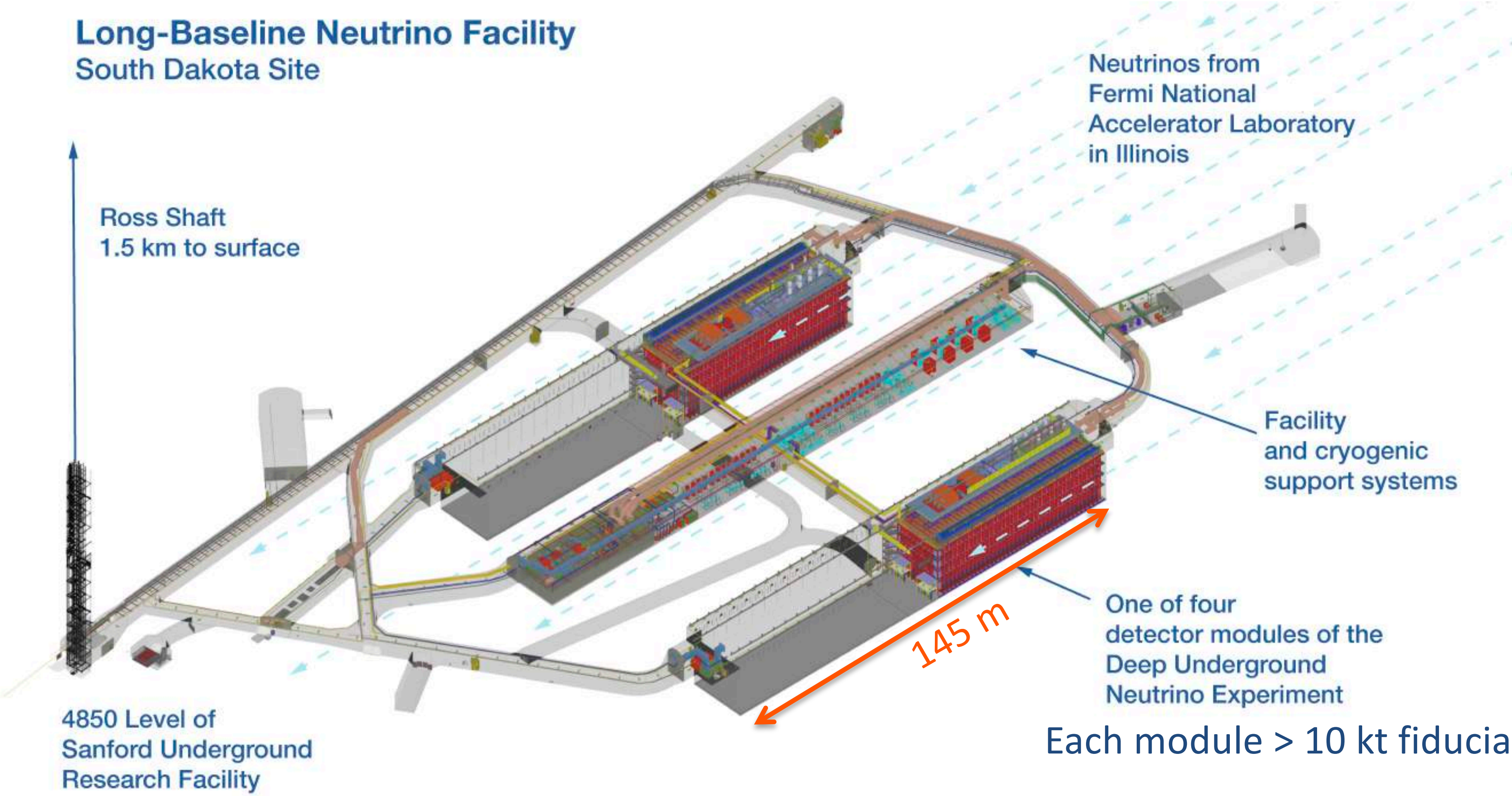
**Event ID**
41055

**Workshop Venue**
Brookhaven National Laboratory
Upton, NY 11973 USA

Getting to Brookhaven Lab

# DUNE and 4th Module of Opportunity

- Four separate 17 kt (> 10 kt fiducial) LAr TPCs
- 4 identically sized cryostats: 2 single phase (SP) + 1 dual phase (DP) +1 “opportunity” (this 2+1+1 plan is described in TDR)




Each module > 10 kt fiducial

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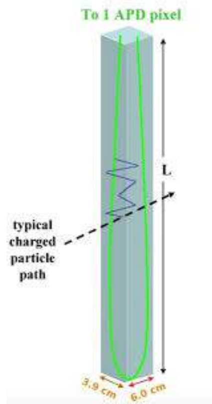
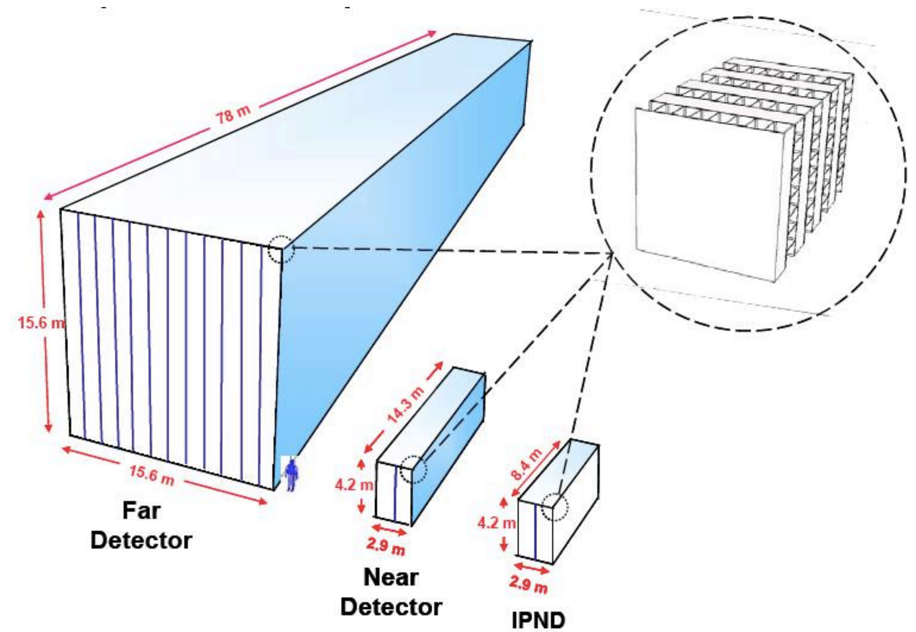
# Scalability

– No showstoppers foreseen when scaling LiquidO to ~10 ktons:

- Invaluable experience from NOvA
- Key difference: avoid light losses due to reflection inside the cells

In NOvA the efficiency of light hitting the fibre is ~12%. For LiquidO expect > 90%



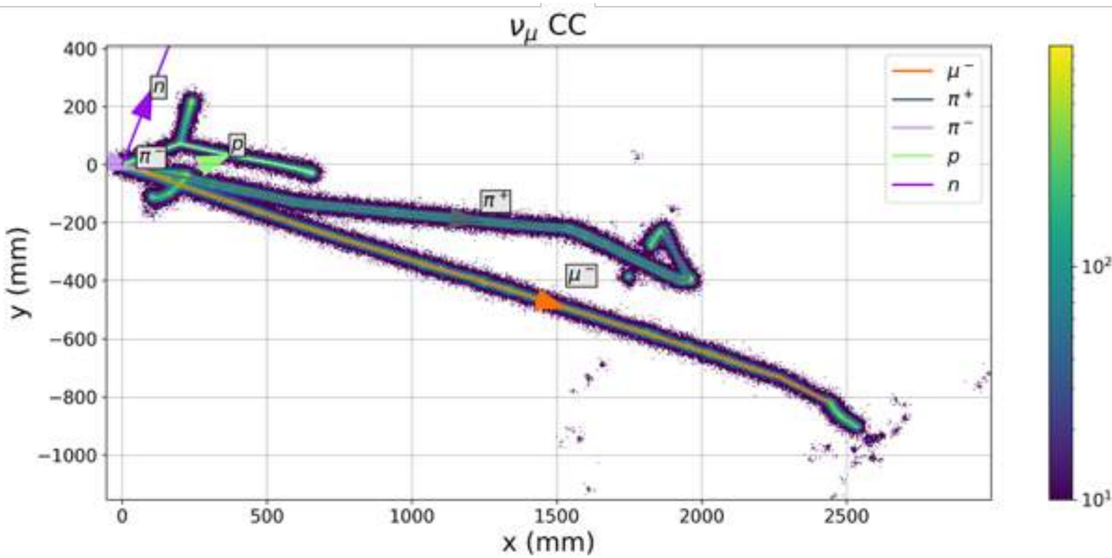

A NOvA-sized LiquidO would achieve at least 100 PEs/MeV with today's technology→ **already excellent for MeV physics**

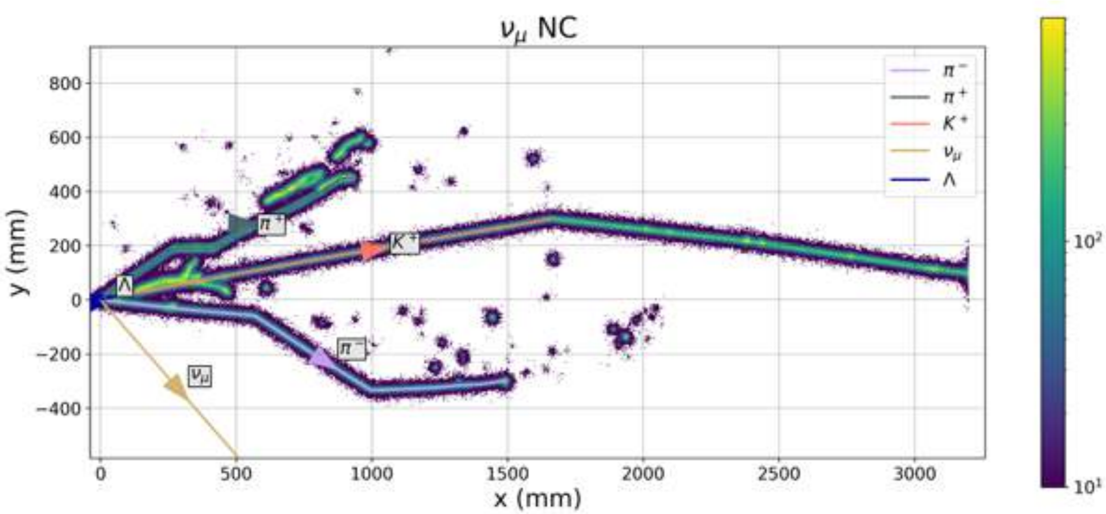
- Rough cost expected to be comparable to NOvA FD

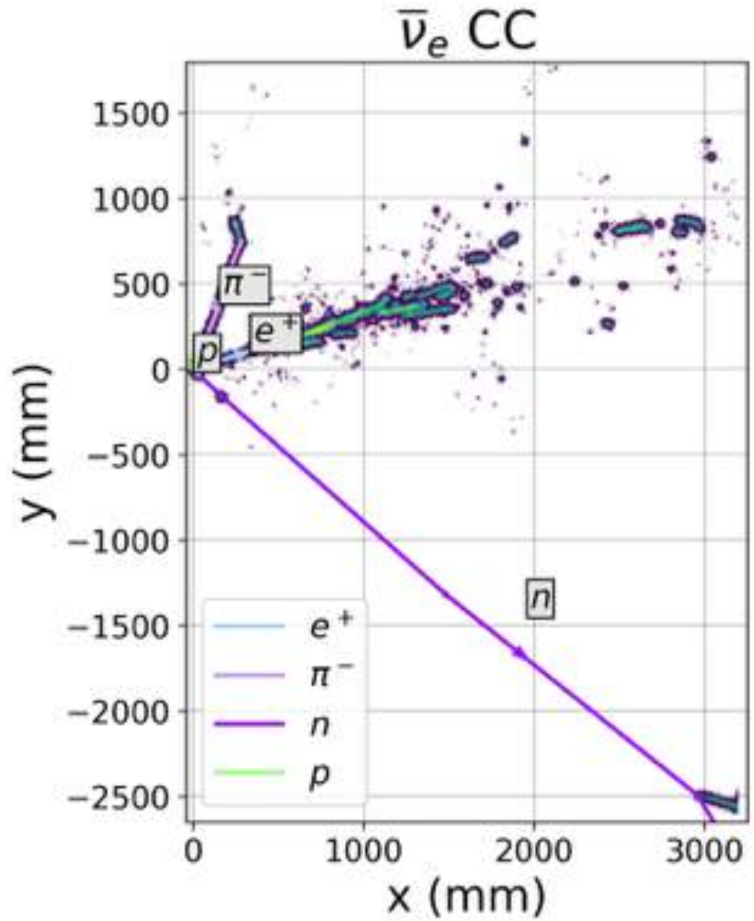
– Other advantages compared to other detectors:

- Room temperature operation (no need for cryostat)
- Self-shielding detector

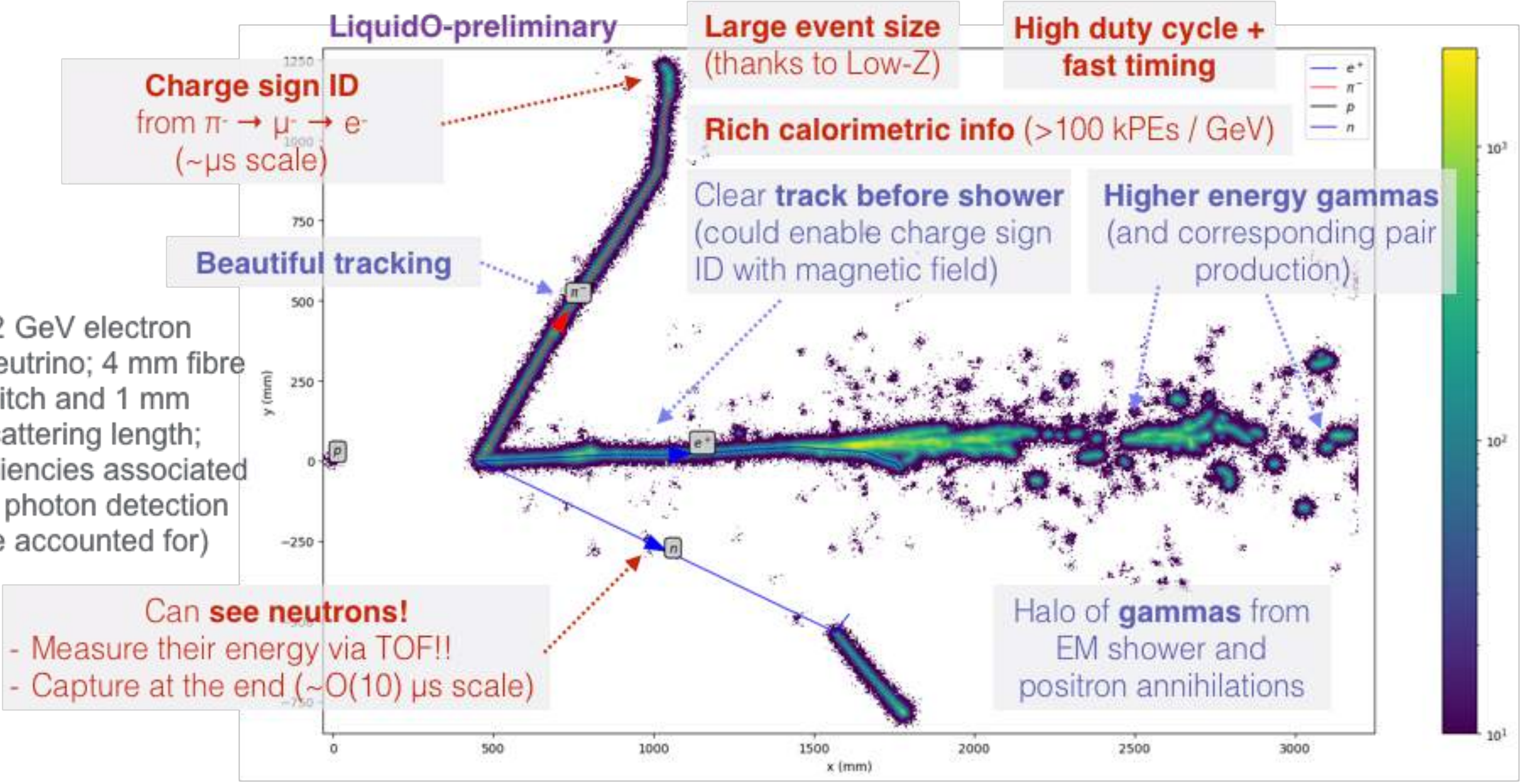
# Beautiful LiquidO beam events



– 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**

# Additional Physics

Supernova neutrinos:

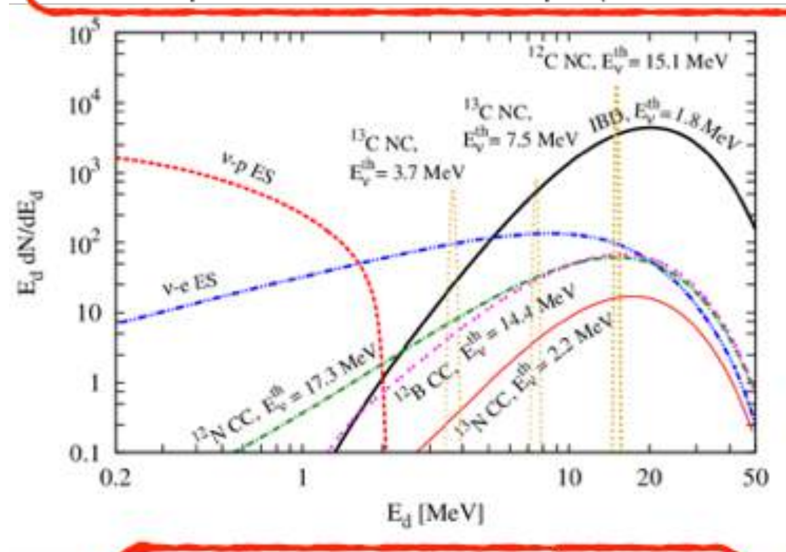
- Low energy threshold (~0.1 MeV)
- Channels not accessible with other detectors
- Charge sign ID (e+/e-)
- Directionality information for events ≳ 10 MeV
- Sensitivity to Diffuse Supernova Neutrino Background

Search for nucleon decay:

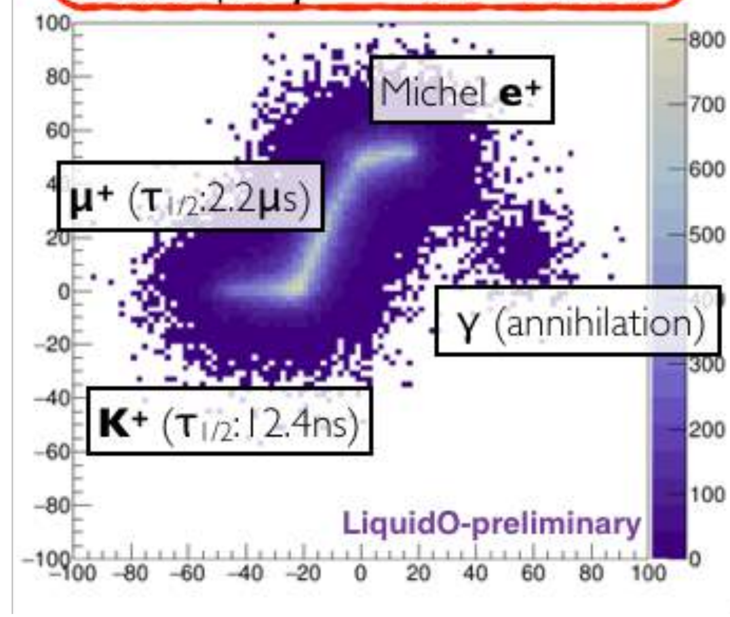
- Very high-efficiency
- Full topological information and sign-ID for some channels through final Michel electron
  - Many exclusive final states

Others (geoneutrinos, reactor antineutrinos… etc)

JUNO spectra for SN @ 10 kpc (for reference)




Example $p \rightarrow \bar{\nu}K^{+}$ event



# Doping

- Doped scintillators used with great success
  - Reactor $\theta_{13}$ experiments (Gadolinium)
  - ZamLAND-Zen (Xe)
- Often a challenge to go to higher loading
  - Can end up making the scintillator opaque

Great! ☺

- For LiquidO, needing opacity removes the transparency requirement
  - New landscape of novel materials/mixtures to consider
  - It's a whole new (counter-intuitive!) way of thinking about scintillator detectors

# Conclusions

- Innovative new “LiquidO” detector technology
  - Opaque scintillator + lattice of fibres
  - Builds on established technology
- Brings new physics opportunities
  - High-resolution imaging and particle identification
  - Low energy threshold
  - Potential for high levels of doping
- R&D progressing rapidly and steadily
  - Proof of principle done. Larger detector data imminent
- LiquidO is a whole new way of thinking about a scintillator detector
  - we’ve only just scratched the surface

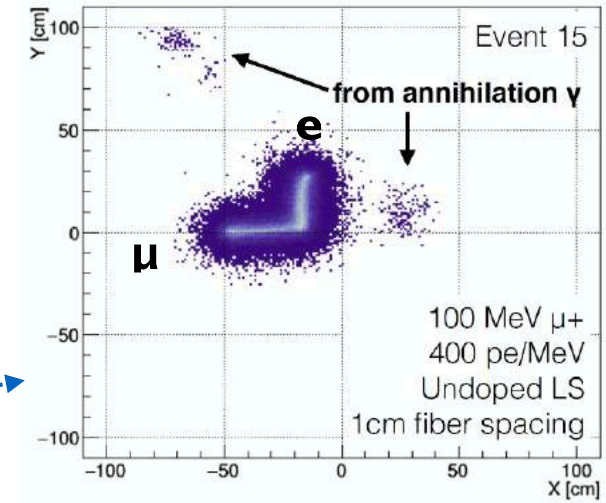
# The End

# Backup slides

# Advantages of LiquidO @ DUNE

– Complementary detector properties and capabilities:

- Low-Z (radiation length 0.5m vs. 0.14m in LArTPC)
- Self-segmenting detector (no dead material & lower cost)
- Largest density of free-protons (without being explosive)
- Low energy threshold
- Sensitivity to neutrons (scattering and capture)
- Charge sign ID from Michel $e^+/e^-$ (separate time scale)
- High duty cycle and fast timing

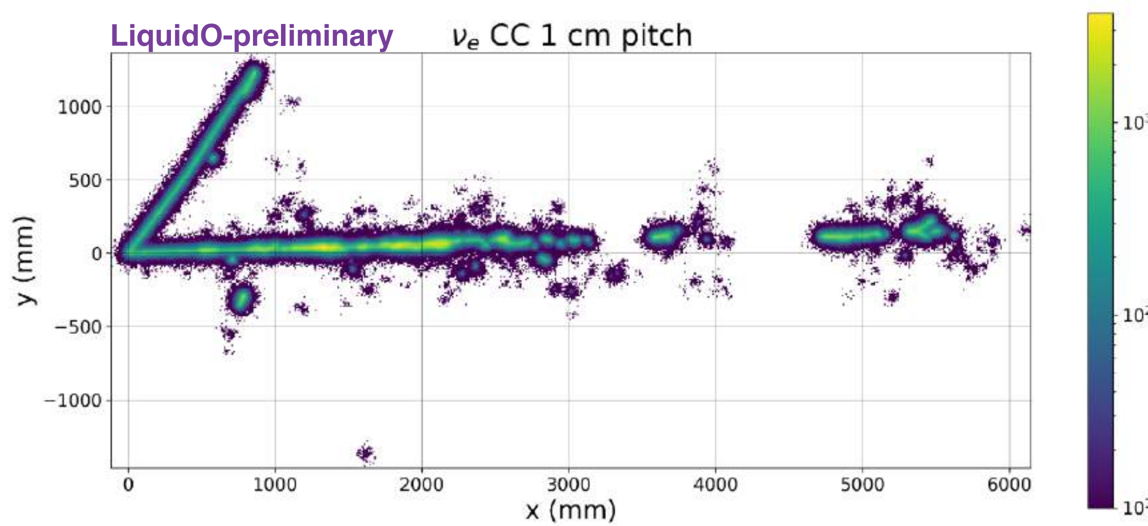



– Other opportunities:

- Plenty of room for optimization depending on physics goals vs. cost

  Example of event with 1 cm fibre pitch

- Room for enhancements such as loading (e.g. Indium) and magnetization



# Measurement