An Opaque Scintillator Detector for Precision Neutrino Physics

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For the LiquidO Consortium

University of Sussex

DUNE ND Phase II Workshop, Imperial College London

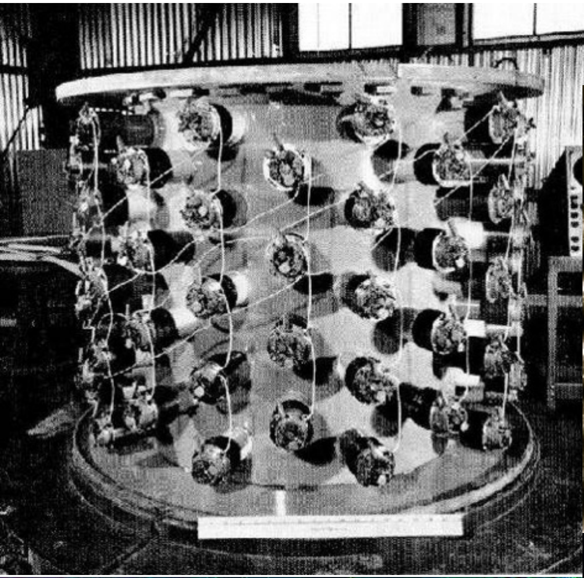
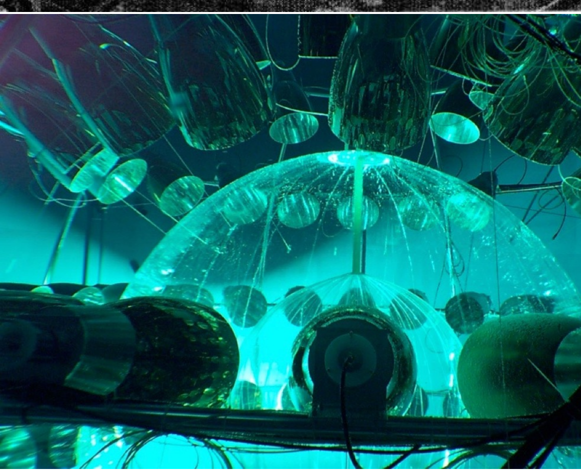
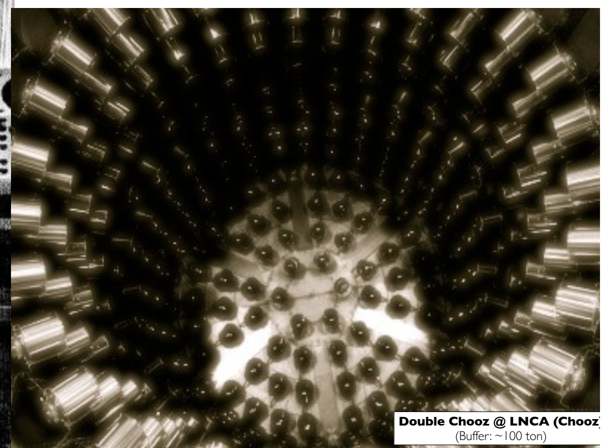
21st June 2023

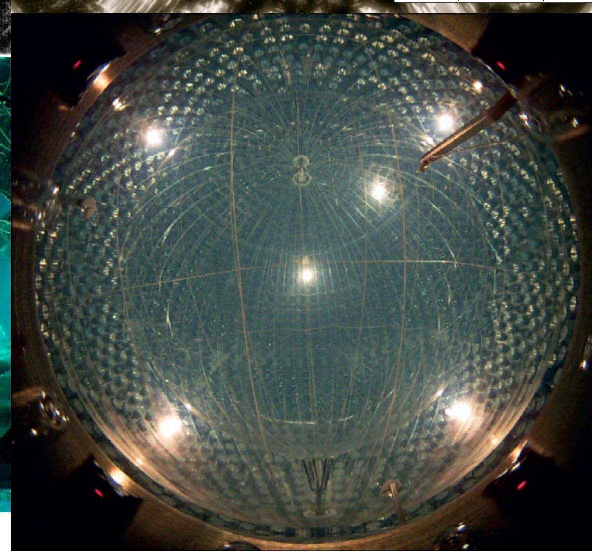
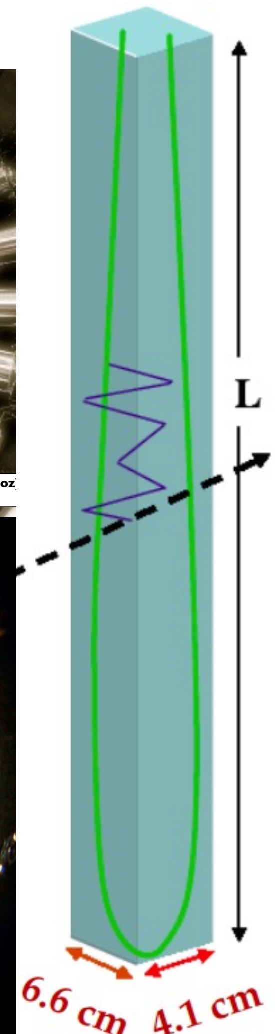
Outline

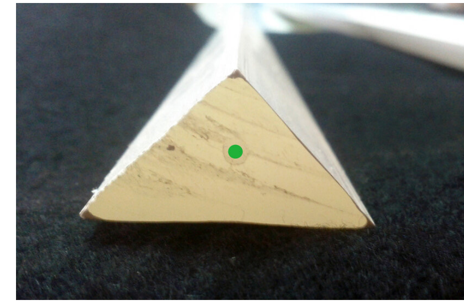
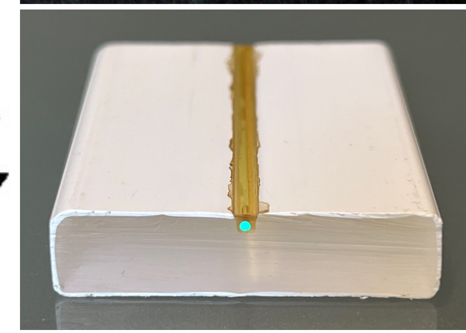
- LiquidO
  - Opaque medium + lattice of optical fibres
- High resolution imaging capabilities
- First papers
- Opaque scintillators
- GeV-scale neutrino event images
- SuperFGD-style LiquidO detector
- Current status of LiquidO projects
  - CLOUD Experiment

Transparent scintillator detectors

A workhorse of neutrino physics

So, why make an opaque detector?

"LiquidO" concept

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Opacity

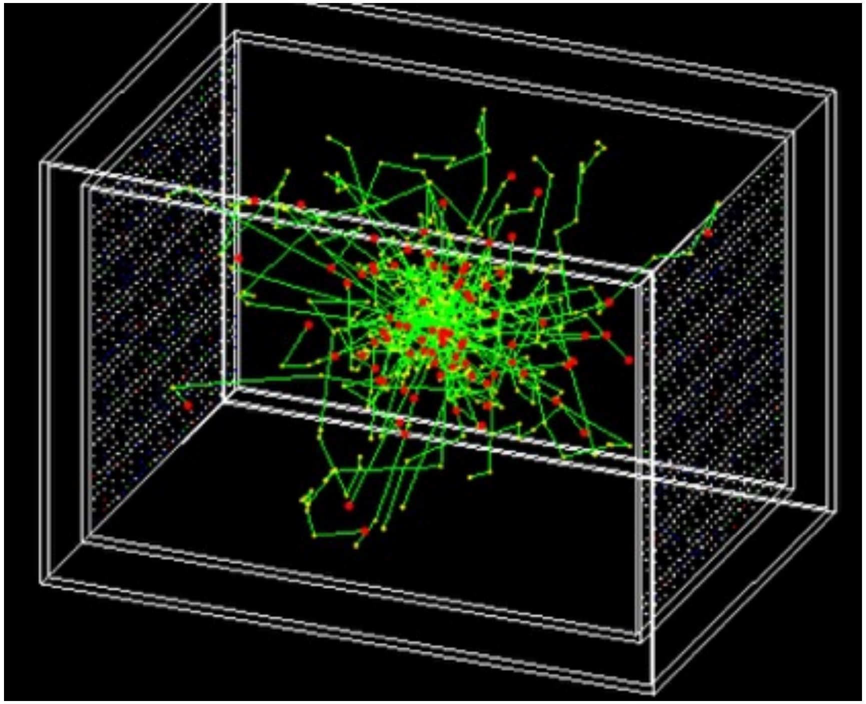
- Two ways to make something opaque
  - Short scattering length
  - Short absorption length

Stochastic confinement of light

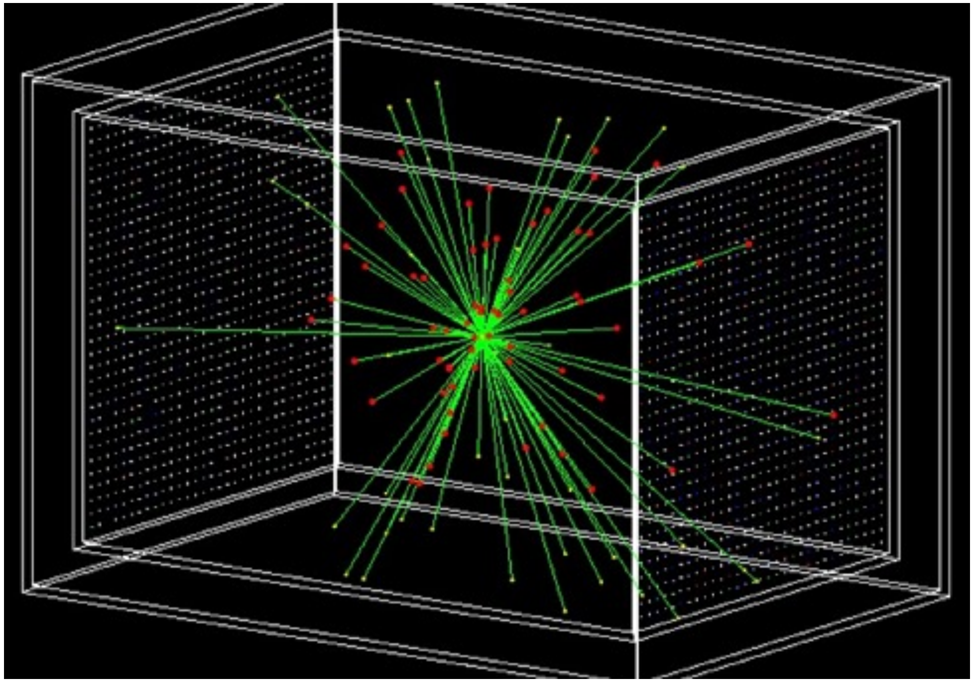
In a scintillator with a short scattering length the light stays near where it is produced

– Each photon undergoes a random walk

Opaque scintillator

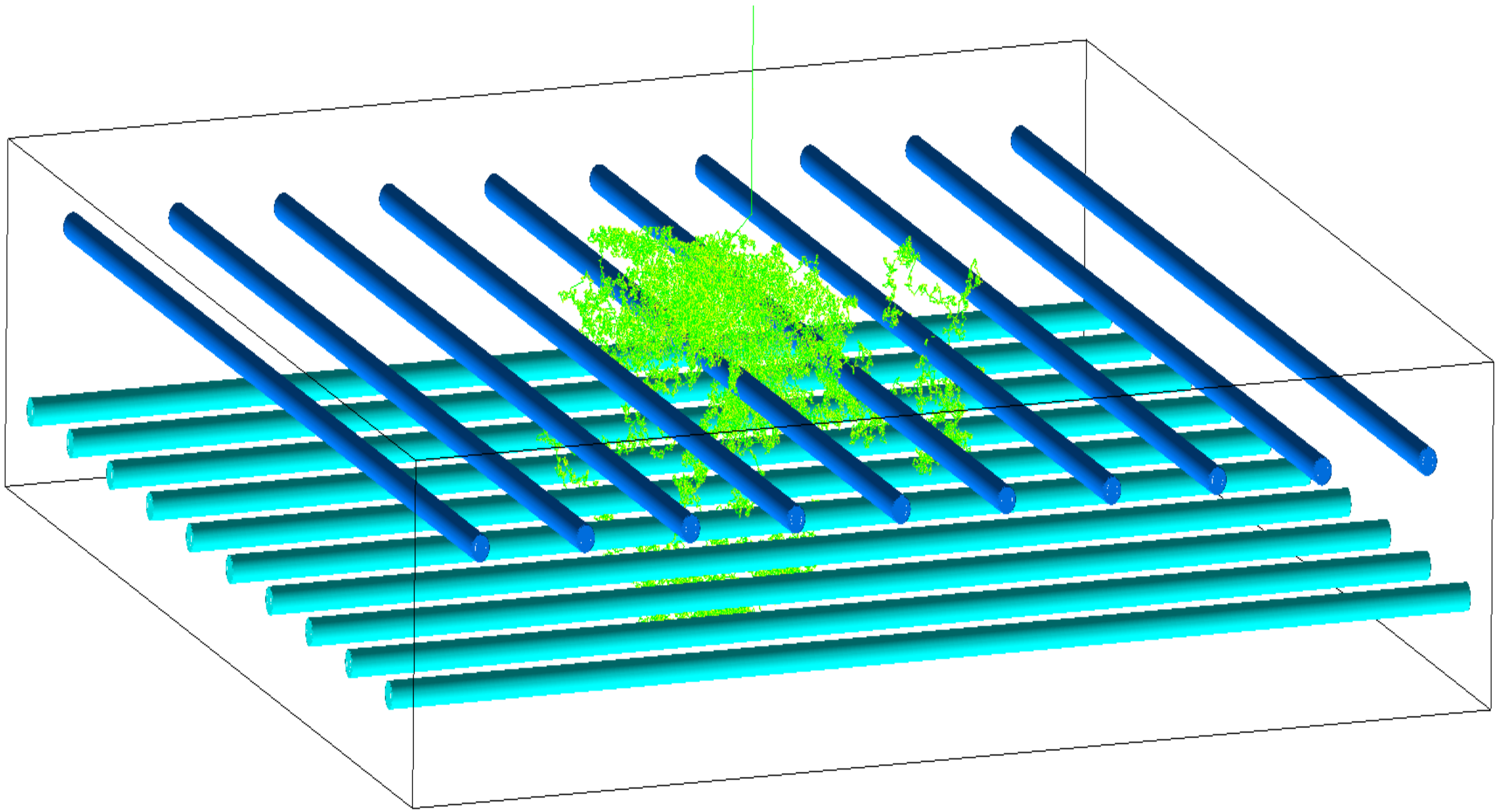


Transparent scintillator



So, how do we measure the light?

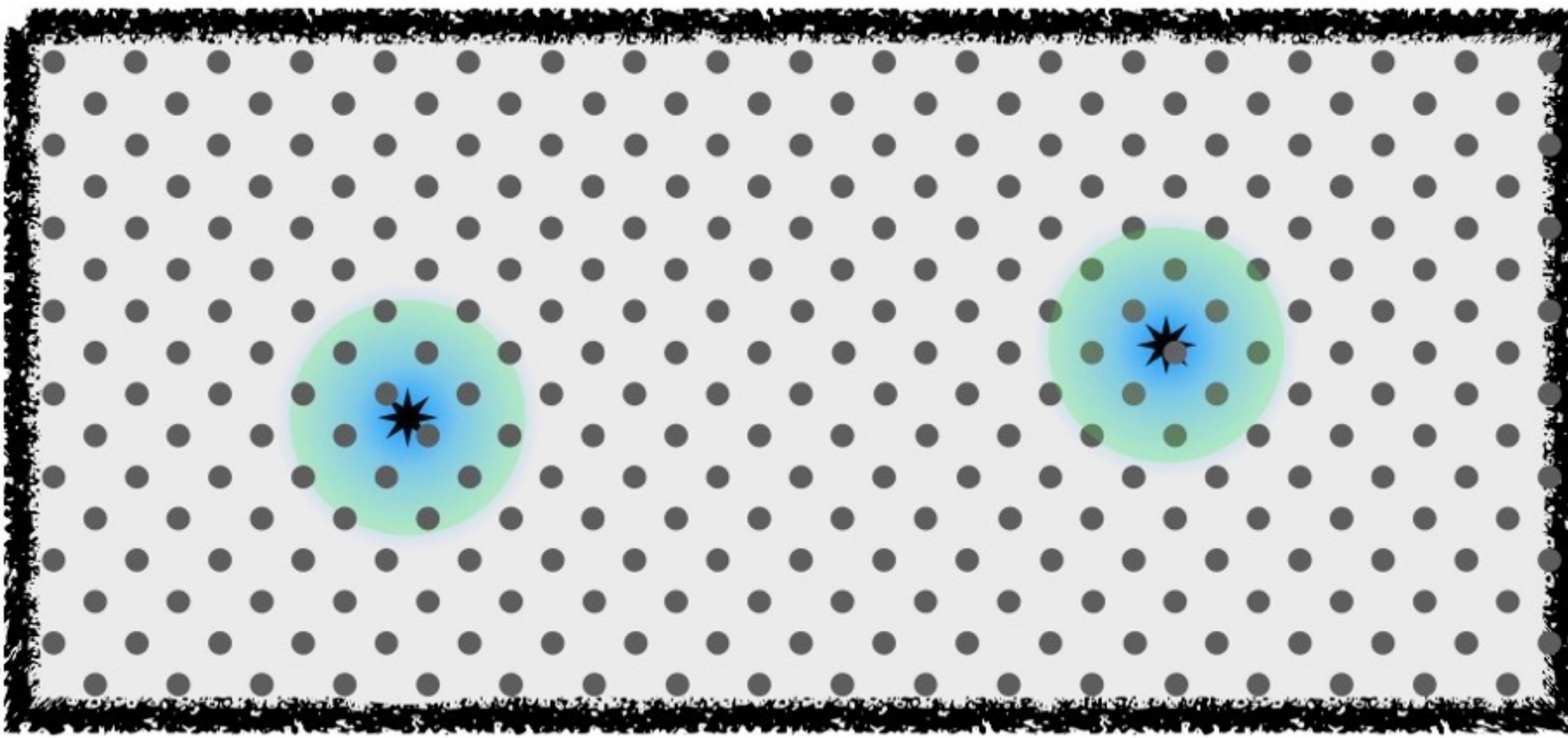
Lattice of Wavelength Shifting Fibres



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

LiquidO: Opaque Scintillator + fibres

Confine light locally → freeze information



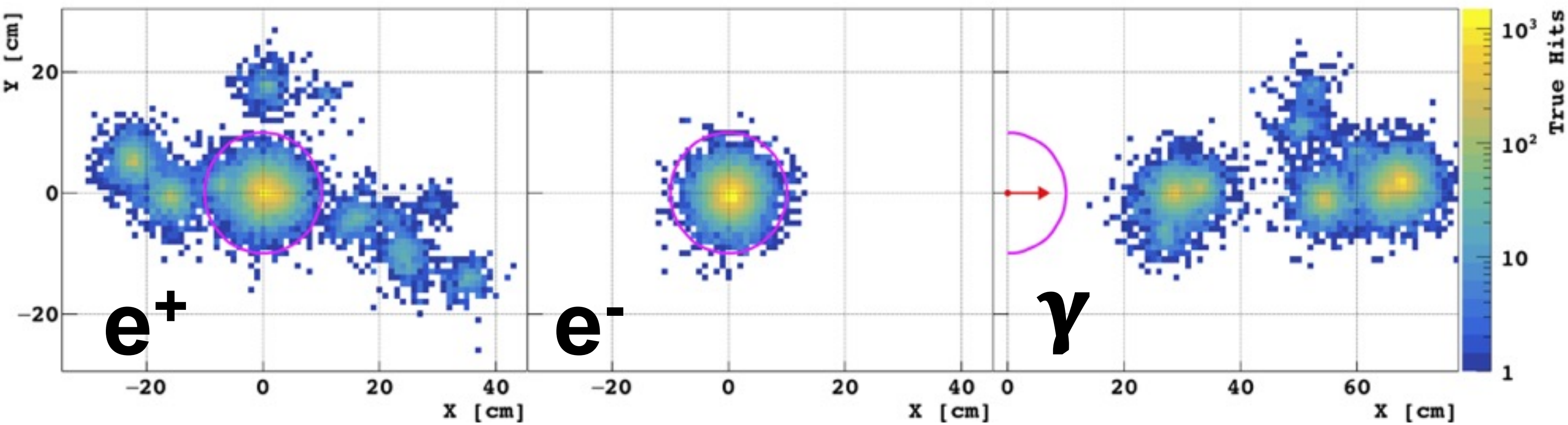
Side-on or top-down view

Potential for high-resolution imaging detector

(without manual segmentation)

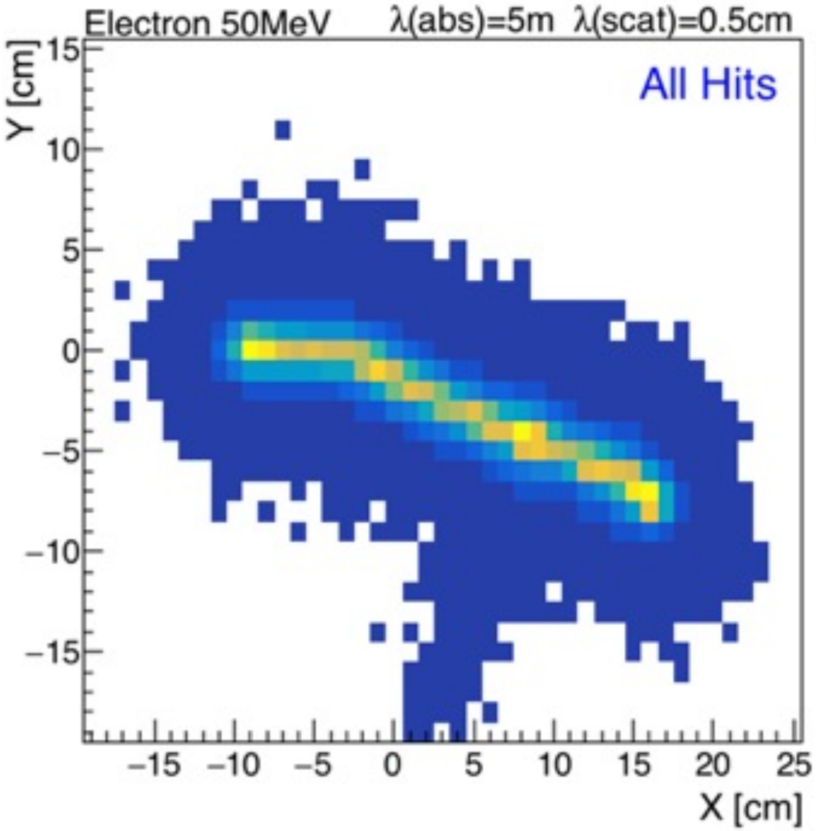
Use high-resolution imaging for particle identification

Low energy: 2 MeV

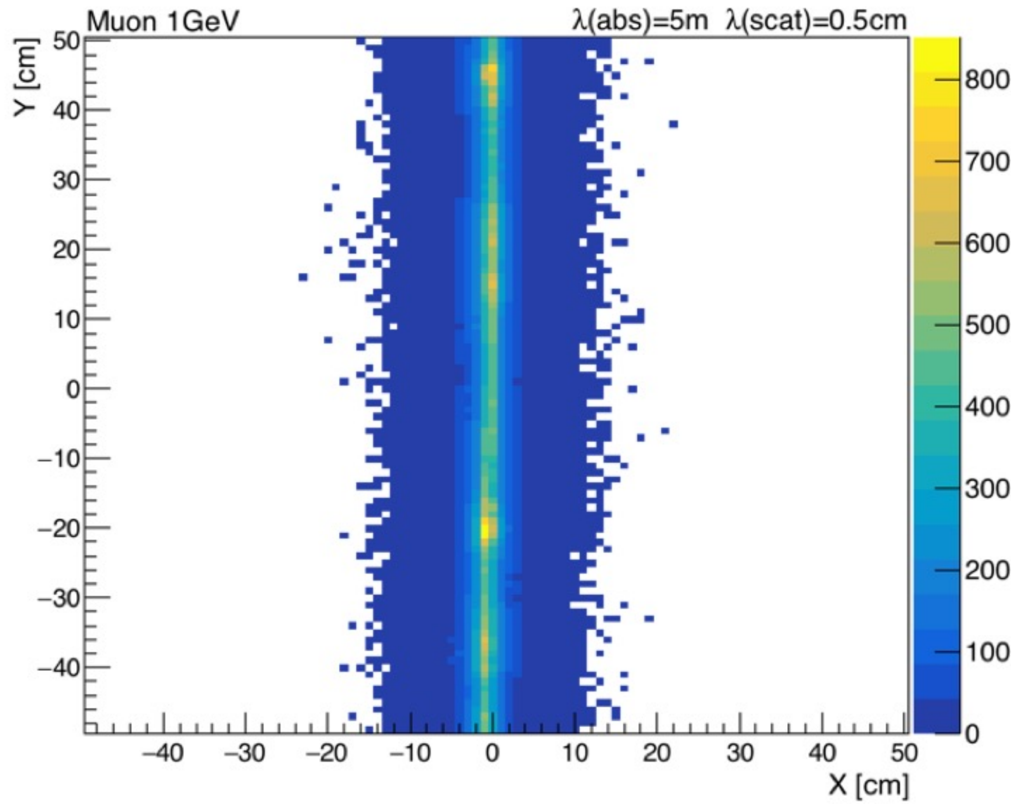


Distinguish positrons from point-like energy depositions (e.g. electrons, protons, alphas)

Use high-resolution imaging for particle identification



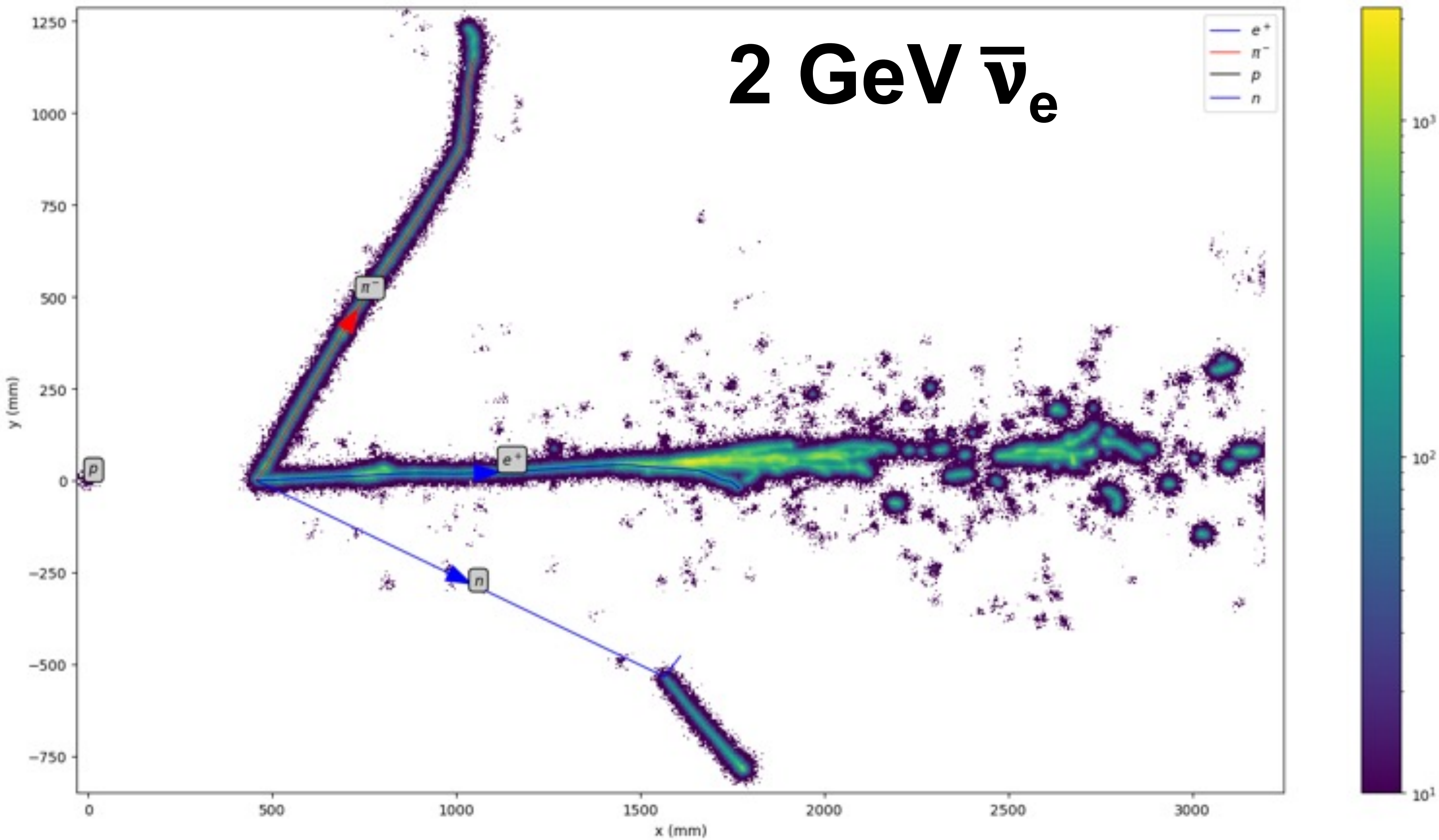
50 MeV e⁻



1 GeV μ

(through-going)

Use high-resolution imaging for particle identification



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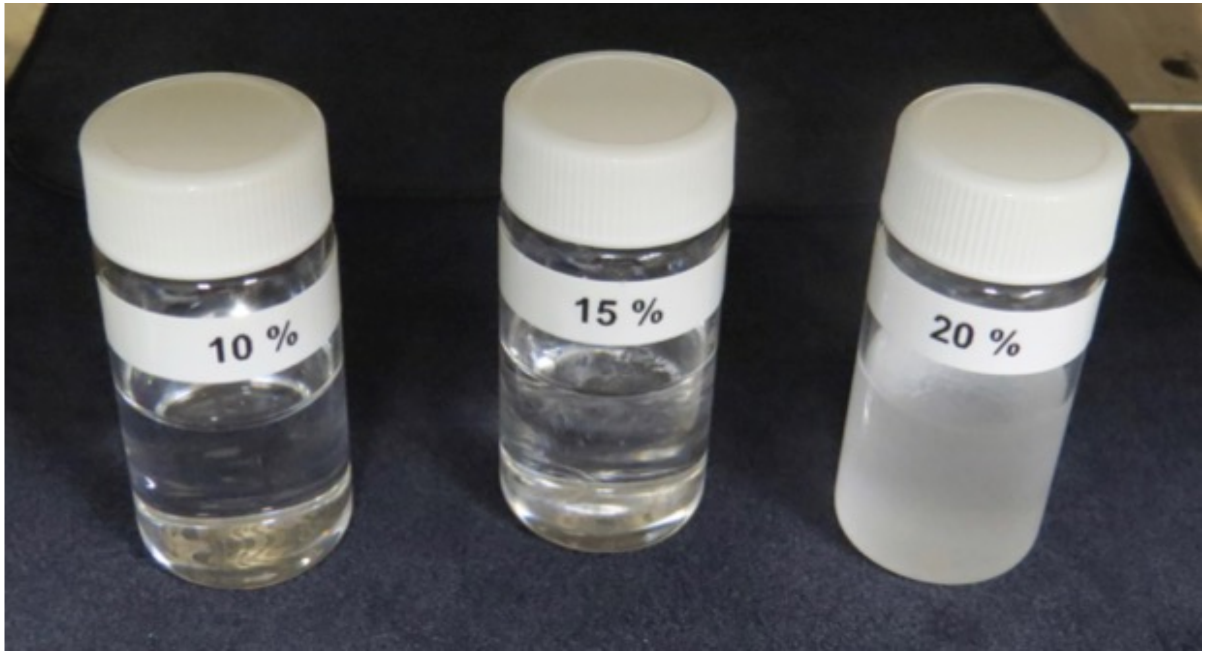
Our First Opaque Scintillator

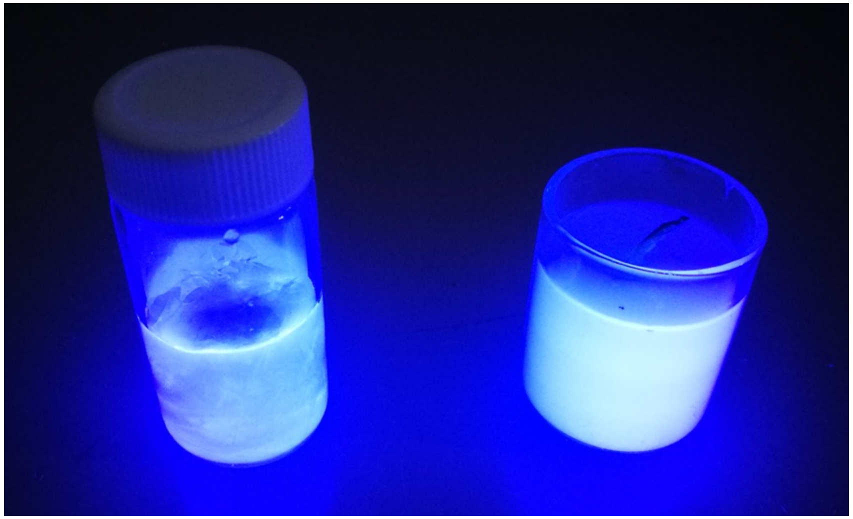


"NoWaSH" = Linear Alkyl Benzene + PPO + Paraffin wax

Two Categories of Opaque Scintillator

(among others)

Wax-induced Opacity



Behaviour similar to a candle

Transparent liquid when warm (>36 degC)

Opaque solid when cooled (~25 degC)

Can also now make viscous (not solid) versions with low wax fractions

Opacity depends on wax type & concentration, which changes crystalisation temperature

Opaque Emulsions

Liquid scintillator + water (plus surfactant)

Currently using low-% water to preserve high light yield of scintillator

(a “butter” rather than a “milk”)

Tests underway

Demo

First Papers

communications physics

ARTICLE

https://doi.org/10.1038/s42005-021-00763-5 OPEN

Neutrino physics with an opaque detector

LiquidO Consortium*

In 1956 Reines & Cowan discovered the neutrino using a liquid scintillator detector. The neutrinos interacted with the scintillator, producing light that propagated across transparent volumes to surrounding photo-sensors. This approach has remained one of the most widespread and successful neutrino detection technologies used since. This article introduces a concept 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 optical fibres. This technique, called LiquidO, can provide high-resolution imaging to enable efficient identification of individual particles event-by-event. A natural affinity for adding dopants at high concentrations is provided by the use of an opaque medium. With these and other capabilities, the potential of our detector concept to unlock opportunities in neutrino physics is presented here, alongside the results of the first experimental validation.

https://www.nature.com/articles/s42005-021-00763-5

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Published by IOP Publishing for Sissa Medialab

Received: *August 12, 2019*
Revised: *September 30, 2019*
Accepted: *October 21, 2019*
Published: *November 5, 2019*

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.

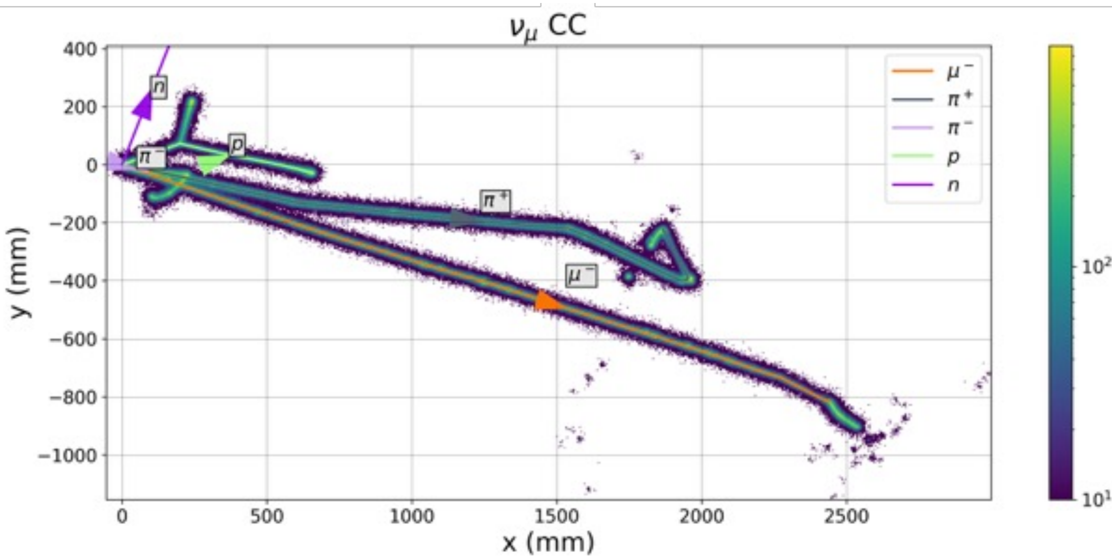
Keywords: Detector design and construction technologies and materials; Neutrino detectors; Scintillators, scintillation and light emission processes (solid, gas and liquid scintillators)

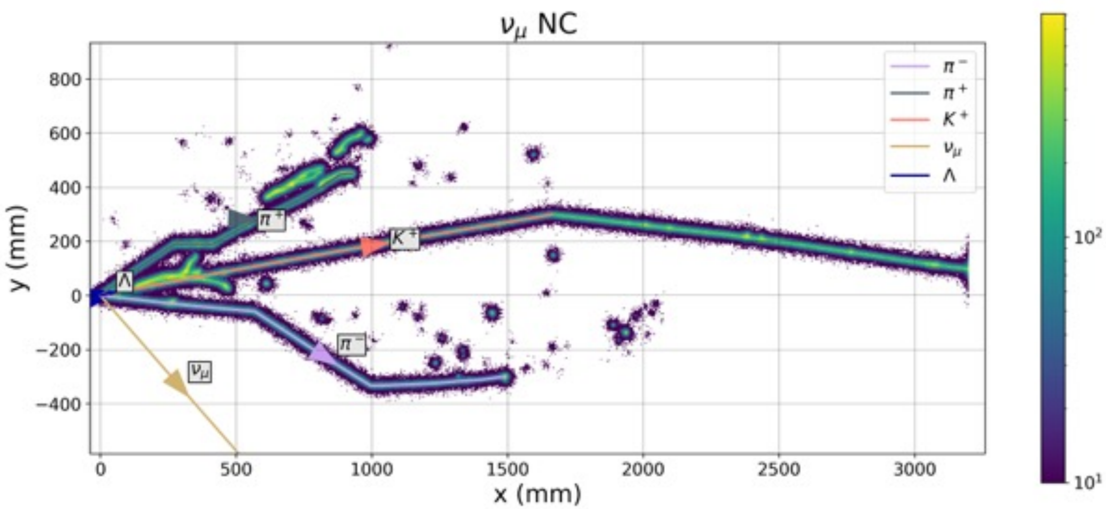
ArXiv ePrint: 1908.03334

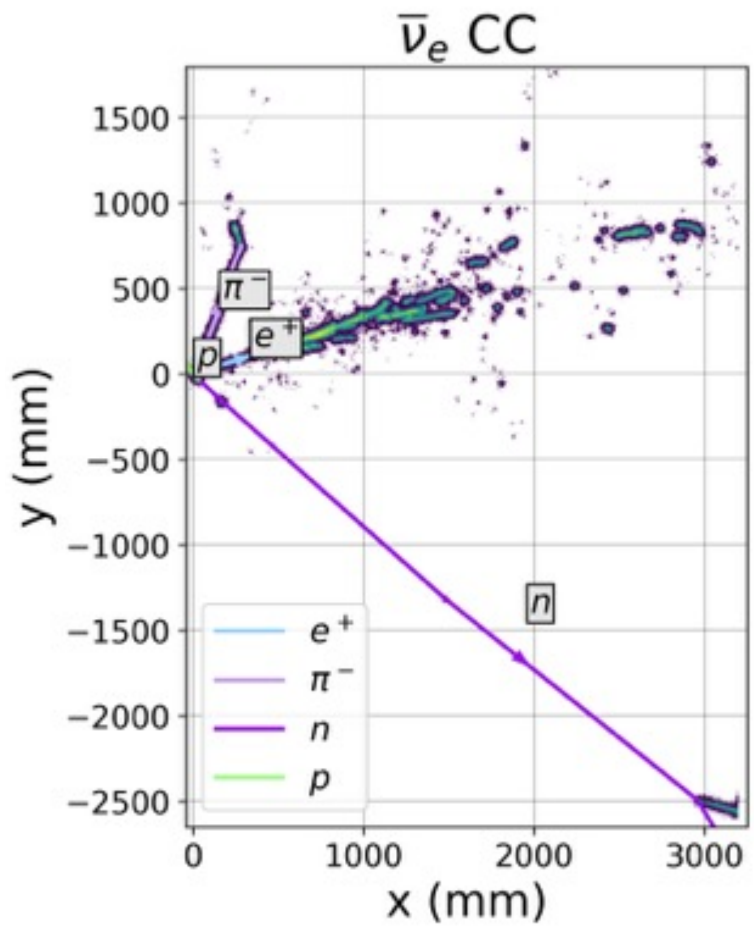
2019 JINST 14 P11007

https://liquido.ijclab.in2p3.fr/

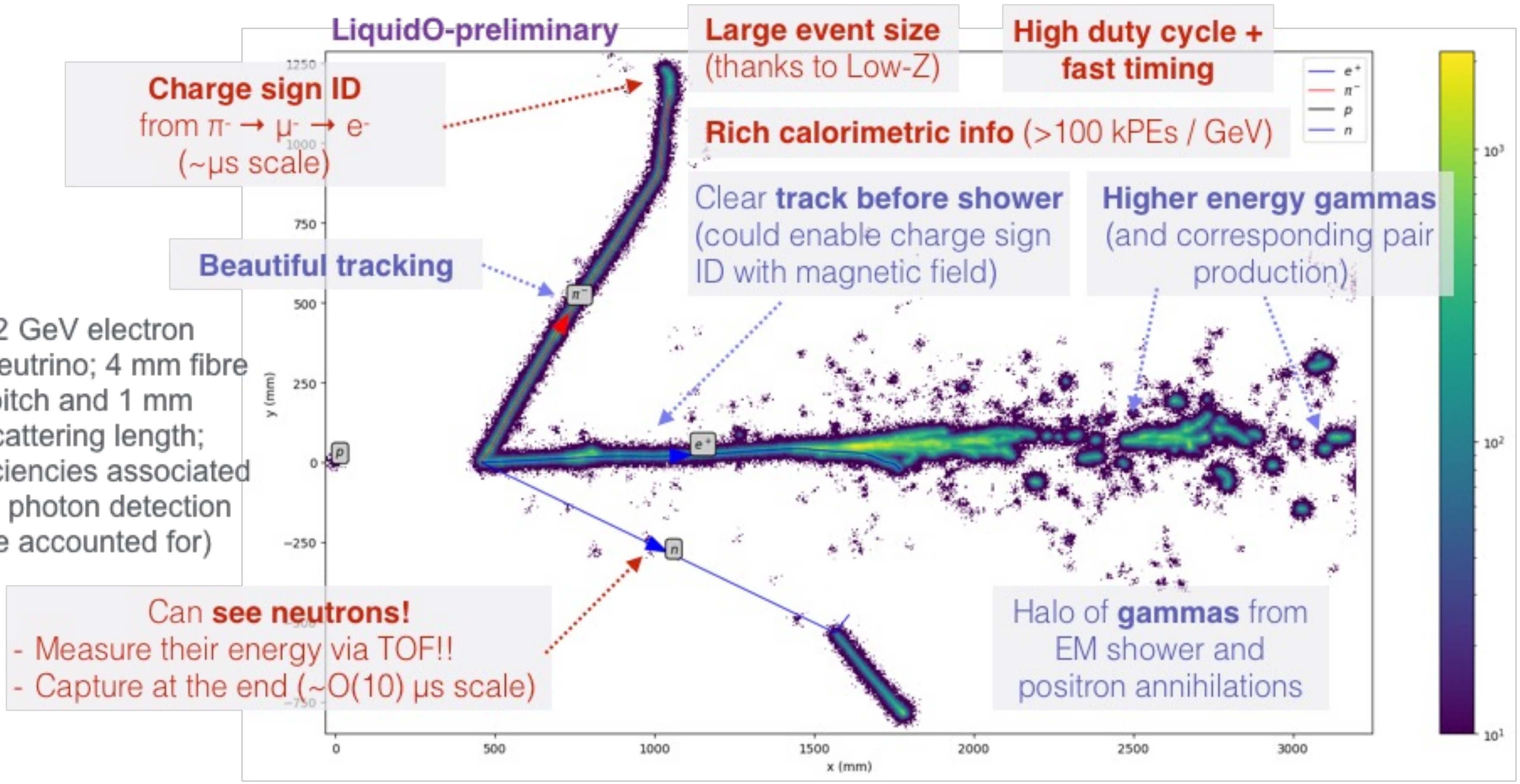
Beautiful LiquidO beam events







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

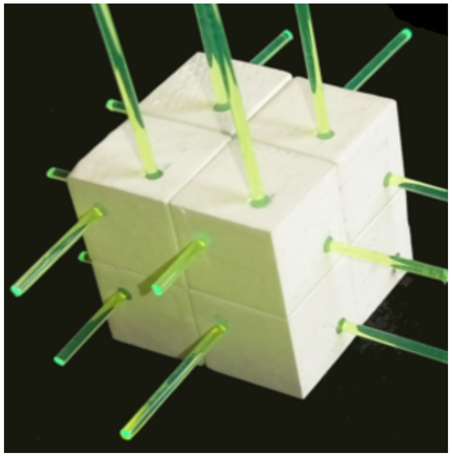


(2 GeV electron antineutrino; 4 mm fibre pitch and 1 mm scattering length; inefficiencies associated with photon detection are accounted for)

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

Apply LiquidO idea to existing neutrino detector concept…

T2K SuperFGD (also SoLiD, 3DST) "Voxelated" Detector

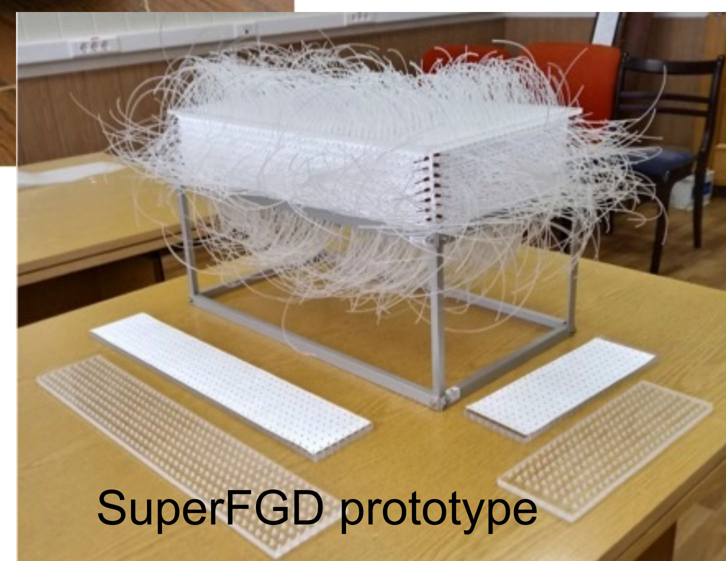


T2K SuperFGD:

1 cm cubes
x2 million!

~2 tons

56,384 channels
(scales with surface area of detector)



Voxelated LiquidO Detector

- Basic concept:
  - Construct a lattice of fibres and pour in the scintillator
- Avoid the need for manual segmentation
  - No manufacture of tiny cubes with reflective surfaces by the million
  - No machining of 3 precise holes in millions of cubes
  - No threading of fibres through millions of cubes
- More precise position reco for given fibre pitch – not limited by segment size
  - Use profile of light across multiple fibres (more information)
- Scales better to achieve even more precise position reco
  - In contrast: reducing fibre pitch by x2 → 8x more cubes (volume effect)
- Scales better to larger masses
  - Longer fibres can instrument more mass without needing lots more cubes
- Use different targets (e.g. high fraction of water, or doping)
  - Can drain and replace the scintillator

Current Status of LiquidO

- LiquidO Consortium has 25 institutions
  - Co-publication model for detector R&D (like papers from a big experiment)
  - Shared simulation software
- Several funded projects underway
  - CLOUD experiment, reactor neutrinos (see next slide)
  - PET scanner concept
  - Muon tomography prototype
  - Software projects, e.g. reconstruction w/ machine learning
- What's next?
  - Proposing SuperFGD-style LiquidO prototype to UK's STFC
    - Do grab me over dinner/coffee to find out more
    - LArTPC reconstruction software may be very useful
  - Lots of other ideas too

CLOUD

European Innovation Council

UKRI
UK Research and Innovation

(Funded: Dec/22 → Nov/26)

CLOUD = "**C**hooz **L**iquid**O** **U**ltranear **D**etector"

European Innovation Council

UK Research and Innovation

CLOUD

Innovation Programme (confidential for now)
Fundamental Science Programme (soon)

- **EDF** (France) — **first time in neutrinos!**
- **CIEMAT** (Spain)
- **IJCLab**/Université Paris-Saclay (France)
- **JGU Mainz** (Germany)
- **Subatech**/Nantes Université (France)
- **Sussex University** (UK)

—

- **BNL** (US)
- **Charles University** (Czech Republic)
- **INFN-Padova** (Italy)
- **Penn State** (US)
- **UC-Irvine** (US)
- **Universidade Estadual de Londrina** (Brazil)
- **Michigan University** (US)
- **PUC-Rio** de Janeiro (Brazil)
- **Queen's University** (Canada)
- **University of Zaragoza** (Spain)
- **Tohoku University** / **RCNS** (Japan)

“Ultra Near” Detector Site

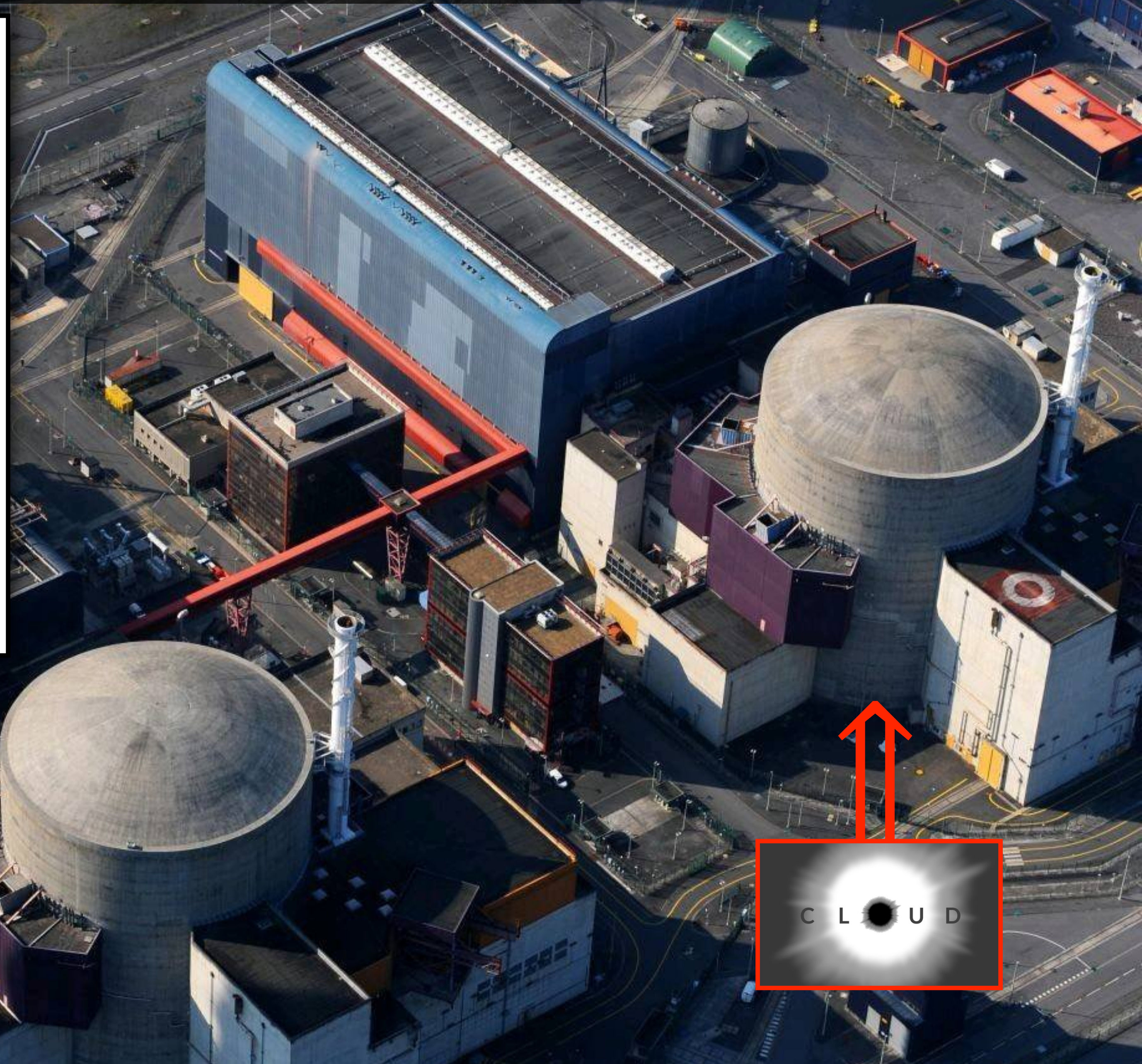
5 ton opaque detector
Fibres in ~1 direction

On the surface

25 m to reactor core

Huge signal
≥ **10,000** ν/day

Use high-resolution imaging to beat down backgrounds



Conclusions

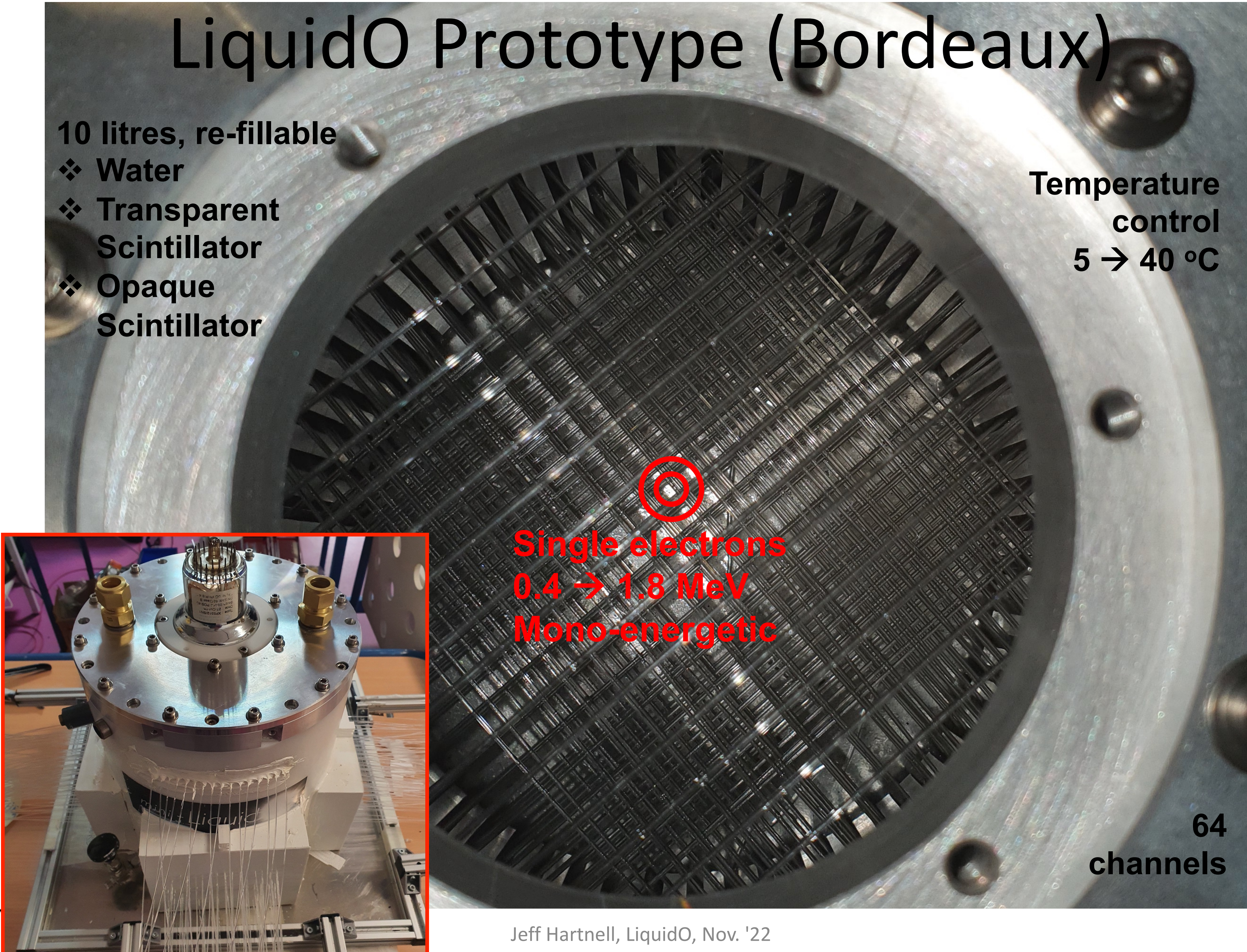
- Innovative new "LiquidO" detector technology
  - Opaque medium + lattice of fibres
  - High-resolution imaging
- SuperFGD style LiquidO detector concept
  - Many advantages over traditional segmented approach
- Many LiquidO projects now funded and underway
- Final thought: LiquidO is a whole new way of thinking about a scintillator detector
  - Expect many great ideas we haven't even imagined yet!

The End

Backup slides

Prototypes and Results

LiquidO Prototype (Bordeaux)



10 litres, re-fillable
- ❖ Water
- ❖ Transparent Scintillator
- ❖ Opaque Scintillator

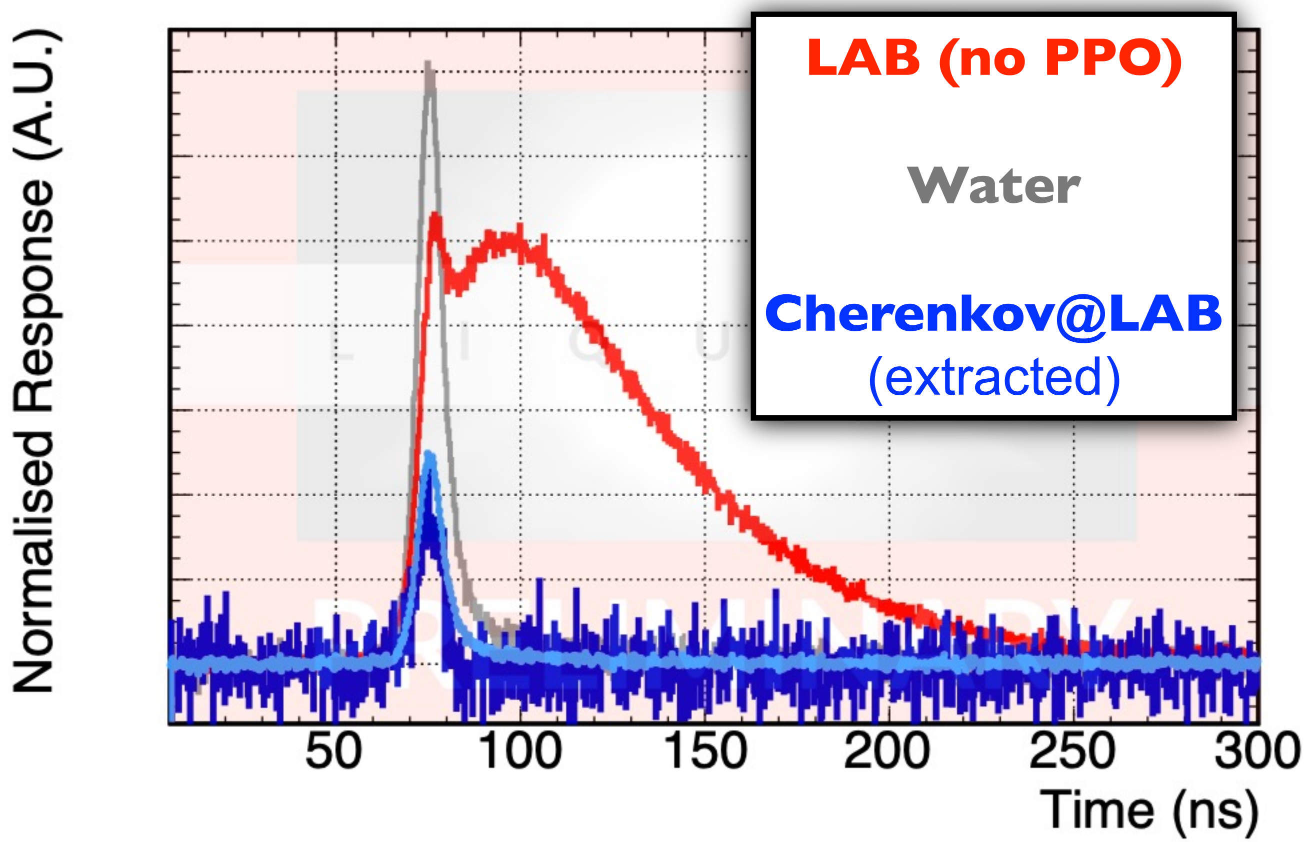
Temperature control
5 → 40 °C

Single electrons
0.4 → 1.8 MeV
Mono-energetic

64 channels

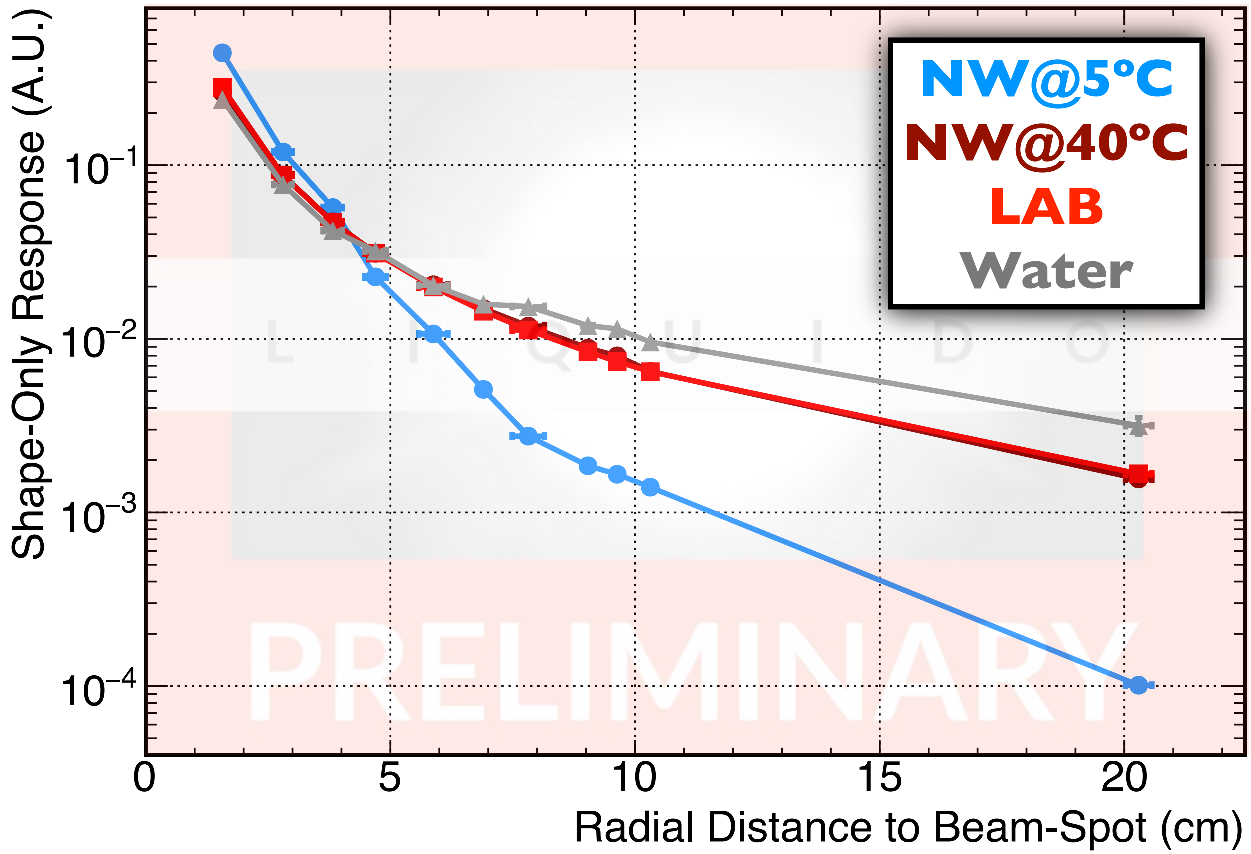
Scintillation and Cherenkov Light

- Start with transparent materials
- Demonstrate fibre/electronics performance
- See "early" light from Ckv
- Later light from scintillation in LAB
- Both components present in pure LAB



Comparing Opaque with Transparent

- NoWaSH (NW) is opaque at 5 ^{o}C, transparent at 40 ^{o}C
- Predicted, yet remarkable feature:
  - More light collected by WLS fibres near the light source with opaque scintillator
  - Less light further from the source



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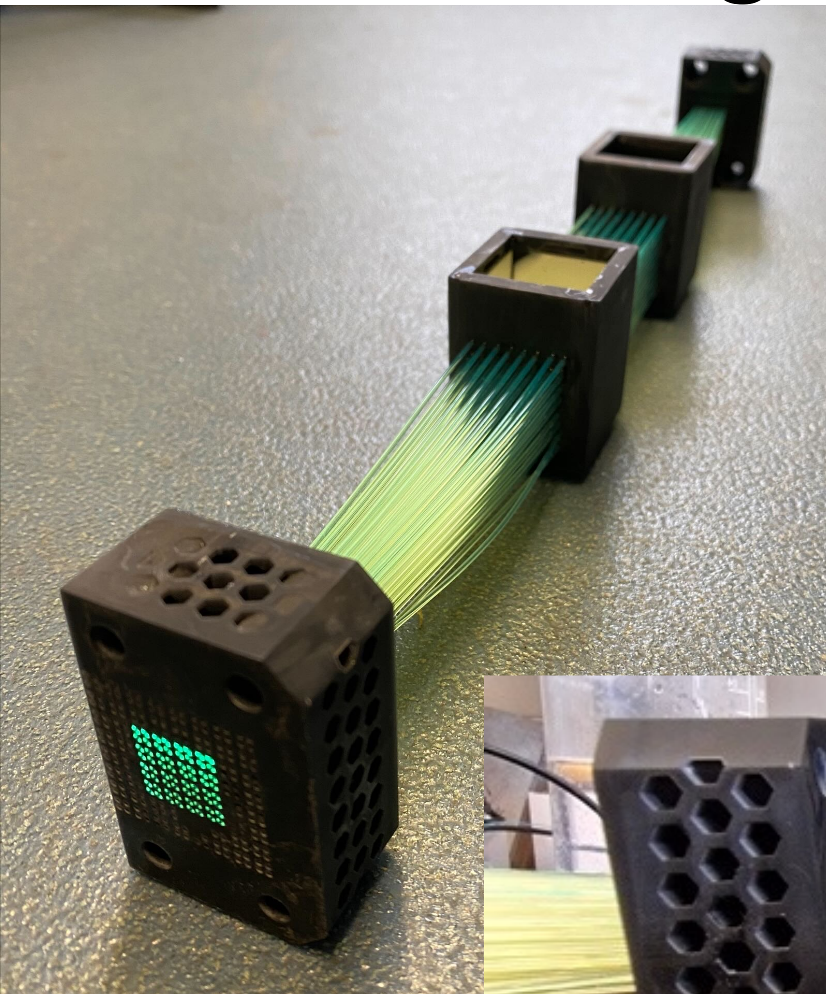
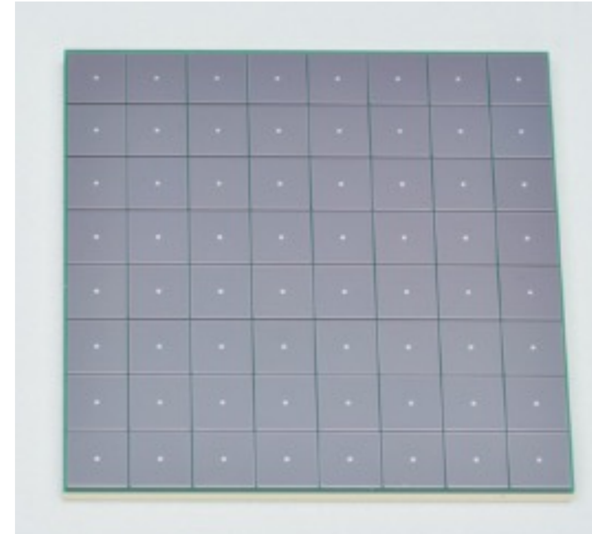
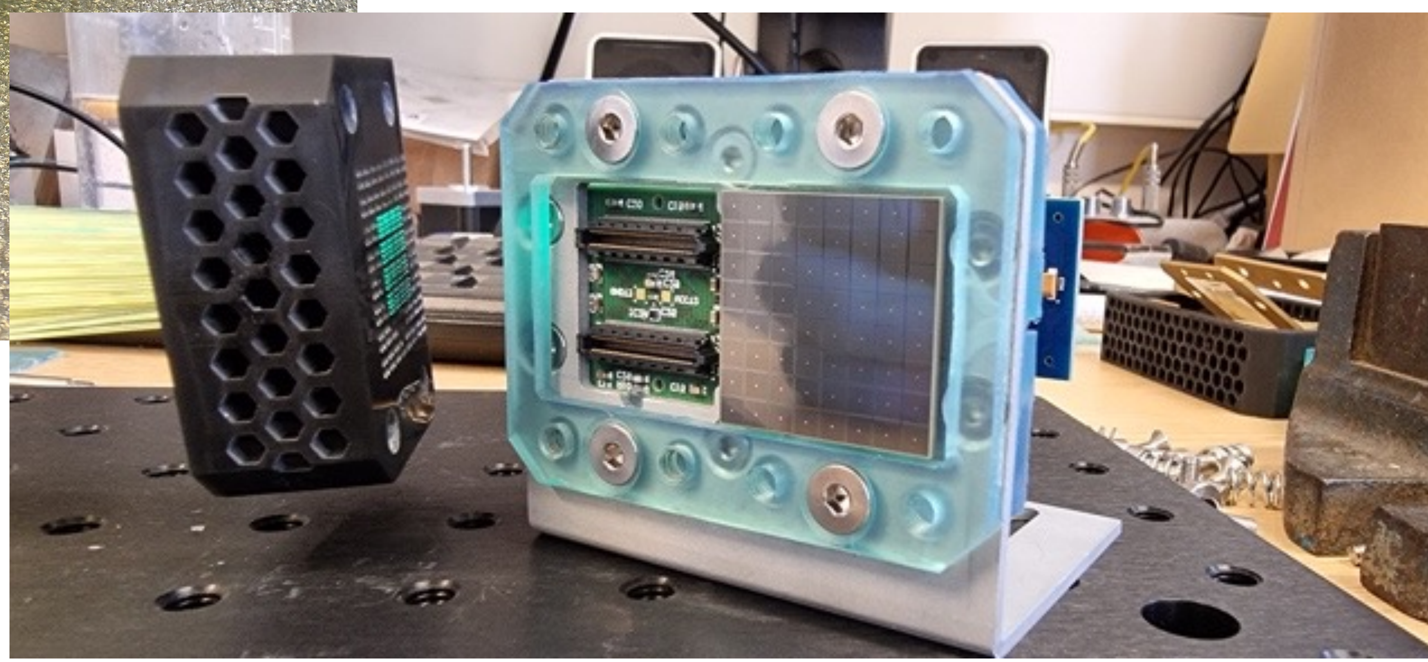
Sussex Engineering Prototype



- 64 fibres
- 4 fibres per pixel
- 32 channels
- Small 3 cm cubes filled with NoWaSH scintillator



Hamamatsu S13361-3050
8x8 MPPC



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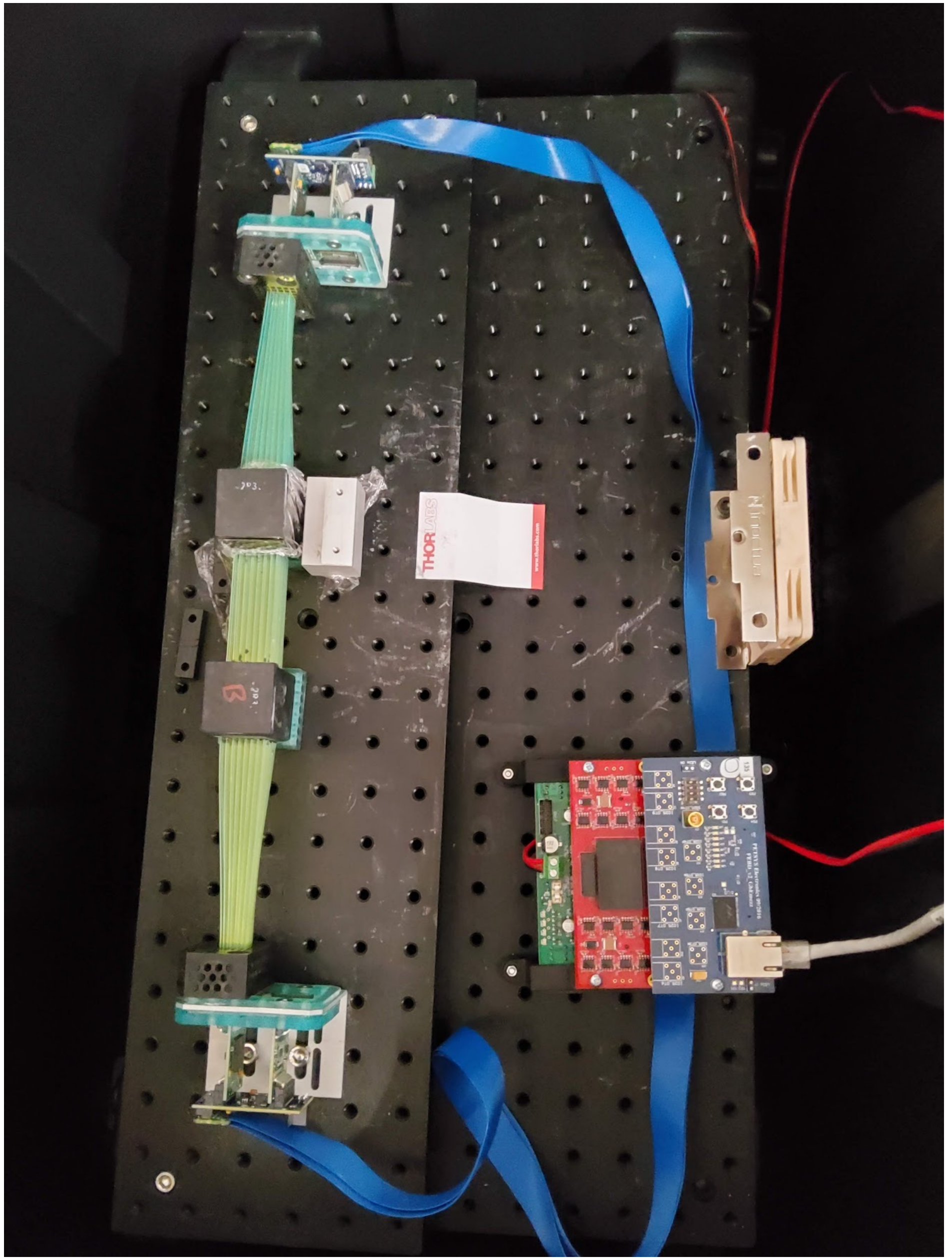
Sussex Engineering Prototype



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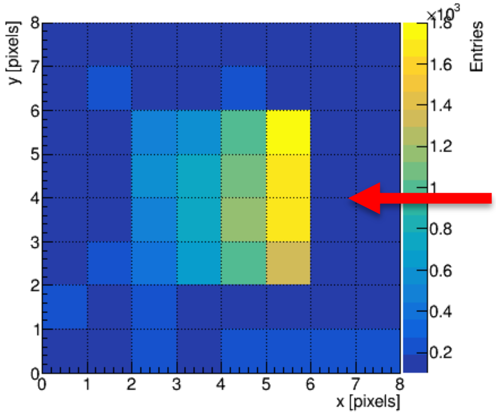
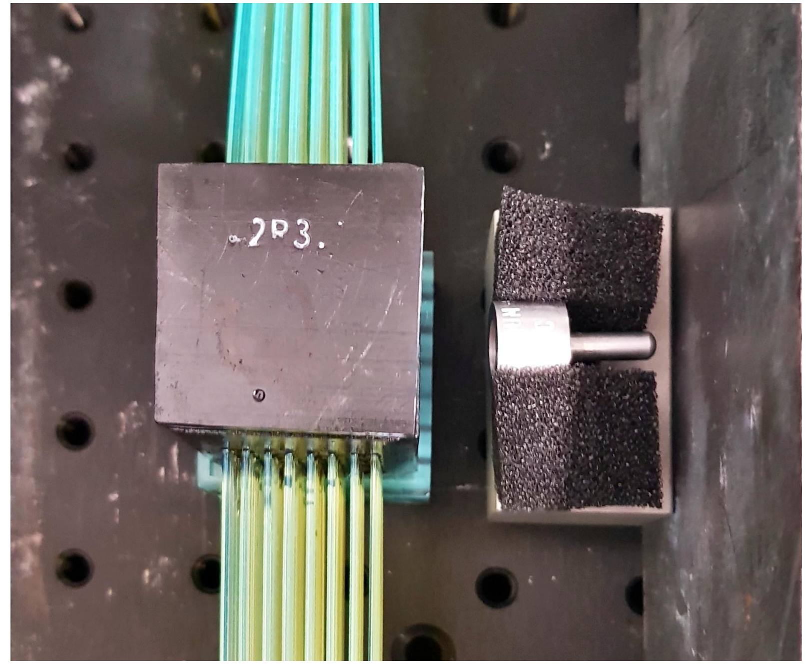
Results

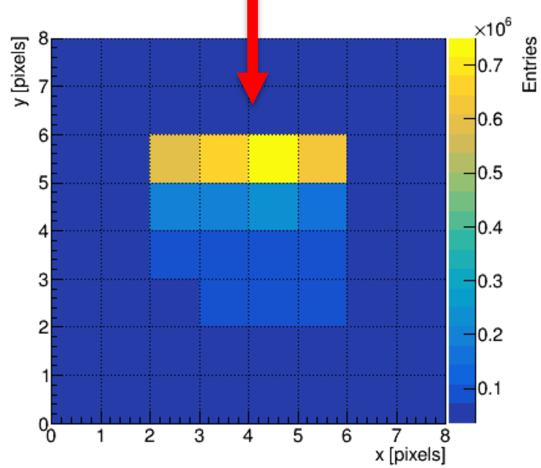


^{90}Sr β^-



^{90}Sr Beta Source

^{90}Sr β^-



Strong position information

~100 PE/MeV
(not optimal fibre)

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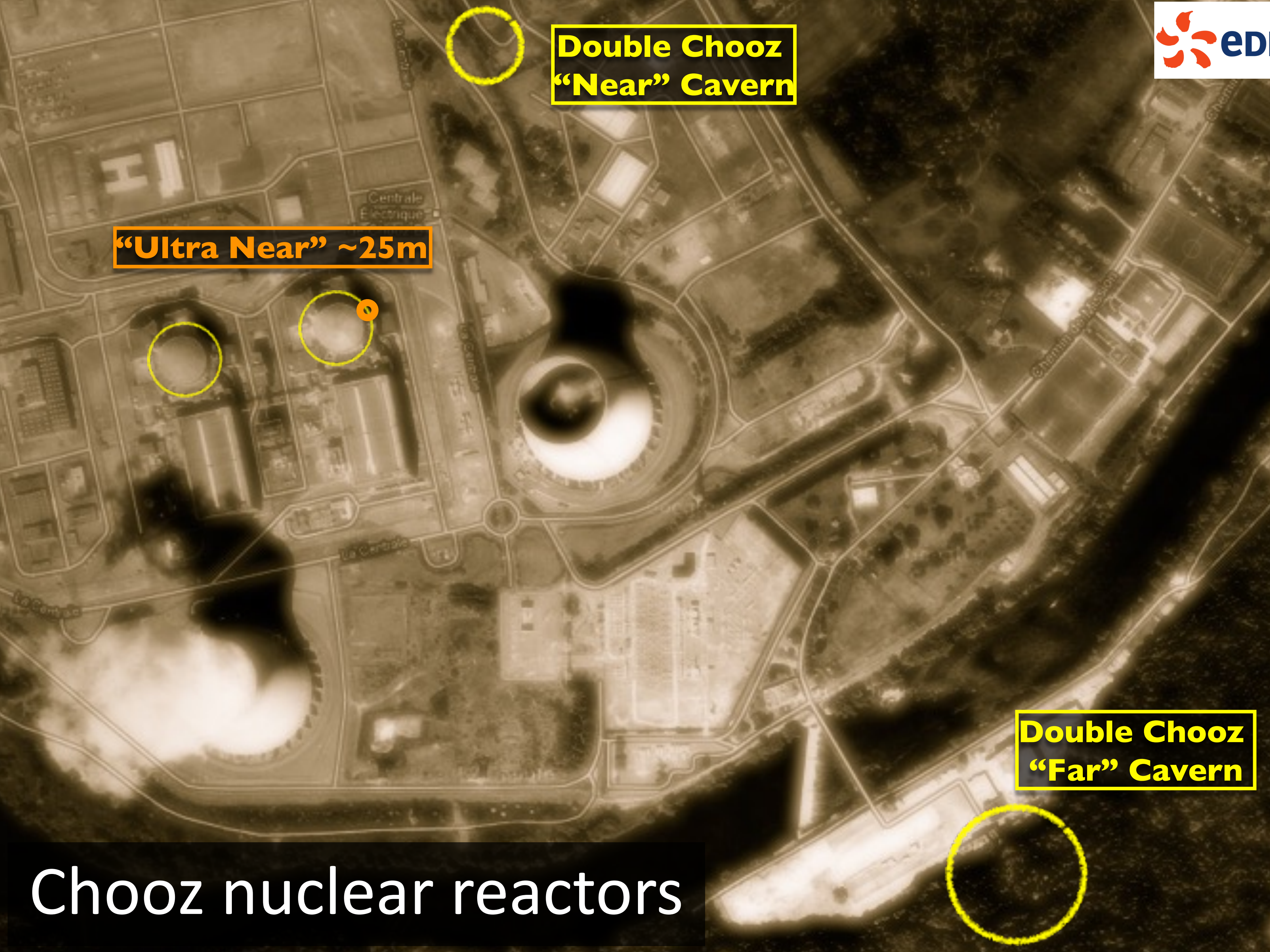
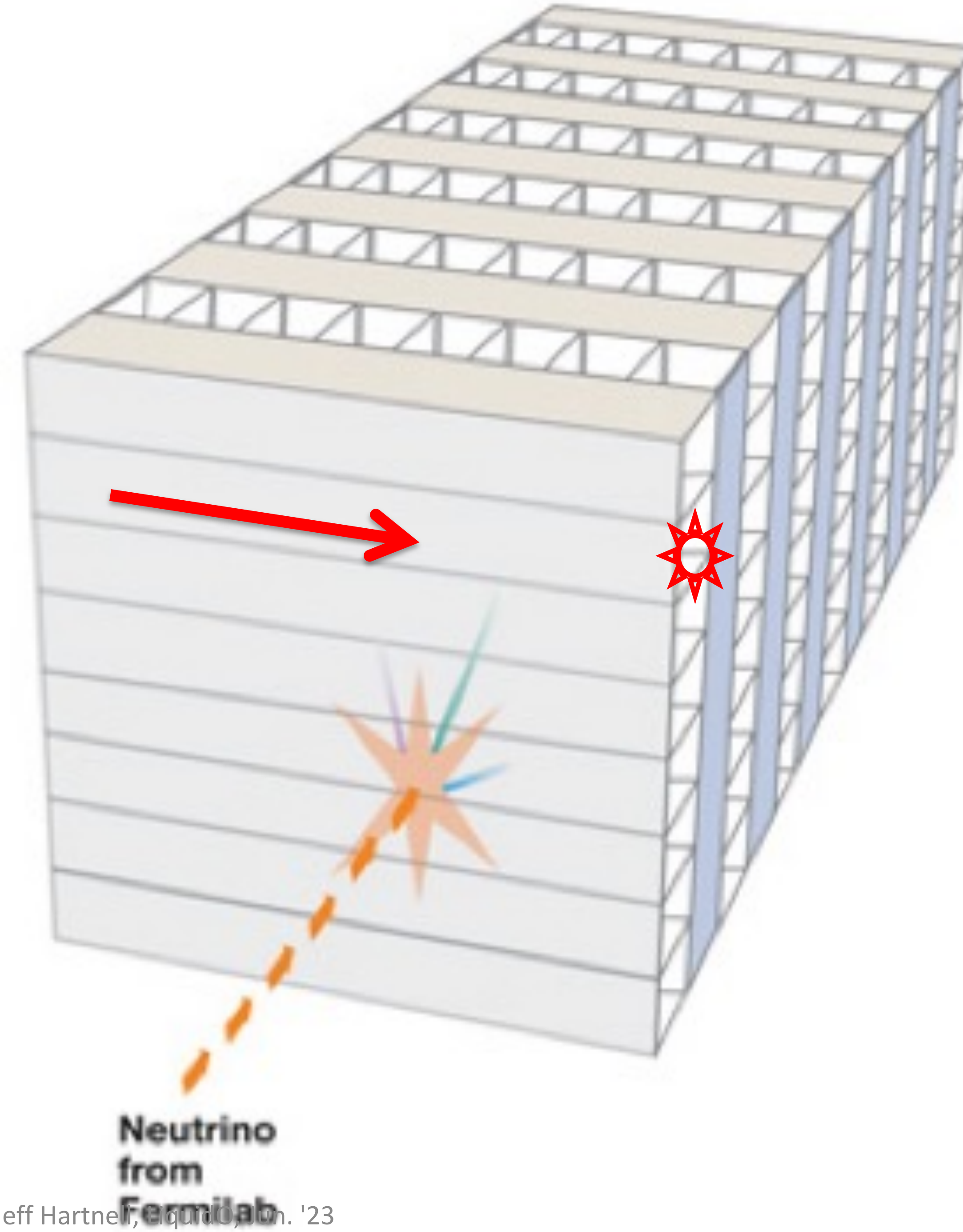
Chooz nuclear reactors



- Problem with planar geometry
- Perpendicular travelling particle (red arrow) might give hit only on one strip
  - No info on where particle was along the strip



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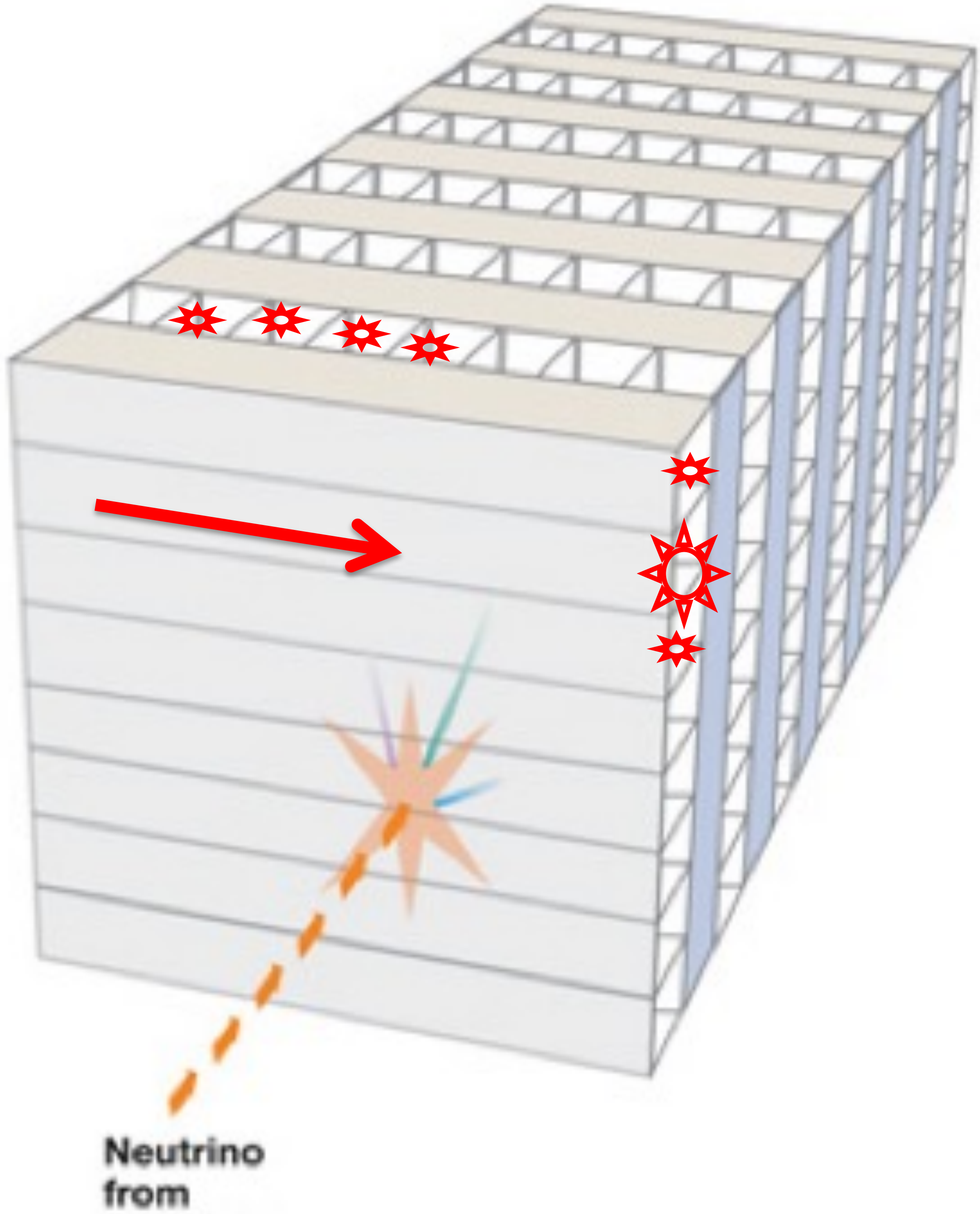
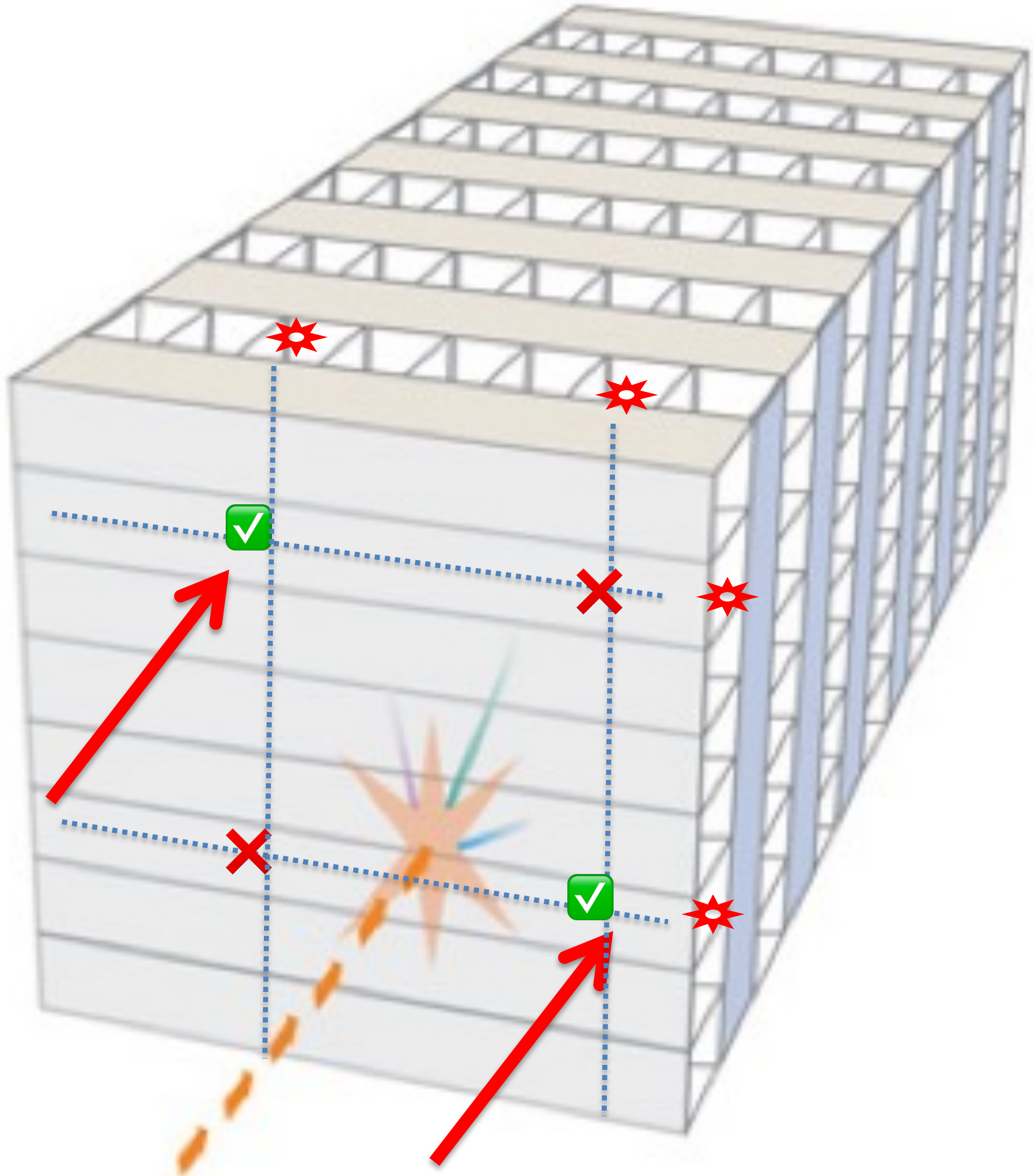
- In LiquidO the light is not confined to one strip
- You get lots of information on where the particle was located along the strip
- The loss of acceptance at “perpendicular angles” should be less of a problem in a LiquidO detector



- However, there is still the problem of multi-particle degeneracy
- Two particles (red arrows) of same length have 4 solutions
- Having fibres in a third direction breaks this degeneracy



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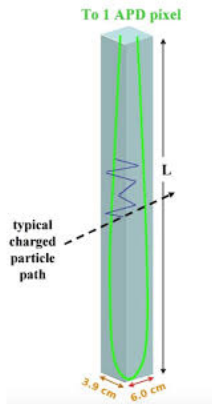
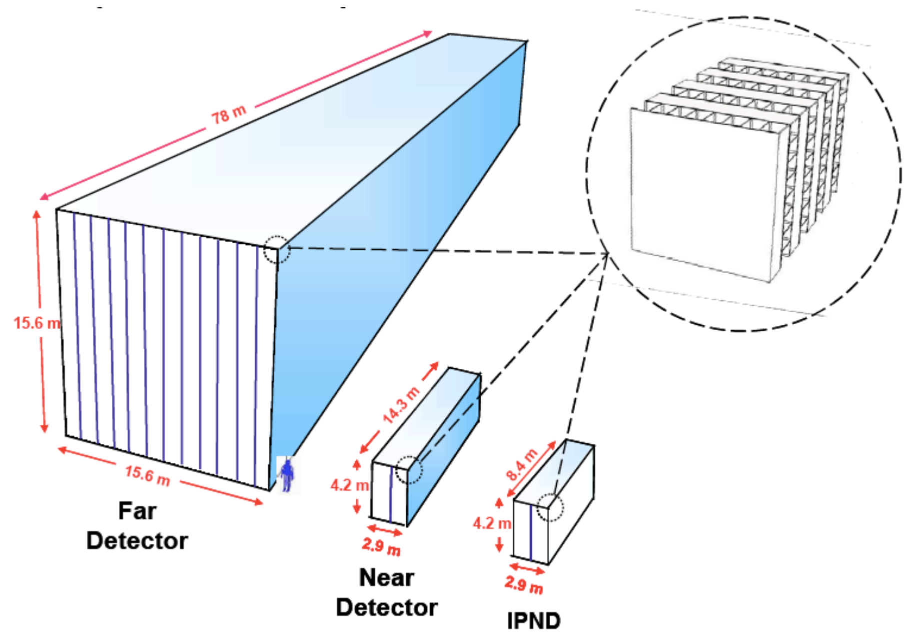
Scalability

– 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:

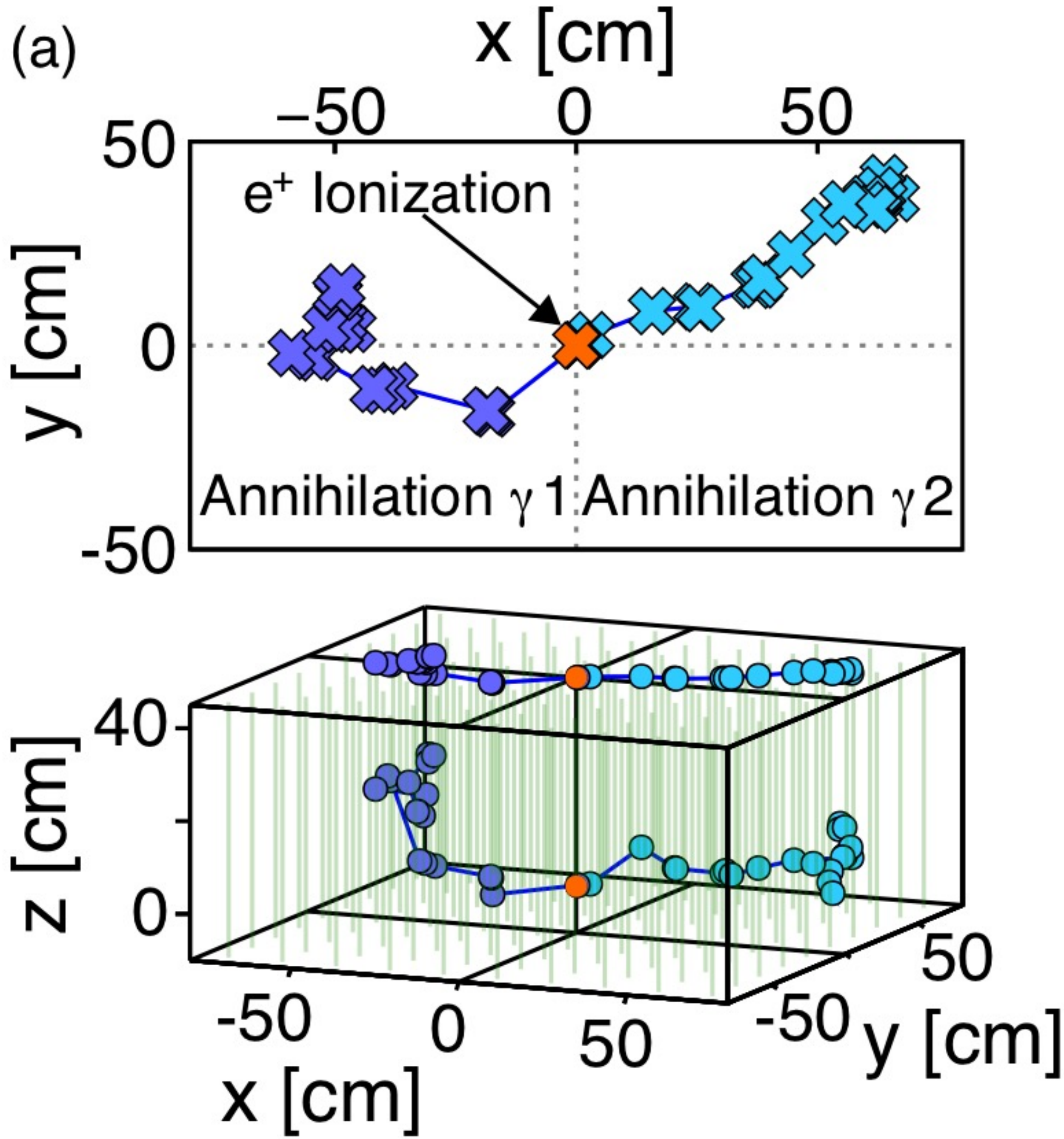
- Room temperature operation (no need for cryostat)
- Self-shielding detector

Simple example detector

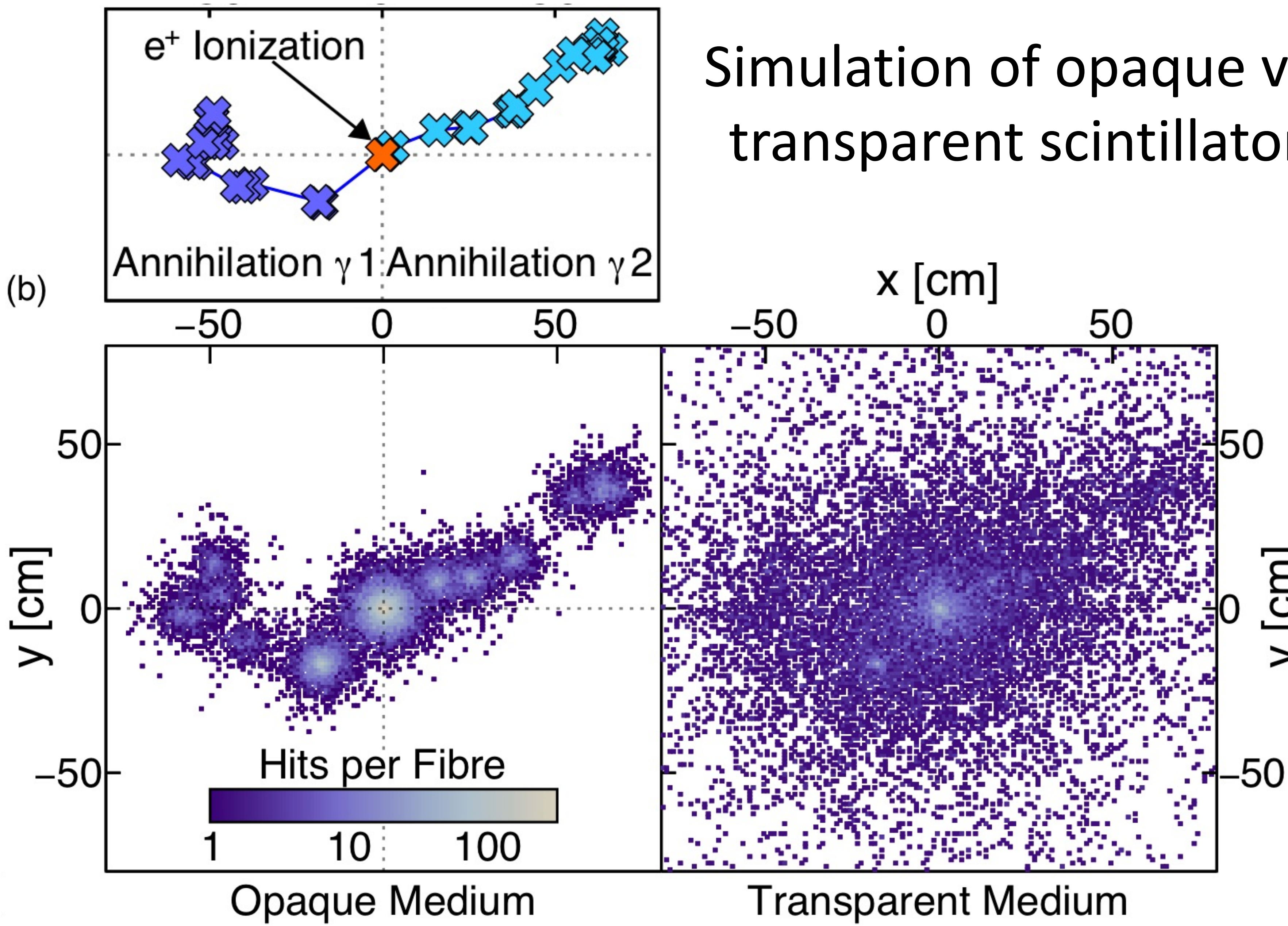
1 cm pitch lattice of fibres, along a single direction

Positron of 1 MeV

Two annihilation gammas



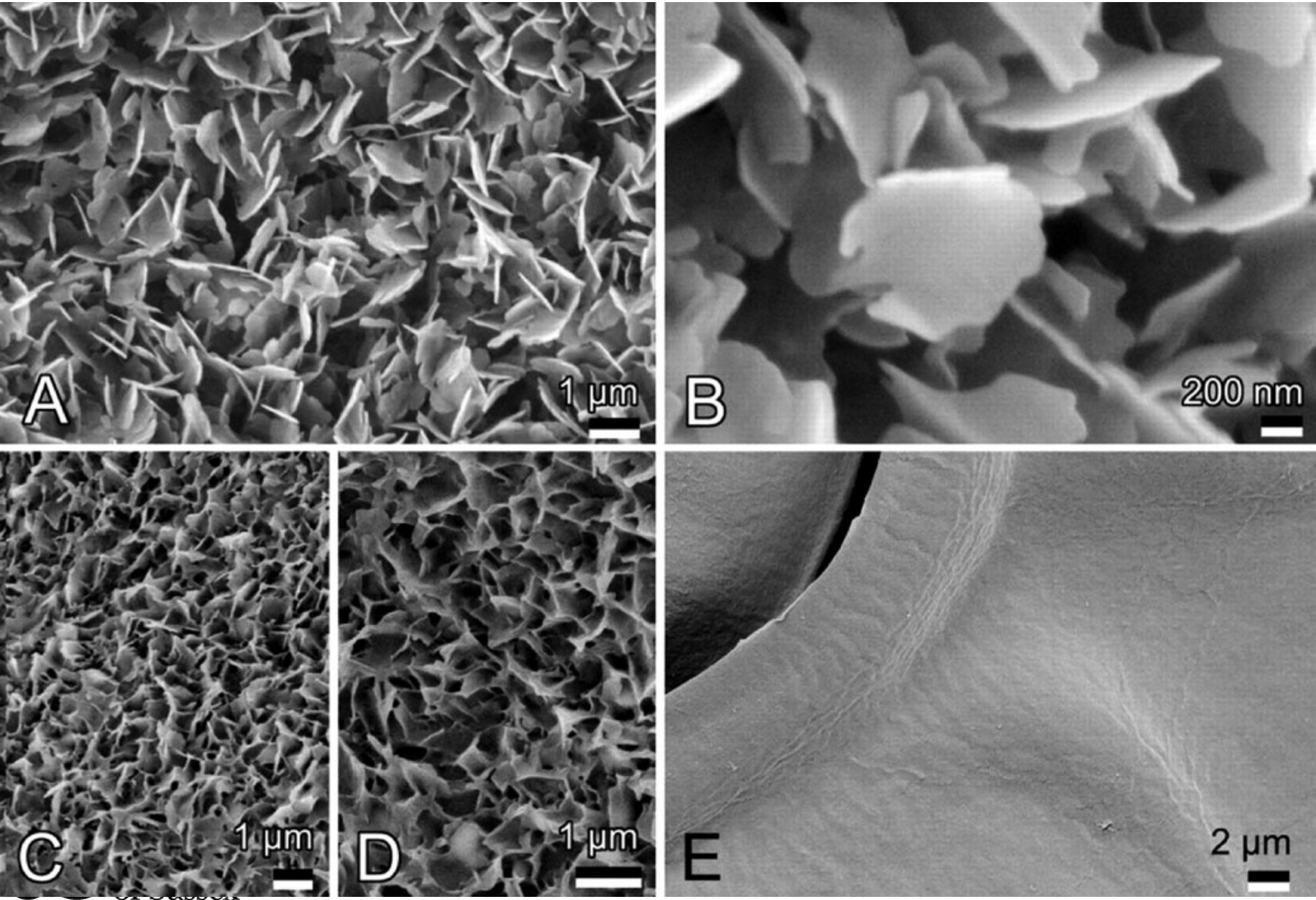
Simulation of opaque vs. transparent scintillator



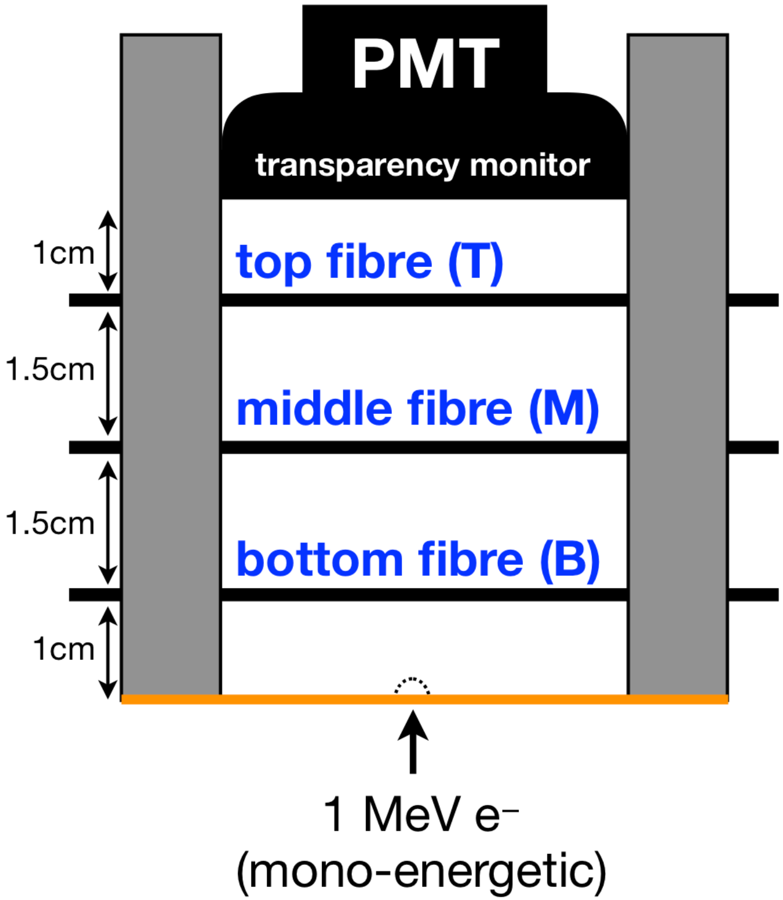
What physics can we do?

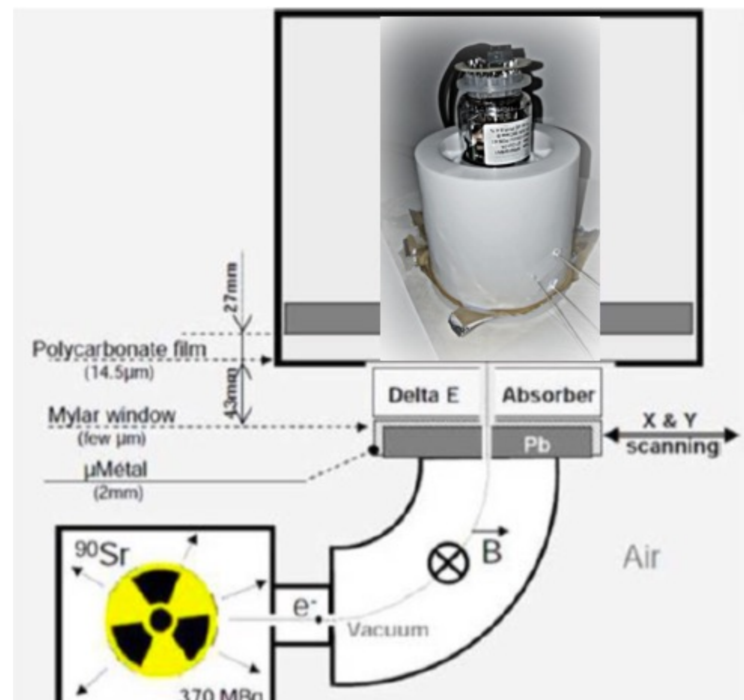
- Lots of ideas
  - Not enough time to cover them all
- Multiple papers in preparation
  - Ultra precise θ_{13} measurement for unitarity test
    - https://indico.cern.ch/event/577856/contributions/3421609/attachments/1878723/3095931/190711-UnitariryLiquidOChooz_EPS-Anatael.pdf
  - ^{40}K geo-neutrino 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…

Wax (random) structure

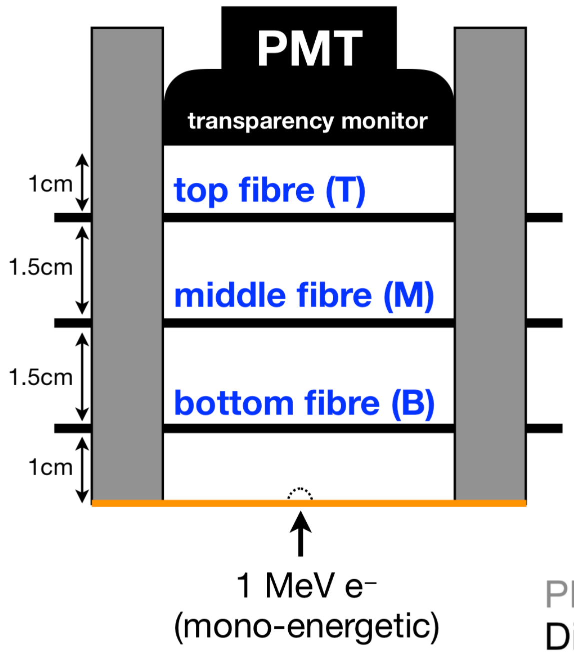


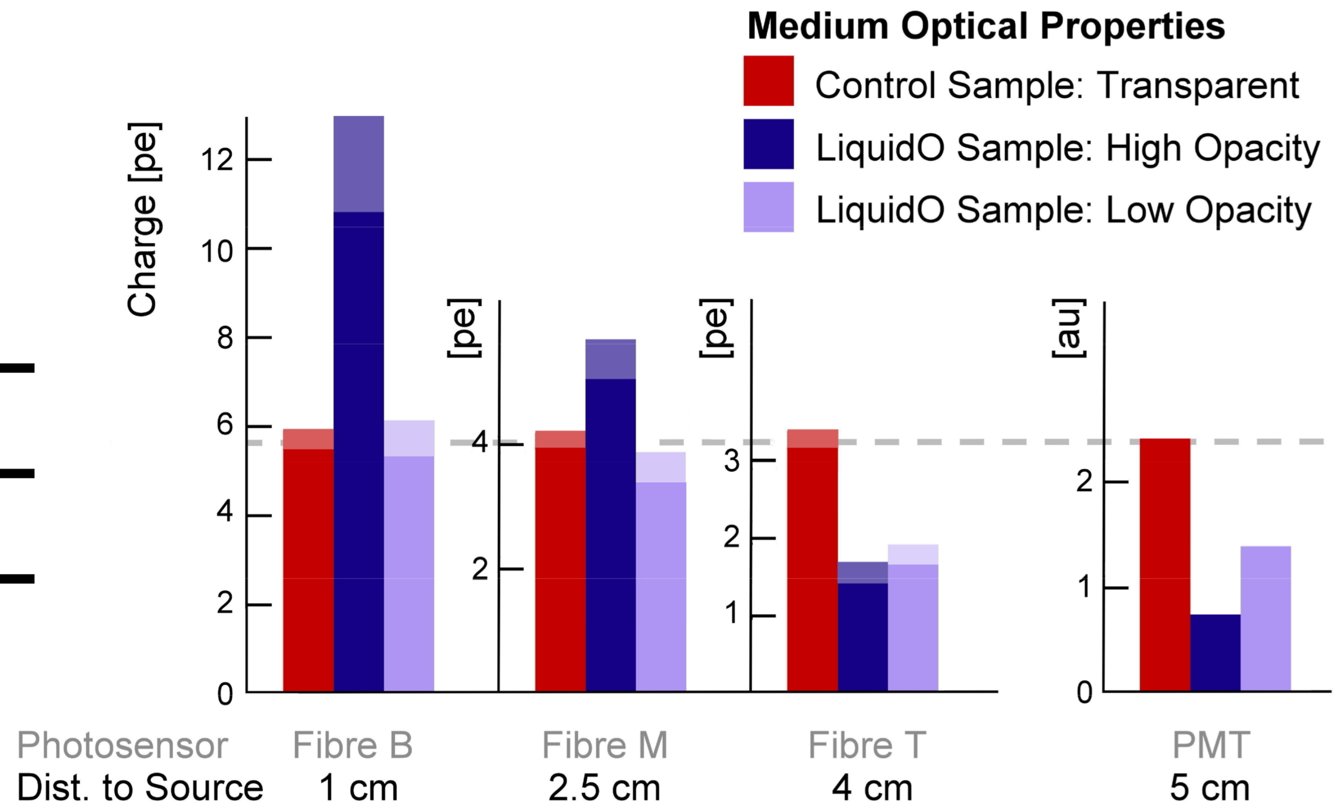
“micro-LiquidO” Proof of Principle





Proof of Principle

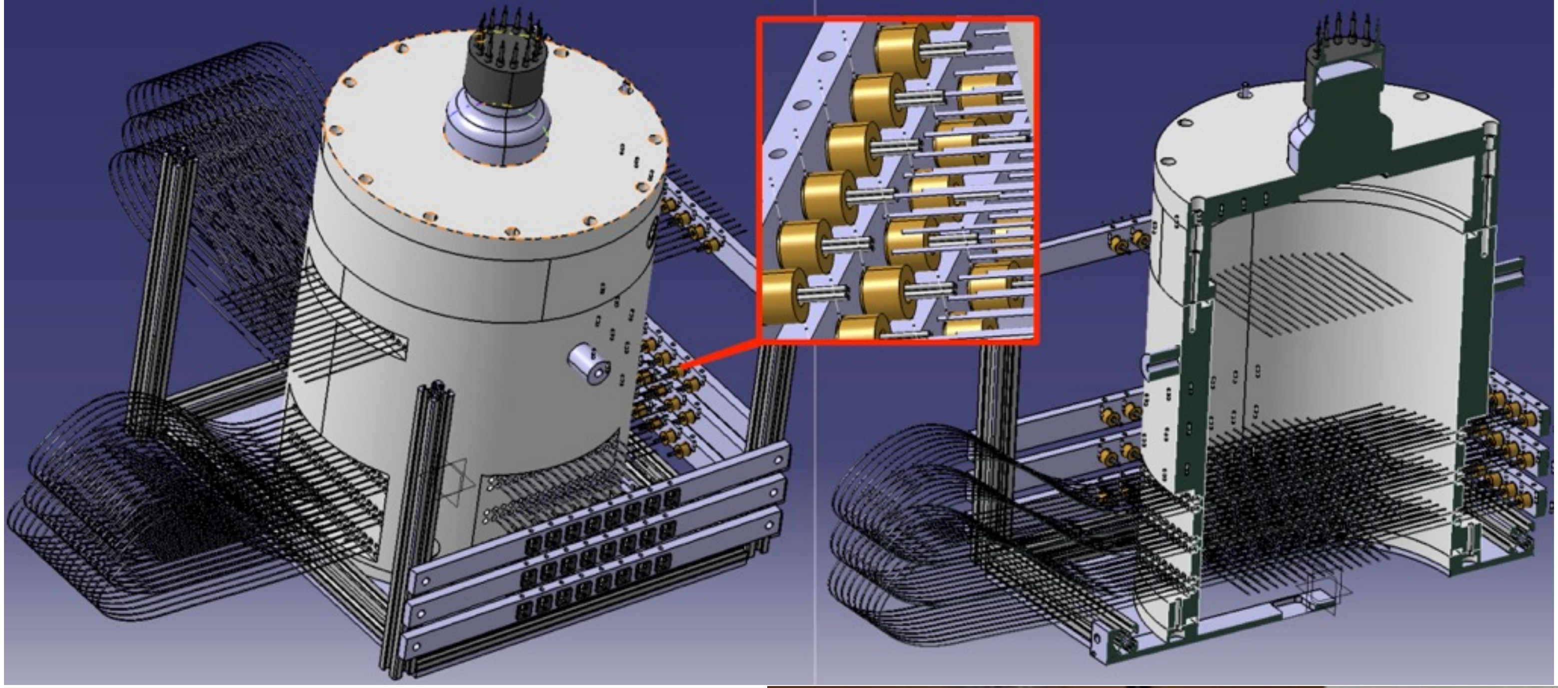




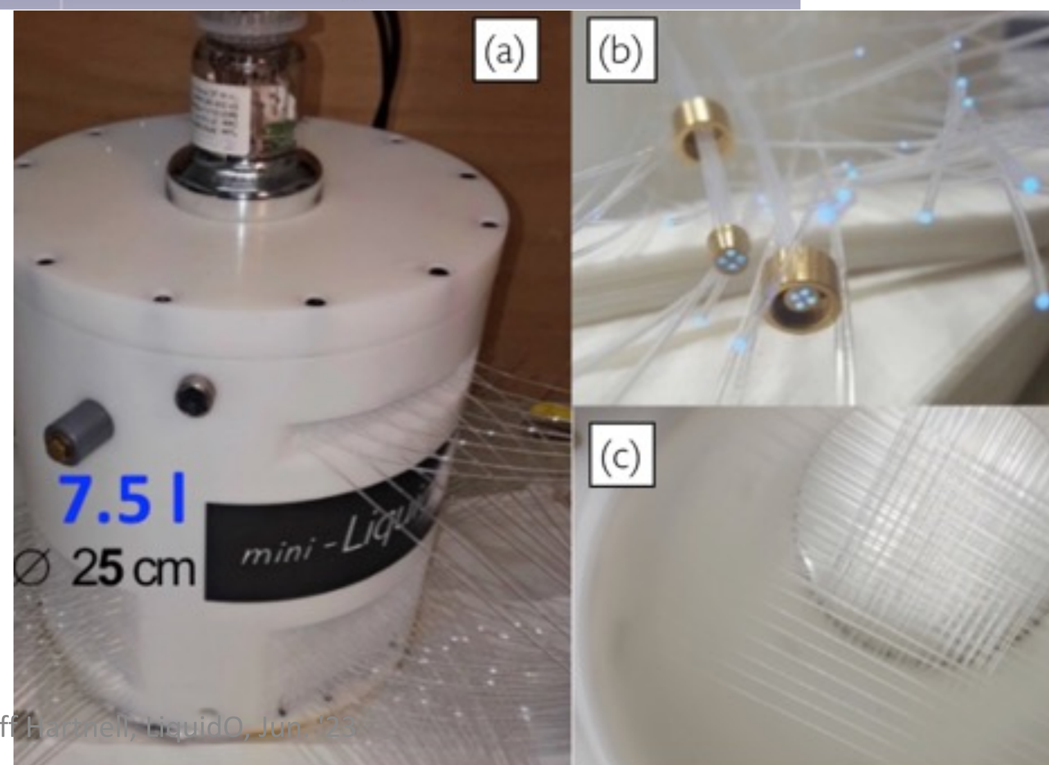
Three scintillators compared

The predicted and yet remarkable feature:

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



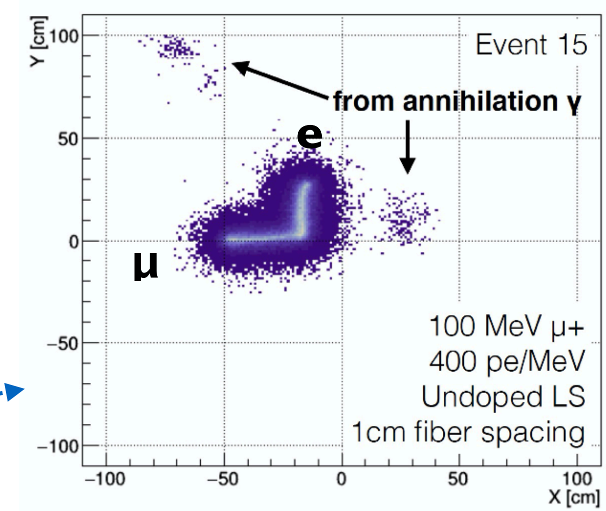
“mini-LiquidO”



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

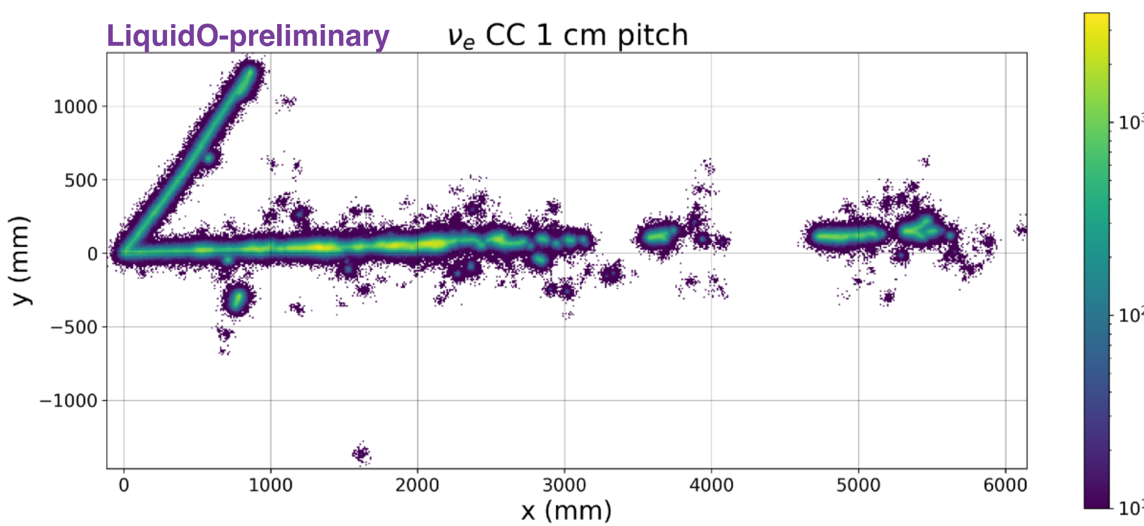


– Other opportunities:

- 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



Additional Physics

Supernova neutrinos:

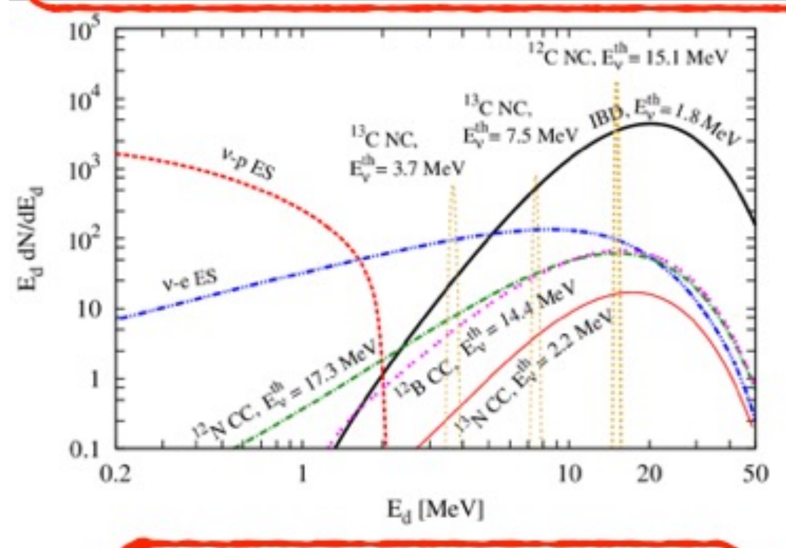
- Low energy threshold (~0.1 MeV)
- Channels not accessible with other detectors
- Charge sign ID (e+/e-)
- Directionality information for events ≳ 10 MeV
- Sensitivity to Diffuse Supernova Neutrino Background

Search for nucleon decay:

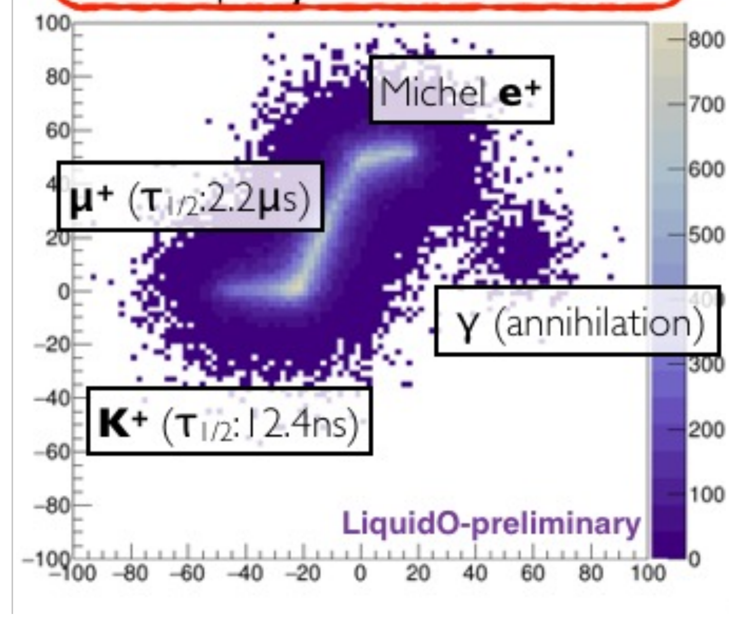
- Very high-efficiency
- Full topological information and sign-ID for some channels through final Michel electron
    - Many exclusive final states

Others (geoneutrinos, reactor antineutrinos… etc)

JUNO spectra for SN @ 10 kpc (for reference)



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



Doping

- Doped scintillators used with great success
  - Reactor θ_{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