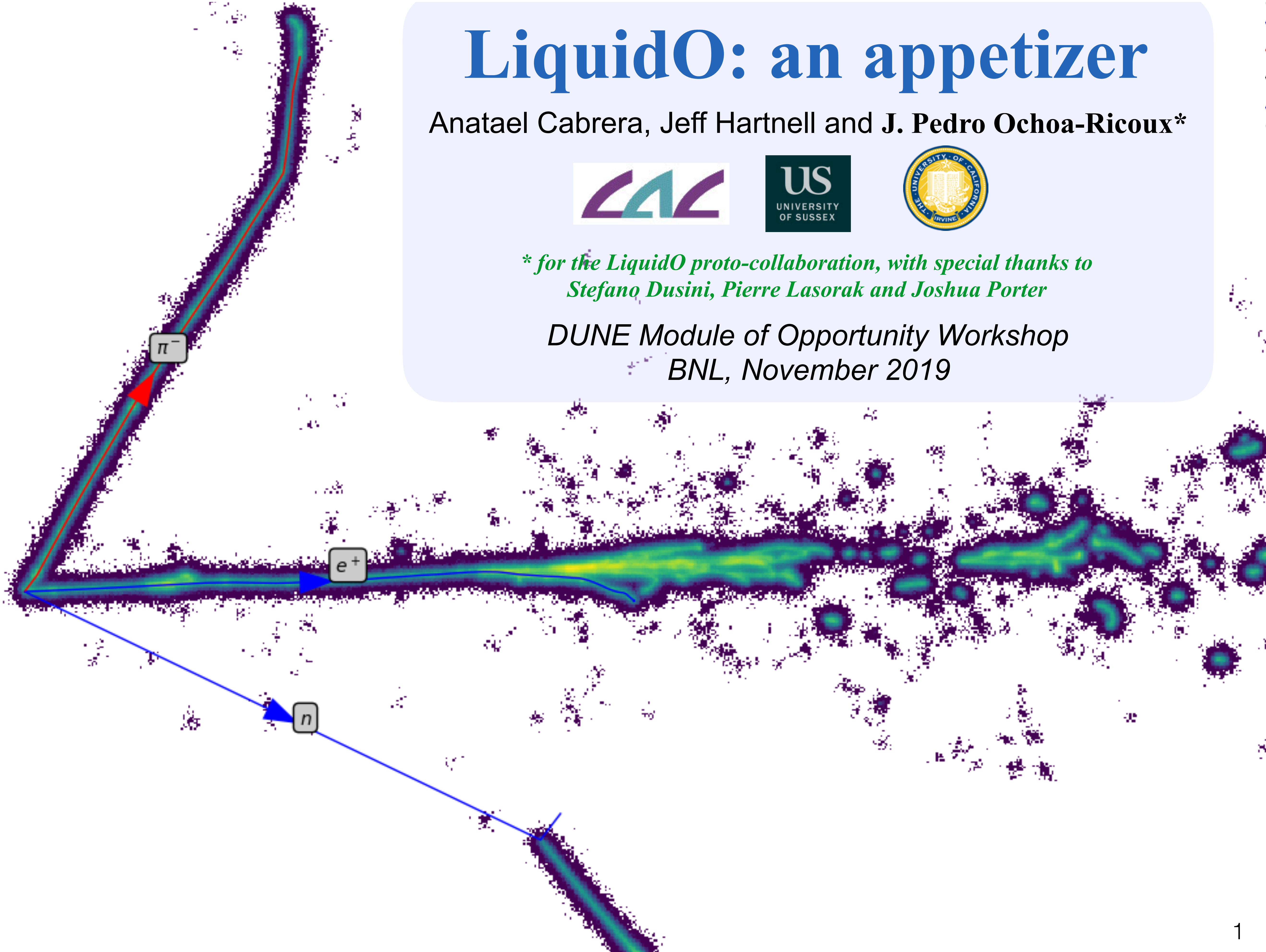
LiquidO: an appetizer

Anatael Cabrera, Jeff Hartnell and **J. Pedro Ochoa-Ricoux***

** for the LiquidO proto-collaboration, with special thanks to Stefano Dusini, Pierre Lasorak and Joshua Porter*

DUNE Module of Opportunity Workshop
BNL, November 2019



A new approach!

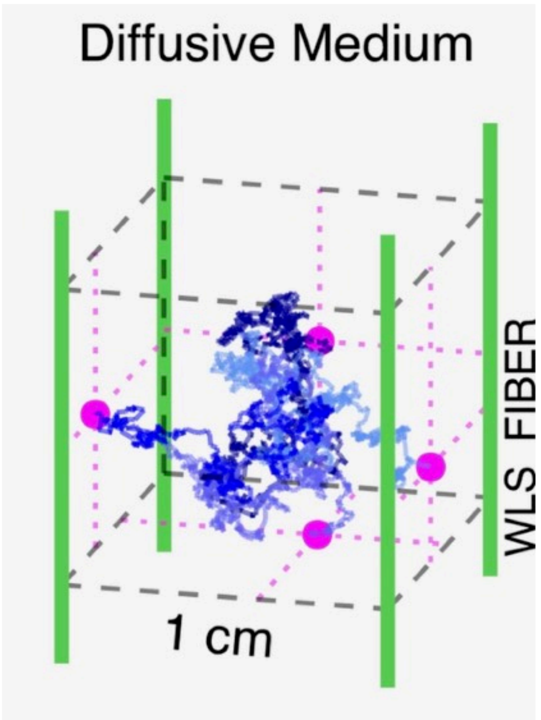
– Liquid Scintillator (LS) detectors have been a workhorse in neutrino physics

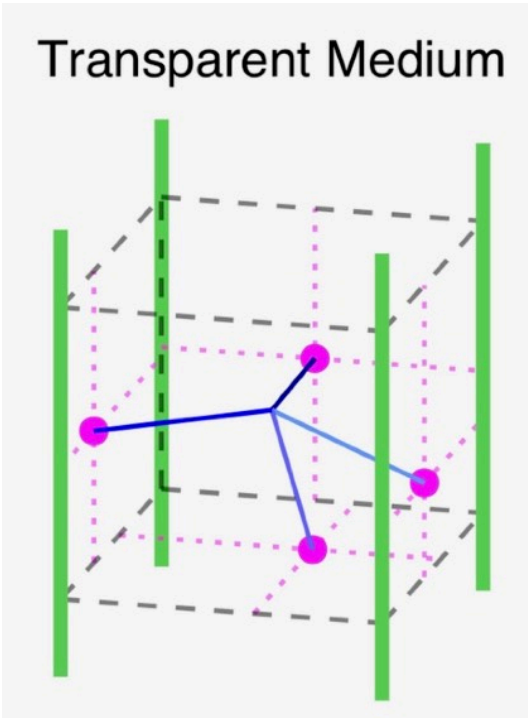
- Conventional strategy: propagate light through the scintillator to surrounding photosensors

– LiquidO is a departure from the conventional paradigm with **two main features**:

1) Use of an opaque scintillator

Main purpose: **stochastically confine light near its creation point**, to preserve the precious topological information of particle interactions





A new and completely counter-intuitive approach!

The right scintillator for LiquidO: short scattering length and moderate absorption length

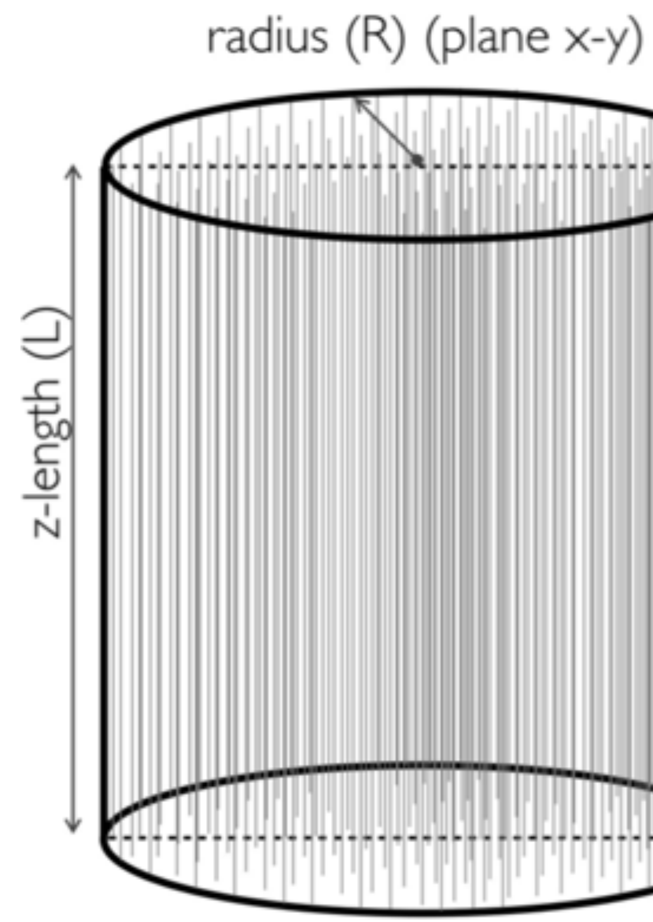
More like milk than like dark beer!

A new approach!

2) Light collection with a dense fiber array running in at least one direction

Main purpose: collect light near its creation point

Archetypical LiquidO detector

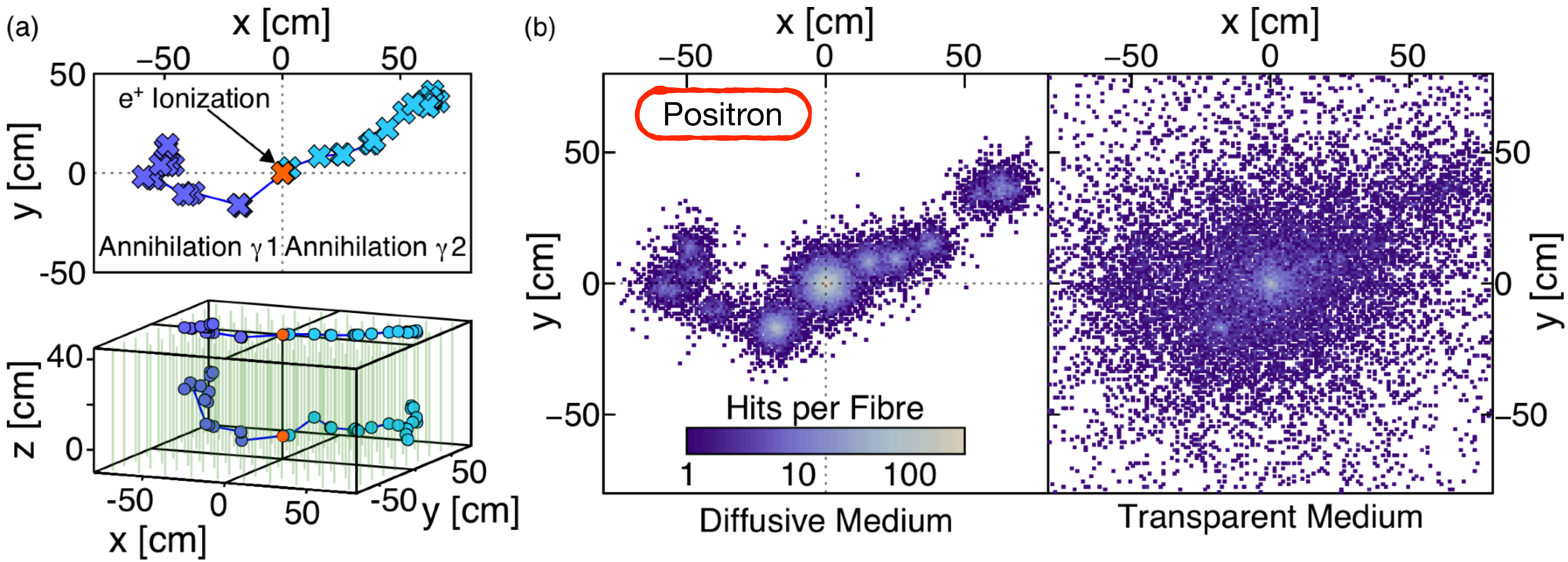


SiPMs are a great choice to readout the fibers (low background, high efficiency, ~0.1ns time resolution)

– LiquidO relies on well-understood, commercially available and relatively inexpensive technology!

Imaging down to the MeV scale!

– Result: **unprecedented imaging** capabilities



Geant4 simulation of 1 MeV positron in a LiquidO detector with fibers running along z direction with a 1 cm pitch. The scintillator has a 5 mm scattering length. Each pixel corresponds to a fiber. The color scale shows all true hits per fiber

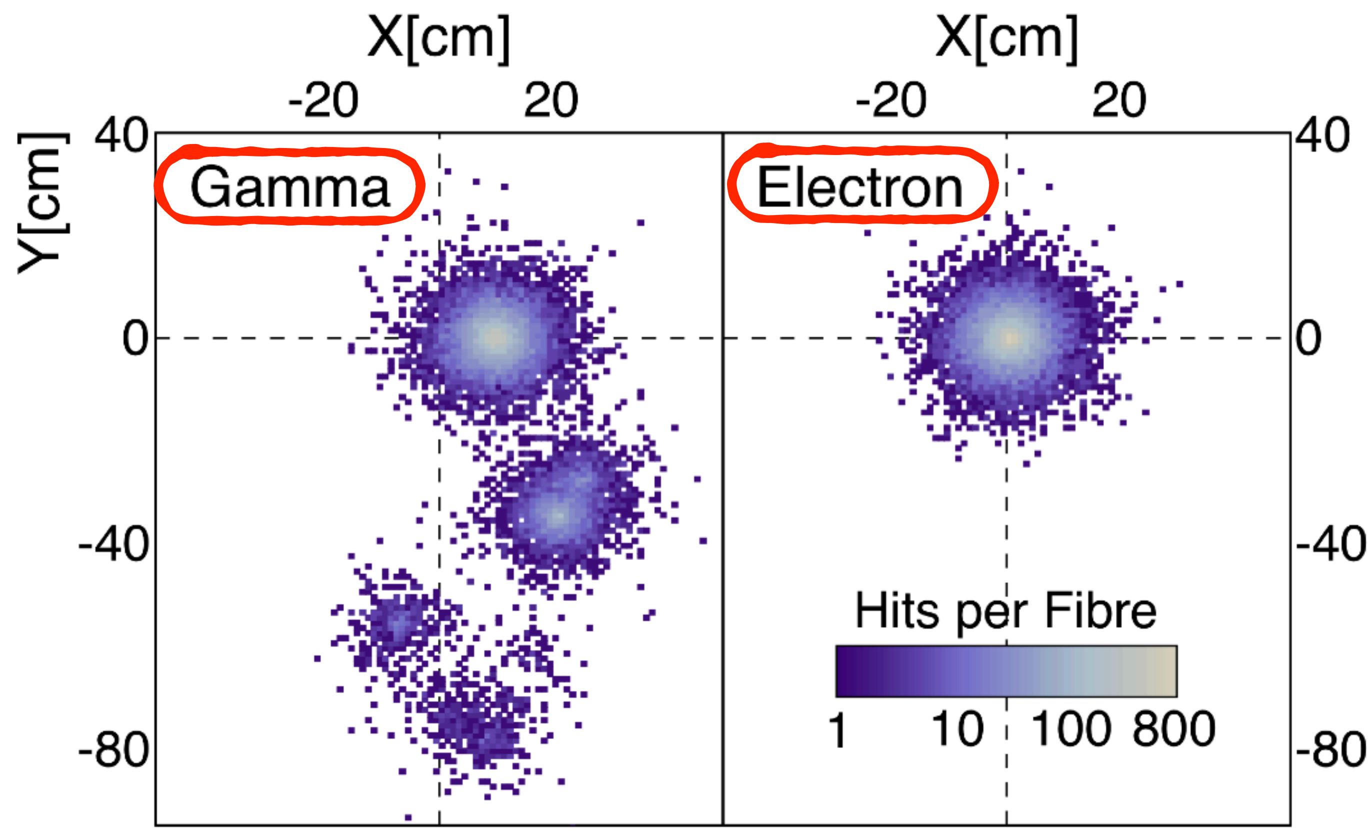
A self-segmenting detector! (no need to introduce dead material)

LiquidO's power

- Can distinguish ~MeV gammas, electrons and positrons on an individual basis

unprecedented!

Using reasonable assumptions we can discriminate electrons from gammas with efficiency > 85% and contamination ~10^{-3}

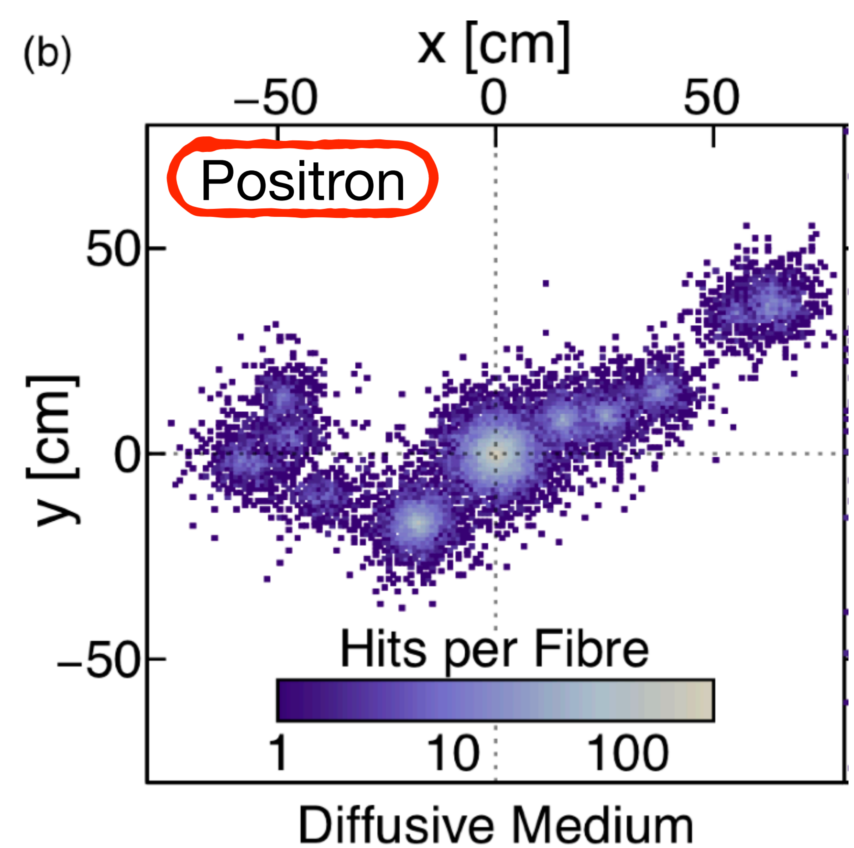


- Additional major advantages:

Unparalleled **affinity for loading** thanks to the large relaxation in transparency requirements

Plenty of room to **explore unconventional scintillators** (e.g. ultra high light-yield) not deemed transparent enough for conventional detectors

(Both events at the top are 2 MeV; simulation details are the same as in previous page)



Essentially impossible to separate these three on an event-by-event basis in conventional Liquid Scintillator detectors!

First papers

More details about LiquidO and its possible applications in low-energy neutrino physics can be found in arXiv:1908:02859 and arXiv:1908.03334

Neutrino Physics with an Opaque Detector

A. Cabrera[*1,9,10], A. Abusleme[15], J. dos Anjos[†3], T. J. C. Bezerra[18], M. Bongrand[9], C. Bourgeois[9], D. Breton[9], C. Buck[12], J. Busto[6], E. Calvo[5], E. Chauveau[4], M. Chen[16], P. Chimenti[11], F. Dal Corso[13], G. De Conto[11], S. Dusini[13], G. Fiorentini[7a,7b], C. Frigerio Martins[11], A. Givaudan[1], P. Govoni[2a,2b], B. Gramlich[12], M. Grassi[1,9], Y. Han[1,9], J. Hartnell[19], C. Hugon[6], S. Jiménez[5], H. de Kerret[‡1], A. Le Nevé[9], P. Loaiza[9], J. Maalmi[9], F. Mantovani[7a,7b], L. Manzanillas[9], C. Marquet[4], J. Martino[18], D. Navas[5], H. Nunokawa[14], M. Obolensky[1], J. P. Ochoa-Ricoux[8,15], G. Ortona[20], C. Palomares[5], F. Pessina[14], A. Pin[4], M. S. Pravikoff[4], M. Roche[4], B. Roskovec[8], N. Roy[9], C. Santos[1], A. Serafini[7a,7b], L. Simard[9], M. Sisti[2a,2b], L. Stanco[13], V. Strati[7a,7b], J.-S. Stutzmann[18], F. Suekane[*§1,17], A. Verdugo[5], B. Viaud[18], C. Volpe[1], C. Vrignon[1], S. Wagner[1], and F. Yermia[18]

[1]APC, CNRS/IN2P3, CEA/IRFU, Observatoire de Paris, Sorbonne Paris Cité University, 75205 Paris Cedex 13, France
[2a]Università di Milano-Bicocca, I-20126 Milano, Italy
[2b]INFN, Sezione di Milano-Bicocca, I-20126 Milano, Italy
[3]Centro Brasileiro de Pesquisas Físicas (CBPF), Rio de Janeiro, RJ, 22290-180, Brazil
[4]CENBG, UMR5797, Université de Bordeaux, CNRS/IN2P3, F-33170, Gradignan, France
[5]CIEMAT, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), E-28040 Madrid, Spain
[6]Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France
[7a]Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44122 Ferrara, Italy
[7b]INFN, Ferrara Section, Via Saragat 1, 44122 Ferrara, Italy
[8]Department of Physics and Astronomy, University of California at Irvine, Irvine, California 92697, USA
[9]LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
[10]LNCA Underground Laboratory, CNRS/IN2P3 - CEA, Chooz, France
[11]Departamento de Física, Universidade Estadual de Londrina, 86051-990, Londrina – PR, Brazil
[12]Max-Planck-Institut für Kernphysik, 69117 Heidelberg, Germany
[13]INFN, Sezione di Padova, via Marzolo 8, I-35131 Padova, Italy
[14]Department of Physics, Pontifícia Universidade Católica do Rio de Janeiro, Rio de Janeiro, RJ, 22451-900, Brazil
[15]Pontificia Universidad Católica de Chile, Santiago, Chile
[16]Department of Physics, Engineering Physics & Astronomy, Queen's University, Kingston, Ontario K7L3N6, Canada
[17]RCNS, Tohoku University, 6-3 AzaAoba, Aramaki, Aoba-ku, 980-8578, Sendai, Japan
[18]SUBATECH, CNRS/IN2P3, Université de Nantes, IMT-Atlantique, 44307 Nantes, France
[19]Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
[20]INFN, Sezione di Torino, I-10125 Torino, Italy

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.

*Contact: anatael@in2p3.fr and suekane@awa.tohoku.ac.jp.
†Also at Observatório Nacional. Rio de Janeiro, Brasil
‡Deceased.
§Blaise Paschal Chaire Fellow.

1

Jinst — 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

C. Buck,[1] B. Gramlich and S. Schoppmann

Max-Planck-Institut für Kernphysik,
Saupfercheckweg 1, 69117 Heidelberg, Germany

E-mail: christian.buck@mpi-hd.mpg.de

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

[1]Corresponding author.

https://doi.org/10.1088/1748-0221/14/11/P11007

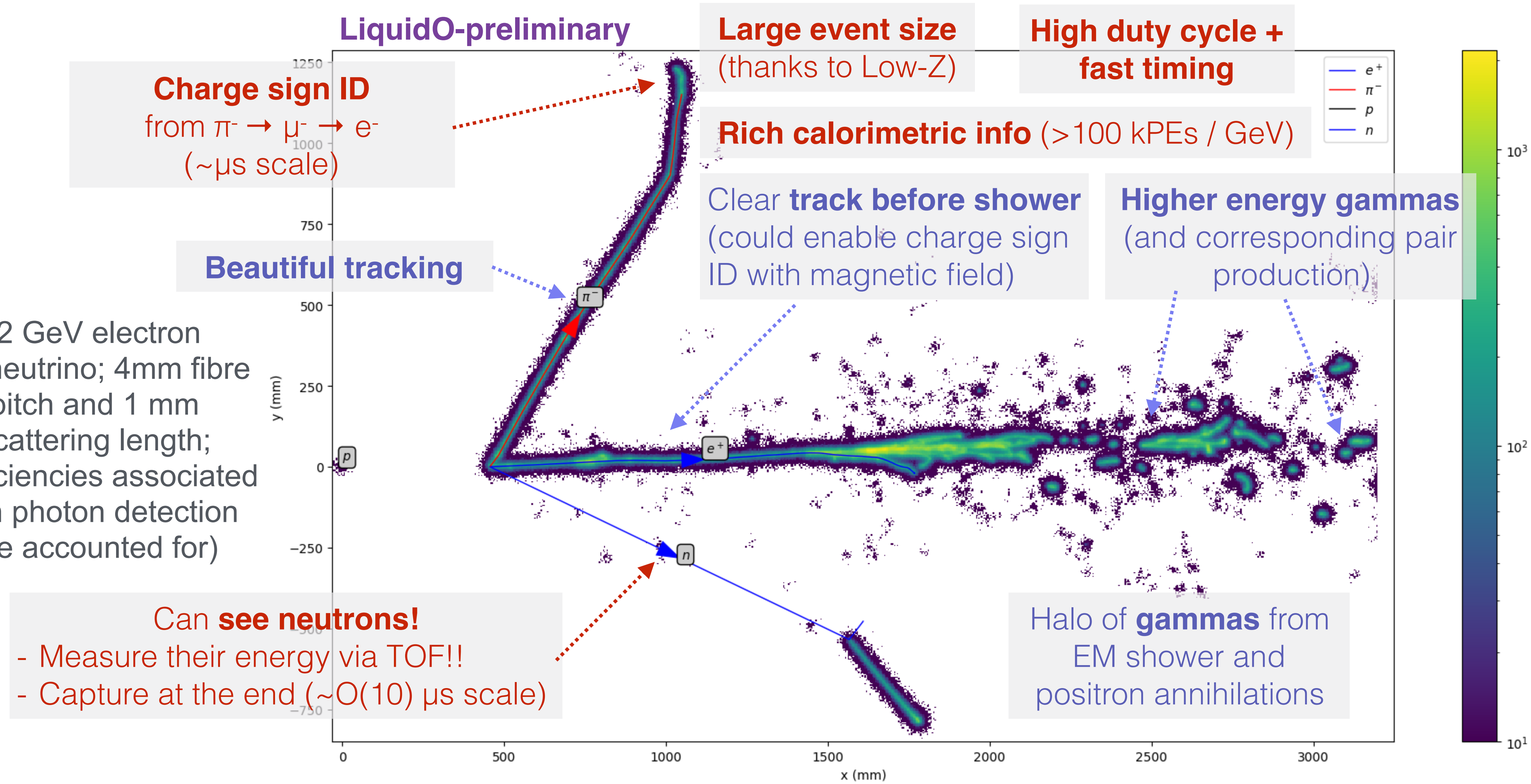
~40 scientists from Europe, Asia and the Americas currently working on LiquidO

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

Beam physics with LiquidO

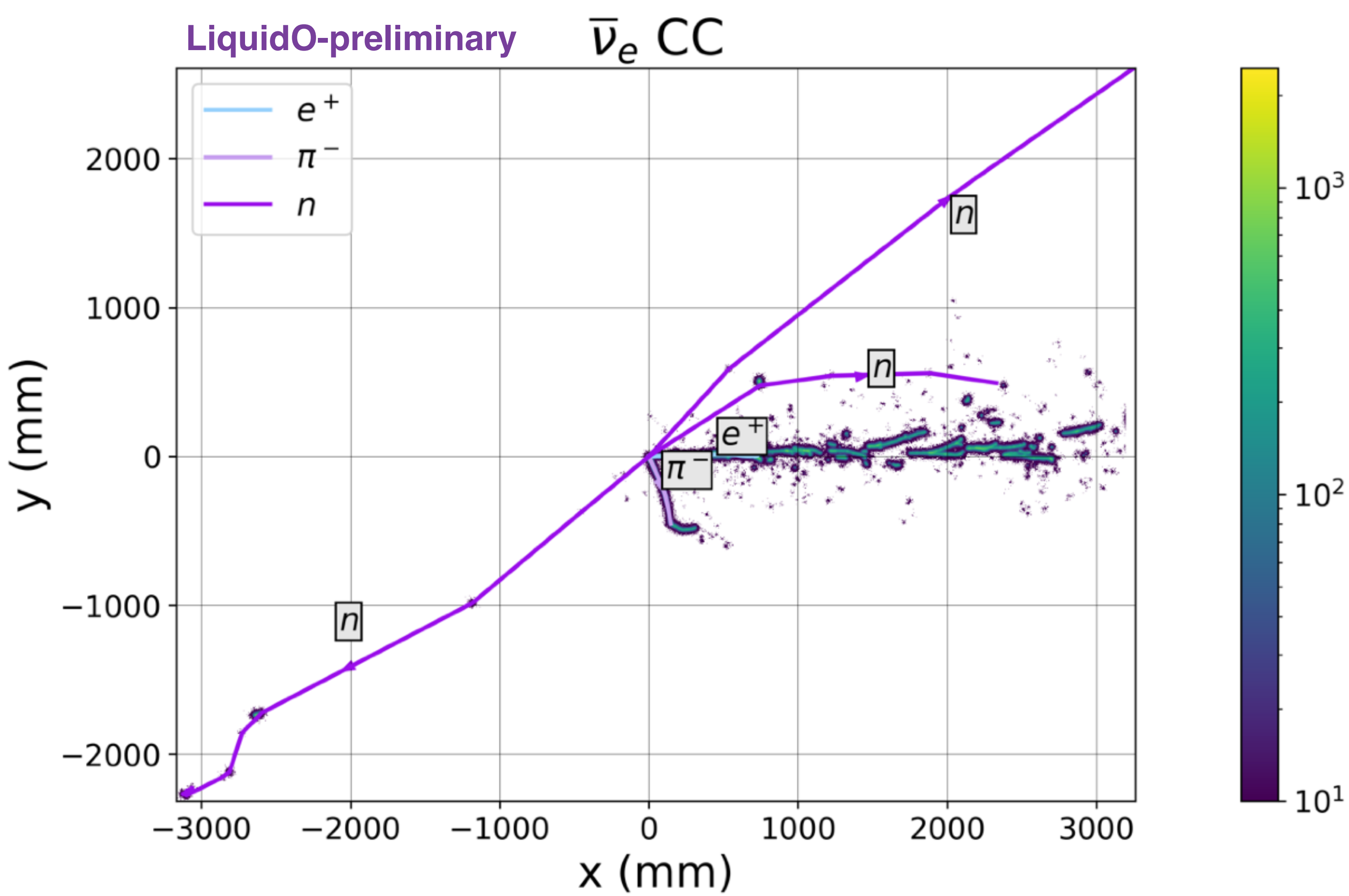
– LiquidO would reveal GeV-neutrino interactions in **extremely powerful** way:

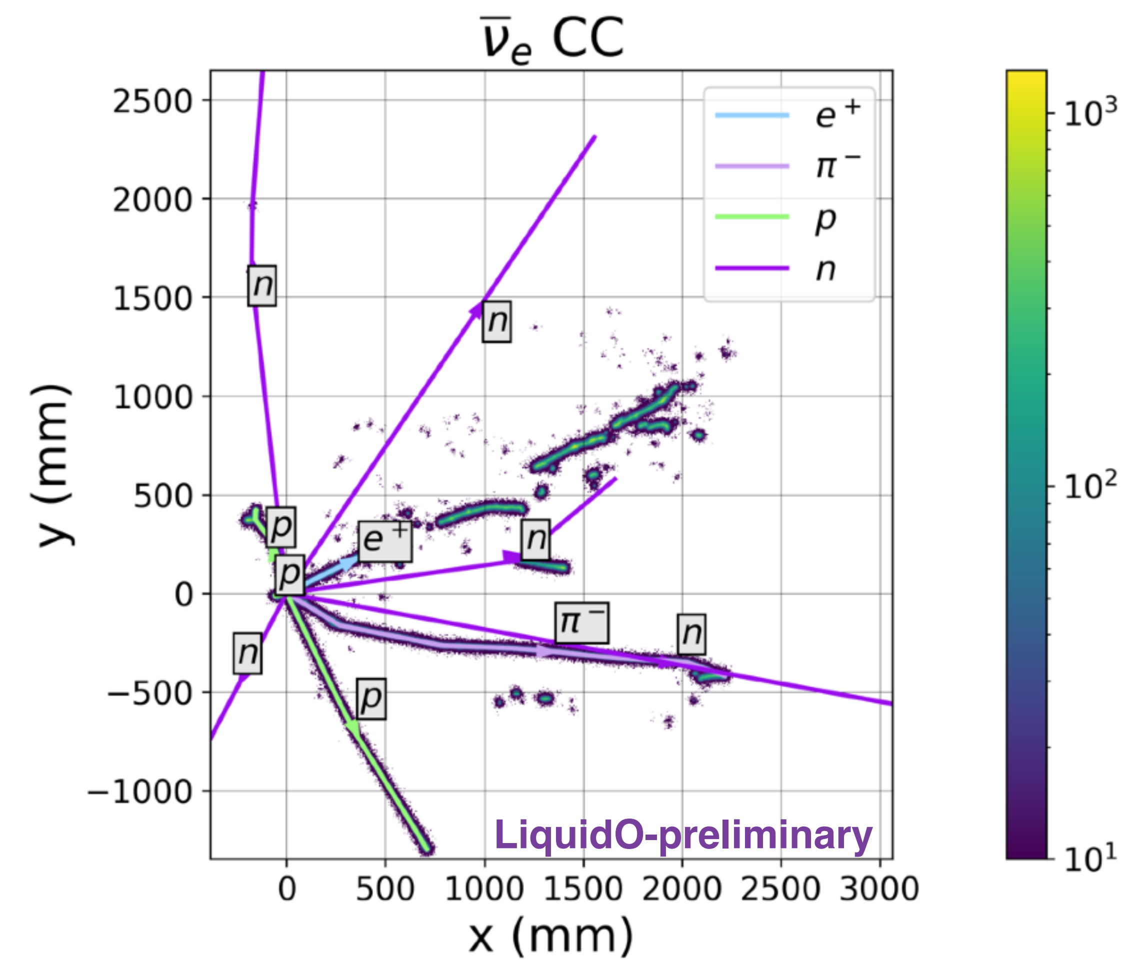
(2 GeV electron antineutrino; 4mm fibre pitch and 1 mm scattering length; inefficiencies associated with photon detection are accounted for)

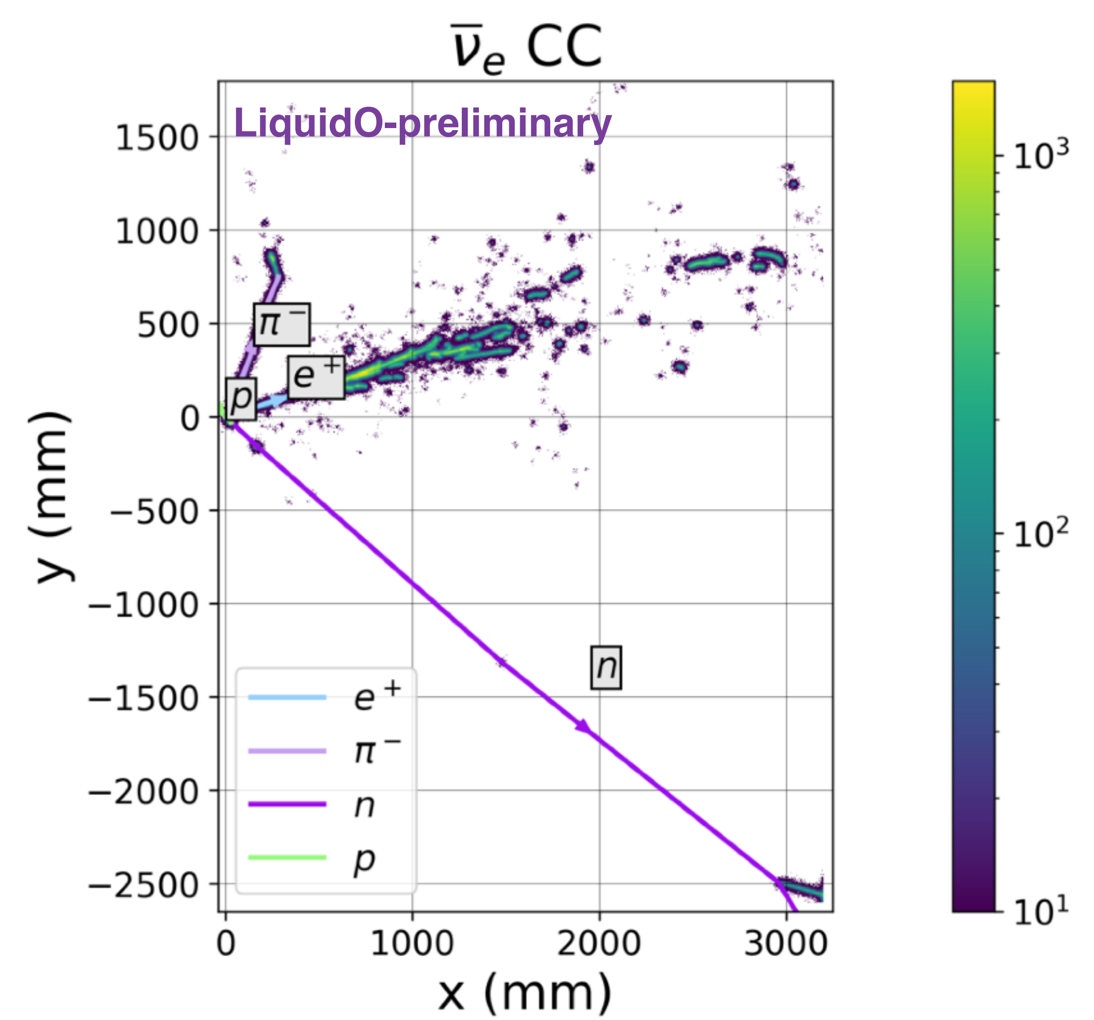


Imaging capabilities comparable to those of LArTPC + **Complementary features unique to LiquidO**

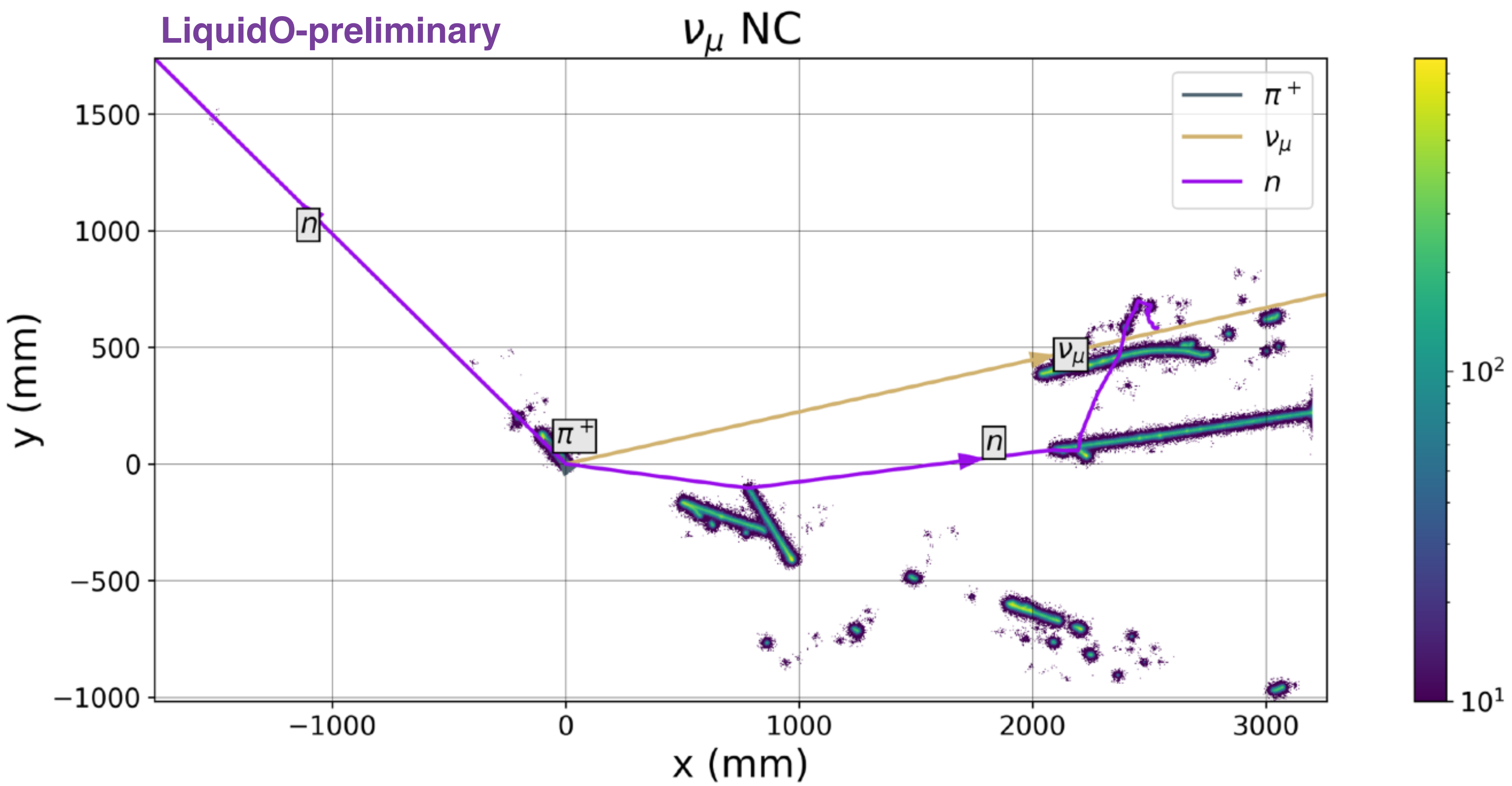
Some $\overline{\nu}_e$ CC events

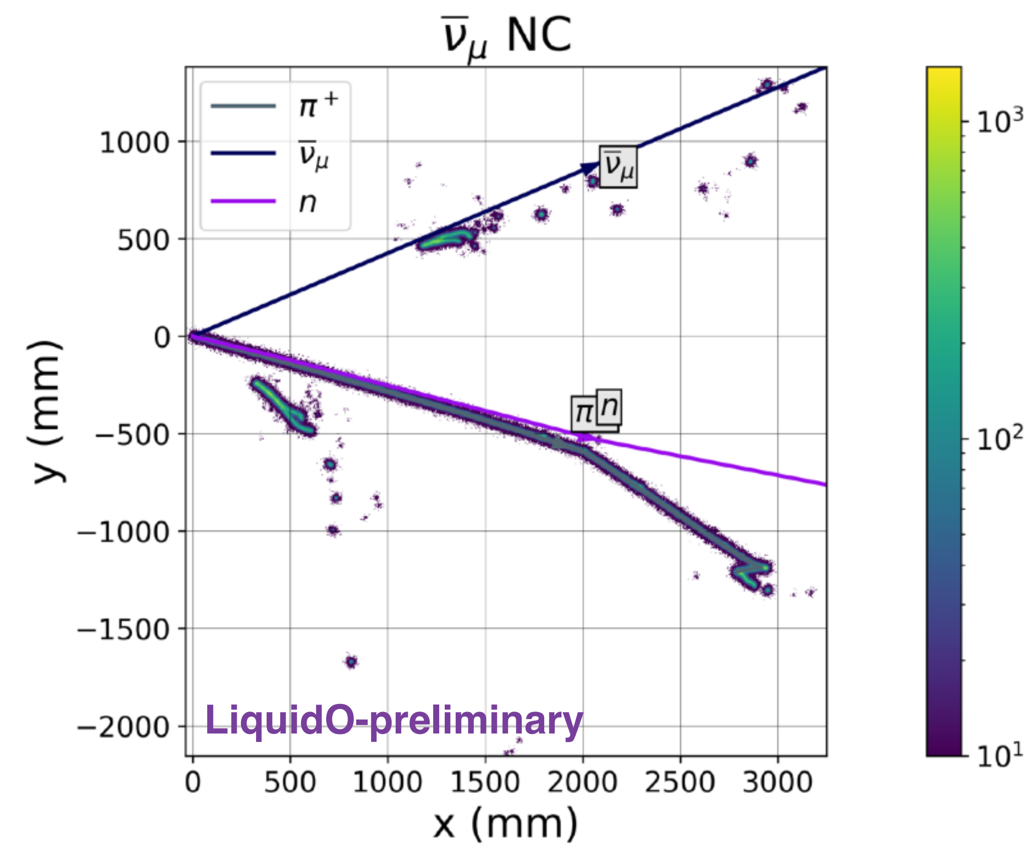


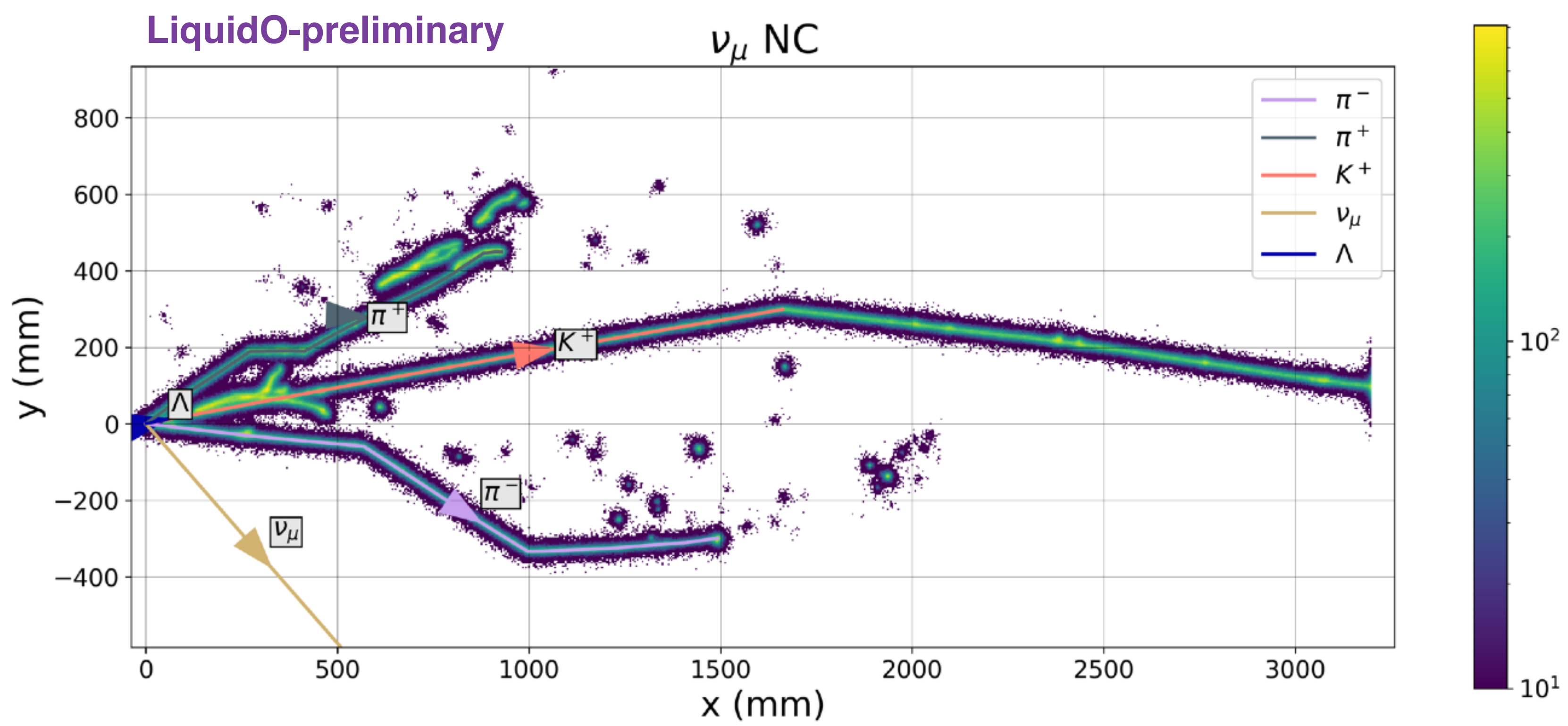




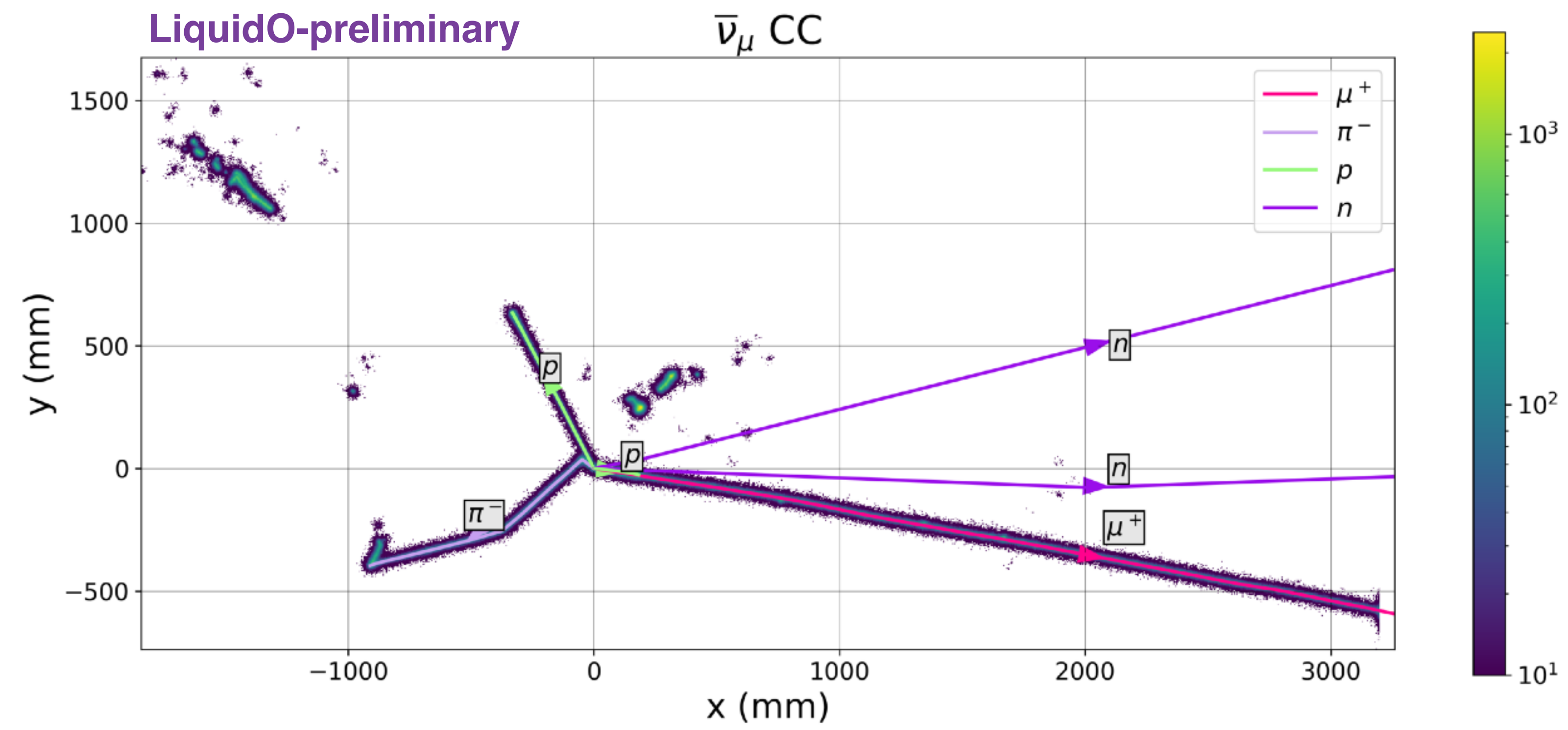
Some ν_μ NC events

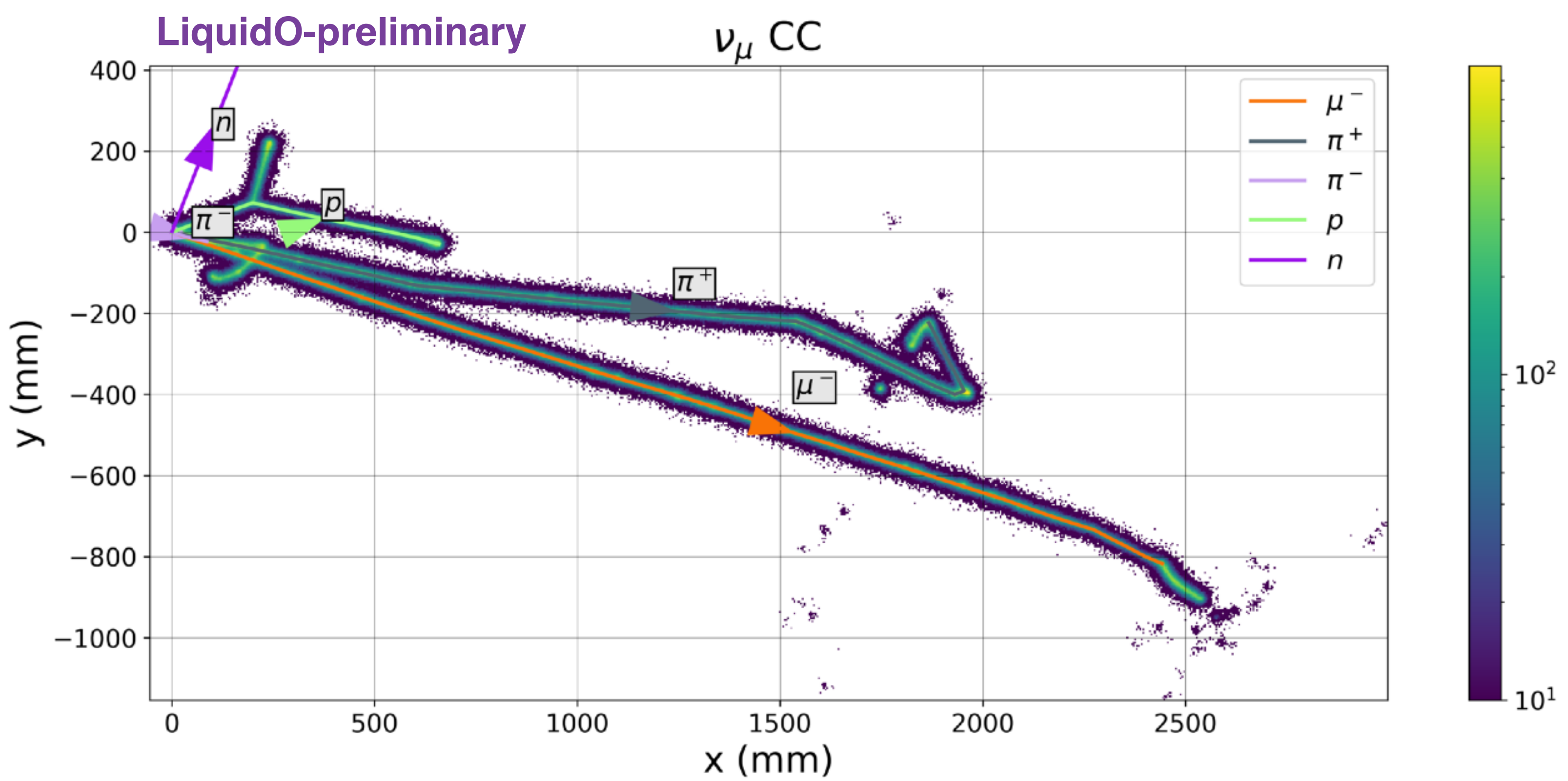


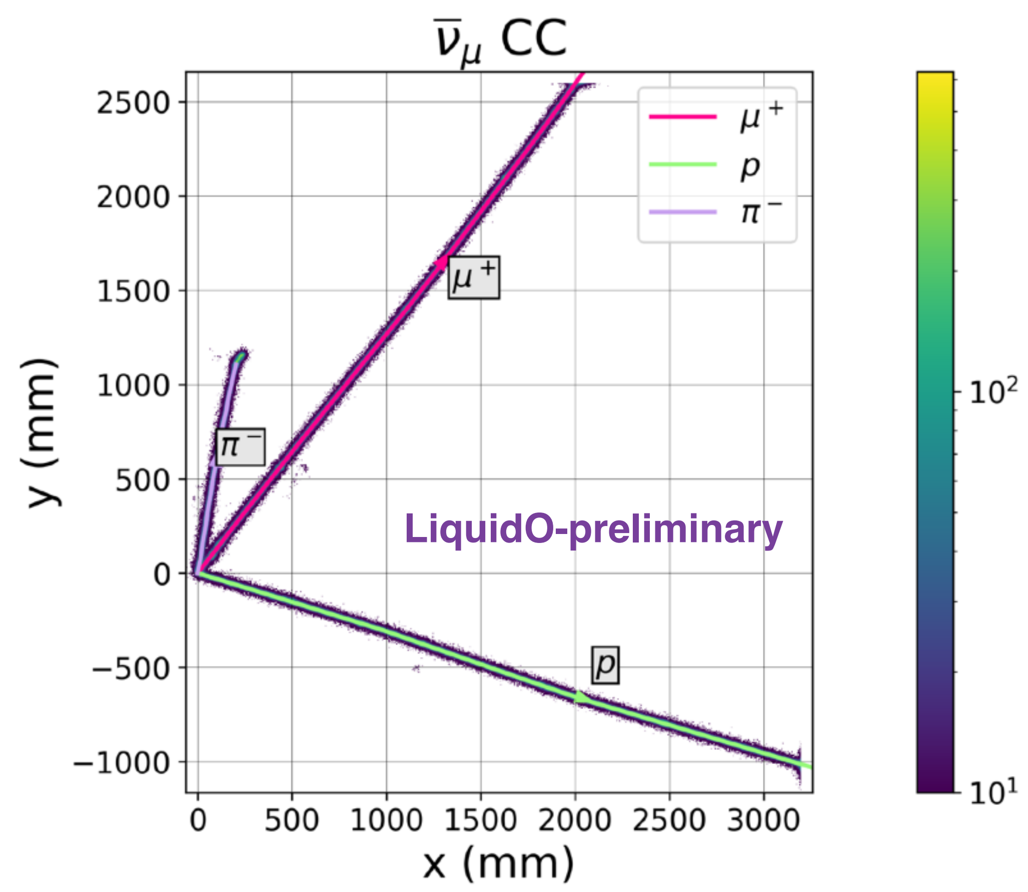




Some ν_μ CC events



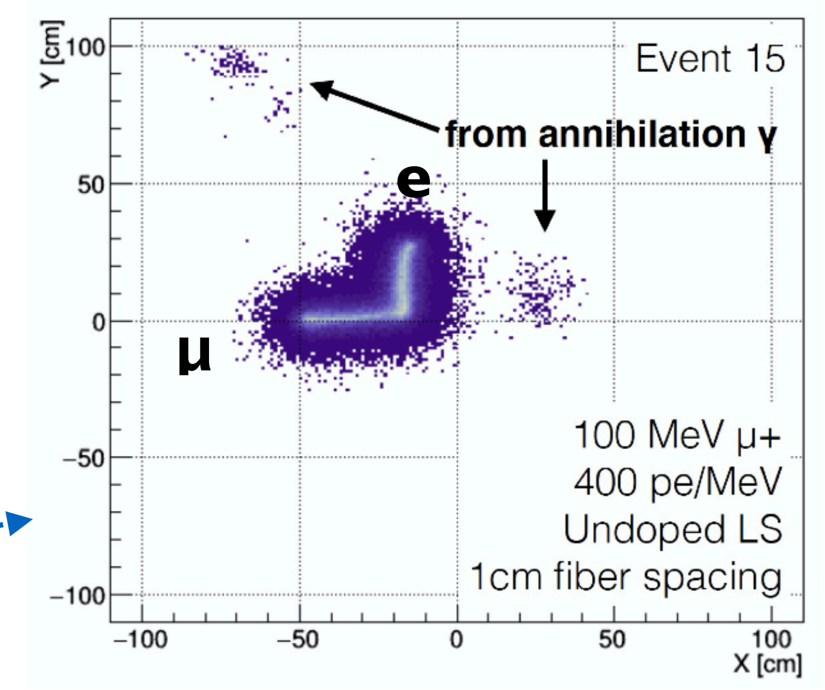




Summary so far: advantages of LiquidO @ DUNE

– Complementary detector properties and capabilities:

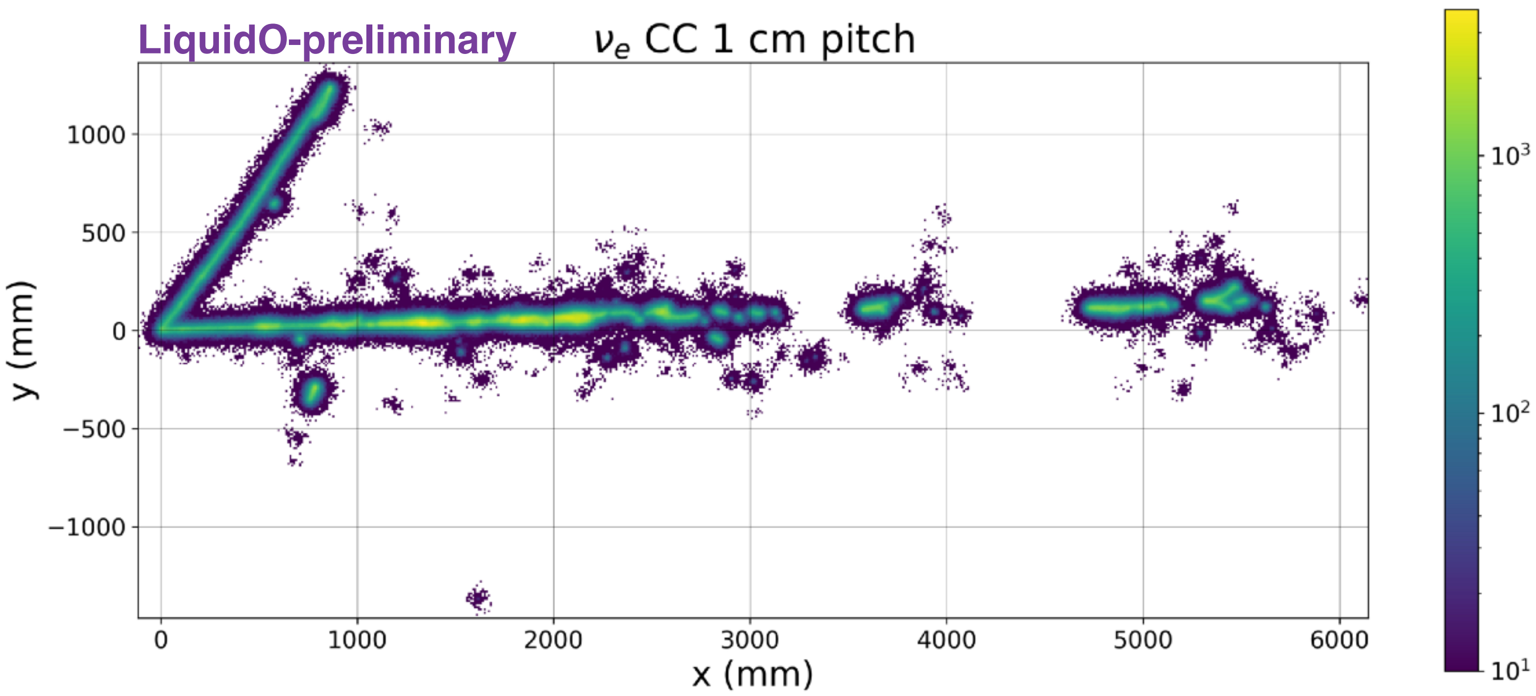
- Low-Z (radiation length 0.5m vs. 0.14m in LArTPC)
- Self-segmenting detector (no dead material & lower cost)
- Largest density of free-protons (without being explosive)
- Low energy threshold
- Sensitivity to neutrons (scattering and capture)
- Charge sign ID from Michel e+/e- (separate time scale)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

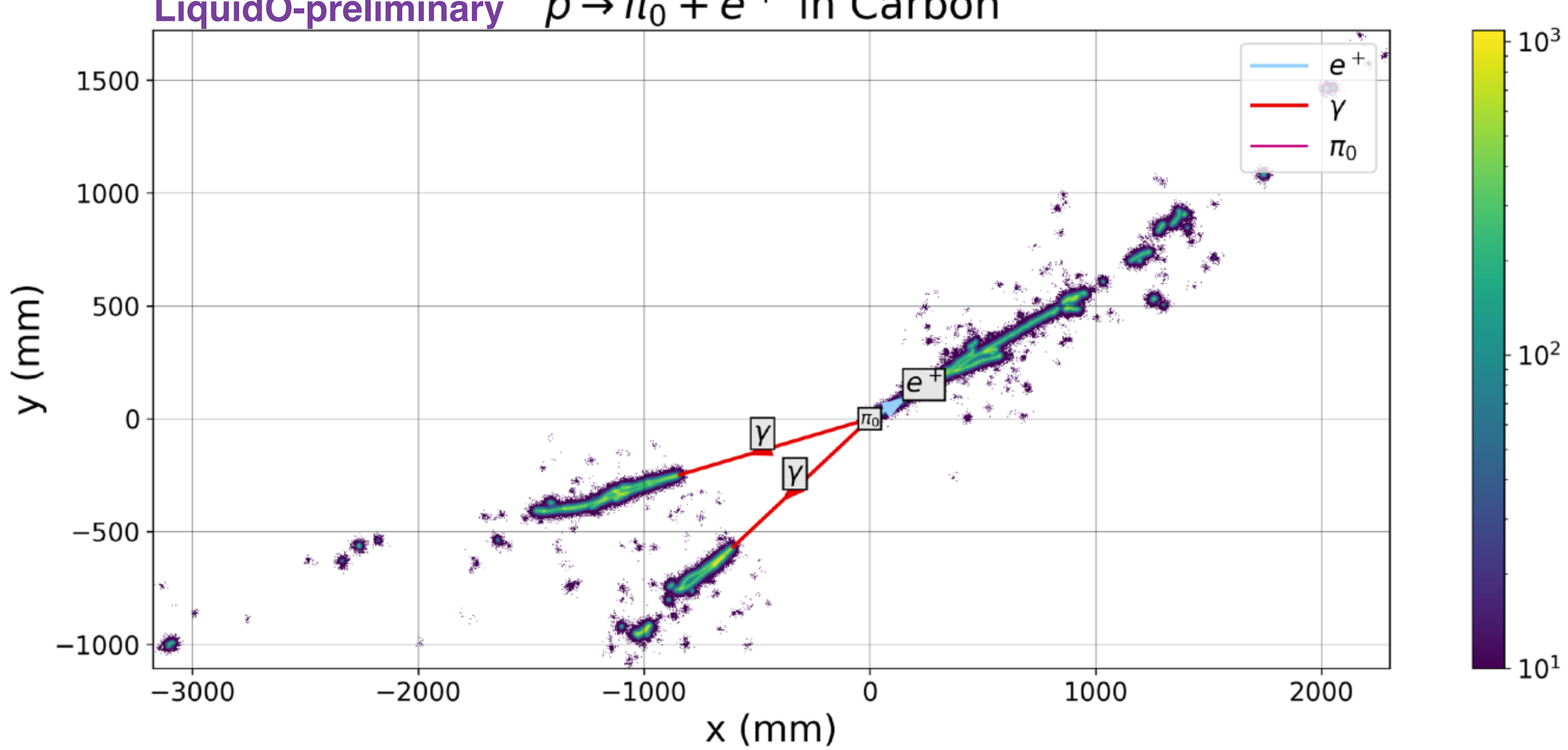
What about non-accelerator physics?

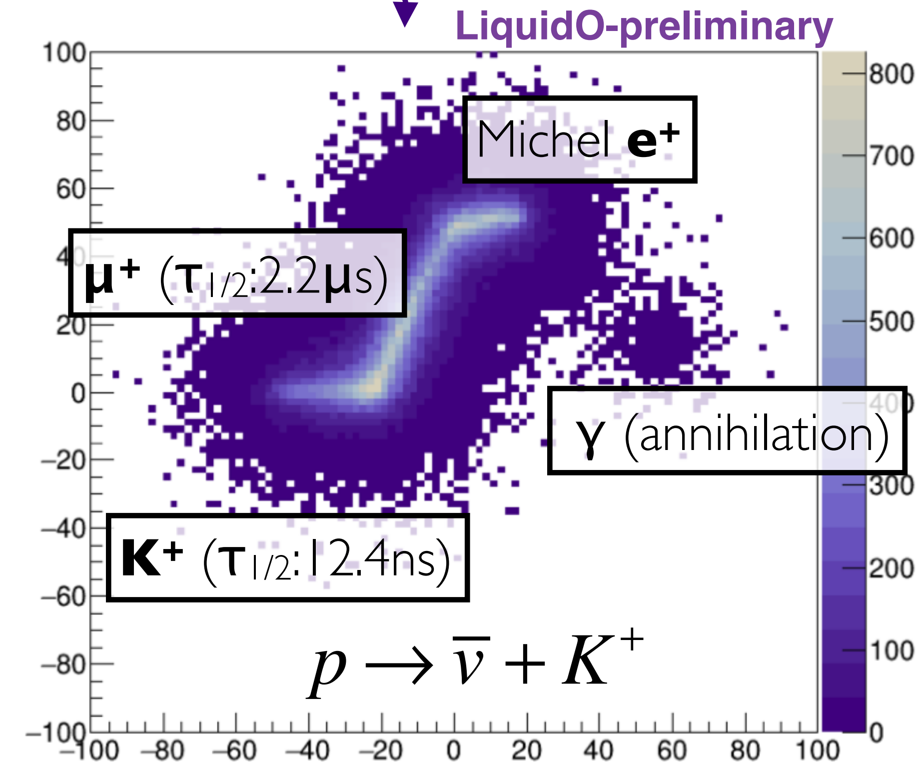
– LiquidO is also an excellent detector for non-beam neutrino physics. These are a few areas relevant to a LiquidO @ DUNE scenario:

- Nucleon decay:

- Can see ***all*** channels
- Largest achievable **density of free protons** (thanks to scintillator)
- Very high-efficiency
- Full topological information and sign-ID for some channels through final Michel electron (could do all if magnetize detector)

$p \rightarrow \bar{\nu}K^{+}$	$n \rightarrow \bar{\nu}\pi^{0}$
$p \rightarrow e^{+}K^{0}$	$p \rightarrow e^{+}\pi^{0}$
$p \rightarrow \mu^{+}K^{0}$	$p \rightarrow \mu^{+}\pi^{0}$
$p \rightarrow \bar{\nu}\pi^{+}$	$n \rightarrow \bar{\nu}K^{0}$



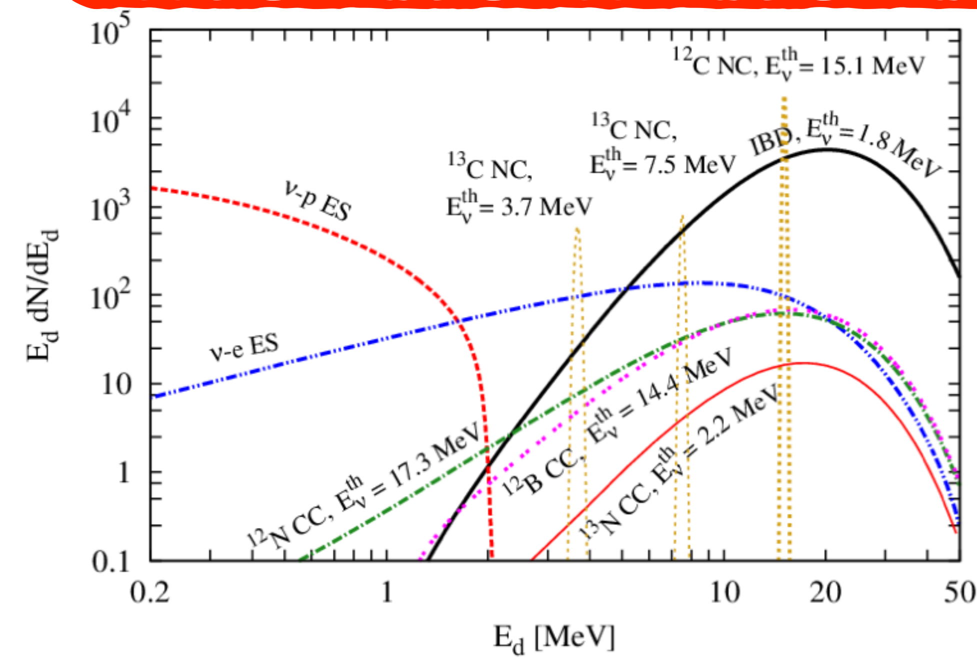


An excellent detector for nucleon decay!

More on non-accelerator 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
  - Very good sensitivity to Diffuse Supernova Neutrino Background

JUNO spectra for SN @ 10kpc (for reference)



- **Solar neutrinos:**

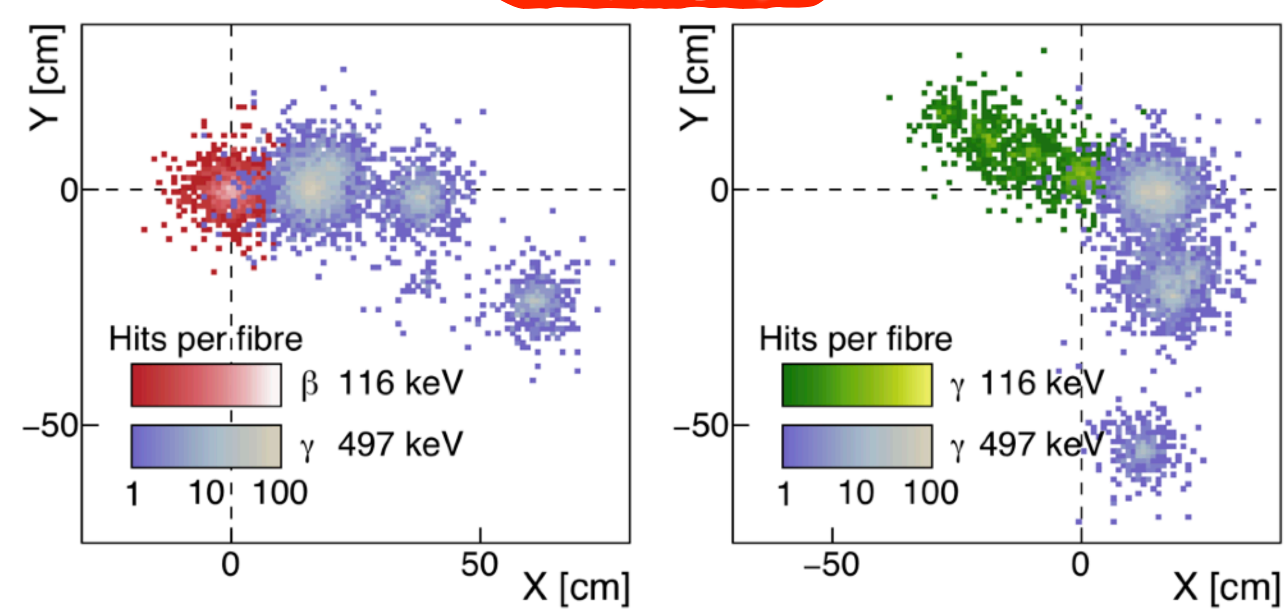
Expect good reach “as is”

Exciting possibility: Indium loading could allow to use the reaction first proposed by Raghavan in 1976 to do *pp* solar neutrino physics

$$\nu_e + {}^{115}\mathrm{In} \rightarrow {}^{115}\mathrm{Sn}^* + e^-$$

$$\mathrm{Sn}^* \rightarrow \gamma + \beta \quad / \quad \gamma + \gamma$$

Sn* decay



- **Geoneutrinos, atmospheric neutrinos, neutrinoless double beta decay … etc**

Very good sensitivity to geoneutrinos from ^{238}U & ^{232}Th with IBD channel

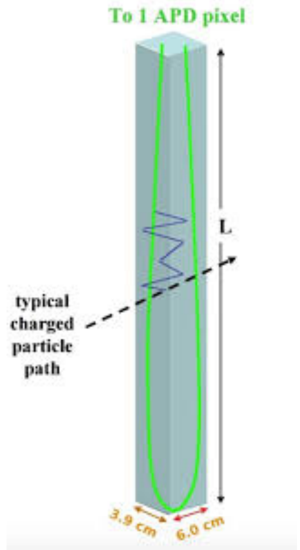
Publications in preparation!

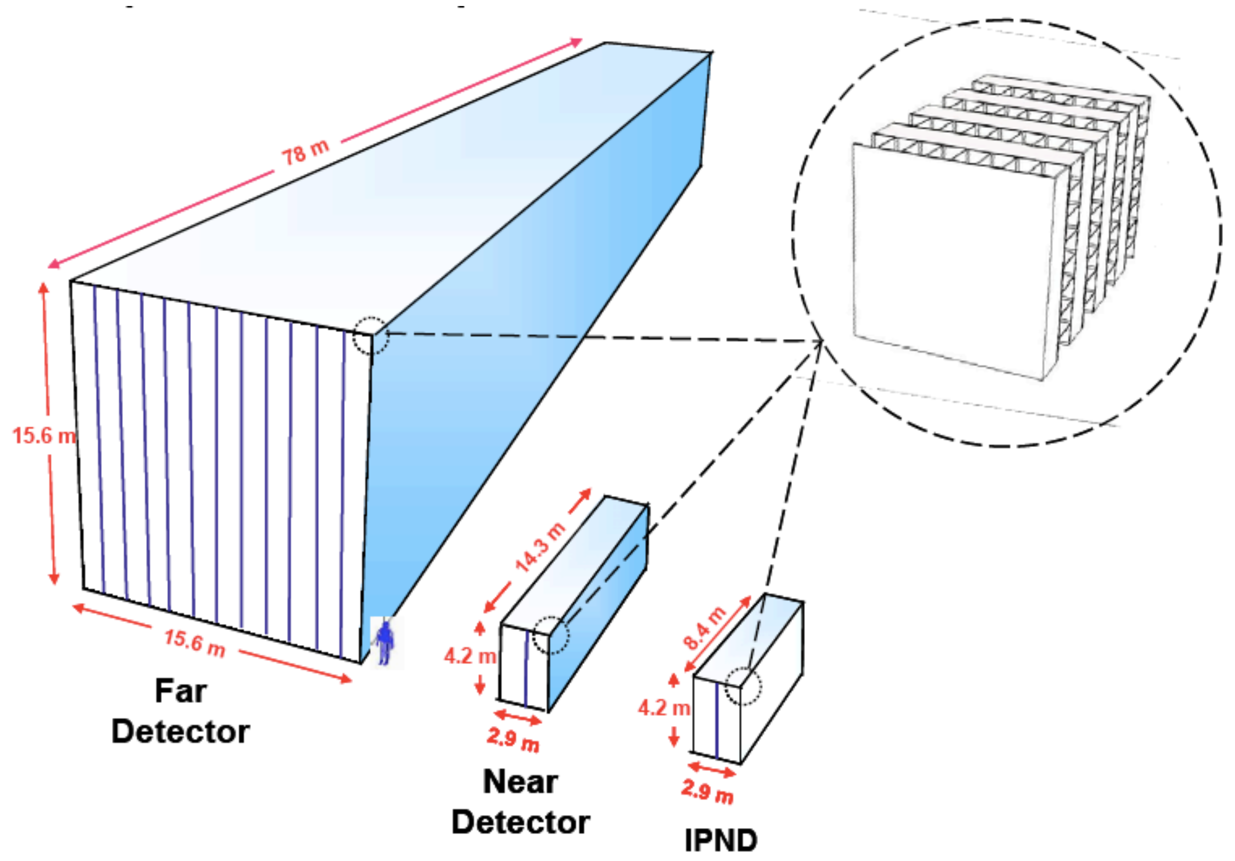
Scalability

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

- Invaluable experience from NOvA
- <u>Key difference</u>: 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**

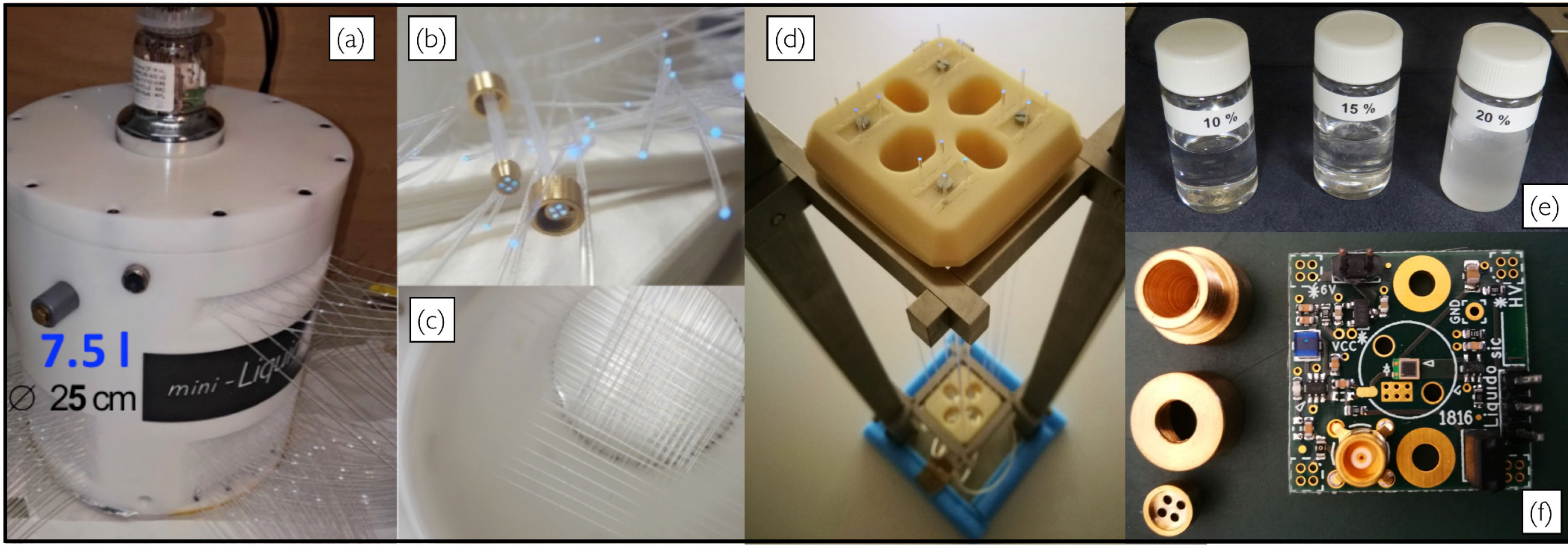
- Rough cost expected to be comparable to NOvA FD

– Other advantages compared to other detectors:

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

Status of R&D

- R&D well advanced in terms of detector, mechanics, optical readout & scintillator:



Already obtained **proof-of-principle of light confinement** with small prototype
(see arXiv:1908.02859 for more details)

- Currently working towards a **multi-ton demonstrator detector**

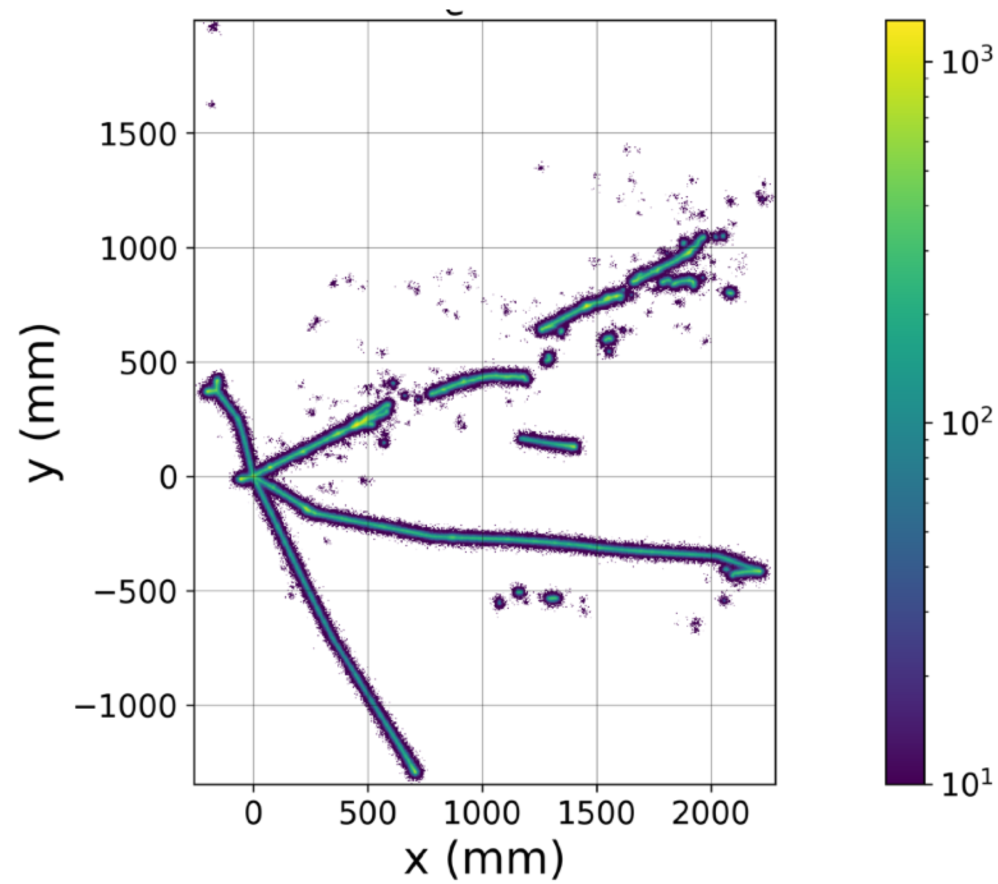
Summary & Conclusions

– LiquidO is an innovative neutrino detection technology that exploits the power in opaque scintillators for the first time:

- Builds on successes of mainstream scintillator detectors but adds unprecedented capabilities

– **LiquidO could bring plenty to DUNE's table:**

- Similar imaging as LArTPC with complementary capabilities
- Very substantial enhancement of low energy physics
- Injection of new human capital and resources



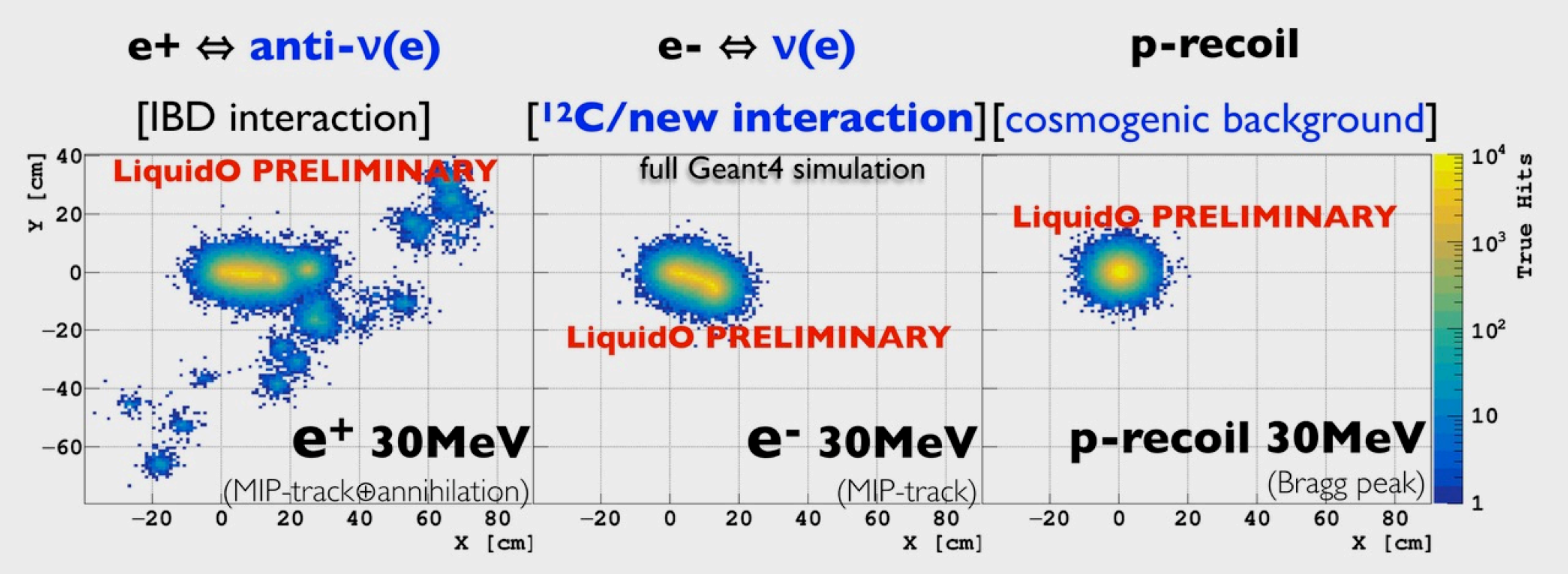
– LiquidO still in early stages, but R&D progressing rapidly and steadily:

- Plan to continue to actively explore potential of LiquidO @ DUNE

We have only scratched the surface so far… stay tuned!!

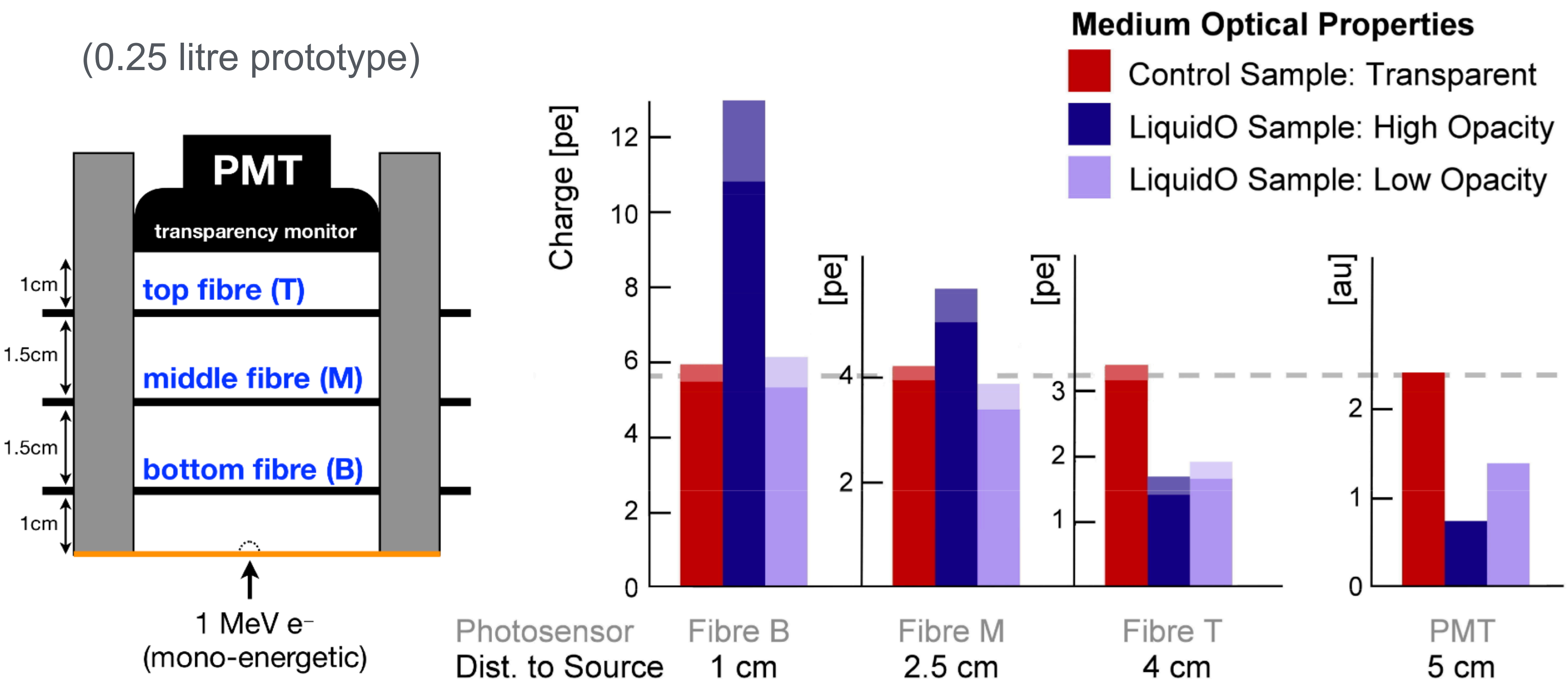
Backup

More Event Examples



Does it work?

- A first-principles validation of LiquidO has already been done in the laboratory:



Observed stochastic confinement of the light with the opaque sample!

(see arXiv:1908:02859 for more details)

Another Beam Event

– Animation of a 2 GeV electron antineutrino:

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