Demonstration of novel, ton-scale LArTPC for the DUNE ND

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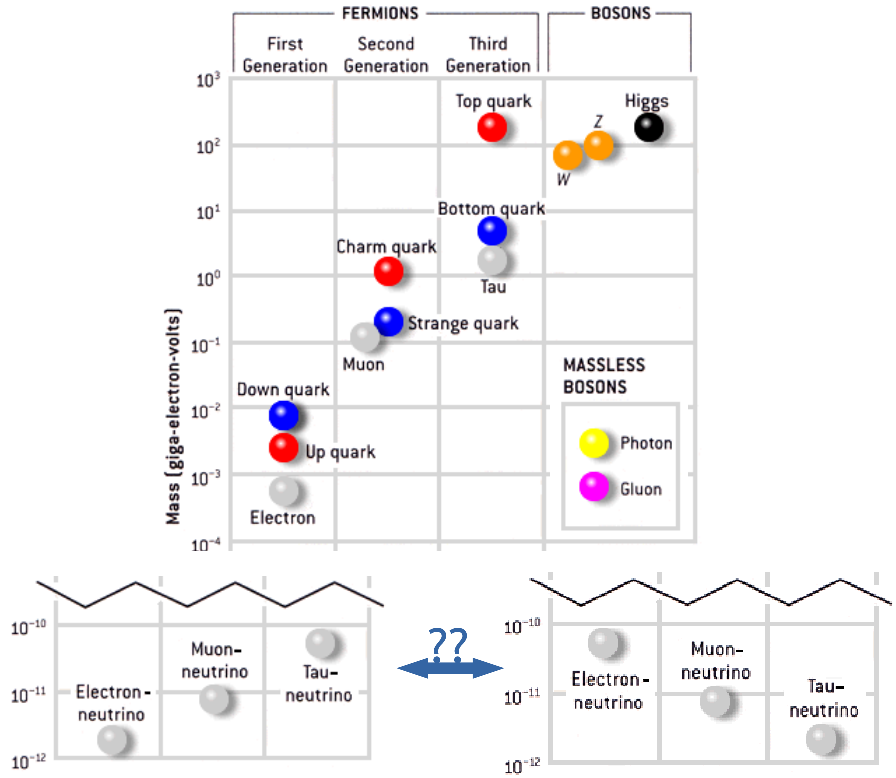
for the DUNE collaboration

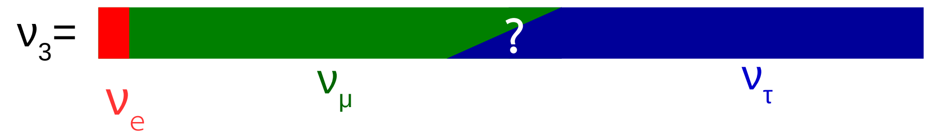
NuFact 2022 ● August 5, 2022

Big questions in neutrino physics



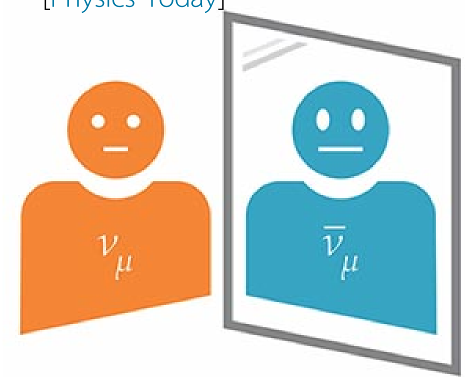
[Adapted from scienceblogs.com]

① How are the mass eigenstates ordered?



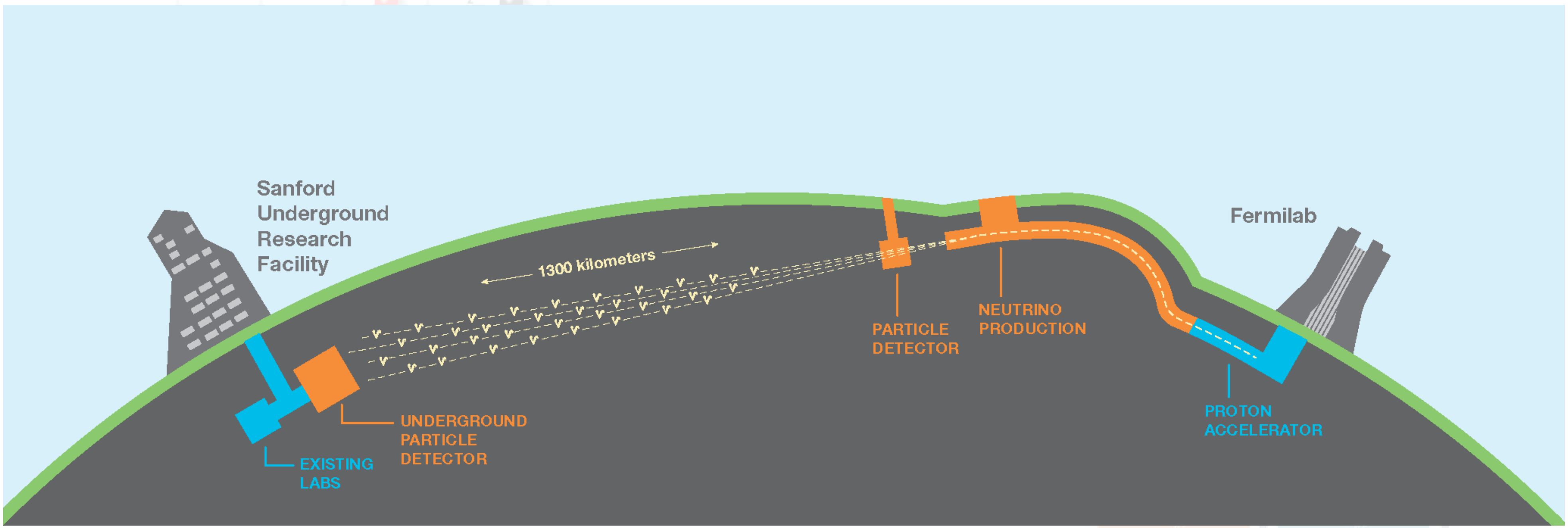
② Is there a symmetry governing mixing between $\boldsymbol{\nu}_\mu$ and $\boldsymbol{\nu}_\tau$?

[Physics Today]



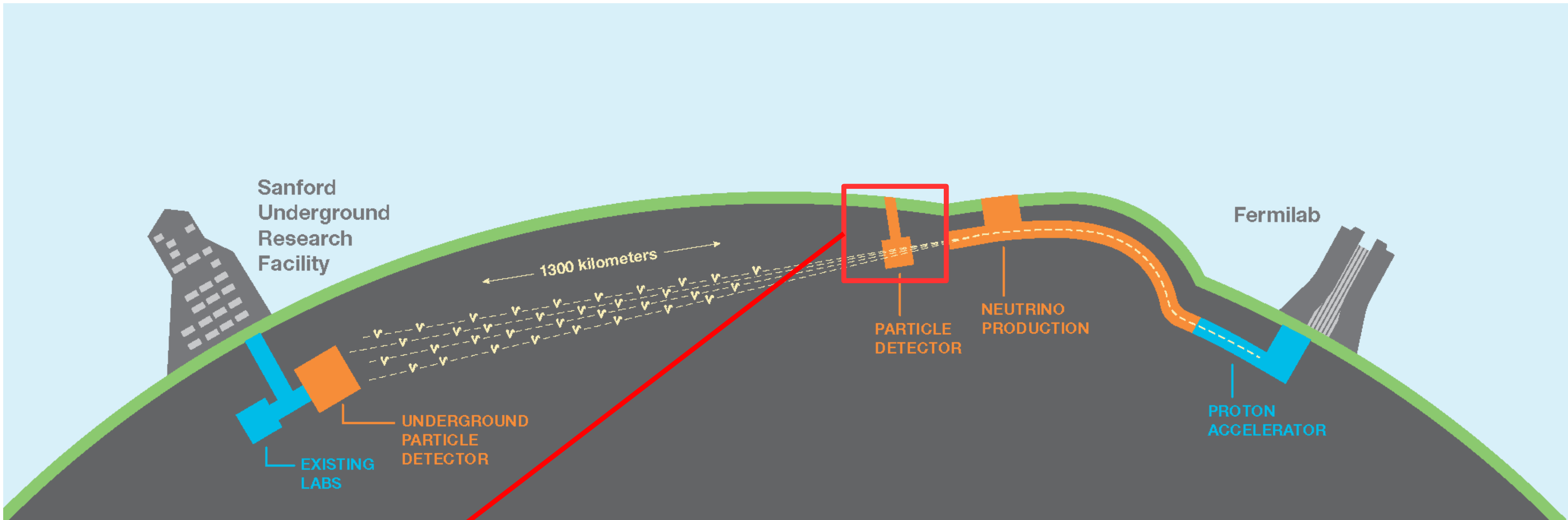
③ Is there CP violation in leptons? (Do neutrinos and antineutrinos oscillate the same way?)

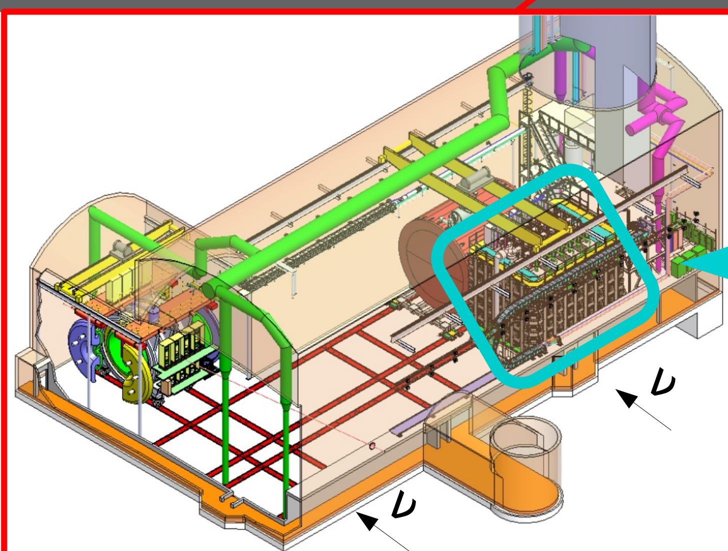
DUNE: world-class ν experiment



DUNE will provide **definitive** answers to all 3 questions, in addition to a broad neutrino physics program

DUNE: world-class ν experiment





World-class Near Detector suite

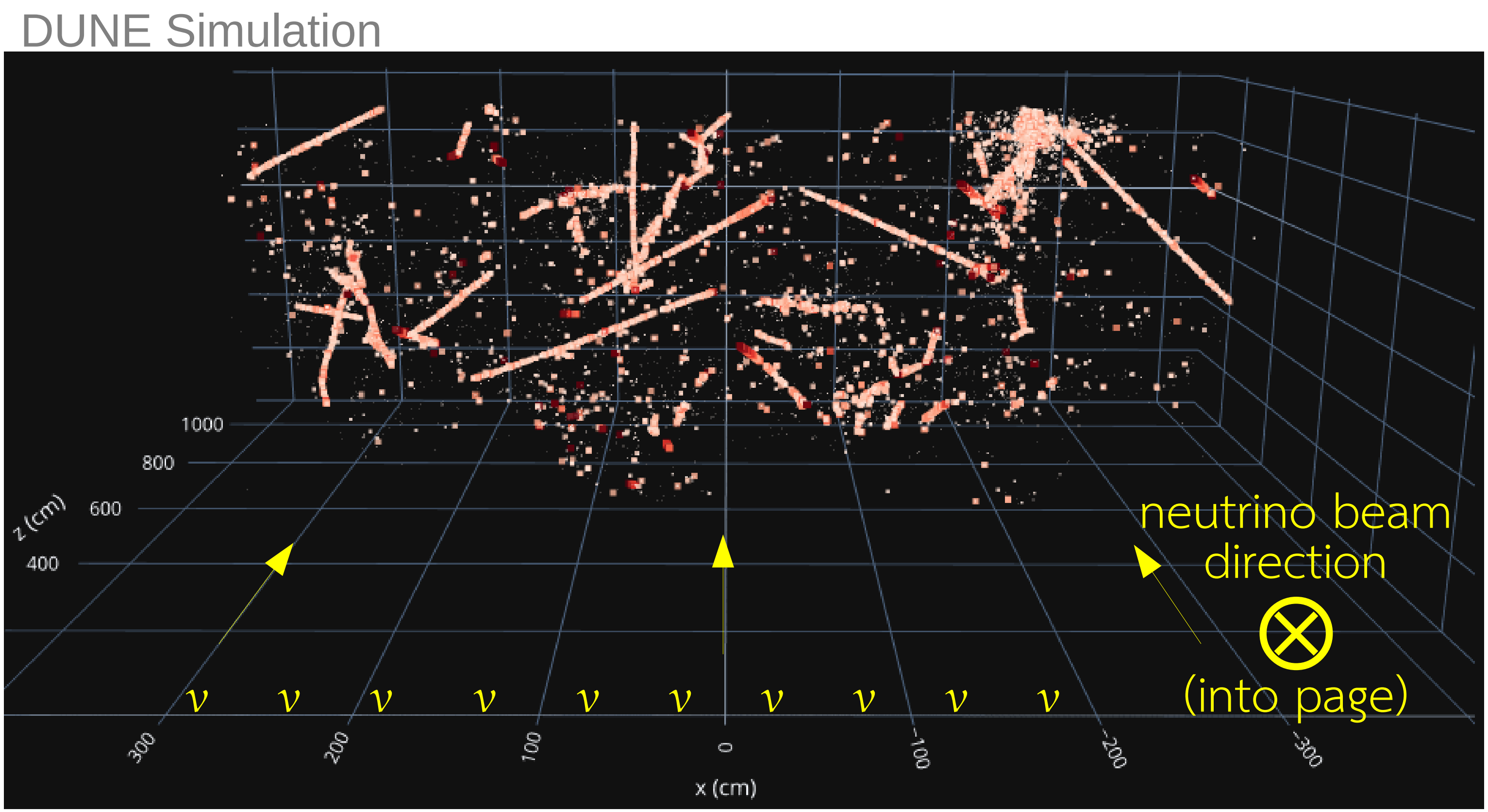
(provides unoscillated prediction):

Liquid Argon Near Detector: ND-LAr

Muon Spectrometer

Beam monitor

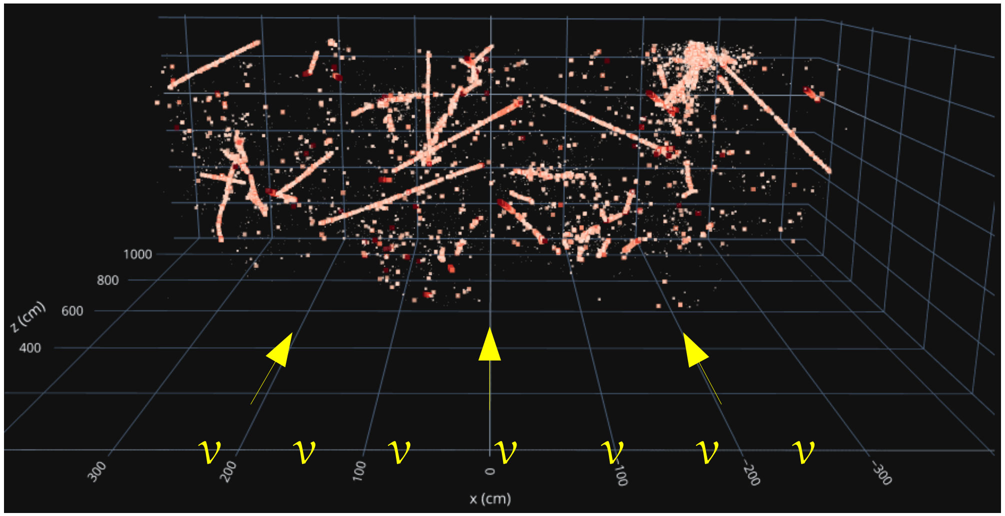
DUNE's liquid argon near detector



Simulated energy deposits in LAr from one 1.2MW neutrino beam pulse

High granularity of ND-LAr
+
High intensity of DUNE neutrino beam
=
Complex events

DUNE's liquid argon near detector



High granularity of LAr

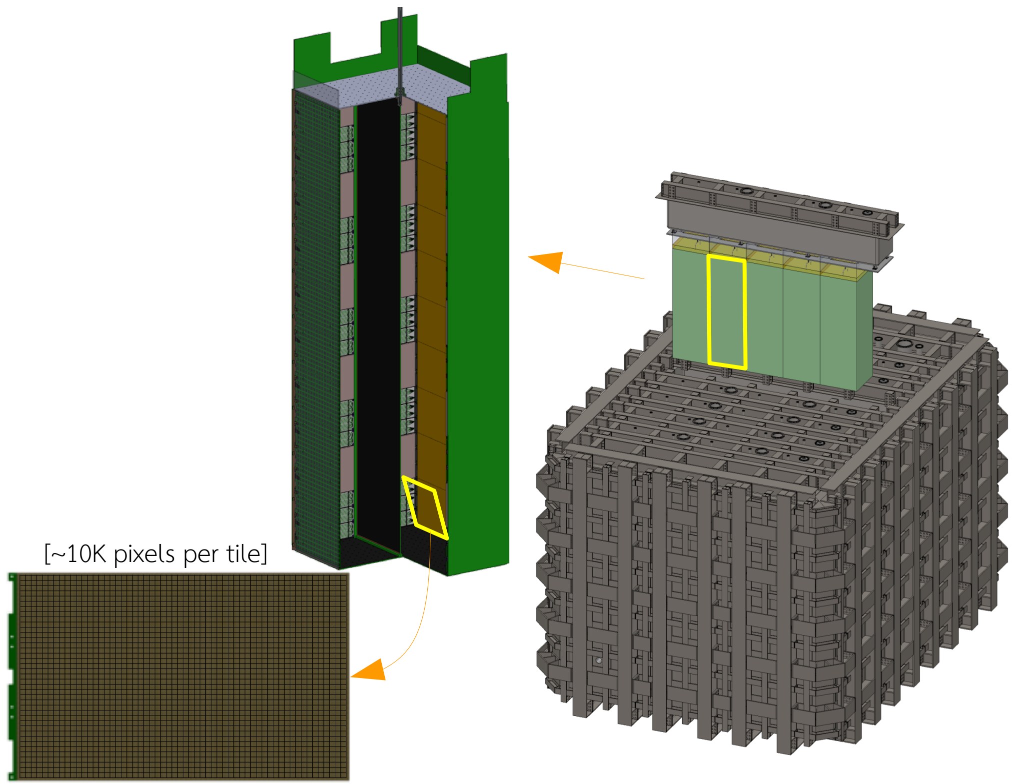
\+

High intensity

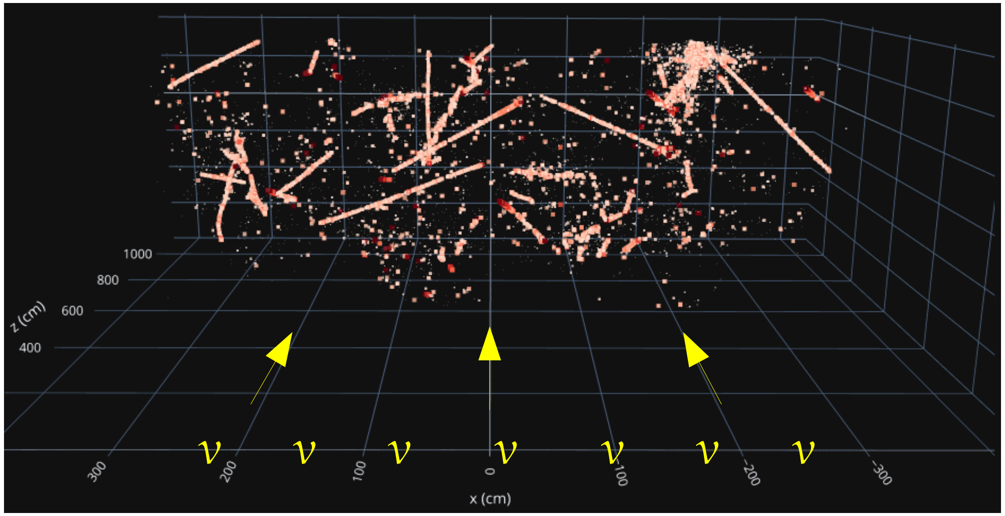
of DUNE neutrino beam

= Complex events

ND-LAr will use novel **modularization,**
true 3D pixelized readout (LArPix),
and **high-coverage photodetectors**
to unambiguously
separate energy deposits



DUNE's liquid argon near detector



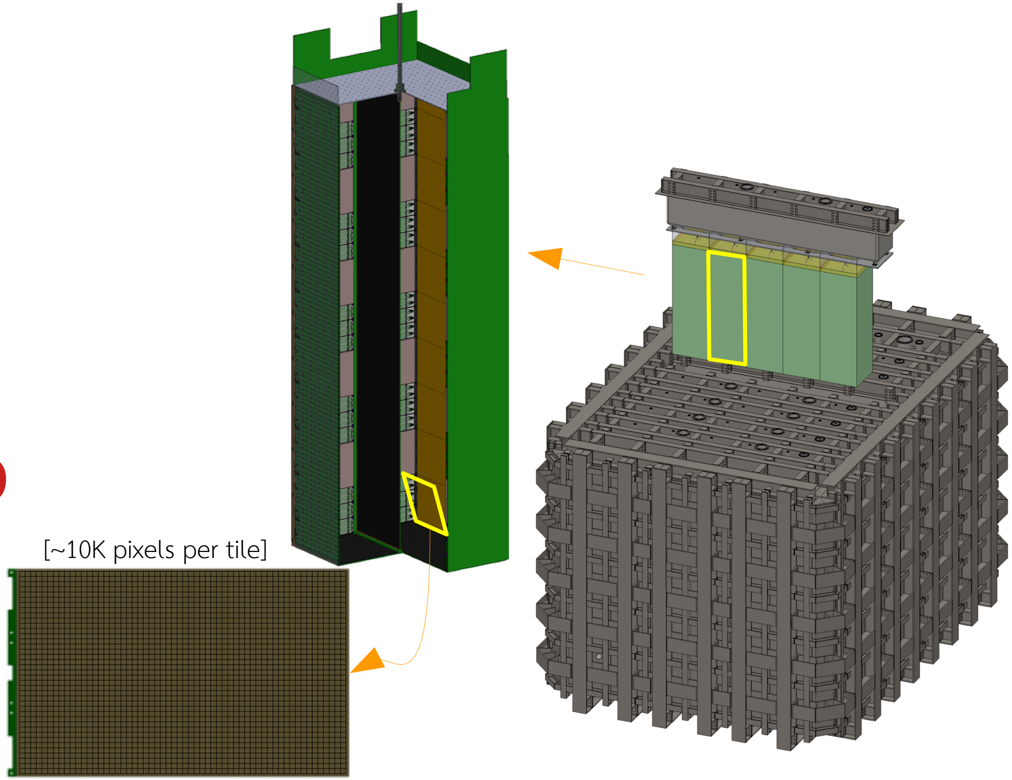
High granularity of LAr

+

High intensity of DUNE neutrino beam

= Complex events

ND-LAr performance required to be equivalent to or better than FD



Robust protyping program

2018 | 2019 | 2020 | 2021 | 2022 | 2023

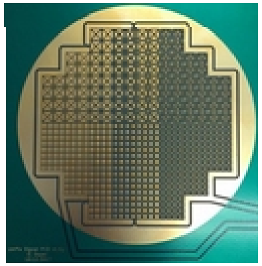
New technology demonstrations

Small-scale integration tests

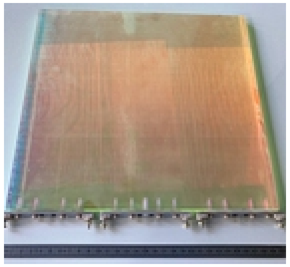
60% (ton-) scale individual modules

Four-module demonstrator in FNAL NuMI neutrino beam

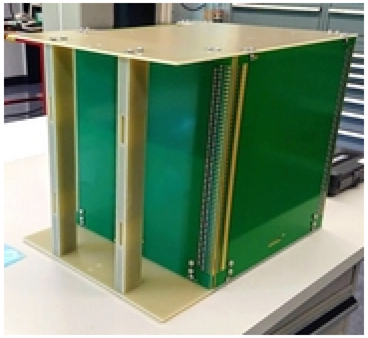
Field cage



Charge readout

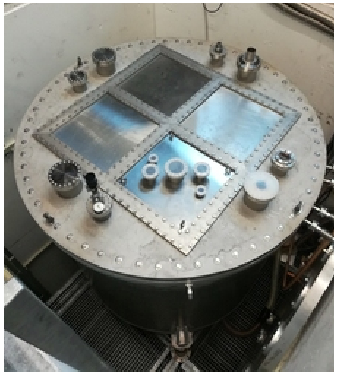


Light readout



~30x30x30 cm^3 "SingleCube" prototypes

"Module 0"



"2x2" cryostat

Robust protyping program

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Field cage

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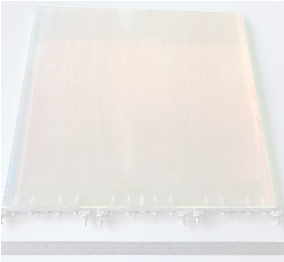
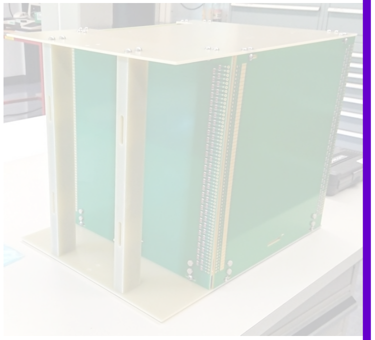


Light readout

Small-scale integration tests



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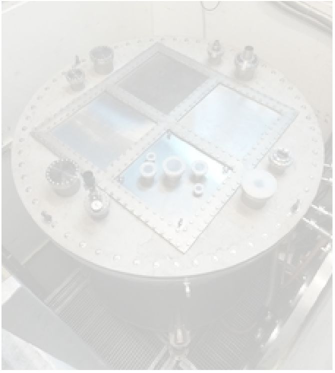
60% (ton-) scale individual modules

"Module 0"

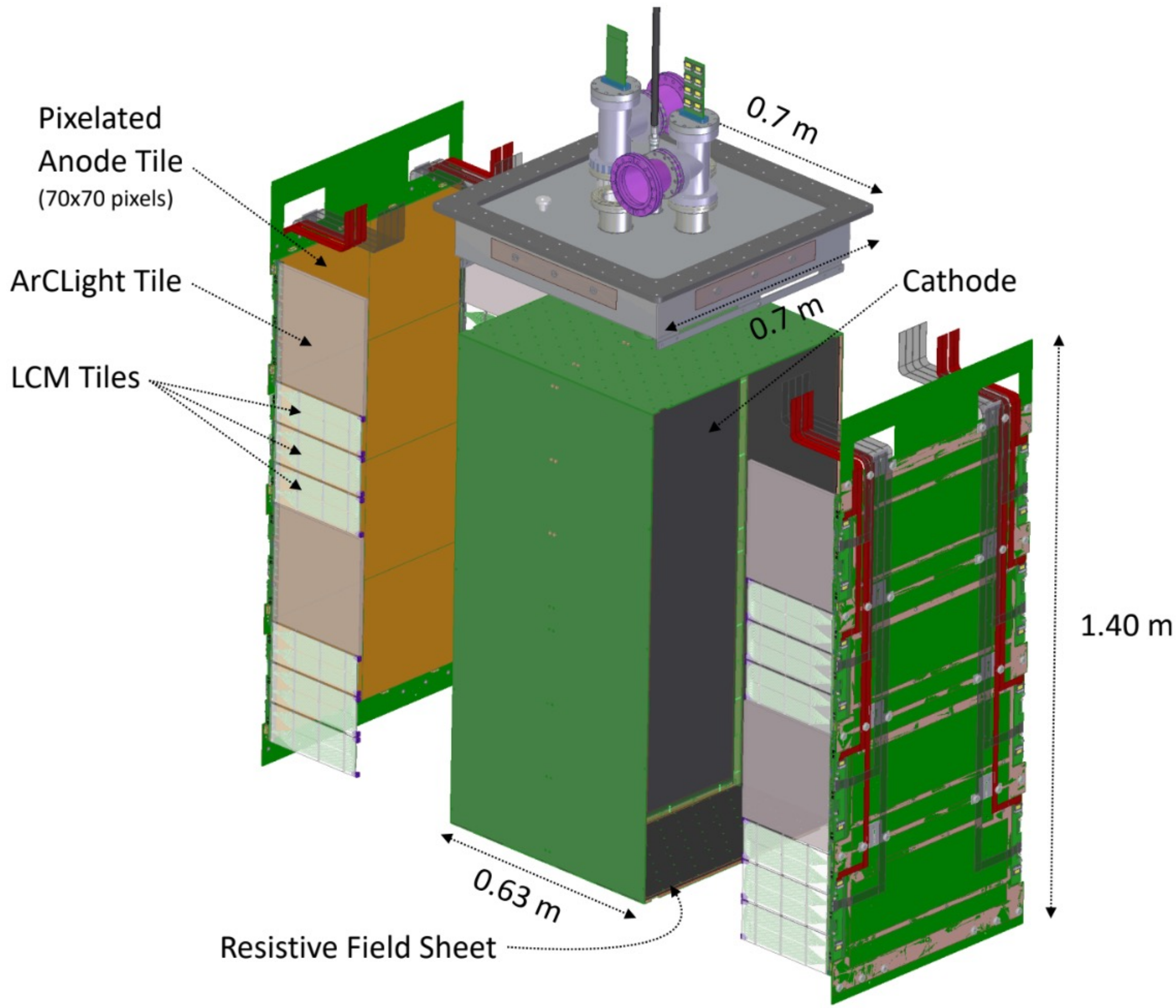
Four-module demonstrator in FNAL NuMI neutrino beam



"2x2" cryostat

Ton-scale prototypes

3 major innovations

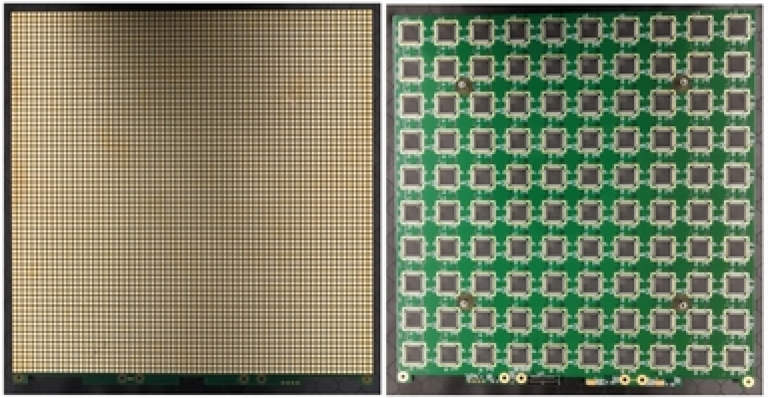


Ton-scale prototypes

3 major innovations

① Pixelated Charge Readout

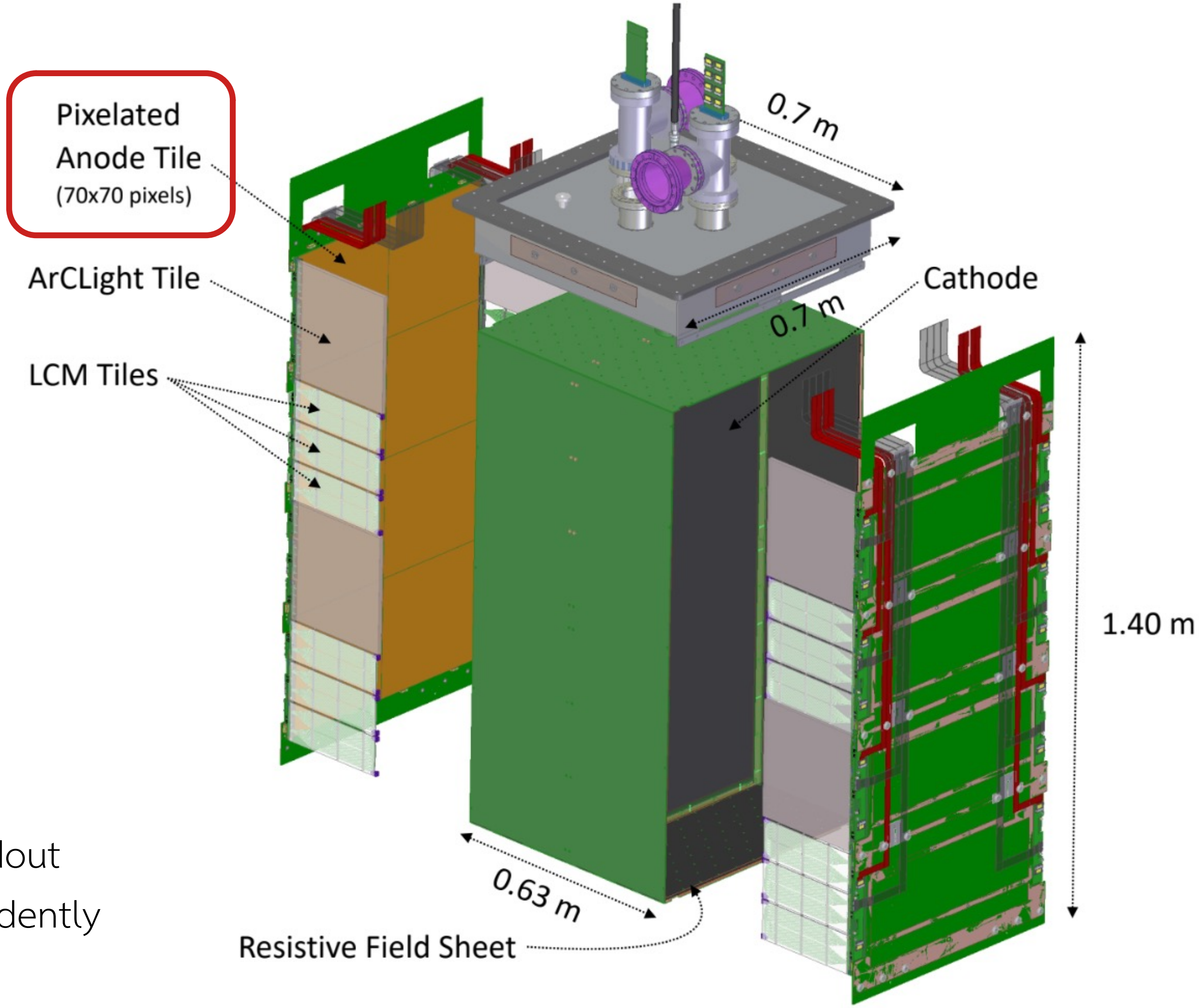
LArPix "tile"



front (pixel pads; 4mm pitch)

back (amplifying/digitizing ASICs)

- Charge-collecting pixels provide true 3D readout
- Always-on, low-power channels are independently self-triggering
- ASICs provide onboard digitization (in-cold)
- Commercial fabrication → fast, scalable production

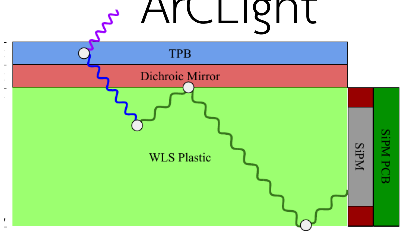


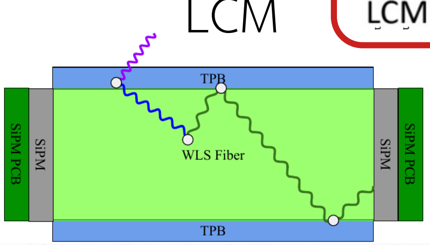
Ton-scale prototypes

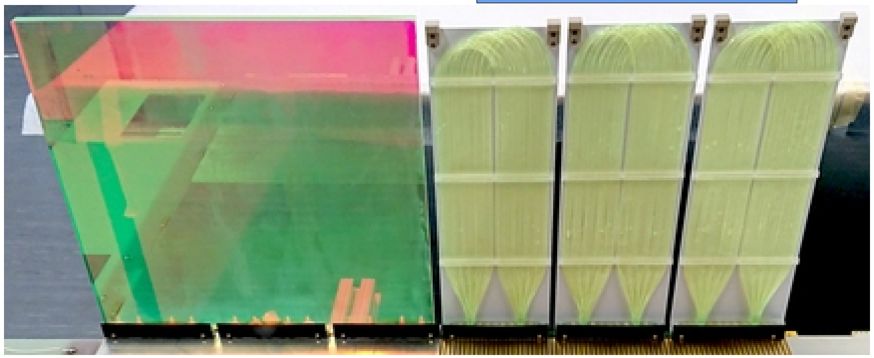
3 major innovations

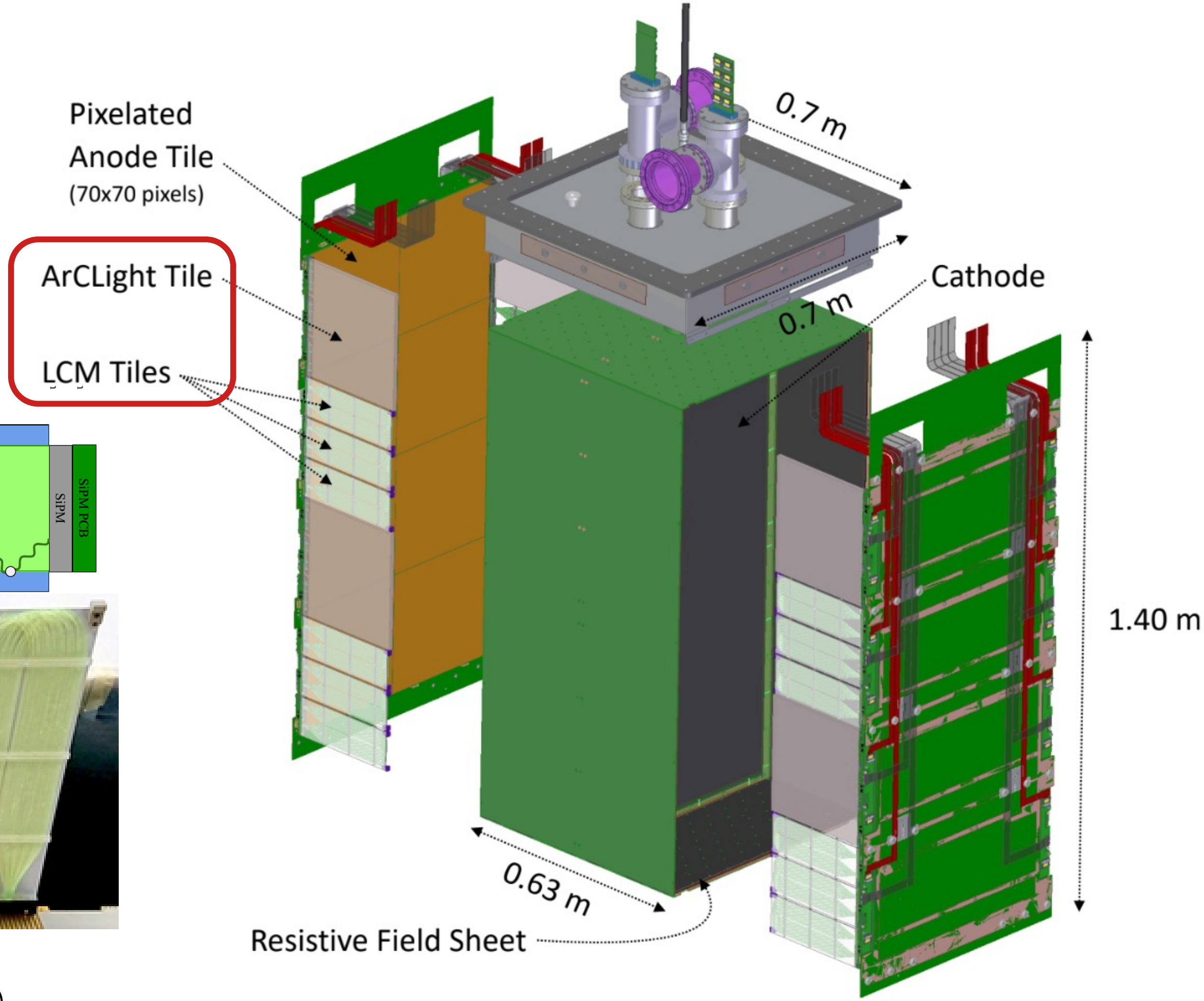
① Pixelated Charge Readout

② Light Readout System









- High (30%) optical coverage
- 0.6% quantum eff. → ~MeV threshold (LCM)
- Dielectric design → *inside* field structure
- Both designs employ wavelength shifters and SiPM readout

Ton-scale prototypes

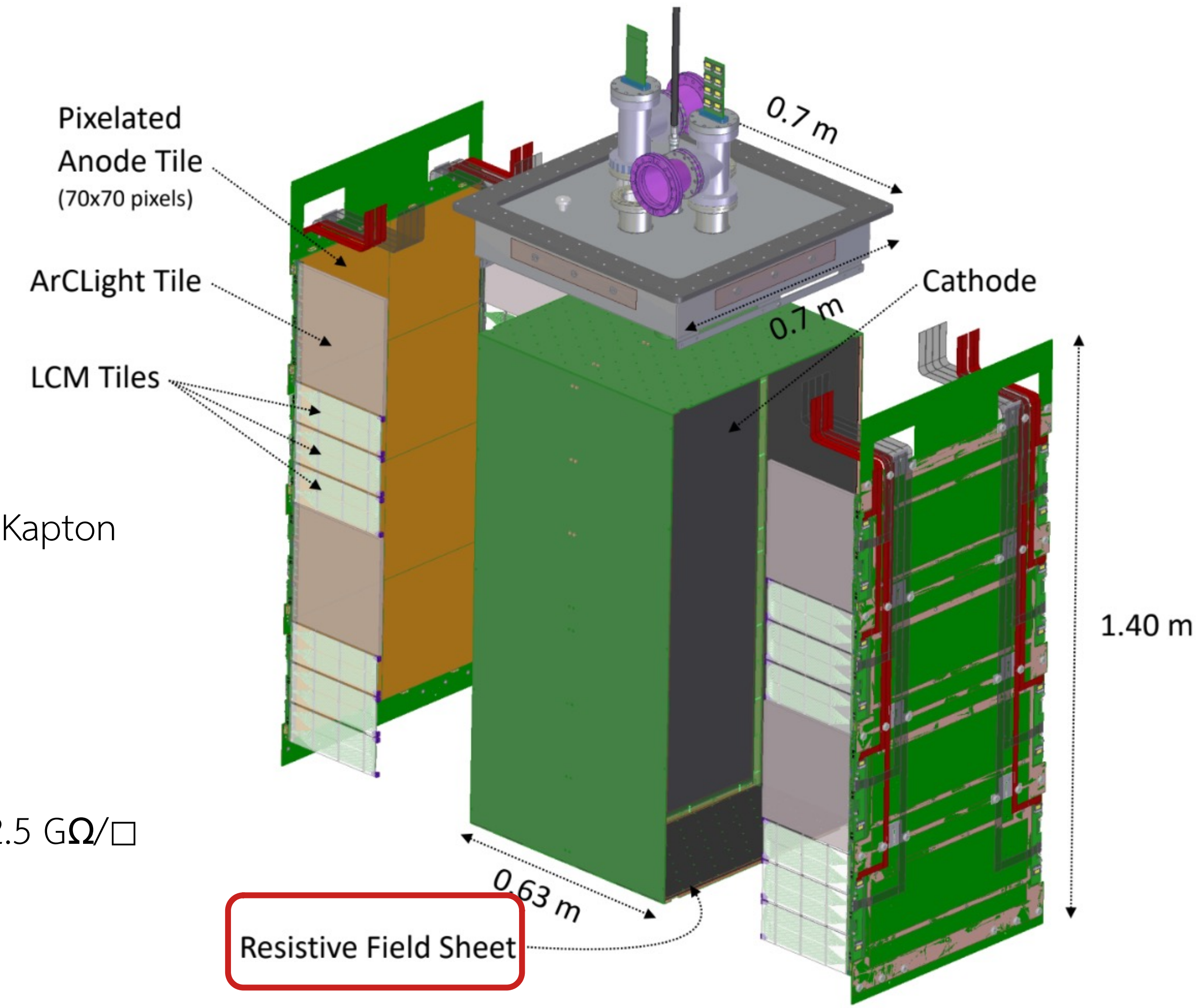
3 major innovations

① Pixelated Charge Readout

② Light Readout System

③ **Resistive field sheet**

- Low-profile shell made from carbon-loaded Kapton
- Lower stored energy and power dissipation, fewer points of failure than resistor chains
- Demonstrated stability up to 1 kV/cm field (nominal field: 500 V/cm)
- Drift distance: 30cm
- Sheet resistance (at 500 V/cm, LAr temp): ~2.5 GΩ/□



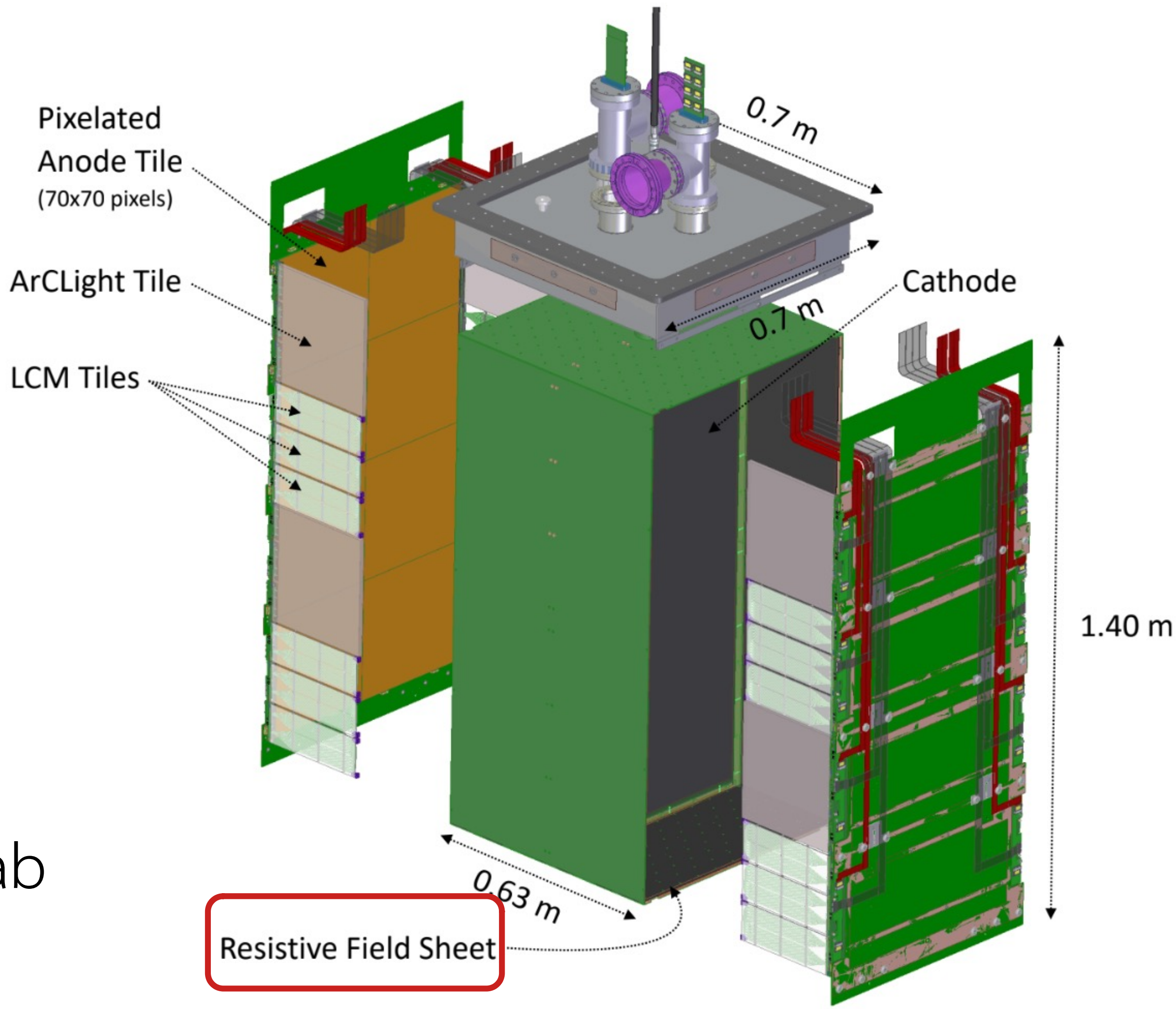
Ton-scale prototypes

3 major innovations

① Pixelated Charge Readout

② Light Readout System

③ Resistive field sheet



Testing at Bern

prior to delivery to Fermilab

“Module 0” testing

First module (“module 0”) was tested with LAr at Bern in 2021

[Subsequent modules tested in 2022 (“module 1”) or currently in production]

Maneuvering module 0 into place

“Module 0” testing

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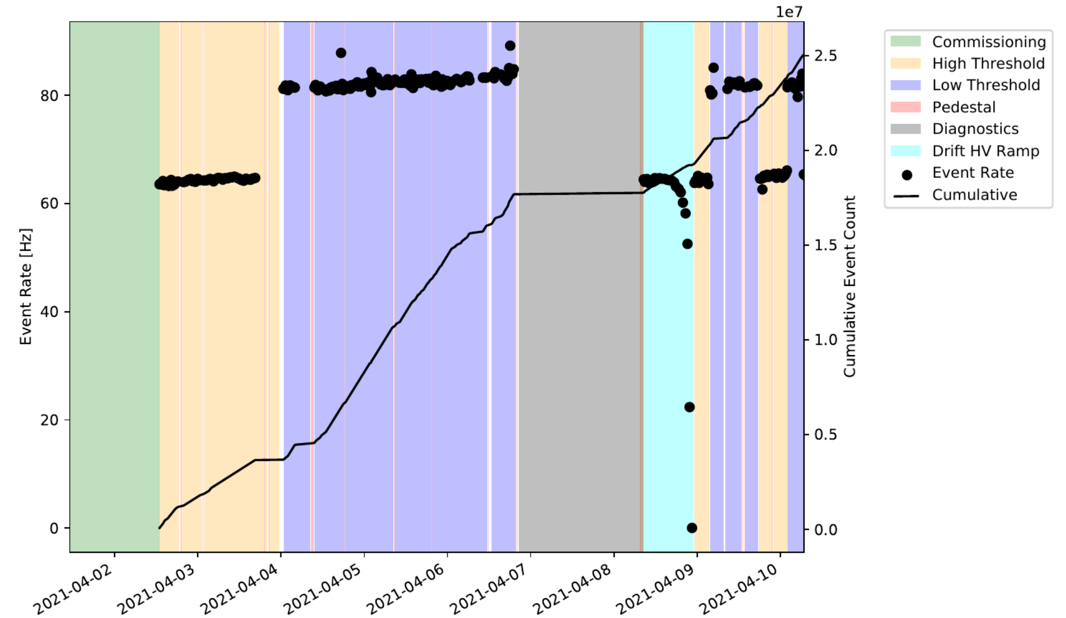
Maneuvering module 0 into place

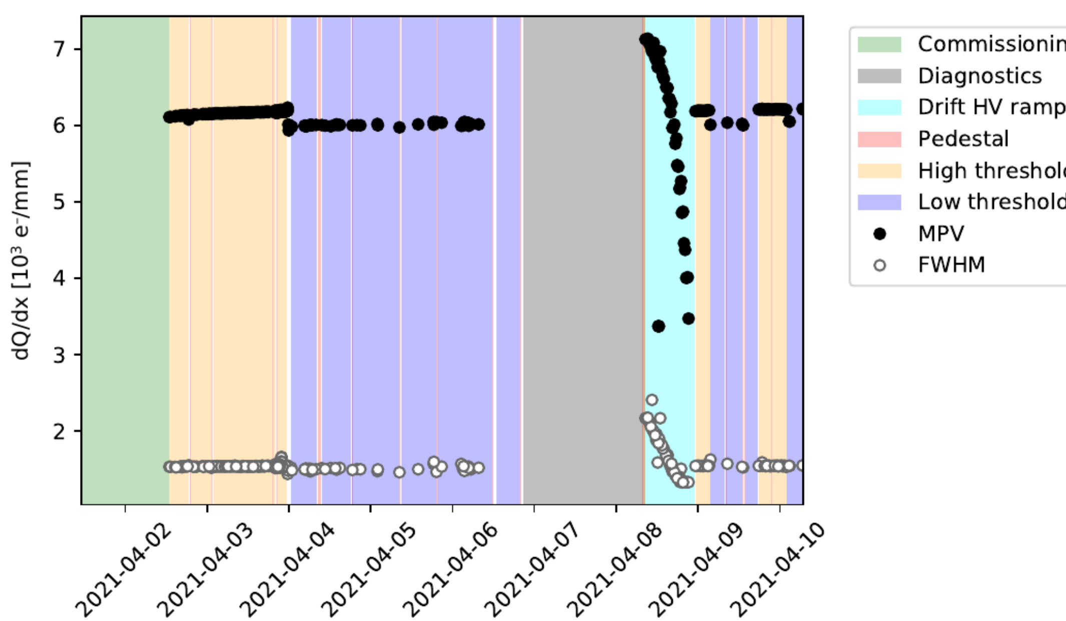
Forthcoming paper: Performance of a modular ton-scale pixel-readout liquid argon Time Projection Chamber → highlights in following slides

“Module 0” testing

First module was tested with LAr at Bern in 2021

- Smooth & stable performance

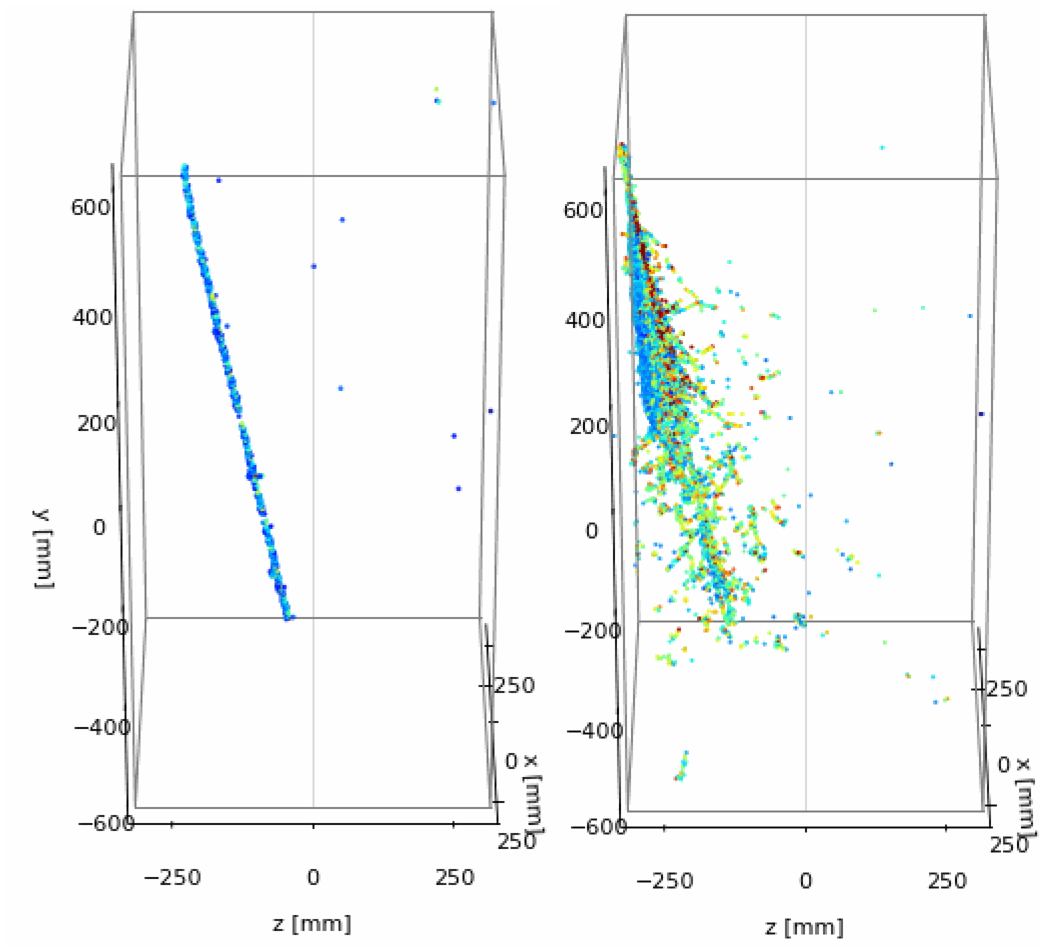




“Module 0” testing

First module was tested with LAr at Bern in 2021

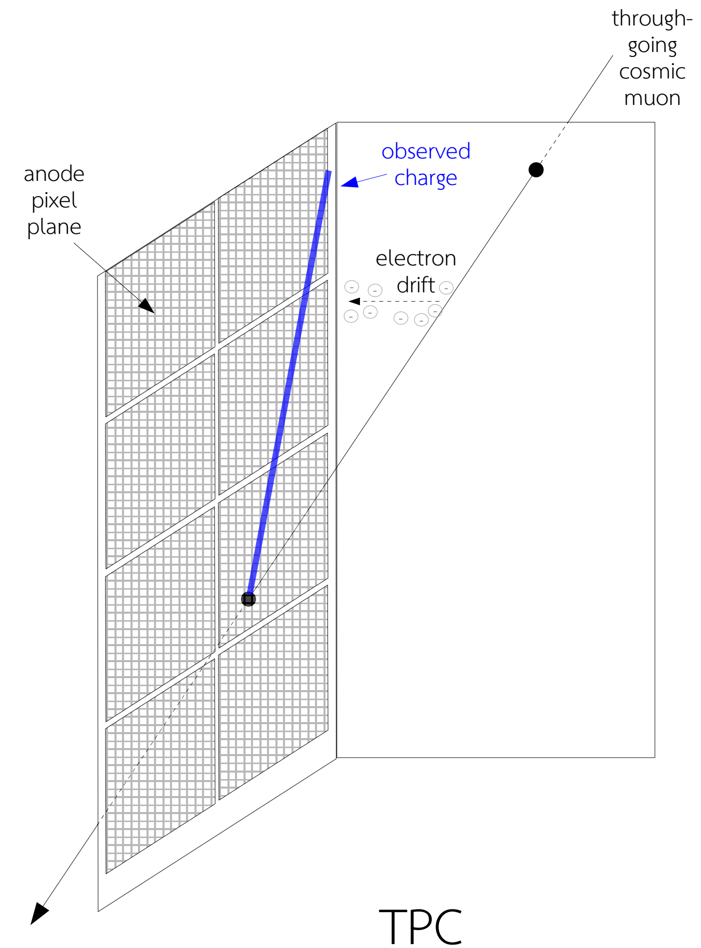
- Smooth & stable performance
- 10s of millions of cosmic rays successfully self-triggered!
  → ~11 TB of data total (~75% from light system)



Sample events from April run

Measuring performance

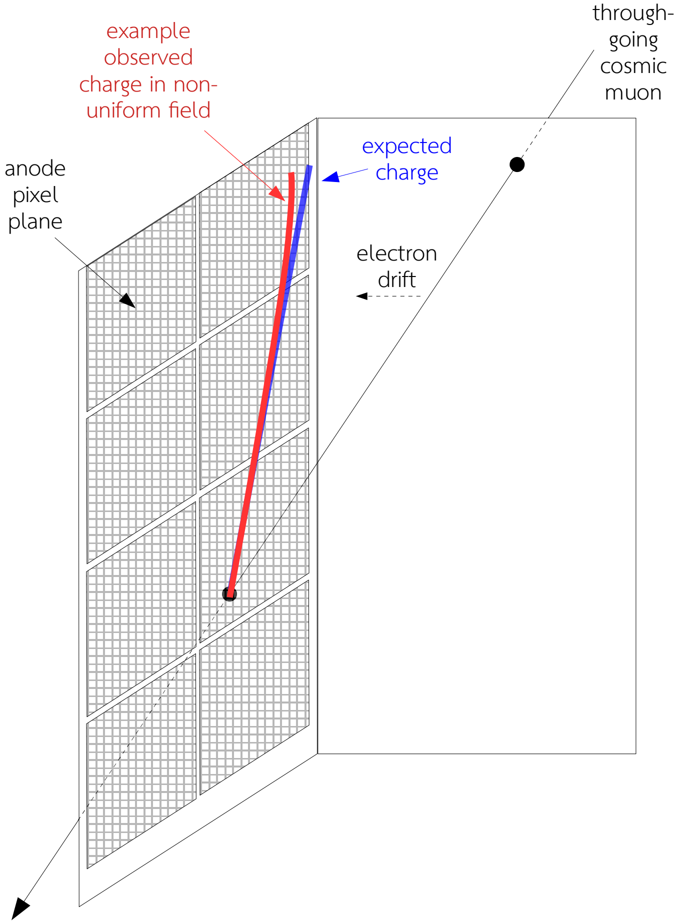
- Cosmic rays are valuable calibration source:
  - Tracks piercing anode have clear "t_0" (~no drift at anode end)
  - Tracks exiting/entering sides have one clear transverse coordinate
  - Simple topology for charge-light matching
  - Stopping muons often emit Michel electrons with known time spectrum



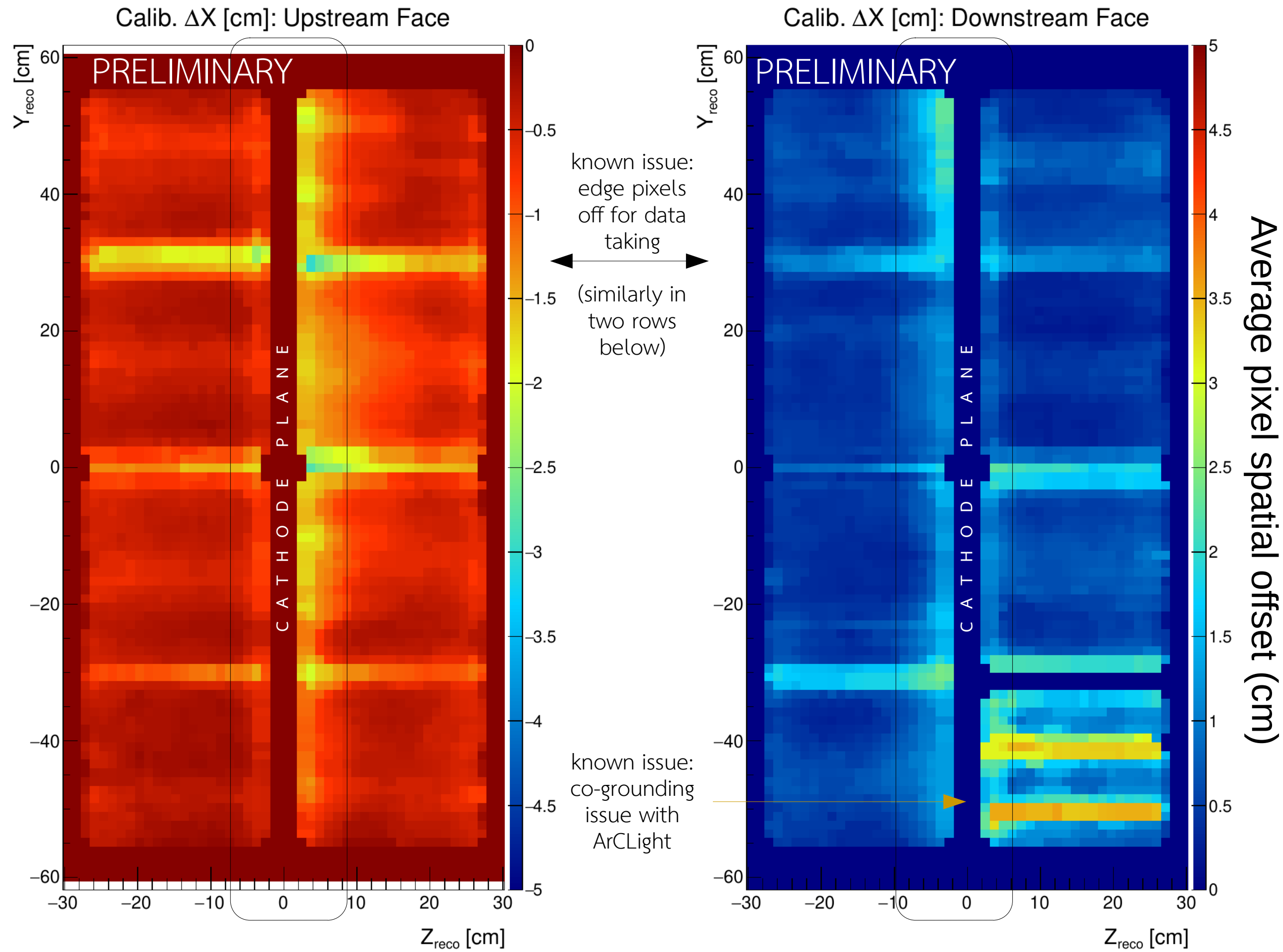
TPC illustration

→ **Following results derived from cosmic data**

Prototype performance



Non-uniformities in electric field result in deflections from expected straight line



Uncalibrated observed deflections near cathode plane (circled)

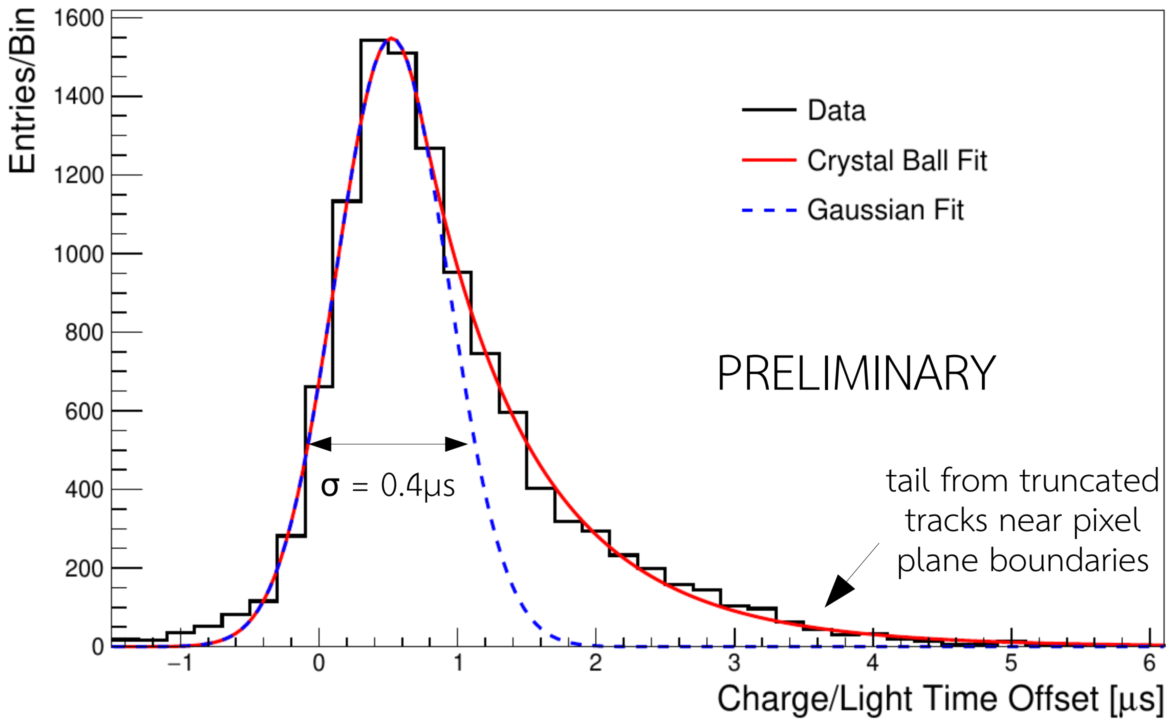
average ~30 V/cm (0.2% effect on field mag.)

(requirement: when calibrated, ≤1%)

Prototype performance

Compare precision GPS times for charge & light system t_0s

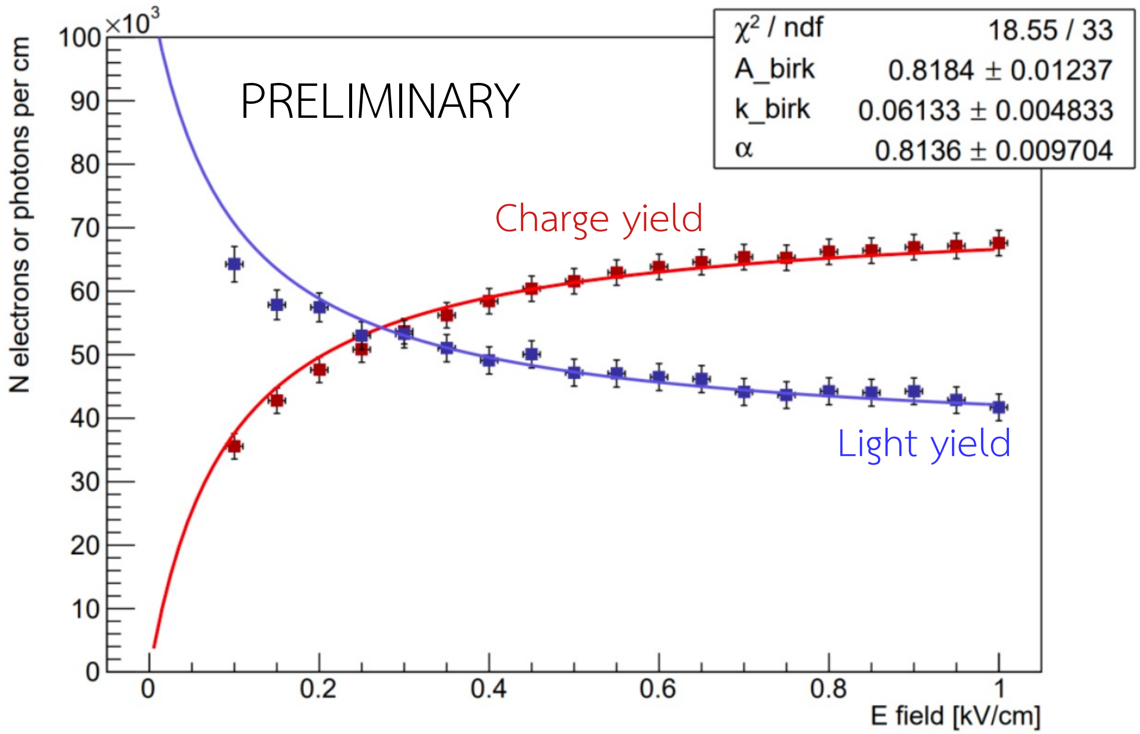
(again use through-going cosmics)



Charge readout timing resolution 0.6mm @ 500 V/cm

(requirement: 1.3mm)

Prototype measurements



Restrict to vertical tracks to examine charge *and* light output together over various field strengths

PRELIMINARY

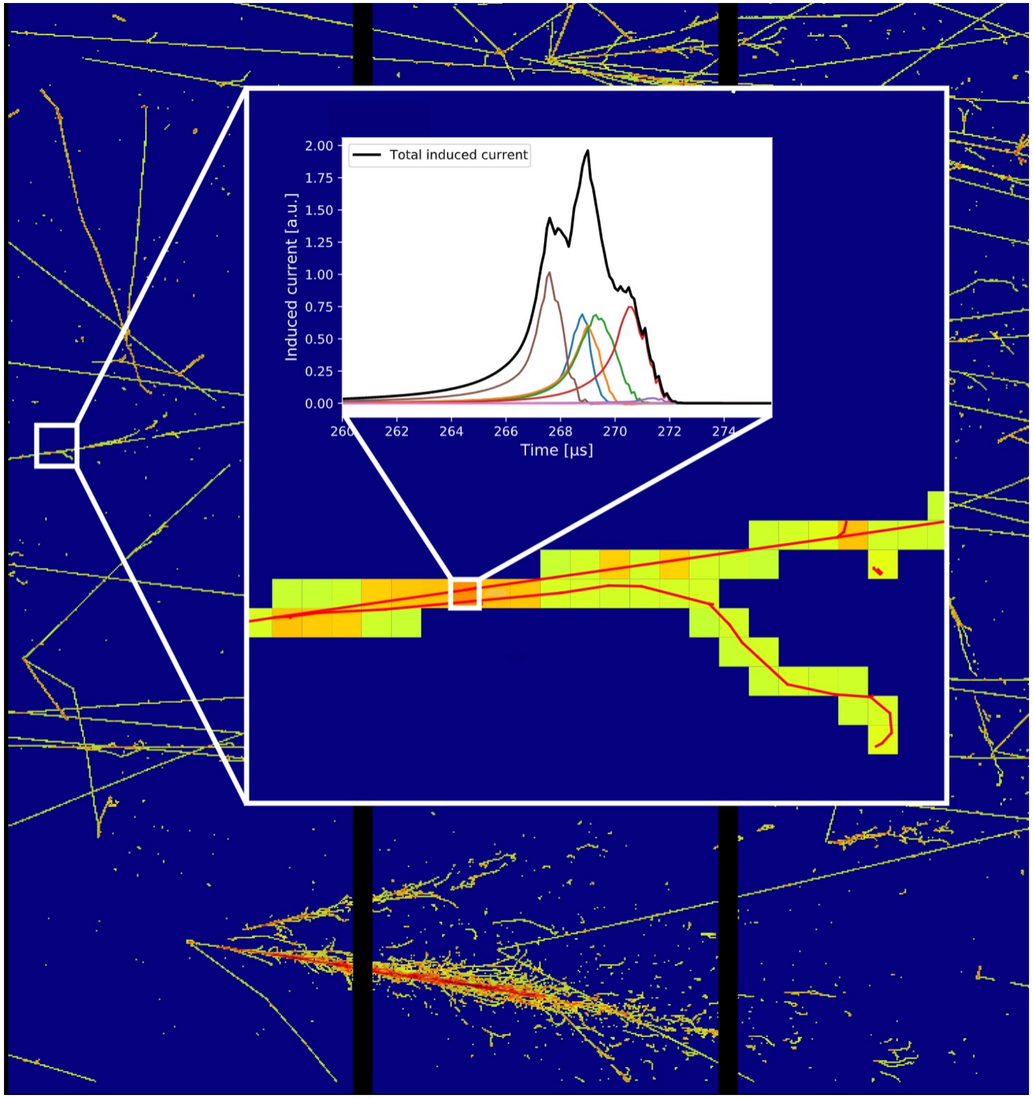
Experiment	A [kV g cm^{-3} MeV^{-1}]	k_E [kV g cm^{-3} MeV^{-1}]
ICARUS	0.800 ± 0.003	0.0486 ± 0.0006
ArgoNeut	0.806 ± 0.010	0.052 ± 0.001
Our measurement	0.794 ± 0.004	0.047 ± 0.002

Physics-quality (competitive) measurements of Birks model parameters

Simulation

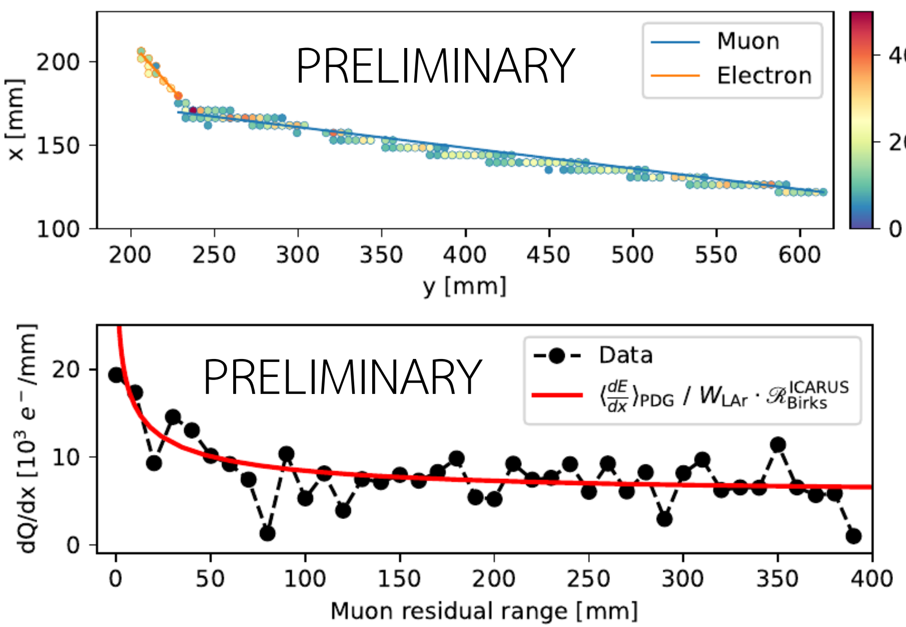
Detector simulation: larnd-sim

- GPU-accelerated using Numba
- Parallelization of electron drift sim. results in speedup of 3+ orders of magnitude (see backups)
- Generalizable to any pixel-based LArTPC

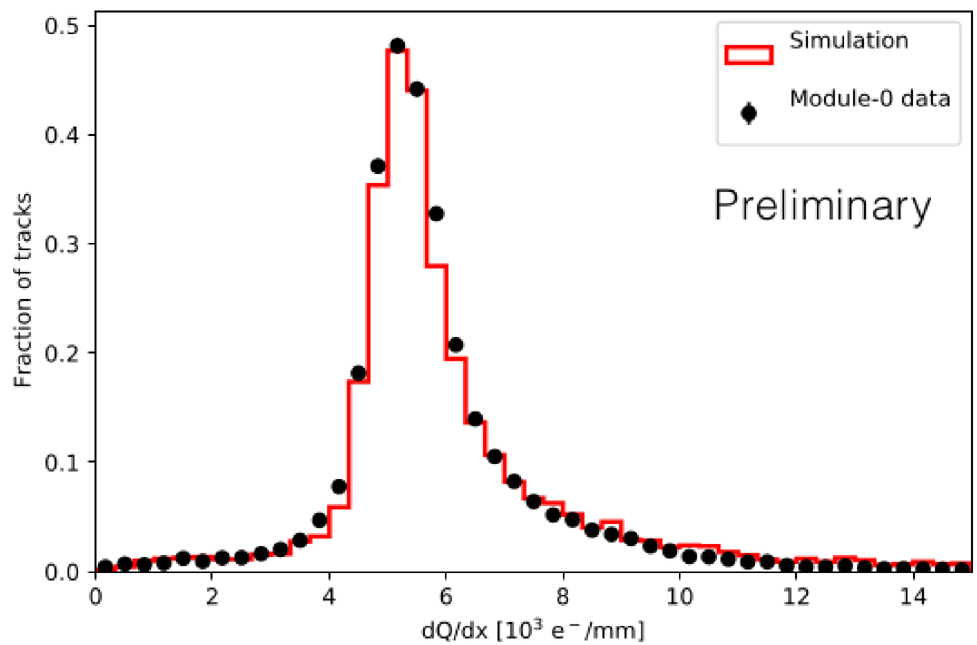


Paper in preparation: “Highly parallelized simulation of a pixelated LArTPC on a GPU”

Prototype simulation benchmarking



Stopping muon data fits well to Birks model



Pixel-level comparisons show dQ/dx simulation is working well

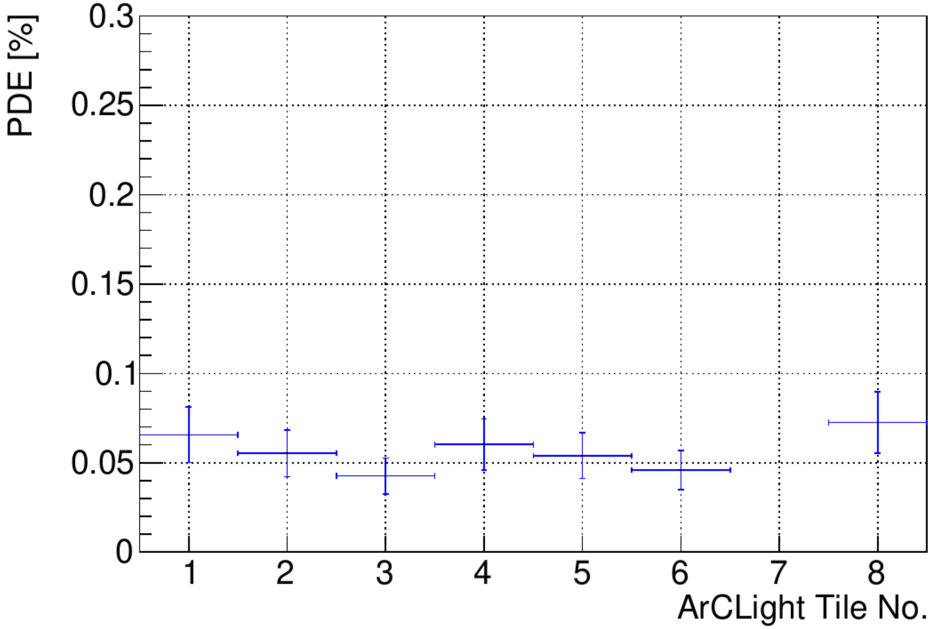
Summary

- DUNE ND-LAr 's **novel technologies** address challenge of working in high-intensity beam
- Robust prototyping program shows **physics requirements being met**
- **Physics-quality data agrees well with detector simulation** and will be used for further improvements

Overflow

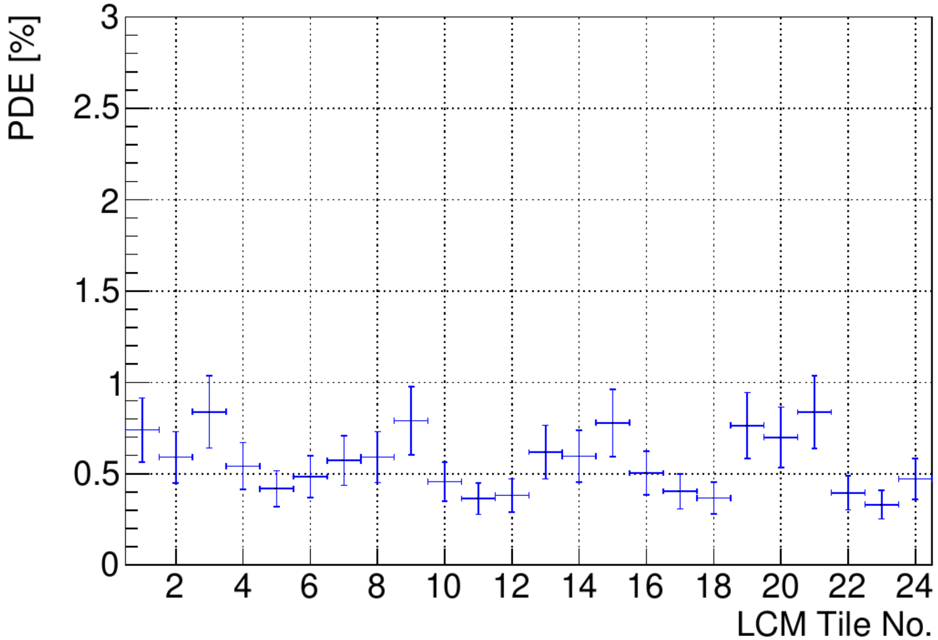
Light system efficiency

ArCLight photon detectors



Lower efficiency allows larger dynamic range

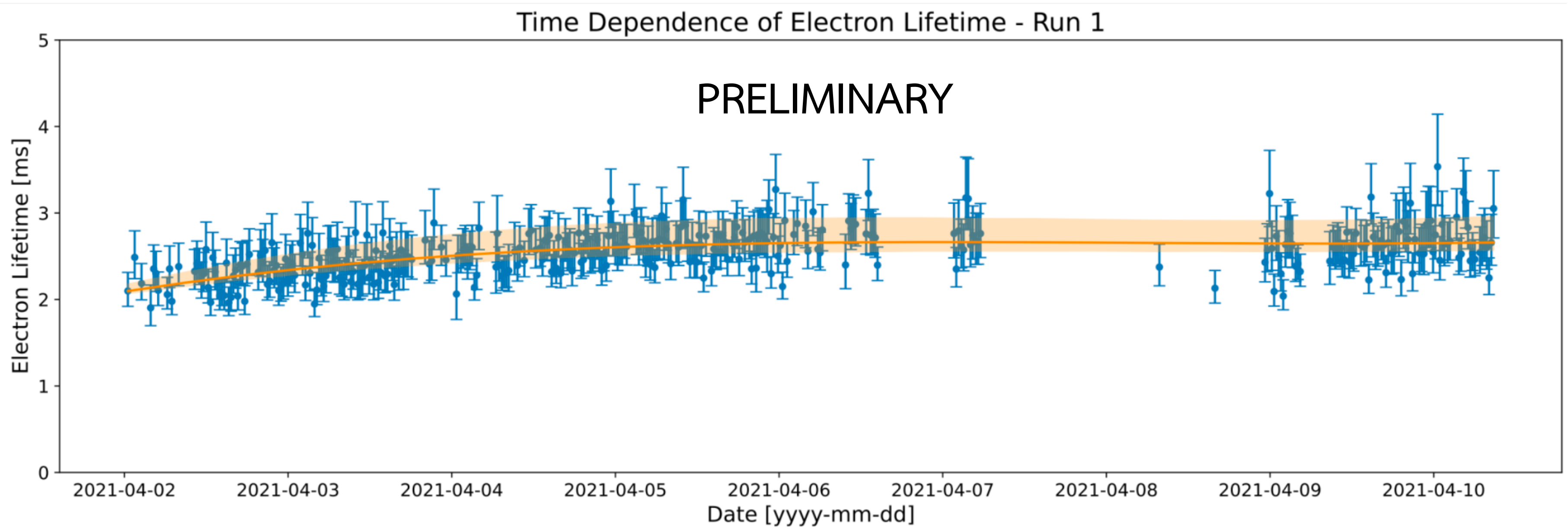
LCM photon detectors



Tiles near the top have lower efficiency due to anisotropy of fiber distribution

0.6% mean efficiency → MeV-scale energy deposits

Prototype performance

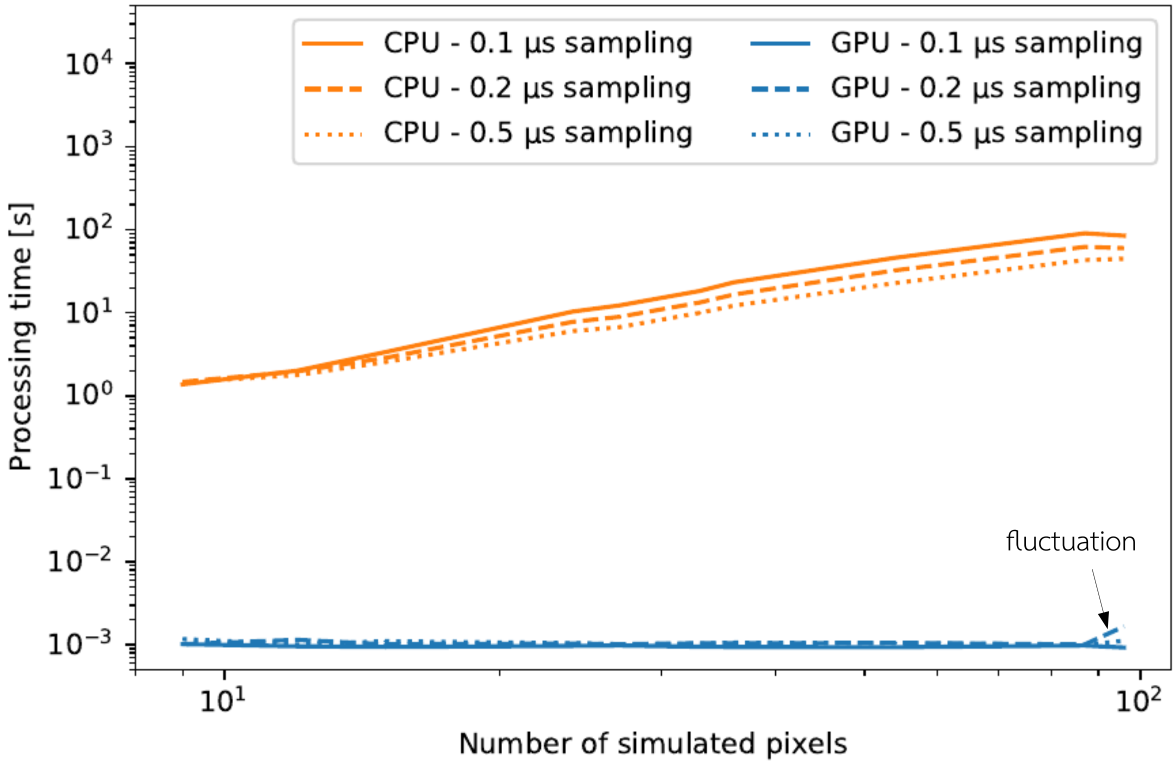


Very good LAr purity → electron lifetime

& stable operation

(~5x better than requirement)

Simulation



Parallelization in GPU-accelerated simulation

results in simulation time ~independent of channel count