DUNE Near Detector ND-LAr Prototype:

2x2 Demonstrator

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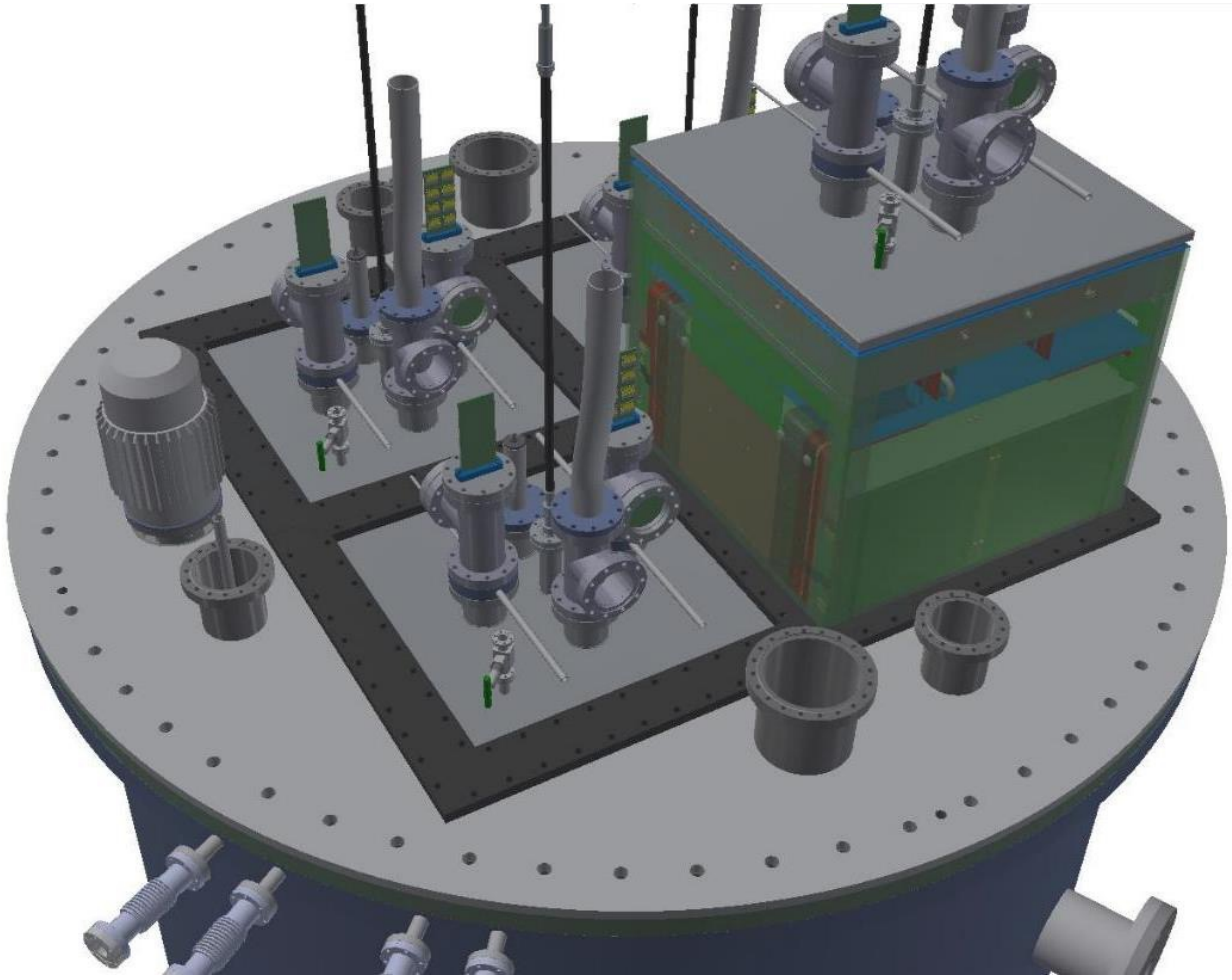
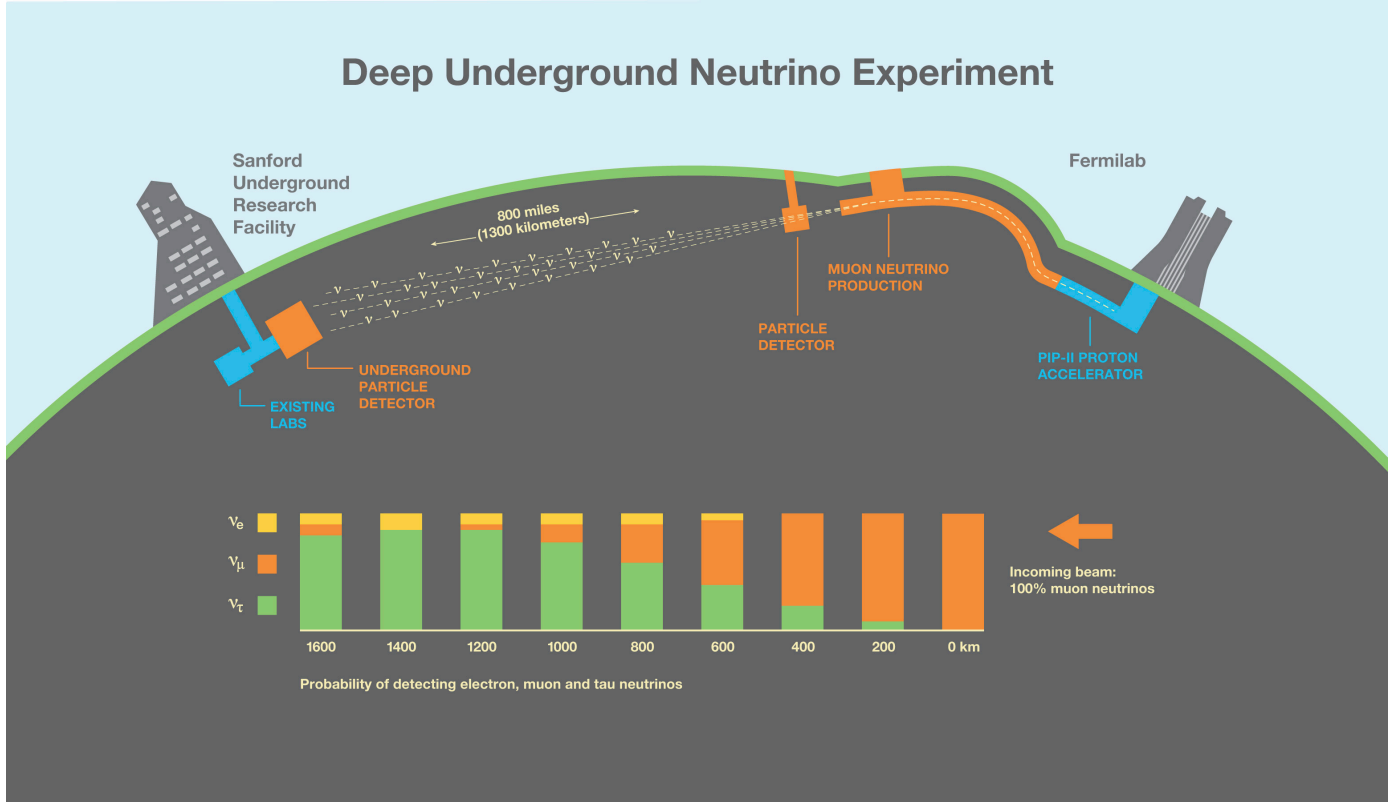
International School of Subnuclear Physics



Deep Underground Neutrino Experiment



Long-baseline: 1300 km

LBNF beamline: Beam power 1.2 – 2.4 MW

Near detector:
Multi technology, including a 67-ton Liquid Argon TPCs

Far detector:
4 Modules, 17.5-kton Liquid Argon TPCs each

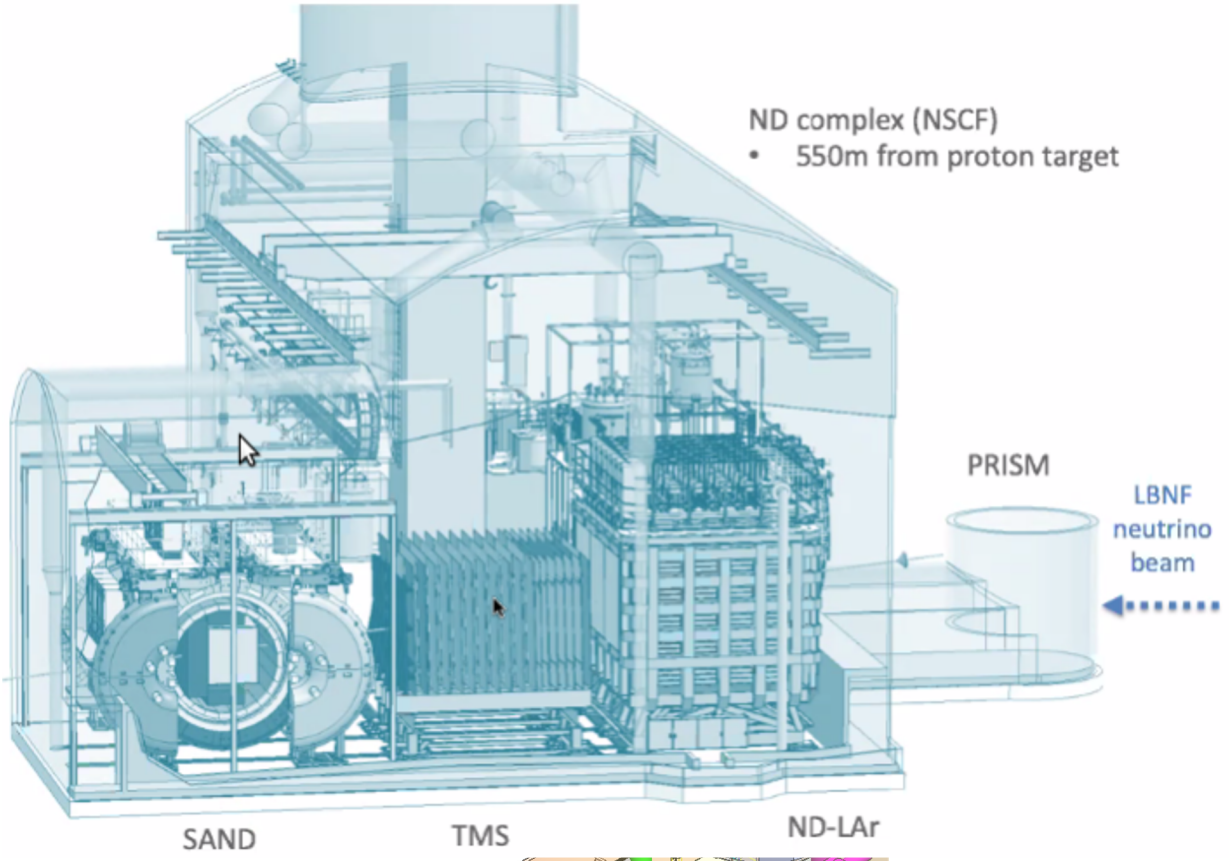
Physics goals:

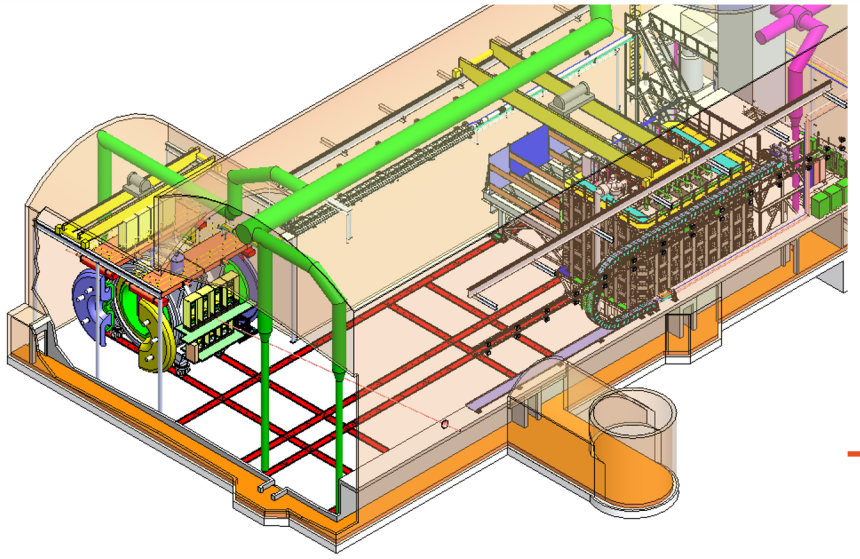
- **Precision measurement of Neutrino Oscillation parameters**
- **CP violation and mass hierarchy**
- **Supernova burst neutrinos**
- **New physics: baryon number violation, sterile neutrinos, non-standard interaction, etc.**

Near Detector complex

Dune ND Located 550 m from the proton beam target constitutes 3 essential detector systems:

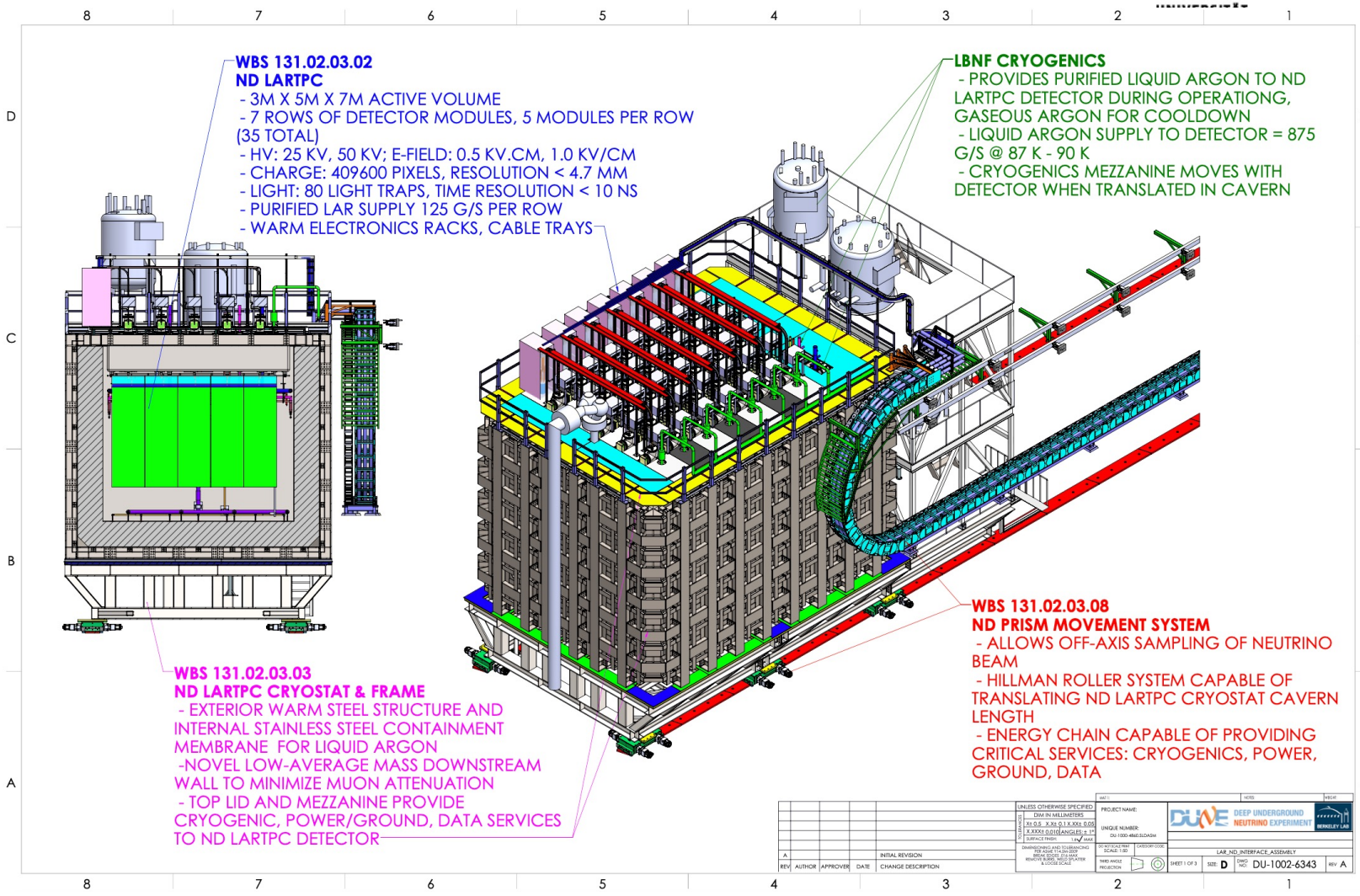
- **ND-LAr: A 67-ton Liquid Argon Time Projection Chamber (TPC).**
  - **LAr Target mass with high resolution imaging capability in high pileup environment**
- TMS: Temporary Muon Spectrometer
  - Measurement of muons momentum and charge
  - To be replaced by the ND-GAr in a later phase
- SAND: System for on-Axis Neutrino Detection
  - Provides continuous on axis beam flux monitoring
- PRISM: A system to move ND-LAr and TMS off-axis
  - Moving up to 28.5 m (2.5 ˚) off-axis, allows to probe different flux profiles





ND-LAr

- Modular design with 35 modules of 1m x 1m x 3m, Optically isolated TPCs
- Dimensions are optimized to fully contain hadronic showers
- Pixelated charge readout with unambiguous 3D imaging capabilities
- High photo-coverage light readout with ns scale time resolution

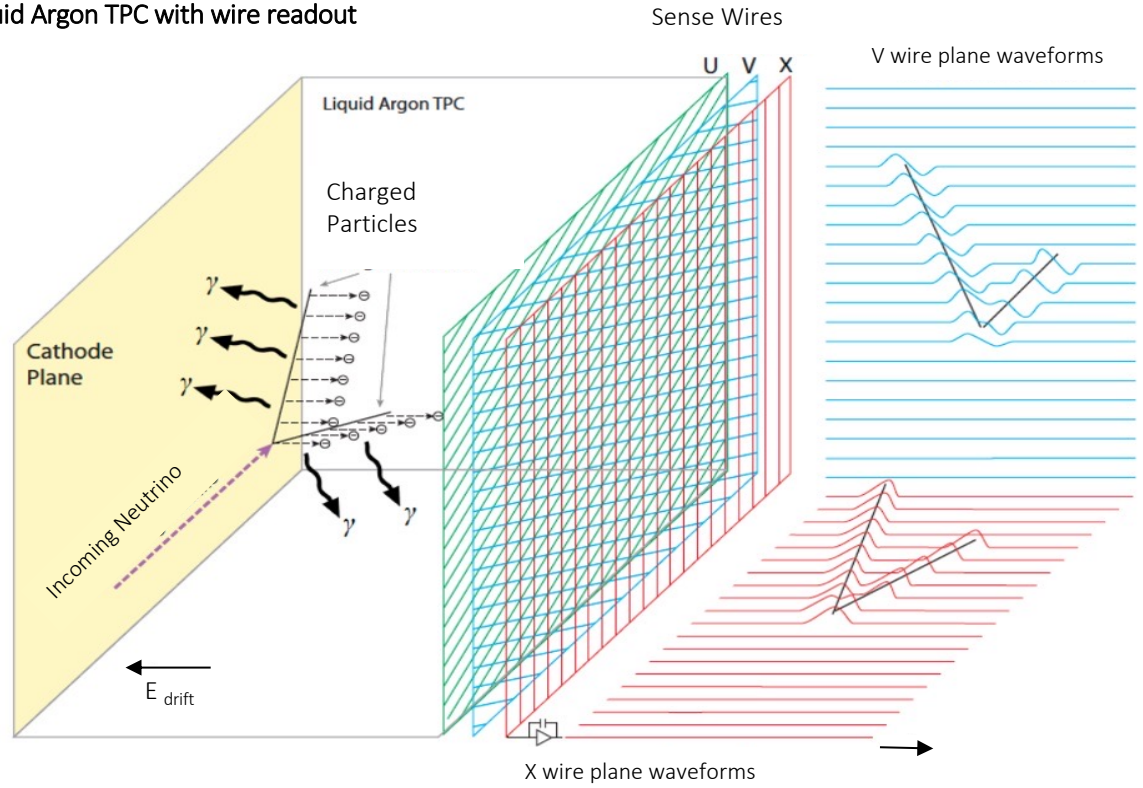


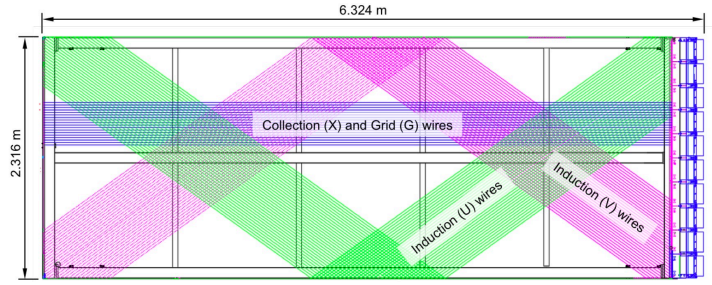
[Link to Conceptual Design Report, CDR]

LAr-TPC working principle

- Charged particles ionize argon atoms, and cause flashes of scintillation light
- The ionized electrons record the position and the amount of energy deposited in LAr.
- By applying an electric field, the electrons drift toward the readout plane located at the Anode.
- There are different charge readout solutions:

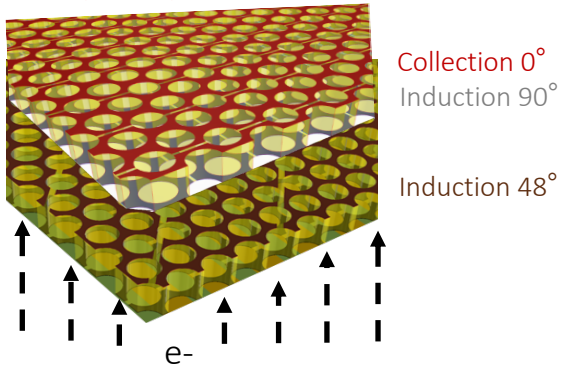
Liquid Argon TPC with wire readout



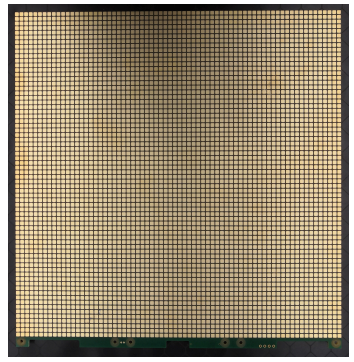


Wire readout (MicroBooNE, ProtoDUNE-HD)

Three planes (3D corner detail)



Perforated PCB (ProtoDUNE-VD)

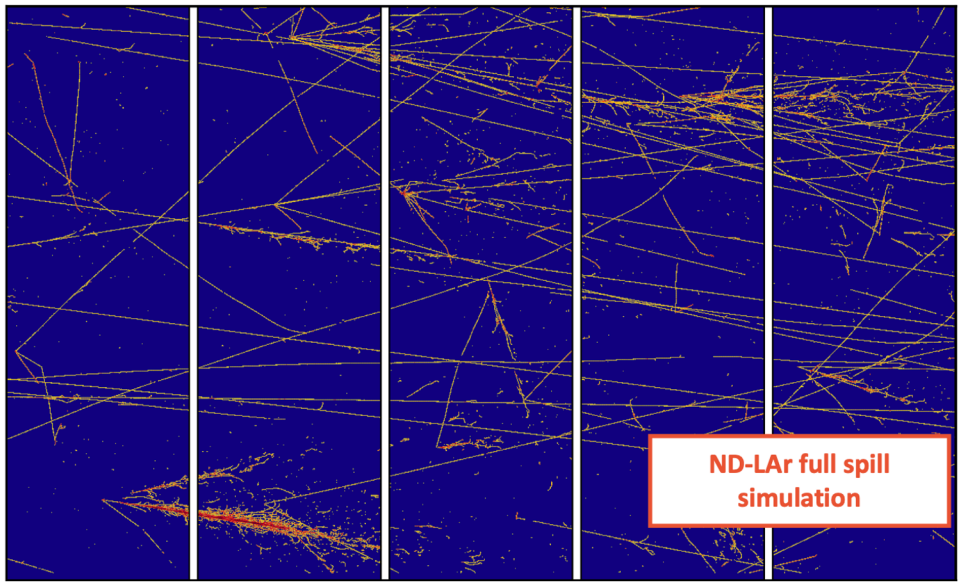


Pixelated readout (ArgonCube)

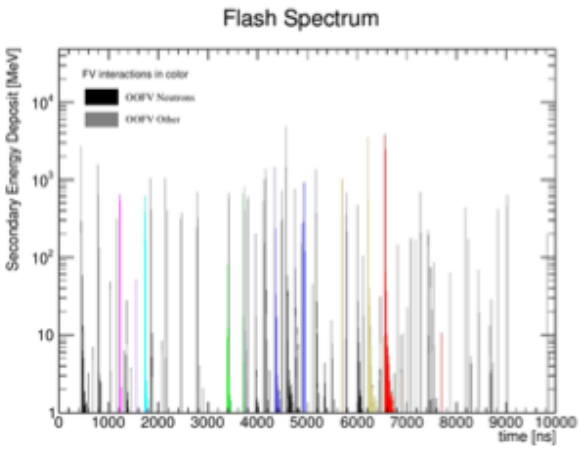
Pileup @ND-LAr

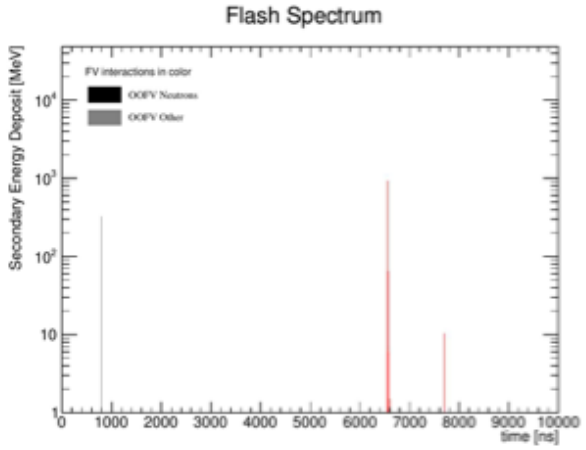
Why a Modular design?

- Unprecedented beam ν pileup at ND-LAr:
  - ~50 v interactions per spill @ 1.2 MW,
  - ~100 v interactions per spill at @ 2.4 MW
- ND-LAr detector design is capable of correct assignment of detached final state particles to neutrino vertex with high fidelity



➢ Optical segmentation (i.e. modularization) enables assignment of light and charge deposits, by drastically reducing the combinatorics of:
  - Fast O(ns) light signal
  - Slow O(ms) charge signal



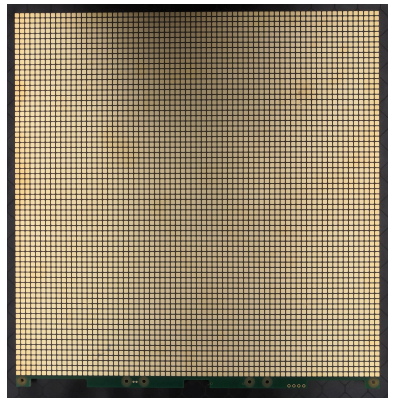


ND-LAr detector systems

Novel technologies developed to realize a modular design of LAr-TPC

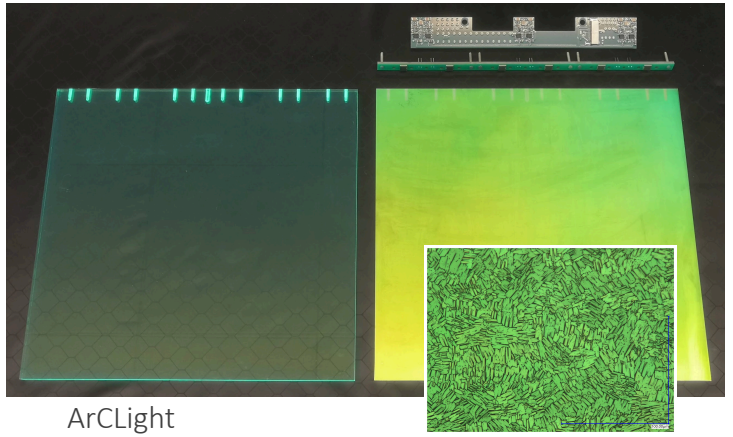
- Pixelated charge readout, LArPix ASIC developed at LBNL
  - Low power, integrating amplifier with self triggered digitization and readout
- Two complementary light collection modules + SiPM readout
  - ArCLight: WLS plastic + dichroic mirror + TPB
  - LCM: Bundle of WLS fibers painted with TPB
- Field structure with resistive shell
  - Laminated Kapton and DR8 on G10

Challenge: Minimize dead volume between adjacent modules and allows back-to-back modules configuration

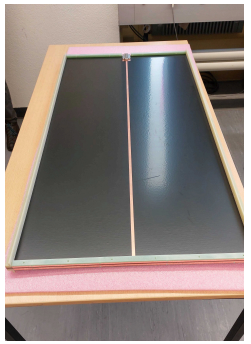


Pixelated anode tile
Front and back

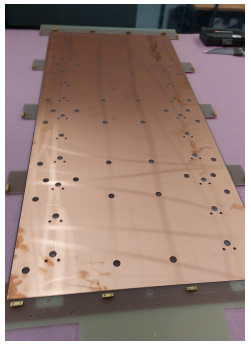
LCM



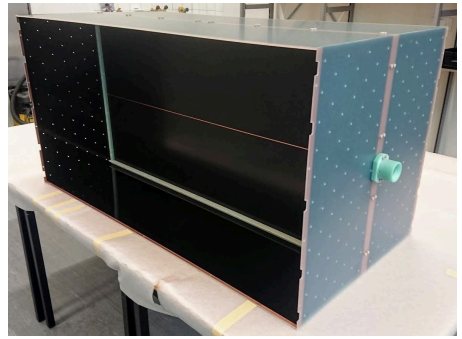
ArCLight



Cathode panel laminated with Kapton

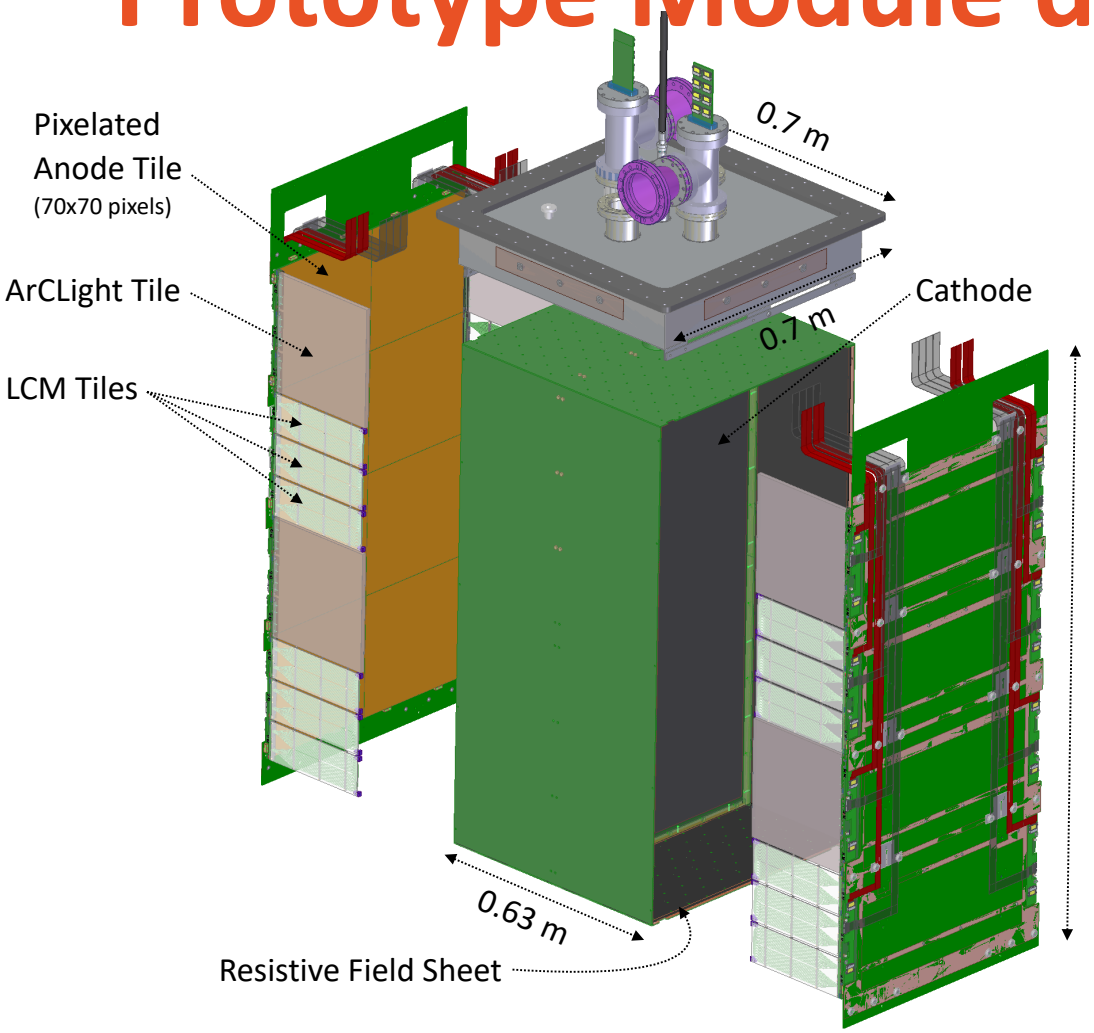


Anode panel supports charge and light modules

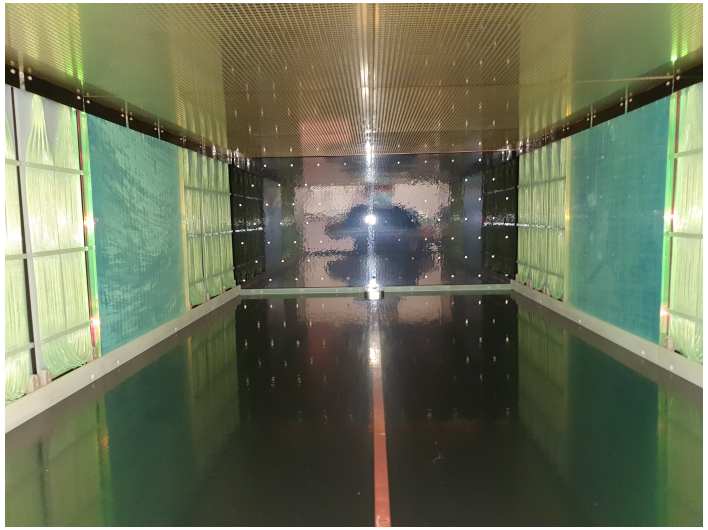


Filed shaping panels laminated with DR8

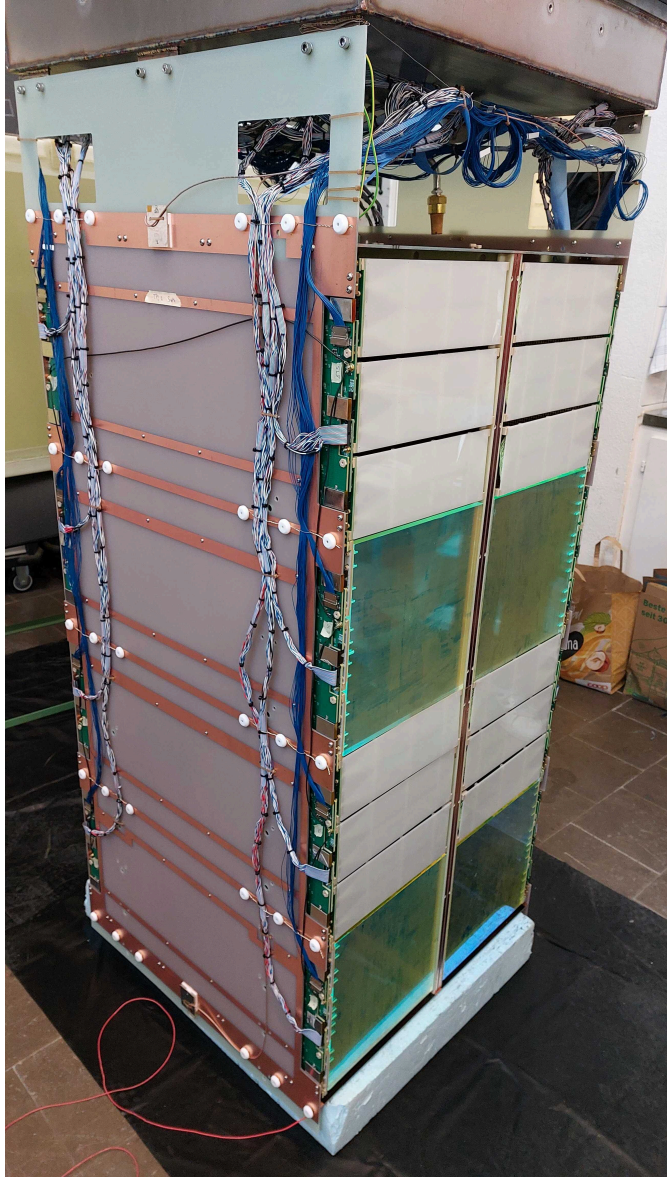
Prototype Module design



Exploded view of a 60% scale Module prototype



View inside a TPC. Pixel tiles on top, Light tiles on the sides and Cathode panel in the bottom are visible.



A Single Module, 60% scale, fully assembled

ArgonCube test facility (Uni Bern)

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2021-2023 successful deployment and operation of four fully-integrated ton-scale O(100k) pixel channel systems

- Module-0 test 1: Mar 27-Apr 12, 2021
- Module-0 test 2: June 21-27, 2021

- Module-1 test 1: Feb 5-13, 2022
- Module-1 cold gas test: Apr 4-6. 2022

- Module-2 test 1: Nov 13-22, 2022
- Module-2 test 2: Nov 28- Dec 5, 2022

- Module-3 test1: Jan 27- Feb 5, 2023
- Module-3 test 2: Feb 20-24, 2023
- Module-3 test 3: Mar 10-19, 2023

Single Module performance

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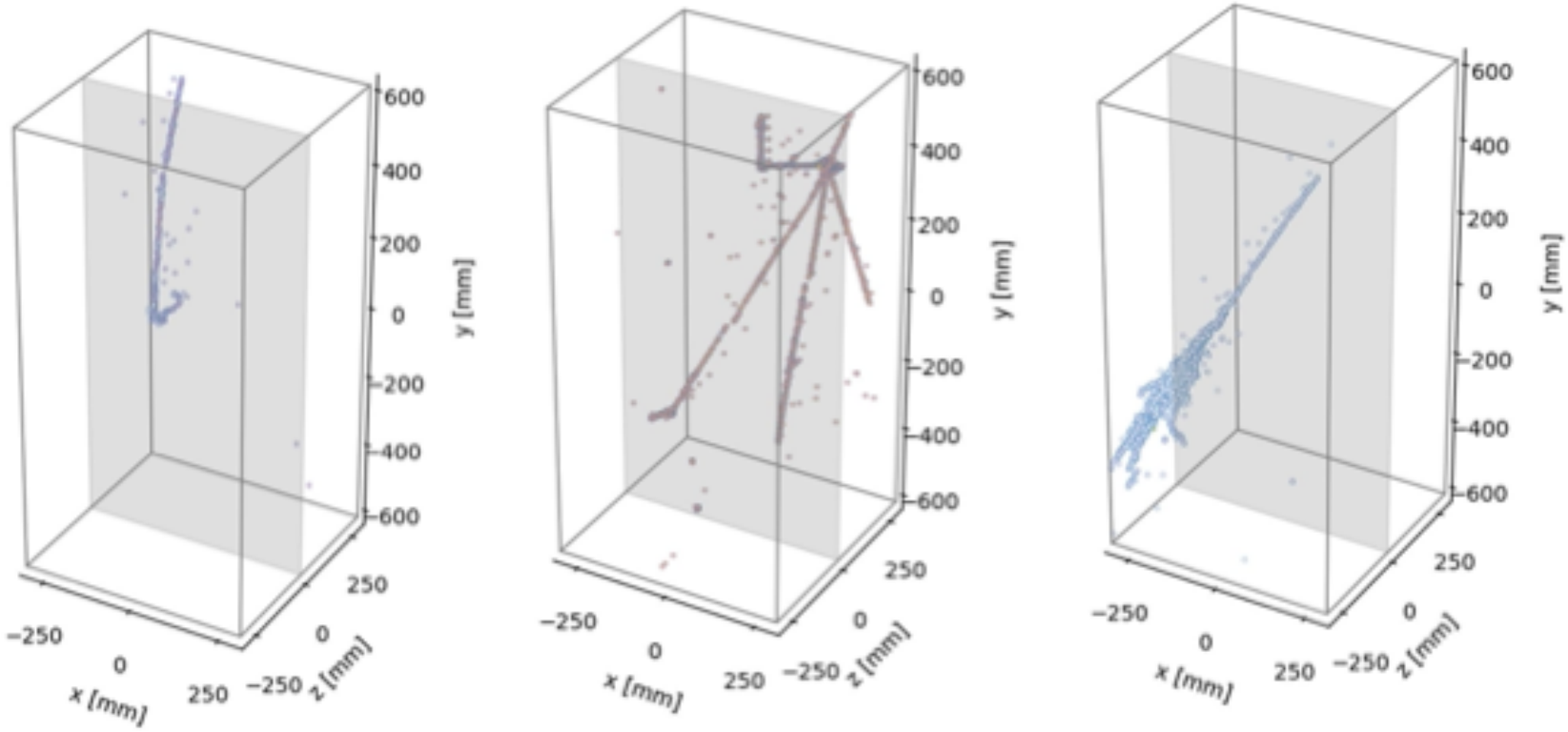
ProtoDUNE-ND Preliminary

- Collected >100 M cosmic-ray events
- Raw data events with ~200 keV channel thresholds
- Tested synchronization between charge and light readouts
- Studied basic LAr physics standard candles, (i.e. dQ/dx, Michel electrons)



Reduced size: 60 x 60 x 120 cm^3

Performance Paper submitted to Jinst
https://arxiv.org/abs/2403.03212

LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN DUNE

2x2 demonstrator @NuMI beam RHC

- **Integration of 4 single modules in a common cryostat in MINOS Hall at Fermilab, on the NuMI beam with Multi-GeV neutrinos**
- MINERνA modules, upstream and downstream 2x2, provide external tracking
- Goal is to demonstrate physics capabilities

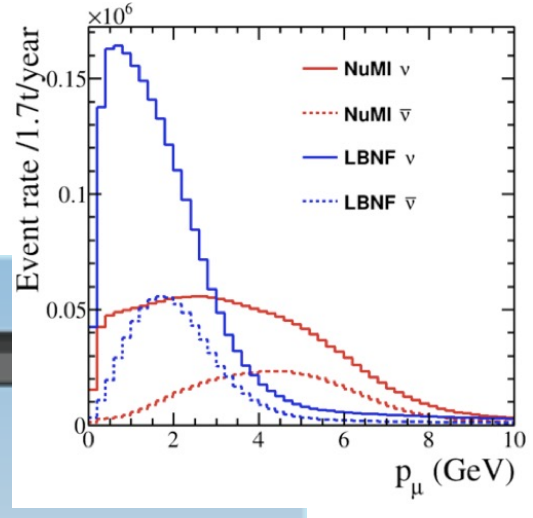
$\bar{\nu}$-Ar physics

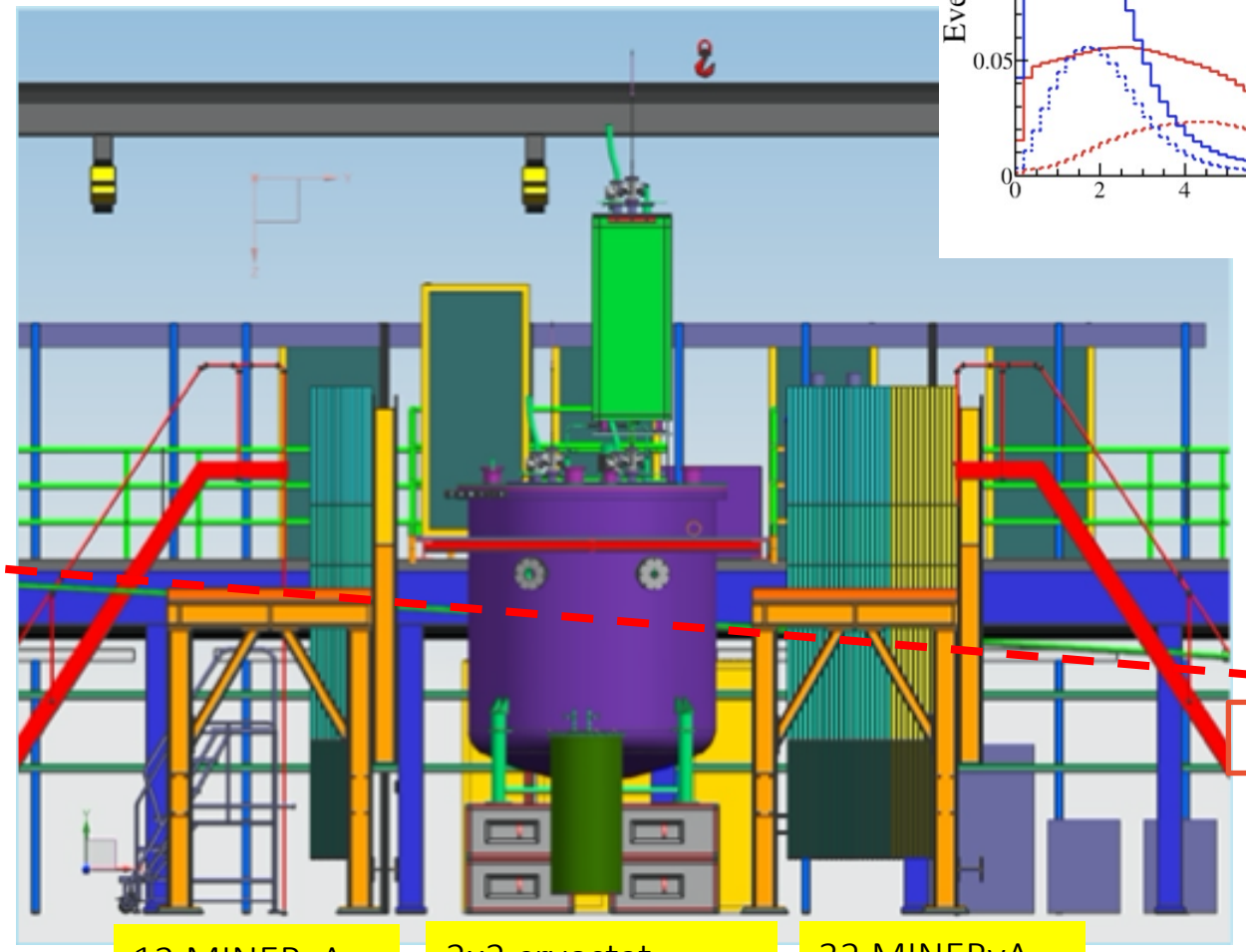
Operating conditions

- On-axis operation in medium energy FNAL NuMI ν beam
- 107 m rock overburden (300 m.w.e.)
- 2.4 metric ton LAr target mass
- 25% optical coverage
- 337k charge-sensitive pixels at 4 mm pitch
- Continuous charge readout, independent of photon system trigger
- ~200 keV charge threshold

Technical demonstrations

- **Signal reconstruction fidelity in high-intensity environment**
- **Assess LArTPC module performance in response to beam ν**
- **Exercise track matching with external trackers**

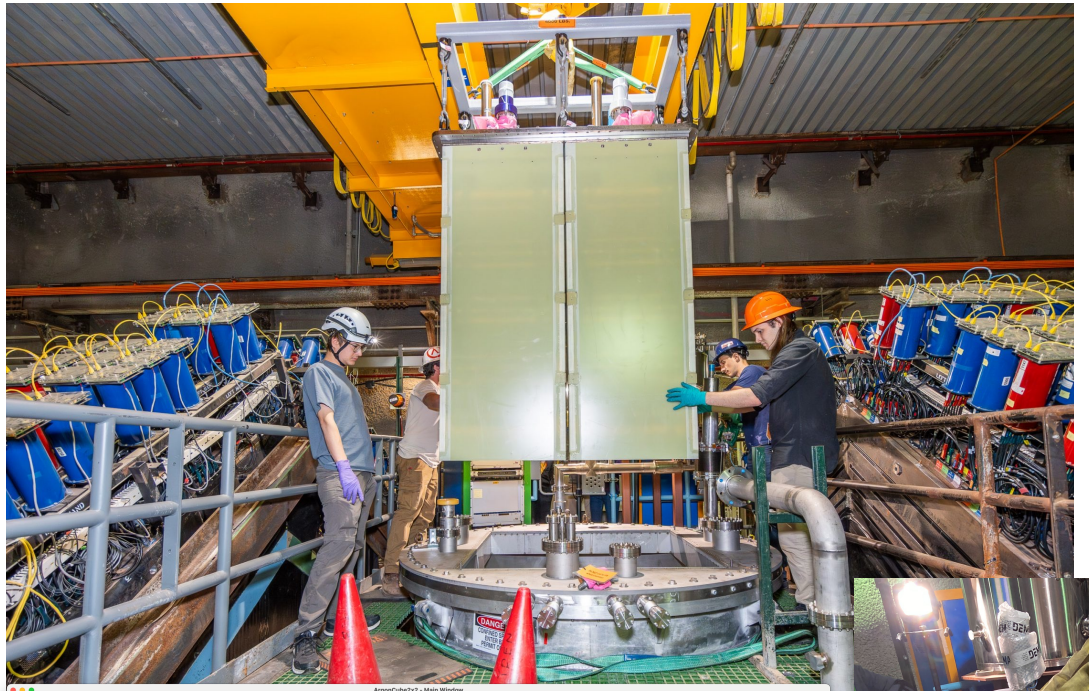


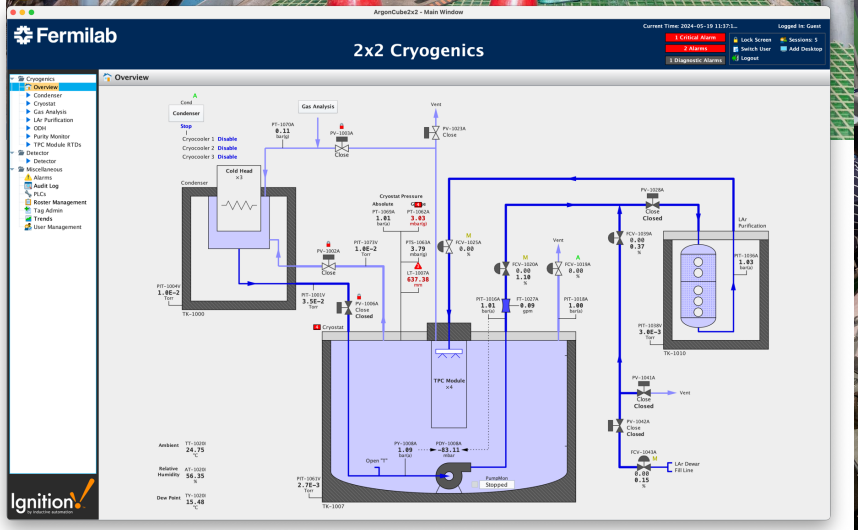


Status of 2x2

- Minerva tracking modules are installed and are taking neutrino data
- All four 2x2 modules were installed in the cryostat in Nov 2023
- Several Facility infrastructure were upgraded
- The Cryostat was filled with LAr earlier this month
- Cold commissioning of detector systems is ongoing
- Focus is on reaching good enough purity as soon as possible to take some neutrino data before the NuMI beam shut down

Neutrino beam summer shutdown scheduled on 12th July 2024!





2x2 is the First DUNE related detector to take neutrino data!

Summary

DUNE is a next-generation long-baseline neutrino oscillation program designed to measure neutrino mixing parameters to high precision

- ND-LAr is a critical component in the DUNE oscillation program
- Single module prototype performance have demonstrated cutting-edge, highly performant LArTPC design

Successfully produced, qualified, and deployed multiple O(100k) channel charge readout systems

- Low-noise, low-power cryogenic-compatible detector readout ASIC
- Self-triggering, ~100% live true 3D pixelated charge readout for LArTPCs
- Full commercial production/assembly of system at O($0.10)/channel

The 2x2 Demonstrator is a testbed to evaluate novel ND-LAr technologies in a ν beam

- 2x2 and Minerva tracking planes are Installed at the MINOS underground hall in Fermilab, and are being commissioned
- Data taking with NuMI RHC beam will start imminently

Thanks!

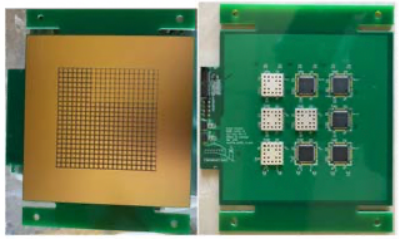
Backup

ND-LAr Prototyping program

- Component prototyping -> 2016-2019
- Single Cube -> 2020
- Single Module (70% size) -> 2021-2023
- 2x2 Demonstrator -> commissioning now - 2025
- Full Size Demonstrator (FSD) -> Late 2024-?

ArgonCube

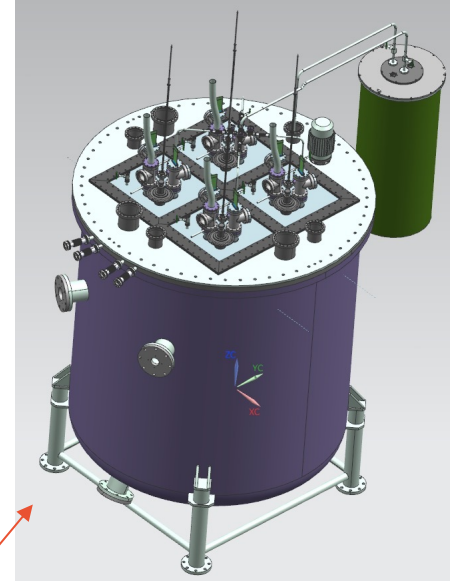
Resistive shell prototype



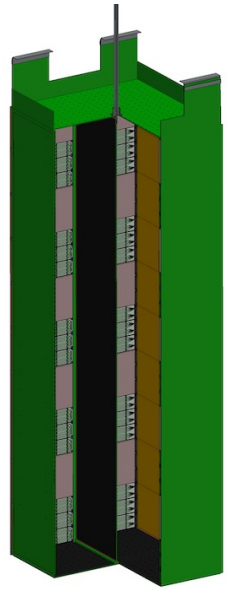
10 cm pixelated readout prototype

Single Cube

Single Module



2x2 Demonstrator



Full Size Demonstrator

Ready for ND-LAr construction

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LArPix ASIC for LAr

Low-power, integrating amplifier with self-triggered digitization and readout

Pixel dormant until signal exceeds tunable threshold

- Integrates charge for ~3μs (4 mm drift), then digitizes
- Ready for next signal

Pixels are continuously active

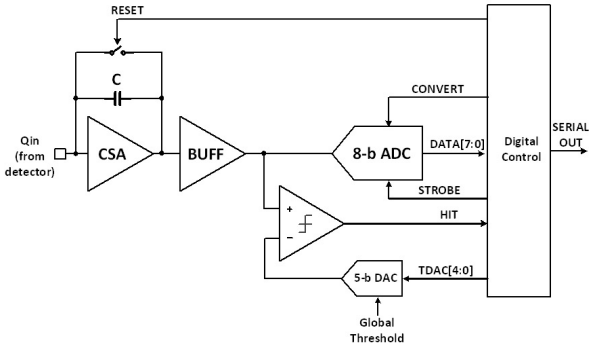
- Serial I/O data rate is slow (~5 Mb/s per I/O channel) to limit digital power
- Modest data volumes: ~1 MB/s per square meter of anode in surface cosmic- ray flux

End-to-end system architecture – *large-format pixel anode tiles, cables, feedthroughs, controller, etc.*

- Hydra networking: dynamic chip-to-chip I/O routing
- Scalable to O(M) channel systems
- Single active component in cryogenic environment
- Minimal and redundant connections to cryostat - Mechanically and cryogenically robust
- O($0.10) per channel system cost, incl. cables/controllers/assembly/et

Specification	Value	Comment
Analog inputs	64	Single-ended input
Gain	4.5 μV/e$^-$	
Power	<200 μW/channel	Static power dissipation
Dynamic range	1.3 V	Chip configurable
ADC resolution	8 bits	
ADC LSB	4 mV	Chip configurable
Threshold range	0 to 1.8 V	Channel configurable
Threshold resolution	1.5 mV	
Channel linearity	< 1.2%	Pre-calibration
Multi-hit separation time	1.2 μs	Chip configurable
Operating temperature	80 to 300 K	

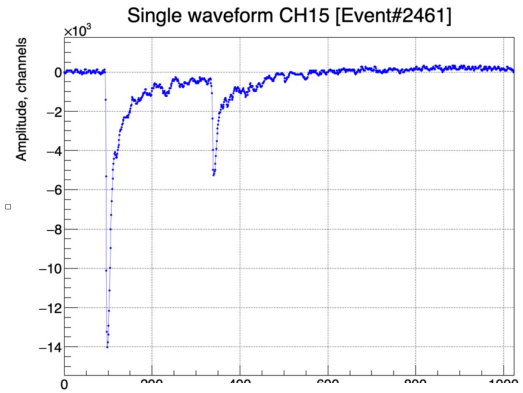
Mature charge readout system



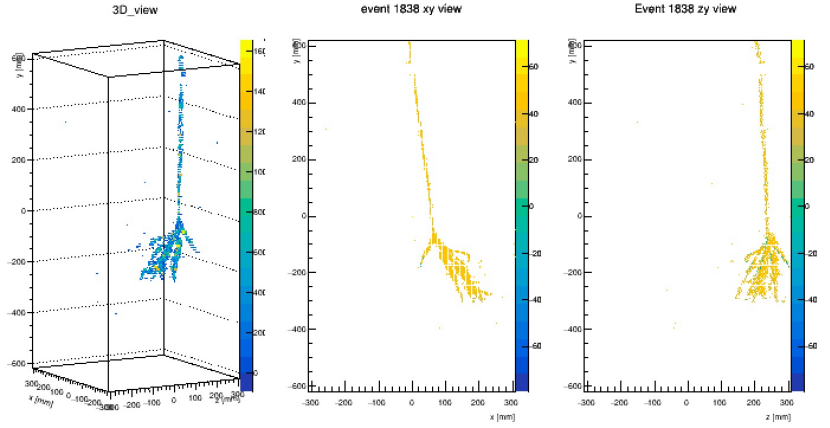
Specification	Value	Comment
Heat density	~13 mW/ASIC	
Pixel multiplexing	6.4k channels/cable	
Noise	~850 e$^-$ ENC	
Tile leakage current	< 5 e$^-$ / 500 μs	
Charge resolution	< 1200 e$^-$	< 5% MIP charge
Spatial resolution	1.1 to 1.3 mm	Geometry dependent
Timing resolution	0.7 μs	Chip configurable
Saturation level	> 200 ke$^-$	
Triggering efficiency	~80% for MIP	
MIP S:N	>20:1	

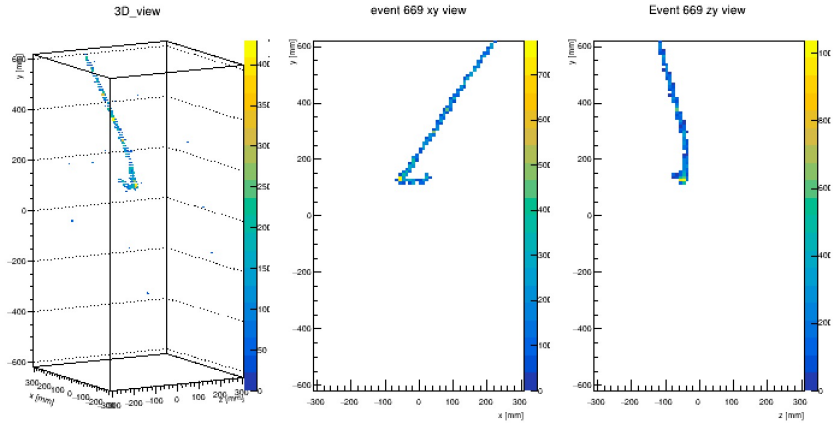
Prototype Single Module

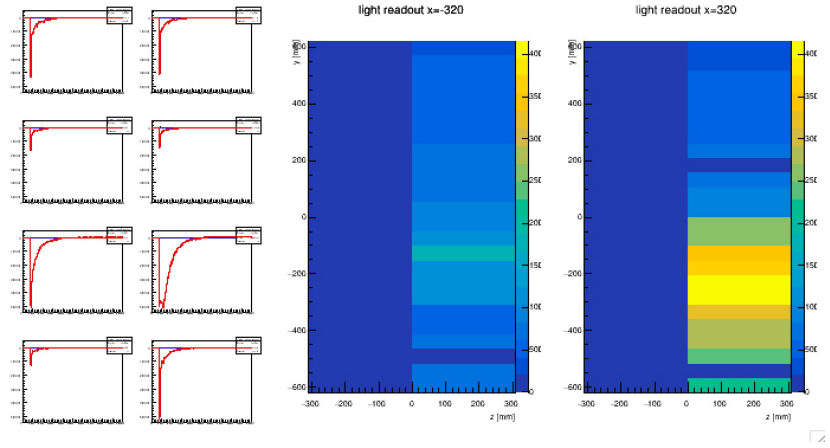
Raw data Event displays from cosmic data



Light signal waveform
Double peak for the Muon and Michel electron







Display with light signal intensity along the y axis.

Light Waveform representation, sum of 6 channels at a time