The DUNE Liquid Argon Near Detector (ND-LAr)

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LHC Far Forward Physics Working Group Meeting

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Today's Talk

- DUNE physics and the role of the Near Detector
- Design of the ND-LAr Detector
- Results from recent prototypes
- Looking forward

The Deep Underground Neutrino Experiment (DUNE)

DUNE Physics:

Accelerator Neutrinos:

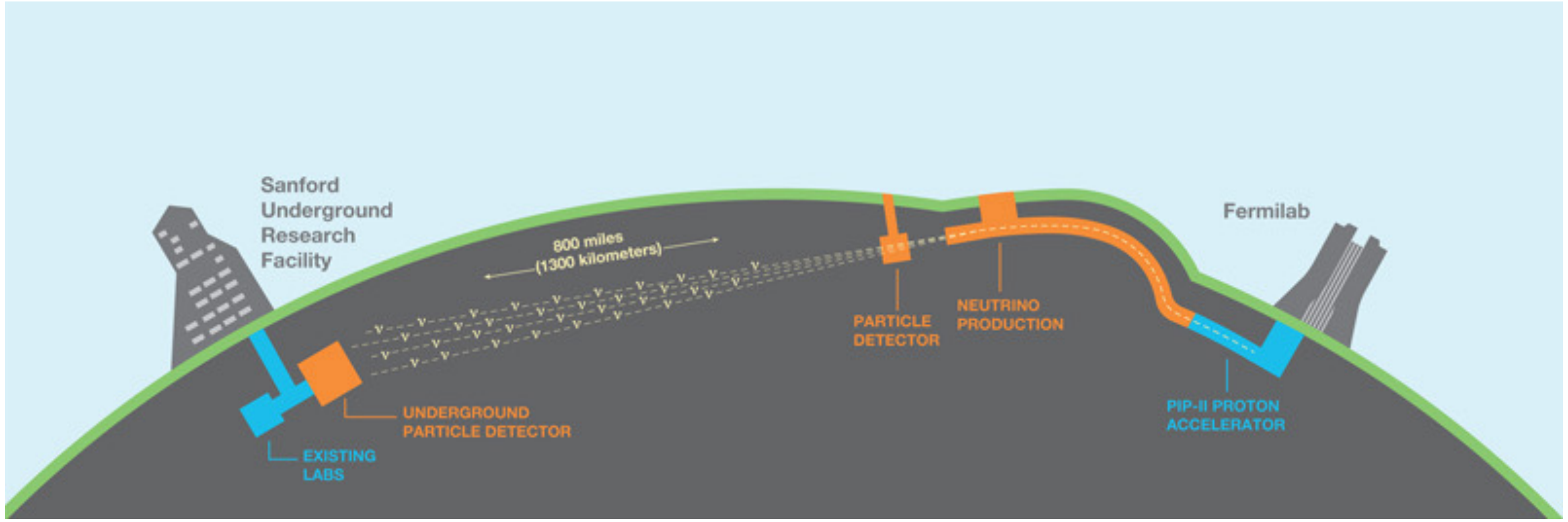
- CP Violation
- Mass Ordering
- Precision Mass and Mixing

← *Headline measurements*

Supernova Neutrino Bursts

Baryon Number Violation

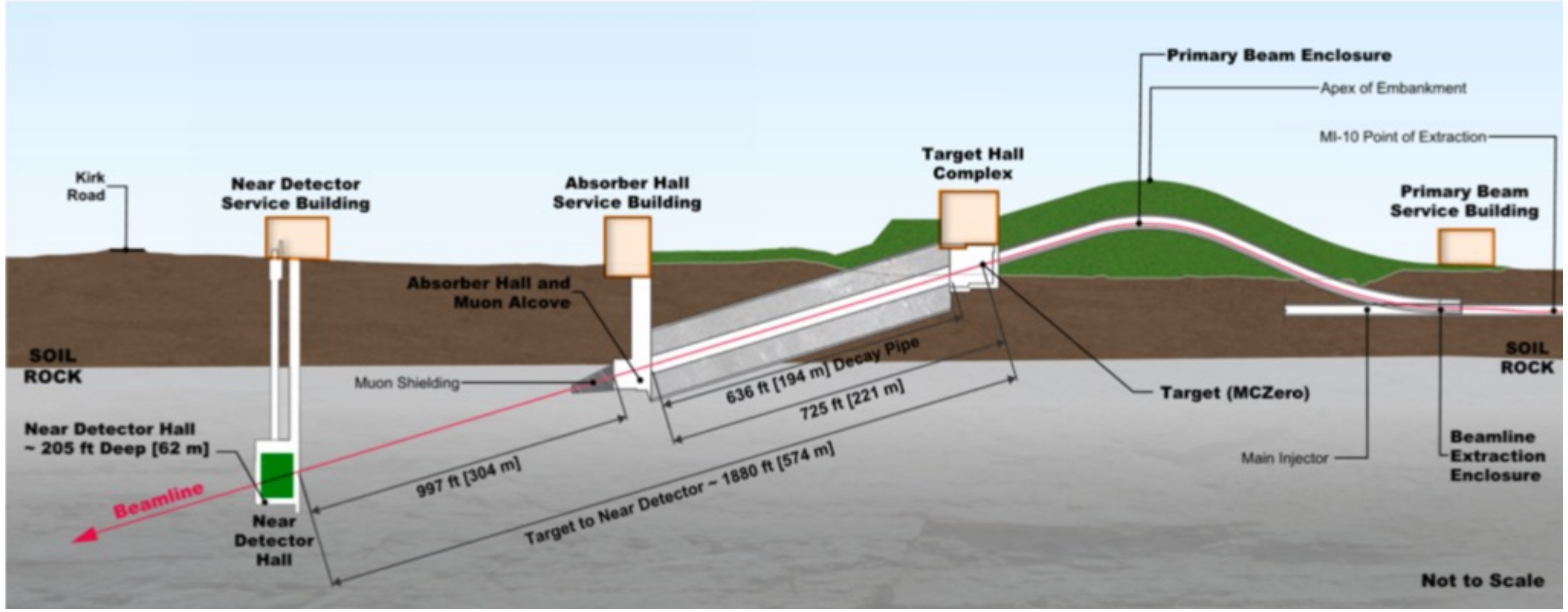
BSM Searches



Key Goal:

Enable the search for CP Violation

Help us understand the matter/antimatter imbalance of the universe.



Physics Target for the Phase-1 Near Detector

The Phase-1 Near Detector:

The Near Detector suite/capabilities needed from the start of LBNF neutrino beam operation.

Phase-1 System Requirement:

Enable a 3σ observation of maximal CP violation

3σ Max-CPV is difficult:

Only modest variation in ν_e signal

In 3.5 yrs (staged), ν-only operation, NO:

~1100 ν_e appearance events

~300 background

Max CPV:

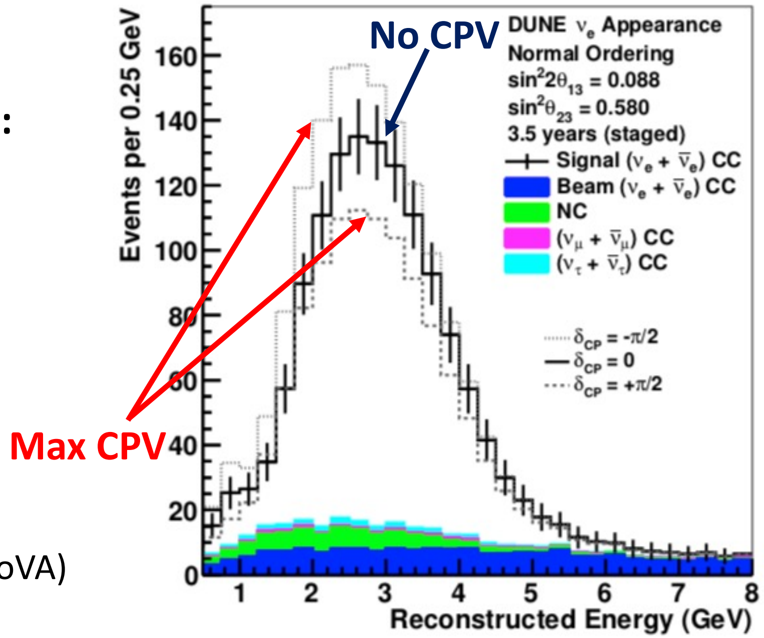
Variation in signal: ~15%

Statistical uncertainty: ~3%

Requires total systematic uncertainty less than ~3%

Compare with state-of-the-art of ~7-8% (T2K, NoVA)

From DUNE TDR



Physics Milestone	Exposure (staged years)
5σ mass ordering ($\delta_{CP} = -\pi/2$)	1
5σ mass ordering (100% of δ_{CP} values)	2
3σ CPV ($\delta_{CP} = -\pi/2$)	3
3σ CPV (50% of δ_{CP} values)	5
5σ CPV ($\delta_{CP} = -\pi/2$)	7
5σ CPV (50% of δ_{CP} values)	10
3σ CPV (75% of δ_{CP} values)	13
δ_{CP} resolution of 10 degrees ($\delta_{CP} = 0$)	8
δ_{CP} resolution of 20 degrees ($\delta_{CP} = -\pi/2$)	12
$\sin^2 2\theta_{13}$ resolution of 0.004	15

DUNE Phase-1 Near Detector Requirements

Note: My abridged summary.

Enable precise prediction of DUNE Far Detector neutrino signal. *Precise → ~2% rate, ~4% shape*

- Measure ν beam flux × cross section (on argon) at Near Site → Active **argon-based detector(s)** at near site
- Precisely characterize FD neutrino interaction, detector response model *→ same, better fidelity as FD* → **LArTPC component** of Near Detector System
  - With sufficient signal rate for relevant neutrino interactions *→ e.g. ν-e⁻ scat.* → **O(100 ton) active volume** in LArTPC
  - Sufficient LAr acceptance/containment of relevant neutrino interactions *→ except forward-going muons.* → Active LArTPC **3m height, 7m width, 5m depth**, with **downstream muon spectrometer**
  - Cope with signal pileup at Near Site → LArTPC with **pixelated readout**, **optical modularity**
  - Disentangle energy-dependence of cross section and detector response → **Off-axis measurements** with LArTPC
  - Verify beam stability when LArTPC off-axis → Supp. **stationary beam monitor** detector: SAND

The DUNE Phase-1 Near Detector

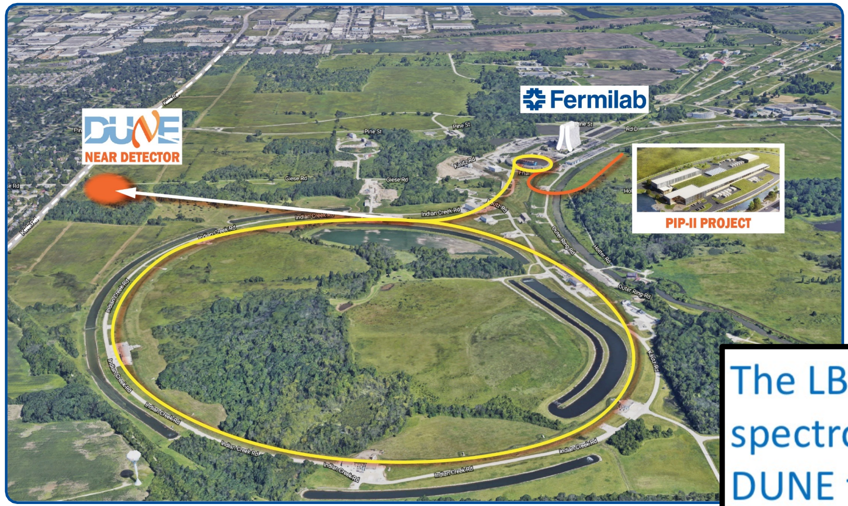
Key Purpose:

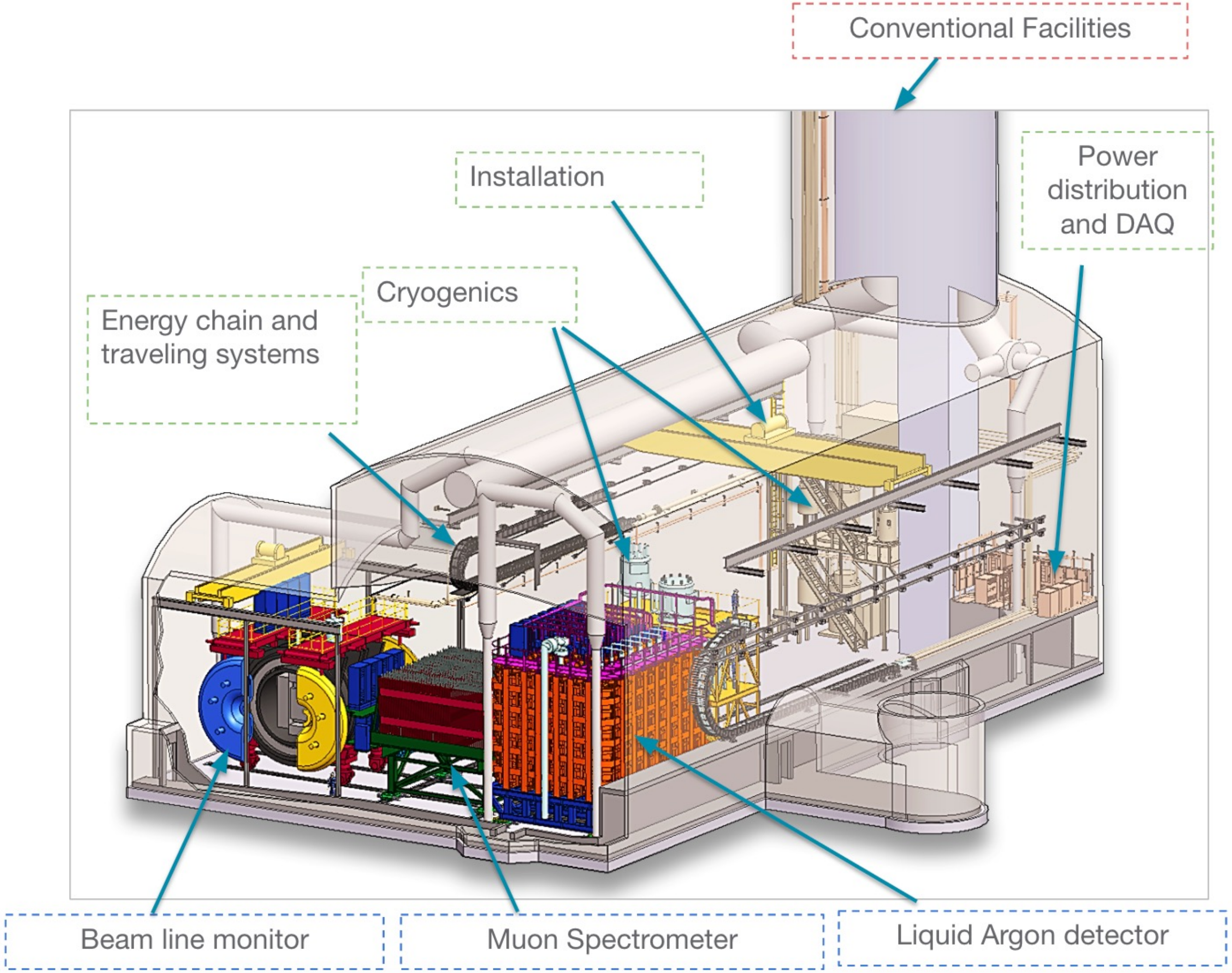
- Enable high-precision prediction of neutrino signal at Far Detector

Details:

- In LBNF Neutrino Beam (574m from target)
- At new underground site (62m deep)

With ~10M neutrino events/yr, it will also provide a rich physics program all on it's own.





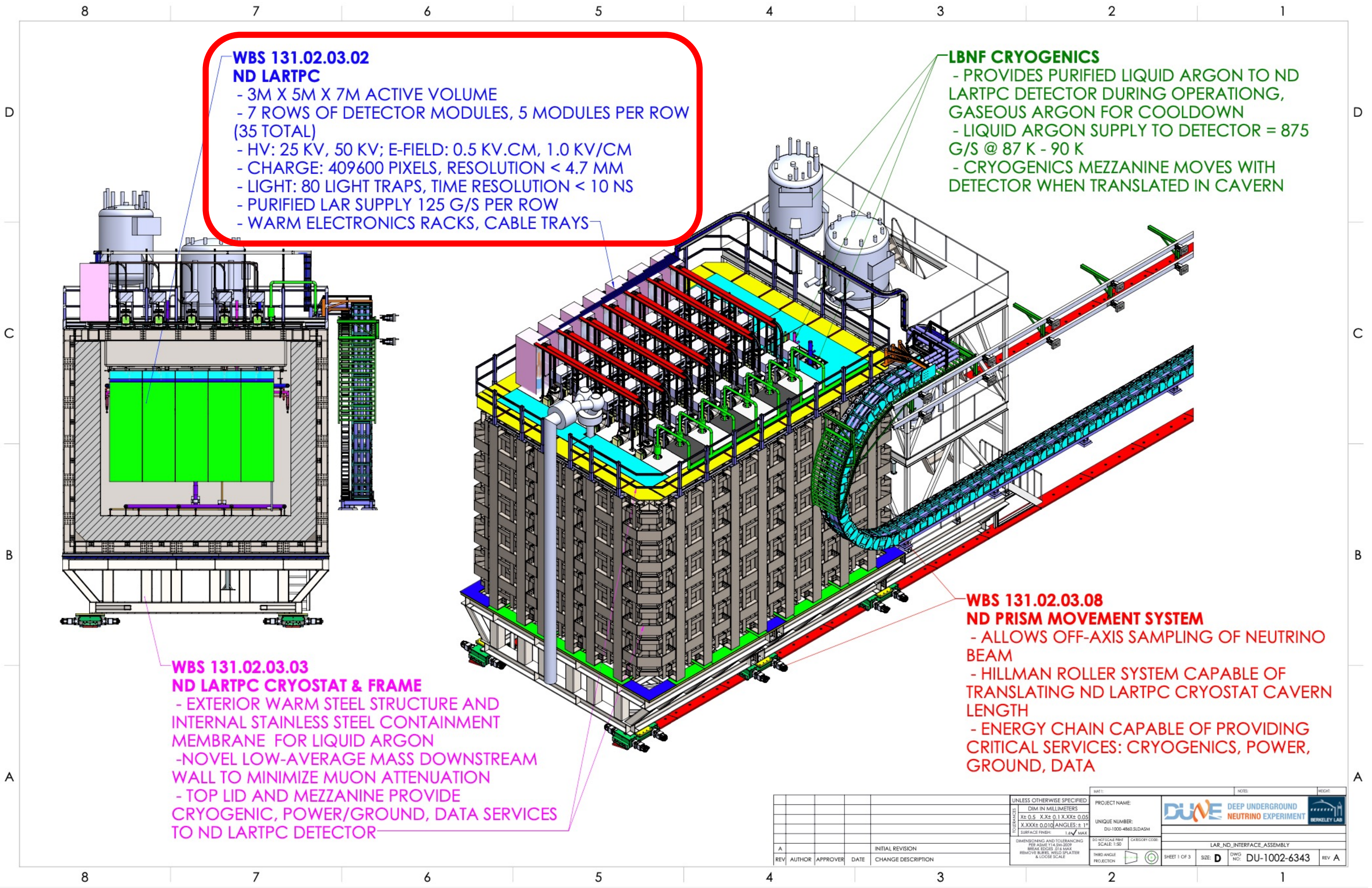
The LBNC strongly endorses the need for a ND containing a movable liquid argon TPC and magnetic spectrometer, and a fixed on-axis beam monitor. These are the minimum elements required for DUNE to achieve its physics goals, and are needed from the start of data-taking.

LBNC Closeout Report, July 2019

The ND-LAr Detector

The ND-LAr Detector

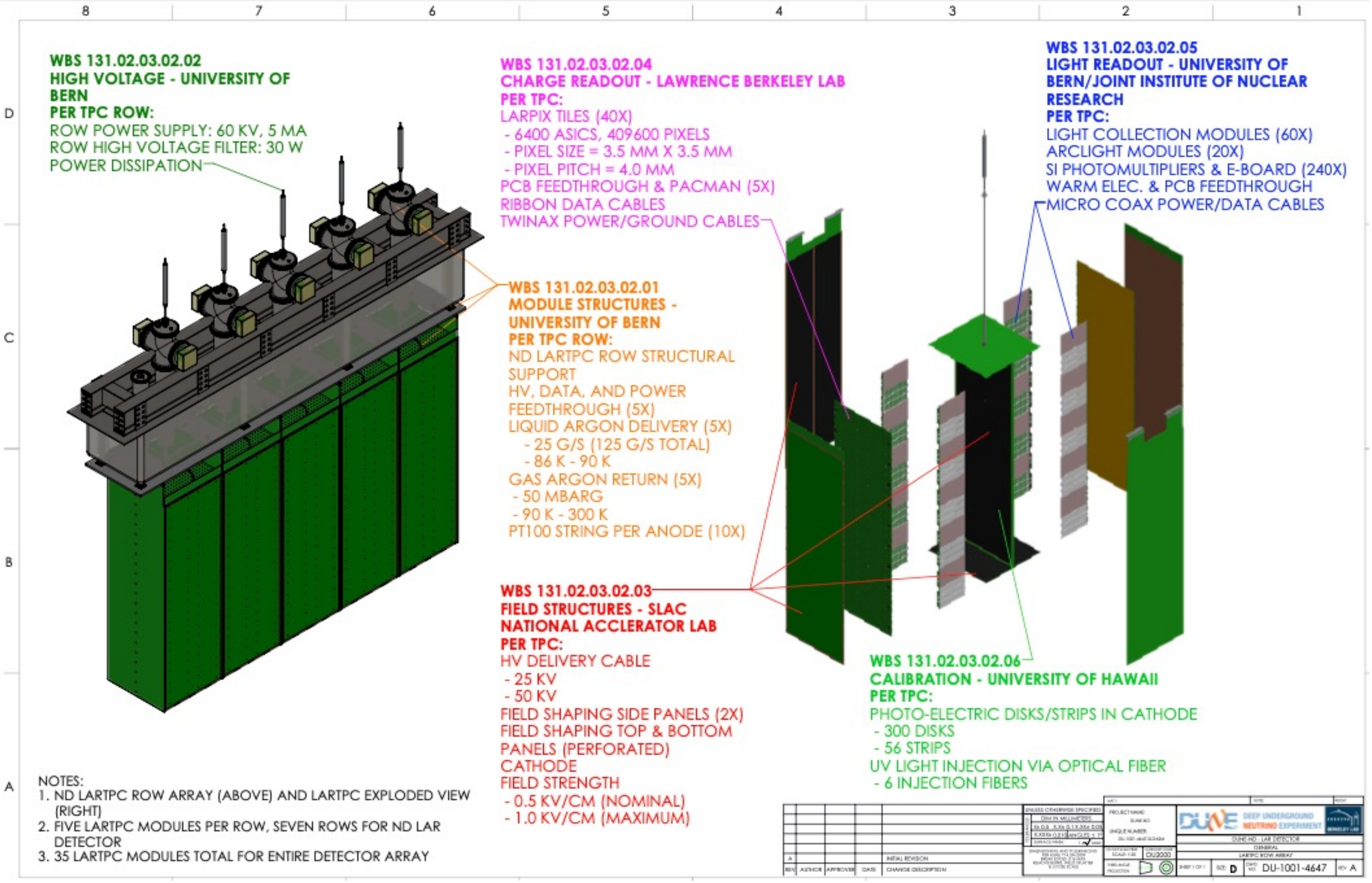
- Active volume:
  3m tall, 7m wide, 5m in beam
  (~150 tons)
- Membrane cryostat
- PRISM rail/rollers allow motion
  transverse to the neutrino beam
- Leverages many design aspects
  of ProtoDUNE and SBND detectors



The ND-LAr TPC Module

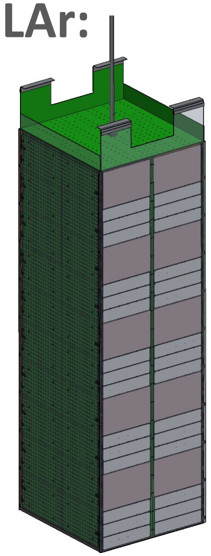
The ND-LAr Detector is composed of 35 modular LArTPCs

- 7 banks of 5 modules
- Each module has a central cathode, two anodes.
- Field cage built of fiberglass (G10), laminated with resistive film
- Light traps cover vertical field cage walls
- Modules sit in shared LAr bath



ND-LAr: Technical Drivers

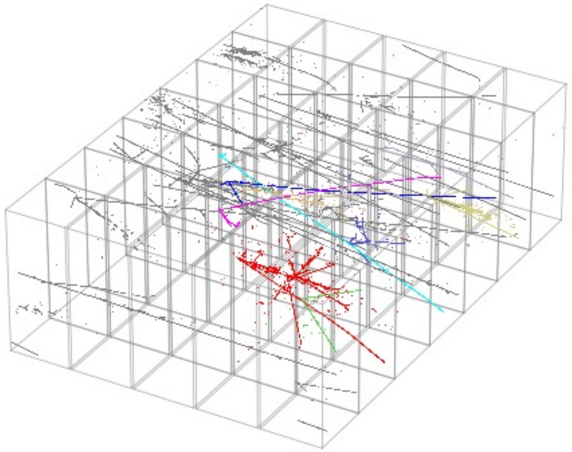
The most significant technical concerns for ND-LAr:



Common to all LArTPCs:
- Unstable or insufficient high voltage
- Insufficient argon purity
- Non-uniform drift field
- Electronics/anode failure in cryogenic environment
- Excess noise in charge readout

Novel for ND-LAr:
- Maintain signal fidelity in high-occupancy environment

One simulated beam spill in ND-LAr, with typical pileup of ~50 neutrinos



The modular ND-LAr design addresses these risks:

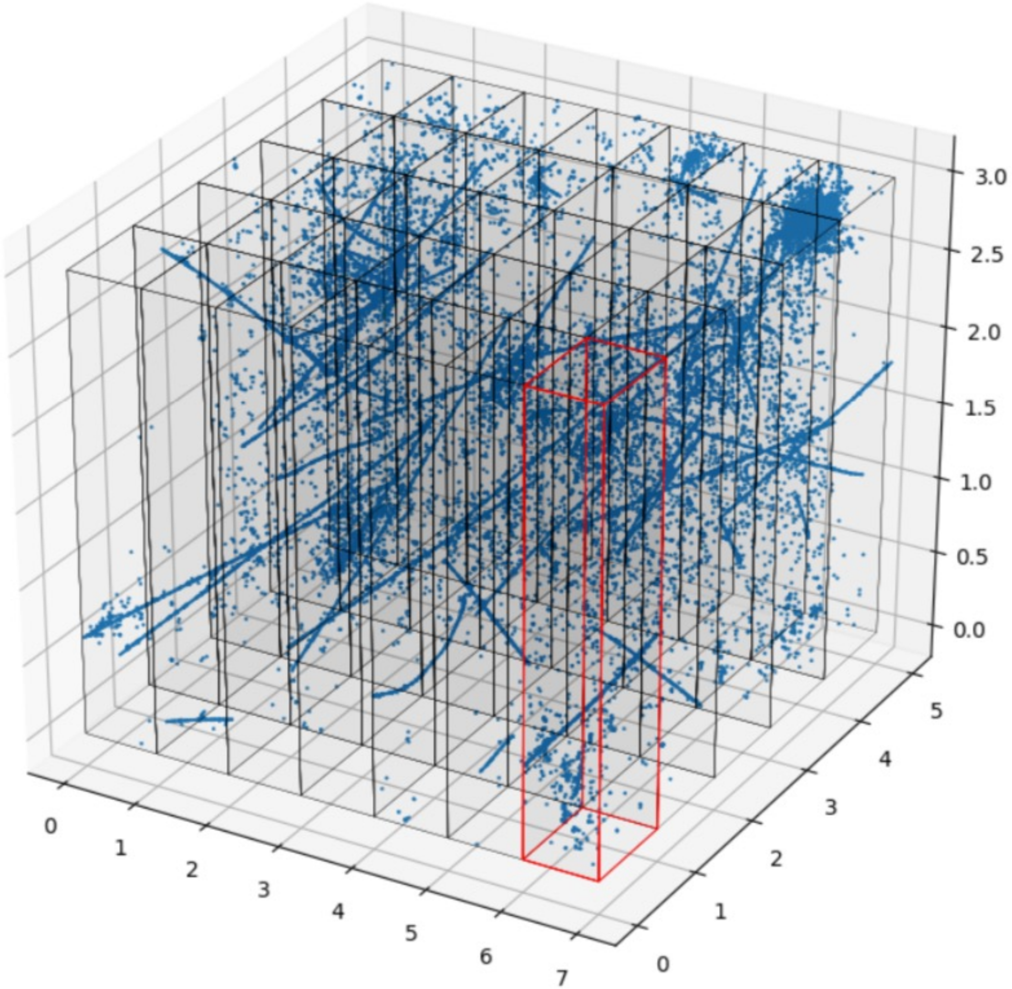
Short drift distance (1/6th of Far Detector):
- Substantially reduces requirements/risks associated with HV, purity, and field uniformity

Modular/independent TPC regions:
- Potential failures contained to finite sub-region; robust system
- Contained scintillation light to mitigate near site signal pileup

Pixelated charge readout:
- True 3D readout mitigates near site signal pileup
- Lower channel capacitance; less sensitive to system noise
- PCB-based construction mechanically robust, scalable

High-performance light readout:
- 30% coverage provides O(10cm) spatial resolution, mitigates pileup

Challenge: Signal Pileup in the DUNE Near Detector



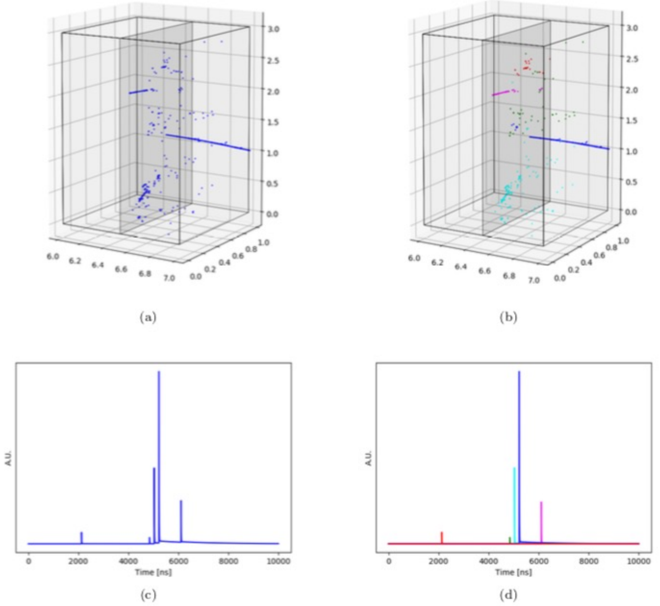
Simulation of one beam pulse in DUNE Near Detector LArTPC

Intense Neutrino Beam at the DUNE Near Site:

- LArTPC has pileup of ~50 neutrino interactions per 1.2 MW spill
- Interactions occurring both inside and outside LArTPC, particularly upstream rock
- Beam spill length (~10 us) much less than TPC drift time, O(1 ms)

Overcoming Pileup in the Near Detector:

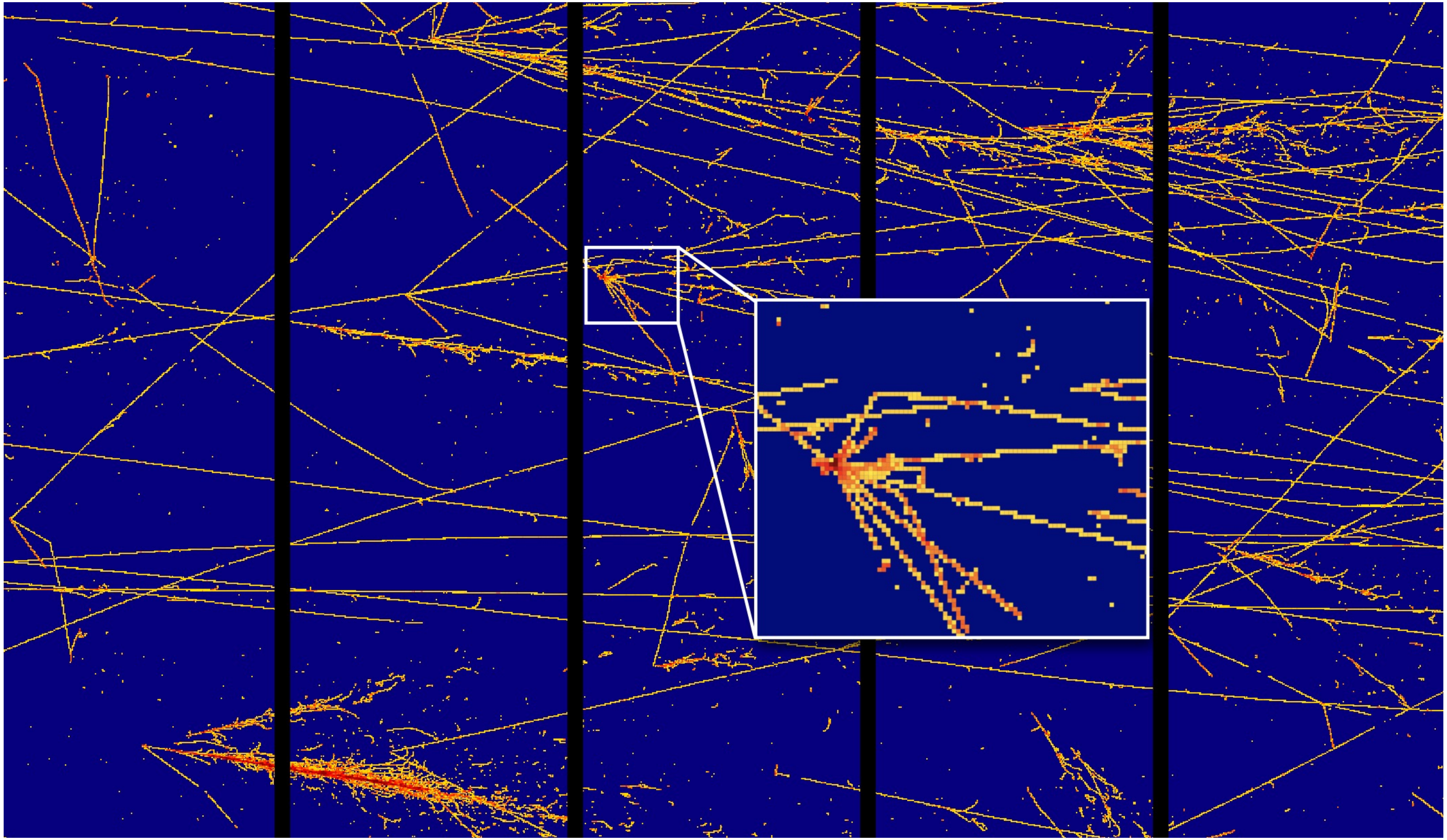
Pixelated Readout: Provides true 3D imaging of TPC ionization
Optical Segmentation: Constrain scintillation light to ~1.5 m^3 regions
High-performance Light Readout: Provides independent vertex and amplitude



"Light-assisted charge clustering"

O(5-to-5) light-to-charge signal combinatorics per TPC with 70 optical segments.

Challenge: Signal Pileup in the DUNE Near Detector



Latest simulations, including complete electronics simulation of all 14M pixels.

Built from the ground-up to use next-generation GPU-based supercomputers.

R. Soleti, LBNL

Past Prototyping: Critical Elements

ArgonCube R&D Collaboration:

2016-2019: Successful program of LArTPC technology demonstrations

Advanced Light Readout:
- LCM and ArCLight dielectric light traps
- Enables high-coverage scintillation light detection

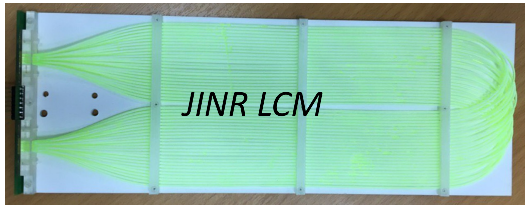
Pixel Charge Readout:
- LArPix ASIC and Integrated Pixel Tile
- Enables true 3D ionization charge readout

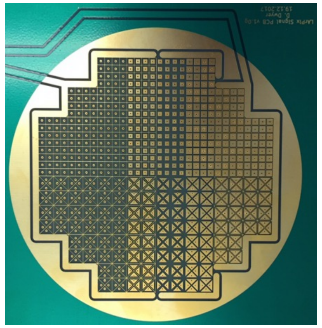
Resistive Field Cage:
- High-resistivity film as continuous resistive field cage
- Enables low-profile field cage

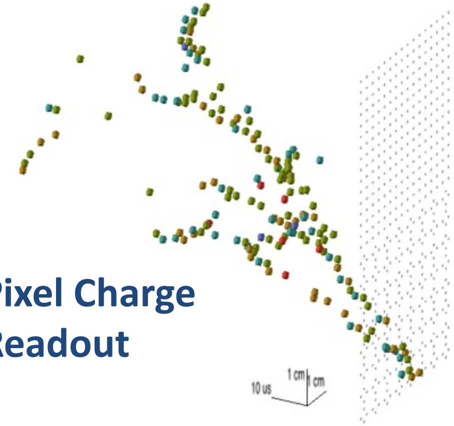
Modular TPC Design:
- All fiberglass (G10) LArTPC structure
- Enables optical segmentation

Prototyping program achieved TRL-4 in 2019.

Advanced Light Readout

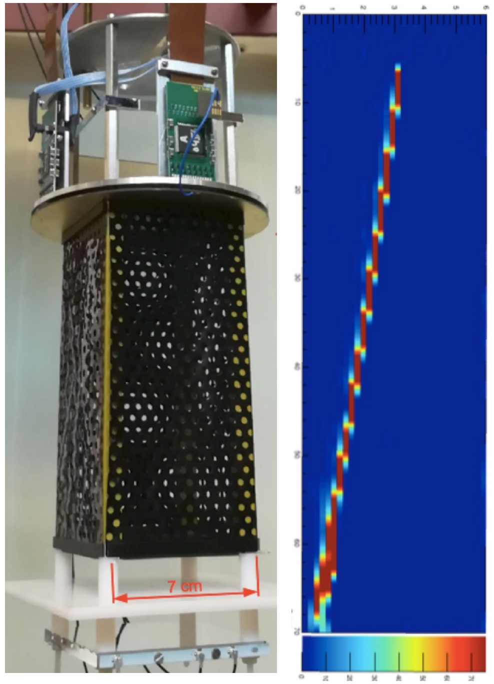






Pixel Charge Readout

Resistive Field Cage



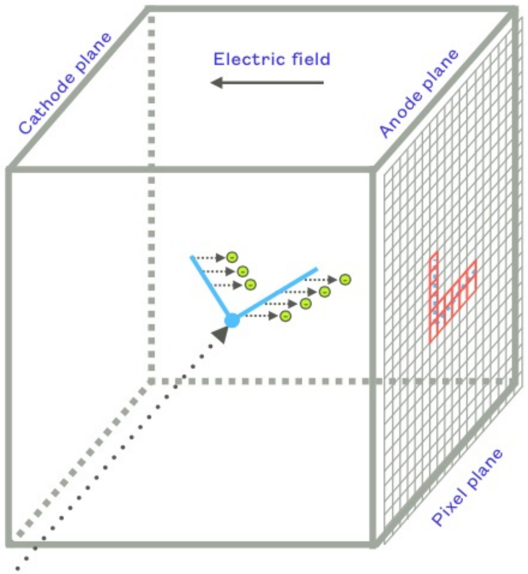
Modular TPC Design

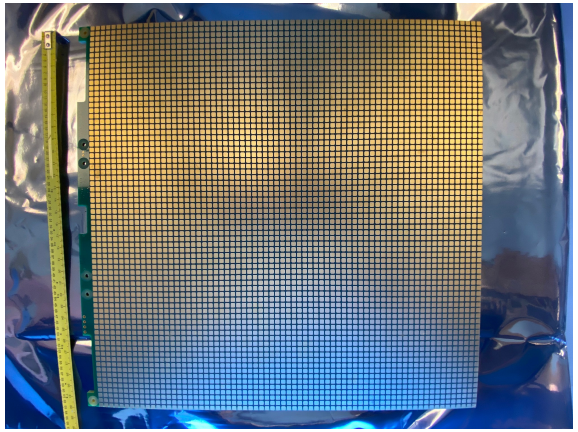
LArPix: Enables LArTPC with true 3D imaging

LArPix Readout:

- Use grid of small charge-collecting pixels for anode
- Provides true 3D imaging of TPC ionization
- **Challenge:** High channel density, O(100k)/m^2
  - Low power: limit heat load in cryogenic environment
  - Digital multiplexing: transmit many pixel signals through few wires
  - Scalability: design and production method must scale to ~10^7 pixels to be viable for the DUNE Near Detector, ~10^9 for Far Detectors

LArPix 3D readout





LArPix Anode Tile

Noise	< 1000 e- ENC	S/N ratio of >20:1 for MIP tracks
Channel Density	64 channels / die	Unique front-end channel for pixels at ~4 mm pitch
Power	< 100 uW / channel	Low-power to avoid boiling LAr
Digital Multiplexing	> O(1k) pixels / I/O channel	Viable cable plant & cryostat feedthoughs
Robustness	< 0.1% tile failures	Minimize single-point failures in cryogenic environment. Tile robust to failed ASICs.
Scalability:	> 200 m^2 anode @ O($10k/$m^2$)	Design compatible with standard large-scale commercial electronics production techniques.

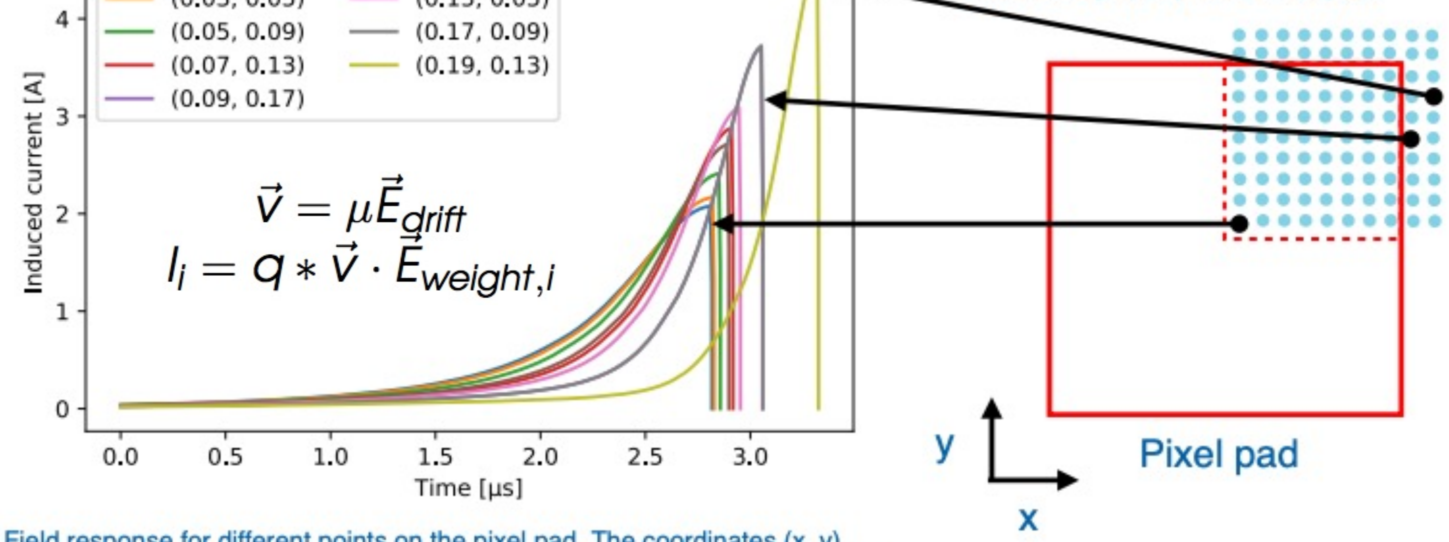
Something about devils and details

Modeling the Pixel Response

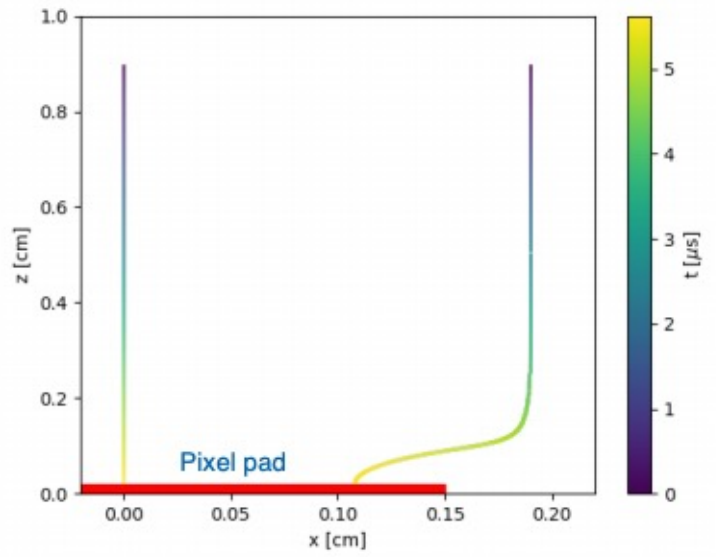
1. Estimate the ideal drift path for single electrons based on the electric field in the LArTPC
2. Determine the ‘mirror current’ induced on the pixel, using the Ramo theorem
3. Calculate for electrons distributed at points across 3 mm square pads at 4 mm pitch

- Signal integrals are constant, equal to collected charge.
- Typical widths of ~1 us

The field response is calculated for *n* points on the pixel pad. Due to symmetry, we can consider only one quarter of the pad.



Field response for different points on the pixel pad. The coordinates (x, y) correspond to the distance in cm from the pixel pad center in the each direction.

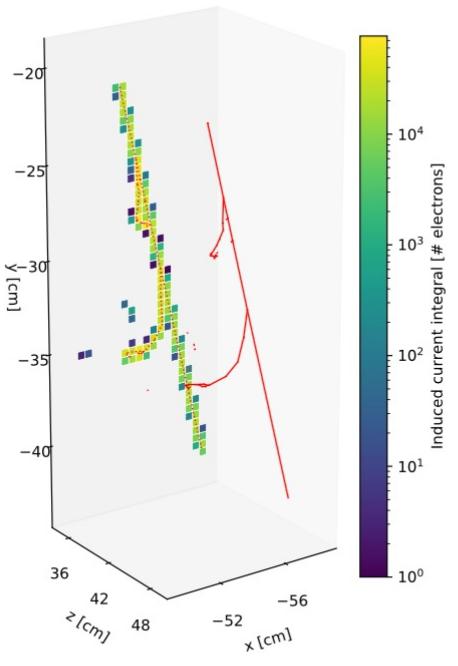


Trajectories of two unit charges collected by the pixel pad and starting from two different points.

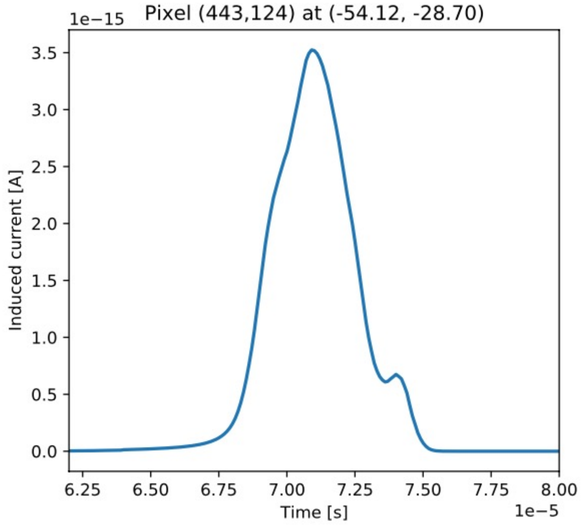
Pixel LArTPC Simulation

Complete pixel LArTPC simulation chain: *(R. Soleti)*

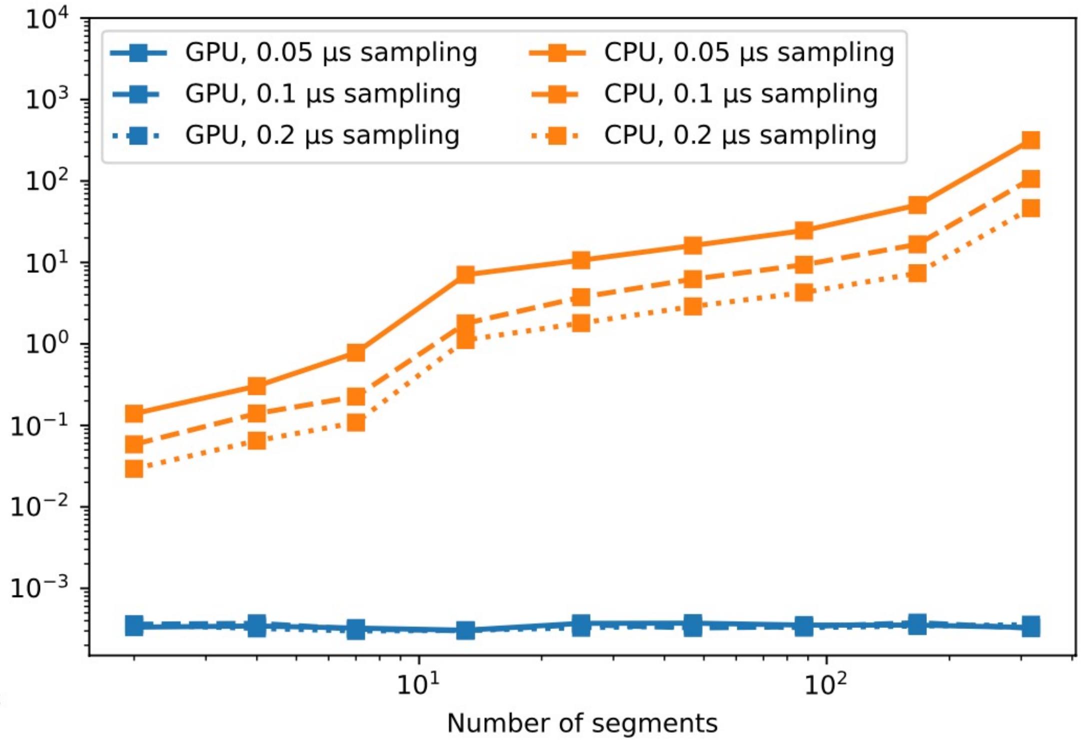
- Input: Geant4 tracks in LArTPC, Output: ‘raw’ digital data in LArPix format
- Includes models of LAr ionization, recombination, drift/diffusion, pixel response, LArPix channel response/digitization
- Designed from ground-up to run on GPUs, ready for NERSC 9 (Perlmutter) supercomputer



(a) 3D event display of a simulated cosmic muon.

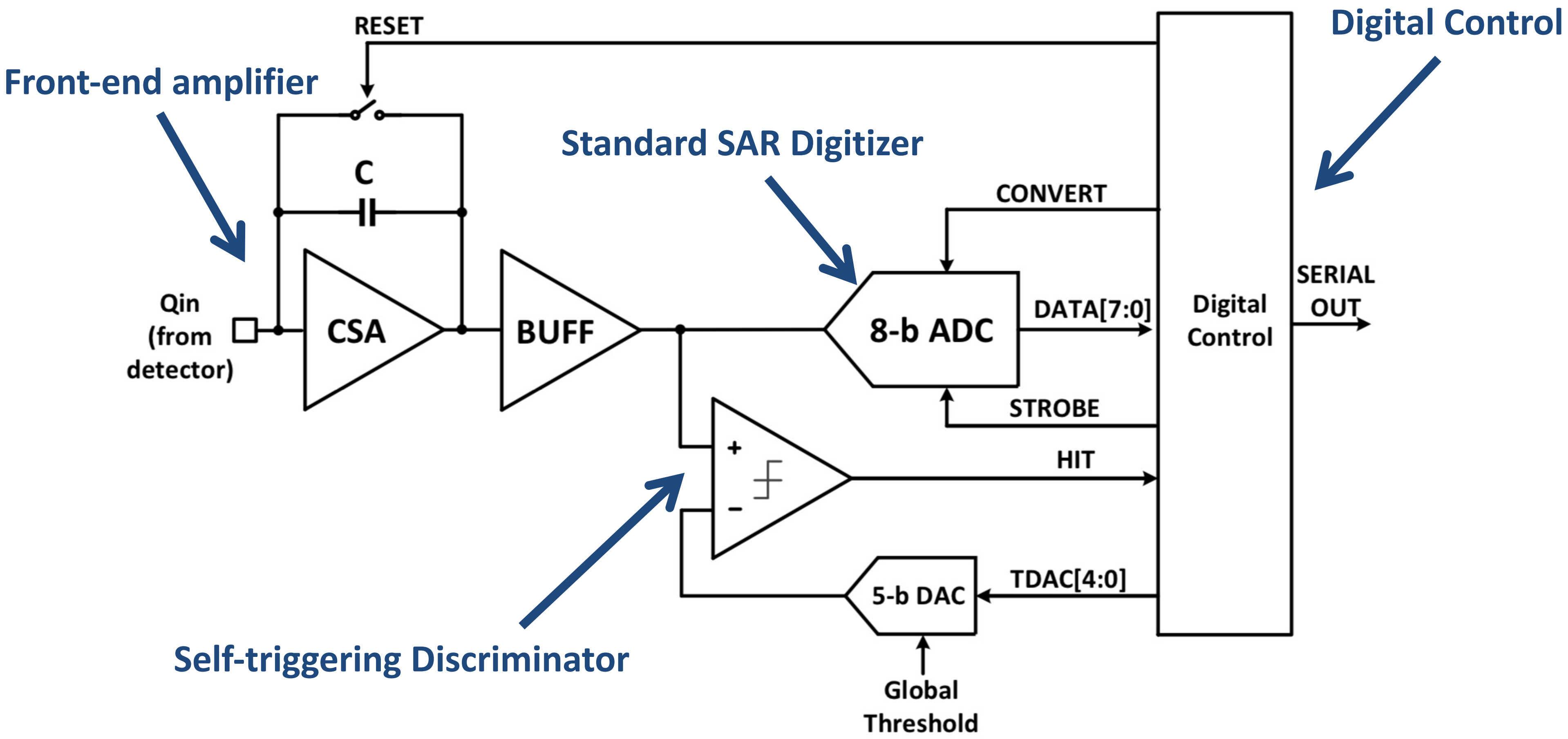


(b) Current induced on a single pixel by the cosmic muon and a delta ray.



LArPix Concept

Approach: Integrating Amplifier with Self-triggered Digitization and Readout



Achieve low power: avoid digitization and readout of mostly quiescent data.

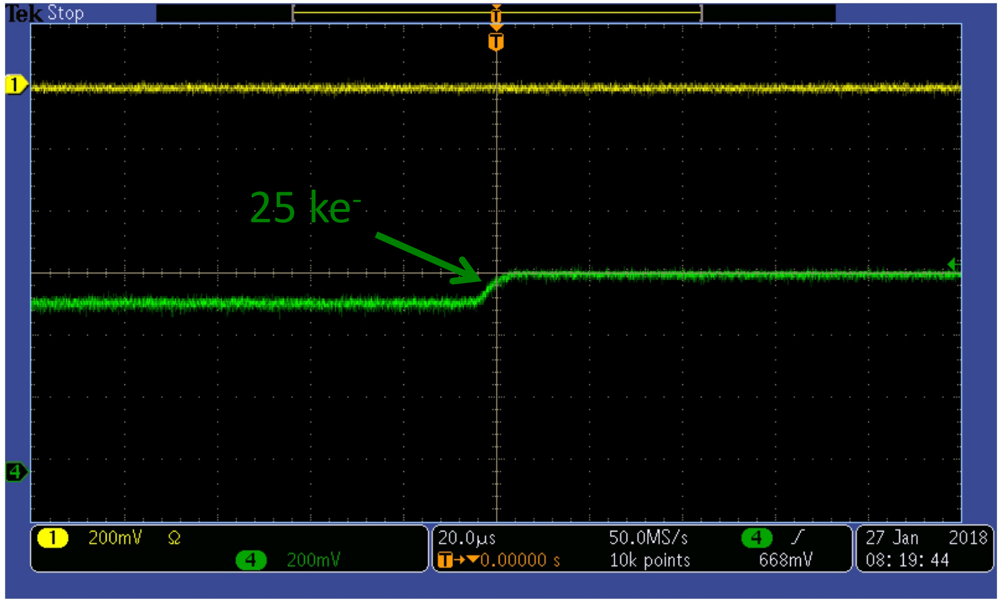
LArPix Triggering

LArPix has no resistive feedback or shaping

→ Charge stays on pixel until you do something with it

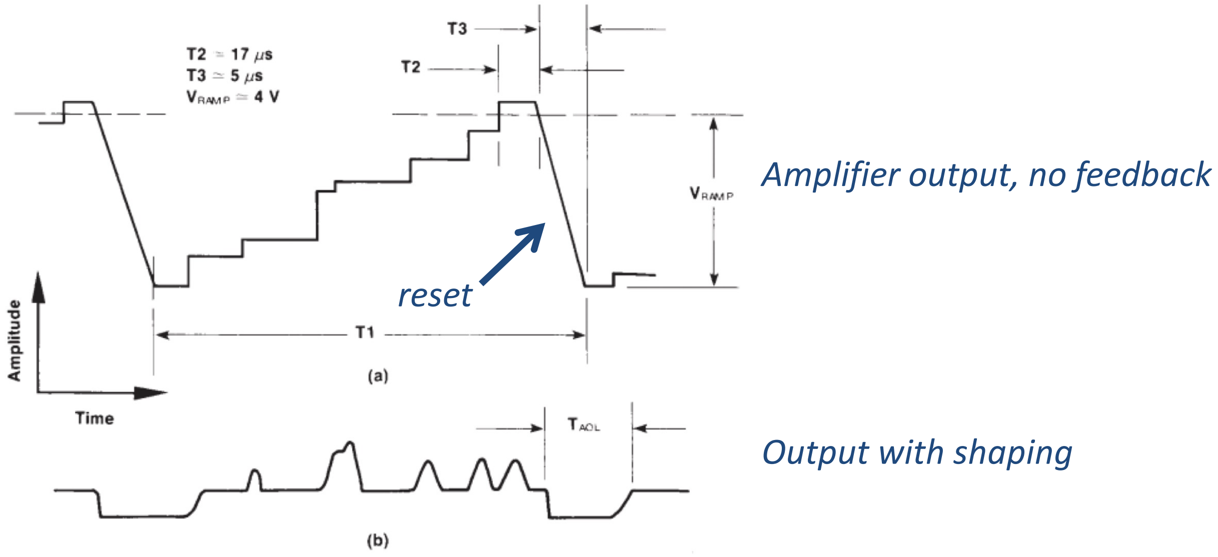
Your choices:

- Self-trigger reset: digitize and drain charge after threshold crossed
- External-trigger reset: digitize and drain sub-threshold charge based on external signal
- Cross-trigger reset: digitize and drain sub-threshold charge based on self-trigger of another pixel
- Periodic reset: periodically discard sub-threshold charge without digitization



LArPix typical MIP-scale signal, without reset

Eg: Knoll, Radiation Detection and Measurement

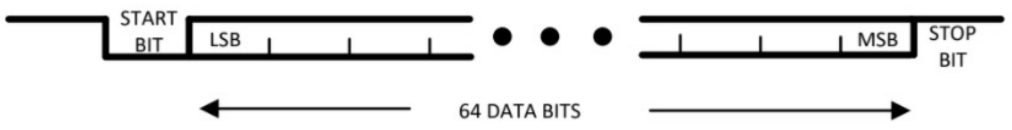


LArPix Data Stream

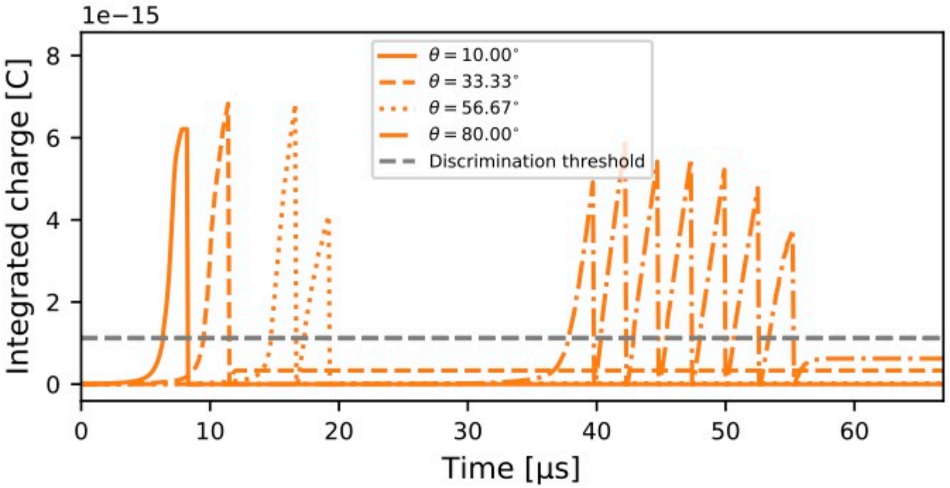
Pixels self-trigger as signals arrive:

- Pixel data readout does not require an external trigger signal
- Serial data packets ‘stream’ out of system as channels self-trigger
- Serial I/O data rate is slow (~5 Mb/s per I/O channel) to limit digital power in cryogenic environment
- Total data volumes rather modest (~1 MB/s per square meter of anode in earth-surface cosmic flux; much less underground)

Single serial packet:



Simulation of self-triggering vs. track orientation to anode



Data packet

Bit Range	Contents	Comment
[1:0]	Packet Declaration	00: data 01: not used 10: configuration write 11: configuration read
[9:2]	Chip ID	Each chip in a Hydra Network needs a unique ID
[15:10]	Channel ID	64-channel chip supported
[47:16]	Time Stamp	32-bit time stamp
[55:48]	Data Word	8-bit ADC data word
[57:56]	Trigger Type	00: Normal, 01: External, 10: Cross, 11: Periodic
[59:58]	Local FIFO Status	Bit 58: FIFO half full, Bit 59: FIFO full
[61:60]	Shared FIFO Status	Bit 60: FIFO half full, Bit 61: FIFO full
[62]	Downstream Marker	0: Upstream Packet, 1: Downstream Packet
[63]	Parity Bit	0 if number of 1s in bits [62:0] is odd (odd parity)

R&D on Feasibility: LArPix-v1 System

LArPix-v1: *2016-2018*

Complete 3D Pixel System for LArTPCs:

- Custom ASIC with amplifier, digitizer, multiplexer
- Integrated Pixelated Anode w/ASICs
- Control electronics and software (outside cryo)

Key R&D Achievement:

Demonstrated **technical feasibility**

-> Successfully imaged cosmic rays in LArTPC

ASIC:

- Cryogenic-compatible
- Low-power: 62 uW/channel
- Low-noise: 275 e- ENC @ 87K

Pixel Anode:

- Cryogenic-compatible
- Low Digital-Analog cross-talk
- O(1k) channel readout via 2 wires

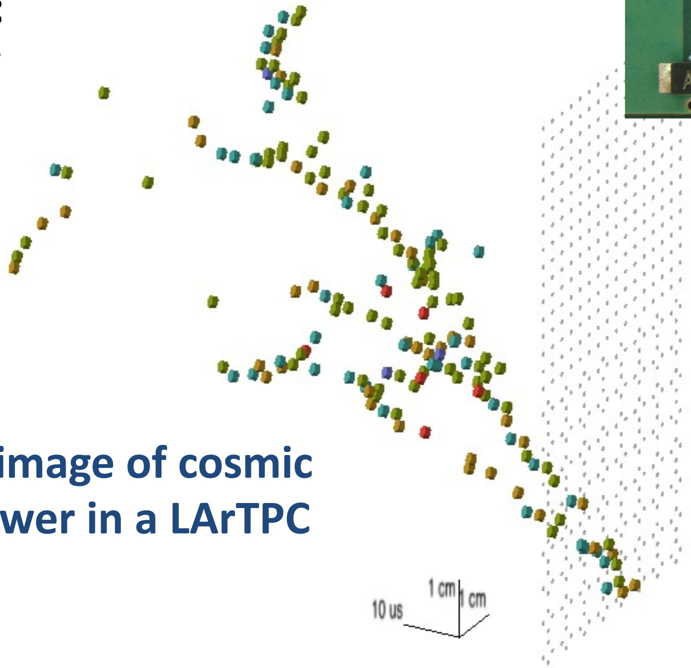
Control electronics:

- Fieldable system: noise-isolated and wifi accessible

Main drawback:

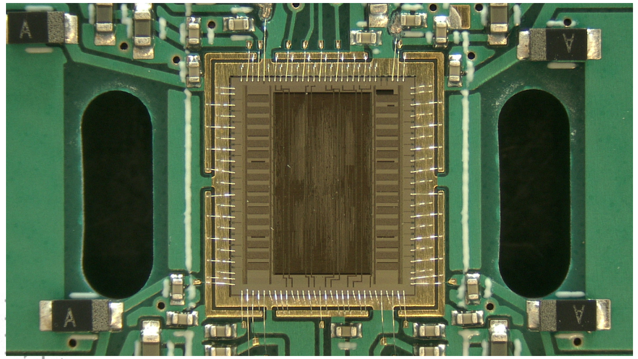
Difficult to scale above O(1k) pixels

- Anode requires manual assembly, bare chip wirebonding

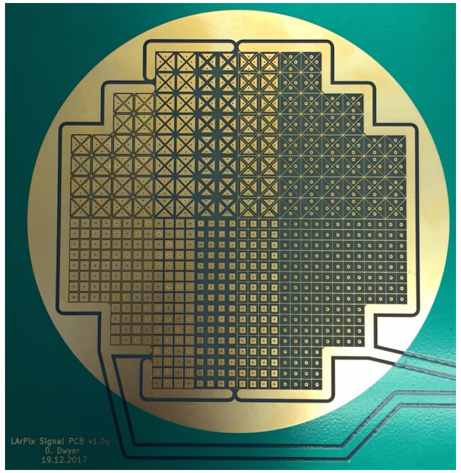


3D image of cosmic shower in a LArTPC

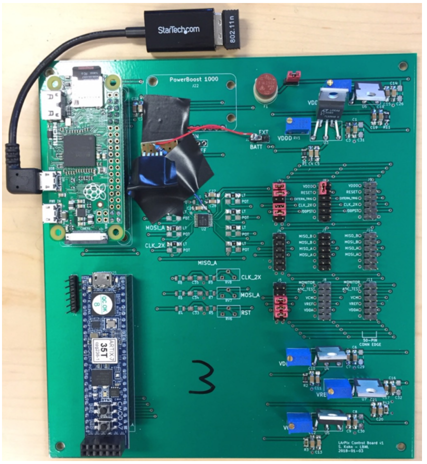
LArPix-v1 ASIC



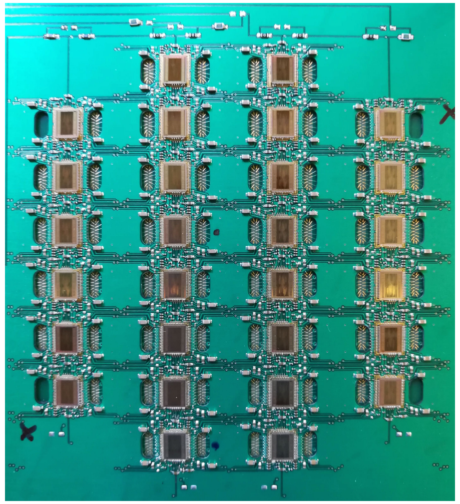
v1 Pixel Anode, Front



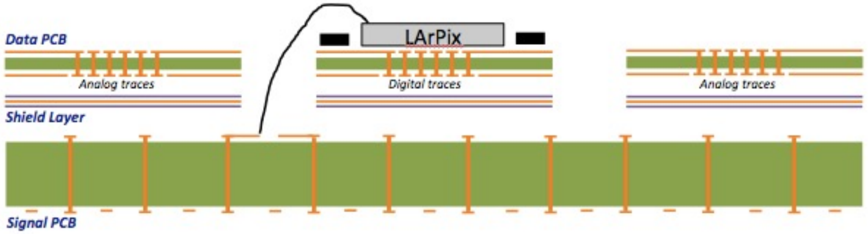
LArPix-v1 Tile Controller



v1 Pixel Anode, Back



Multi-layer anode cross-section



JINST 13 (2018) P10007

R&D on Scalability: LArPix-v2 System

LArPix-v2: *2019-2021*

Substantial Design Evolution:

ASIC Improvements:
- 64 channels/ASIC (twice channel density of v1)
- Hydra-I/O: Dynamic routing, robust to chip failure
- Cryogenic-compatible custom SRAM memory
- Improved tunability, testability
- Packaged to facilitate commercial mass production

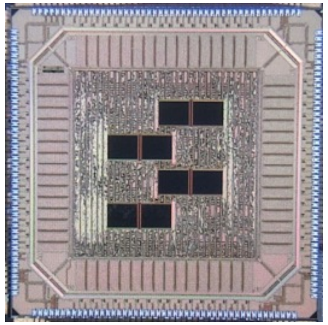
Pixel Anode Design Overhaul:
- ‘Tileable’ design to cover anodes of arbitrary scale
- 32cm by 32cm pixel anode PCB tile
- Frontside: 4900 square pixels, 4.4 mm spacing
- Backside: 10x10 grid of ASICs
- Enable fully-commercial mass production and assembly

Warm Controller (PACMAN) Redesign:
- Noise-isolated, compact, flange-mounted

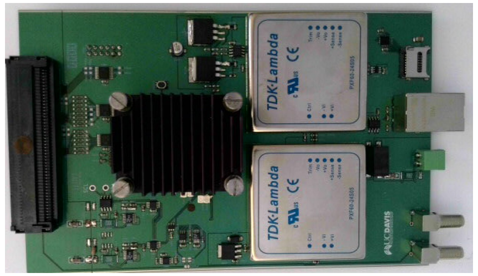
Key R&D Achievement:

Demonstrated **robust and scalable pixel anode**
- Fast (~few weeks) fully-commercial production/assembly
- Robust to repeated cryogenic cycling
- Successfully imaged cosmic rays in LArTPC on first try

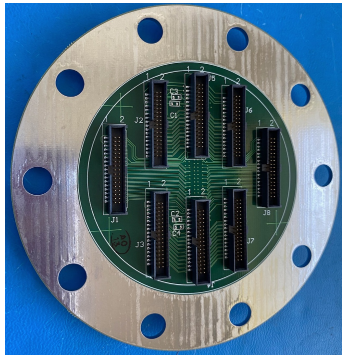
LArPix-v2 ASIC



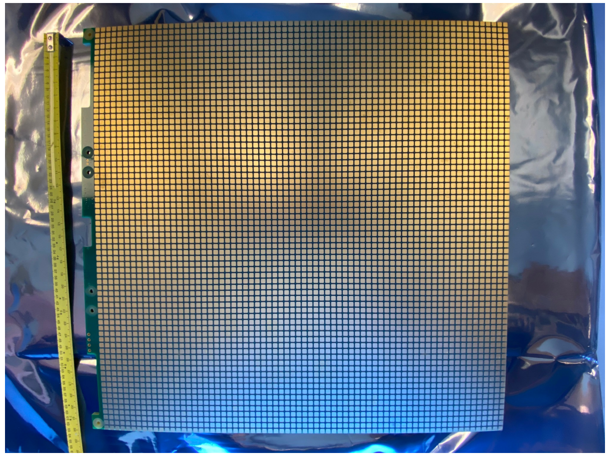
PACMAN Tile Controller

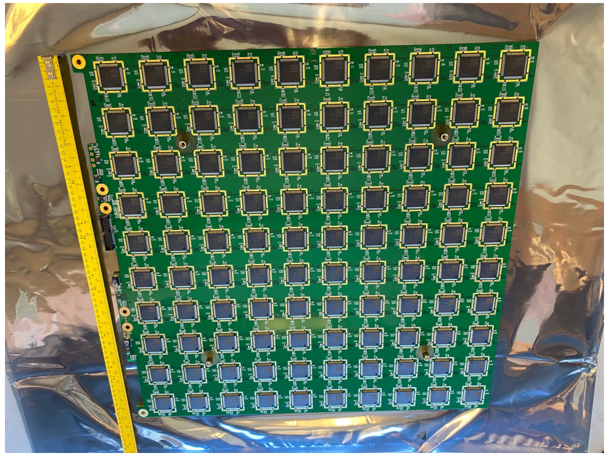


8-Tile Feedthrough

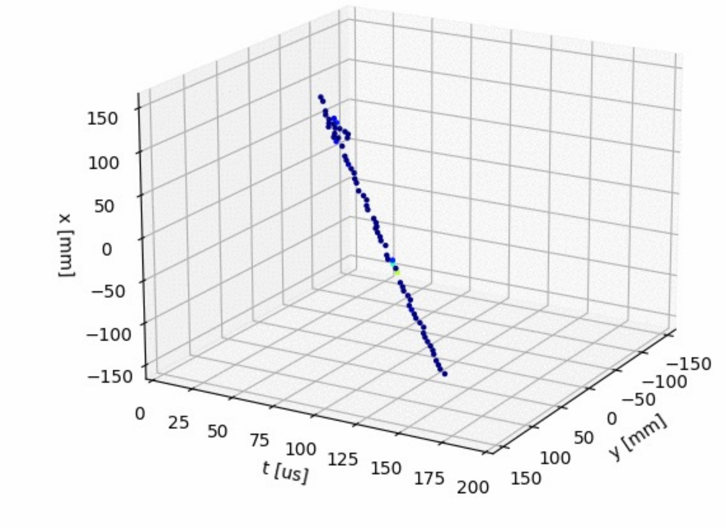


Production-scale LArPix-v2 Pixel Anode

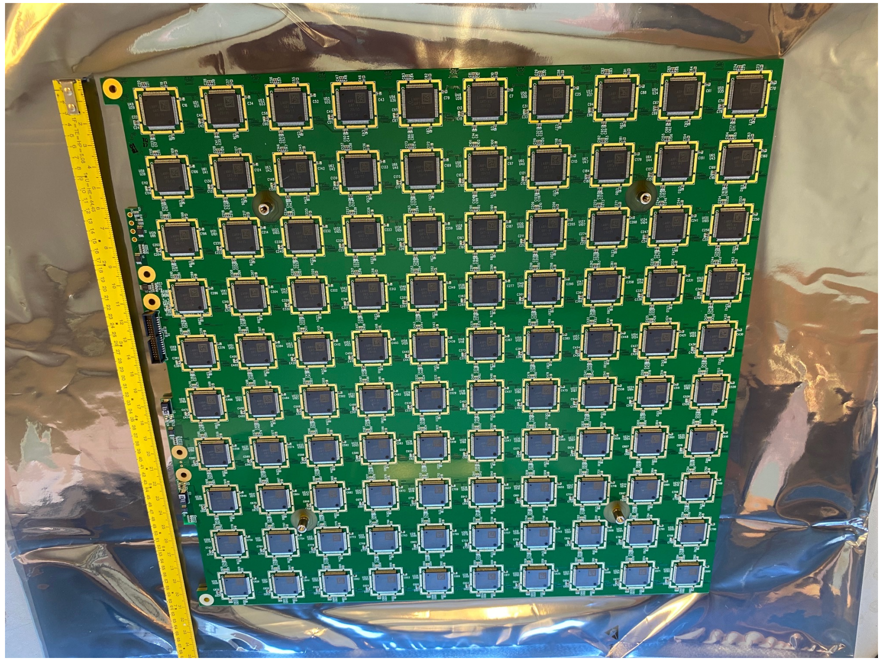




Raw 3D images of cosmic rays from initial single-tile test



Pixel Tile Reliability



Reliability of the pixel tiles drives design choices

DUNE Near Detector:

- 1400 pixel tiles (160 ASICs each)
- Loss of an entire anode would be catastrophic for the ND physics program
- Loss of an entire pixel tile very problematic
- Loss of individual pixels or single chip region (3x3cm) likely tolerable at the few-percent level (can 'interpolate' missing signal)

Current Approach:

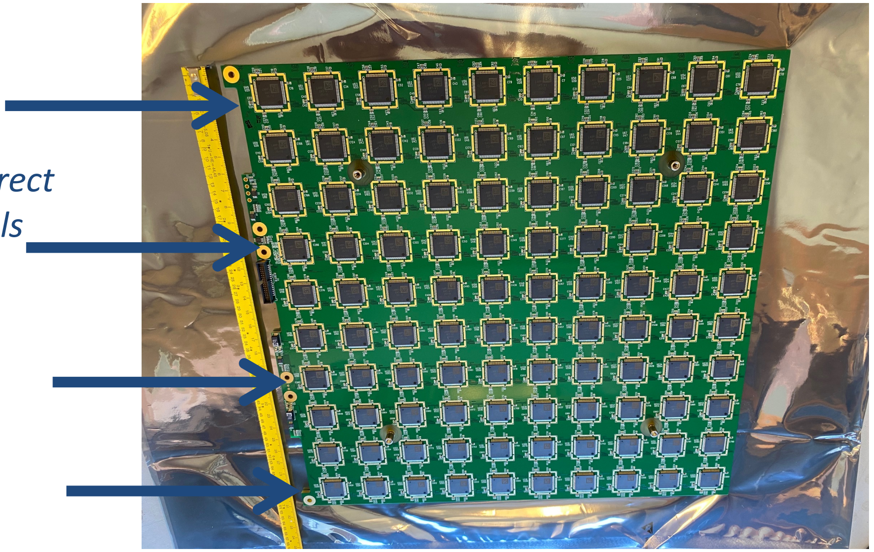
- LArPix ASIC is the only active component in cryogenic environment
  Remaining components all passive: decoupling capacitors, resistors, ESD protection diodes, one cable connector.
- Pixel tile designed to be robust to typical failures of individual LArPix ASICs
  Typical failures: chip unresponsive, chip constantly emitting data packets and saturating I/O
- Each tile has an independent cable (power and I/O) to the outside world, with fully-redundant I/O channels (x4).

R&D on Robustness: Hydra-I/O

New design for robust I/O and control architecture

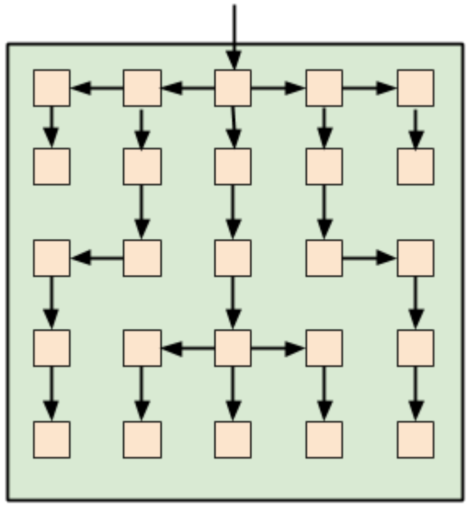
Repurpose existing LArPix-v1 low-power data I/O circuit
Very slight change enables richer, dynamic I/O architecture
- I/O can occur between any neighboring chips on pixel tile
- Network is built by explicitly connecting neighboring ASICs in a determined fashion

Successfully exercised with LArPix-v2 chip

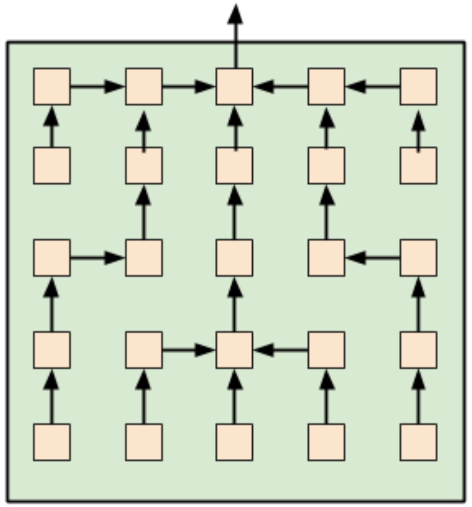


Four chips have direct off-tile I/O channels (10 MHz, < 4 m)

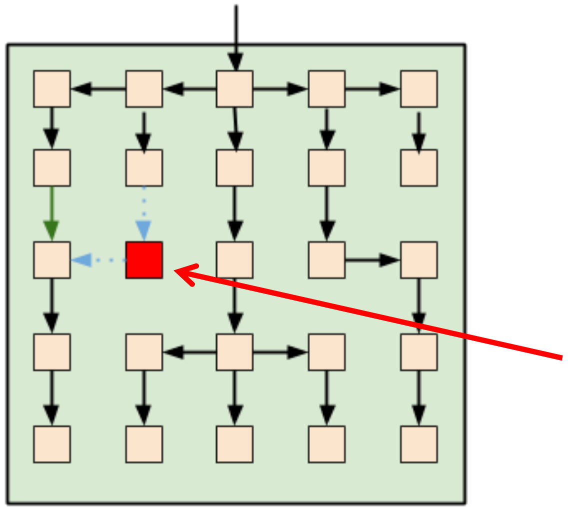
Example: 5 x 5 Pixel Tile



Upstream configuration commands



Downstream data flow



Network reconfigured to avoid failed ASIC

AD-HOC NETWORK OF READOUT APPLICATION-SPECIFIC INTEGRATED CIRCUITS FOR RELIABLE DETECTOR INSTRUMENTATION
U.S. Patent Application Ser. No: 63/140,434

LArPix Team @ LBNL

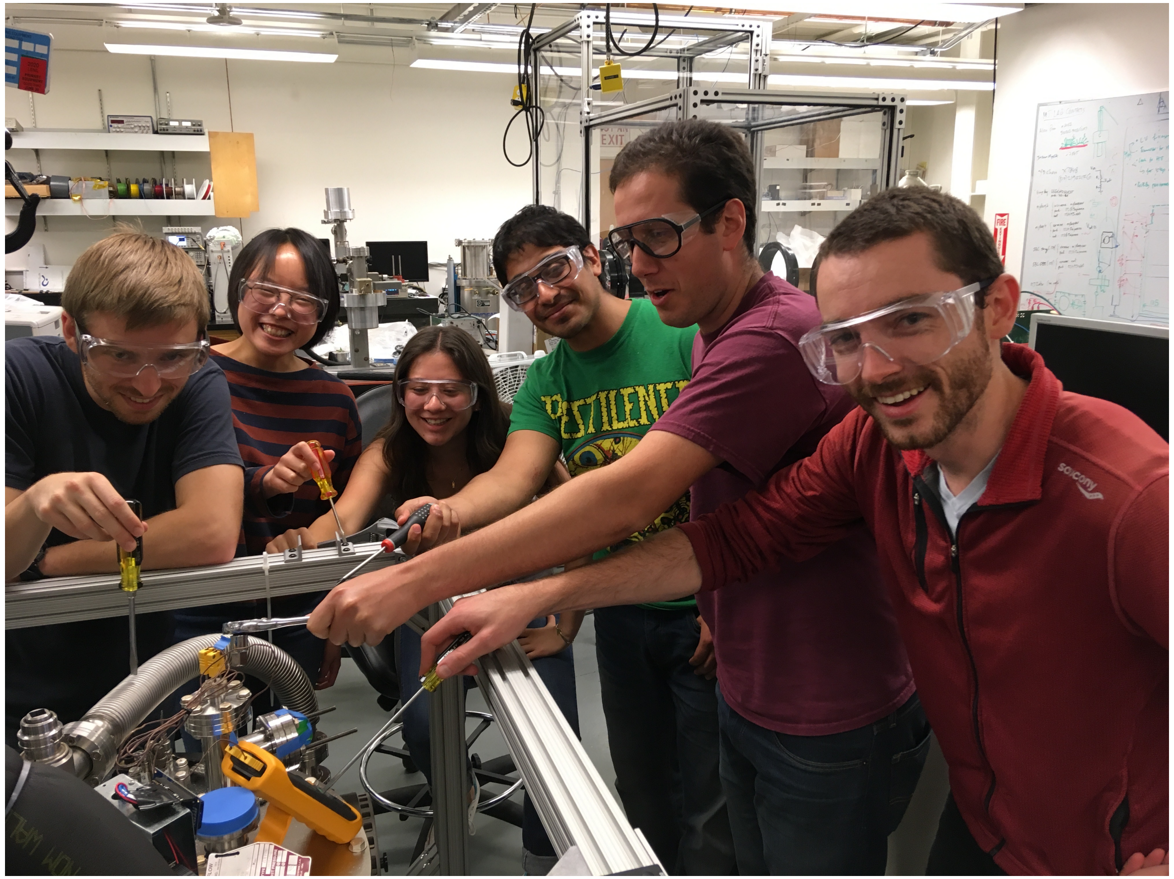
ASIC Design:
Carl Grace, Dario Gnani, Amanda Krieger

System Design:
Armin Karcher

LArPix-v1 Testing:
Peter Madigan, Sam Kohn, Gael Flores, Robin Xiong, Madeleine Liebovitch, Theophilus Human

LArPix-v2 Testing:
(a.k.a. The Pandemic Crew)
Brooke Russell, Peter Madigan, Roberto Soleti

LArPix Tyrant:
Dan Dwyer



From left to right: Theophilus Human, Robin Xiong, Madeleine Liebovitch, Gael Flores, Sam Kohn, Peter Madigan

Carl Grace

Brooke Russell

Dan Dwyer

LArPix Partners

BERKELEY LAB

Berkeley
UNIVERSITY OF CALIFORNIA

RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

UCDAVIS
UNIVERSITY OF CALIFORNIA

Caltech

UC SANTA BARBARA

u^b
b
UNIVERSITÄT
BERN

Penn

UCI University of California, Irvine

ArgonCube 2x2 Demonstrator Program: Prototyping Stages

Staged testing enables faster, progressive demonstration of integrated LArTPC performance

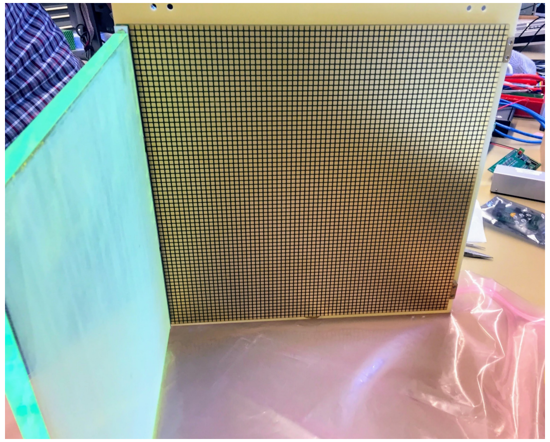
SingleCube: First run Oct. 2020 @ Bern, COVID-19 mitigation strategy, distributed prototyping at multiple sites (Bern, CSU, LBNL, SLAC, UTA, etc.)
- Integrated test of **smallest 'quanta'** of 2x2: hosts a single charge/light detector element of the 2x2 Demonstrator.

Module 0: First run Apr. 2021 @ Bern
- Integrated test of **one complete 2x2-scale module**

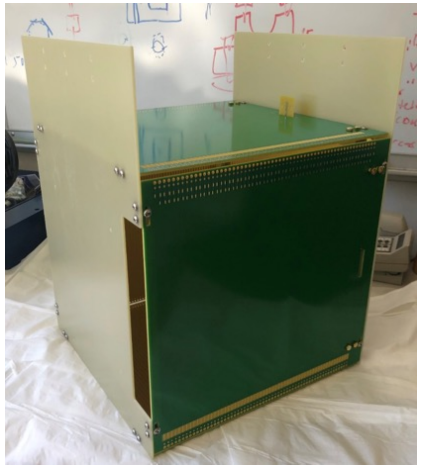
ArgonCube 2x2 Demonstrator: 2022-2023 @ FNAL
- **Four modules** in shared LAr bath in NuMI beam

Operation turn-around:
SingleCube: ~2 weeks
Module 0: ~1 month
2x2 Demonstrator: ~3-4 months

2x2 Detector Element
5k pixels, 6 SiPMs (ArCLight version)



SingleCube LArTPC
Hosts 1 detector element



Module 0 LArTPC
Hosts 16 detector elements

Module 0 Cryostat
Hosts 1 LArTPC module

2x2 Demonstrator Cryostat
Hosts 4 LArTPC modules

SingleCube LArTPC

SingleCube LArTPC Prototype:

Integrated test of ArgonCube readout:

- Production-scale pixel tile (32 cm x 32 cm, 4.9k pixels)
- Production-scale ArCLight scintillation light trap
- Same system interfaces as 2x2 Demonstrator
- Same 30-cm drift as 2x2 Demonstrator (3/5 of ND)

Progress:

- Assembled and installed in medium cryostat @ Bern
- Uses 2x2 Demonstrator High-purity LAr system
- Initial cooldown and fill: *26 Oct 2020*

Initial Result:

- Imaged cosmic rays within a few hours of filling!

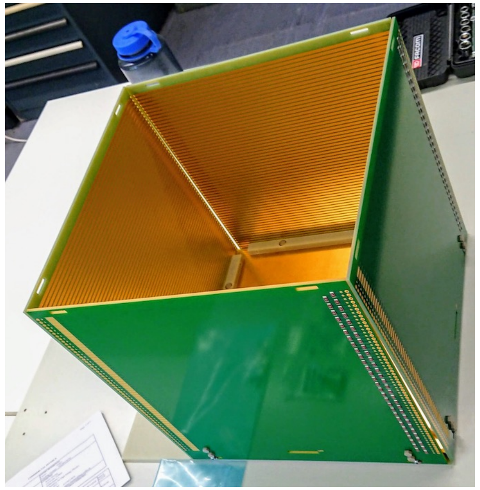
Successfully achieved many technical targets:

- **Charge & Light readout integration,** with low-noise and low-power
- **LAr Purity,** > 500 us e- lifetime
- **HV stability,** up to 1 kV/cm

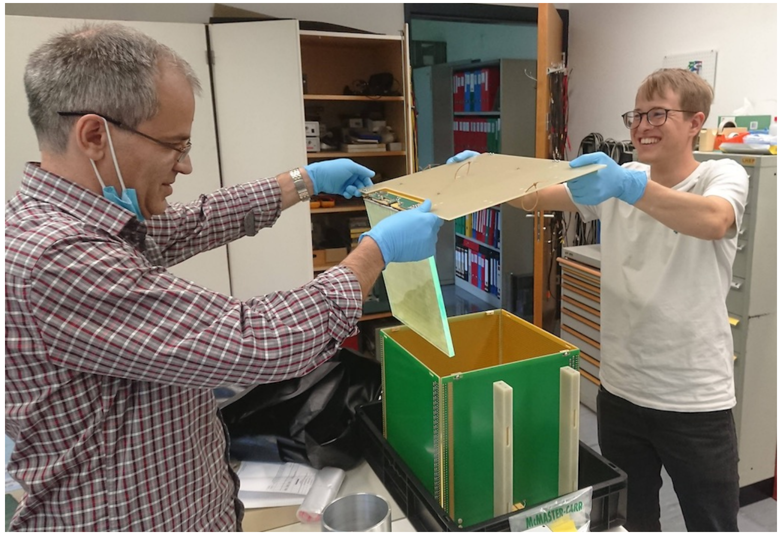
Prototyping program achieved TRL-5 in 2020.

SingleCube LArTPC

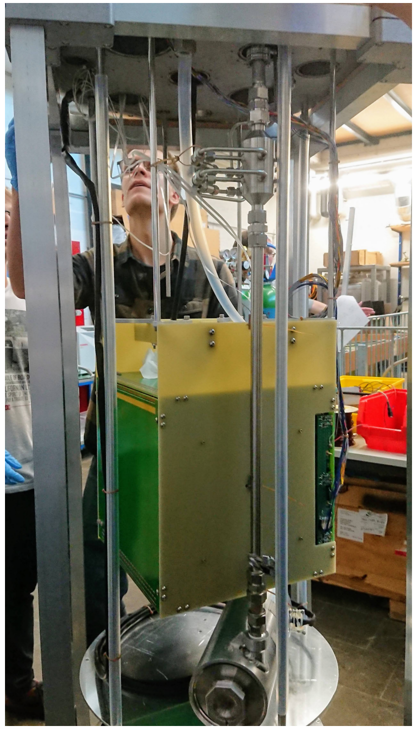
Full 30-cm drift



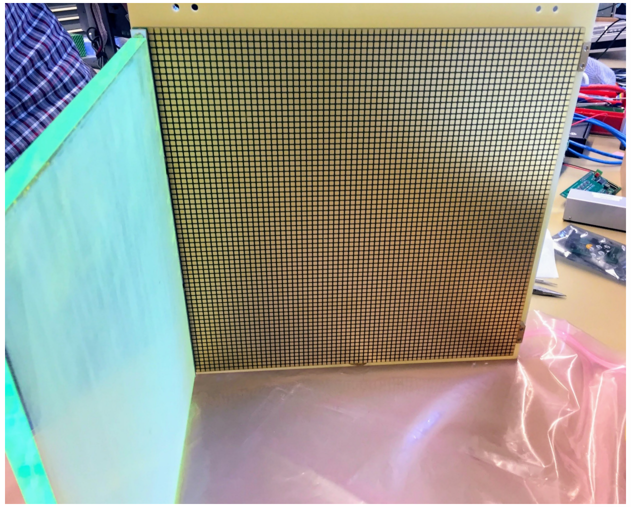
Installation of Integrated Charge & Light Readout



Integration with LAr Cryo-system

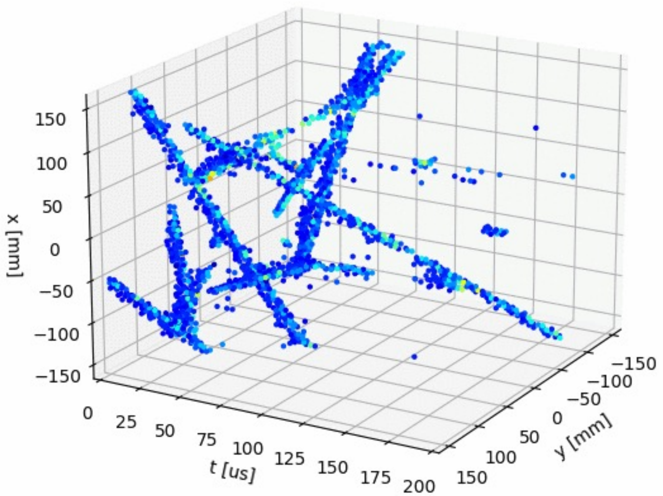


Charge & Light Readout



3D images of cosmic rays

in SingleCube LArTPC, 8 events overlayed

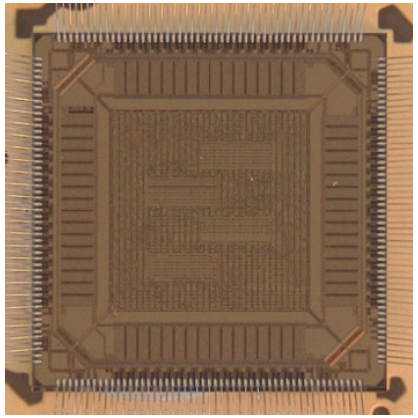


ND-LAr Technical Highlights: Charge Readout

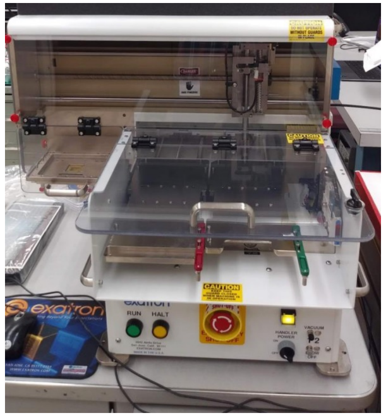
- **40 LArPix-v2a pixel tiles** (~200,000 pixels, for Modules 0 & 1) produced/tested [LBNL]
- **LArPix-v2b ASIC** produced and tested. Achieved design targets: 50x reduction of digital-to-analog crosstalk using novel low-swing differential digital I/O. [LBNL]
- Produced and packaged **~7000 v2b ASICs for Modules 2 and 3**, shipped to Caltech [LBNL]
- **ASIC Testing robot** purchased and commissioned, now in use for mass testing of v2b ASICs [Caltech]
- **Pixel tile redesigned** to support v2b ASICs, first boards now under test [LBNL]
- Prototype **v2b-compatible PACMAN controller** designed, produced, and tested. PACMAN production for Modules 2 and 3 now complete. [UC-Davis/LBNL]
- Design of **DUNE clock recovery firmware** for PACMAN progressing [UC-Irvine]
- **Alternate pixel tile cables** (i.e. flat flex cables for data, twisted pair for power) identified and prototypes in testing [Rutgers]
- **Revised LArPix feedthrough,** modified to support new cabling. Preparing for production for Modules 2 and 3 [Rutgers]
- **LArPix SingleCube TPC kits** for SLAC, York, Yale, Syracuse in various stages of production / distribution / commissioning [LBNL]

20 LArPix-v2a Pixel Tiles

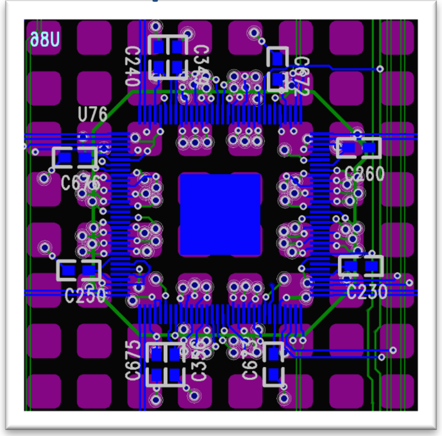
LArPix-v2b ASIC



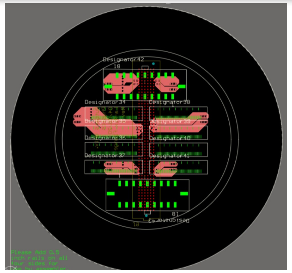
ASIC Testing Robot



v2b-compatible Pixel Tile



Alternate Pixel Tile Cables



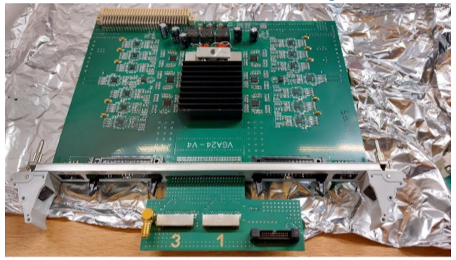
Revised LArPix Feedthrough

ND-LAr Technical Highlights: Light Readout

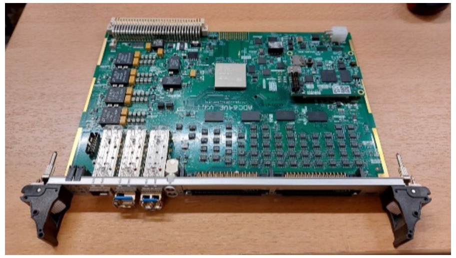
- **New SiPM Bias supply** supports tunable biasing of each SiPM [JINR]
- **Modified SiPM PCBs, 'E-board' PCBs, and feedthrough PCBs** to support new approach to SiPM biasing [JINR]
- **White Rabbit timing synchronization** implemented and tested [JINR]
- **Complete Light Readout electronics system** (for Module 1) produced and delivered to Bern [JINR]
- Optimization of **TPB deposition process** for light traps [Bern]
- **24 LCMs and 8 ArCLight light traps** (96 SiPMs, for Module 1) produced and tested [JINR/Bern]

New SiPM Bias Supply

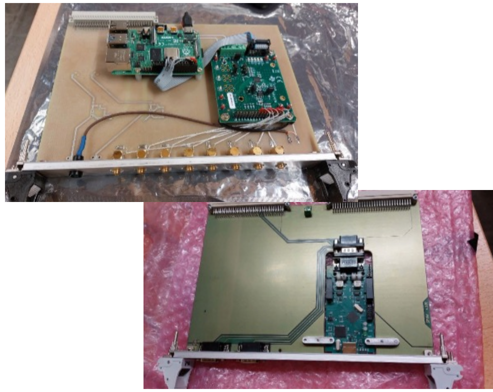
Variable Gain Amplifier

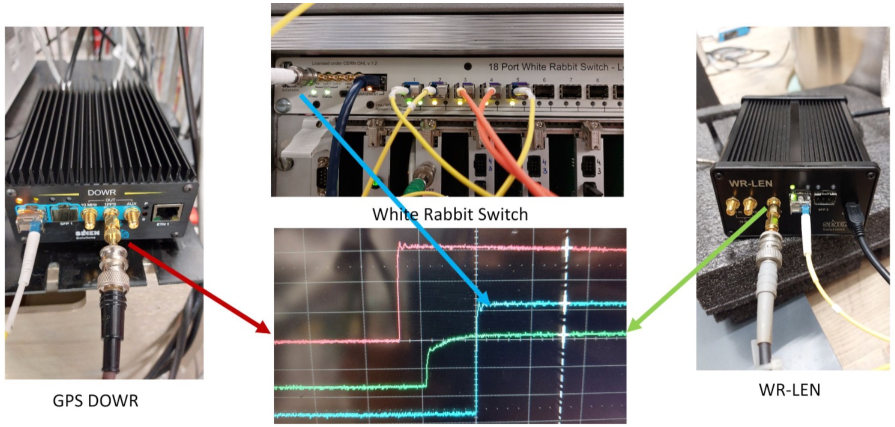


Analog-Digital Converter

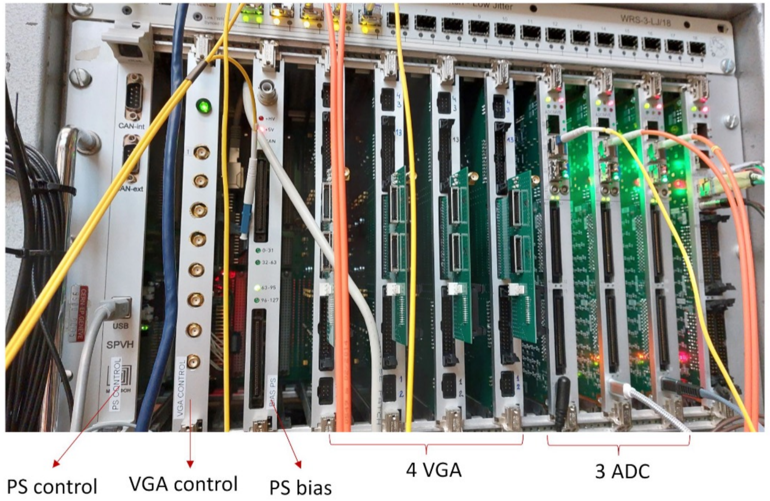


VGA, PS Controllers

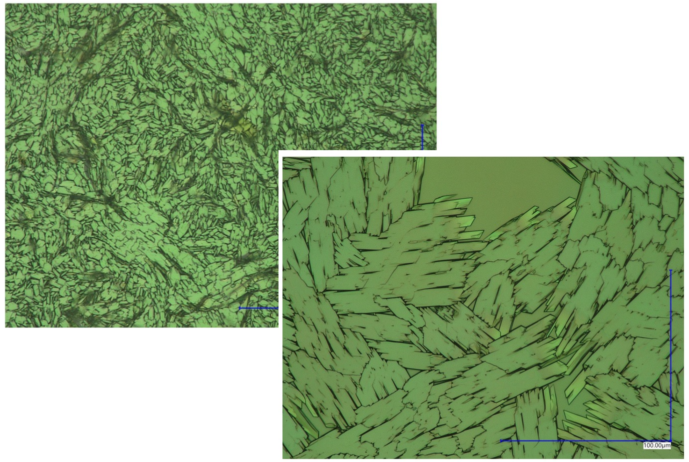




White Rabbit timing synchronization



Complete Light Readout Electronics system

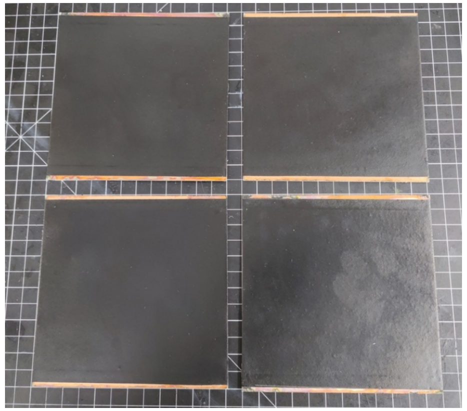


TPB deposition process

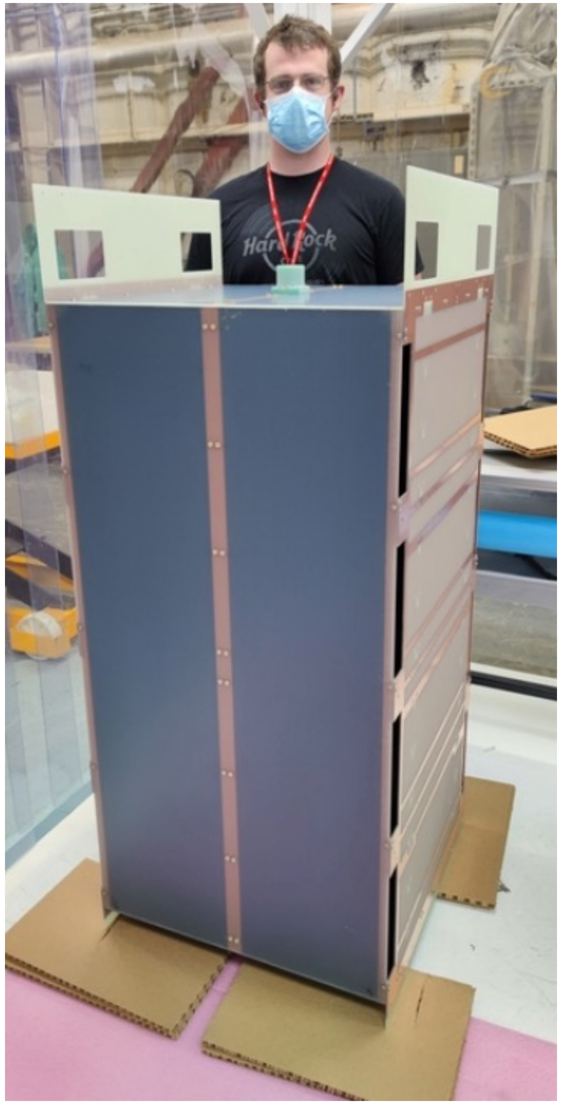
ND-LAr Technical Highlights: Field Structures

- **Module 1 field cage** produced and delivered to Bern [SLAC]
- **Module 2 and 3 field cages** in production [SLAC]
- Prototyping of **alternative high-resistivity materials** (e.g. carbon-loaded epoxy) in progress. [SLAC]

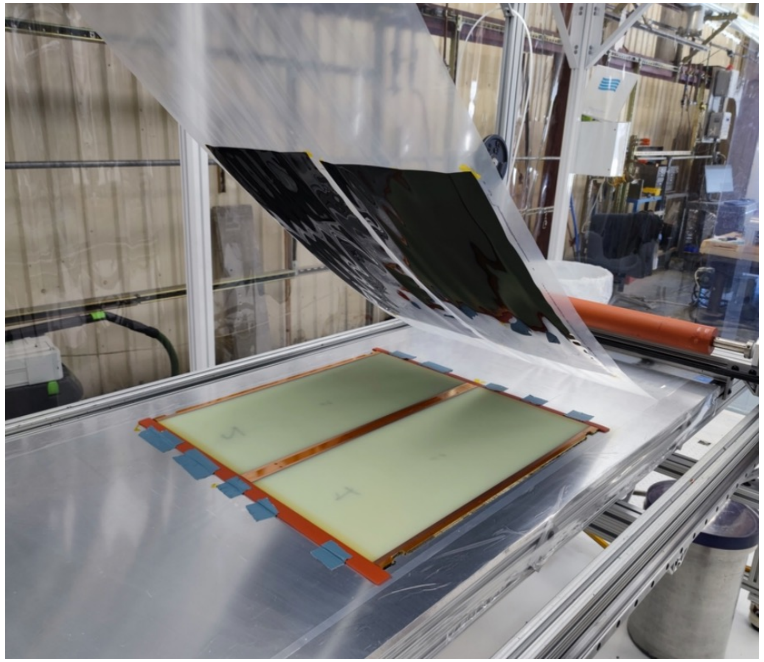
Prototyping of alternative high-resistivity materials



Test assembly of Module 1 field cage



Lamination of resistive Kapton on fiberglass



Field cage panel, post-lamination

ArgonCube Module 0 LArTPC

Ton-scale Prototype LArTPC to validate Near Detector Design

Details:

- Active Size: 0.7m x 0.7m x 1.25m
- 16 pixel tiles, with ~80k pixel channels total
- 16 light collection modules, with 96 light sensors (SiPMs)
- Resistive-film-on-fiberglass field cage

Progress:

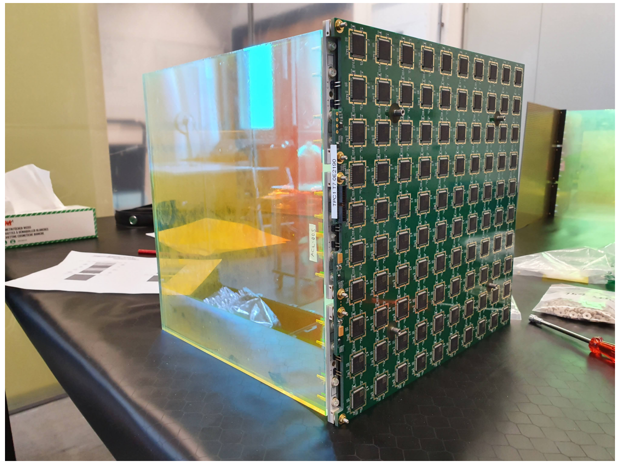
- Assembled and successfully operated at Univ. of Bern, *Apr. 1-10, 2021*

Achievements:

Demonstrated fully-integrated prototype detector module at a scale relevant to the DUNE Near Detector

Achieved TRL-6 in 2021.

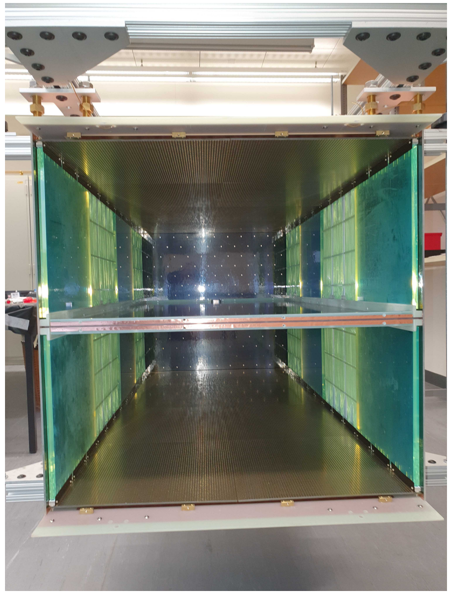
Single pixel tile & light module assembly



LArTPC module attached to cryostat lid

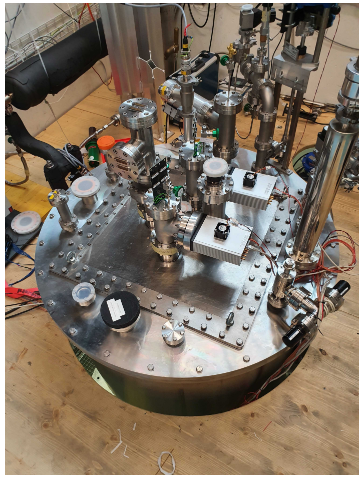
One anode, fully-assembled

Two anodes, installed inside field cage



Single Module Cryostat

LArTPC inside cryostat



ArgonCube Module 0 LArTPC

*Typical **raw data** from cosmic ray interactions imaged in 3D in Module 0 prototype detector*

Key Results

- Continuous operation over >1 week
- Collected >10^7 cosmic ray events
- Stable **HV** at ~30kV (~1 kV/cm drift, 2x target)
- Stable **Purity** at >2ms (>4x target)
- MIP Charge Signal-to-**Noise** >20:1 (at target)
- No component failures during operation

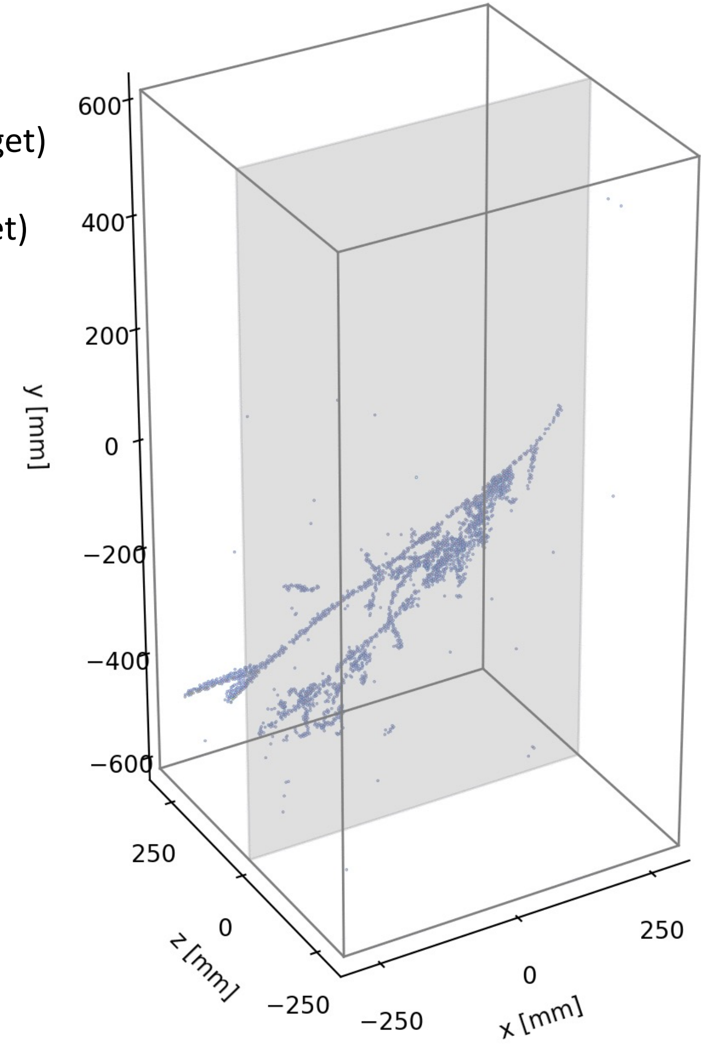
Observations:

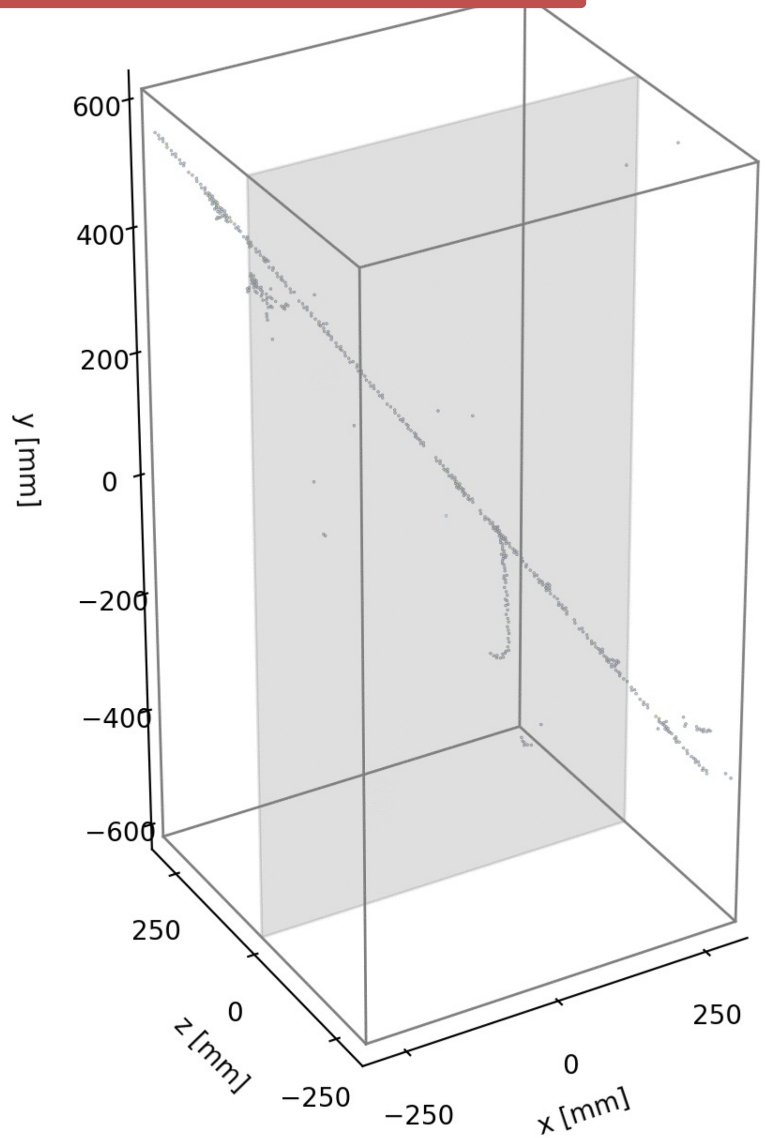
- Need to reduce charge system clock cross-talk into light system
- ~4% of pixels at tile edge biased due to existing grounding scheme

Retired the most significant technical risks in ND-LAr design.

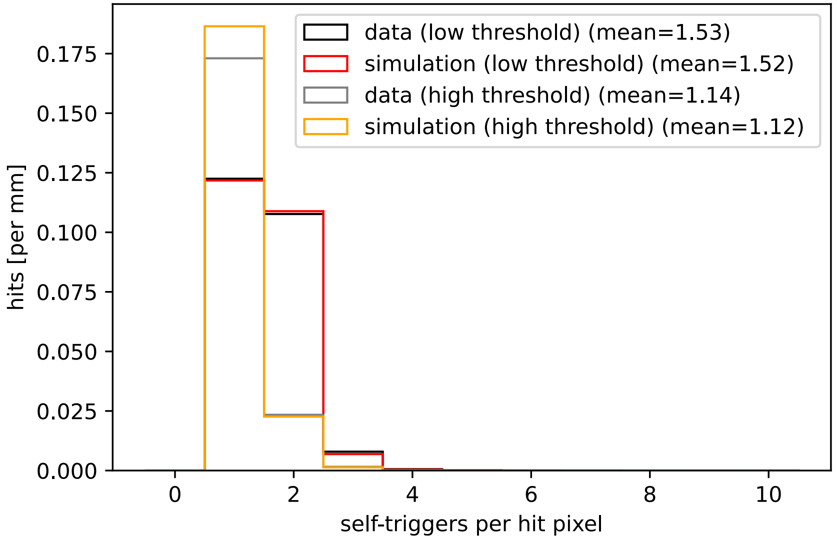
Arguably the most performant ton-scale LArTPC to date.

Achieved TRL-6 in 2021.



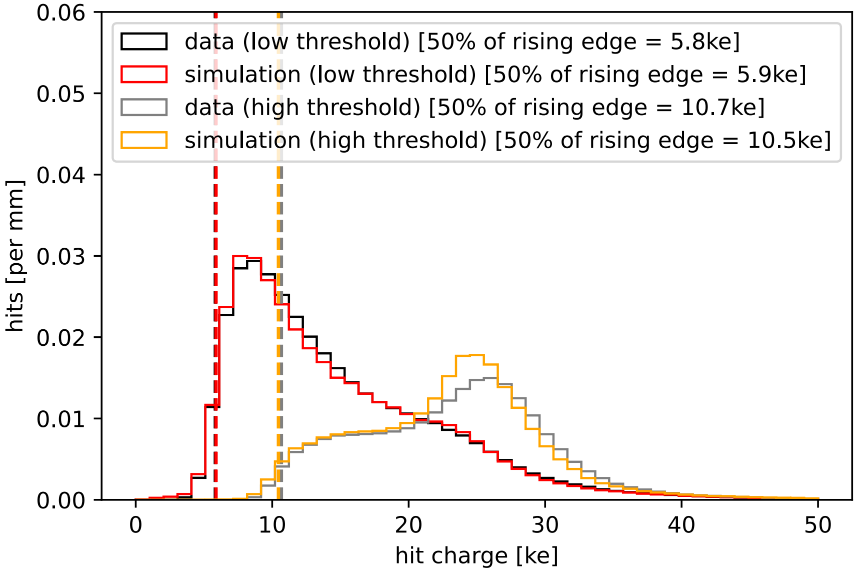


Module 0 Physics Performance

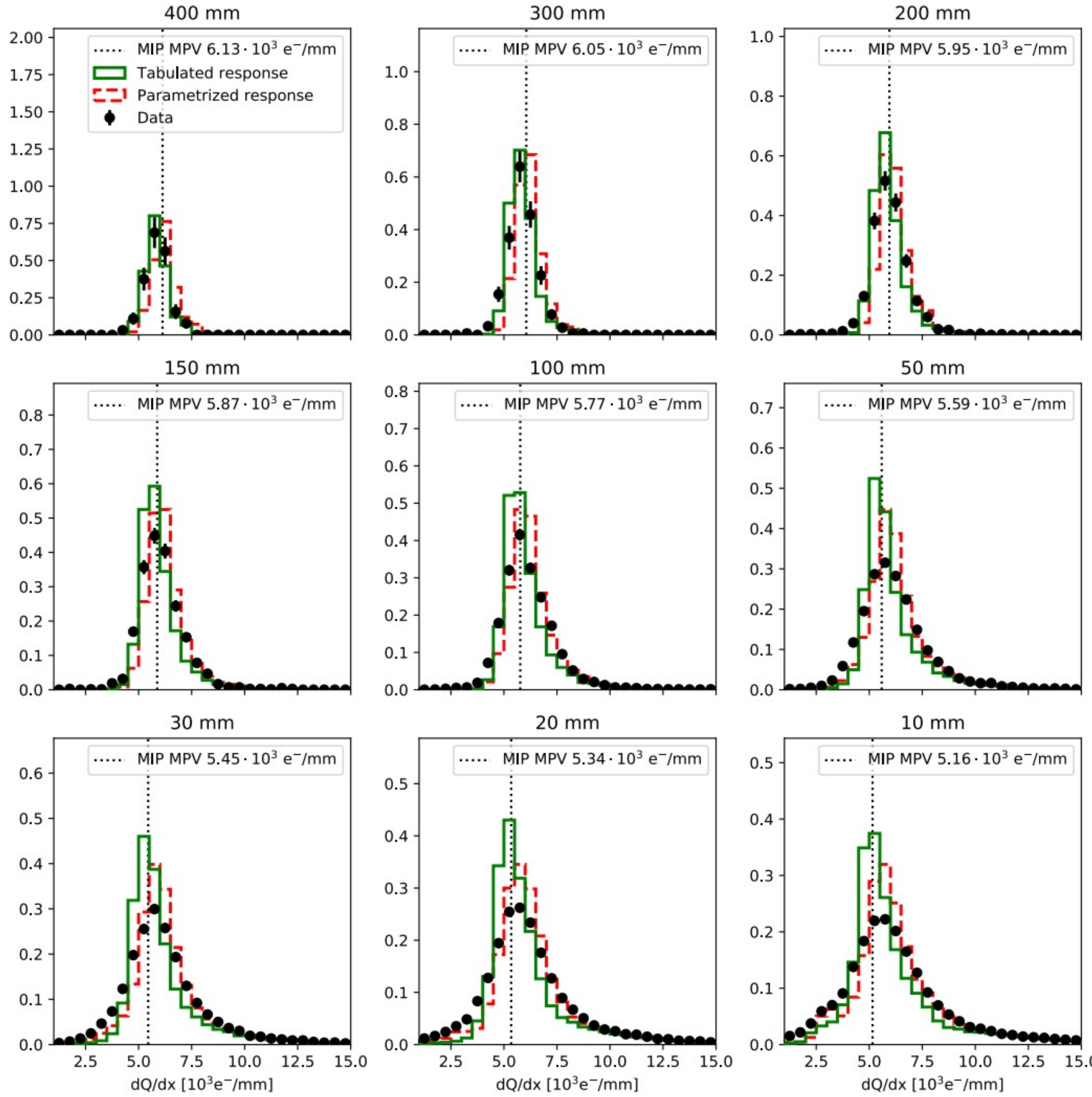


Number of pixel hits for muon tracks

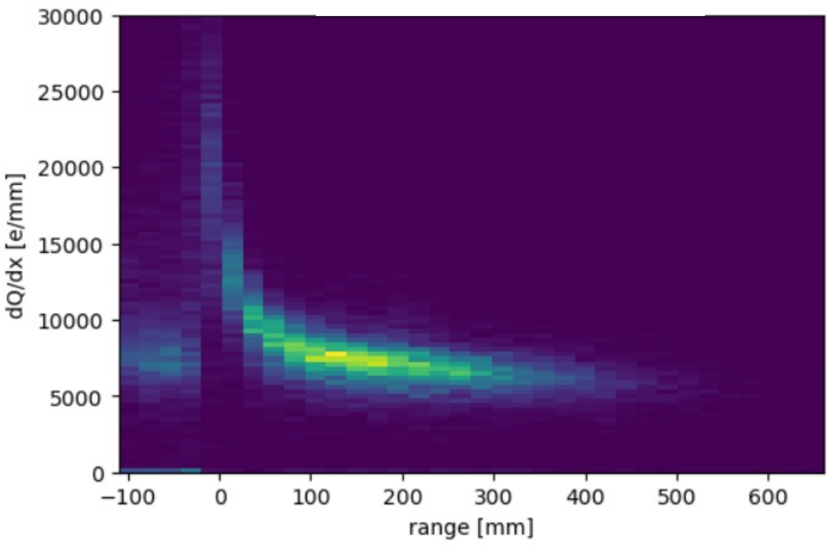
Pixel hit charge for muon tracks



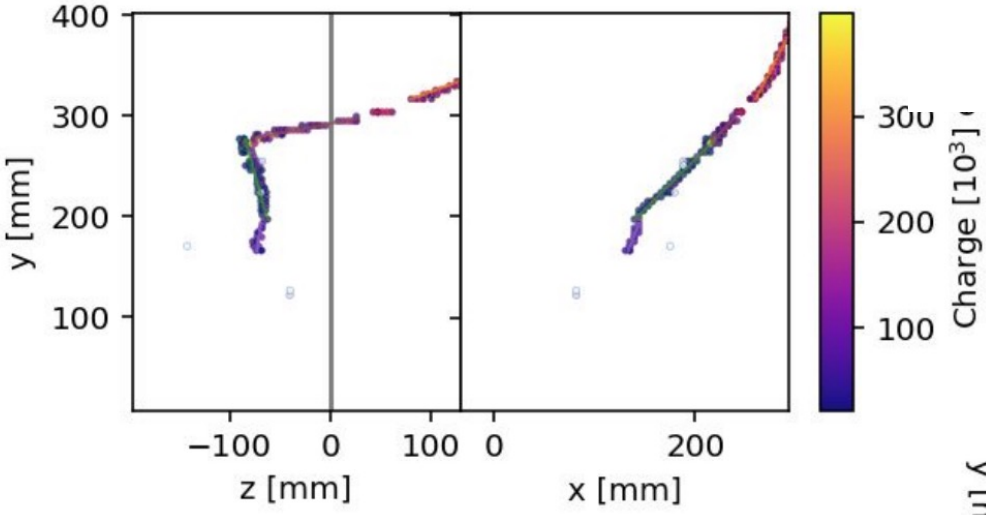
Energy loss for minimum ionizing muons (dQ/dx)



Module 0 Physics Performance

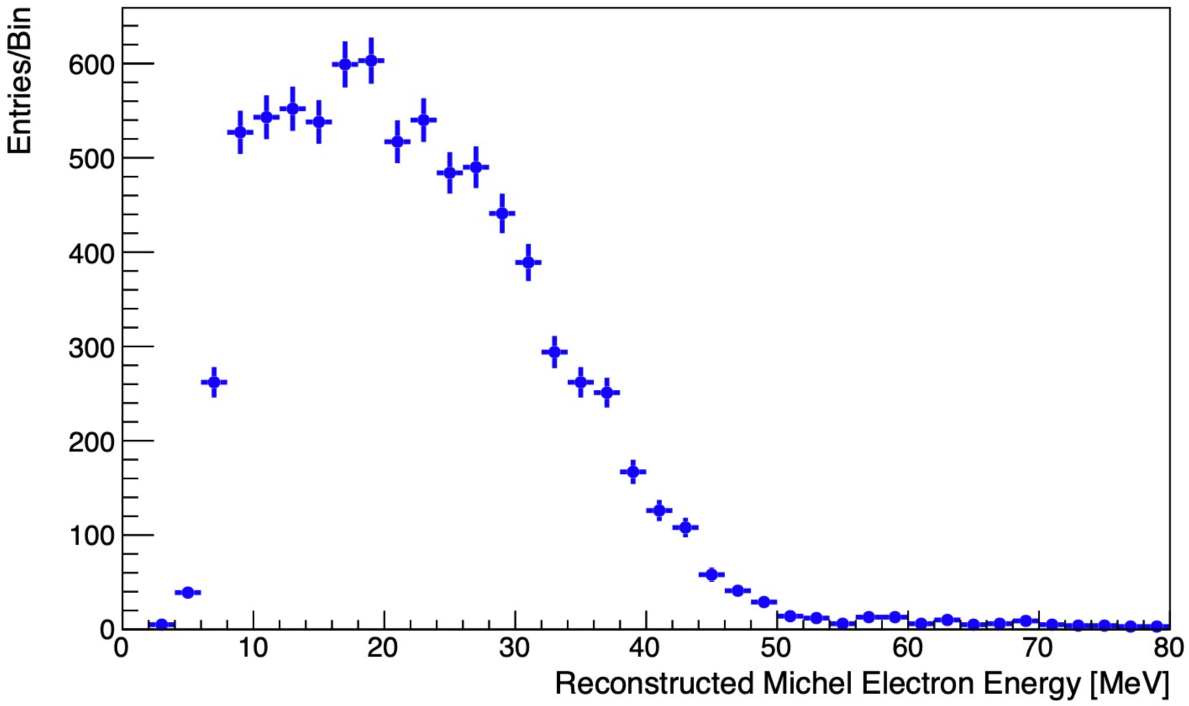


Energy loss for stopping muons



Observation of positron decay

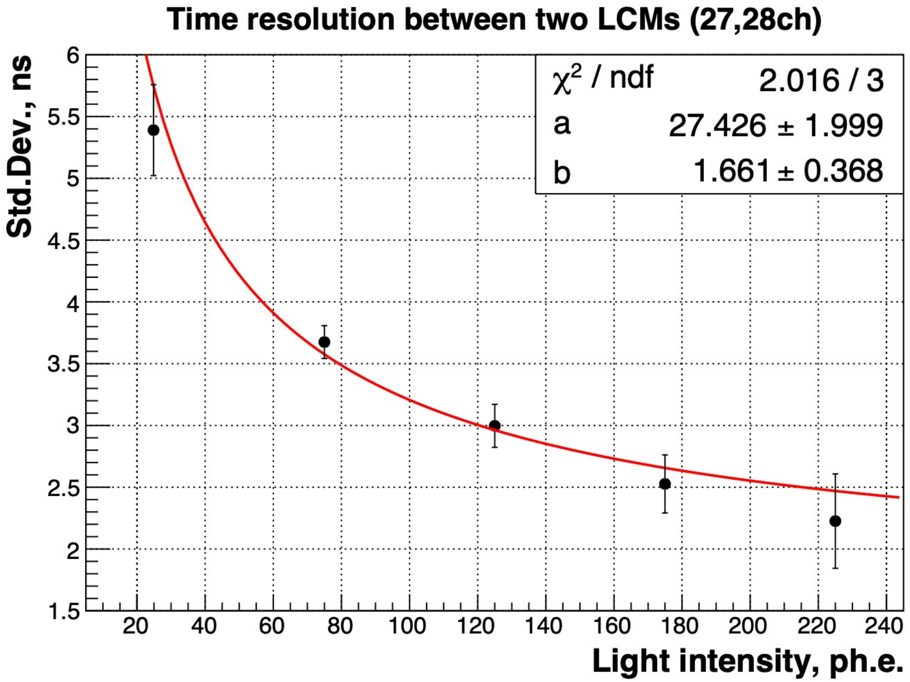
Michel e- energy spectrum



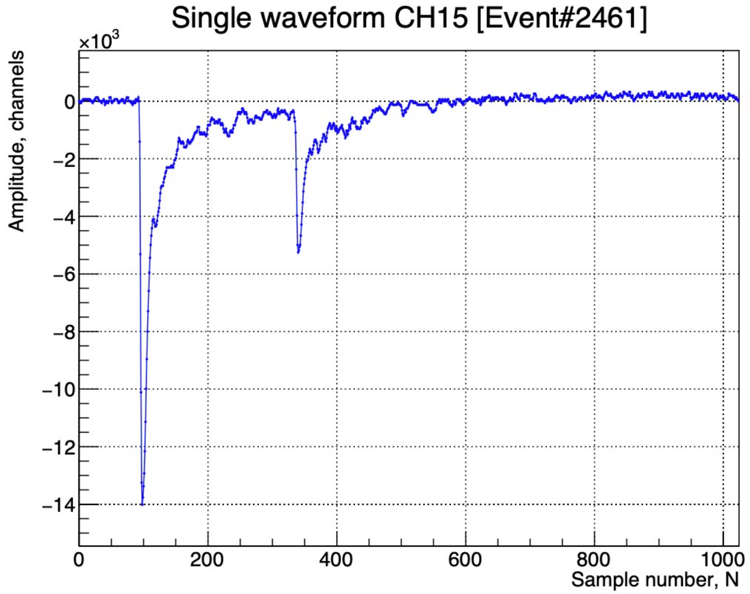
Publication Pending

Module 0 Physics Performance

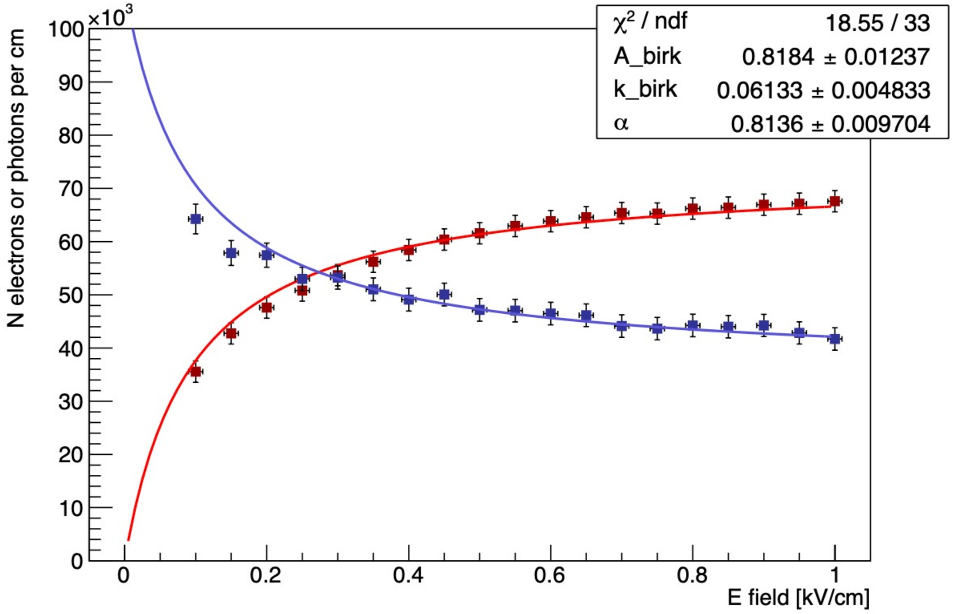
Time resolution of Light readout system < 2ns (x5 target)



High efficiency light readout gives clear signals for muon decays



Anticorrelation of charge and light signal amplitude vs. drift field strength



Publication Pending

ArgonCube Module 1 LArTPC

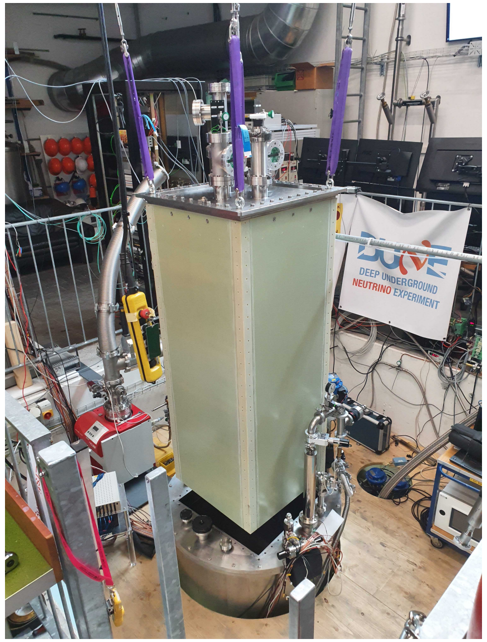
Key Changes and Results

- **Improved SiPM readout electronics:**
  Enables independent biasing/optimization of each SiPMs
- **Improved shielding in SiPM PCBs:**
  Removed dominant noise from charge system clock crosstalk into SiPM analog signal
- **Modified pixel tile grounding scheme:**
  Reduced pixel thresholds by ~40% (from ~6.5ke- to ~4ke-)
  Removed major source of out-of-spec pixels (from 92% to 97.5% active pixels)
- **Operated without active LAr circulation and cooling**
  Demonstrated stable operation in this extreme condition, without boiling argon

Other Observations:

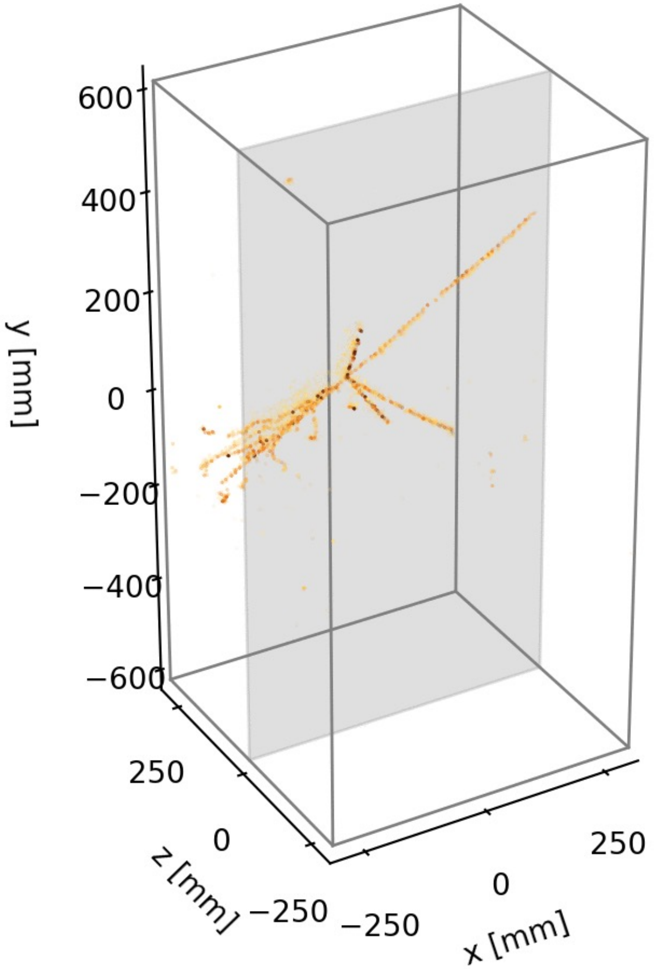
- Demonstrated full TPC assembly in ~1 day
- Lost communication, power to one tile. Under investigation.

Module 1 and G10 'sleeve'

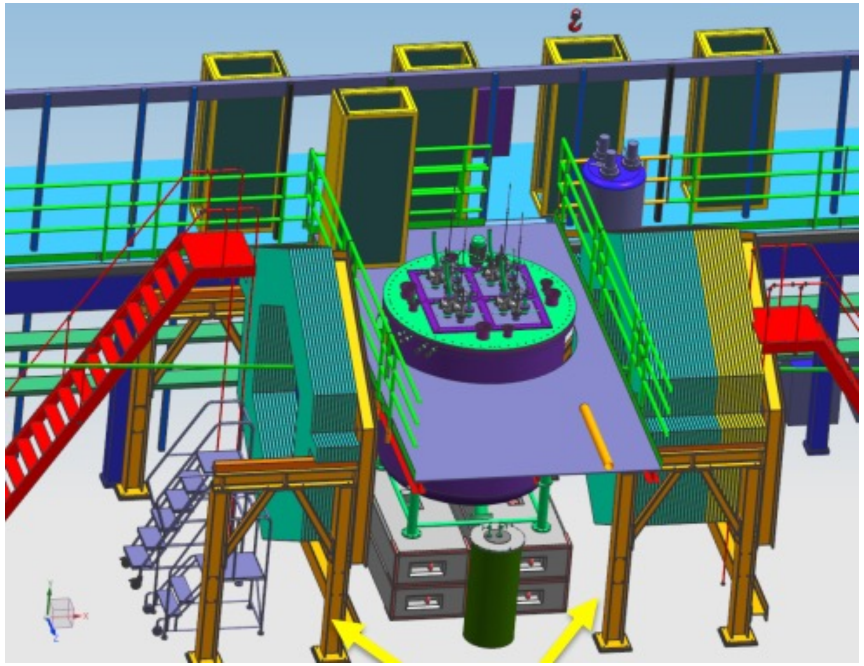


Module 1 cryostat insertion

Raw cosmic ray data



ArgonCube 2x2 @ NuMI

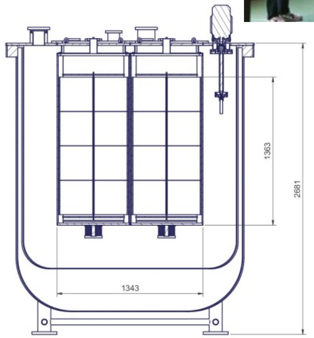


2x2 Operation in NuMI Neutrino Beam: 2022-2023

- Install four TPC modules in former location of MINOS-ND
- Includes upstream/downstream trackers, repurposed from Minerva

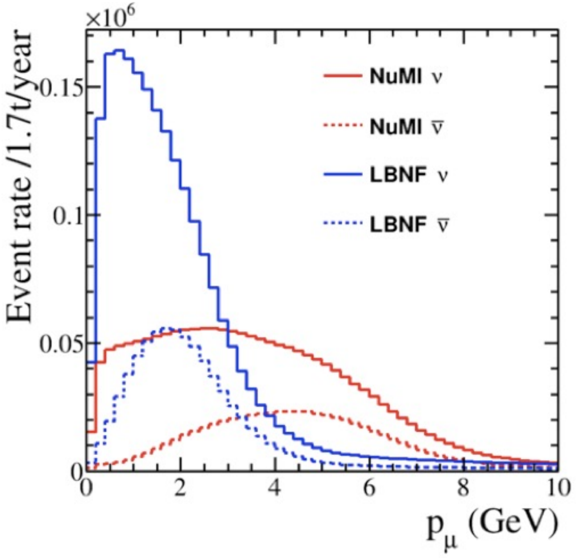
Goals:

- Develop neutrino signal analysis and reconstruction techniques
  - 3D reconstruction of neutrino signals
  - Charge-light signal correlations, tolerance to beam pileup
  - Track matching with external trackers



Context on the 2x2 Effort:

- Plan pre-dates the ND-LAr detector in the DUNE-US ND project
- Cemented via an iCRADA between Univ. of Bern and FNAL
- Effort is off-project, supported by substantial contributions from many institutions
- TPCs assembled and tested at Bern, shipped to FNAL for installation and commissioning



Major Commitments:

Bern:
- Cryostat and most of cryogenics components (pumps, LAr purifier, valves, feedthroughs, etc)
- Pre-assembled TPCs, tested and ready for installation
- HV supply and filters, half of scintillation light traps

FNAL: Cryocoolers, cryogenics integration, PLC system, support platform, onsite facilities support and management
JINR: Light readout system, including all electronics & prototype DAQ
LBNL: Charge readout system, including all electronics & prototype DAQ
SLAC: Field structures (cathodes, field cages, HV feedthroughs)
CSU: Assembly fixtures

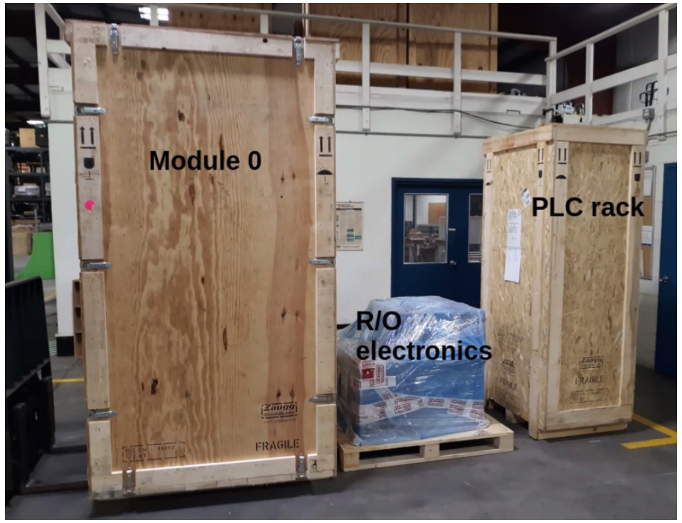
and 20+ institutions providing scientific labor

ArgonCube 2x2 @ NuMI

2x2 Status:

- Cryostat & controls commissioned at Bern
  Delivered to FNAL: July 2021
- TPC Module 0 commissioned at Bern
  Delivered to FNAL: Oct. 2021
  Acceptance testing in progress.
- TPC Modules 1-3 currently in production
  To be delivered to FNAL: Spring/Summer 2022
- Remaining cryogenics system procurements/production
  To be delivered to FNAL: ~Spring 2022
- Installation and commissioning in NuMI hall
  Targeting ~Autumn/Winter 2022

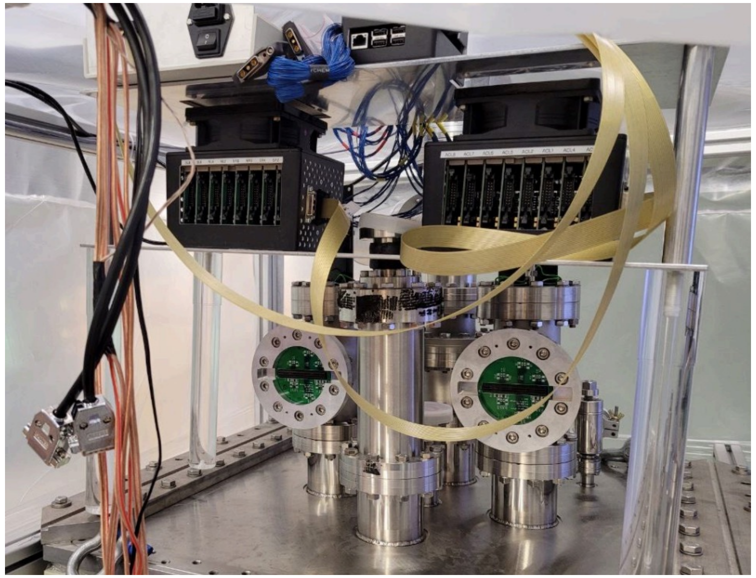
‘Physics’ demonstration of TRL-7.



Module 0, electronics, and PLC en-route to FNAL

Module 0 in shock-isolated shipping frame

Module 0 acceptance testing at FNAL



Future Prototyping: Full-Scale Demonstrator Program

Demonstrate engineering readiness for Near Detector LArTPC module production

Key Goals:

- Validate the **integrated performance** of actual **Full-scale ND LArTPC module** before initiating production
- Demonstrate the **production processes** for the full-scale ND LArTPC components
- Establish and exercise the **component QA/QC program** in preparation for ND production
- Develop the **assembly and testing program** for the TPC Module Integration Facility

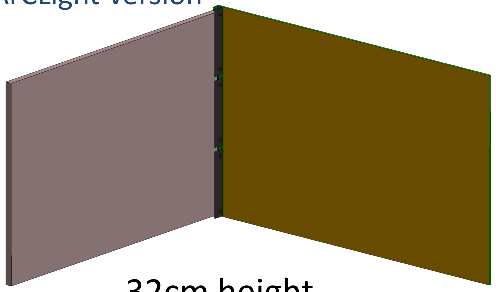
System Concept:

- Similar to Module 0 system (hosts one TPC module), but full size (~3.0m tall active region)
- Planning for 2 cycles of operation
- Informs ND-LAr Final Design Review and Production Readiness Review

'Engineering' demonstration of TRL-7.

ND Detector Element

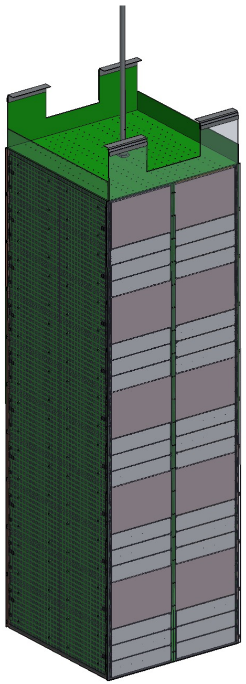
ArCLight-version



32cm height
48cm width

Full-scale ND Module

3.0m height
1.0m width
40 elements

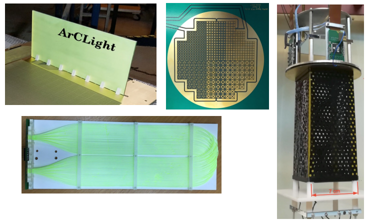


Full-scale ND Module Test Cryostat

4.5m height
1.5m diameter

ND-LAr: Technical Plan (one slide summary)

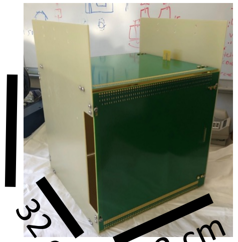
2016-2019
ArgonCube R&D
Demonstrations of component technologies



TRL-4
- Ready for CD-1

2020
SingleCube
Integrated TPC test at small-scale

32 cm



32 cm
32 cm

TRL-5

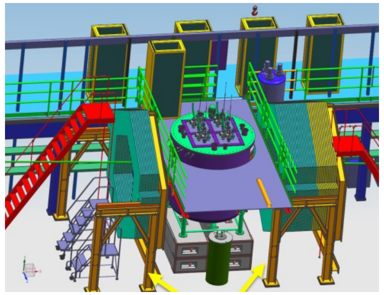
2021
ArgonCube Module 0
One mid-scale TPC module in single-module cryostat

125 cm

70 cm
70 cm

TRL-6
- Ready for CD-2

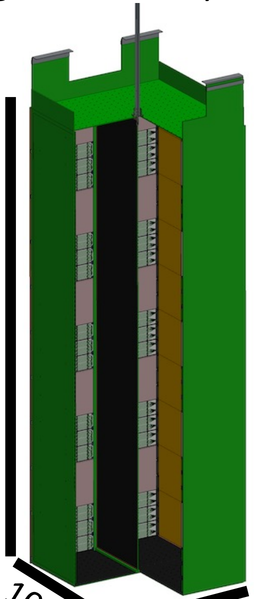
2022-2023
ArgonCube 2x2 Demonstrator
Four mid-scale TPC modules in neutrino beam



TRL-7
(physics)

Full-scale ND Demonstrator
1 Full-scale ND-LAr TPC module in single-module cryostat

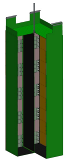
300 cm



100 cm
100 cm

TRL-7
(engineering)
- Ready for CD-3

Production



1 production 'first article'

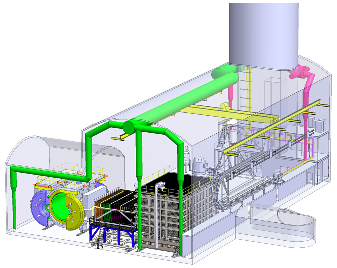
35 (+5) production modules each fully tested in a single-module cryostat

Deliverable: modules packed and ready for installation underground

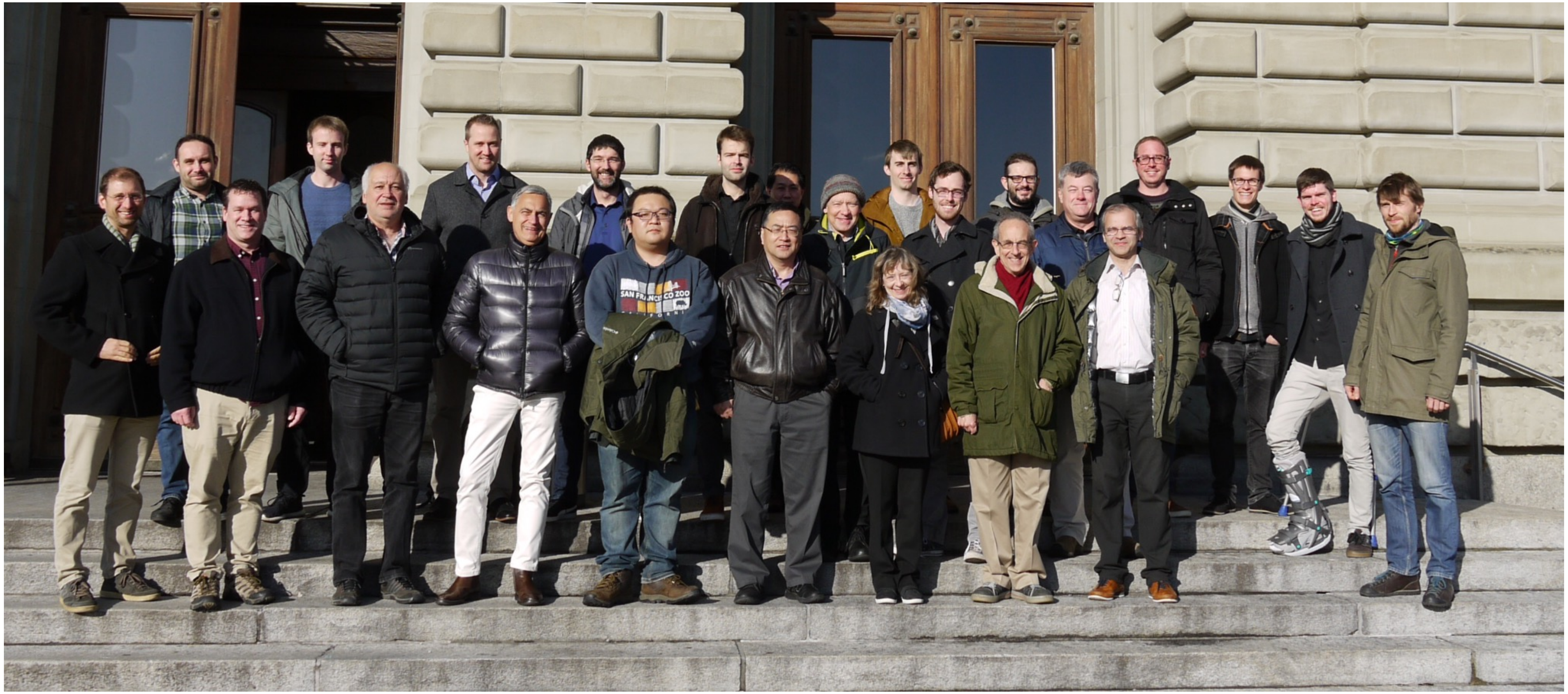
Installation

Support of TPC module installation in Near Site

Activity driven by Near Site Integration (NSI)



DUNE Near Detector LArTPC (ArgonCube) Consortium



ANL
Caltech
Cambridge
CSU
FNAL
JINR
LBNL
MSU
Rutgers
SLAC
Syracuse Univ.
Tufts Univ.
UC Berkeley
UC Davis
UC Irvine
UCSB
Univ. of Bern
Univ. of Iowa
Univ. of Colorado
Univ. of Houston
Univ. of Manchester
Univ. of Minnesota
Univ. of Lancaster
Univ. of Rochester
Univ. of Sheffield
U-Penn
UTA
Warwick
Wichita State Univ.
William and Mary
Yale Univ.
York Univ.

The DUNE ND-LAr Detector

The DUNE Liquid Argon Near Detector

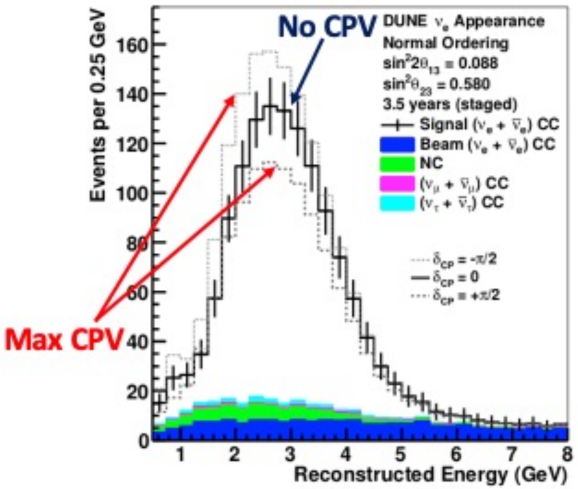
- Constrains main systematic uncertainties for DUNE Experiment

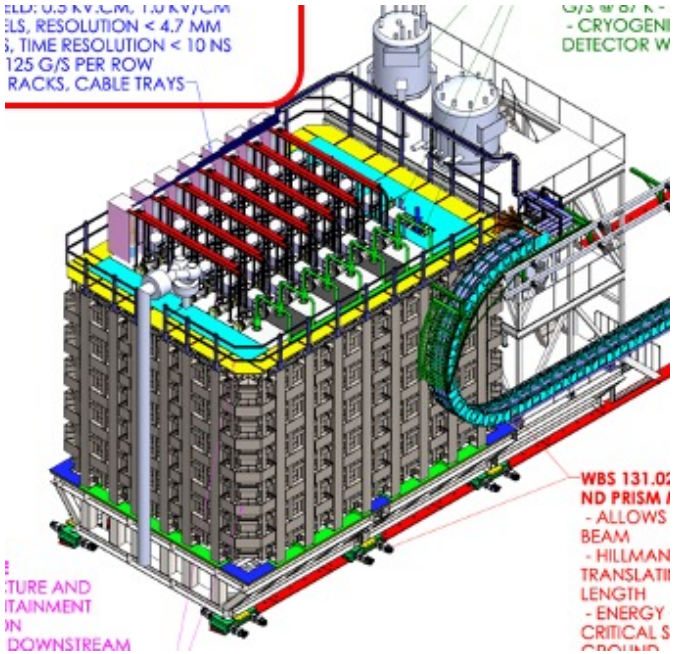
High-performance LArTPC:

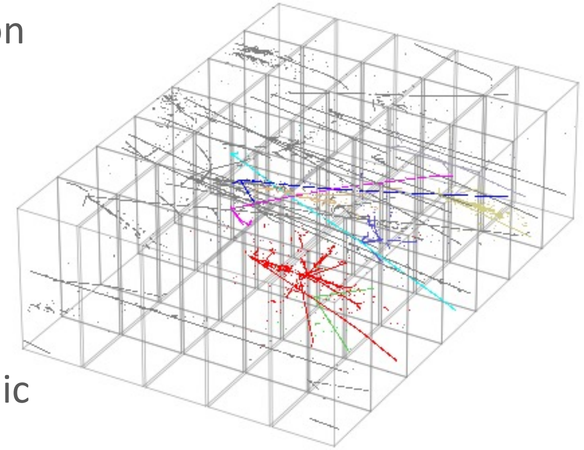
- True 3D pixelated charge readout
- High-coverage light readout; independent charge and position
- Resistive sheet field cage, segmented design
- Capable of operation in intense environment

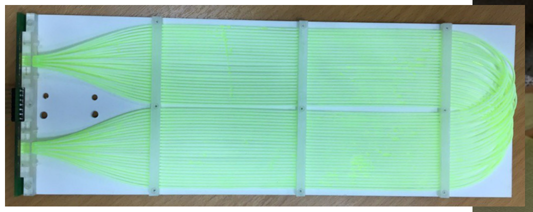
Technical Progress:

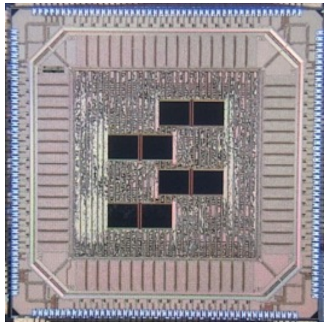
- Significant progress in engineering design
- Ton-scale prototypes besting performance goals
- Effective team delivering working detectors, despite pandemic

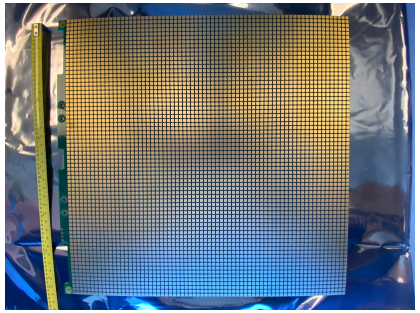


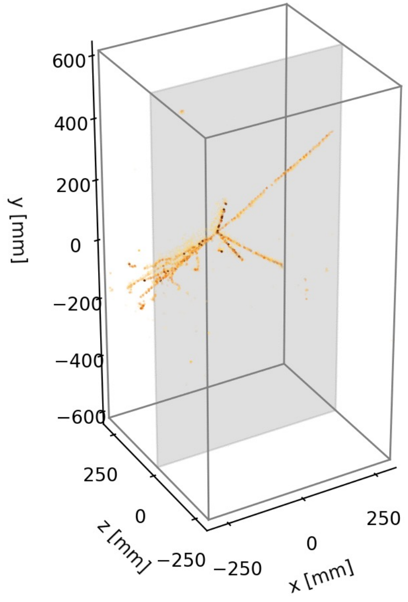








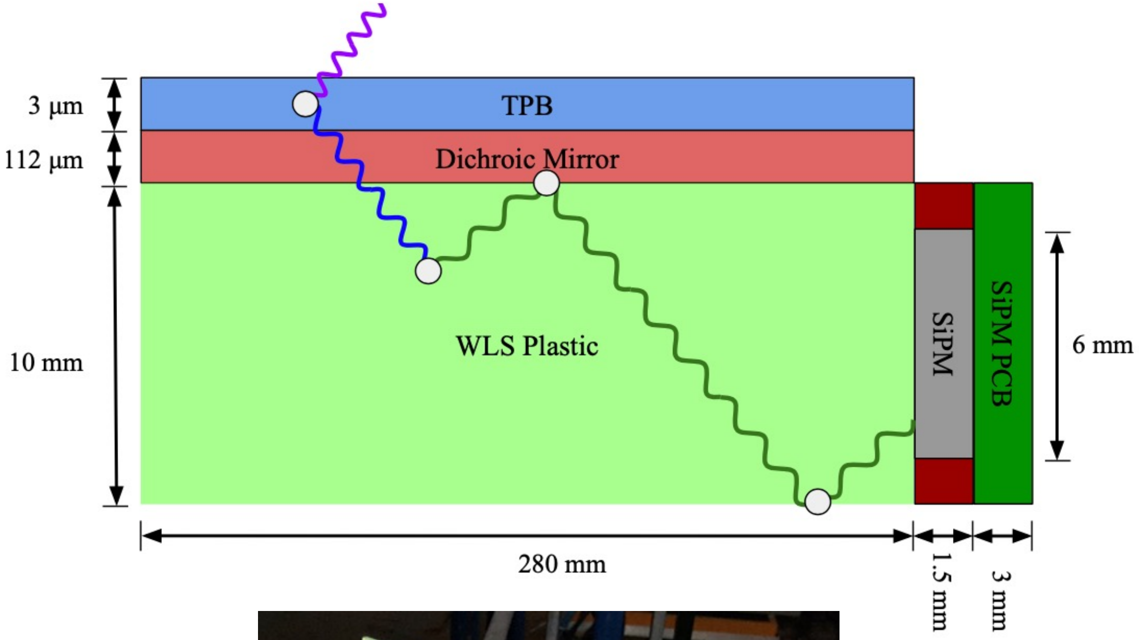




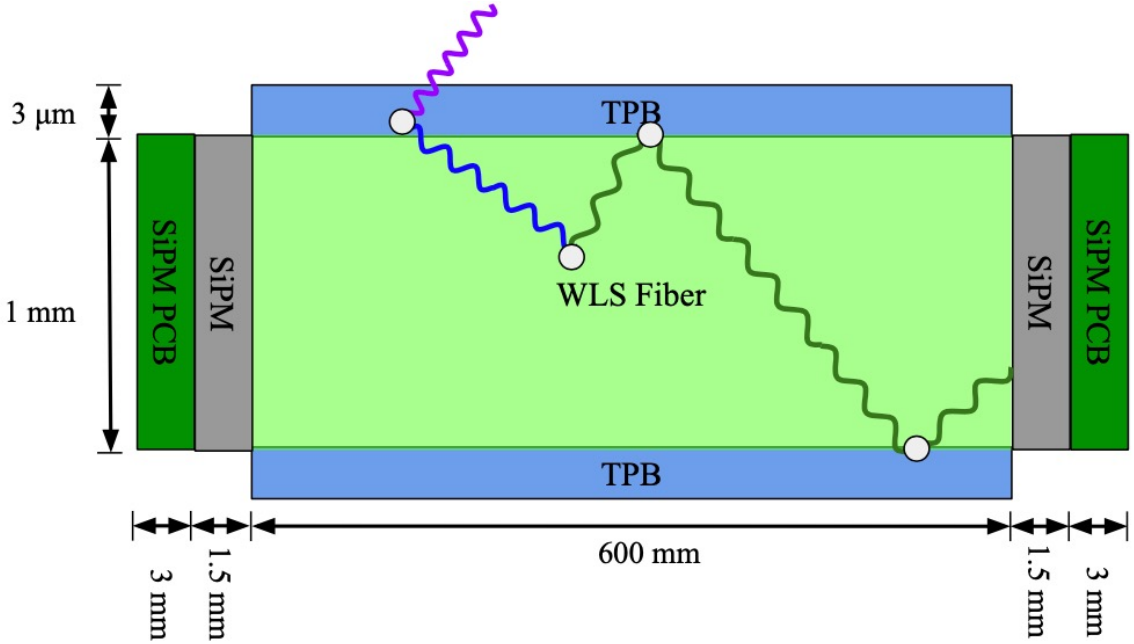
Backup

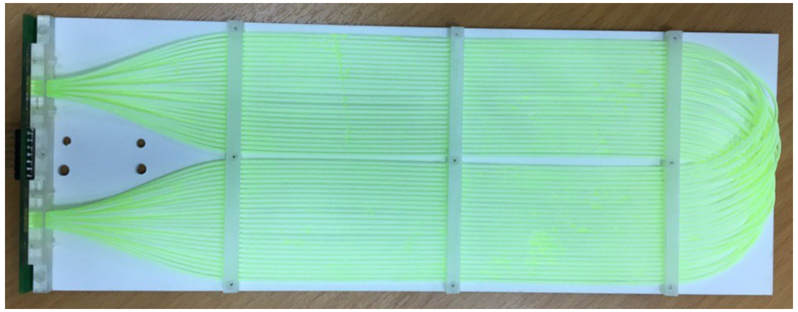
ArgonCube: Light Traps

ArCLight



LCM

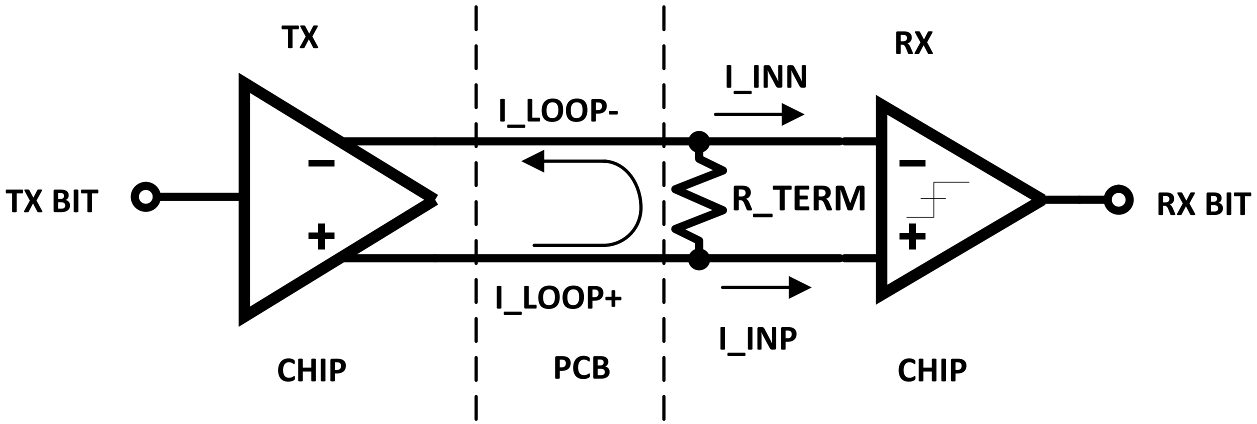


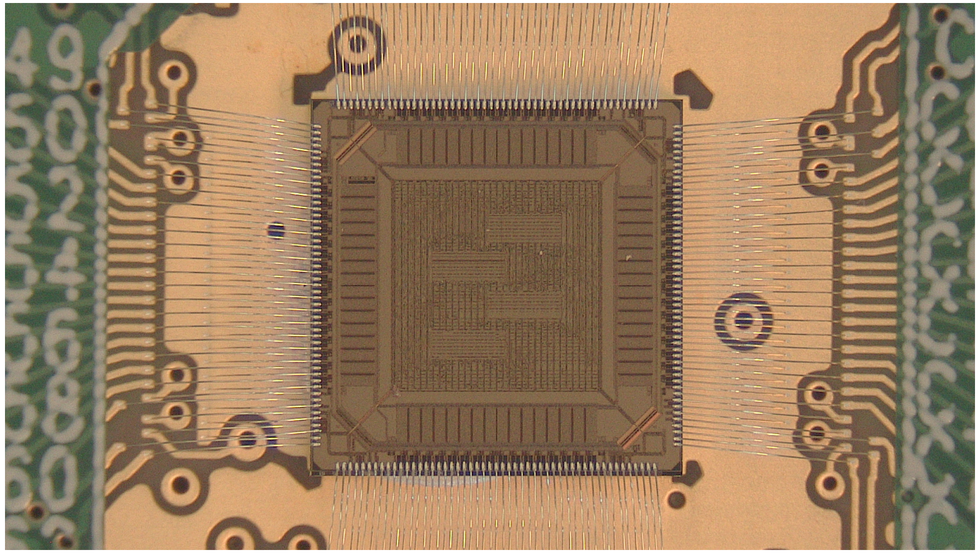


LArPix-v2b: Very low-voltage low-power digital I/O

Custom tunable low-voltage digital transmitter and receiver

- Similar to LVDS in concept, but much lower power: O(10 uW) per transmitter & receiver
- Highly-tunable loop current and termination resistance supports multiple modes of operation (chip-to-chip, multi-drop, etc.)
- Optional mode for automatic transmitter power-down when no data

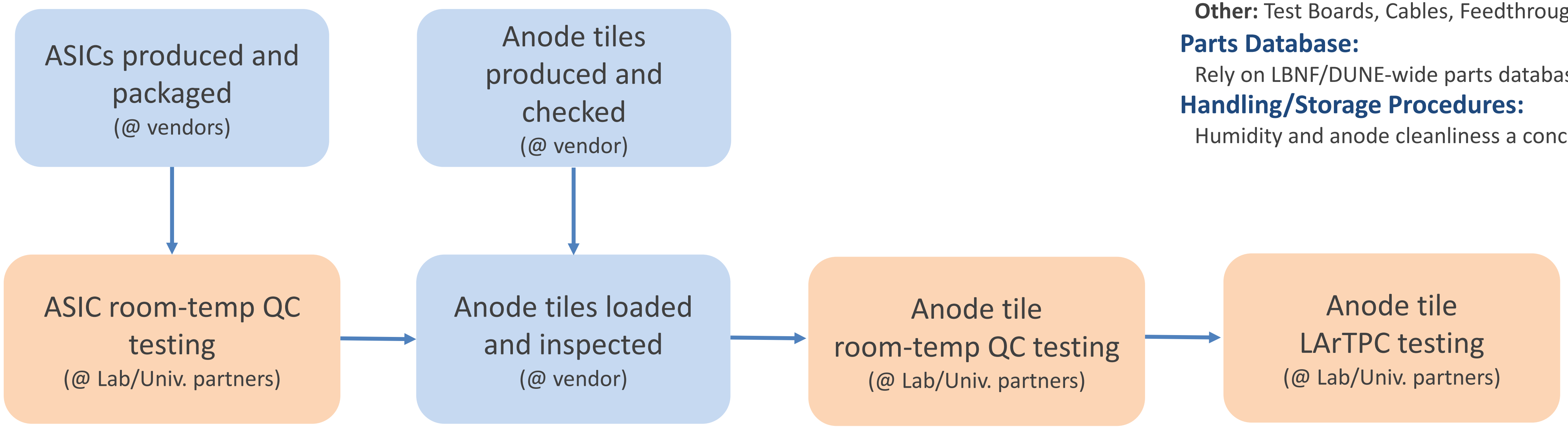




- LArPix-v2b ASICs received Aug. 2021
- Low-voltage I/O working as designed
- Prototype v2b-based pixel tiles now in production

Production and Testing Process

LArPix-v2 informing the production and testing plan:



LArPix-v2 testing:
>8000 ASICs tested
~1 min/chip

Results:
~1% DOA
~10% sub-spec performance

LArPix-v2 testing:
~40 tiles tested (so far)
~1 hr/tile

Results:
O(few) chip failed post-assembly
Chip replacement: ~30 min

LArPix-v2 testing:
~40 tiles tested (so far)
~? hrs/tile (varies by system fill/empty time)

Results:
One cryo-failure now under investigation

Other details:

Unique IDs: Items marked with unique identifier
- **ASICs:** Serial number and QR, laser etched
- **Pixel Tiles:** Current: manual marking. Future: at vendor
- **Other:** Test Boards, Cables, Feedthroughs, Controllers: TBD

Parts Database:
Rely on LBNF/DUNE-wide parts database?

Handling/Storage Procedures:
Humidity and anode cleanliness a concern (leakage current)

Progress: 2x2 Cryogenics System

Cryogenics Infrastructure @ Bern:

- Recirculation system provides LAr purification and cooling
- Gas analysis for system characterization
- Controls and monitoring system
- Designed to support multiple cryostats:
  - Existing ‘Medium’ cryostat
  - New ’Single Module’
  - Existing ‘2x2’ cryostat

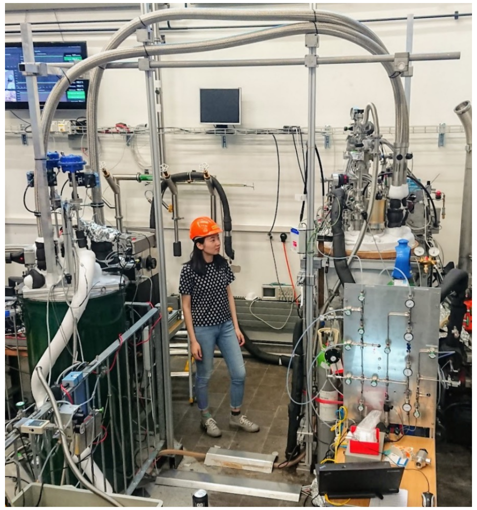
Status:

- Commissioned system at Bern
- Verified LAr purification via O_2 poisoning and recovery

Institutions:

Univ. of Bern, FNAL

Cryogenics Infrastructure



Single Module Cryostat

2x2 Demonstrator Cryostat

Slow controls, monitoring, and DAQ

Photo of LAr fill with Module 0 TPC