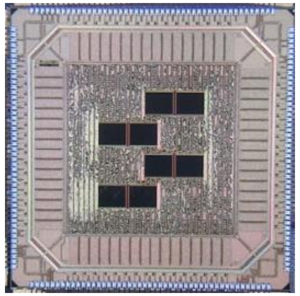
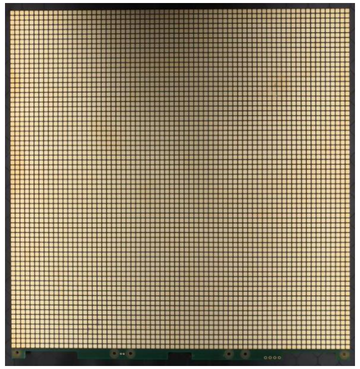
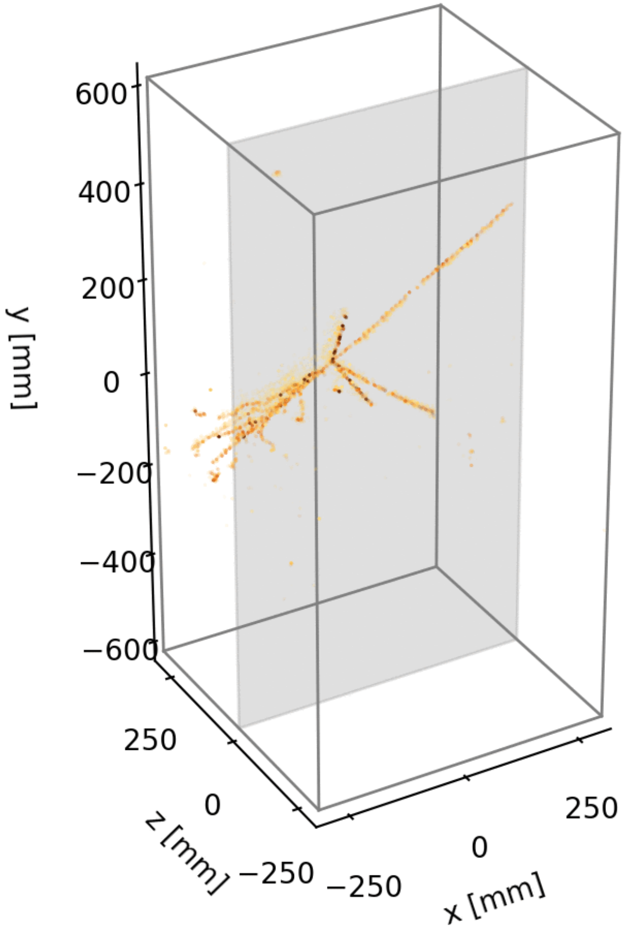
Pixel Readout
for Large Cryogenic Detectors



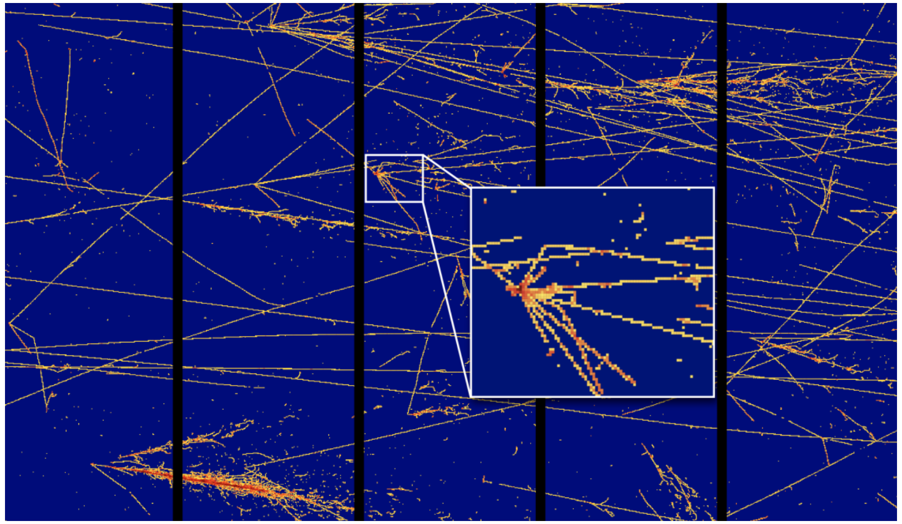




Dan Dwyer (LBNL)

Pixel 2022 (Santa Fe, NM)

12 Dec 2022

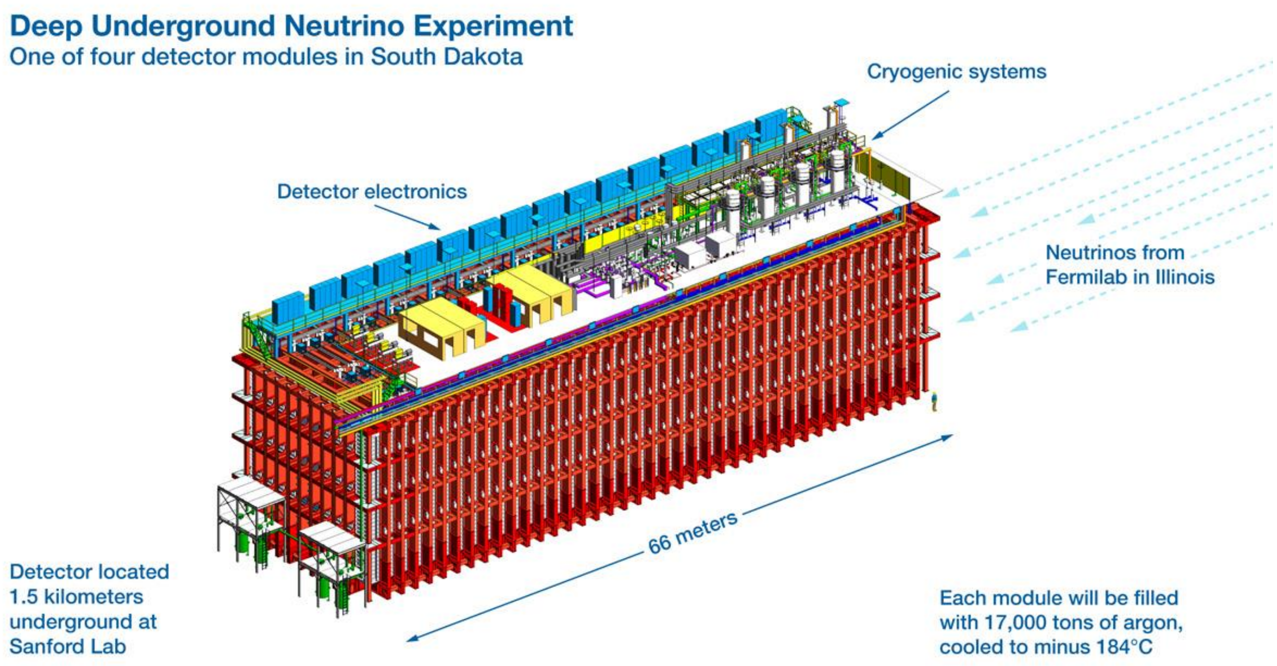


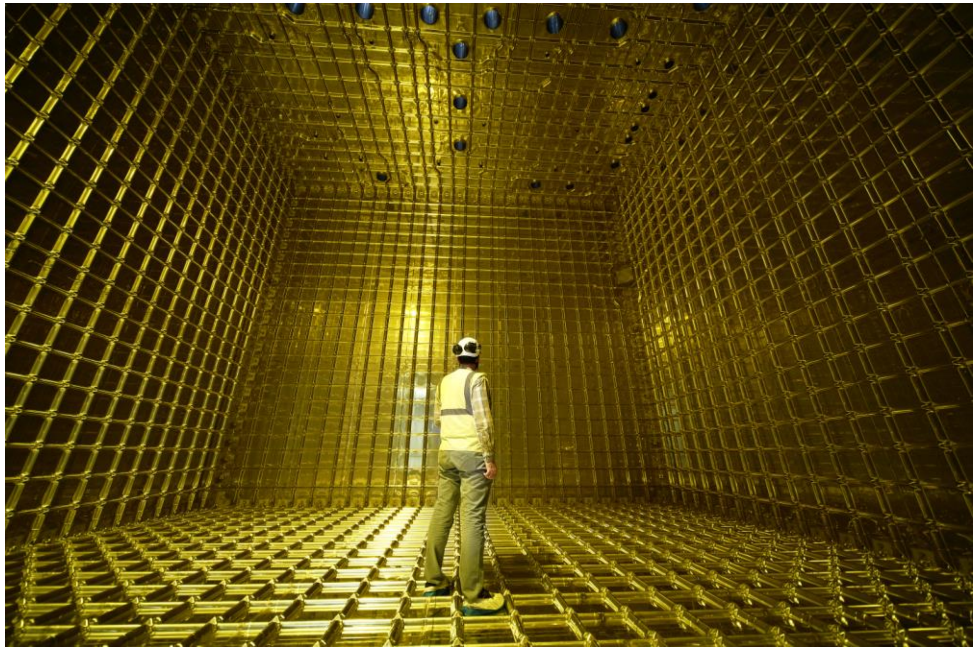
Neutrino Instrumentation Challenge

Deliver mm-scale spatial granularity for stadium-sized detectors.

Example: DUNE

- DUNE consists of four Far Detector modules, with a total volume on the order of **50,000 cubic meters**.
- To achieve the required precision, a **spatial granularity of ~4mm** is required over this volume.
- Corresponds to a detector with a total of **~1 trillion spatial voxels**.





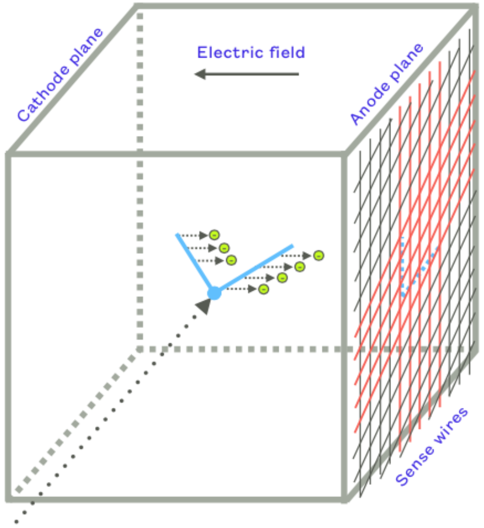
DUNE prototype cyrostat (~1/200th of a DUNE Module)

2D vs. 3D LArTPCs

2D Wire Plane TPC:

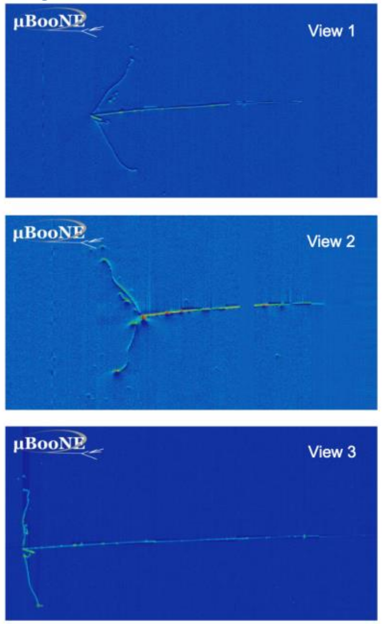
- Established technology, demonstrated in ProtoDUNE-HD
- Multiple 2D views used to estimate 3D signal
- Baseline technology for Far Detector #1 (& Strip variant planned for FD #2)

2D Projective TPC



DUNE prototype anode plane on winding machine

2D Projections in MicroBooNE



3D Pixel TPC:

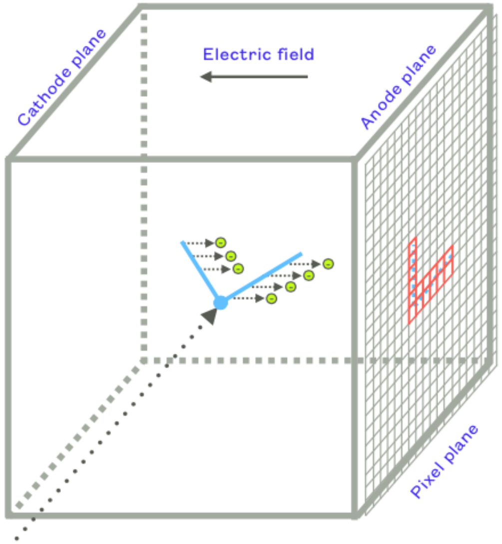
- True 3D imaging
- Continuous readout, ~100% uptime
- Intrinsically sparse data, low data volume

Science Gains:

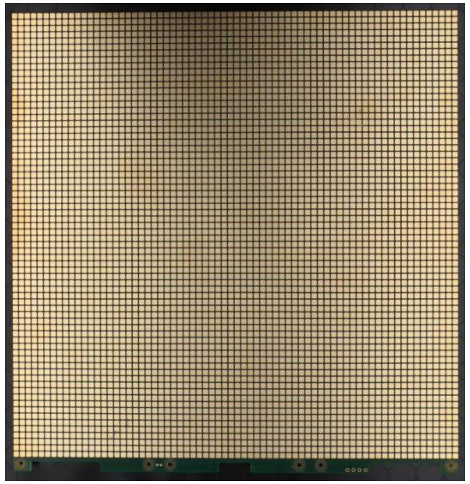
- Improved signal fidelity, S/B
- Enhanced low-energy program

[*JINST* **15** P04009](#)
[arXiv:2203.12109](#)

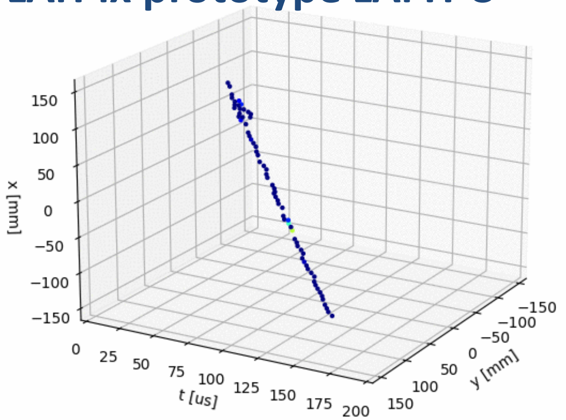
3D TPC



6.4k-channel LArPix prototype pixel anode tile



Raw 3D Cosmic Ray images in LArPix prototype LArTPC



True 3D Readout Technical Targets

For the upcoming large cryogenic detectors *(e.g. DUNE)*

Resolution and noise

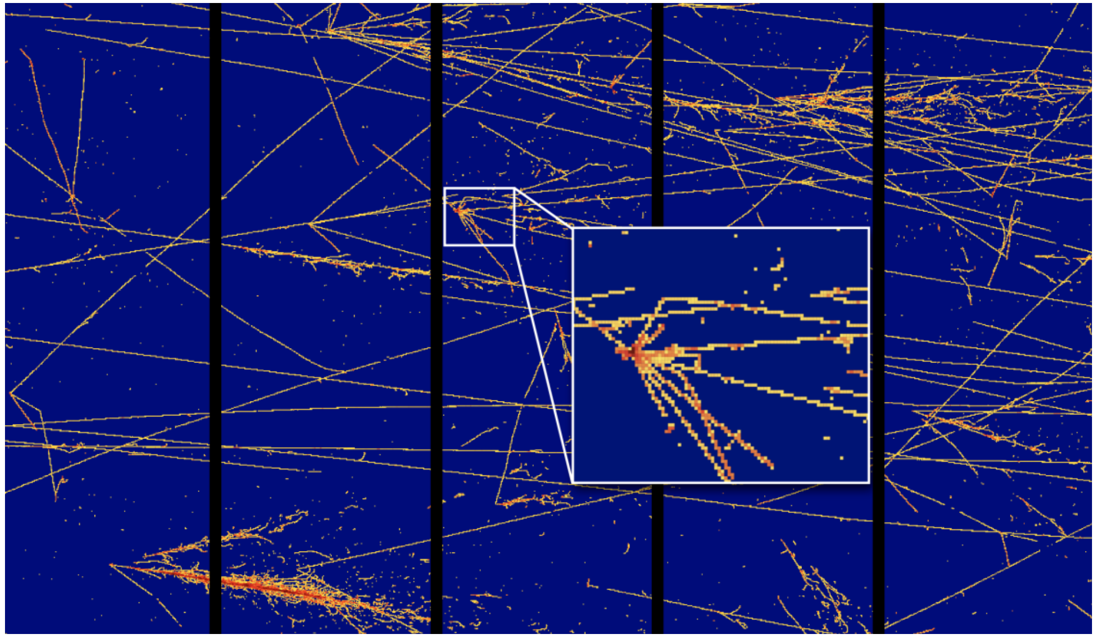
- A granularity of **O(mm)** in space and **O(μs)** in time
- Triggering and charge resolution of signals of **O(1000 electrons)**

Cryogenic compatibility

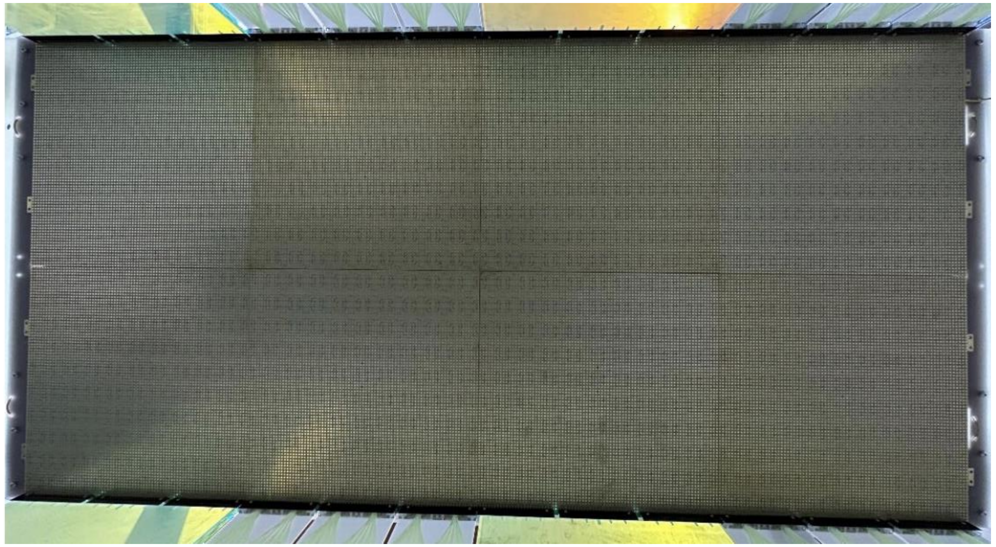
- Long-term reliable operation at **87 K** (in liquid argon)
- Total power dissipation of **O(100 μW) per pixel**, **O(10 W/m^2)** of sensitive anode

Scalability

- Low-power reliable digital multiplexing of **O(10,000 pixels)**
- Viable production path for anodes of **O(1000 m^2)**
- Full system production cost of **O($10k / m^2)** at detector scale



Simulation of one neutrino beam spill in the DUNE LArTPC Near Detector



Prototype LArPix 50k-pixel (0.8 m^2) anode

LArPix

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

S

UCI University of California, Irvine

Yale

YORK
UNIVERSITÉ
UNIVERSITY

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**

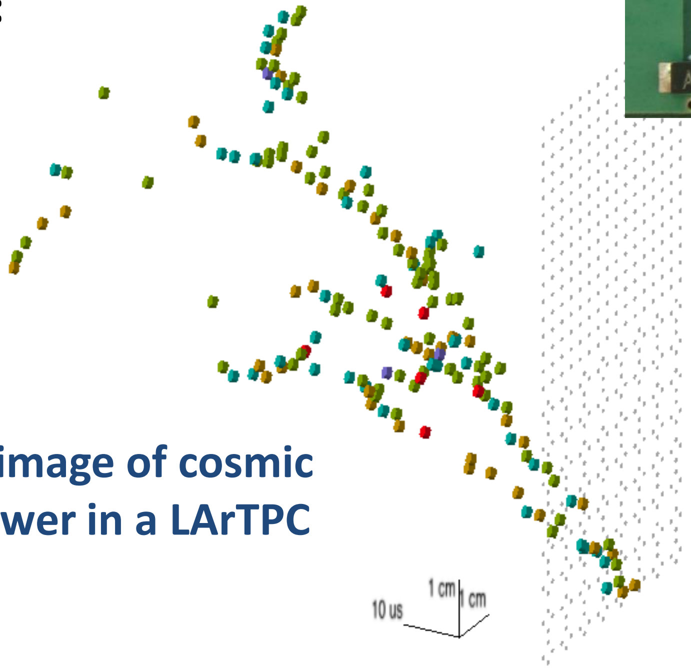
-> Successfully imaged cosmic rays in LArTPC

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

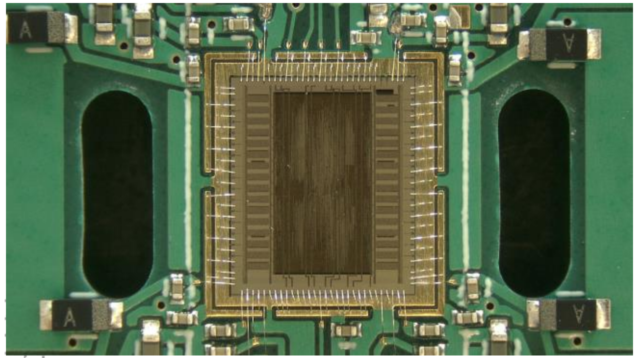
Control electronics:
- Fieldable system: noise-isolated and wifi accessible

Main drawback:
Difficult to scale above O(1k) pixels
- Anode requires manual assembly, bare chip wirebonding

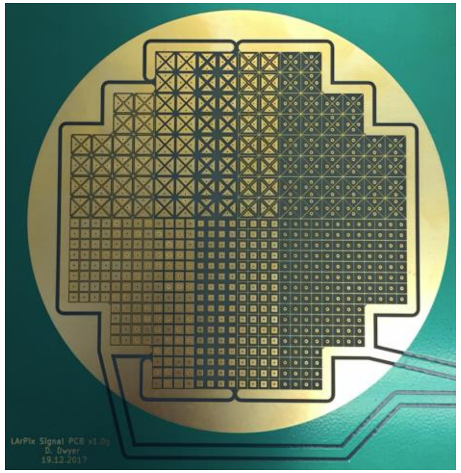


3D image of cosmic shower in a LArTPC

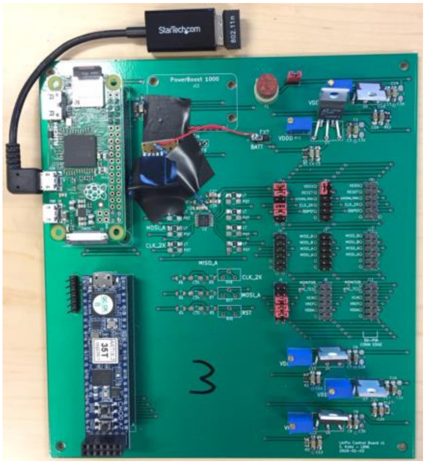
LArPix-v1 ASIC



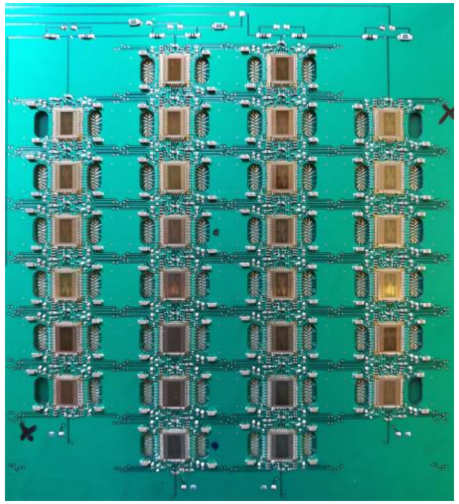
v1 Pixel Anode, Front



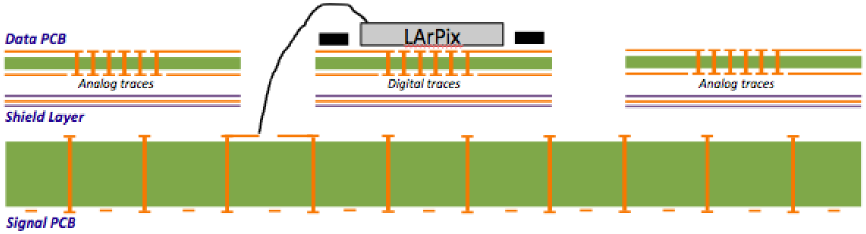
LArPix-v1 Tile Controller



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

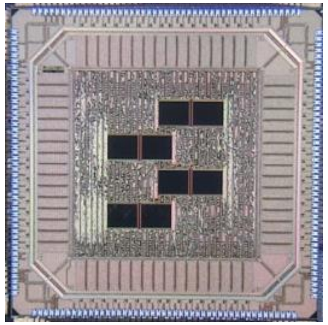
Pixel Anode Design Overhaul:
- ‘Tileable’ design to cover anodes of arbitrary scale
- 32cm by 32cm pixel anode PCB tile
- Frontside: 4900 square pixels, 4.4 mm spacing
- Backside: 10x10 grid of ASICs
- Enable fully-commercial mass production and assembly

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

Key R&D Achievement:

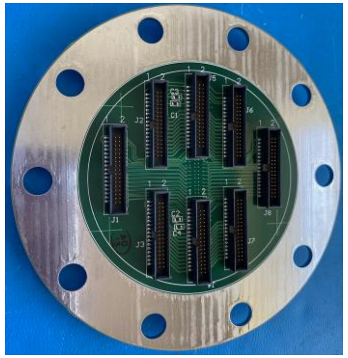
Demonstrated **robust and scalable pixel anode**
- Fast (~few weeks) fully-commercial production/assembly
- Robust to repeated cryogenic cycling
- Successfully imaged cosmic rays in LArTPC on first try

LArPix-v2 ASIC

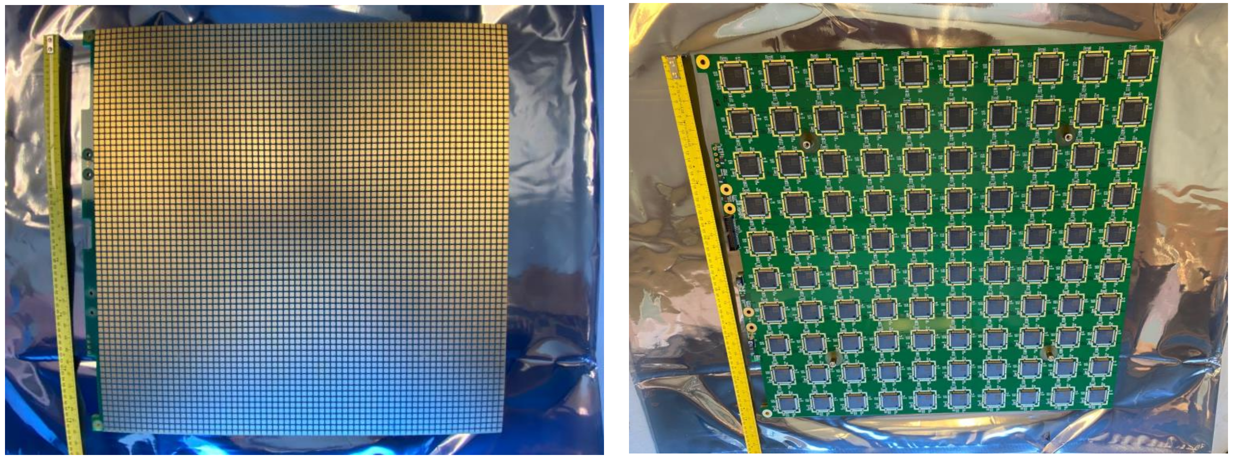


PACMAN Tile Controller

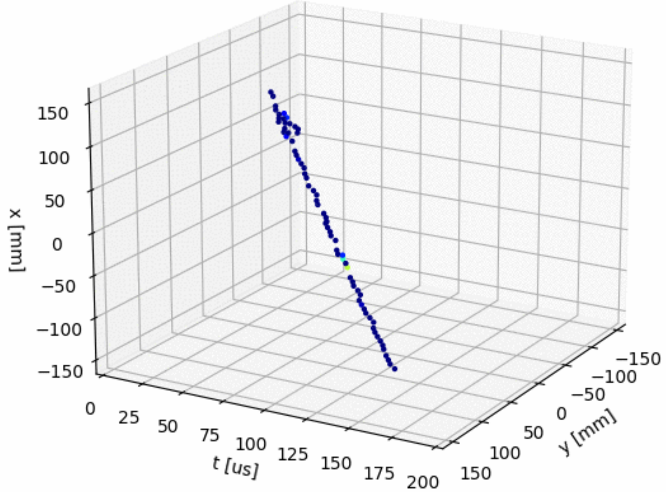
8-Tile Feedthrough



Production-scale LArPix-v2 Pixel Anode



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



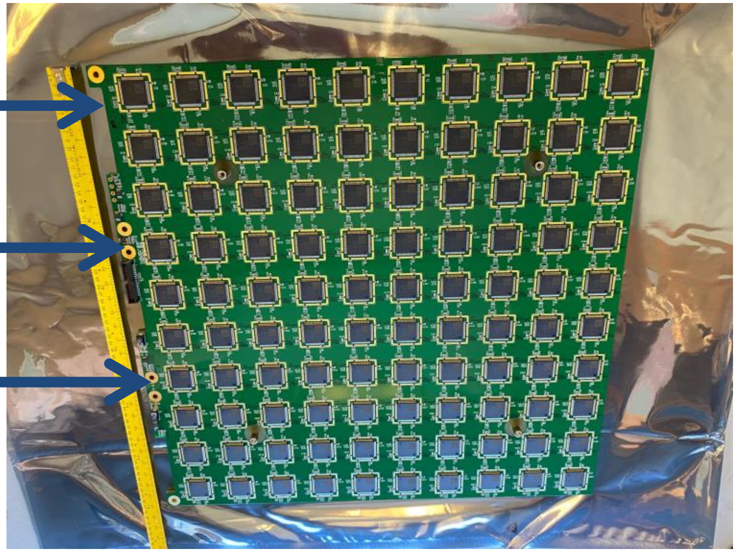
“LArPix-v2: a commercially scalable large-format 3D charge-readout scheme for LArTPCs” publication in preparation

R&D on Robustness: Hydra-I/O

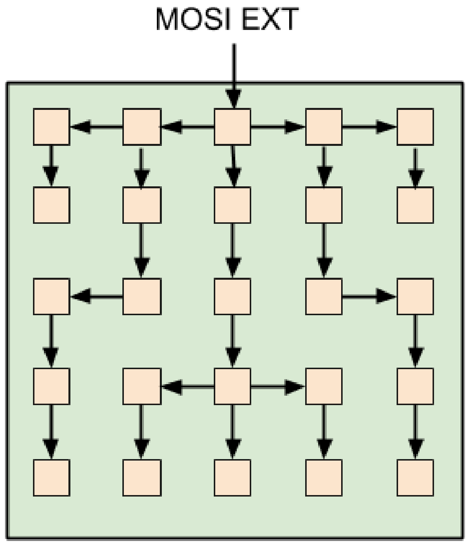
New design for robust I/O and control architecture

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

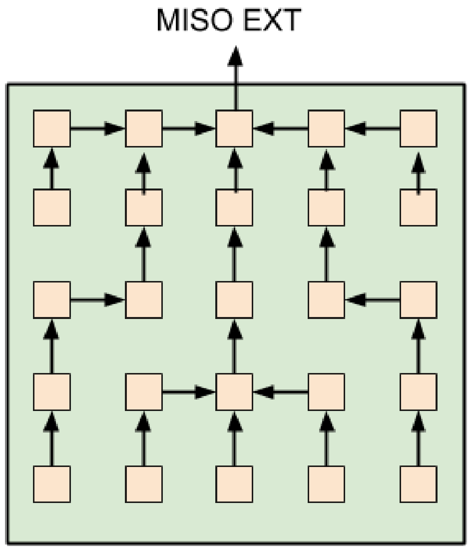
Four chips have direct off-tile I/O channels (10 MHz, < 4 m)



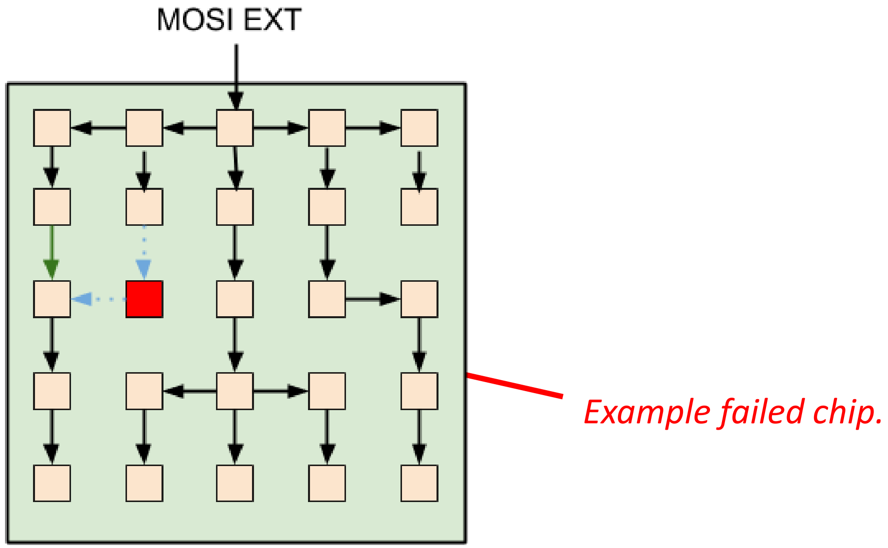
Example: 5 x 5 Pixel Tile



Upstream configuration commands



Downstream data flow



Network reconfigured to avoid failed ASIC

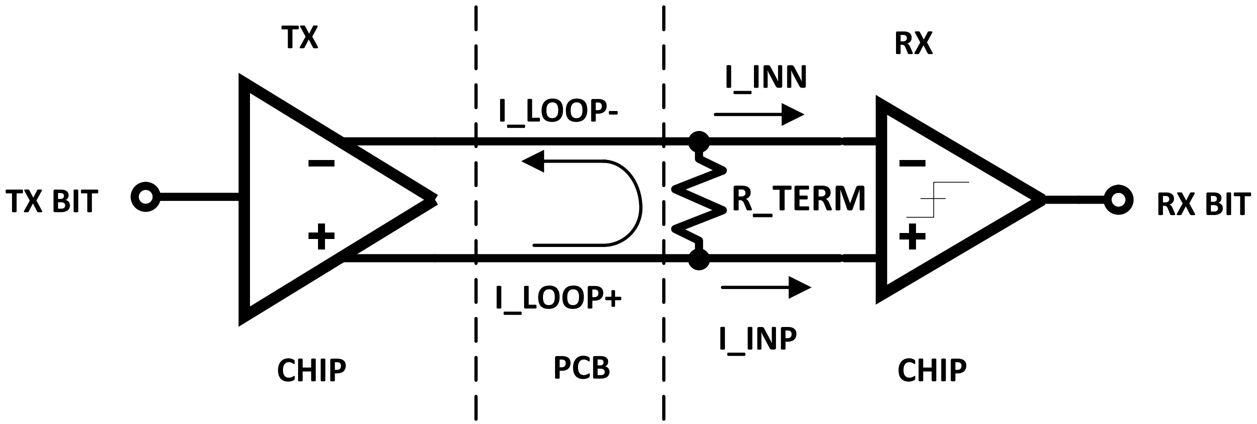
AD-HOC NETWORK OF READOUT APPLICATION-SPECIFIC INTEGRATED CIRCUITS FOR RELIABLE DETECTOR INSTRUMENTATION
U.S. Patent Application Ser. No: 63/140,434

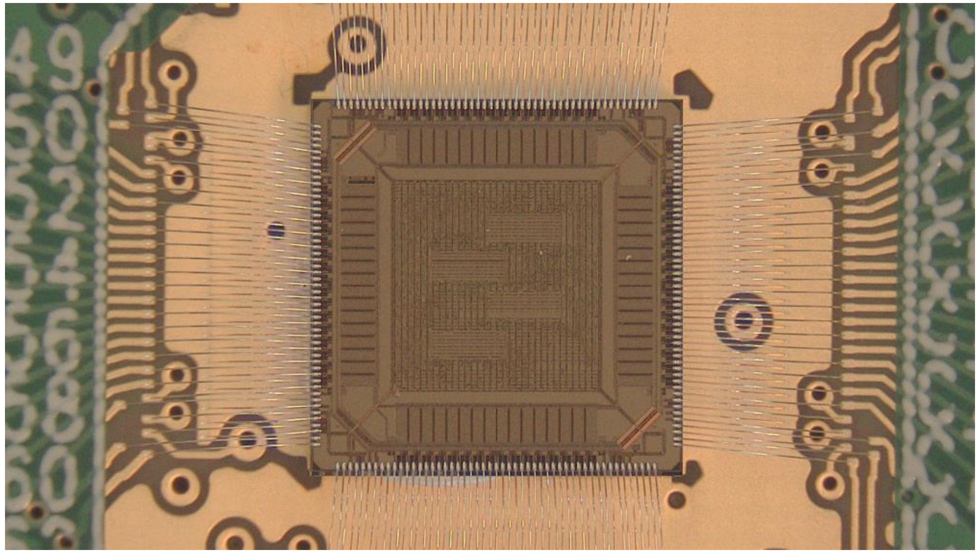
2022 R&D 100 Award

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

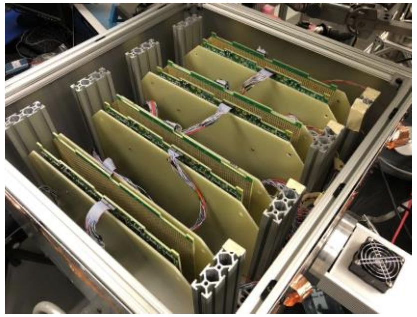




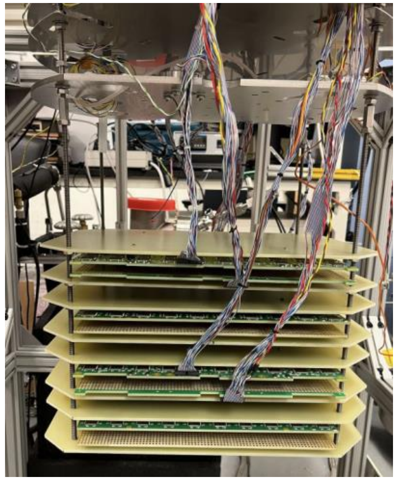
- LArPix-v2b ASICs received Aug. 2021
- Low-voltage I/O working as designed
- Prototype v2b-based pixel tiles now in production

LArPix-v2: Scalable Production and Testing Process

All production/assembly done via commercial vendors; QC testing performed by scientific staff



Room-temp System Test



Cryo-test of Pixel Tiles

ASICs produced and packaged
(@ vendors)

↓

ASIC room-temp QC testing
(@ Lab/Univ. partners)

→

Anode tiles produced and checked
(@ vendor)

↓

Anode tiles loaded and inspected
(@ vendor)

→

Controllers, cables, feedthroughs produced and checked
(@ vendor)

↓

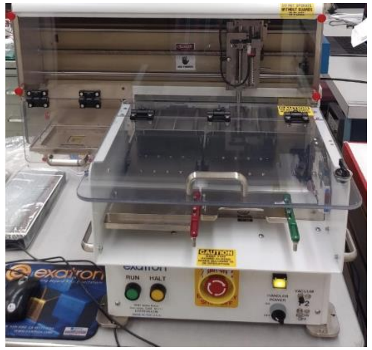
LArPix System room-temp QC testing
(@ Lab/Univ. partners)

→

LArPix System QC Cryo-testing
(@ Lab/Univ. partners)

LArPix-v2 testing:
~8,000 ASICs tested (so far)
~600 chips/day (1 robot)

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



ASIC Testing Robot

LArPix-v2 testing:
~60 tiles tested (so far)
~8 tile batches, ~1hr

Results:
~0.5% chips failed post-assembly
Chip replacement: ~30 min

LArPix-v2 testing:
~60 tiles tested (so far)
~8 tile batches (time limited by LN fill/empty)

Results:
No cryo-failures yet

Prototyping: ArgonCube 2x2 LArTPCs

Four ton-scale Prototype TPC Modules to validate DUNE Near Detector Design

Each TPC Module:

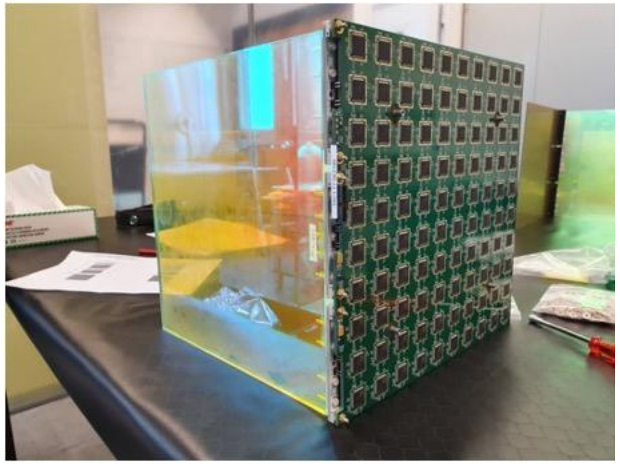
- Active Size: 0.7m x 0.7m x 1.25m
- 16 pixel tiles, with ~80k pixel channels total
- 16 light collection modules, with 96 light sensors (SiPMs)
- Resistive-film-on-fiberglass field cage

Progress @ Univ. of Bern:

- TPC Module 0:
  Run 1 (Demonstration): *Apr. 1-10, 2021*
  Run 2 (Extra Cryo-test): *Jun. 21-26, 2021*
- TPC Module 1 Operation:
  Feb. 5-13, 2022

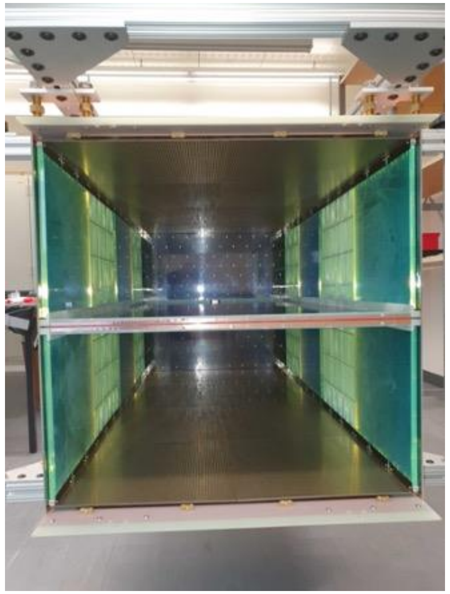
Achievements:

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


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

Prototyping: ArgonCube 2x2 LArTPCs

*Typical **raw data** from cosmic ray interactions imaged in 3D prototype detectors*

Verified design meets technical requirements:

- 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)

Continuous readout:

~100% live, independent of light system

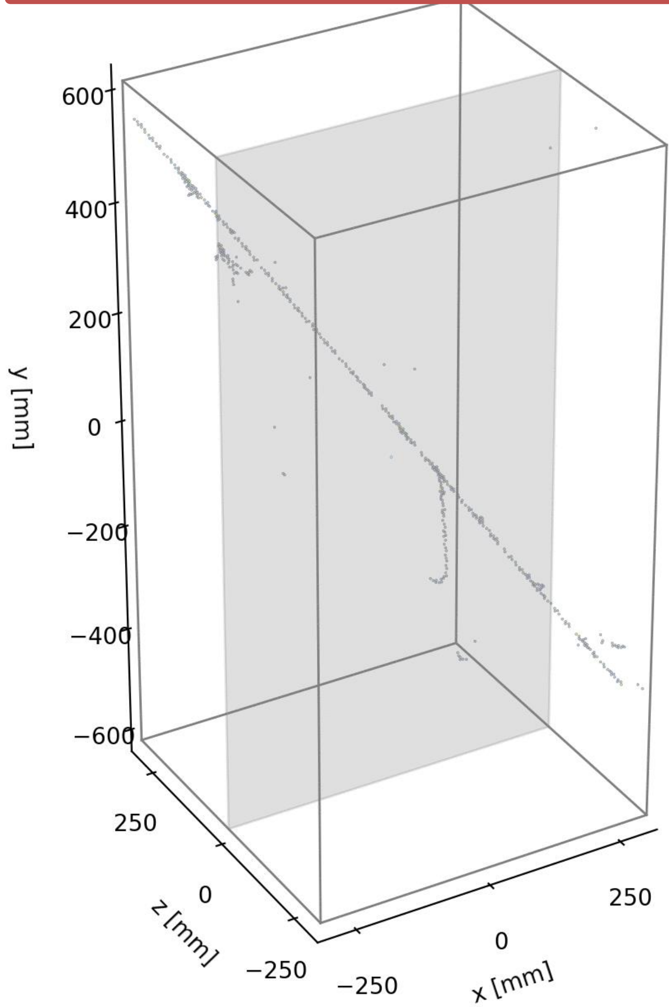
Low data rate due to self-triggered design

Arguably the most performant ton-scale LArTPC to date.

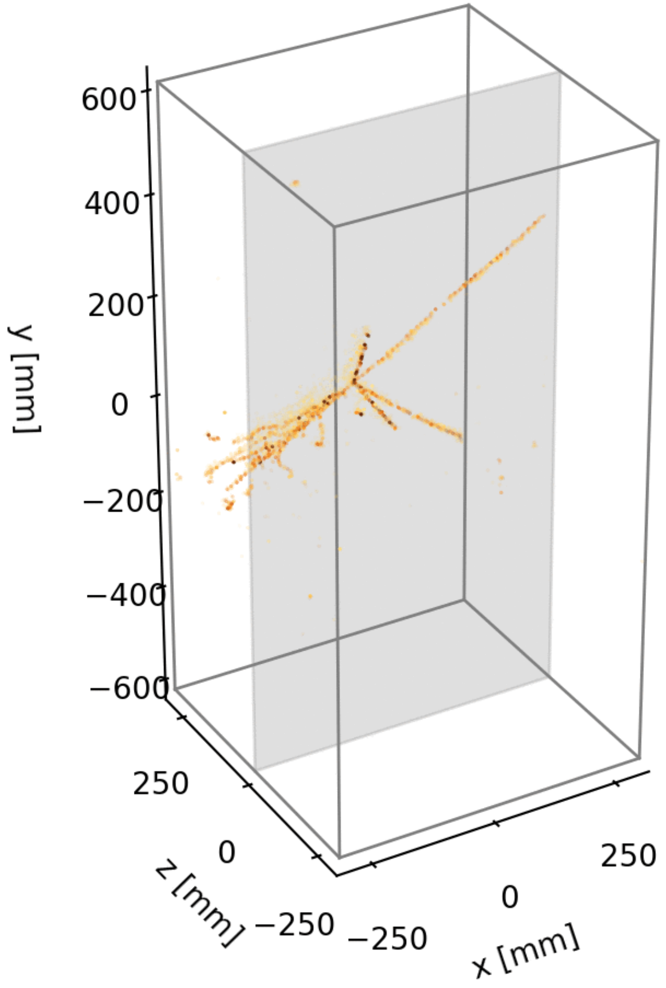
Feb 2023: Four ton-scale TPC modules ready

Mid 2023: Operation in NuMI Neutrino Beam

Prototype for the DUNE Near Detector



Module 0 LArTPC

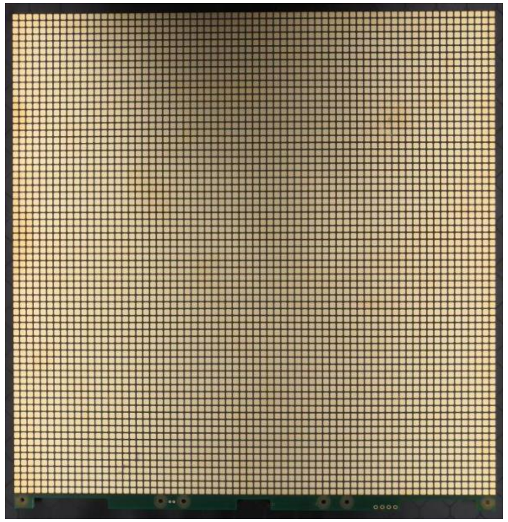


Module 1 LArTPC

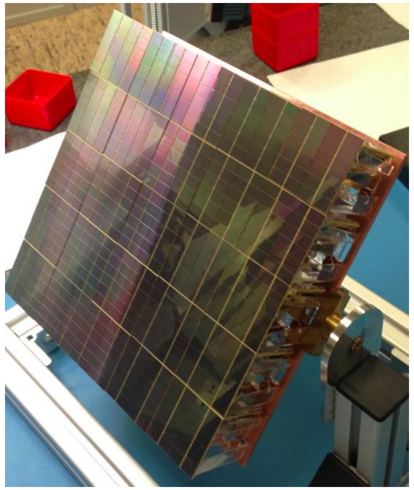
LightPix: Scalable Cryogenic SiPM Readout Electronics

- **Readout Electronics Needs:**
  - Low-power cryogenic-compatible scalable SiPM readout electronics at very low system cost
- **R&D Plan:**
  - **LightPix:**
    - Adapt existing LArPix ASIC to provide scalable readout for many (e.g. >10^6) Silicon Photomultipliers
    - Reuse all of LArPix system architecture (low-power, cryo-compatible, scalable, O($0.10)/channel system cost)
    - Provide a path for highly-granular photodetection systems for very large detectors

***Rough concept:** Replace LArPix charge-collection pixels with SiPMs*



e.g. Prototype 6.4k-channel LArPix-v2 tile



e.g. Darkside-20k prototype light sensor

Why LightPix:
Existing readout electronics are either too high power or too high cost for our cryogenic detector needs.

Looking ahead:
Personally, I think LightPix fits some specific near-term HEP needs (next 5yrs). In the long-term (5-10yrs), my guess is that digitally-integrated SiPMs may eventually provide better performance at lower cost.

LightPix ASIC

LightPix-v1:

- Develop and test dedicated time-to-digital converter (TDC) to provide < 10ns time resolution
- Add multi-channel coincidence triggering mode to suppress excess data from dark noise at room temp

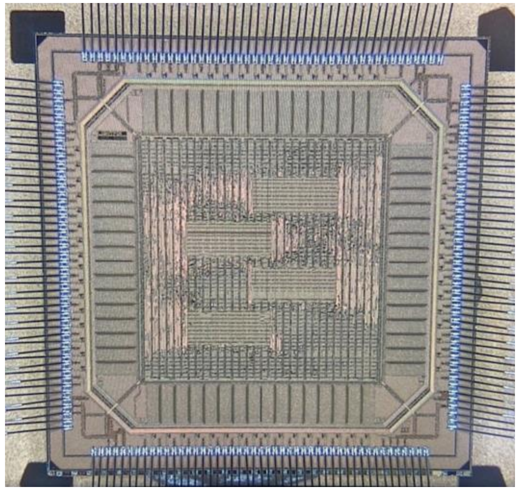
Progress:

- Received Aug. 2021
- Power-up, configuration successful
- TDC meets design targets

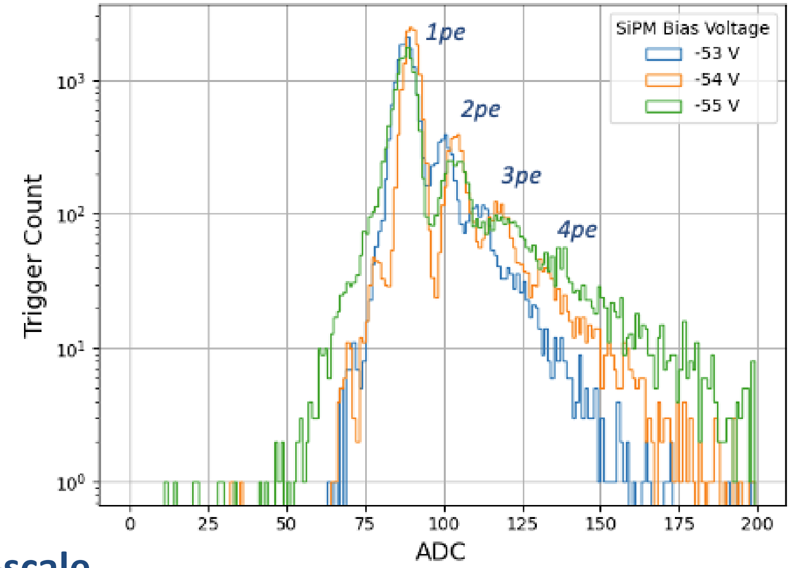
Next Steps:

- LightPix-v2:
  Provide both TDC and ADC functionality
- Deployment and testing of light detector system in prototype LArTPC
- Exploration/optimization of light detector formats

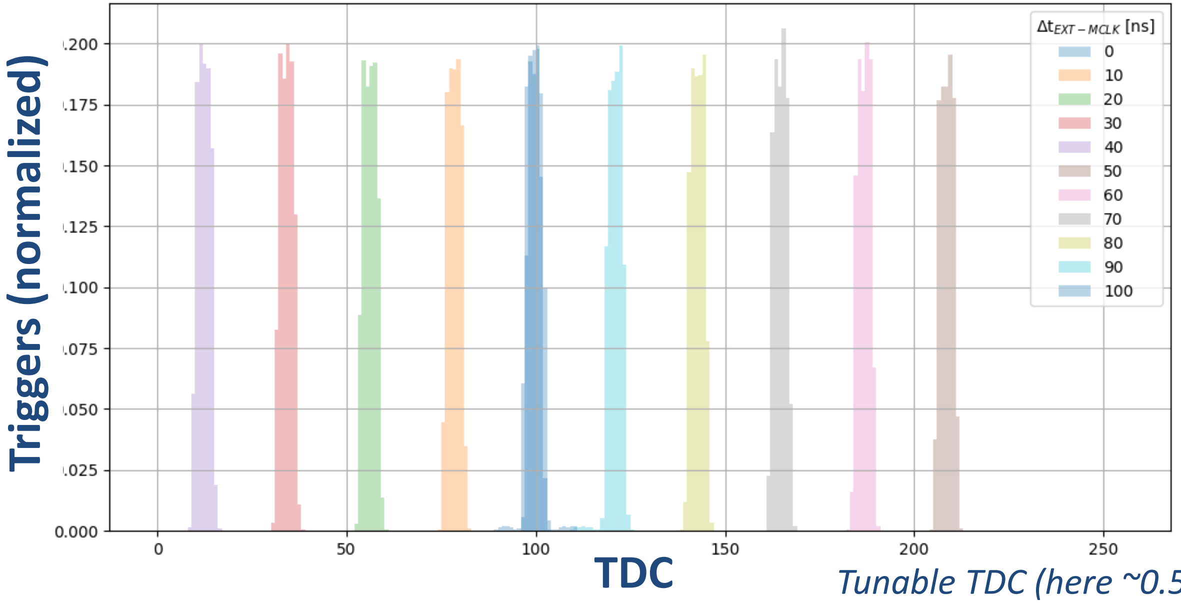
LightPix-v1b ASIC



Photoelectron signal spectrum vs. SiPM bias



Very-low-power TDC achieves ~ns-scale precision in response to external pulse



Tunable TDC (here ~0.5ns/tick)

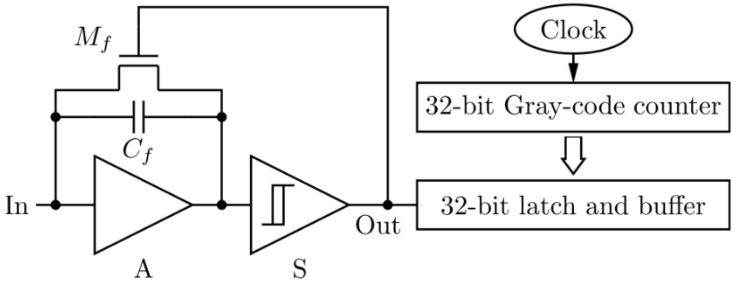
Offset between external pulse and TDC stop signal

QPix

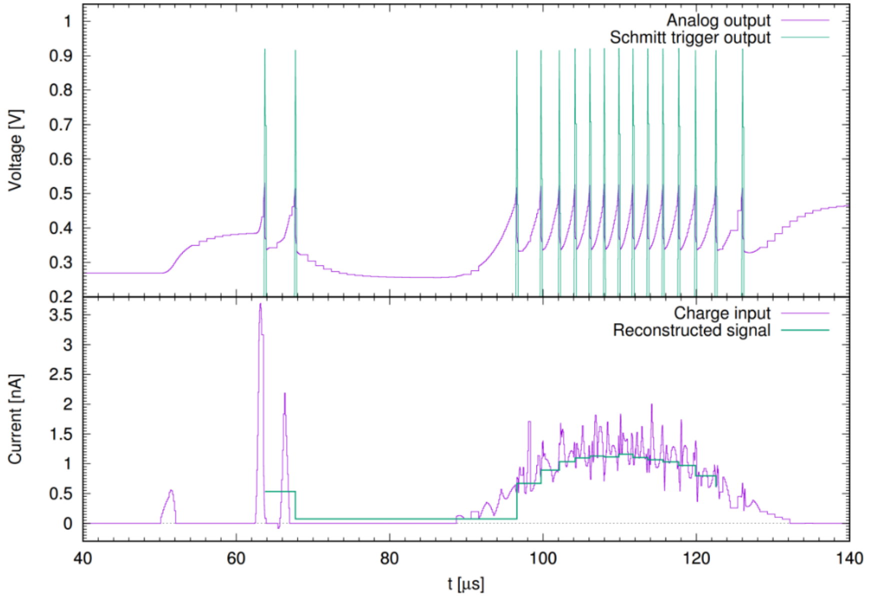
QPix: Concept and Progress

Concept: [arXiv:1809.10213]

Report ‘time between resets’ instead of digitizing charge

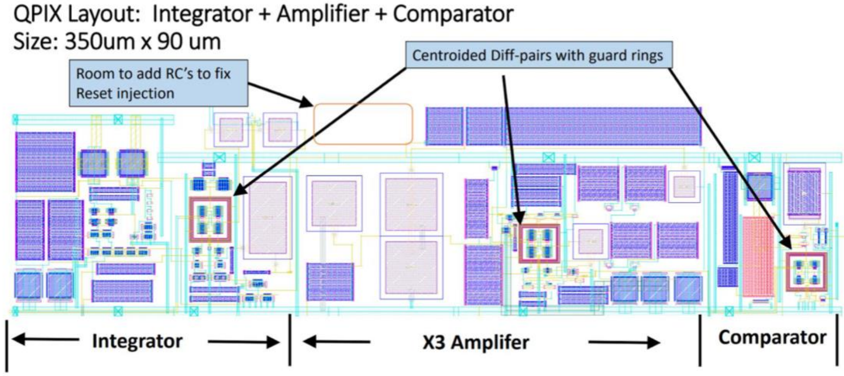


Distribution of reset times proxy for signal current on pixel



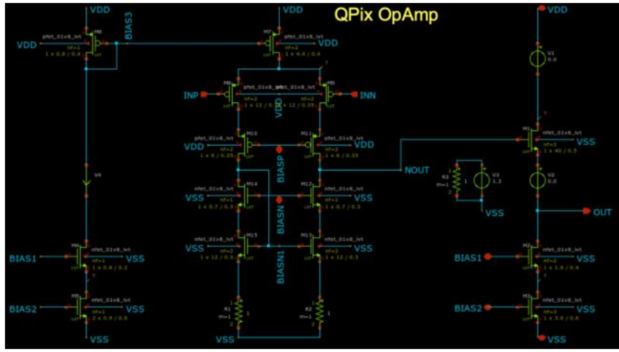
Front-end Prototype ASIC

(180nm, UPenn)



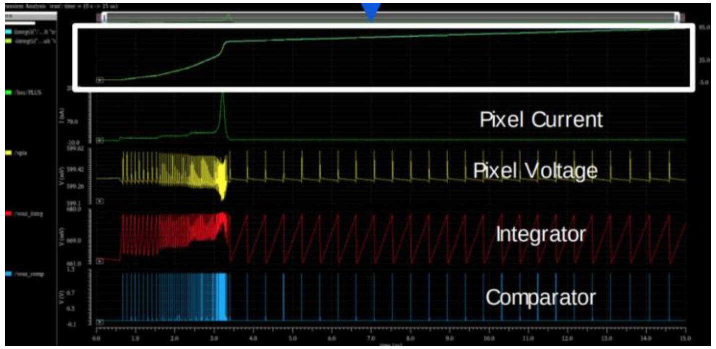
Front-end Prototype ASIC

(130nm, UTA)



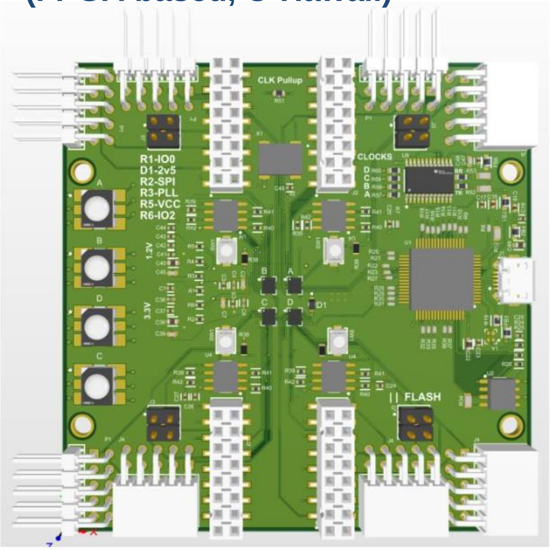
Front-end Design

(65nm, FNAL)



Digital Back-end Prototype

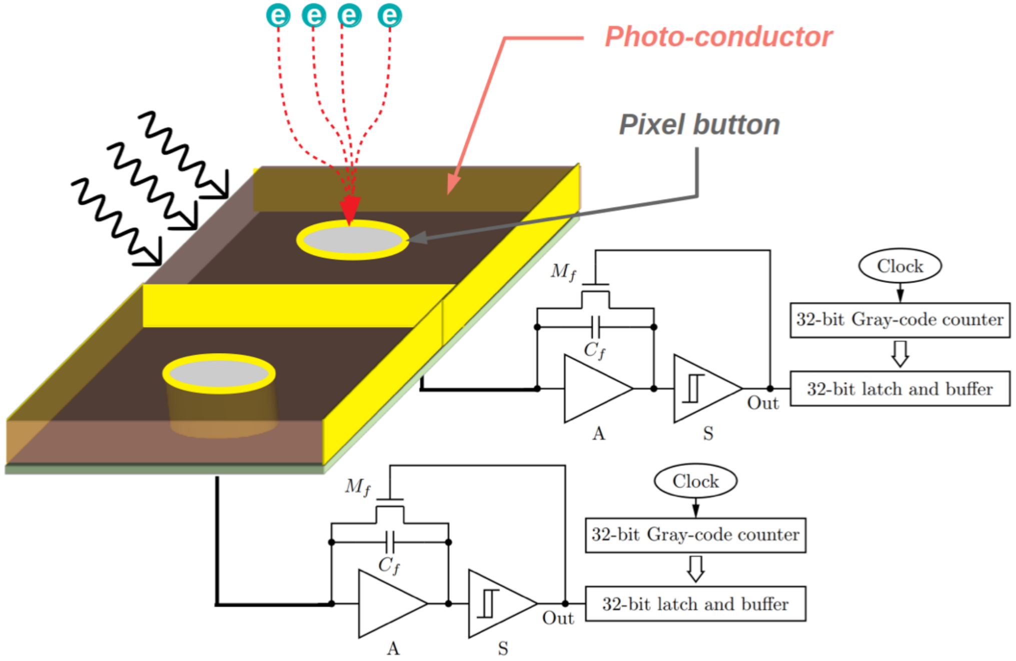
(FPGA-based, U-Hawaii)



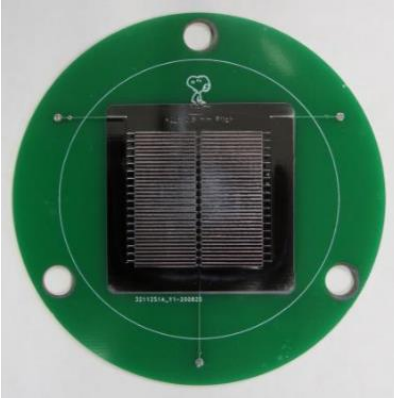
QPix: Light-sensitive Pixels

Concept:

Add photoconductive (ASe) film to pixel anode to make pixels sensitive to both TPC charge and scintillation light

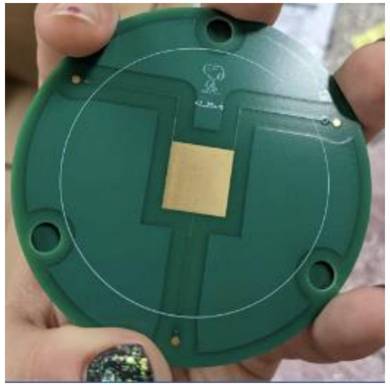


Prototype PCBs with biased traces coated in ASe



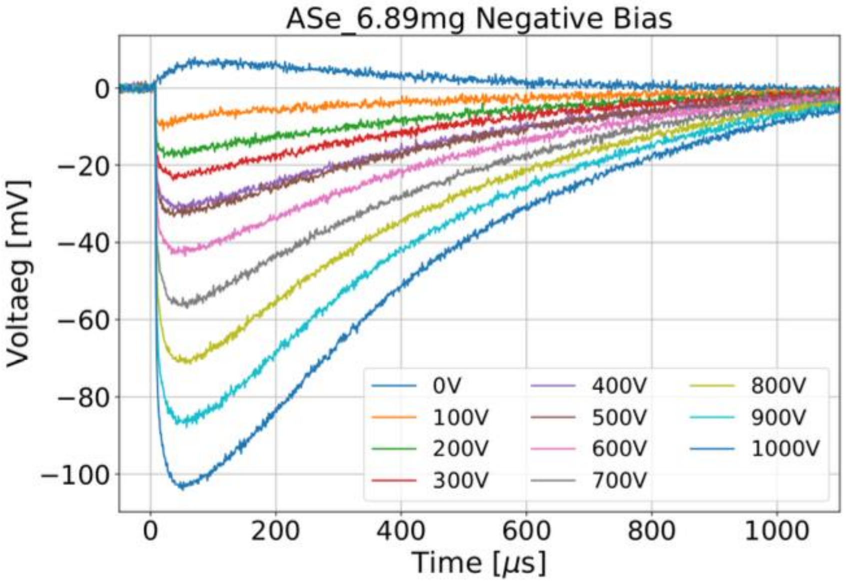
127 um trace spacing
5V/um max field
UTA/ORNL

127 um trace spacing
5V/um max field
UTA/ORNL



25 um trace spacing
40V/um max field
UCSC/UTA/FNAL

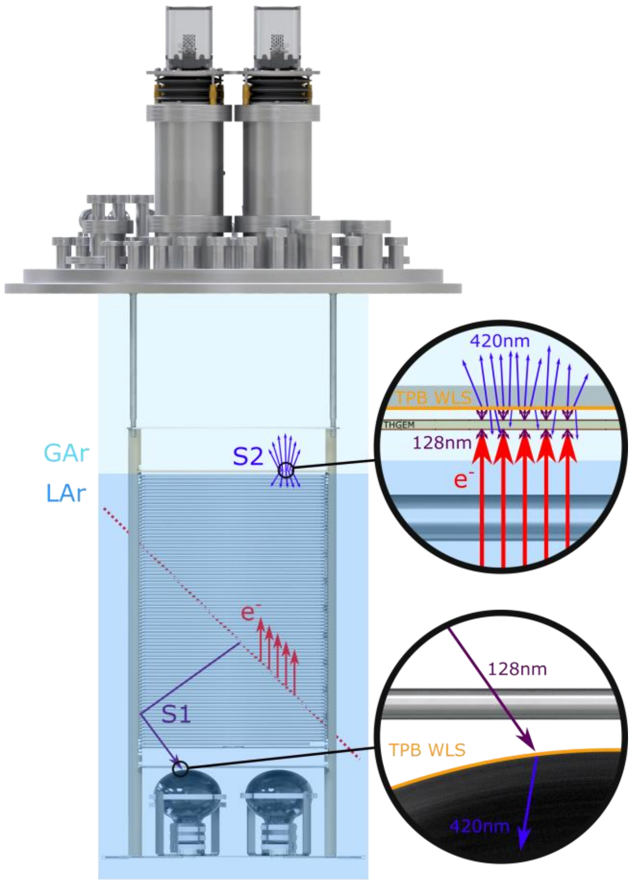
Example signal traces in response to light pulses



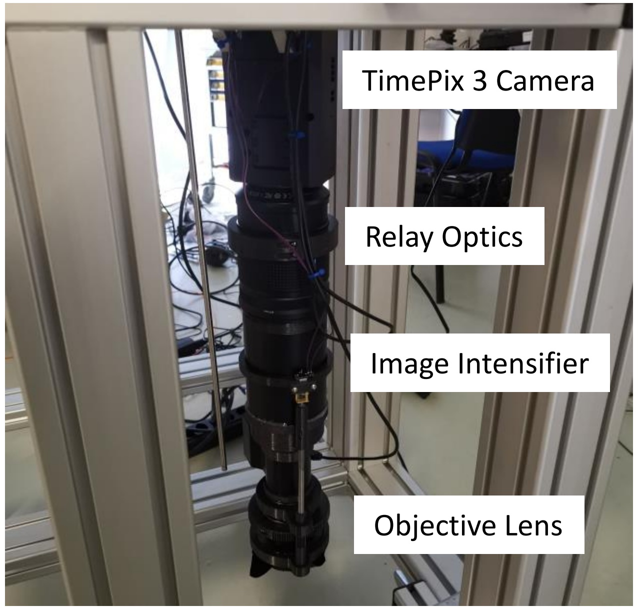
ARIADNE+

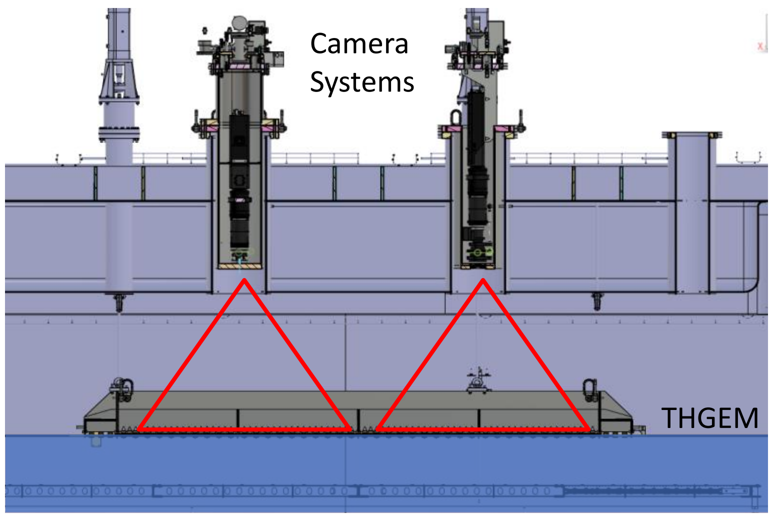
Concept:

Achieve Dual-phase TPC 3D readout by imaging electroluminescence in THGEM with fast optical cameras



Camera System





Advantages:

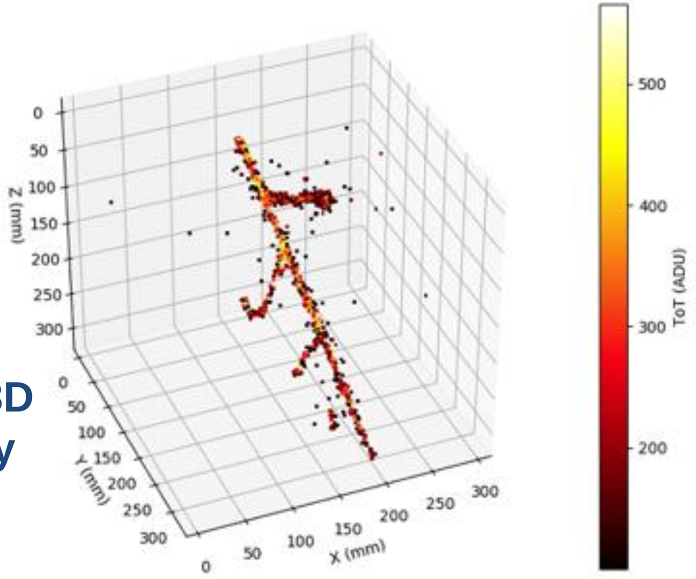
Low noise via optical-only readout
Low threshold due to gas amplification
Accessible/upgradeable: Cameras outside cryostat

Disadvantages:

Only viable in a dual-phase TPC
- High cathode voltage
- High-field e- extraction region
- THGEM amplification

Scattered/indirect light

Example 3D cosmic ray imaged in prototype



Summary: Neutrino Pixels

LArPix:

- True 3D pixelated charge readout for LArTPCs
- Low-noise, low-power, cryogenic-compatible
- Self-triggering, 100% live
- Scalable anode design leverages commercial production
- Two recent 80k-pixel ton-scale prototype exceeded expectations
- Baseline technology for the DUNE Near Detector

LightPix:

- Highly-scalable readout for cryogenic SiPMs
- Reuses much of LArPix system design

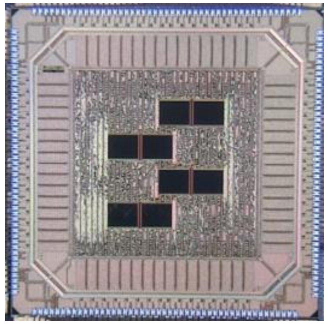
QPix:

- Record trigger time distribution instead of digitizing charge
- R&D on ASe coating to make pixels light-sensitive

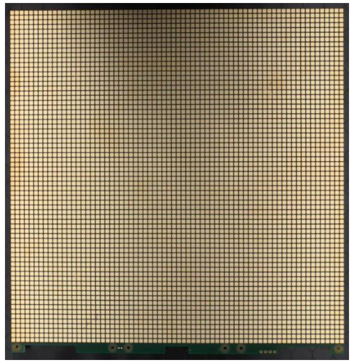
ARIADNE+:

- Optical 3D readout for dual-phase TPCs
- Successful mid-scale prototyping at CERN

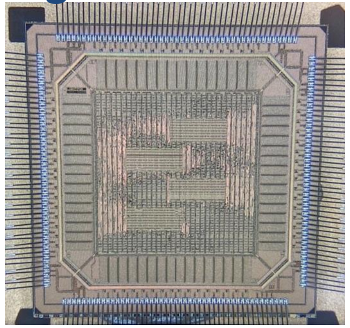
LArPix-v2 ASIC



LArPix-v2 Tile

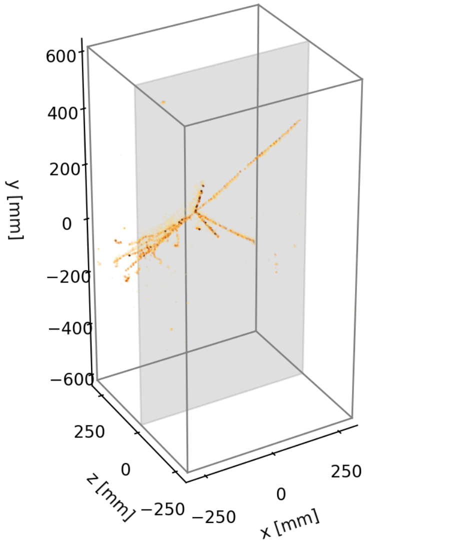


LIghtPix-v1 ASIC

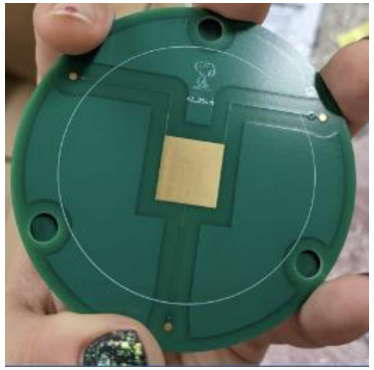


DUNE Near Detector Prototype LArTPC

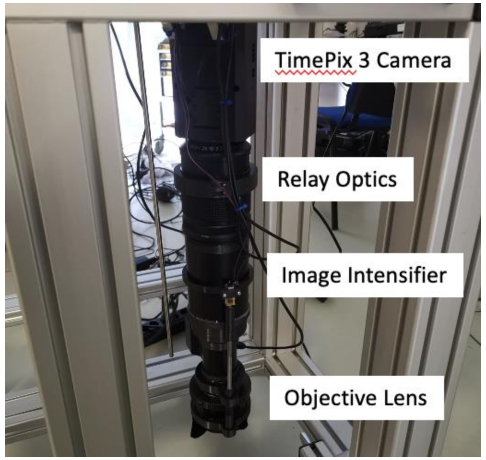
Cosmic ray 3D images from prototype

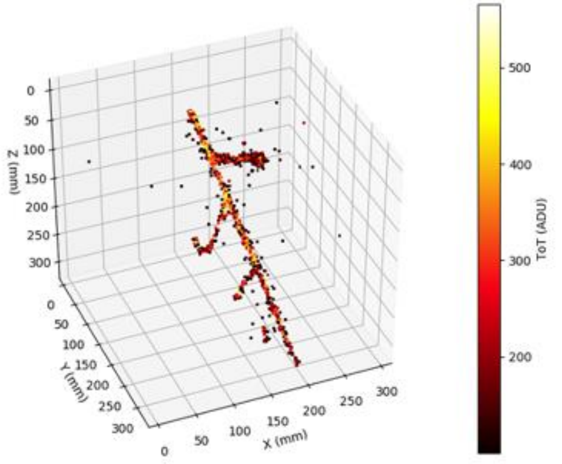


QPix ASe prototype



ARIADNE+ Camera System and 3D imaging





Potential technologies for future highly-granular detectors

Backup

2x2 Module 0 Physics Performance

Data/MC comparison of low-level self-trigger charge distribution versus pixel threshold.

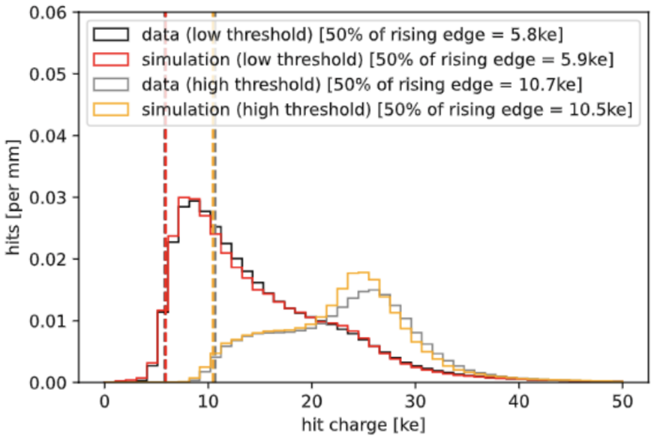


Figure 13. Self-trigger charge distribution for MIP tracks measured in thousands of electrons (ke); 50% of the rising edge are shown as indicators of the charge readout self-trigger thresholds. The MC simulation shown in comparison is described in Section 4.

Energy loss for minimum ionizing muons (dQ/dx)

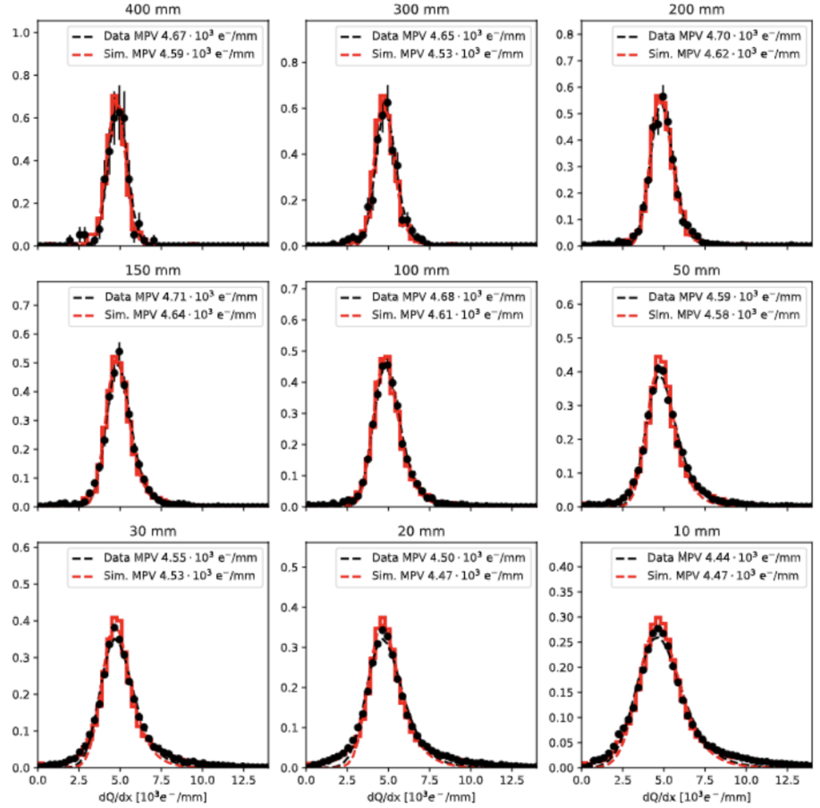
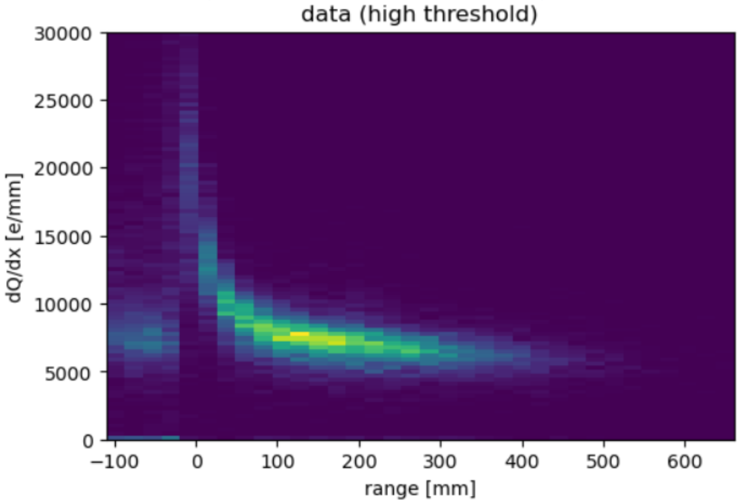
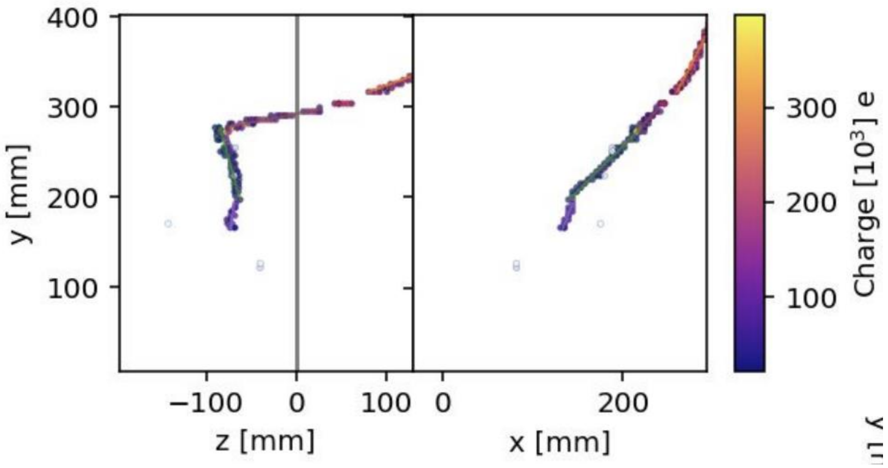


Figure 15: dQ/dx measured for segments of different lengths for low threshold runs (black dots) and a sample of simulated cosmic rays (red line). The distributions have been fitted with a Gaussian-convoluted Moyal function (dashed lines).

Energy loss for stopping muons



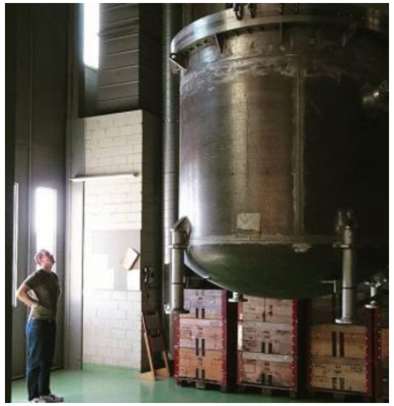
Observation of positron decay

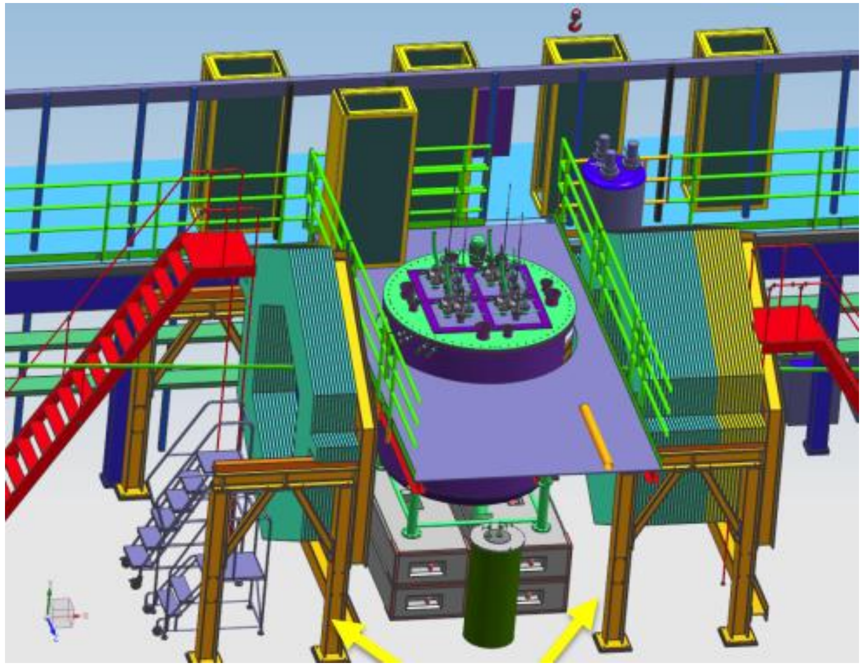


ArgonCube 2x2 @ NuMI

2x2 Operation in NuMI Neutrino Beam ***2022-2023***

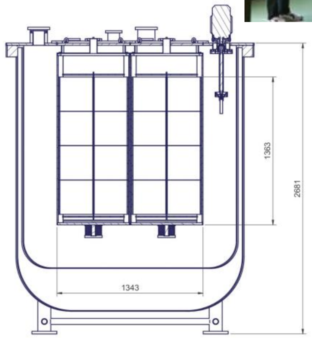
- Install four TPC modules in former location of MINOS-ND
- Includes upstream/downstream trackers, repurposed from Minerva





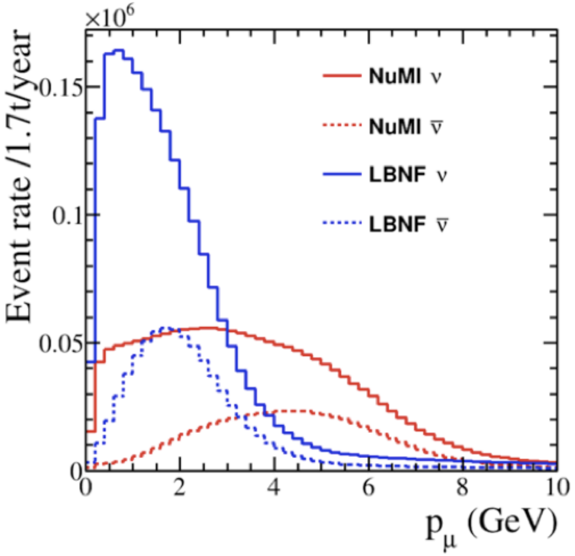
Goals:

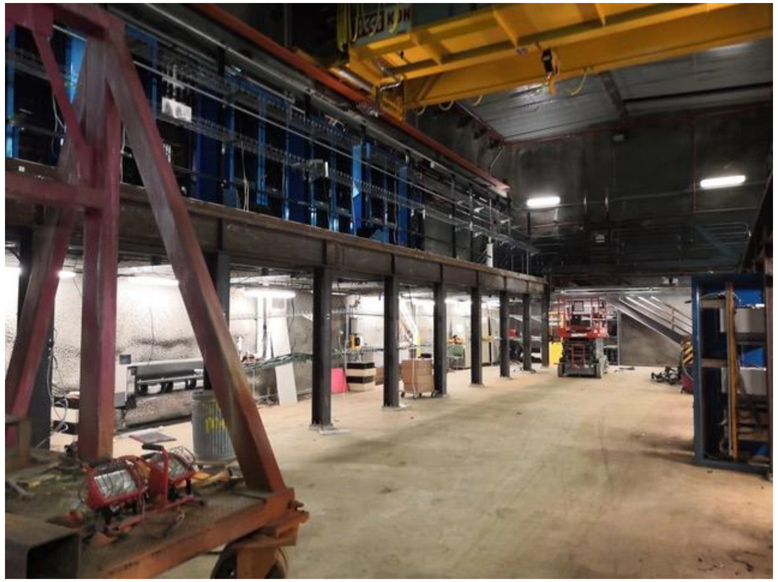
- Develop neutrino signal analysis and reconstruction techniques
    - 3D reconstruction of neutrino signals
    - Charge-light signal correlations, tolerance to beam pileup
    - Track matching with external trackers



Status:

- Cryostat & controls commissioned at Bern
  Delivered to FNAL: July 2021
- TPC Module 0, 1 commissioned at Bern
  Delivered to FNAL: Oct. 2021, June 2022
- TPC Modules 2, 3 currently in production
  To be delivered to FNAL: Winter 2022/2023
- Remaining cryogenics system procurements/production
  To be delivered to FNAL: Winter 2022/2023
- Installation and commissioning in NuMI hall
  Targeting Spring 2023





Demonstration of ½-million pixel detector in a GeV neutrino beam!

Far Detector Pixel Readout: Key Requirements

My summary of the requirements that would drive system design and production for a future Far Detector

	Requirement	Approx. Value	LArPix	Comment
Science	**Granularity**	< 4.7 mm	3.8 mm	Latest LArPix-v2b design has 3.8mm pixel pitch
	Noise	< 1000 e- ENC	900 e- ENC	Noise as measured in ~100k-pixel TPC with LArPix-v2a
	Threshold	< 200 keV	200 keV	1/4-MIP signal efficiency currently marginal for both ND and FD
Engineering	**Power**	< 20 W/m^2	14 W/m^2	Anode heat flux less than heat from cryostat walls. Mitigate boiling at anode.
	Digital Multiplexing	> 10^6 pixels/channel	10^5 pixels/channel	Ok for ND. O(10x) digital aggregator needed to reduce FD cabling/feedthroughs
	Reliability/Longevity	< 5% failure/10yrs	*(Unknown)*	Cryo-longevity to be assessed as part of ND prototyping program
Production	**Total system cost**	< \$20k/m^2	\$10k/m^2	Total production cost includes full system assembly, cold/warm electronics, etc.
	Production throughput	> 1000 m^2/yr	O(200) m^2/yr	OK for ND. 5x needed for FD. May be possible with current or additional vendors.
	Testing throughput	> 1000 m^2/yr	O(50) m^2/yr	4x needed for ND; 20x needed for FD. More QC testing partners needed.

Most important steps toward Pixelization of a Far Detector:

- Design and prototype a cryo-robust digital aggregator

- Develop plan and partners to achieve FD-scale QC testing throughput