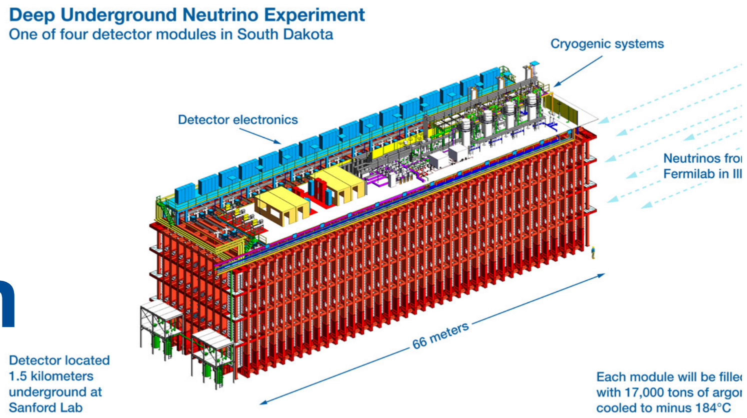
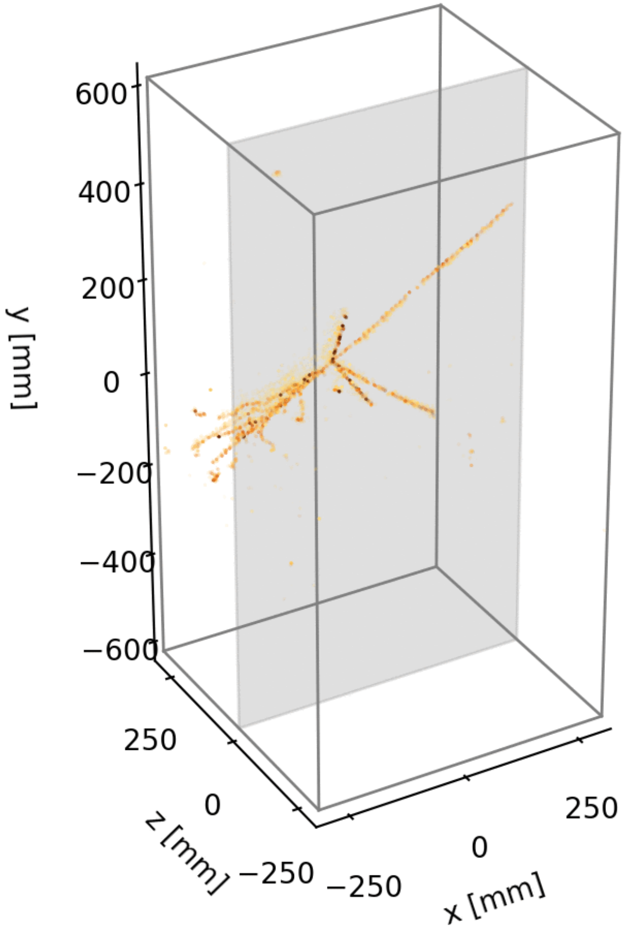
LArPix, LightPix, and Photon Detection in DUNE FD3



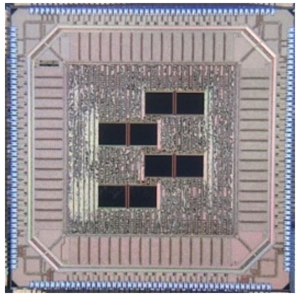


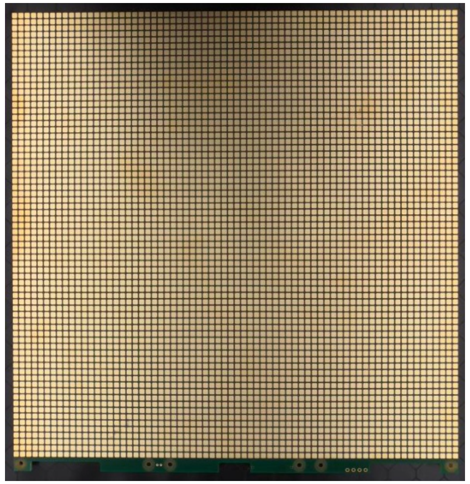
Dan Dwyer

DUNE FD3 PD Workshop

Stonybrook

27 June 2023



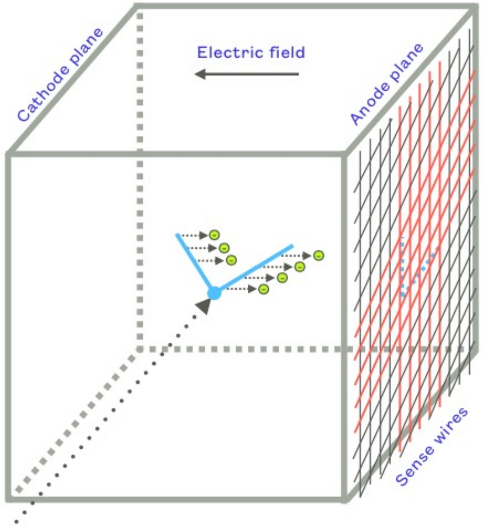


2D vs. 3D LArTPCs

2D Wire Plane TPC:

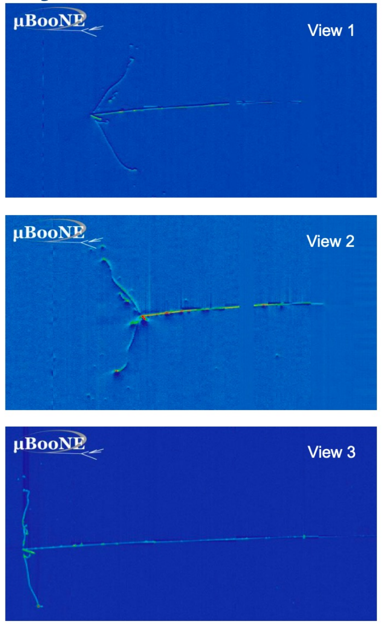
- Established technology, demonstrated in ProtoDUNE-HD
- Multiple 2D views used to estimate 3D signal
- Baseline technology for Far Detector #1 (& Strip variant planned for FD #2)

2D Projective TPC



DUNE prototype anode plane on winding machine

2D Projections in MicroBooNE



3D Pixel TPC:

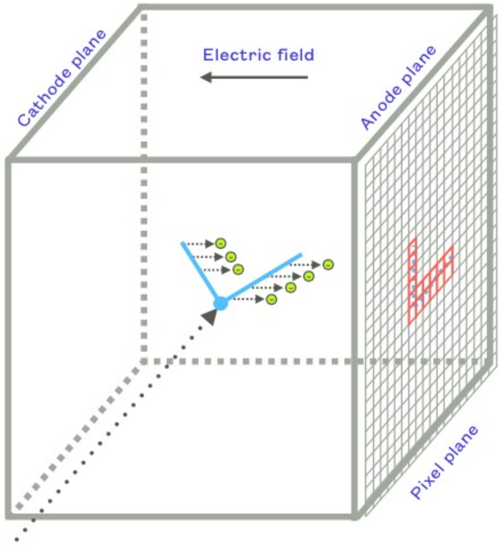
- True 3D imaging
- Continuous readout, ~100% uptime
- Intrinsically sparse data, low data volume

Science Gains:

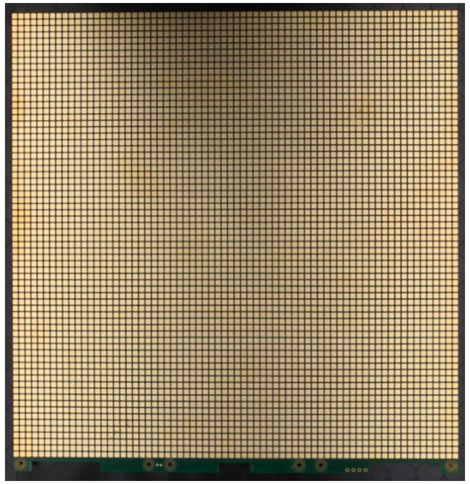
- Improved signal fidelity, S/B
- Enhanced low-energy program

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

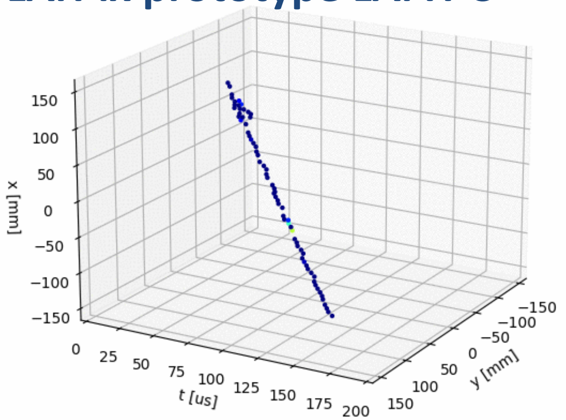
3D TPC



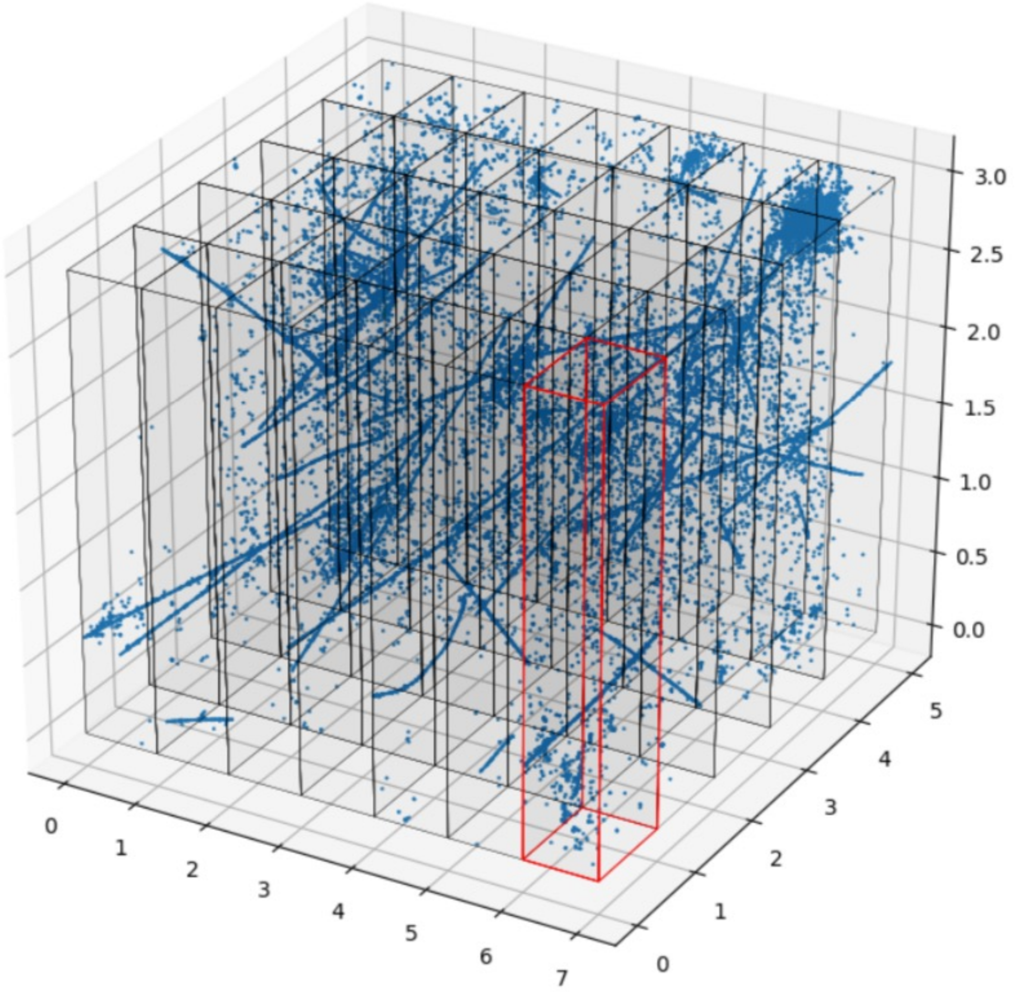
6.4k-channel LArPix prototype pixel anode tile



Raw 3D Cosmic Ray images in LArPix prototype LArTPC



Motivation: Signal Pileup in the DUNE Near Detector



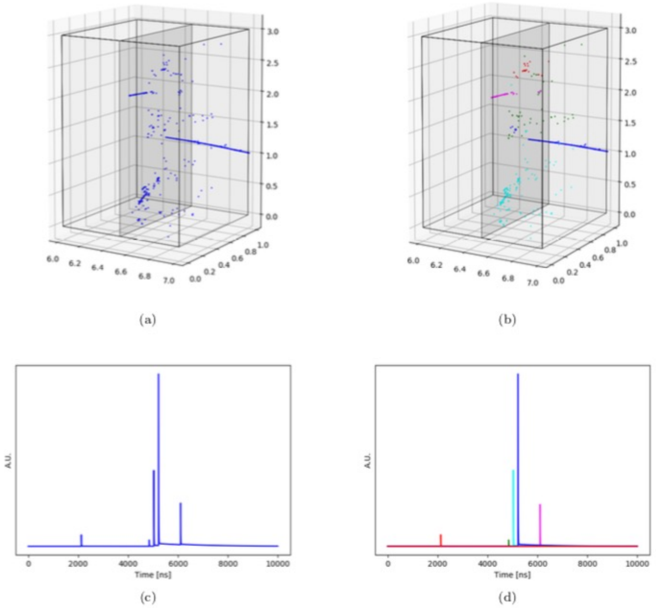
Simulation of one beam pulse in DUNE Near Detector LArTPC

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 (~300 us)

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 and charge signal pileup manageable within one TPC segment

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

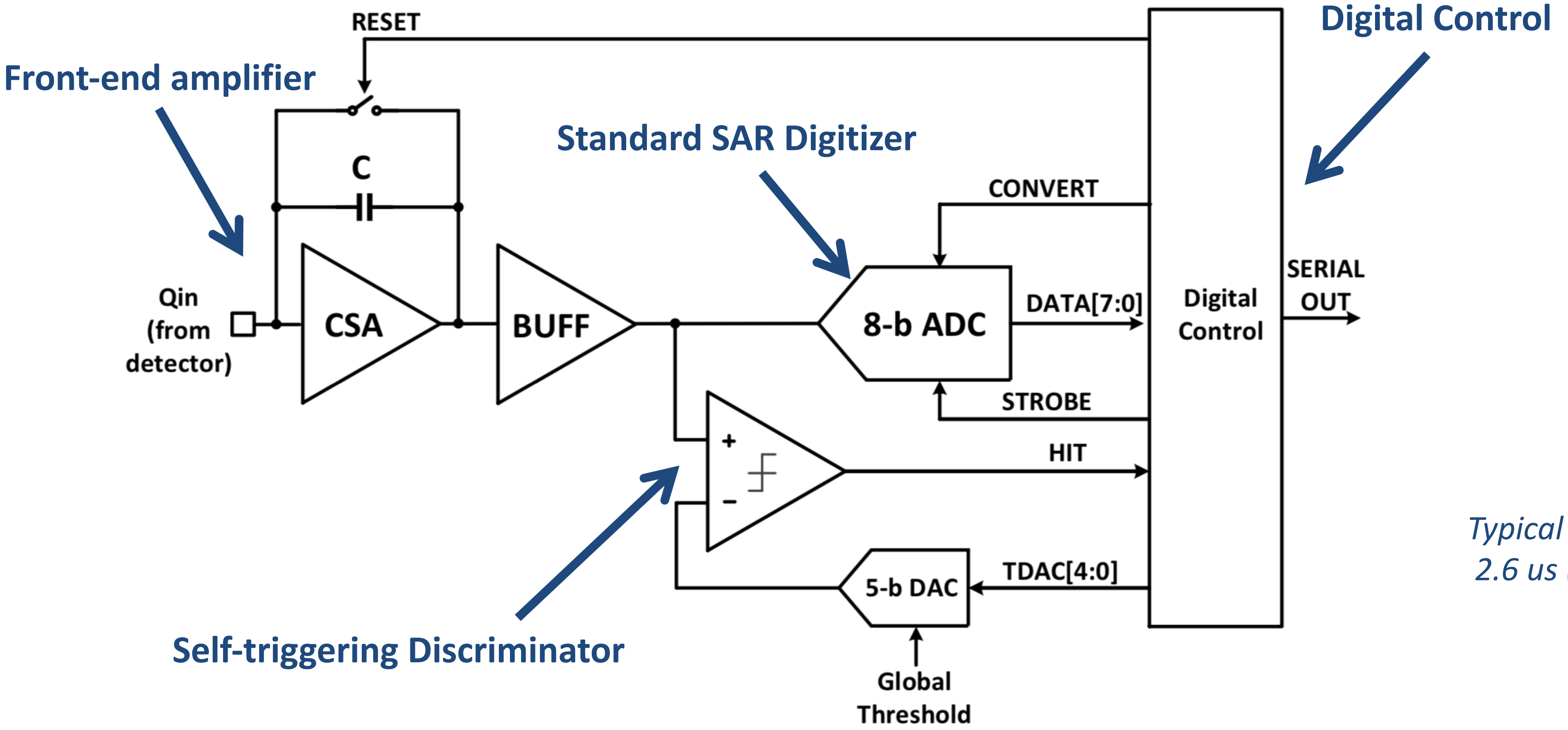
UCI University of California, Irvine

Yale

YORK U
UNIVERSITÉ
UNIVERSITY

LArPix Concept

Approach: Integrating Amplifier with Self-triggered Digitization and Readout



Typical hit cycle time:
2.6 us (4mm drift)

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

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**

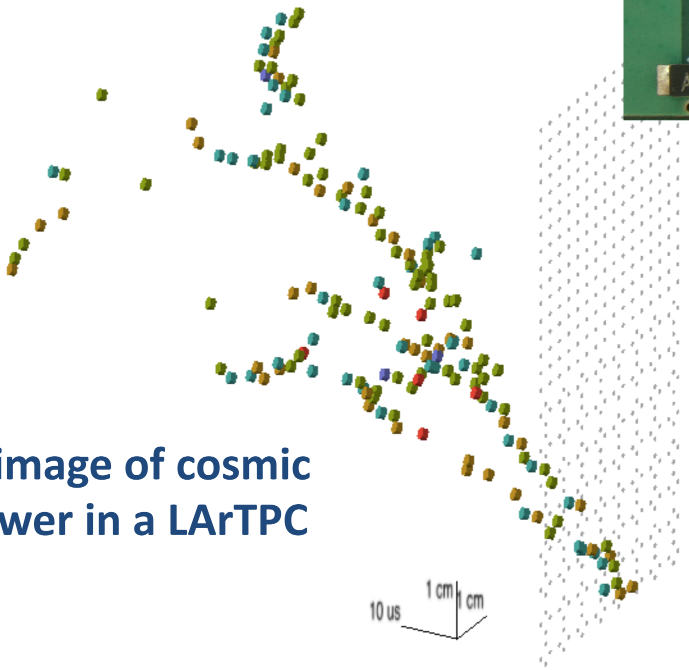
-> Successfully imaged cosmic rays in LArTPC

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

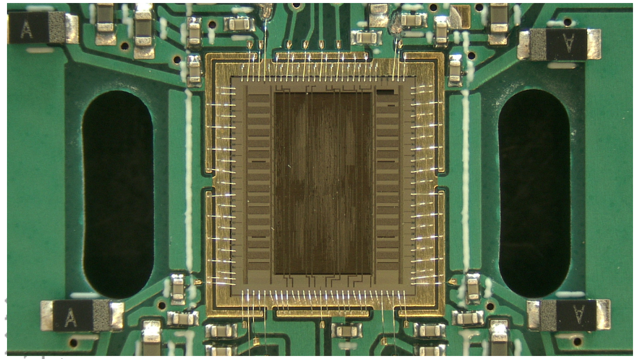
Control electronics:
- Fieldable system: noise-isolated and wifi accessible

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

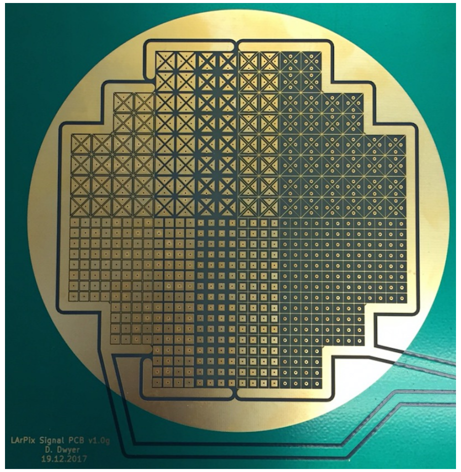


3D image of cosmic shower in a LArTPC

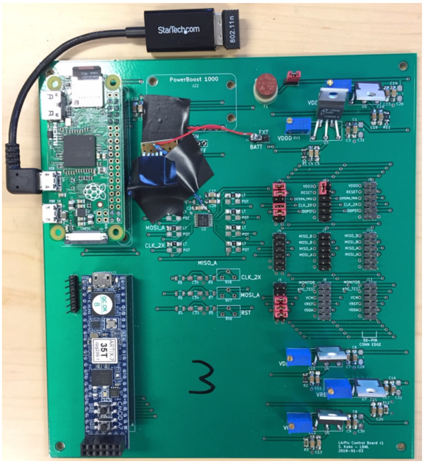
LArPix-v1 ASIC



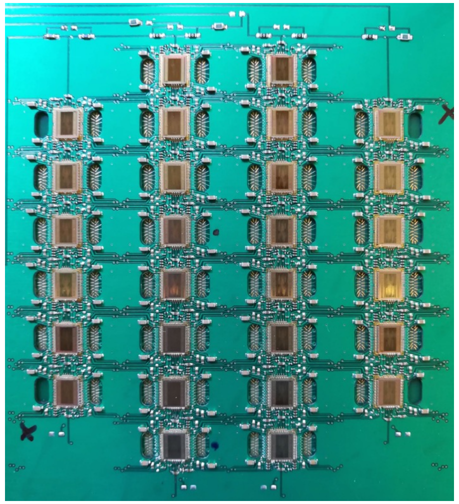
v1 Pixel Anode, Front



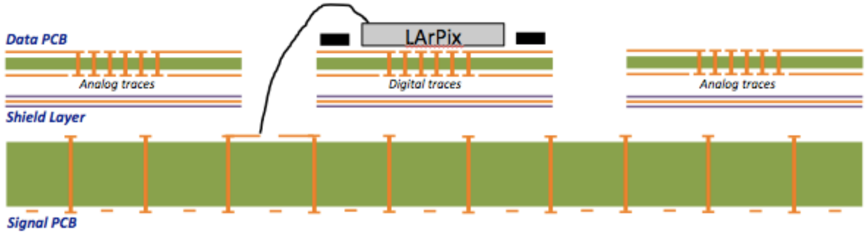
LArPix-v1 Tile Controller



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

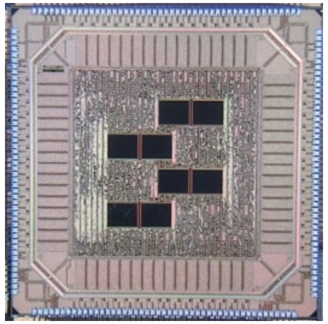
Pixel Anode Design Overhaul:
- 'Tileable' design to cover anodes of arbitrary scale
- 32cm by 32cm pixel anode PCB tile
- Frontside:
  - v2a: 4900 square pixels, 4.4 mm spacing
  - v2b: 6400 square pixels, 3.8 mm spacing
- Backside: 10x10 grid of ASICs
- Enable fully-commercial mass production and assembly

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

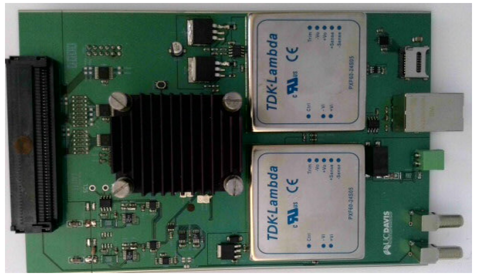
Key R&D Achievement:

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

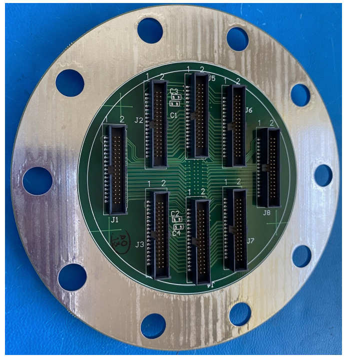
LArPix-v2 ASIC



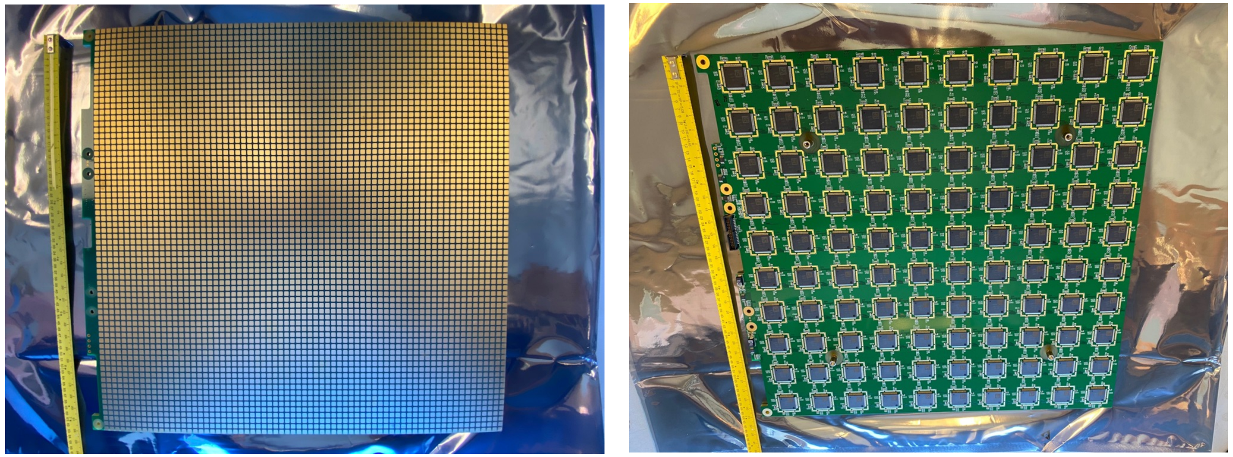
PACMAN Tile Controller



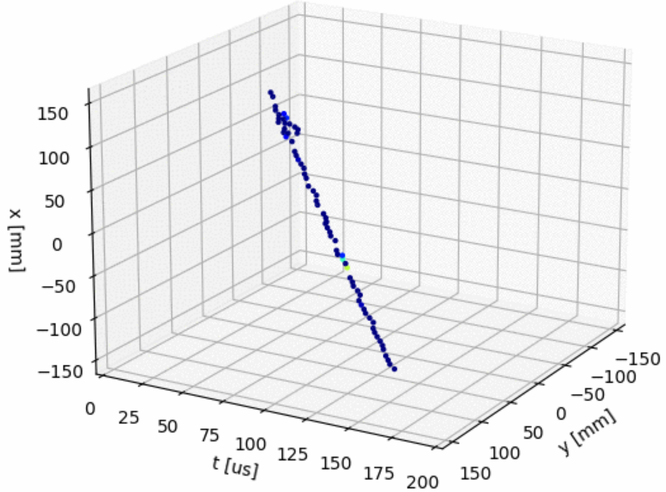
8-Tile Feedthrough



Production-scale LArPix-v2 Pixel Anode



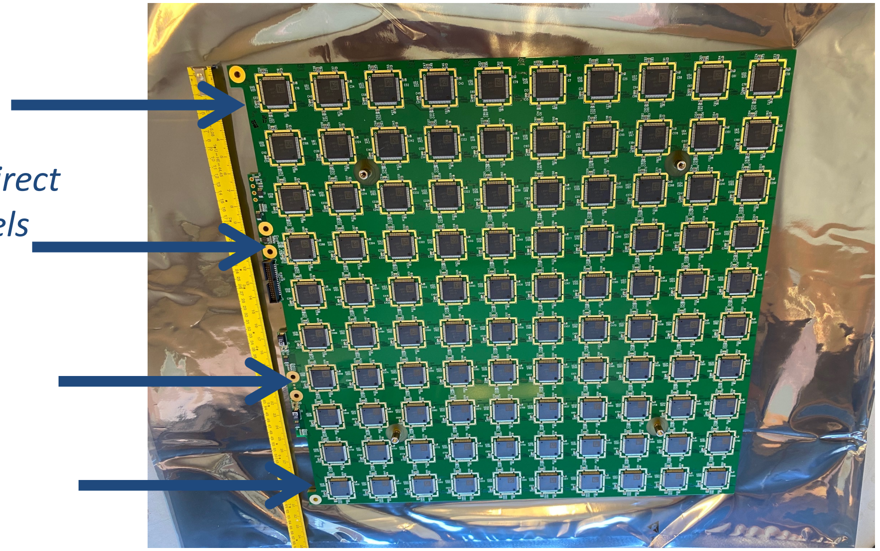
Raw 3D images of cosmic rays from initial single-tile test



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

R&D on Robustness: Hydra-I/O

2022 R&D 100 Award



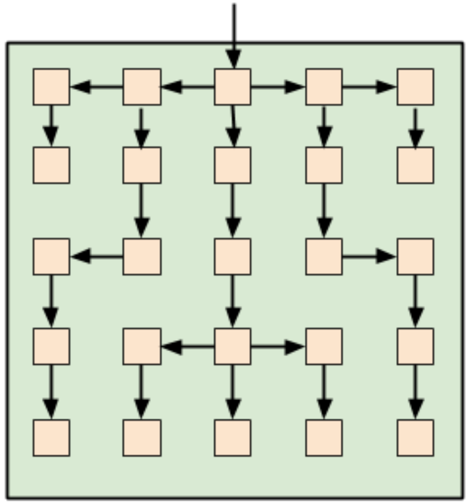
Four chips have direct off-tile I/O channels (10 MHz, < 4 m)

New design for robust I/O and control architecture

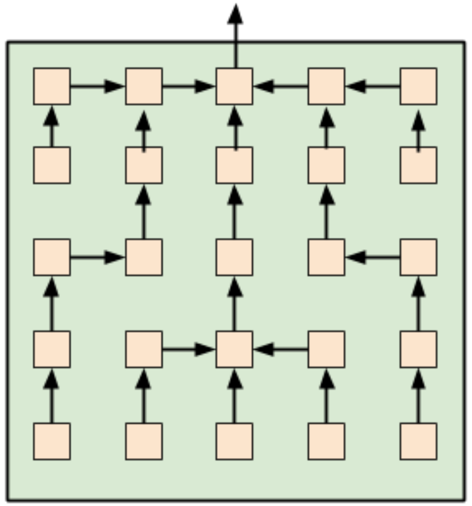
Repurpose existing LArPix-v1 low-power data I/O circuit
Very slight change enables richer, dynamic I/O architecture
- I/O can occur between any neighboring chips on pixel tile
- Network is built by explicitly connecting neighboring ASICs in a determined fashion

Successfully exercised with LArPix-v2 chip

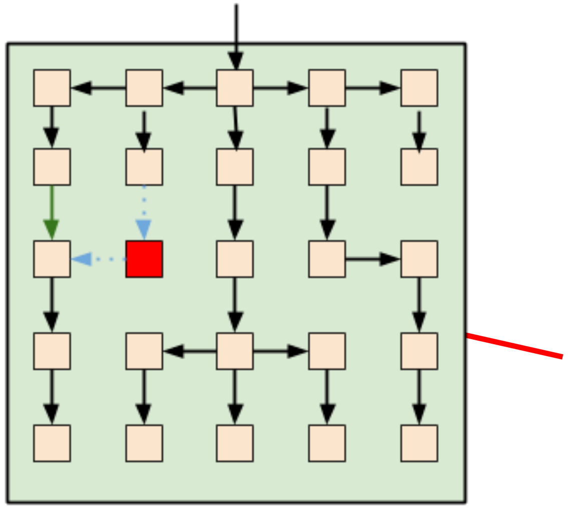
Example: 5 x 5 Pixel Tile



Upstream configuration commands



Downstream data flow



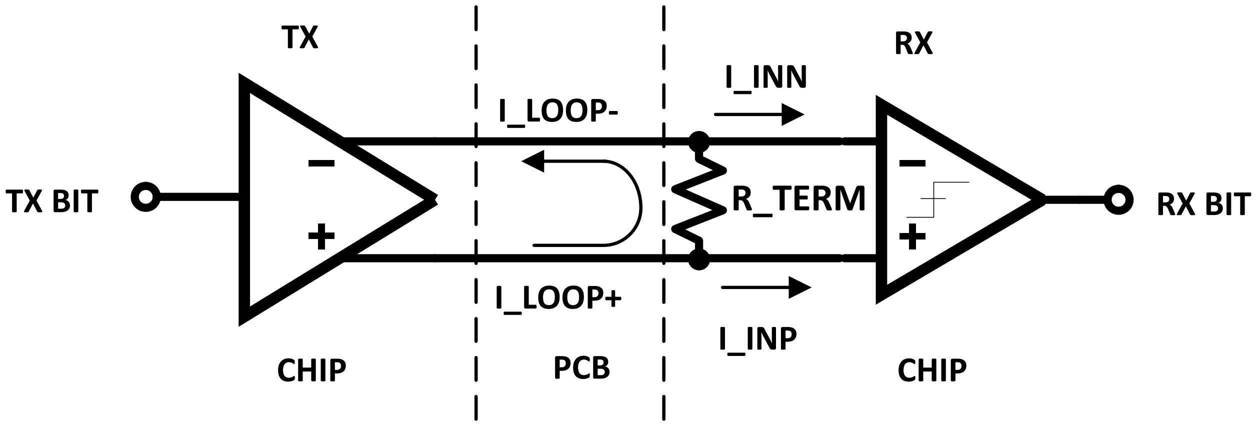
Example failed chip.

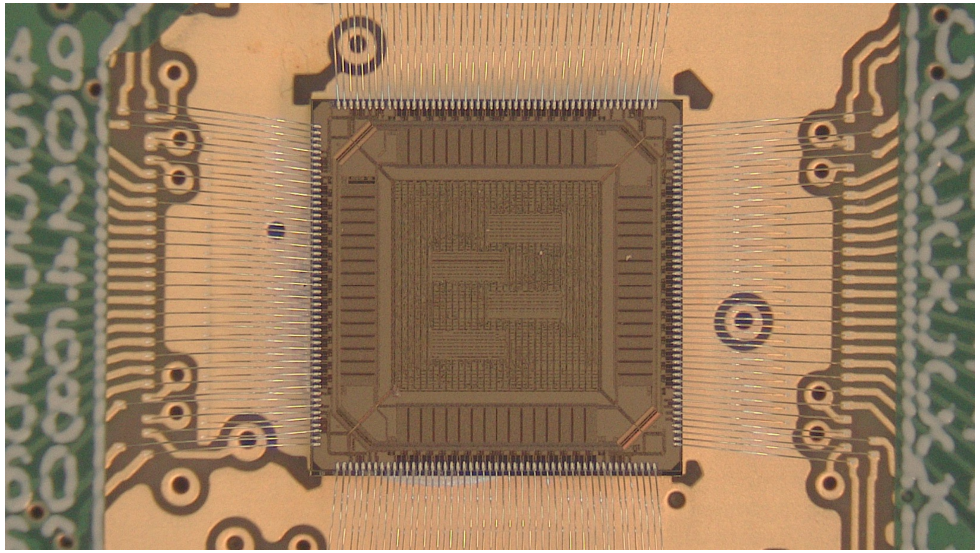
Network reconfigured to avoid failed ASIC

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 produced/tested

Prototyping: ArgonCube 2x2 LArTPCs

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

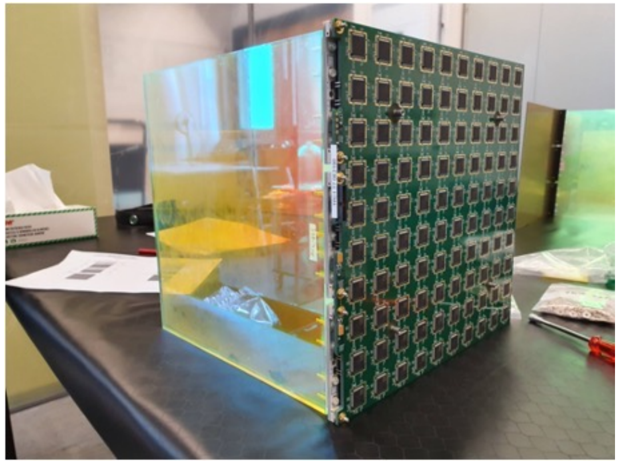
Each TPC Module:

- Active Size: 0.7m x 0.7m x 1.25m
- 16 pixel tiles, with 78k v2a (102k v2b) pixel channels/module
- 16 light collection modules, with 96 light sensors (SiPMs)
- Resistive-film-on-fiberglass field cage

Achievements @ Univ. of Bern:

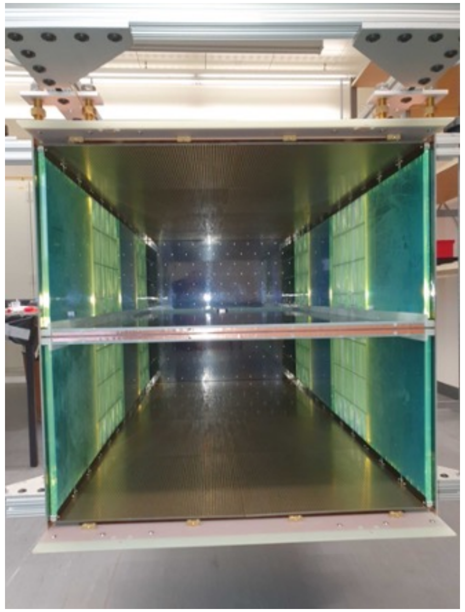
Demonstrated fully-integrated prototype detector module at a scale relevant to the DUNE Near Detector

Single pixel tile & light module assembly



One anode (8 tiles), fully-assembled

Two anodes, installed inside field cage



LArTPC module attached to cryostat lid

Single Module Cryostat

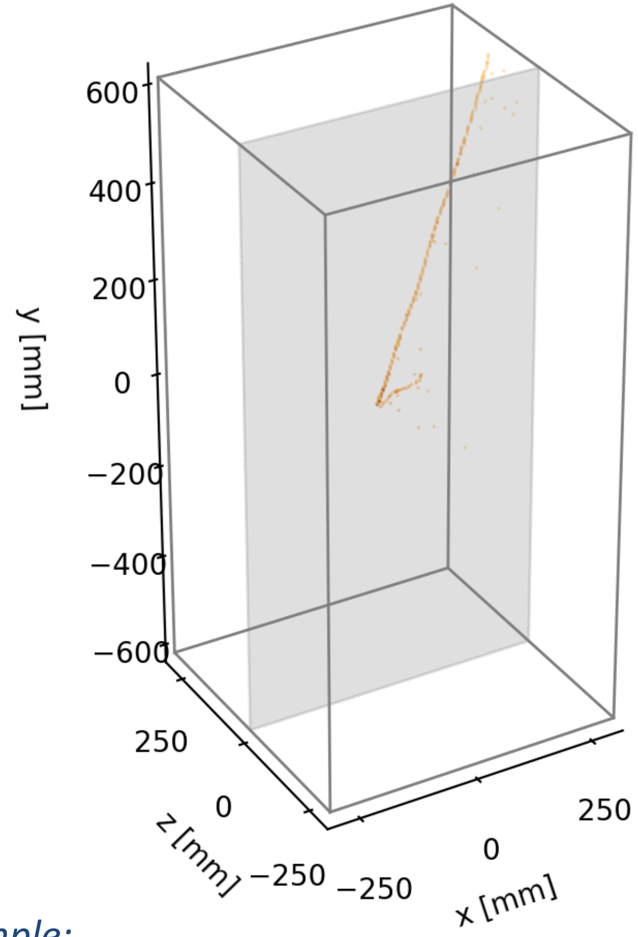
LArTPC inside cryostat

Near Detector Prototyping: ArgonCube 2x2 LArTPCs

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)

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



Continuous streaming readout:

~100% live, independent of light system
Achieved ~200 keV thresholds
Low data rate due to self-triggered design

Arguably the most performant ton-scale LArTPC to date.

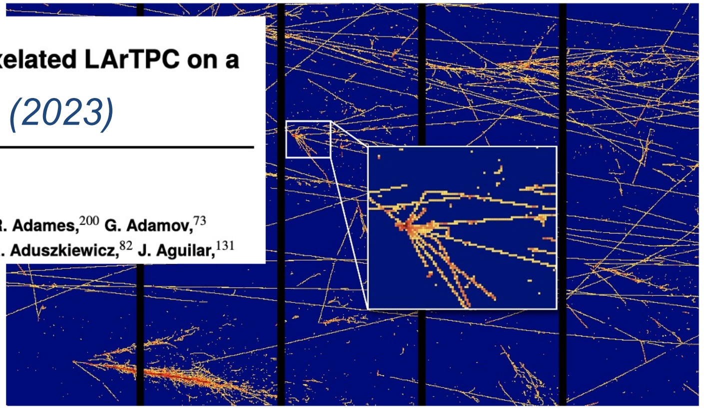
Example:
LArPix-v2b system, 102,400 pixels, 3.8mm spacing

2x2 Module 0 Physics Performance

Highly-parallelized simulation of a pixelated LArTPC on a GPU *JINST 18 P04034 (2023)*

The DUNE Collaboration

A. Abed Abud,[34] B. Abi,[163] R. Acciarri,[67] M. A. Acero,[10] M. R. Adames,[200] G. Adamov,[73] M. Adamowski,[67] D. Adams,[19] M. Adinolfi,[18] C. Adriano,[29] A. Aduszkiewicz,[82] J. Aguilar,[131]



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

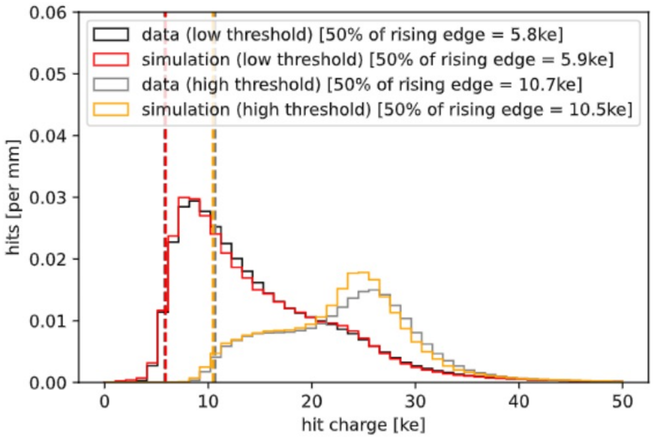
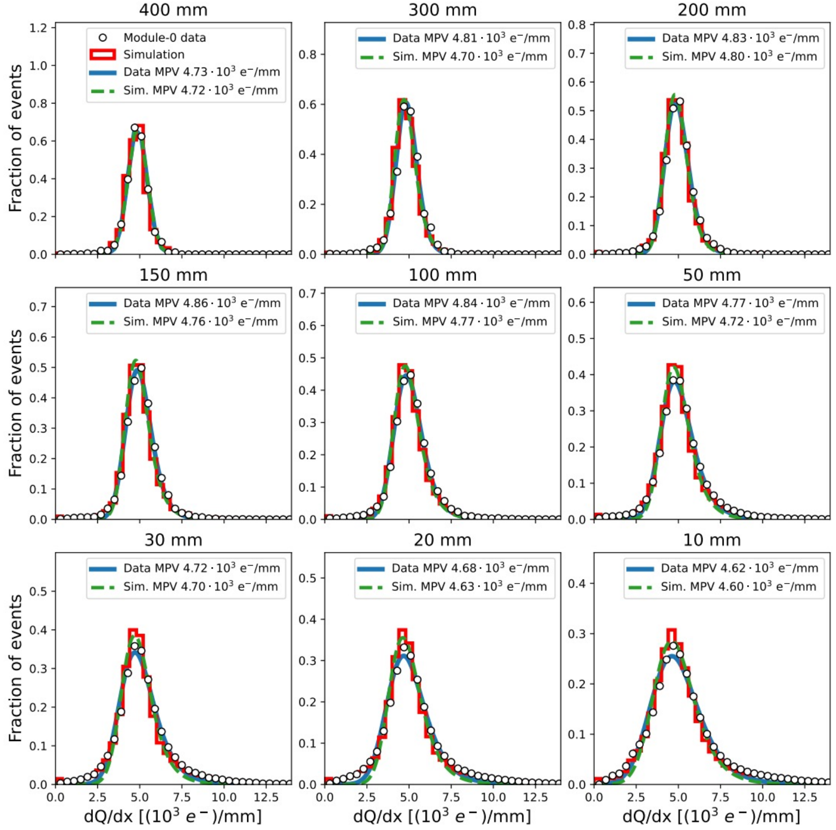
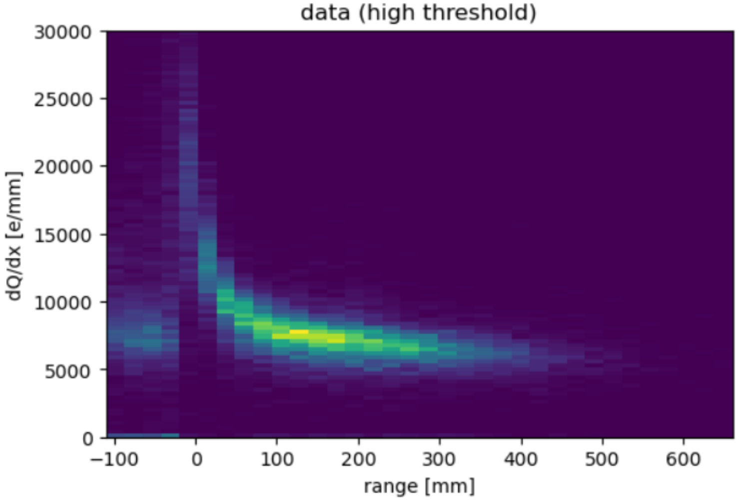


Figure 13. Self-trigger charge distribution for MIP tracks measured in thousands of electrons (ke); 50% of the rising edge are shown as indicators of the charge readout self-trigger thresholds. The MC simulation shown in comparison is described in Section 4.

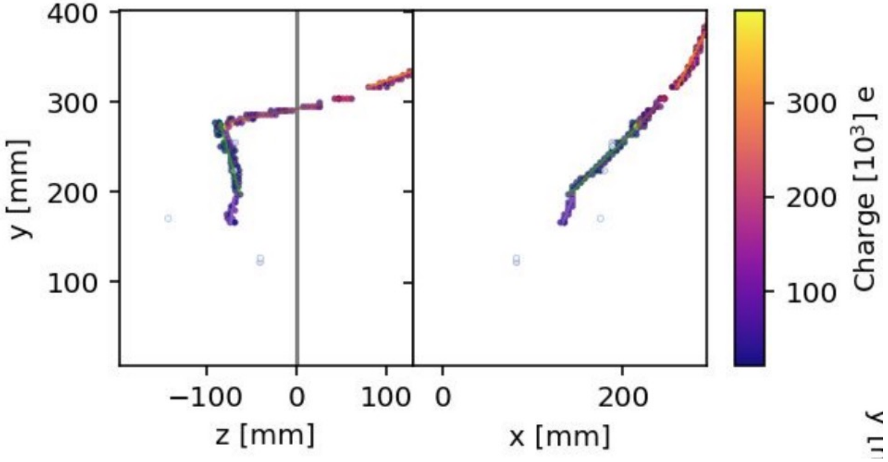
Energy loss for minimum ionizing muons (dQ/dx)



Energy loss for stopping muons

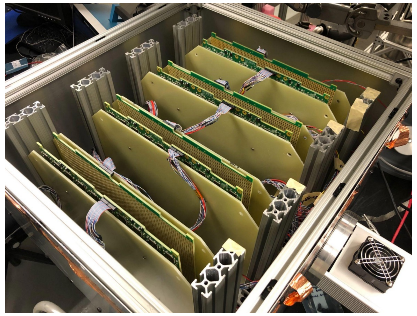


Observation of positron decay

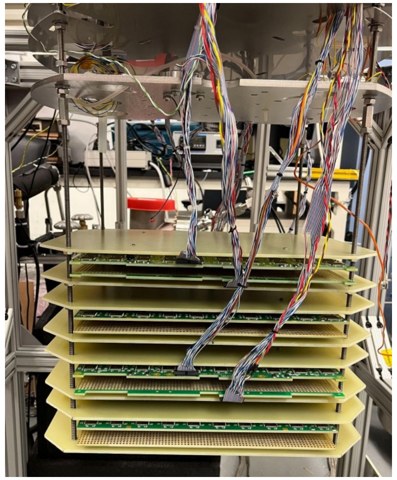


LArPix-v2: Scalable Production and Testing Process

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)

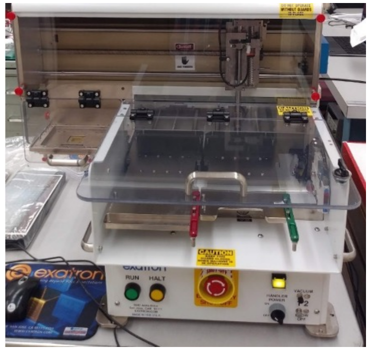
Anode tiles produced and checked (@ vendor) → Anode tiles loaded and inspected (@ vendor)

Controllers, cables, feedthroughs produced and checked (@ vendor) → LArPix System room-temp QC testing (@ Lab/Univ. partners)

ASIC room-temp QC testing (@ Lab/Univ. partners) → Anode tiles loaded and inspected (@ vendor) → LArPix System room-temp QC testing (@ Lab/Univ. partners) → LArPix System QC Cryo-testing (@ Lab/Univ. partners)

LArPix-v2 testing:
~10,000 ASICs tested (so far)
~600 chips/day (1 robot)

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



ASIC Testing Robot

LArPix-v2 testing:
~80 tiles tested (so far)
~8 tile batches, ~1hr

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

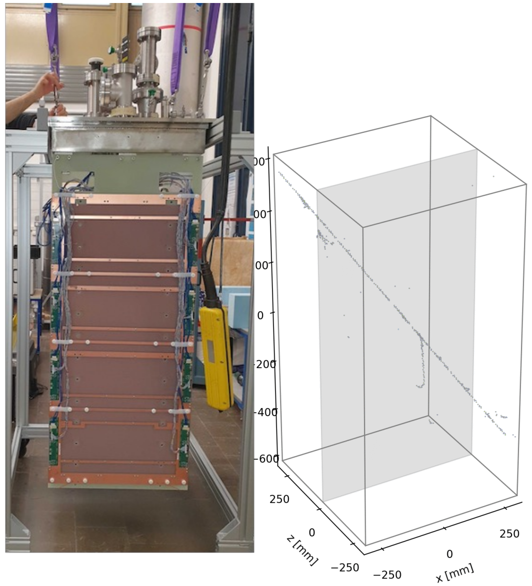
LArPix-v2 testing:
~80 tiles tested (so far)
~8 tile batches (time limited by LN fill/empty)

Results:
No cryo-failures yet

Near Detector Prototyping: ArgonCube 2x2 LArTPCs @ Bern

Produced and operated LArPix systems for four ton-scale LArTPCs, with a total of ~300k channels

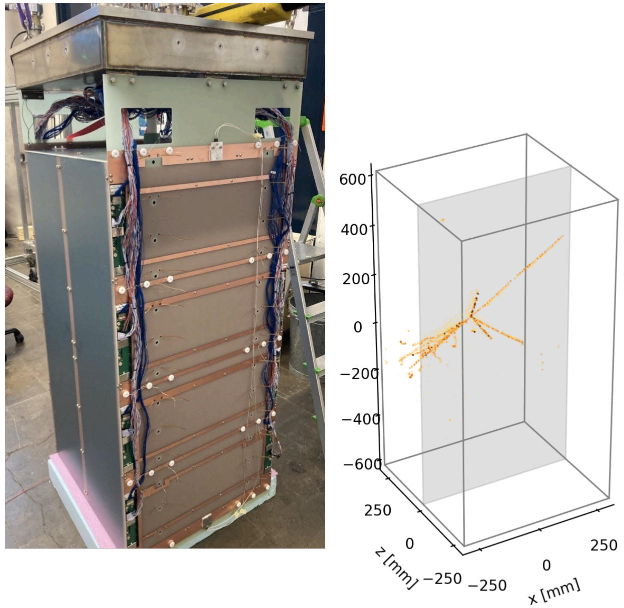
Module 0



Operations:

Apr. 1-10, 2021
Jun. 21-26, 2021

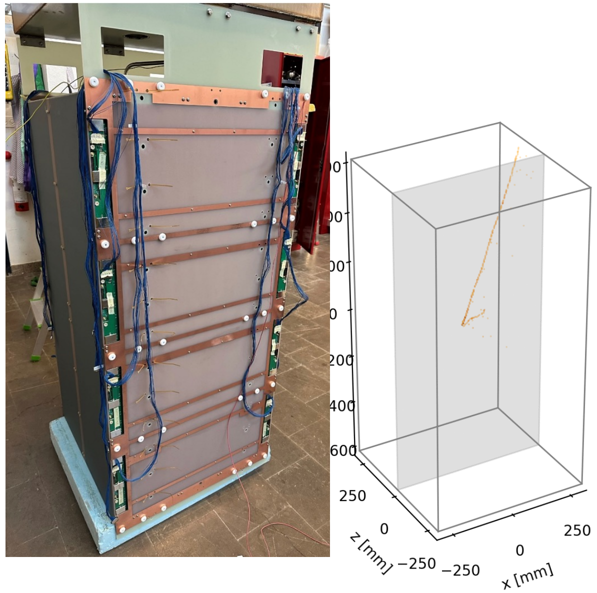
Module 1



Operation:

Feb. 5-13, 2022

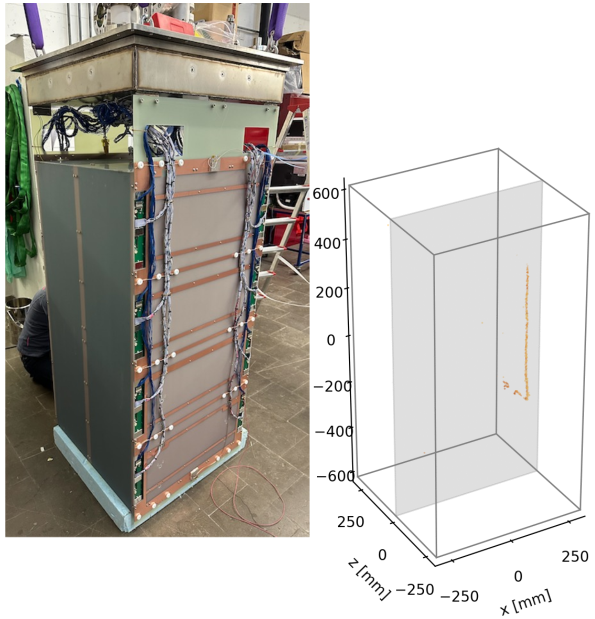
Module 2



Operations:

Nov. 14-22, 2022
Nov. 29-Dec. 6, 2022

Module 3



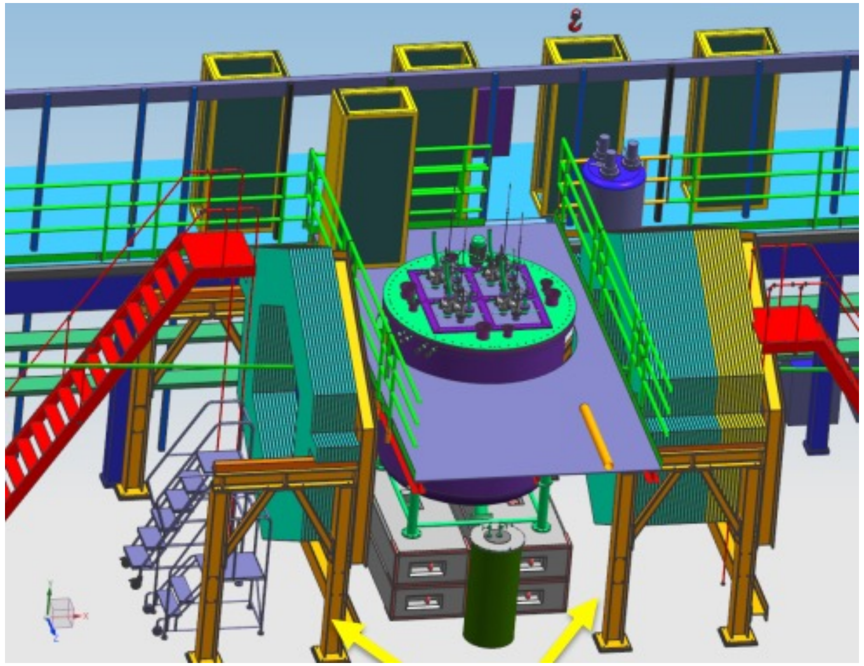
Operations:

Jan. 27-Feb. 5, 2023
Feb. 21-23, 2023
Mar. 13-16, 2023

Roughly 100 million cosmic events collected!

Next Step: Operation in NuMI Neutrino Beam

ArgonCube 2x2 @ NuMI

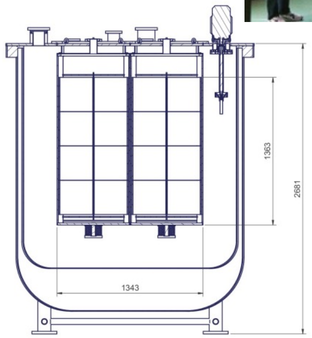


2x2 Operation in NuMI Neutrino Beam ***2023-2024***

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

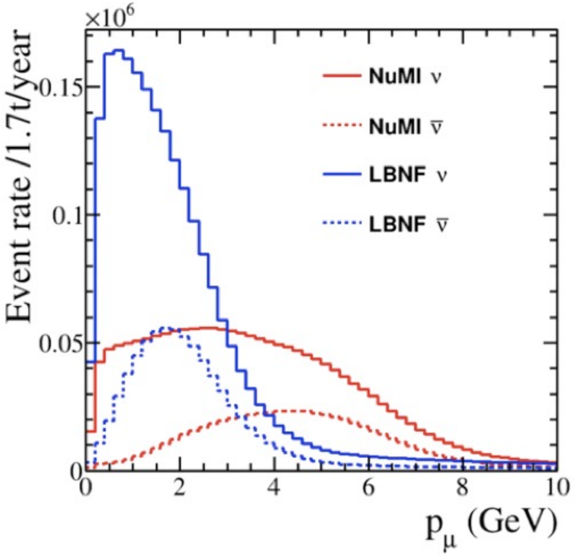
Goals:

- 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
- Cryostat shipped to FNAL, installed in NuMI hall
- All four TPC Modules delivered to FNAL, unpacked, and passed electrical checkouts
- Reconfigured MINERvA tracking planes installed and now commissioning
- Aiming for operations start in Autumn 2023



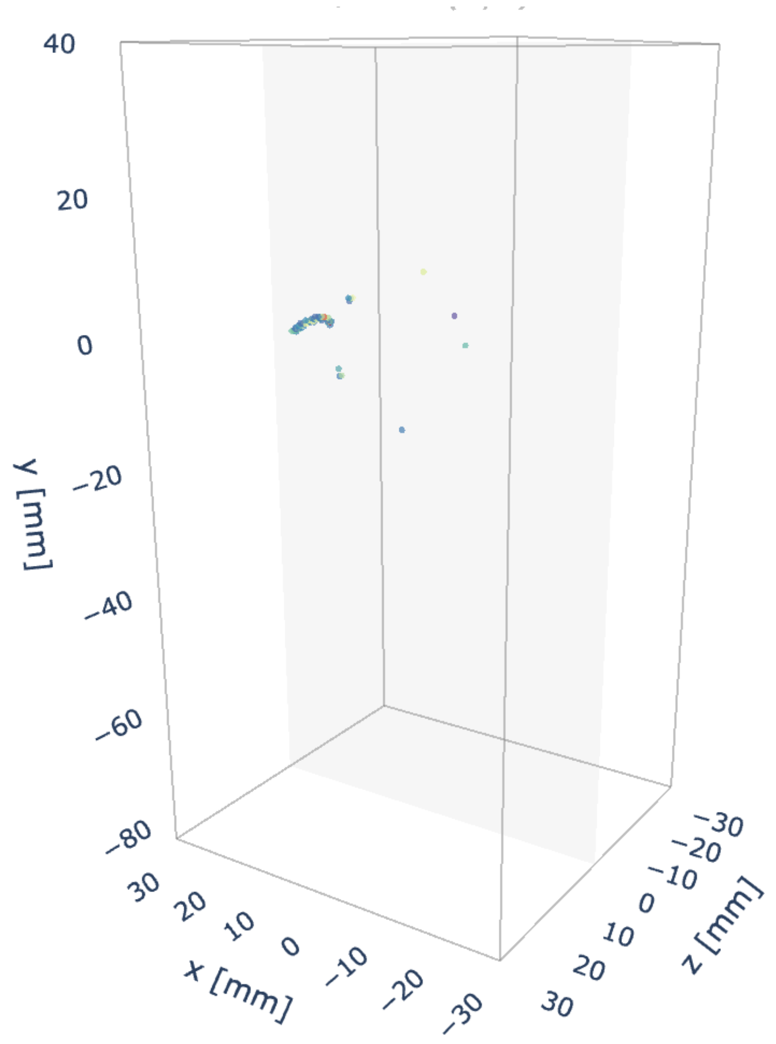
Demonstration of ½-million pixel detector in a GeV neutrino beam!

LArPix: Toward a LArPix DUNE FD Module

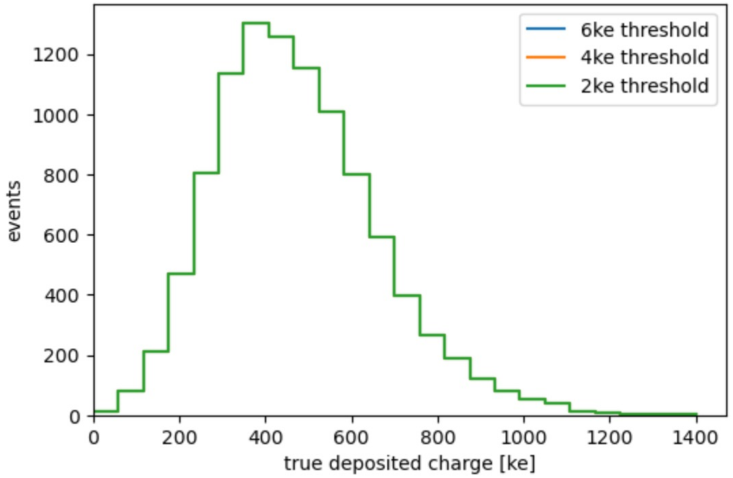
Scientific Advantages:
- Unambiguous 3D imaging
- Continuous readout, independent of photon system trigger
- Enhanced low-energy program (capture everything above ~200 keV/pixel)

Example: Supernova Burst Neutrino Signal
- Charge data captured regardless of photon system efficiency
- Existing pixel thresholds seem sufficient for supernova signals
- Energy spectrum and resolution are reasonable

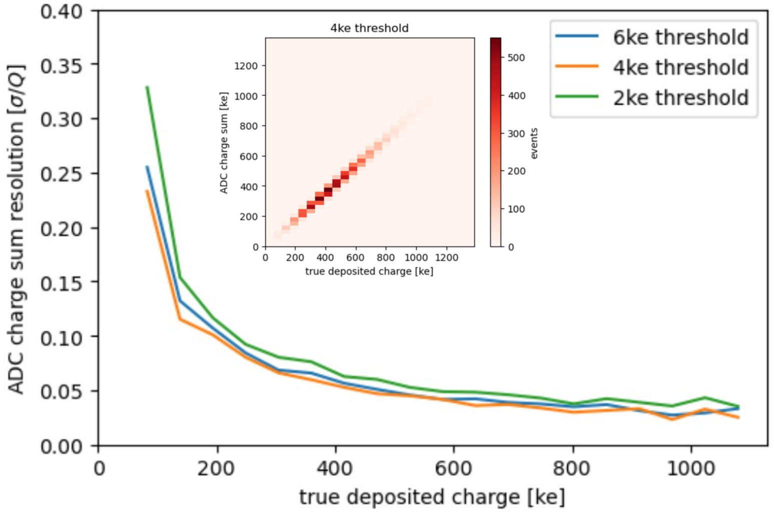
Example Supernova Neutrino signal with LArPix
- Uses current MARLEY neutrino-Ar interaction generator
- Self-triggered LArPix electronics simulation
- MC benchmarked with Module 0, 1 data
- Using Module 0 TPC geometry for convenience only



Deposited charge for supernova burst neutrinos



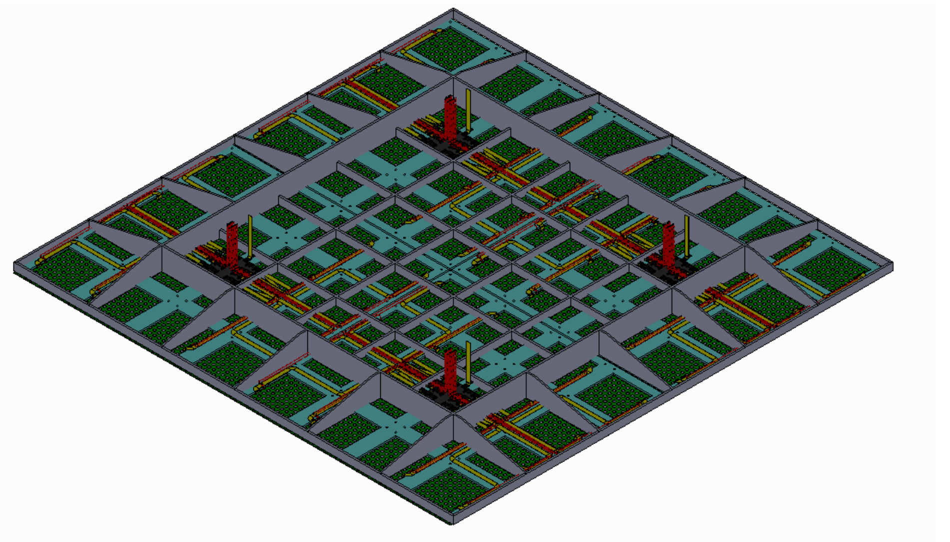
LArPix charge sum resolution



LArPix: Toward a LArPix DUNE FD Module

For a credible technical design, a 3D Pixel FD likely needs:

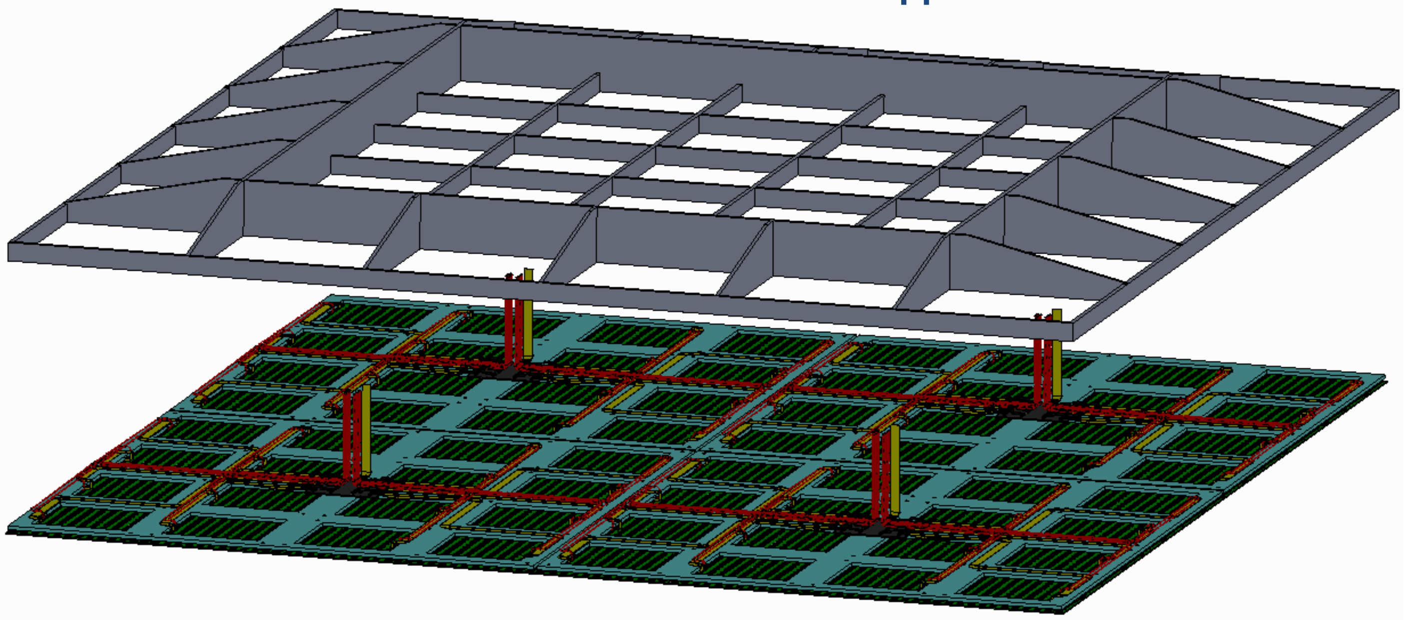
- Viable production and testing plans
- Reasonable mechanical/electrical interfaces to existing DUNE FD cryostat
- Credible process for assembly and installation in detector
- Demonstrations of assembly/installation/operation at the ProtoDUNE scale



8 x 8 grid of LArPix tiles (3m x 3m) interfaced to FD-VD anode support structure

A Minimal Concept: LArPix in a DUNE Vertical Drift Far Detector

- Replace 2D strip PCBs with LArPix tiles
- Grid of 8 x 8 tiles forming 3m x 3m anode segments
- Digital aggregator multiplexes data I/O for 16 tiles
- Reuse existing 3m x 3m VD mechanical support structure
- Light collection in the cathode or along field cage walls
- Prototype in future ProtoDUNE-VD run?
- **Note that such an FD design requires:**
  - ~1500 m^2 of anode area (half at top, half at bottom)
  - ~100 million pixels



Other potential concepts:

- SoLAr integrated light & charge, ArgonCube (Modular), etc.

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:

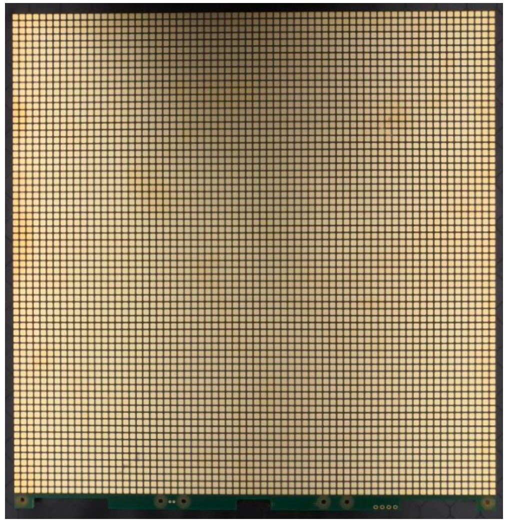
- Design and prototype a cryo-robust digital aggregator

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

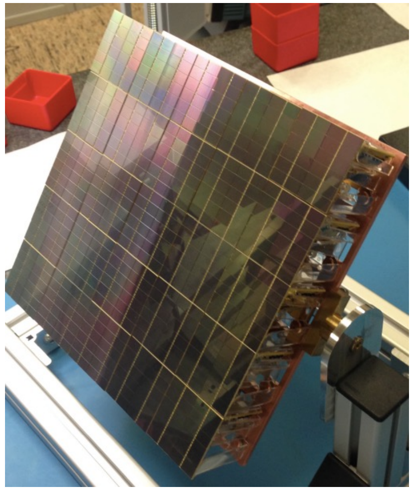
LightPix: Scalable Cryogenic SiPM Readout Electronics

- **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, highly-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 interests.

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: Comments on Front-End Optimization

Front-end requirements depend strongly on channel occupancy

High-Occupancy Regime: $N_{photoelectrons}/channel \gg 1$

- Important to capture signal waveform
  - Accurate calorimetry
  - Pulse shape discrimination
- Demanding requirements on readout electronics performance:
  - High-bandwidth (i.e. high-power) front-end / ADC / readout.
    - → Gang SiPMs to reduce channel count / power budget
  - Or pursue novel techniques (e.g. digital SiPMs)

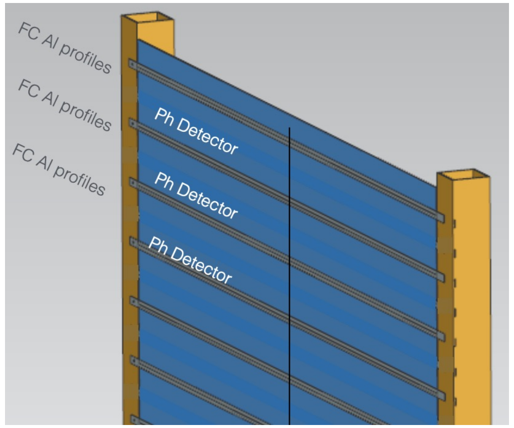
Low-Occupancy Regime: $N_{photoelectrons}/channel \lesssim 1$

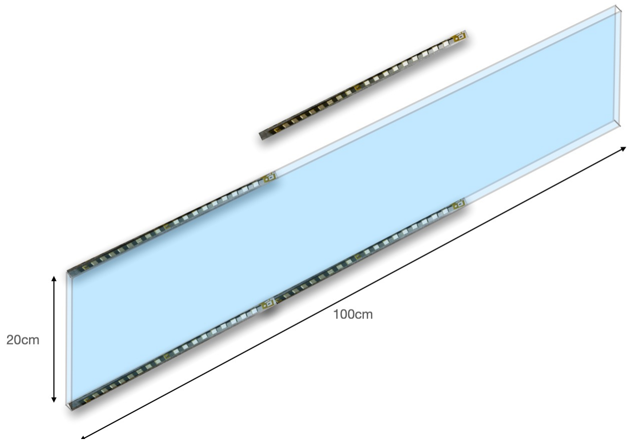
- Important to capture hit time (not charge/waveform)
- Calorimetry and PSD come from aggregate (many-channel) data
  - Example: Performance of KamLAND hit/no-hit reconstruction
- Front-end can be primitive (e.g. single-photon discriminator & TDC)
  - Low power per channel

Many many SiPMs in low-occupancy regime
→ Target of LightPix R&D

KamLAND Detector:
~1 kton of liquid scintillator surrounded by ~2000 photomultipliers, MeV-scale physics

Maximizing light collector coverage for DUNE Far Detector #3:
SiPMs likely in low-occupancy regime





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

Shares LArPix scalable system design:

- 64 channels per chip
- 6,400 channels per cable
- 51,200 channels per controller

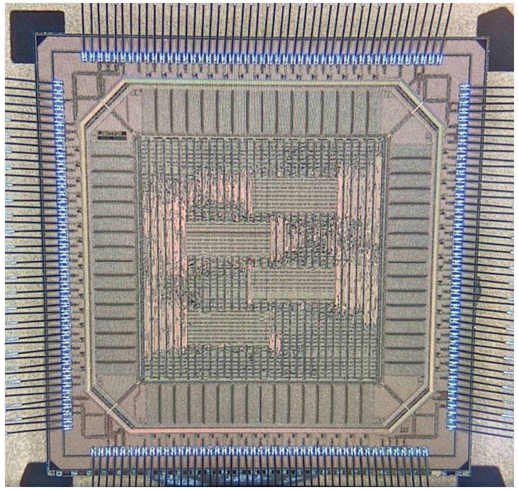
Progress:

- Received Aug. 2021
- Power-up, configuration successful
- TDC meets design targets
- Testing performance of existing front-end performance with Hamamatsu and FBK VUV SiPMs

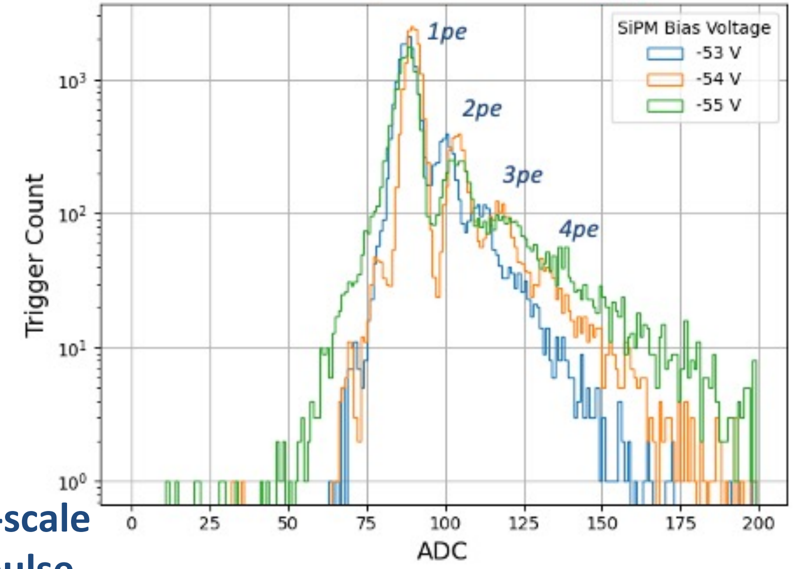
Next Steps:

- Optimize front-end for SiPM signals
- Deployment and testing of light detector system in prototype LArTPC
- Exploration/optimization of light detector formats

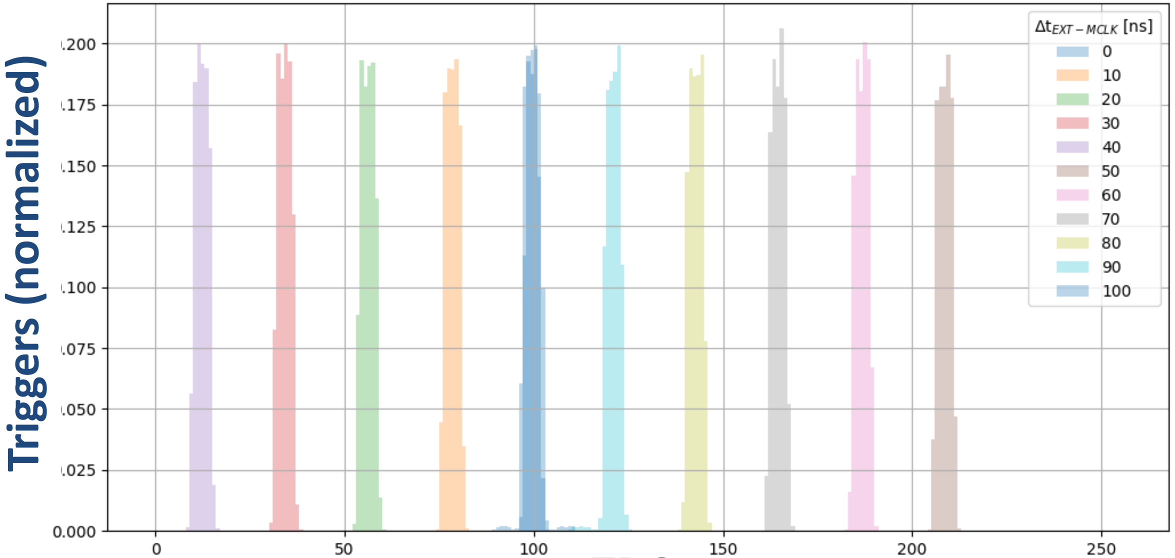
LightPix-v1b ASIC



Photoelectron signal spectrum vs. SiPM bias with unoptimized LArPix CSA



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



Offset between external pulse and TDC stop signal

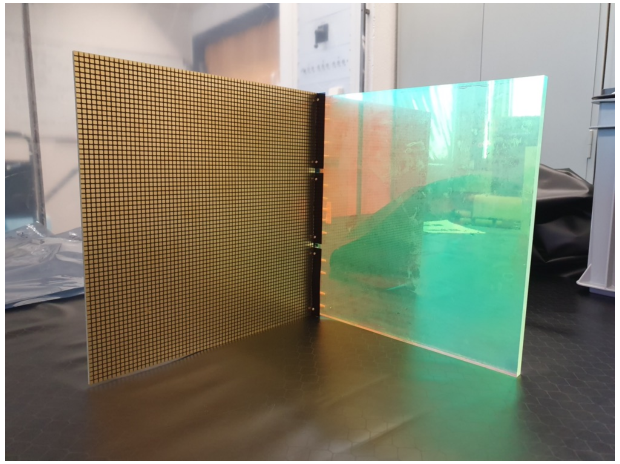
Tunable TDC (here ~0.5ns/tick)

Photon Detector Systems: ArCLight (U-Bern) and LCMs (JINR)

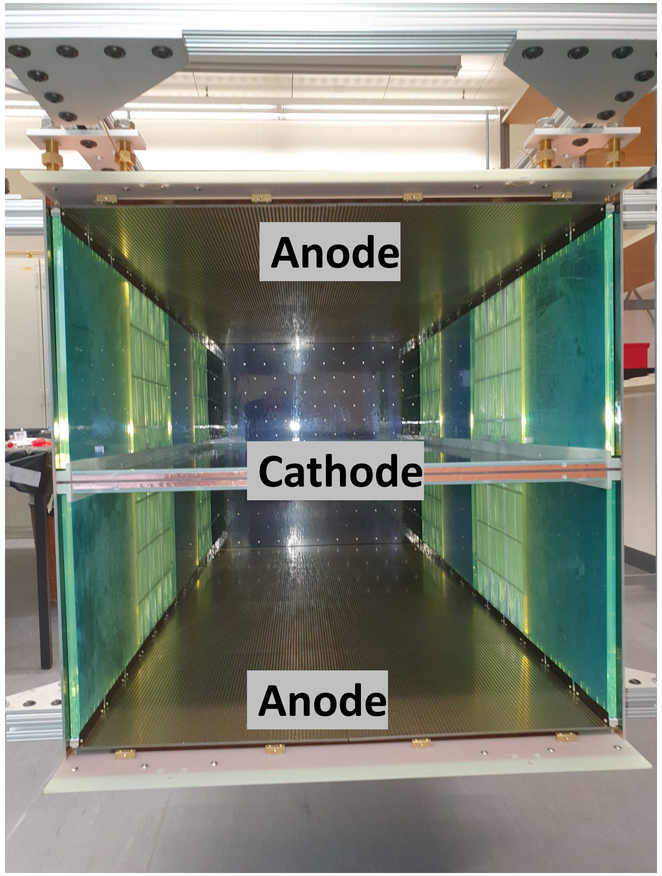
- **Lessons from Near Detector Light Trap Technologies for a DUNE Far Detector?**
  - ND achieves ~40% light trap coverage by covering field cage with dielectric light traps
  - TBP coating converts LAr scintillation UV to blue, WLS plate/fibers shift blue to green, dichroic film traps, funnels photons to SiPMs

Example: Existing DUNE-ND design

- SiPMs at anode (low field)
- Trap extends into drift field along field cage
- Two styles: WLS plastic core vs. WLS fiber bundle
- Occludes ~3% of volume, charge readout anode

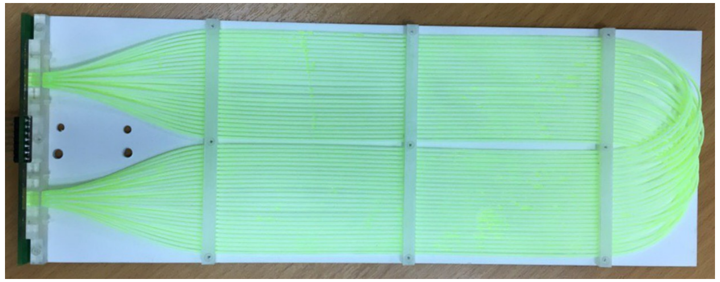


One pixel tile with one WLS plastic light trap attached
Bern ArCLight *Instruments 2018, 2(1), 3*



Two complete anodes (16 tiles) with light traps attached, inside field cage (bottom open for viewing)

Fiber-bundle style light trap: JINR LCMs



Summary: LArPix

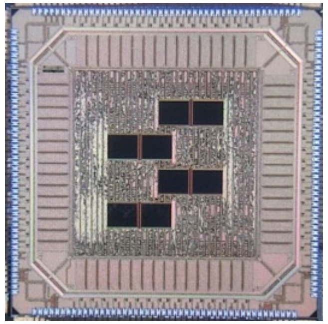
LArPix:
- True 3D pixelated charge readout for LArTPCs
- Low-noise, low-power, cryogenic-compatible
- Self-triggering, ~100% live
- Scalable anode design leverages commercial production
- Two recent 80k-pixel ton-scale prototypes exceeded expectations
- Baseline technology for the DUNE Near Detector

A LArPix Far Detector?
- Existing LArPix performance specs (for ND) seem viable for FD
- For FD-scale deployment, need:
  - Digital aggregator to reduce cabling and feedthroughs
  - Expanded QC testing program to provide sufficient throughput
  - ProtoDUNE-scale demonstration

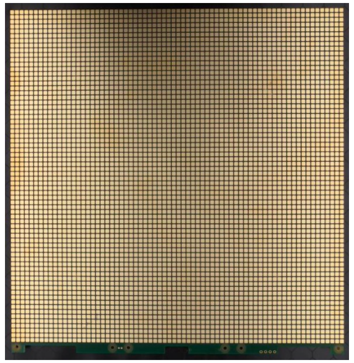
LightPix:
- Highly-scalable readout for cryogenic SiPMs
- Reuses much of LArPix system design
- Well-suited to low-occupancy regime

Potential technologies for future DUNE Far Detectors

LArPix-v2 ASIC

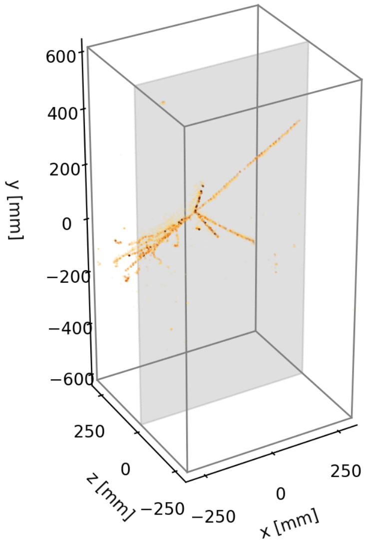


LArPix-v2 Tile

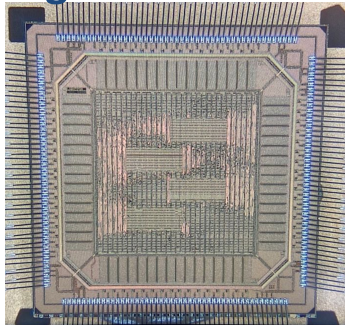


DUNE Near Detector Prototype LArTPC

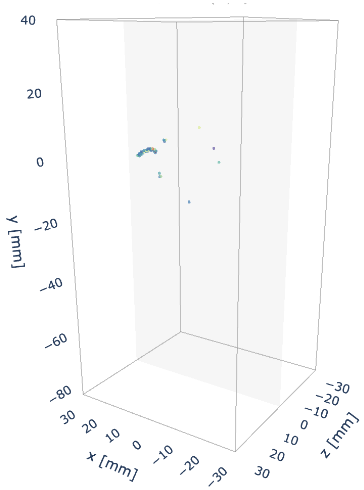
Cosmic ray 3D images from prototype

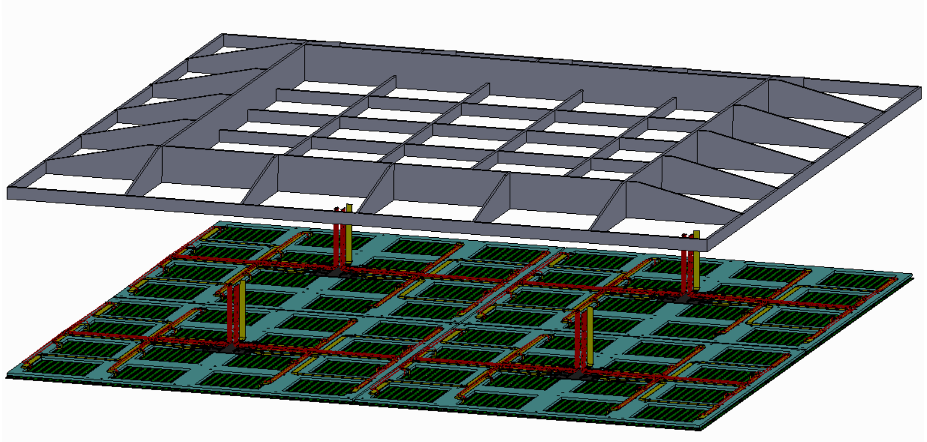


LIghtPix-v1 ASIC



LArPix Supernova Simulation





Concept: LArPix in a Vertical Drift FD