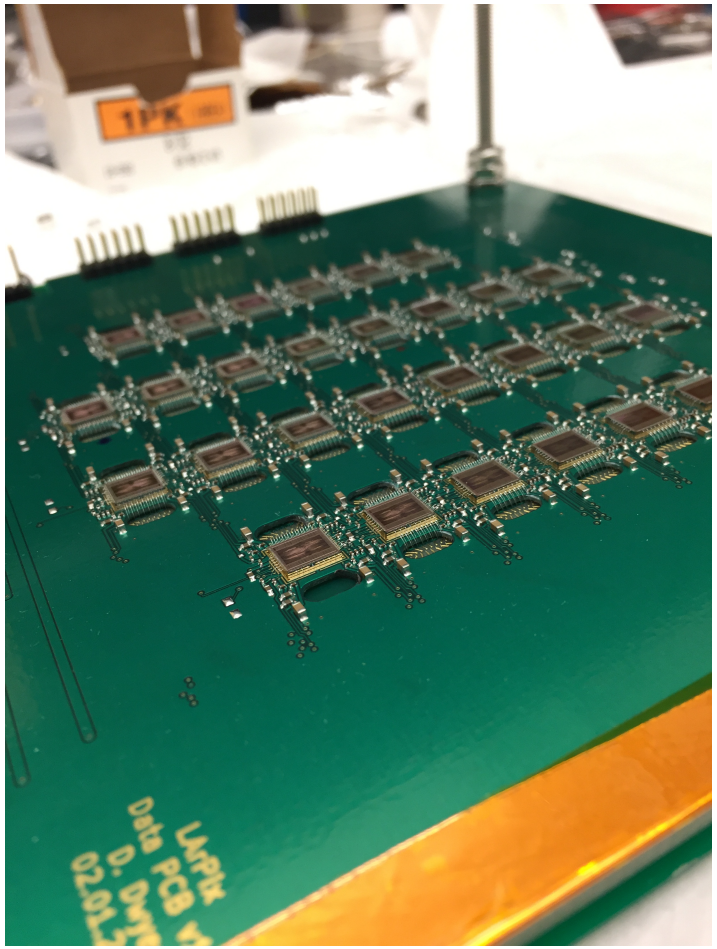
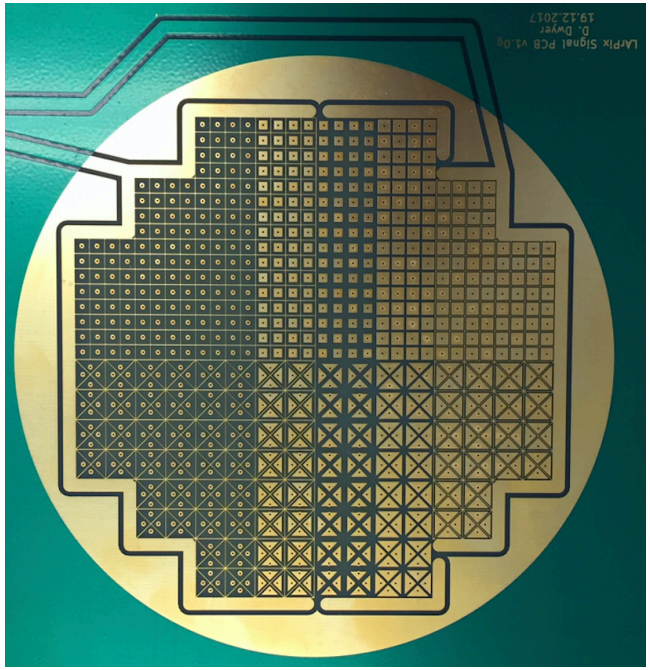
Pixel R&D for Neutrino Detectors

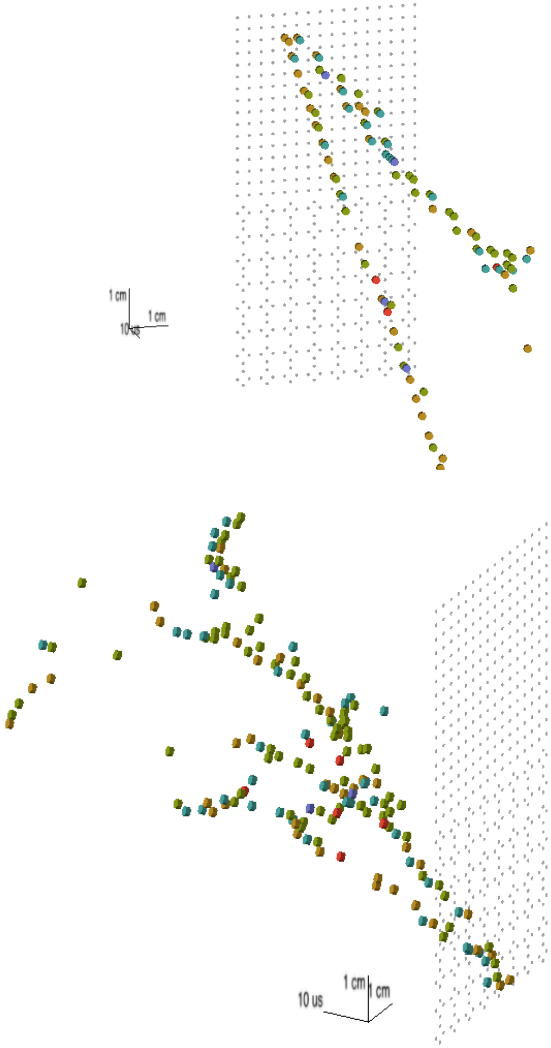
Dan Dwyer (LBNL)

The 2018 CPAD Instrumentation Frontier Workshop

Dec. 9, 2018







Neutrino Oscillation

Neutrinos change flavor (e,μ,τ) with time

Principle: Interaction (flavor) eigenstates ≠ Mass eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \times \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

We want to know θ's and Δm^2's

Physical Parameters:

θ:

3 angles between mass/flavor eigenstates set **oscillation amplitude**

$\theta_{12}, \theta_{23}, \theta_{13}$

Δm^2:

Differences in 3 neutrino masses determine **oscillation frequency** (distance)

$\Delta m^2_{21} = m^2_2 - m^2_1$

$\Delta m^2_{31} = m^2_3 - m^2_1$

$(\Delta m^2_{32} = \Delta m^2_{31} - \Delta m^2_{21})$

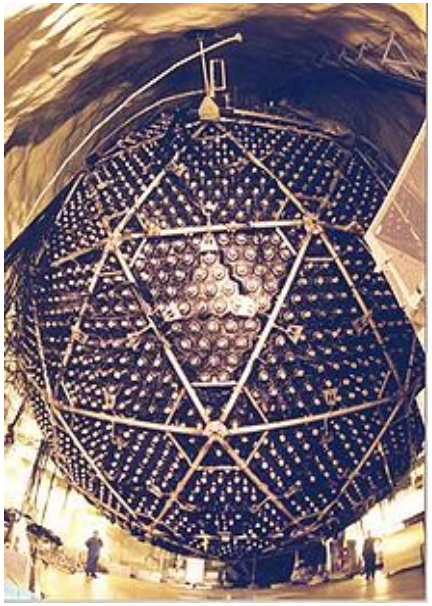
δ_{CP}: Off-diagonal phase

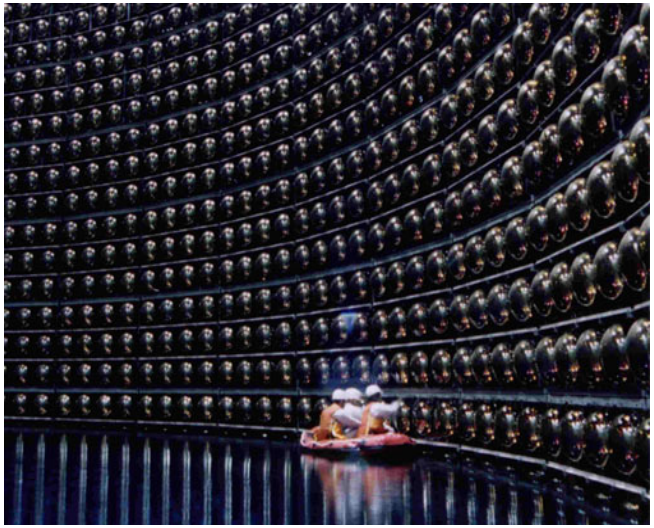
Current Status

→ *See overview by S. Gollapinni on Dec. 9*

$\sin^2(\theta_{12})=0.307^{+0.013}_{-0.012}$

$\sin^2(\theta_{23})=0.417^{+0.025}_{-0.028}$ *(assuming normal hierarchy, quadrant 1)*

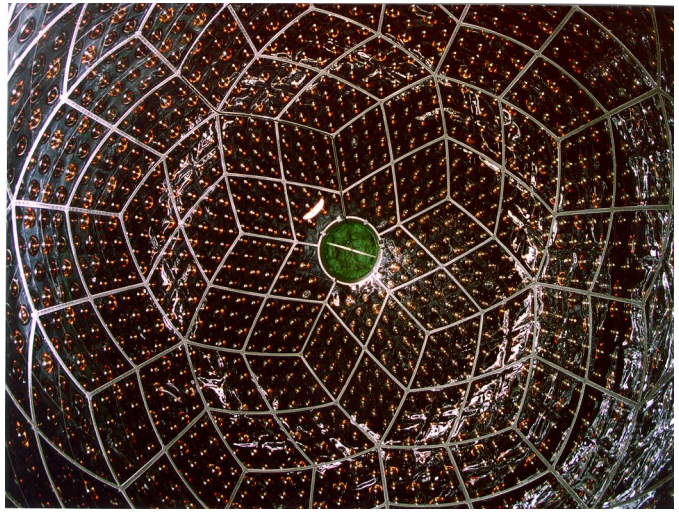




$\Delta m^2_{32}=(2.51 \pm 0.05) \times 10^{-3}\ eV^2$

(assuming normal hierarchy)

$\Delta m^2_{21}=(7.53 \pm 0.18) \times 10^{-5}\ eV^2$



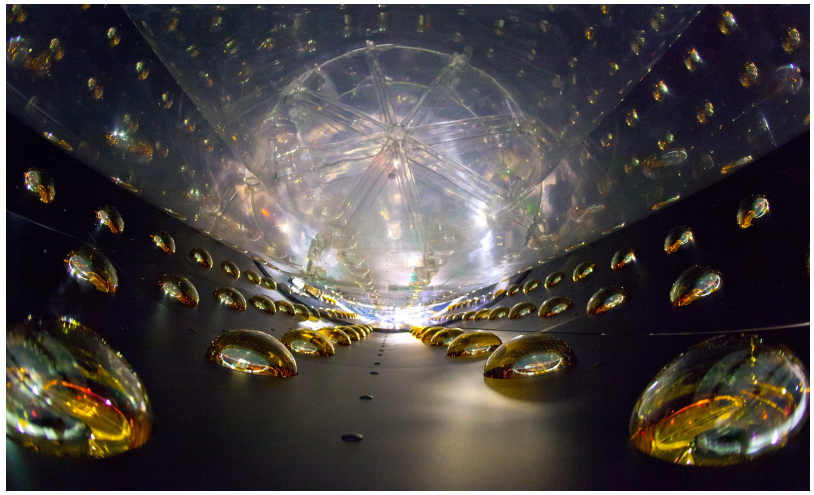
Open Questions:

Mass Hierarchy:

$\Delta m^2_{32} > 0?$

CP Violation:

$\delta_{CP}=?$



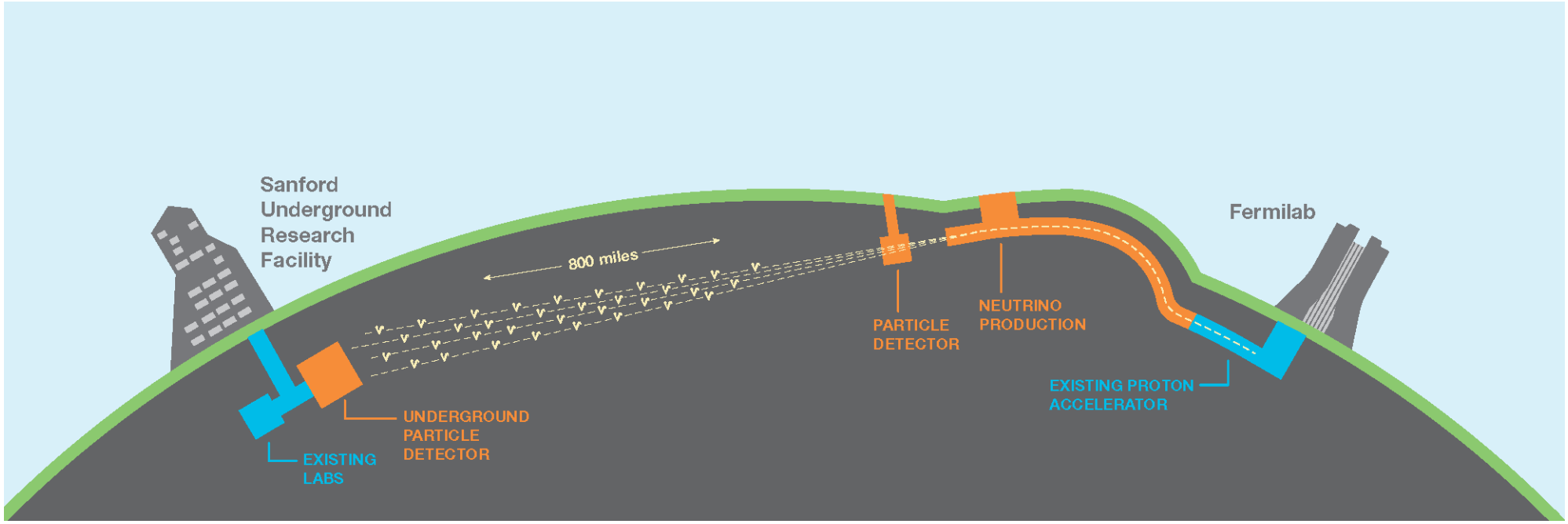
$\sin^2(\theta_{13})=(2.12 \pm 0.08) \times 10^{-2}$

DUNE

The Deep Underground Neutrino Experiment (DUNE):

Major international effort in neutrino physics

Targets: CP-violation, Neutrino Mass Hierarchy, Supernova ν, Nucleon Decay

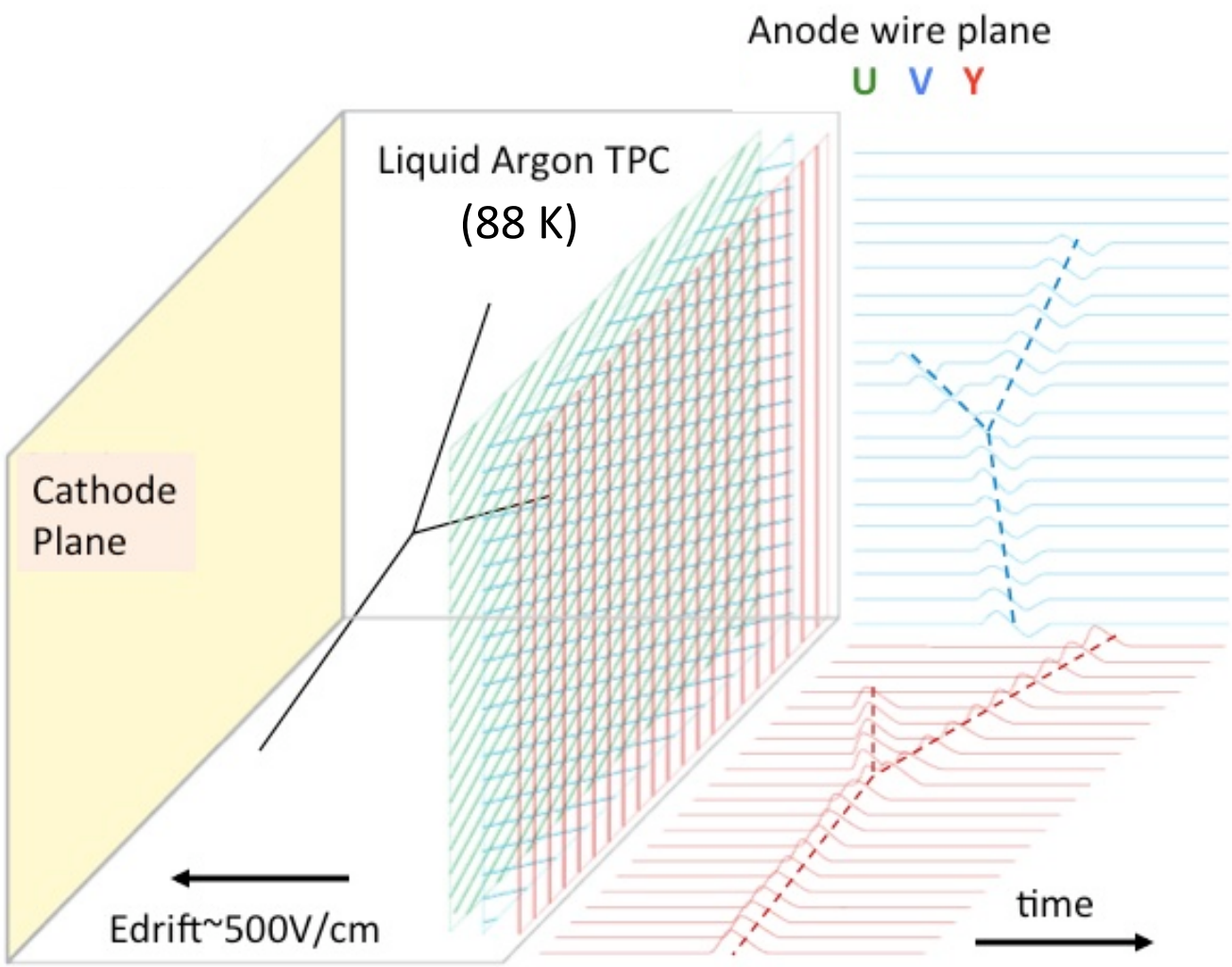


Key Features:

Source: Wide-band neutrino beam produced using 1 MW proton beam at Fermilab

Detector: four 10-kton liquid argon time-projection chambers (LArTPCs) at SURF

LArTPC Signals



Ionization electrons:
23.6 eV per e-
→ ~42,000 e- / MeV

Recombination loss: *@500V/cm*
MIP: ~30%
Proton: ~70%

Drift velocity: *@500V/cm*
~1.6 mm/μs

Drift loss:
Few-% to ~50%, depending on LAr purity and drift distance.

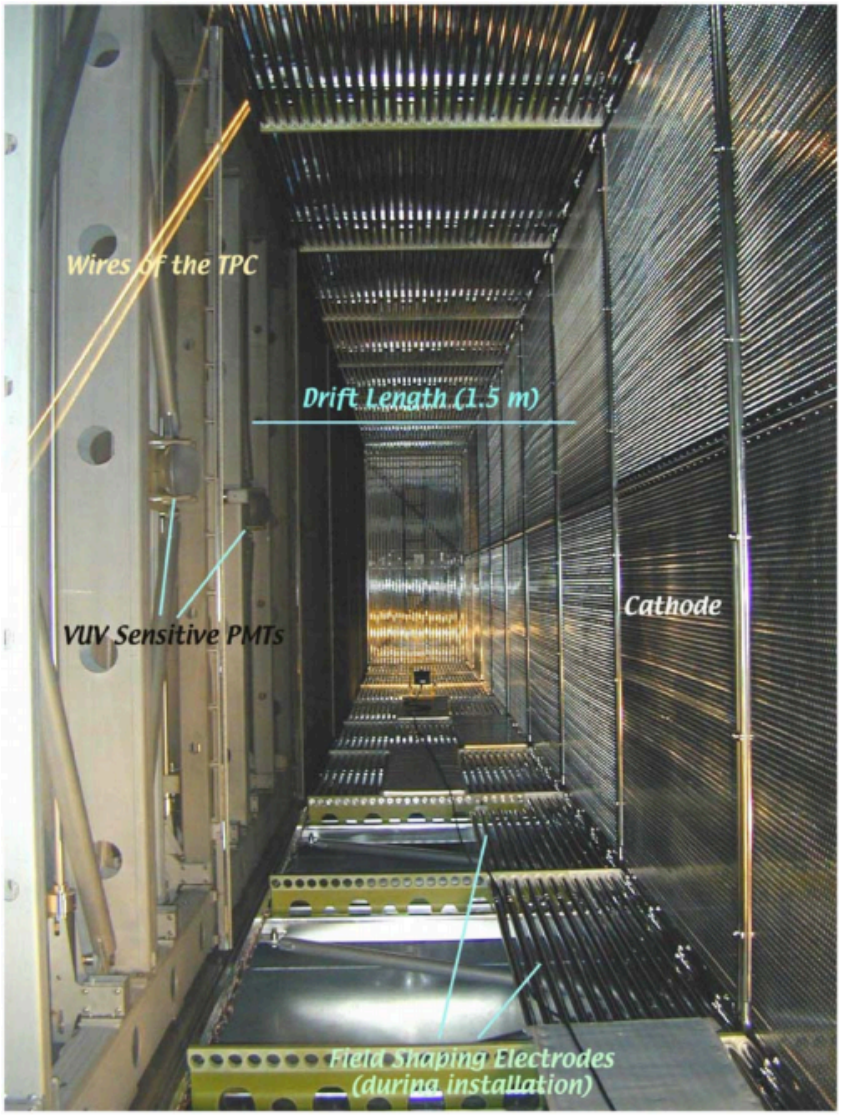
Charge signals: (approx.)
MIP: ~15k e-
Multi-proton: ~250k e-
(assuming 3mm pitch)

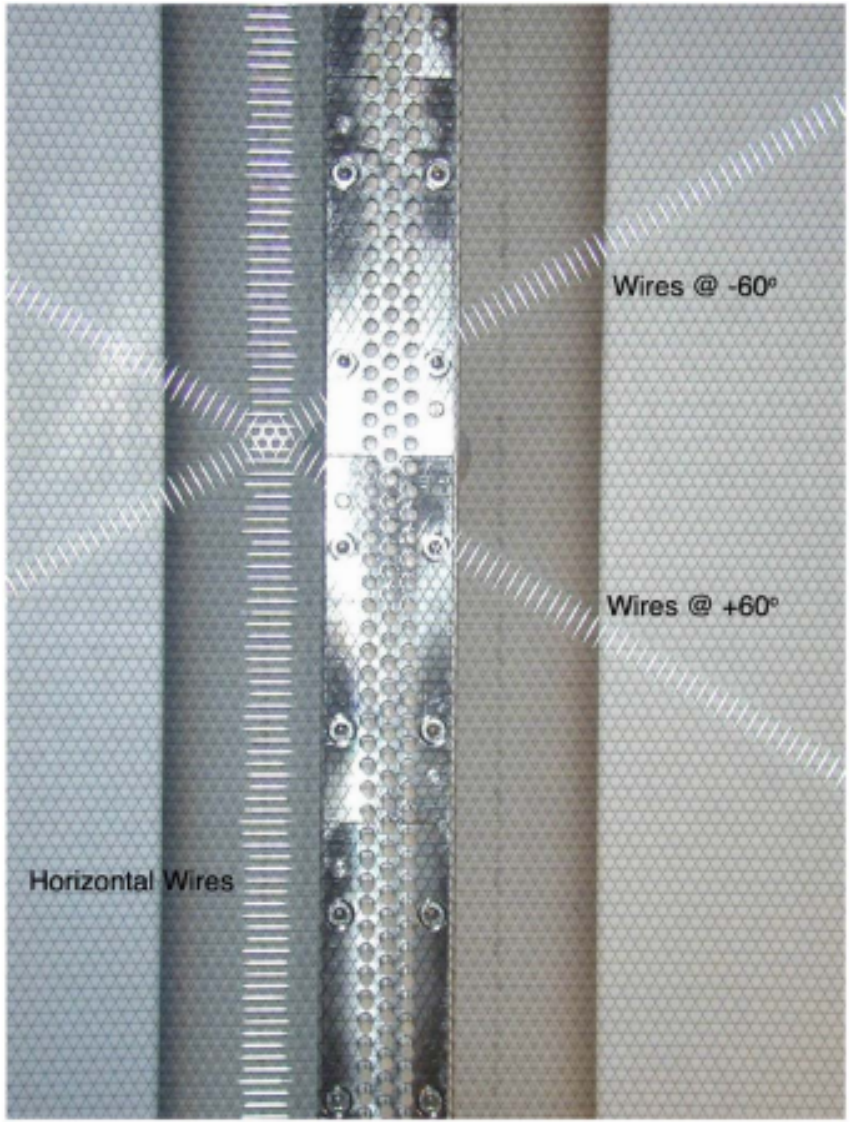
Standard detection technique: Wire planes
Provide three views of interaction, each 1-D vs. Z (i.e. drift direction)
arXiv:1107.5112

Argon also an effective scintillator, provides accurate timing.

Example: ICARUS

ICARUS T600 @ CNGS:

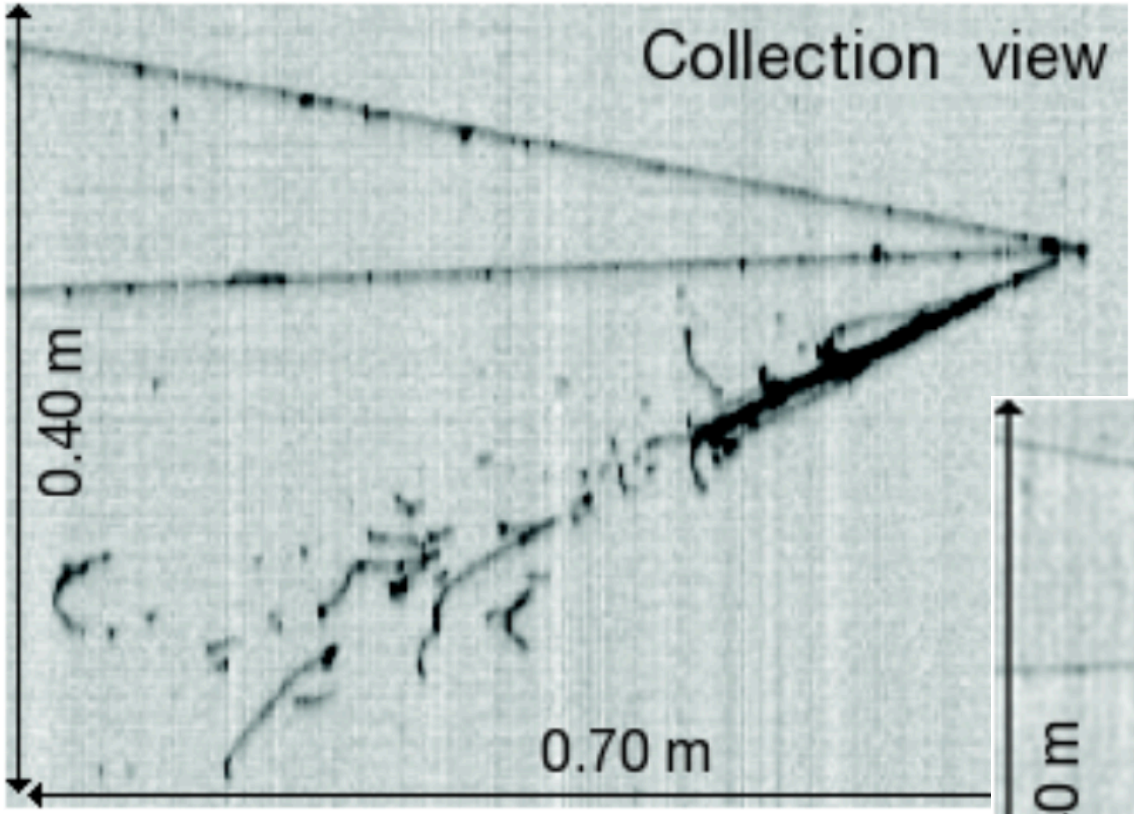


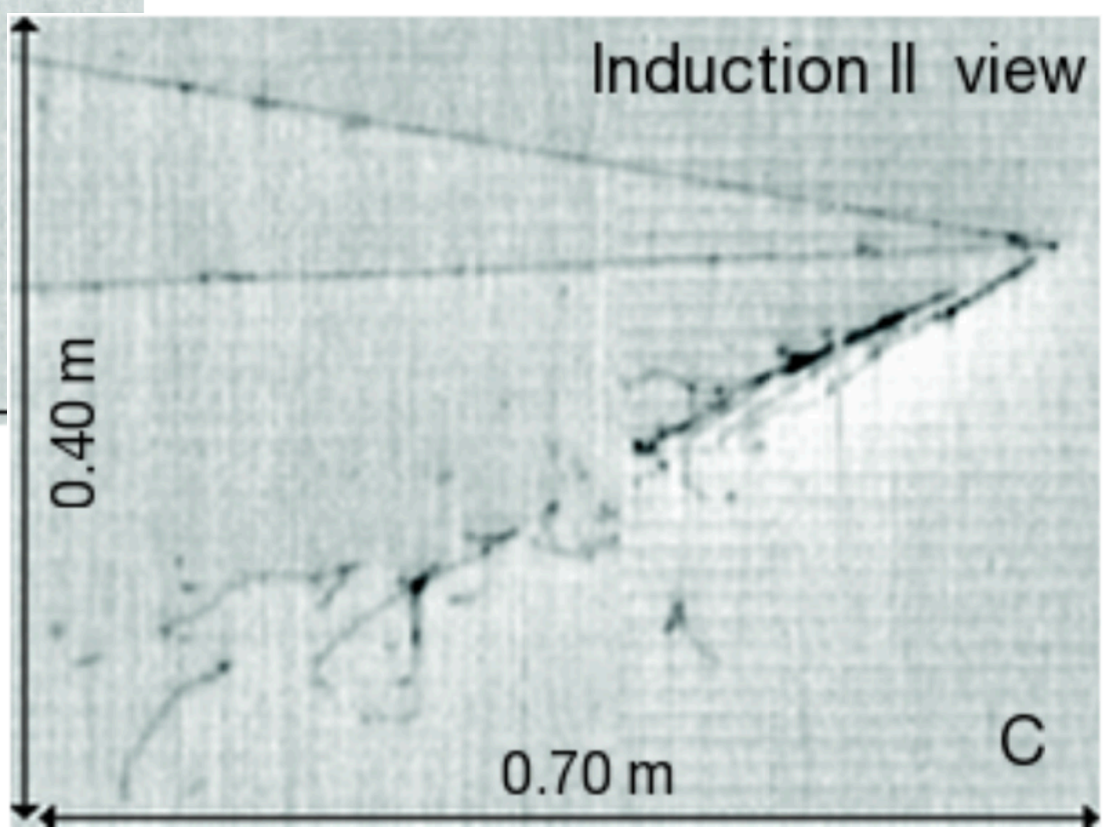


NIM A527 (2004) 329

Example: ICARUS

ICARUS T600 @ CNGS:

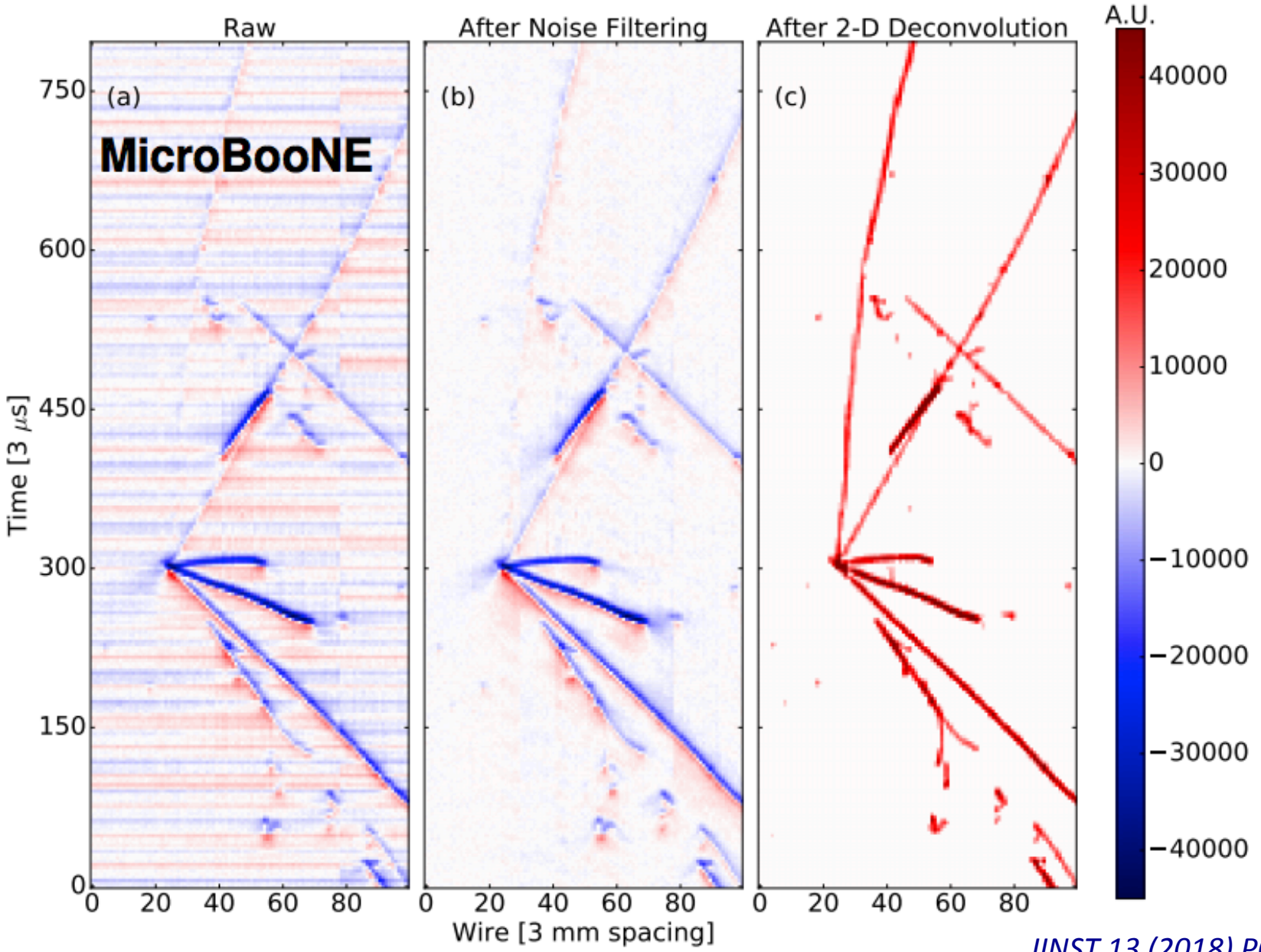




JINST 6 (2011) P07011

Example: MicroBooNE

MicroBooNE @ Fermilab:

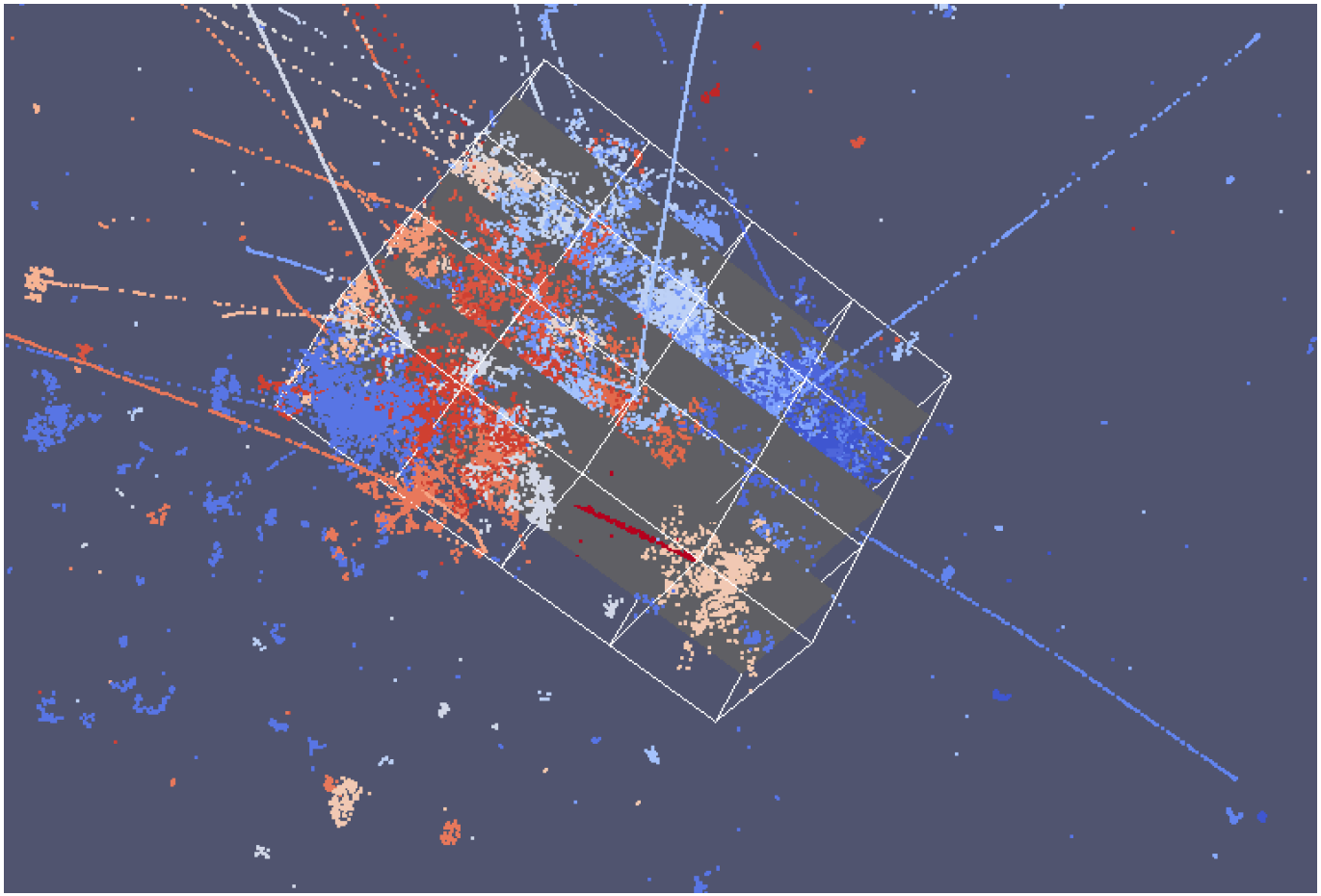


JINST 13 (2018) P07007

Neutrino Pile-up

DUNE Near Detector:

High-rate environment overwhelms standard readout technique.



Example simulation of neutrino pile-up for a single neutrino beam pulse.

Each color represents a separate neutrino interaction.

Does not include background of similar rate from neutrino interactions outside LAr-TPC.

Simulation by J. Sinclair

True 3D readout would enable LArTPC near detector

True 3D Readout

Consider pad-based readout for LArTPCs, as used in gas TPCs?

ALICE TPC @ CERN

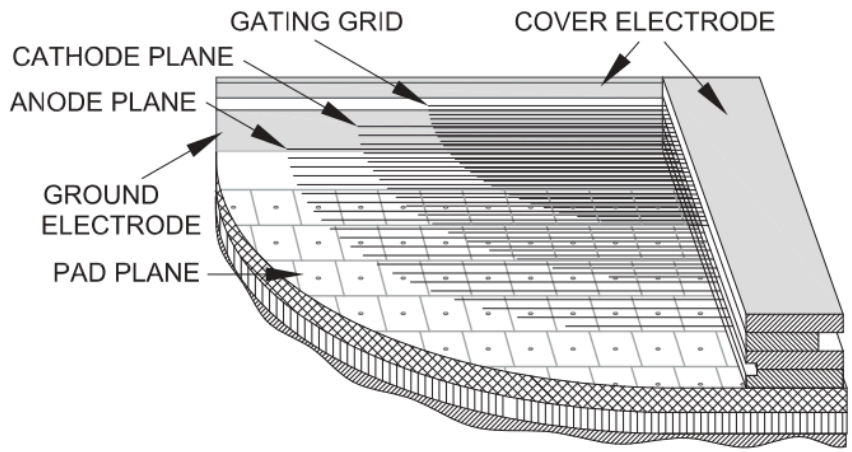


Fig. 9. Cross-section through a readout chamber showing the pad plane, the wire planes and the cover electrode.

NIM A622 (2010) 316

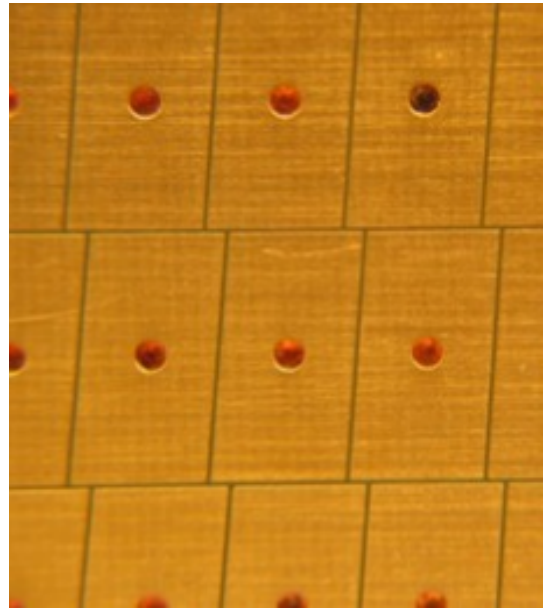


Photo of ALICE TPC pads

Pad Spacing (mm)	Pad Density (m^{-2})
3	111,111
4	62,500
5	40,000

Pad densities of interest for LArTPCs

Key Challenges:

Power:

No gas amplification in LArTPCs; must rely on electronic amplification.

Existing electronics (~10 mW/channel) would boil LArTPC; need ~10^{-2} reduction.

Complexity:

Requires cryogenic digital multiplexing of O(10^5) channels / m^2. Must scale to ~100 m^2 for ND.

Development:

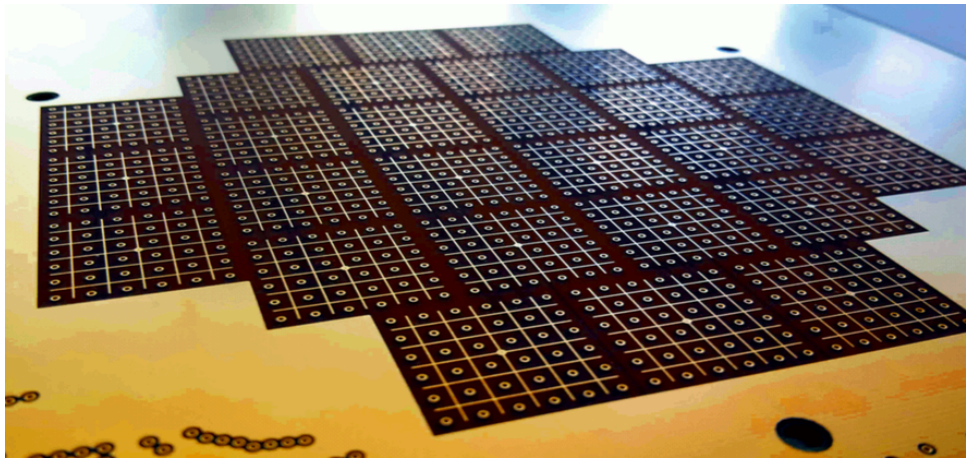
Requires new cryogenic-compatible integrated circuit. Too slow/difficult to develop?

Production Cost:

Must be able to produce ~10^7 channels at a reasonable cost.

Pixel R&D: ArgonCube

Pixel spacing: 3mm

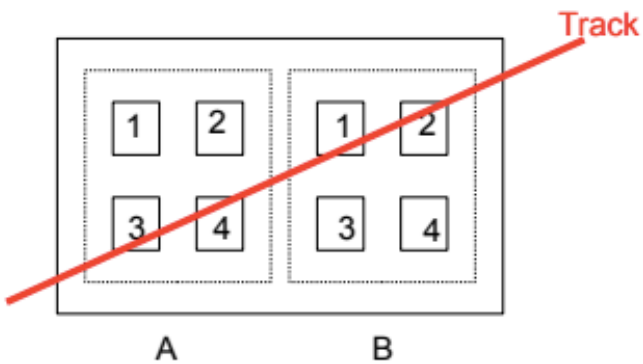


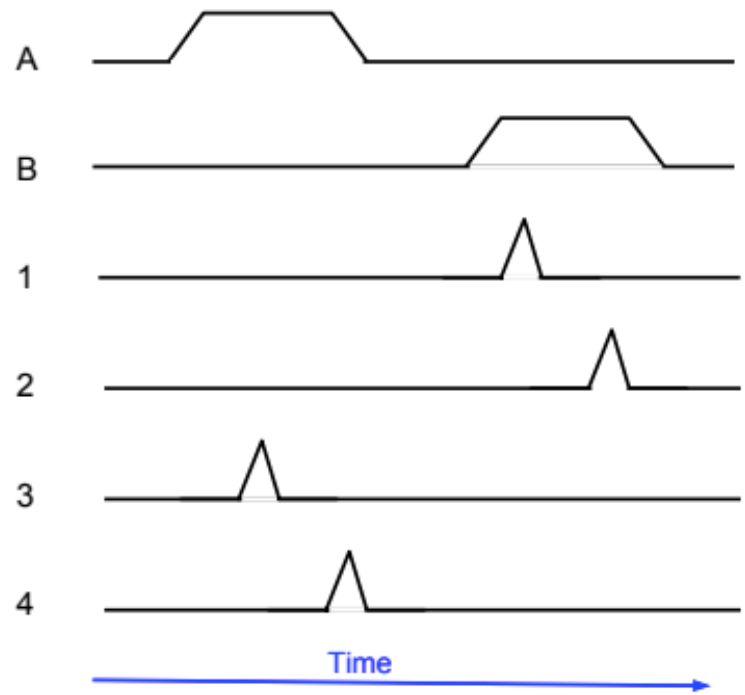
LHEP group at Univ. of Bern / ArgonCube:

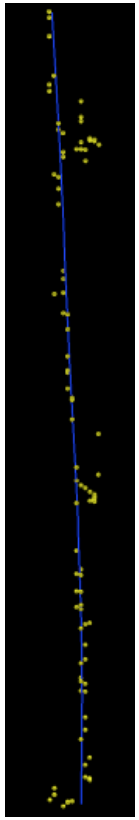
- Demonstrated pixel readout in LAr (Summer 2016)
- Combined pixel signals to dramatically reduce channel count
- Used clever approach of 'inductive regions' to disambiguate signals.

arXiv:1801.08884

Conceptual diagram:





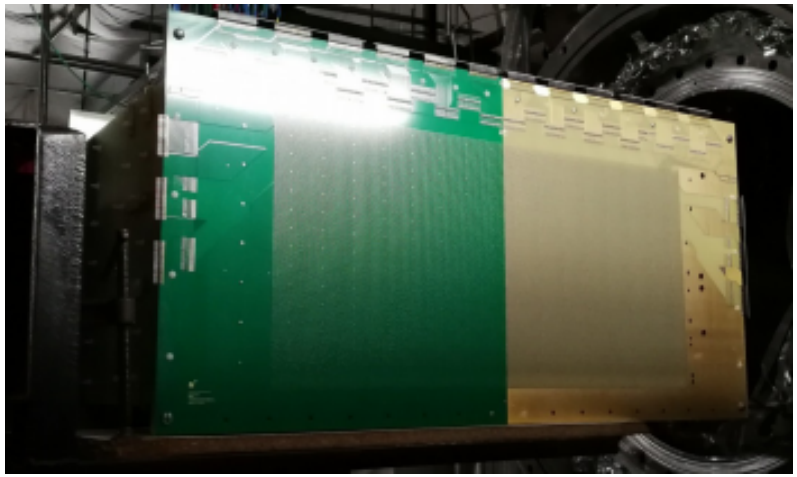


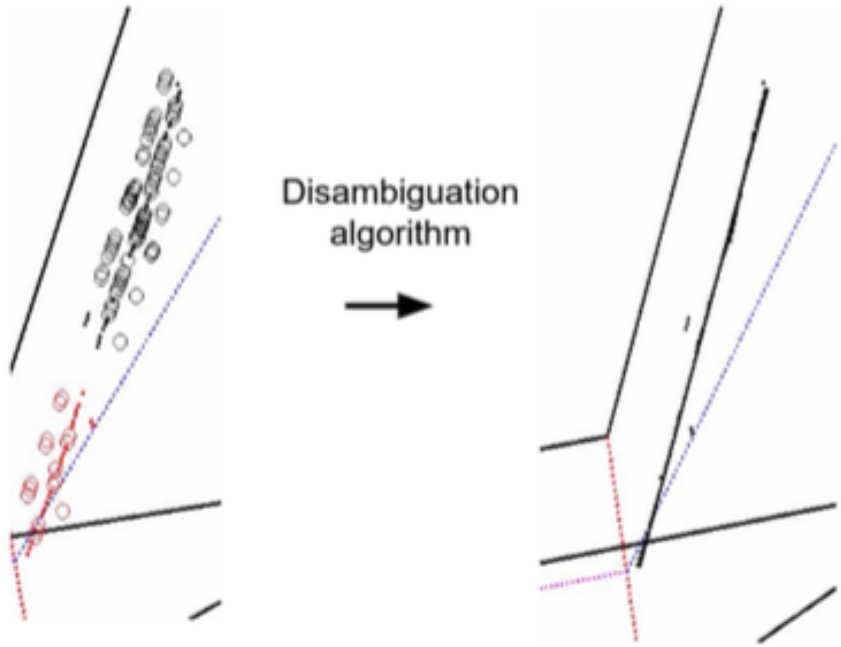
See ArgonCube talk on Dec. 11

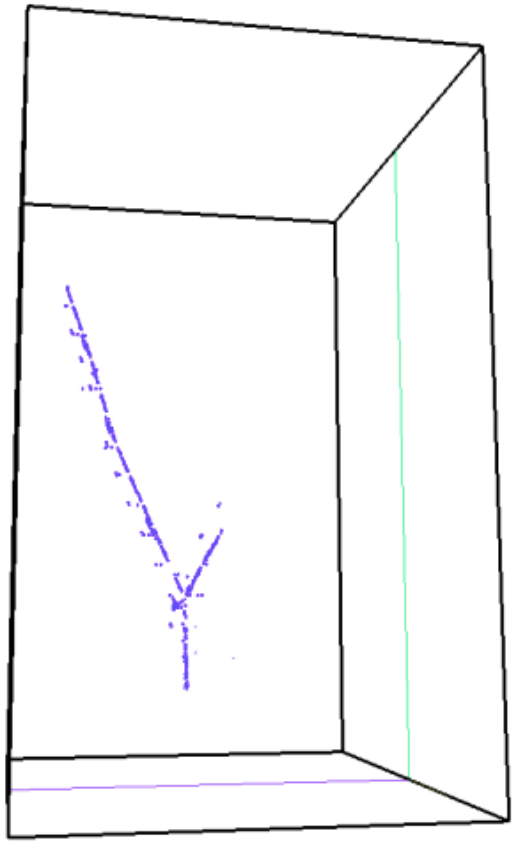
Pixel R&D: PixLAr/LArIAT

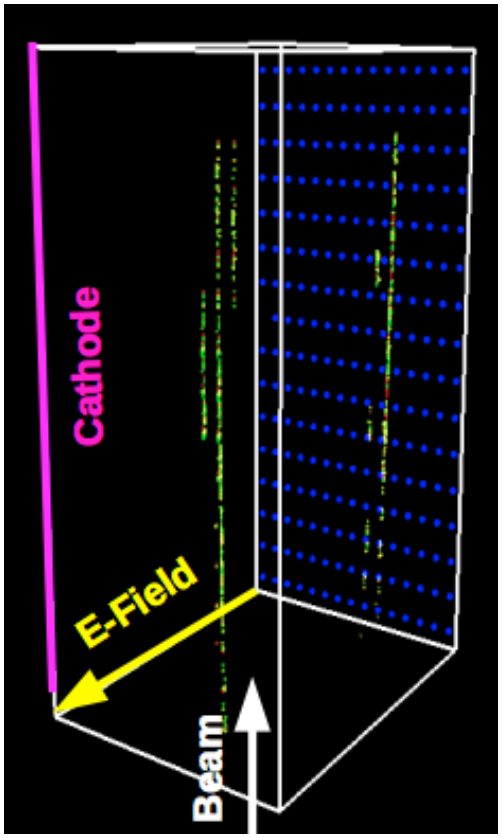
PixLAr Test: UTA (J. Asaadi) + LHEP group

- Large-area LHEP-style pixel sensor in LArIAT TPC
- 28,800 pixels merged into 480 channels
- Collected data in FNAL test beam Dec. 2017 – Jan. 2018
- Also tested new ArCLight technique for photon detection

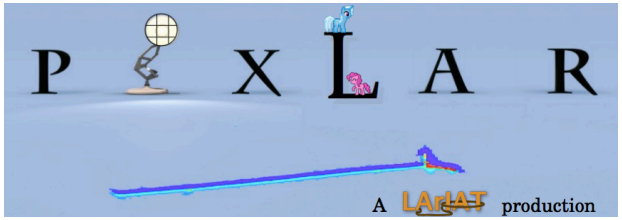








Plus substantial progress in development of 3D reconstruction techniques

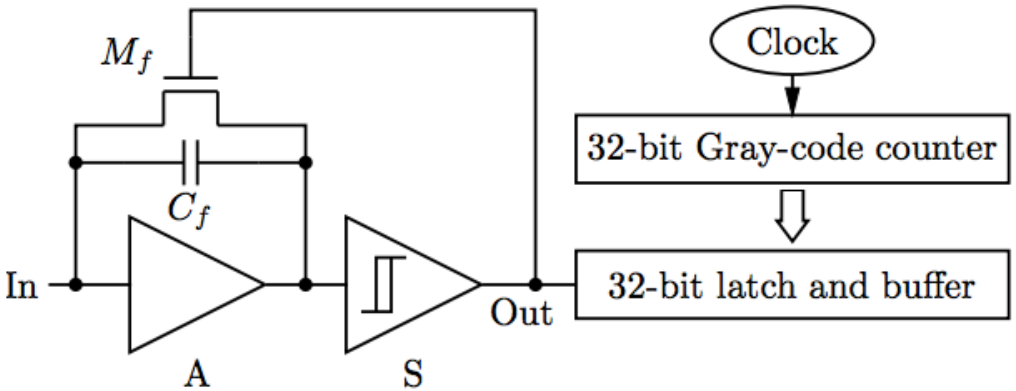


Pixel R&D: NetPix

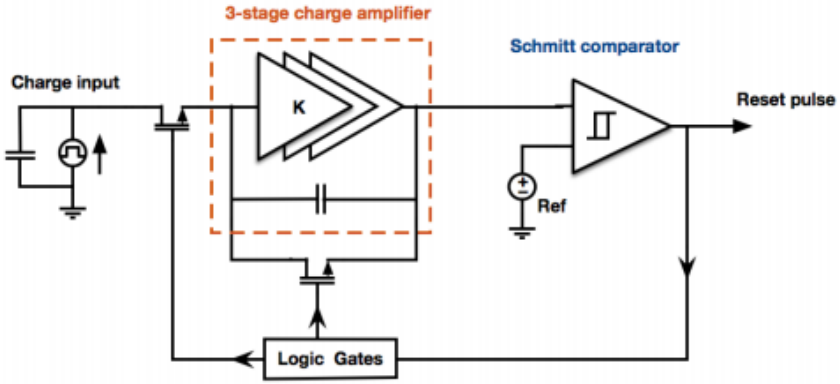
Q-Pix / NetPix Concept: UTA (D. Nygren), LBNL (Y. Mei), UPenn

- Novel concept using a unique CSA, Schmitt trigger for each pixel
- Each pixel produces a series of digital trigger pulses
- Given Schmitt threshold dQ, current arriving at pixel in interval dt between triggers is dQ/dt

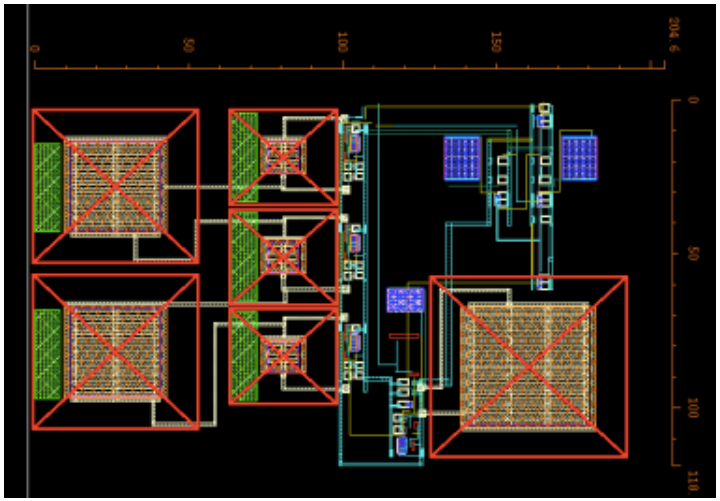
Schmitt trigger with local clock



Design Study (65nm CMOS): UPenn (M. Newcomer, P. Wang, L. Du)



Conceptual output:

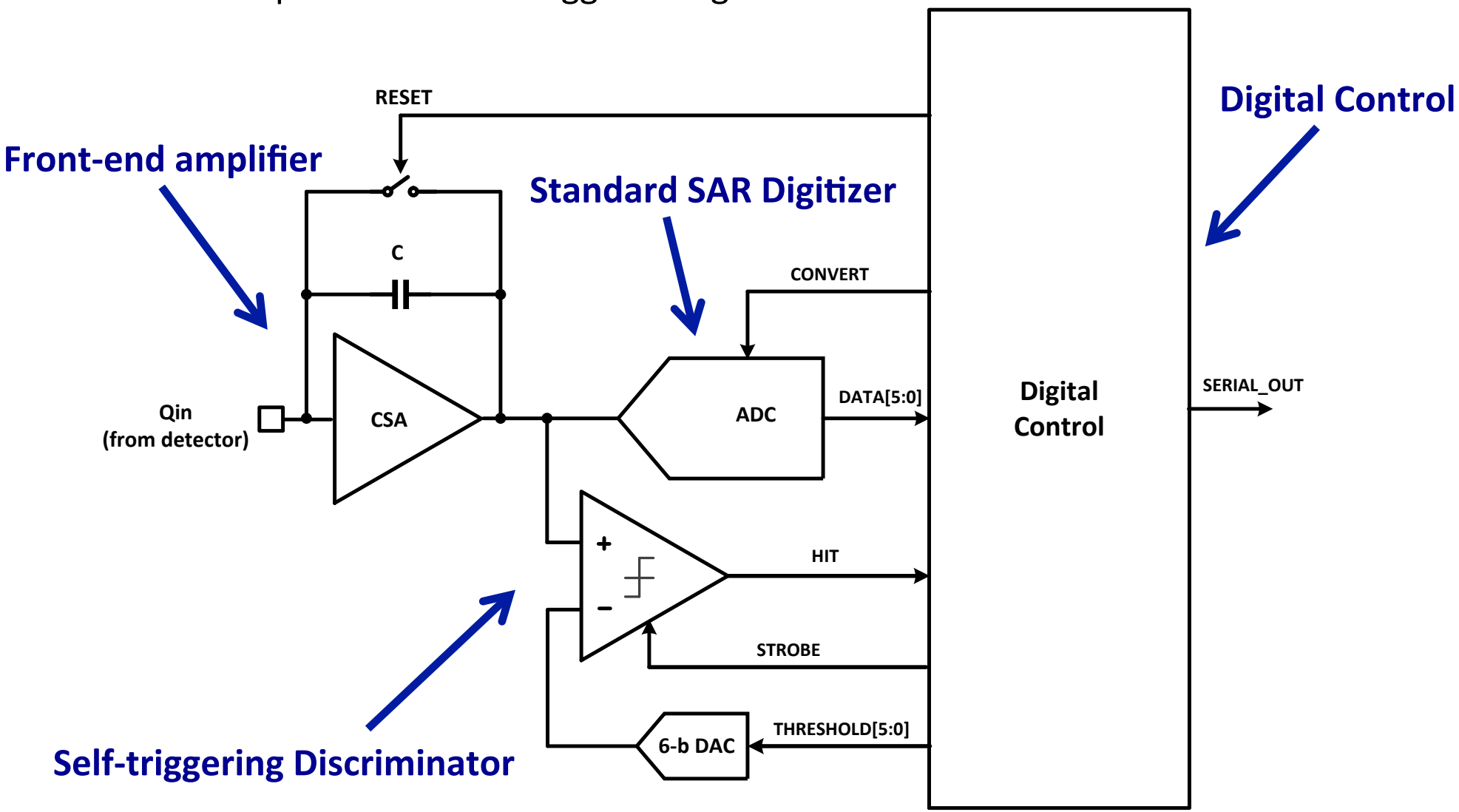


arXiv:1809.10213

Pixel R&D: LArPix

LArPix System: LBNL with ArgonCube (Univ. of Bern, UTA, etc.)

- Independent front-end channel for every pixel
- Pulsed-reset amplifier with self-triggered digitization and readout



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

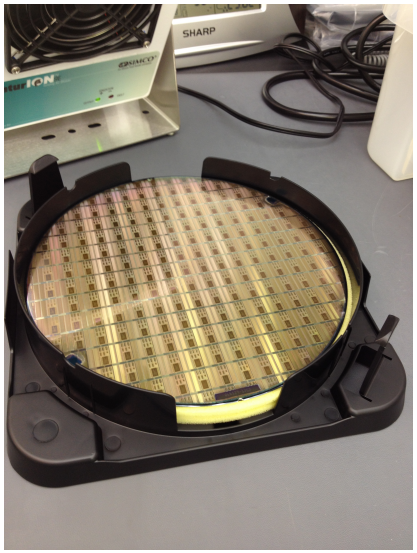
LArPix-v1 Progress

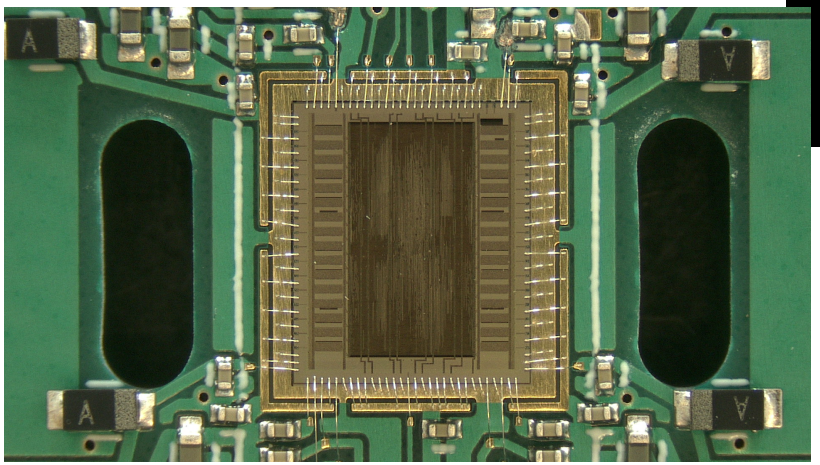
LArPix-v1 ASIC:

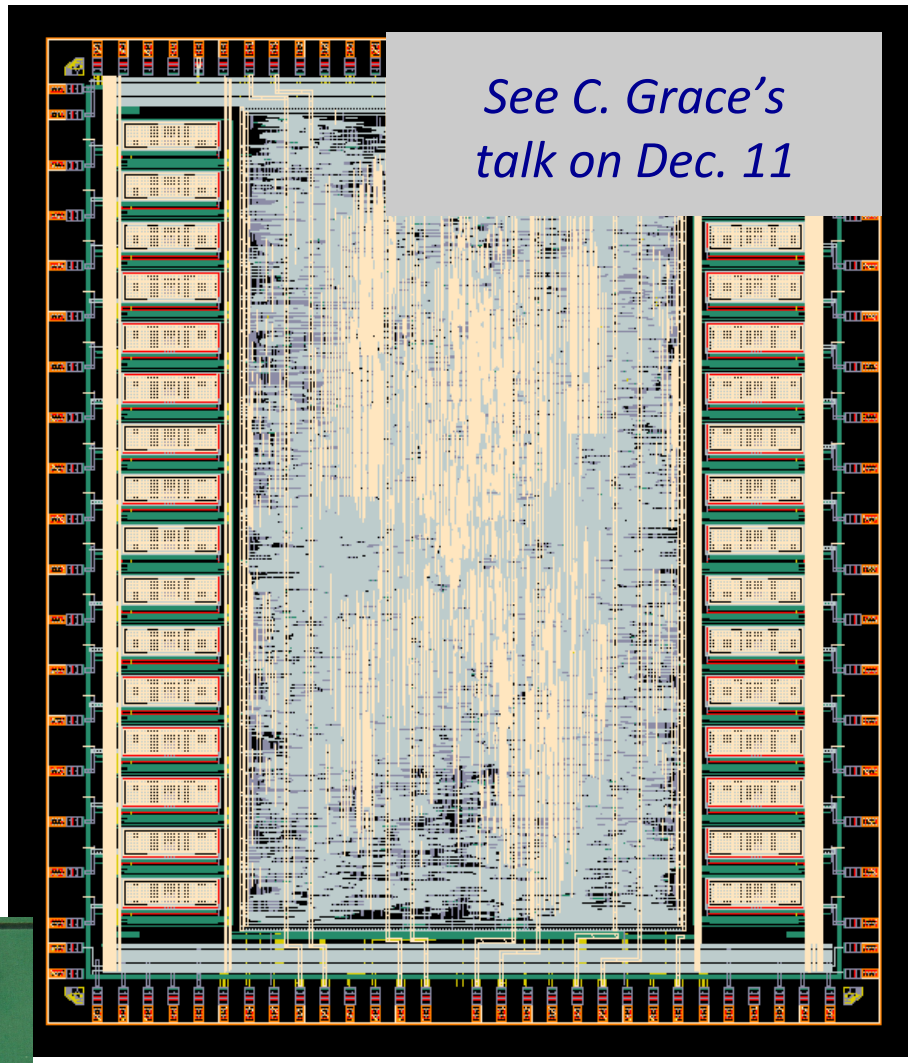
- Dec. 2016: Design began
- June 2017: Submitted for fabrication
- Oct. 2017: First chips, test boards @ LBNL
- Dec. 2017: Bench tests successfully completed
- Jan. 2018: Assembled sensor, integrated LArTPC

Recent Progress:

- Feb. 2018: First tracks from true 3D LArTPC @ LBNL
- Mar. 2018: Developed integrated control system
- Apr. 2018: Assembled scalable 512-channel system, operated in 60-cm-drift TPC @ Bern
- May 2018: Operated 832-channel system @ LBNL







Process: 180nm bulk CMOS

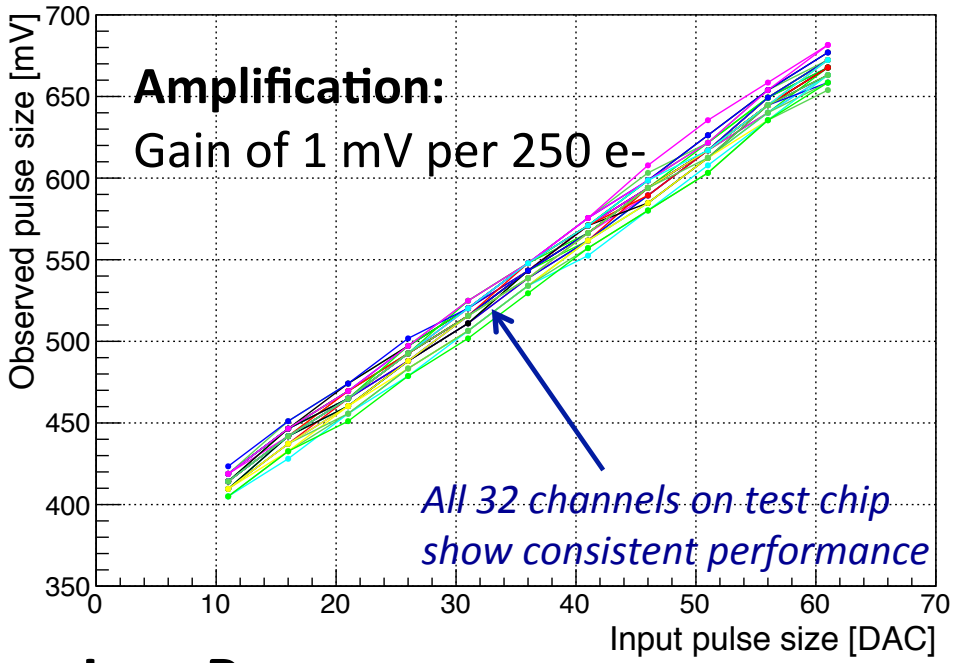
Design and testing team @ LBNL:

D. Dwyer, C. Grace, M. Garcia-Sciveres, A. Krieger, D. Gnani, T. Stezelberger, S. Kohn, P. Madigan, H. Steiner

+ helpful advice from Y. Mei

Initial Bench-testing Results

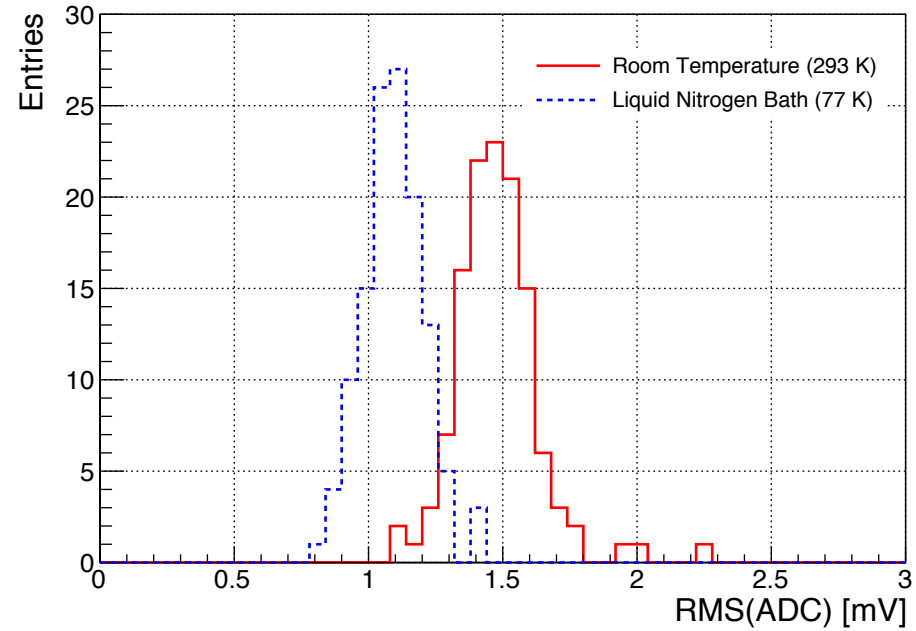
Demonstrated low-noise low-power cryogenic amplification, digitization, and readout:



Low Noise:

~1.5 mV (~375 e-) at room temp

~1.1 mV (~275 e-) in LN^2 bath



Low Power:

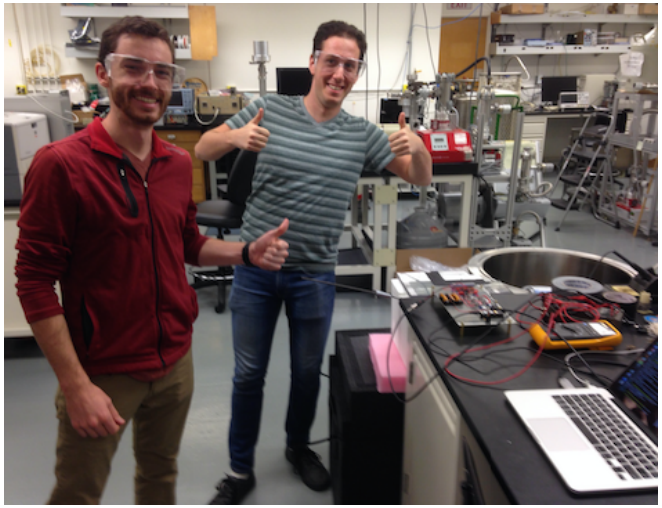
Average power for 128-channel readout:

- Analog: 24 µW/channel
- Digital: 38 µW/channel
- **Total: 62 µW/channel**

Performance exceeds design targets:

< 500 e- ENC

< 100 µW/channel



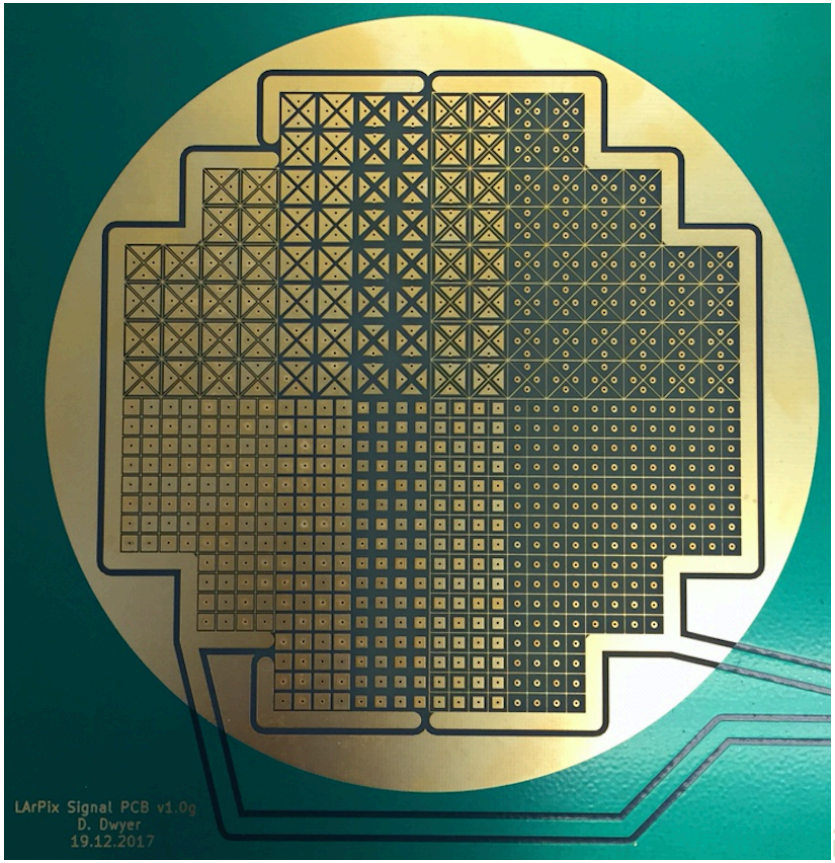
P. Madigan, S. Kohn: drove testing program

See P. Madigan's talk on Dec. 10.

LArPix-v1: Readout Assembly

Pixel Board:

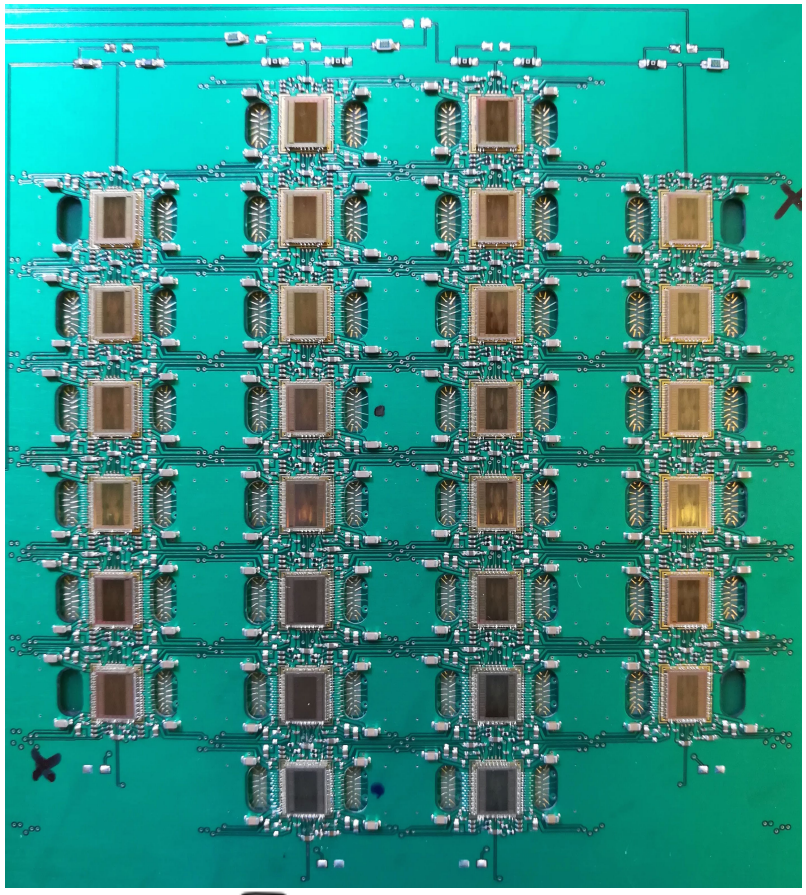
Standard printed circuit board
Fits Bern Pixel Demonstrator TPC
10 different pixel geometries

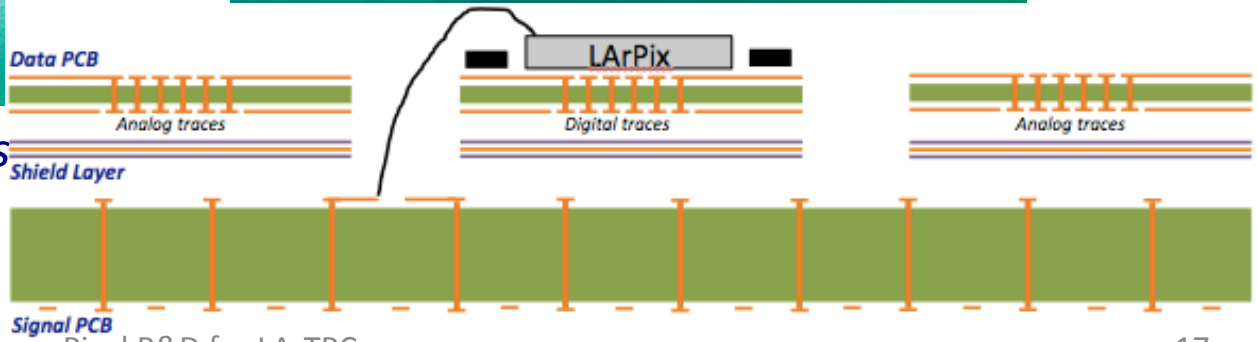


10 cm diameter, 3mm pitch, 832 pixels

Complete readout assembly

28-chip LArPix data board sandwiched to pixel board

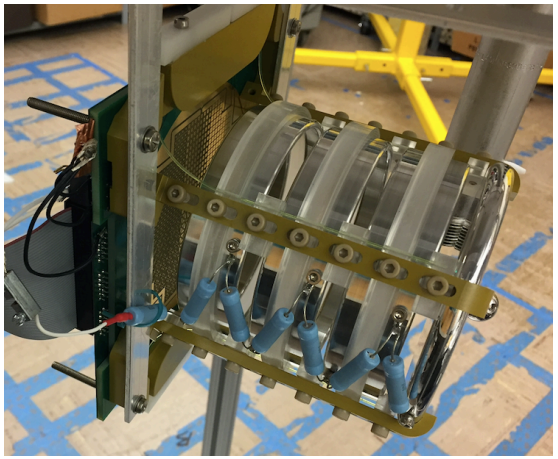


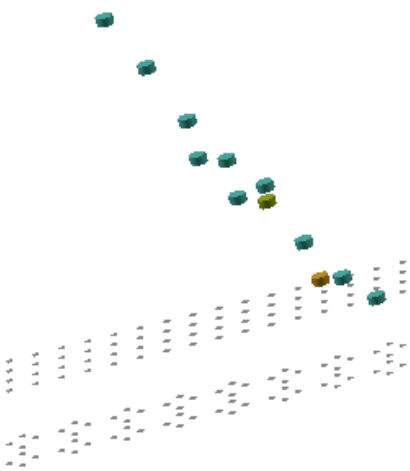


LArTPC Operation

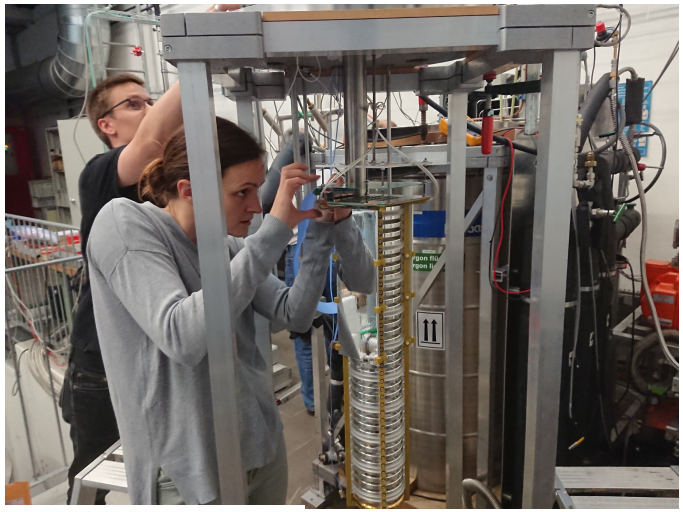
Demonstration of cosmic ray detection at increasing scales

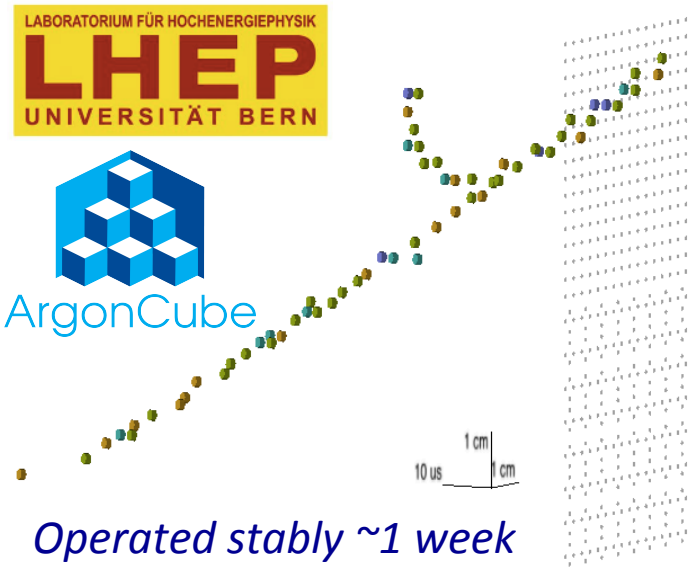
Feb 2018:
128-pixel system @ LBNL
10 cm drift, 200 V/cm





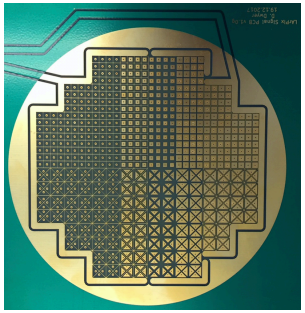
Apr 2018:
512-pixel system @ Bern
60 cm drift, 1 kV/cm

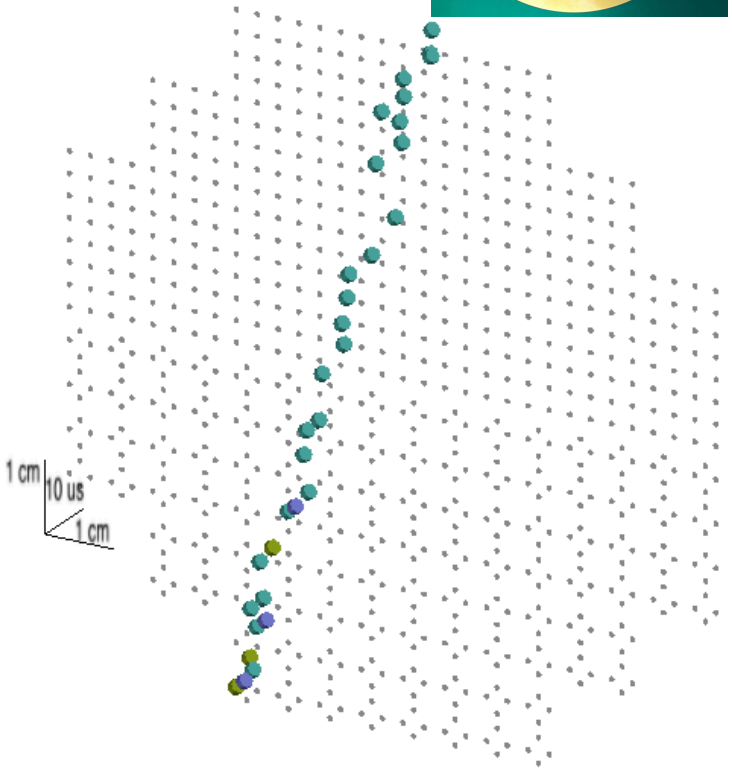




Operated stably ~1 week

May 2018:
832-pixel system @ LBNL





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LArPix Raw Data

Brief description of raw LArPix data

54-bit hit record: Pixel ID, ADC value, timestamp, status bits

Each colored point shows one self-triggered hit

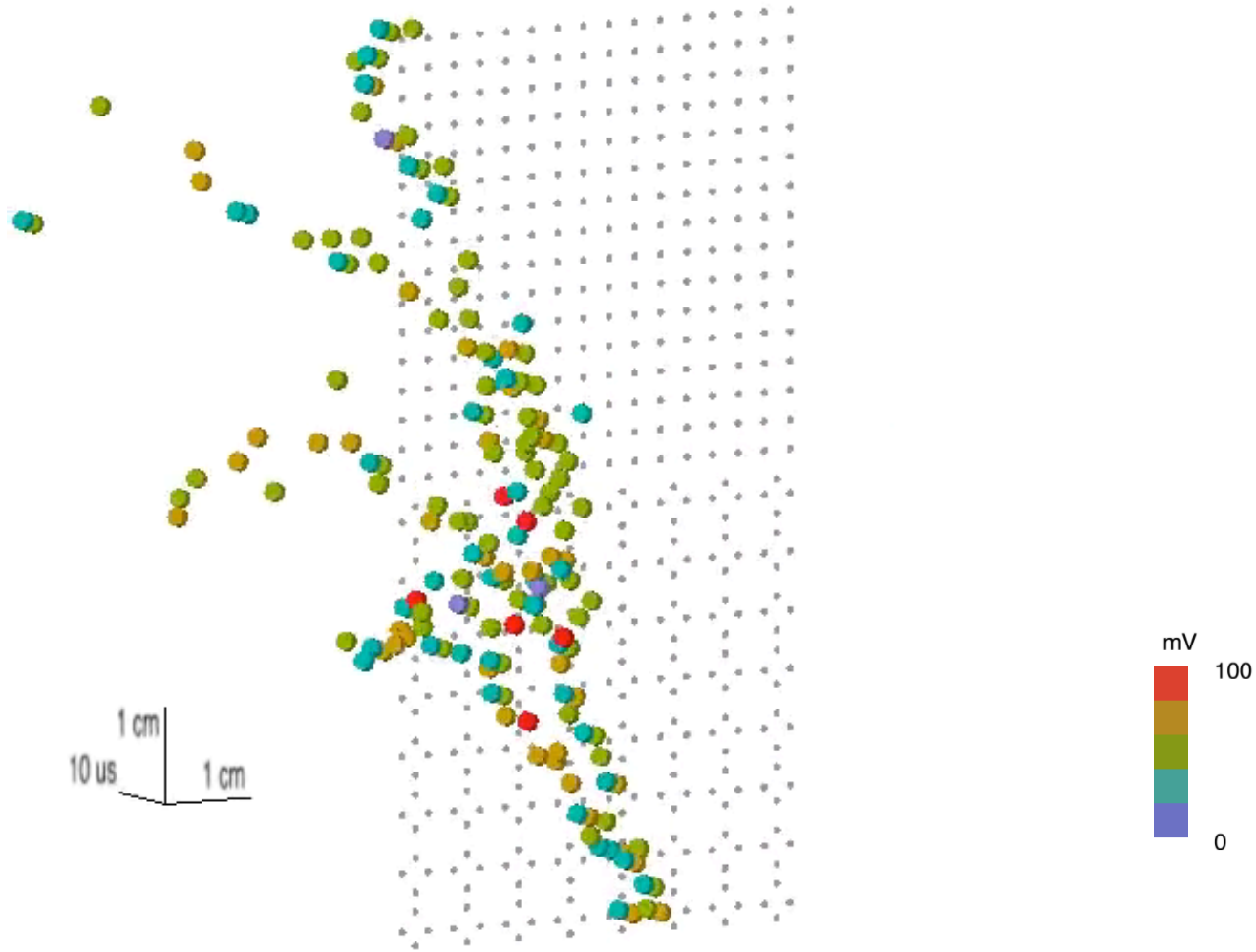
- Hit x, y position from pixel location
  3 mm precision
- Drift position given by timestamp
  200 ns precision
- Color shows hit amplitude
  2 mV precision
- ADC value converted to mV
  based on initial calibration

No filtering, manipulation applied to raw data.

→ Noise is very low

>20:1 SNR for MIPs

Video of Cosmic Rays imaged in 3D:



See: https://goo.gl/AdVC9s

LArPix-v1: Pixel Hit Rates

Self-triggered pixels give low data rates:

LArPix-v1 operation: Dominated by cosmic rays

60 cm drift @ Bern:

512 pixels, ~0.3 Hz/pixel

→ **~3 kB/s total rate**

10 cm drift @ LBNL:

832 pixels, ~0.05 Hz/pixel

→ **~1 kB/s total rate**

DUNE Near Detector: *(estimate)*

50 cm drift, detector underground

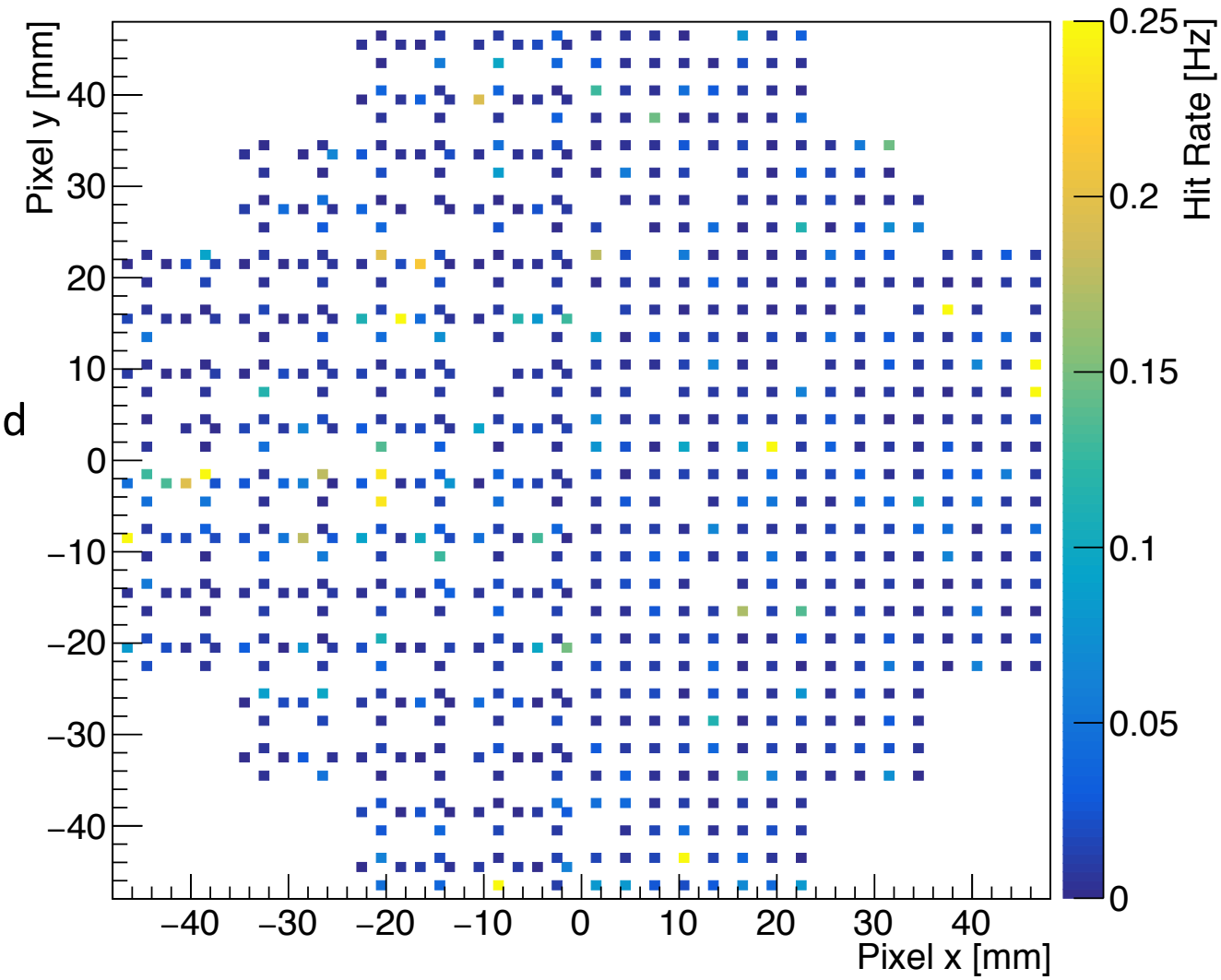
8M pixels, ~0.01 Hz / pixel

→ **~2 MB/s total rate**

Issue:

Few percent of pixels have higher rates or were disabled due to insufficient trim of pixel thresholds.

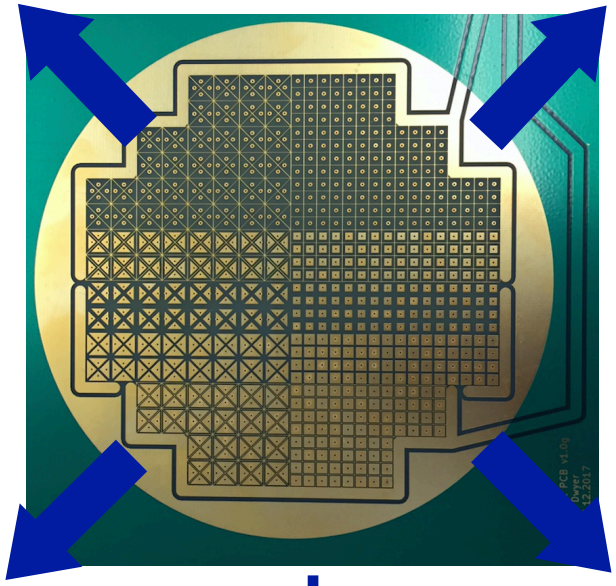
Pixel trigger rates for 10 cm drift LArTPC @ LBNL



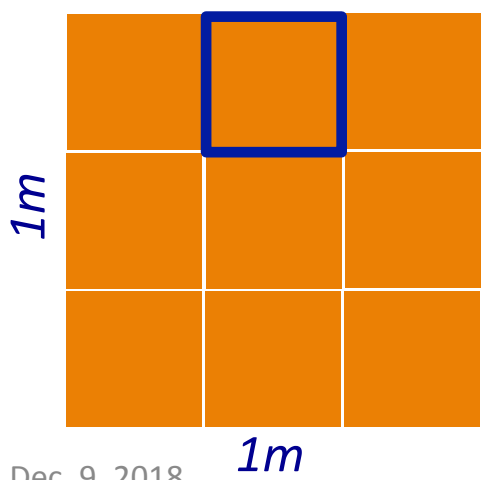
LArPix: Next Steps

Modular pixel tile for large LArTPCs

Extend pixels edge-to-edge



Tile anode:



Developing LArPix-v2 ASIC for scalable assembly and improved physics performance:

- Increase resolution for charge signal
- Double number of channels per chip (32→64)
- Improved I/O, robust to chip failure.
- Substantially reduce external circuitry
- Improve hit timestamp accuracy
- Increase channel threshold tunability
- Improve front-end pulser
- Tailor characteristics of discriminator
- *Plus a number of other changes*

ASIC Packaging:

- Testing v1 ASIC in QFP packaged format
- Revising tile design assuming v2 ASIC is packaged

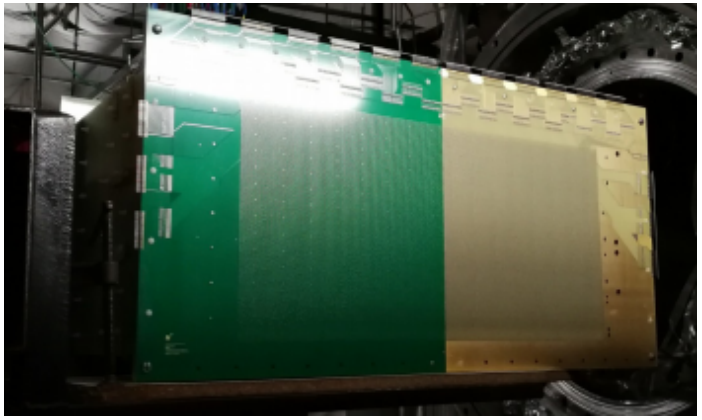
Production Approach:

- Rely on commercial fabrication: ASICs, PCBs, tile assembly
- Pixel tile production cost: ~$5k / m^2 (still in development)

Next Steps: Demonstrators

Roadmap of potential LArPix demonstrations at larger scales:

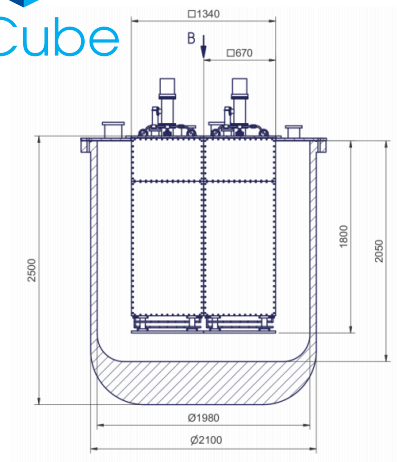
LArIAT LArTPC



Readout area: 0.36 m^2
pixels: 22.5k
ASICs: 350
Target: Mid 2019

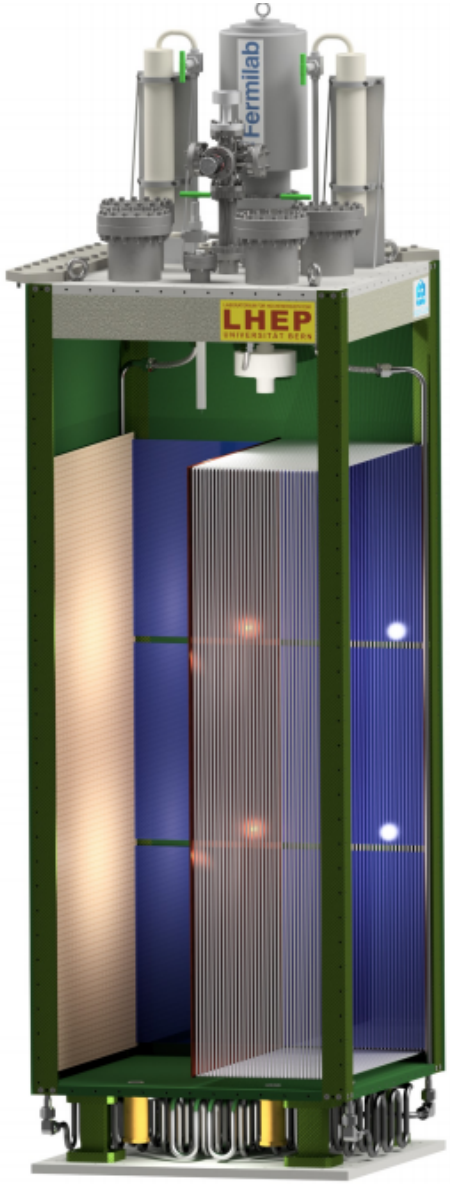
Provide known particle beam for detailed assessment of PID and energy performance.

ArgonCube 2x2 Demonstrator



Readout area: 6.4 m^2
pixels: 400k
ASICs: 6.3k
Target: Late 2019

First module currently under construction. Demonstrator for DUNE Near Detector



Also pursuing LArPix readout for High-pressure Ar gas TPC Near Detector Module with FNAL, others

→ See talk by T. Mohayai on Dec. 11

3D Pixel Reconstruction

Developing reconstruction tools tailored for 3D LArTPC data

Existing tools primarily fit tracks in 2D projections, combine to 3D event

2D problems: ambiguities, track/shower overlap, gaps, dead channels

Recent Progress:

Conventional Algorithms:

Native 3D algorithms for LArTPC track and shower reconstruction *[T. Usher, Y. Tsai]*

Machine Learning:

Comparison of 2D vs. 3D signal-to-background performance *[C. Adams, R. Guenette, et al.]*

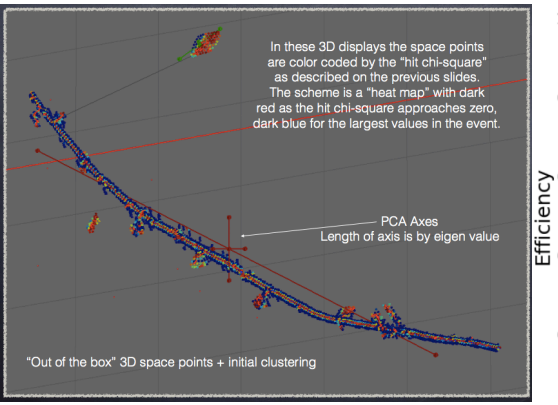
Pixel-level hit classification and clustering *[K. Terao et al.]*

→ *See talk by K. Terao on Dec. 11*

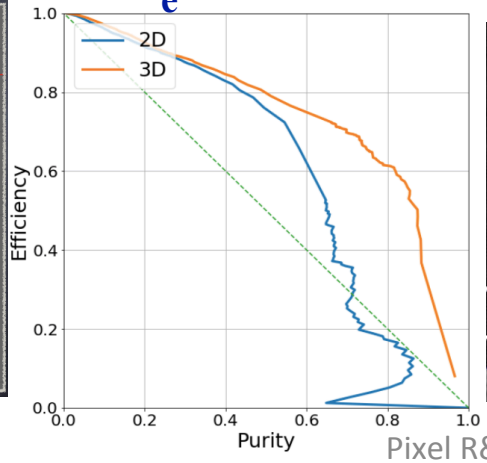
Looking forward:

Development of algorithms addressing DUNE Near Detector pileup

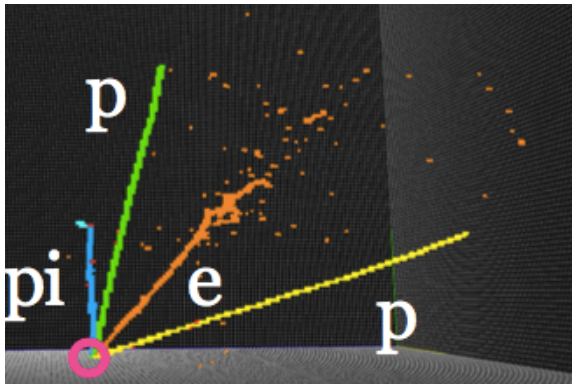
Native 3D algorithms



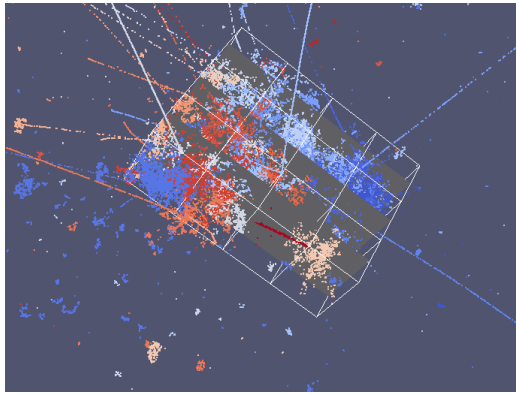
2D vs. 3D ML ν_e selection



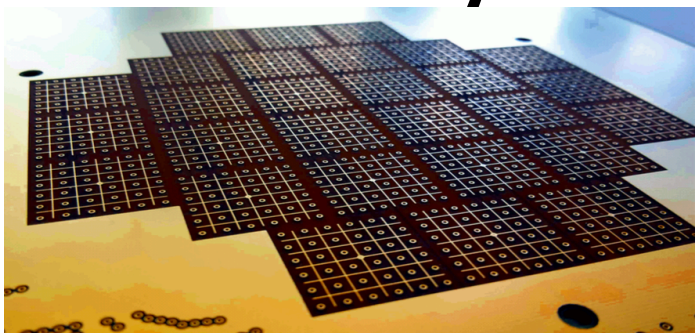
3D ML hit classification



Pileup in DUNE ND



Neutrino Pixel R&D Summary



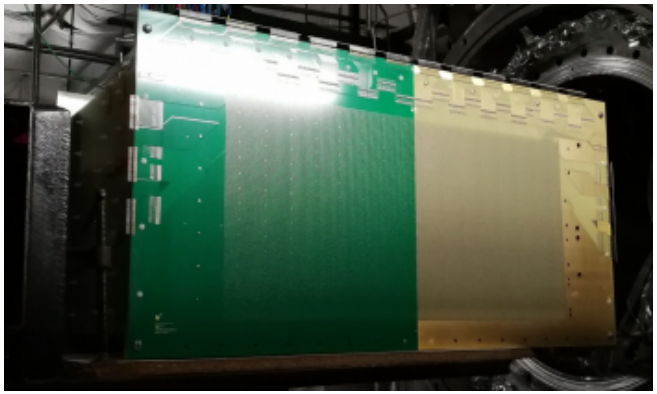
Pixel R&D for LArTPCs:

Resolve signal ambiguities in LArTPCs, with potential for DUNE

Recent Developments:

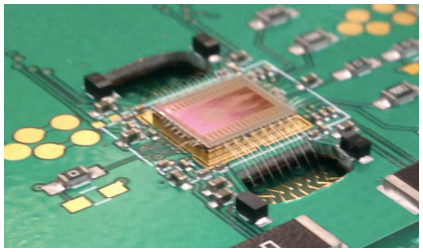
Initial Pixel LArTPC demonstrations:

ArgonCube Pixel Demonstrator: ~1000 pixels in 64 channels
PixLAr/LArIAT: ~28k pixels in 480 channels



Towards independent readout of each pixel

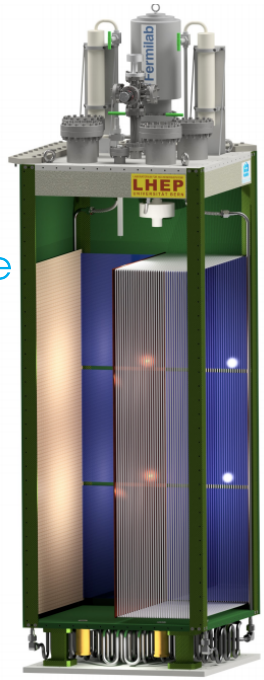
Q-Pix/NetPix Concept: Novel approach for low-power readout
LArPix-v1: Demonstrated low-power 3D imaging of cosmic rays

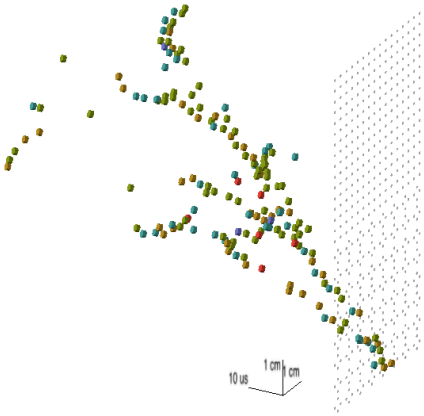


Looking Forward:

Preparing for technical demonstrations at large scales
→ LArIAT, ArgonCube 2x2 Demonstrator
Exploring other potential uses:
→ DUNE Near HP-GAr TPC, DUNE Far Detector, CYGNUS, etc.
Development of dedicated 3D Pixel reconstruction techniques

ArgonCube





Preliminary statement from DUNE:

"The ND CD group recommends that DUNE should have a LArTPC that is optically segmented, with a short drift and 2D pixelized readout, like the concept under study by the ArgonCube collaboration."