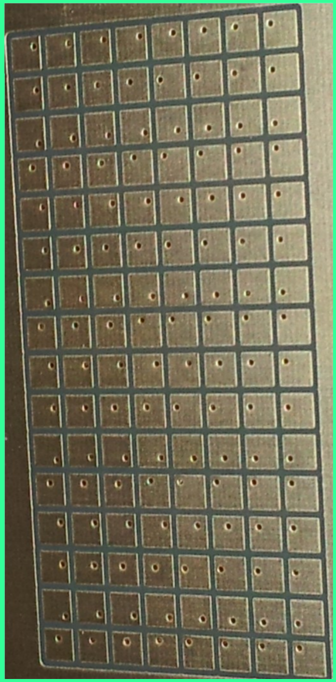
ArgonCube



архитектура масштабируемых
нейтринных детекторов большой массы

Petersburg Nuclear Physics Institute, 25.06.19

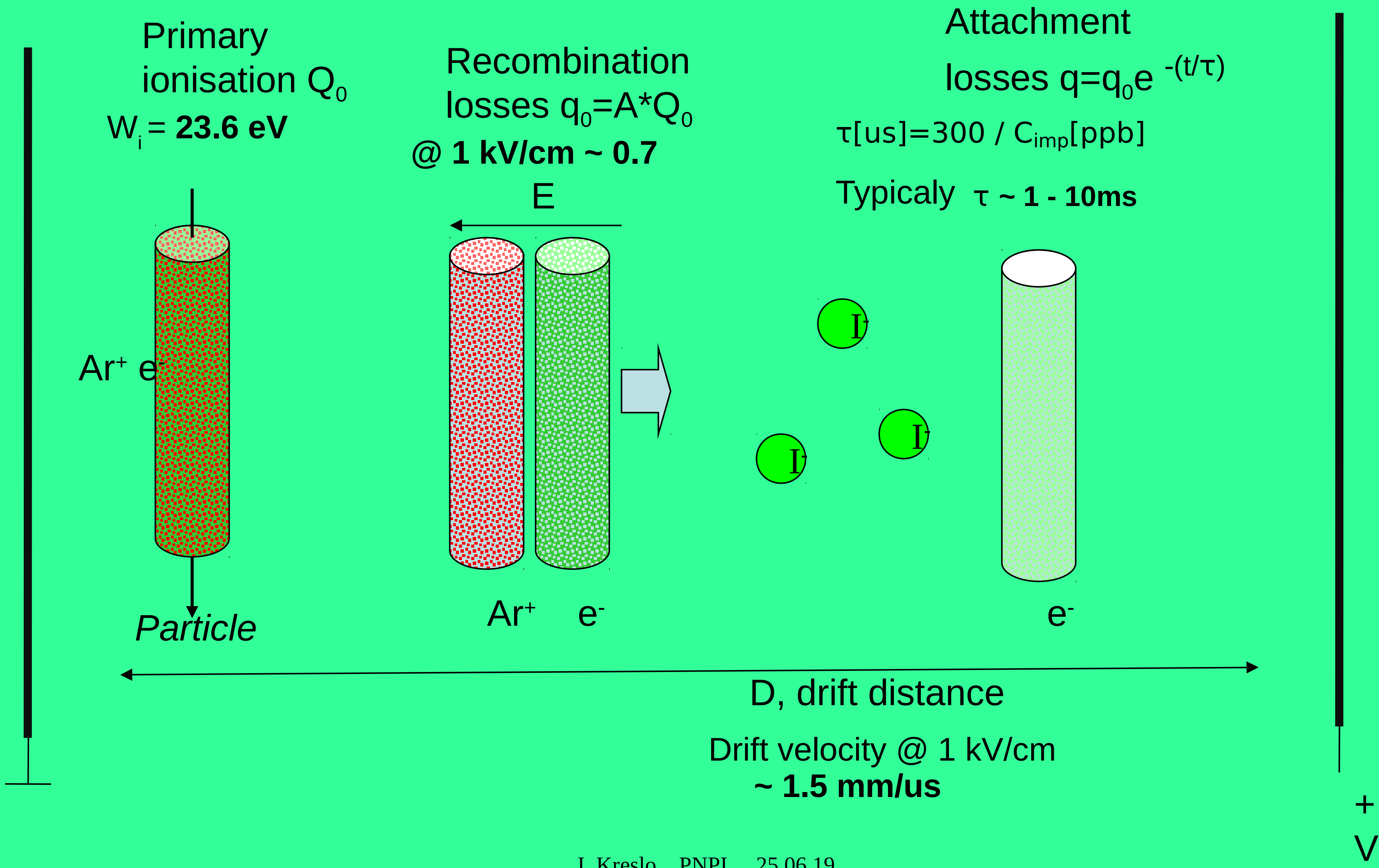
Igor Kreslo
AEC/LHEP University of Bern
on behalf of ARGONCUBE collaboration:

Bern, BNL, CSU, EMPA, FNAL, I3N, Iowa, Harvard, JINR, LBNL, METU, Sheffield, SLAC, South Carolina, Stony Brook, Syracuse, TUBITAK, UTA, Yale

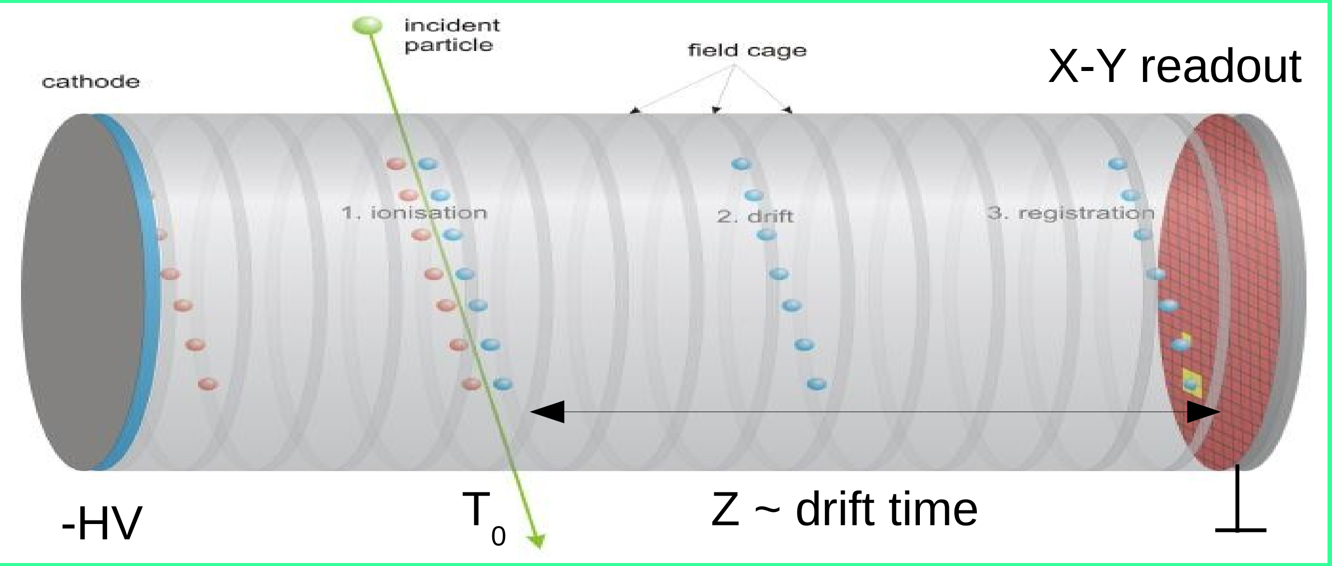
Liquid Argon as detection medium

Density 1.4 g/cm^3 X_o = 14 cm λ_{INT} = 83.5 cm

dE/dx = **2.1 MeV/cm** for MIP



Liquid Argon Time Projection Chamber

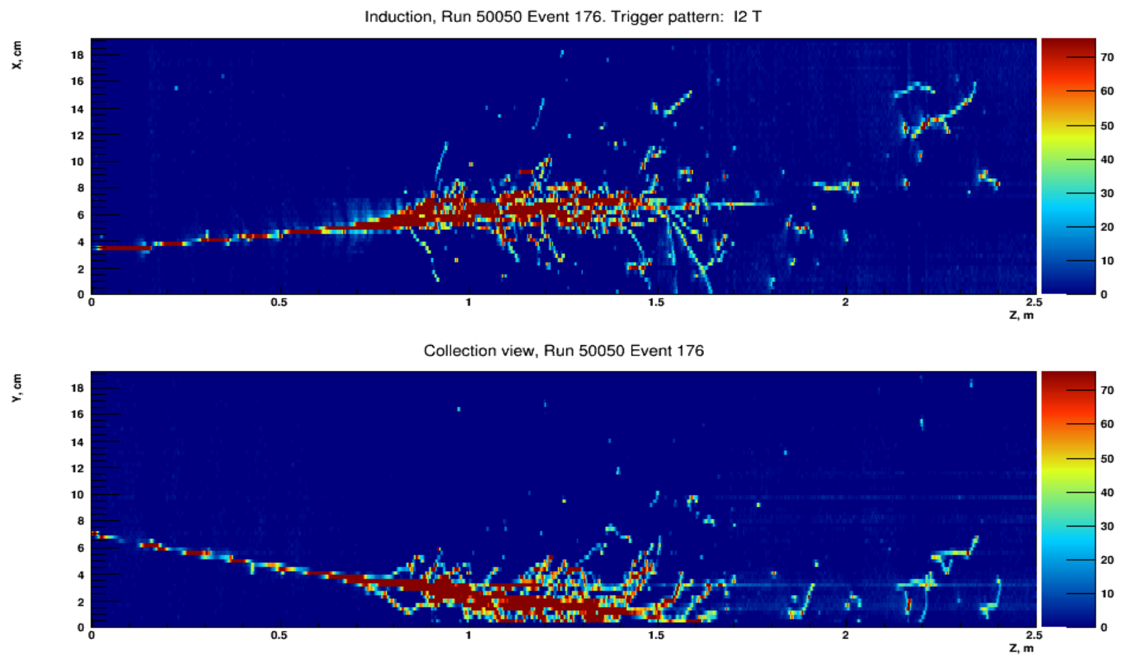


Recombination
field dependent,

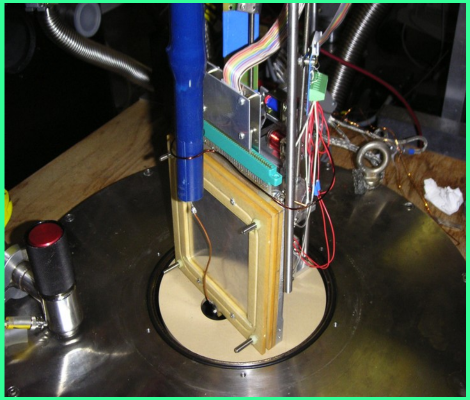
Charge yield (MIP)
~ 6400 e/mm (1 fC/mm)

T_0 by scintillation (**5000 γ/mm**)

Charge readout:
X: Induction (non-destructive)
Y: Collection

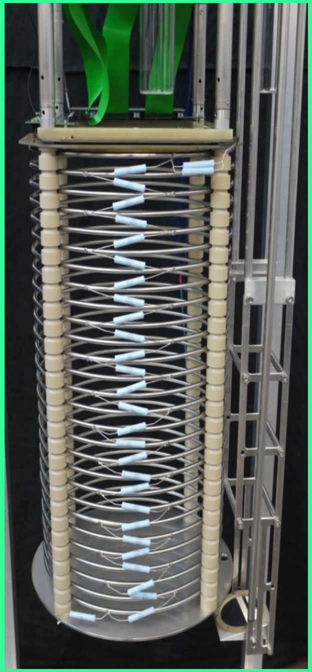


Evolution of LAr TPCs at Bern



L=0.5 cm

L=25 cm



L=57 cm

ARGONTUBE
L=500 cm

JINST 4, P07011 (2009)

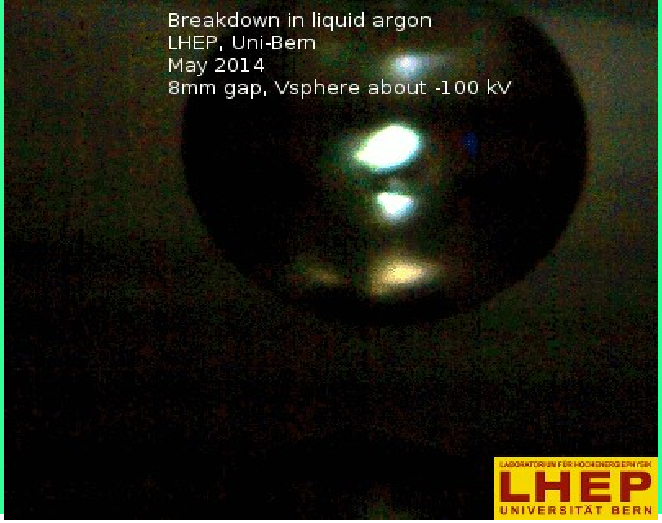
New J. Phys. 12, 113024 (2010)

JINST 5, P10009 (2010)

JINST 7 (2012) C02011

JINST 1307 (2013) P07002

Breakdown in liquid Argon: detailed study at Bern



1. Abnormally low dielectric strength at long distances

2. Studied V/A characteristics

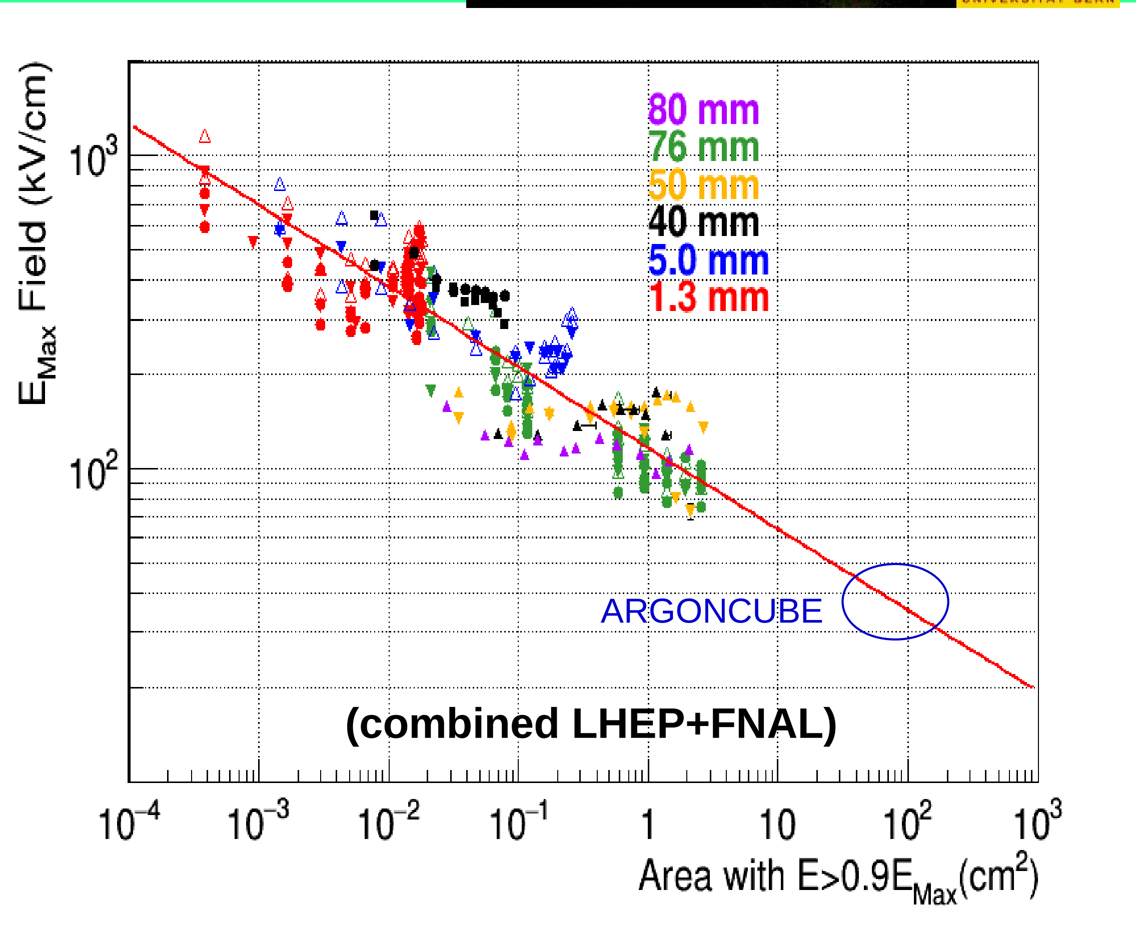
3. Studied time-resolved light emission spectra

4. Discovered slow streamers in LAr discharge

5. Measured 1st Townsend coefficient at fields O(100 kV/cm)

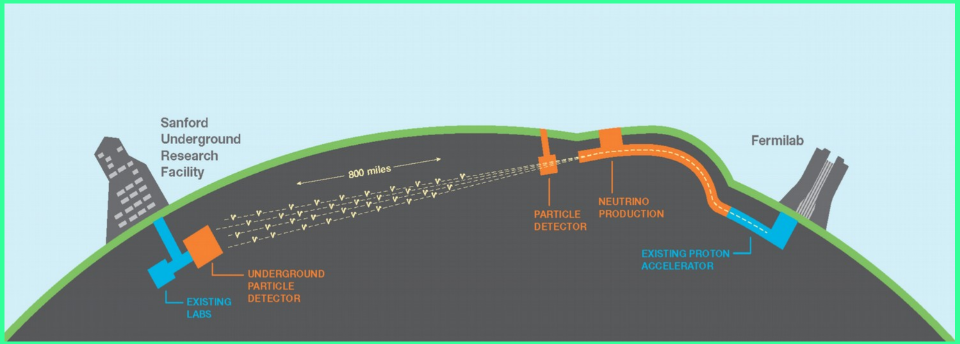
6. Suggested method to improve breakdown field by factor of 10

M. Auger et al., JINST 9, P07023 (2014)
A. Blatter et al., JINST 9, P04006 (2014)
M. Auger et al., JINST 11 (2016) no.03, P03017.



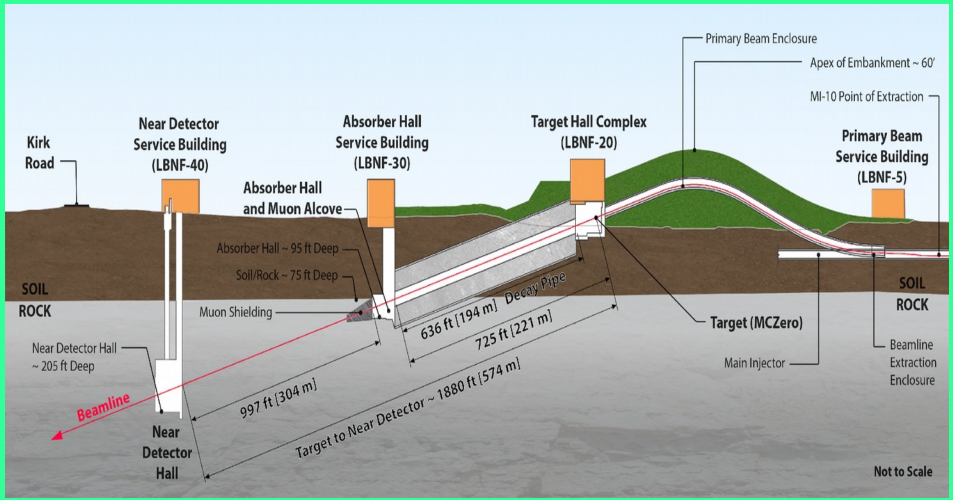
ArgonCube: design inspired by LBNO→ LBNE→ LBNX→ DUNE requirements

Multi MW LBNF beam from FNAL 1280 km to the LAr DUNE far detector (FD) at SURF



LAr is desirable in the near detector(ND), to uncertainties near to far, and constrain the flux.

At the near detector, 574 m from the first focusing horn, a 1.2 MW beam corresponds to ~0.16 neutrino events per tonne of argon per spill (10 μs).



Why liquid argon at DUNE ND?

Sample the unoscillated beam usingthe same target material as the FD.
Essential in order to constrain uncertainties on neutrino cross sections.

Major uncertainties (event topology, secondary interactions) are primarily common near-far.
High multiplicity at near site necessitates differences in design, differences are likely second-order.

The energy and angular resolution and mass is sufficient to extract a high-statistics sample of neutrino-electron elastic scattering events, which have a known cross section.
Can be used to constrain the flux to better than 2%.
(MINERvA arXiv:1906.00111)

Constrain electron neutrino contamination.
Use e/γ separation to reduce NC background.

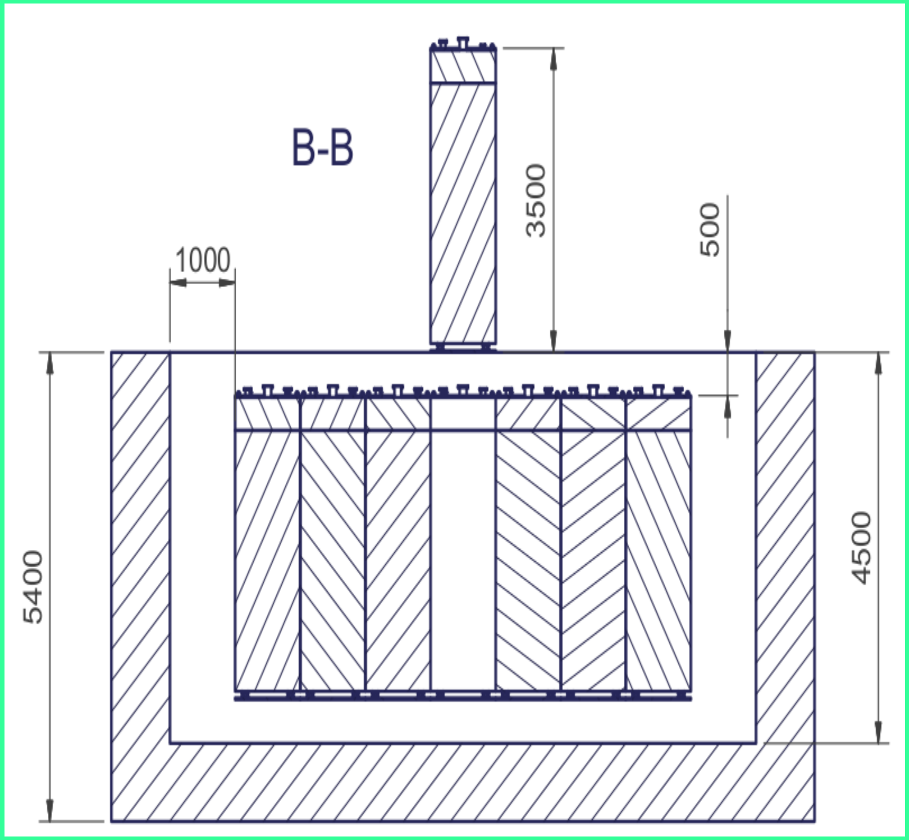
The Solution – ArgonCube

Instead of a monolithic detector volume, divide the detector into a number of self-contained TPC modules sharing a common cryostat. - M. Weber & I. Kreslo c. 2014

Short drift distances
Low cathode voltage
Reduced stored energy
Reduce purity requirements
Contained scintillation light
Upgradeable/repairable sans downtime

Also

Unambiguous charge readout



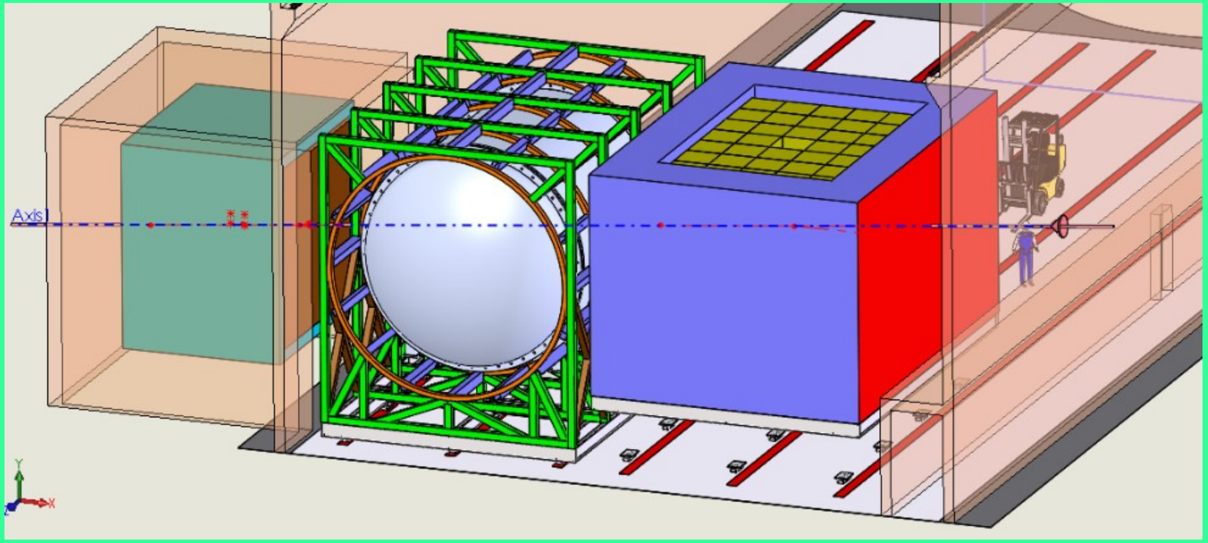
All of which is good for reducing pileup

The Solution – ArgonCube

In January 2016 ArgonCube was proposed as a LAr TPC.

In 2019 ArgonCube became the baseline.

Therefore, DUNE ND requirements have been driving the development of ArgonCube.



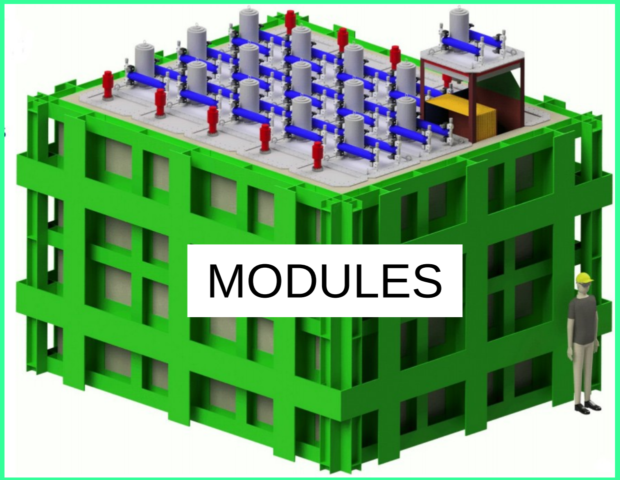
ARGONCUBE

Design motivations — mainly by DUNE ND requirements

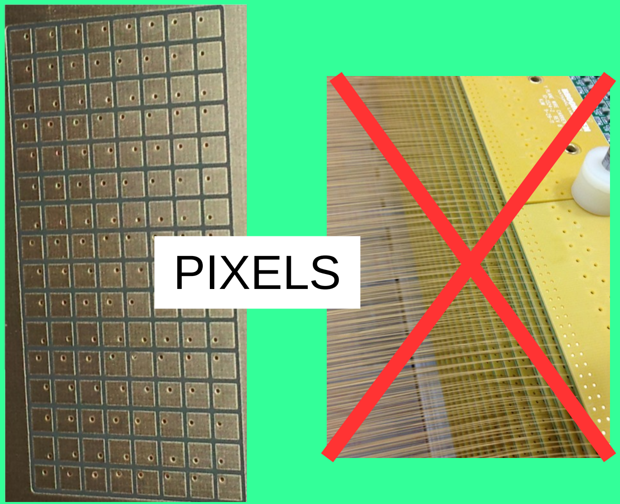
Large mass (>80t)

Space charge

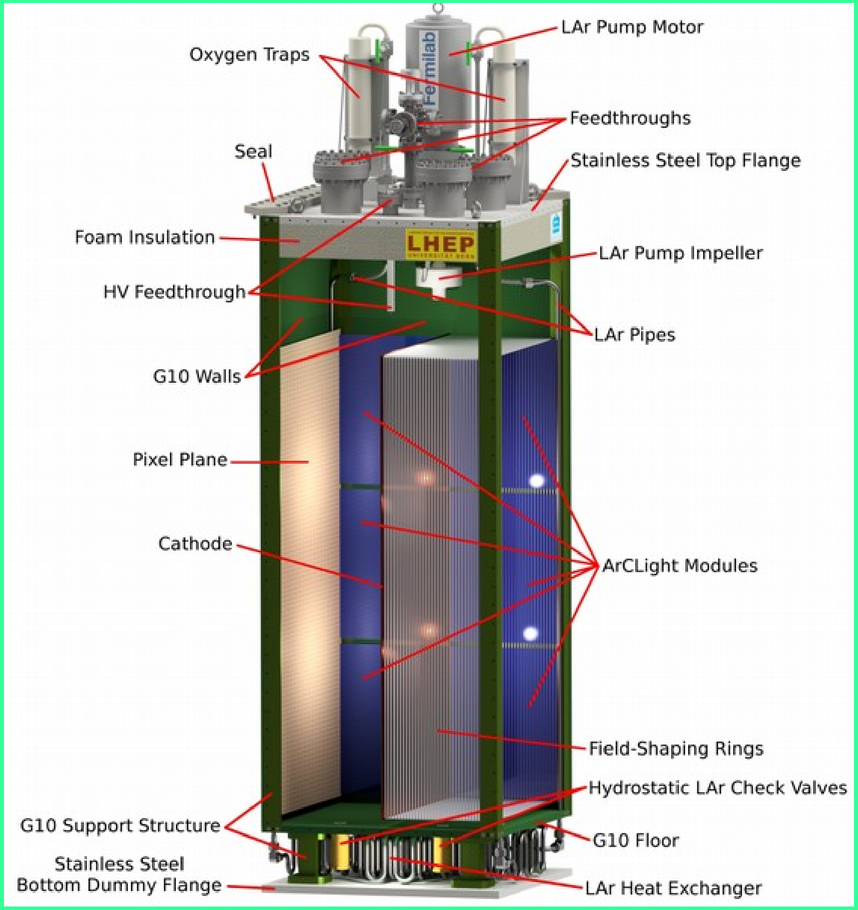
Low HV (<100 kV)



High event rate at (DUNE) ND (pileup)



ARGONCUBE
Module design features

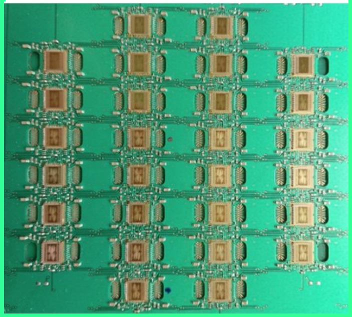


Thin walls

Min. material budget

Resistive shell

LarPix ASIC



Limited LAr convection

Heat management

< 100 W/module overall

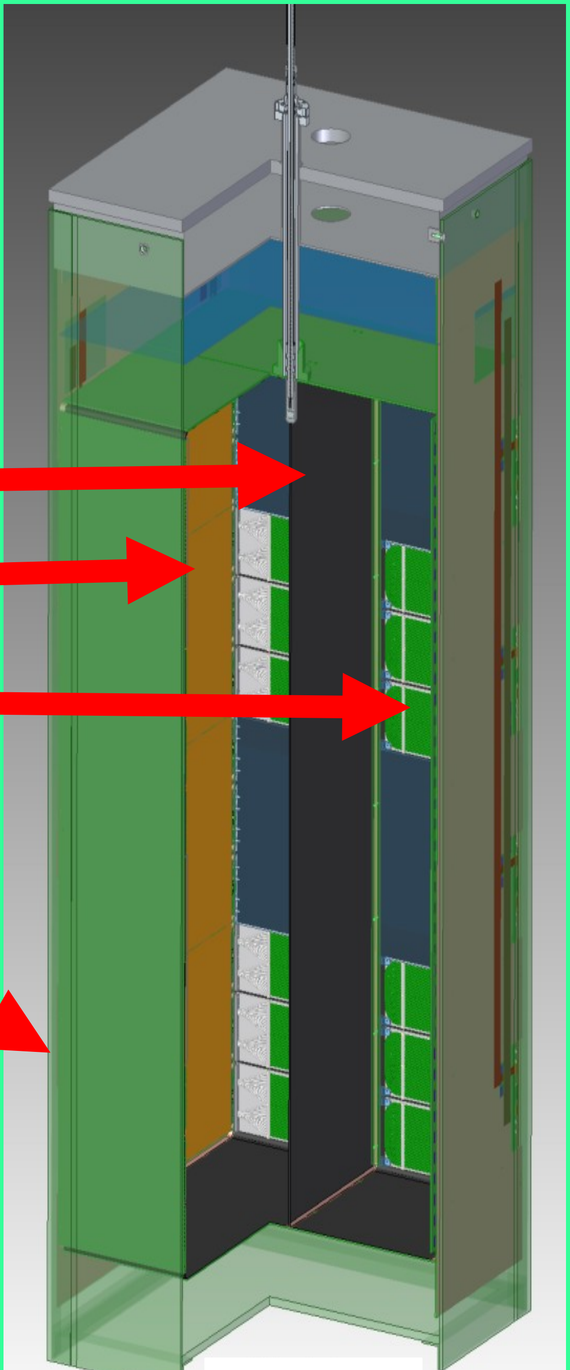
An ArgonCube Module

Central Cathode: splits the module into 2 TPCs

Pixelated anode plane

Dielectric light readout within TPCs

G10 structure: good dielectric shielding, and comparable radiation & hadronic interaction lengths to LAr

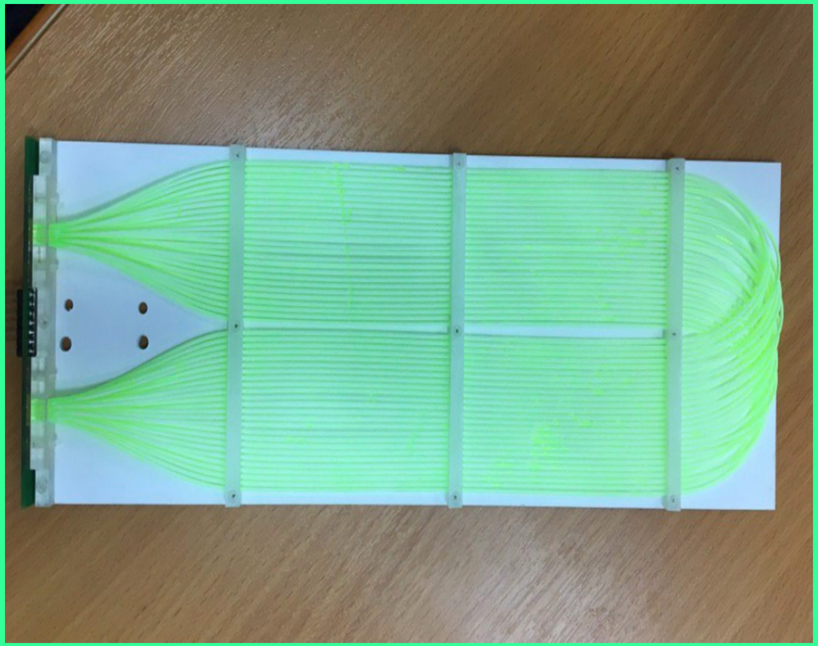


K. Skarpass
SLAC

Light Readout

Two complementary dielectric light R/O systems have been developed: Bern's ArCLight and JINR's Light Collection Module(LCM). Both use the same SiPMs, and TPB to convert from 128 nm to 425. ArCLight uses sheets WLS plastic and dichroic mirrors. LCM uses WLS fibres. ArCLight has better position resolution(size of SiPMs), while LCM has higher efficiency.

Prototype ArCLight tile (Instruments 2 (2018) no.1, 3).



JINR's Prototype LCM

Light Readout Electronics - JINR TQDC

14-bit @ 125 MS/s (8 ns)
Buffer of 2048 kSamples = 16 μs > beam spill time (10 μs)

HPTDC provides 25 ps time resolution

16 channels, 1-unit wide 6U VME64 module

VME64 and 10 Gbit Ethernet

Embedded trigger logic:
Fast comparators (250 ps) & FPGA-programmable logic (10-20 ns delay)

ArCLight: Inspired by ARAPUCA

A.A. Machado and E. Segreto 2016 JINST 11 C02004

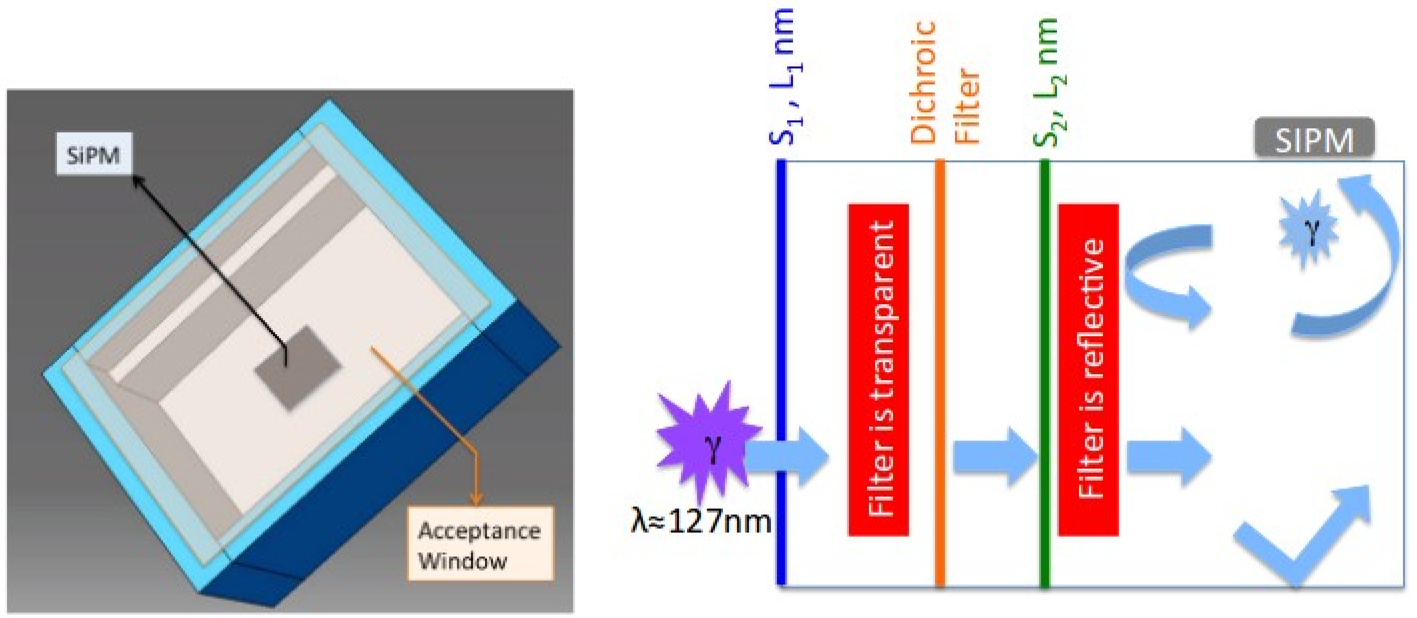
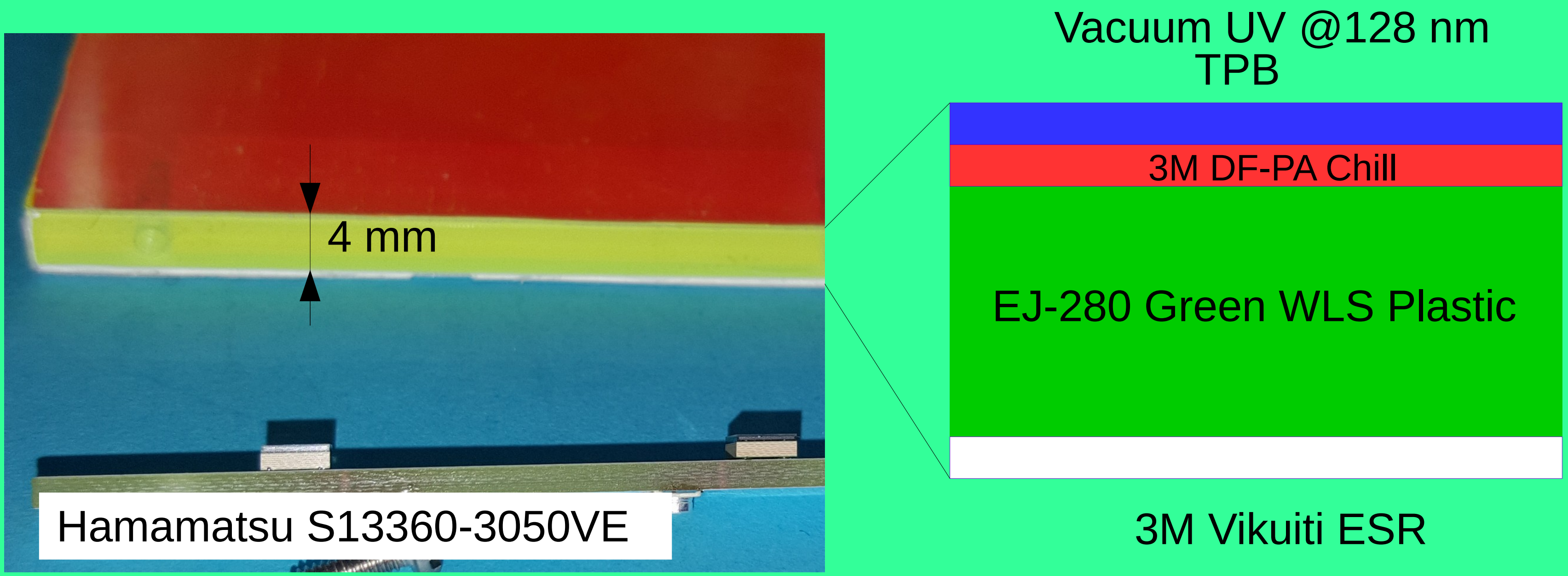


Figure 1. Left: pictorial representation of the ARAPUCA. Here are represented the box with internal reflective surfaces (in blue), the dichroic window and the photo-sensor (SiPM). Right: operating principle of ARAPUCA.

Great idea!!! but...

Fragile membrane, void inside, heavy frame, thermal deformations...

ArCLight - ArgonCube light detector

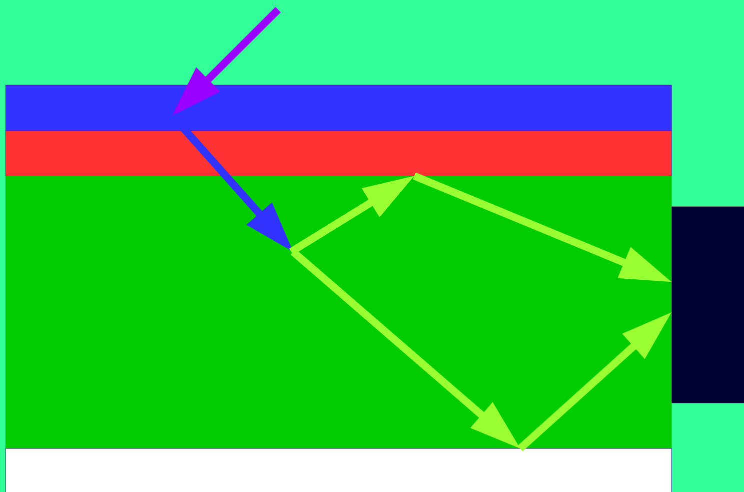


Self-supporting
SiPM can be placed at one edge only
No frame — no deformations in cold
Can be placed in high field region (parallel to the the drift)

Auger M. et al., Instruments 2 (2018) no.1, 3

Photon Detection Efficiency

Theoretical view



E. Segreto 2012 JINST 7 P05008 :

$$\epsilon_{coll} = \frac{f}{1 - \langle R_{490} \rangle (1-f)} = 0.077$$

TPB conv. efficiency ε_{tpb}= 1.3/2

Dichroic transparency for blue T_{430}= 0.87

EJ-280 conv. efficiency ε_{WLS}= 0.86

Dichroic reflectance for green R_{490}= 0.98

ESR reflectance for green R_{490}= 0.98

Total surface area S_{tot}= 216 cm^2

SiPM covered S_{det}=0.36 cm^2

$f = S_{det} / S_{tot} = 0.0017$

Absorbtion is neglected! (λ ~ meters)

Putting it all together:

$$PDE = \epsilon_{tpb} \cdot 1/2 \cdot T_{430} \cdot \epsilon_{WLS} \cdot \epsilon_{SA} \cdot \epsilon_{SiPM} = 0.01$$

ArCLight 43x15 cm with TPB coating
Installed in PixLAr detector (Fermilab)

Tile 43x15cm:

total surface area S_{tot}= 1336 cm^2 SiPM covered S_{det}= 0.72 cm^2
$f = S_{det} / S_{tot} =$ 0.0005 **PDE=0.34%**

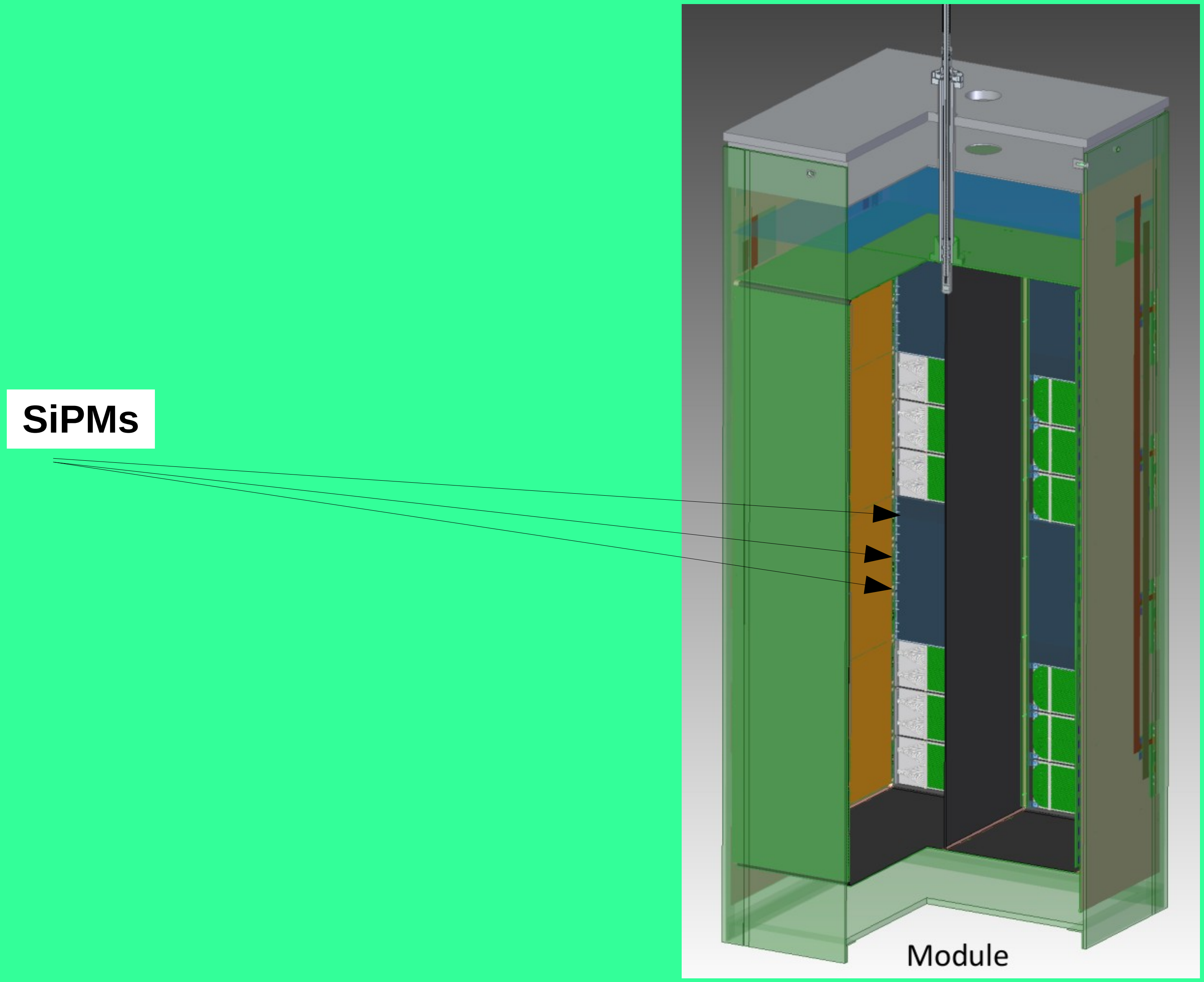
From 1 m away: solid angle Ω= 0.06 (worst case)

LAr scintillation produces ~26000 photons/MeV @1kV/cm

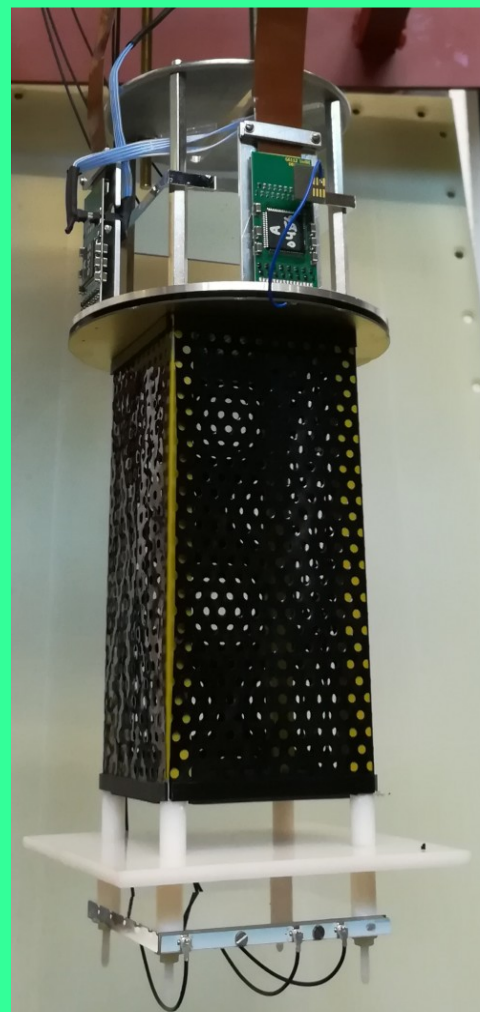
1560 photons/tyle → ~ 5.3 pe/MeV detected. For MIP 1 MeV=> 5mm,

So we have **1 p.e. per mm of MIP track**.

ArCLight in ArgonCUBE



Resitive Shell TPC



Resistive carbon-loaded polymer films

Desired surface resistance ~ 10 G/sq

A number of materials tested.

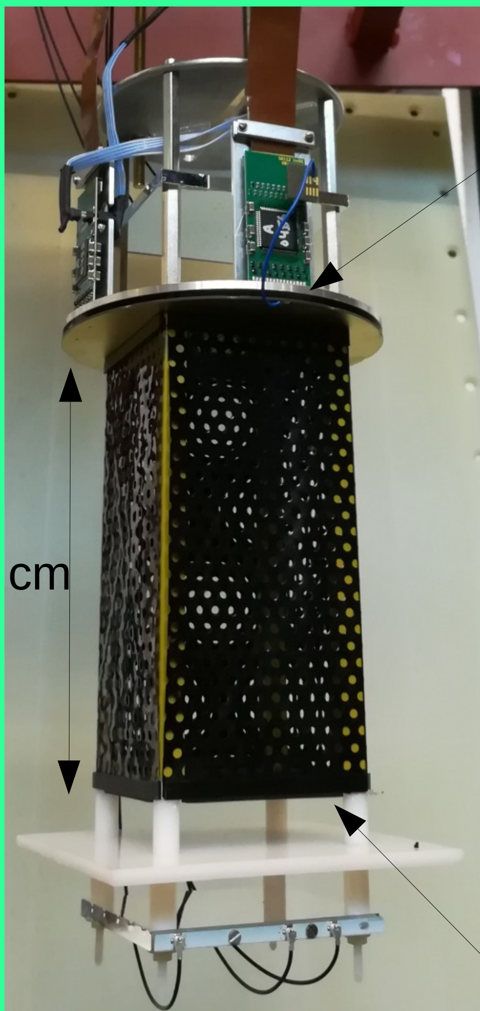
A subsample of results:

Sample #	T=290K	T=77K
1	1.3 M/sq	1.6 M/sq
2	0.5 M/sq	5.2 M/sq
3	350 M/sq	16 G/sq
4	2.6 G/sq	120 G/sq

Testing resistive film strip at LHEP, Uni-Bern, 2018

Thanks to Fermilab team for providing this component!

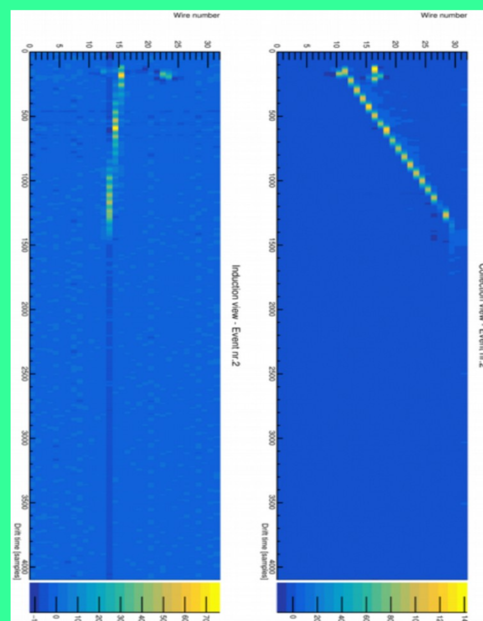
First Resistive Shell LArTPC (RSTPC)



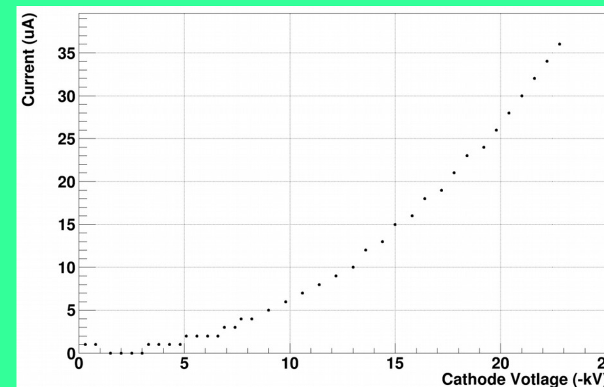
15 cm

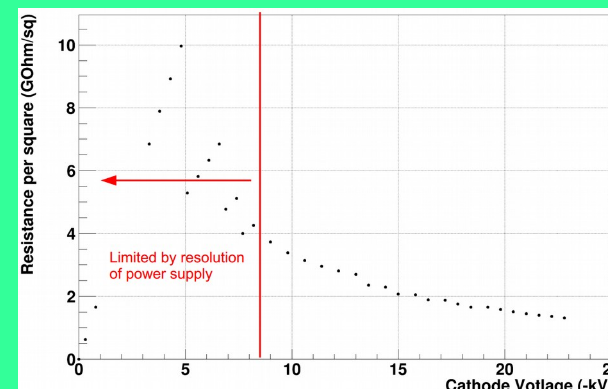
Anode at GND

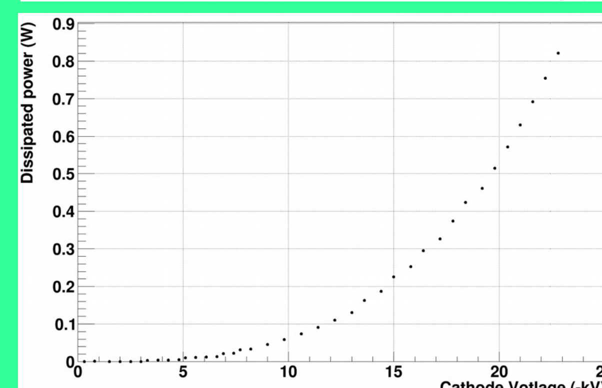
Field uniformity test is conducted, data analysis in progress.



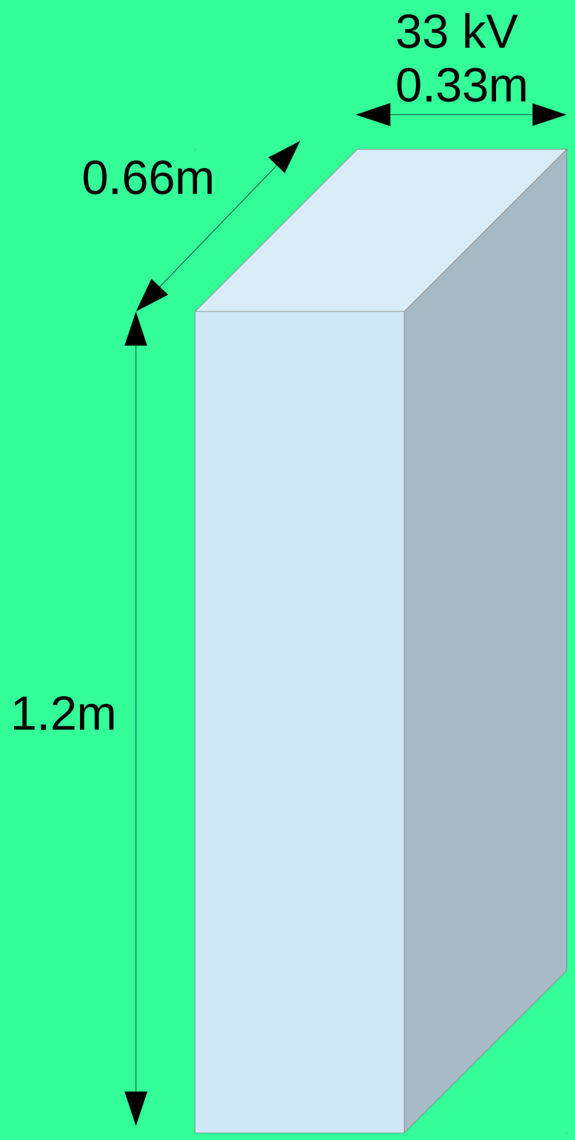
Cathode at -HV(up to 25 kV)

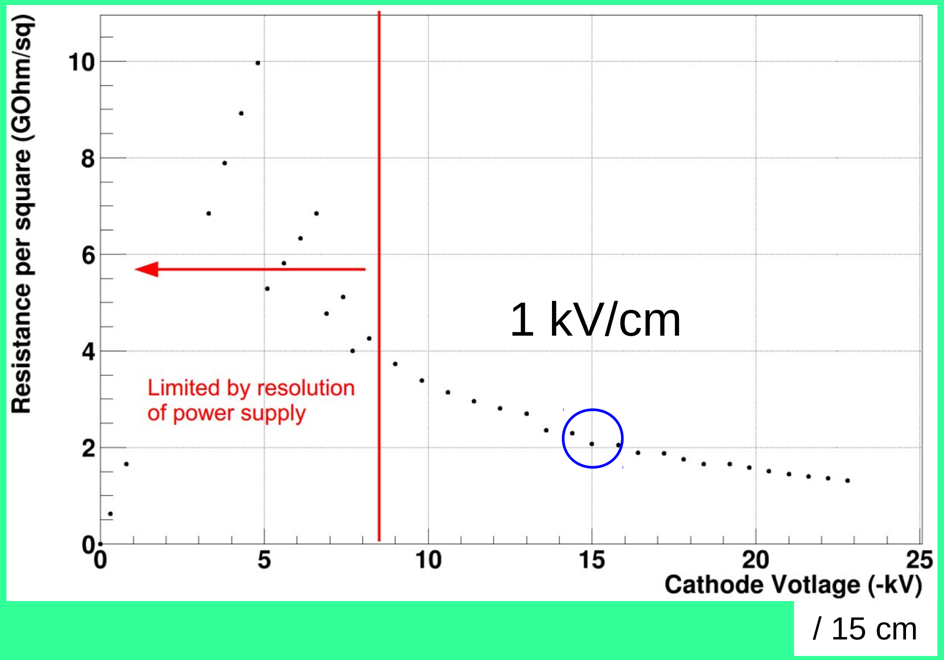






AROGONCUBE 2x2 module with RS





2 G/sq, L=0.33cm, W=3.72m,

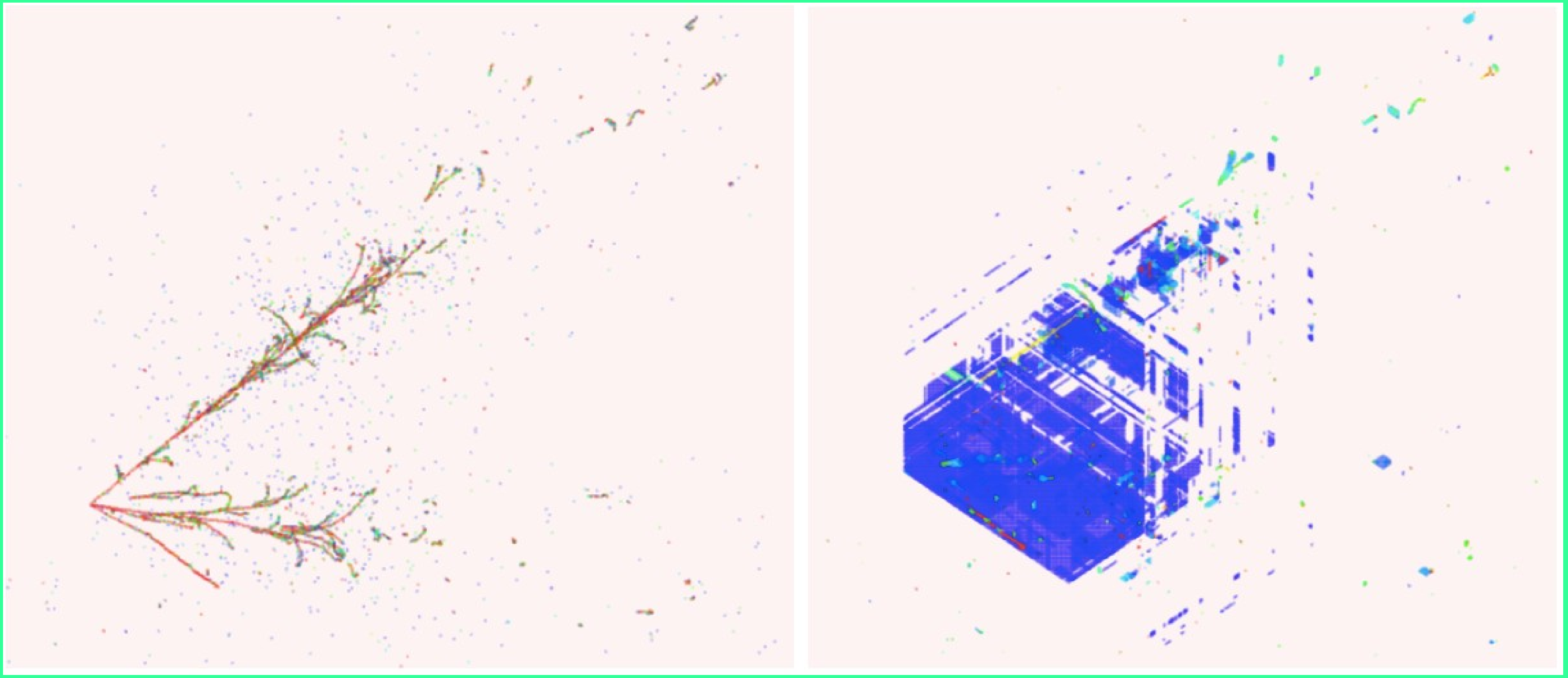
Q=0.9 sq, R=0.2 G, U=33kV : P=5.4W

S=1.2 $m^2 \rightarrow$ 4.5 W/m^2

~10 W/module — acceptable.

Pixelated charge readout — why?

Classic wire readout:
3 GeV ν_e simulated in BNL's Wire-Cell



First approach to pixels: LHEP 2016-2017

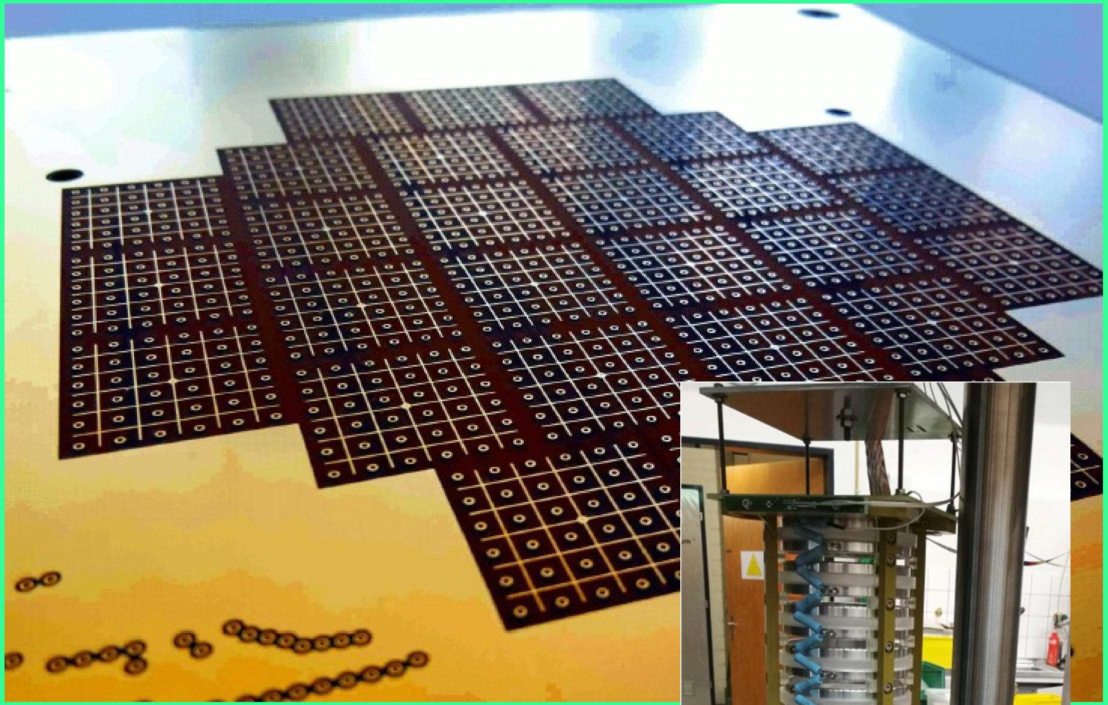
Compromise: multiplexed R/O

6x6 ROI with induction grid

BNL LARASIC4 as cold preamp

60 cm drift test LArTPC

2 runs: 2016 & 2017



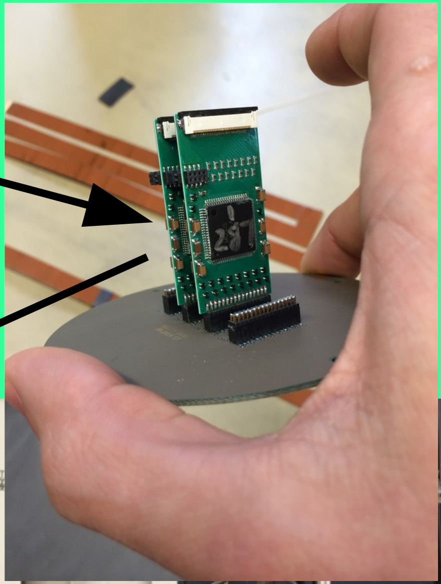
Number of R/O channels: nROI + nPixel

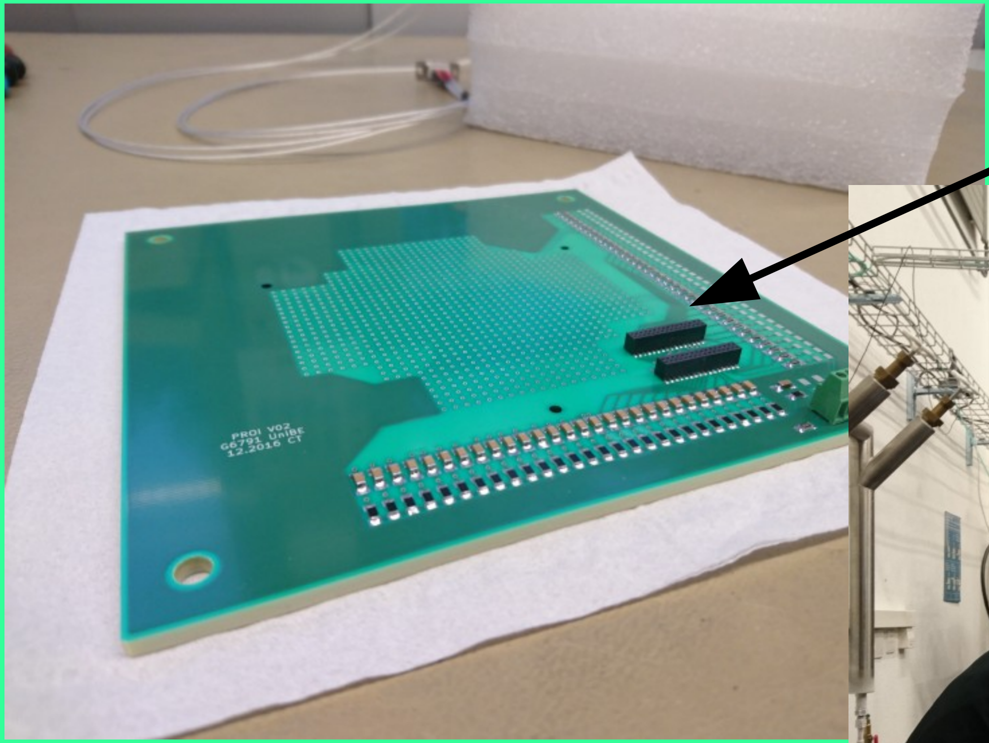
28 ROIs, each 6 × 6 pixels ⇒ **1008** pixels total @ 2.48 mm pitch

28 + 36 = **64** R/O channels

First approach to pixels: LHEP 2016-2017

4x LARASIC4 on very compact PCB

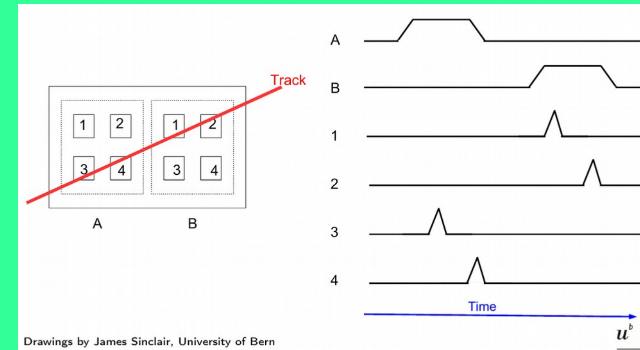


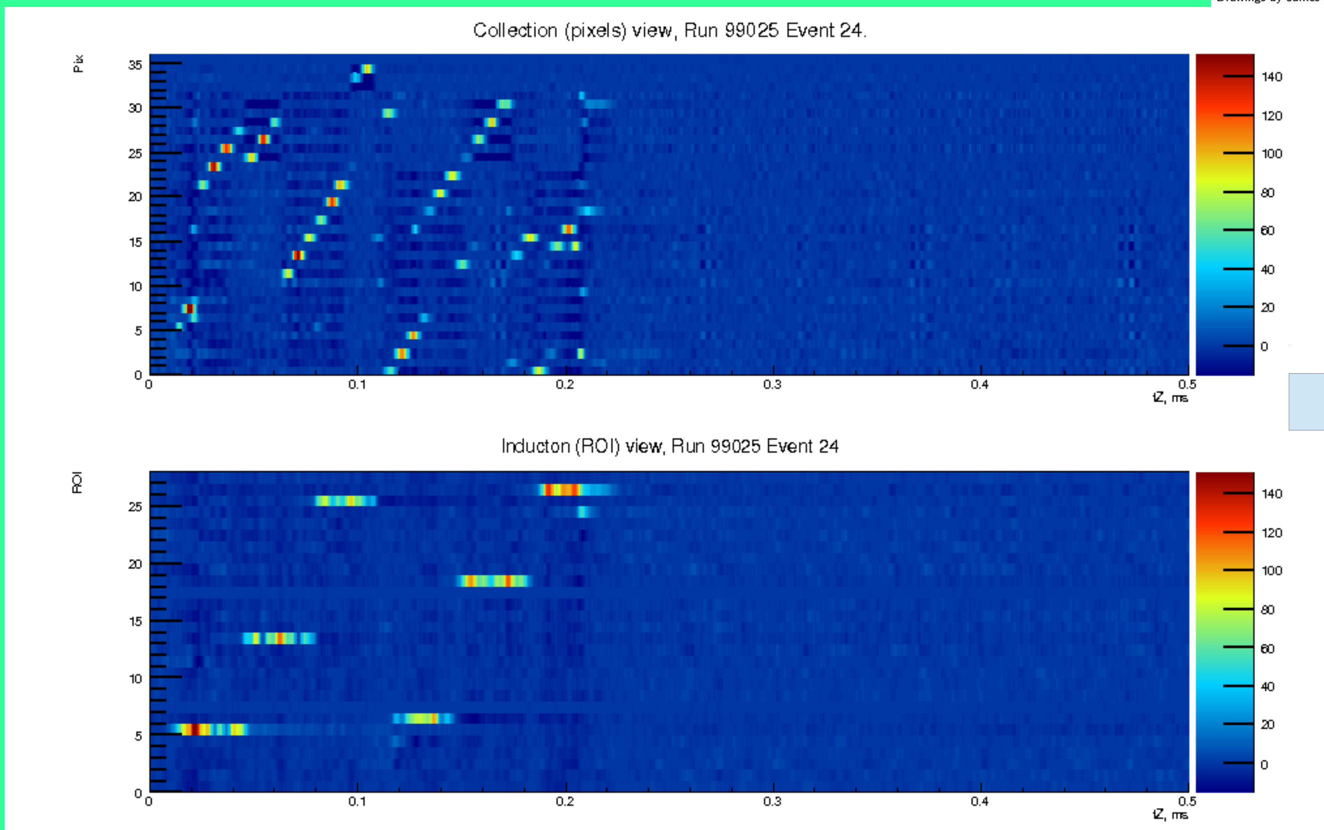


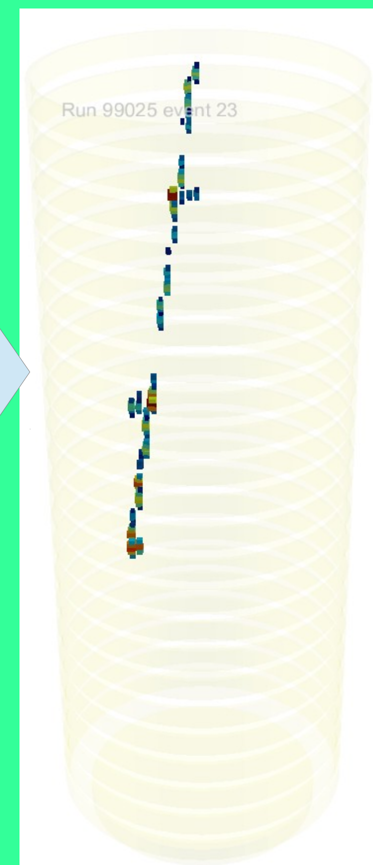
Two data taking runs conducted.

First approach to pixels: LHEP 2016-2017

Reconstruction: simple «enable» by Induction signal

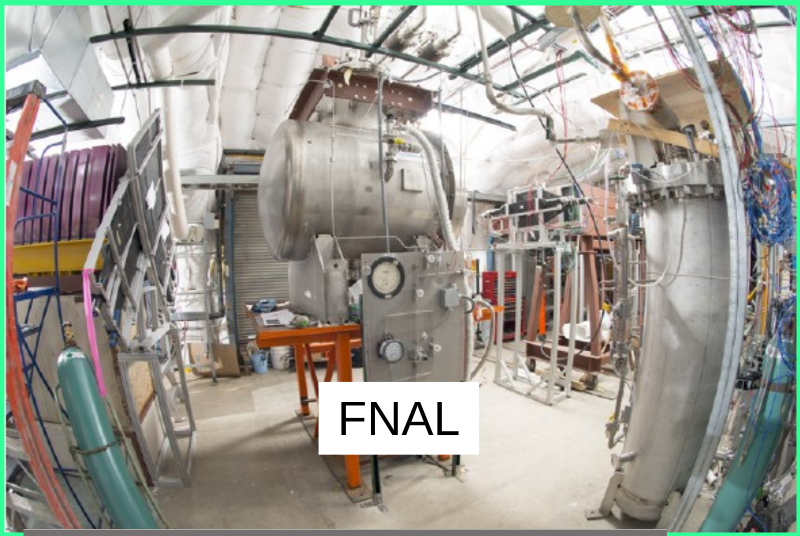


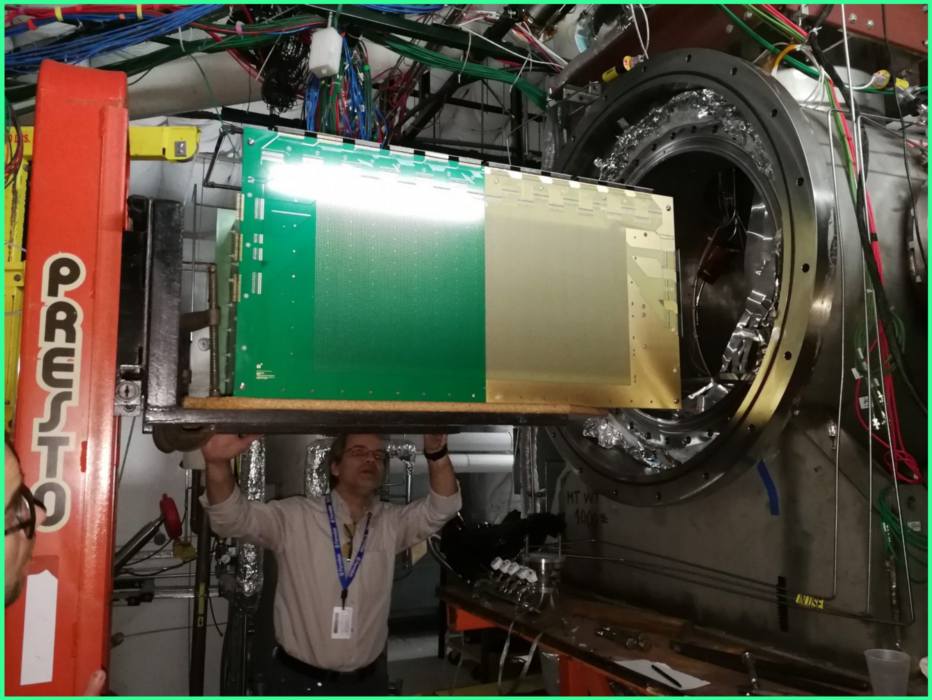


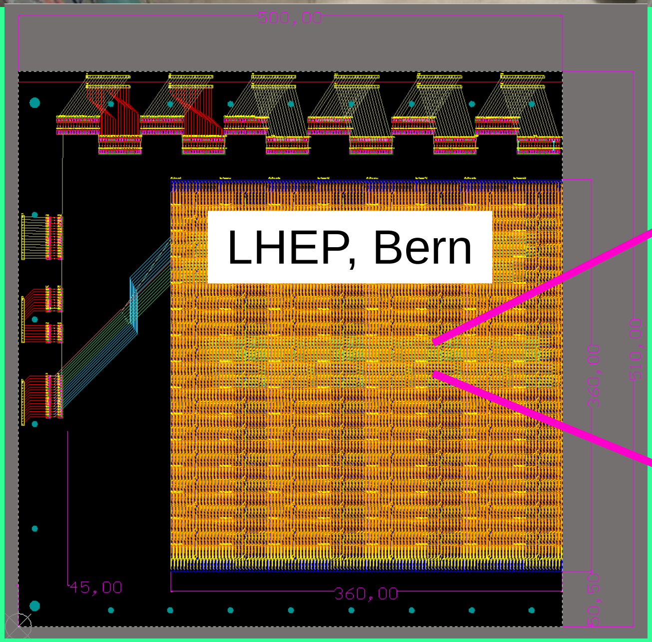


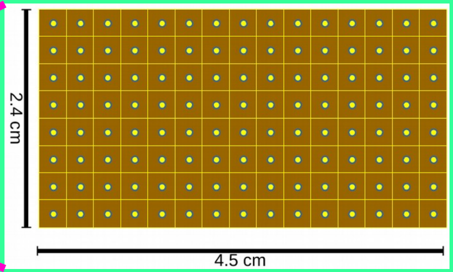
SNR for MIP in worst orientation: **~15**

Test of our Pixel plane in LArIAT: PixLAr TPC
Run: end of 2017 — beginning of 2018









8x15=120 pix/RoI
240 RoI, 72 cm^2
28800 pixels
480 R/O channels

Medium-sized pixel readout test

Test of our Pixel plane in LArIAT: PixLAr TPC
Run: end of 2017 — beginning of 2018

11 Dec 2017 — 1 Feb 2018

426 runs are taken

Several hundred thousands events

Simple reco → 3D event display

Analysis is in progress…

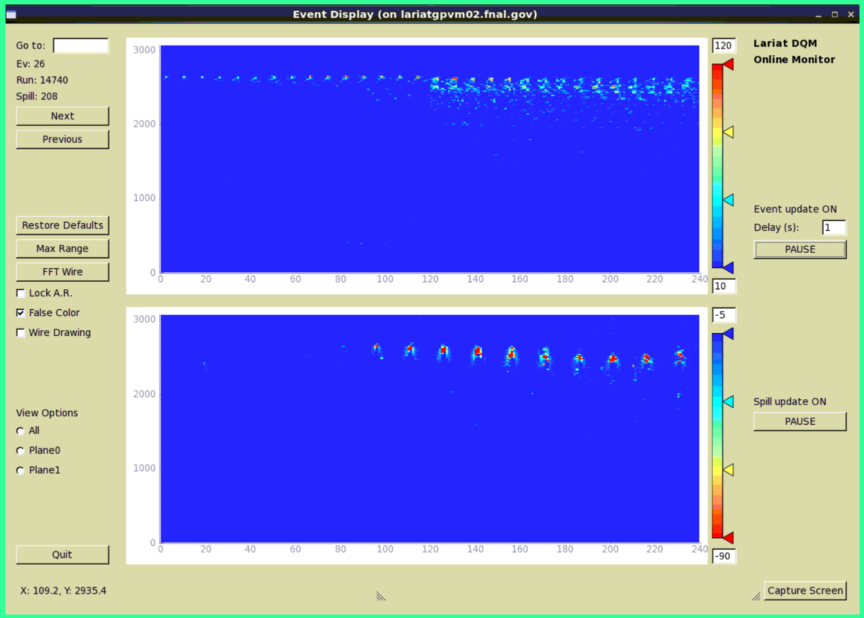
May expect:

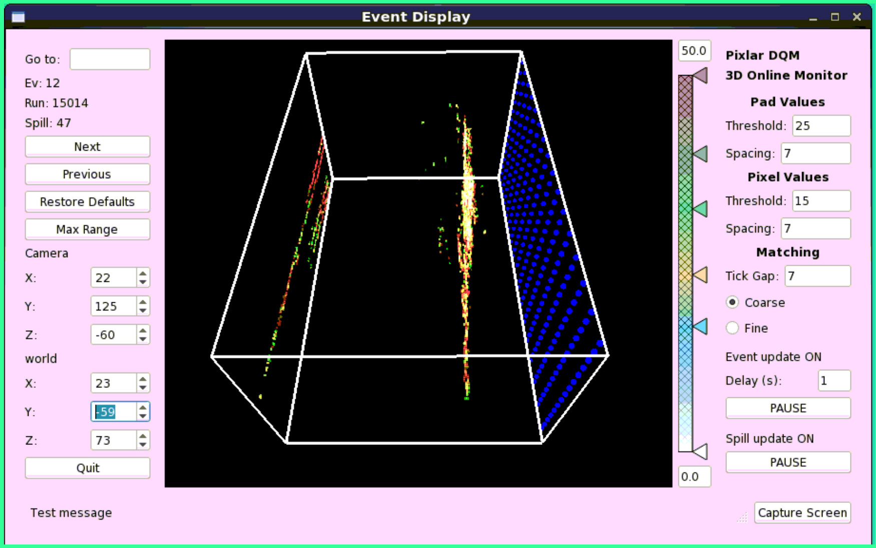
- Pion reco efficiency

- dE/dx uncertainty (vs angle)

- EM shower reco, energy uncertainty

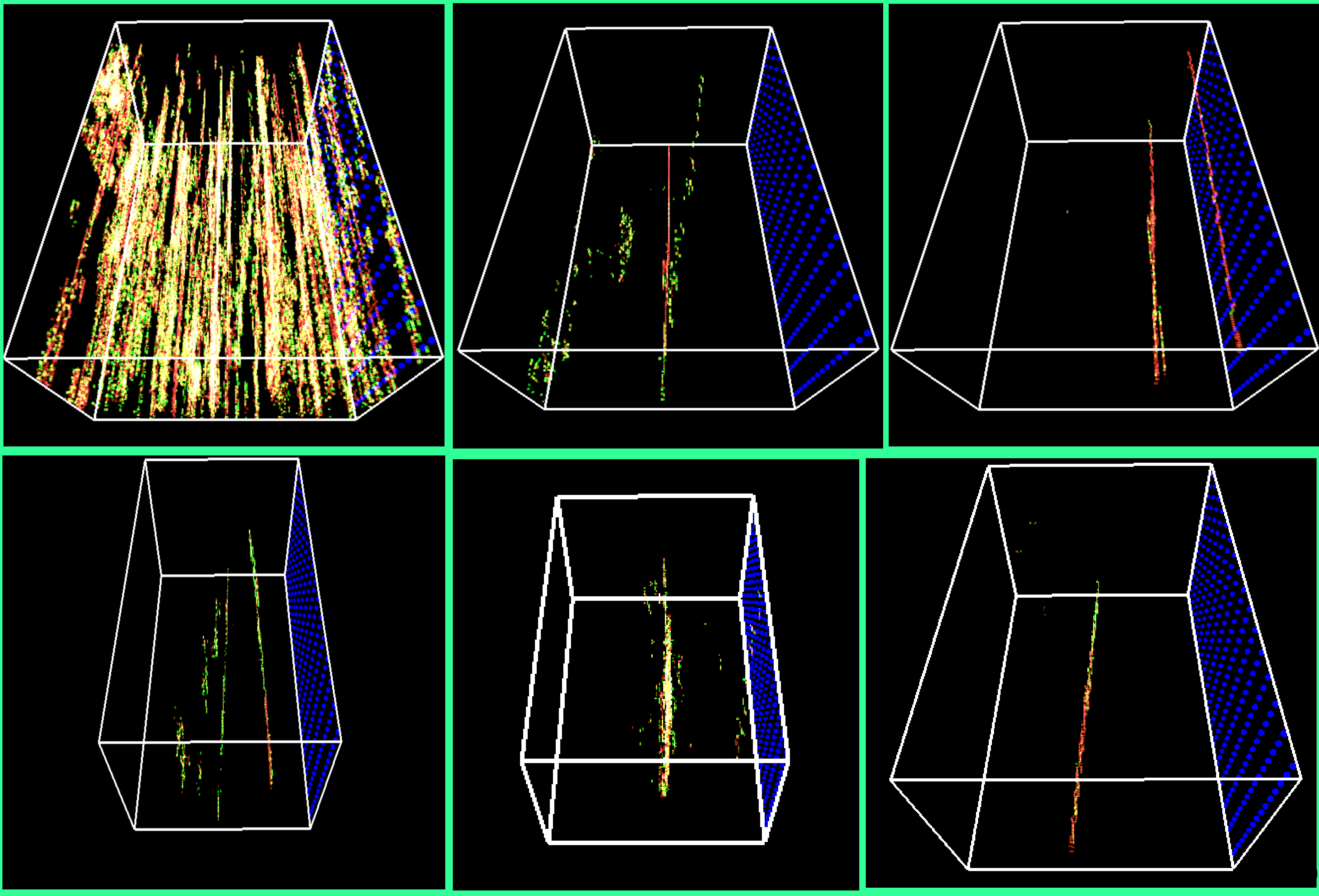
- Pileup limit, two event separation efficiency



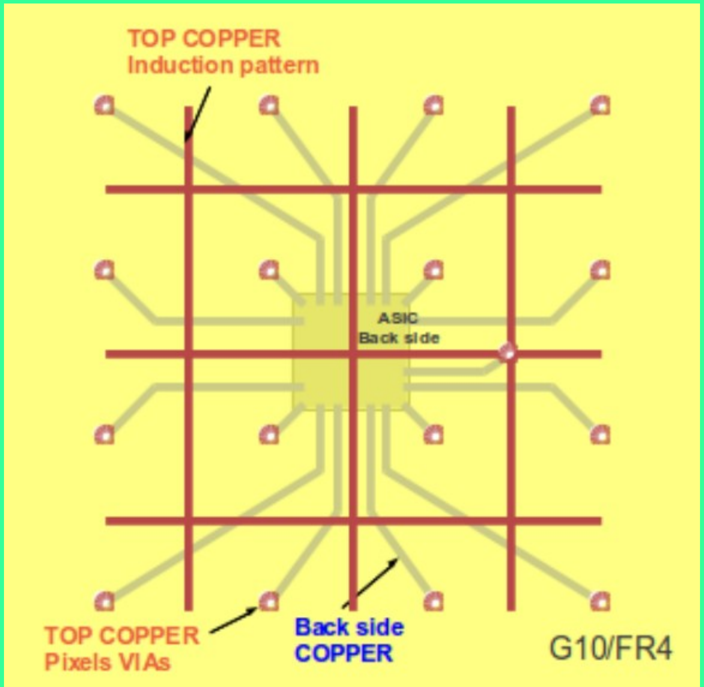


Pixels are good! Precious data in hands!

PixLAr Event Gallery



<u>Unambiguous</u> readout: requirements for pixel R/O ASIC



Number of physical pixels: nROI ∗ nPixel

Can use ROIs induction signal to wake up ASIC to save power.

For ND module: 2planes x 1m x 3.5m, ~5 tons of LAr per module
3x3 mm pixels → ~800000 pixels/module
If we reach 50 μW/pixel we are at 40 W/module and 8 W/ton — safe!

Need to keep heat low at very high number of channels

Requirements for pixel R/O ASIC

SNR of >10 for MIP (signal is ~19000 electrons ~3 fC for 3x3 pixel)

Noise ENC<1900 electrons

Heat dissipation < 50 μW/pixel

≥16 channels/ASIC

≥10 bits ADC

Time slice ≤ 1 us

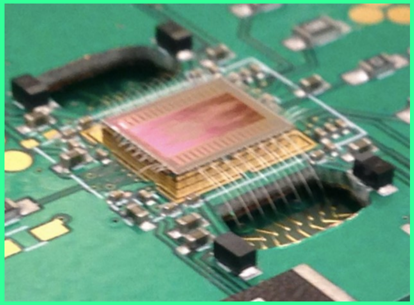
Smart zero suppression

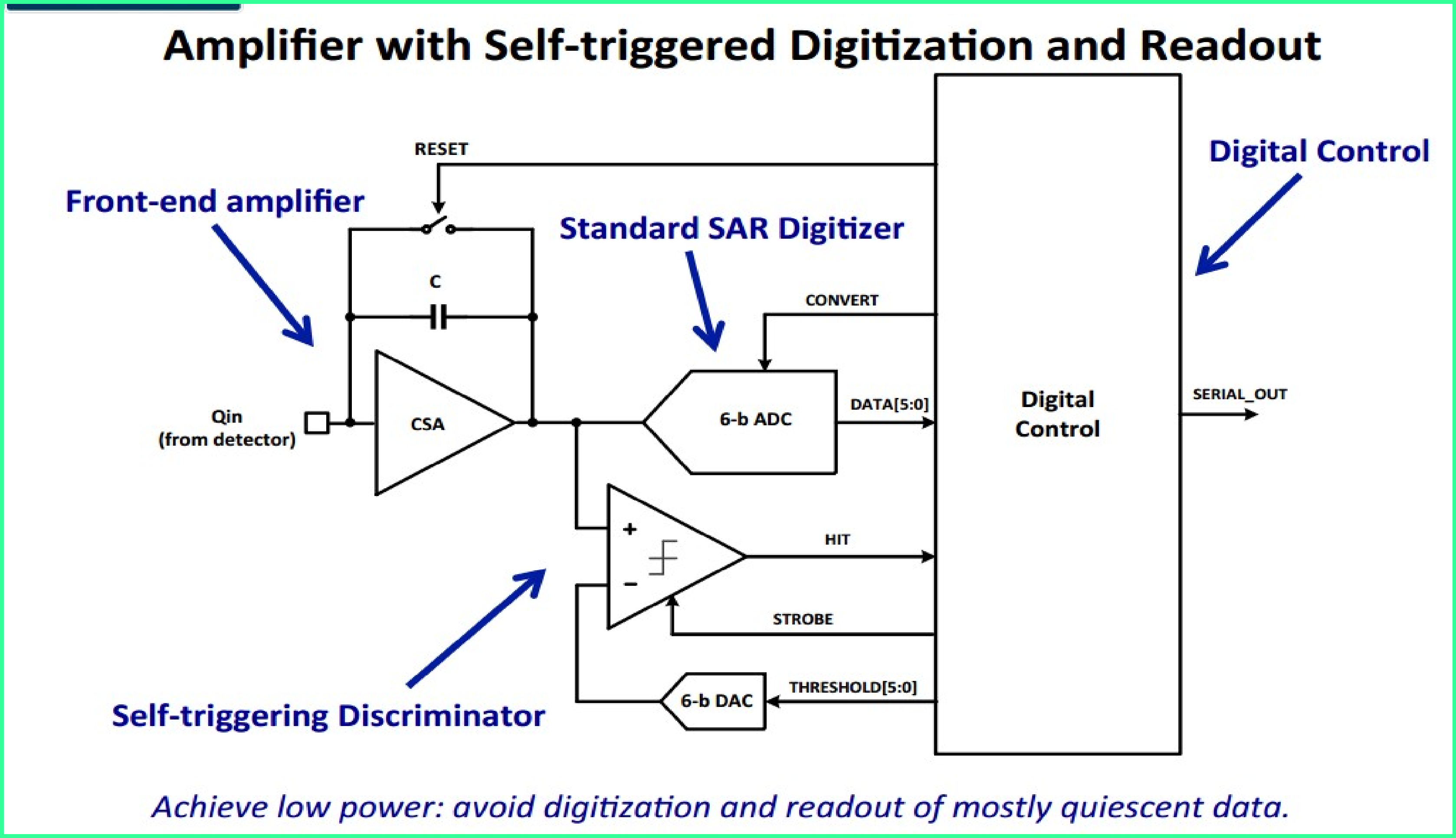
Multiplexing at the data output lines

Concept for pixel R/O ASIC

(courtesy of Dan Dwyer, LBNL)

Process: TSMC 180nm





Concept for pixel R/O ASIC

(courtesy of Dan Dwyer, LBNL)

Target 1: Demonstrate low-noise low-power cryogenic amplifier (CSA)

Design goal: Power use (heat generation) less than heat flux through cryostat walls

→ Total pixel electronics power consumption ~< 10 W/m^2

Pixel Pitch	Pixels/m^2	Power/m^2 (assuming 100 μW/channel)
3 mm	111.1k	11.1 W
4 mm	62.5k	6.3 W
5 mm	40.0k	4.0 W

Analog Power:

- ASIC Simulation: 24 μW/channel
- Bench Measurement: 24 μW/channel

Unexpected surprise: Digital power also very low!

Mode:	Core Voltage	I/O Voltage	Power (Dig.) [μW/ch]	Power (Ana.+Dig.) [μW/ch]
Default	1.8 V	3.3 V	233	257
Low-power	1.1 V	2.0 V	37	61

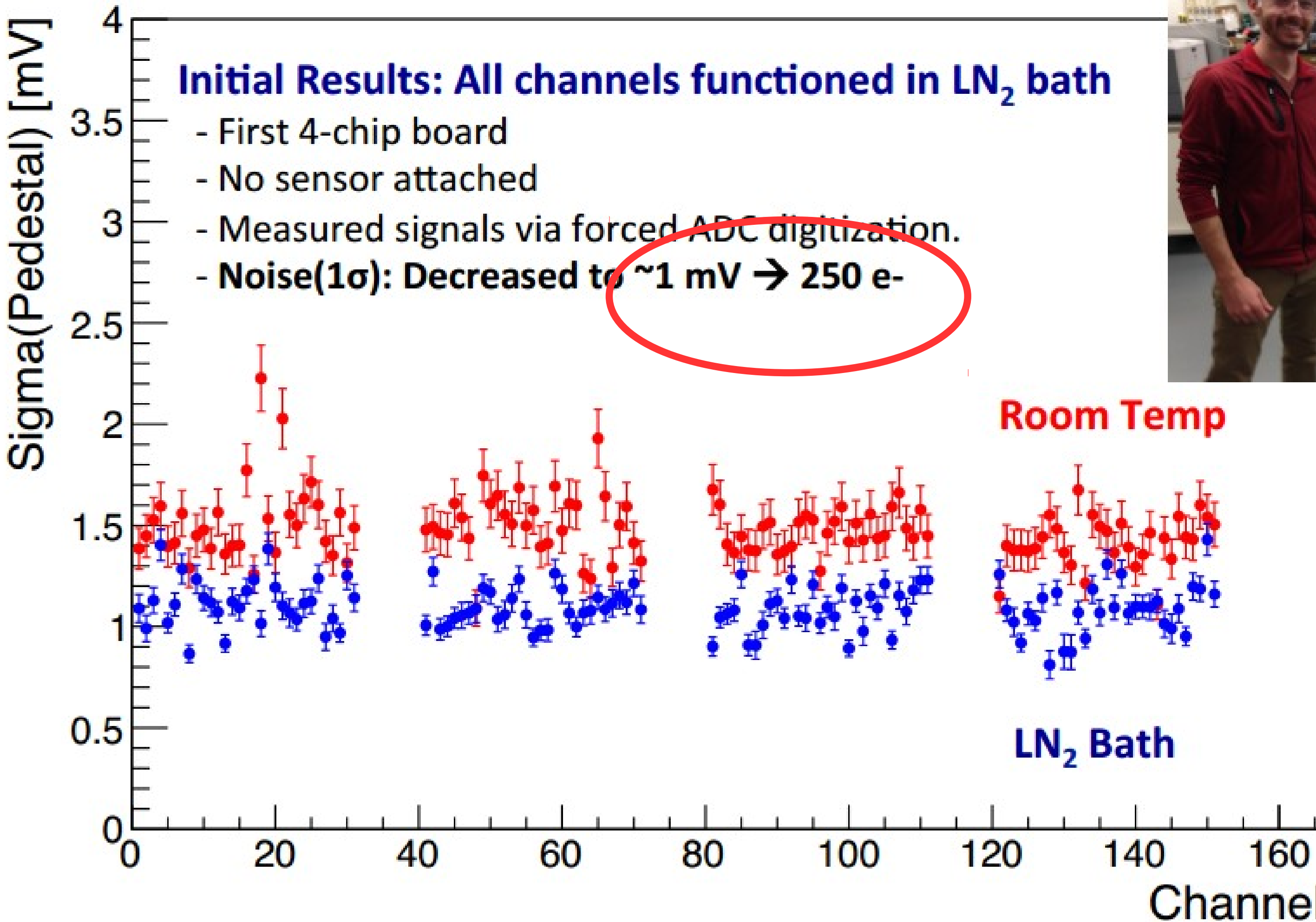
→ *Still some room for tuning I/O voltage to bring power down further.*

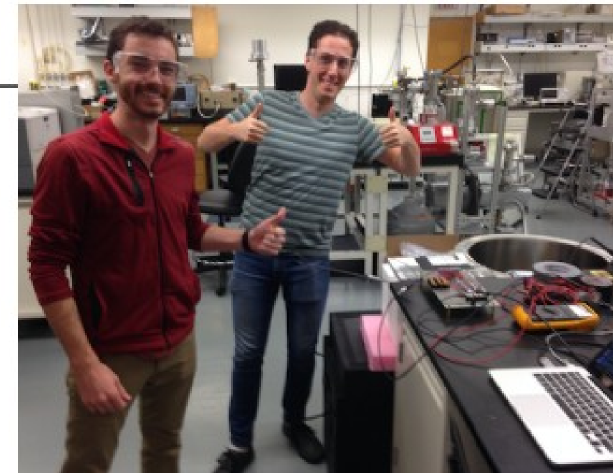
Concept for pixel R/O ASIC

(courtesy of Dan Dwyer, LBNL)

Target 1: Demonstrate low-noise low-power cryogenic amplifier (CSA)

Design goal: Operate at liquid argon temperature





Concept for pixel R/O ASIC

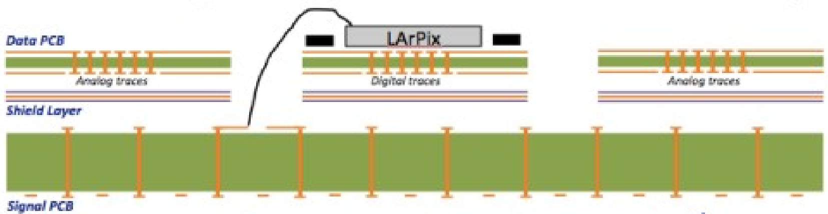
(courtesy of Dan Dwyer, LBNL)

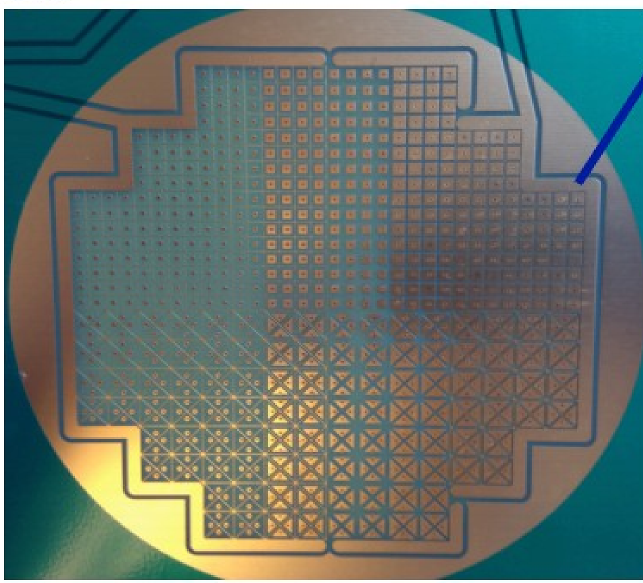
Prototype Scalable Sensor

BERKELEY LAB · ArgonCube · LABORATORIUM FÜR HOCHENERGIEPHYSIK LHEP UNIVERSITÄT BERN

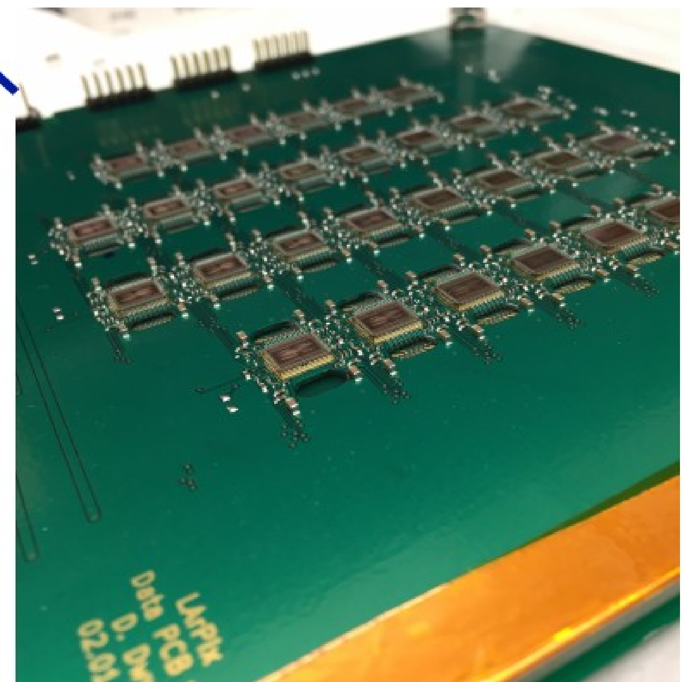
New Sensor:

- Uses new digital data board to provide scalable sensor (dense pixel packing)
- Coupled to 10-cm diameter pixel sensor board
  → Designed to fit both 10-cm-drift TPC (@LBNL) and 60-cm drift TPC (@Bern).





- 832 pixels
- 28 Chips



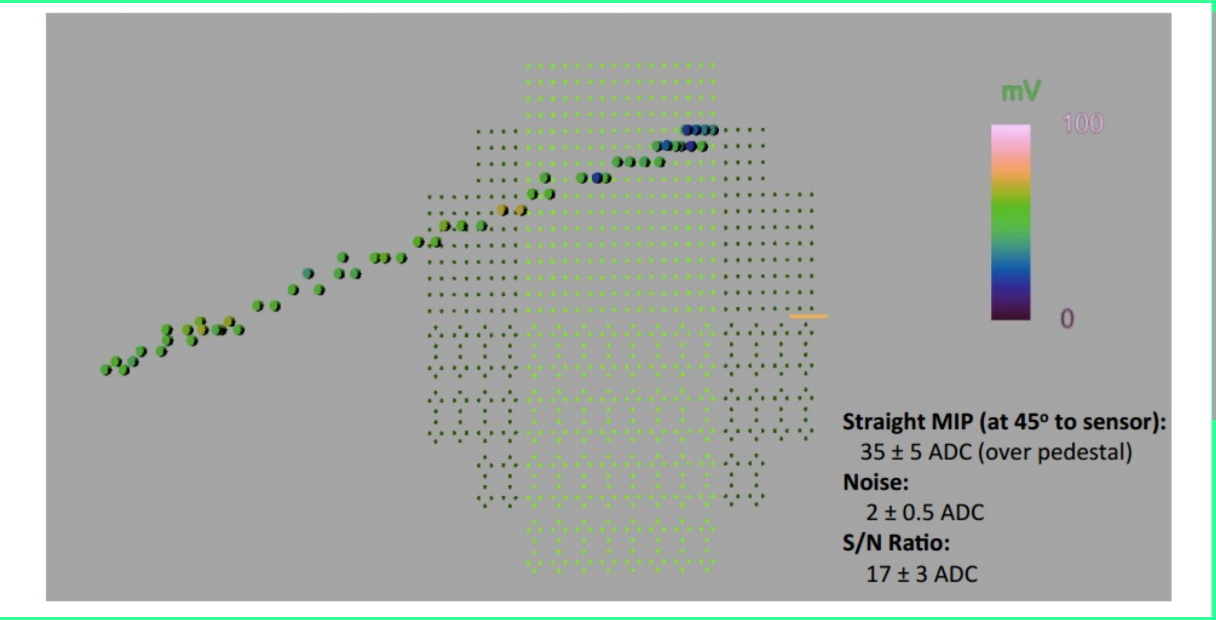
First test in a Lar TPC at Bern

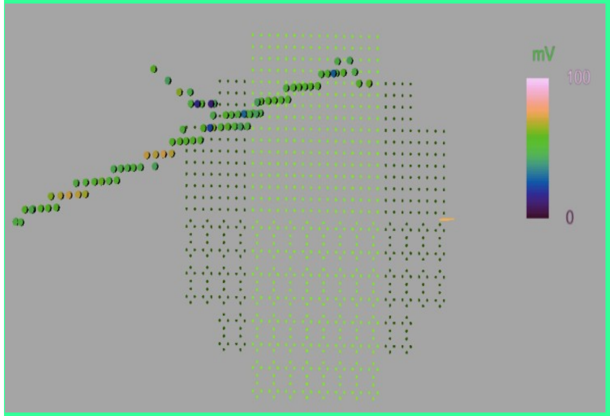
LArPix Sensor

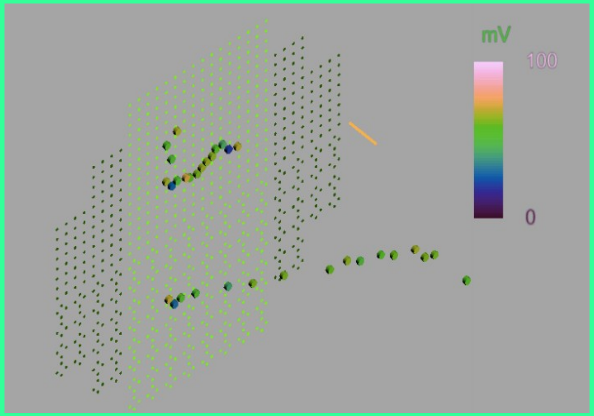
ArCLight Sensor

ArgonCube
Pixel
Demonstrator
(60-cm-drift
TPC)

First test in a Lar TPC at Bern







TPC operating at 60 kV, 1kV/cm drift field

A Large scale ArgonCube Prototype

LArTPCs of this scale (150 t) and larger have been operated. Although, none in a ND environment.

All novel aspects of ArgonCube have been demonstrated:

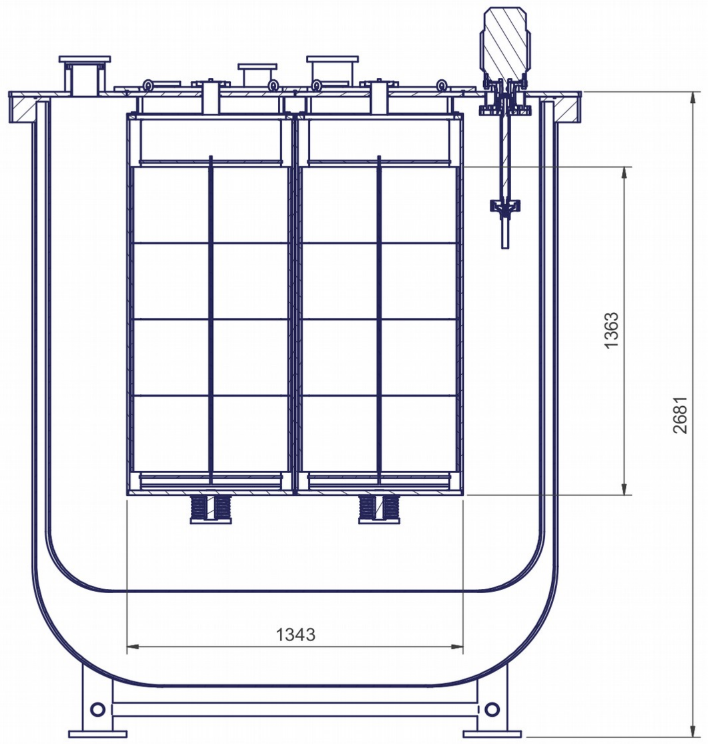
Charge R/O – arXiv:1801.08884, JINST 13 (2018) no.10, P10007
Light R/O – Instruments 2 (2018) no.1, 3
Field shell – Instruments 3 (2019) no.2, 28

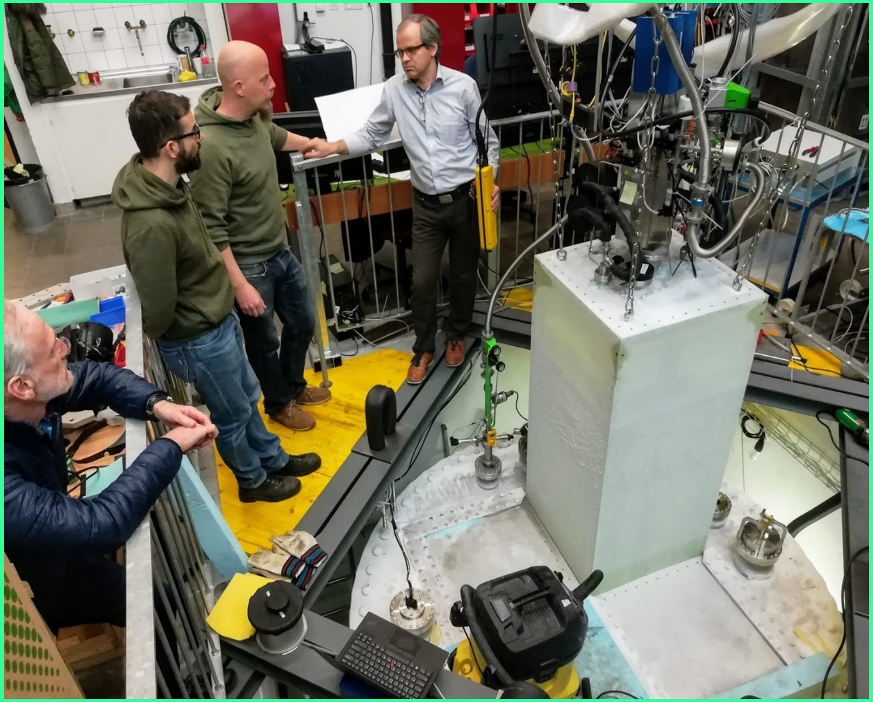
All the design elements will be incorporated into ~⅔ scale ND prototype (ProtoDUNE-ND) that will operate on-axis in NuMI in 2020.

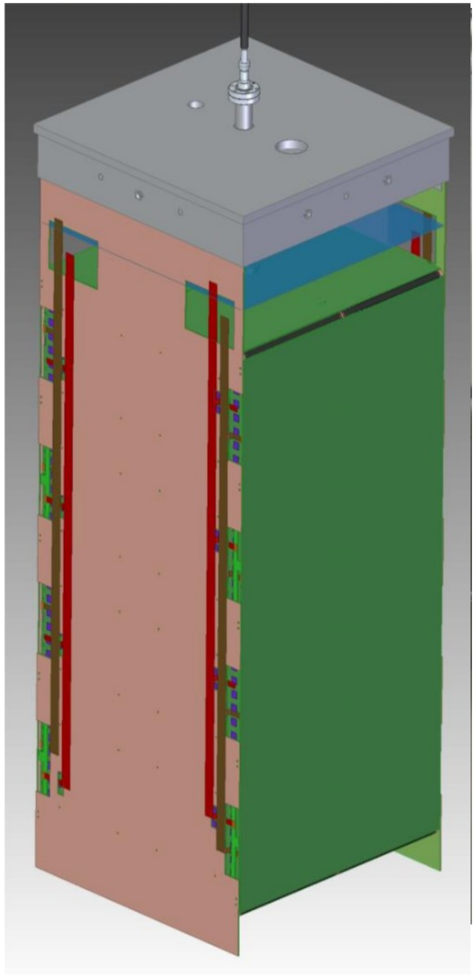
- Bern has secured funding for production of 4 modules.
- FNAL is providing support for facilities to deployment in NuMI.
- JINR is providing the light R/O.
- LBNL has secured funding for the charge R/O (supplemented by Bern).
- Rochester is providing a high level DAQ, beam trigger, and muon tagger.
- SLAC is providing the mechanical module design & production of TPC components.

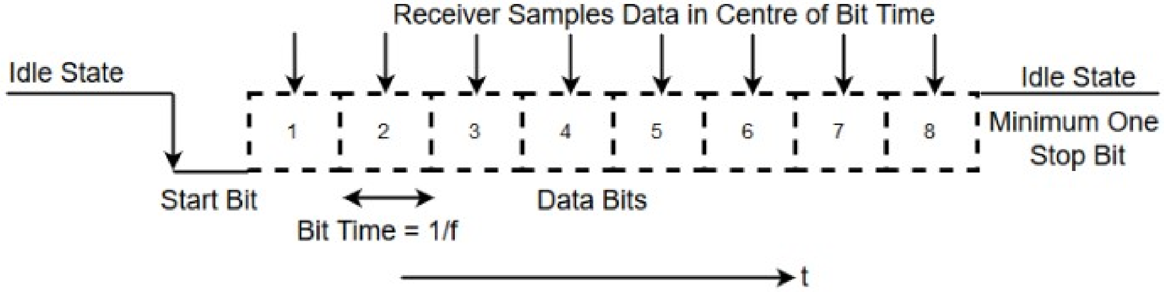
The 2x2 Demonstrator

Vacuum insulated LN2-cooled cryostat, housing 4 modules, 2.4t active LAr







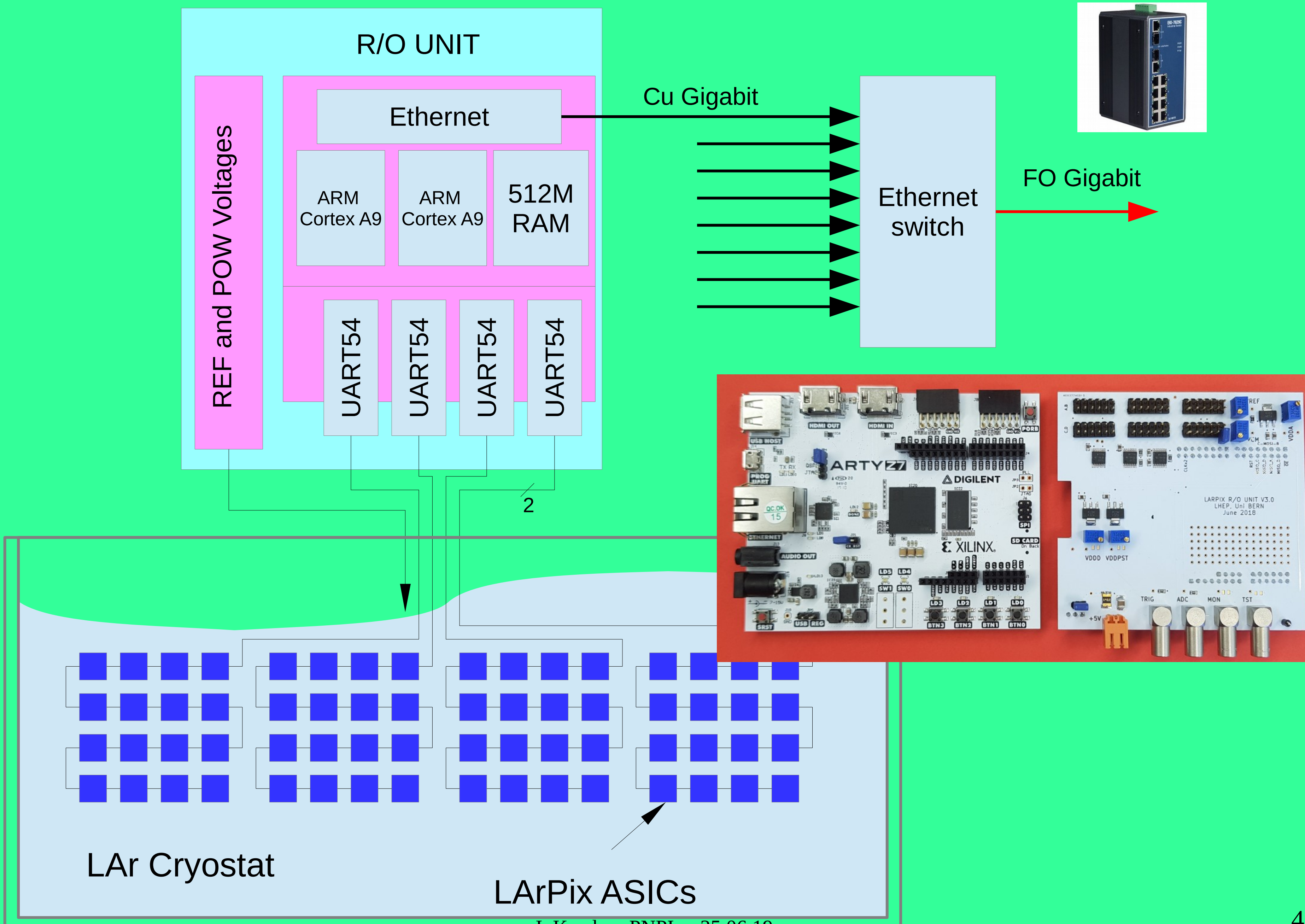


UART-like communication with a 54 bit data word

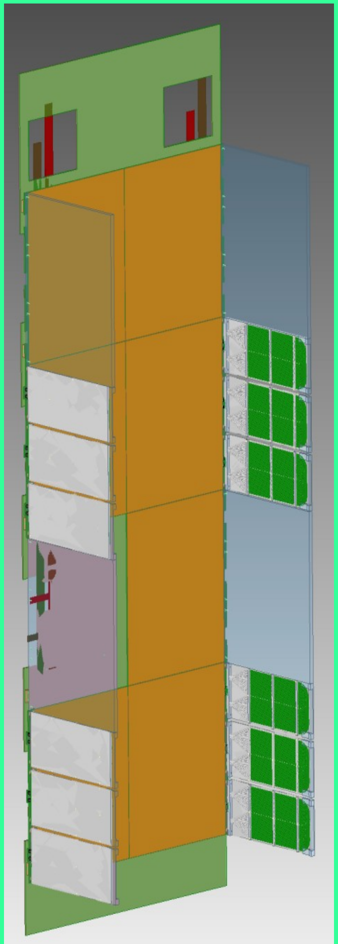
300Hz	54 bit, 16 chips, 60cm drift
~10Hz	54 bit, 1 chips, 30cm drift

1 chip	540 bit/s
5000 chip	2,7 Mbit/s

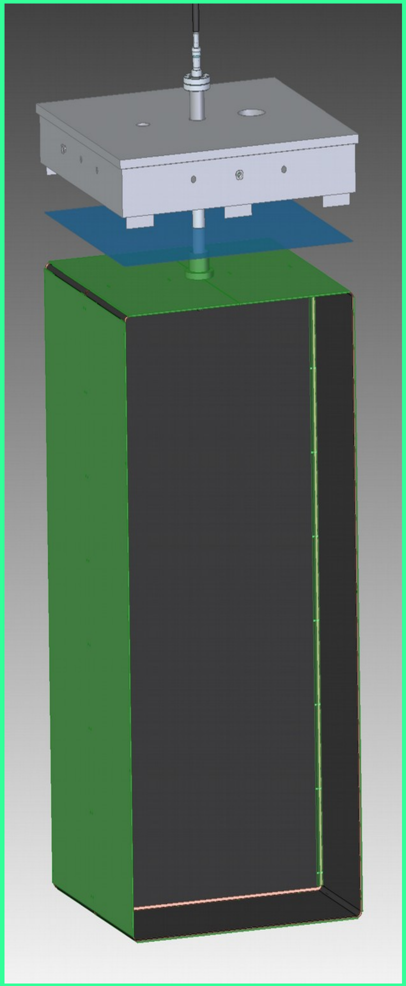
Warm F/E electronics



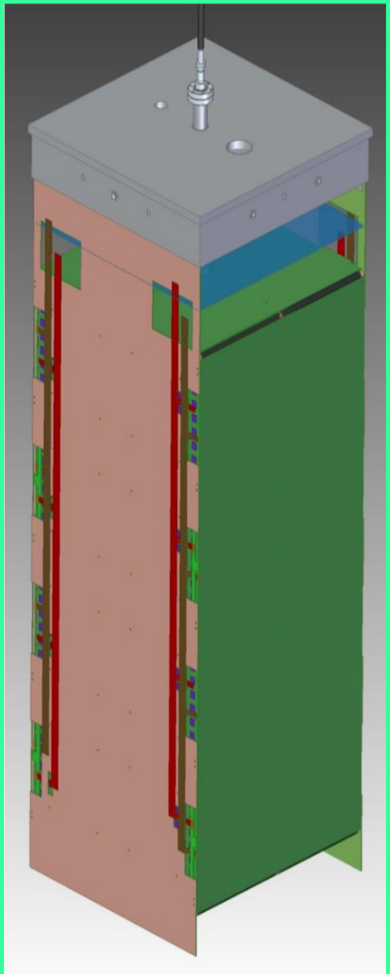
Module Structure (Knut's Bucket)



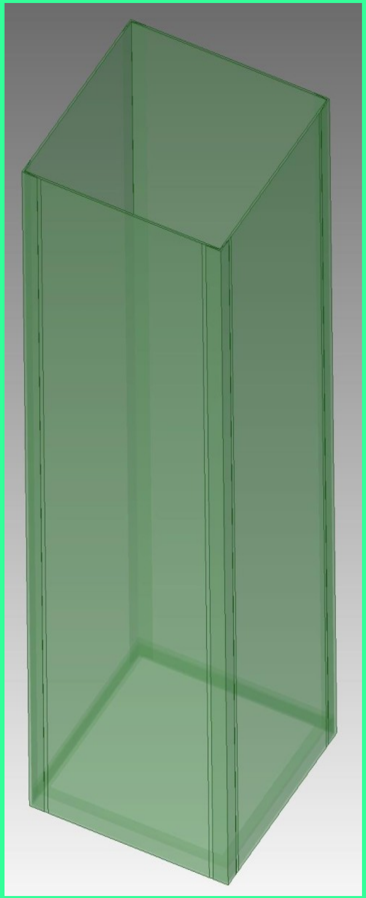
Light &Charge R/O, half detector



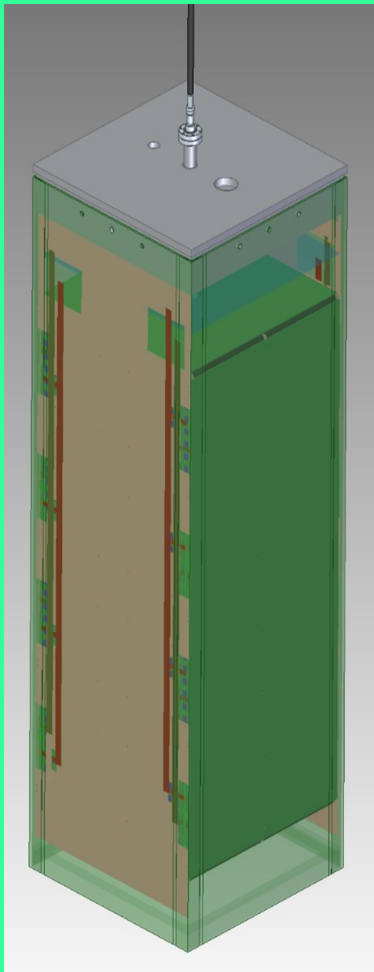
Resistive shell TPC



Naked detector



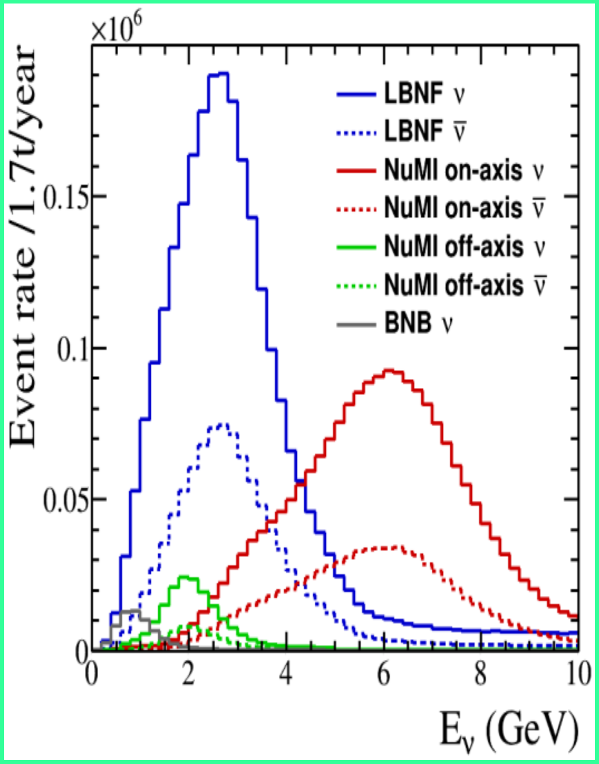
Module bucket



Module

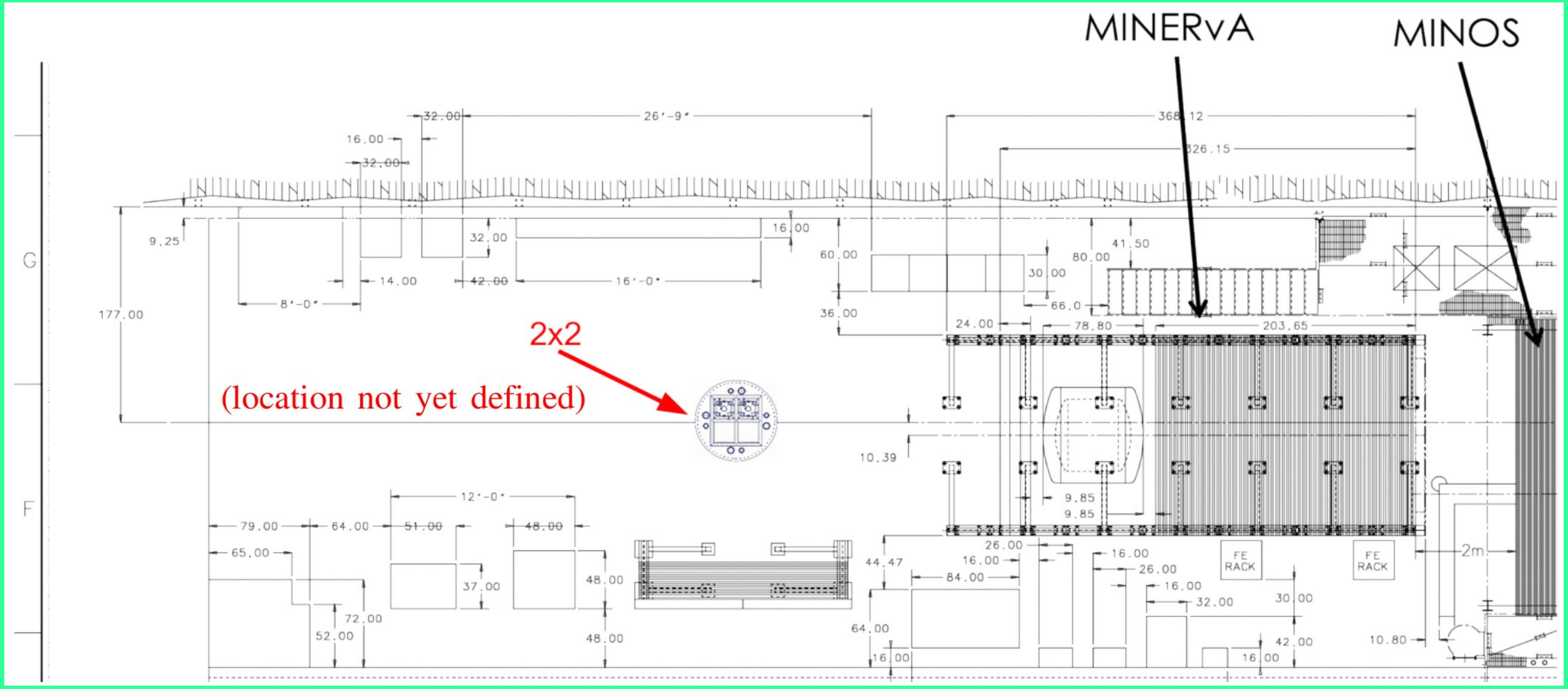
2x2 in ProtoDUNE-ND

In spring of 2020, the 2x2 will be moved into the MINOS-ND hall forming ProtoDUNE-ND



2x2 in ProtoDUNE-ND

In spring of 2020, the 2x2 will be moved into the MINOS-ND hall forming ProtoDUNE-ND



ProtoDUNE-ND Detector Physics Goals

Combining light and charge readout.

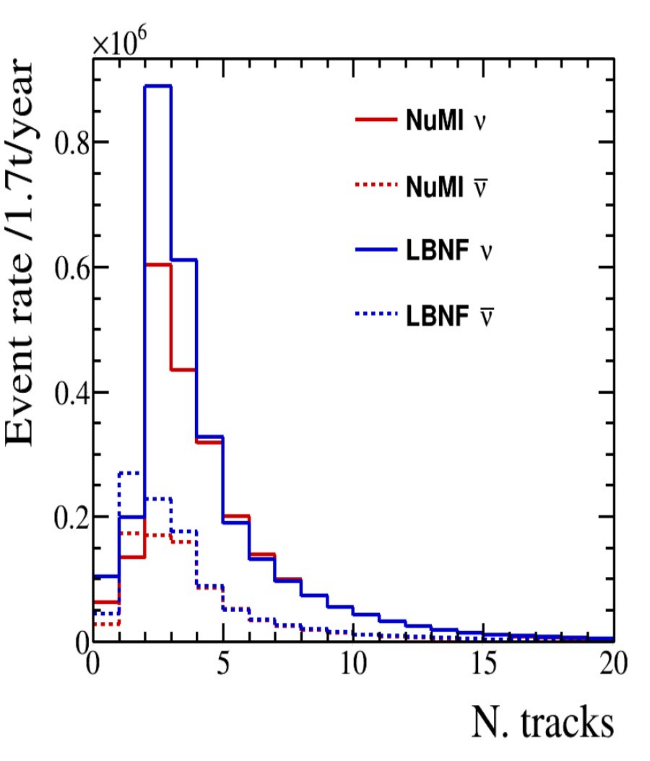
Reconstructing showers and tracks with charge sharing across modules.

Reconstructing events between fast (scintillator), and slow (LAr) detector components.

Validate MCS for momentum determination.

Reconstruct contained showers for π^0 mass peak, standard candle for electron energy scale.

Verify e/γ separation with a pixelated charge readout.

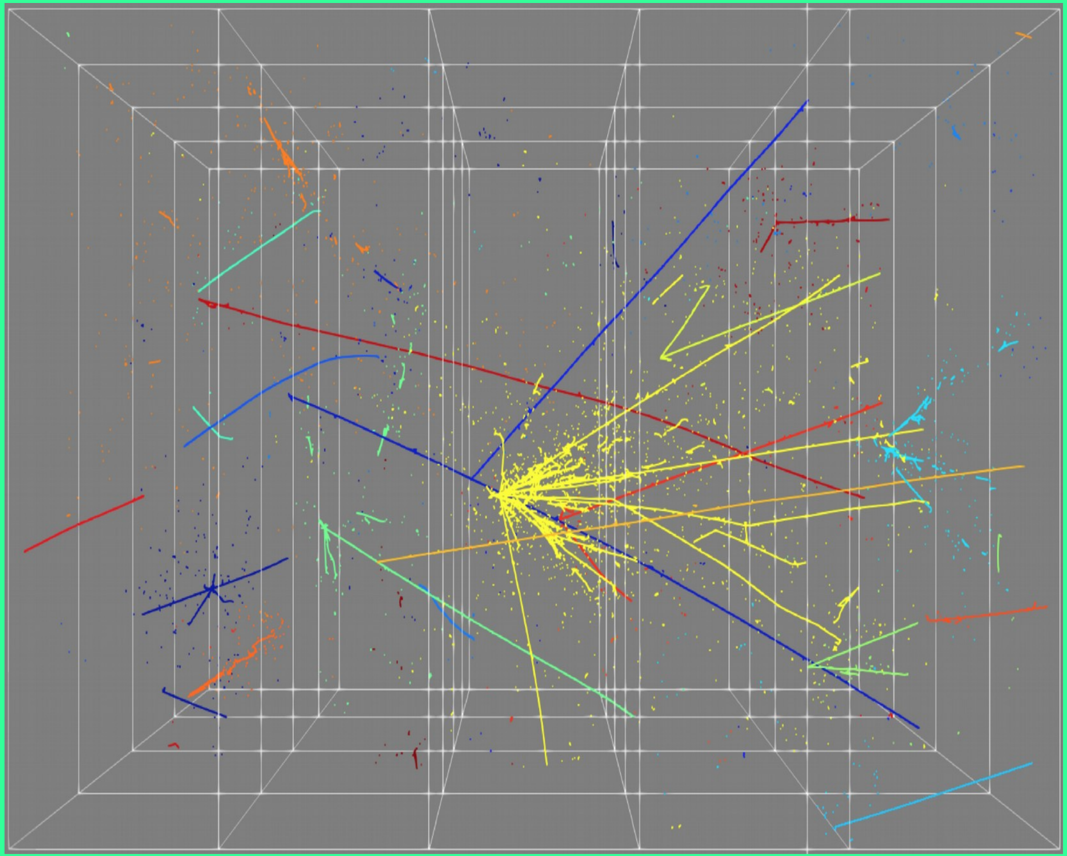


Pixelated R/O : towards detector-scale implementation...

LArPix ASICs: Integrated circuits for charge signal amplification, digitization, and readout
Pixel Anode Boards: Circuit boards which host charge-sensitive pads and readout ASICs
Internal Cabling: Transmits power and I/O from feedthrough to anode
Anode Frame: Provides structural support for anode PCBs and cabling
Readout Feedthroughs: Transmits power and I/O passage through cryostat
Isolation Electronics: Provides isolation and filtering of power and I/O at feedthrough
External Cabling: Transmits power and I/O from DAQ electronics to Isolation electronics
Power Supplies: Provide power needed to drive the electronics
DAQ Electronics: Generates clock and provides I/O bridge from ASICs to DAQ computer
DAQ Computer: Issues input commands, receives output data packets, records data
DAQ Software: Formats input commands, interprets output data packets.
Pixel LArTPC Analysis: Studies, simulation, algorithms needed to guide development and prepare for large-scale pixelated data analysis.

Many open roles for partners for design, production, and testing of all system aspects!

Thank you!



Cathode potential

Single-volume TPC	ARGONCUBE
1-2 MV:	100 kV
- Feedthrough is a challenge	- Feedthrough home-made or commercial
	- Wide choice of PS units
- Drift time > 10 ms	- Drift time ~ 1ms

Charge attenuation → calorimetry constant term

LAR Purity ~ 0.01 ppb	Purity ~0.1 ppb (reached in ARGON**T**UBE)

Accumulation of volume charge

	Low distortions (~3%, in MicroBooNE 10%)

Risk of breakdowns (arcing)

Stored charge ~ 1nF x 1 MV = 1 mC	~ 1nF x 100 kV = 0.1 mC / module
Stored energy 1 mC x 1 MV = **1 kJ**	0.1 mC x 100 kV = **10 J / module**

LarPix V2:
64 channels/chip

4 mm pitch:
3.2x3.2cm/chip

10x10 ASICs for a 32cm by 32cm tile

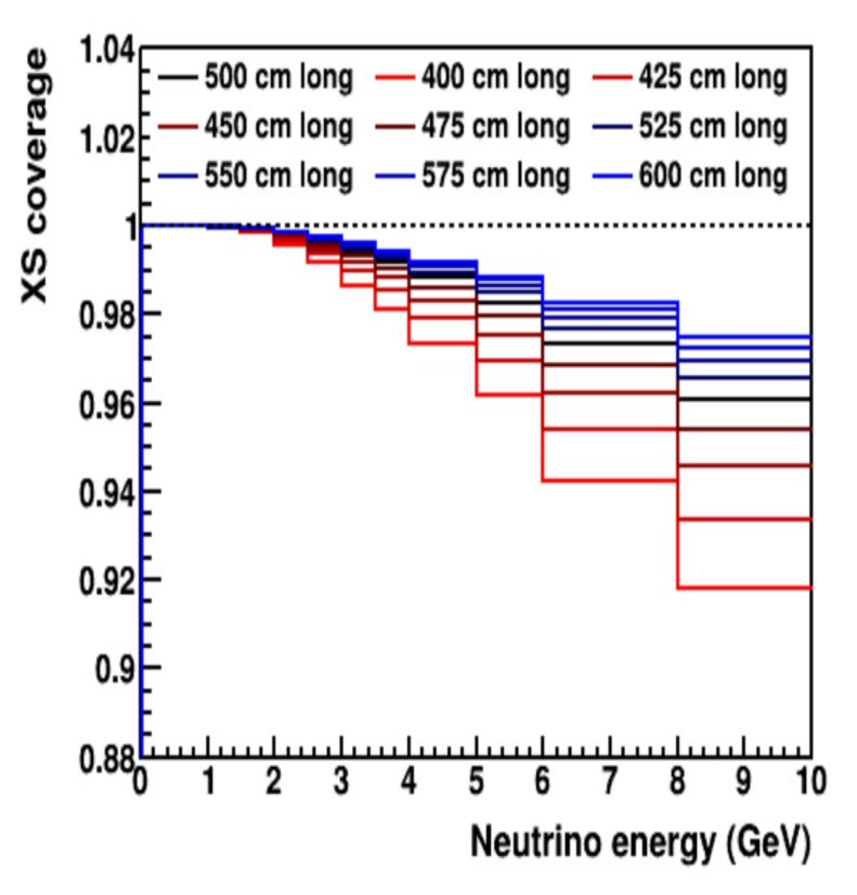
8 tyles/side, 16 tyles/module (102400 pix), 1600 chips/module, 16 lines/module,
4 (8) R/O units/module

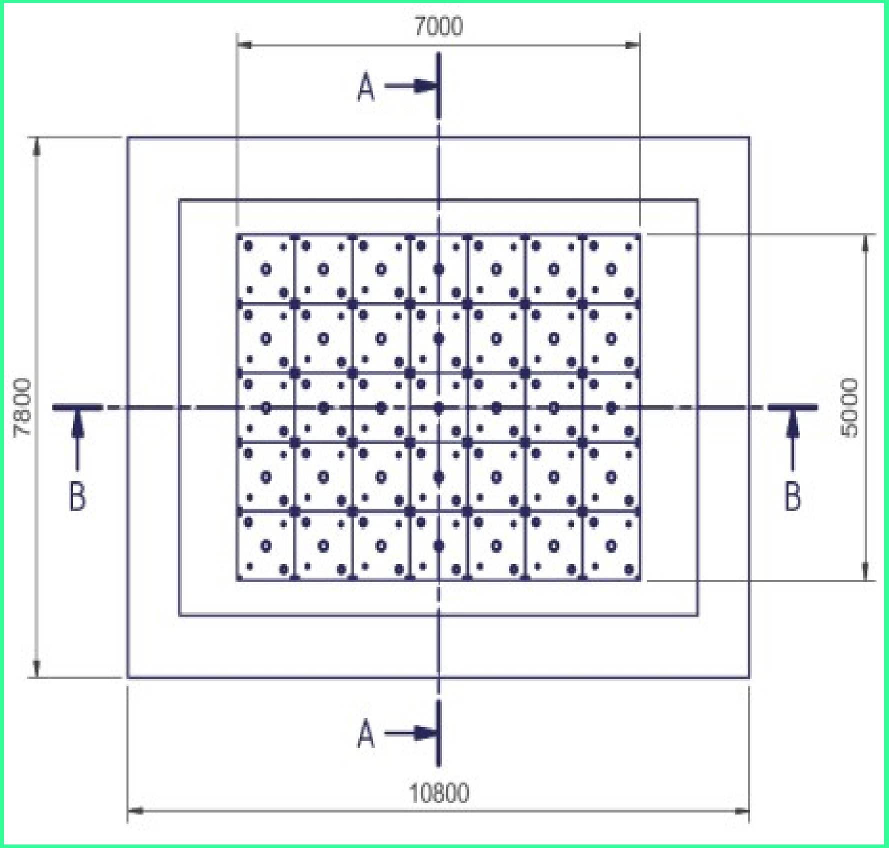
Feedthrough: 32 pins data, 32 pins gnd, clock and power.

Typical rate: 0.1Hz/pix, => overal 10 kHz, 2.5 (1.25) kHz / R/O Unit

Data rate 640 kbps/module, 2.6 Mbps overal for 2x2 TPC

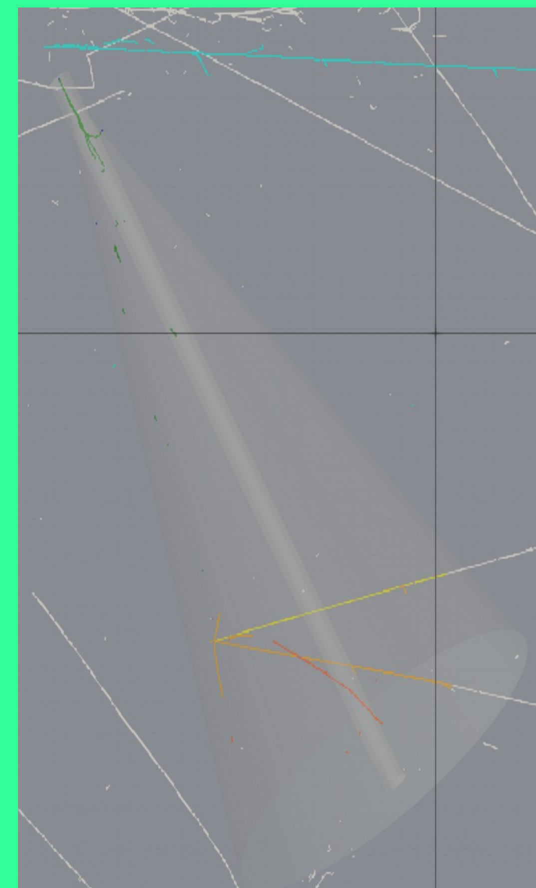
Optimizing DUNE ND Detector Dimensions





Pixelated Charge Readout

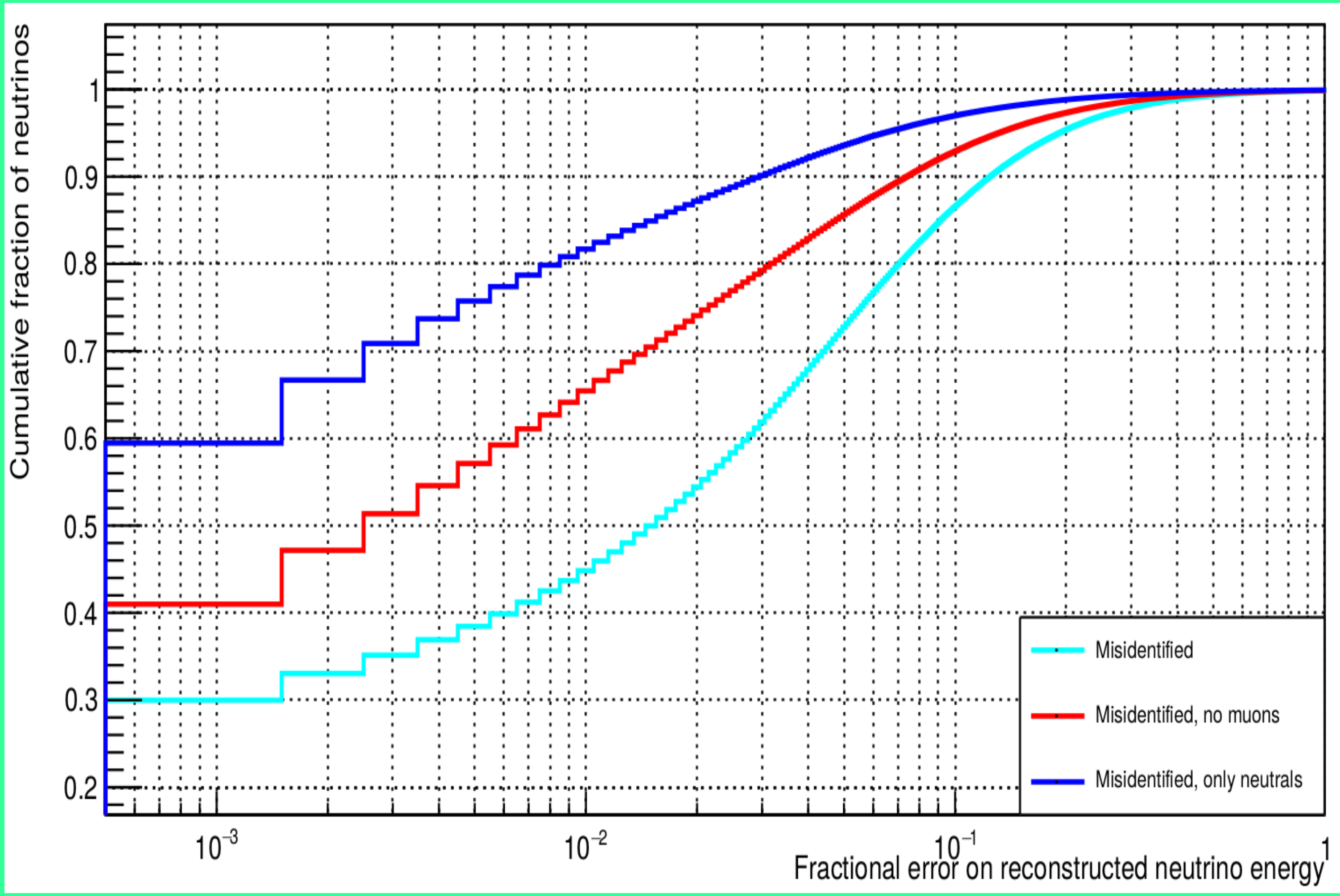
Using 3D information, it was shown that pileup in π^0 reconstruction is < 1% for > 70% of events.



Event display showing simulated LBNF beam spill in ArgonCube (5 x 4 x 3 m^3) FHC 2 MW beam, 80 GeV protons, including rock events.
D. Goeldi, 2018 JINST TH 002.

Pixelated Charge Readout

Using 3D information, it was shown that pileup in π^0 reconstruction is < 1% for > 70% of events.



Cumulative fraction of neutrinos versus misidentified energy fraction for 3D π^0 shower reconstruction. FHC 2 MW beam, 80 GeV protons. D. Goeldi, 2018 JINST TH 002.

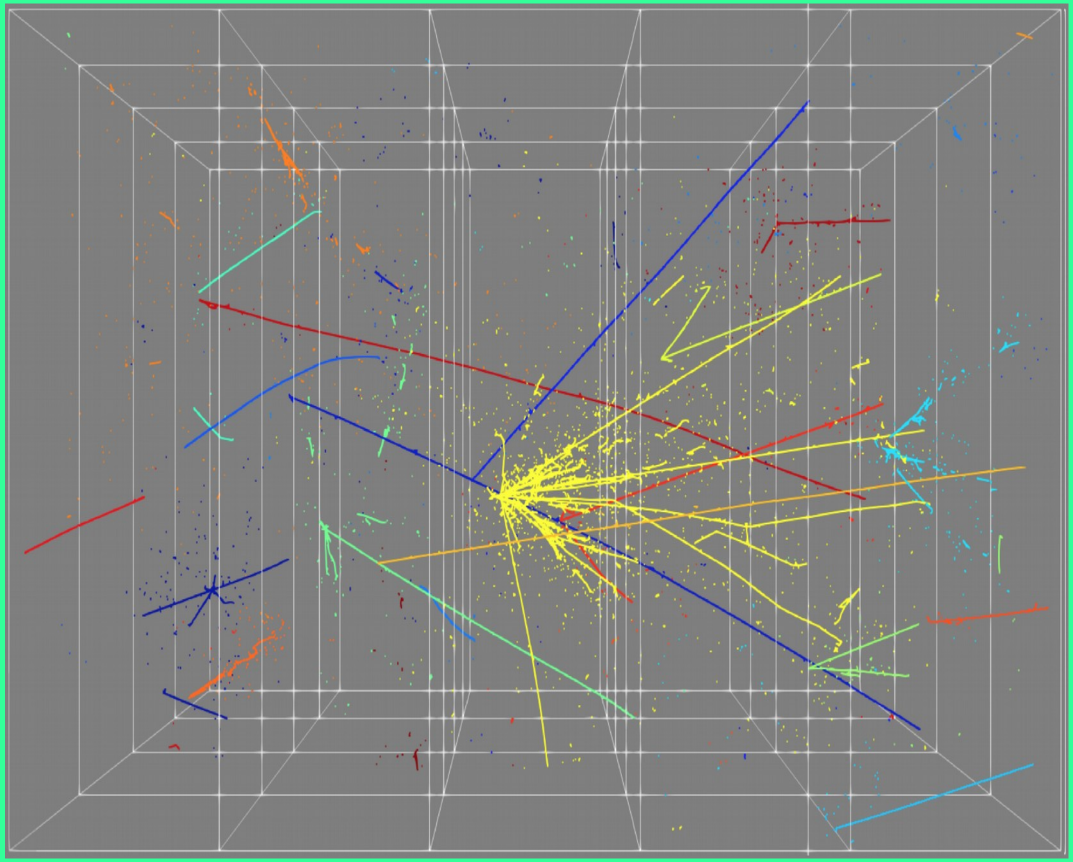
Detached Energy Deposits

Unambiguous charge R/O will simplify reconstruction, but it is still timing limited:

Drift window = 250 μs.
Spill =10 μs.

It is not trivial associating isolated/ detached deposits to correct vertex – fast neutrons.

Contained scintillation can help, light R/O with ~ns resolution needed.

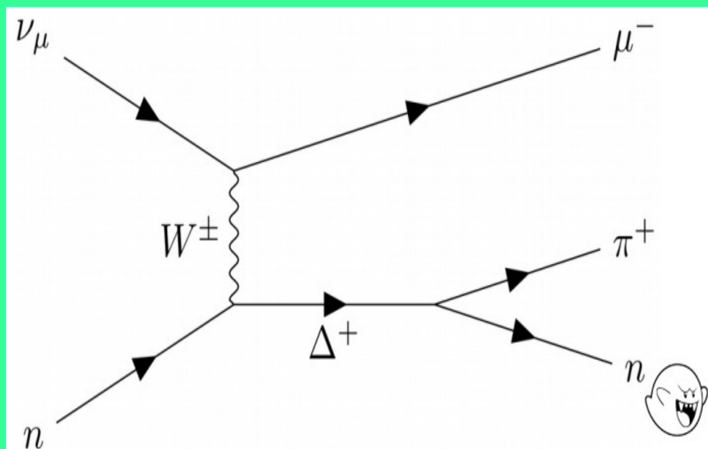


1 MW 3 horn optimised spill, FHC, including rock. 4x5 geometry.

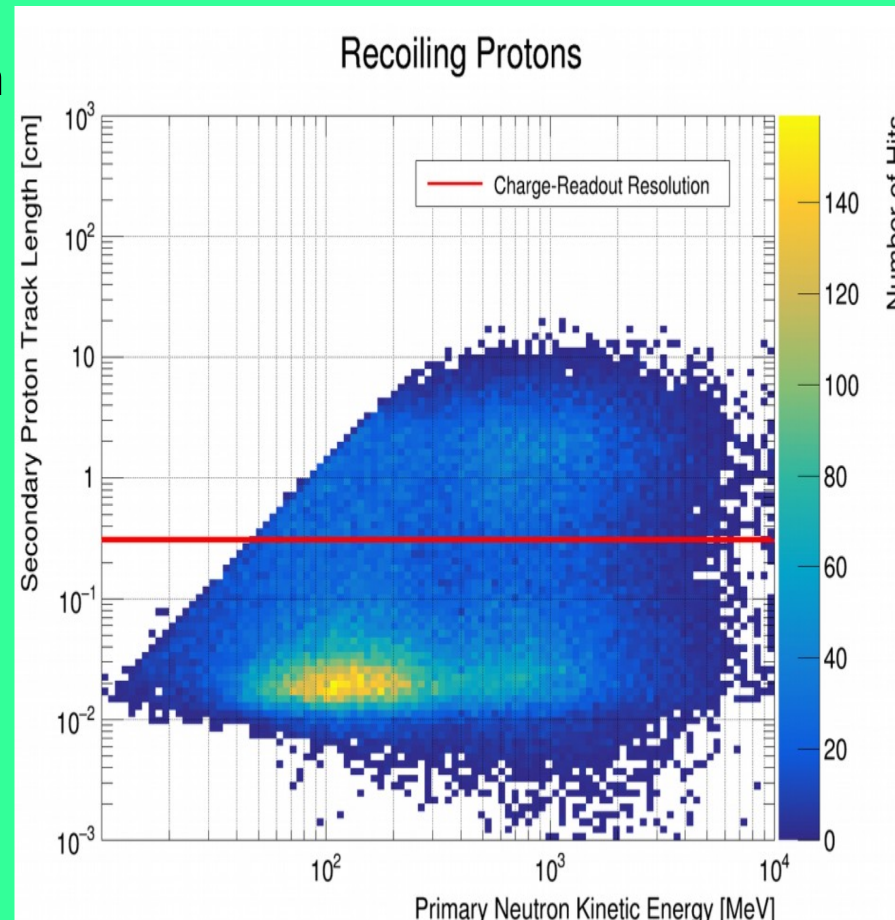
Colouring by nu.

Detached Energy Deposits Are Important

A large uncertantiy in energy reconstruction

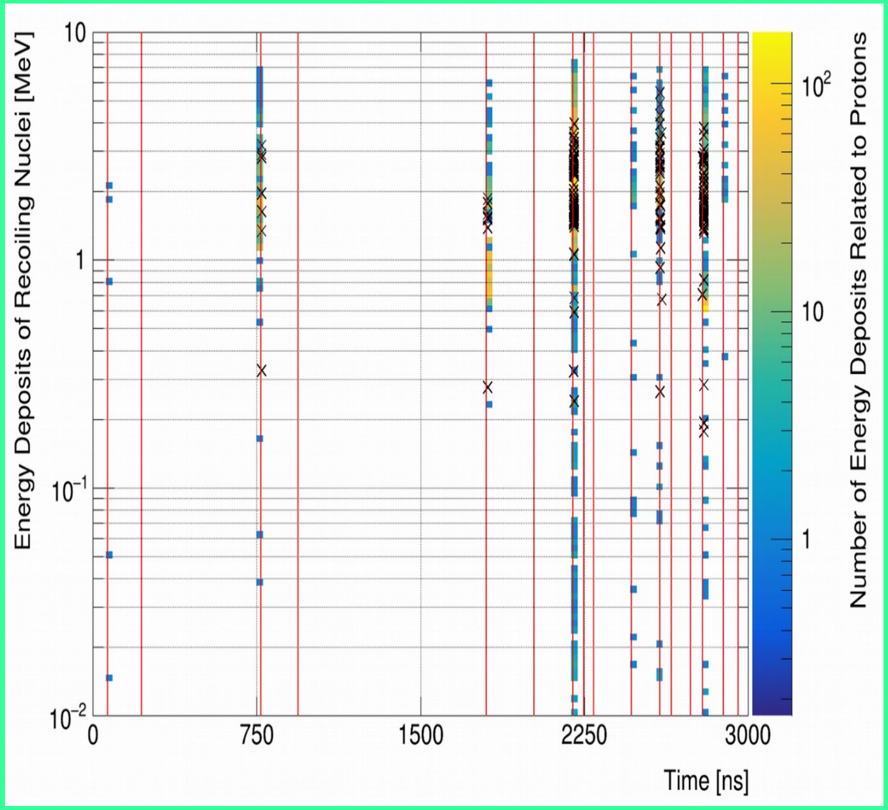


$$E_{\nu,reco} = \underbrace{E_\mu}_{leptonic} + \underbrace{\sum_{i=p,\pi^\pm} E_i}_{hadronic} + \underbrace{\sum_{i=\pi^0,e,\gamma} E_i}_{EM-showers} + \underbrace{\sum E_n}_{neutrons}$$

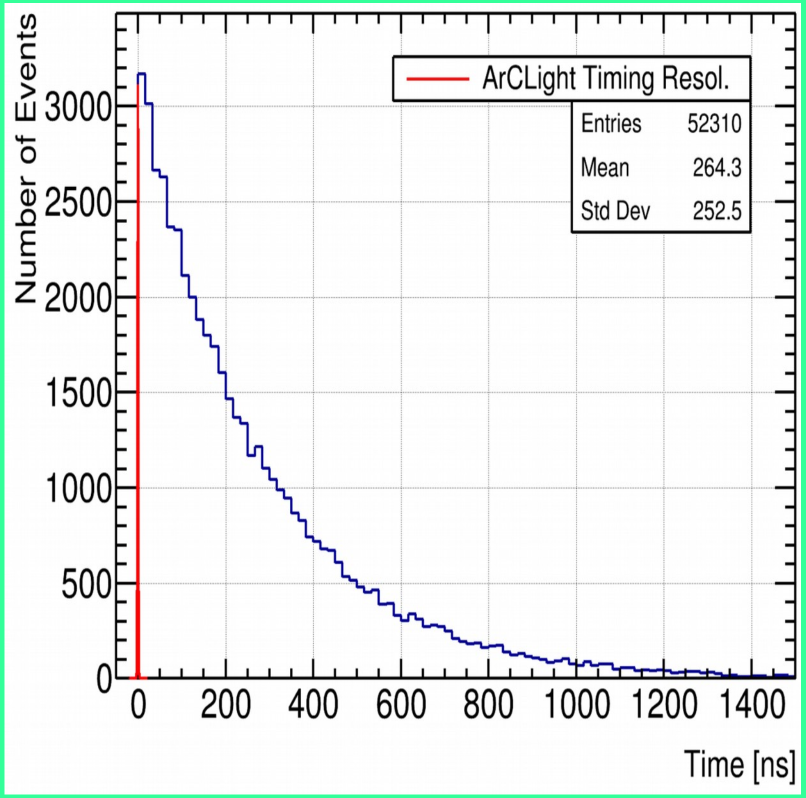


~30% of all recoiling protons from tracks, these are caused by fast neutrons (> 50 MeV)

Neutrino Vertex Temporal Separation



A 3rd of a LBNF spill (1 MW 3 horn optimised, FHC)
Nu vertex (red), recoiling p (coloured), nuclear recoil (X)



Nu separation within a LBNF beam spill. Only events entering the 60 m³ active volume of ~ 100’000 neutrino events. Mean 264 ns.

Use prompt light from protons and vertex to associate tagged fast neutrons with correct ν-interactions.