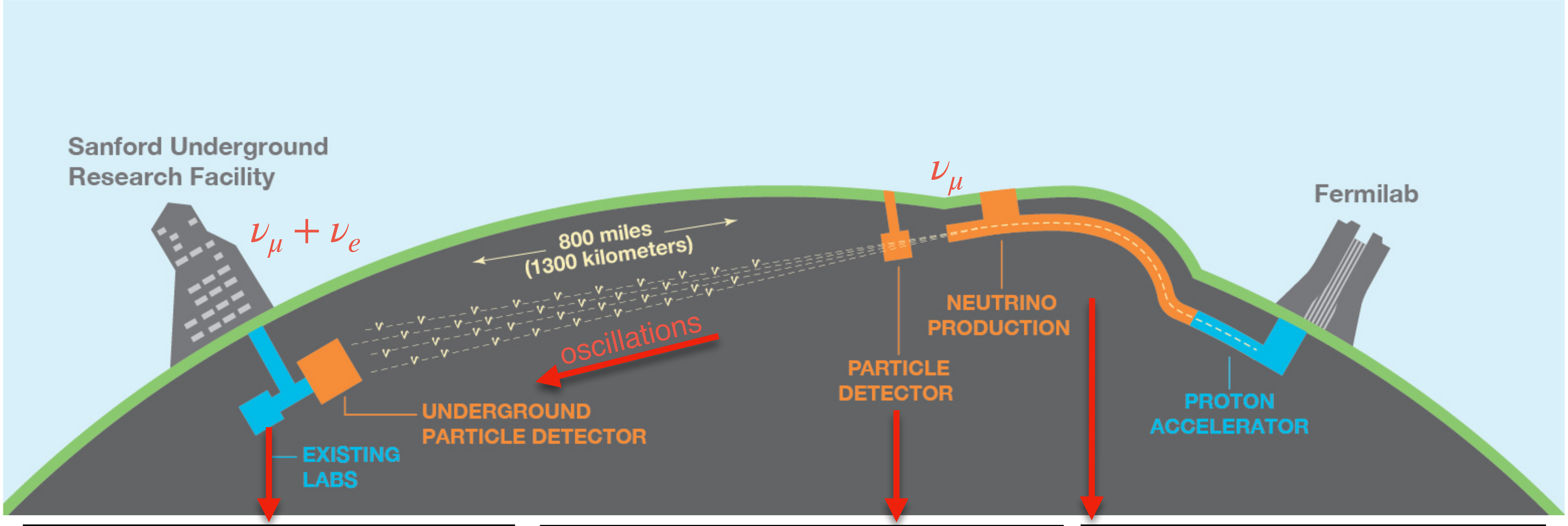
Charge-Light Matching of Ambient Low-Energy Activity in the DUNE Near Detector Prototypes

Sam Fogarty on behalf of the DUNE collaboration
LIDINE August 26th, 2024

COLORADO STATE UNIVERSITY

The Deep Underground Neutrino Experiment (DUNE)

DUNE Far Detector Technical Design Report, Volume II: arxiv:2002.03005



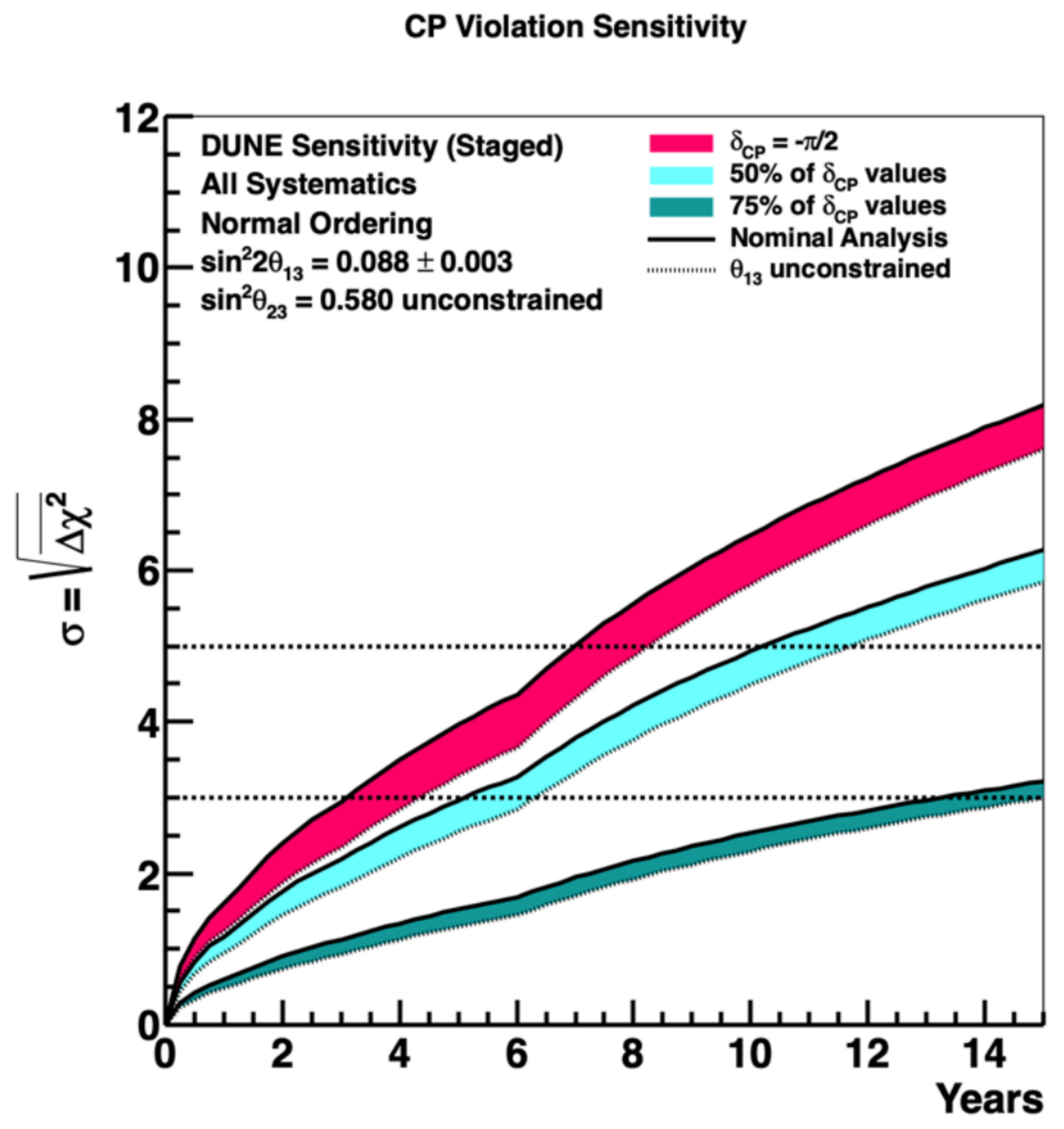
Far Detector (FD) Complex
- Measures beam neutrino rate and energy spectra after oscillations take place

Near Detector (ND) Complex
- Measures unoscillated rate and energy spectra of the beam neutrinos

Intense neutrino beam source
- 1.2MW (upgradable to 2.4MW)

DUNE Physics and Goals

- **Primary physics program**
  - Precise measurement of neutrino oscillation parameters, e.g. CP violating phase δ_{CP}
  - Determination of neutrino mass ordering
- **Extensive secondary physics program**
  - Neutrino detection from core-collapse supernovae
  - Proton decay discovery potential
  - And more (e.g. solar neutrinos, BSM searches, atmospheric neutrinos, …)

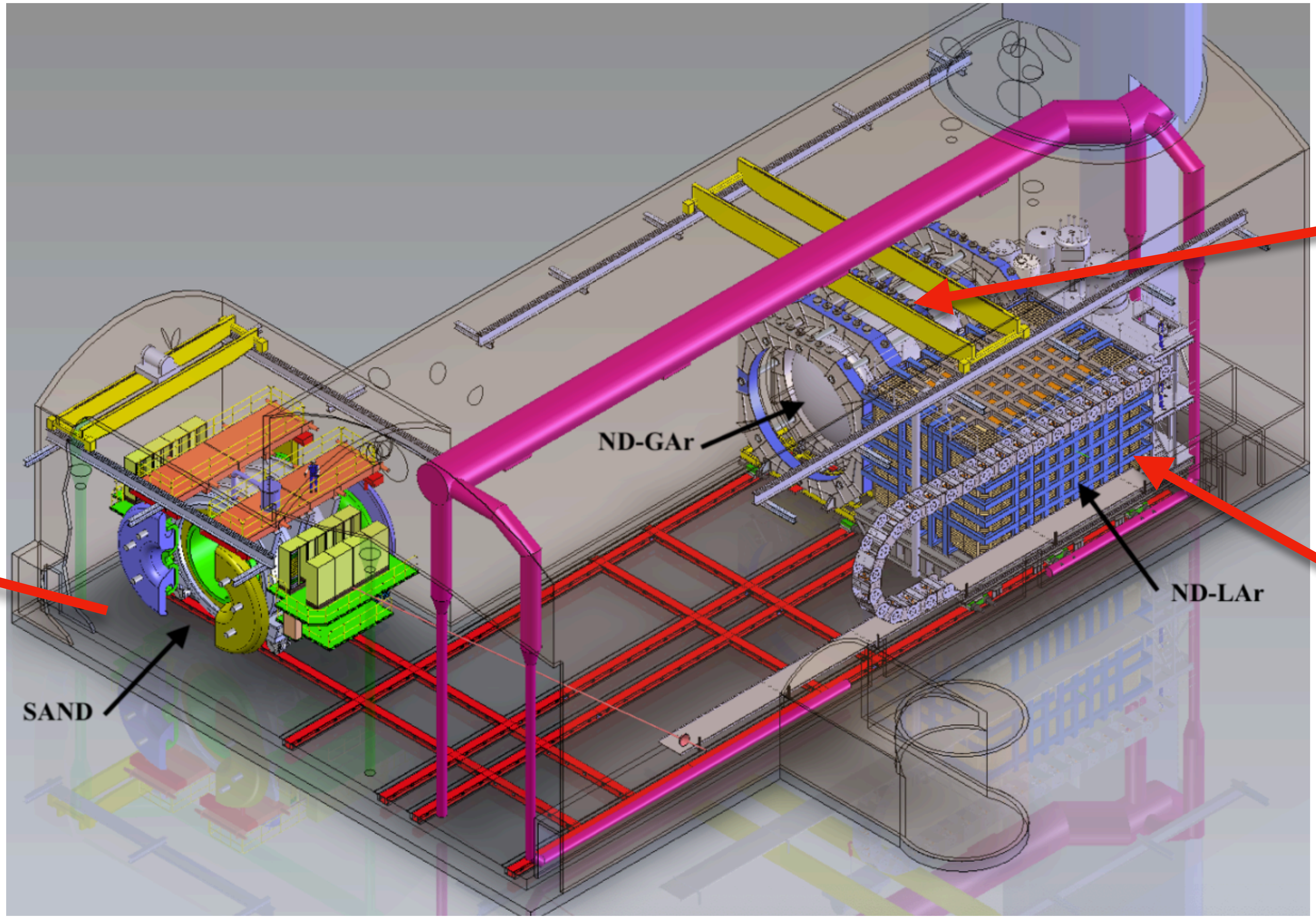


DUNE Far Detector Technical Design Report, Volume II: arxiv:2002.03005

Near Detector Complex

DUNE ND CDR: arXiv:2103.13910

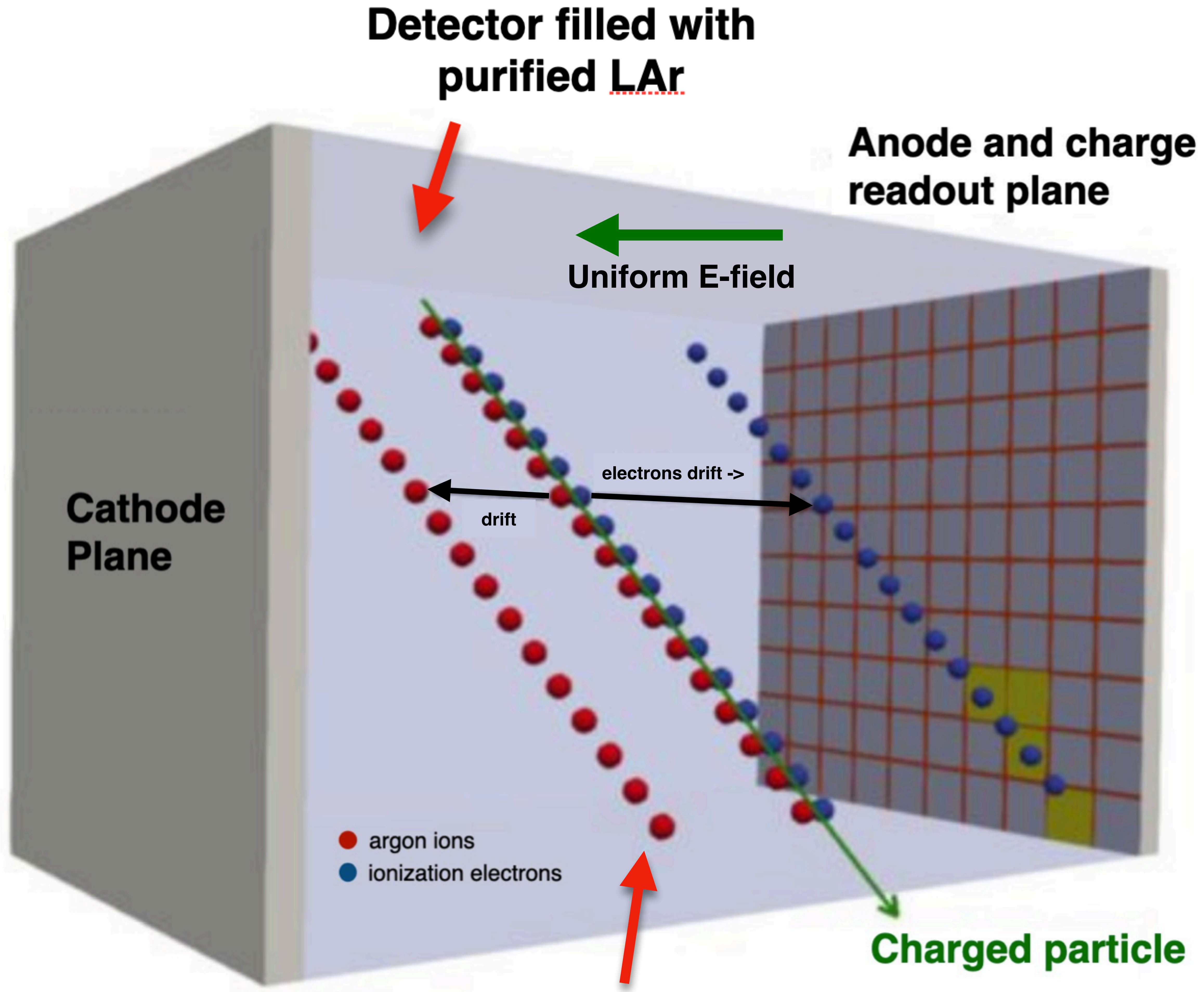
SAND (System for on-Axis Neutrino Monitoring)
- Magnetized beam monitor
- Measures beam flux going to the FD



ND-GAr (Gaseous Argon Near Detector)
- Magnetic spectrometer
- Measures muon momentum and energy

ND-LAr (Liquid Argon Near Detector)
- Uses the Liquid Argon Time-Projection Chamber (LArTPC) technology
- Measures unoscillated neutrino flux and spectra

Liquid Argon Time-Projection Chambers (LArTPCs)

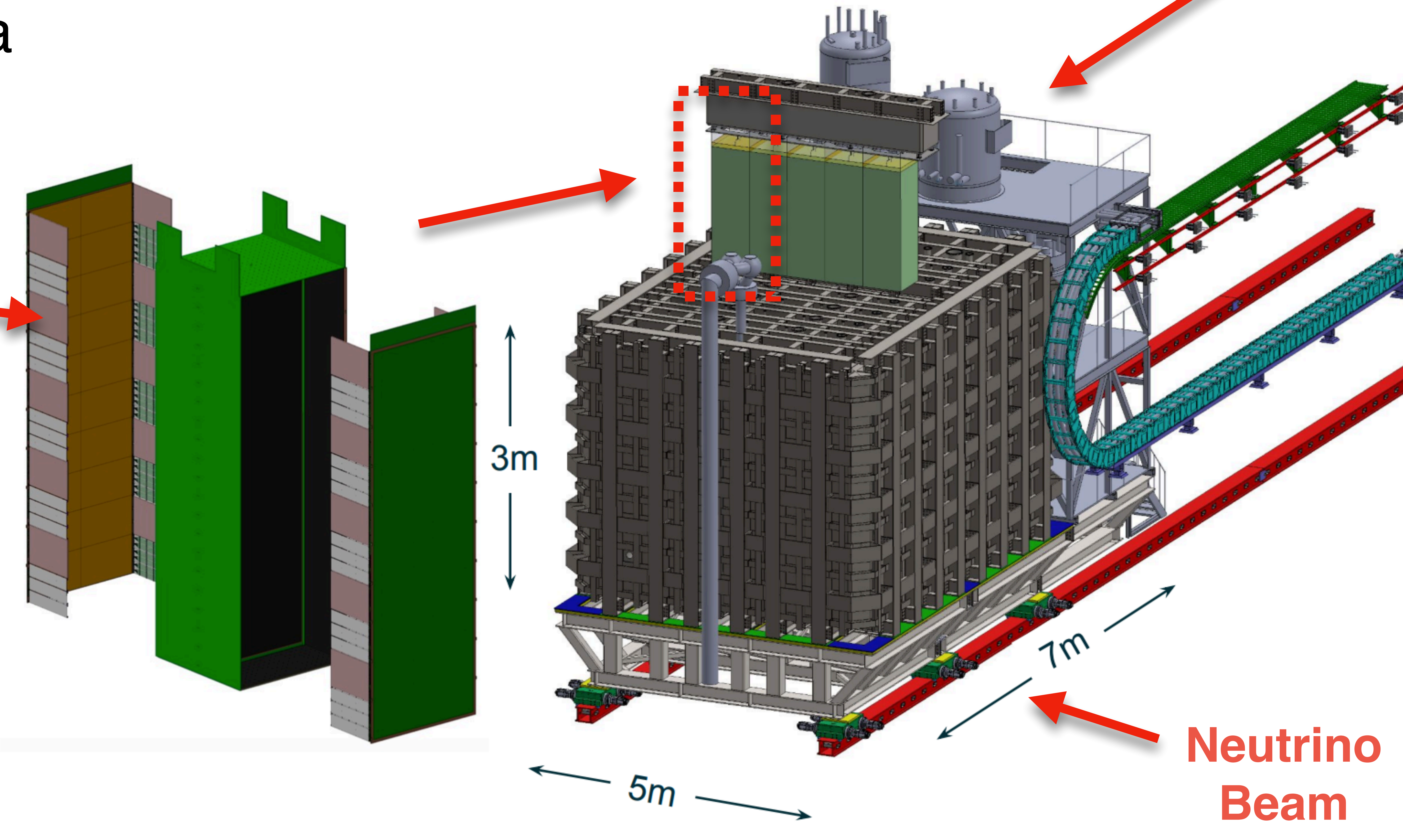


Argon ions drift in the opposite direction, but they are not very relevant for ND-LAr

- Charged particles leave a path of ionization electrons
  - Electrons drift in the E-field to the anode to make signals on the charge readout pixels
- Charged particles also create scintillation light in LAr
  - Detected by photon detectors
  - Used to reconstruct interaction time and position

ND-LAr Overview

- 35 1x1x3 m^3 LArTPC modules in a 5x7 array
- Compact light readout with 25% coverage of active LAr
- TPC module optical isolation: **interaction-level timing info**
- 3D readout using pixelated charge readout to handle high neutrino pileup → **~60 ν interactions per 1.2 MW beam spill**

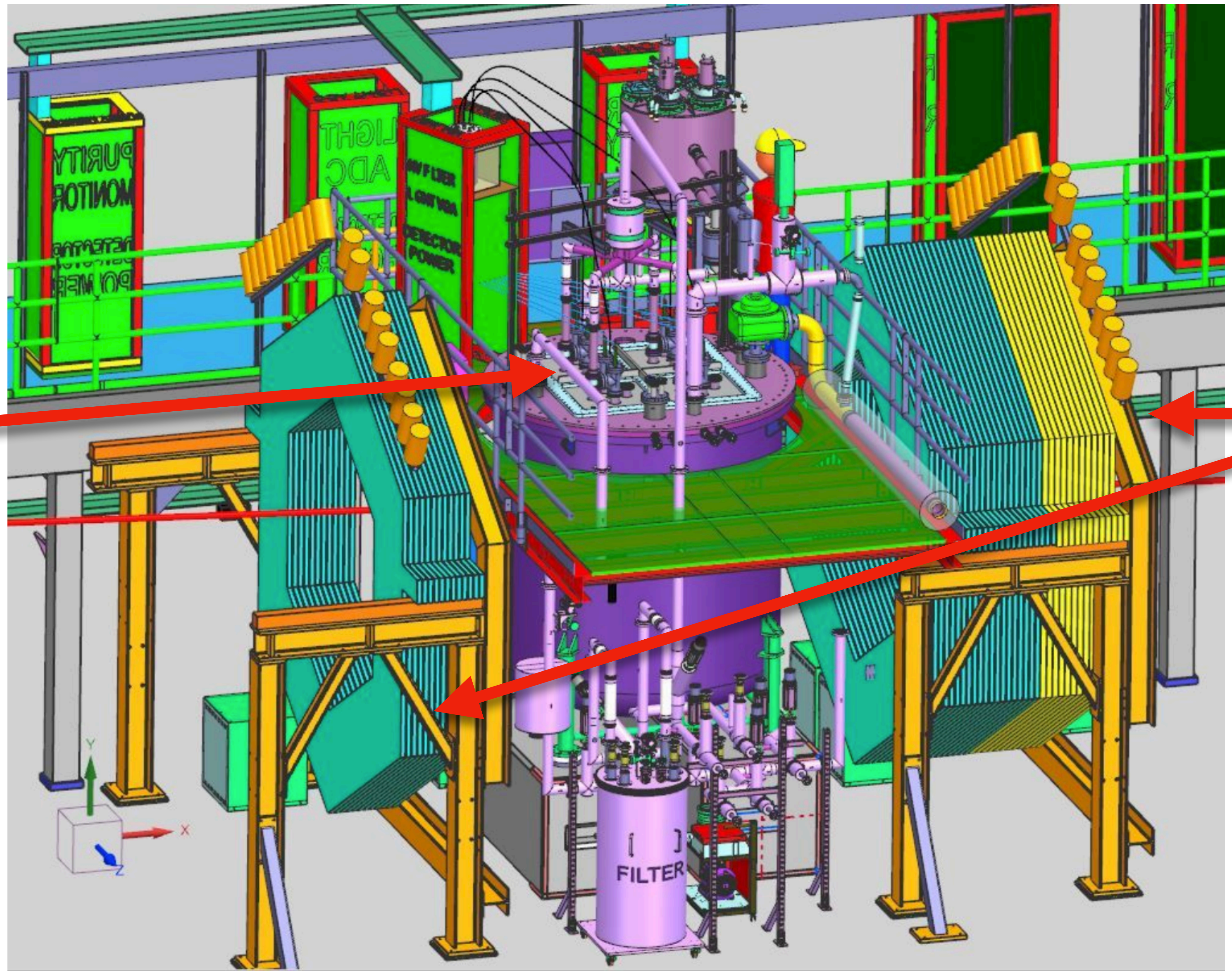


DUNE ND CDR: arXiv:2103.13910

The ArgonCube 2x2 Demonstrator

Prototype of ND-LAr operated at Fermilab underground in MINOS hall using the NuMI beam line

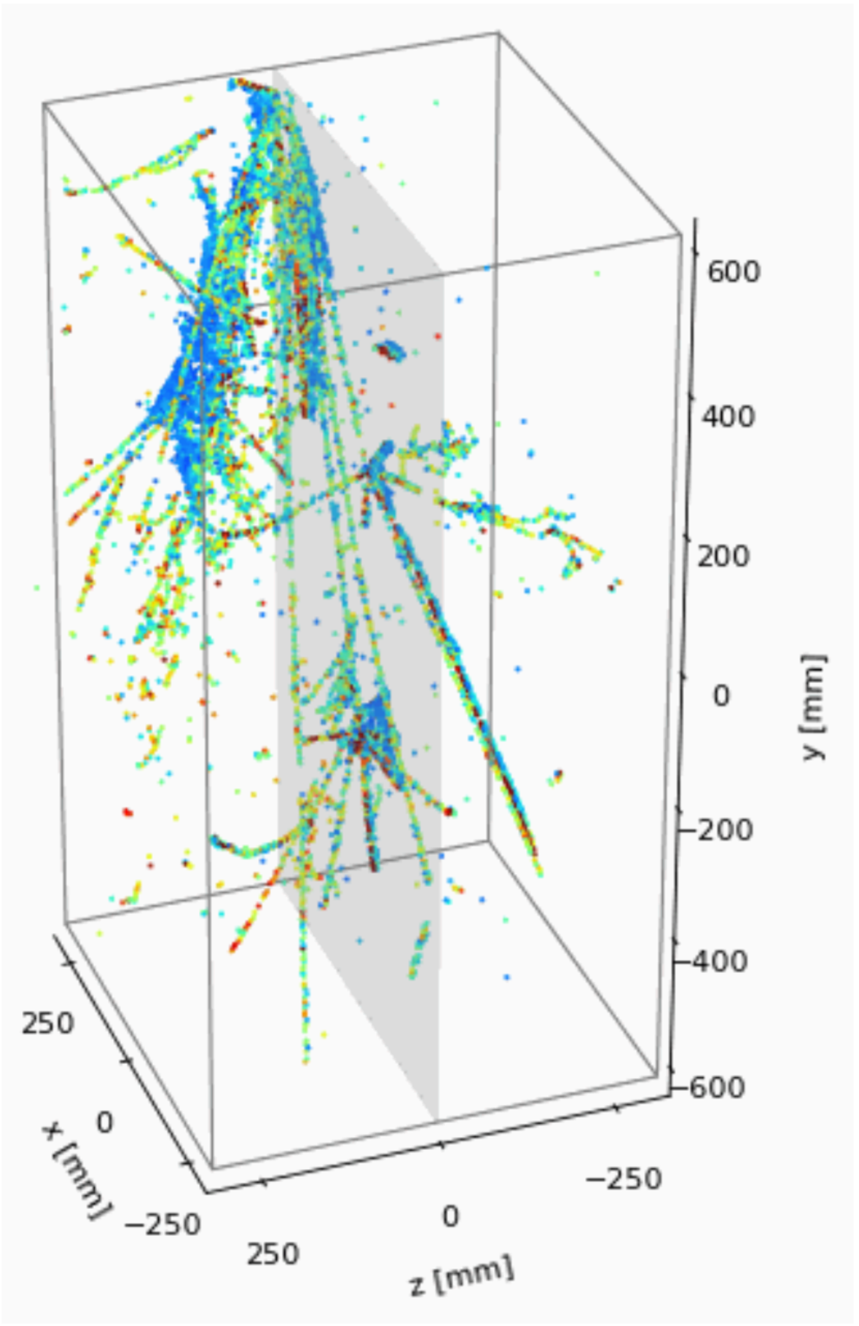
Four 1.2 x 0.6 x 0.6 m^3 LArTPC modules in a 2x2 array (smaller than the ND-LAr modules)



Repurposed MINERvA planes for muon reconstruction and tracking

The ArgonCube 2x2 Demonstrator

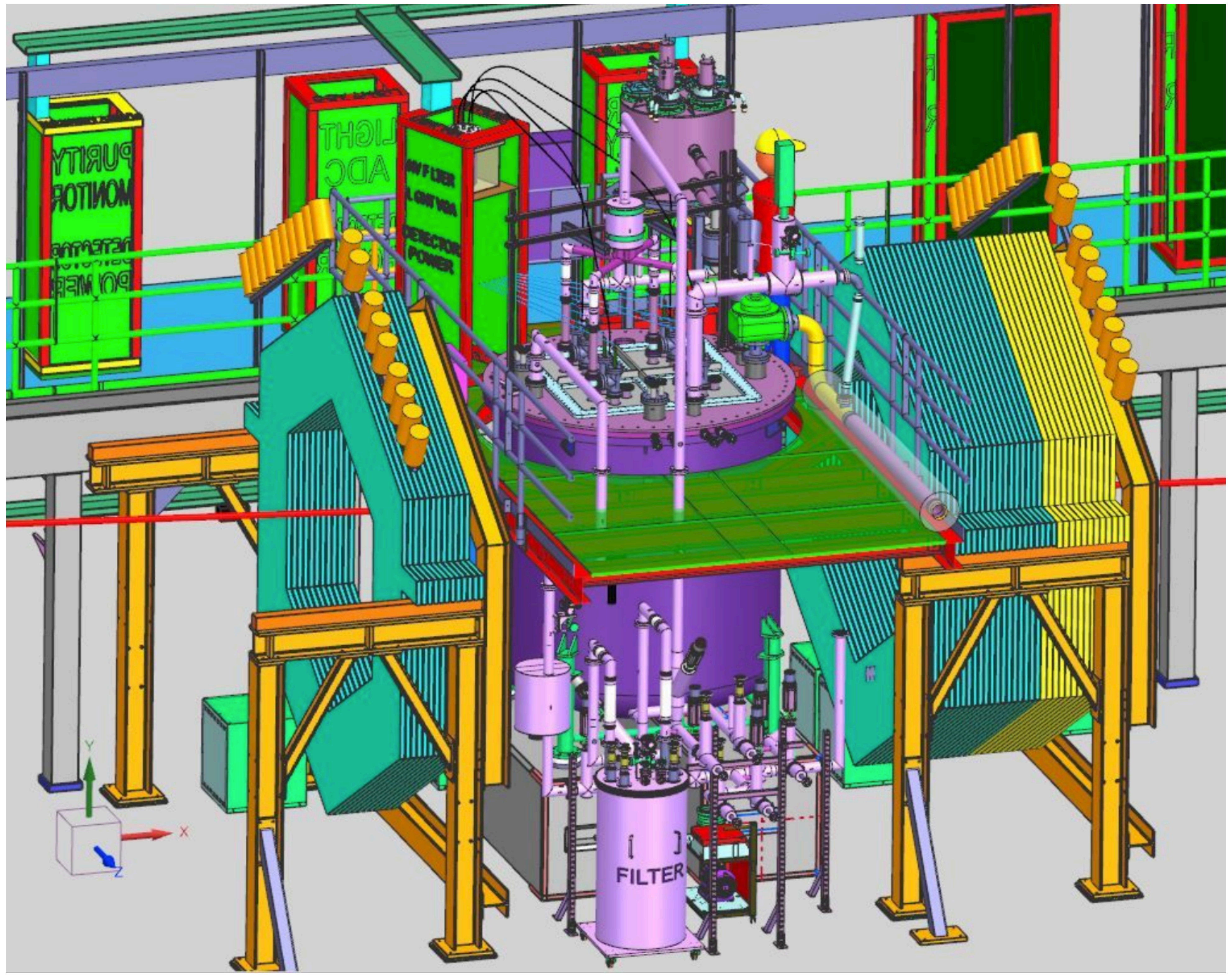
Module-0 Cosmic Ray Event
(on-surface @ Univ. of Bern)



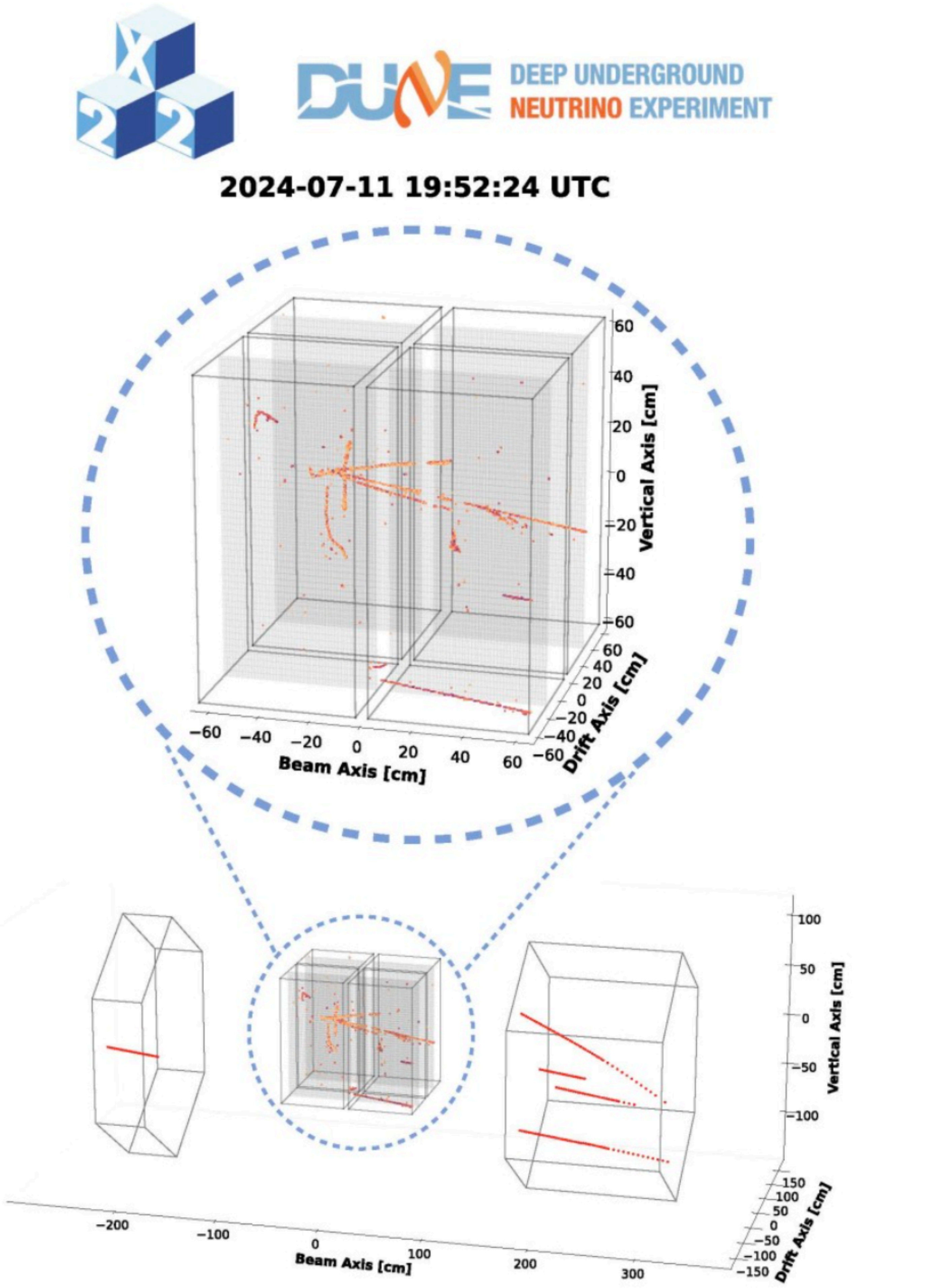
Module-0 Performance Paper: arXiv:2403.03212

The individual 2x2 modules were first tested at the Univ. of Bern with cosmic rays

Prototype of ND-LAr operated at Fermilab underground in MINOS hall using the NuMI beam line



2x2 Candidate Neutrino Interaction



First run in a neutrino beam in early 2024 — **demonstrated successful operation at nominal configuration**

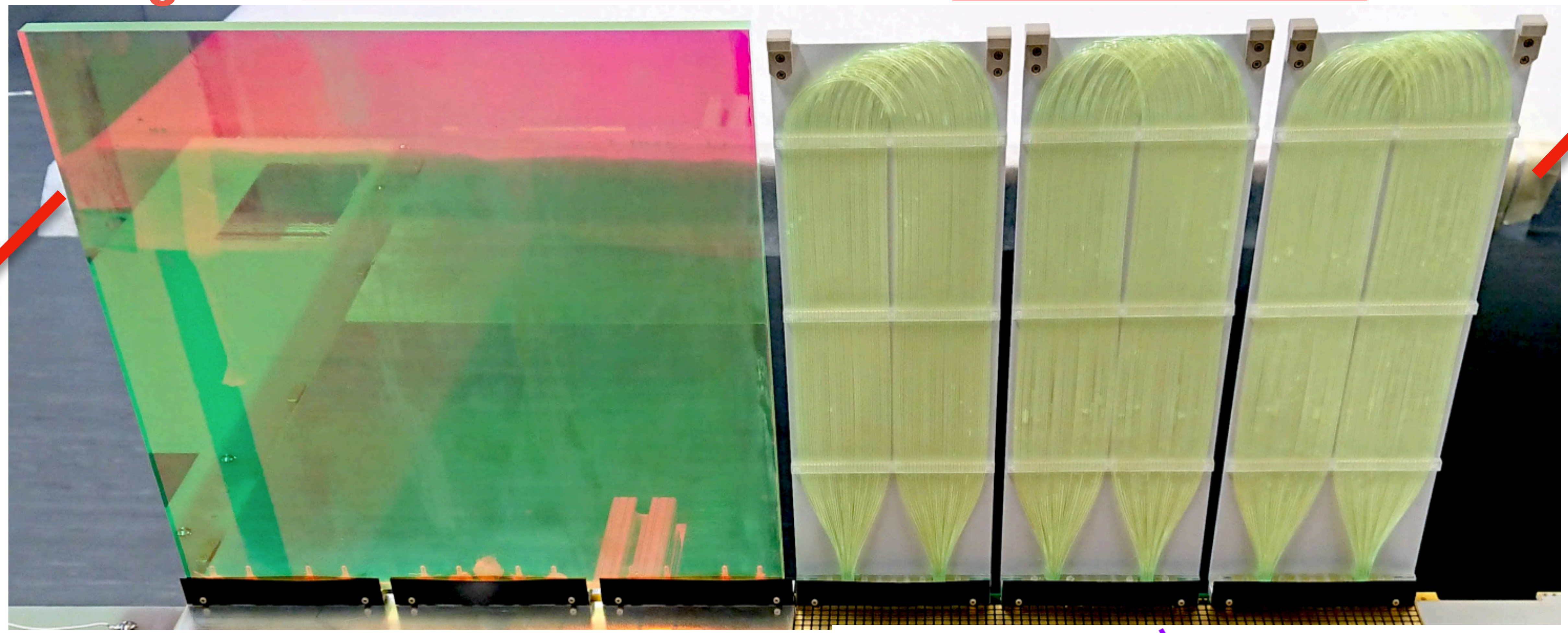
2x2 Photon Detectors

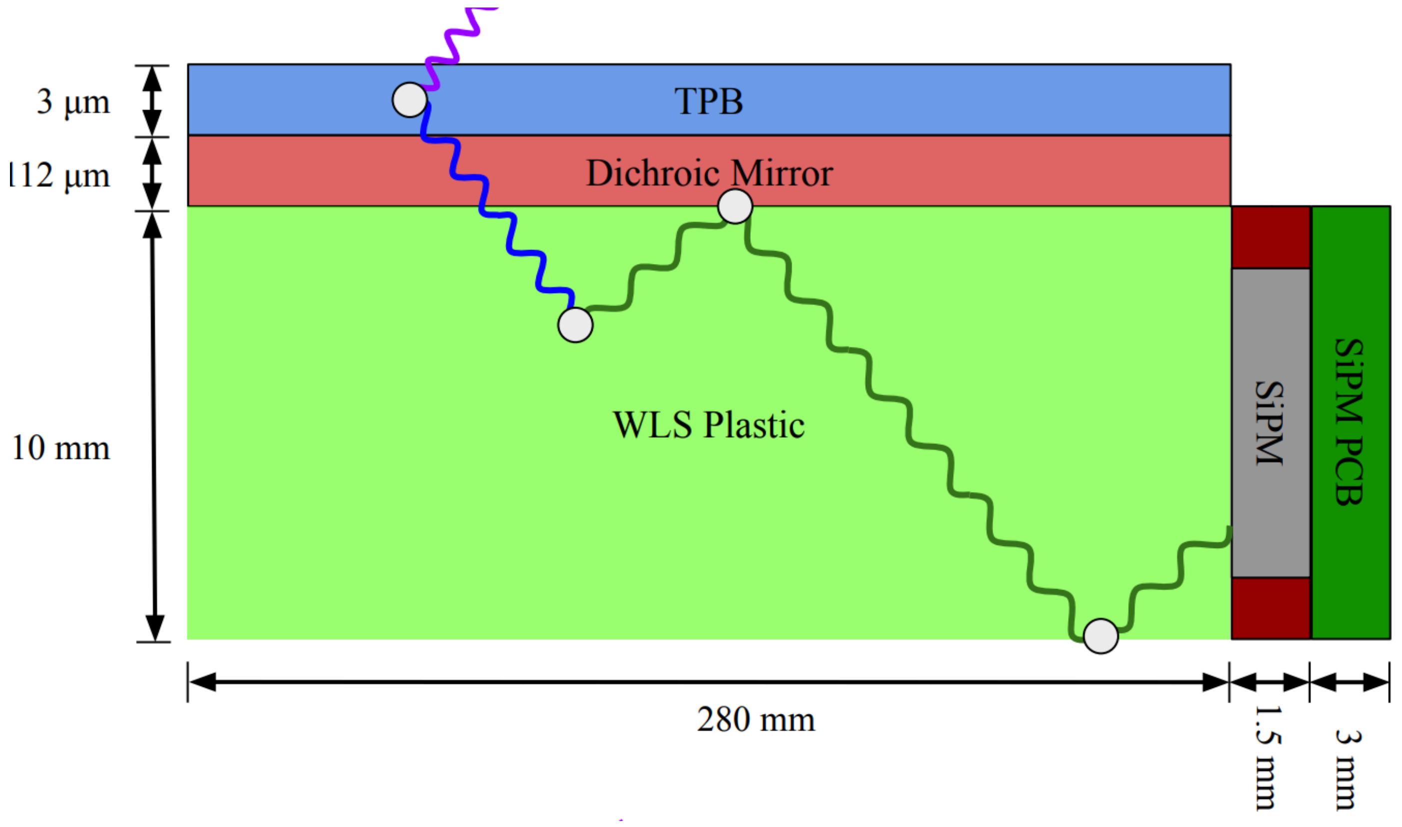
Two complementary photon detector technologies utilized for the 2x2 and ND-LAr

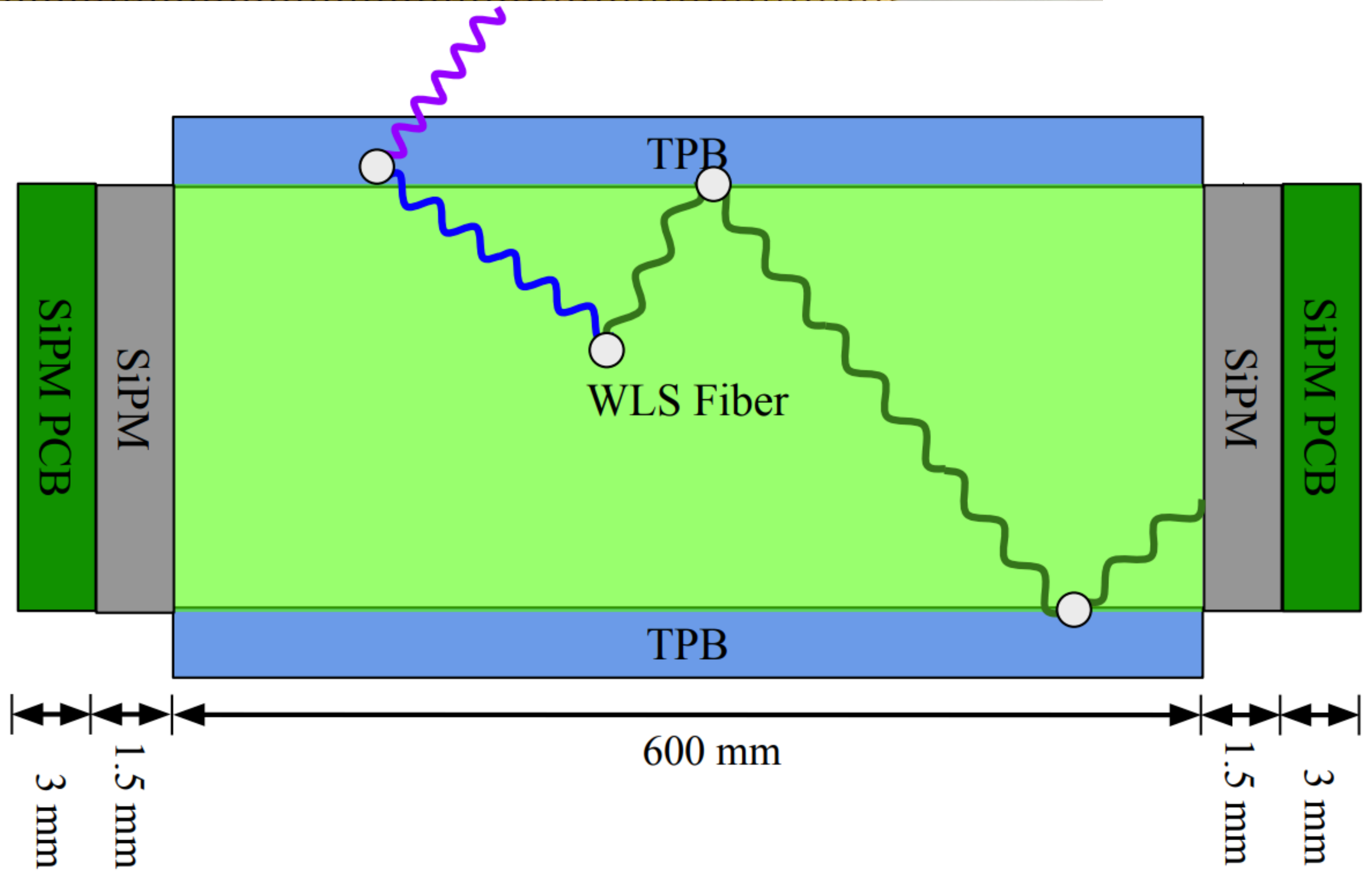
ArCLight - Instruments 2018 **LCM - JINST 15 C07022**

- Shifts scintillation light with TPB and bulk WLS
- Shifted light trapped and reflected by a dichroic mirror
- ~0.2% photon detection efficiency

- High position resolution





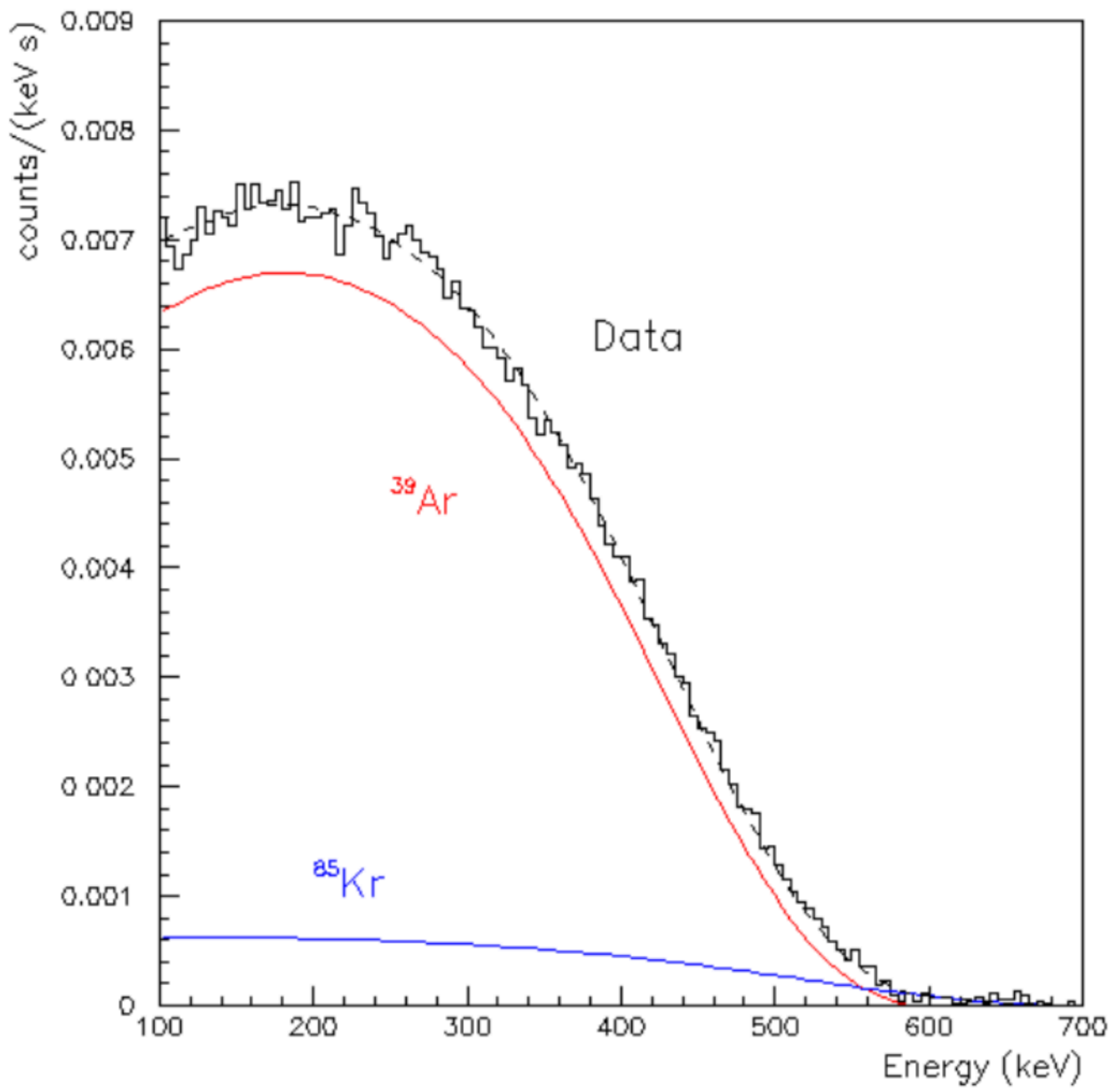


- Shifts scintillation light with TPB and WLS fiber
- Shifted light trapped via total internal reflection
- ~0.6% photon detection efficiency

- High light yield
- Good timing resolution

Low Energy Radioactivity in LAr

- Radioactive decays present in LAr
  - e.g. 39Ar, 85Kr
  - 39Ar rate is 1 Bq/kg: **~8.5M per hour in the 2x2**



Spectral contribution from 39Ar and 85Kr beta decays in the WARP LArTPC

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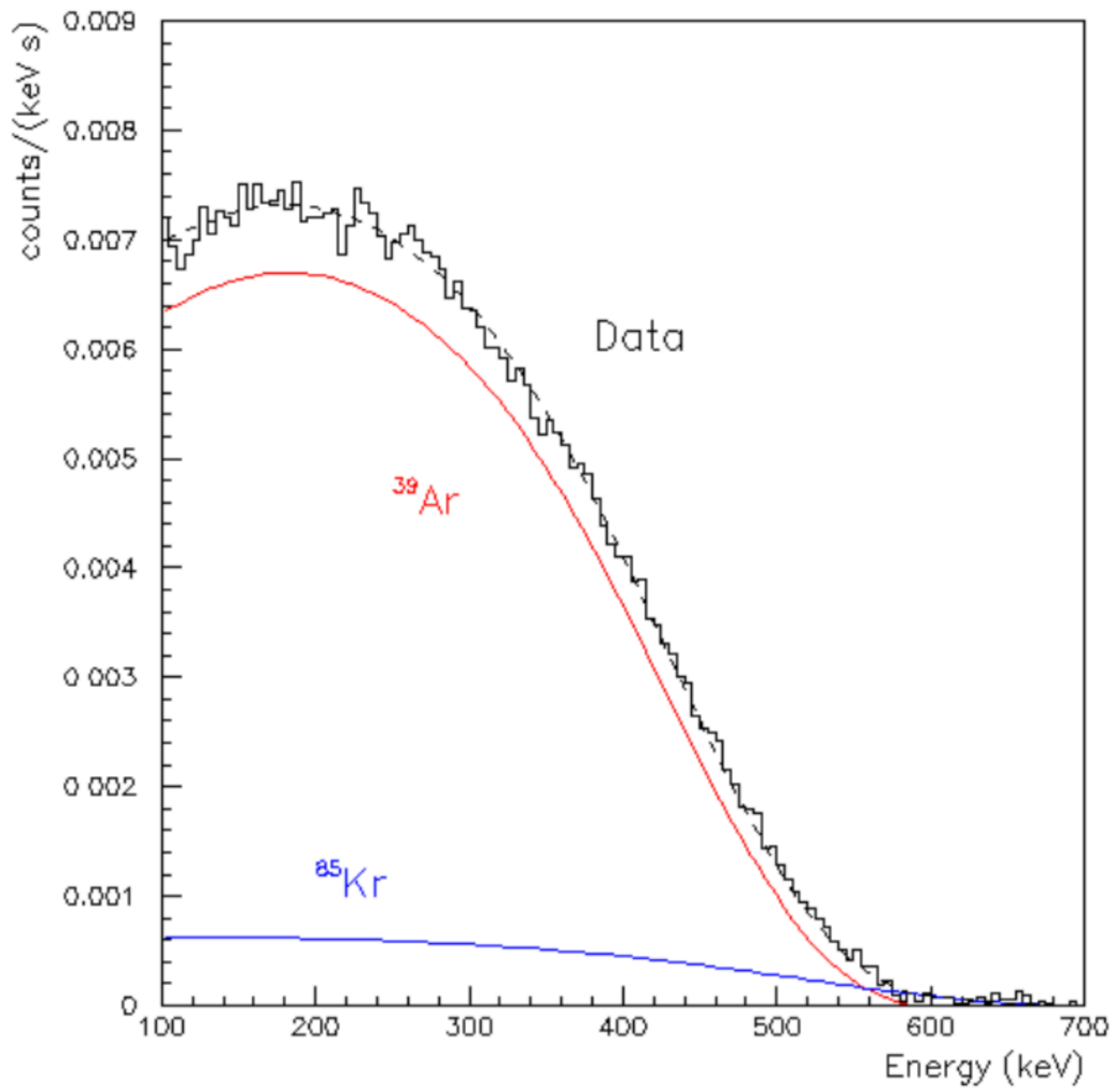
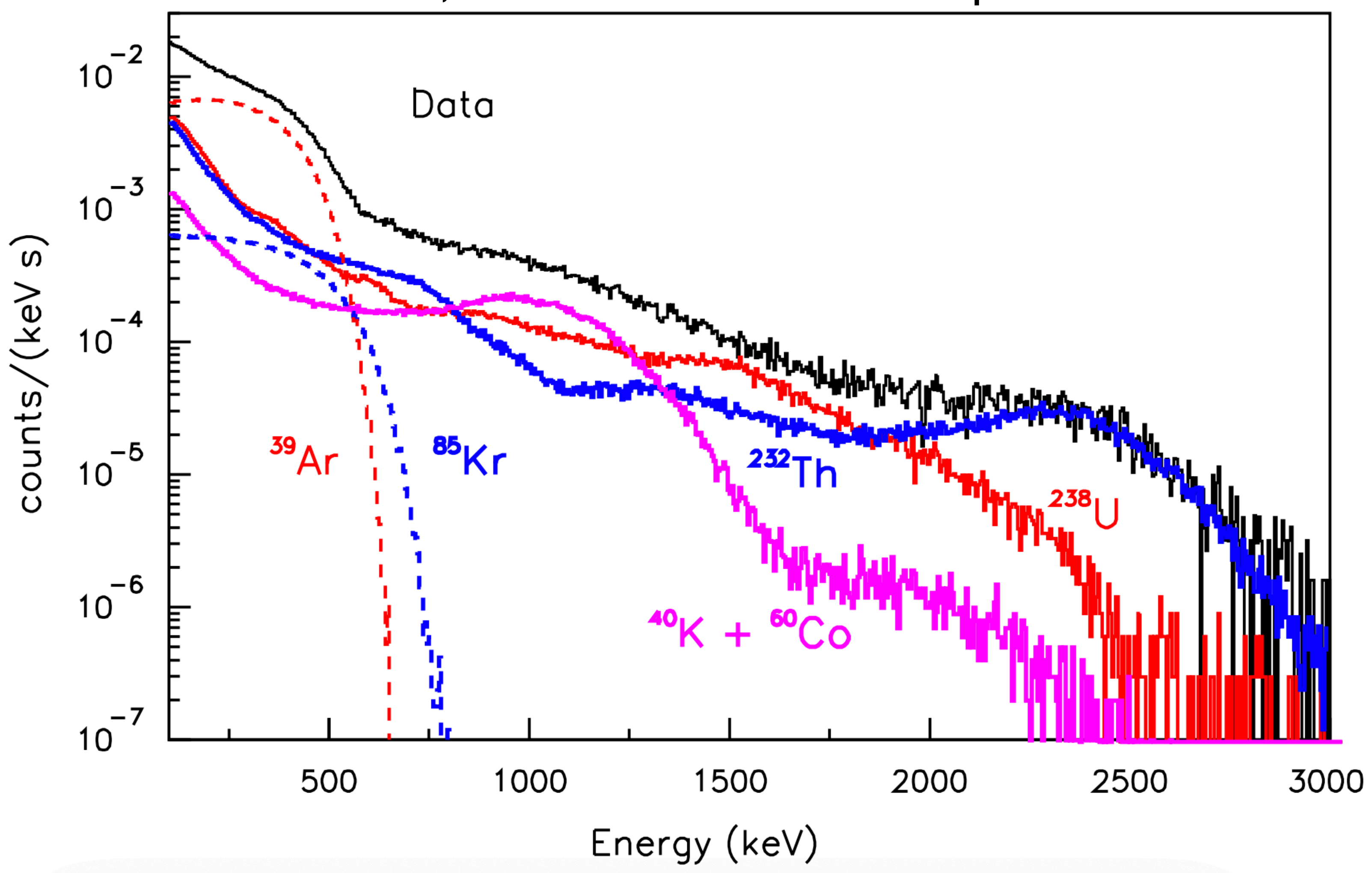


Spectral contribution from 39Ar and 85Kr beta decays in the WARP LArTPC

Benetti, et al. 2007 arXiv:astro-ph/0603131



Spectral contribution from external gamma rays in the WARP LArTPC

- Other radioactive decays potentially from detector materials
  - e.g. 40K, 60Co, 232Th and 238U decay chains
  - Beta, alpha, and gamma sources

Analysis Goals

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- Reconstruct the radiological background in the 2x2 LArTPC using **charge and light**
  - Reconstructing using light brings extra challenge
    - Low scintillation light produced in the decay interactions in LAr
    - Detection efficiency highly dependent on light readout thresholds

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- Use the reconstruction and analysis to calibrate the 2x2, demonstrating the potential for calibrating ND-LAr the same way
- Demonstrate how effective the ND-LAr technology is at detecting low energy activity with charge and light → **relevant for higher energy activity, such as supernova neutrinos**

Applications to Detector Calibrations

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- Can be used to calibrate the detector:
  - When the neutrino beam is **off**
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- Light yield measurement as a function of position in the detector
  - More straightforward to use **point-like topologies**, instead of line-like topologies (e.g. from cosmic rays, rock muons)
- Electron lifetime measurement
  - Alternative to using cosmic rays, which are not common underground, or rock muons, which are not always available (unlike low energy decays)

Data Readout Summary

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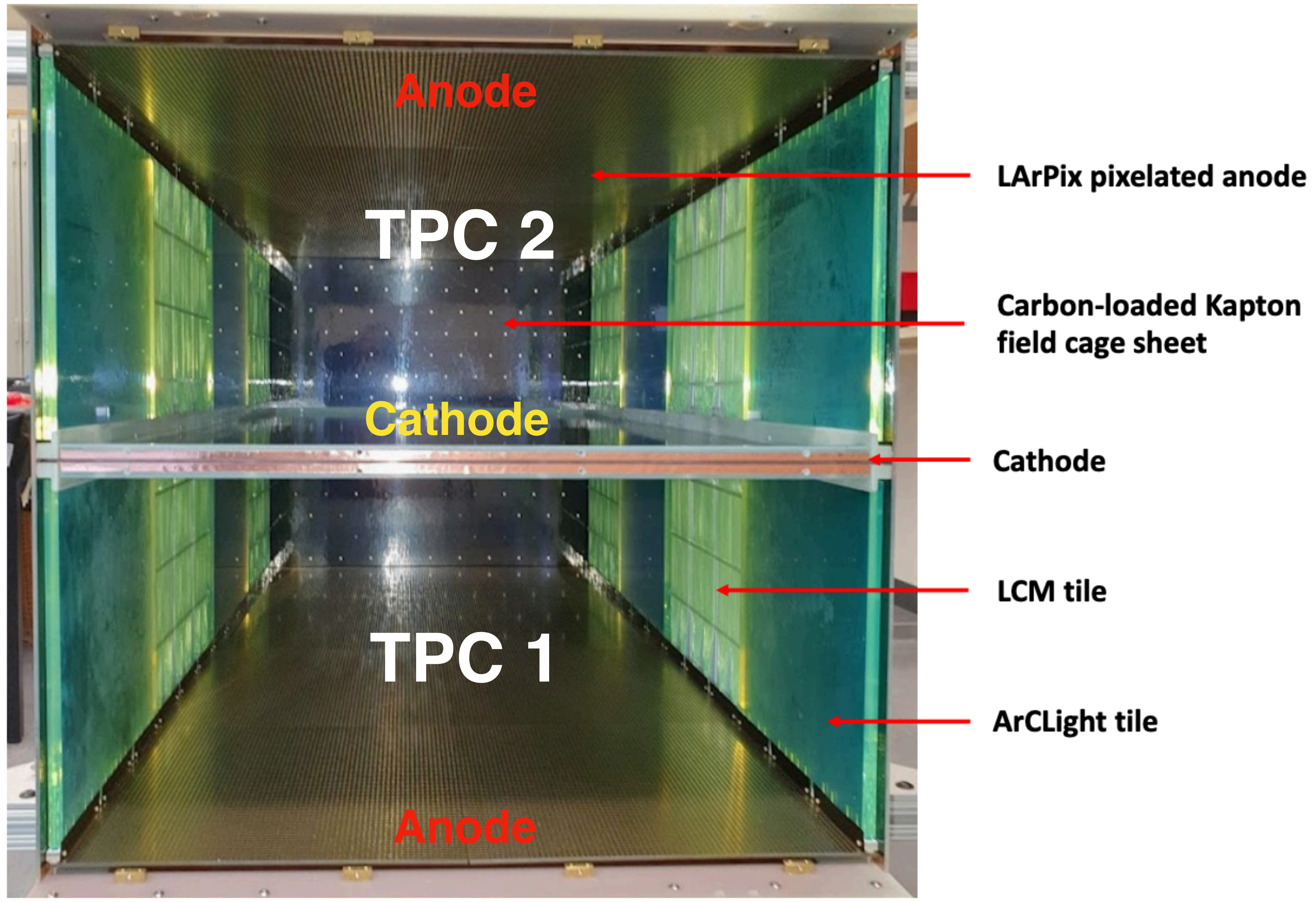
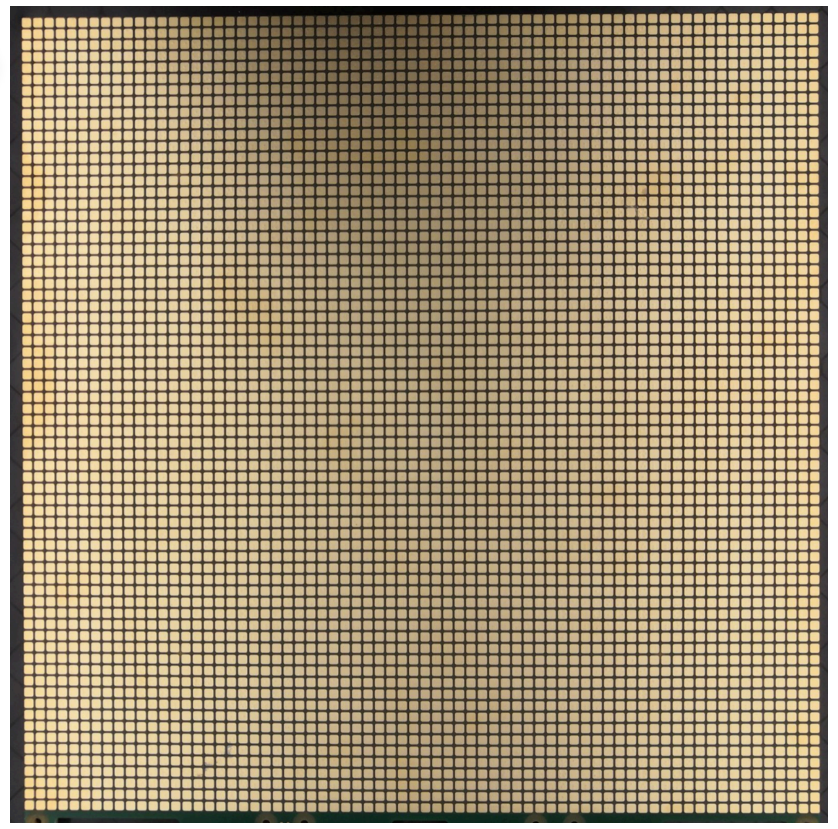


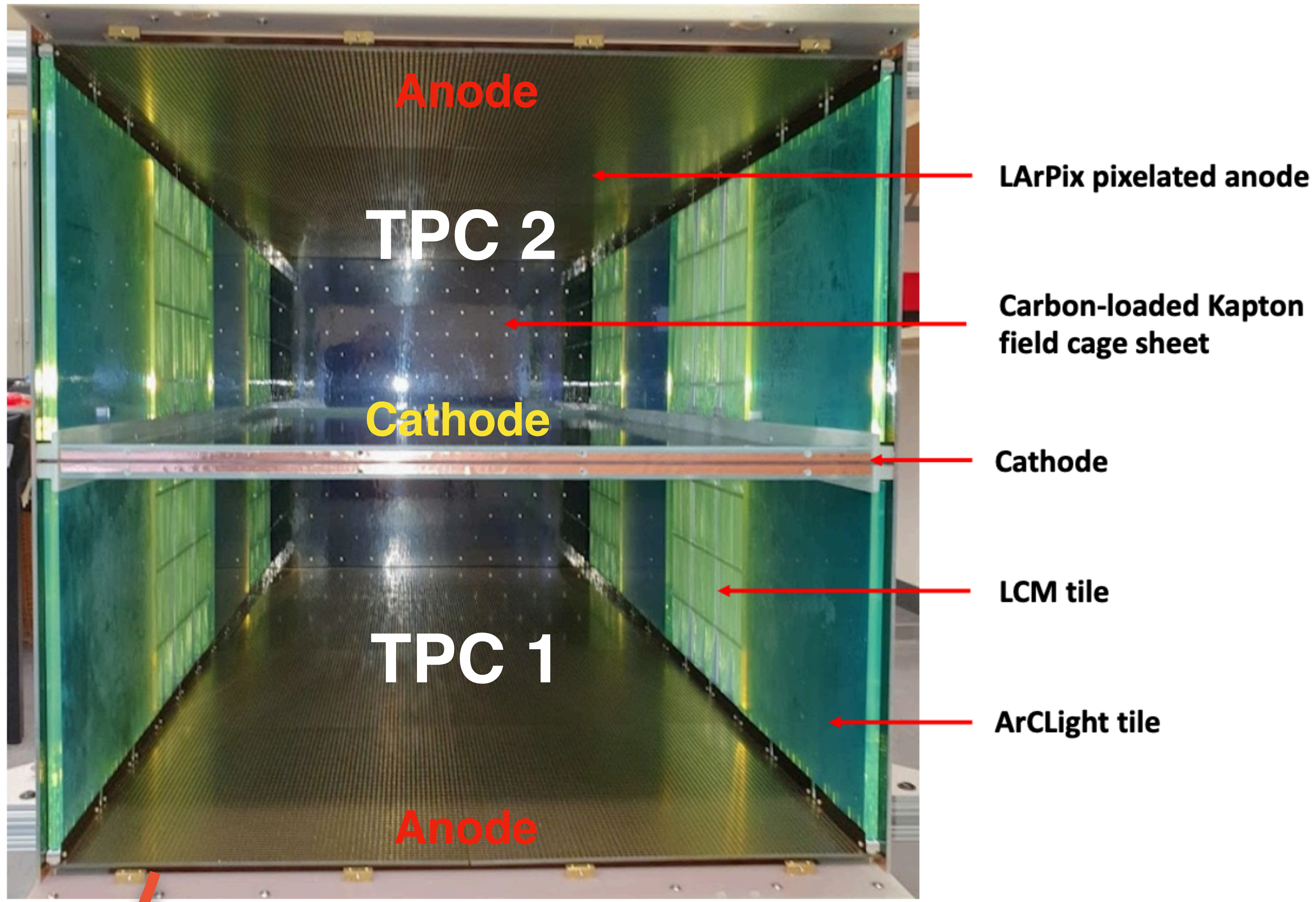
Data Readout Summary

Individually self-triggered pixels detect drifted charge ($\lesssim$4mm pixel pitch)

LArPix: JINST 13 P10007



Pixel array



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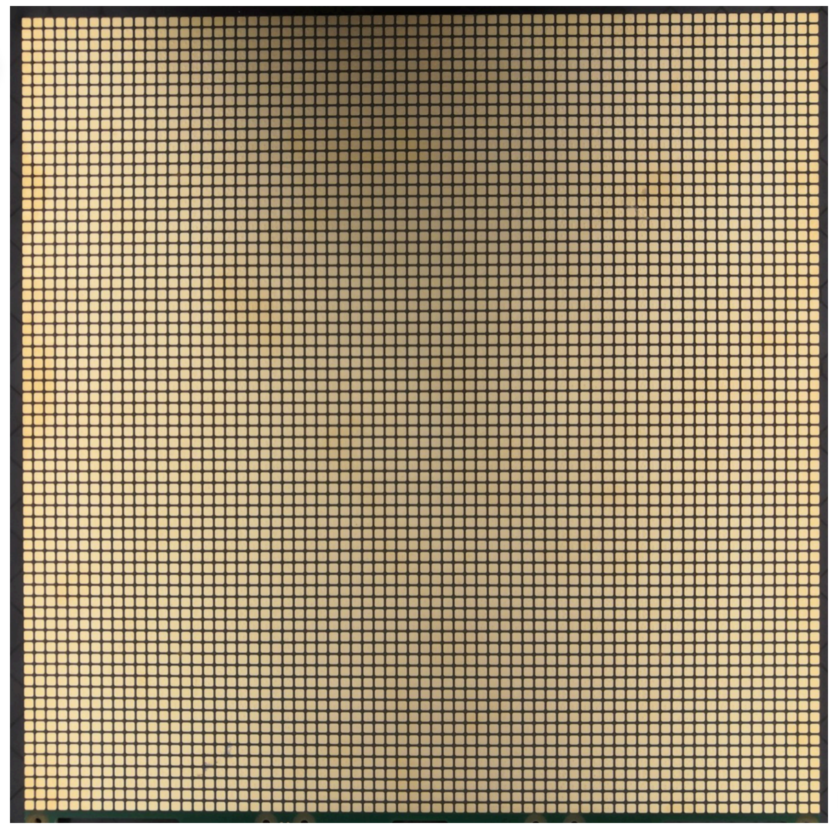

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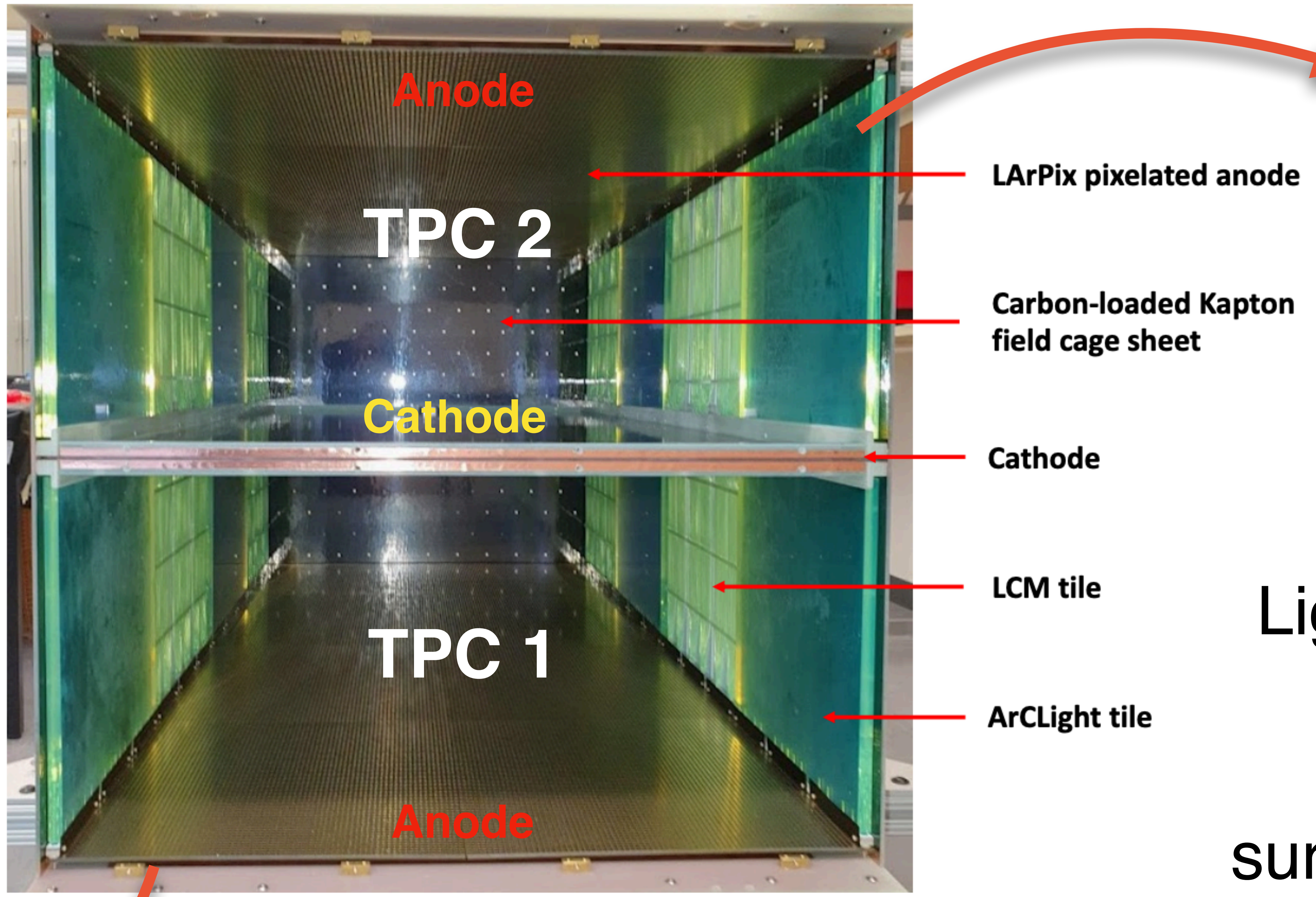

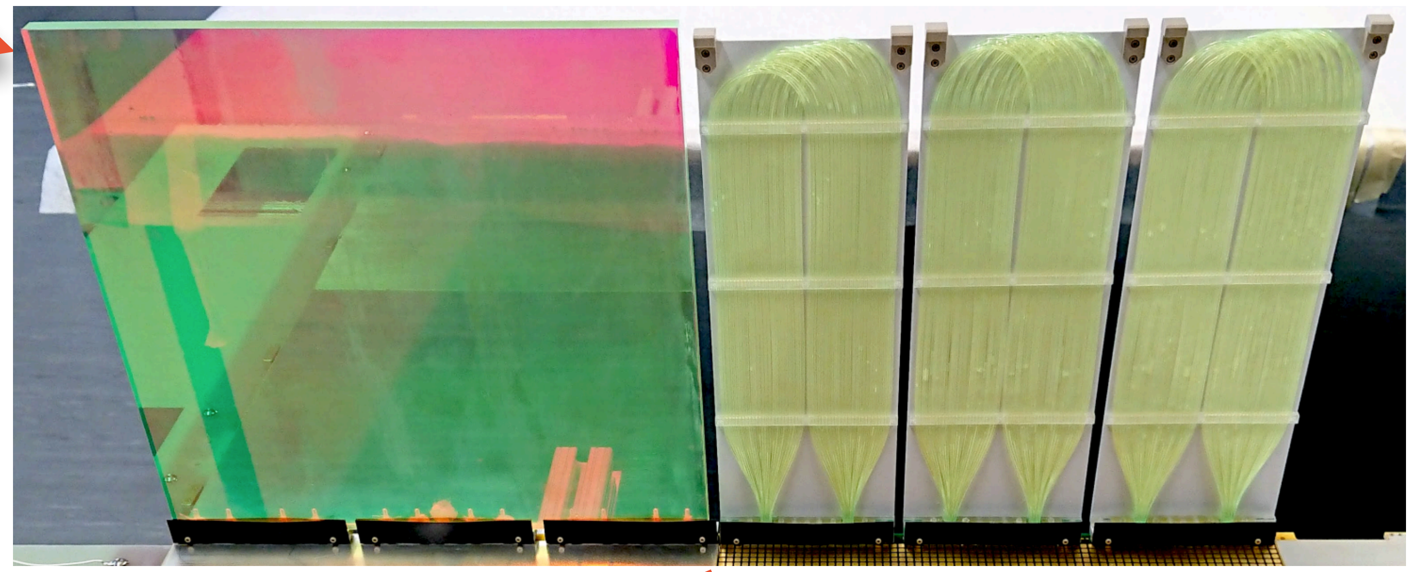

Light detectors digitized when a waveform from 1 ArCLight or 3 LCMs surpasses a self-trigger threshold (Or digitized when a beam signal is received)

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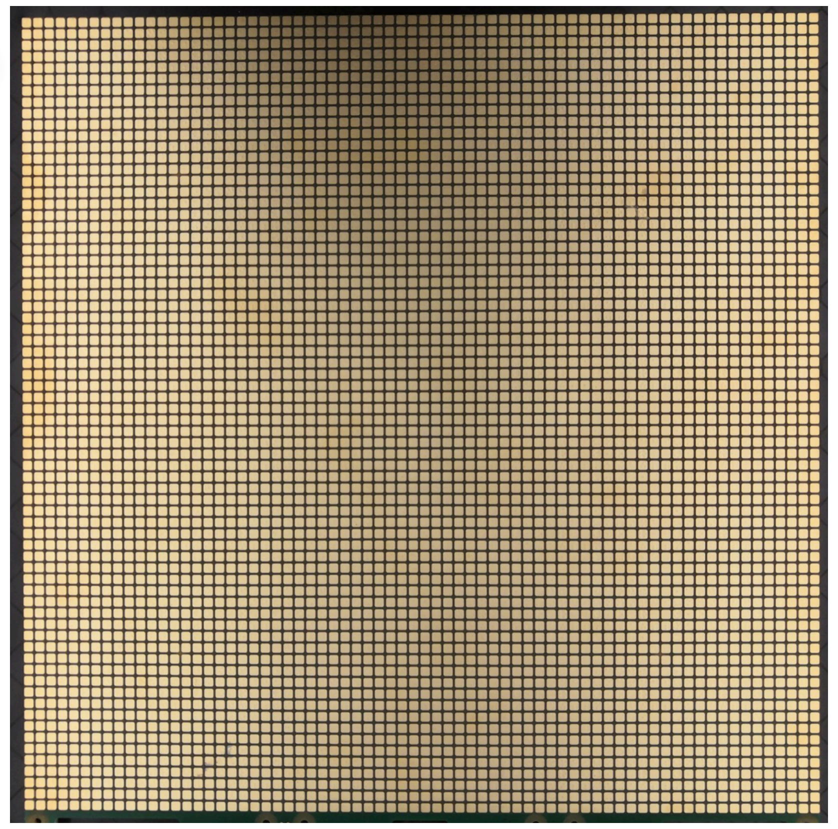

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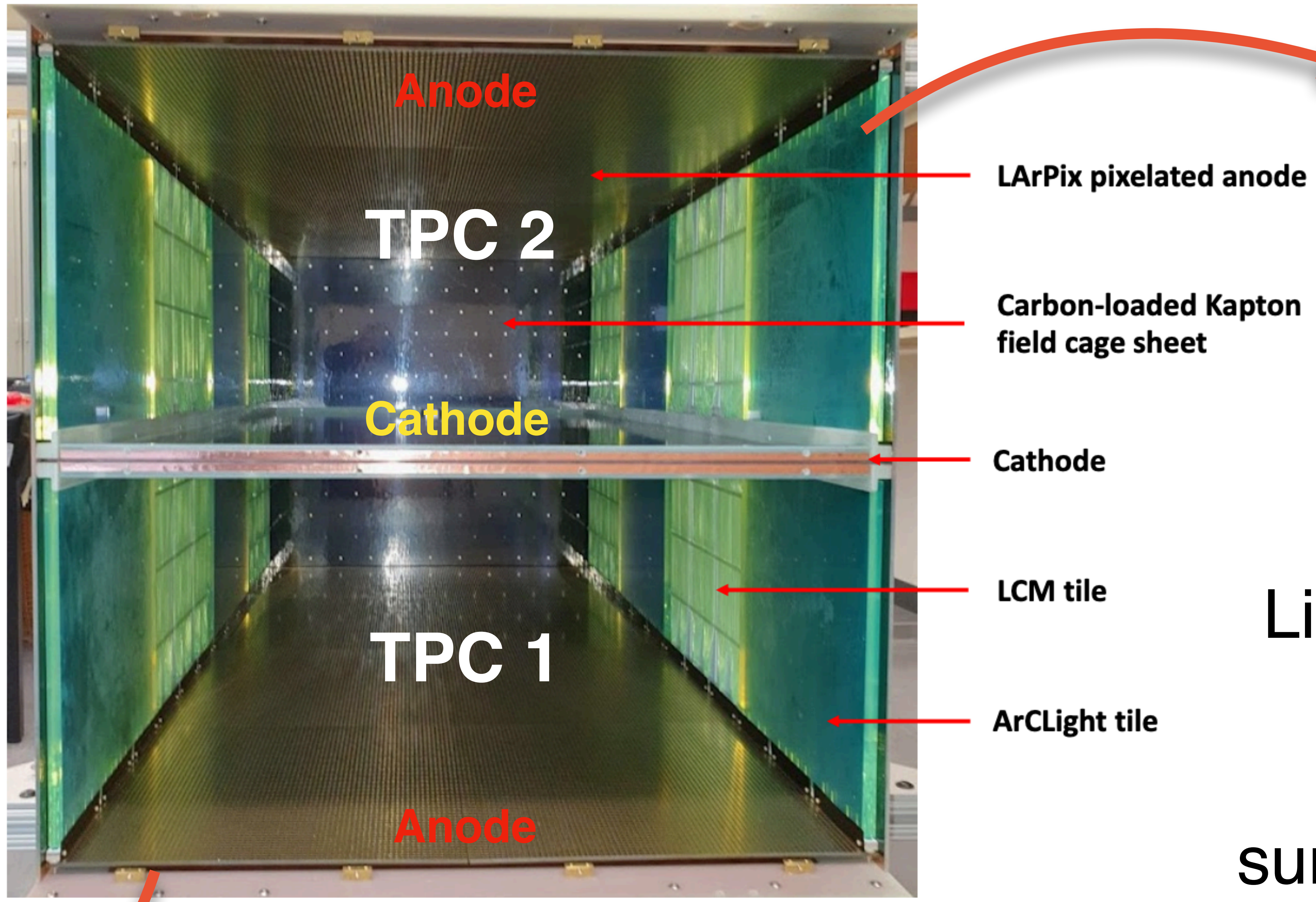
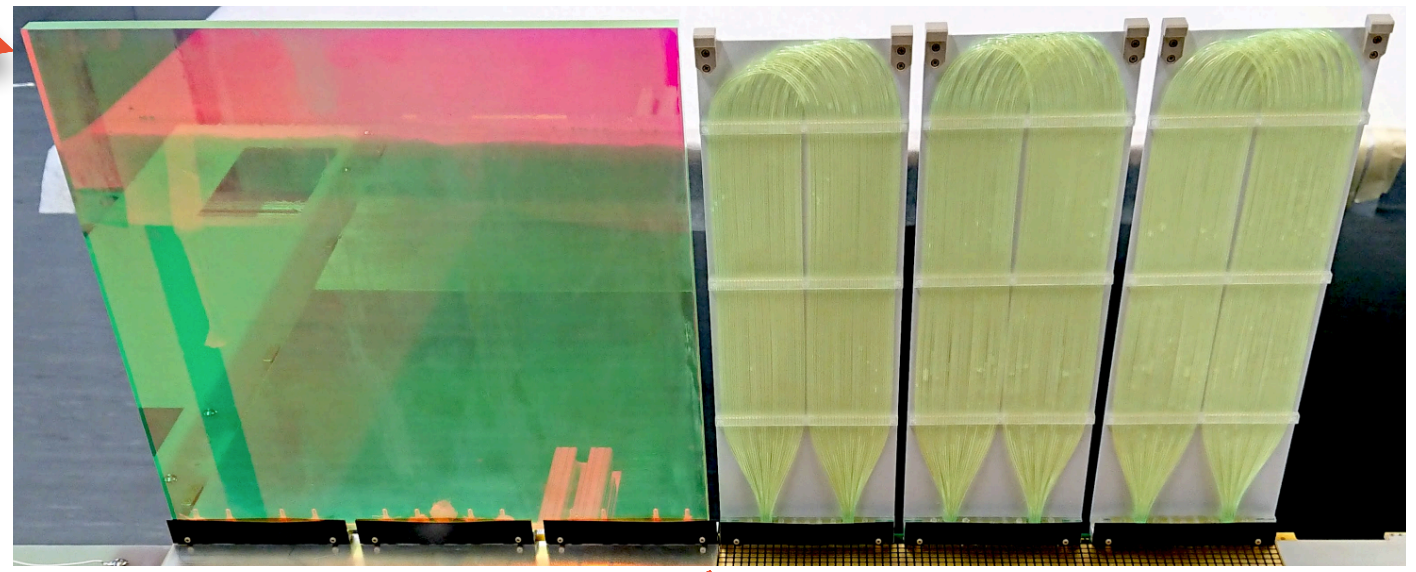




Light detectors digitized when a waveform from 1 ArCLight or 3 LCMs surpasses a self-trigger threshold (Or digitized when a beam signal is received)

Charge and light data synchronized offline using timestamps

Reconstruction Summary

The reconstruction process is relatively straightforward:

Step 1: Cluster charge packets in time and space (DBSCAN)

Step 2: Group charge clusters around light readout triggers in time using a time window of -150 μs to ~189 μs^* + 150 μs

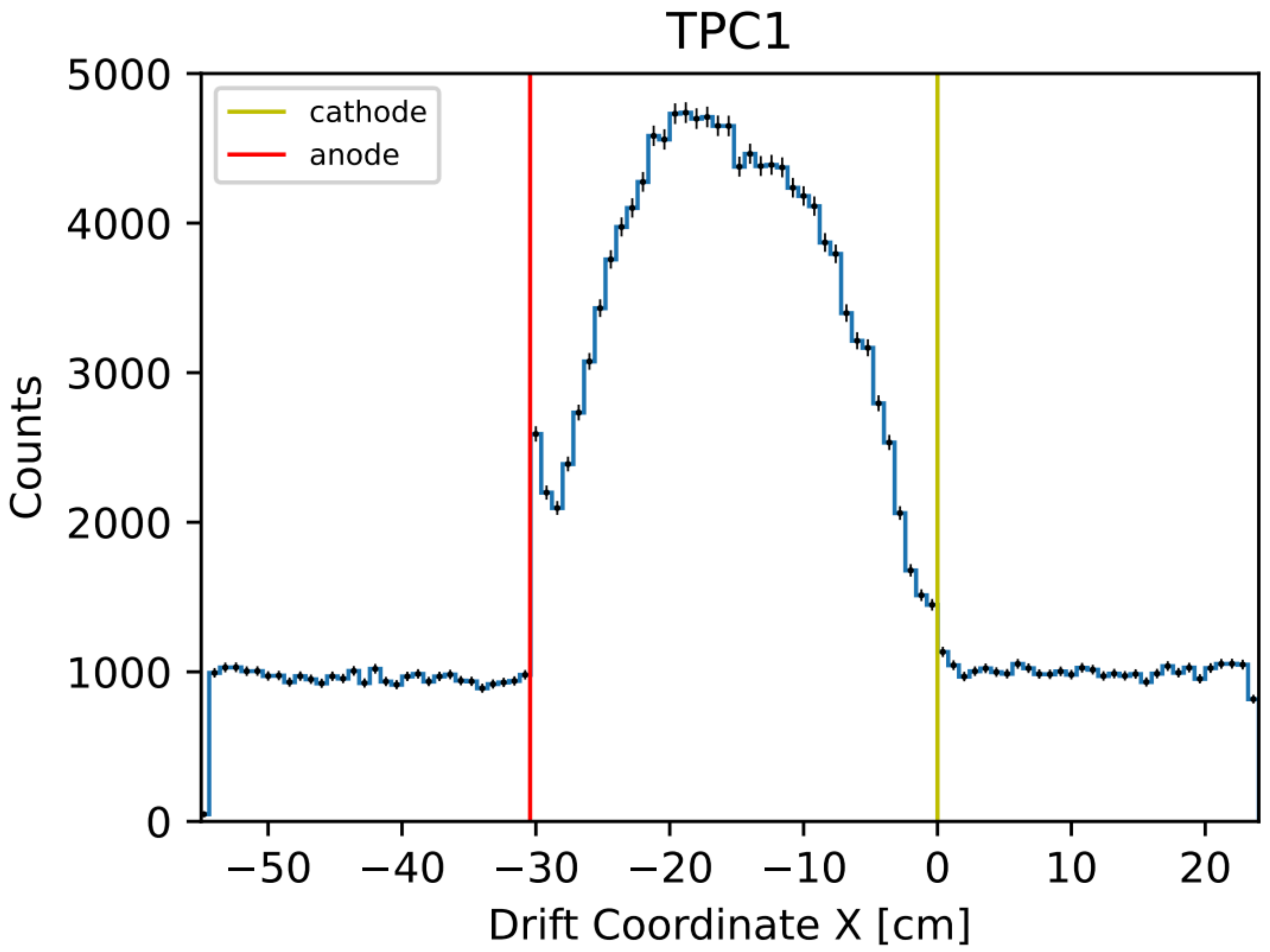
Step 3: Using the time difference between matched charge and light, calculate drift coordinate and interaction time for charge clusters (assuming a constant drift velocity)

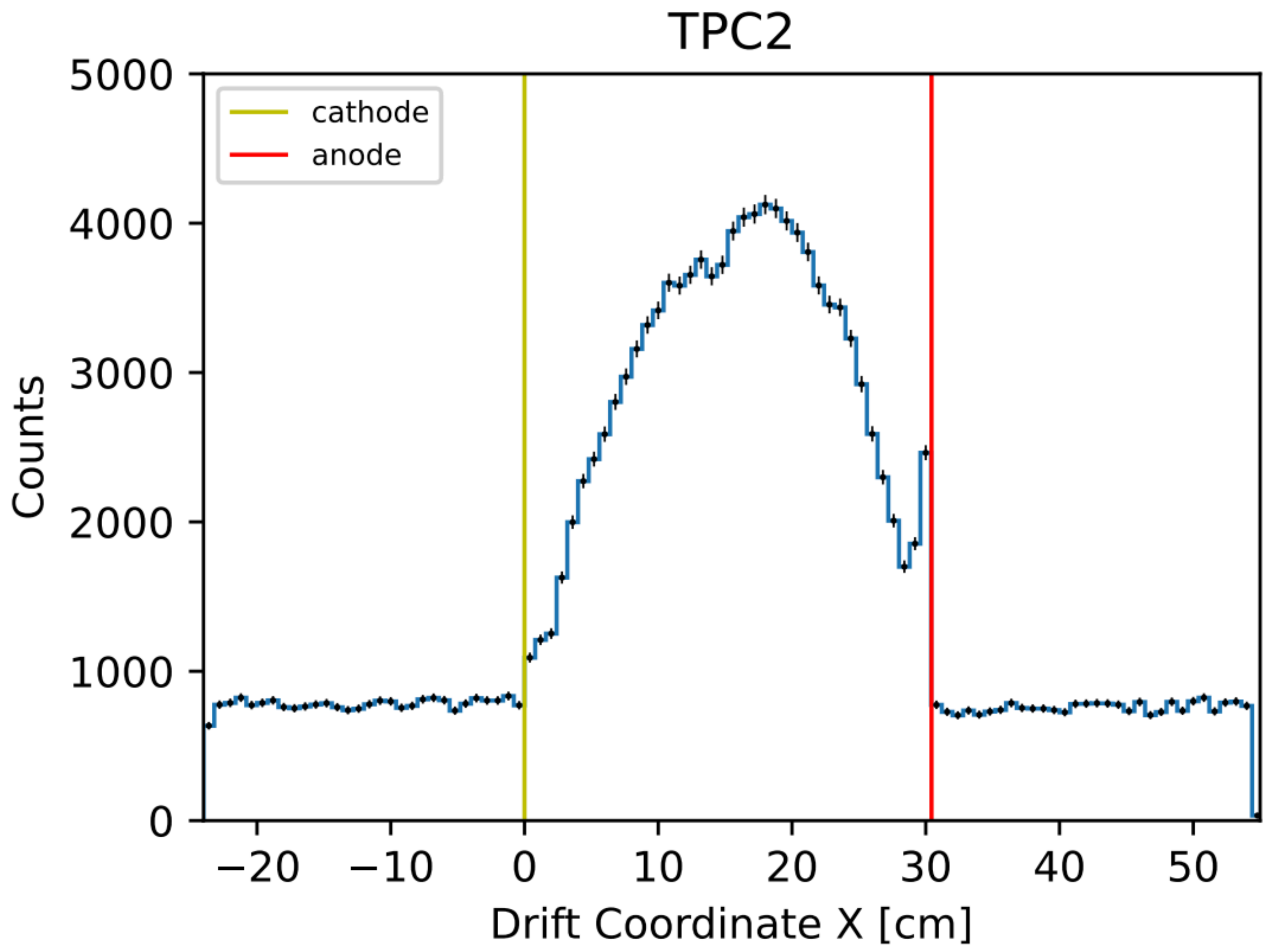
Step 4: Apply cuts to improve selection purity

* total drift time in the 2x2

Reconstructed Drift Coordinate Example

Note on plot: Module-0 from Univ. of Bern test at the surface





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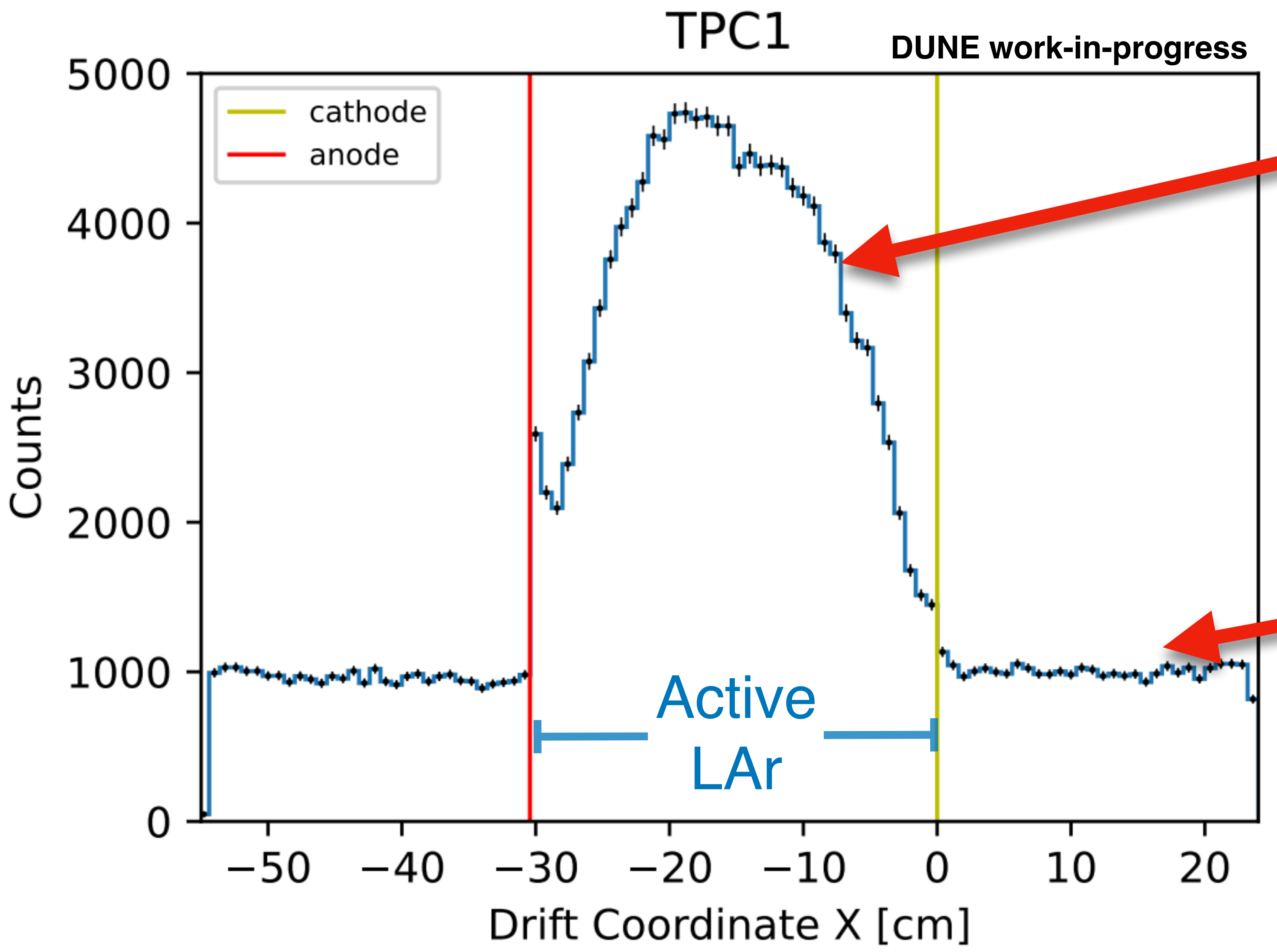
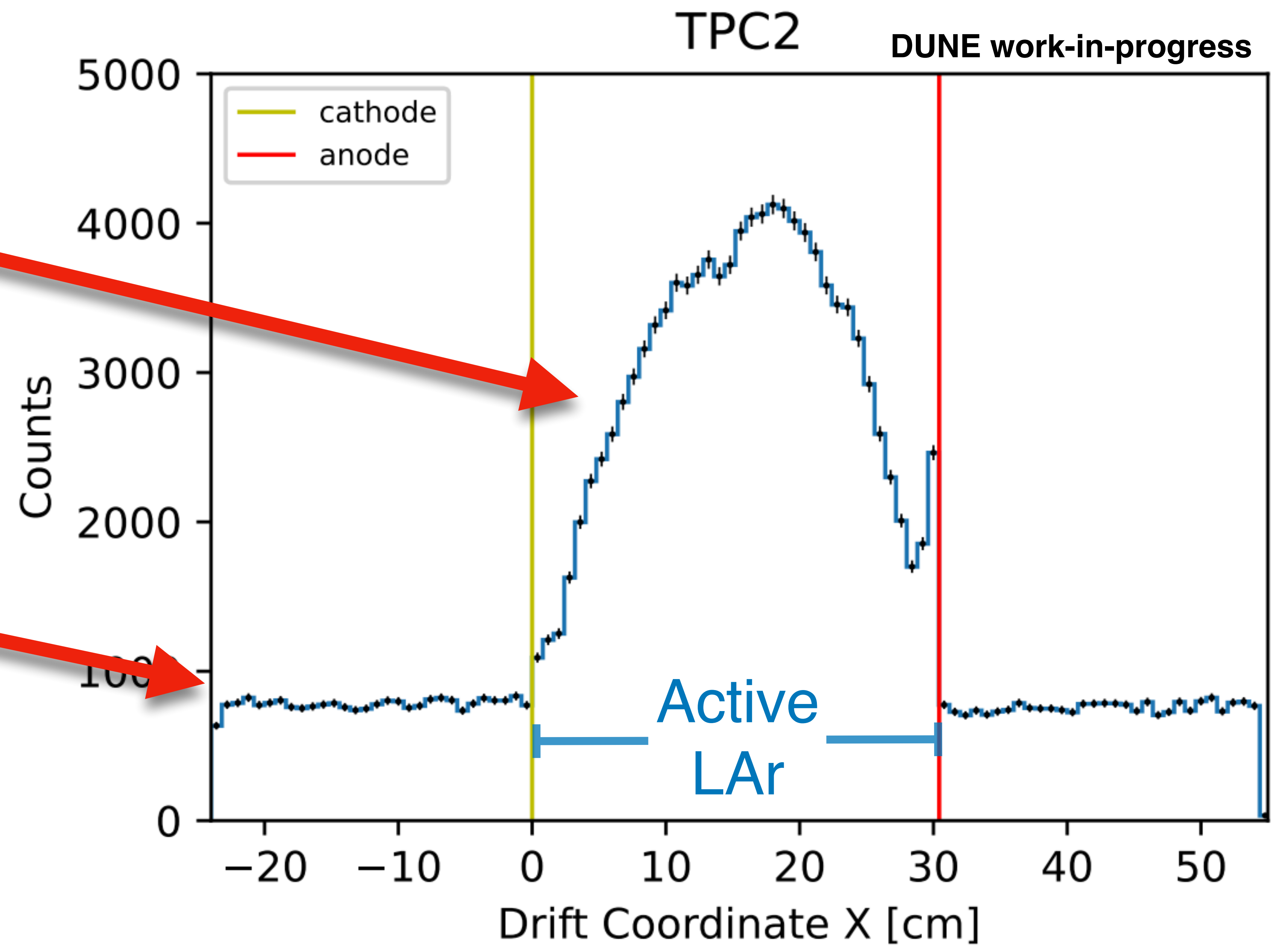


Excess of clusters reconstructed in active region → **corresponding to correctly associated charge and light**

Flat regions outside active region → **correspond to random matching of charge and light**



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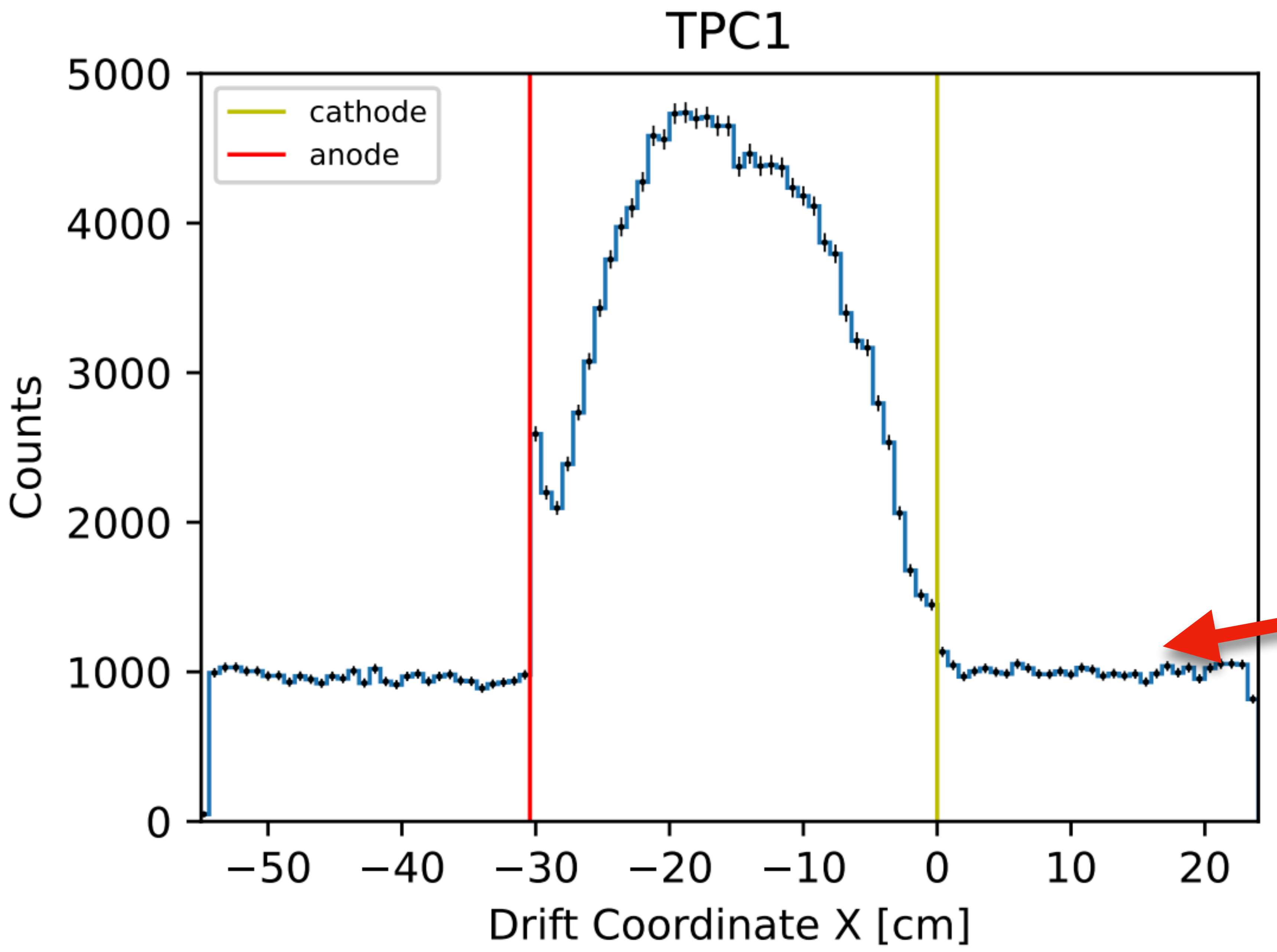
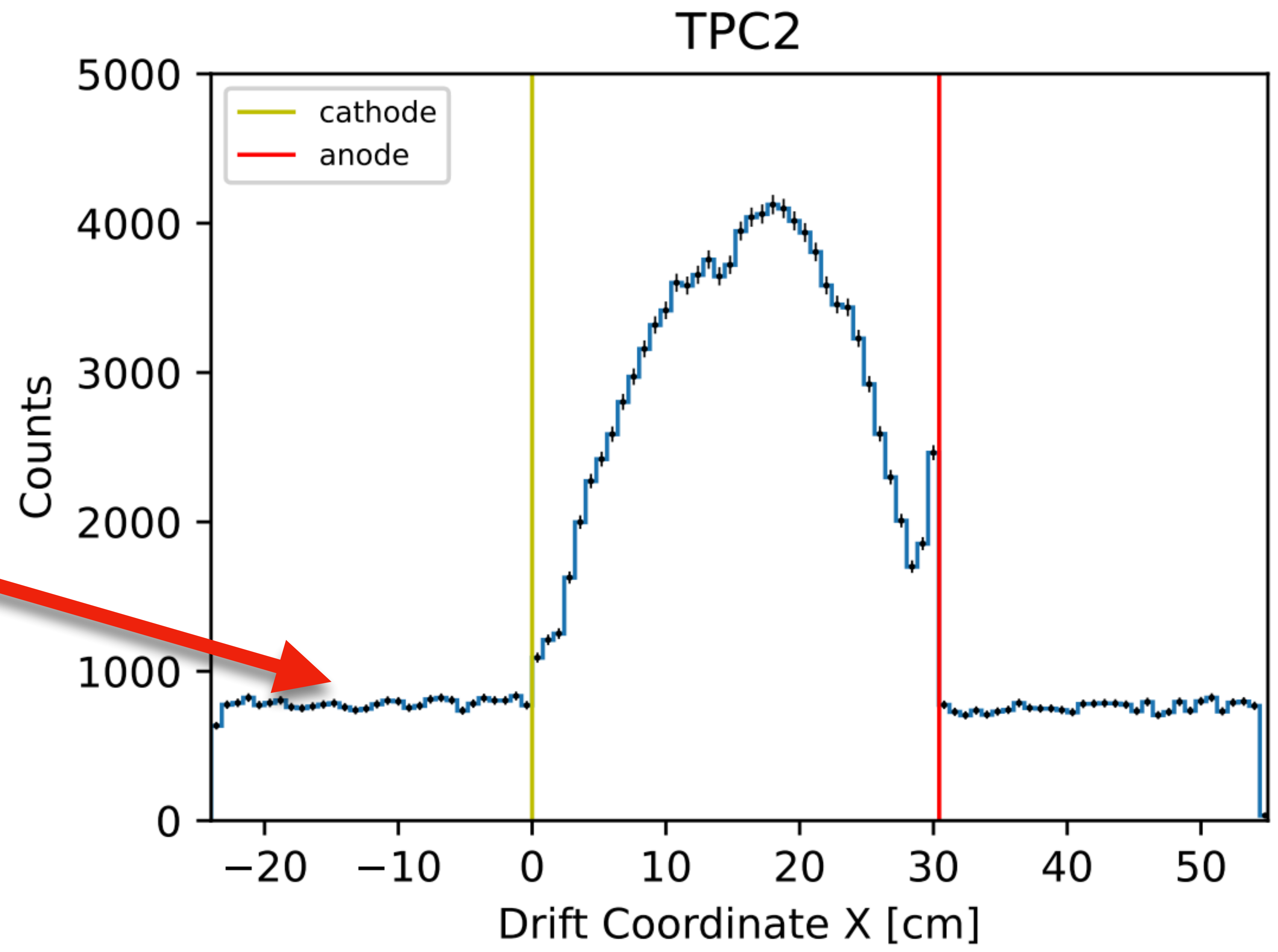


The extended window allows us to estimate purity using the flat sidebands



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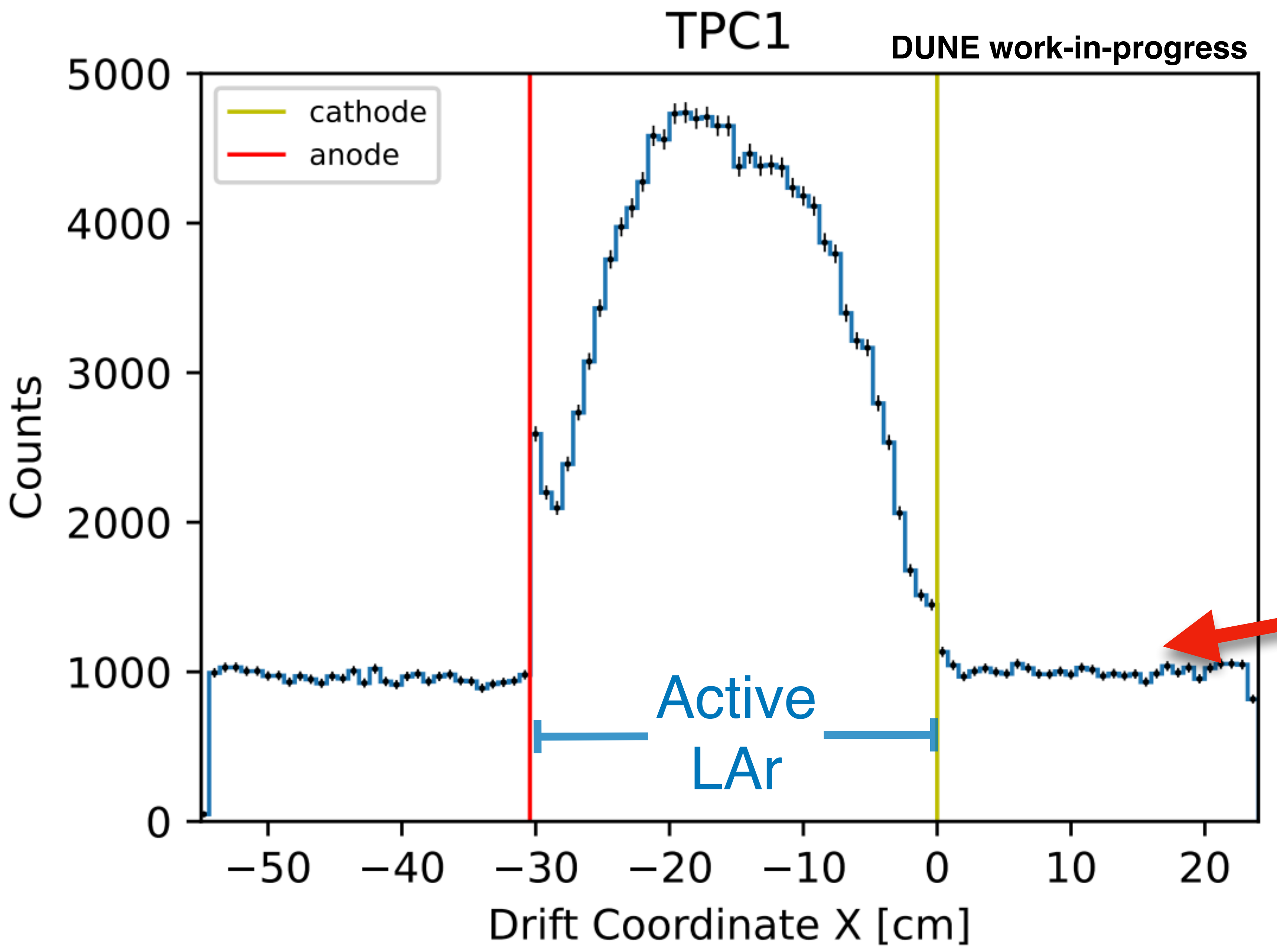

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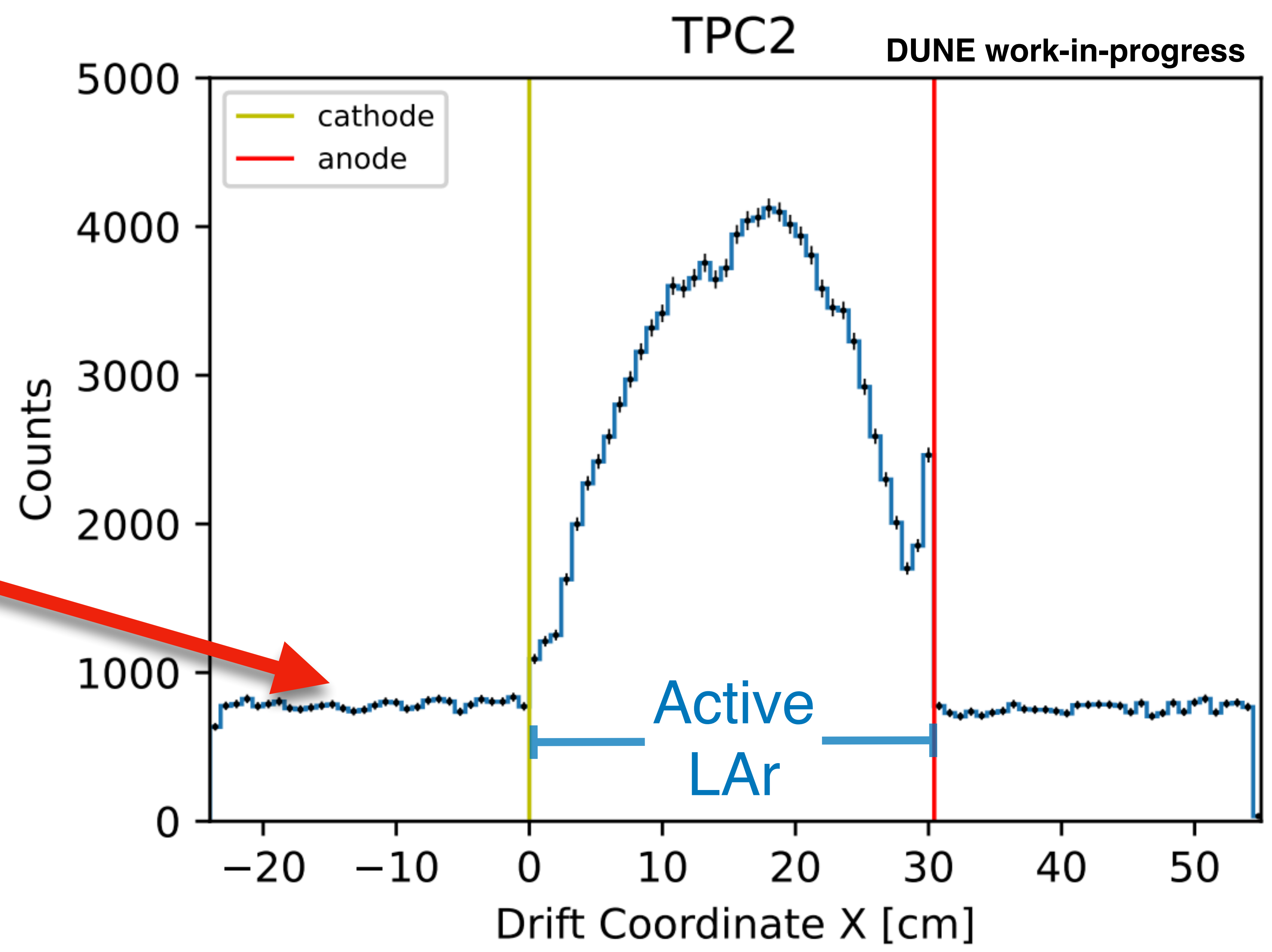


Sample Purity Estimation

- Integrate portion of sideband and scale it to the size of active LAr region, i.e.:

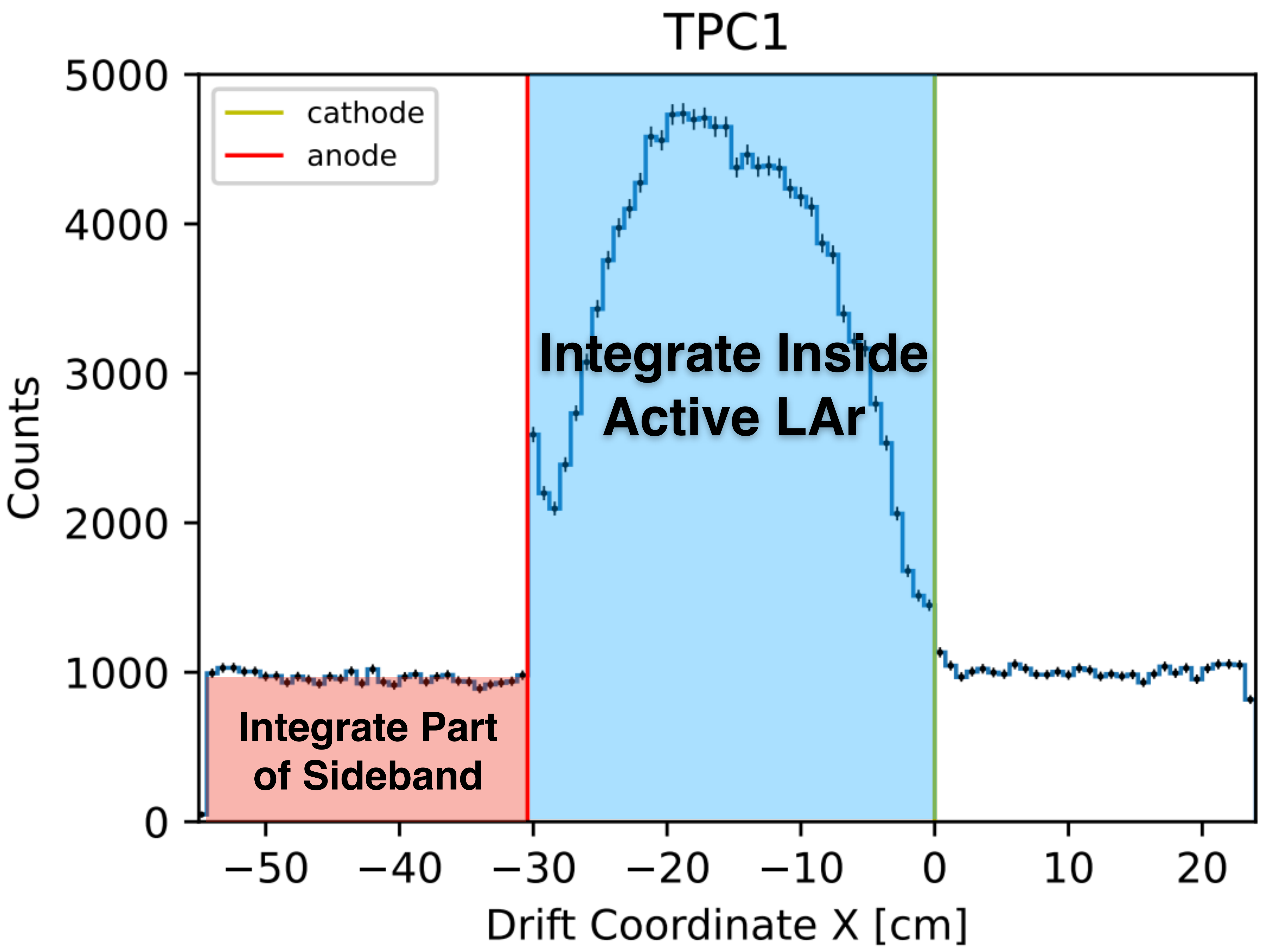
$$B = (\text{integral of sideband}) \times \frac{\text{size of active LAr volume}}{\text{size of sideband selection}}$$

Estimated number of incorrect charge-light matches in active LAr region

- Integrate inside active LAr and subtract B, i.e.:

$$S = (\text{integral of active LAr region}) - B$$

Estimated number of correct charge-light matches in active LAr region

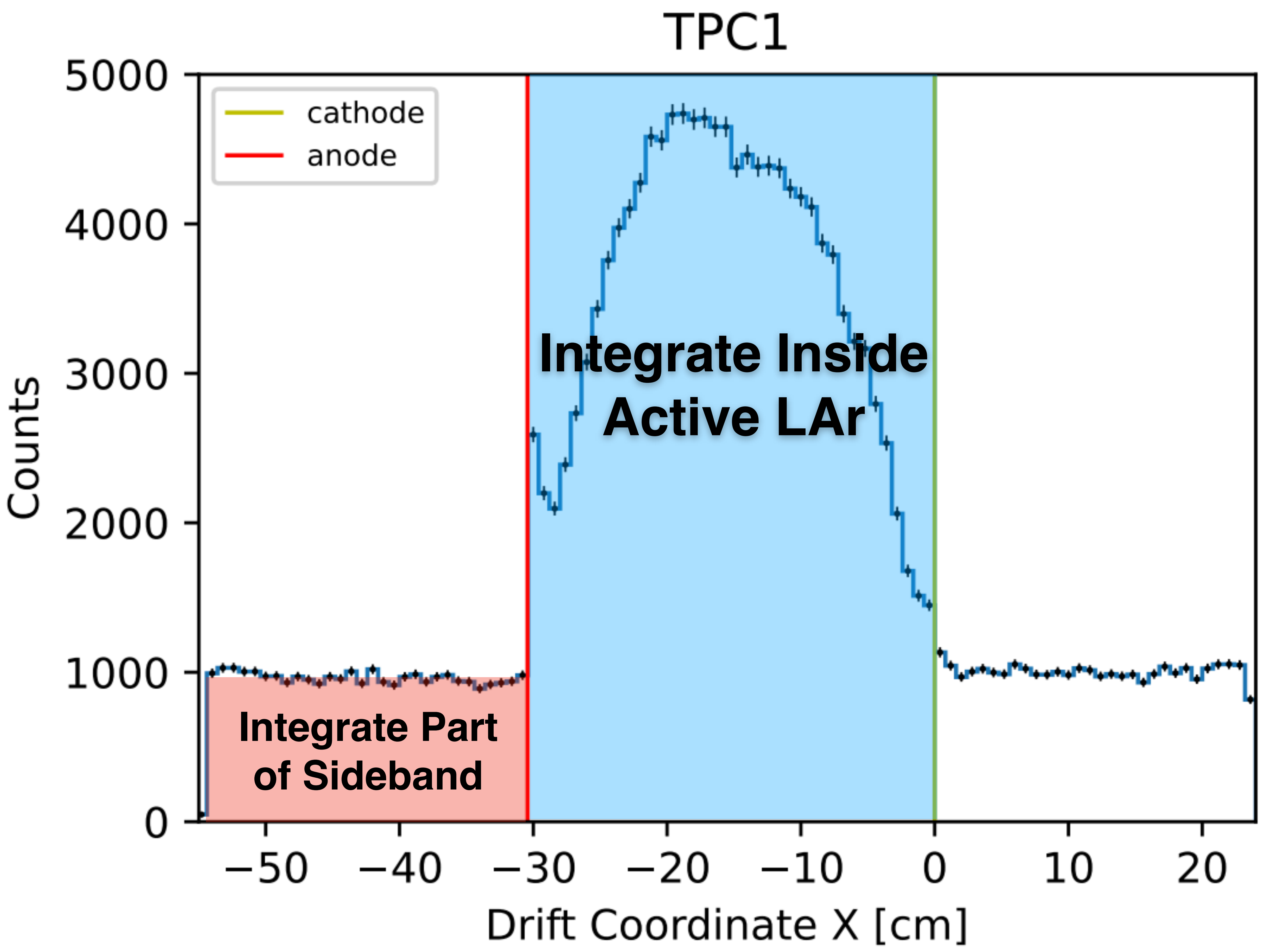


Sample Purity Estimation

- Then purity is calculated simply as:

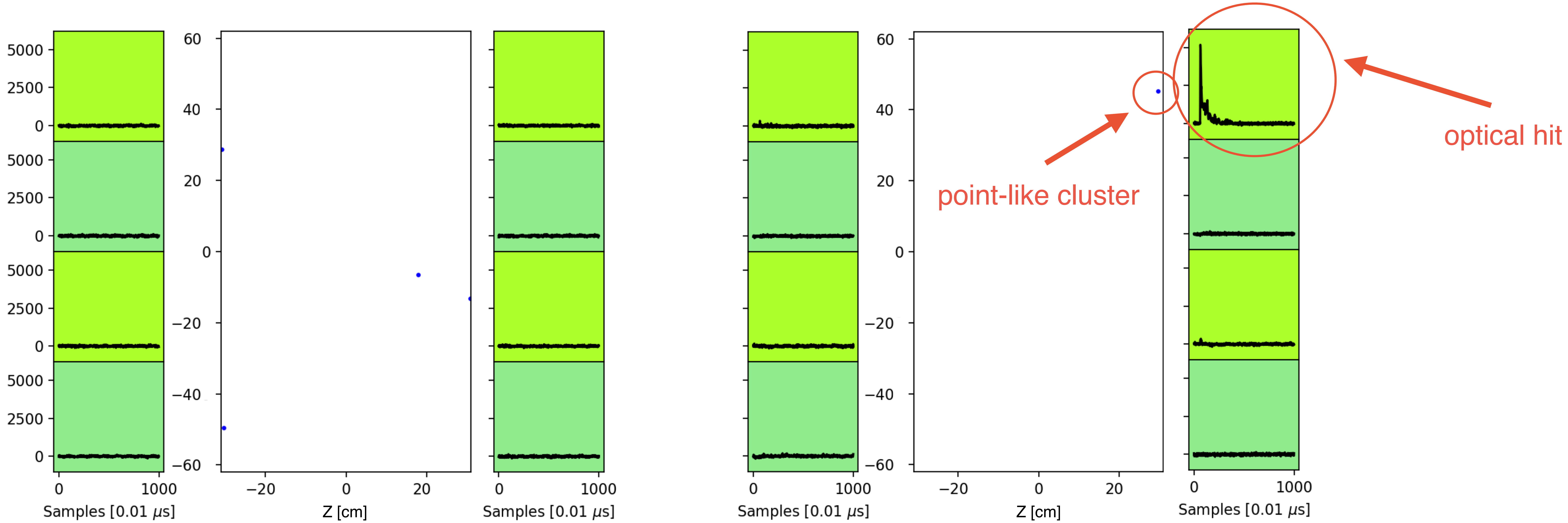
$$\text{Purity} = \frac{S}{S + B}$$

- Now we have a **data-driven handle** on how often we correctly match charge to light
- This can inform us about how effective data cuts are at improving the sample purity



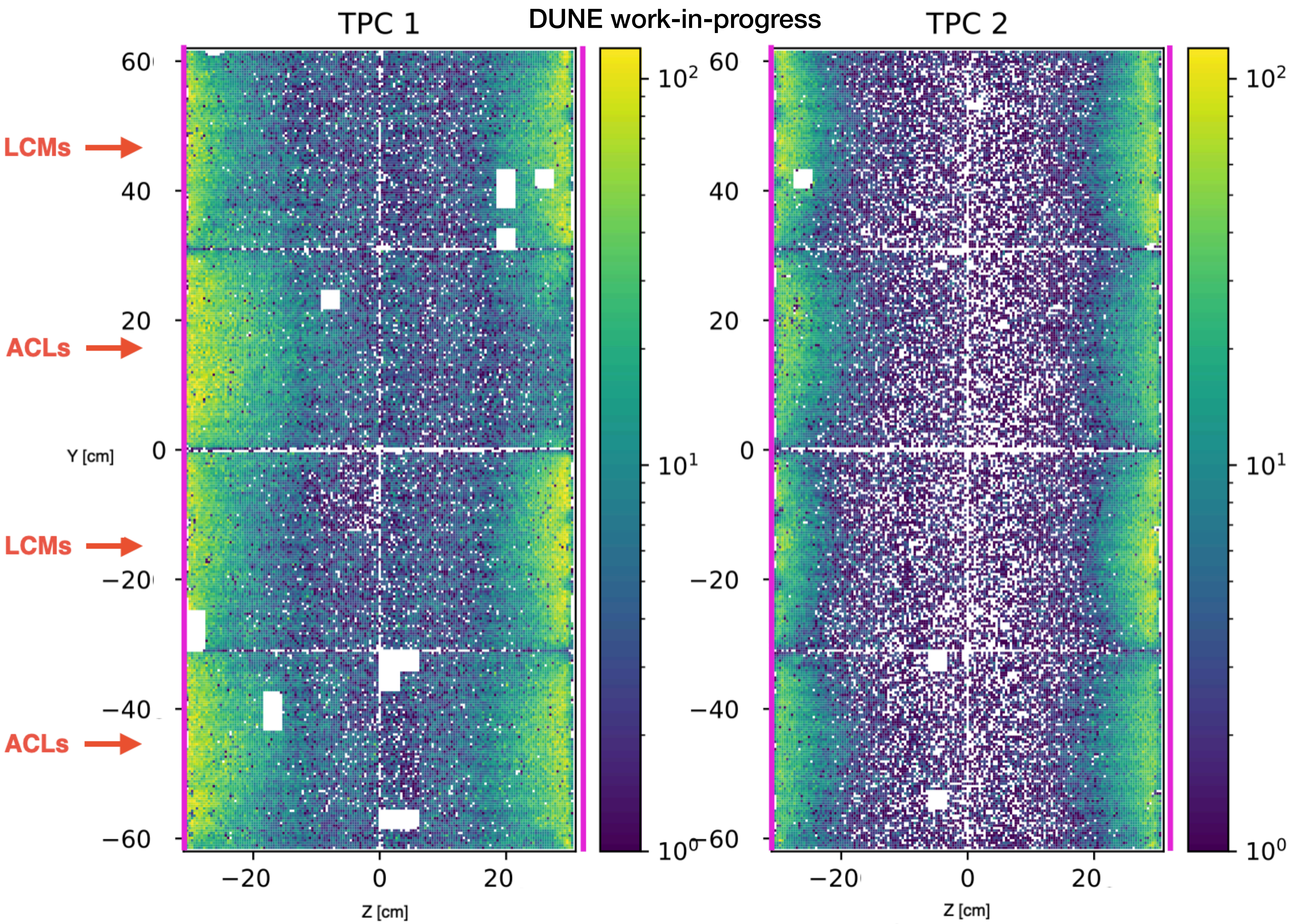
Optical Proximity Requirement

- To improve selection purity, I use the following technique:
  - In a given light trigger, look for waveforms above a threshold (defined as optical "hits")
  - Find the physical detectors these waveforms correspond to, then require matched clusters to be in close proximity to it
  - **Motivation**: We are most likely to see the light from a decay if it interacts close to a light detector

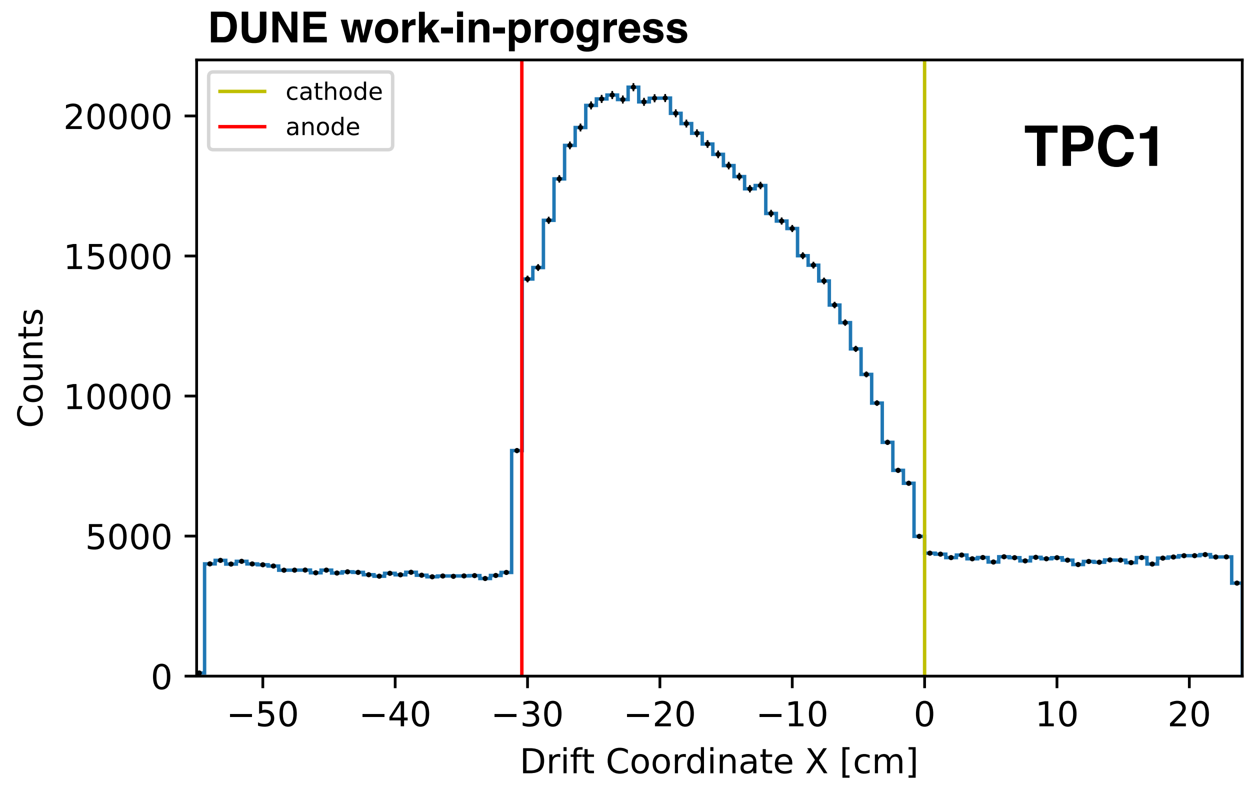


Note on plot: **Module-2** from Univ. of Bern test at the surface

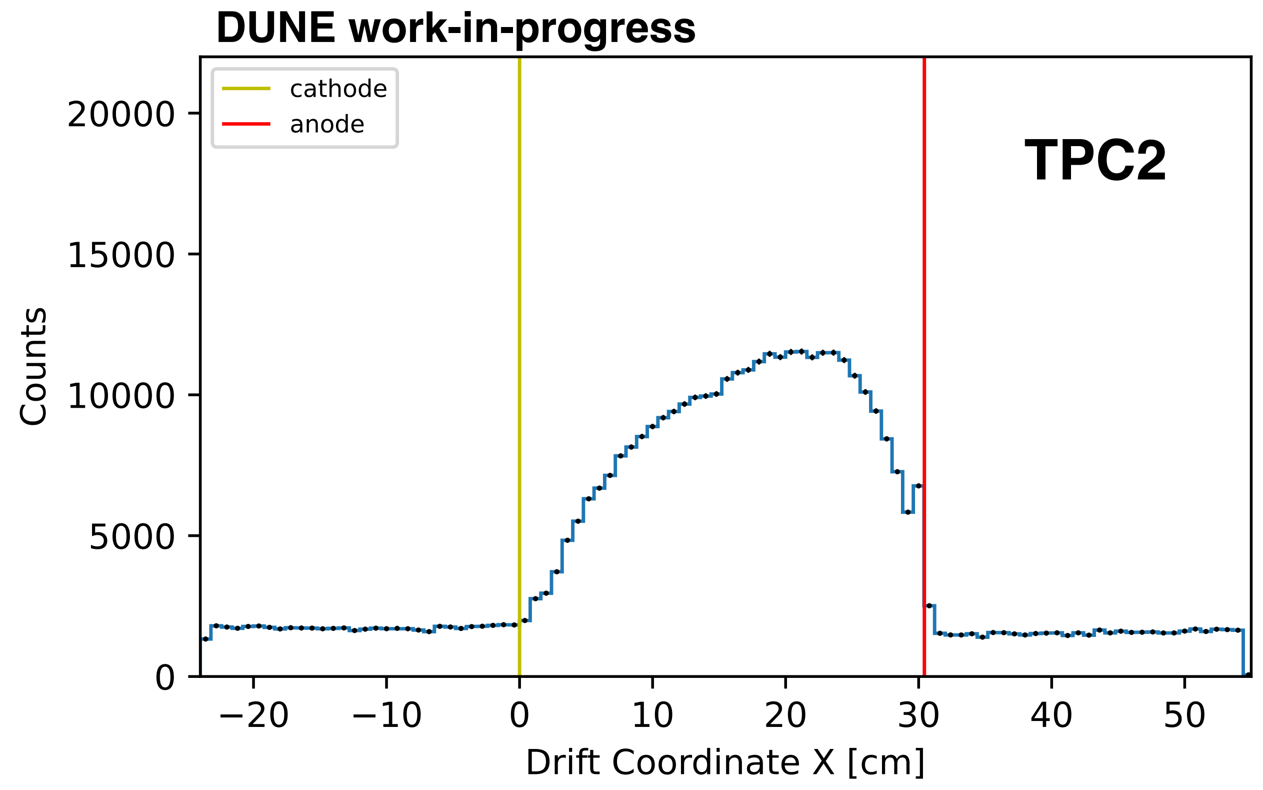
Reconstruction Results



Clear excess of activity observed near the photon detectors (no optical proximity cut applied yet)



→ **~76% selection purity**



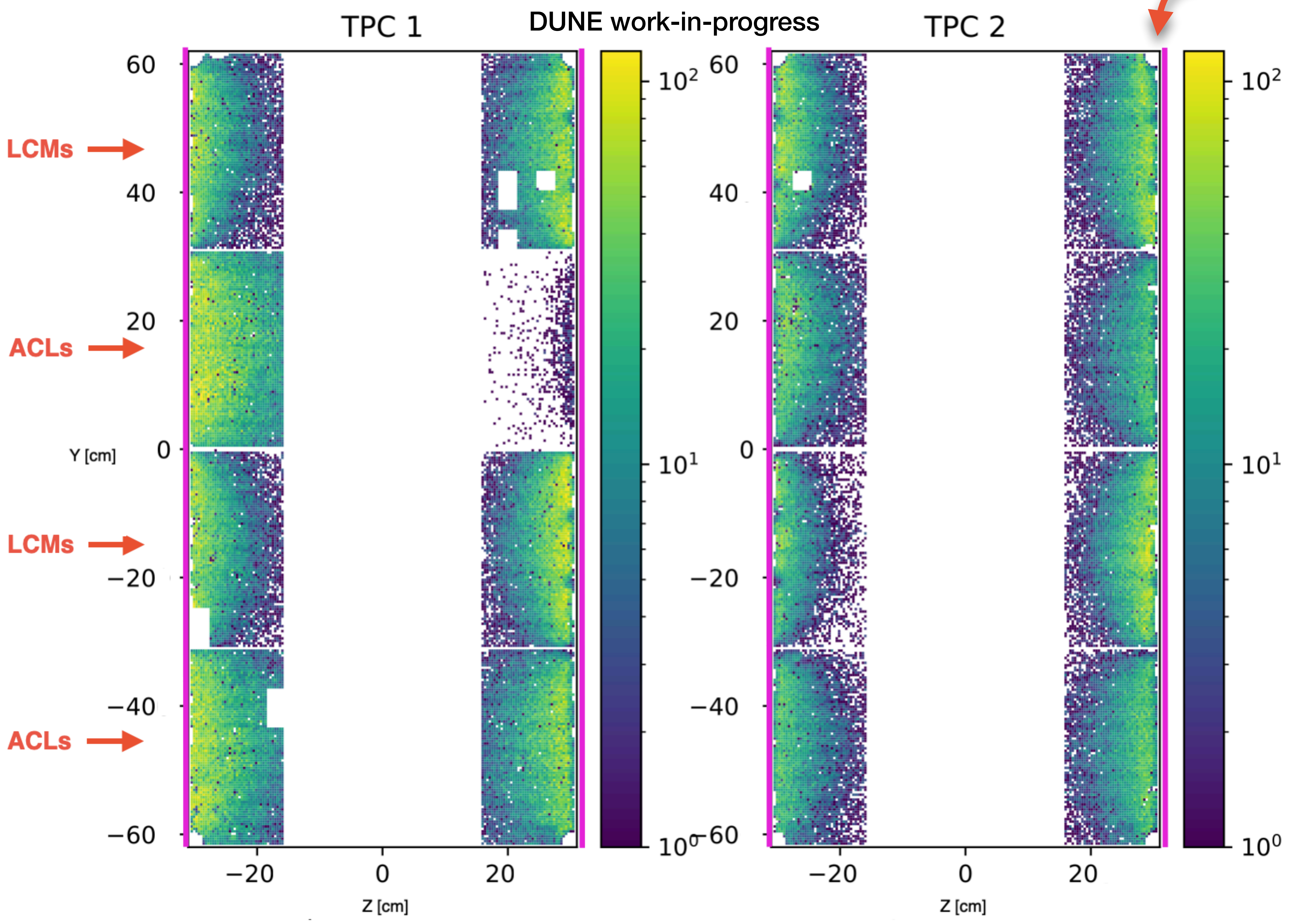
→ **~82% selection purity**

Note: Gaps are disabled channels due primarily to self-triggering instabilities, most of which were resolved for 2x2 thanks to significant improvements due to improved grounding, noise mitigation and ASIC configuration.

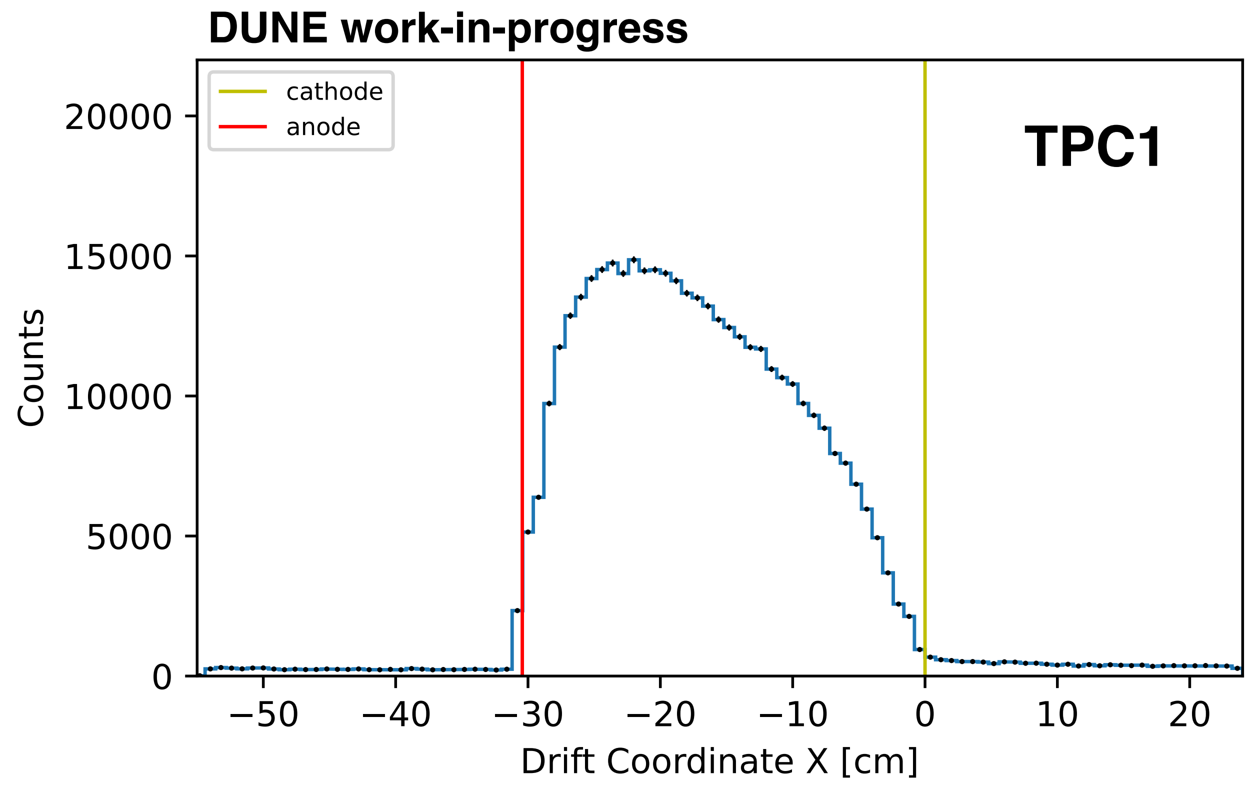
Reconstruction Results

Note on plot: **Module-2** from Univ. of Bern test at the surface

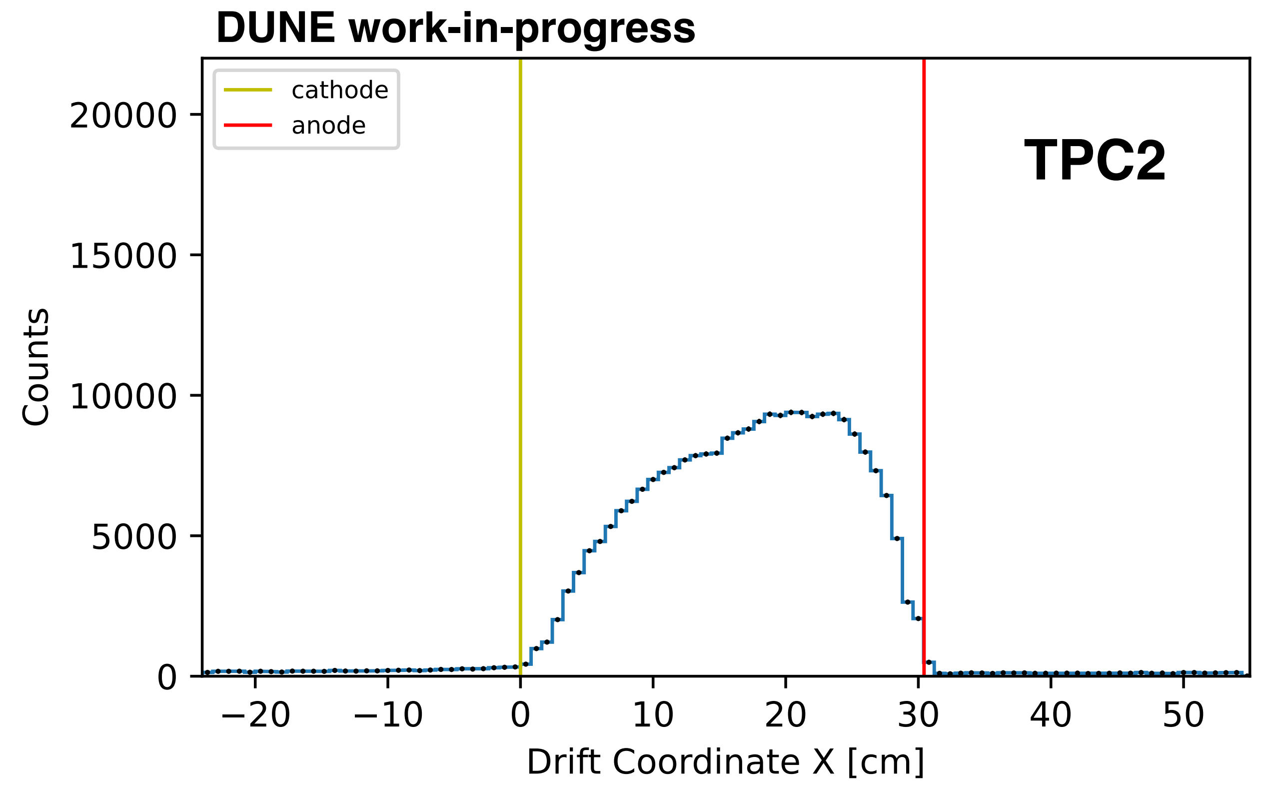
Corners removed due to cosmic ray muons clipping TPC edges, passing selection



Selection purity approaches 100% by applying optical proximity requirement



→ **~97% selection purity**



→ **~98% selection purity**

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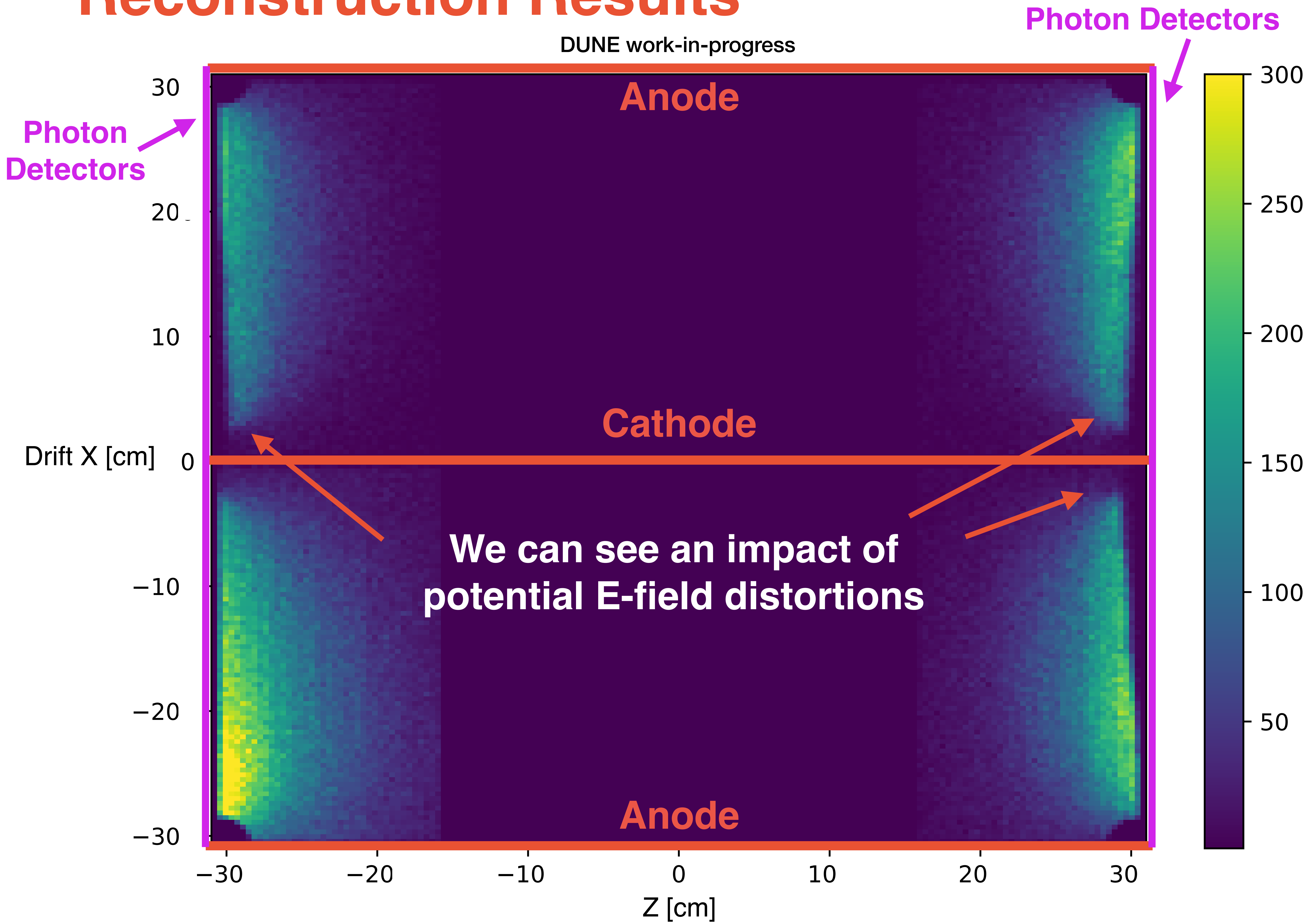


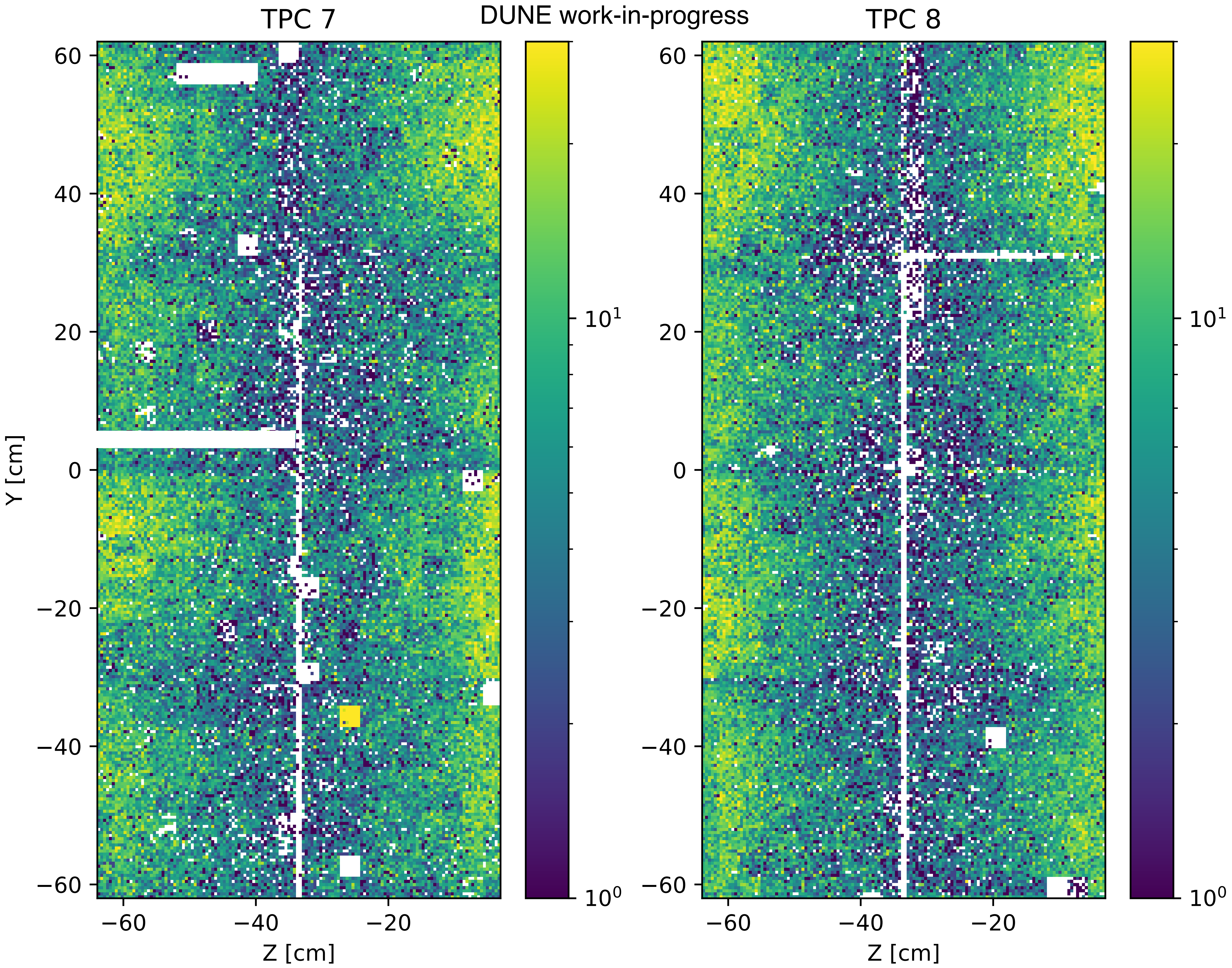
The "top-down" view of the module

- We can see features in the distribution consistent with E-field distortion
  - Could be caused by a non-zero transverse E-field component
- This shows we can use this reconstruction technique to monitor E-field uniformity in the 2x2

Reconstruction Results - 2x2

Note on plot: **Module-2** from 2x2 test

- On the right: an example of the distribution of reconstructed low energy candidates in Module-2 of the 2x2
  - Corresponds to 1 hour of data taking
- We were able to achieve the lowest thresholds so far in a special 2x2 run to support low energy reconstruction
  - Appears we are able to reconstruct low energy activity in much of the module's active volume



Note: Only ~3% channels disabled in 2x2

Reconstruction Results - 2x2

- While the optical proximity cut for 2x2 is still in progress, we can see another way to increase selection purity
  - Requiring higher charge values yields higher purity
    - Rate is lower, but still pretty high despite the cut
- However, the proximity cut should yield even better selection purity with improved rate

cluster q > 0 ke

	M0	M1	M2	M3
Purity Fraction	0.87	0.84	0.90	0.86
Candidate Rate [Hz]	129	101	185	225

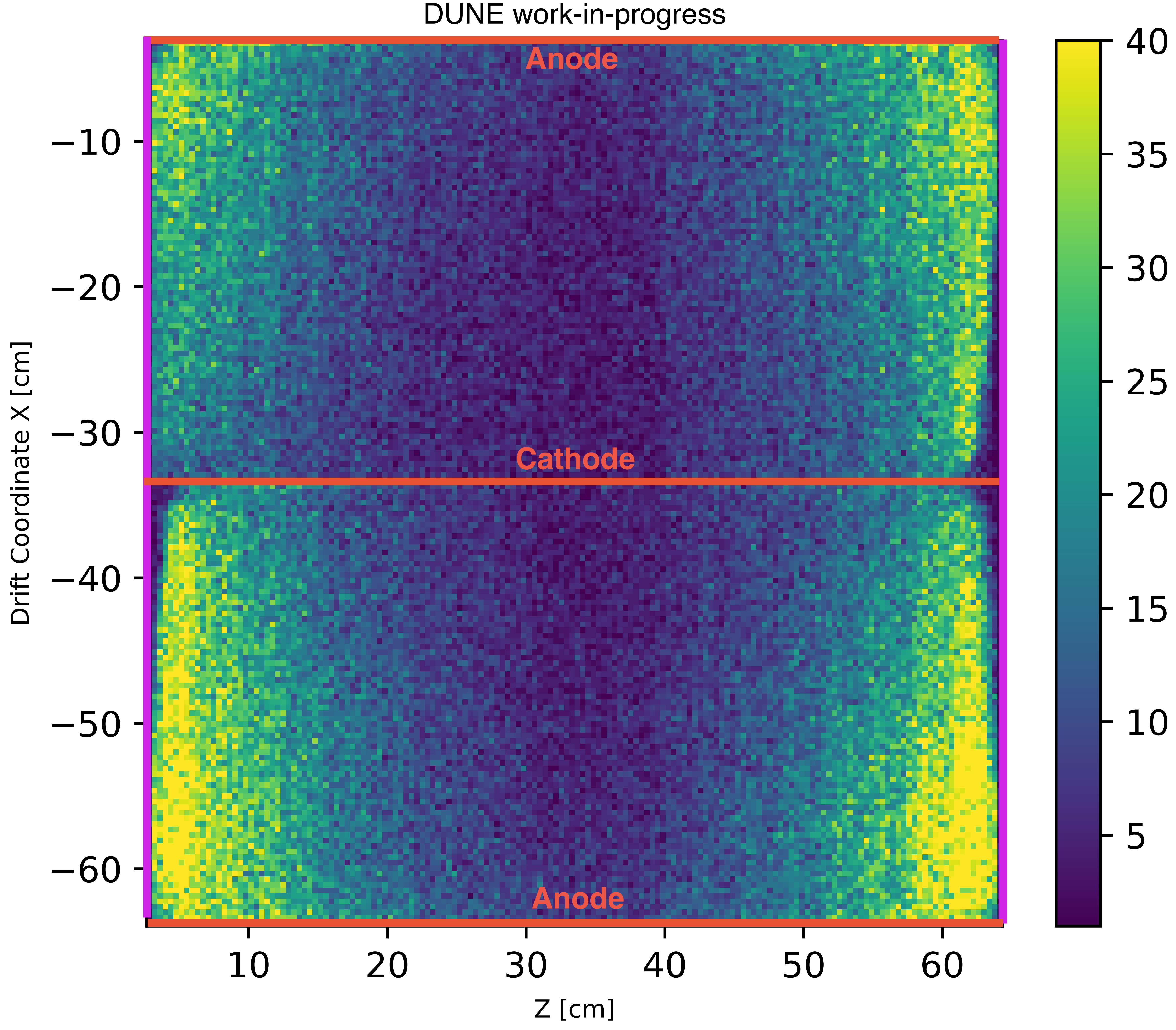
Compared to ~600 Hz/module expected from 39Ar alone

cluster q > 20 ke

	M0	M1	M2	M3
Purity Fraction	0.95	0.93	0.92	0.95
Candidate Rate [Hz]	62	42	123	101

Note: Candidate rate = total rate in module * purity fraction

Reconstruction Results - 2x2

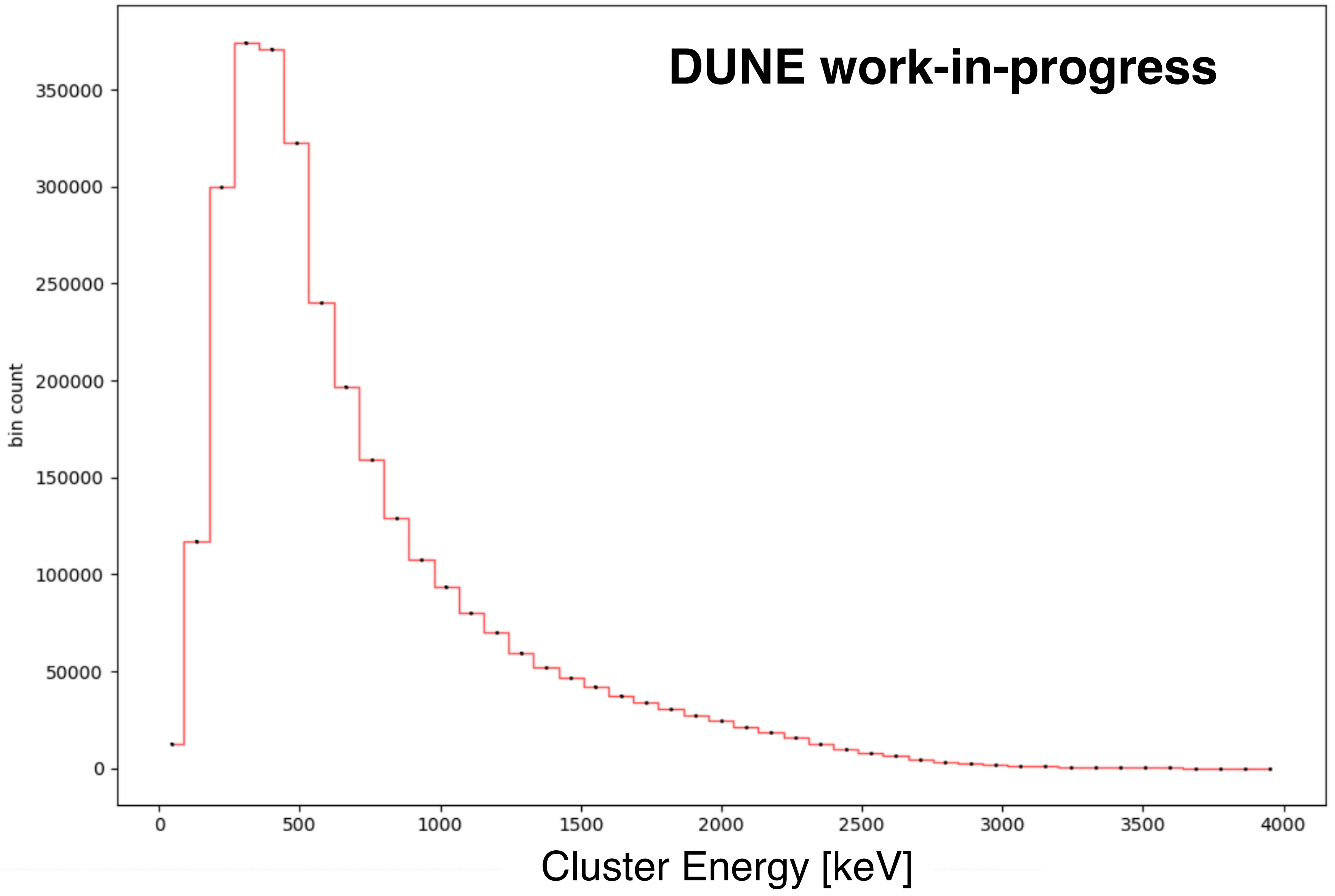


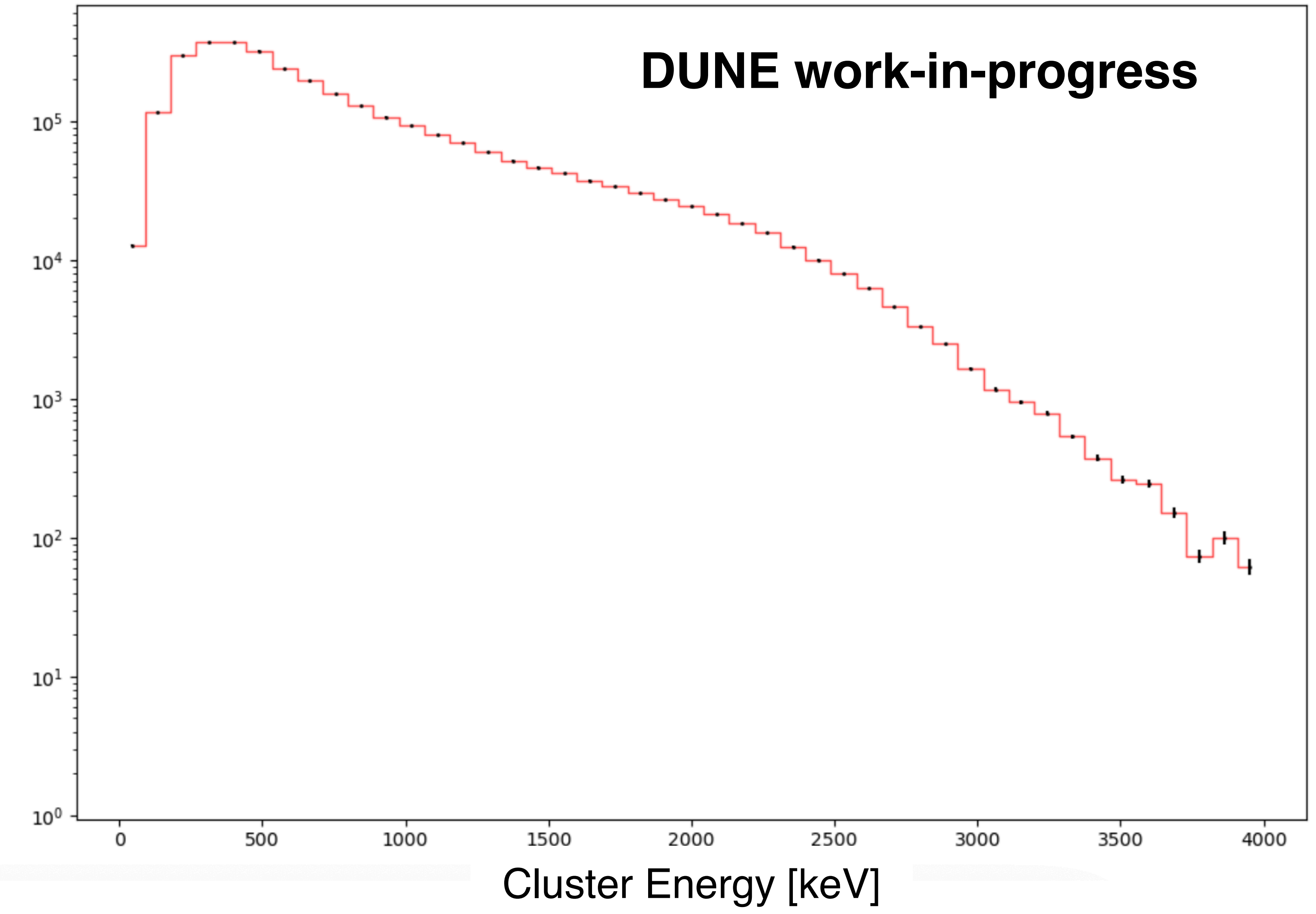
All charge values included in this plot.

The "top-down" view of the module

- We also observe evidence of E-field distortion in the 2x2 modules
  - Behavior varies between modules, not completely consistent with previous LAr tests
  - Generally the effects are small

Reconstructed Energy Spectrum

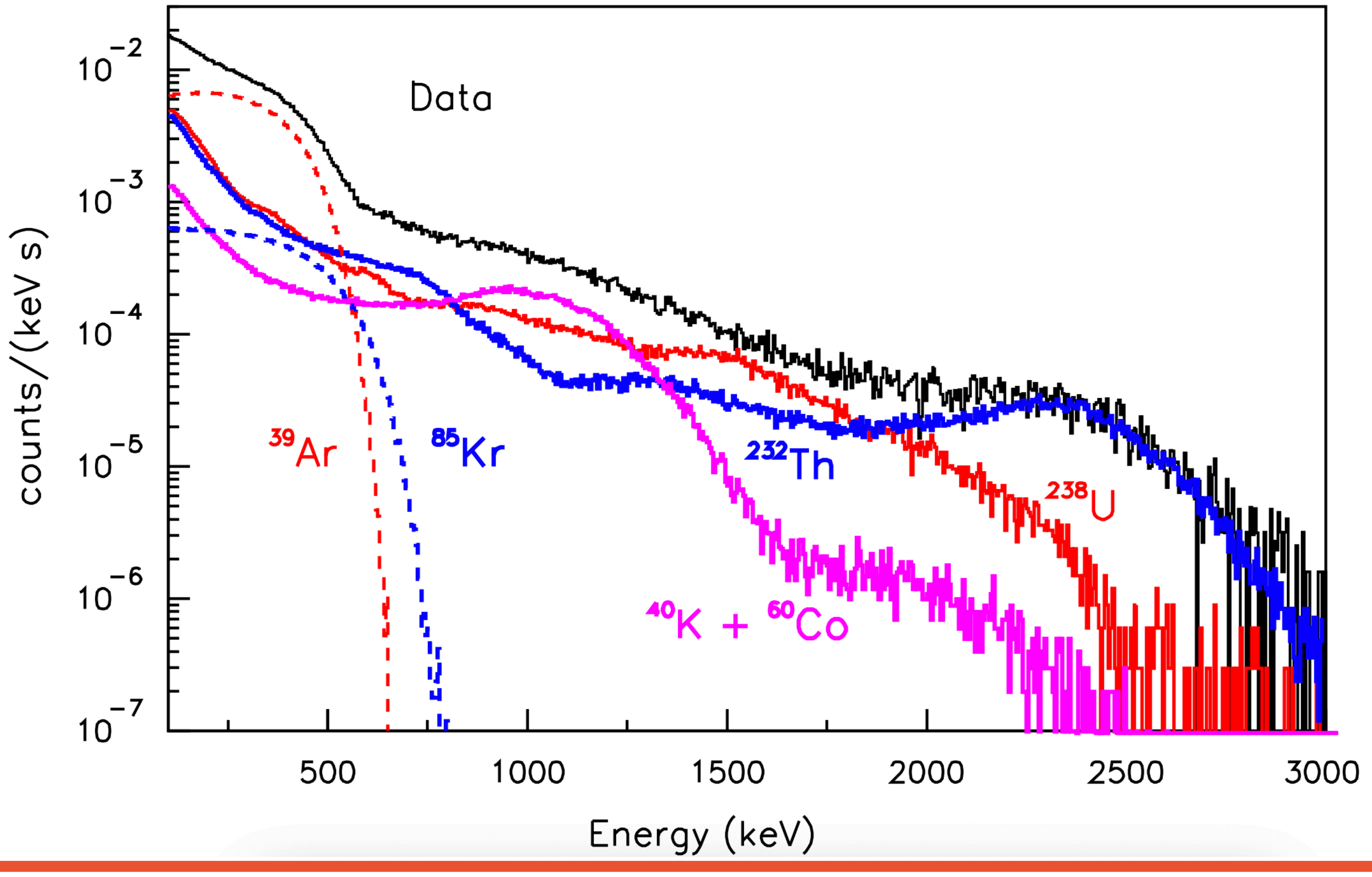




High-energy background

Clusters up to 4 MeV

Benetti, et al. 2007 arXiv:astro-ph/0603131



Conclusions

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- The results show that we can:
  - Reconstruct the radiological background in a large fraction of the 2x2 active volume with sufficiently low light readout thresholds
  - Achieve high selection purity by applying data cuts
  - Assess E-field uniformity near the detector edges

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- The results show that we can:
  - Reconstruct the radiological background in a large fraction of the 2x2 active volume with sufficiently low light readout thresholds
  - Achieve high selection purity by applying data cuts
  - Assess E-field uniformity near the detector edges
- Next steps and plans
  - Electron lifetime measurement study, validate using results from other measurements (i.e. using rock muons, cosmic ray muons) or simulations
  - Extend E-field distortion study by measuring transverse E-field magnitude
  - Explore other applications (e.g. light yield measurement)