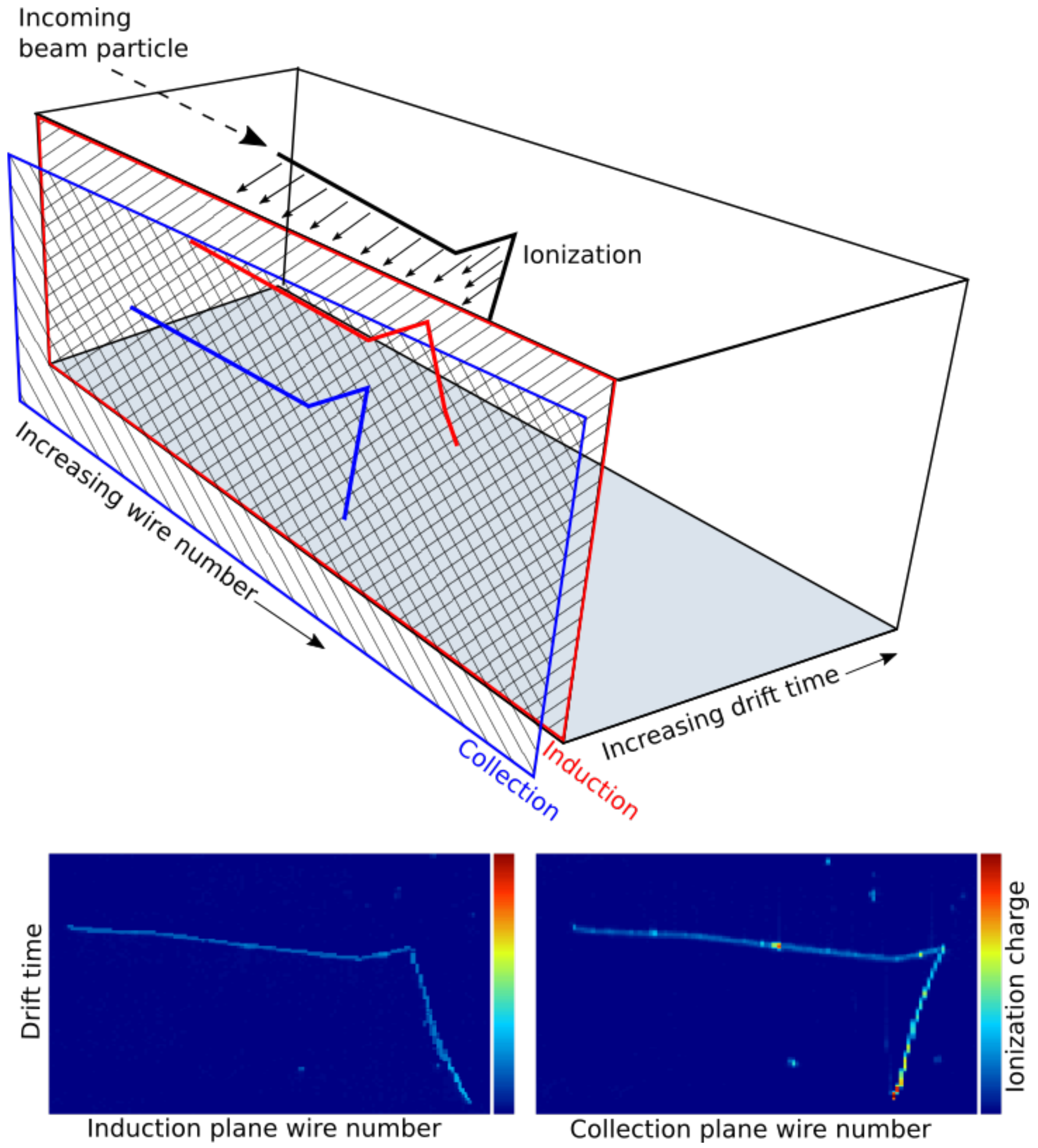
Pixels for the DUNE module of opportunity

Johnny Ho
On behalf of the Q-Pix consortium

5 May 2021

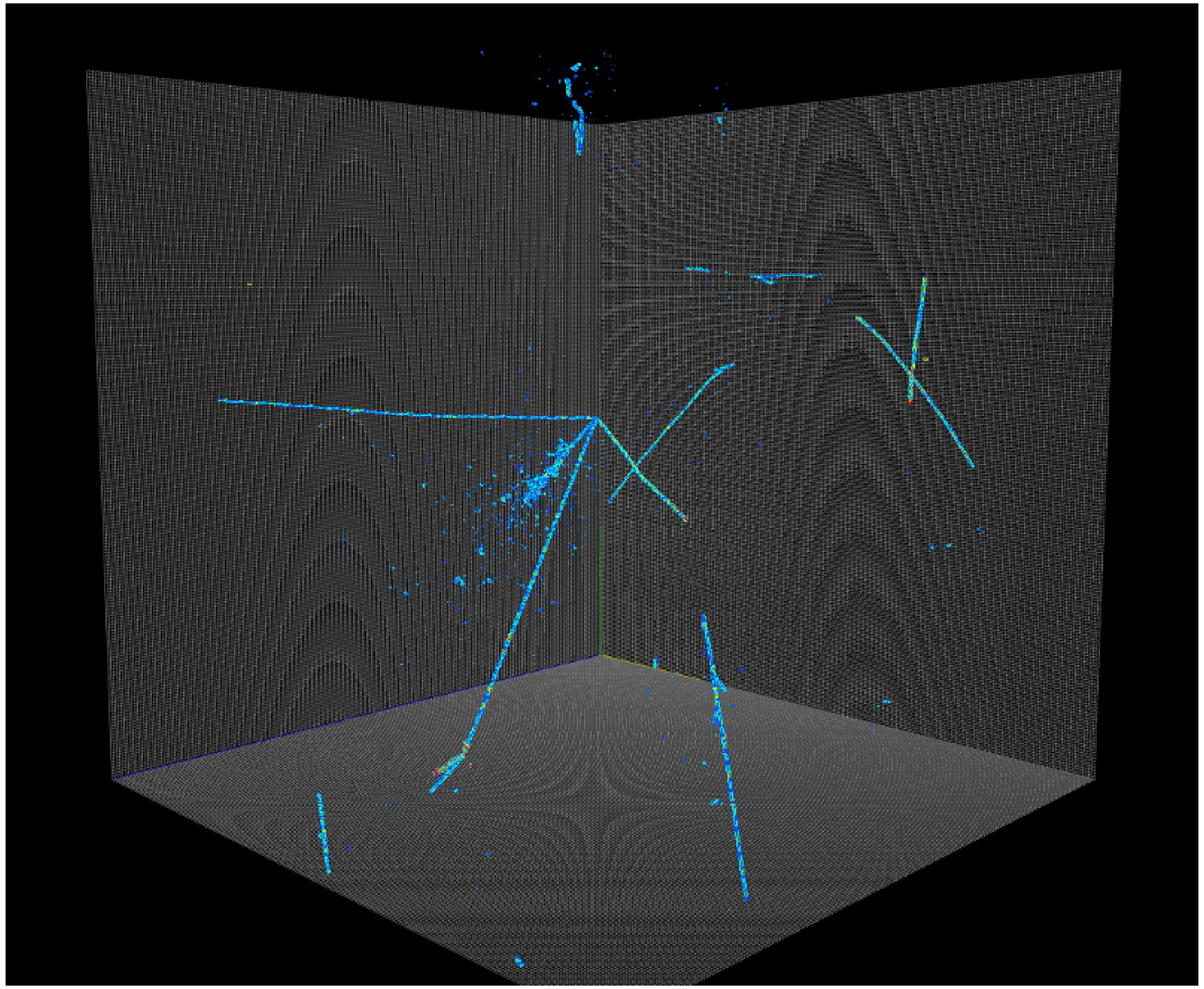
Why pixelated liquid noble TPCs?

- Noble element-based time projection chambers offer access to high quality information
- Leveraging this information allows unprecedented access to detailed neutrino interaction specifics from MeV to GeV scales
- Capturing this data without compromise and maintaining the intrinsic 3D quality is an essential component of all readouts
- Conventional charge readout uses sets of wire placed at different orientations to reconstruct 3D events
  - Some event topologies are challenging to reconstruct in this manner
- Pixel-based charge readout is a natural solution



What is to be gained? (3D vs. 2D readout)

- Using pixels instead of wires can solve the shortcomings of projective wire readout
- How much better is a pixel-based detector?
  - In an ideal world, we would compare the complete readout and reconstruction of two detectors side-by-side to answer this question
- Using modern machine learning techniques, we trained two parallel networks on identical simulated neutrino interactions
  - Network 1: 3D pixel-based readout
  - Network 2: 2D projective wire readout
- For both of these networks, we assumed ideal detectors with perfect response and no reconstruction pathologies



Credit: Phys. Rev. D 102 (2020) 1, 012005, arXiv:1903.05663 [hep-ex]

What is to be gained? (3D vs. 2D readout)

- Simulated studies of LArTPCs comparing the readout of 2D projective wire to 3D pixelated readout show that the 3D-based readout offers significant improvement in all physics categories
  - ν_e CC inclusive: 17% gain in efficiency and 12% gain in purity
  - ν_μ CC inclusive: 10% gain in efficiency for 99% purity
  - NCπ^0: 13% gain in efficiency and 6% gain in purity
  - Also offers gains neutrino event classification and final state topology identification

Table 2: Confusion matrix for the neutrino interaction classification.

	3D Truth Label			2D Truth Label		
Pred. Label	ν_e CC	ν_μ CC	NC	ν_e CC	ν_μ CC	NC
ν_e CC	**0.959**	0.013	0.019	0.928	0.019	0.025
ν_μ CC	0.018	**0.952**	0.072	0.020	0.908	0.070
NC	0.023	0.035	**0.908**	0.052	0.073	0.904

Table 3: Confusion matrix for the proton multiplicity classification.

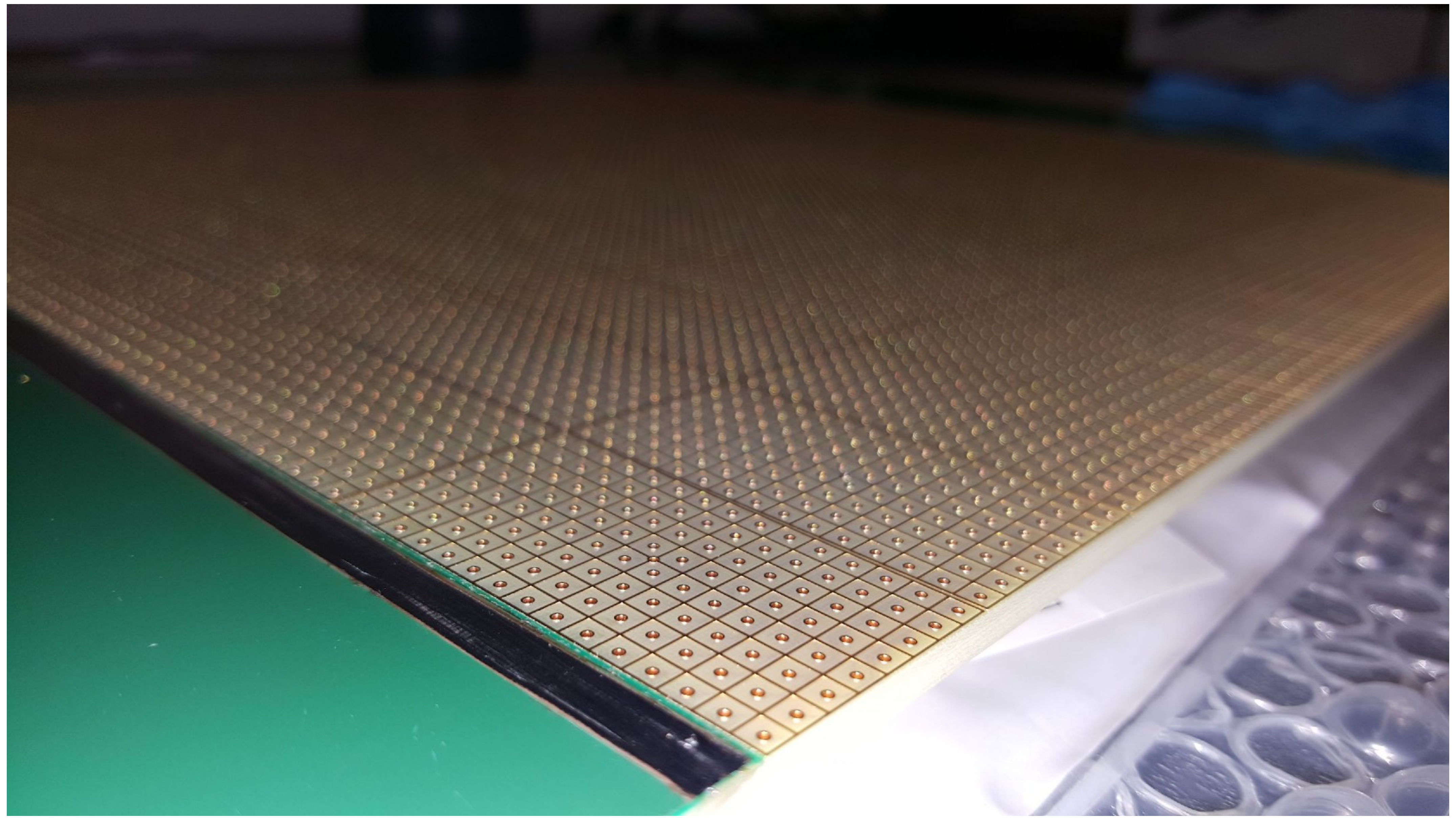
	3D Truth Label			2D Truth Label		
Pred. Label	$N_p = 0$	$N_p = 1$	$N_p \geq 2$	$N_p = 0$	$N_p = 1$	$N_p \geq 2$
$N_p = 0$	**0.928**	0.076	0.005	0.841	0.064	0.005
$N_p = 1$	0.062	**0.884**	0.059	0.143	0.853	0.069
$N_p \geq 2$	0.010	0.040	**0.936**	0.016	0.084	0.926

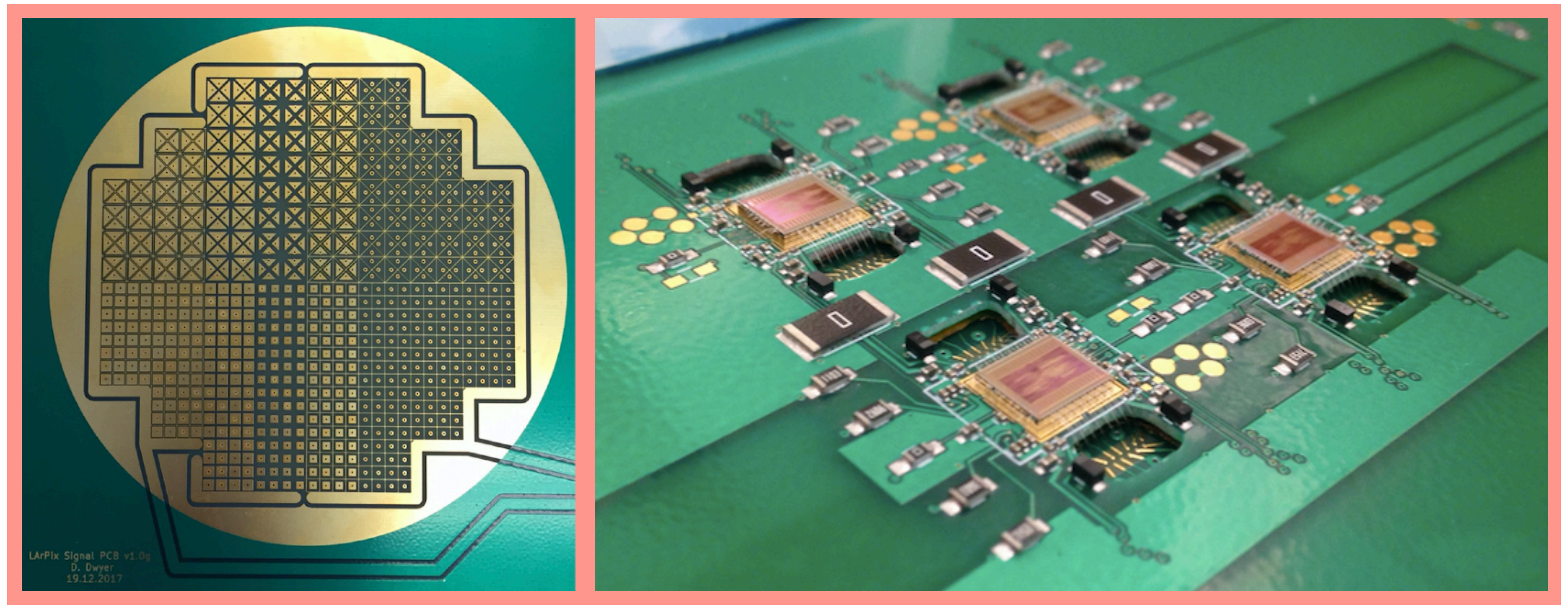
JINST 15 P04009 (arXiv:1912.10133)

*** Improvements like these can lead to significantly shorter experimental running time required to meet desired physics goals!

So pixelate them, what's so hard?

- Readout of a TPC using pixels instead of wires comes at the "cost" of many more channels. For example, in a 2×2 m^2 readout:
  - 3 mm wire pitch with three projective wire planes: 2450 channels
  - 3 mm pixel pitch: 422,000 channels
- The LArPix (JINST 13 P10007) readout has pioneered this frontier showing a low-power pixel-based readout can be done
  - Currently targeted for the DUNE near detector to allow a LArTPC to handle the high event rates
- Other solutions are being explored for kiloton-scale underground LArTPCs

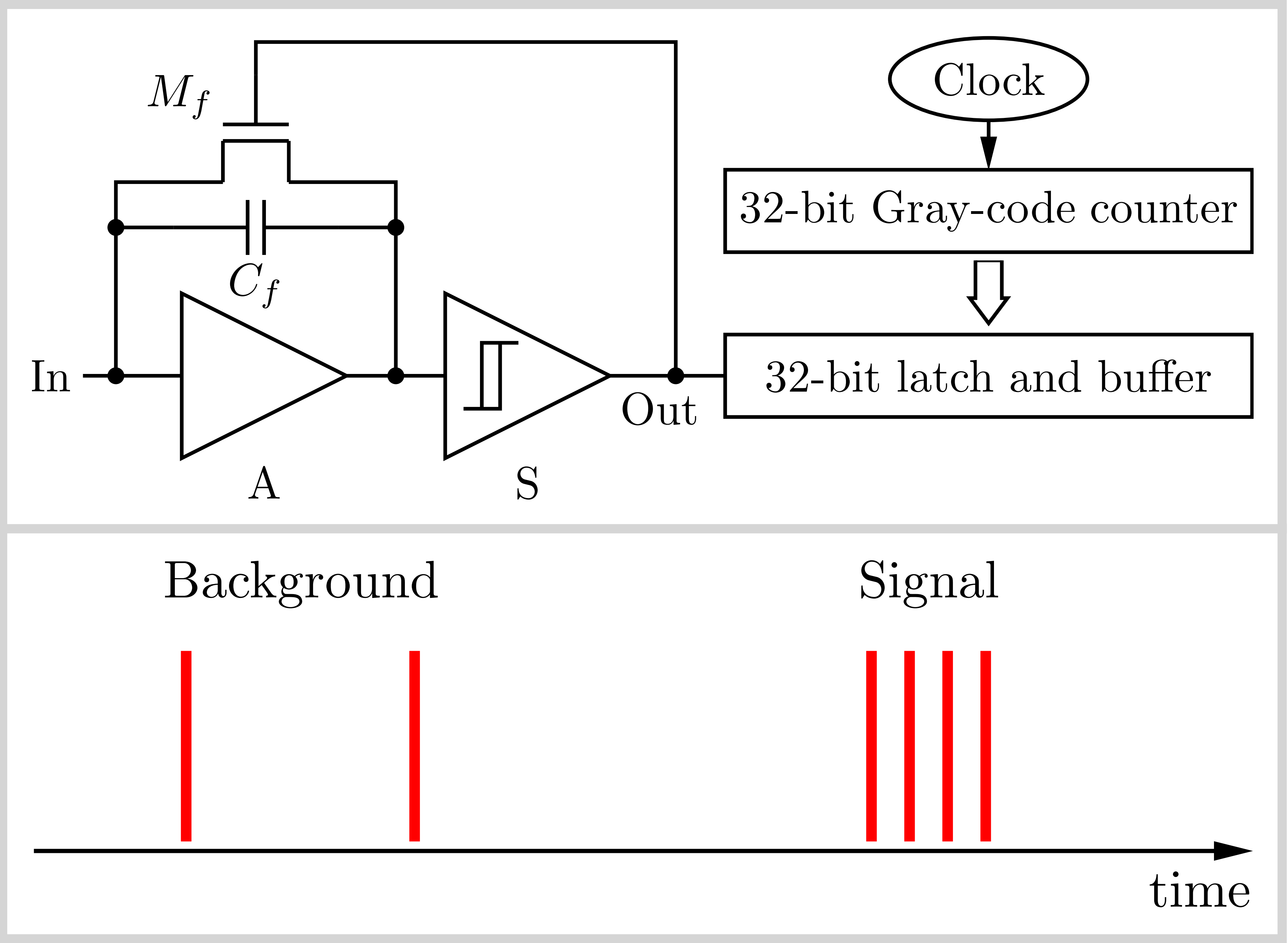




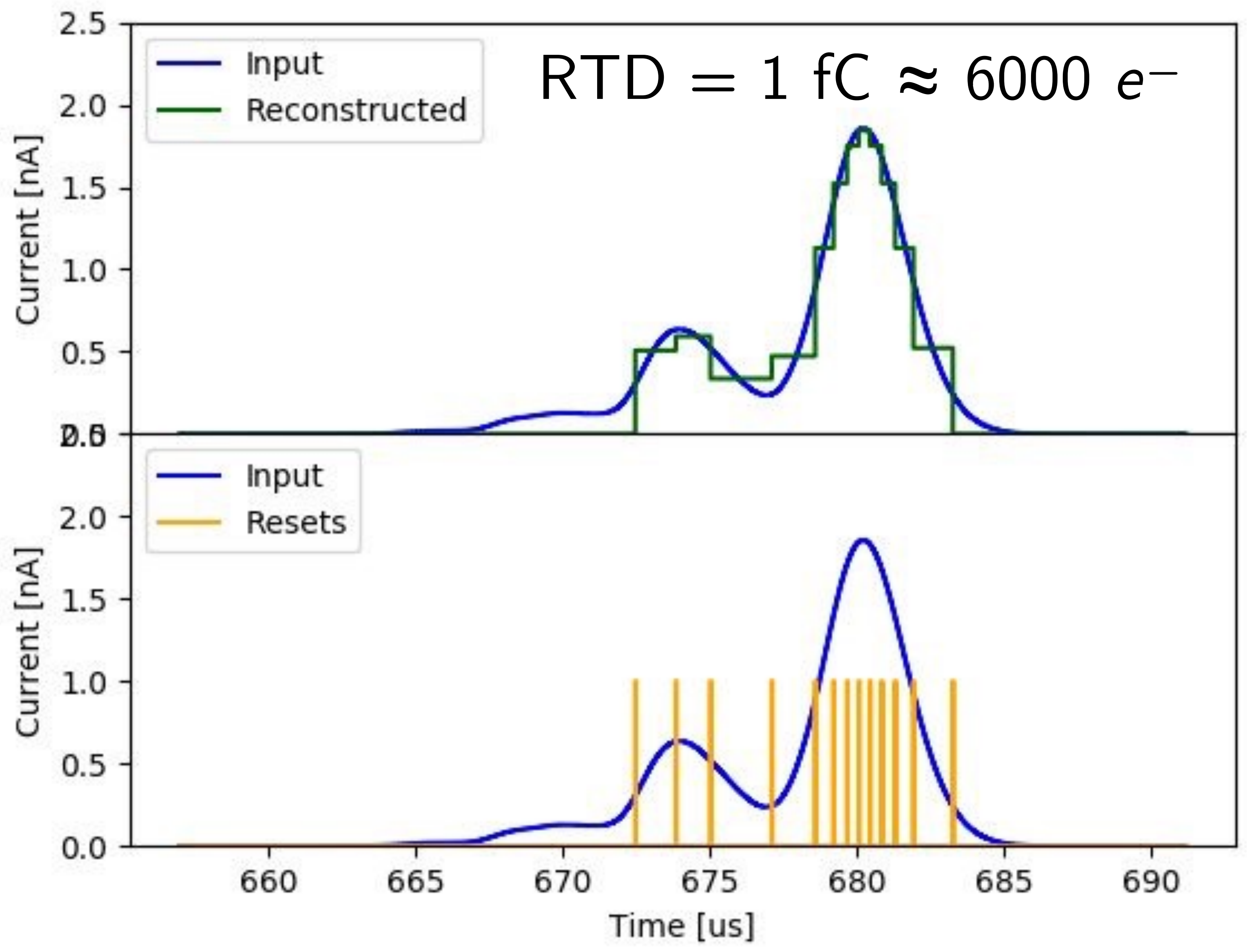
JINST 13 P10007 (arXiv:1808.02969)

An unorthodox solution: Q-Pix

- The Q-Pix pixel-based readout follows the "electronic principle of least action"
  - Don't do anything unless there is something to do
- Offers an innovative signal capture with a new approach in measure time-to-charge
  - Keeps the detailed waveforms of the LArTPC
- Takes the difference between sequential resets
  - Reset Time Difference = RTD = ΔQ
- RTDs measure the instantaneous current and captures the waveform
  - Small average current (background) = large RTD
    - Background from ^{39}Ar ~100 aA
  - Large average current (signal) = small RTD
    - Typical minimum ionizing track ~1.5 nA



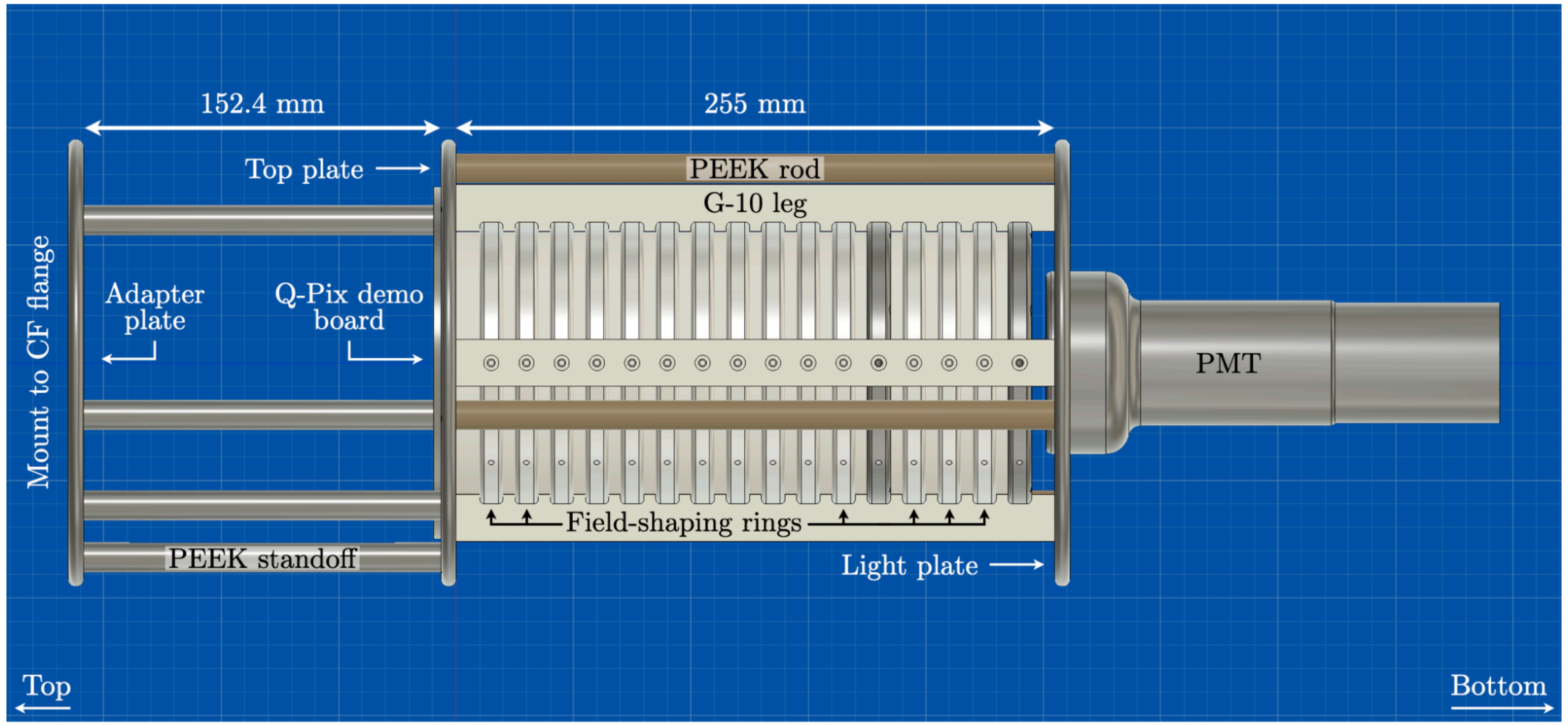
Y. Mei & D. Nygren, arXiv:1809.10213

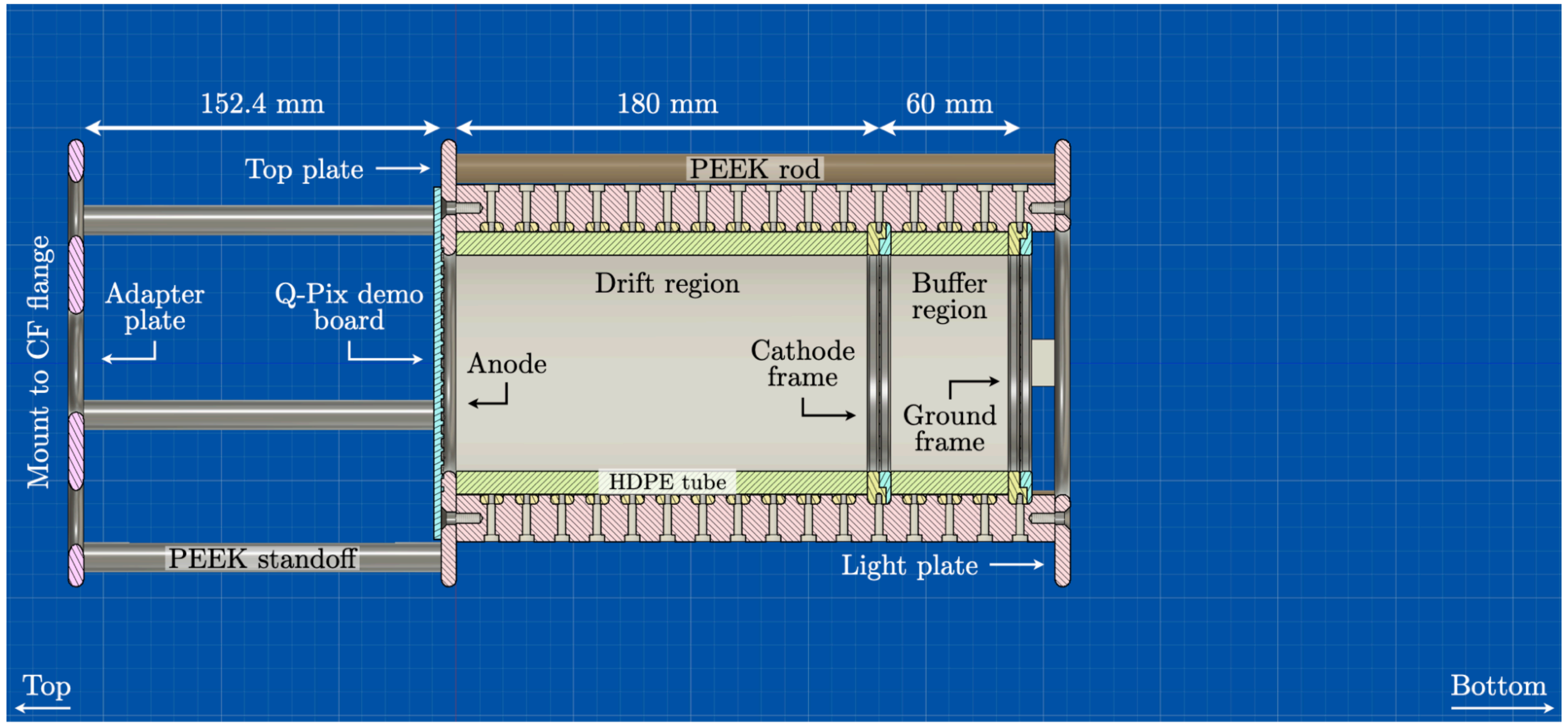


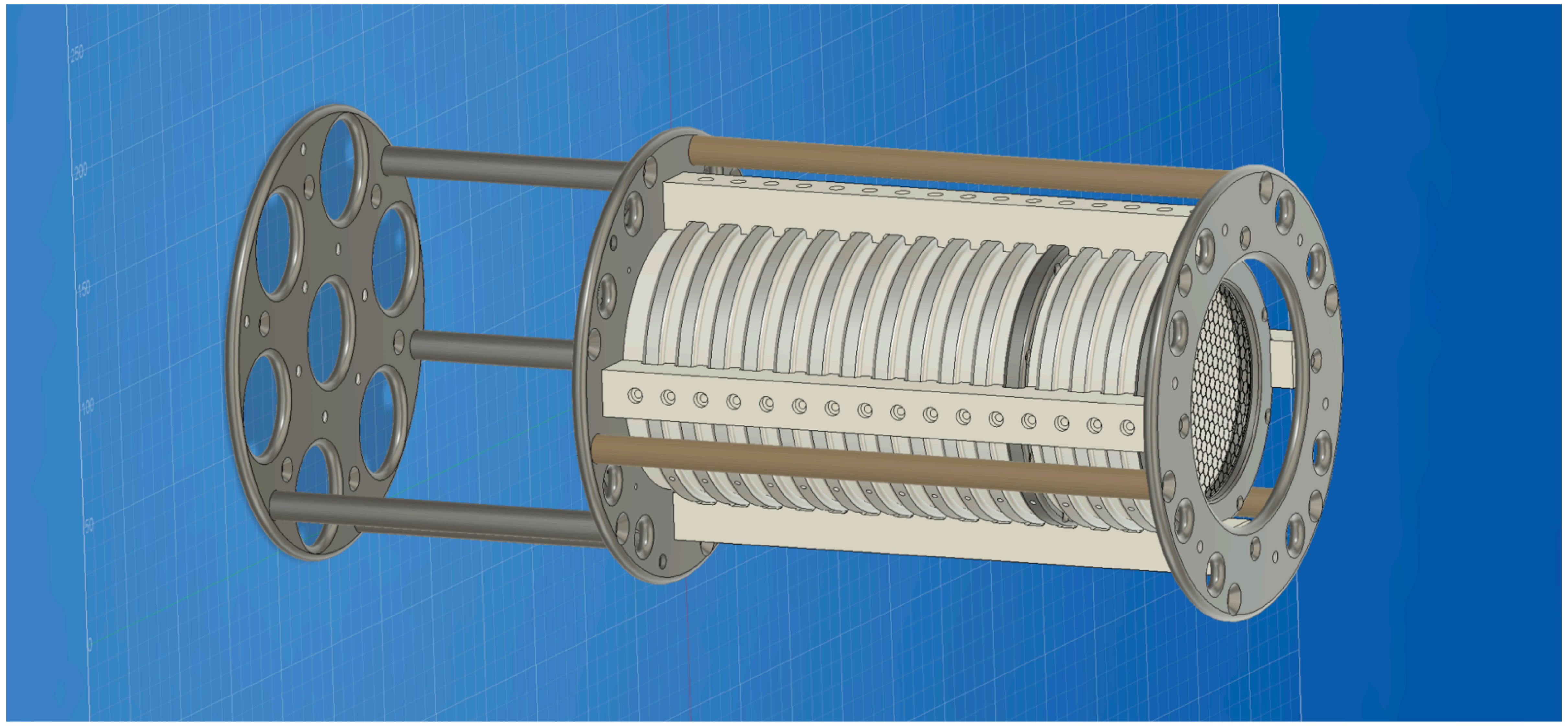
Current status of Q-Pix

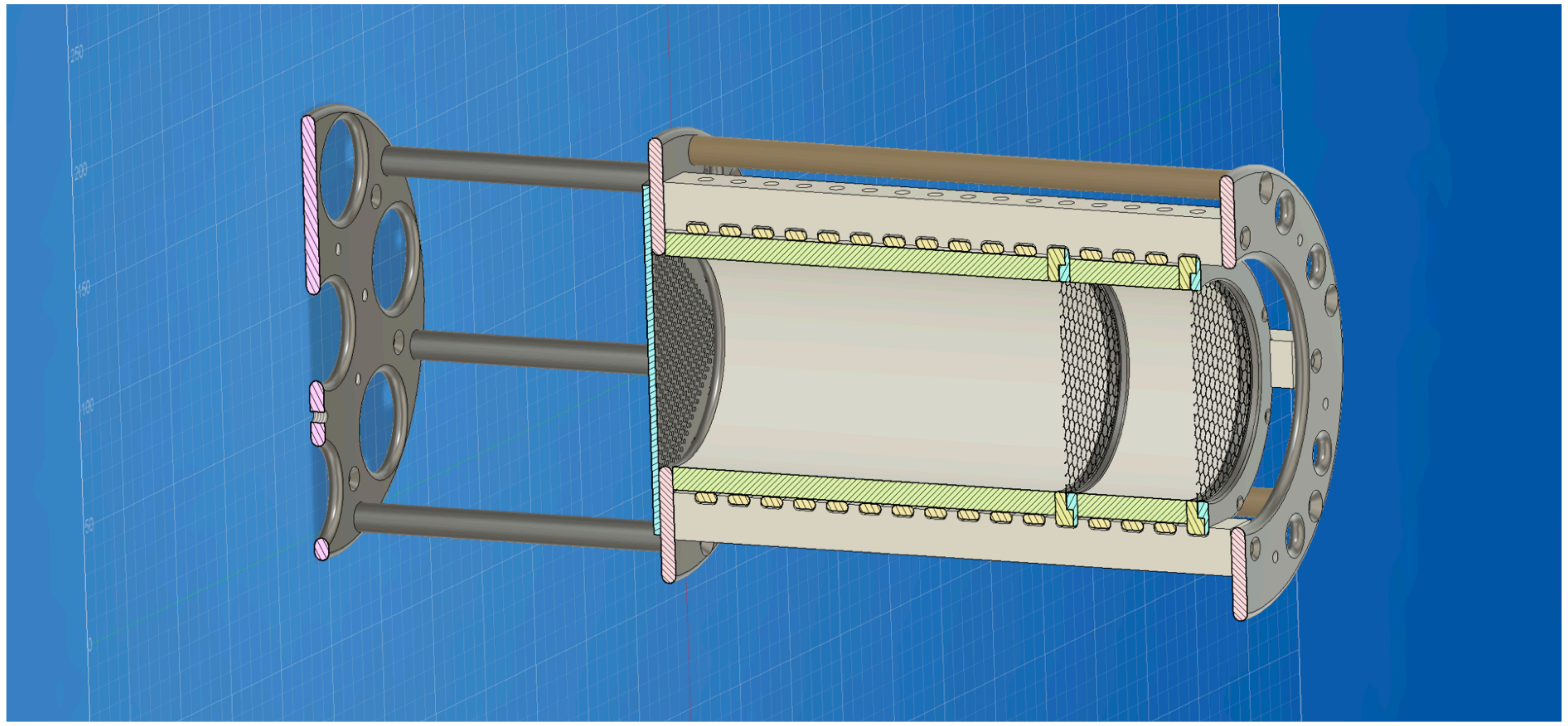
- First prototype Q-Pix ASIC will read 16-32 pixels
  - We envision each pixel will have a 4 mm pitch
- The first version of the ASIC's front-end and digital logic is nearing completion
  - Target of 2021 for the first chip submission
- Simulated data suggests that the front end and digital logic can handle high energy (DUNE scale) neutrino interactions with no foreseen problems
  - DUNE FD data rate ~9 GB/s per APA (from the DUNE FD Interim Design Report)
  - Q-Pix data rate ~250 kB/s per APA
- Currently building two sister TPCs to test the Q-Pix readout and explore the low-energy detection limits

Planned Q-Pix test stand

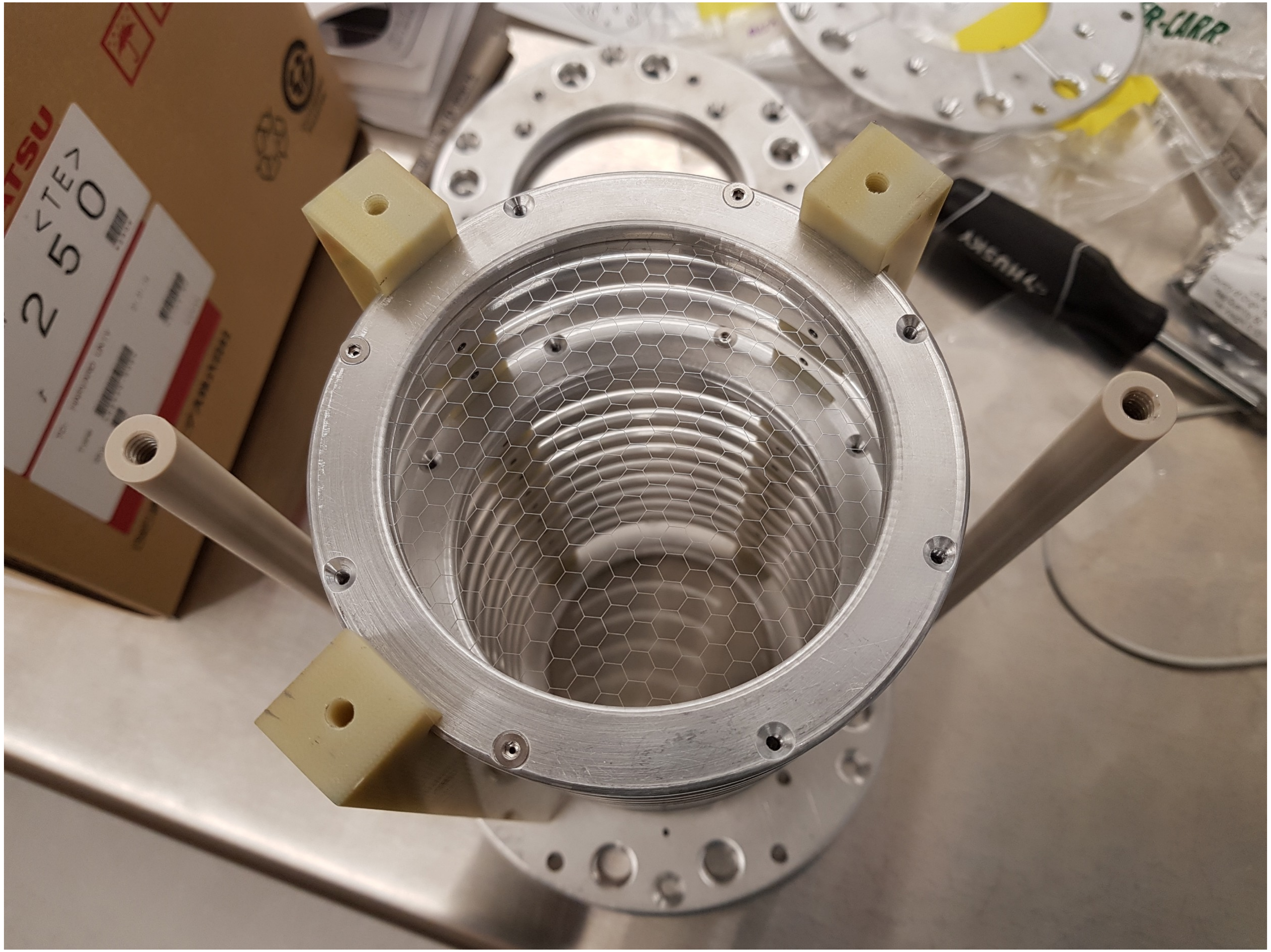




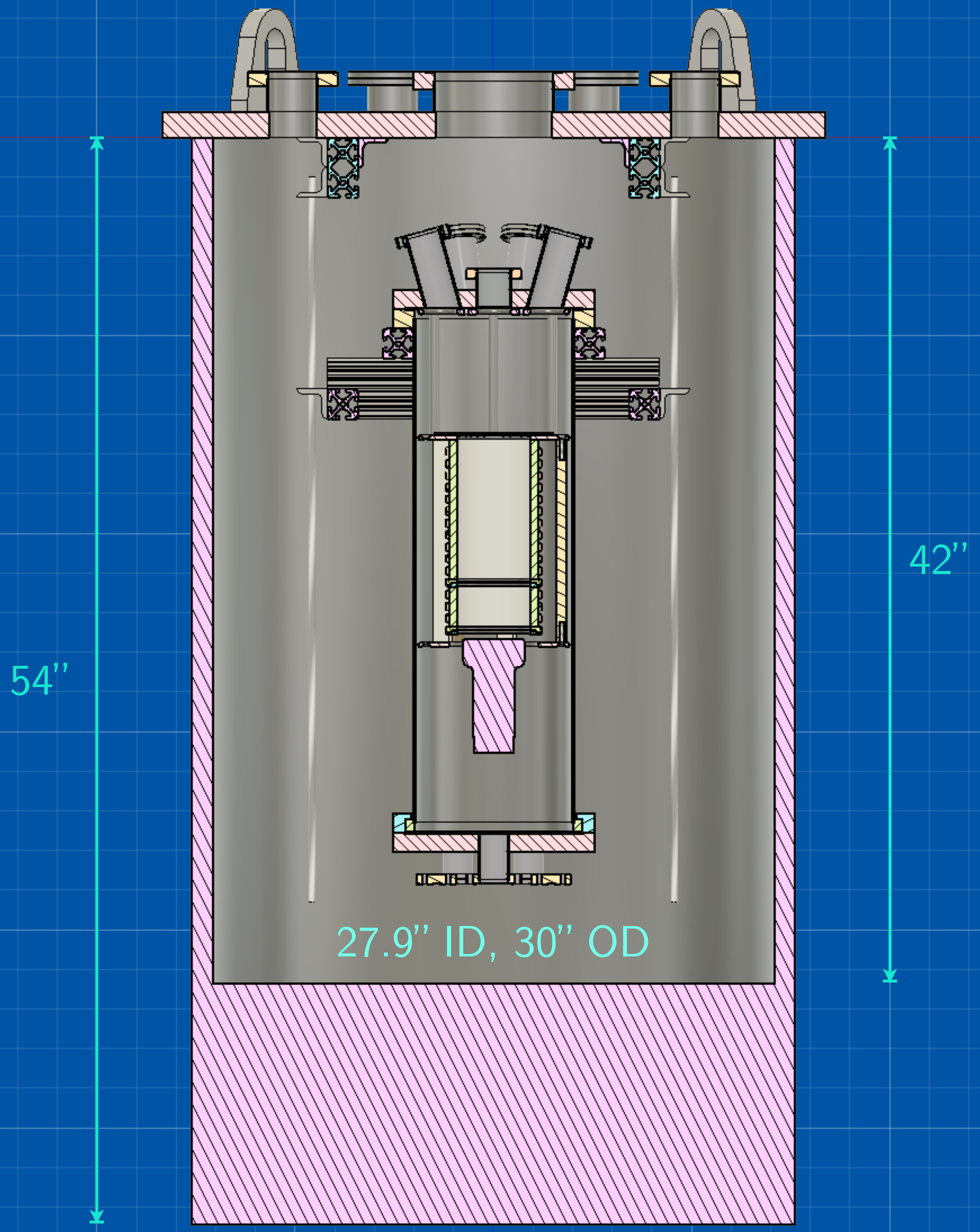




Planned Q-Pix test stand

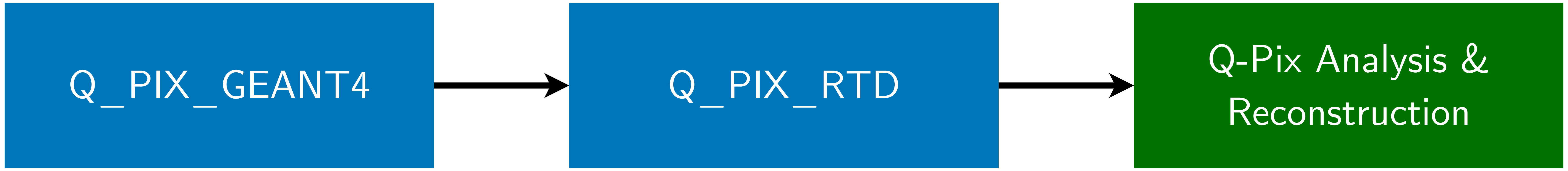


Planned Q-Pix test stand



Physics potential assessment of pixelated FD

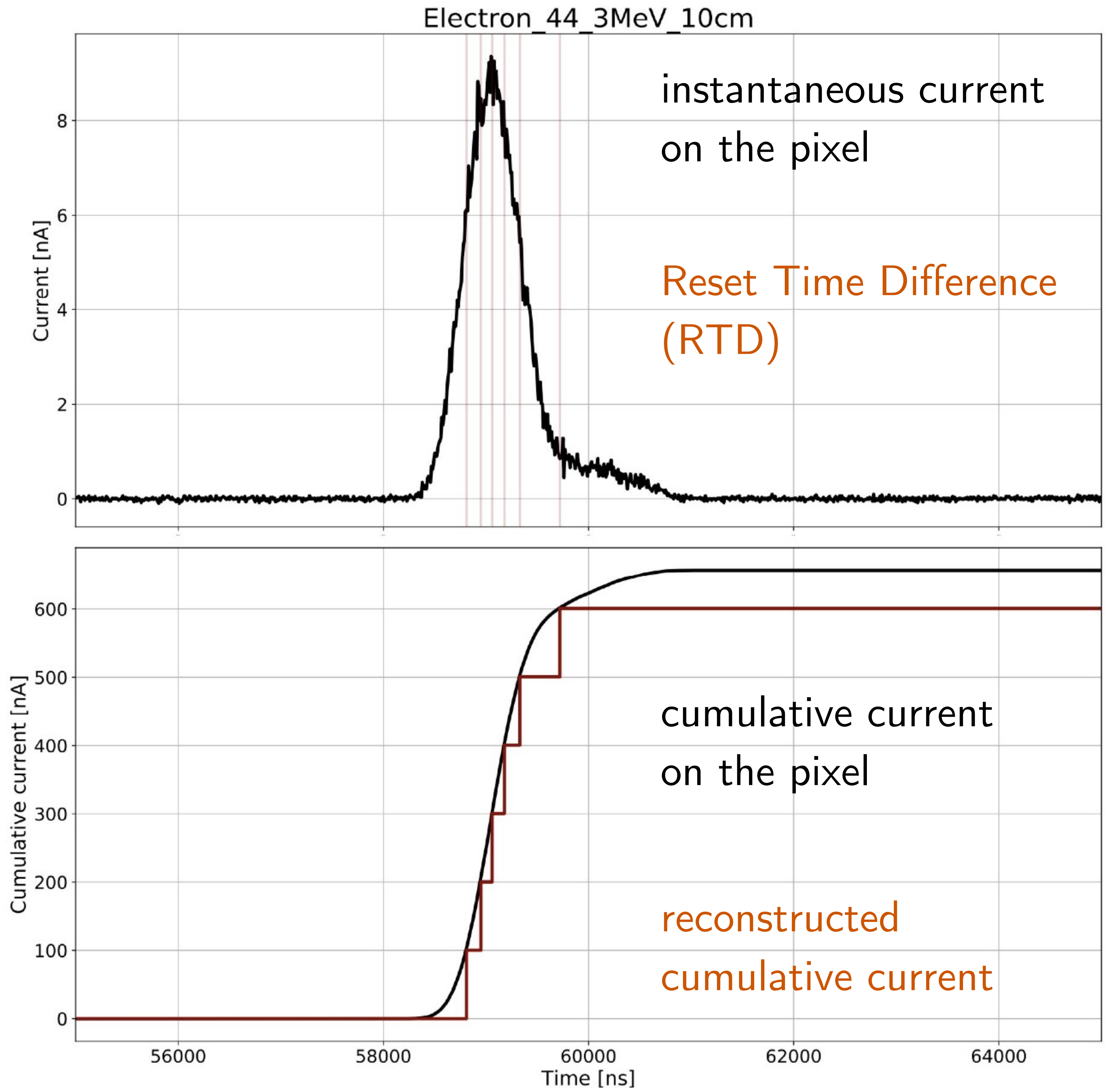
- We have developed custom software to produce current profiles from GEANT4

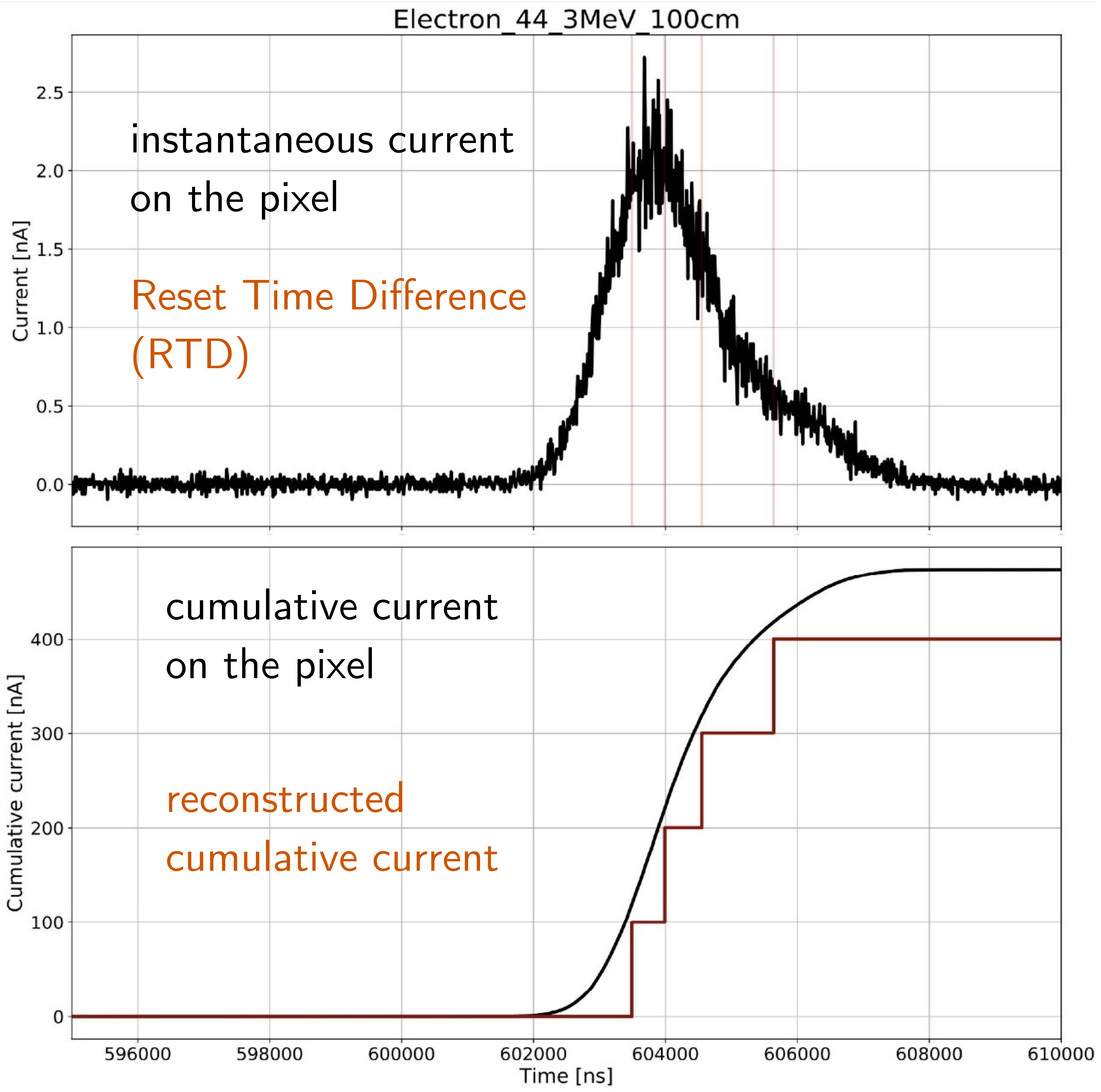


- The simulated geometry is a single APA drift region (6 m tall $\times$ 2.3 m wide $\times$ 3.6 m drift)
  - An APA region holds ~50,000 L or ~70,000 kg of LAr (~70 tons)
- A single 10 kt DUNE FD SP module consists of 200 APA drift regions, which amounts to a ~13.9 kt total volume
- Our current (simplified) methodology is to only simulate 1 APA drift region, then 200 of these would mimic a single DUNE FD SP module response

Physics potential assessment of pixelated FD

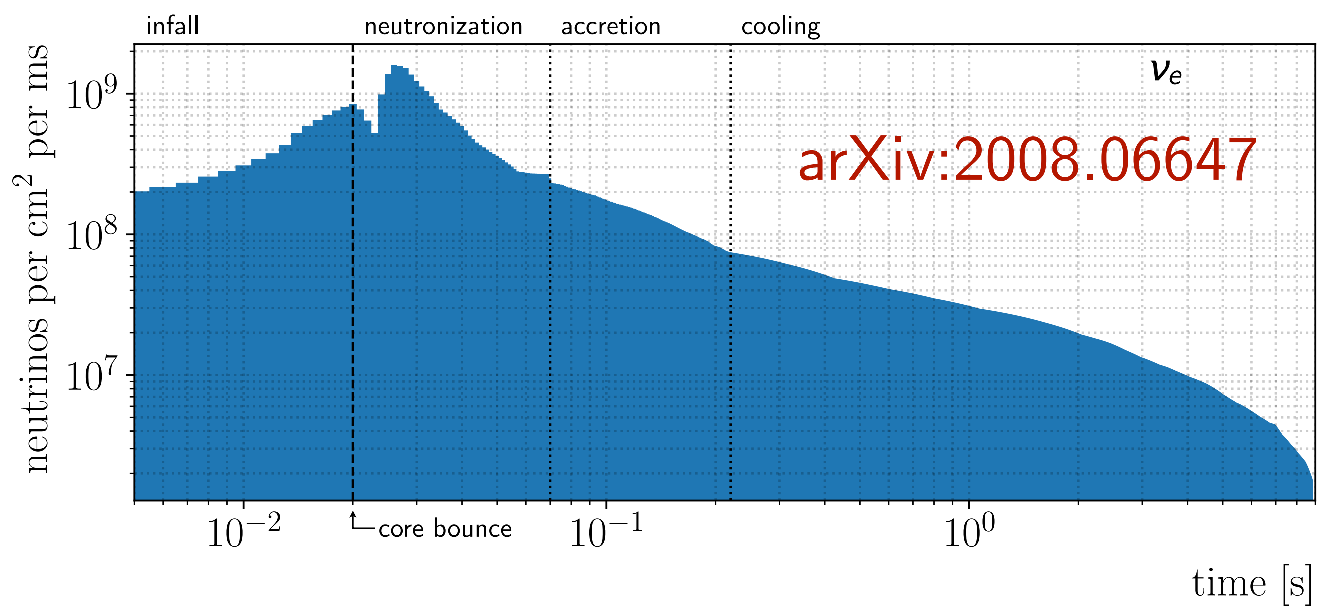
- The Q-Pix RTD simulation produces ionized electrons from GEANT4 hits, and are projected to the pixel plane (recombination is factored in, and the remaining electrons are diffused according to their starting drift position)
- They are then integrated on a pixel until the reset threshold is met





Physics potential assessment of pixelated FD

- Defined a supernova time window of 10 seconds
- The first step is to see if supernova events are observable above the DUNE radiogenic backgrounds



Isotope	Rate [Bq/kg]	Region	Region mass [kg]	Rate [Bq]	Time window	Number of decays
Po-210	0.2	PD [Bq/m^2]	2.46856	0.493712	10	4.93712
Co-60	0.0455	CPA	90	4.095	10	40.95
K-40	4.9	APA	258	1,264.2	10	12,642
Ar-39	1.010	bulk LAr	70,000	70,700	10	707,000
Ar-42	0.000092	bulk LAr	70,000	6.44	10	64.4
K-42	0.000092	bulk LAr	70,000	6.44	10	64.4
Rn-222	0.04	bulk LAr	70,000	2,800	10	28,000
Pb-214	0.01	bulk LAr	70,000	700	10	7,000
Bi-214	0.01	bulk LAr	70,000	700	10	7,000
Kr-85	0.115	bulk LAr	70,000	8,050	10	80,500

(There are 200 APA drift volumes in a 10 kton SP module.)

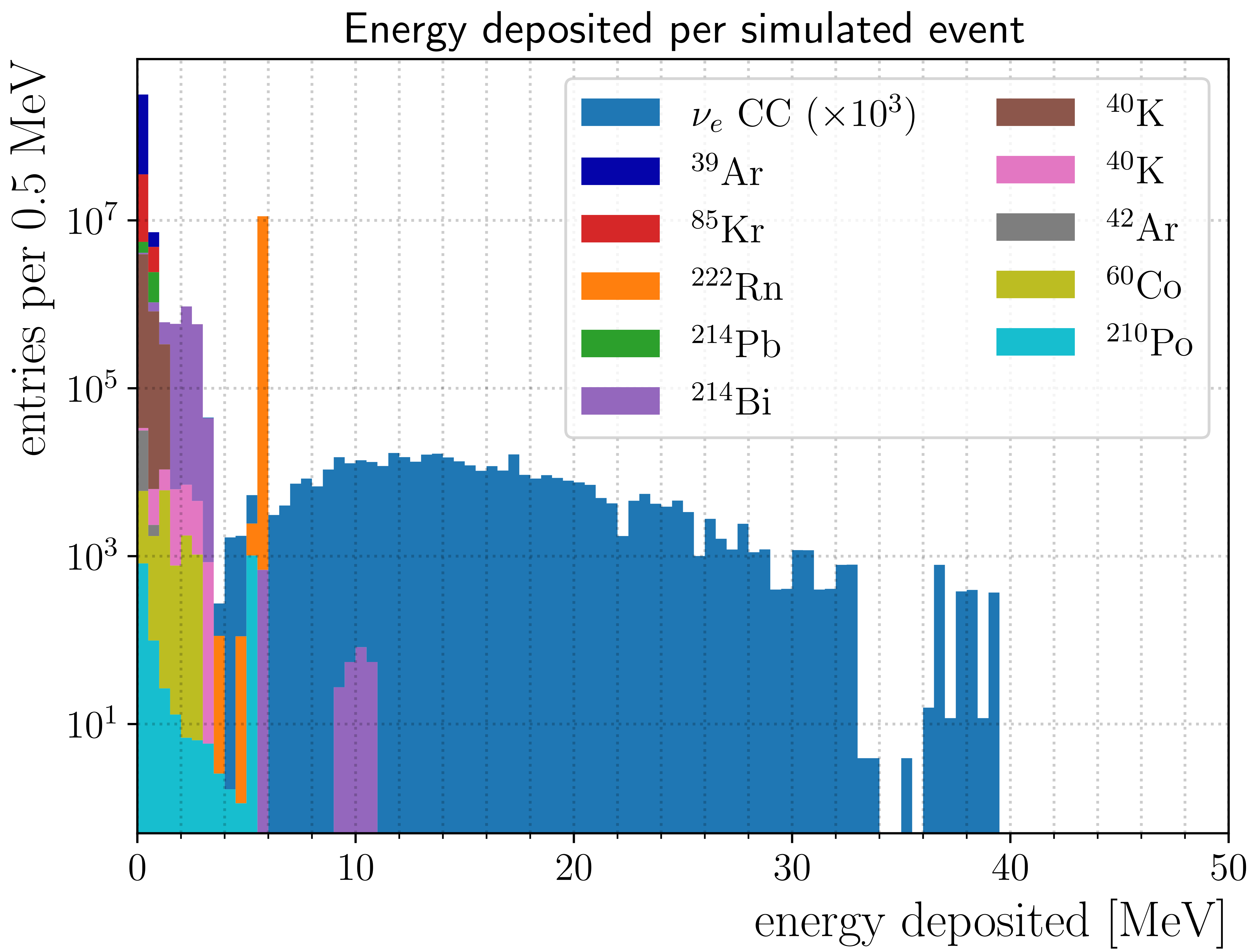
- Here, the sources for the CPA and APA were generated in the appropriate locations
- This does not account for any of the neutrons in the lab

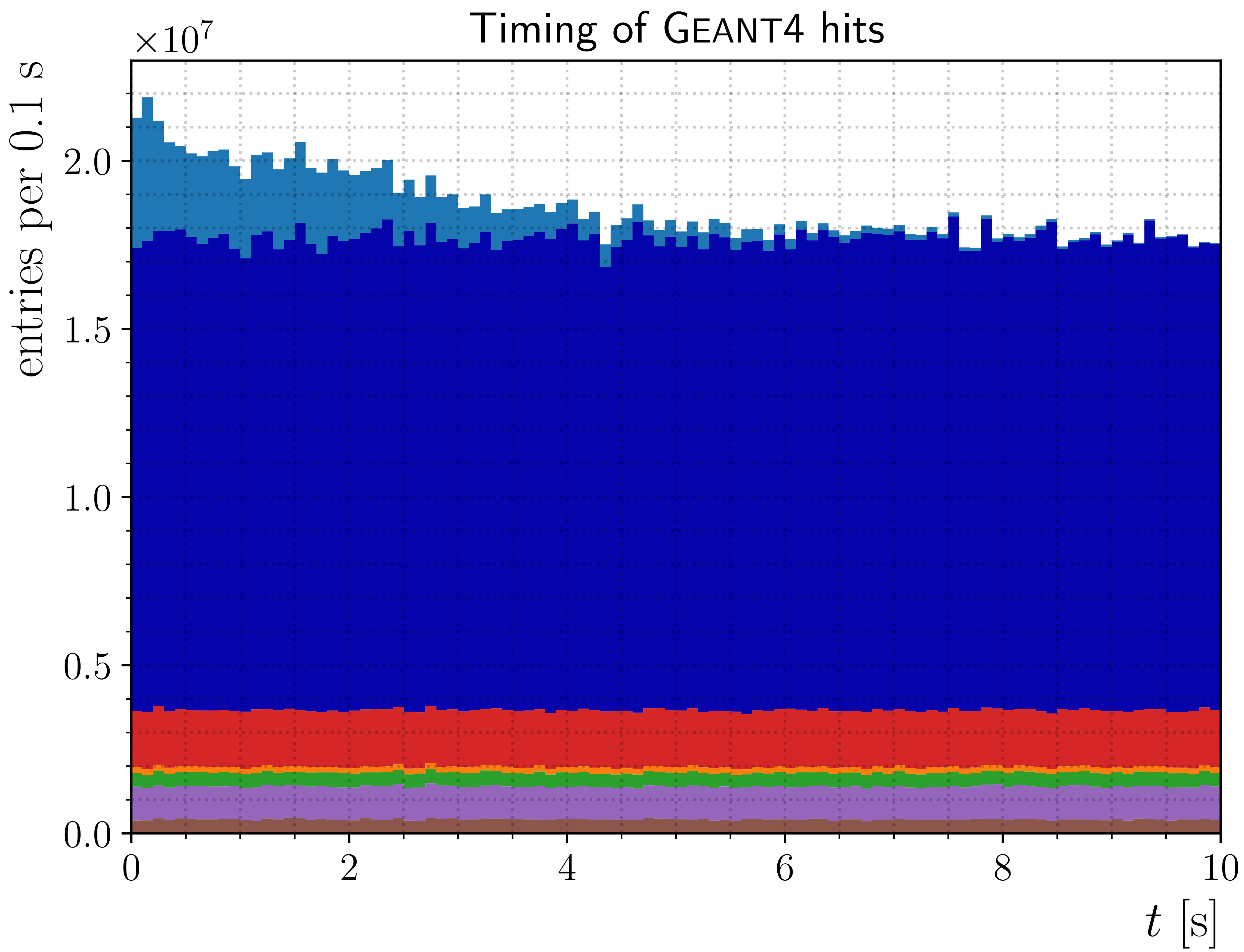
[1] J. Shi, "Studies of Radiological Backgrounds in the Dune Far Detector and the Sensitivity to the Solar Neutrino Day-Night Effect Using the Photon-Detector System," (2019), (Master Thesis), University of Manchester. Retrieved from http://www.manchester.ac.uk/escholar/uk-ac-man-scw:322661

[2] B. Abi, et al. (DUNE), "Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume IV: Far Detector Single-phase Technology," (2020), arXiv:2002.03010 [hep-ex].

Physics potential assessment of pixelated FD

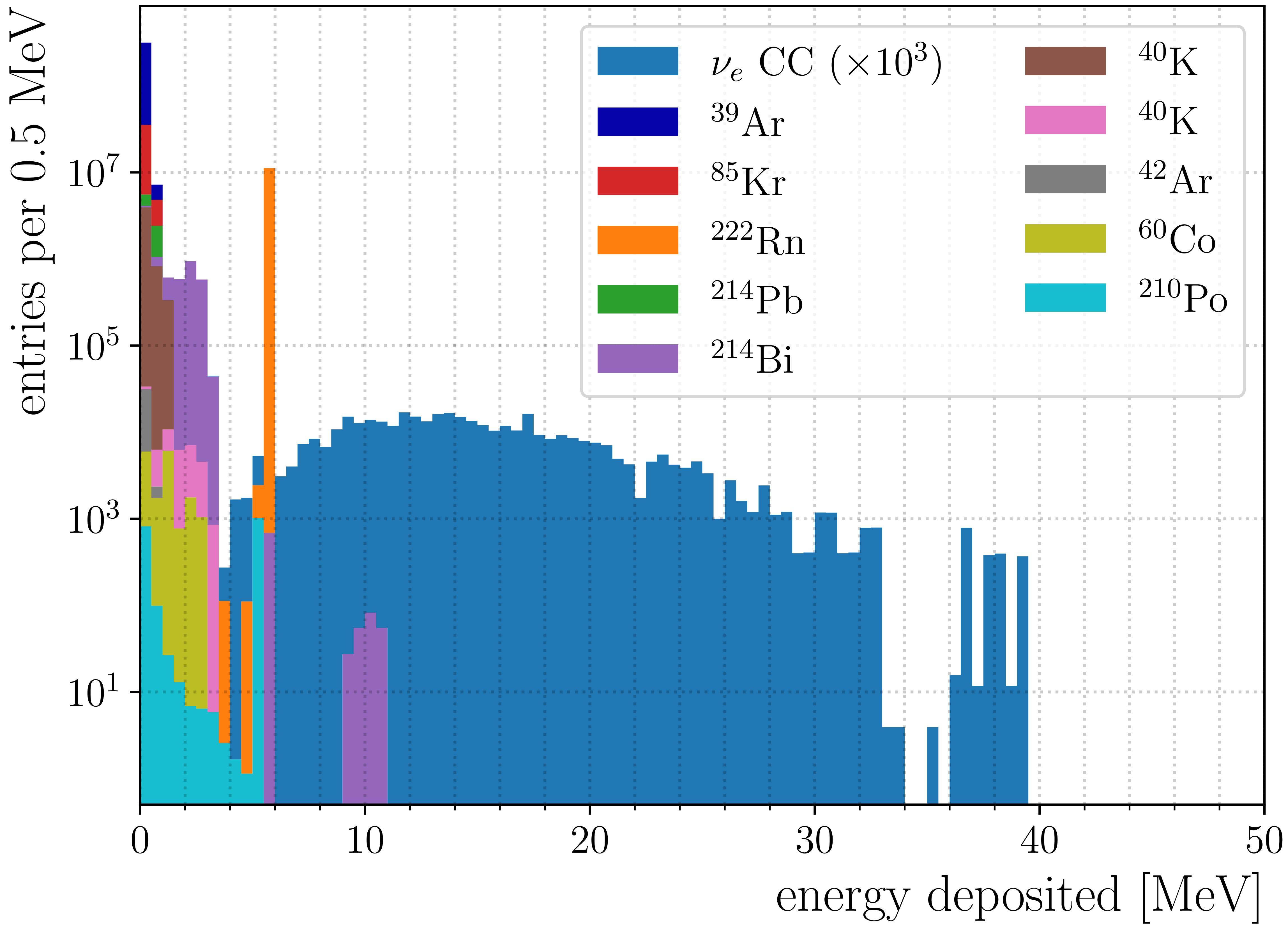
- Energy and time distributions of G4 hits from the supernova MC sample

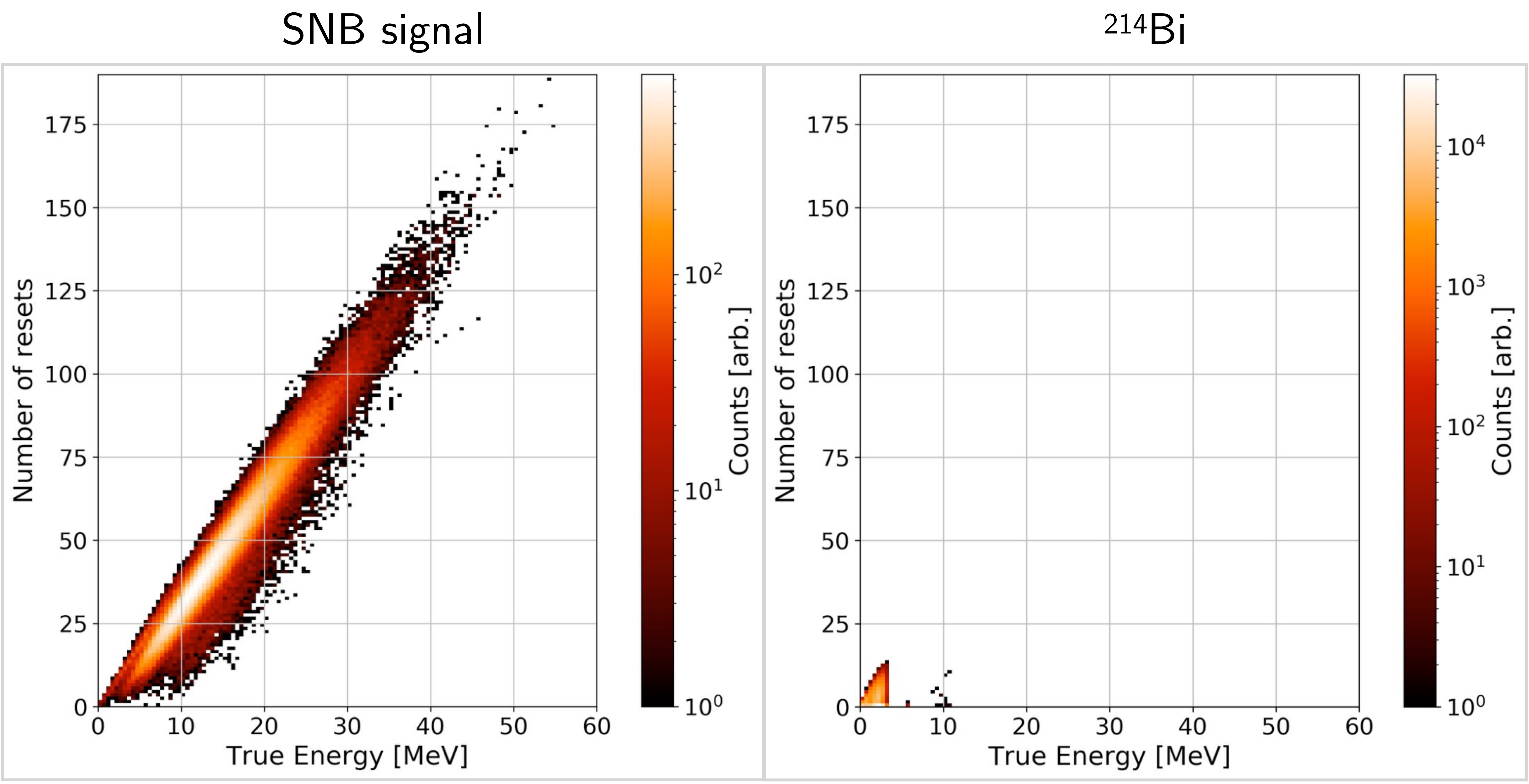




Physics potential assessment of pixelated FD

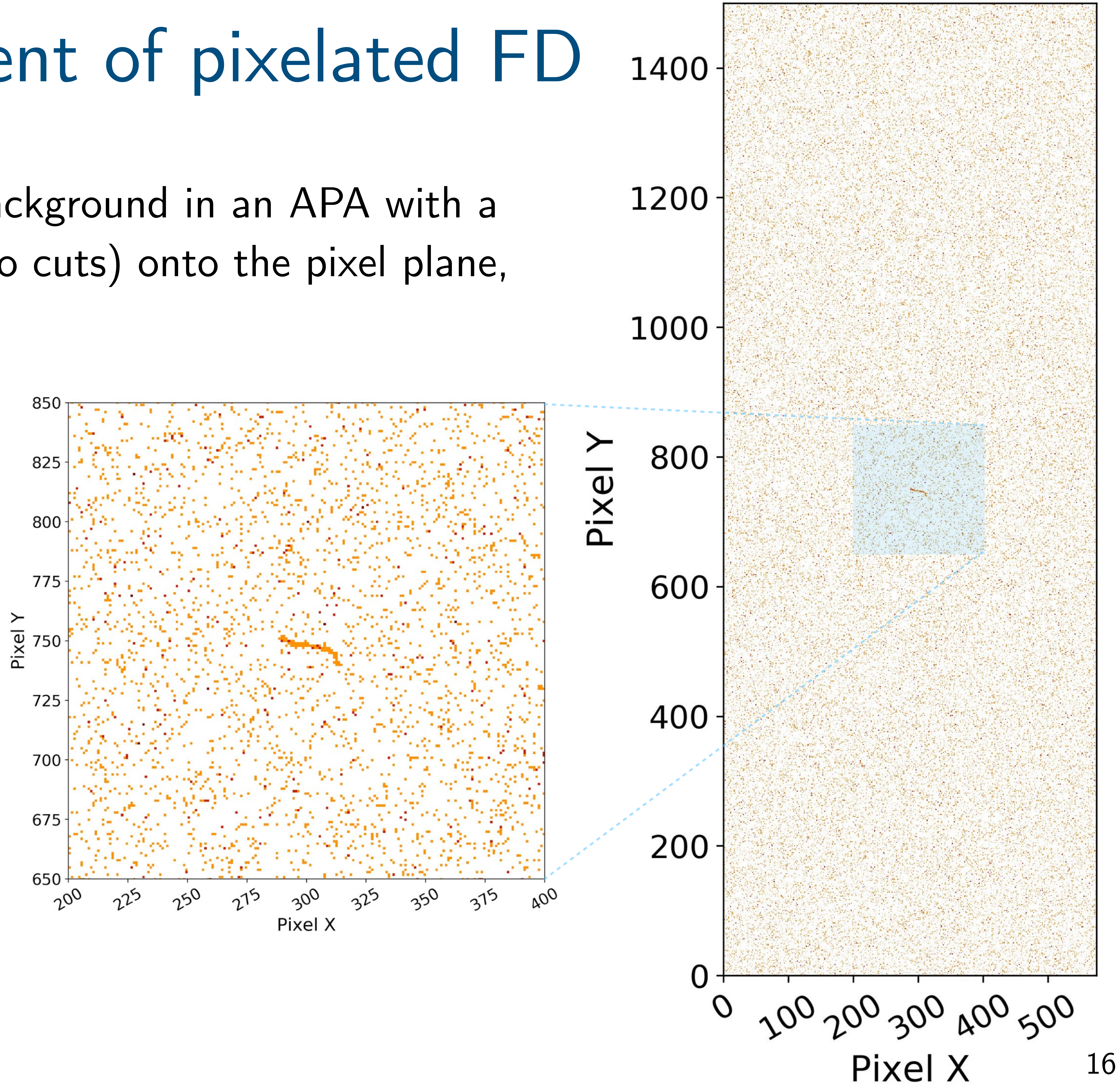
- After running the supernova MC sample through the RTD simulation, a simple reset-based cut can filter out the background





Physics potential assessment of pixelated FD

- When we project a full 10 seconds of background in an APA with a single supernova neutrino interaction (no cuts) onto the pixel plane, the electron track is clearly visible
- This readout doesn't require a trigger (the data is read out from the pixel plane automatically)
    - Can (potentially) use diffusion to place the event in the volume
    - Any light detection system will aid in finding the t_0 (R&D on-going)
- Represents ~2 MB of readout

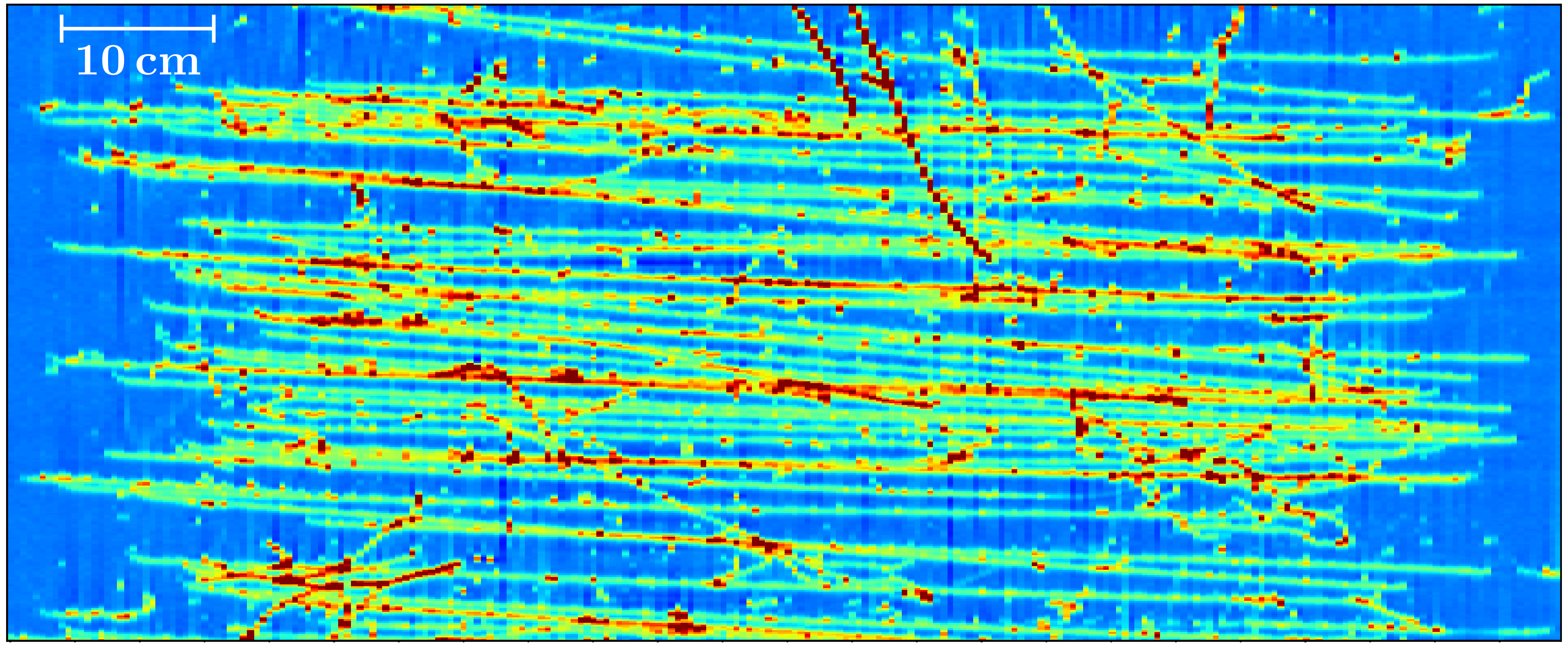


Near-term plans

- R&D studies will be performed using the planned Q-Pix test stand starting in the autumn of 2021
  - Cosmic ray muons and radioactive sources
- Simulations for the physics potential assessment of pixelated detectors
  - Working on understanding the low-energy physics detection limits:
    How low can we push the energy threshold of Q-Pix to enable the low-energy physics that we can achieve?
  - Supernova neutrinos
  - Solar neutrinos

One thing to note...

- We are new to low-energy physics and are not experts
  - This is what I'm used to seeing (from the LArIAT experiment)



- Any guidance or suggestions would be greatly appreciated!

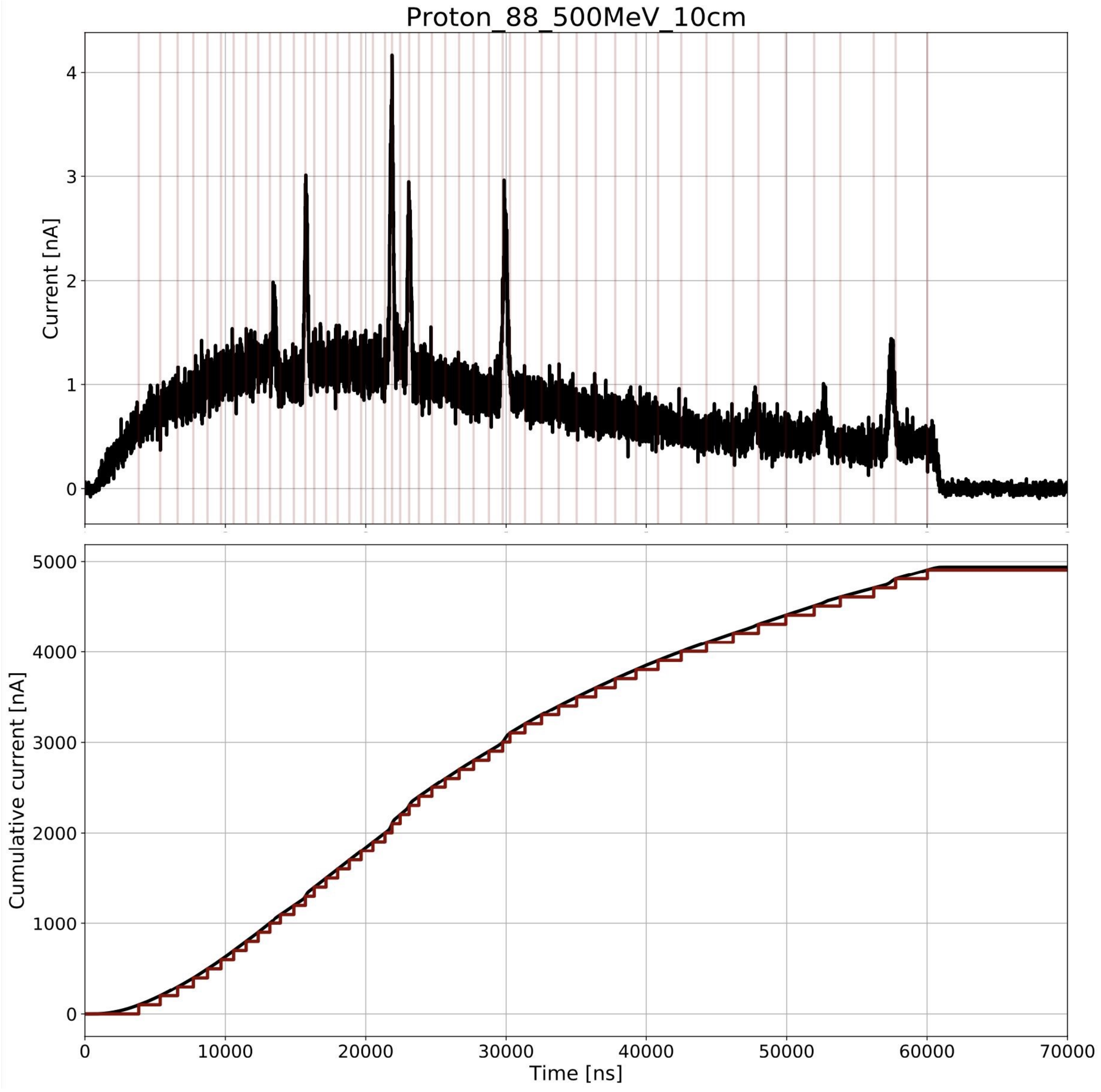
Summary

- Q-Pix is a new technology that is well-suited for large-scale detectors whose default state is to "do nothing," e.g., rare event searches
- Q-Pix will be capable of doing all of the same physics as "vanilla" DUNE with intrinsic 3D readout, significantly lower data rates, and continuous un-triggered readout
  - Promising early studies suggest that its low-energy physics capabilities will be even better
  - A more detailed study is underway and will be incorporated into the Q-Pix white paper

Backup

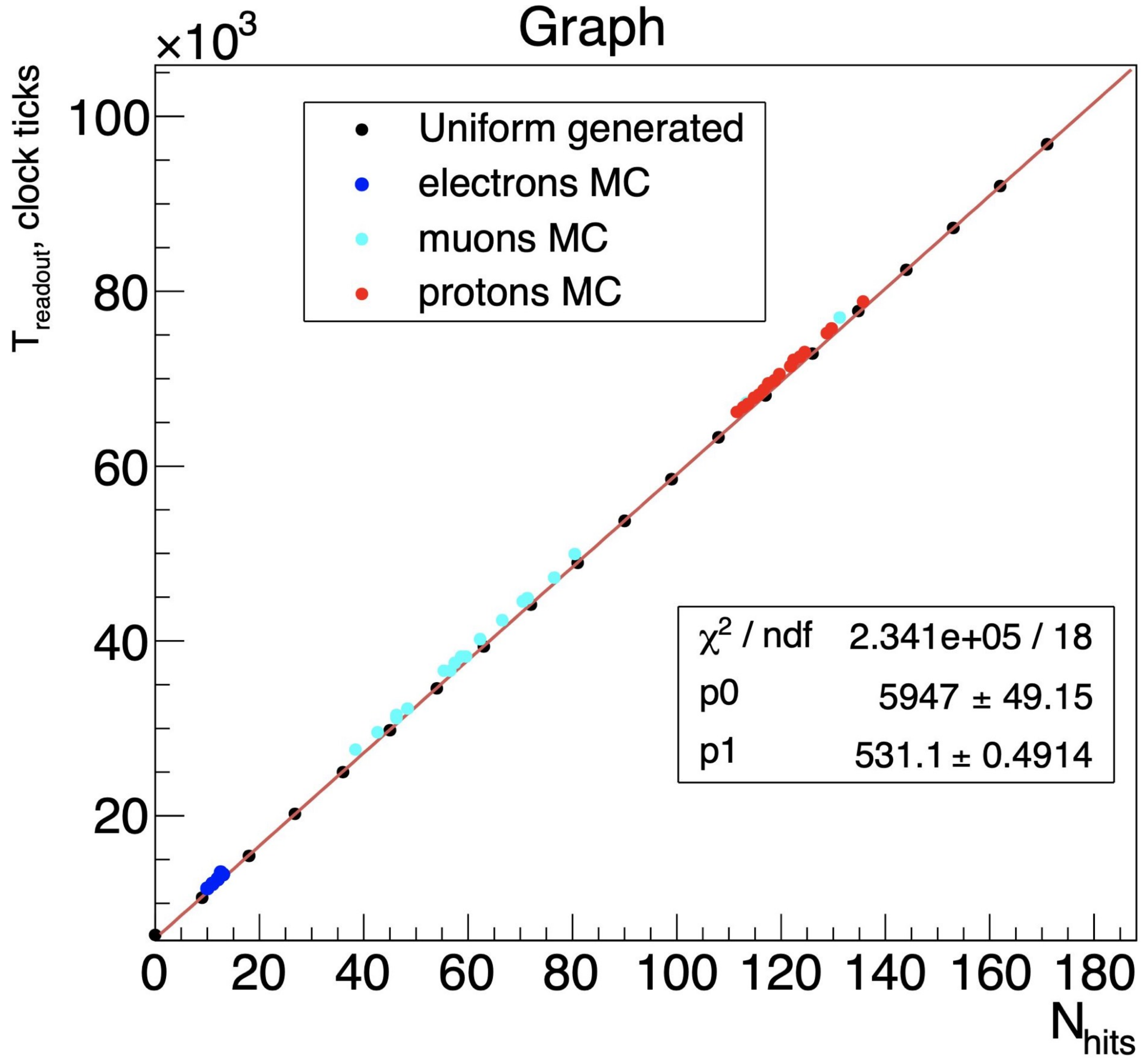
Physics potential assessment of pixelated FD

- The Q-Pix RTD simulation produces ionized electrons from GEANT4 hits, and are projected to the pixel plane (recombination is factored in, and the remaining electrons are diffused according to their starting drift position)
- They are then integrated on a pixel until the reset threshold is met
- This is a 500 MeV proton propagating in the direction of the pixel plane



Q-Pix digital logic test running on a FPGA

- Uniform time response to read out all resets stored in the local buffers



Time from diffusion

Calculation from Nucl. Instrum. Meth. A 816 (2016) 160-170, arXiv:1508.07059

- Measurement of longitudinal diffusion
  - Using a small sample of muons a novel technique in Q-Pix can be done

The electron current measured on a plane perpendicular to the drift direction at a distance d from a point source is given by

$$j(t) = \frac{n_0}{\sqrt{4\pi D_L t}} \exp\left(-\frac{(d - vt)^2}{4D_L t} - \lambda vt\right) \quad (2)$$

where n_0 is the initial electron density, v is the drift speed, t is the arrival time of the electrons on the plane, and λ is equal to the inverse of the mean free path of the electron.

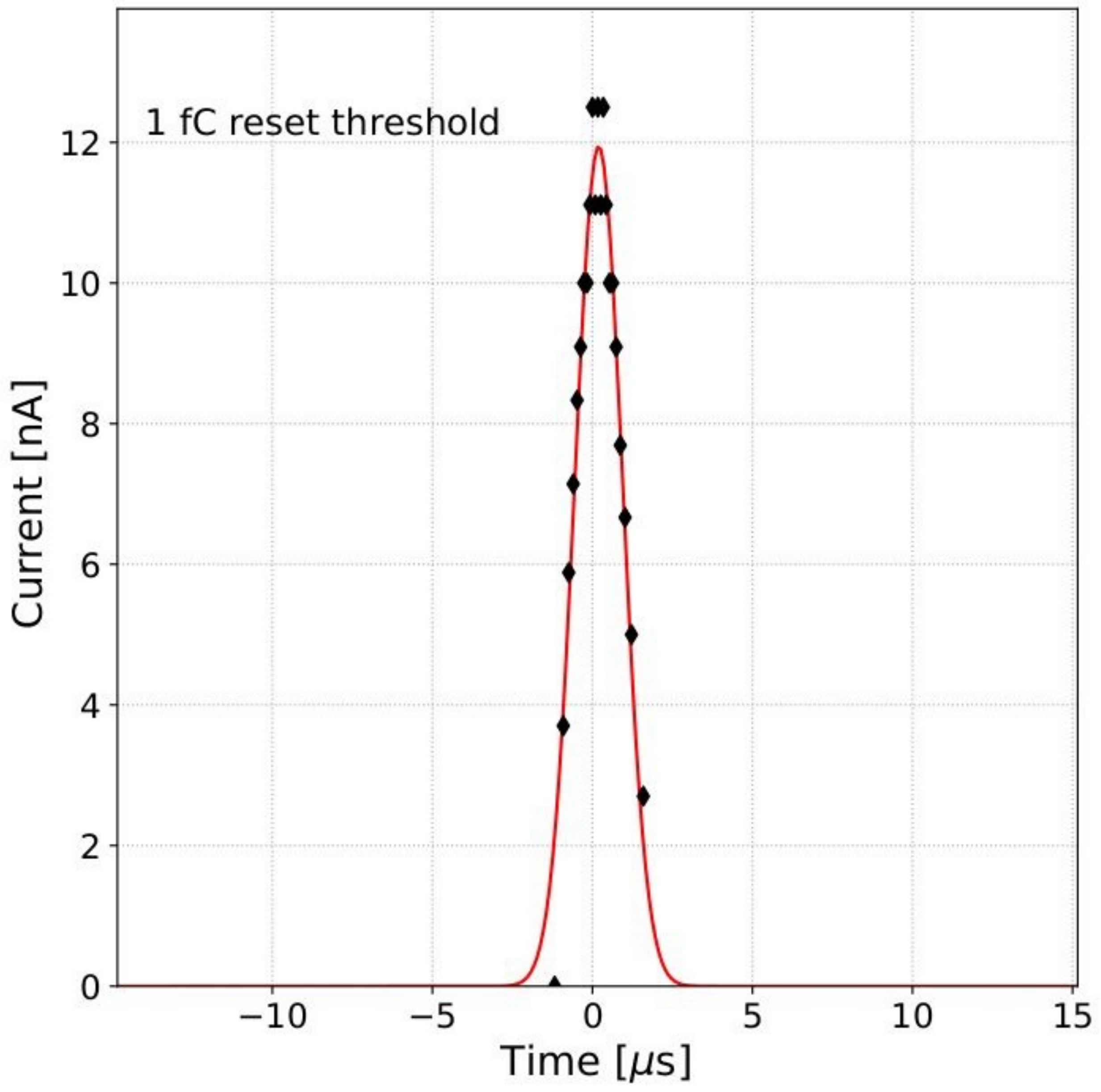
This function approaches a true Gaussian when $d \cdot v$ is large and D_L is small. For the case being considered $v = 0.1648 cm/\mu s$ and $d > 10cm$ so, $d \cdot v \geq 1.6 \times 10^5 cm^2/s$. This is large when compared to $D_L = 6.82 cm^2/s$.

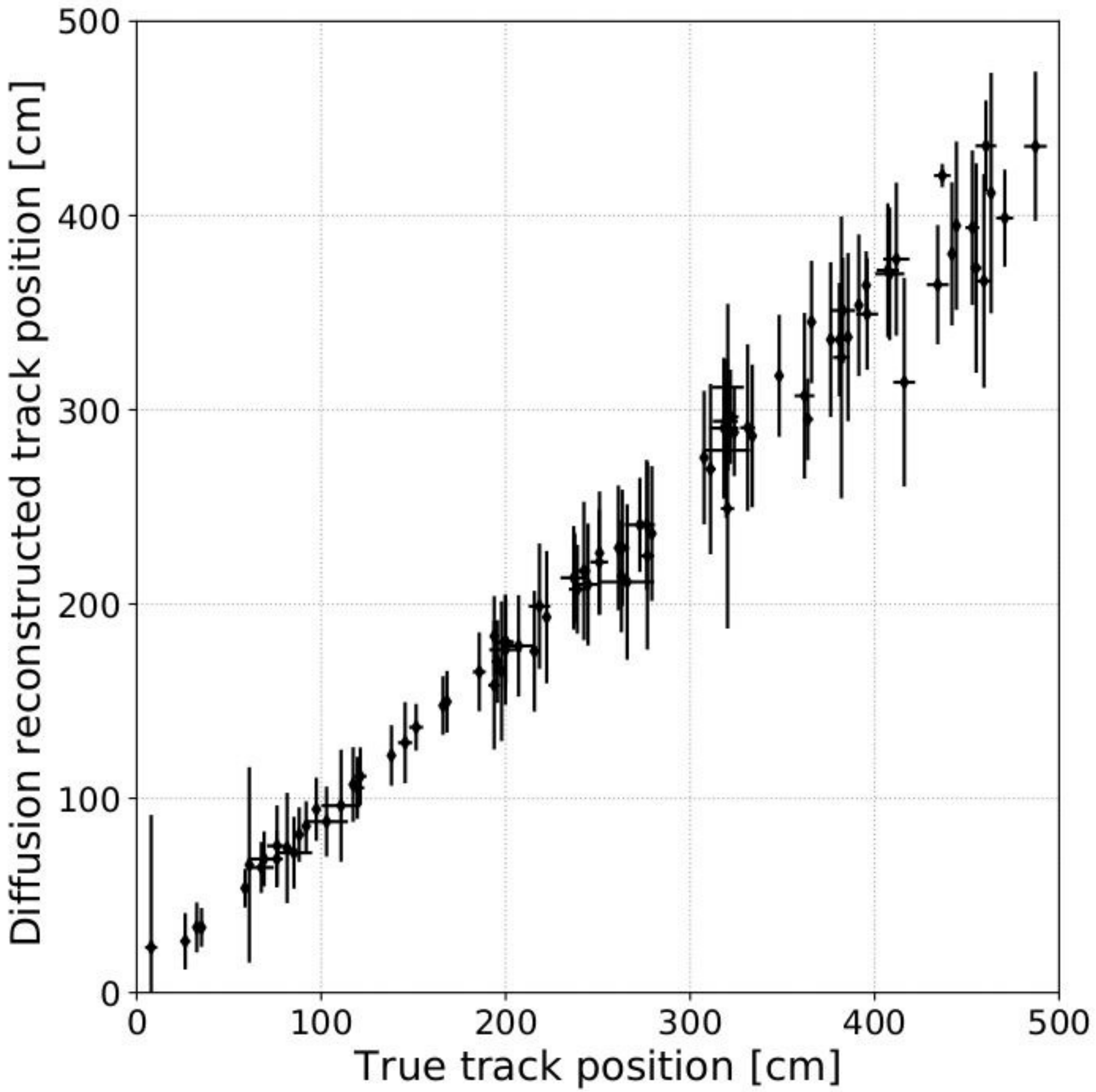
The Reset Time Difference (RTD) literally stands for

$$RTD = \frac{\Delta Q}{\Delta t} = j(t) \quad (6)$$

Thus if we plot the average RTD seen over a sample as a function of the drift distance, we should see the Gaussian relationship

Time from diffusion





- By looking at the RMS distribution of the RTDs, you can work the problem the other way
  - Assume the diffusion constants
  - Drift velocity is known (at a given E-field)
  - Solve for the reconstructed drift distance
- This could (potentially) allow you to reconstruct an event's t_0 without a photo-detector

Q-Pix and light detection using amorphous selenium

- Literature search suggests that the absorption coefficient for a-Se at 128 nm is 130 μm^{-1}
    - This would suggest a 1 μm thick thin film would already have >99% QE for converting 128 nm light into charge