QPIX, a novel pixel technology for very large noble element detectors

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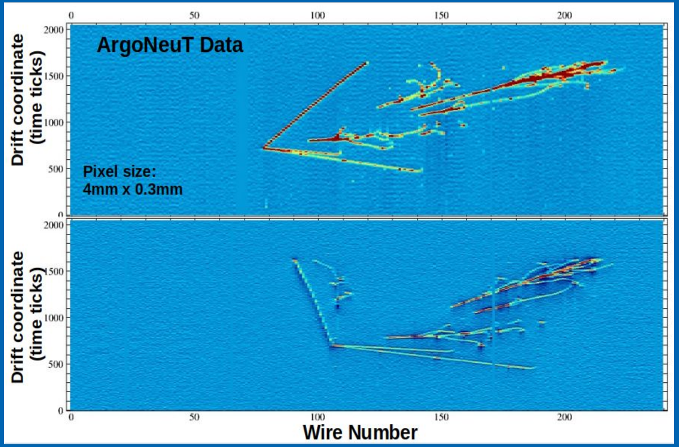
On behalf of the Q-Pix consortium

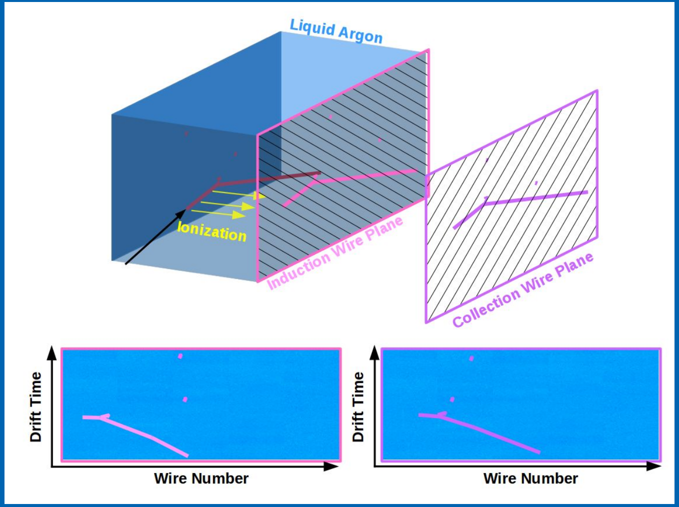
Q-Pix consortium would like the thank the DOE for its support via DE-SC0020065 award, DE-SC 0000253485 award, and FNAL-LDRD-2020-027

Work based on original paper by Dave Nygren (UTA) and Yuan Mei (LBNL): arXiv:1809.10213

Why pixelated liquid noble TPCs?

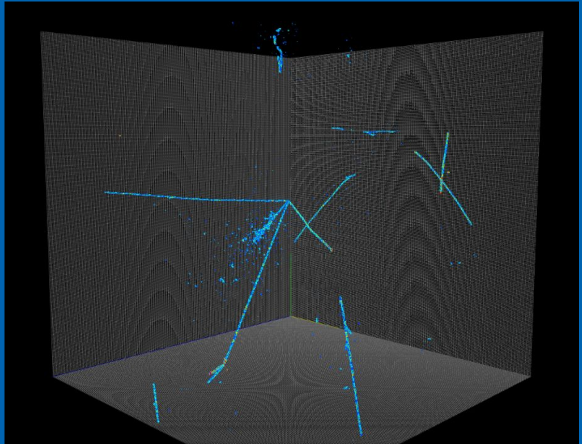
- Noble Element Time Projection Chambers offer access to very high quality information
- Leveraging this information allows unprecedented access to detailed neutrino interaction specifics from MeV - GeV scales
- Capturing this data w/o compromise and maintaining the intrinsic 3-D quality is an essential component of all readouts!
- Conventional charge readout uses sets of wire planes at different orientations to reconstruct the 3D image
  - *Challenge in reconstruction of some topologies*
- 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 detector?**
  - **In a perfect world we would compare the complete readout and reconstruction of two detectors side by side to do this**
    - *Such a chain doesn't exist!*



Credit: arxiv: 1903.05663

- **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

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

- Simulation studies comparing the readout of 2D projective Liquid Argon TPCs (LArTPC's) to 3D pixel LArTPC's shows that **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 in Neutrino-ID classification and final state topology ID

Table 2: Confusion matrix for neutrino interaction.

Predicted Label	3D Truth Label ν_e CC	3D ν_μ CC	3D NC	2D Truth Label ν_e CC	2D ν_μ CC	2D NC
ν_e CC	**0.96**	0.01	0.02	0.93	0.02	0.03
ν_μ CC	0.02	**0.95**	0.07	0.02	0.91	0.07
NC	0.02	0.04	**0.91**	0.05	0.07	0.90

Table 3: Confusion matrix for the proton multiplicity classification.

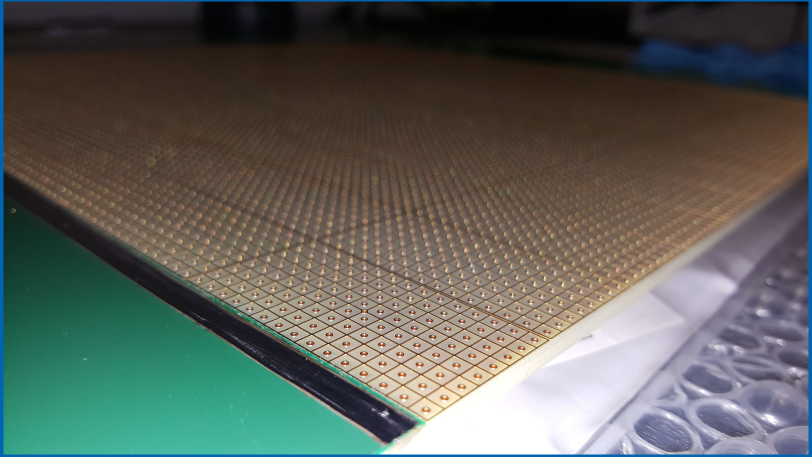
Pred. Label	3D Truth Label $N_p = 0$	3D $N_p = 1$	3D $N_p \geq 2$	2D Truth Label $N_p = 0$	2D $N_p = 1$	2D $N_p \geq 2$
$N_p = 0$	**0.928**	0.076	0.005	0.841	0.064	0.005
$N_p = 1$	0.062	**0.884**	0.059	0.143	0.853	0.069
$N_p \geq 2$	0.010	0.040	**0.936**	0.016	0.084	0.926

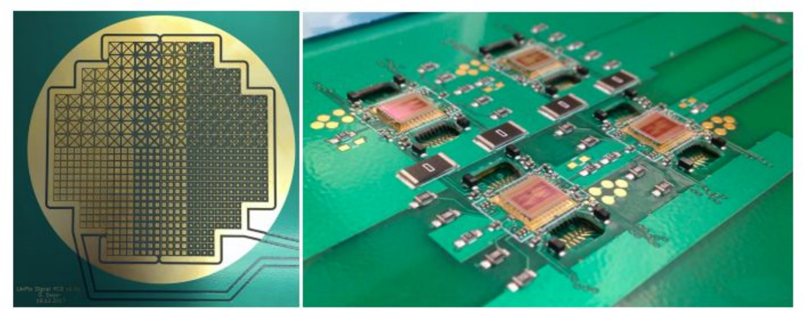
JINST **15** P04009 *(arXiv:1912.10133)*

****** 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 (Example: 2 meter x 2 meter readout)
  - 3mm wire pitch w/ three planes = 2450 channels
  - 3mm pixel pitch = 422,000 channels
- LArPix (JINST 13 P10007) readout has pioneered this frontier showing a low power pixel based readout can be done
  - Currently targeted to the DUNE near detector to allow a LArTPC to cope with the high event rates
  - Other solutions are being explored for kiloton scale underground LArTPCs

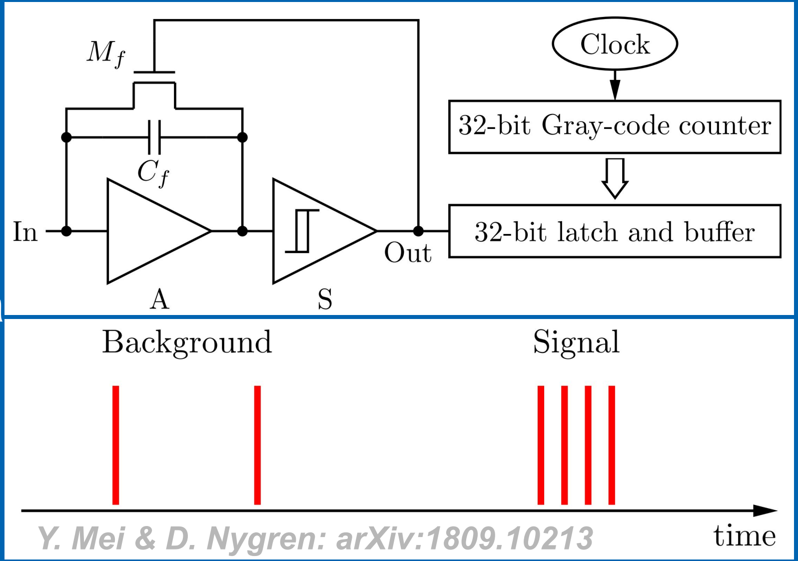


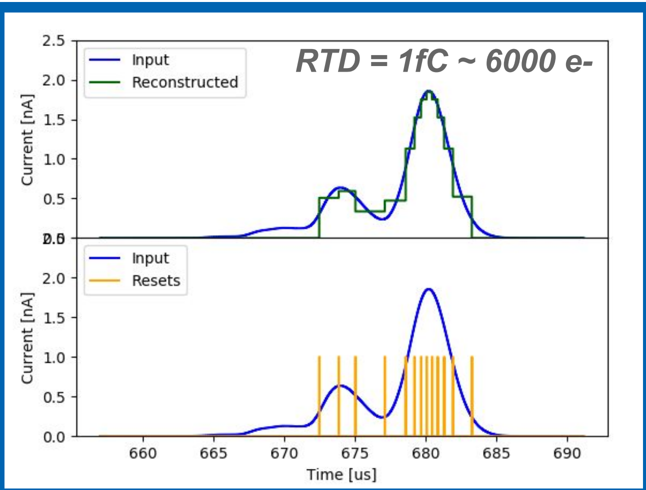


(JINST 13 P10007)

An unorthodox solution: Q-Pix

- The Q-Pix pixel readout follows the "electronic principle of least action"
  - Don't do anything unless there is something to do
- Offers an innovation in signal capture with a new approach in measuring time-to-charge:(ΔQ)
  - Keeps the detailed waveforms of the LArTPC
- Take the <u>difference</u> between <u>sequential</u> resets
  - Reset Time Difference = RTD = ΔQ
- RTD's 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





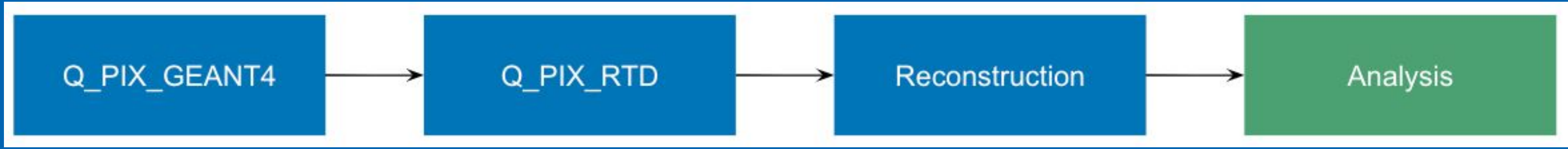
Current state of Q-Pix (pardon the pun)

- First prototype Q-Pix ASIC will read 16-32 pixels
  - We envision each pixel will have a 4mm 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 the front end and digital logic can handle high energy (DUNE scale) neutrino interactions with no foreseen problems
  - DUNE data rate ~9 GB/s per APA (DUNE TDR Deep Underground Neutrino Experiment)
  - Q-Pix data rate ~ 250 kB/s per APA
- Currently building a set of sister TPC's at UTA and Harvard (UTA/H) to test the Q-Pix readout, and explore the low energy detection limits.
  - Also imagining various physics prototype detectors

See Gang Liu's Talk
https://indico.fnal.gov/event/46746/contributions/210447/

Q-Pix work in the context of DUNE

We have developed custom software to produce current profiles from Geant4



The simulated geometry is a single APA drift region (6 m tall × 2.3 m wide × 3.6 m drift). An APA region holds ~50,000 L which is ~70,000 kg of LAr (~70 tons).

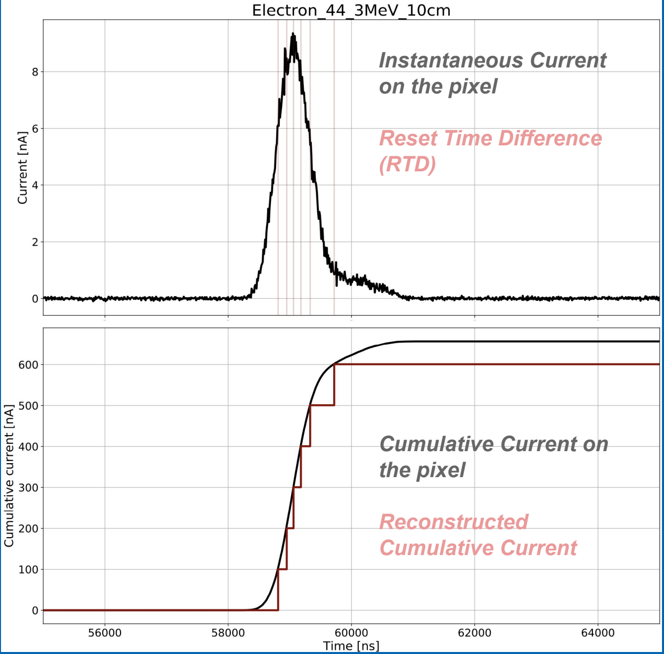
A 10 kT SP DUNE module is 200 APA drift regions which is about 13.9 kT of total volume

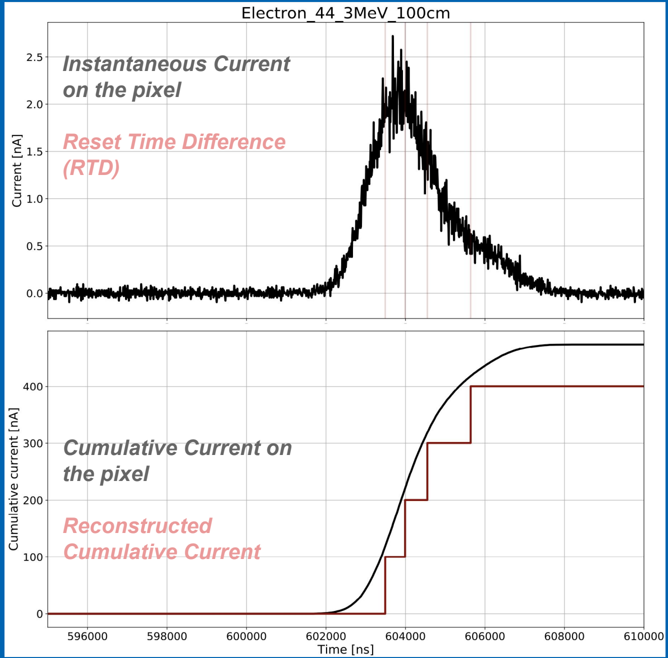
Here the methodology is to only simulate 1 APA, then 200 of those would mimic a single DUNE module response

We are simulating a 2.3 m × 6 m pixel readout area with a 3.6 m drift length

Q-Pix work in the context of DUNE

The RTD code produces a list of “real” electrons from the Geant4 hits, recombination has been factored in and the remaining electrons are then diffused according to there true position. Then they are integrated on a pixel until the reset threshold is met.

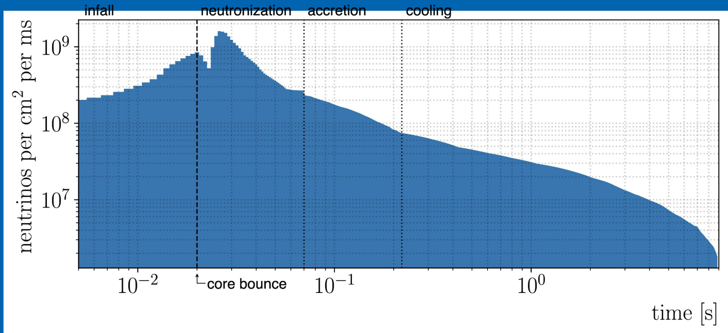




Q-Pix work in the context of DUNE (Supernova)

Defined a supernova time window of 10s to account for the burst.

The first step was to see if a supernova is observable above the DUNE radiogenic backgrounds.



Here the sources for the CPA/APA were generated in the appropriate XY locations at the border of the LAr volume

This does not account for any of the lab neutrons.

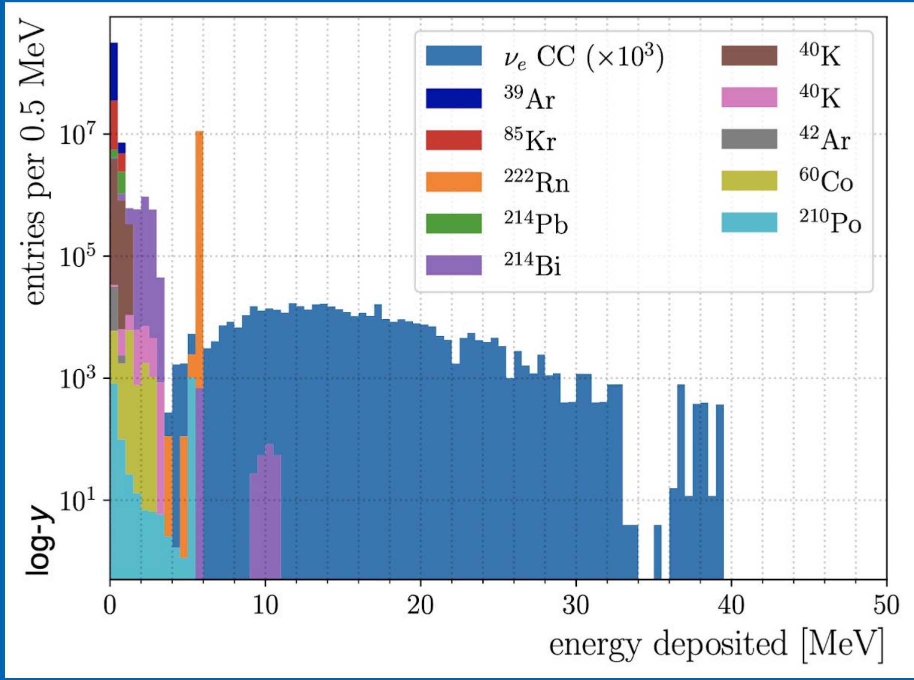
Isotope	Rate [Bq/kg]	Region	Region mass [kg]	Rate [Bq]	Time window	Number of decays
Po-210	0.2	PD [Bq/m^2]	2.46856	0.493712	10	4.93712
Co-60	0.0455	CPA	90	4.095	10	40.95
K-40	4.9	APA	258	1,264.2	10	12,642
Ar-39	1.010	bulk LAr	70,000	70,700	10	707,000
Ar-42	0.000092	bulk LAr	70,000	6.44	10	64.4
K-42	0.000092	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

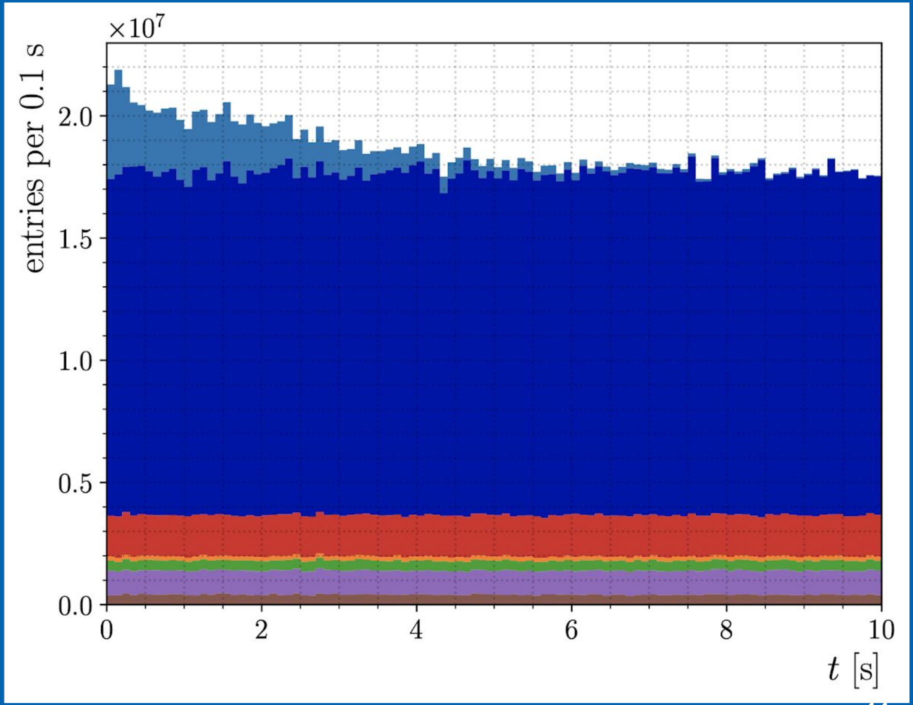
(There are 200 APA drift volumes in a 10 kton SP module.)

[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].

Q-Pix work in the context of DUNE (Supernova)

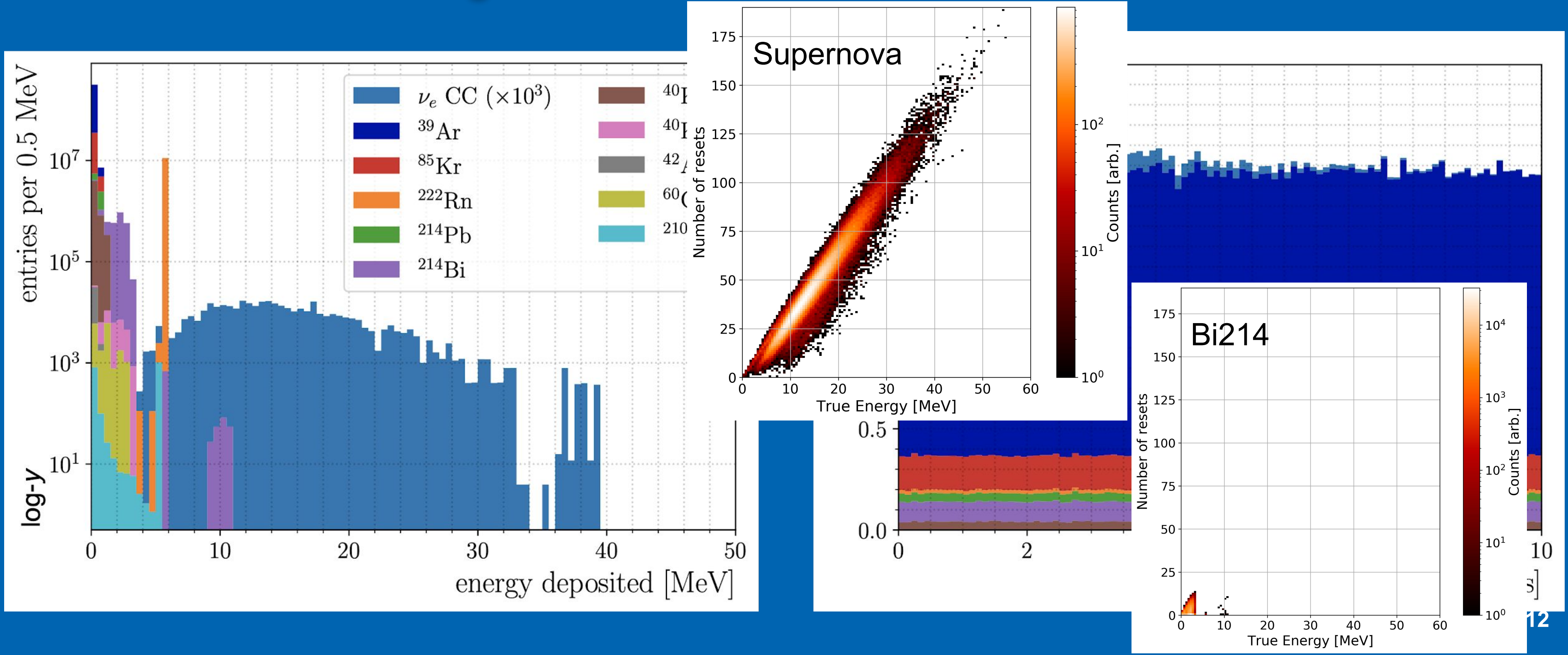
The Geant4 time and energy distributions form the sample production for the full 10s window.





Q-Pix work in the context of DUNE (Supernova)

After running the files through the RTD software an obvious reset based cut would filter out the background.



Q-Pix work in the context of DUNE (Supernova)

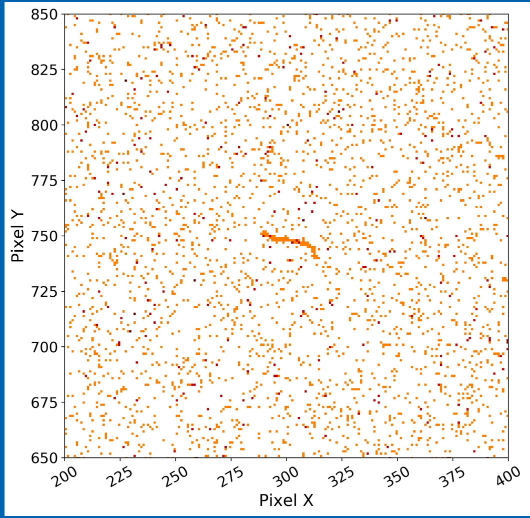
Compressing a **full 10s of background in an APA with a single supernova neutrino** (no cuts) on to the pixel plane the neutrino track is clearly visible.

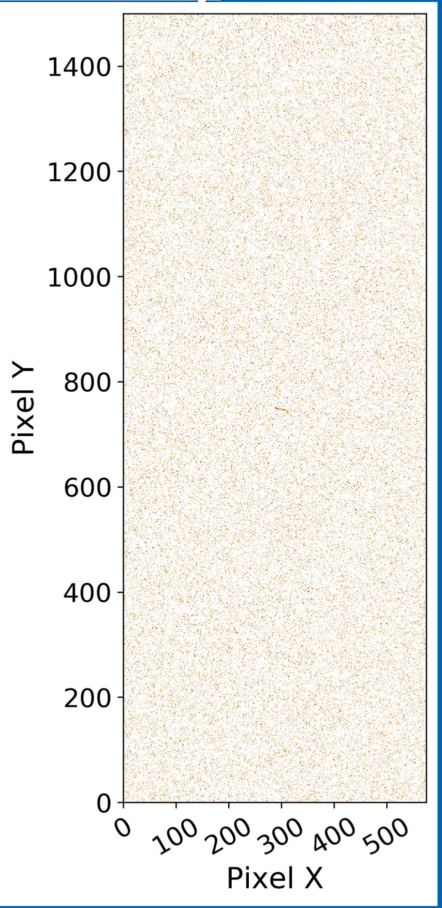
This readout doesn't require a trigger (the data is readout from the pixel plane automatically)

-- Can (potentially) use diffusion to place the event in the volume

-- Any light detection system will aid in finding the t_0 (R&D ongoing)

-- Represents ~2MB of readout





Physics Simulation

Calculation from: https://arxiv.org/pdf/1508.07059.pdf

- **Measurement of Longitudinal Diffusion**
  - Using a small sample muons a novel technique in Q-Pix can be seen

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

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

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.

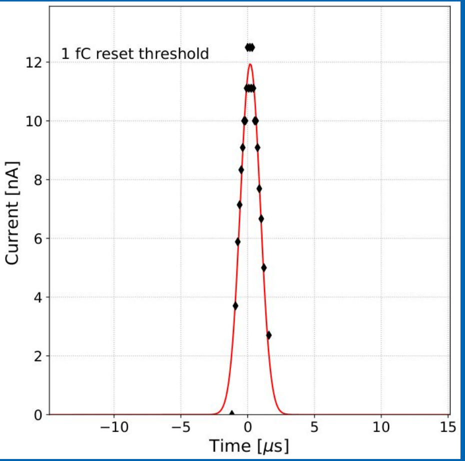
This function approaches a true Gaussian when $d \cdot v$ is large and D_L is small. For the case being considered $v = 0.1648cm/\mu s$ and $d > 10cm$ so, $d \cdot v \geq 1.6 \times 10^5 cm^2/s$. This is large when compared to $D_L = 6.82cm^2/s$.

The Reset Time Difference (RTD) literally stands for

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

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

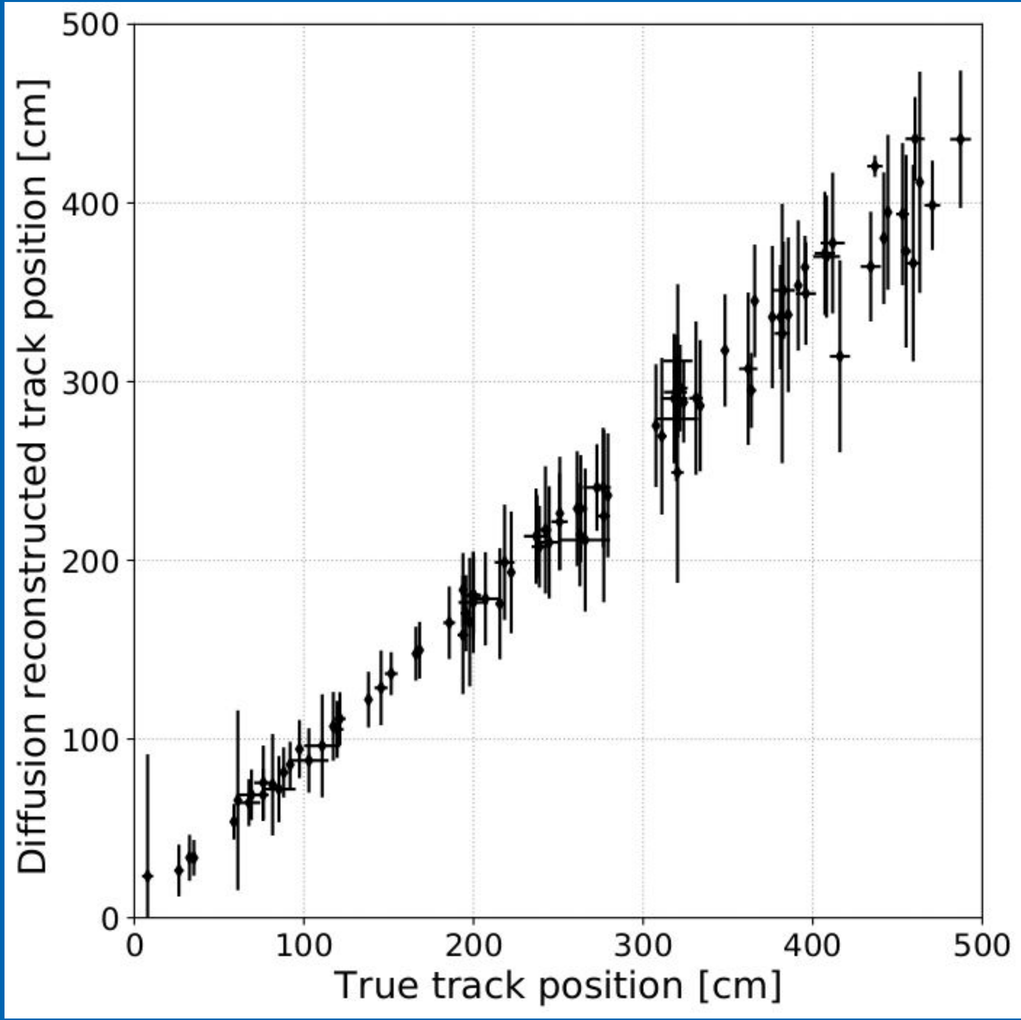
Time from Diffusion



By looking at the RMS distribution of the RTD's you can work the problem the other way!

- ***Assume the diffusion constants***
- ***Drift speed is known (at a given field)***
- ***Solve for the reconstructed drift distance***

This could (potentially) allow you to reconstruct an event's t0 without a photon detector



Q-Pix work in the context of DUNE

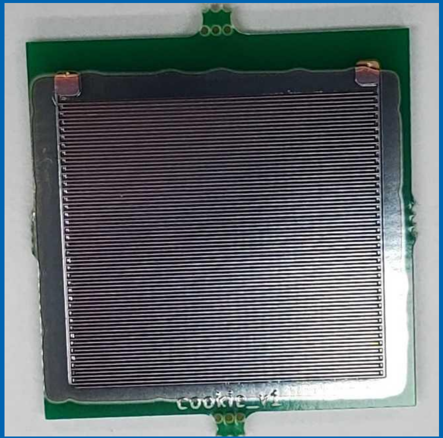
- Further work is underway to understand the detection limits.
- However, the preliminary results are promising!
  - A more complete analysis of beam & supernova neutrino performance will be part of the Q-Pix white paper.
- A particularly interesting aspect is determined t0 via diffusion and work is ongoing.
- Beam simulations are being developed in order to gauge Q-Pix's performance.

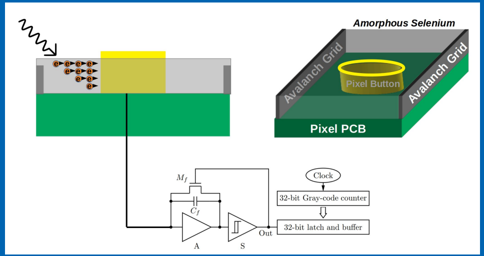
Q-Pix and Light Detection? (Amorphous Selenium)

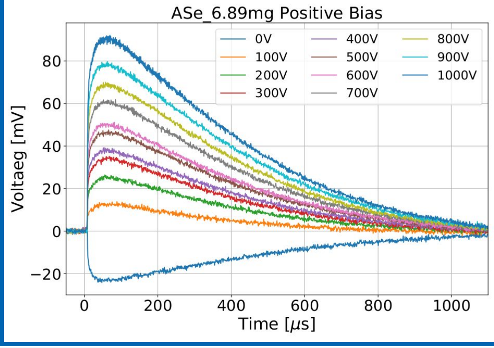
Literature search suggests the absorption coefficient for a-Se at 128nm is 130 μm^{-1}

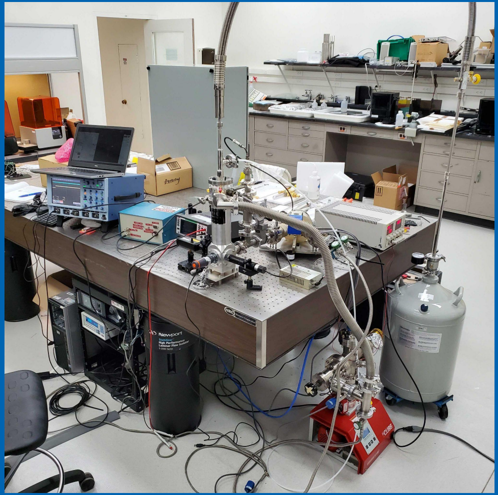
- This would suggest a **1μm thick thin film would already be >99% QE** for converting 128 nm light to charge!

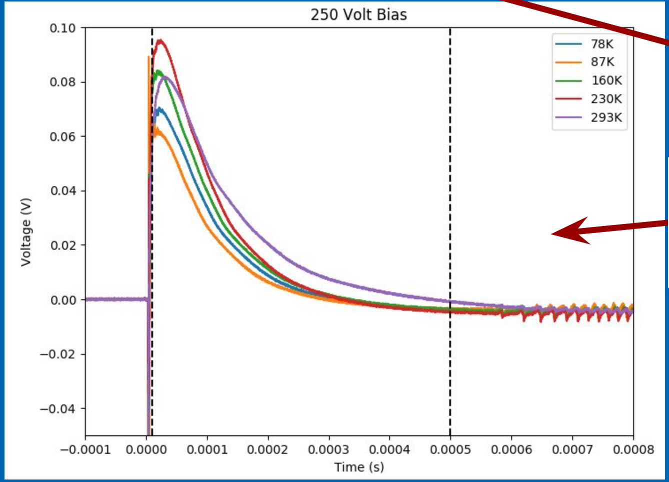
Demonstrated response in vacuum under exposure to a xenon flash lamp











Recent measurements at ORNL show response at cryogenic temperatures!

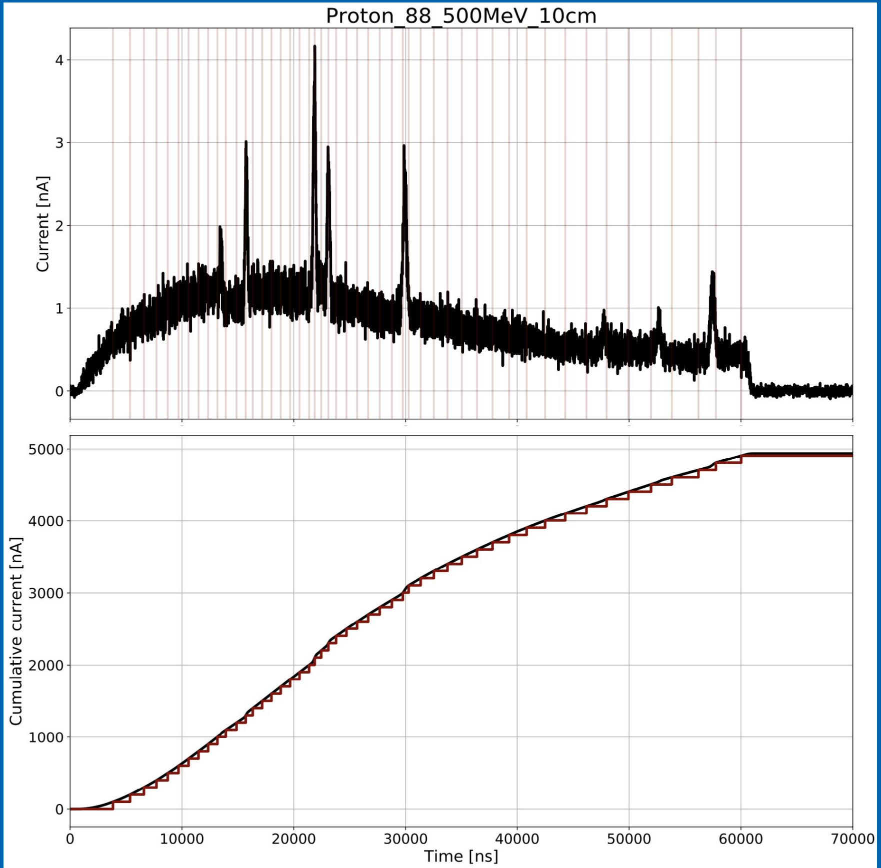
See Elena Gramellini's Talk
https://indico.fnal.gov/event/46746/contributions/210180/

Conclusions

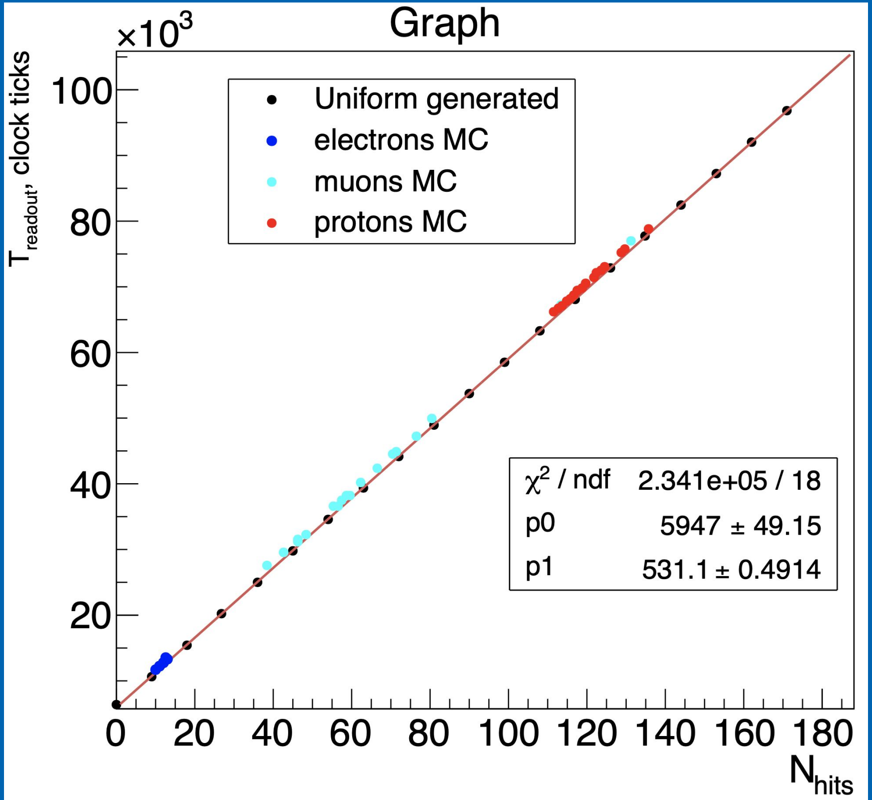
- Q-Pix is a new technology which is suited for large detectors whos standard state is “do nothing” e.g. rare events.
- Q-Pix will be capable of doing all of the same physics as “vanilla DUNE” with intrinsic 3D readout, significantly lower data rates, continuous untriggered readout
    - Promising early studies suggest it should be capable of doing the low energy physics even better!
    - A more detailed study is underway and will be incorporated into the Q-Pix white paper.
- Promising progress is being made on obtaining t0 from diffusion.
- Development of a “all in one” charge + light sensor is underway with permosing preliminarily results.

Backup

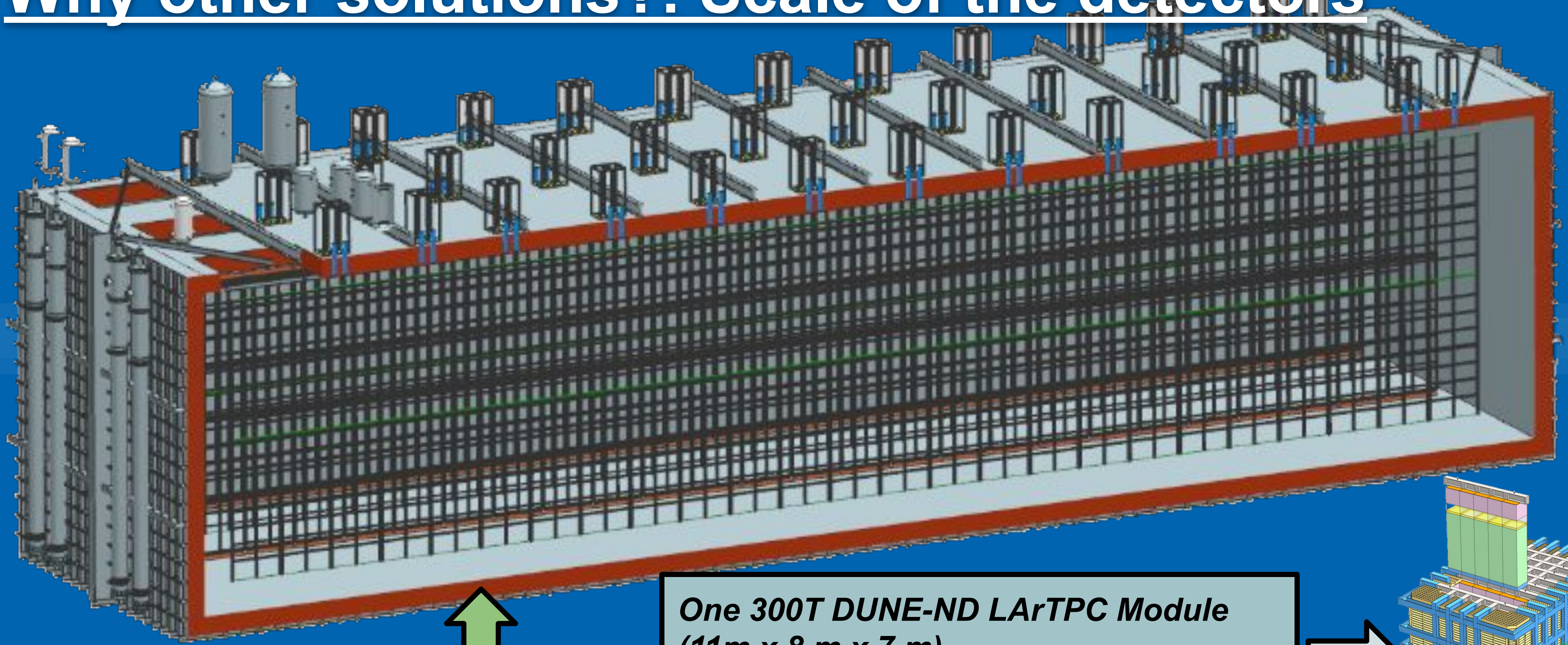
Q-Pix response to the “higher limit” of the expected physics. This beaning a 500 MeV proton shot in the direction of the readout board.



Q-Pix digital logic test (running on an FPGA). Shows a uniform time response to readout all resets stored in the local buffers.

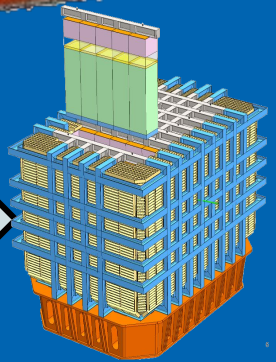


Why other solutions?: Scale of the detectors



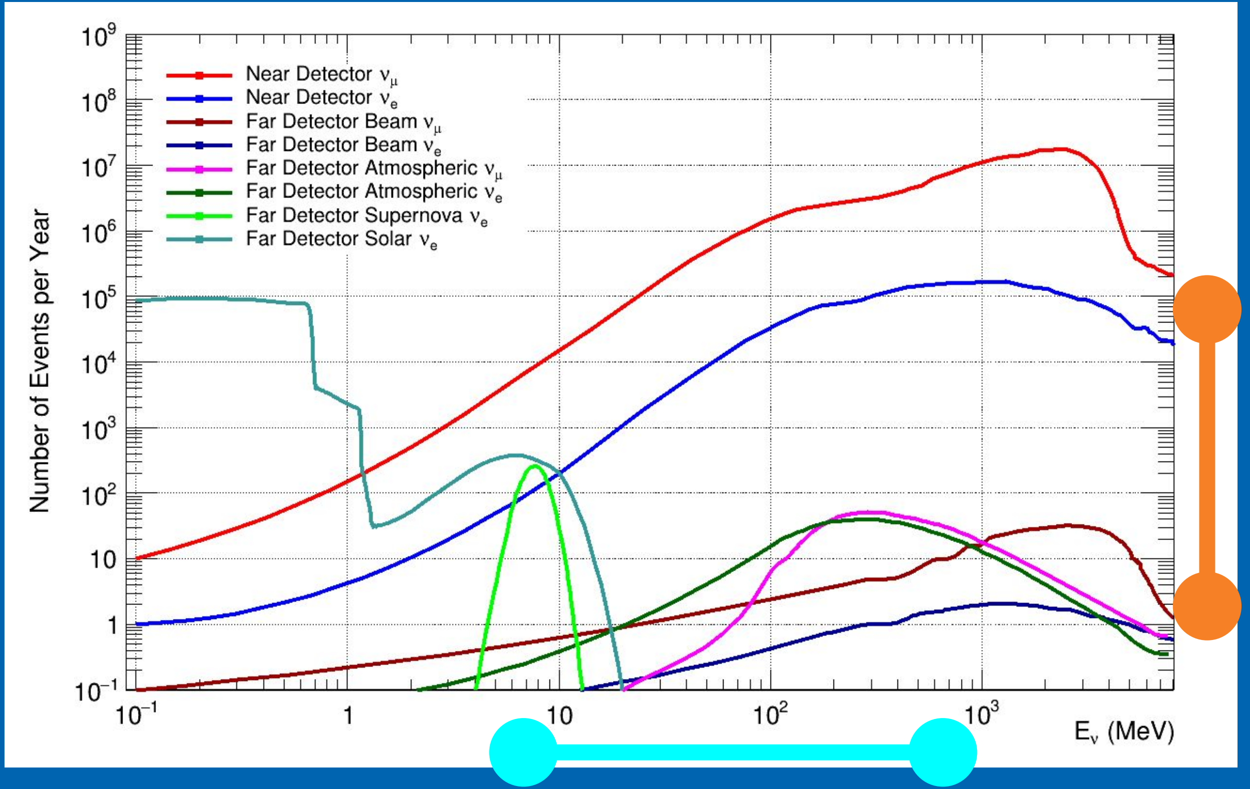
One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE
$\mathcal{O}$(130 million) 4mm pixels

One 300T DUNE-ND LArTPC Module (11m x 8 m x 7 m)
$\mathcal{O}$(7 million) 4mm pixels



~18x more channels Far/Near

Scale of the detectors



Estimated event rates in the DUNE LArTPC Near Detector (ArgonCube) and a single DUNE 10kTon Far Detector Module

- **10^5 - 10^6 difference in event rate from beam events near/far**
- **Same number of events from the beam as from astrophysical sources**
  - **Spans 10^2 MeV energy range**

Scaling pixel based readout to the multi-kiloton detector may require an “unorthodox” solution