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

LE physics readout for pixel based LArTPC

Austin McDonald
On behalf of the Q-Pix consortium

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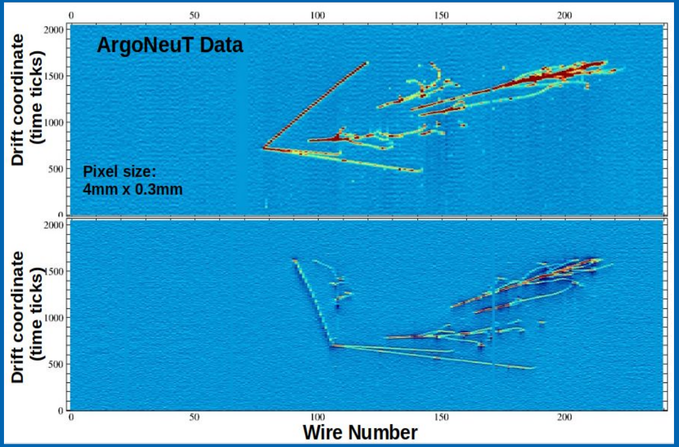
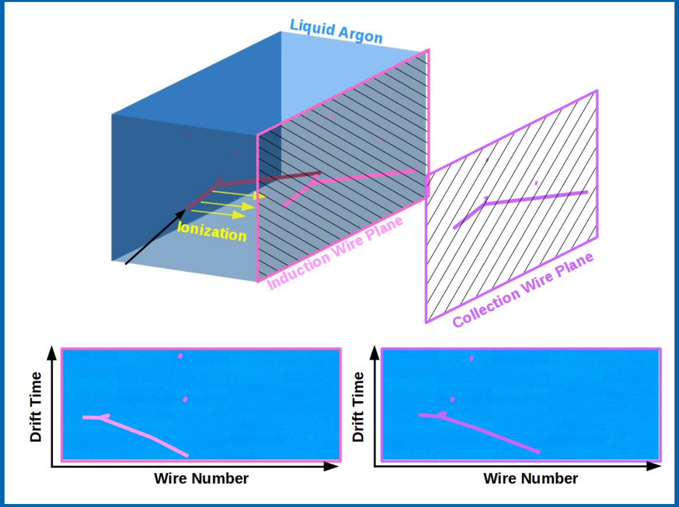
Why pixelated liquid noble TPCs?

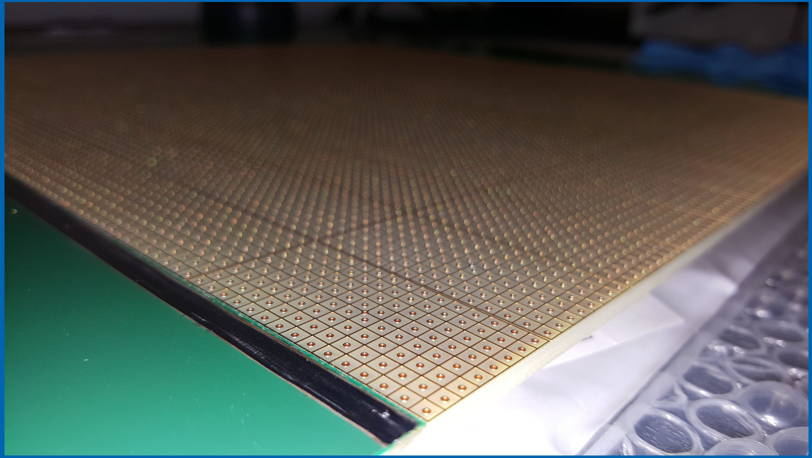
- Noble Element Time Projection Chambers offer access to very high quality information
- Leveraging this information allows **unprecedented access to detailed neutrino interaction** specifics from MeV - GeV scales
- Capturing this data **w/o compromise and maintaining the intrinsic 3-D quality** is an 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**

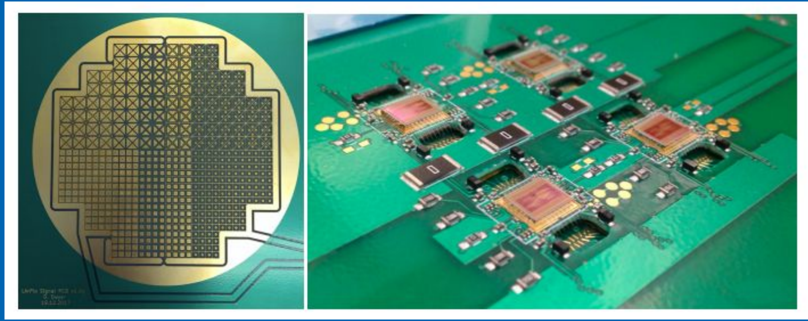




So pixelate them, what's so hard?

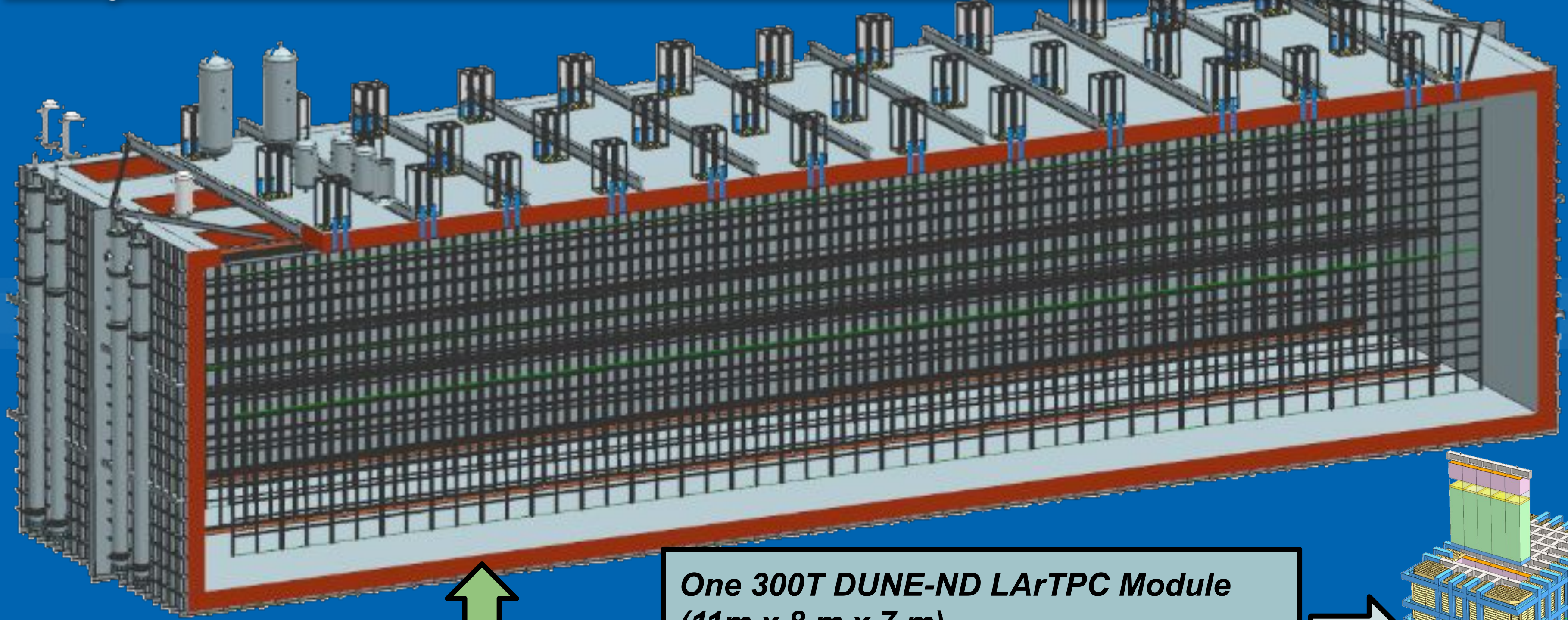
- Readout of a TPC using pixels instead of wires comes at the "cost" of many more channels (Example: 2 meter x 2 meter readout)
  - 3mm wire pitch w/ three planes = 2450 channels
  - 3mm pixel pitch = 422,000 channels
- LArPix (JINST 13 P10007) readout has pioneered this frontier showing a low power 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



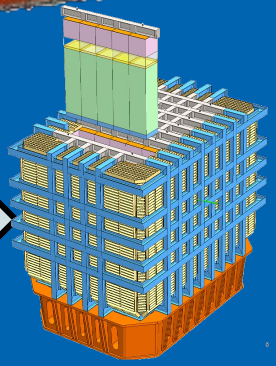


(JINST 13 P10007)

Why other solutions?: Scale of the detectors



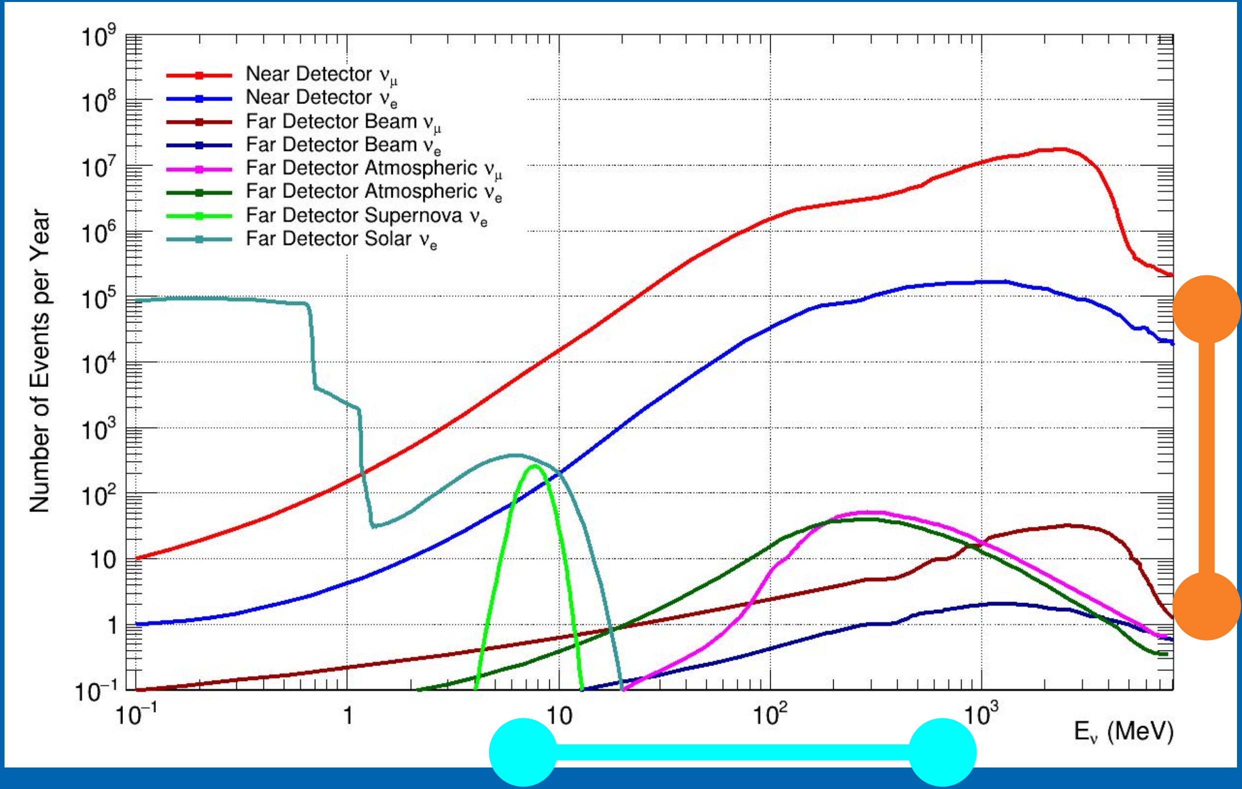
One 300T DUNE-ND LArTPC Module
(11m x 8 m x 7 m)
$\mathcal{O}$ (7 million) 4mm pixels



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

~18x more channels Far/Near

Scale of the detectors



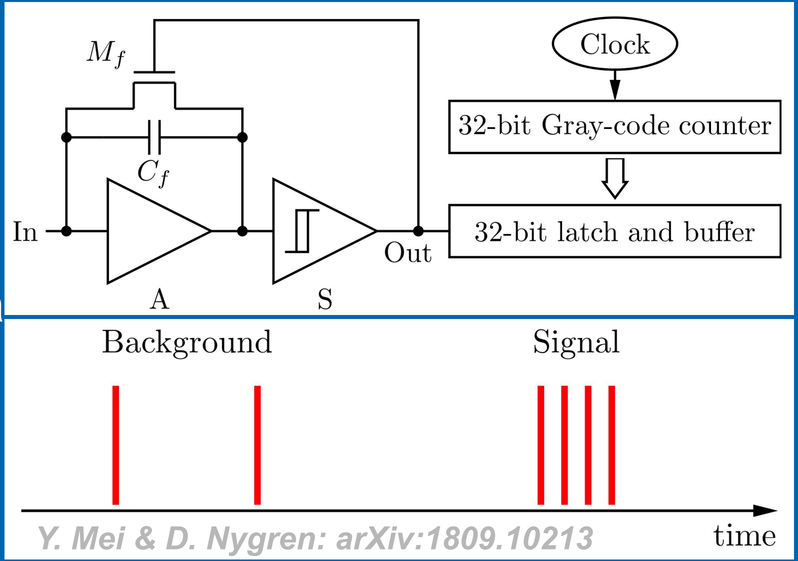
Scaling pixel based readout to the multi-kiloton detector may require an "unorthodox" solution

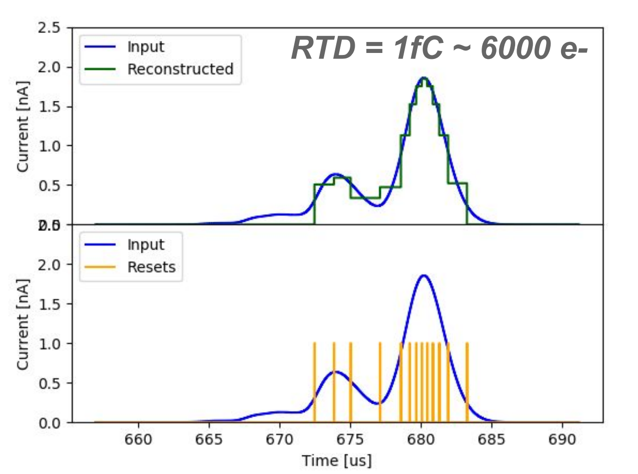
Estimated event rates in the DUNE LArTPC Near Detector (ArgonCube) and a single DUNE 10kTon Far Detector Module

- 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

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 difference between sequential 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



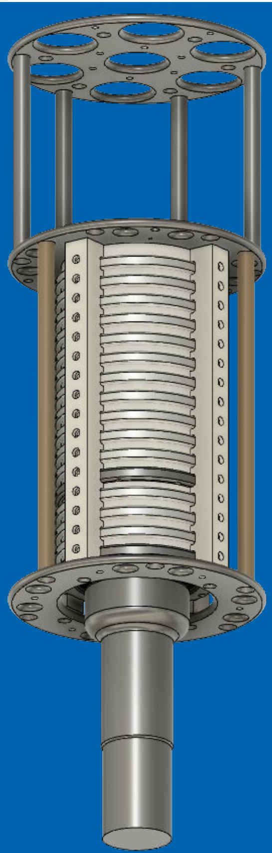


Current state of Q-Pix (pardon the pun)

- **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 April 2021 for the first chip production.
- **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

UTA/H TPC's

The UTA/H TPC is designed to efficiently collect charge and light. This is done with an asymmetric design requiring a buffer region to protect the PMT's.

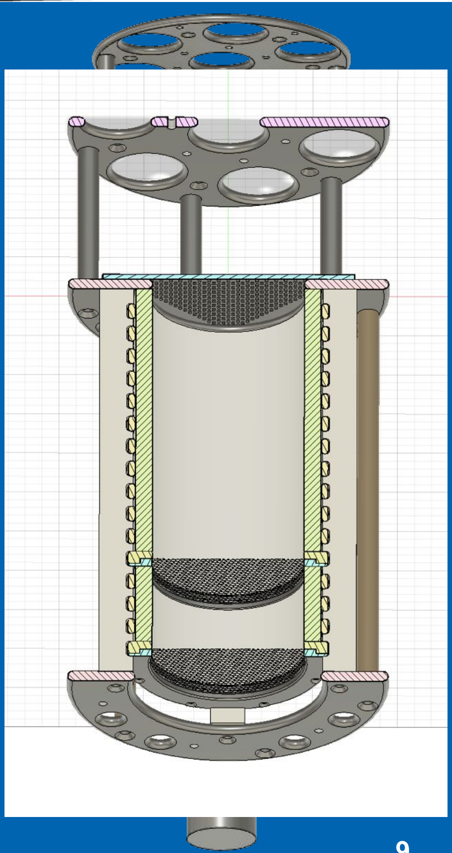


UTA/H TPC’s

The UTA/H TPC is designed to efficiently collect charge and light. This is done with an asymmetric design requiring a buffer region to protect the PMT’s.

The drift region is 35cm long and is designed to handle drift fields up to 1.5kv/cm. Outfitted with HDPE reflector tubes which will be coated in TPB in order to maximize the light collection.

This TPC will allow is to test Q-Pix for functionality and explore how it responds to “low” energy (~100s of keV)



UTA/H TPC’s

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The drift region is 35cm l … fields
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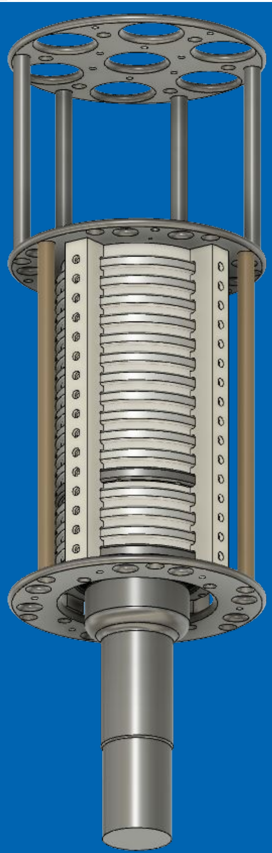
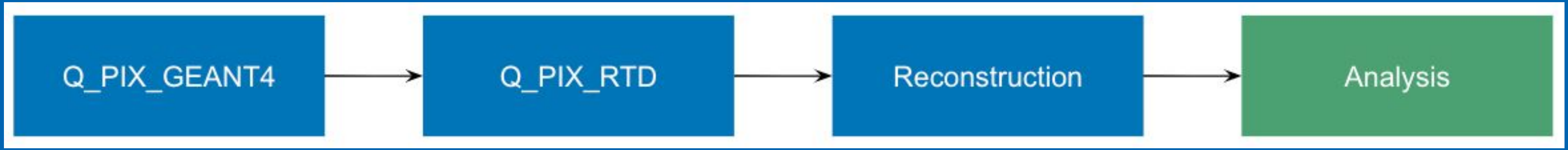


Q-Pix work in the context of DUNE

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).

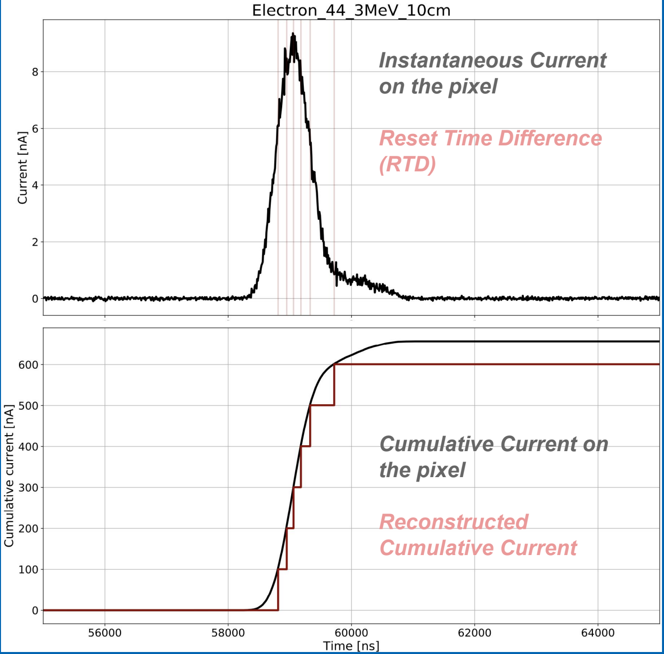
A 10 kT SP DUNE module is 200 APA drift regions which is about 13.9 kT of total volume

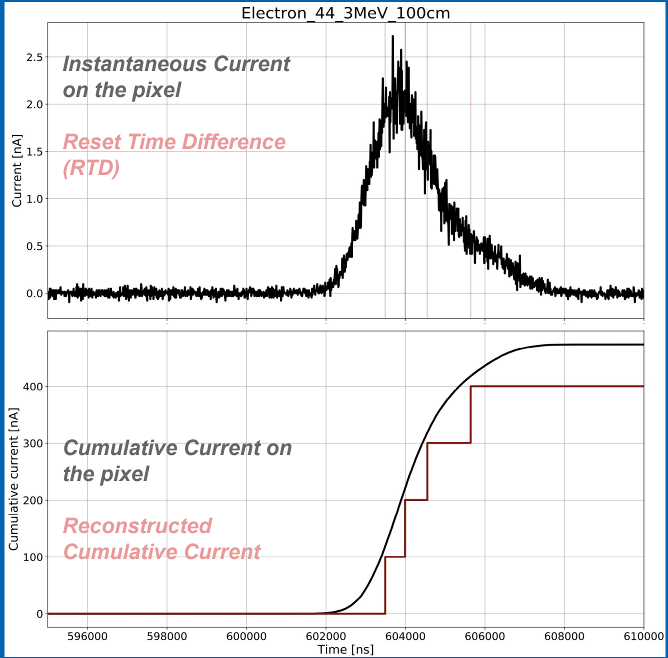
Here the methodology is to only simulate 1 APA, then 200 of those would mimic a single DUNE module response

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

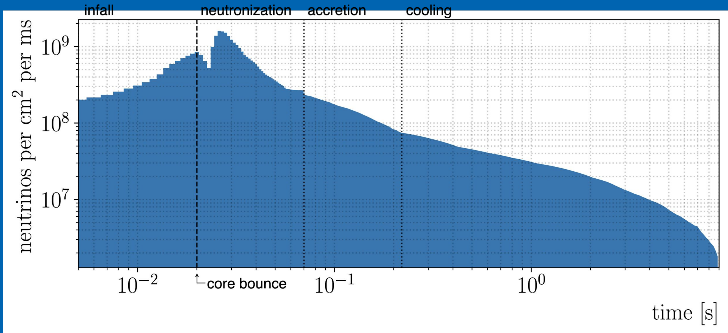
Q-Pix work in the context of DUNE

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.

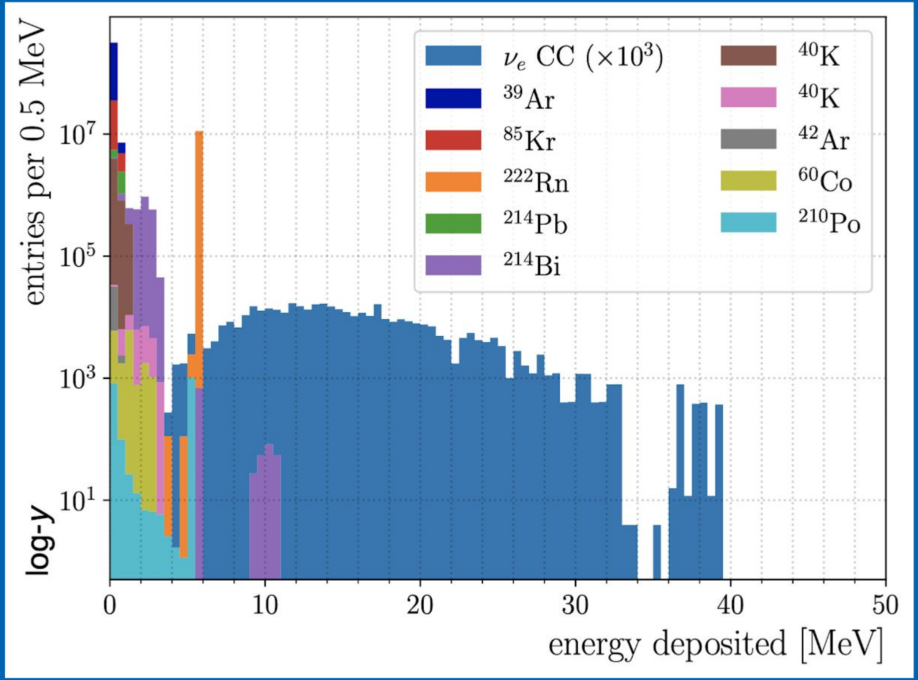
Isotope	Rate [Bq/kg]	Region	Region mass [kg]	Rate [Bq]	Time window	Number of decays
Po-210	0.2	PD [Bq/m²]	2.46856	0.493712	10	4.93712
Co-60	0.0455	CPA	90	4.095	10	40.95
K-40	4.9	APA	258	1,264.2	10	12,642
Ar-39	1.010	bulk LAr	70,000	70,700	10	707,000
Ar-42	0.000092	bulk LAr	70,000	6.44	10	64.4
K-42	0.000092	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

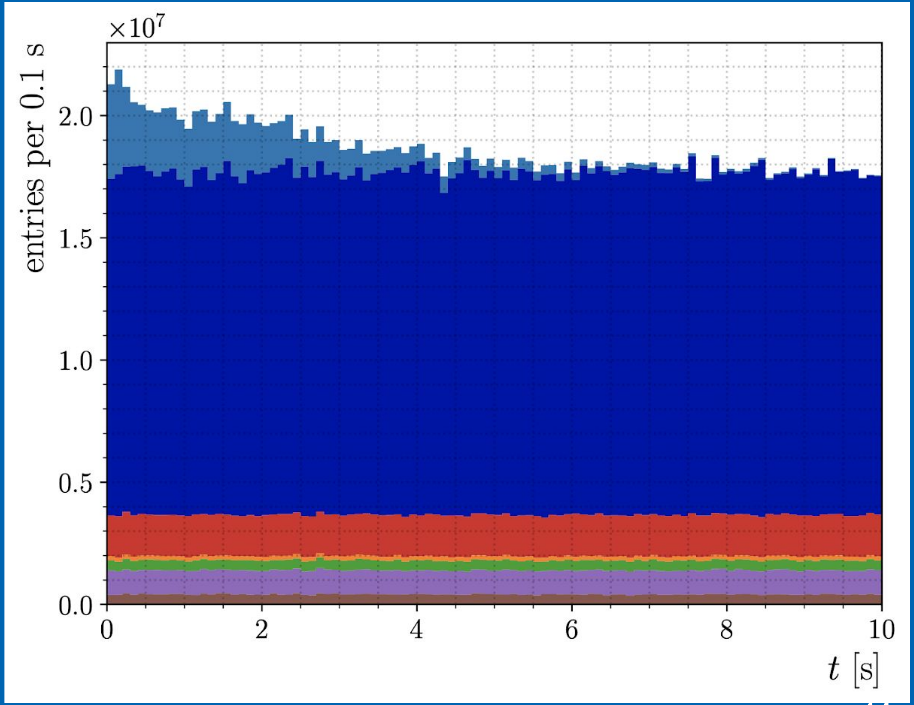
(There are 200 APA drift volumes in a 10 kton SP module.)

[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)

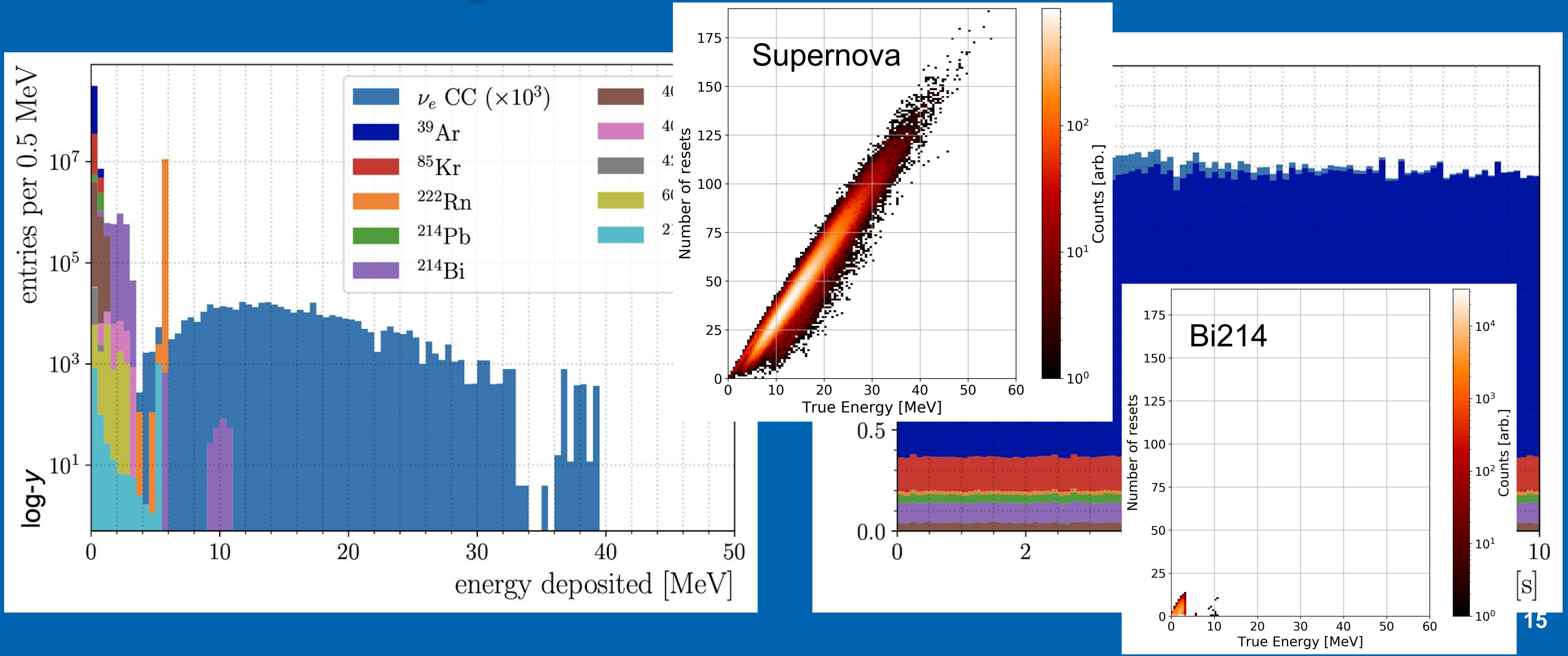
The Geant4 time and energy distributions form the sample production for the full 10s window.





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.

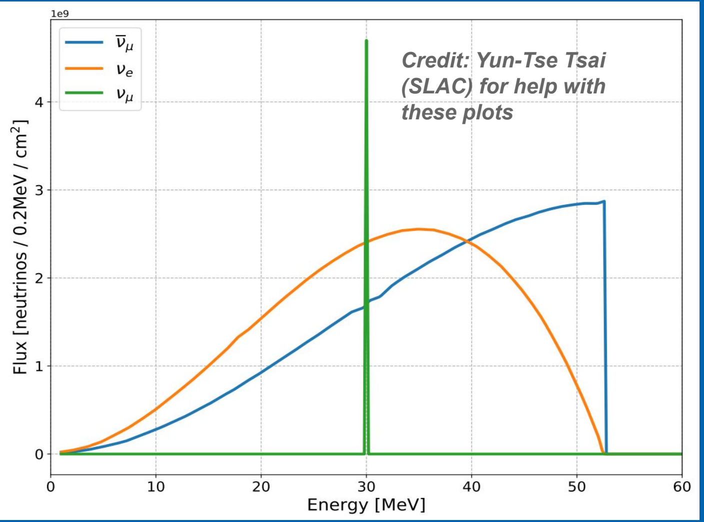


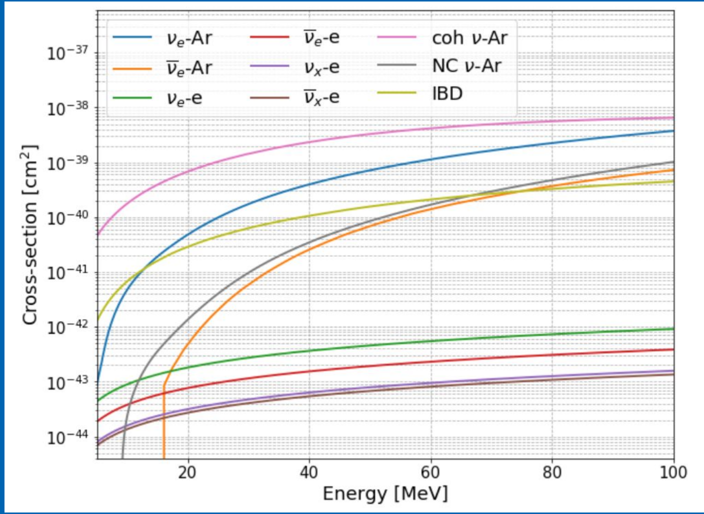
Q-Pix work in the context of DUNE (Supernova)

- 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 to verify the technology and simulations beyond what the UTA/H TPC's will is the physics prospects at the Oak Ridge Spallation Neutron Source (SNS).

Opportunities for Q-Pix at ORNL

- **ORNL SNS offers a unique neutrino source for the study of low energy neutrino physics!**
- **The combination of a unique beam and a growing facility makes this an attractive place for physics demonstrator for the Q-Pix readout**
  - **Enables unique neutrino measurements which DUNE will benefit from**

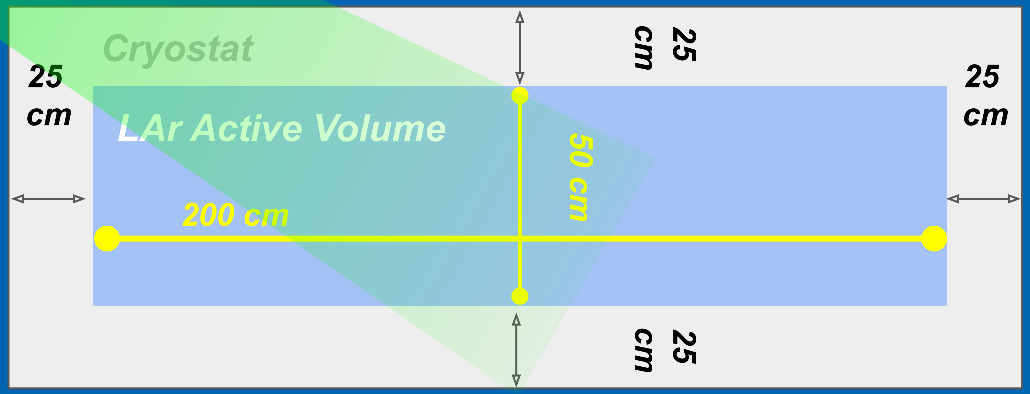




View from above

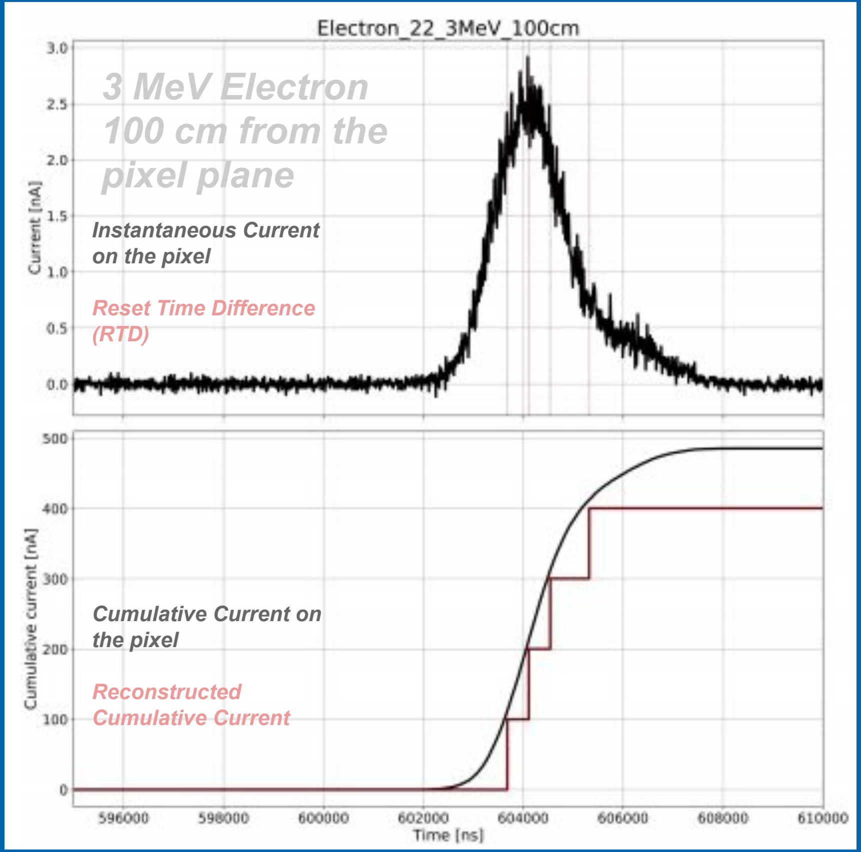
- $1m^3$ detector which might be able to fit into neutrino alley could be 2m (L) x 0.5m (w) x 1.0m (h) active volume
  - Cryostat would be 2.5m (L) x 1m (w) x 1.5 m (h)
- Cathode in the middle giving 1 meter drift
  - 50 kV on the cathode (very do able)

This could be readout with 50 cm x 50 cm tiles with 4 mm pixel spacing → 62,500 pixels in total for both readout planes



What is the physics you can do with $1m^3$ at SNS

- This obviously depends on what your detector is capable of….
- But for some reasonable assumptions about the threshold charge an early version Q-Pix could achieve:
    - RTD ΔQ: ~ 1fC = 6240 electrons
    - Minimum number of RTD's to separate ionization activity from neutrinos from radiogenic background (39Ar, Rn, Bi-Po): 3 RTD's in 6 μs
    - Assumed 100 aA leakage current



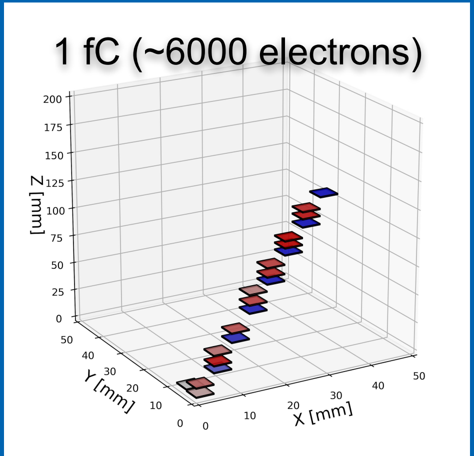
What is the physics you can do with $1m^3$ at SNS

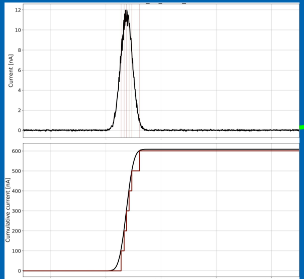
Special thanks to Yun-Tse Tsai (SLAC)for her help with these calculations

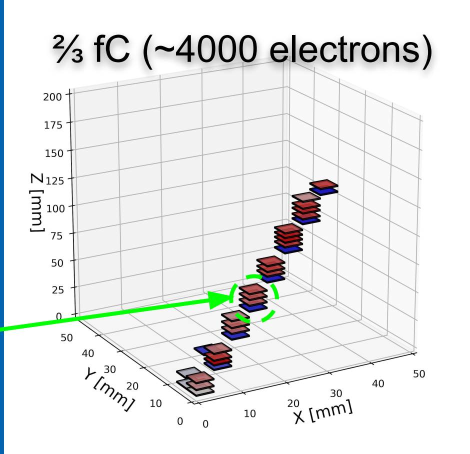
- **ν - e scattering**
  - 17 events per year
    - ~90% events above 1 MeV (thus they have an extent of 3 pixels)
    - Events should have directionality with the SNS source
      - Eases their identification and validates our ability to do pointing with low energy electrons
    - First measurement of its kind on argon!
- **Low Energy ν_e - *Ar Charged Current interactions***
  - 758 events per year
    - ~90% Events with neutrino energy above 10 MeV (thus gives electrons with energy we can see)
    - Provides critical experimental test of cross-sections for supernova neutrinos
    - First measurement of its kind on argon!
- ***Insert your good idea here! (open to further collaboration)***
  - Larger detector = more events!
    - Possible path to an upgraded detector at the second target station

What is the physics you can do with 1m^3 at SNS

- For an illustrative example, this is a 30 MeV Q-Pix electron track (what you would expect from an electron scatter).
- A possibility to improve the energy threshold is to reduce the **ΔQ** which will give more information about the event
  - Our collaborators suggest that the limit is ~1/10 fC, however reducing the threshold by ⅓ makes a drastic change.
- Understanding the threshold and noise to physics relationship is a goal of the UTA/H TPC’s and will inform the limits of the technology and design choices for demonstrator detectors





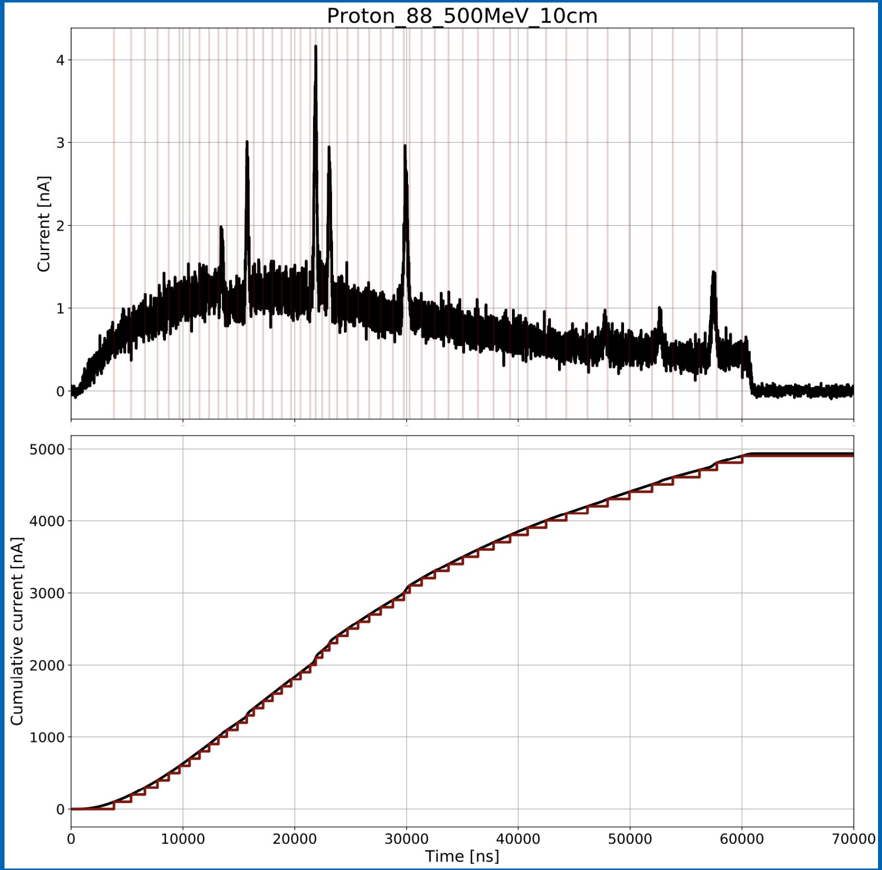


Conclusions

- 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.
- The prospects for a Q-Pix based LAr detector at the SNS appears promising and studies are ongoing
- Demonstrator TPC (UTA/H) operating at UTA and Harvard in 2021 should provide many low energy measurements that will test the capabilities of this technology

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.