Kiloton-scale pixelated liquid noble TPCs

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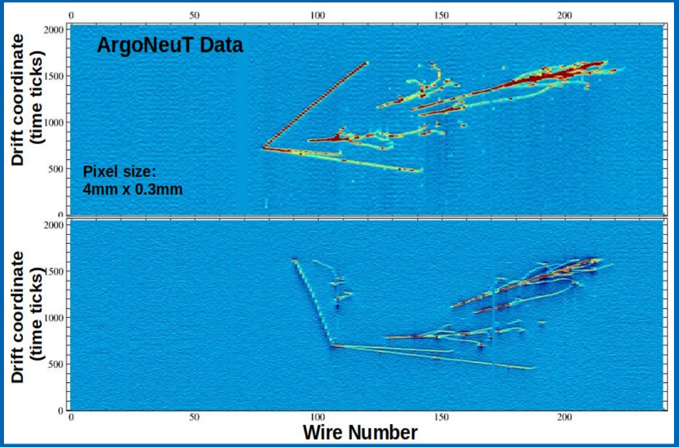
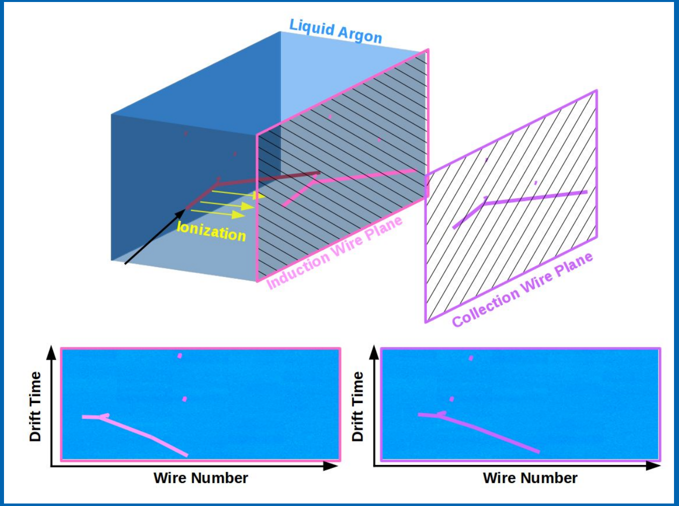
Why pixelated liquid noble TPCs?

- Noble Element Time Projection Chambers offer access to very high quality and detailed 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 TPC's use 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)

- **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.

		3D Truth Label			2D Truth Label		
		ν_e CC	ν_μ CC	NC	ν_e CC	ν_μ CC	NC
Predicted Label	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.

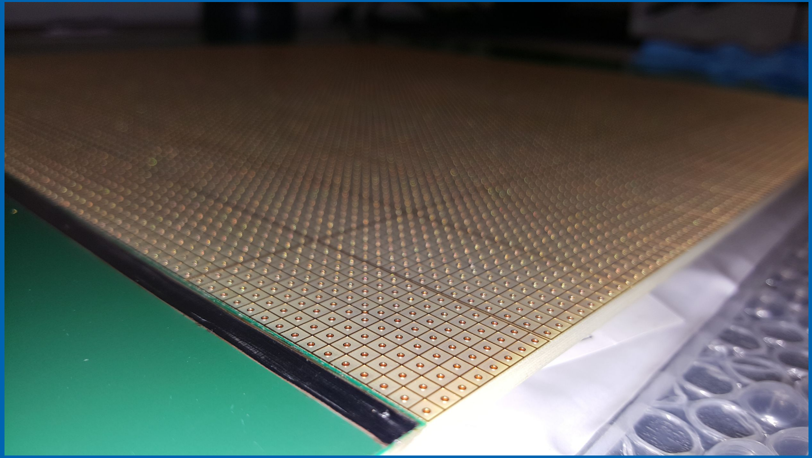
		3D Truth Label			2D Truth Label		
		$N_p = 0$	$N_p = 1$	$N_p \geq 2$	$N_p = 0$	$N_p = 1$	$N_p \geq 2$
Pred. Label	$N_p = 0$	**0.928**	0.076	0.005	0.841	0.064	0.005
	$N_p = 1$	0.062	**0.884**	0.059	0.143	0.853	0.069
	$N_p \geq 2$	0.010	0.040	**0.936**	0.016	0.084	0.926

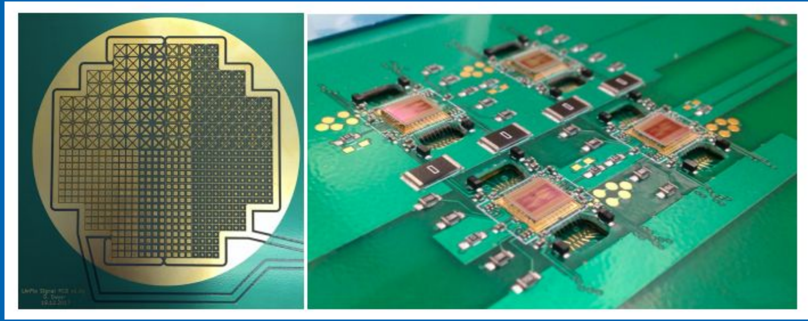
JINST **15** P04009 *(arXiv:1912.10133)*

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

So pixelate them, what's so hard?

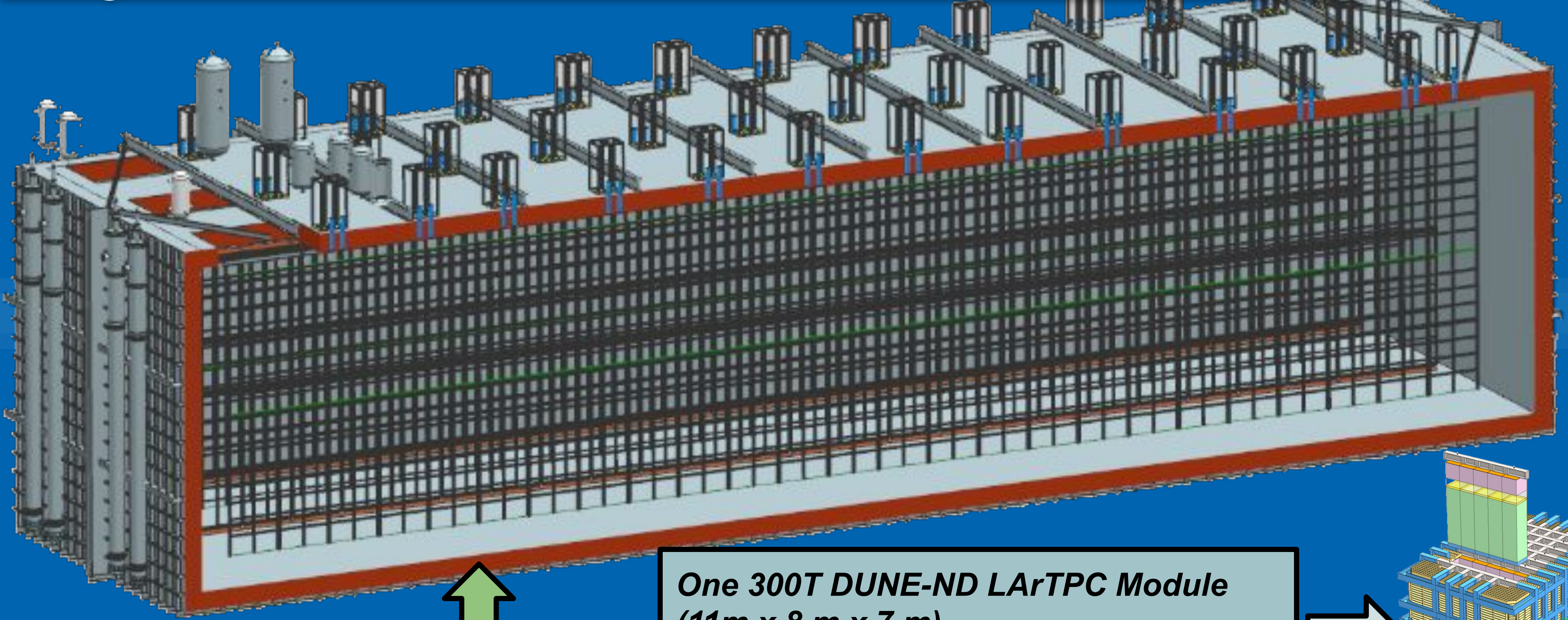
- Readout of a TPC using pixels instead of wires comes at the "cost" of many more channels (Example: 2 meter x 2 meter readout)
  - 3mm wire pitch w/ three planes = 2450 channels
  - 3mm pixel pitch = 422,000 channels
- LArPix (JINST 13 P10007) readout has pioneered this frontier showing a low power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





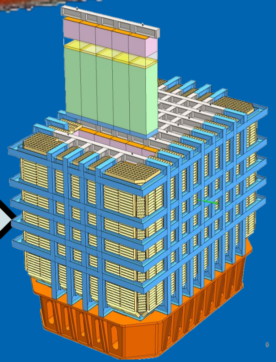
(JINST 13 P10007)

Why other solutions?: Scale of the detectors



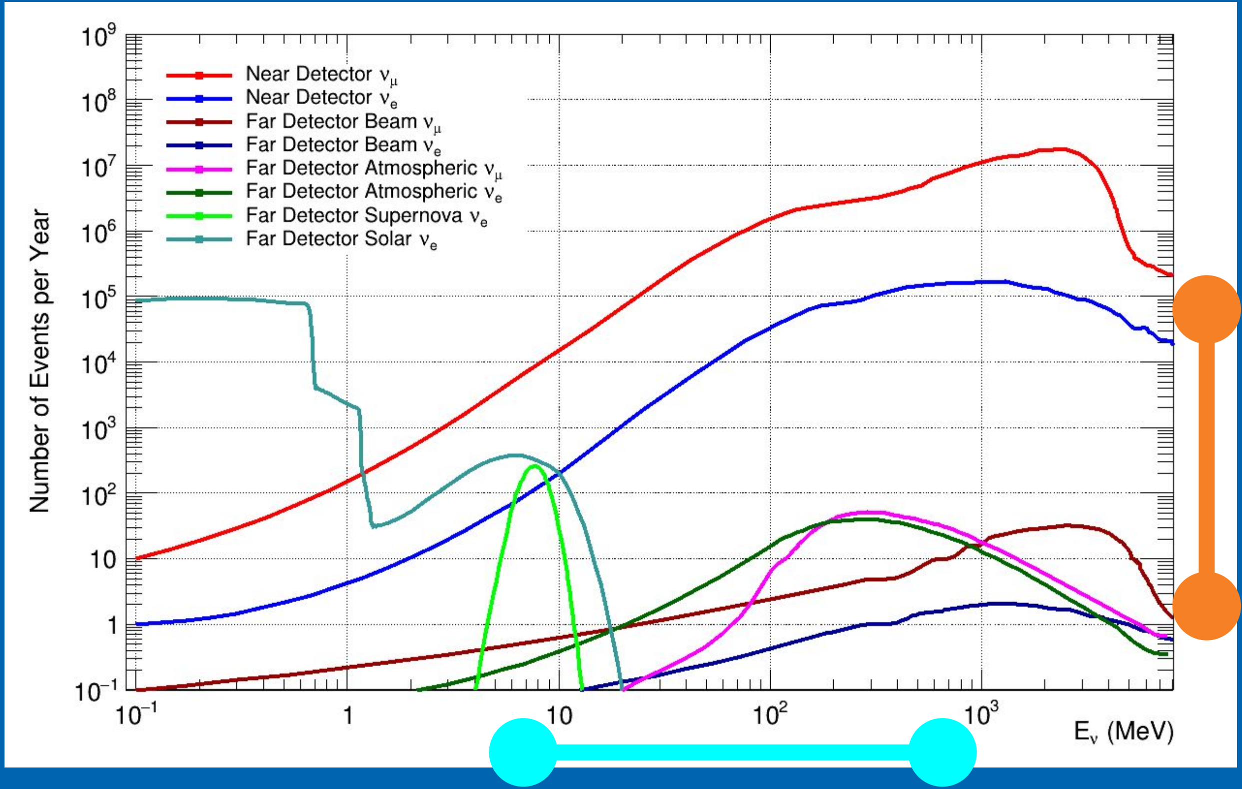
One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE
$\mathcal{O}$(130 million) 4mm pixels

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



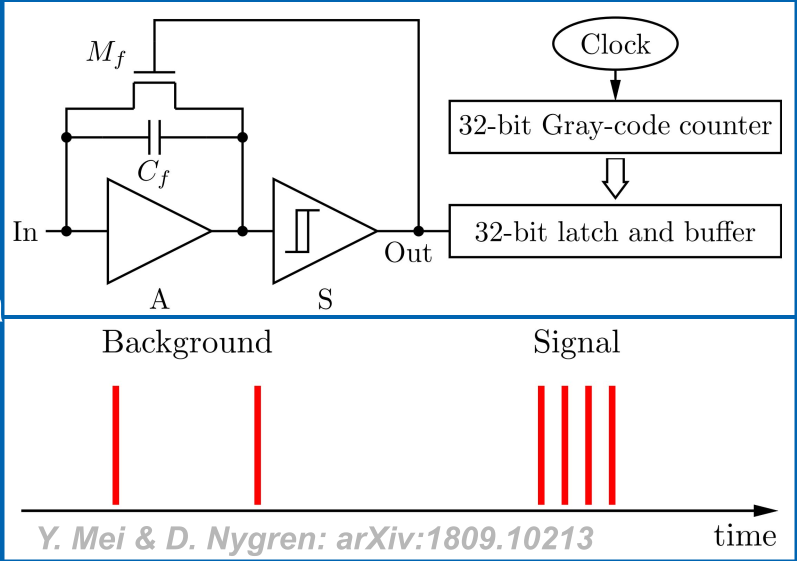
Scaling pixel based readout to the multi-kiloton detector may require an "unorthodox" solution

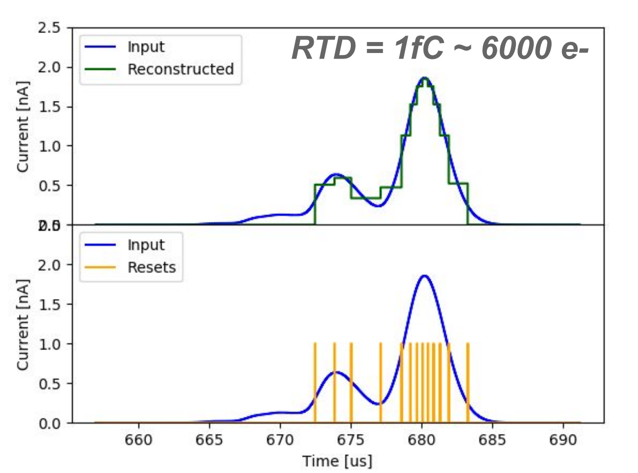
Estimated event rates in the DUNE LArTPC Near Detector (ArgonCube) and a single DUNE 10kTon Far Detector Module

- **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 <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

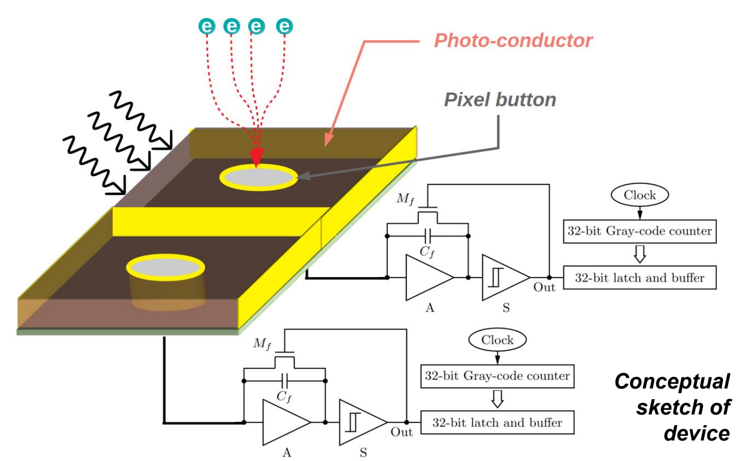


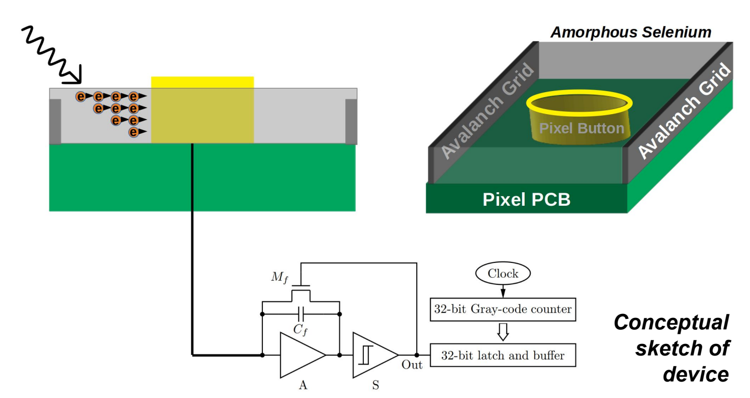


An unorthodox solution: Q-Pix

Such a low power & low threshold charge readout of Q-Pix opens the opportunity to "blue sky" R&D into an integrated Q+L pixel sensor

- If realized, offers a transformative opportunity in NETPC's
- Currently exploring different thin-film photo-conductors (e.g. a-Se, ZnO, PZT, etc)
    - Possible to be sensitive to a broad range of wavelengths (including directly to VUV)
    - Can greatly enhance the photo-coverage of a TPC by making the charge sensitive area the same as the photon sensitive area
        - *Current surface area instrumentation is < 1%*





Much to be worked on: Q-Pix Consortium

- Six central ideas being worked on
  - Circuit Design: A prototype of the front-end + oscillator is expected to be completed in the next 6 months
  - Physics Simulations: Quantify the conferred benefit of pixel vs. wire readout and the requirements of the ASIC design
  - CIR Input: all extraneous leakage current at the input node needs to be small (aA)
  - Clock: $\delta f/f \sim 10^{-6}$ per second
  - Digital Network: Robust readout through dynamic networks
  - Light Detection: Exploring new ideas using photoconductors on the surface of the pixels
- Many more interesting ideas/applications than what can be squeezed into this flash talk (more to come out during Snowmass process)
  - Happy to collaborate & talk about ideas with interested parties!