Current and Near Term Projects

(Q-Pix, novel photon detectors, and Photonics for cryogenic detectors)

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A (potentially) unique perspective

- **The UT Arlington HEP group is not historically an IC group**
  - Recently, through some developing partnerships, we are hoping to become more active in this area
- **Instead, we find ourselves chasing down transformative detector development by partnering and collaborating with groups and labs who are IC experts**
  - Much of the work you will hear about in this talk is built on the effort and collaboration with other groups who are presenting
- **This perspective has lead to a fruitful back and forth between people who know and understand the technology and those who know and understand the physics**
  - This has lead the UTA group to try to better equip itself with both technical understanding and capabilities using IC design tools as well as implement and simulate details into our physics packages
  - We hope to continue down this path and look forward to further collaboration with others at this workshop!

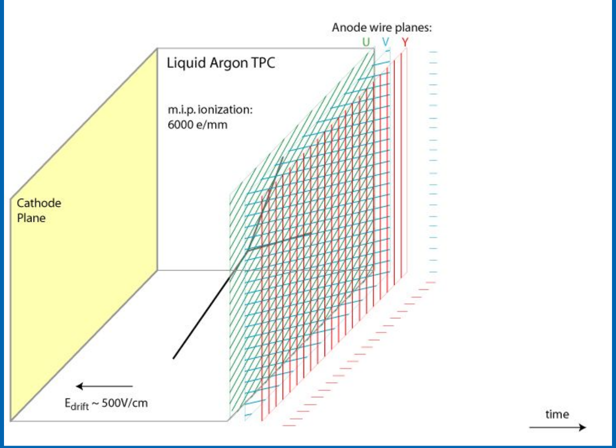
Q-Pix consortium would like the thank the DOE for its support via DE-SC0020065 award, DE-SC 0000253485 award, and FNAL-LDRD-2020-027

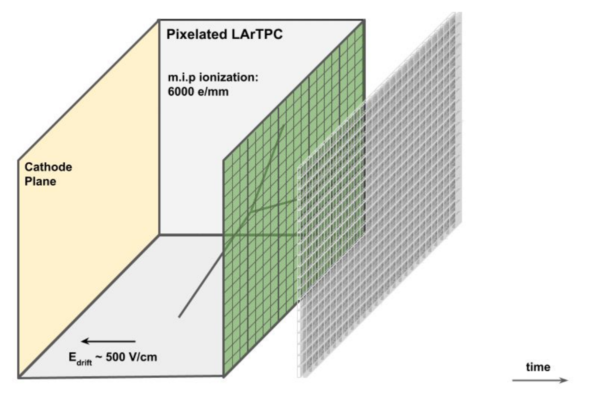
Projects

- **Q-Pix**
    - 180nm
    - 65nm
    - eFabless Open MPW (Skywater 130nm)
- **Novel Photoconductors**
    - Current R&D work towards integrating with Q-Pix'ish design
- **Exploration into photonics for cryogenic detectors**
    - Some early thoughts and musings

The Q-Pix Concept

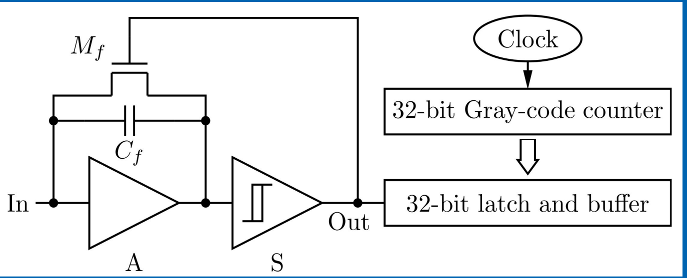
- The original concept put down by Yuan Mei (LBNL) and Dave Nygren (UTA) outlined a novel ionization signal capture and waveform digitization scheme for kiloton-scale liquid argon Time Projection Chamber (TPC) detectors
    - https://arxiv.org/abs/1809.10213
- The goal of this readout is to **"maximize the discovery potential"** of a kiloton scale LArTPC
    - This can be achieved by lowering the readout thresholds, maximizing the protection to single point failure, vastly reducing the data rates, and keeping the intrinsic 3D nature of the signals found in a LArTPC
- Q-Pix is targeting its design around an environment where most of the time there is nothing of interest happening (e.g. large scale, underground detector), but where you want to be ready instantly to capture **signals at the very threshold of detection**

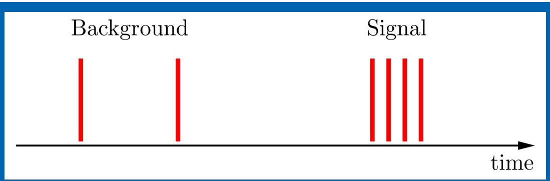


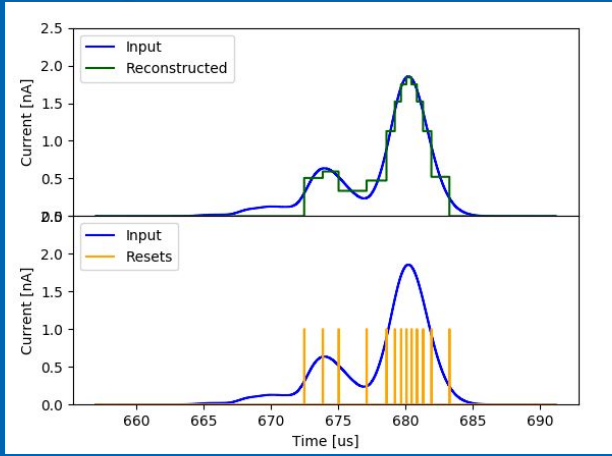


Q-Pix: The Charge Integrate-Reset (CIR) Block

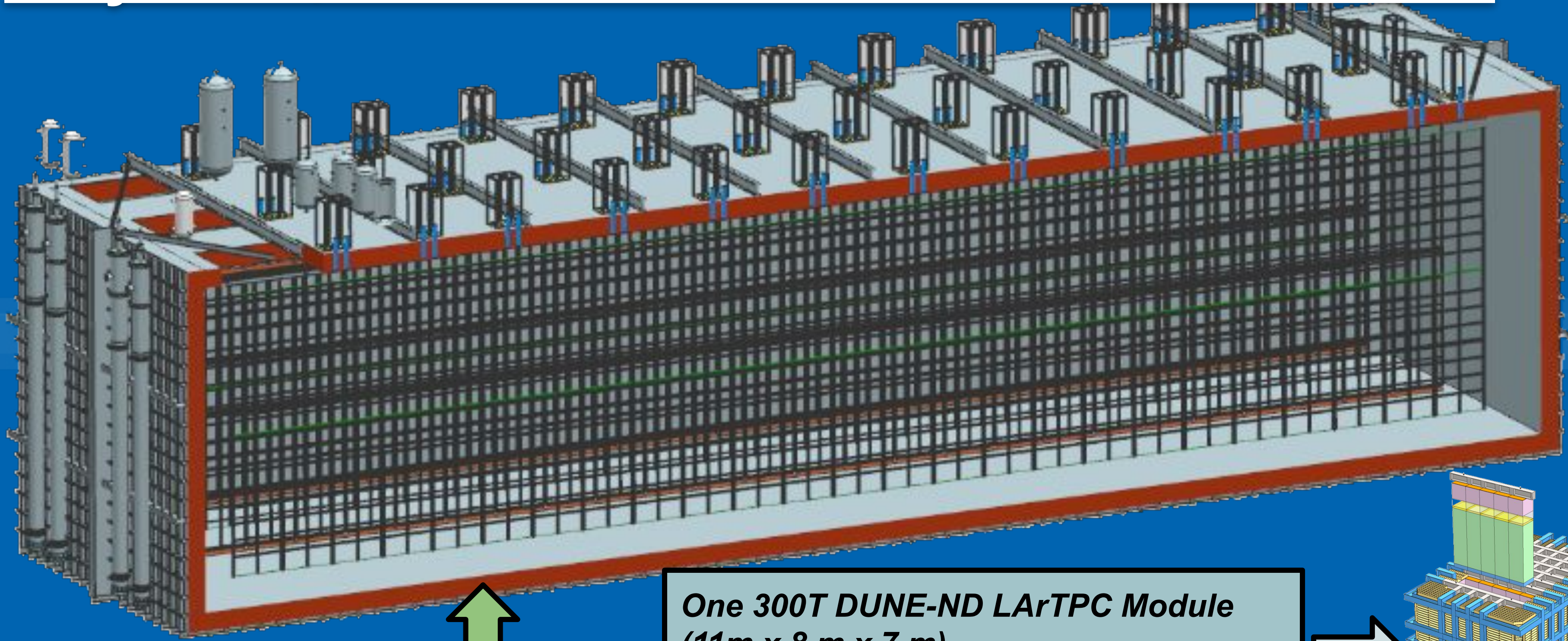
- **Charge from a pixel (In) integrates on a charge sensitive amplifier (A) until a threshold (V_{th}~$\Delta Q/C_f$) is met which fires the Schmitt Trigger which causes a reset (M_f) and the loop repeats**
- **Measure the time of the "reset" using a local clock (within the ASIC)**
  - **Basic datum is 64 bits**
    - 32 bit time + pixel address + ASIC ID + Configuration + …
- **Take the <u>difference</u> between <u>sequential</u> resets (Reset Time Difference = RTD)**
  - **Total charge for any RTD = ΔQ**
- **RTD's measure the instantaneous current and captures the waveform**





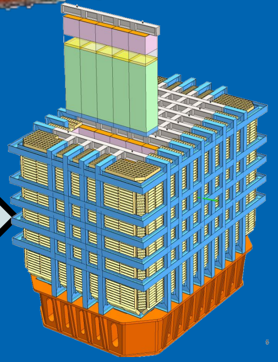


Why the Q-Pix solutions?: Scale of the detectors



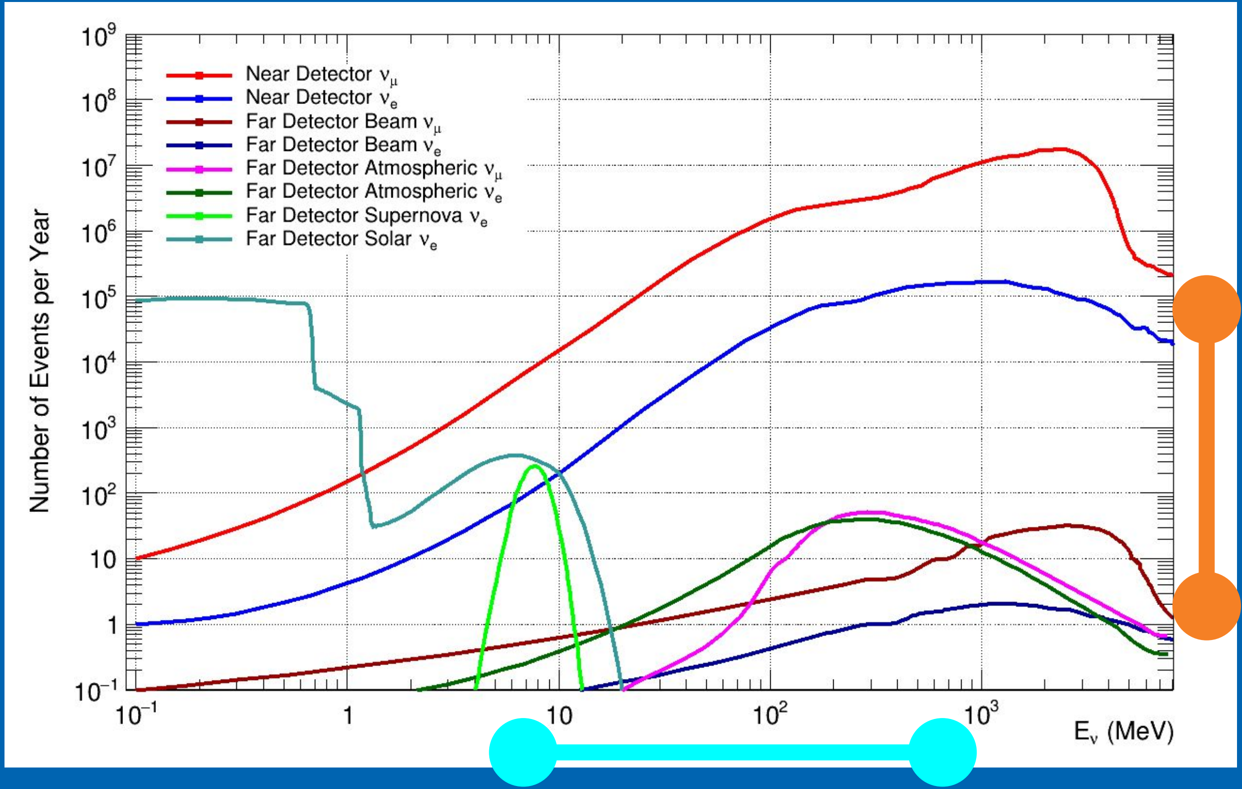
One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE
$\mathcal{O}$(130 million) 4mm pixels

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

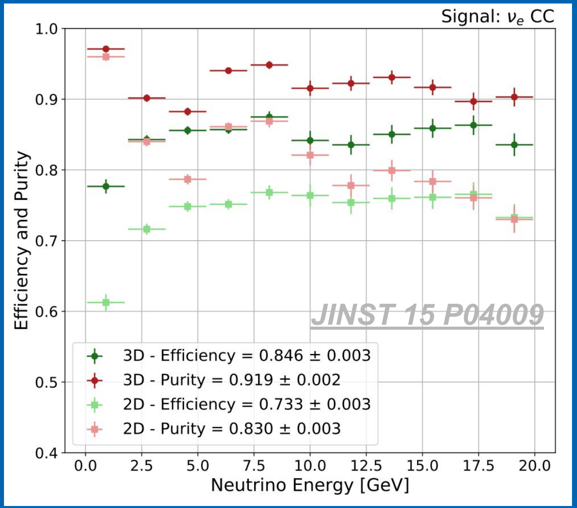
Estimated event rates in the DUNE LArTPC Near Detector (ArgonCube) and a single DUNE 10kTon Far Detector Module

- **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**

What is to be gained by using Q-Pix?

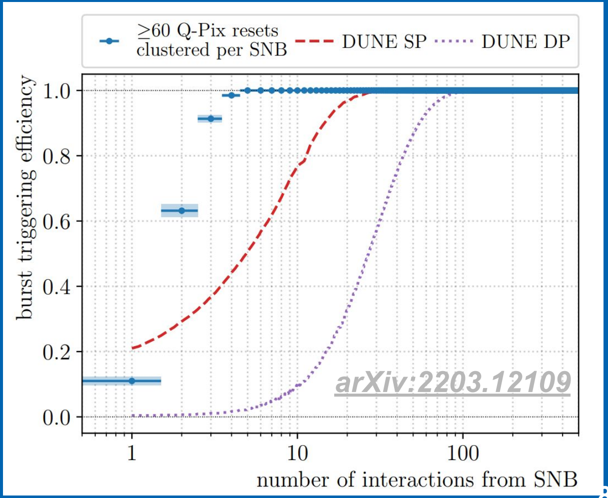
JINST 15 P04009 (arXiv:1912.10133)

- Comparing the readout of an ideal 2D projective Liquid Argon TPCs (LArTPC's) to 3D pixel LArTPC's shows that 3D based readout significantly improves 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



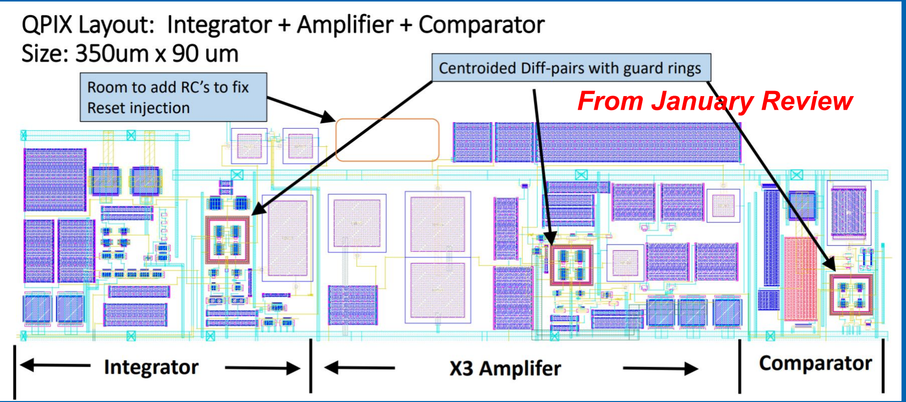
arXiv:2203.12109 / Submitted to PRD

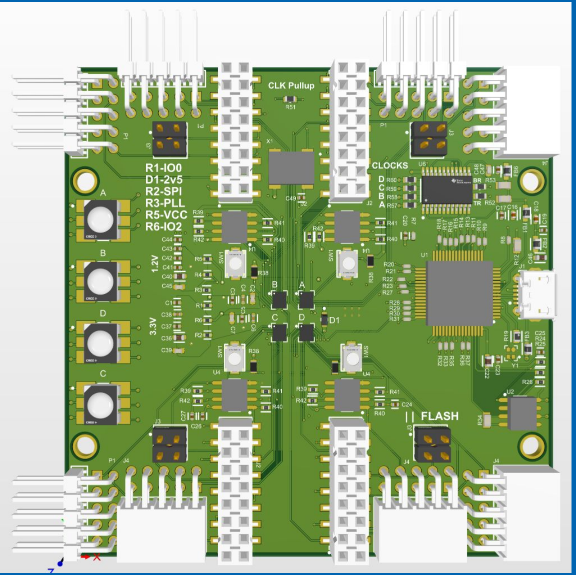
- Study shows an example of how the Q-Pix architecture enhances the low energy physics capabilities of a kiloton scale LArTPC (e.g. DUNE) focusing on supernova neutrinos
  - Q-Pix significantly enhances the efficiency of reconstructing low energy supernova neutrino events
  - Even in the presence of radiological backgrounds, the Q-Pix architecture allows for a high purity and high efficiency identification of supernova neutrino candidates
  - The data rate is orders of magnitude (~10^6) less for the same energy threshold and manageable at lower energy thresholds (5.7 MB/s for 10kTon at 147 keV threshold)
  - 3D pixelization allows for supernova burst pointing accuracy to <20 degrees from a single 10kTon module



Work in 180 nm

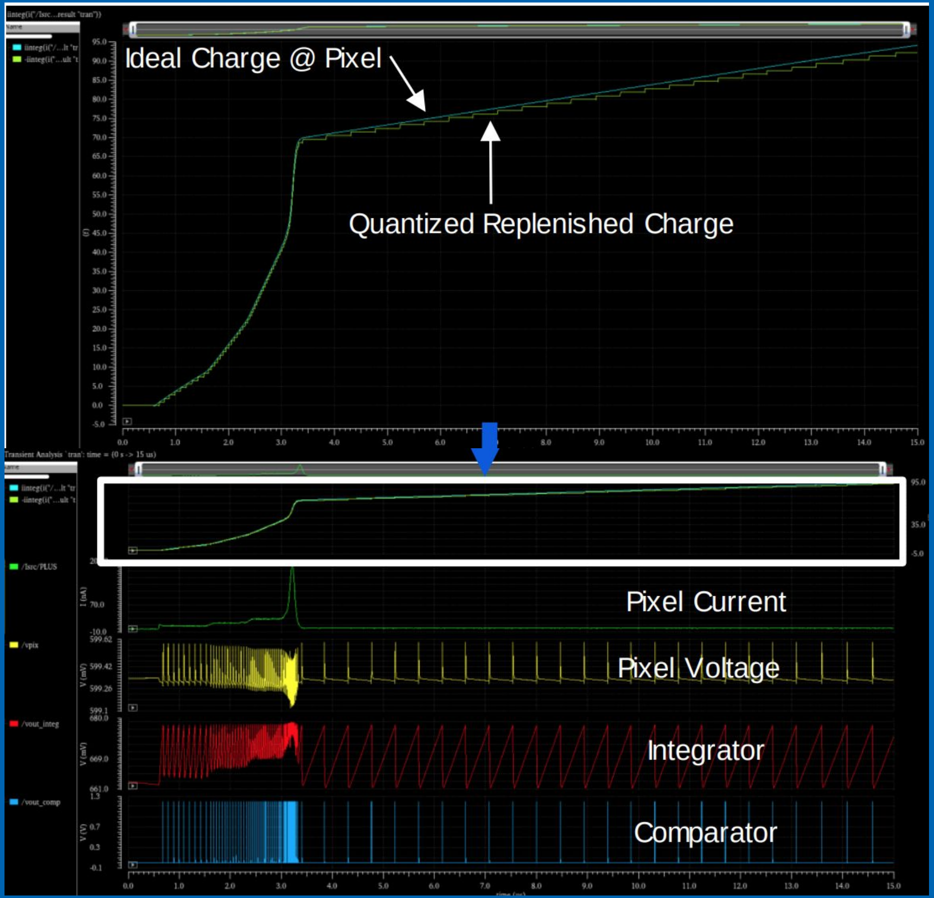
- **Work on the first prototype of the front-end has been ongoing and reaching a mature state (Penn)**
  - Extensive studies using physics based input currents lead us to explore a charge replenishment design as well as the “basic” reset concept
- **Design of Ring Oscillator and 10-bit r2r DAC ongoing (Hawaii)**
  - Currently working on incorporating lessons from other TSMC 180nm projects
- **Prototyping the digital readout in an FPGA board (Hawaii)**
  - 4 (2x2) Digital FPGAs with 16 optional IO pins per FPGA to connect to prototypes
  - Optional 50 MHz “global” clock or 4x48 MHz Internal
- **The target will be to have a submission in late spring / early summer 2022 (June/August?)**
  - Single channel, Test structures, 16 channel chip(s)





Analog Front-end 65nm

- **Kyle Woodworth and Davide Braga (FNAL) worked on implementing the charge replenishment circuit in 65nm as well as exploring other designs**
  - **Phase 1 – Charge Replenishment Evaluation**
    - Reset via charge replenishment
      - Performed bandwidth study with ideal components to evaluate requirements
      - First version of low power front end amplifier
  - **Phase 1 – DVS Evaluation**
    - Dynamic Vision Sensing, used for asynchronous photon detection
      - https://ieeexplore.ieee.org/document/8094907
    - Evaluated ideal model
      - Reset requires careful design in order to avoid input signal loss
- **Further work dependent on resources being available at FNAL**
  - Target a 16 channel 65nm design sometime in the next 12-15 months



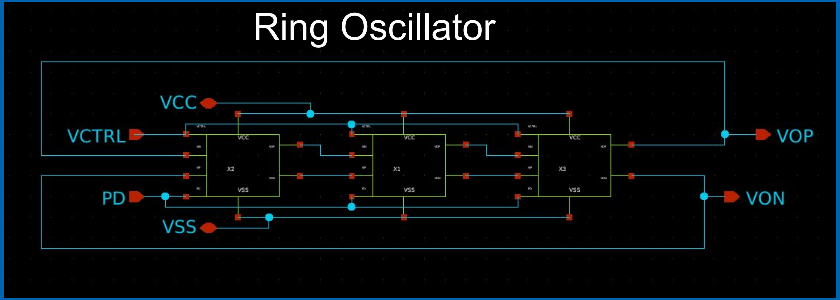
Skywater 130nm

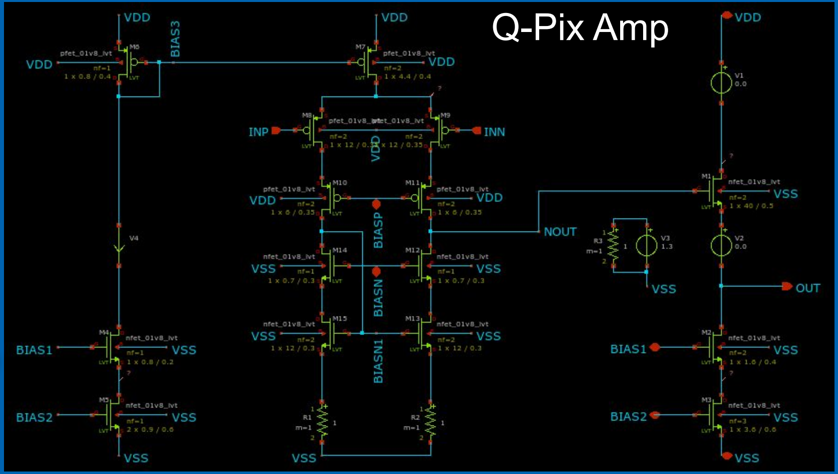
eFabless + Skywater + Google have released an open source process design kit in 130nm which enables entry into the world of ASIC design

- In this early stage, Google will pay for a limited shuttle run for open source designs chosen to be included

Yuan Mei (LBNL) brought this to UTA as an opportunity to help broaden our consortiums ability to prototype and to engage people who will be charged with testing our ASICs into the design world

- With guidance, lots of time, and sage like patience from Mitch Newcomer, Nandor Dressnandt, and Yuan Mei folks at UTA (Austin McDonald and Ilker Parmaksiz) have been learning this toolkit to target a submission for next month (May 2022)
- The goal is to submit some “basic” designs that are central to the Q-Pix idea for testing and characterization in the cold (and hopefully we get this for free
    - Ring Oscillator
    - Relaxation Oscillator (TBC)
    - Q-Pix OpAmp





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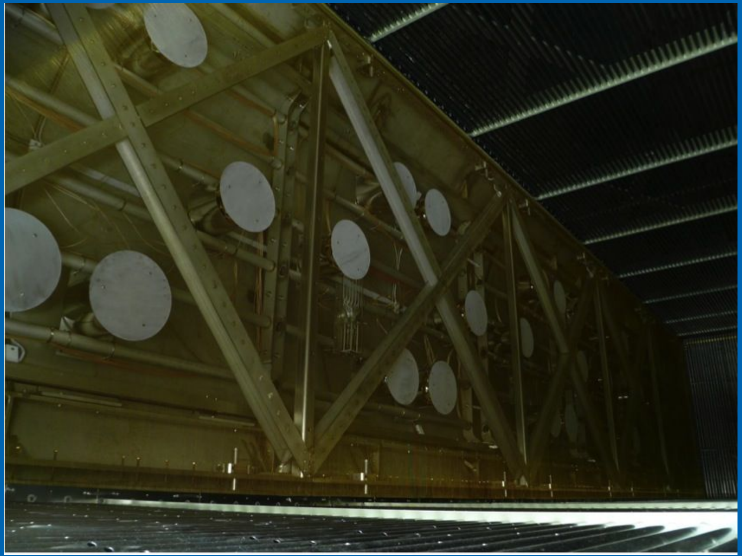
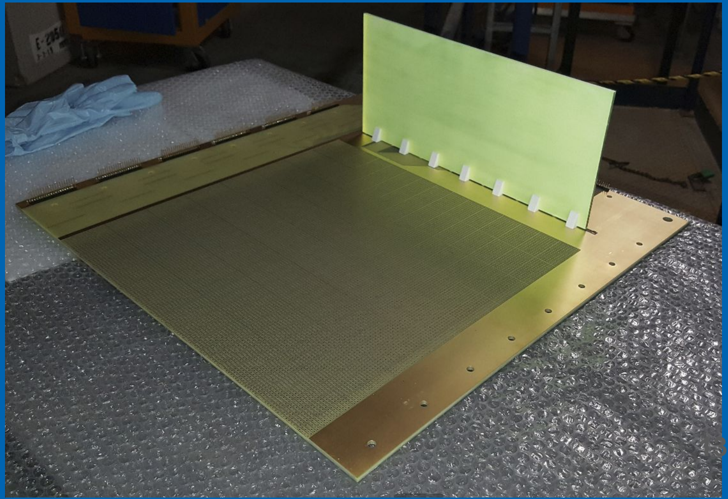
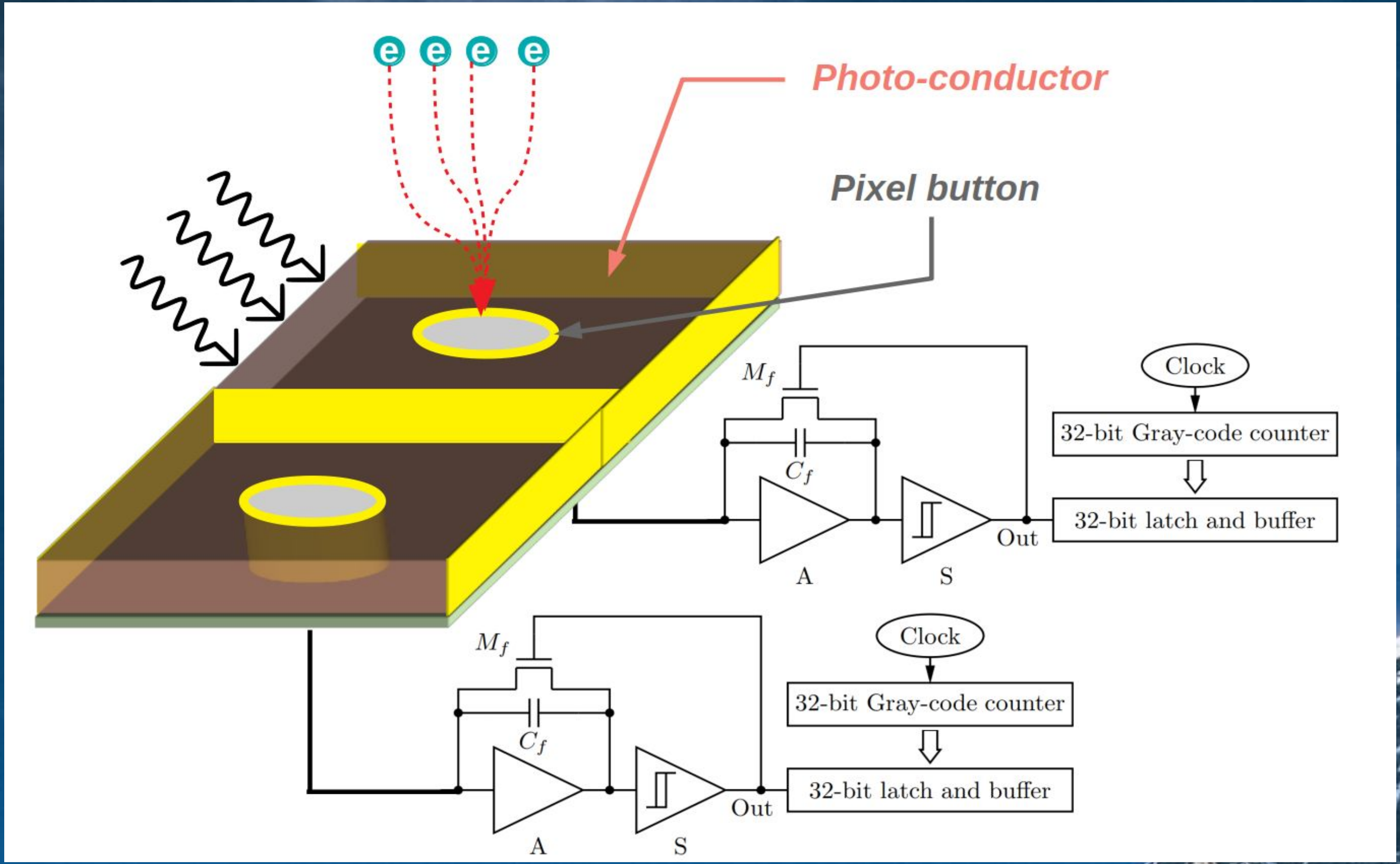
Light Detection

- **Conventional LArTPC's use the semi-transparent wires to their advantage and place their photon detectors behind the wire planes**
  - **Requires WLS**
- **Pixel detectors have an opaque charge collection surface making use of this solution impossible**
  - Alternative mounting schemes have been / are being explored
- **What if the whole APA could collect light?**
  - **A pixel plane sensitive to UV photons and ionization charge SIMULTANEOUSLY would be a major breakthrough**
    - Your effective instrumented area becomes enormous!
    - Even if the device has low efficiency you have a huge gain
    - **Q-Pix could be an "enabling technology" to realize this for LArTPC's**



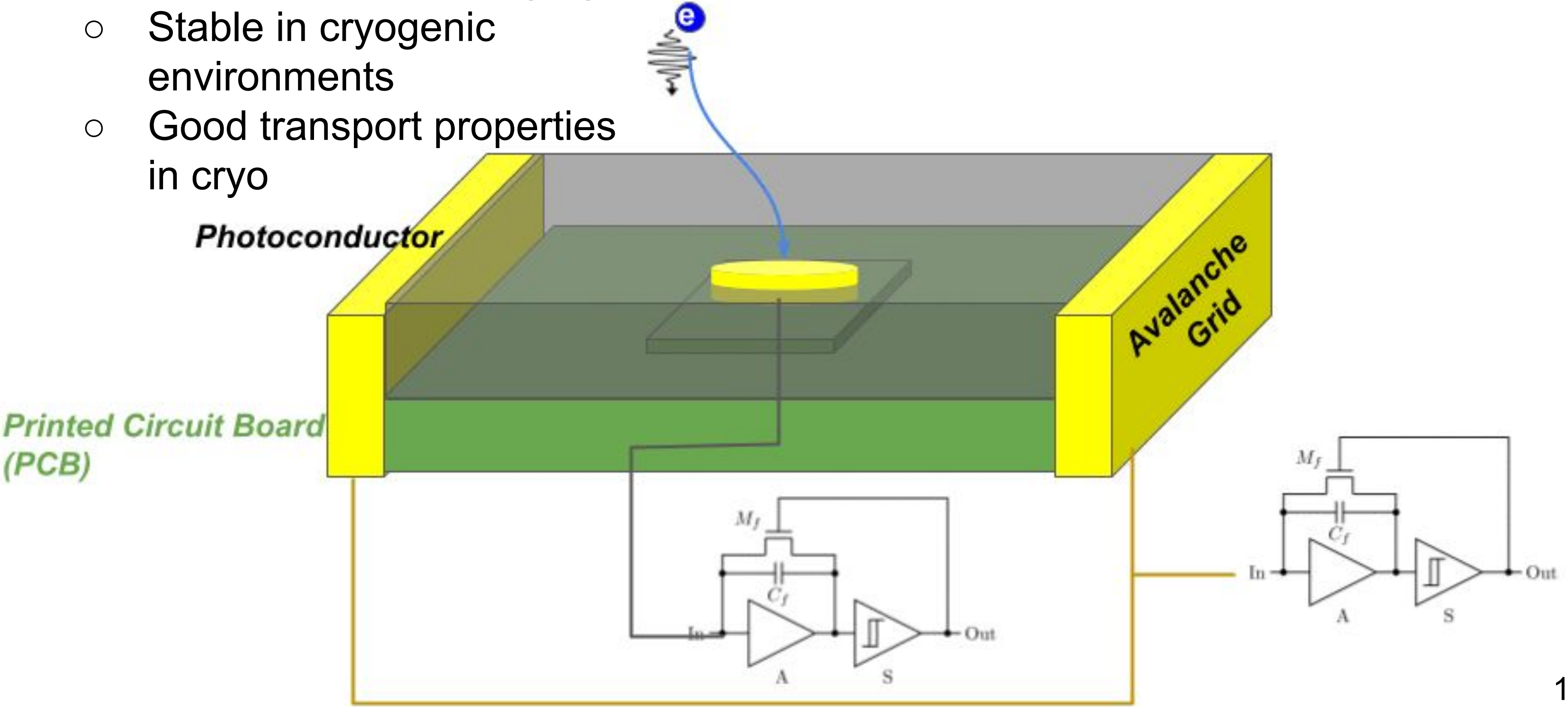


Multi-modal Pixel (conceptual sketch)



- **Searching for a material with:**
  - Good optical absorption for VUV photons (<200 nm)
  - Able to achieve charge gain
  - Stable in cryogenic environments
  - Good transport properties in cryo

*Speed of light: 11.23 cm/ns (**112,300 mm/μs**)*
*Speed of charge (at 500 V/cm): 0.00016 cm/ns **(1.6 mm/μs)***



- **This has also opened research into electrodes which are transparent to VUV light and development of pulsed VUV light sources for characterization and testing**

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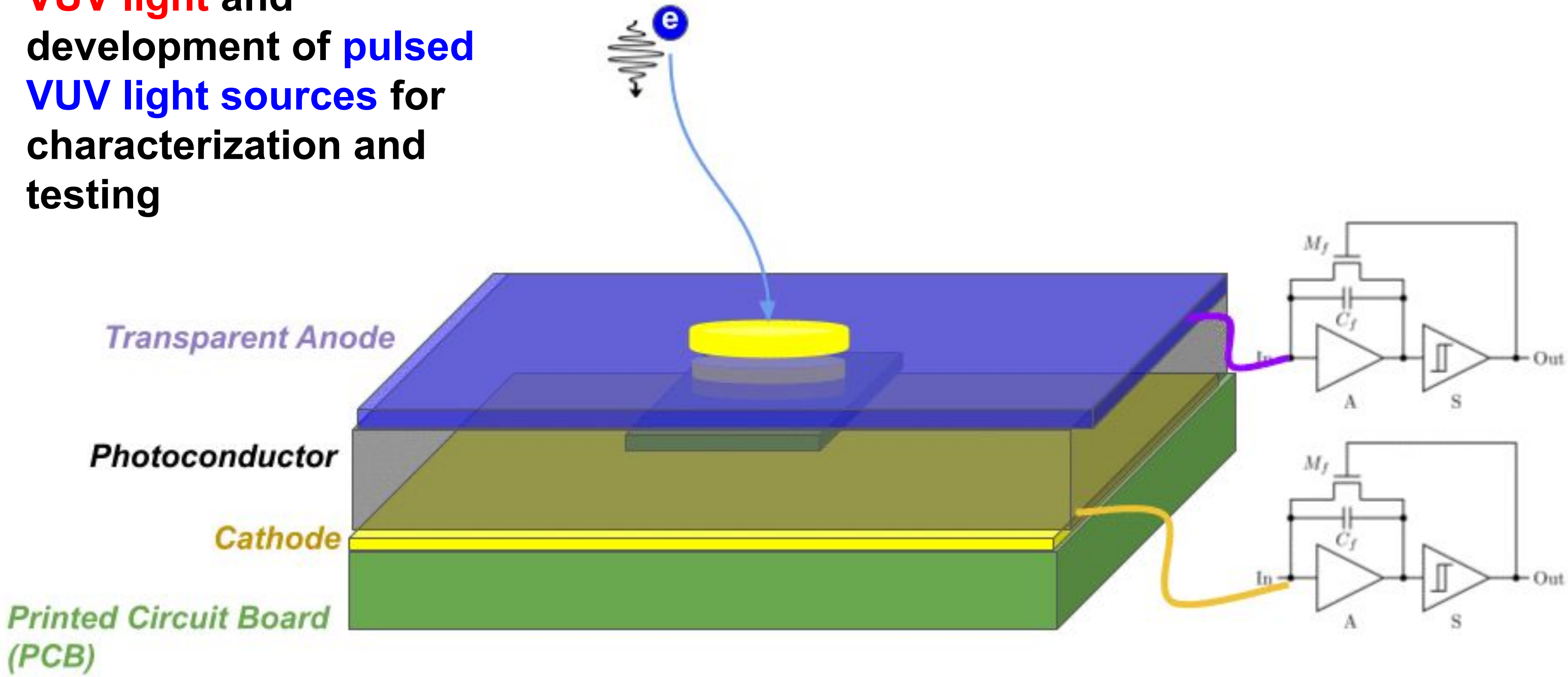
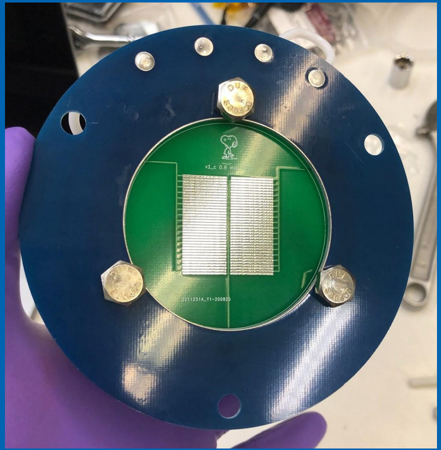
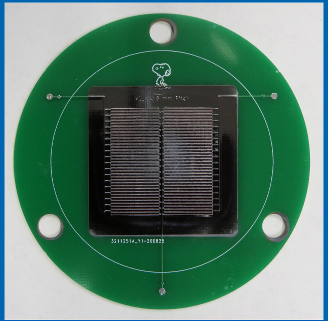
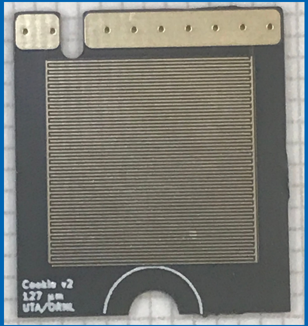


Evolution of prototyping using conventional readout





Work at UTA / ORNL



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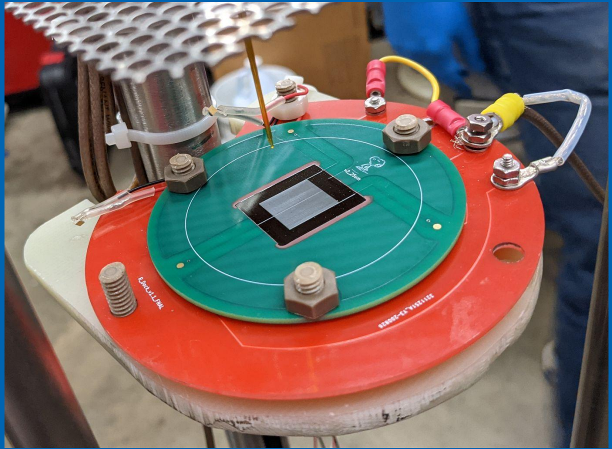
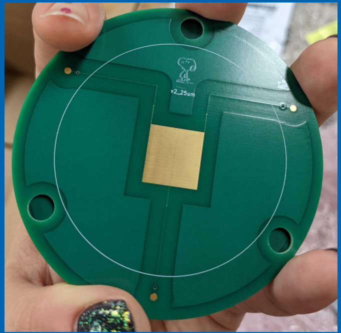




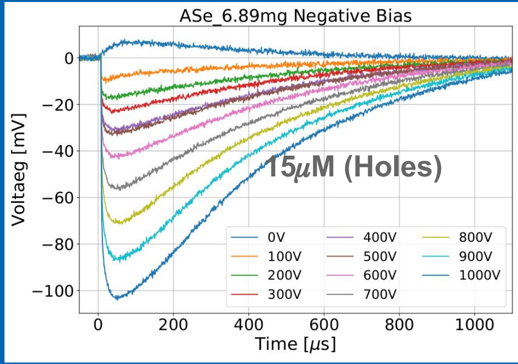
Work at UCSC / UTA / FNAL

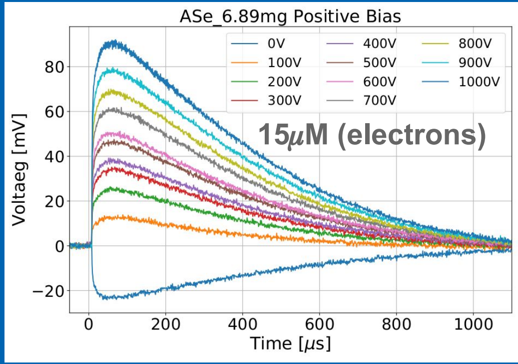
Commercial PCB with 127 μm trace spacing
Max field (5 V/μm)

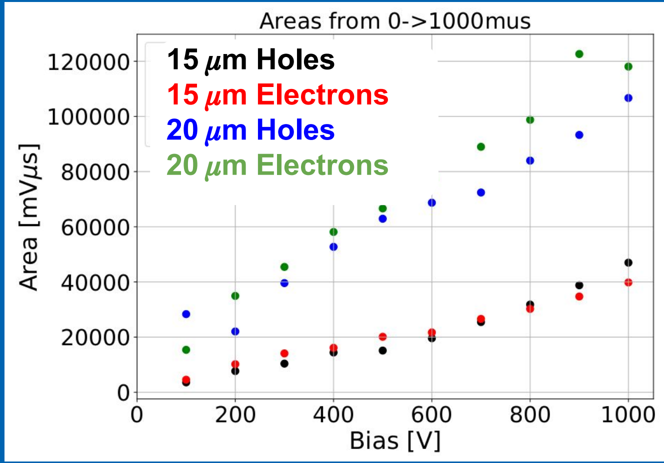
Commercial PCB with 127 μm trace spacing (cold electronics)
Max field (5 V/μm)

Custom PCB with 25 μm trace spacing
Target field (40 V/μm)

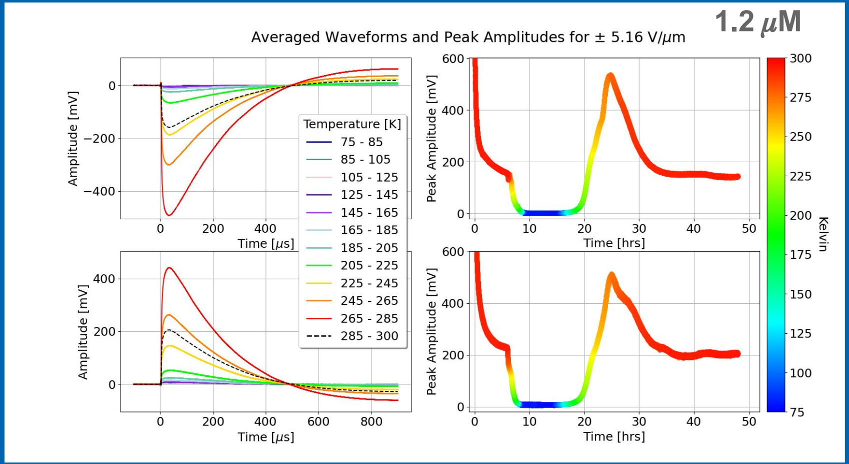
First test results (low field)

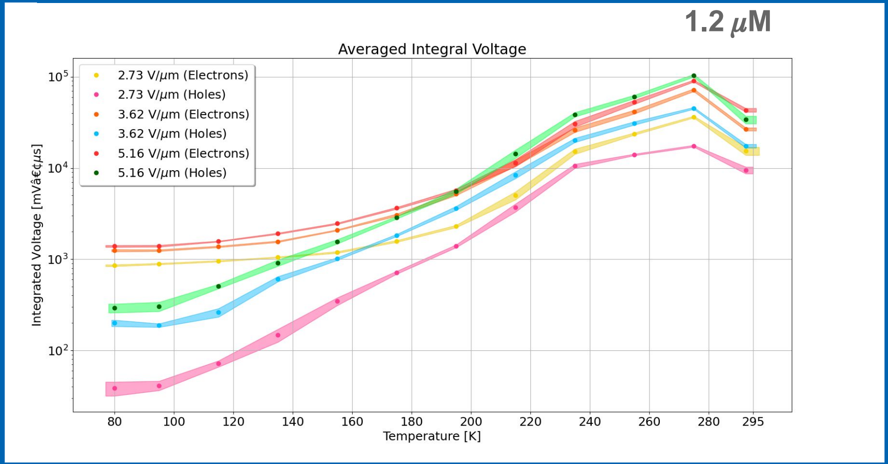






Vacuum Tests





Cryogenic Tests

Projects

- **Q-Pix**
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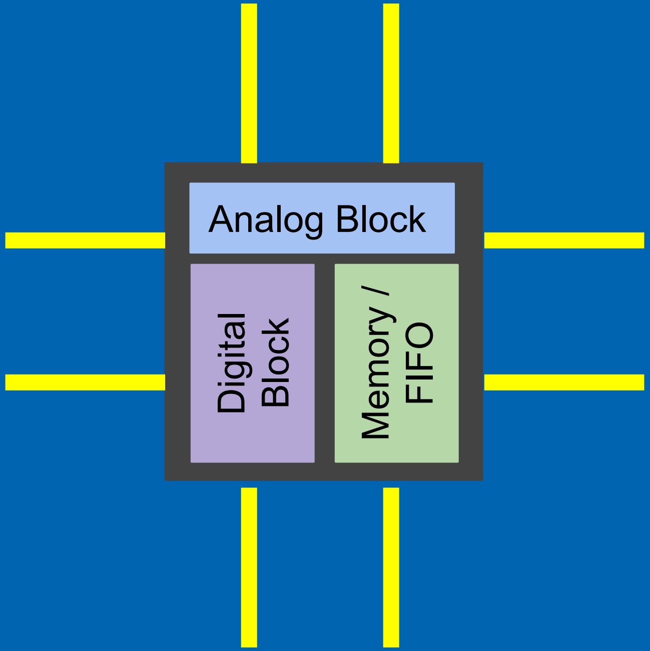
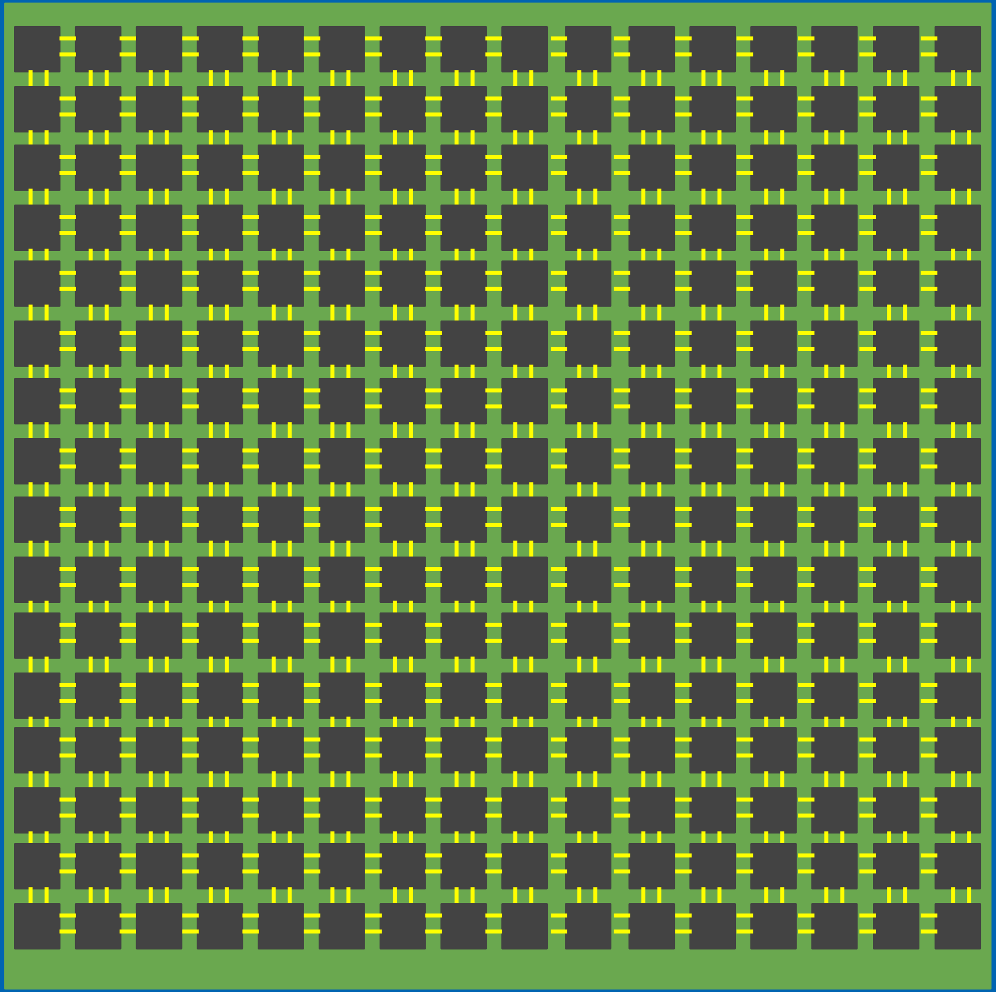
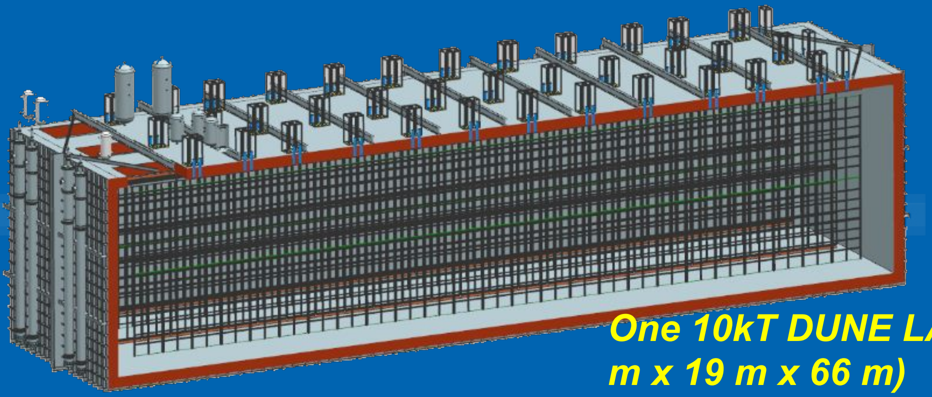
  - 65nm
  - eFabless Open MPW (Skywater 130nm)
- **Novel Photoconductors**
  - Current R&D work towards integrating with Q-Pix'ish design
- **Exploration into photonics for cryogenic detectors**
  - Some early thoughts and musings



- **Mixed-signal designs (analog and digital in one chip) are always susceptible to noise due to cross-talk**
  - There are volumes written on the design best practices to avoid this and many successful examples of working around this
  - One unsavory solution often proposed is to have “deadtime” during digital transmission to ensure fidelity in your analog signals
- **As we look for ever smaller and smaller charge-based signals, this problem becomes increasingly difficult to escape**
  - **Q-Pix first prototype:** Reset Threshold ~ 6250 e-
  - **Q-Pix target:** Reset Threshold ~ 1500e-
  - **Q-Pix Ideal:** Reset Threshold < 300e-
    - Currently, dealing with all the sources of noise is a limiting factor



- **Another source of noise is the inter-ASIC connections required to get the data off one chip and transmitted to another chip**
    - Every wire introduces some parasitic capacitance, leakage current, and a potential source of noise and/or cross-talk
    - Q-Pix tile has an absence of extensive data bus networks as goal to minimize sources of noise
- **16x16 ASICs (4096 pixels) has many (~1024) of these inter-ASIC connections**
    - This source of noise and problems with data fidelity transmission and path has already been identified in LArPix and has required non-trivial solutions
    - Board-level noise problems are very time-consuming and costly to fix!

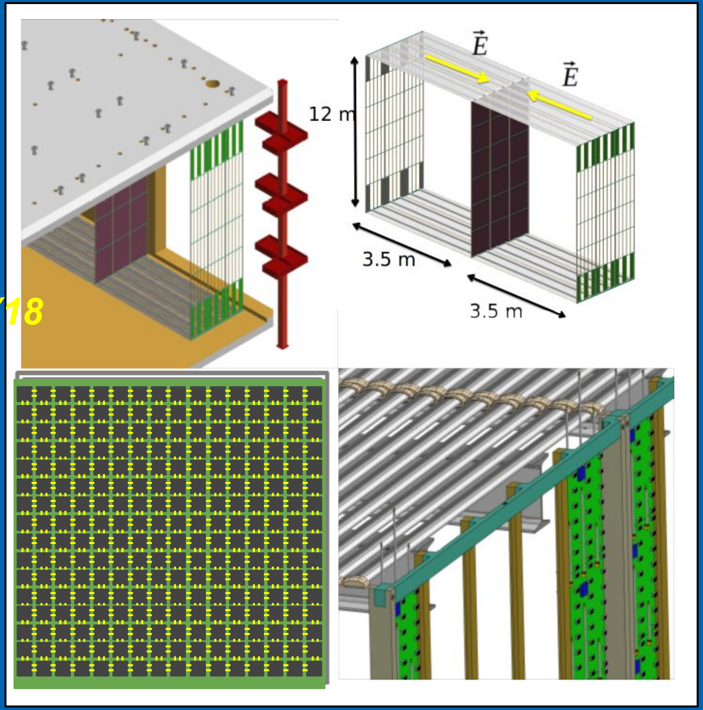


One 10kT DUNE LArTPC Module (18 m x 19 m x 66 m)
¼ the total size of DUNE

In a detector the size of DUNE, 120k of these tiles exist, each with copper lines that send data to an aggregator, which then sends that data out over readout cables (between 2m and 6m long).

This arrangement introduces a natural place for external noise to couple into your detector and potentially degrade your small signal sensitivity.

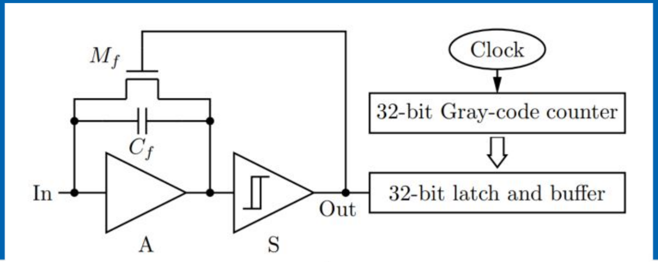
Is there a better way which hasn't been explored in this context?

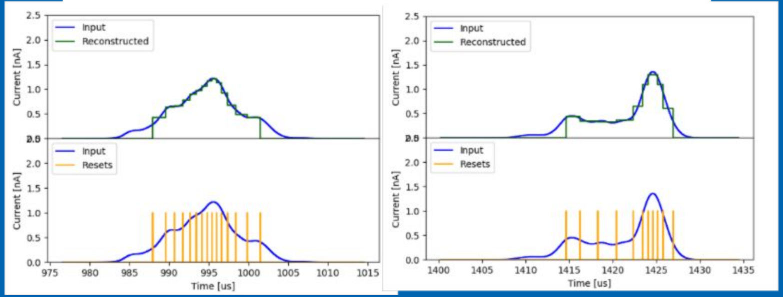


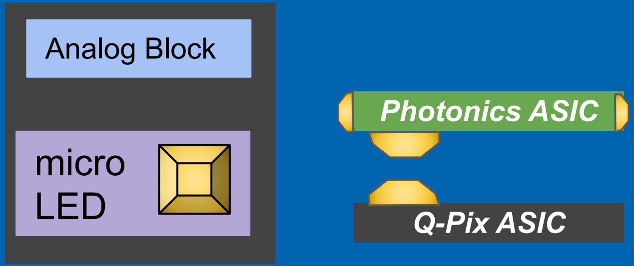
Conceptual layout for Q-Pix in 10kTon module with data aggregator (shown in blue) for a subset of tiles

What about photonics?

- A solution for data transmission in high rate, high radiation dose environments which has been explored in HEP is to integrate photonics into the system
  - *What about this application in the area of low-noise low threshold cryogenic detectors?*
    - Offers a (possible) solution to eliminating most of the interconnects and thus most sources of noise that come along with copper interconnects.
- Q-Pix seems like a natural test structure to explore the feasibility of this solution
  - The fundamental output is a pulse at a given time (whether that pulse is a voltage or a pulse of light doesn't matter)
  - The design is intended for an environment where data rates are low and the sensitivity to the low energy physics is key (so eliminating noise is essential)
    - This is not unique to Q-Pix (e.g. dark matter detectors)



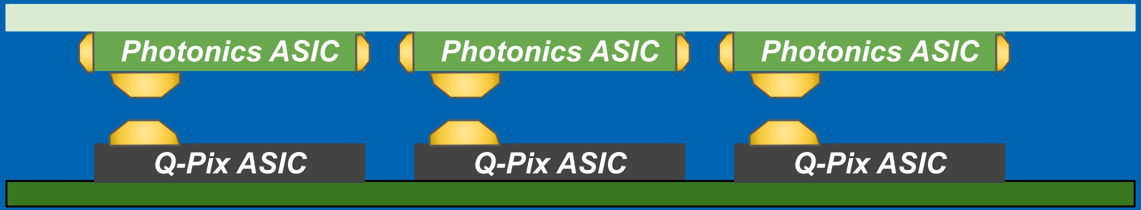




What's the concept?

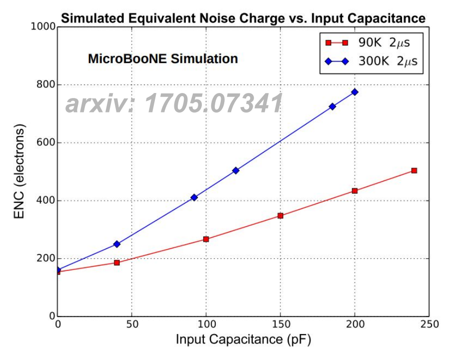
- **We decouple the data transmission and digital side of the readout from low-noise/low power cryogenic detectors to a photonics based solution which uses micro-LED's (or other applicable solution).**
  - Micro-LED's provide an attractive solution because of their low-power and low swing needed
  - The amount of light we need is only a few photons to transmit Q-Pix's reset to the photonics ASIC, and then the photonics can use low levels of light to transmit this information ASIC-to-ASIC (no copper coupling)
  - We can then use an optical readout to take the signals from the tile to outside the detector (again, eliminating any coupling the external world to our low threshold ASIC

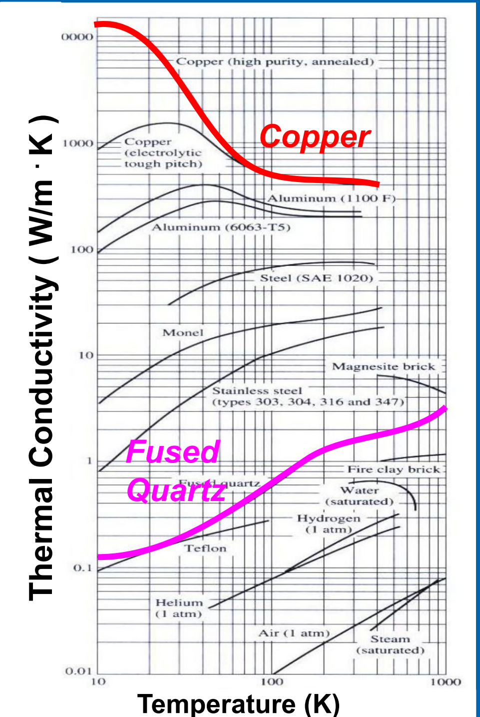
Not a bump bond (just an artistic conception of the idea)



What is to be gained?

- **Significant reduction in noise due to parasitic capacitance**
  - Should allow us to approach the noise limit of the CMOS front end
- **Reduction in heat load for cryogenic detectors**
  - 1 meter of SMA cable copper cable carries 40 mW of heat between 290K and 80K
  - Optical fibers have between 100-10,000x less thermal conduction
- **Elimination of electromagnetic interference and crosstalk on long cables**
  - Optical fibers have negligible signal losses at the length scales needed for cryogenic readout (typically 0.2-0.5 dB/km), which are also frequency independent





Experimental Techniques for Low Temperature Measurement

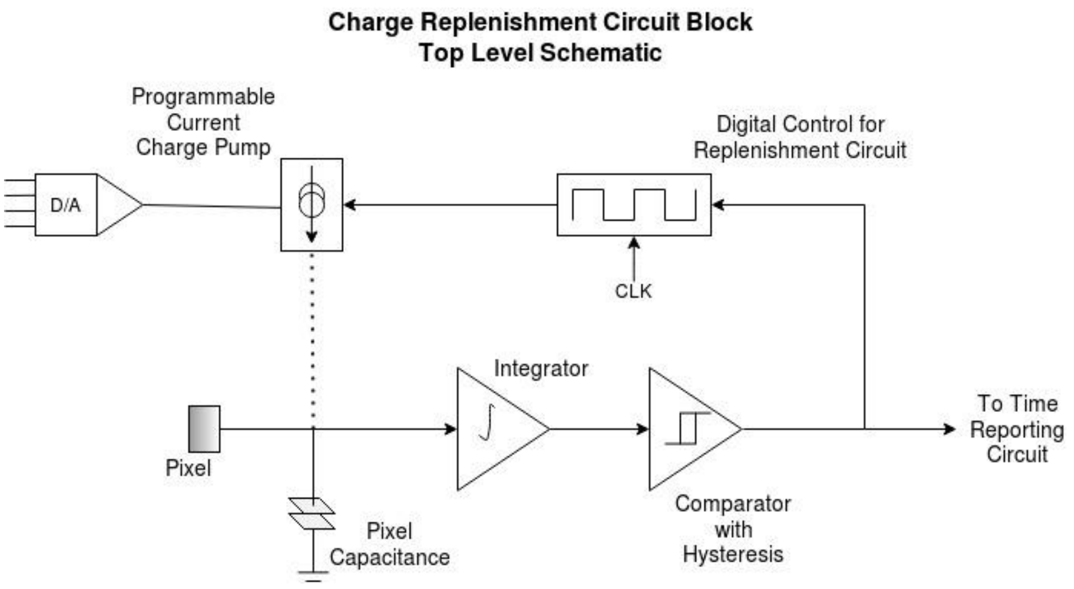
Who’s the team and what’s the goal?

- **We foresee this being something explored at UTA with 4 PI’s in a joint effort between our EE department and the physics department**
  - **Physics** Jonathan Asaadi and Dave Nygren
  - **Electrical Engineering:** Jim Coleman & Sungyoung Jung
    - Coleman: National Academy of Engineering and the National Academy of Inventors
      - Expert in photonics
    - Jung: Opto-electronic integrated circuits and Analog and mixed signal expert
- **We think this fits in a 3 year R&D profile quite nicely**
  - **Year 01:** Proof of concept and development of test structures for tests in cryogenic environment
  - **Year 02:** Example in small scale (2-4 ASIC) demonstrator (using Q-Pix prototypes) and further development of photonics aspects at cryogenic temps
  - **Year 03:** Scaled demonstration on a 3x3(?) ASIC array (hopefully showing the reduction in noise and its proof of concept scaling)
    - We are currently working on studies and demonstrators which we can do now with existing tools to set a plan for a forthcoming proposal

Conclusions

- **UTA is a group who is pursuing new and novel detector ideas to maximize the discovery potential of current and future experiments**
- **We are only able to do this because of a collaborative and friendly environment with HEP-IC experts at universities and national labs**
  - The “back and forth” between physicists and instrumentation experts plays a central and critical role in both the training of the next generation of scientists as well as forming a knowledgeable foundation of experimentalist
- **Open source IC tools and partnerships with UTA’s EE group is allowing us to gain experience and expertise to explore new and novel ideas**
- **We look forward to continuing to collaborate with this community and contributing where we can!**

Backups



Working : Brief

1) Ionization current from charged particle tracks in liquid Argon, are collected by pixels in the detector.

2) This front end is intended to replenish the charge on the pixel in increments of ΔQ, metered out by an on chip clock.

3) The time associated with the replenishment charge is recorded.