Novel VUV Light Detection in a Pixelated Liquid Argon Time Projection Chambers

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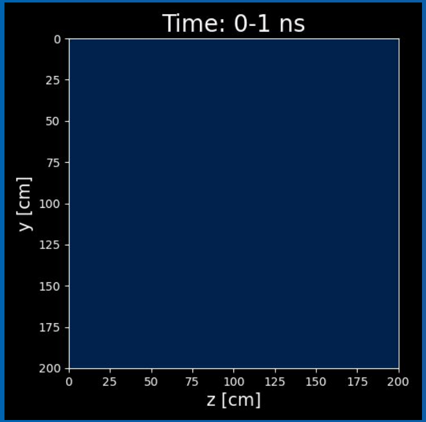
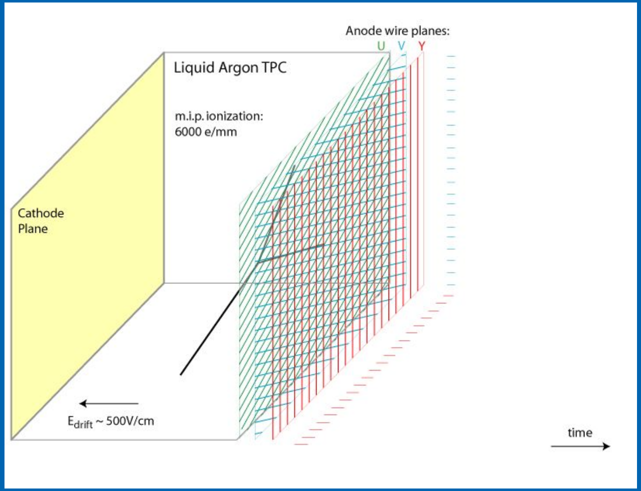


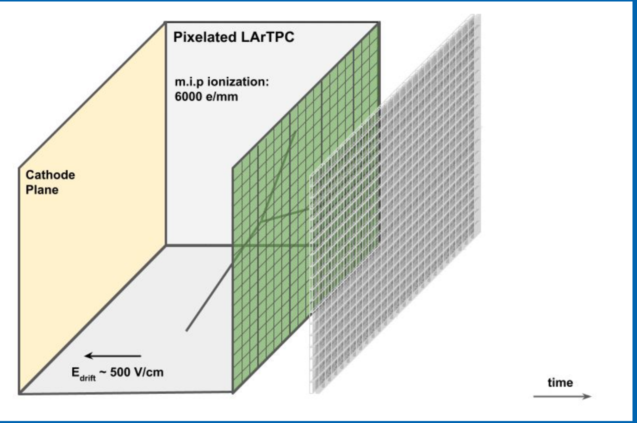
Simulation of pixelated photon detector

Research is supported via DE-SC0020065, DE-SC 0000253485 award, and FNAL-LDRD-2020-027

Pixelated Liquid Argon TPC

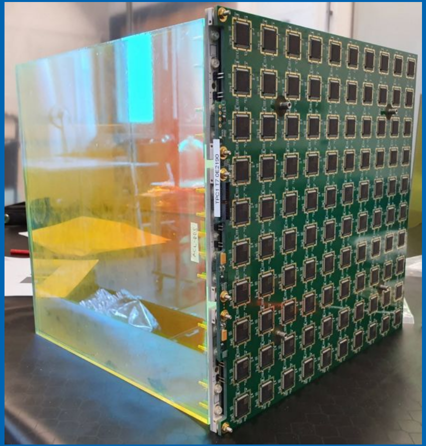
- **Liquid Argon Time Projection Chambers (LArTPC's) offer access to high quality, detailed information about neutrino interactions from MeV - GeV scales**
  - Conventional wire readout uses the 2D projection from multiple views to reconstruct the 3D interaction
    - ***A very challenging endeavor!***
  - Dedicated pixel based readout preserves the native 3D information
    - ***Comes at the cost of many more channels***
      - LArPix ([1] and Q-Pix [2] have addressed this challenge by developing low power dedicated electronics for large scale LArTPC pixel readout
- **The advantages of a native 3D readout have been shown to increase both neutrino signal efficiency and background rejections**
  - Paper: JINST 15 P04009
- **The novel readout solution known as Q-Pix has also shown the enhancement to low energy neutrinos (e.g. supernova neutrinos) which are possible with a pixelated low-power, low-threshold sensor**
  - Paper: Phys. Rev. D 106, 032011 (2022)

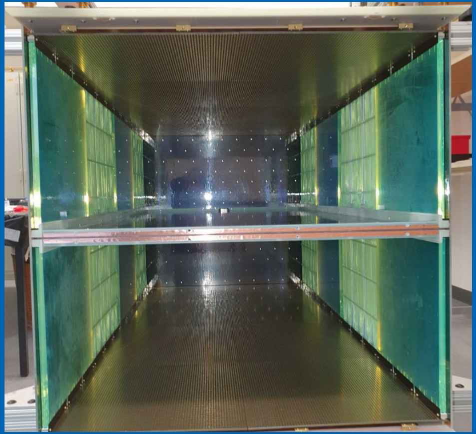


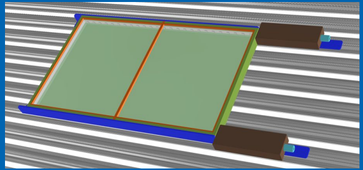


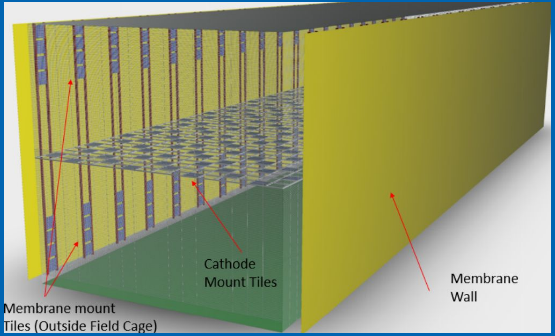
Photon Detection w/ Pixel Based Detector

- **The pixel readout is opaque, and thus the conventional positioning of the light readout behind the charge collection plane is not possible**
- **A few different solutions have been explored to tackle this**
    - Dielectric waveguide which penetrates into the active volume and guides the light to SiPMs mounted on the pixel plane
        - Paper: Instruments 2018, 2(1), 3
    - Electrically floating photosensors and electronics mounted to the cathode and field cage
        - Paper: JINST 17 (2022) 01, C01067
    - Solutions give you 20-30% photon coverage with *O*(%) level efficiency



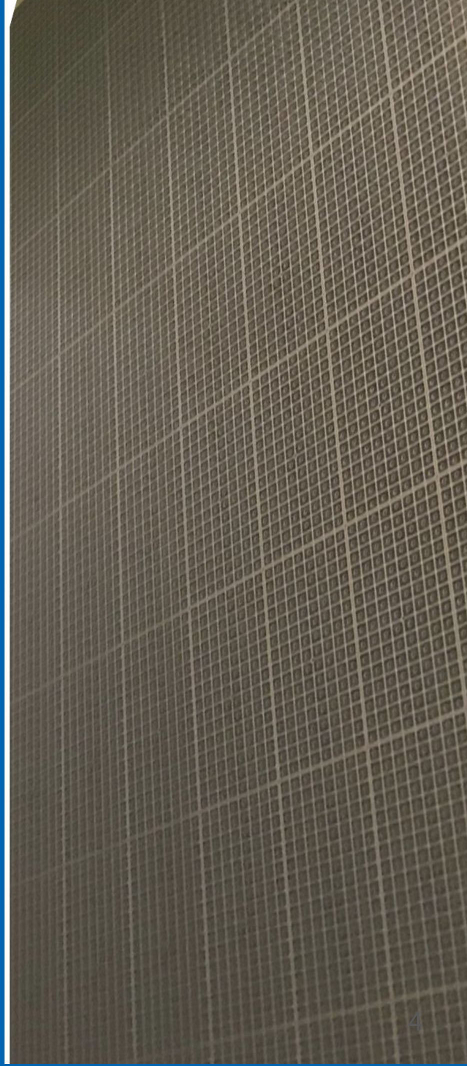






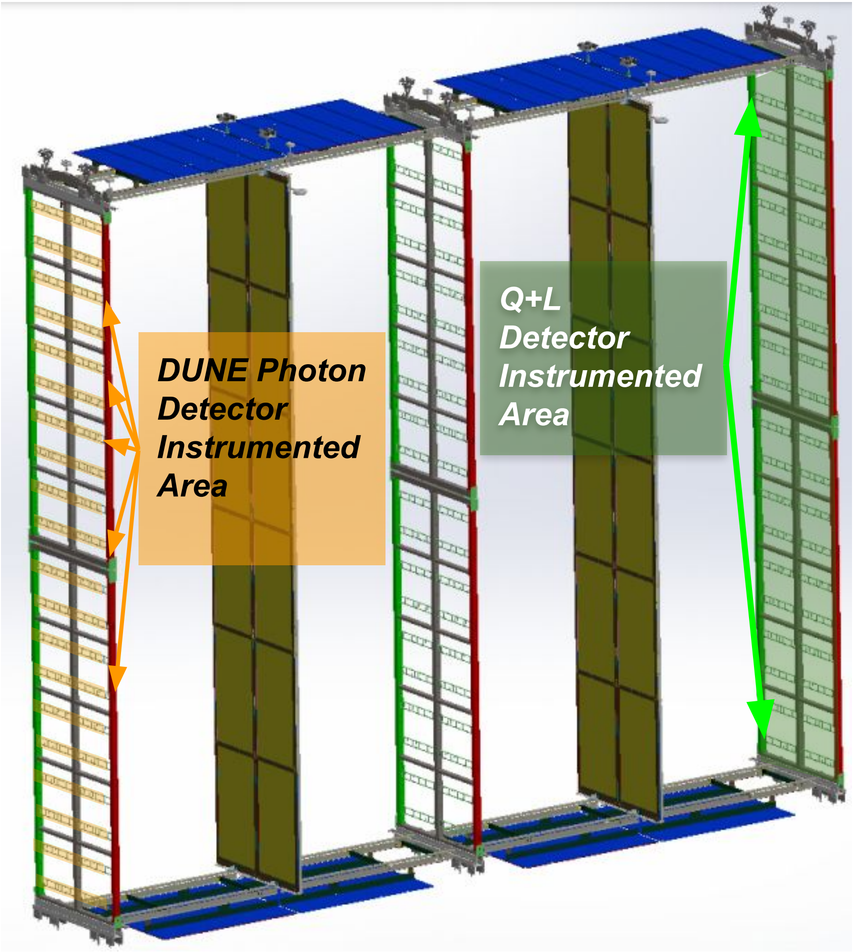
Pixels which also are photo-sensitive?

- **What if the whole pixel plane 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**

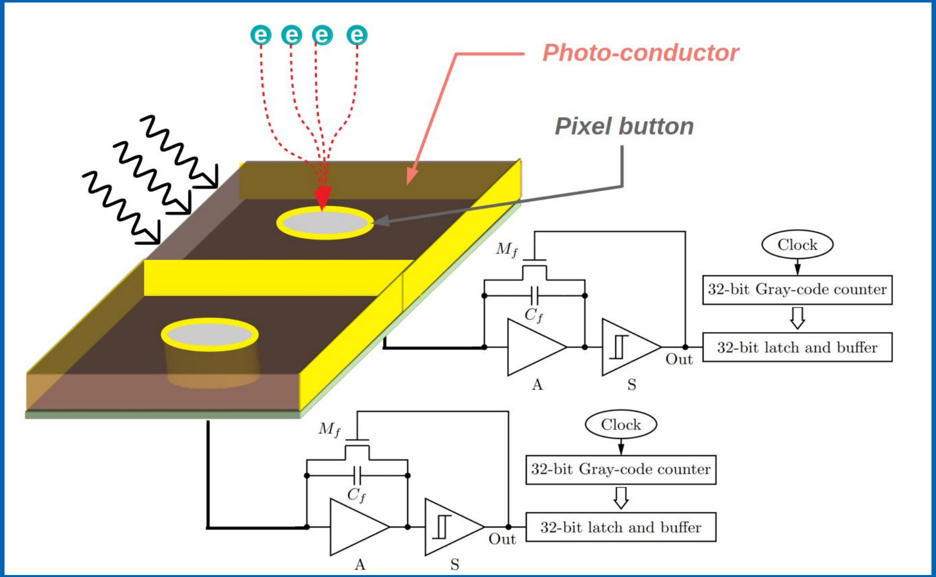


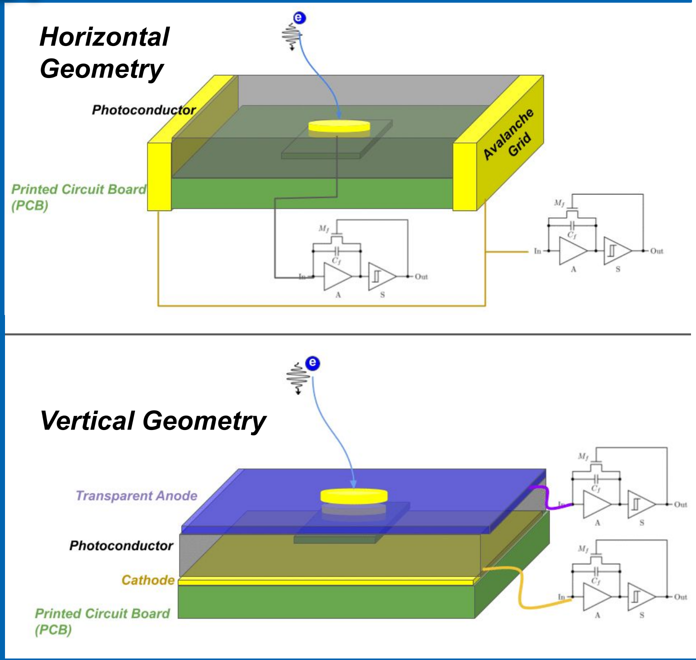
What’s can be gained?

- Currently DUNE Horizontal drift 10kT photon detector coverage is 130 m^2/10kT
  - Window area for each XArapuca supercell (435.24 cm^2) x 10 supercells/APA x 152 APA’s per 10kT x 2 (Double sided)
- If a Q+L Pixel Sensor can be realized, then your photon detector coverage is 200,000 m^2/ 10kT
  - APA Surface area (135,700 cm^2) x 152 APAs/10kT



Concept of an integrated Q+L Sensor



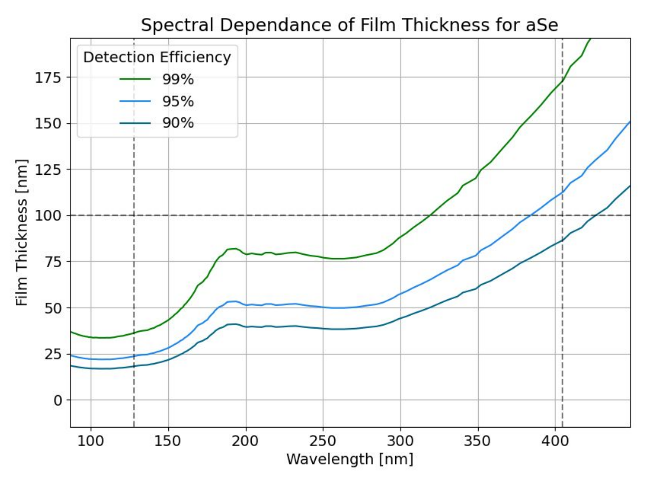


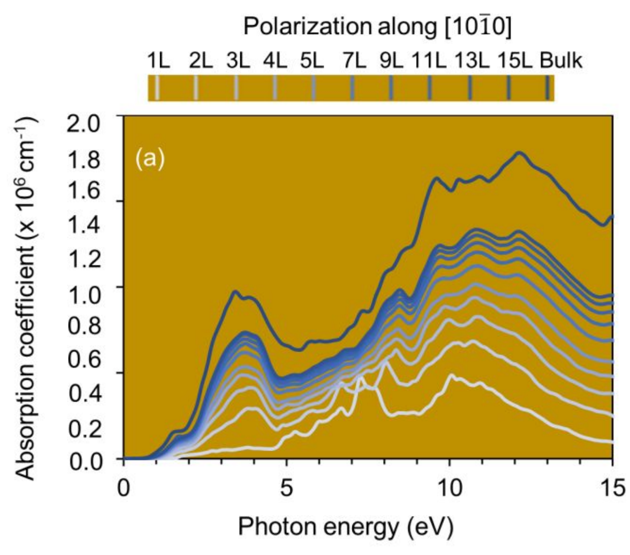
Can a photoconductive substrate applied to the pixel plane allow for the integration of charge (Q) and light (L) into one single sensor?

- **Lots of questions to be answered (photoconductor?, geometry?, electronics?, gain?, etc….)**

Searching for a novel photoconductor

- There are a large number of potential photoconductors to be explored which could satisfy what we would like to do
  - Perovskites, Nanoplatelets, Organic Photodiodes, Selenium, etc.…
  - Good opportunity to collaborate broadly with material science experts, national labs, and university groups
- We began with an investigation into amorphous selenium
  - Broadly used in medical imaging devices
  - Relatively cheap and has an easy manufacturing process (thermal evaporation)
  - Largely unexplored (but very promising) properties in VUV wavelengths
    - Example of a DFT calculation done with condensed matter theorist to understand selenium properties ([Langmuir 2022, 38, 28, 8485–8494](#))





The strategy for exploring amorphous selenium

- **Proof of concept**
  - Understand selenium properties to VUV light ([Langmuir 2022, 38, 28, 8485–8494])
  - Develop a pulsed VUV light source for calibration ([Review of Scientific Instruments 93, 053103])
  - Test its application on printed circuit board at cryogenic temperatures ([arXiv:2207.11127] / Submitted to JINST)

We've just completed this phase (see coming slides)

- **Low Photon Yield Demonstration**
  - Show viability of detector to have sensitivity to low VUV photon flux
  - Explore different geometries in detector construction
    - (windowless horizontal vs VUV transparent window vertical geometry)
  - Perform simulation studies to show the conferred benefit of a Q+L sensor for LArTPC's
  - Detailed simulations of amorphous selenium with various doping schemes

We'll show some preliminary results from these efforts which are currently ongoing

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Hope to achieve this in the next 12-18 months

- **Build a scaled up demonstrator**
  - Operation of a small scale Q+L pixel based TPC
  - Construct large(r) scale pixel plane ($O(100cm^2)$) with aSe pixel based photon detector

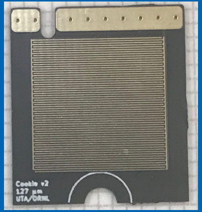
Proof of Concept

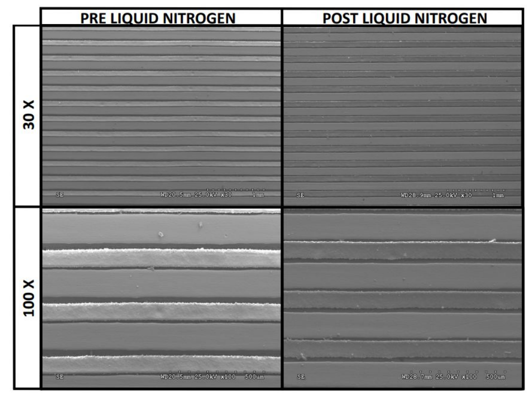
Development of a novel, windowless, amorphous selenium based photodetector for use in liquid noble detectors *arXiv:2207.11127 / Submitted to JINST*

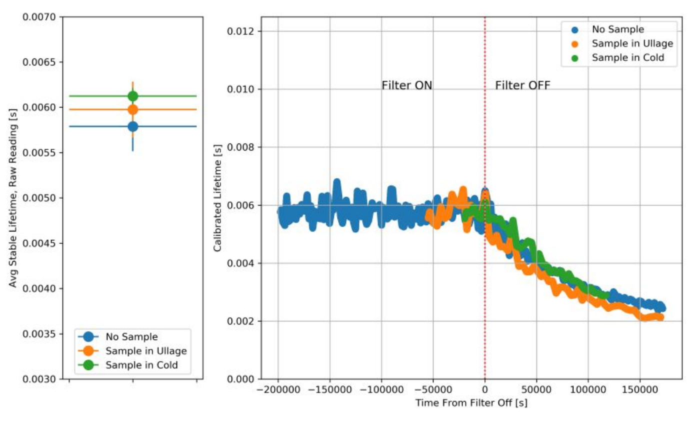
M. Rooks,[a] S. Abbaszadeh,[b] J. Asaadi,[a] M. Febbraro,[c] R.W. Gladen[a,2] E. Gramellini,[d] K. Hellier,[b] F. Maria Blaszczyk[d] A.D. McDonald[a]

First check if aSe based detector is robust during cryogenic cycling

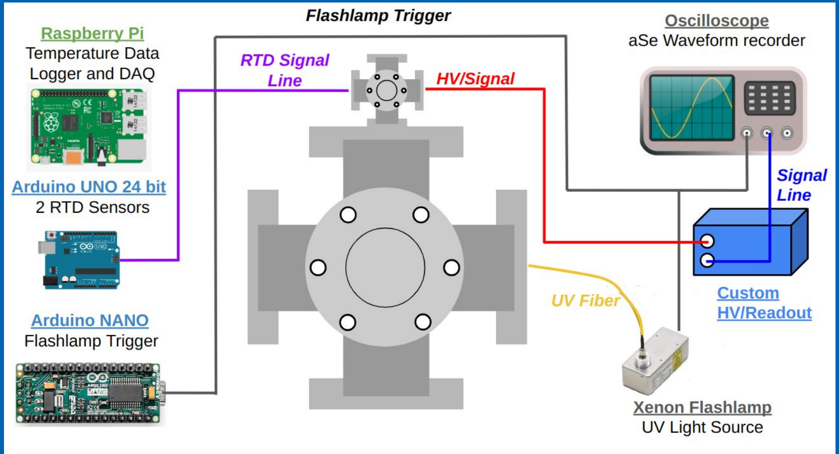
- Visual inspection and SEM imaging of aSe coated interdigitated electrode (IDE) after cryo-cycling in LN2
    - ***No degradation observed in the samples!***
- Test to see if aSe PCB introduces unwanted electronegativities into liquid argon
    - Tests done at FNAL Material Test Stand (MTS)
    - ***No significant decrease in electron lifetime!***

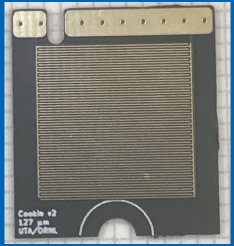






Proof of Concept





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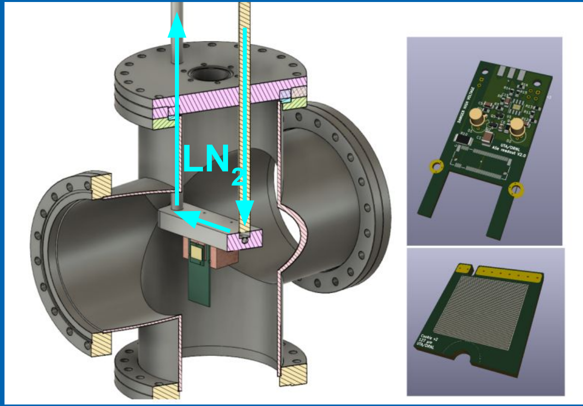


We construct a vacuum chamber which we can input a VUV light source to impinge on an IDE PCB

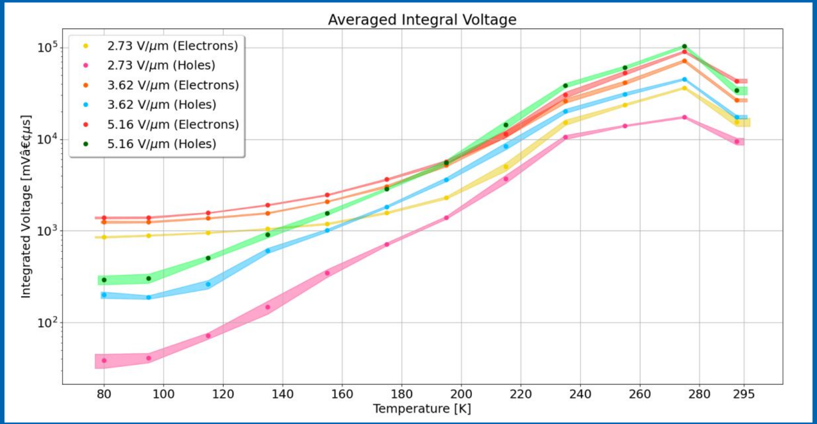
The PCB is mounted to a copper block which is in contact with a heat exchanger which allow liquid nitrogen to flow through it and allows us to control the rate of cooling to ~1 Kelvin / minute between 290K - 77K

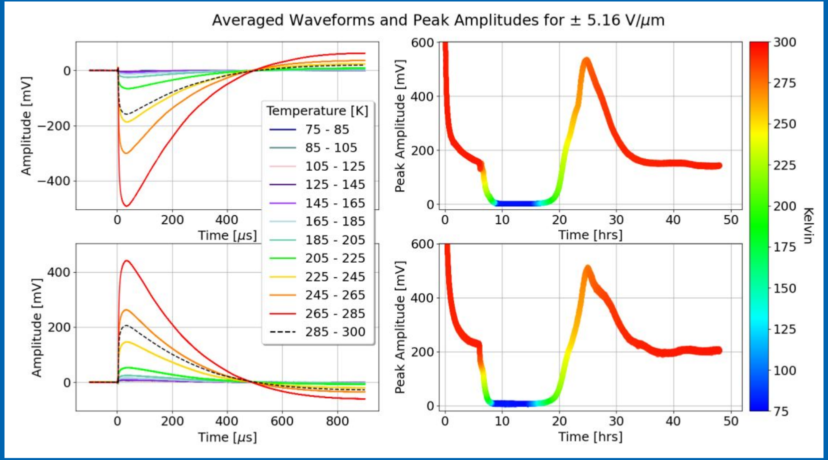
Commercial PCB with 127 μm trace spacing (Max field (5.17 V/μm))

Proof of Concept

Four Key Findings

1. While the magnitude of the **peak amplitude is noticeably reduced at the lowest temperatures, it is definitively non-zero** and has a pulse shape consistent with a response due to signal from the flashlamp
2. The **magnitude of the peak amplitude scales approximately with the size of the applied field**
3. The peak amplitude at the lowest temperatures is consistently **higher when collecting electrons rather than holes**.
4. We observe a **reduction of the signal peak amplitude under repeated pulses** of light from the xenon lamp. This phenomenon is consistent with a phenomenon known as ghosting.



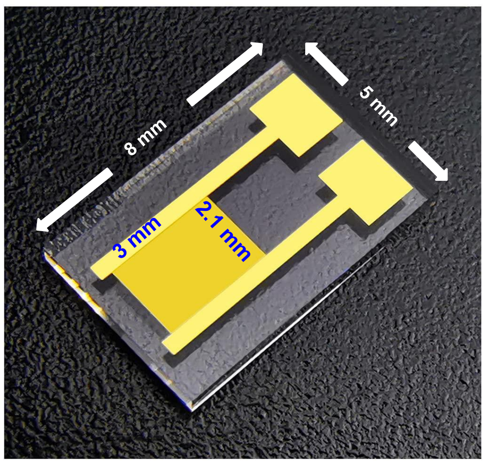


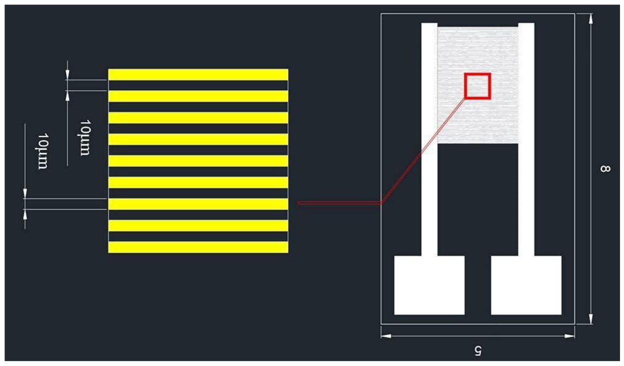
Pushing to lower photon yield and gain

To allow us to push to lower photon yield, we have to go to higher electric fields.

- This requires going to smaller pitch in the IDE's
- Using a commercially available IDE on quartz with conductor layer 30 nm tin and 100 nm gold
- Apply 100 - 150 nm of aSe

IDE Coated in selenium



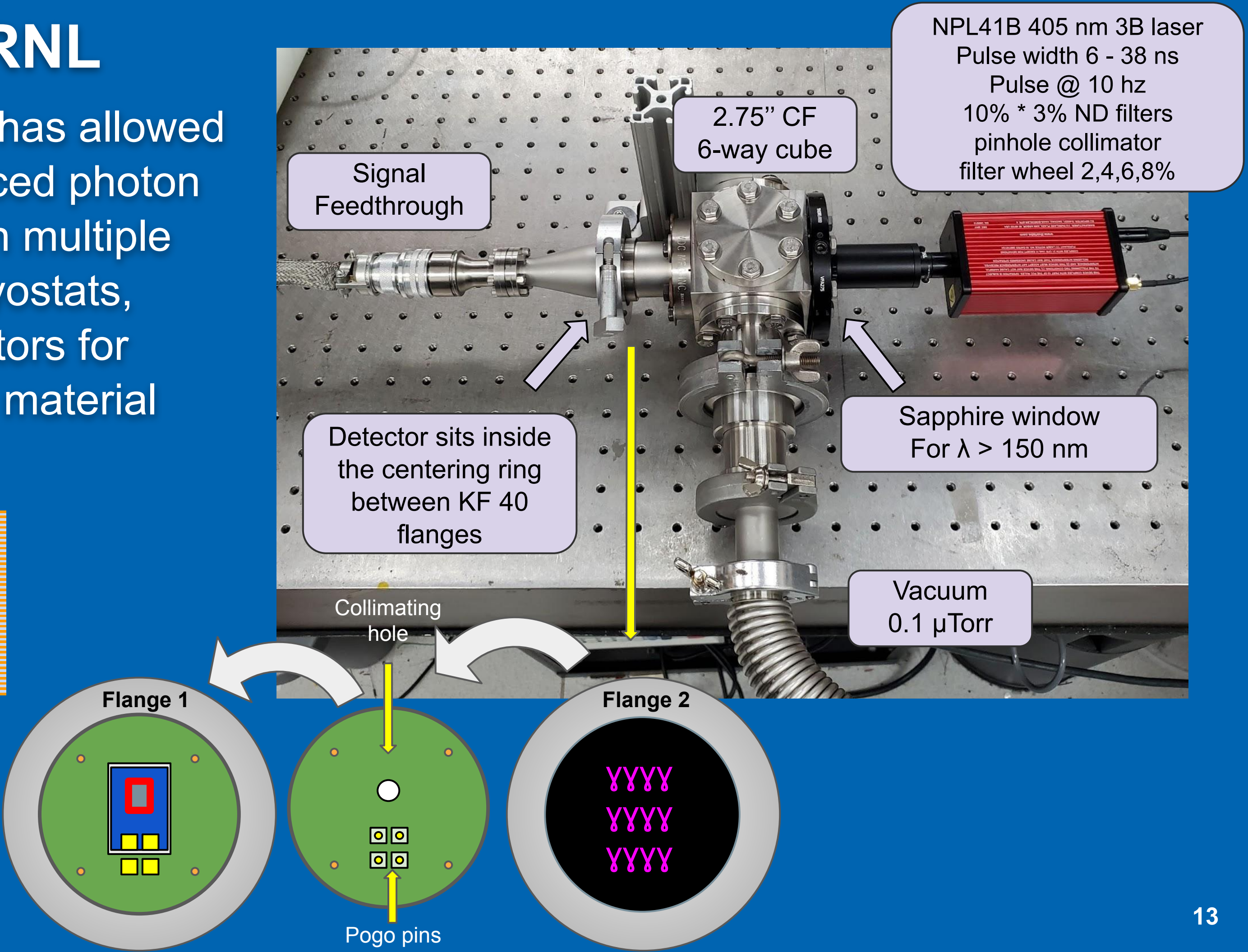


This allows us to achieve electric fields ~40 V/μm without a blocking layer

- Need to get to fields > 80 V/μm to achieve gain
- Currently exploring various blocking layers

Test setup at ORNL

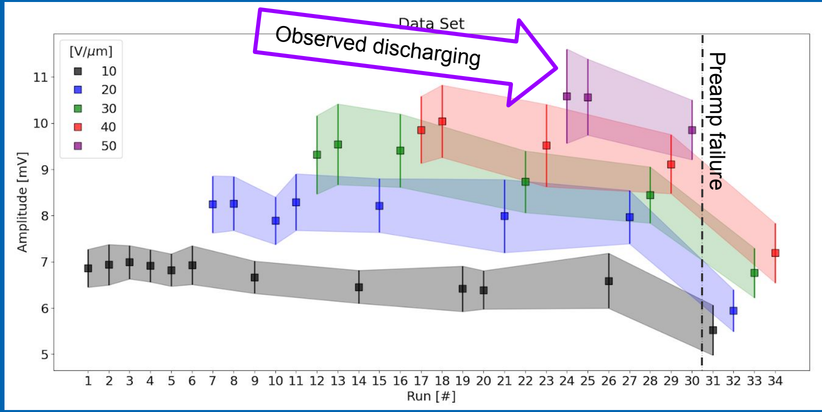
Partnership with ORNL has allowed us to utilize their advanced photon detector test stands with multiple light sources, optical cryostats, calibrated photon detectors for cross-comparisons and material fabrication capabilities

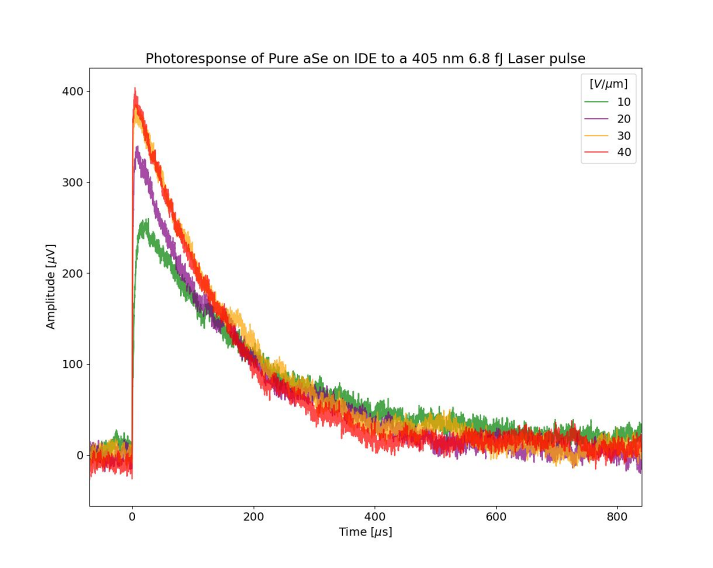


Early results at low photon yield

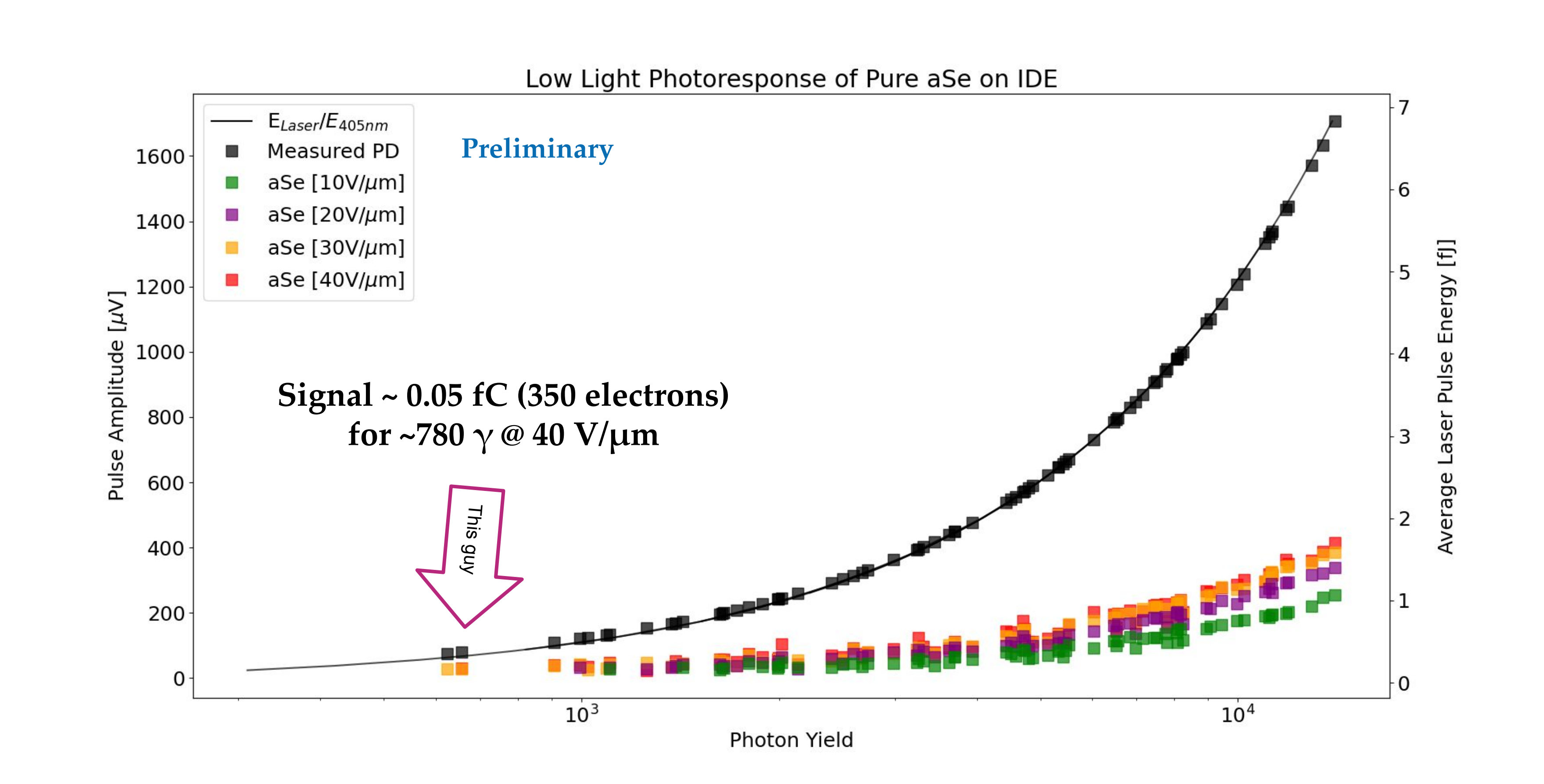
Using a photodiode to calibrate the overall photon yield we have performed three important tests (at room temperature)

1) **Confirm the stability** of the setup while pushing the IDE to the breakdown voltage in selenium w/o a blocking layer (40-50 V/μm)
2) Observe **signal in aSe for 405 nm light** at 35 V/μm down to **~780 photons**
3) Begin **calibration for VUV light source** to reliably go below 500 photons
   a) Once done, will go down in temperature to LN_2 temps



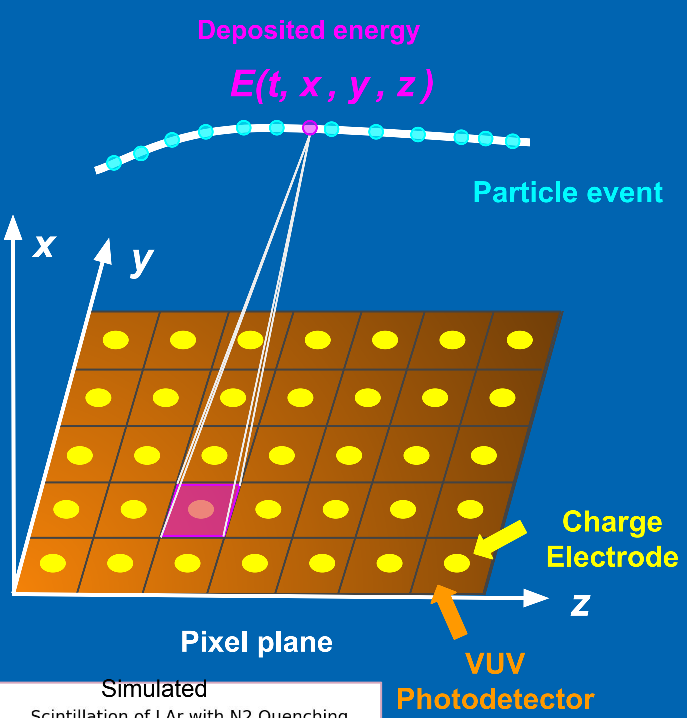


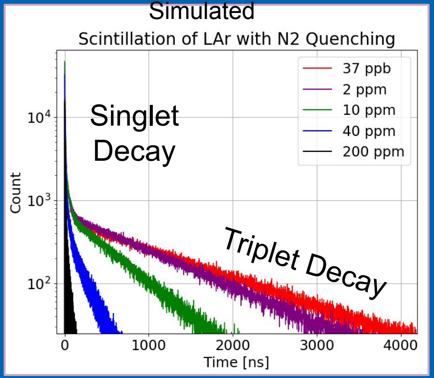
Early results at low photon yield

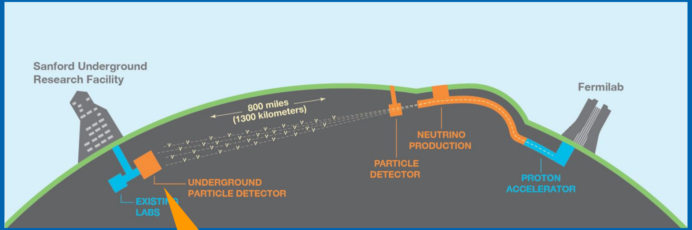


Simulation of a pixelated Q+L Sensor

- **To study how a Q+L sensor could enhance the physics of a pixel based detector we utilize various simulation techniques developed in the community**
  - One challenge is the number of “detectors” is enormous for a large size pixel array
    - Brute force Geant4 photon propagation just takes too long
    - Currently exploring Opticks (GPU for G4)
- **We use Geant4 to handle the charge depositions and then use:**
  - **LArQL model for recombination (JINST 17 C07009)**
  - **Semi-Analytic Method (Eur.Phys.J.C 81 (2021) 4, 349) to predict the # of photons and their arrival time at each pixel**
    - We have added effects due to nitrogen contamination to model quenching in the simulation as well






Sanford Underground
Research Facility
800 miles
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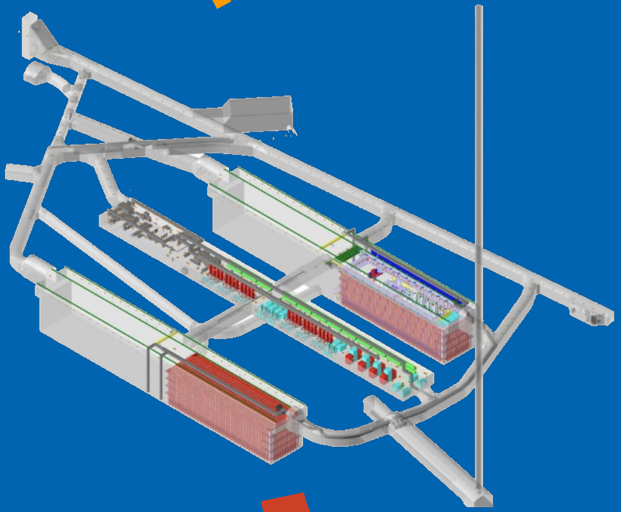
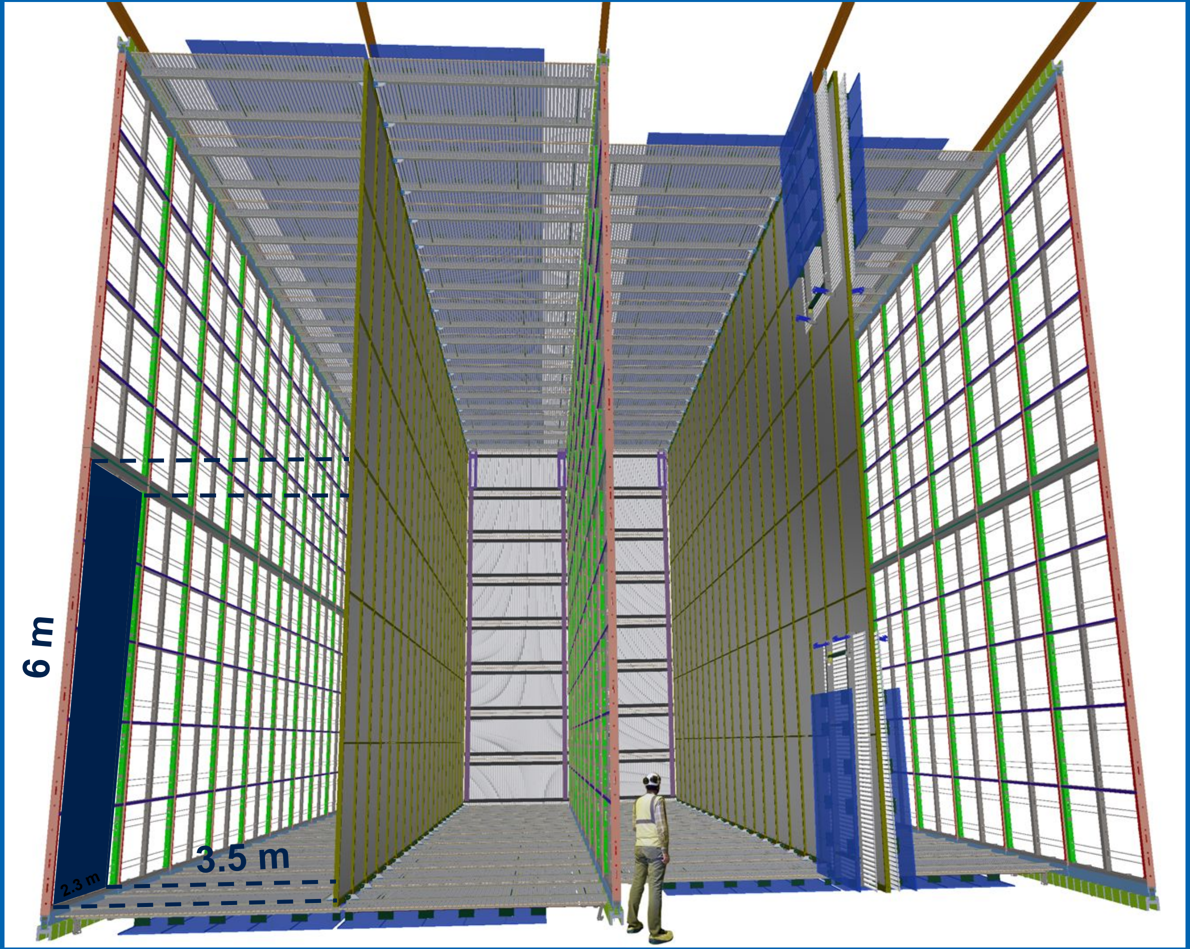
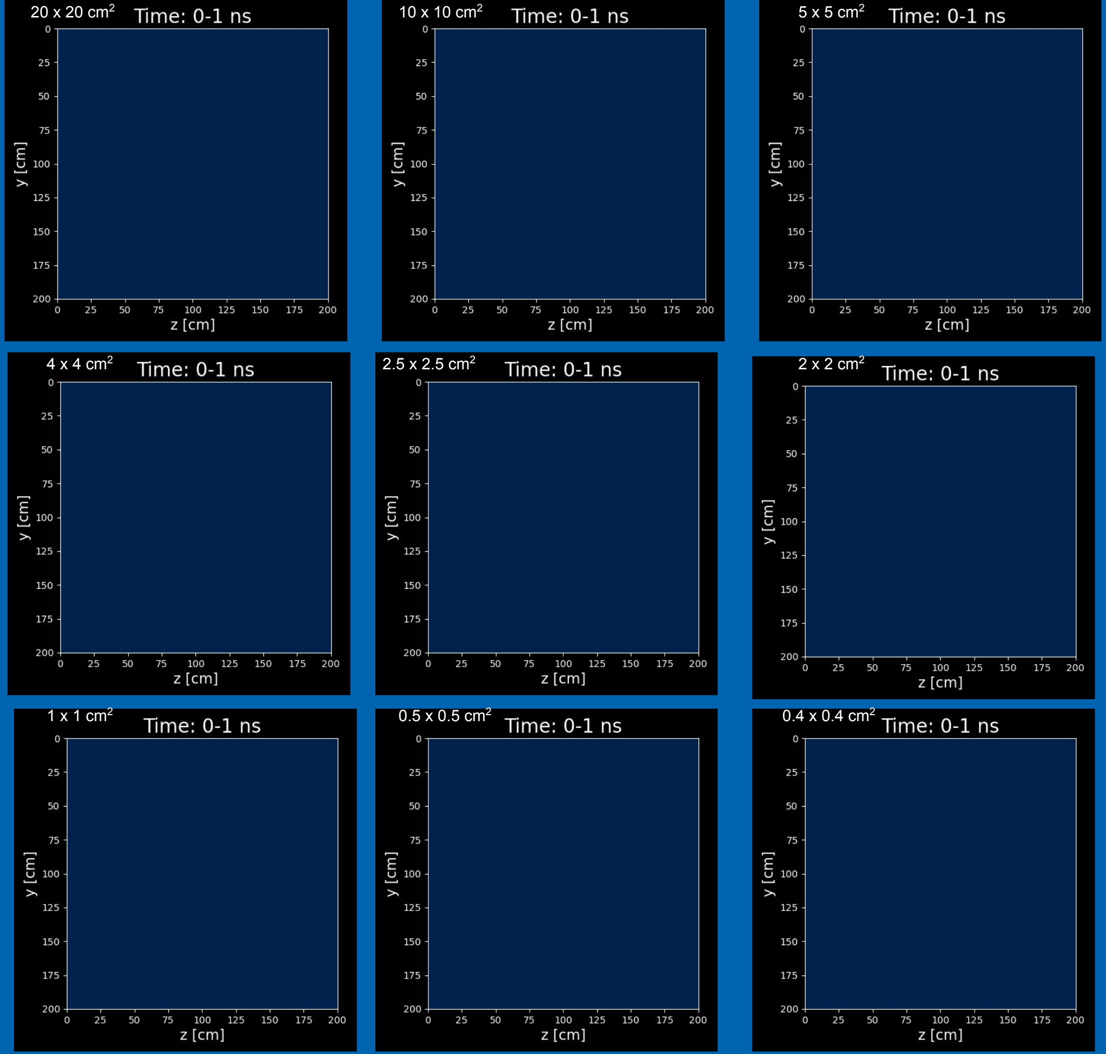



6 m
3.5 m
2.3 m

What does granularity get you

We simulate a (unphysical) "neutrino" energy deposition at 5 cm from a 2 meter x 2 meter pixel plane with different Q+L pixel sizes ($20\text{x}20\ \text{cm}^2 \rightarrow 0.4\text{x}0.4\ \text{cm}^2$)

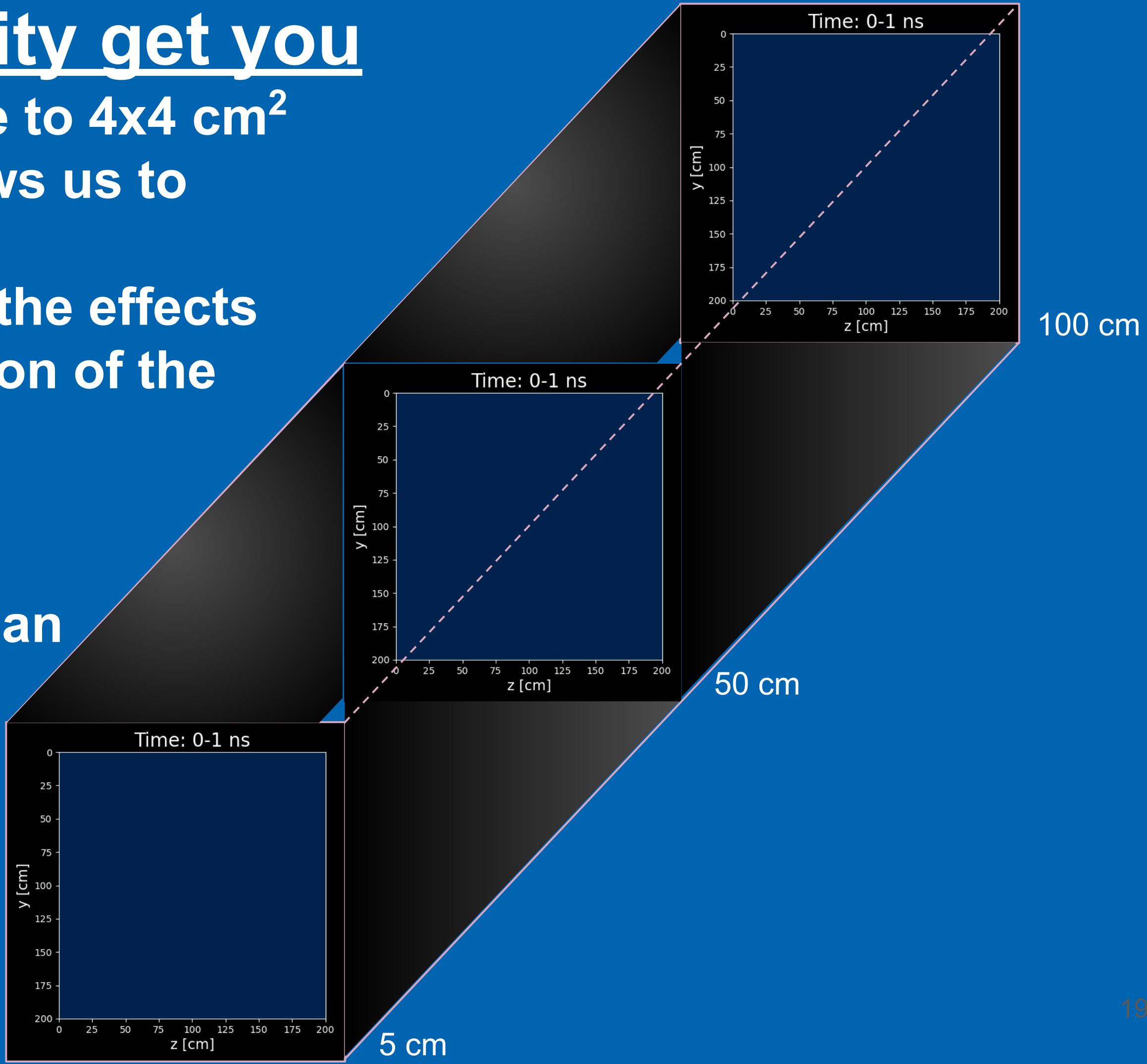
This helps illustrate how the granularity and timing characteristics give you topological information

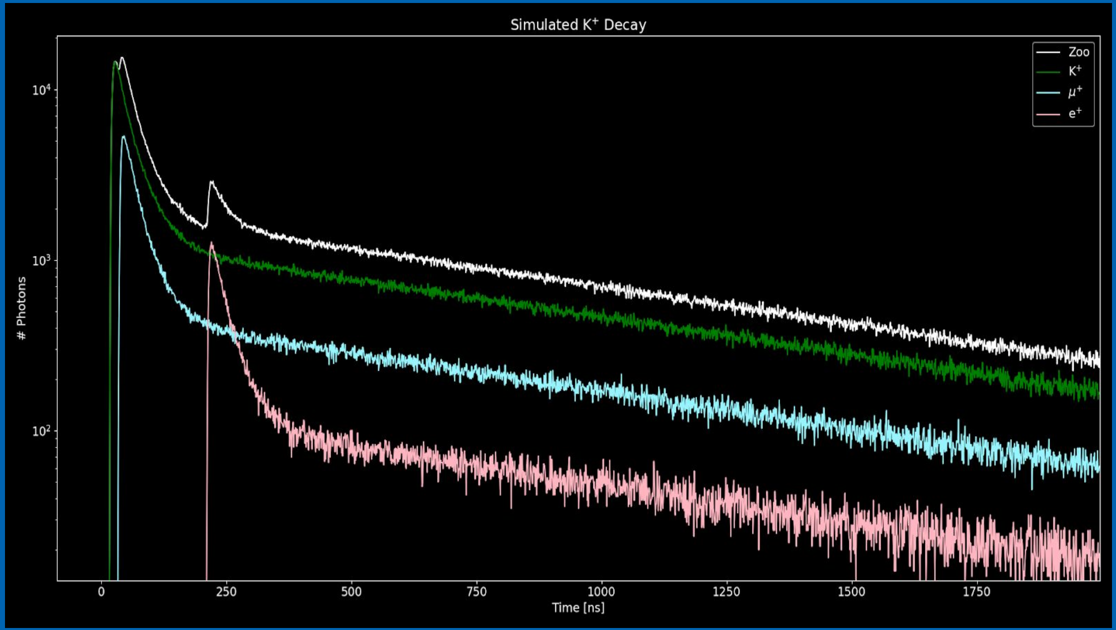


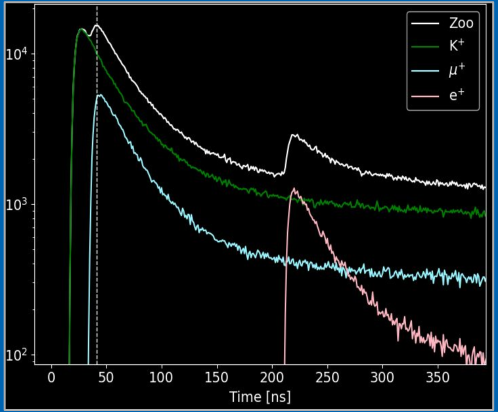
What does granularity get you

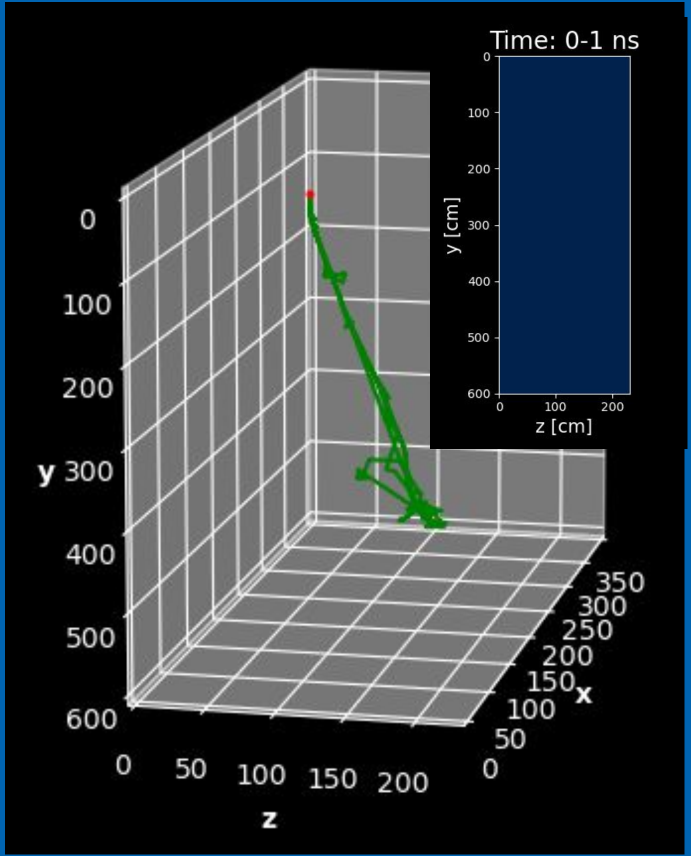
If we fix the Q+L sensor size to 4x4 cm^2 tile the simulation also allows us to analyze how the topological advantages are effected by the effects of scattering and the diffusion of the light

We are now working to find an optimization of the photon sensor size.





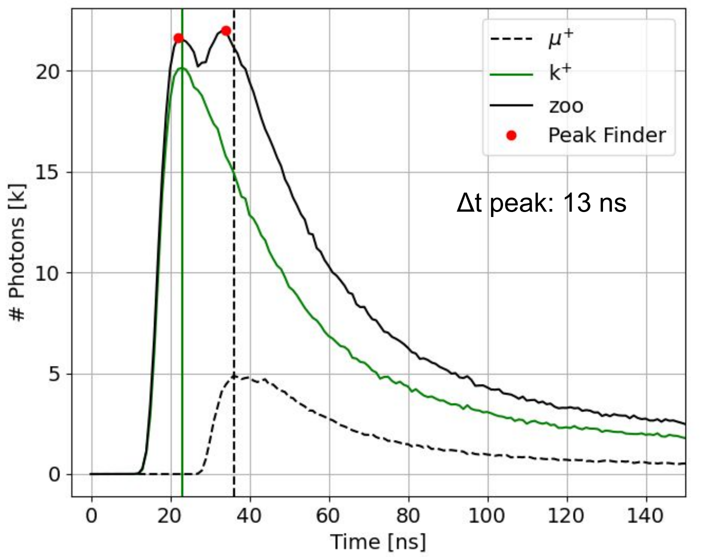


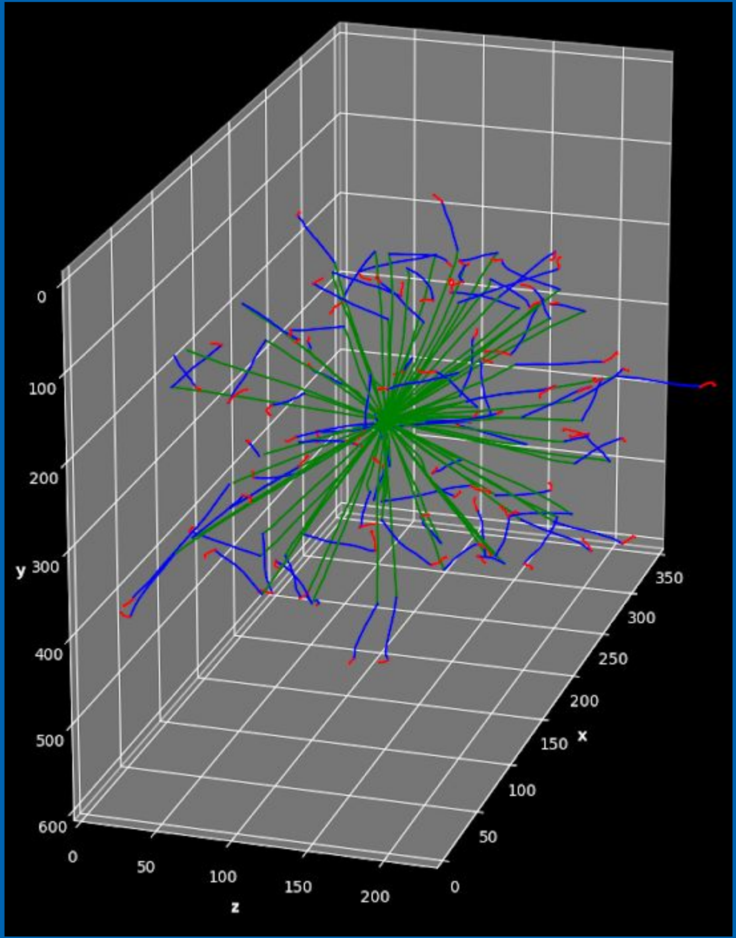


Here, the granularity and timing can provide, topological reconstruction with light, enhancement to calorimetry as well as the potential to enhance particle identification ($K \rightarrow \mu \rightarrow e$) shows up as a “multi-bang” event)

Simulation of a pixelated Q+L Sensor

- Proton decay in the $p \rightarrow K \bar{\nu}$ channel
  - High efficiency Kaon ID is **paramount**
- Simple "fast double-bang" selection,
  - agnostic to K decay mode
  - **Light only selection is already 50% efficient**
  - Working now on addition of Charge and Light selection efficiencies!





Conclusions

- **An integrated Q+L pixel based liquid noble TPC could be a major step forward in increasing the overall capabilities of these detectors**
    - Pixel based charge readout offers intrinsic 3D information and potentially lower charge detection thresholds
    - If a proper photoconductor and detector design can be found, the same electronics used for charge readout may be capable of also being a direct VUV photon detector
    - Simulation studies are underway to demonstrate what physics can be enabled by a Q+L pixel sensor in large scale liquid argon detectors
- **Amorphous Selenium seems like a promising photoconductor for R&D**
    - Proof-of-principle studies show promising results
        - aSe based detector responds to VUV light under cryogenic conditions
        - aSe based PCB solutions are robust under cryocycling and don't introduce electronegative impurities
    - Early studies into aSe detectors at low('ish) photon flux show initial promise
        - More R&D needed to achieve higher fields and response to lower flux
- **More work than can fit into a 15 min talk is ongoing**
    - Happy to collaborate with others on exploring novel photoconductors, detector ideas, and calibration techniques

Thank you for your attention

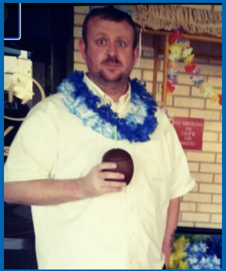
Special thanks to my collaborators

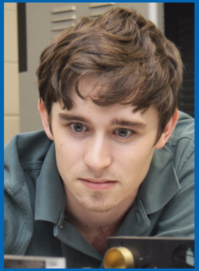
FNAL: Flor Maria Blaszczyk and Elena Gramellini

ORNL: Mike Febbraro

UCSC: Shiva Abbaszadeh and Katie Hellier

This work was lead by a UTA grad student Michael Rooks with support from Randall Gladen and Austin McDonald





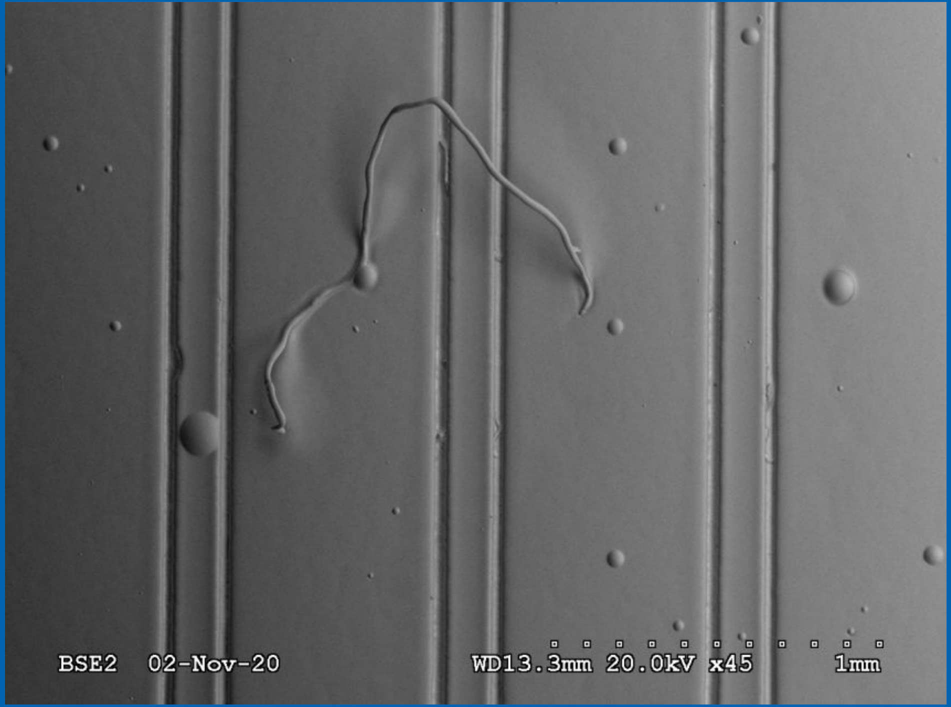
Backup Slides

SEM of the 15 μm board (before cryocycle)

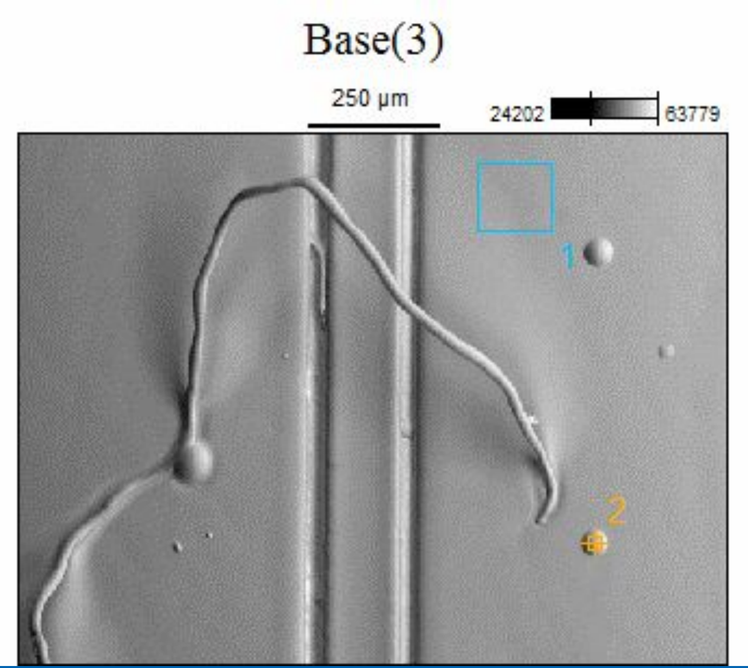
We looked at different spots on the board and saw some of the features of the evaporations

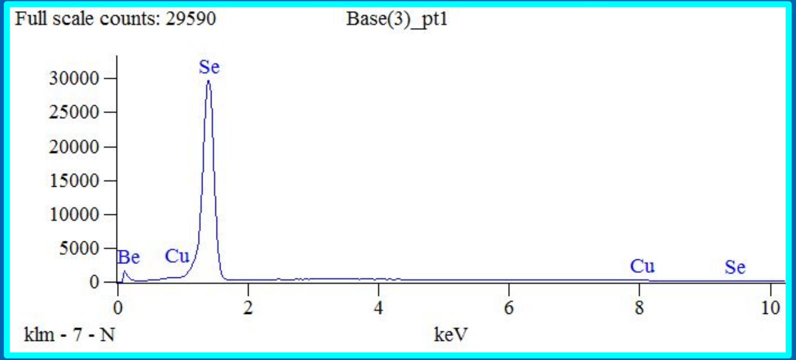
We picked this spot to look at before and after because this “strand” is an easy landmark to come back to

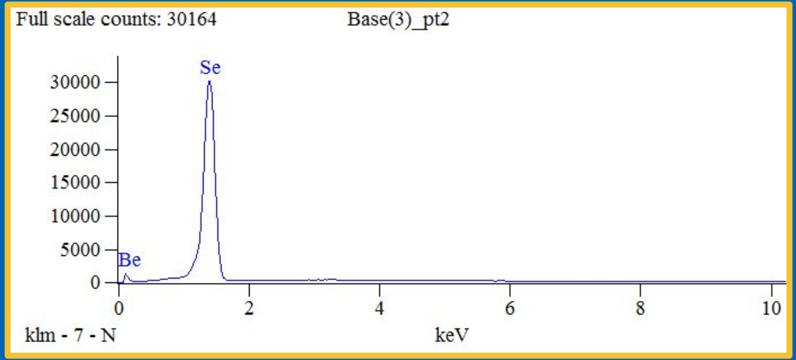
The SEM also has a Energy Dispersive Analysis of X-Rays (EDAX) system, so we are able to characterize what the material is we are seeing is



SEM of the 15 μm board (before cryocycle)



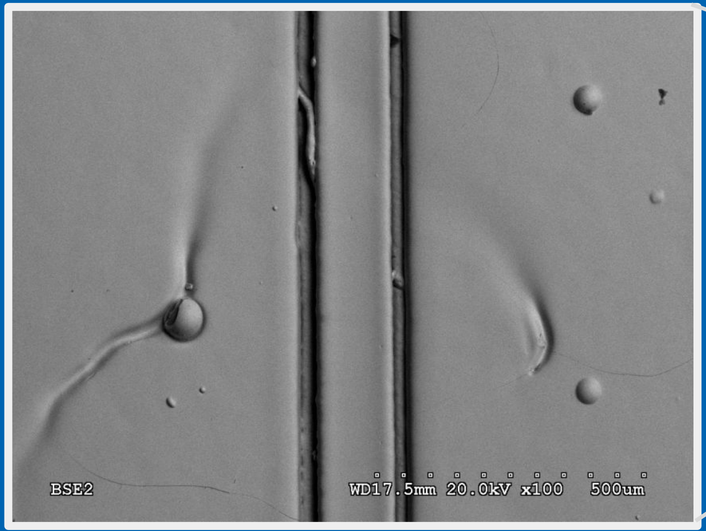


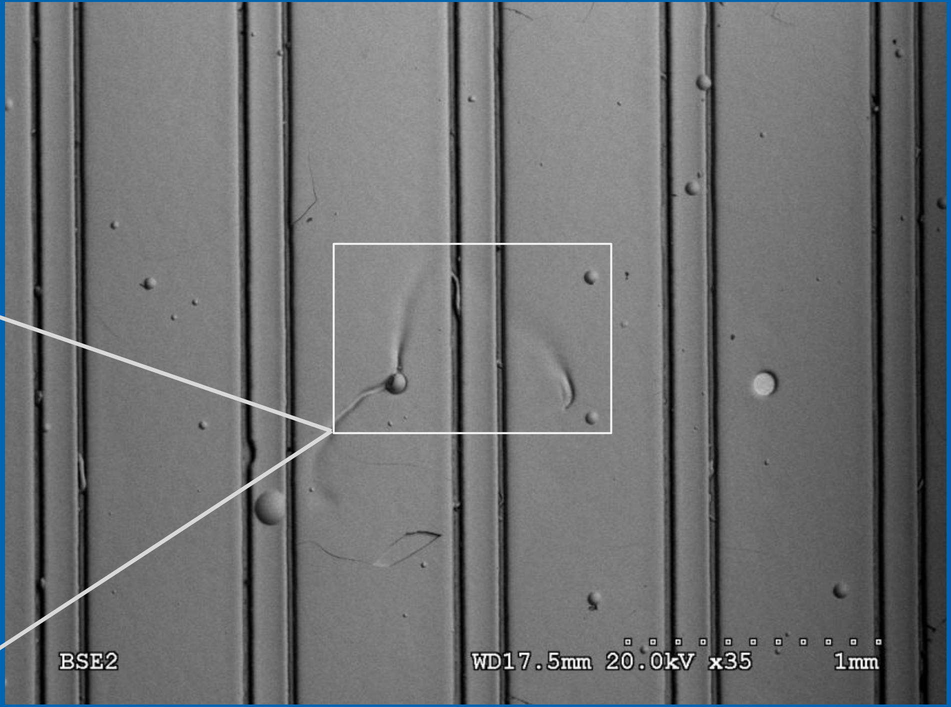


EDAX of some of the features confirm we are looks at Se (for the most part)

SEM of the 15 μm board (after cryocycle)

A broader scan of the same area shows our “strand” friend is gone as well as some other “cracks” that seem to have appeared in the board





SEM side by side

Note: these have slightly different magnifications and slightly different centering's on the object (we are still getting used to how to use this device)