Detector R&D for Coherent Elastic Neutrino Nucleus Scattering

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UC SANTA BARBARA

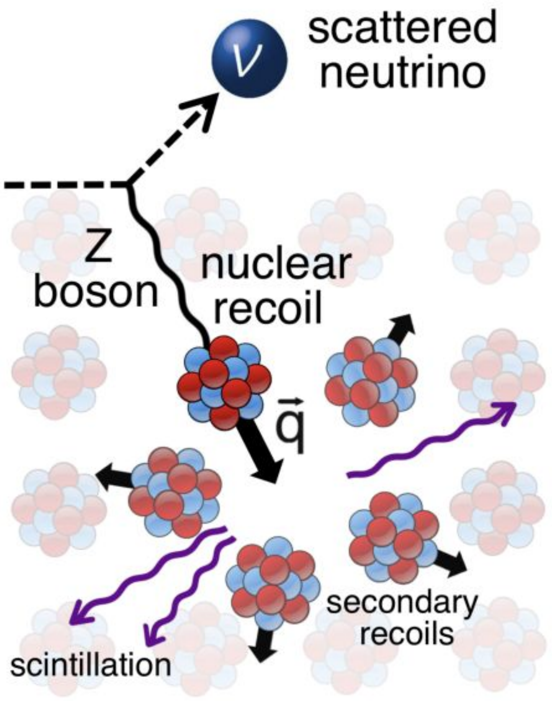
Overview

- ➢ Introduction and Motivation
- ➢ LArCADe R&D project
- ➢ Simulation & Fabrication
- ➢ Testing at Fermilab
- ➢ Current/Future Work

What is CEvNS?

- Coherent Elastic Neutrino Nucleus Scattering (CEvNS)
- Neutral Current Interaction with a well-known and large cross section
- Very few measurements exist and no measurements of the angular spectrum

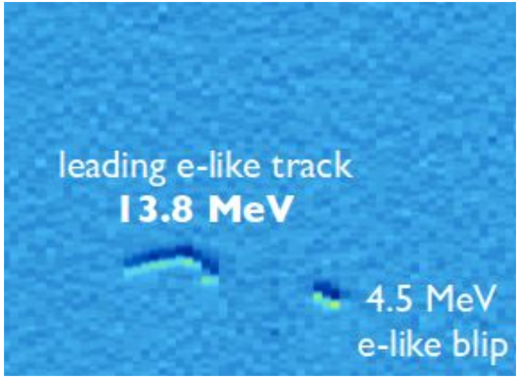
Why is this the case?

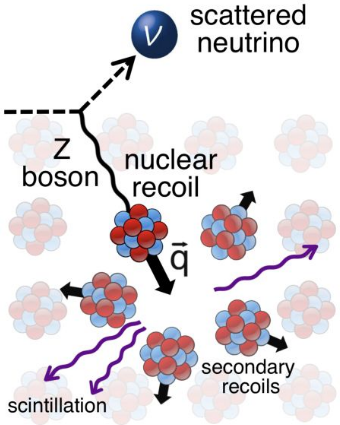


Motivations for Instrumentation R&D

- ➢ CEvNS cross section is large but the only detector observable is a recoiling nucleus from a low energy neutrino (~50 MeV)!
- ➢ Faint keV signatures with very small tracks (few hundred microns at most in argon gas)

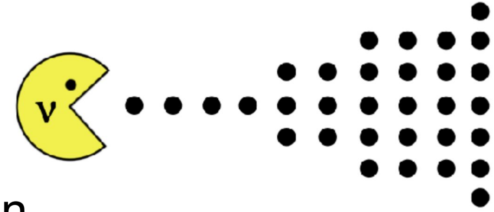
Single Phase LAr-TPCs

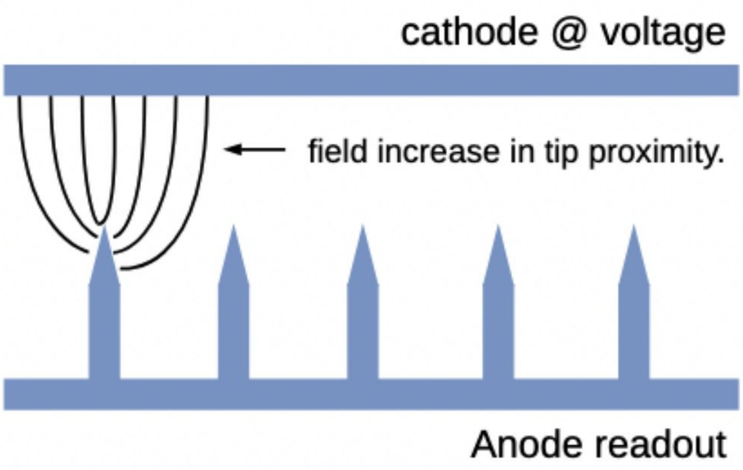


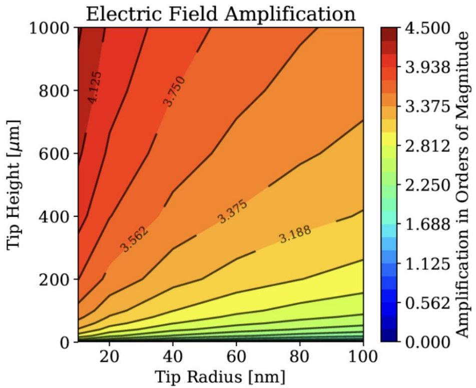


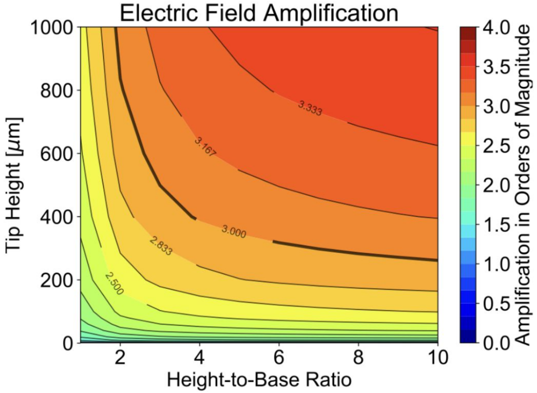
GeV — MeV — keV

- Liquid Argon Charge Amplification Devices (LArCADe)
- Idea is to modify the anode with pixels of conducting tip arrays to produce highly localized electric field amplification





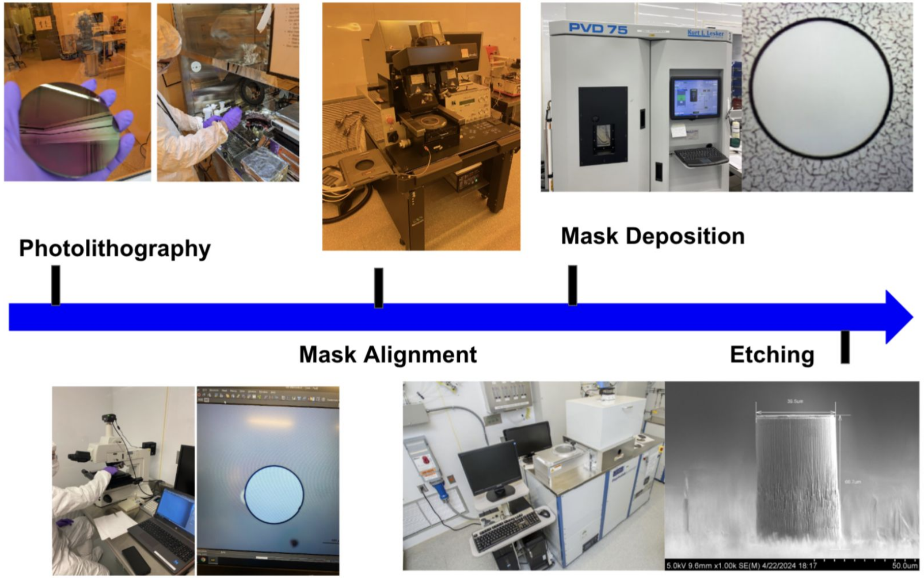


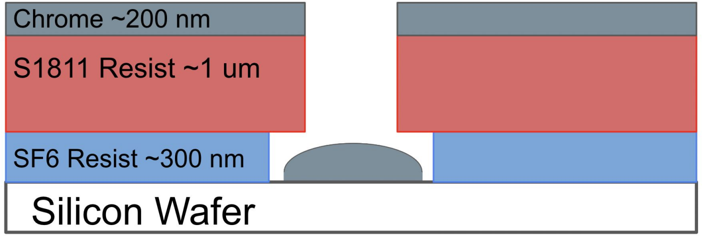


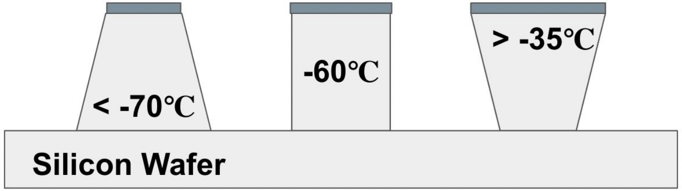
R&D effort launched by Angela Fava (FNAL) with LDRD

LArCADe Pixel Fabrication

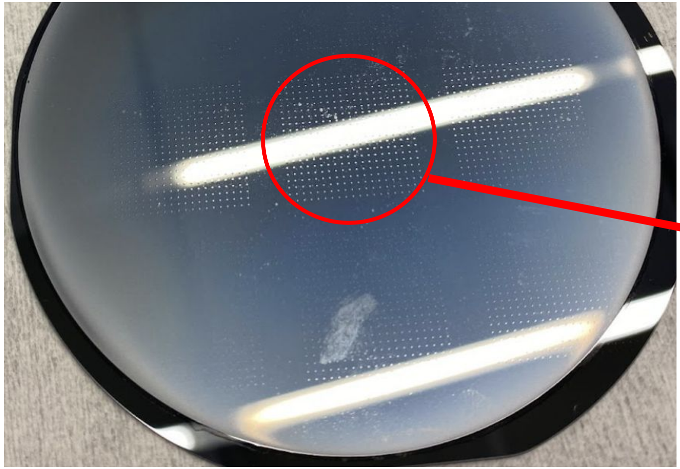
- Went to the Brookhaven National Lab Center for Functional Nanomaterials in Spring 2024
- Used a dry etching technique to produce very small tip arrays

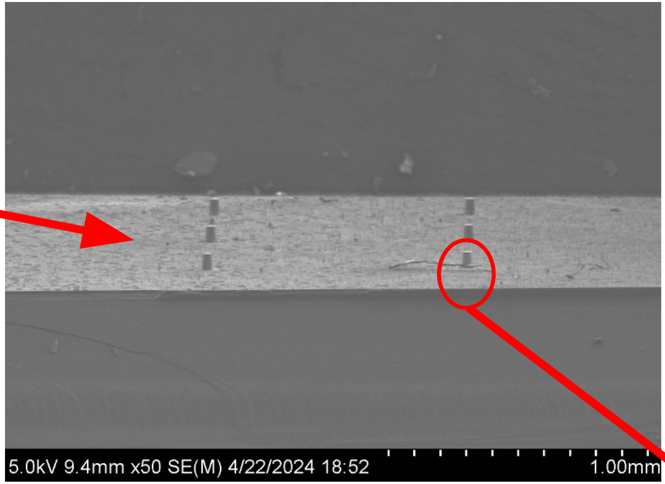


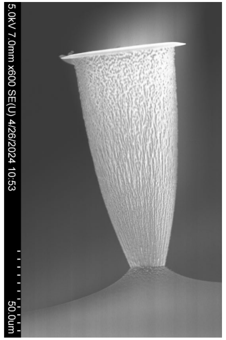


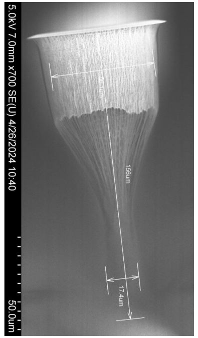


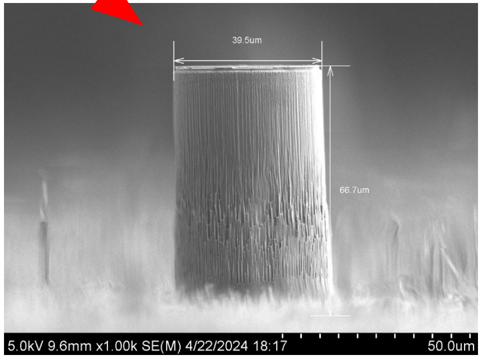
LArCADe Pixel Fabrication







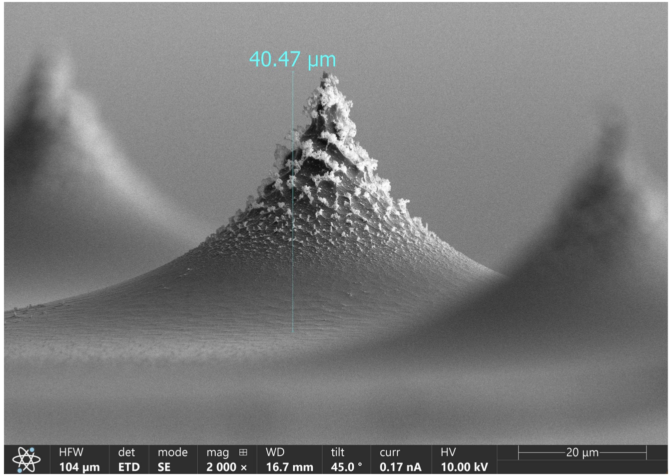


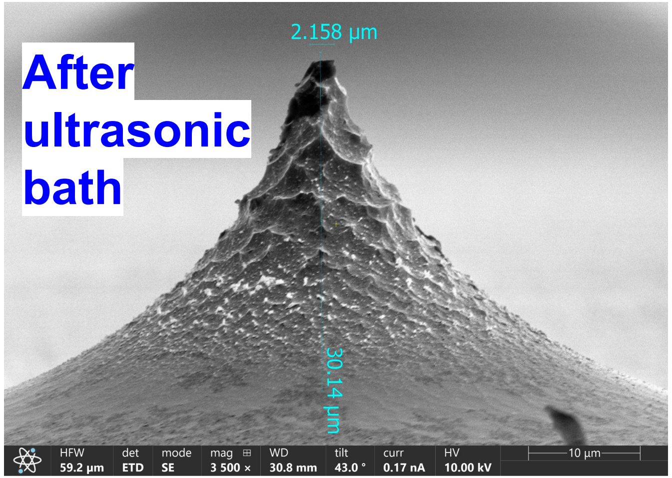


Electron Microscope images during the etching phase

We tested various temperatures to see different trends

LArCADe Pixel Fabrication: Final Result

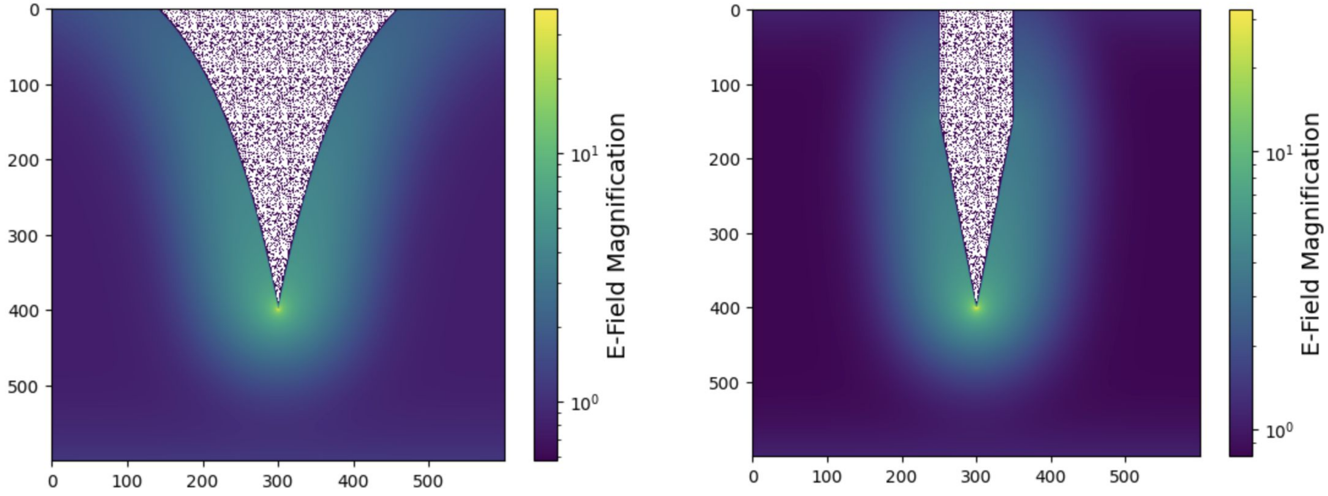




- ➢ We developed a multi-stage etching recipe that produces tip structures from an array of circular chrome mask sites
- ➢ We did not have time to produce a sample that meets the design specs, but we were able to produce one conservative tip array (~40 um height)
- ➢ These tips are too small in height to produce amplification in LAr but should work in GAr

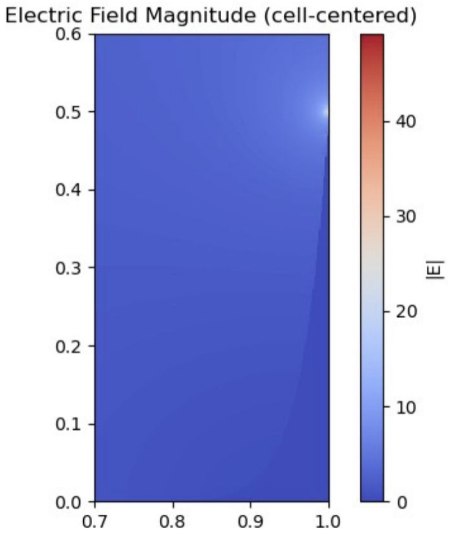
Tip Geometry Simulations

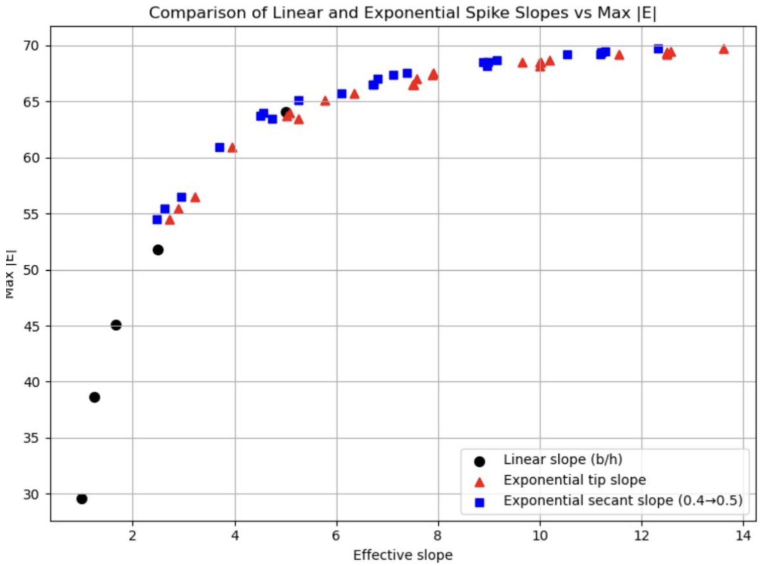
- After making our sample tip geometries at BNL, we wanted to investigate whether they would have similar performance to previous geometries in simulation
- Hypothesis: the tip amplification near the apex should be driven by the tip slope near the apex
- First, I made my own numerical solver for these tests:

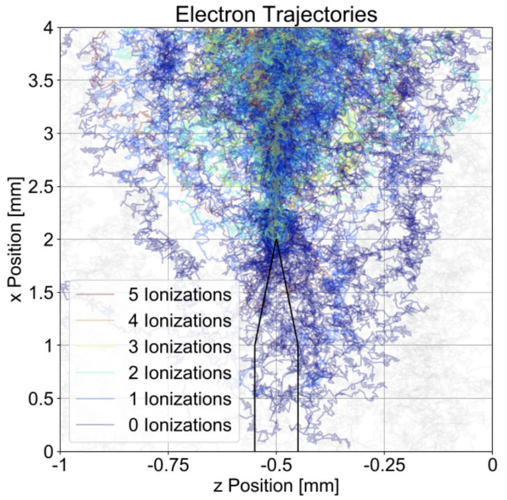


Tip Geometry Simulations

- ➢ To investigate the tip geometries further, I've been working with my undergraduate mentee Vansh Agarwal to use more detailed simulation packages/numerical solvers
- ➢ We have been able to verify the static solution is driven by the slope at the tip apex and we have begun multi-tip simulations



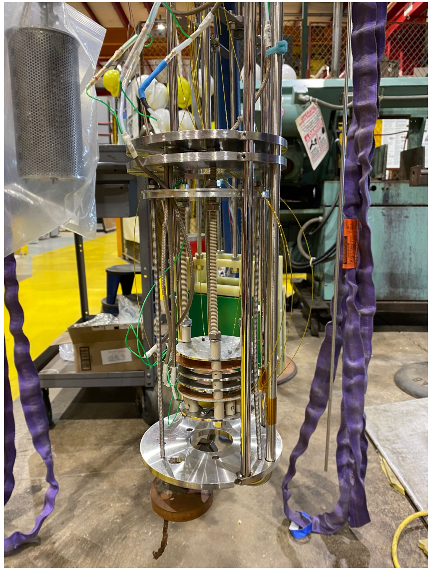


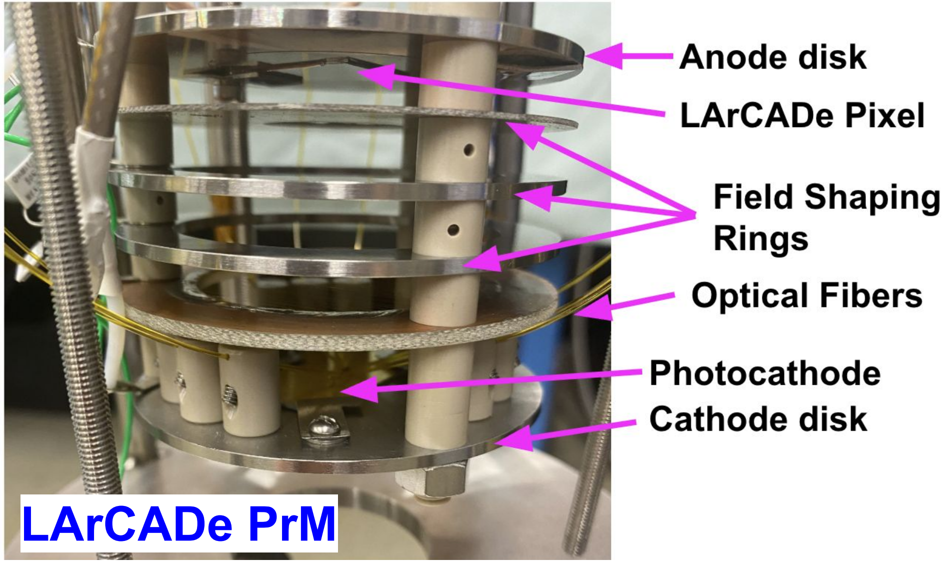


TRANSLATE Simulation of electron transport: arXiv:2211.12645

Testing at Fermilab

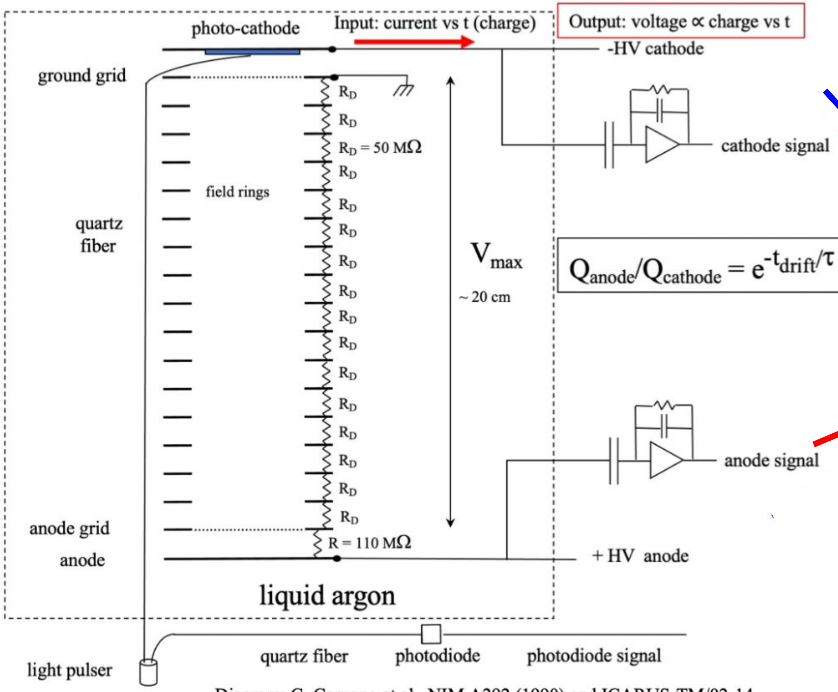
- We tested the LArCADe pixel in the Blanche cryostat at Fermilab using a custom purity monitor (PrM)
- A PrM is a single pixel TPC detector – controls input signal with the photoelectric effect





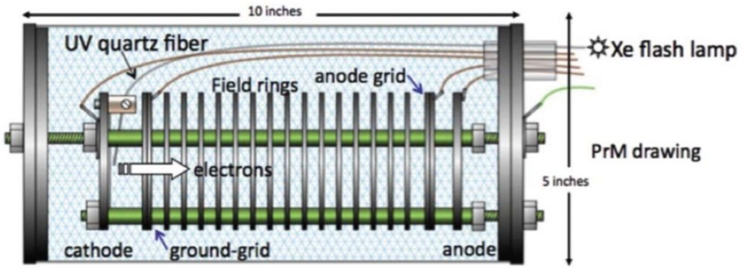
Testing at Fermilab: Purity Monitors

Standard PrM Schematics

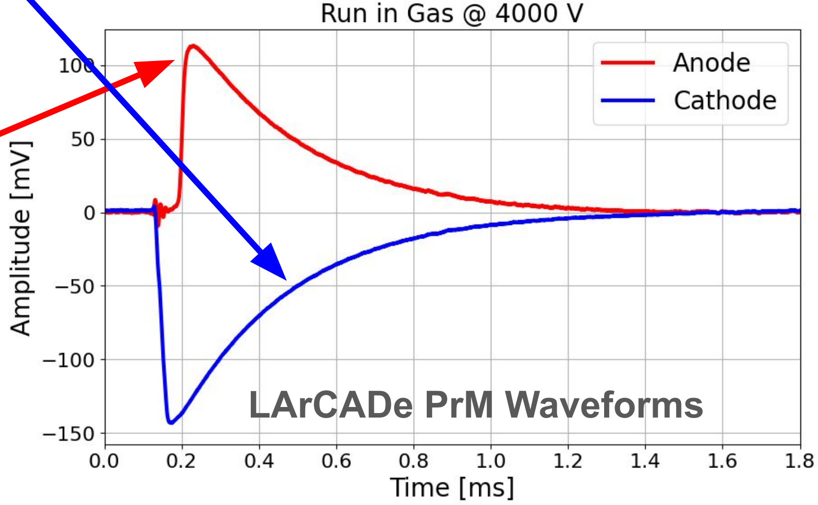


$Q_{anode}/Q_{cathode} = e^{-t_{drift}/\tau}$

Diagram: G. Carugno et al., NIM A292 (1990) and ICARUS-TM/02-14

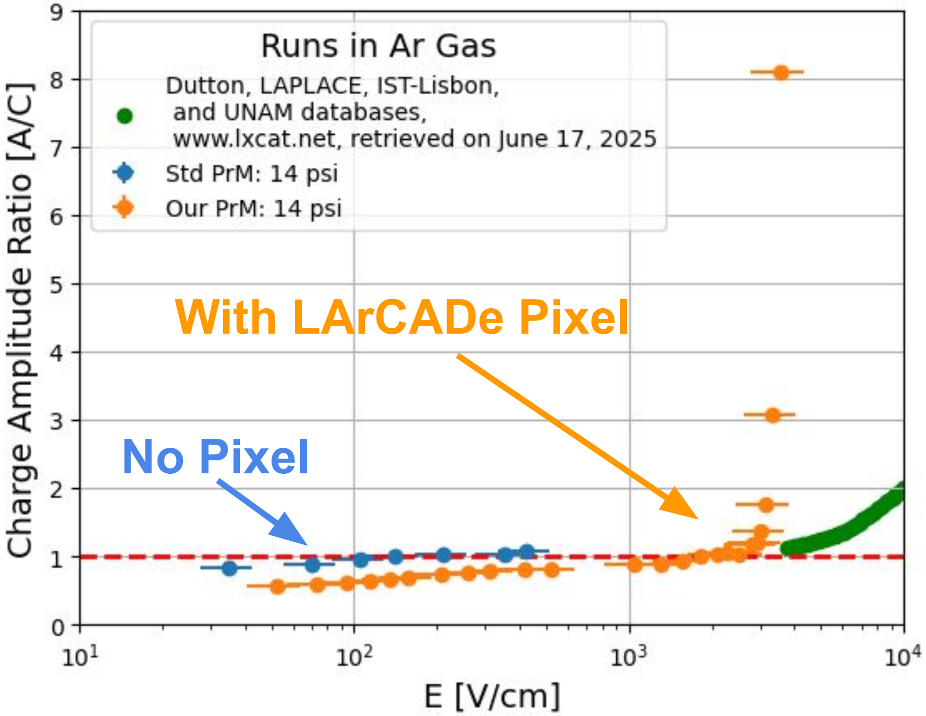


M. Adamowski et al., JINST 9, P07005 (2014).



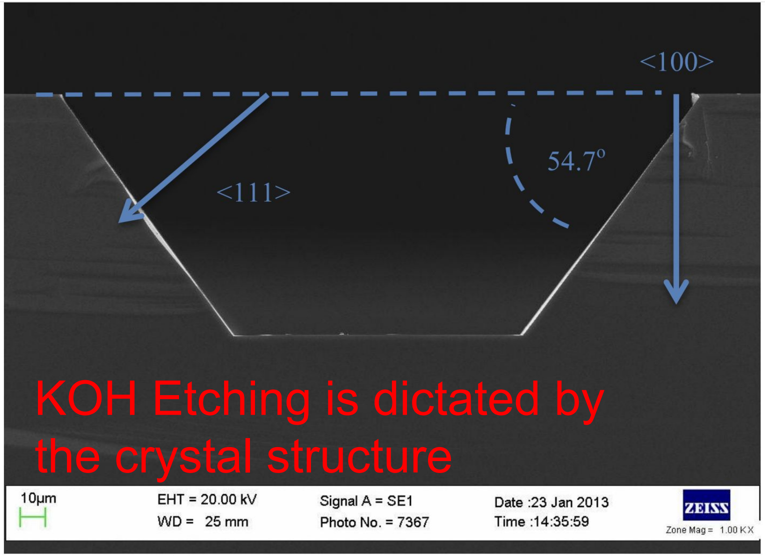
LArCADe Testing Results

- We took data with PrMs in both Liquid Argon (LAr) and gas (GAr)
- As expected, no amplification was observed in LAr
- **We do observe amplification in GAr where no amplification is expected from the bulk field**
- We compared with the lxcat database Townsend coefficients to extrapolate when amplification would turn on for the bulk field (shown in green)



Alternative Fabrication Methods: KOH Etching

- At UCSB we are collaborating with our campus Nanofab to explore alternative fabrication techniques and improve upon our past results
- A promising method is known as KOH etching



250um wide trench, etched to 89.3um, <100> orientation

IOP Publishing Journal of Micromechanics and Microengineering

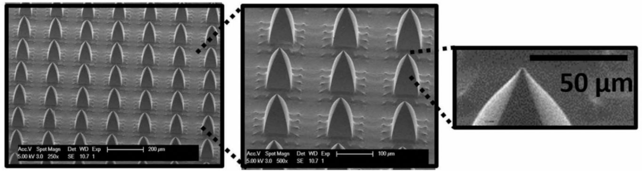
J. Micromech. Microeng. **28** (2018) 035007 (13pp) https://doi.org/10.1088/1361-6439/aaa6a8

A repeatable and scalable fabrication method for sharp, hollow silicon microneedles

H Kim[1], L S Theogarajan[2] and S Pennathur[1]

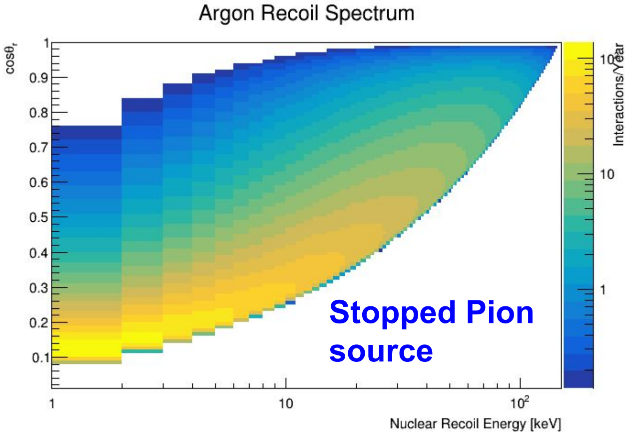
[1] Mechanical Engineering Department, University of California—Santa Barbara, Santa Barbara, CA 93106, United States of America

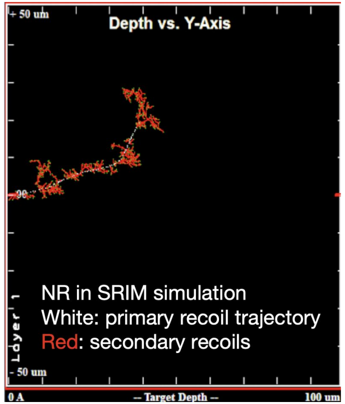
[2] Electrical and Computer Engineering Department, University of California—Santa Barbara, Santa Barbara, CA 93106, United States of America

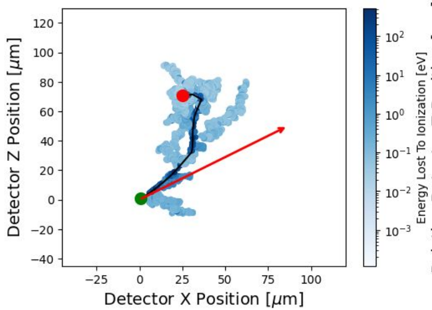


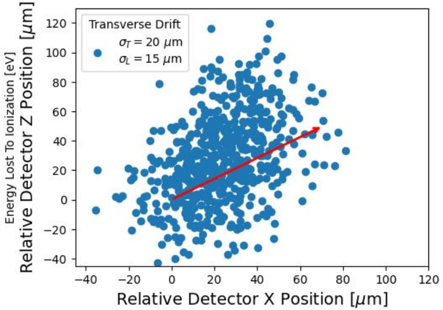
More advanced techniques from our UCSB colleagues

Nuclear Recoil Imaging

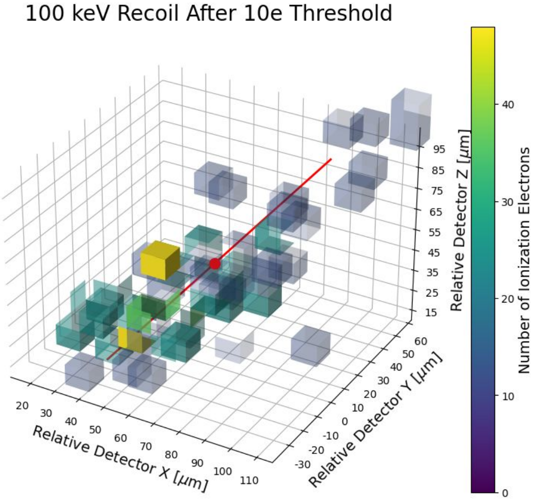








- ➢ We are working on simulation tools to study the detector requirements necessary to resolve nuclear recoils
- ➢ Measurement of the recoil angle allows one to reconstruct the neutrino energy!



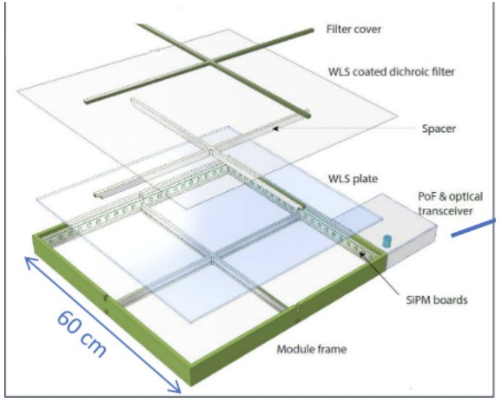
$$E_r = \frac{2m_N E_\nu^2 \cos^2\theta_r}{(E_\nu + m_N)^2 - E_\nu^2 \cos^2\theta_r}$$

"Coherent elastic neutrino-nucleus scattering with directional detectors"
PRD 102 (2020) 1, 015009
M. Abdullah, D. Aristizabal Sierra, B. Dutta, L. Strigari

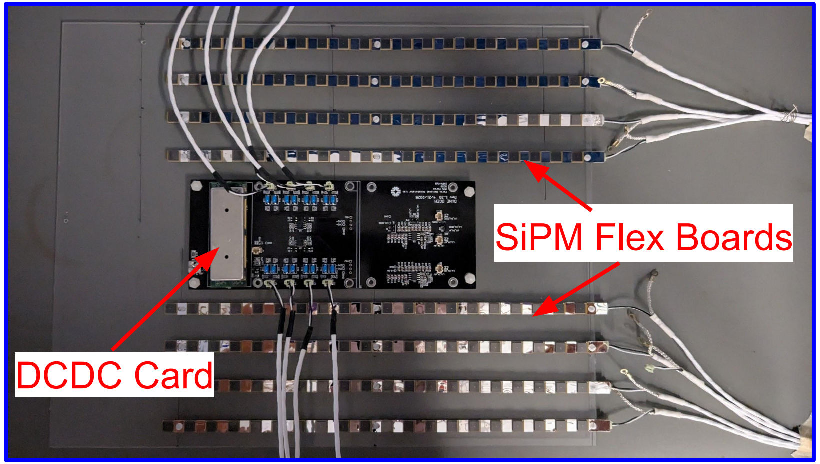
Other Hardware at UCSB

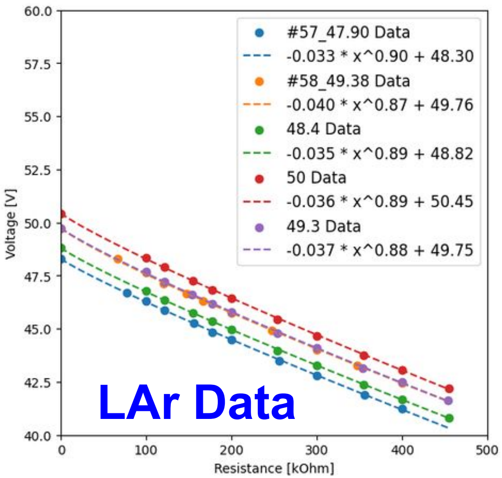
- We are also working on hardware testing for the future DUNE experiment
- Recently we started tuning the voltage regulation needed for the X-Arapuca SiPMs
- These modules will be mounted directly on the high voltage cathode plane → powered and readout using signals sent via optical fibers (Power-Over-Fiber (PoF) technology)
- Our next step is to quantify the signal-to-noise ratio for the SiPMs using the laser card system

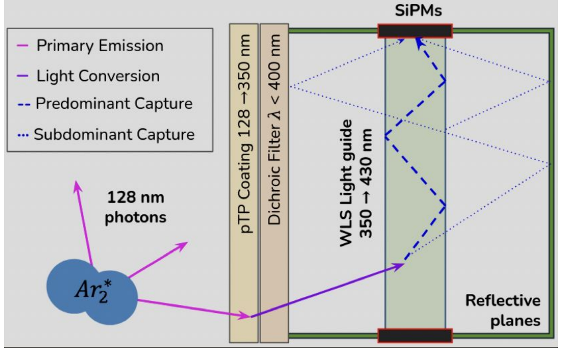
DUNE VD Cathode X-Arapuca



UCSB DCEM Cold Electronics







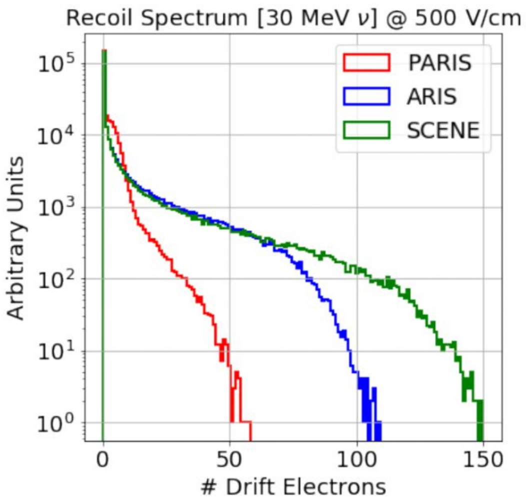
Conclusions & Future Work

- We successfully produced a LArCADe tip array at Brookhaven National Lab
- The LArCADe pixel geometry produced is conservative and only expected to provide amplification in argon gas
- We tested this pixel at Fermilab and observed amplification in gas at sufficient field strengths
- Our new simulations show that our fabricated (curved) tip geometries should provide the same field amplification as the comsol cone-like geometries for the same tip slope
- We are working with colleagues in the UCSB nanofab to explore alternative fabrication methods and to produce a sample that is expected to provide amplification in liquid argon
- Continue testing DUNE cold electronics for the X-Arapuca photon detection system

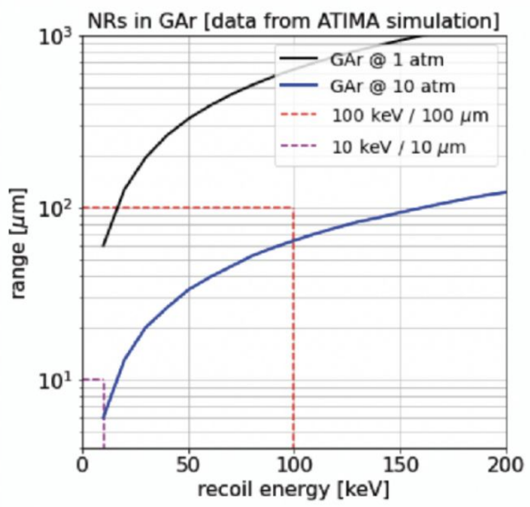
Backup

Nuclear Recoil Imaging Challenges

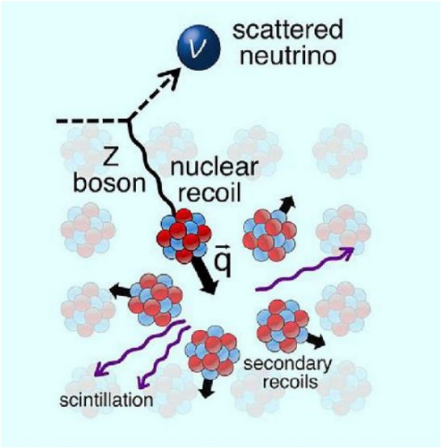
keV-scale imaging in argon-based detectors



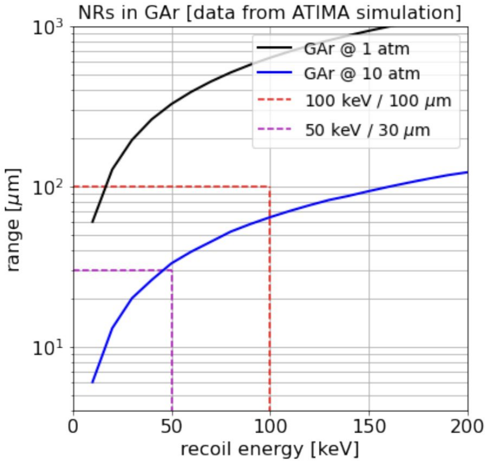
~few hundred "ENC" noise for LArTPC vs. ~tens of e- for NR signature



O(mm) resolution in LAr vs. O(10s um) NR range in GAr



Nuclear Recoils in Argon



$$E_r = \frac{2m_N E_\nu^2 \cos^2\theta_r}{(E_\nu + m_N)^2 - E_\nu^2 \cos^2\theta_r}$$

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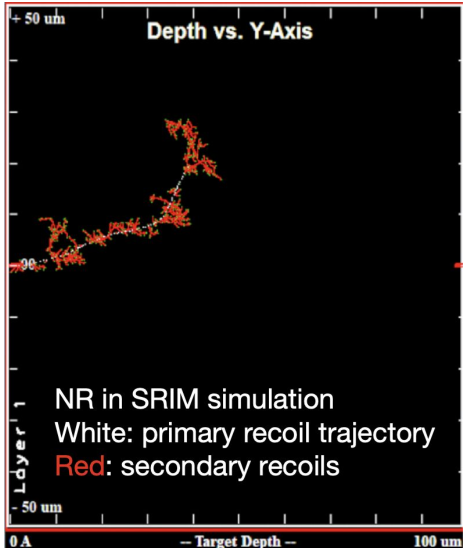
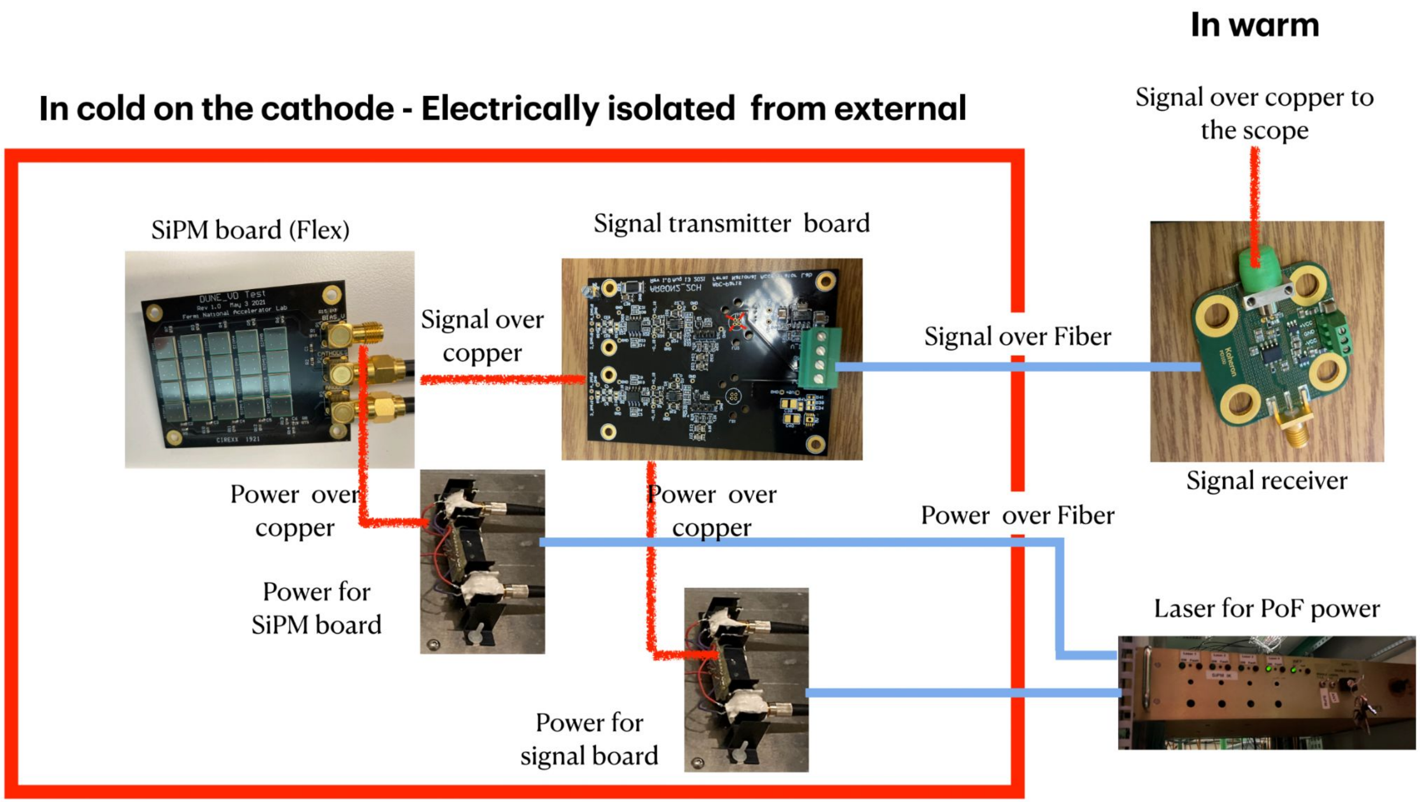


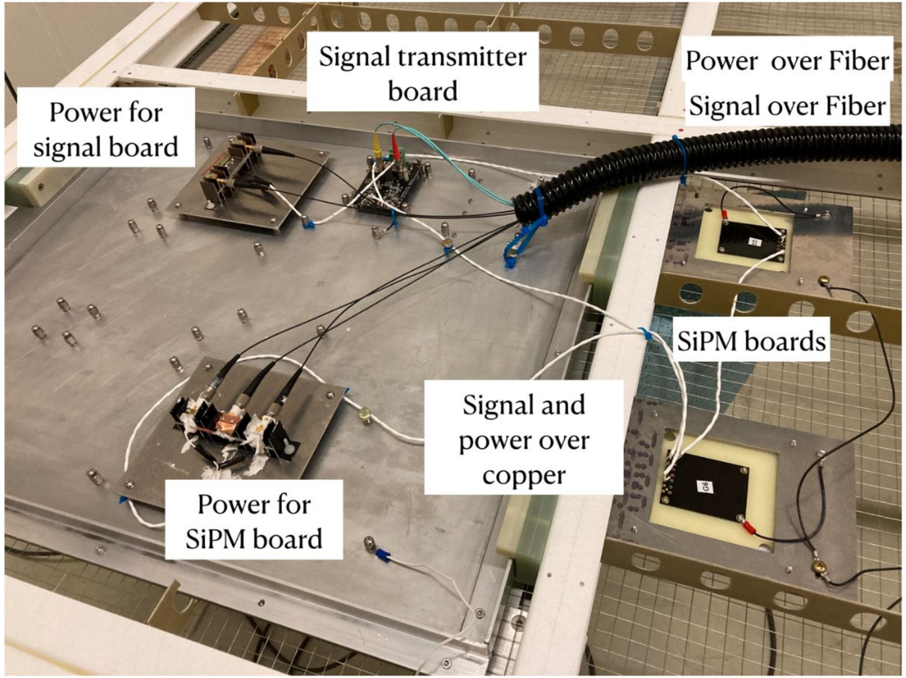
Other UCSB Hardware: DUNE X-Arapucas



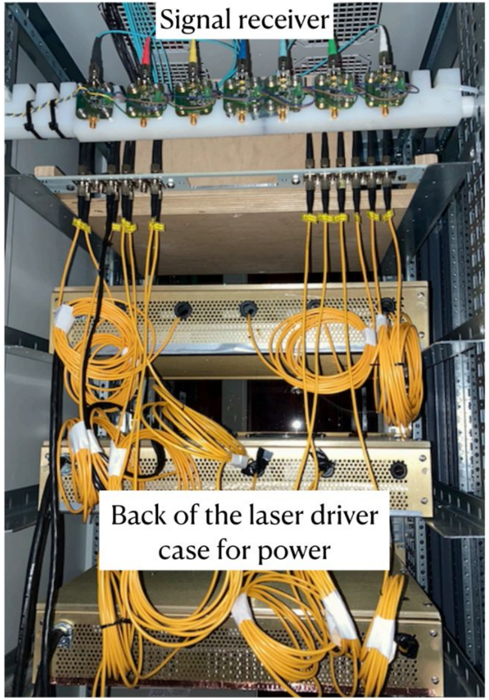
From Dante Totani

Other UCSB Hardware: DUNE X-Arapucas

In cold on the cathode - Electrically isolated from external

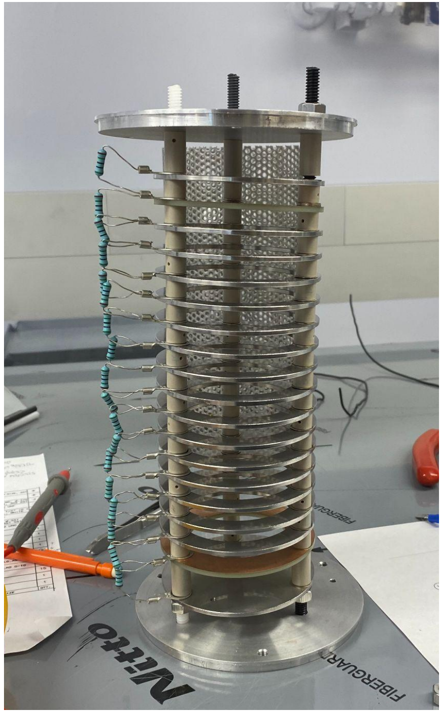


In warm



From Dante Totani

Other UCSB Hardware: Cryostat Test Stand



CEvNS Theory

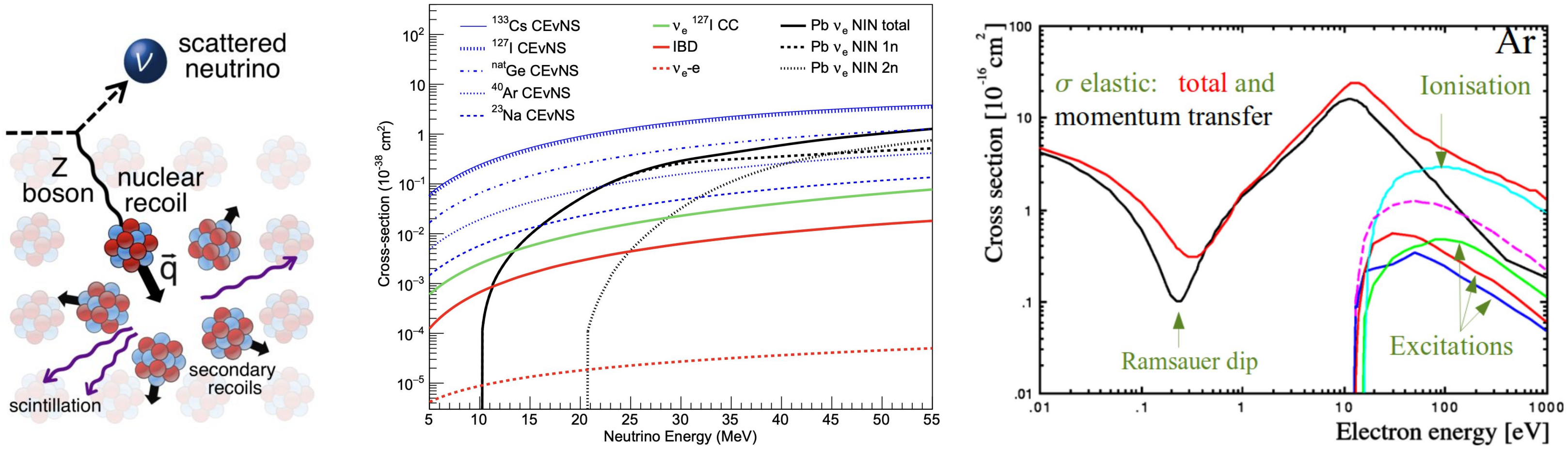
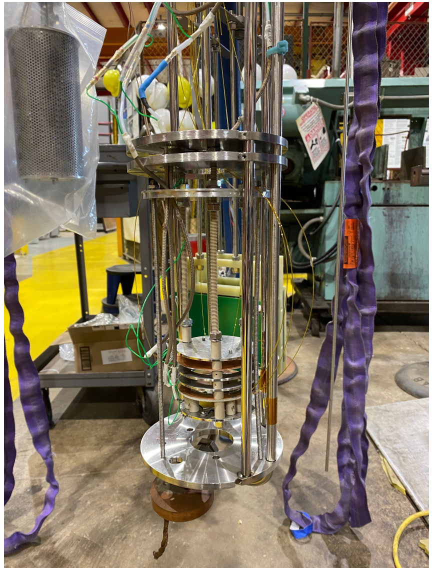
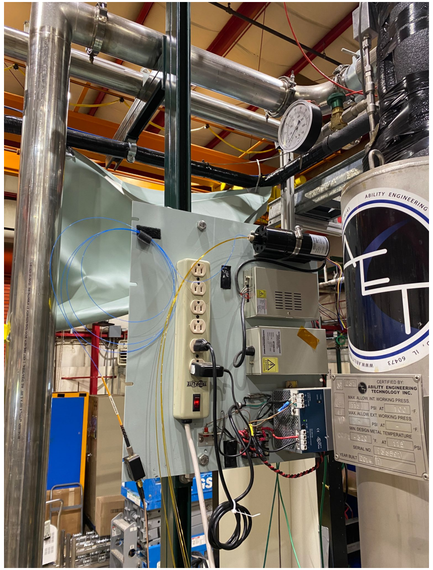


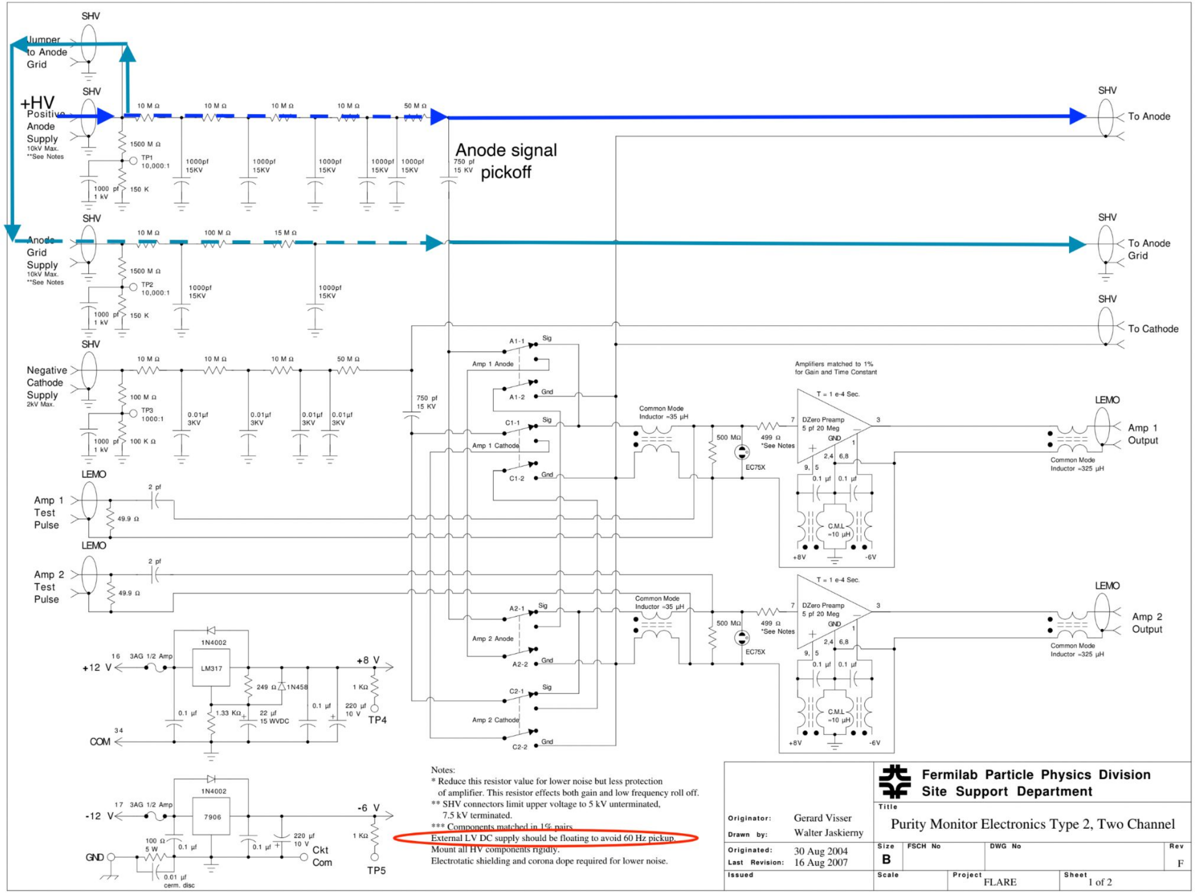
Figure 1: (Left) The Coherent Elastic Neutrino Nucleus Scattering (CEvNS) process. The only detector observable is the recoiling nucleus. (Middle) CEvNS Cross-section as a function of the incident neutrino energy for various target materials. CEvNS is orders of magnitude larger than other neutrino cross sections in this energy regime. (Right) Electron scattering cross sections in argon. Amplification in liquid is difficult due to the growing momentum transfer cross section after the Ramsauer dip and the high density of the liquid environment.

Fermilab Testing Pictures

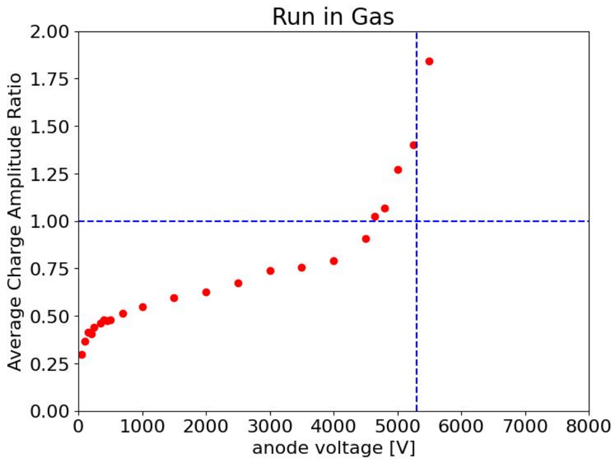


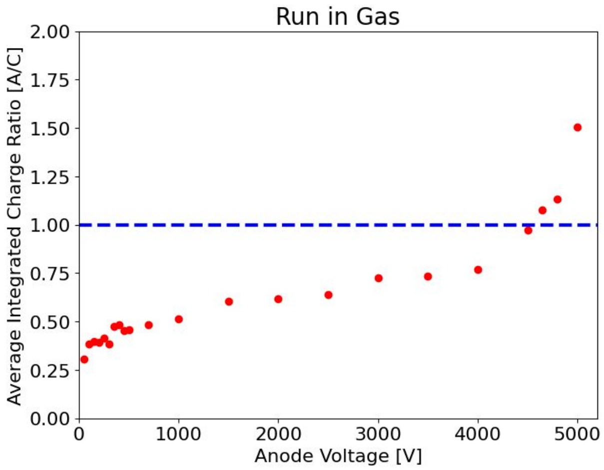


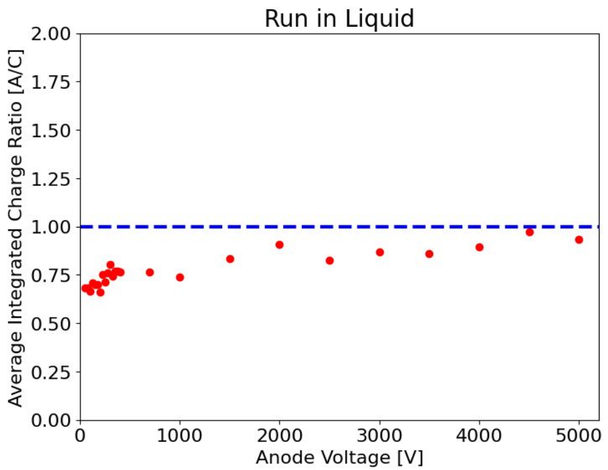
Front End Electronics



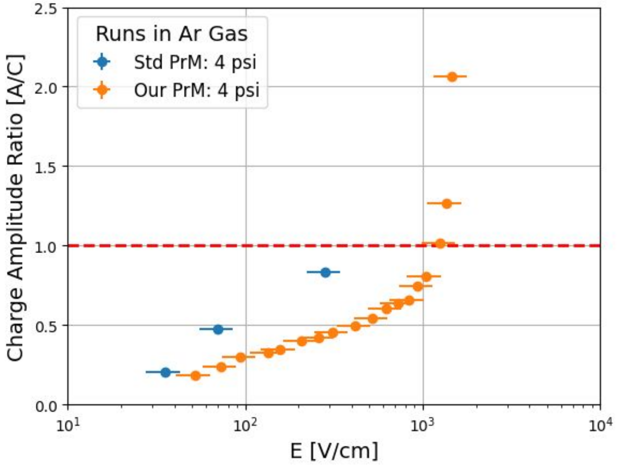
LArCADe Testing Results: Run 1

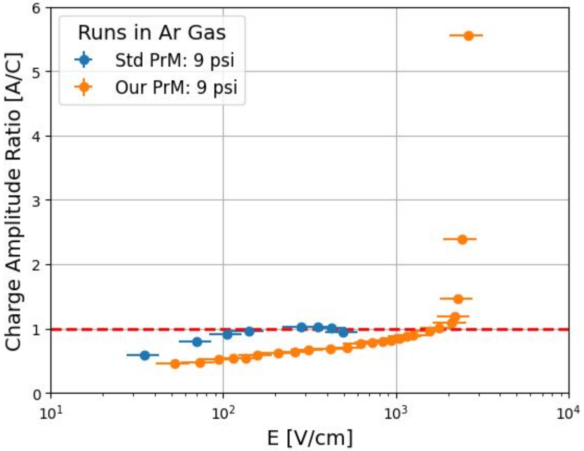


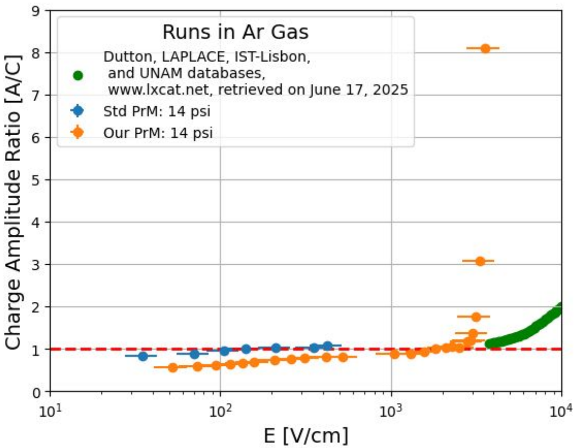




LArCADe Testing Results: Run 2

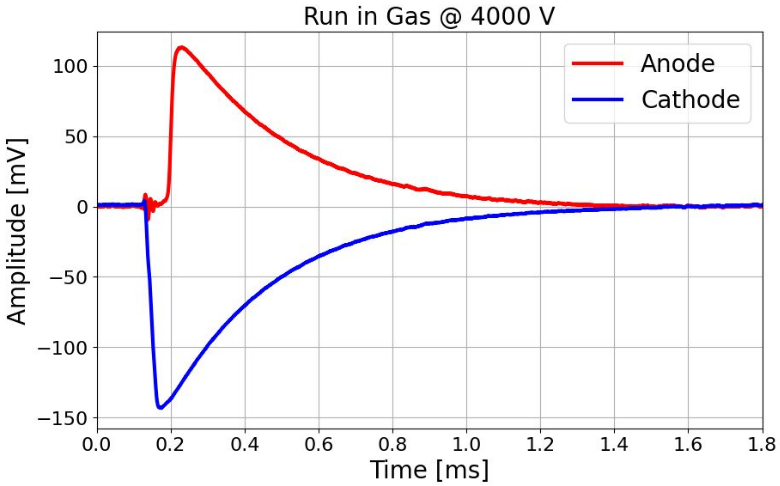


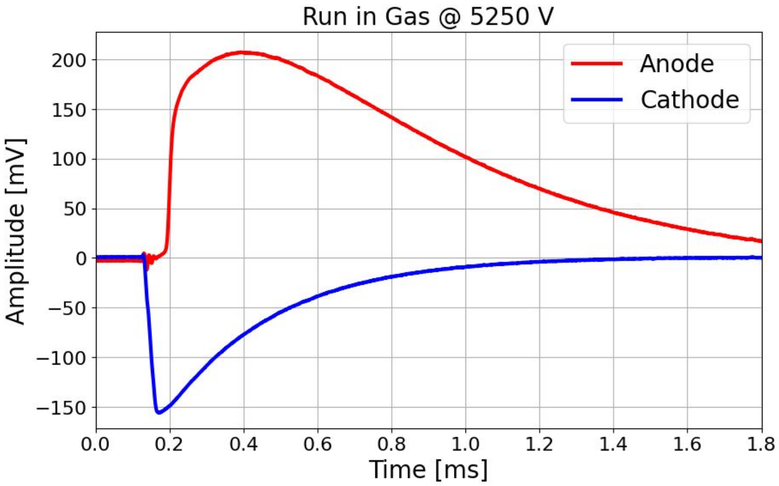




Pulse Broadening

- Pulse broadening is observed at large field strengths with the LArCADe PrM
- May be due to an additional delayed signal from ions traveling away from the pixel





Signal Processing

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