Physics Case for DUNE PDS and PoWER, and Small-Scale R&D @ CSU

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PoWER Online Call
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Introduction

- Covering two topics in this presentation:
  - A brief review of the physics case for the DUNE PDS, including the PoWER approach
  - Progress on small-scale R&D relevant for PoWER at CSU
- Major input to physics requirements of PDS is DUNE TDR, Volume IV (DUNE FD Single-Phase Technology), Section 5.16 (Appendix of PDS Chapter)
  - Link: https://arxiv.org/pdf/2002.03010
  - Alex Himmel: "best write-up of DUNE FD PDS requirements"
- Physics case discussion focuses more on *open questions* beyond TDR studies

DUNE PDS: Why, in a Nutshell

- "Why do we need the DUNE PDS?"
- From DUNE TDR, list of primary uses of PDS at DUNE:
  - Nucleon decay: fiducialization (and energy reconstruction) with t_o
    - Noted that this is same energy regime as atmospheric neutrinos
  - Supernova neutrinos: burst triggering, TPC energy measurement and time resolution with t_o, calorimetric energy reconstruction
  - Beam neutrinos: calorimetric energy reconstruction, tag Michels
- Some things not mentioned in TDR:
  - Solar neutrinos (similar energy regime to supernova neutrinos)
  - Use of Cherenkov light for event reconstruction
  - Neutron TOF (time of flight) energy measurements
  - Detector calibrations

TDR Synthesis (Details in Backup)

- Looking across all physics requirements set in the TDR, seems to culminate in following detector requirements:
  - Minimum light yield (at cathode): > 0.5 PE/MeV (nucleon decay)
  - Average light yield: > 20 PE/MeV (supernova neutrinos)
  - Average light yield: < 21 PE/MeV (saturation for beam neutrinos)
  - Timing resolution: ~1 μs (all, though neglects Michel tagging)
- Sets basic requirements for light yield in PE/MeV; collection efficiency requirements will be different for PoWER
  - For HD FD, > 20 PE/MeV translates to > 2.5% collection efficiency
- Some requirements do not seem well motivated/addressed:
  - Not clear if saturation requirement needed
  - Michel tagging not well studied, timing resolution requirement inappropriate

What is Missing?

- First, would be useful to update physics requirements with more updated DUNE simulation/reconstruction
  - No reason to doubt any result from TDR studies, but still good idea
  - Need simulation studies for optimizing PoWER design at any rate
- Several things not mentioned explicitly in TDR:
  - Solar neutrinos, though needs for t_o, energy reconstruction probably similar to those for supernova neutrinos
  - Cherenkov light for better reconstructing event activity, including particle energies – requires much better timing resolution, O(ns)
  - Measuring energy of neutrons using TOF (time of flight) – not clear how much we gain from this at DUNE FD for beam physics
  - Detector calibration – some ideas on following slides

^{220}Rn Source Injection in LAr

- Idea for calibrating DUNE FD PDS: injection of radioactive sources directly into the LAr – specifically, radon:
  - **^{222}Rn** explored at MicroBooNE (see **here**); useful if avoid LAr filter (copper getter removes ^{222}Rn) but long-lived decay product ^{210}Pb plates out on light detectors (long-term background source)
  - **^{220}Rn** used in LXe dark matter detectors (see **here**) but not yet explored in LAr detectors (to knowledge of M. Mooney)
- <u>Proposal by M. Mooney</u>: investigate ^{220}Rn for DUNE FD and ND-LAr calibrations, with preliminary tests at both the 2x2 ND-LAr prototype and ProtoDUNE II – detailed talk **here**
  - Provides means to **calibrate light yield visibility map** throughout detector – hard to do with cosmics underground!
  - Need to tag light from low-energy activity, more on later slide

Calibrations w/ $^{212}Bi \rightarrow {}^{212}Po \rightarrow {}^{208}Pb$

^{220}RnPo α-decays: **measure LAr flow… *maybe***

^{212}Pb β^--decay: **low-energy calibration**

^{212}BiPo decay: **a ton of applications!**

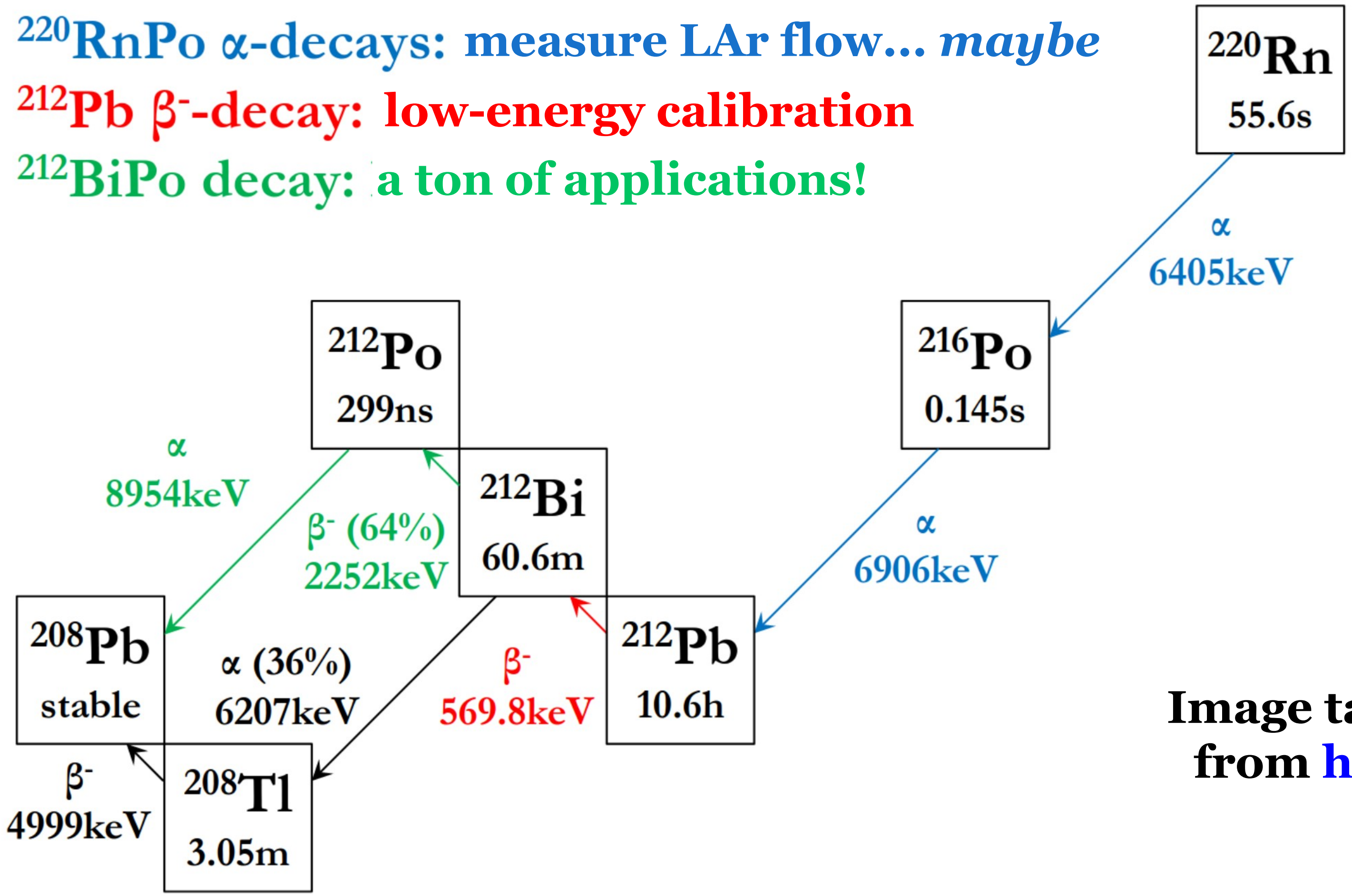
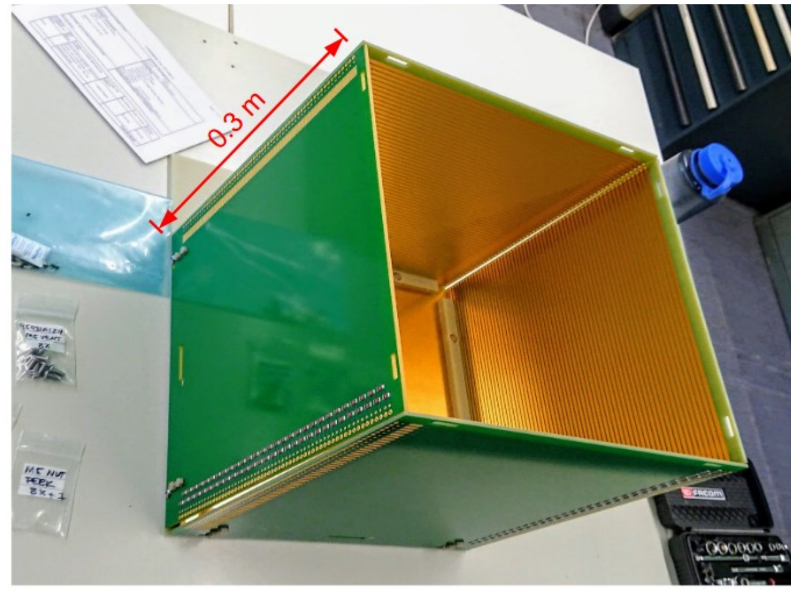


Image taken from here

Calibrations w/ $^{212}Bi \rightarrow {}^{212}Po \rightarrow {}^{208}Pb$

- ^{212}Pb (parent isotope of ^{212}Bi) half-life of 10.6 hours long enough to enable spreading throughout even large LArTPC detectors
  - Convective currents will mix isotope into and throughout active volume
- $^{212}Bi \rightarrow {}^{212}Po$ **beta electron end point of 2.3 MeV** produces charge yield well above charge readout threshold (100-300 keV)
- $^{212}Po \rightarrow {}^{208}Pb$ **alpha energy of 9 MeV** ~300 ns later yields "huge" amount of light for t_0 tag (reconstruct point-like activity **in 3D**)
  - Roughly 350,000 photons produced at single point in detector
- Calibration applications (a sampling, potentially more):
  - **Extract spatial variations in light yield – tune "optical library"**
  - **Light detector timing resolution studies (~300 ns between decays)**
  - Electron lifetime measurement
  - **Measure electric field** (spatial offsets, recomb. E-field dependence)
  - Mapping LAr flow via migration of decays through detector over time

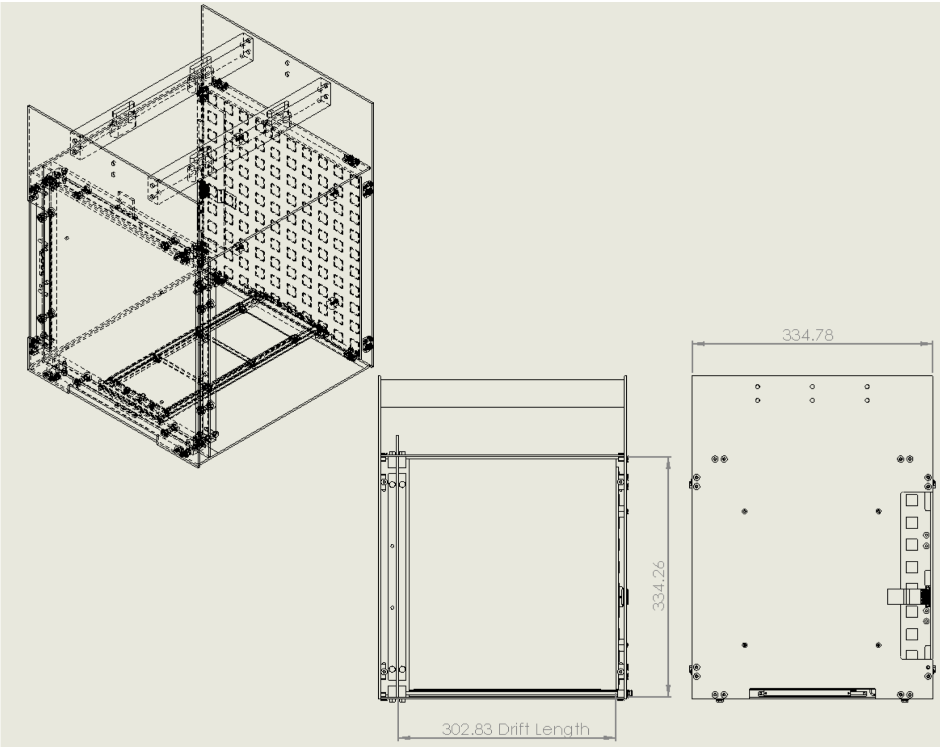
CATS TPC



The pixel PCB is 32 x 32 cm^2, with 10 x 10 LArPix serving 4900 pixels at 4.4 mm pitch.

- CATS (Colorado Argon Test Stand) – scaled down (cubic foot) single "unit" test of ND LArTPC charge readout (LArPix)
  - Pixelated charge readout produces 3D images as raw data
  - Operational at CSU since 2021; used for LArPix development and other detector R&D

CATS TPC



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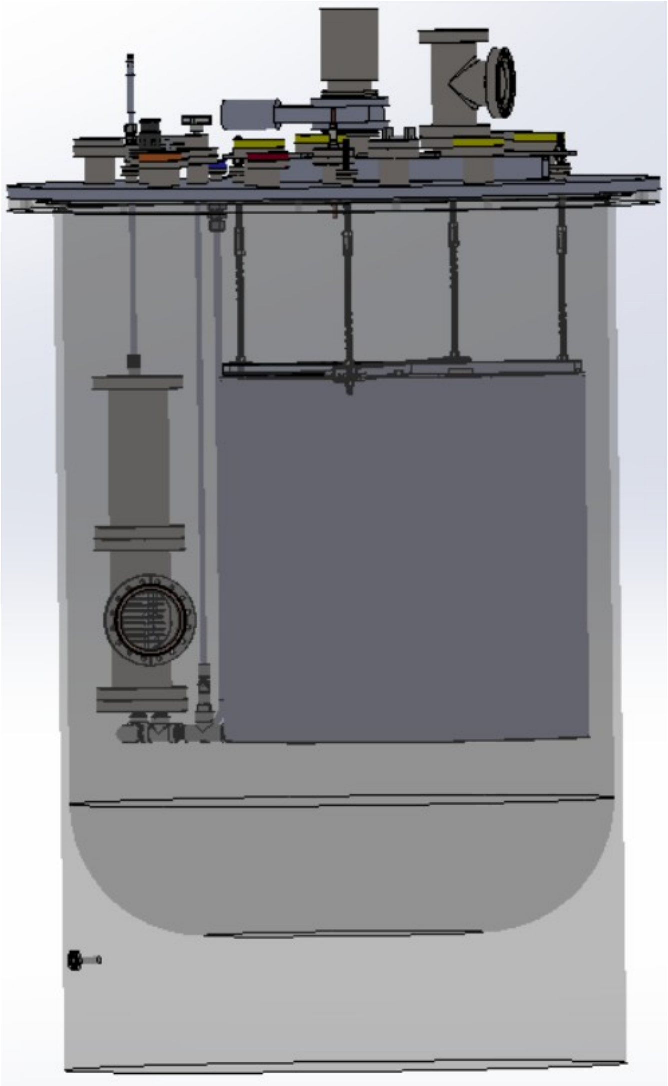
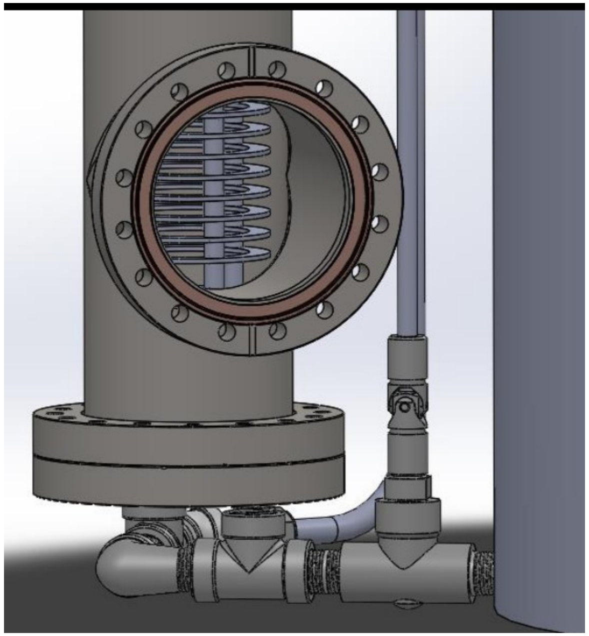
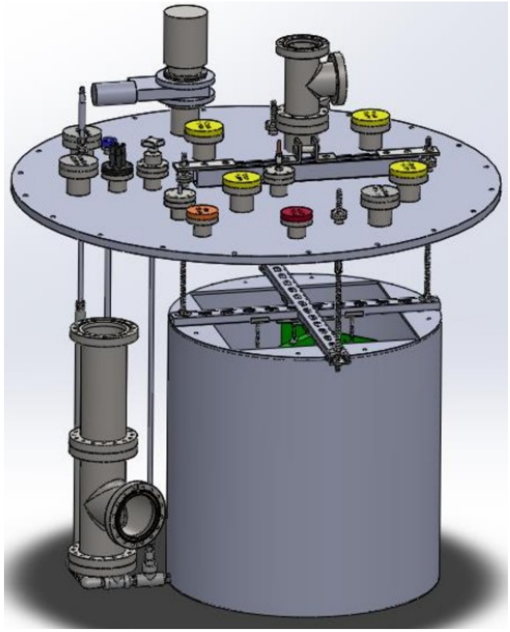
CATS Cryostat

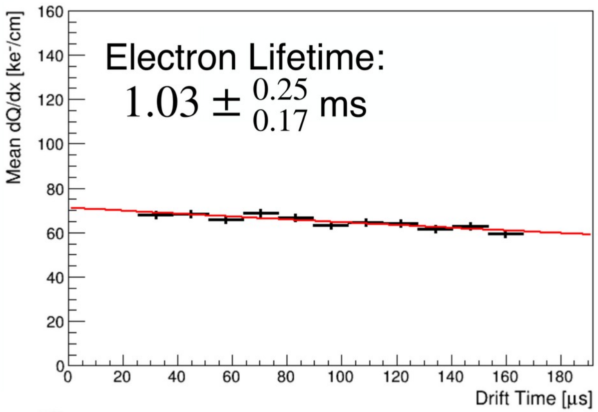


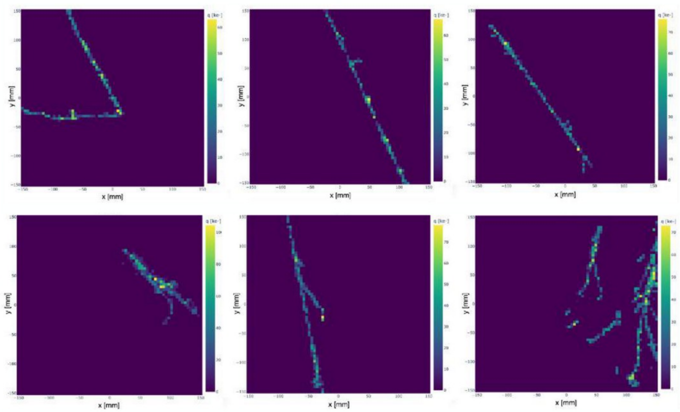
- CSU senior designer Jay Jablonski developed cryostat design for CATS
    - Includes bucket to reduce LAr volume, separate vessel to house purity monitor, readout/utility flanges
    - Purity monitor now external to cryostat





Improved Purity, ^{220}Rn Source

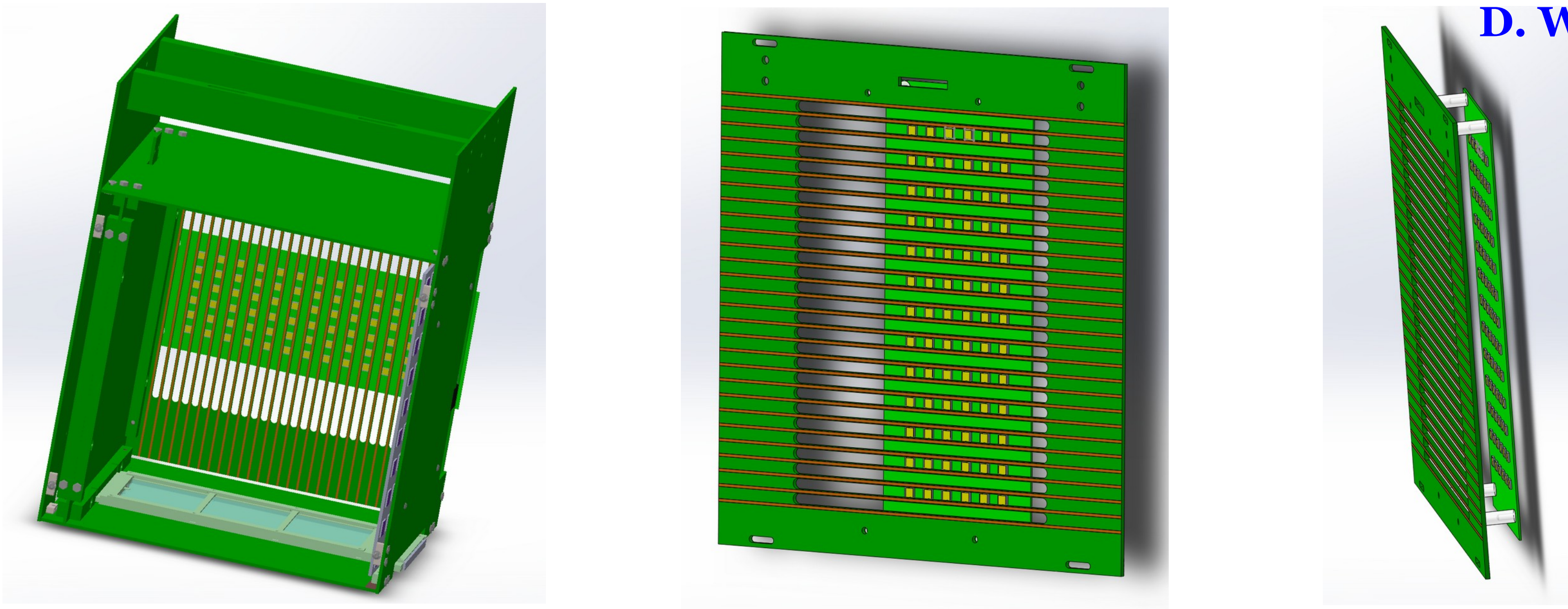




- More recently (last year), after upgrades to LAr filter (increased volume of filter material) and reducing LAr fill rate, have achieved electron lifetime of **~1 ms**
- Have also installed **^{220}Rn injection source** (^{228}Th source from Eckert & Ziegler) for tests of radon injection into liquid argon for calibration purposes

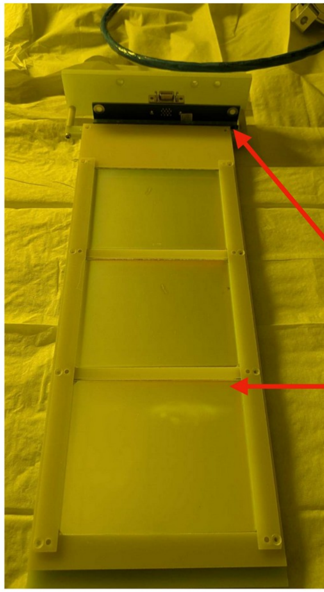
Light Detectors for CATS

D. Warner



- Plan to install two light detectors in CATS:
  - X-ARAPUCA-style light detector, as reference detector, on bottom
  - PoWER-style light detector, as test of concept, on side
- <u>Update</u>: X-ARAPUCA-style light detector now installed and works very well – used to confirm ^{220}Rn injection works!
  - Next include PoWER-style light detector – **work in progress**

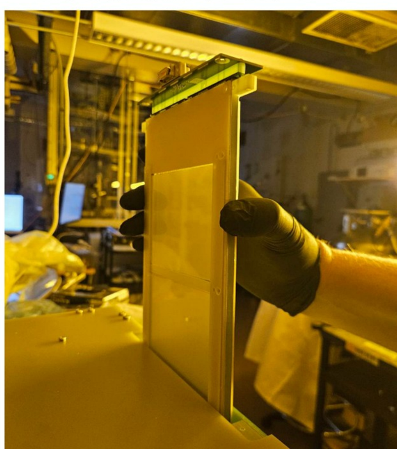
Light Detector Installation



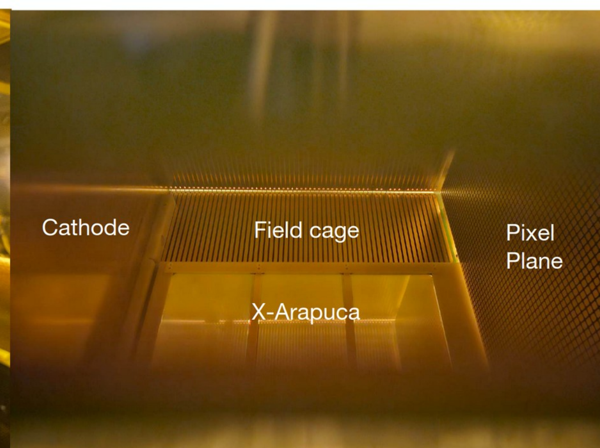
To allow for reconstructing drift coordinate of activity in TPC, we installed a custom light detector, designed at CSU, based on X-Arapuca technology (not included in SingleCube TPC kit).

- Components:
  - 6 SiPMs on the end independently readout
  - pTP-coated dichroic filters and wavelength shifting bar
    - Shifts LAr scintillation light to visible range for detection with Hamamatsu SiPMs (same as used in DUNE)

Light detector is inserted into a slot in the bottom of the TPC



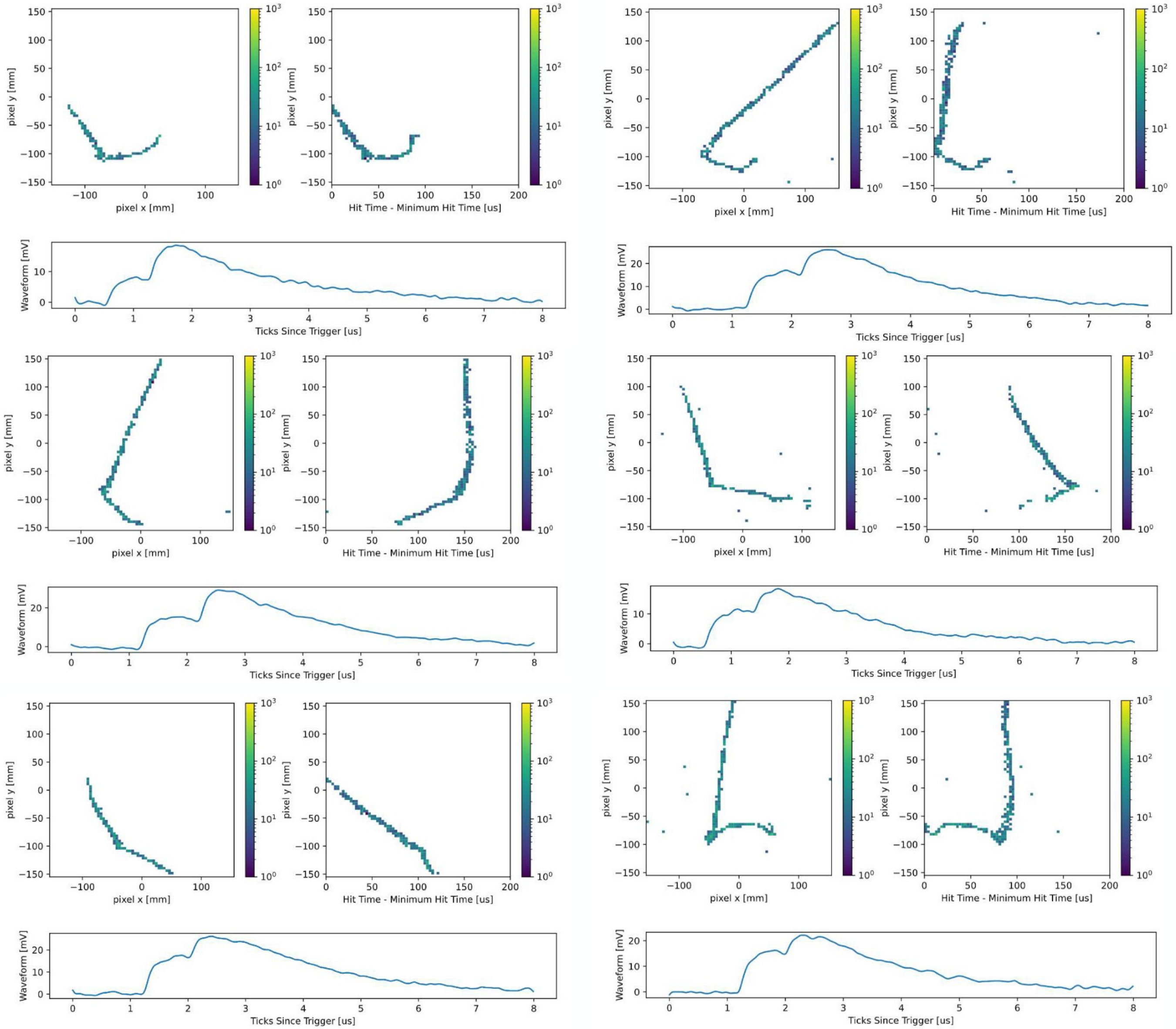
View inside TPC after installing light detector



TPC after installing light detector

Michel Electrons @ CATS

S. Fogarty

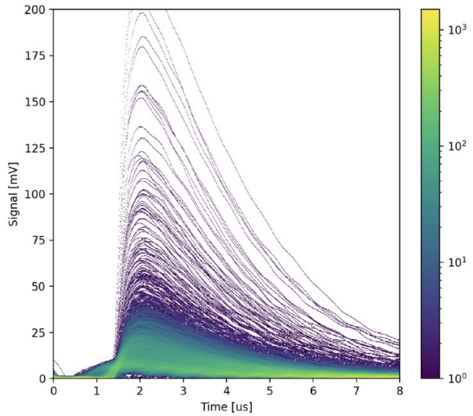


Charge + Light Matching of Michel Electrons

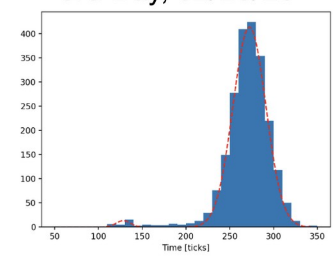
Radon Injection @ CATS

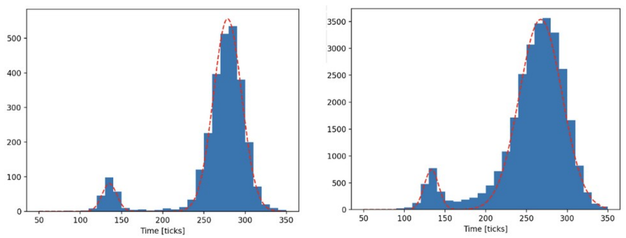
S. Fogarty

LAr Run w/ Radon Injection + TPC

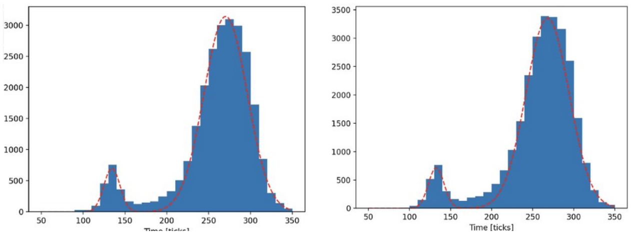


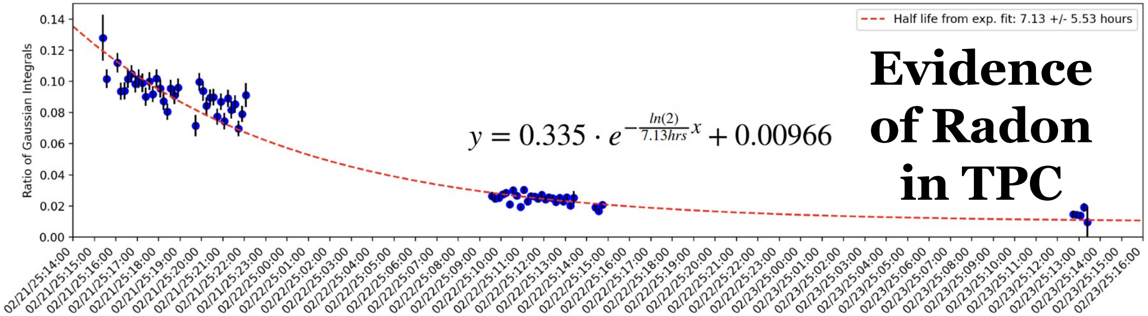
3rd Day, 02/23/25



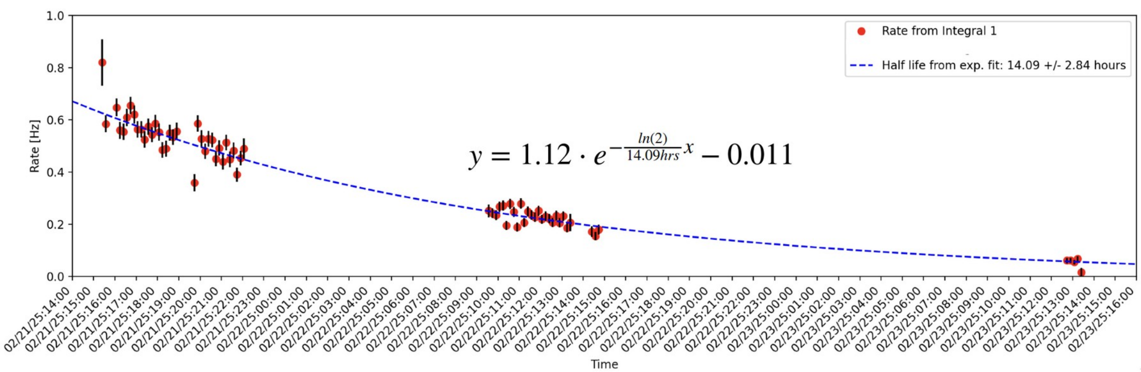


FWHM in some 30min periods (near start)





Evidence of Radon in TPC



Conclusions/Discussion

- Reviewed TDR physics requirements for DUNE PDS
- Should consider updating physics requirements with more updated DUNE sim/reco to optimize PoWER detector design
  - Also include additional considerations not included in TDR?
- Some brief thoughts from myself (opinions):
  - Would be very interesting to see what we can do with improved timing resolution (Michel tagging, use of Cherenkov light)
  - The "more light is better" argument may be true, but the strong physics motivation does not exist yet – it may be there, but will need further detailed simulation studies
  - Given above point, seems very useful to pursue *scalable* design: make system as cheap as possible if physics case isn't there, scale up light yield if it is – PoWER design seems well suited for this!
- CATS (Colorado Argon Test Stand) ready for PoWER R&D!

BACKUP SLIDES

TDR: Nucleon Decay

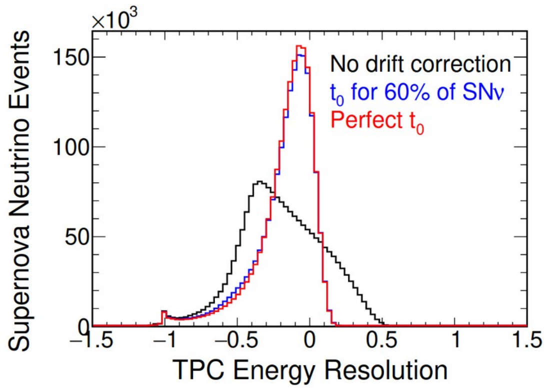
- Physics deliverable: PDS must determine t_o w/ ~1 µs timing resolution for events w/ visible energy greater > 200 MeV throughout the active volume w/ > 99% ID efficiency
  - Time measurement is needed for event localization for optimal energy resolution and rejection of entering backgrounds
  - Timing resolution requirement of ~1 µs set by TPC limitations
- The t_o ID efficiency of > 99% sets *minimum* light yield requirement of > 0.5 PE/MeV (> 1.3% collection efficiency)
  - Requirement on light from "hardest" events (near cathode)

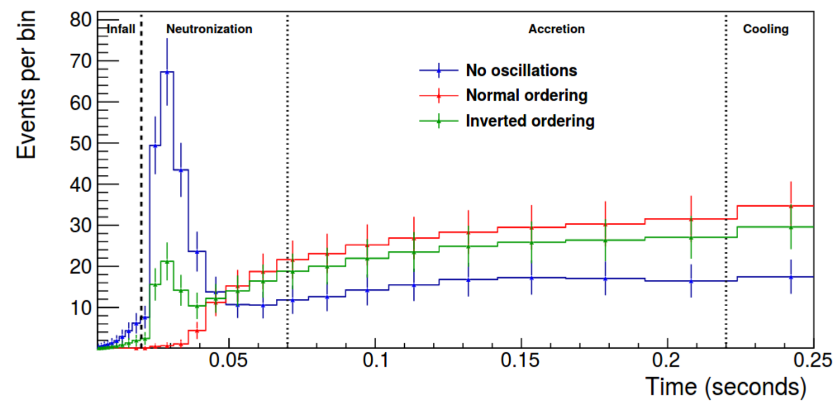
CPA Light yield (PE/MeV)	Collection Efficiency (%)	Efficiency at the CPA (%)
0.09	0.24	93.8 ± 0.4
0.28	0.75	97.7 ± 0.4
0.33	0.88	98.4 ± 0.2
0.50	1.3	98.9 ± 0.2

TDR: Supernova Neutrinos

- Physics deliverable #1: the PDS must be able to trigger on SNBs involving ~50 neutrino interactions in a FD module with ~100% efficiency, false positive rate of < 1/month
  - This deliverable is most important for distant supernovae (at the far side of the Milky Way or in the Large Magellanic Cloud), where event triggering is focus
- Studies using ~10 neutrino interactions (pessimistic event rate for LMC) found ~80% burst trigger efficiency if *average* light yield > 7 PE/MeV (> 0.9% collection efficiency)
  - Note redundancy of PDS trigger with TPC trigger – thus 80% for PDS alone is perhaps fine, especially given pessimistic assumptions in study
- Not leading consideration in setting PDS requirements

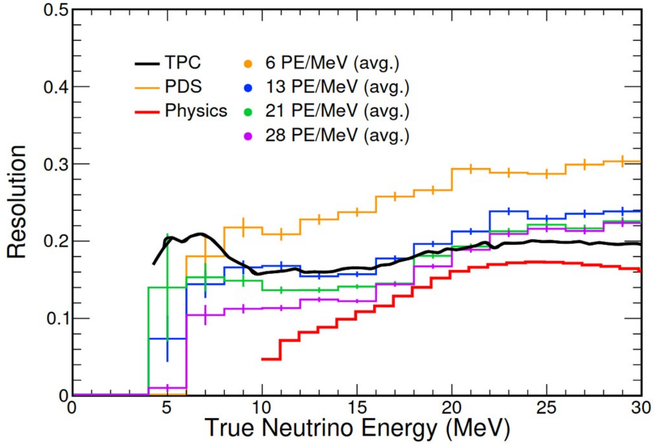
TDR: Supernova Neutrinos





- Physics deliverable #2: PDS must determine t_o w/ ~1 μs timing resolution for events for > 60% of the neutrinos in a typical SNB energy spectrum
  - Correct measured energy for electron lifetime attenuation w/ t_o
  - Provide more precise absolute event times for resolving short time features in the SNB neutrino event rate
- Significant improvement for collection efficiency of > 0.25%
  - Equivalent to > 0.5 PE/MeV for ~60% of the detector volume
- Not leading consideration in setting PDS requirements

TDR: Supernova Neutrinos



- Physics deliverable #3: PDS should be able to provide a calorimetric energy measurement for low-energy events, like SNBs, complementary to the TPC energy measurement
  - Goal is to achieve comparable energy resolution to that from TPC
  - Take advantage of charge+light anti-correlation for energy reconstruction, redundancy if TPC offline (e.g. purity issues)
- Lowest-energy (< 7 MeV) supernova neutrinos achieve similar energy resolution for TPC and PDS when *average* light yield > 20 PE/MeV (collection efficiency > 2.5%)

TDR: Beam Neutrinos

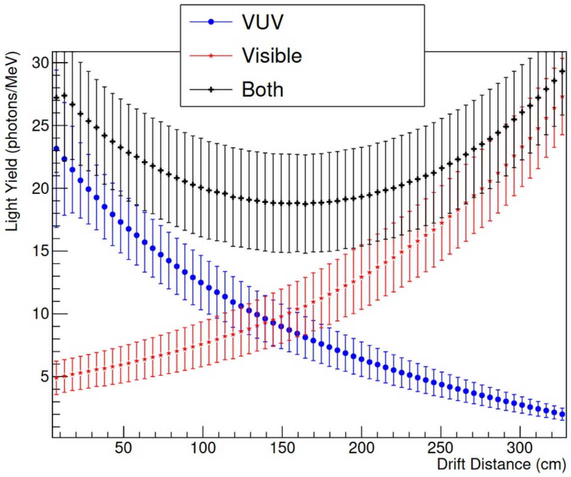
- Physics deliverable #1: PDS should be able to provide a calorimetric energy measurement for high-energy events, like LBNF beam neutrinos, complementary to the TPC energy measurement
  - Cross-check that reduces systematic uncertainties
  - PDS may improve energy resolution for "some types of events"
- PDS channel saturation fraction focused on for study, claiming < 20% required (< 21 PE/MeV or < 2.6% col. eff.)
  - Driven by ability to apply corrections for energy measurements

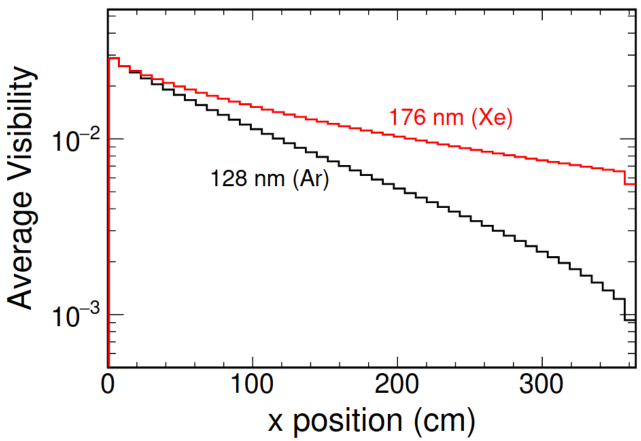
Avg. Light Yield (PE/MeV)	Collection Efficiency (%)	Saturation Fraction (%)
6	0.88	6
13	1.8	13
21	2.6	20
28	3.5	24

TDR: Beam Neutrinos

- Physics deliverable #2: PDS should be able to identify events with Michel electrons from muon and pion decays
  - The identification of Michel electrons can improve background rejection for both beam neutrinos and nucleon decay searches
  - Utilize ~2.2 μs time constant of Michel decay to tag
  - Michel tagging improves further when doping argon with xenon, as light from Michel electron no longer buried in late light (~1.6 μs time constant) from parent muon
- No DUNE FD studies carried out to support setting any particular physics requirement on PDS
  - Studies from LArIAT referenced as "proof of principle"
  - Timing resolution requirement would need to be much better than one set by other considerations, O(ns) instead of ~1 μs

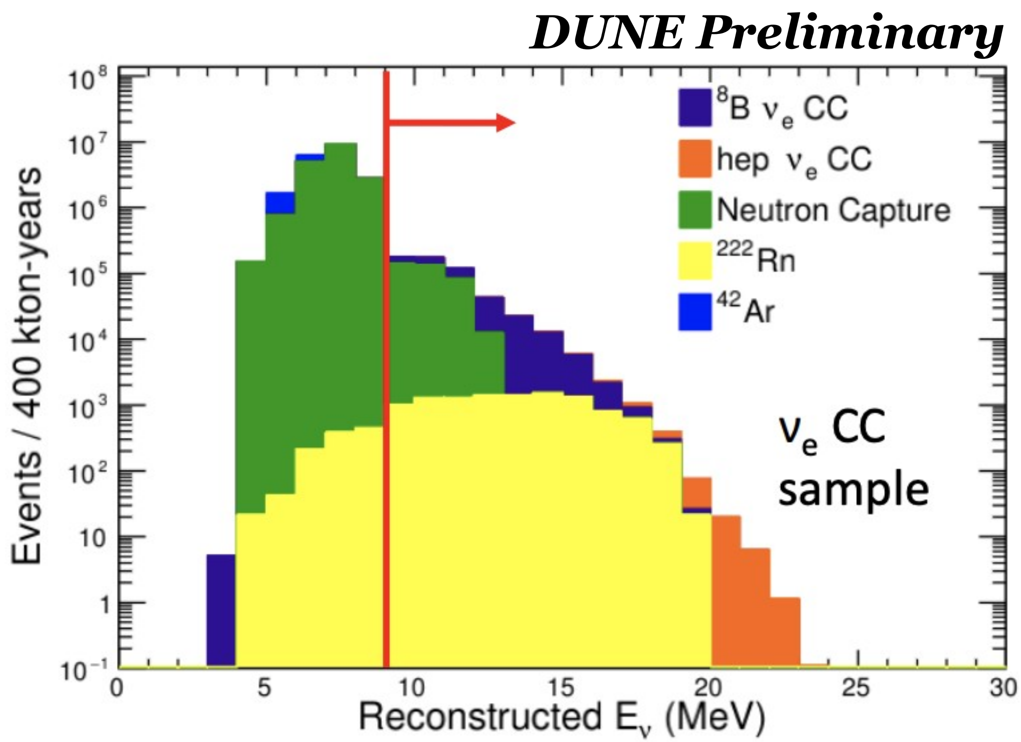
TDR: Enhancing Uniformity





- Two options listed in TDR to enhance light yield uniformity:
  - Coated reflector foils on TPC cathode (improve "hardest" events)
  - Doping argon with xenon (shifts late light to prompt light)
- Both approaches mitigate the impact of a short Rayleigh scattering length (~60 cm assumed in TDR study)
  - Convert 127 nm scintillation photons to longer wavelength photons with a significantly longer Rayleigh scattering length
- Both relevant for PoWER PDS concept

Solar Neutrinos



- Also sensitive to other low-energy neutrinos: **solar neutrinos**
  - **^{8}B solar neutrinos**
  - **hep solar neutrinos**
- Challenging at DUNE due to backgrounds, but still promising!

^{220}Rn Injection Summary

- Exploring injection of ^{220}Rn into argon for calibrations making use of correlated ^{212}Bi + ^{212}Po decays (beta + alpha) at DUNE FD (and also DUNE ND-LAr)
  - **Cost-effective** way to calibrate spatial variations in light yield, monitor electric field distortions, and validate CFD model (et al.)
- Test w/ ^{220}Rn at CSU R&D LArTPC to ensure viability
  - Already have ~30 kBq ^{228}Th source and working charge readout; installing light detector this summer prior to test of ^{220}Rn injection
- Proposal on table to test at ProtoDUNE II and/or ND-LAr 2x2 prototype in early 2025 (or later)
  - Should be straightforward to introduce source into LAr after the LAr filters via separate gas line (using additional filter for GAr)
- Will continue to study potential deployment in DUNE FD