Positron Emission Tomography with Pixelized Liquid Argon Detectors

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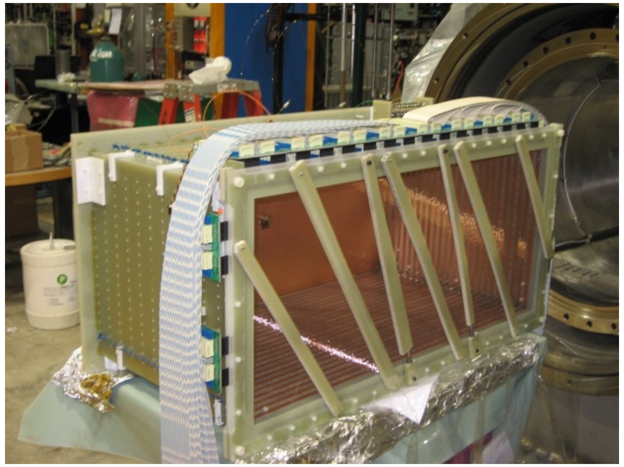
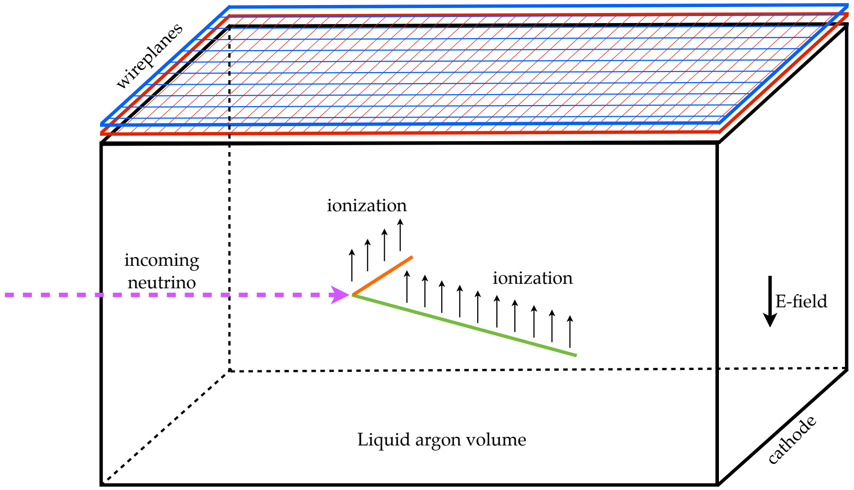
Outline

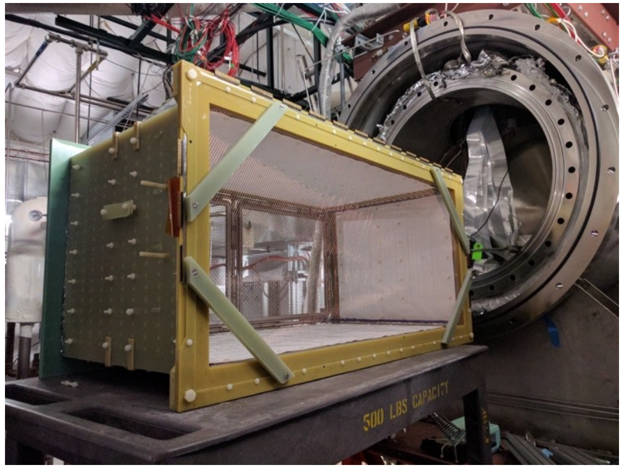
- Brief reminder of Liquid Argon Time Projection Chambers (LArTPCs) and Positron Emission Tomography (PET)
- Using a pixelized LArTPC to perform PET
- Preliminary studies and R&D work
- Future plans

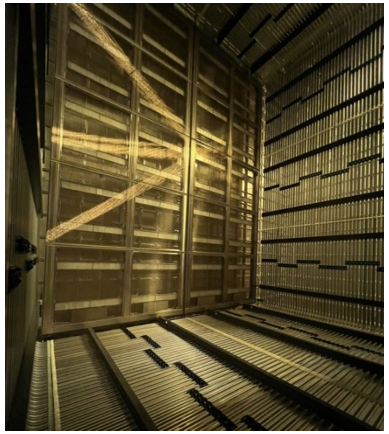
Liquid Argon Time Projection Chambers (for neutrinos)

Past ~15 years has seen great progress in operational experience at increasingly larger sizes (e.g. ArgoNeuT (0.25 tons) through ProtoDUNE-SP (~1000 tons)).

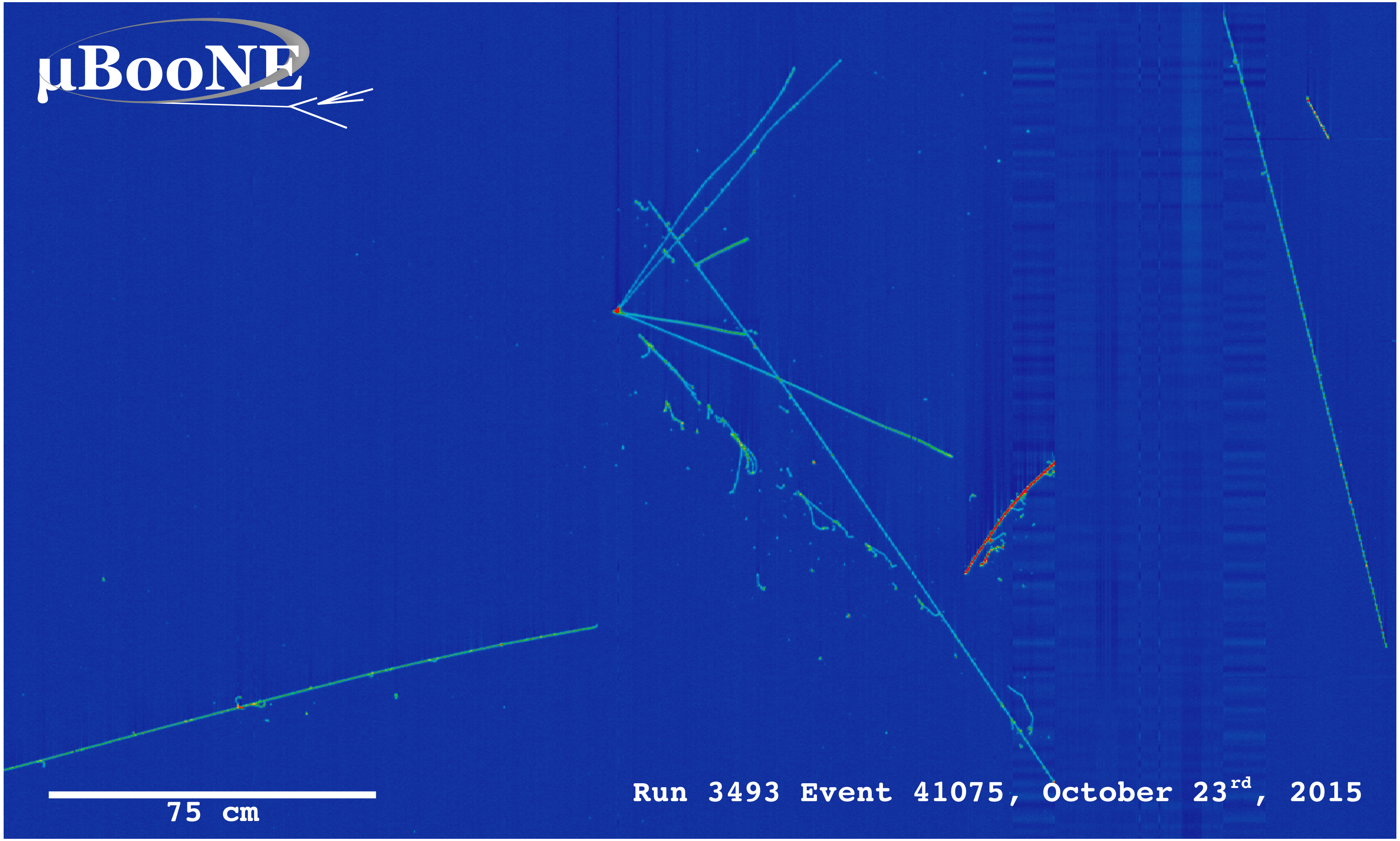








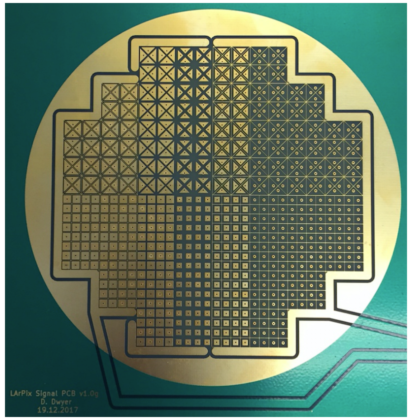
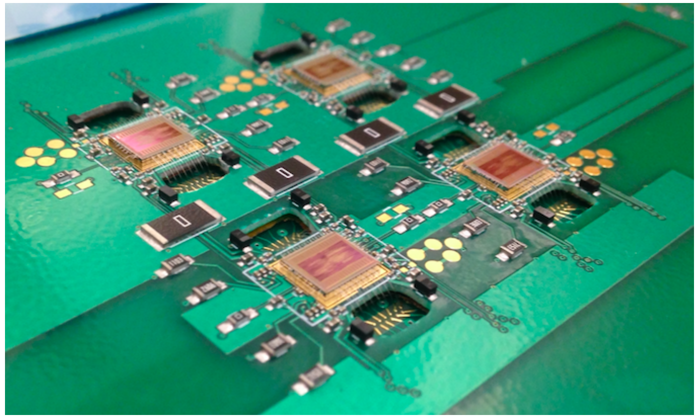
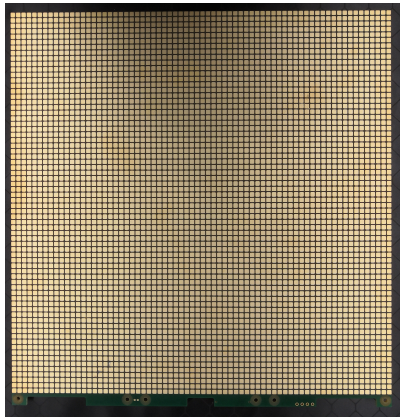
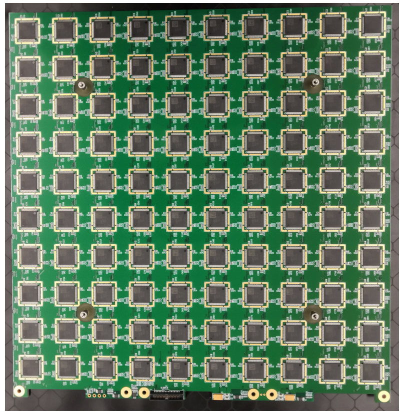
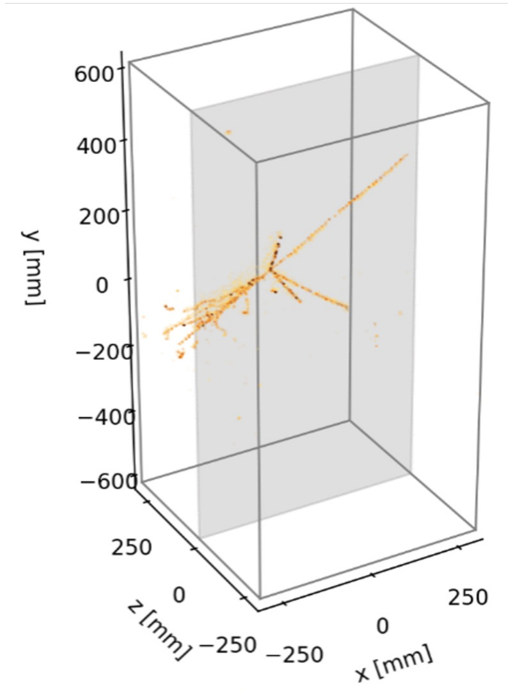
Liquid Argon Time Projection Chambers (for neutrinos)



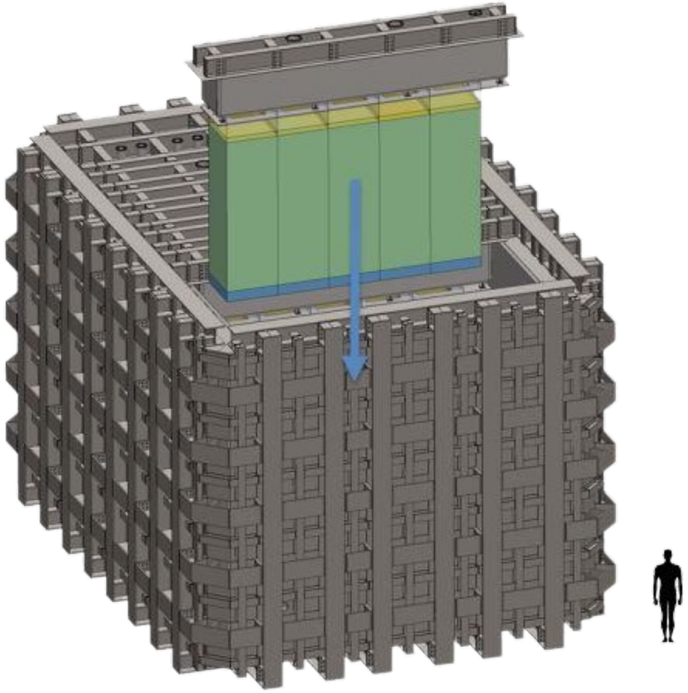
Refs:
1.) https://microboone-exp.fnal.gov/public/approved_plots/index.html

Liquid Argon Time Projection Chambers (for neutrinos)

- Recent developments in replacing TPC wireplanes with pixels and integrated custom electronics (e.g. LArPix, Q-Pix).
- Integral to plan for eventual DUNE Near Detector LArTPC.

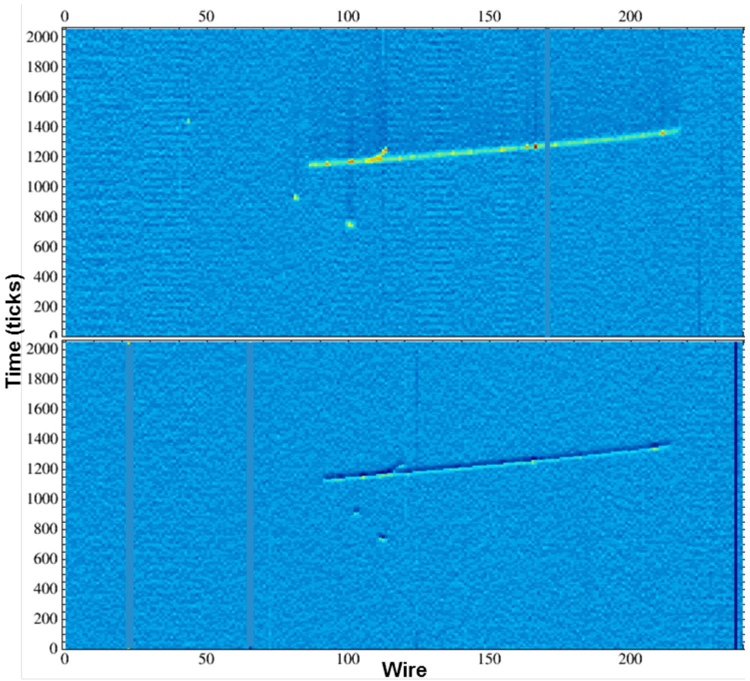
Module 1 LArTPC

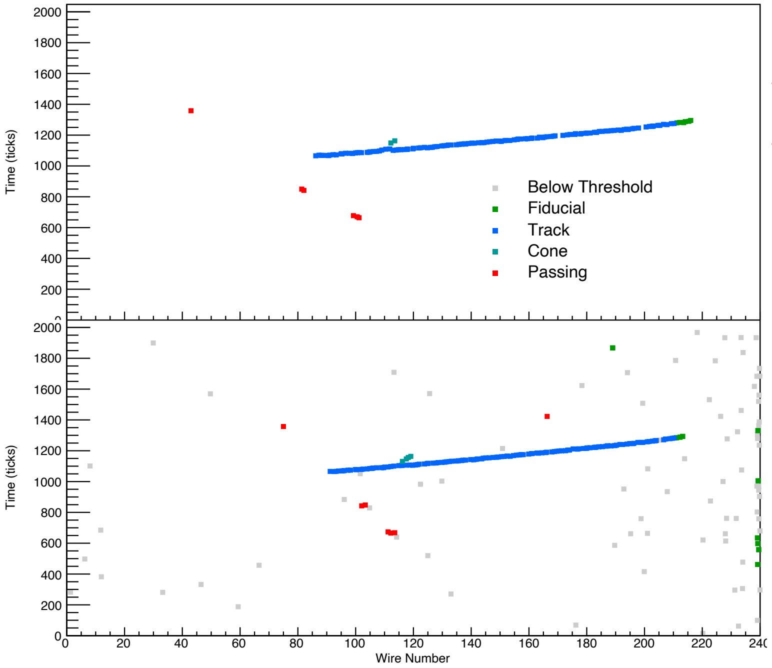


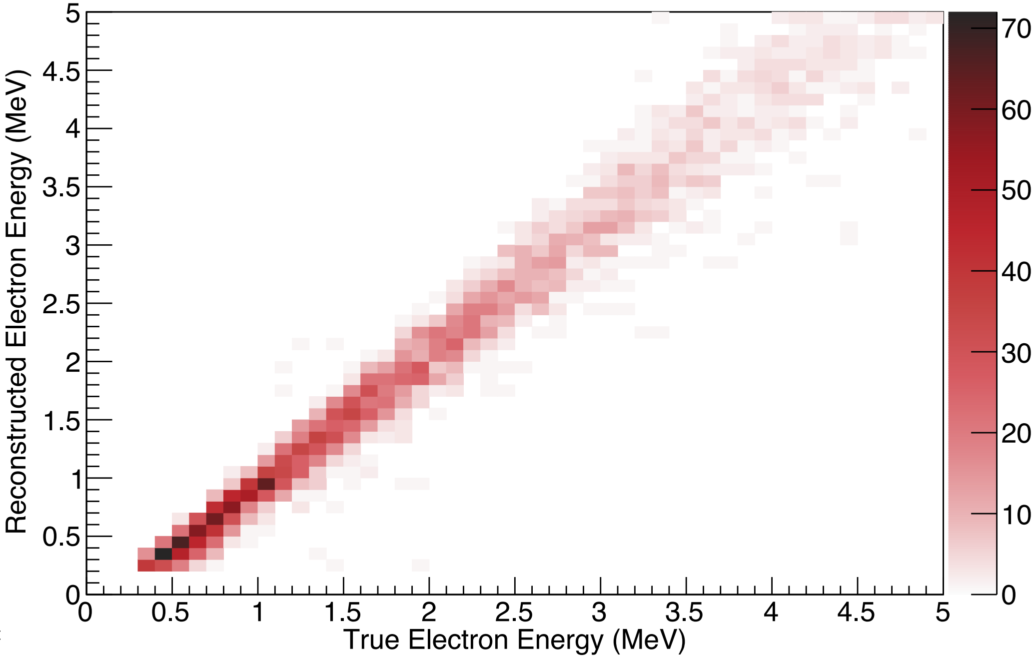
Refs:
1.) “LArPix: Demonstration of low-power 3D pixelated charge readout for liquid argon time projection chambers”, D. A. Dwyer et al, JINST 13 P10007 (2018)
2.) “Q-Pix: Pixel-scale Signal Capture for Kiloton Liquid Argon TPC Detectors: Time-to-Charge Waveform Capture, Local Clocks, Dynamic Networks”, D. Nygren and Y. Mei, arXiv:1809.10213 (2018)

Liquid Argon Time Projection Chambers (for neutrinos)

- Capability has been demonstrated to reconstruct energy depositions down to O(100 keV) in wire-based TPCs that were not optimized for this regime.
- Signals are a mix of de-excitation photons, neutron scatters, Ar-39, etc…



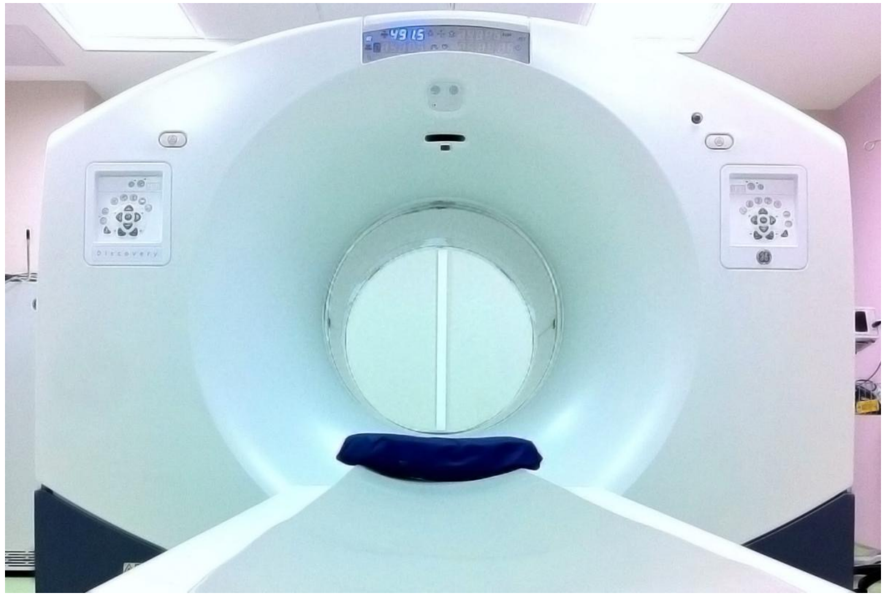


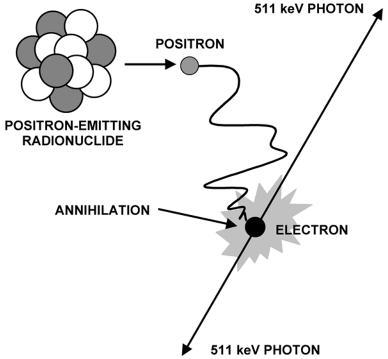


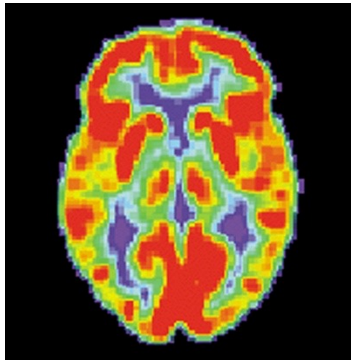
Refs:
1.) "Demonstration of MeV-Scale Physics in Liquid Argon Time Projection Chambers Using ArgoNeuT", ArgoNeuT Collaboration, Phys. Rev. D 99, 012002 (2019)
2.) "MeV Scale Physics in MicroBooNE", A. Bhat, PhD Dissertation (Syracuse University), 2021.

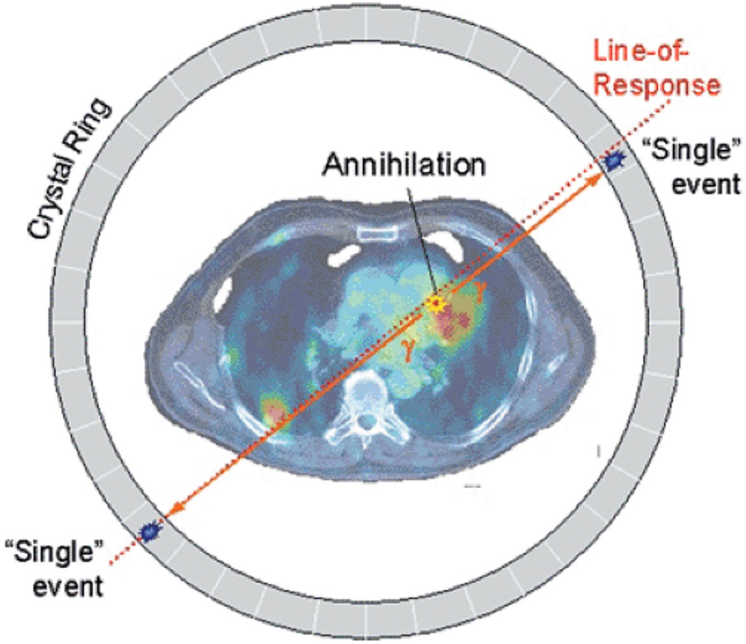
Positron Emission Tomography

- Radioactive tracers (e.g. F-18) ingested in patient undergo β^+ decay, and subsequent positron annihilation produces two back-to-back 511 keV gammas.
- Traditional PET scanner surrounds patient with a ring of scintillation crystals (e.g. BGO, LSO) coupled to photodetectors.
- Coincident hits in scanner form lines-of-responses, which can be utilized to reconstruct position of annihilation candidates, and eventually show function of organs.





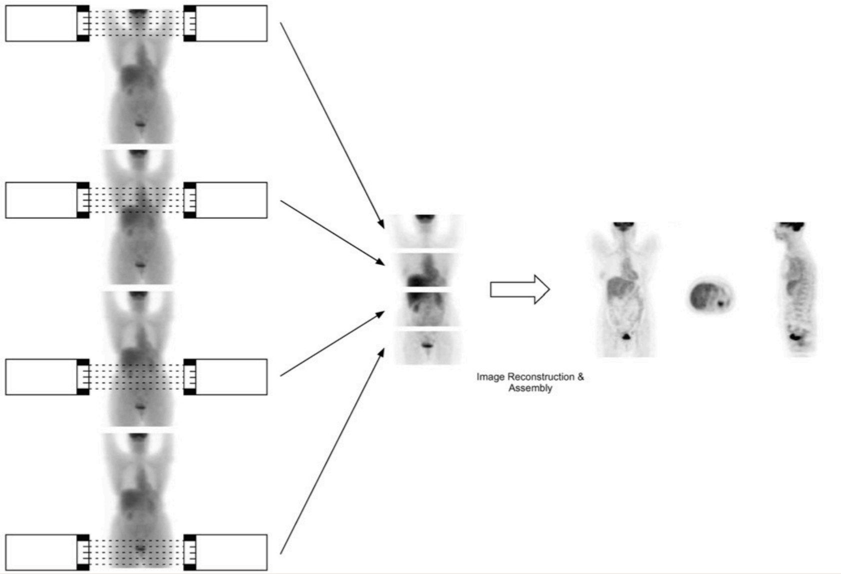




Refs:
1.) “PET: Physics, Instrumentation, and Scanners”, Magnus Dahlbom and Simon Cherry, pages 1–117. 01 2006.
2.) US National Institute on Aging. https://www.nia.nih.gov/.

LArTPCs for PET

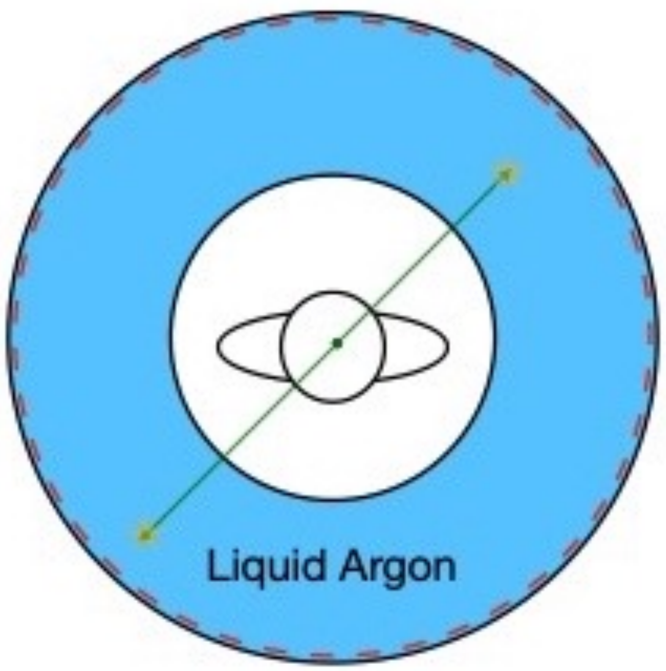
- Leveraging technological advances in LArTPCs from neutrino (and elsewhere) for PET scans offers potential for significant improvements.
- Several goals:
  - Faster scans ("full body" instead of segmented) with lower dose required.
  - Better resolution resulting in enhanced diagnostic information.
  - Cheaper? Would be great if so, but far too early to make any claims.

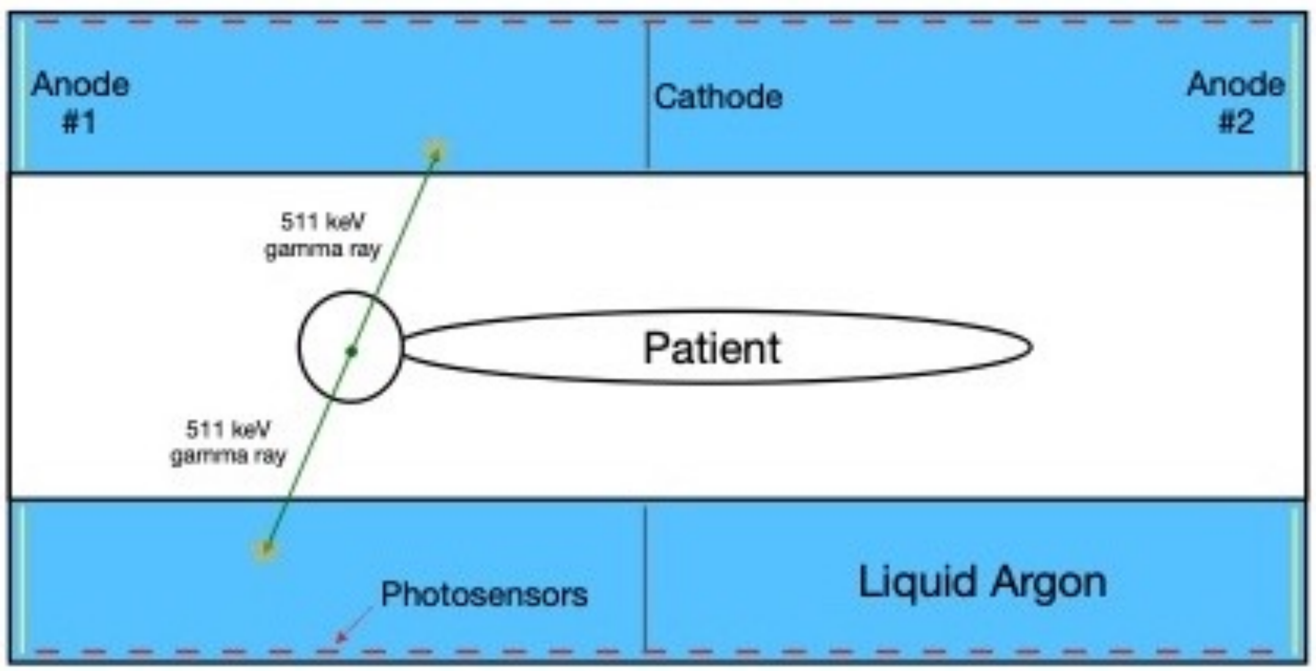


Refs:
1.) "PET: Physics, Instrumentation, and Scanners", Magnus Dahlbom and Simon Cherry, pages 1–117. 01 2006.

LArTPCs for PET

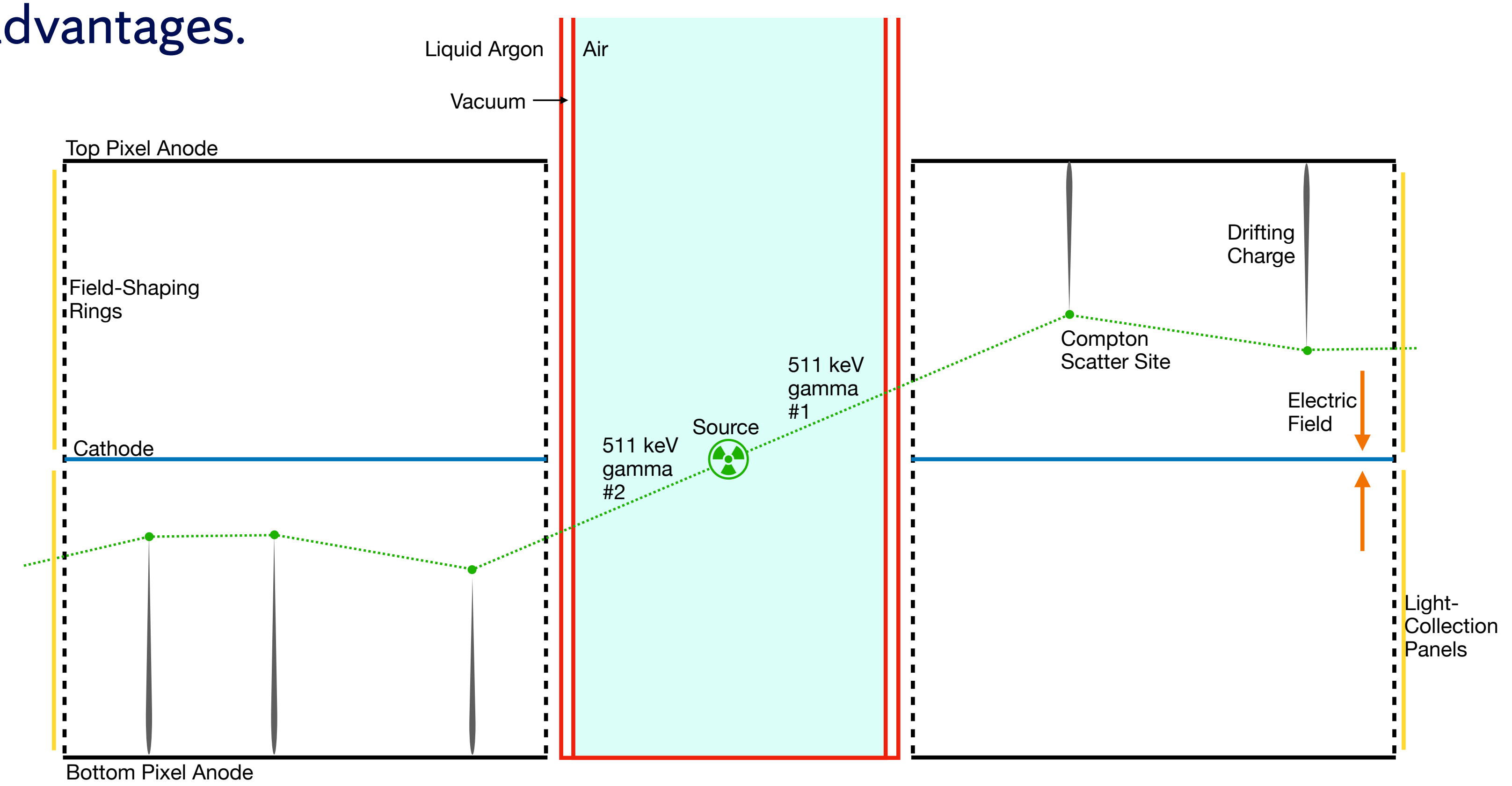
- Working concept is full-body length cylindrical cryostat with central bore.
- Dual-drift TPC with central cathode, and pixelated anodes on either end.
- Photosensors integrated with field cage to provide "S1" timing.





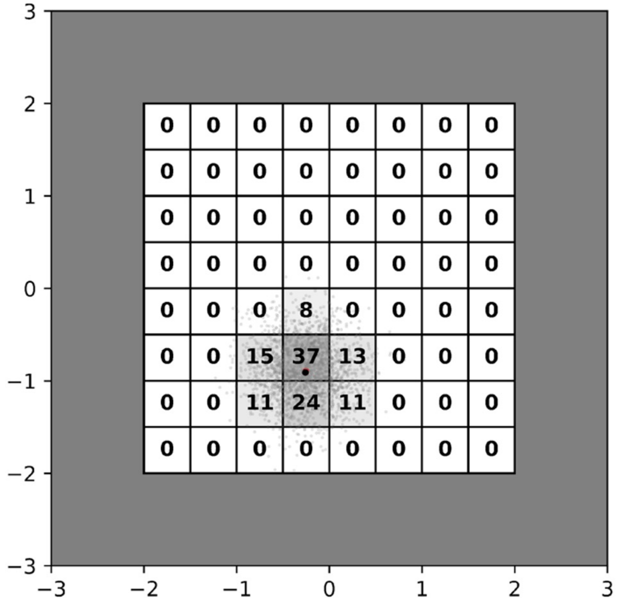
LArTPCs for PET

- Annihilations from source(s) inside excluded region of TPC yield 511 keV gamma into the TPC.
- Gammas will undergo Compton scatter(s), producing low-energy electrons and scintillation light.
- Want thickness of surrounding LAr sufficient to guarantee at least one scatter for most photons. Multiple scattering allows direction of incident gamma to be determined standalone, which may offer other advantages.

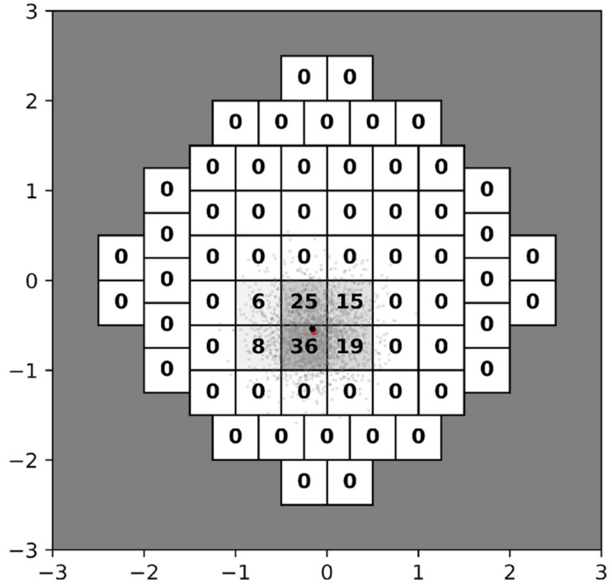


Preliminary Simulation Studies

- Have made a preliminary GEANT4 simulation of a LArTPC for PET, inspired heavily from existing simulation package from DUNE ND-LAr. Includes signal formation on pixels due to drifting charge, same as considered for LArPix ND-Lar simulation.
- Looking at reconstruction of signals seen on simple 64-channel pixelized LArTPC, for two different pixel arrangements ("square" and "packed"), and using charge-averaging to reconstruct position of charge liberated in Compton scatters.



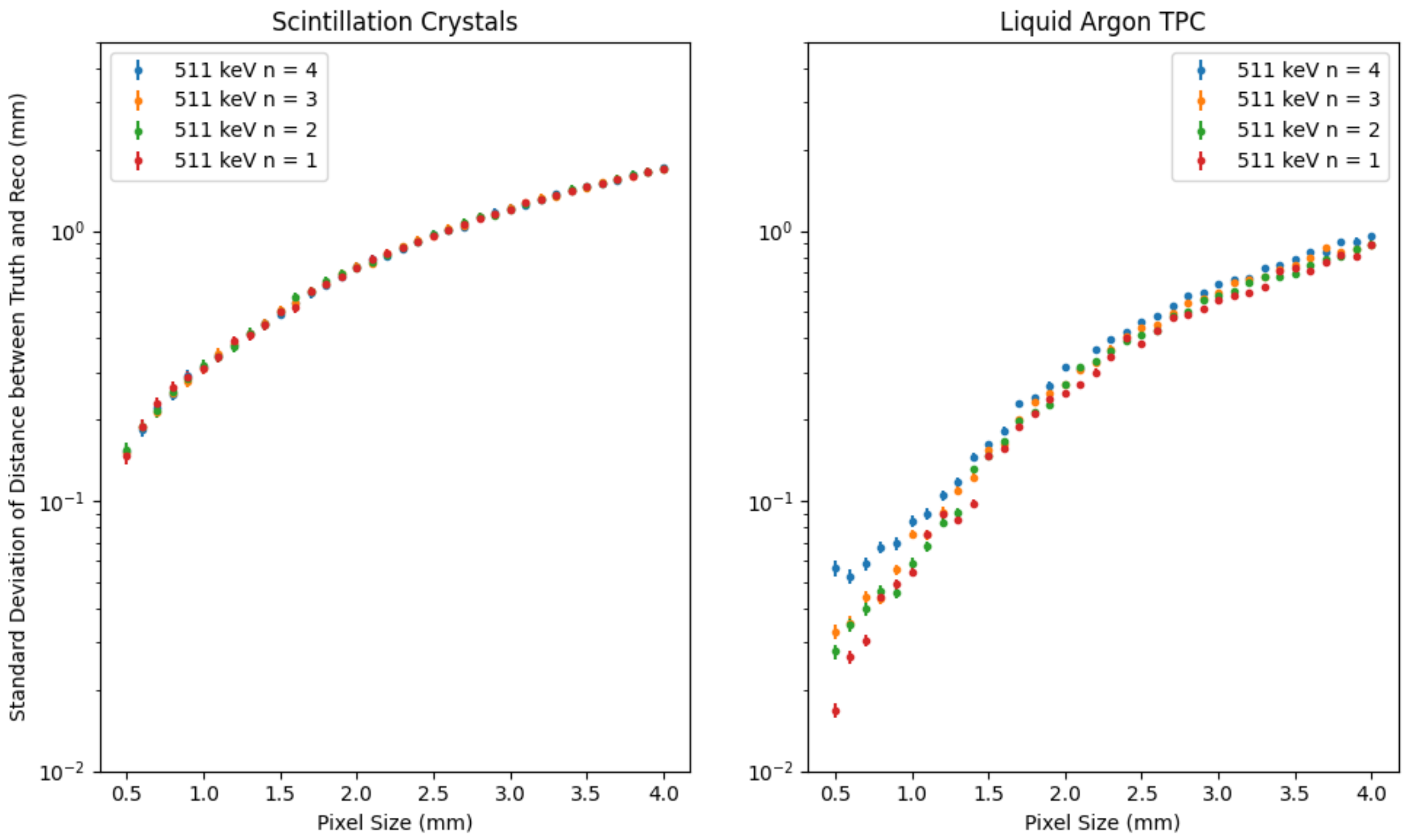
Square



Packed

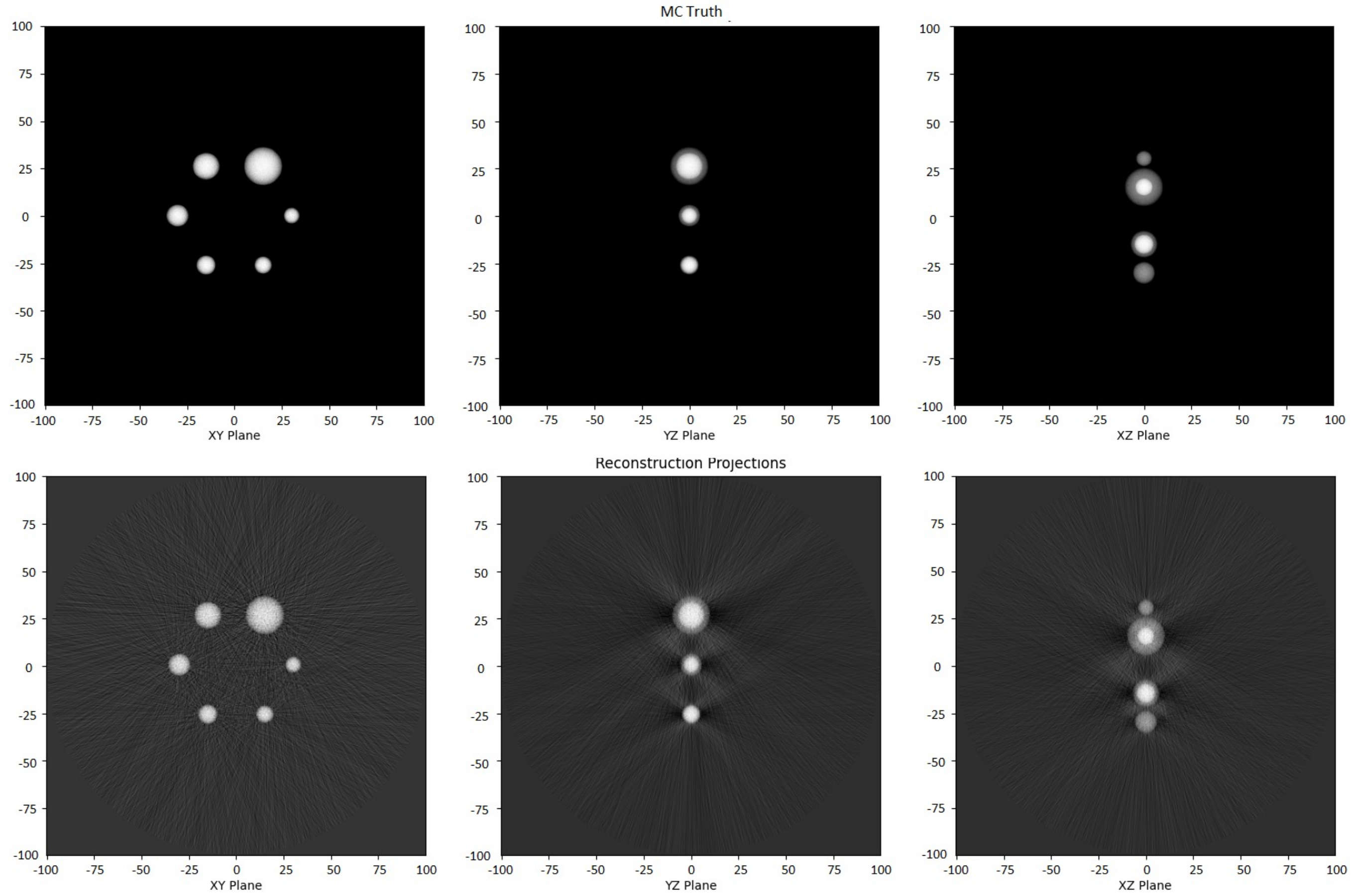
Preliminary Simulation Studies

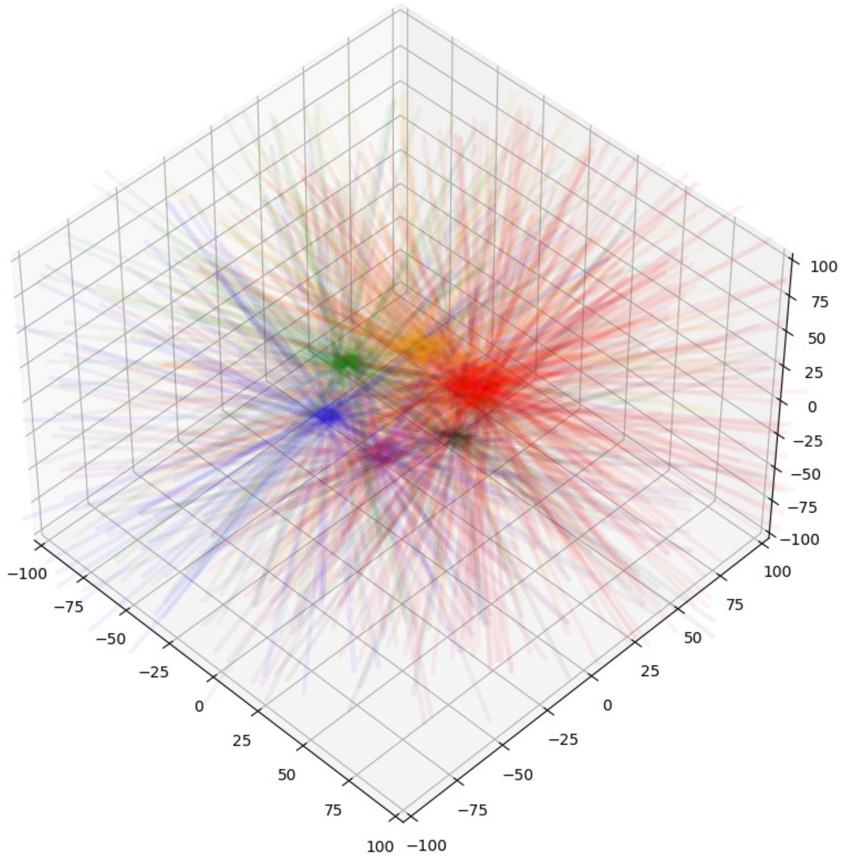
- Comparing position resolution of traditional PET (left) against LAr PET (right), as a function of photosensor/pixel size. Shows promise for improvement.
- Graphs show performance for 1st, 2nd, 3rd, 4th Compton scatter sites for incident 511 keV gamma.



Preliminary Simulation Studies

- Simulate detector response to array of sources as specified by NEMA IEC Body Phantom Set, which is used to qualify real PET scanners.
- Six sources of varying diameter arranged in hexagonal pattern each produce 511 keV gammas, and figures shown are LOR (right) collected by detector, reconstructed objects (bottom) after processing., and Truth (top).

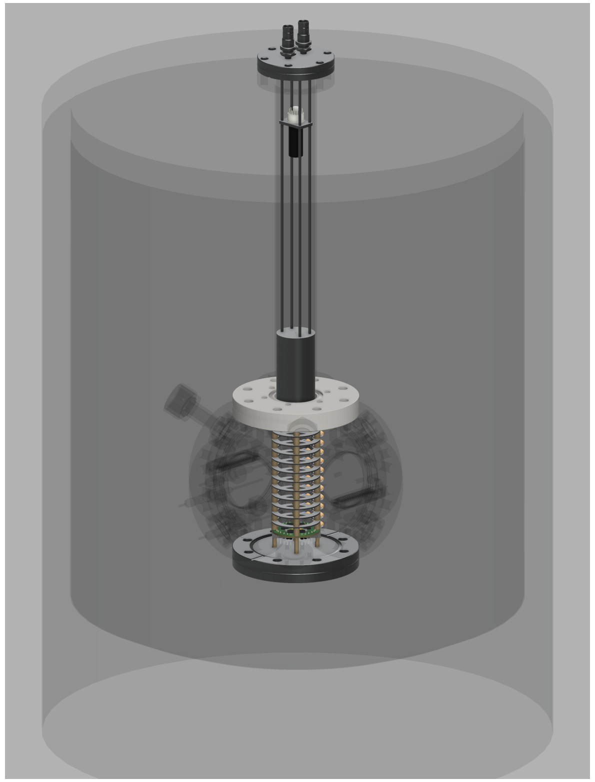


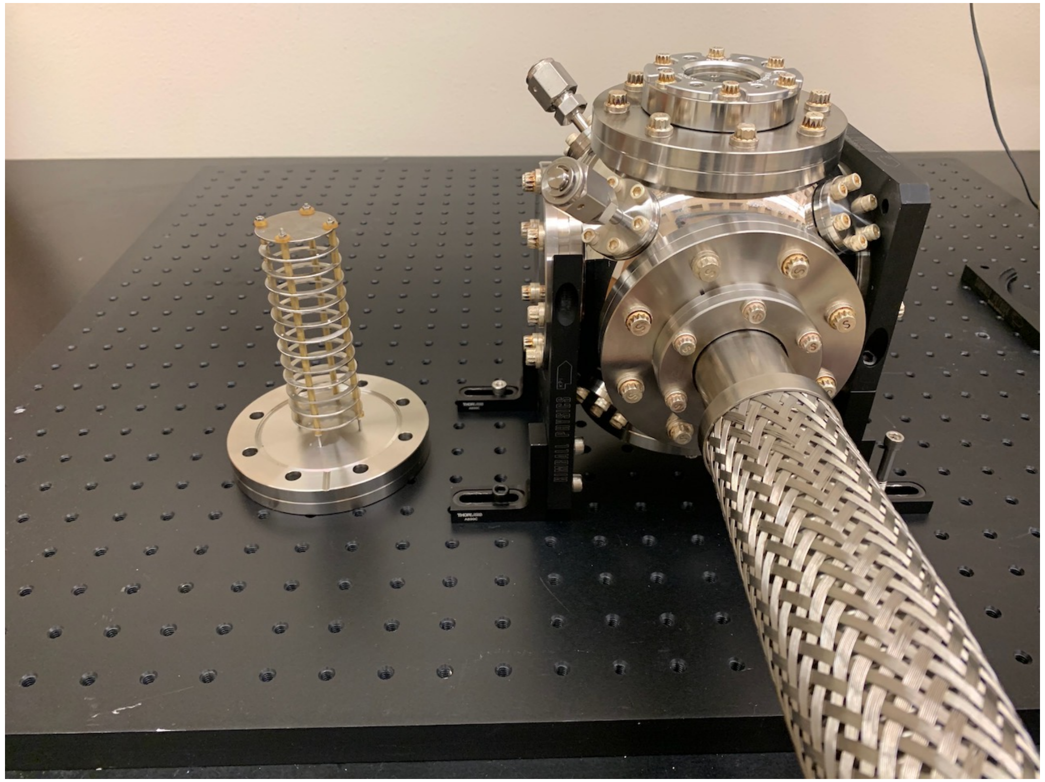


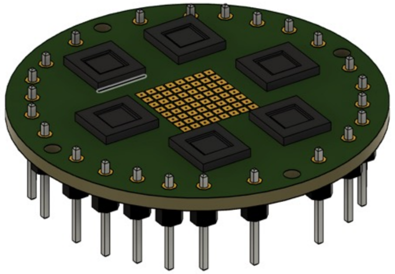
Refs:
1.) National Electrical Manufacturers Association. NEMA Standards Publication NU 2–2007, Performance measurements of positron emission tomographs. Rosslyn, VA. 26–33, 2007.

Prototyping Efforts

- Working on miniature 64-pixel TPC augmented with a few Hamamatsu VUV-sensitive Multi Pixel Photon Counters (MPPCs). Planning for Q-Pix electronics.
- External β^+ source (e.g. Na-22) separated from chamber by thin titanium window.
- External photodetector (CAEN gamma stream with NaI scintillator) coupled to source via collimator provides trigger for TPC (in conjuncton with MPPCs).

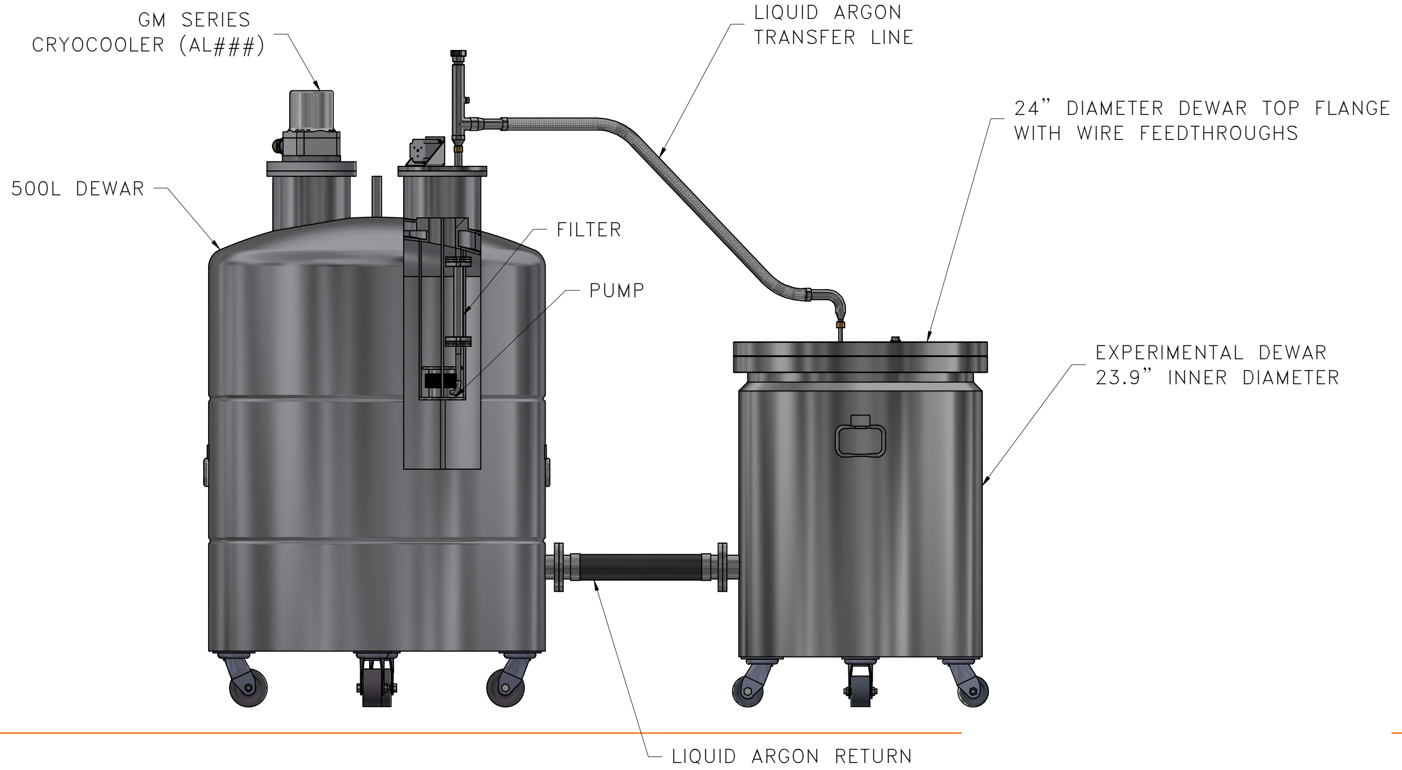






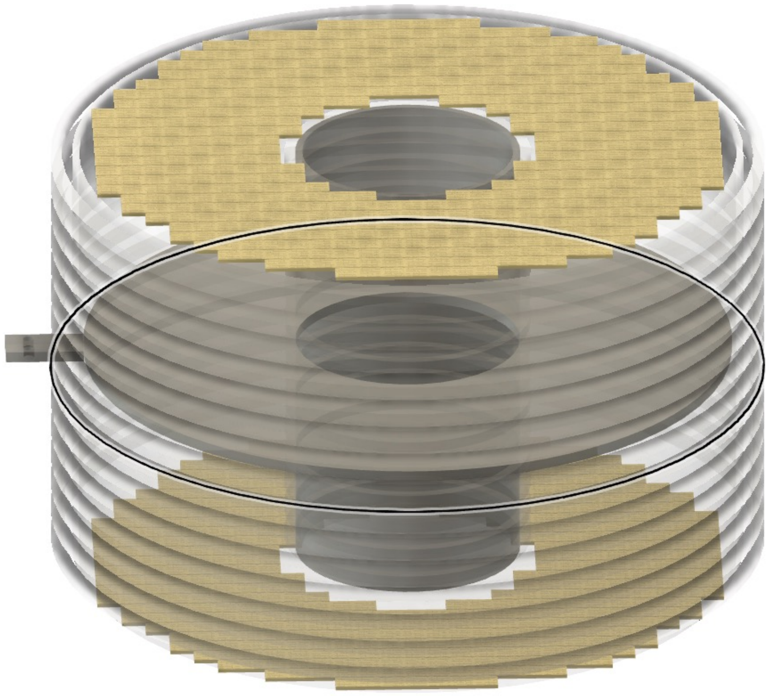
Future Plans

- Need much better capability to create and maintain a volume of ultrapure liquid argon for this, and other, LArTPC research. This is age old tale, sadly.
- Good news! Have worked with Cryomech, whose headquarters happens to be near campus in Syracuse, to develop a university lab-sized LAr recirculation and purification system. Arriving summer 2024.



Future Plans

- PET TPC with central bore will reside in experimental dewar.
- Considering 2 mm pixel size, but this will be a function of cost/channel, and realistic production schedule of 10,000+ channels of electronics.
- Need “excluder” flange for source deployment, minimizing material thickness.



Conclusions

- LArTPCs offer very attractive capabilities for PET, and we are focusing on developing an approach that emphasizes charge collection with pixels.
- Have created a preliminary simulation using realistic geometry and pixel signal formation.
- This coming year we will perform small-scale tests (64 channels) with Na-22 source and Q-Pix electronics.
- Anticipating new LAr recirculation and purification system in summer 2024 to enable a larger scale test of this concept.

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Thank you!