Fermilab U.S. DEPARTMENT OF ENERGY Office of Science

LArTPC R&D

A. Fava, Fermilab

S19: New Neutrino Technology

June 4, 2022

NEUTRINO 2022

XXX International Conference on Neutrino Physics and Astrophysics

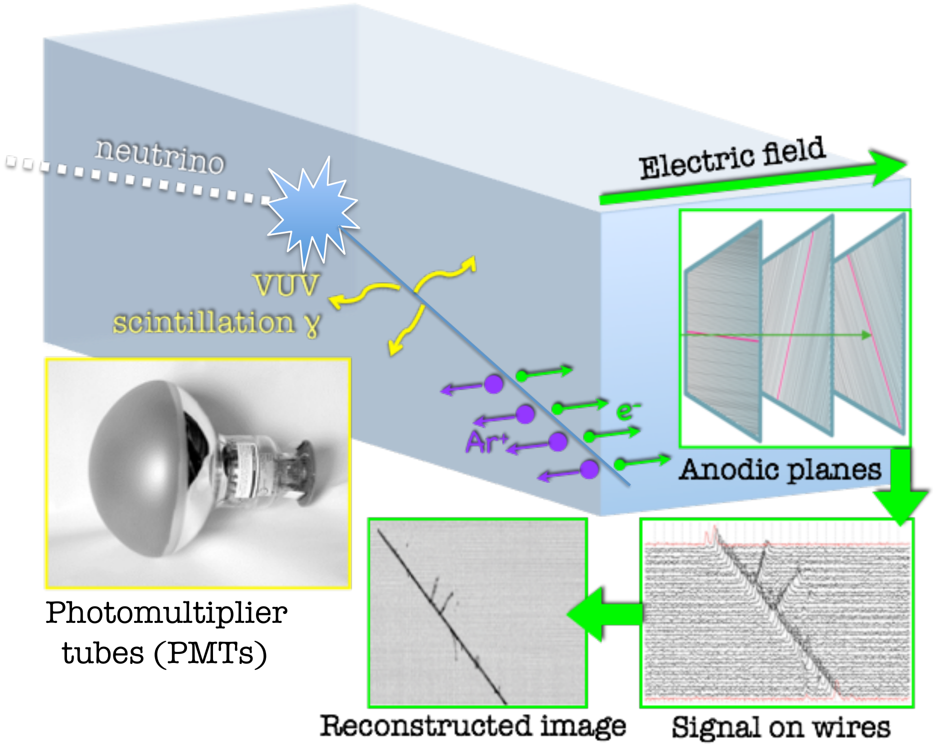
Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022

Overview

- The exploitation of LAr-TPC detectors in neutrino and rare event Physics flourished in the last decades, since the pioneering work of the ICARUS Collaboration in the ’90s.
- While the technique gets more mature and consolidated with the realization of several large mass LAr-TPC detectors for present and future experiments, lively R&D is ongoing worldwide:
  - improve the performance of existing detectors _ pixelated detectors, charge readout with strips, photodetectors for instrumenting high voltage surfaces, light reflector foils, new wavelength shifting materials, metalenses, high voltage distribution systems, magnetization
  - extend their range of applications, for instance to reduce energy thresholds in terms of both scintillation light and drift charge, for applications in neutrino physics (recovering missing energy, Supernovae neutrino, coherent neutrino scattering CEvNS) and dark matter _ proportional charge or light amplification, doping with photoionizing elements, infrared light, combined light&charge readout with pixel detectors
  - realize novel designs _ cylindrical geometry, dual-readout
- A few highlights are captured in this talk, for single phase only. There are certainly many more interesting ideas!

Liquid Argon TPC detection technique

Massive yet homogeneous target, excellent tracking & calorimetric capabilities.



λ = 128 nm scintillation light:

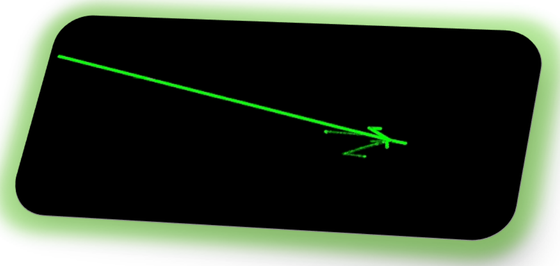
40000 γ/MeV wo electric field.

Response time ~ 6 ns ÷ 1.6 μs.

Ionisation electrons:

42000 e^-/MeV.

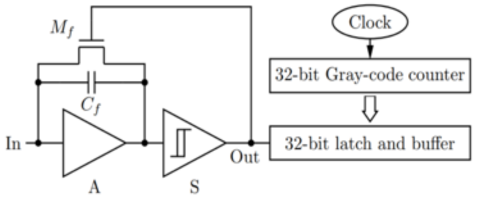
Drifted (E) toward planes of wires on which they induce a signal. Response time = drift time (ms).

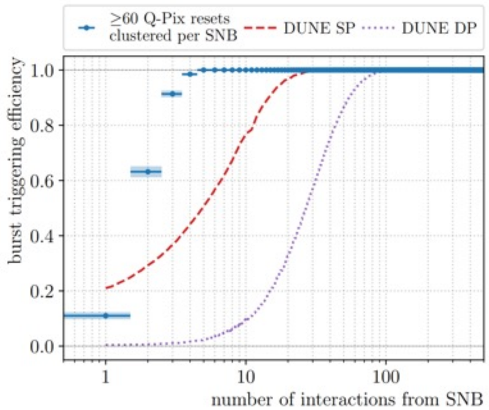


Q-Pix: Kiloton Scale Pixelated LArTPC’s

Courtesy of J. Asaadi (UTA)

- Q-Pix is a charge readout technology for kiloton scale LArTPC’s. Needs low-power, low-noise readout for multitude of channels
  - novel signal capture approach that measures time-to-charge: each reset represents a fixed amount of charge (ΔQ) and the time between resets gives a known interval (ΔT) and thus measures the instantaneous current
  - keeps all the detailed waveforms of the LArTPC while staying in a quiescent state when there is no charge arriving
- Benefits include intrinsic 3D readout that enhances signal efficiency and purity ([JINST 15 P04009]), and lowering of threshold that improves DUNE’s capabilities for supernova neutrino identification while drastically cutting data rates ([arXiv:2203.12109])
- A consortium of universities and national labs have come together to simulate, fabricate, test and deploy the Q-Pix concept. Prototype expected later this year (2022)
  - Q-Pix consortium thanks the DOE for its support via DE-SC0020065 award, DE-SC 0000253485 award, and FNAL-LDRD-2020-027

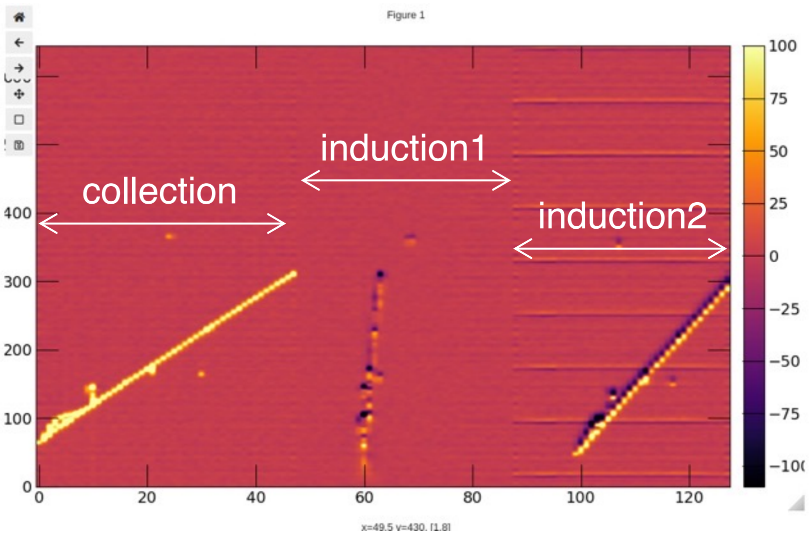


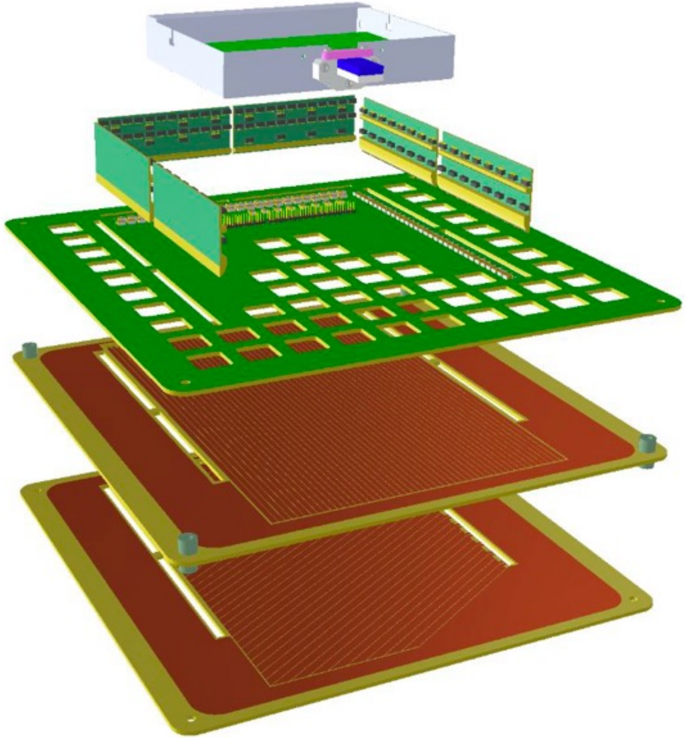


Charge readout with PCB strips

Courtesy of S. Tufanli (CERN)

- Perforated PCB anodes first proposed in [JINST 13 T03001 (2018)]
- Successfully deployed in many configurations in 50l LAr-TPC test-stand at CERN. Scaled to 3x3 m^2 also successful
  - Shield and induction-1 on the first PCB, induction-2 and collection on the second PCB at ±60°

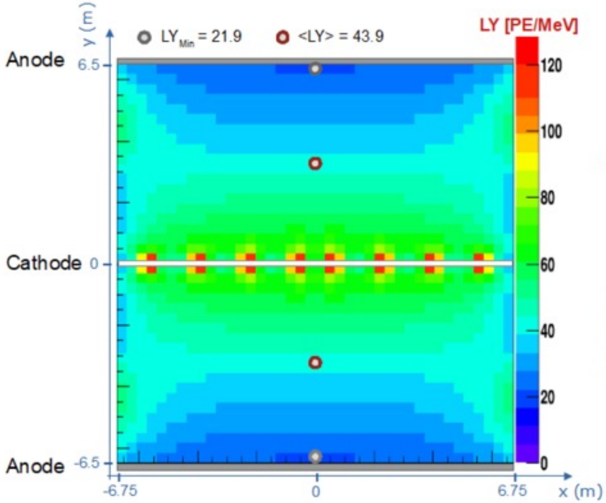


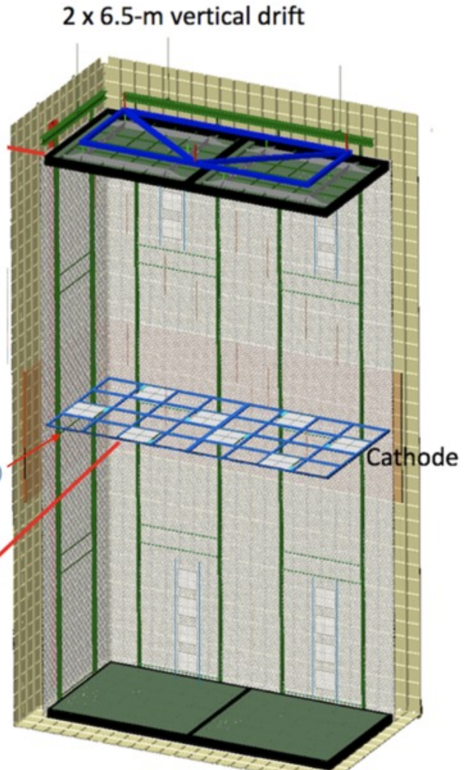


Photodetectors for high voltage surfaces (DUNE VD)

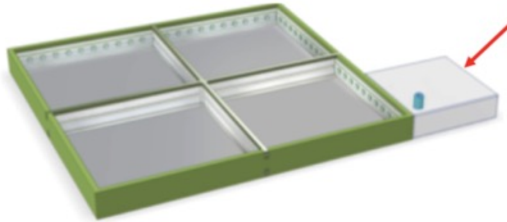
Courtesy of F. Cavanna (FNAL)

- Scintillation light readout (PDS) in LAr-TPC complementary to charge.
  PDS particularly important for detection & reconstruction of low energy underground events and background rejection
- In DUNE Vertical Drift (VD) light yield <LY> = 44 PE/MeV achieved with optical coverage 14% of cathode and 8% behind field cage walls
- Operating photodetectors on HV surface (300 kV) requires electrically floating Photo-sensors and r/o Electronics ⇒ Power (IN) and Signal (OUT) transmitted via optical Fibers (commercial technique).





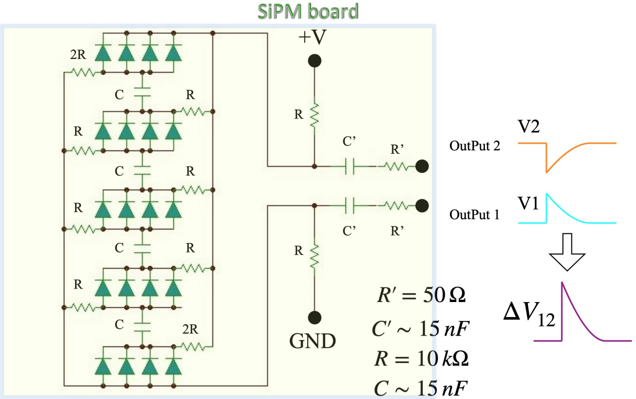
Photon Detectors (PDs)



xARAPUCA technology - large area, 2 readout channels (each 4x20 SiPMs in hybrid ganging)

DUNE VD: analog Signal over Fiber (SoF) concept

Courtesy of F. Cavanna (FNAL)



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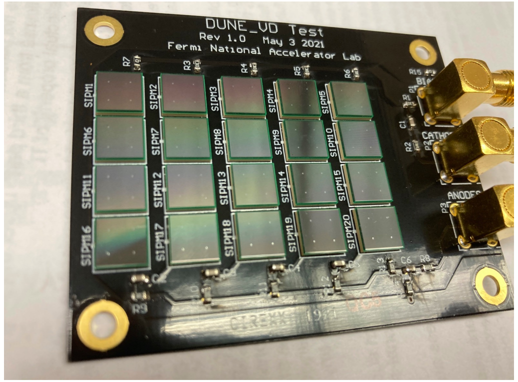
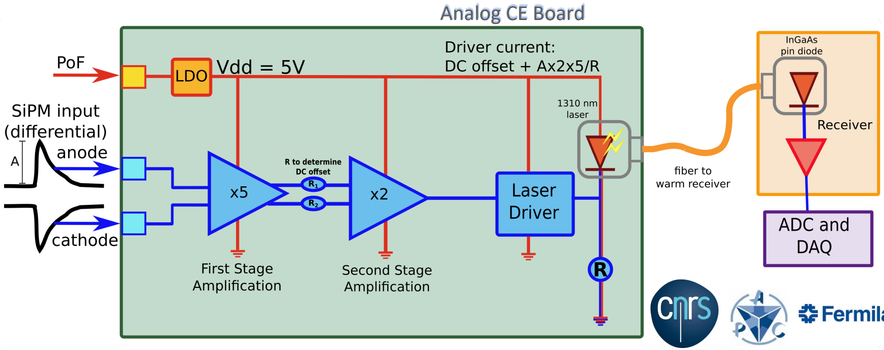


the 20 SiPM Board(s) in passive Hybrid ganging



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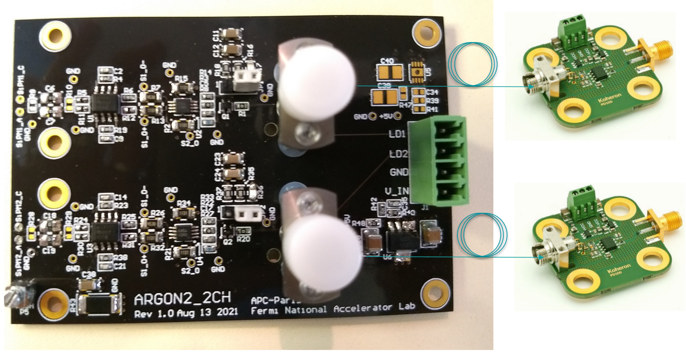


the Analog CE Board Active ganging/Ampli & SoF

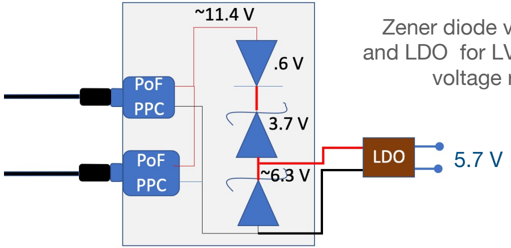
DUNE VD: Power over Fiber (PoF) concept

multimode fiber with FC connector

Fermilab/AD

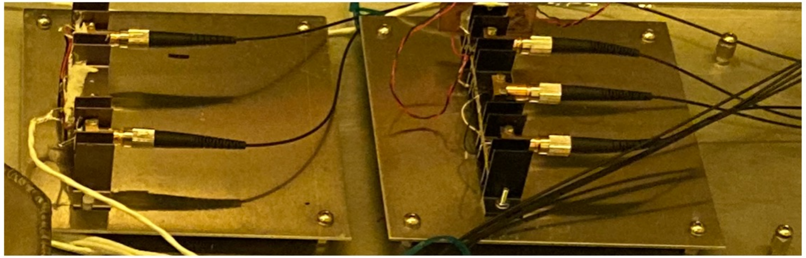
PoF Transmitter
Photonic Power Module (PPM)
976 nm laser diode

PoF Receiver Si-based high intensity
Photovoltaic Power Converter (PPC) on heatsink



Zener diode voltage divider and LDO for LV-HC PoF output voltage regulator

PoF - Power housing unit *(5 warm Transmitter laser diodes)*

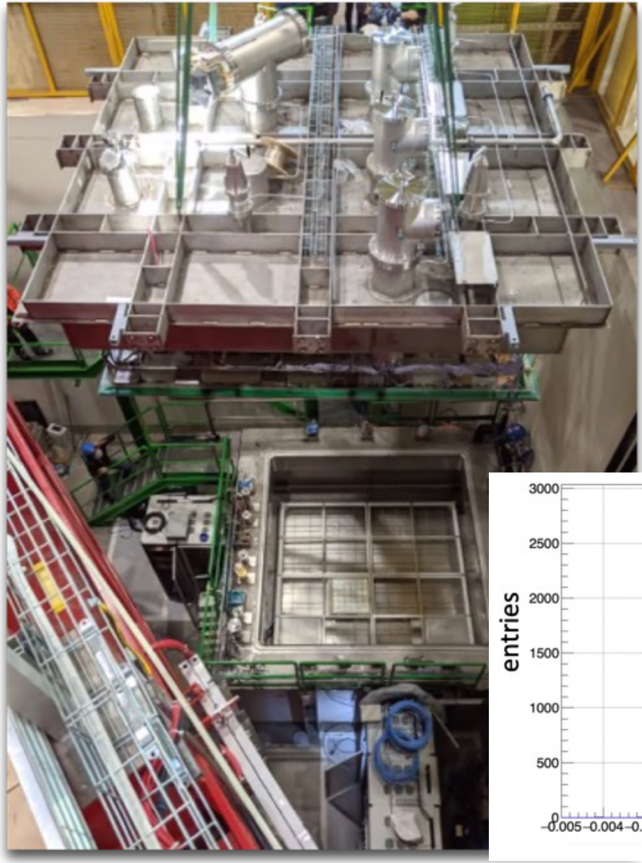


LV-HC PoF supply board
(2 cold Receivers on heatsink)

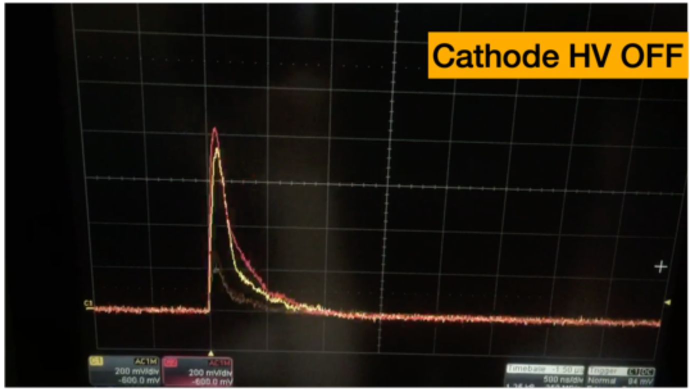
HV-LC PoF supply cold board
(3 cold Receivers on heatsink)

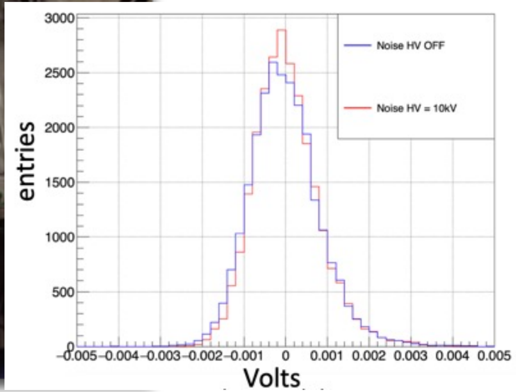
DUNE VD: successful tests at CERN

Courtesy of F. Cavanna (FNAL)



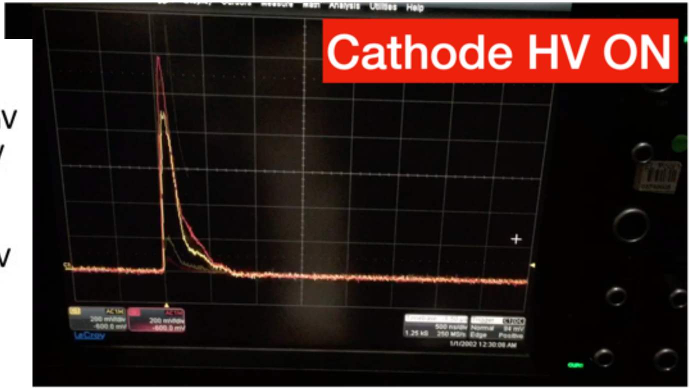
- Tested at CERN Dec 2021
- Clean signals, no noise increase or signal distortion when HV ON.
- Needs to demonstrate stability and durability, and develop control feedback





HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

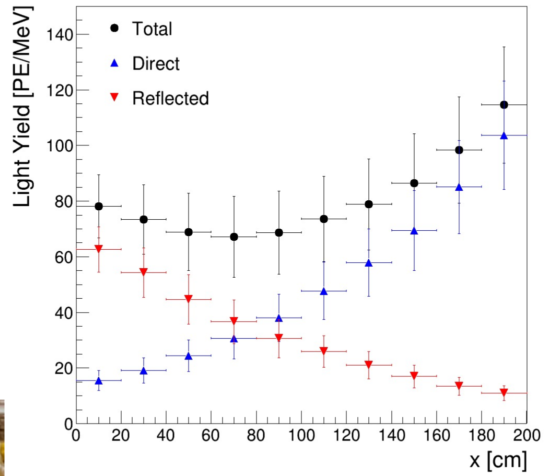
HV = 10 kV
Mean =-0.02 mV
Sigma=0.71 mV

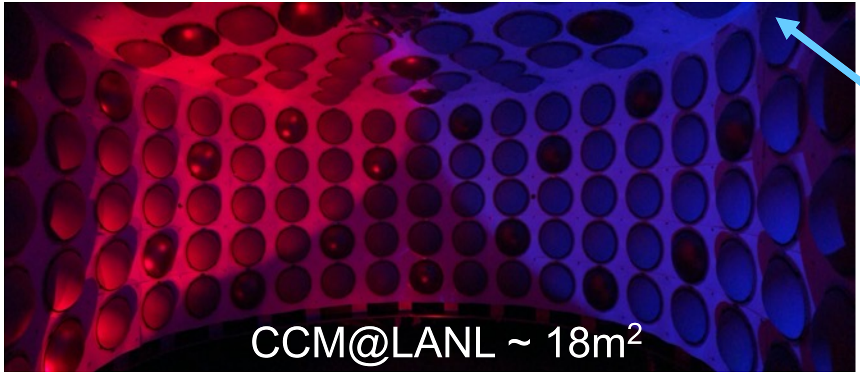


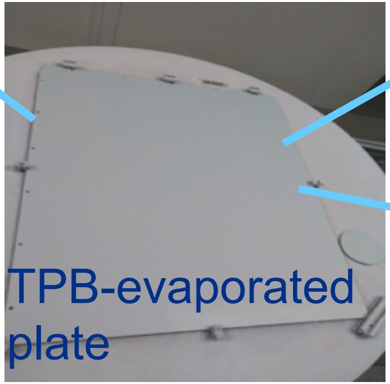
Large light reflecting surfaces

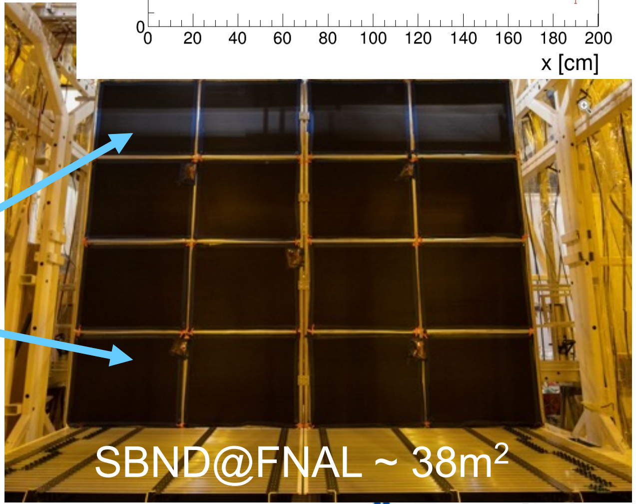
Courtesy of A. Szelc (University of Edinburgh)

- Covering the surfaces with reflectors coated with wavelength shifters (WLS) recovers VUV light that would normally be lost:
  - increased collection efficiency far away from photon detectors
  - enhanced position reconstruction and timing
- Low Temperature Evaporation gives best performance of TPB coating but is challenging on large surfaces required by large detectors.









Scalable WLS for large LAr-TPC

Courtesy of M. Kuźniak (AstroCeNT/CAMK PAN)

- Large detectors need up to thousands m² of WLS surfaces for efficient light collection
- Vacuum-evaporated tetraphenyl butadiene (TPB) coatings are well proven but scale-up challenging (also evidence for emanation)
- Polymeric PEN foils are a simple alternative:
  EPJ C 79, 291 (2019)
  - Commercial (technical) grades have 35-75% of TPB WLS yield
  - Recent comparisons to TPB in-situ (@87 K with 128 nm excitation)

EPJ C 81, 1099 (2021), Y. Abraham et al., JINST 16, P07017 (2021)

PEN sample	Relative LY	Reflector	Temperature
Molded PEN	~ 50% [18]	No	RT
Film (125 μm)[(s)]	~ 50% [32]	No	RT
Film (125 μm)	80 (23)% [15]	No	LAr[a]
Film (125 μm)	34 (1)% [27]	ESR	LAr
Film (25 μm)	39 (2)% [28]	ESR	LAr
Film (125 μm)[(s)]	**75 (7)%**	TTX	LAr

[a] The value from [15] corresponds to the relative efficiency measured at RT and projected at LAr temperature

G. Araujo et al., EPJ C 82, 442 (2022)

Ongoing and planned PEN R&D:

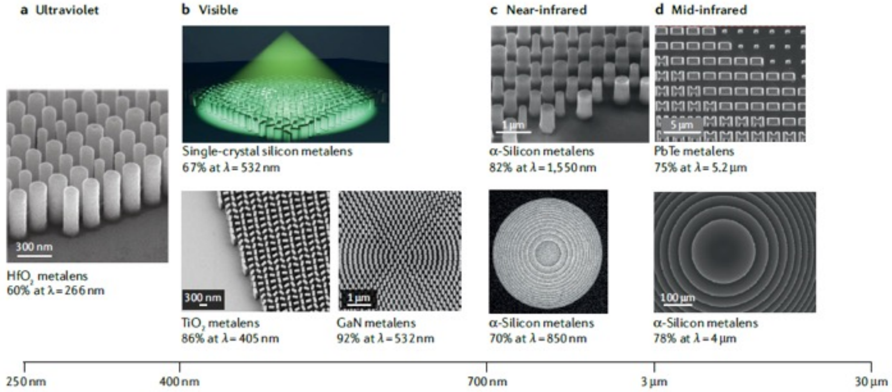
- Identifying optimal WLS-reflector (joint cross-collaboration effort of AstroCeNT, CERN, Edinburgh, NIKHEF, TUM and Uni Zurich researchers)
- PEN optimization specifically for high WLS yield in LAr (custom synthesis, production and storage/handling)

Other WLS (promising, but ...)
Instruments 5, 4 (2021)

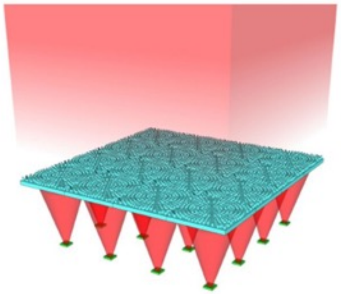
- Perovskite quantum nanodots (emission peak >500 nm), nanostructured organosilicon luminophores (expensive), inorganic nanoparticles (τ>O(10ns))
  - Likely solvable with more work
  - Long term cryogenic/mechanical stability to be demonstrated
- Xe doping (concerns about stability/uniformity of the mixture)

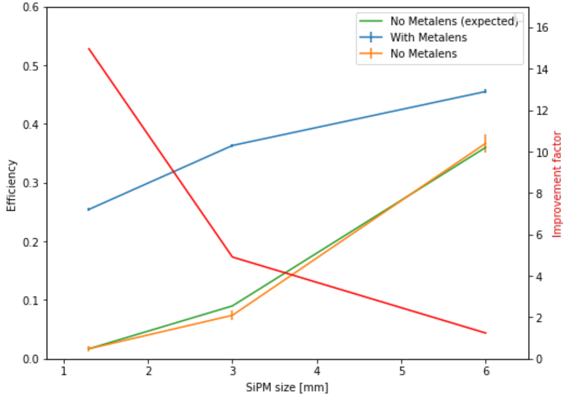
Metalenses as light concentrators

- Metalenses: flat optics achieved through controlling the wave front of light (amplitude and phase) by way of subwavelength-spaced nanostructures
- R&D at FNAL, Harvard and Manchester to use them as light concentrators instead of imagine devices
- Estimated increase in light collection of up to a factor of 15 if used in combination with small area (1.3 mm x 1.3 mm) SiPMs [AA.Loya Villalpando et al. arXiv: 2007.06678]
- Many challenges:
  - Cryogenic environment
  - VUV part of the spectrum



Chen, Zhu, Capasso: Nature Reviews Materials 5, 604–620(2020)





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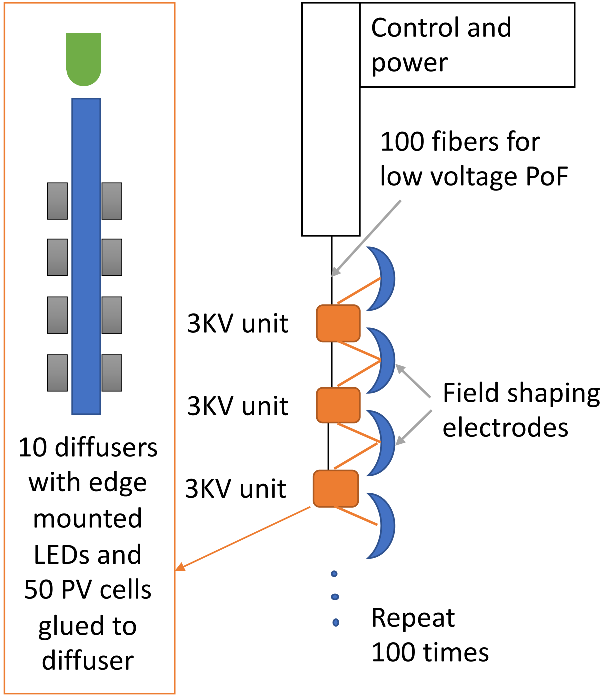
HV over fiber

Courtesy of P. Rubinov (FNAL)

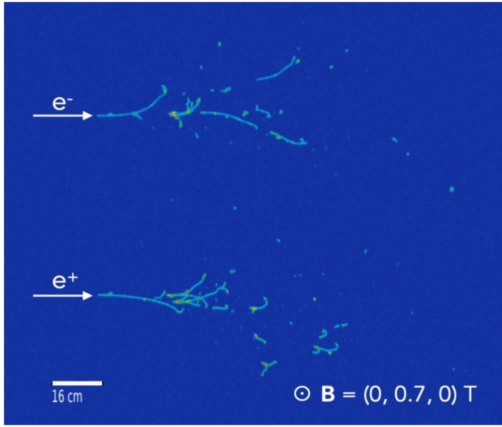
- Pitfalls of conventional high voltage for large LAr-TPCs (300 kV):
  - resistive divider for the field cage requires currents a hundred times larger than necessary
  - feedthroughs and power supplies can be problematic
  - a short at the feedthrough would be fatal to the experiment.
- Idea: use solar cells in series to generate HV
  - light diffuser (ex. frosted glass developed for LCD screens)
  - LEDs (ex. green) mounted along one edge
  - small solar cells glued to the diffuser (single junction of vertical multi junction), connected in series to build voltage equivalent to voltage between field shaping electrodes (need approximately 500 single junction cells)
- Benefits: safe (no paths to ground) and noiseless
- Need to study lifetime in cold and develop voltage control

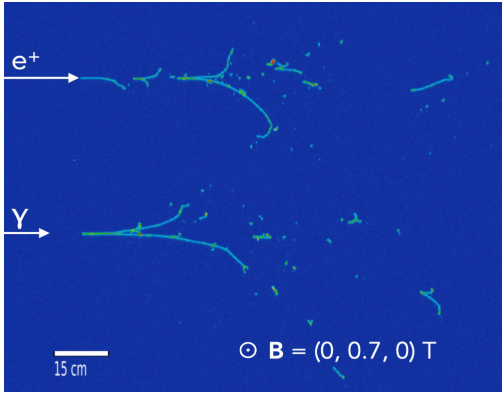


Magnetized LAr-TPC detectors

Courtesy of M. Del Tutto (FNAL)

- LArTPC detectors would greatly benefit from a **magnetic field** to unambiguously discriminate particle charges.
- **Current R&D efforts** exist to
  - (i) study LArTPCs inside a magnetic field (ArCS, next slide)
  - (ii) develop superconducting materials to build in-cryostat coils for large-scale detector magnetization.
- **Final goal**: enable magnetization of large-scale LArTPCs, like SBND, DUNE's fourth module, and future LArTPCs.
- **Magnetic field allows to measure**:
  - particle's charge sign (enabling electron/positron discrimination and increasing electron/photon separation)
  - momentum of particles via curvature (especially important for muons and pions exiting the detector, for which we cannot rely on calorimetry)
- **Some physics applications**:
  - Charge ID of final state lepton allows:
    - measuring neutrino and anti-neutrino cross sections separately
    - rejecting background of wrong sign neutrinos
    - increased DUNE CP violation sensitivity with atmospheric neutrinos
  - Improved electron/photon separation allows further rejecting background for events with π^0 and Δ.
  - Curvature of particles in the magnetic field allows:
    - increasing sensitivity to BSM physics signals with two collinear leptons of opposite sign in the final state
    - increasing momentum resolution for muons and pions exiting the detector, for which we cannot rely on calorimetry



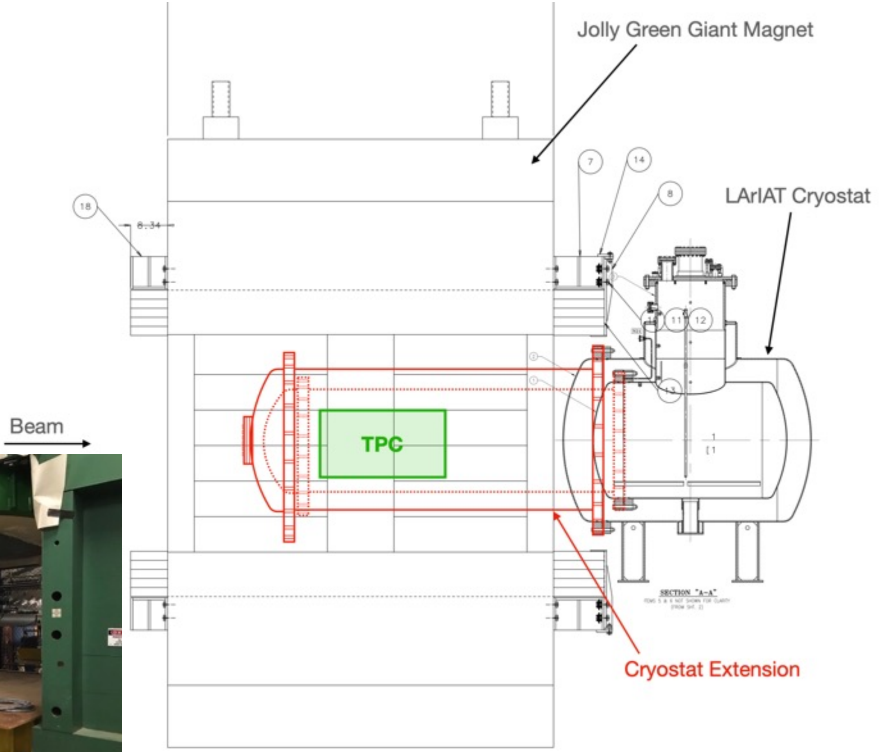


ArCS: Argon detector with Charge Separation

Courtesy of M. Del Tutto (FNAL)

- Fermilab LDRD project whose goal is to run a LArTPC inside a ~ 0.7T magnetic field to:
  - establish minimum required magnetic filed for electron-photon separation of O(100)MeV
  - demonstrate electron/photon separation
  - measure electron diffusion in the presence of a magnetic field

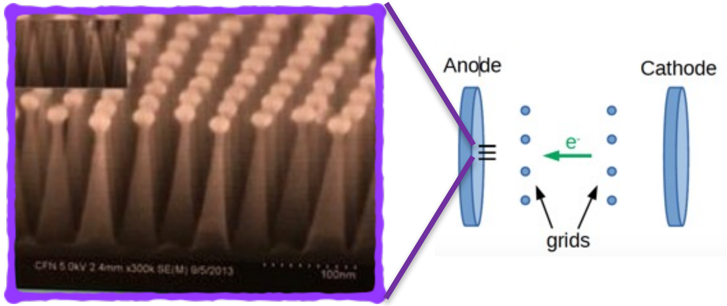
- ArCS will reuse the LArIAT TPC, placing it inside the Jolly Green Giant magnet at the Fermilab's Test Beam Facility.

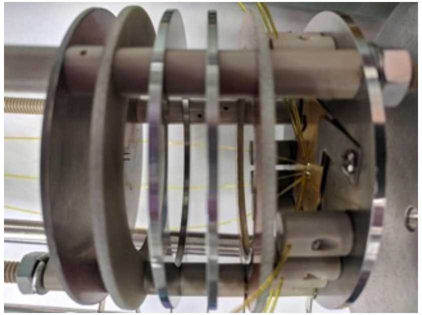


Electron multiplication in liquid argon

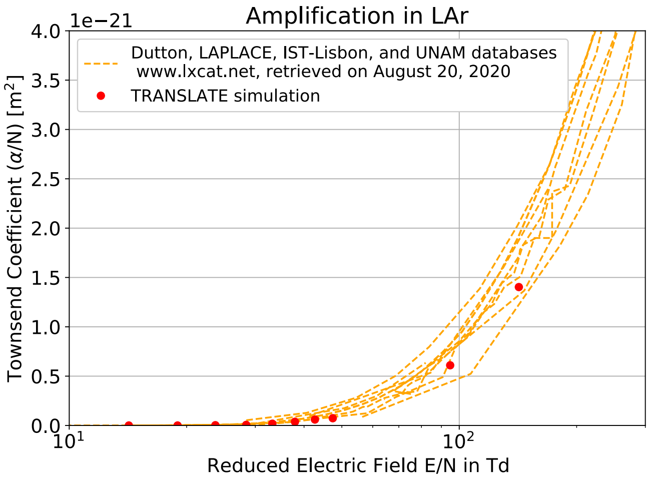
- Current limits of charge detection in single phase LAr-TPC ~ 1 MeV [Phys. Rev. D 99 (2019) 012002]
  Perspective to lower the threshold < 100 keV intriguing for Dark Matter and CEvNS applications

- R&D at Fermilab and CERN to investigate if multiplication of ionization charge in liquid argon TPC detectors is feasible directly in the liquid phase.
  - small tips installed on the anode of a purity monitor for locally intensifying the electric field enough to possibly trigger the multiplication of drifting electrons.





- Microphysics simulation of propagation of drift electrons suggests secondary ionization is achievable for local electric field O(10^6 V/cm)



The 50th Anniversary NEUTRINO 2022 Virtual Seoul May 30 (Mon) - June 4 (Sat), 2022
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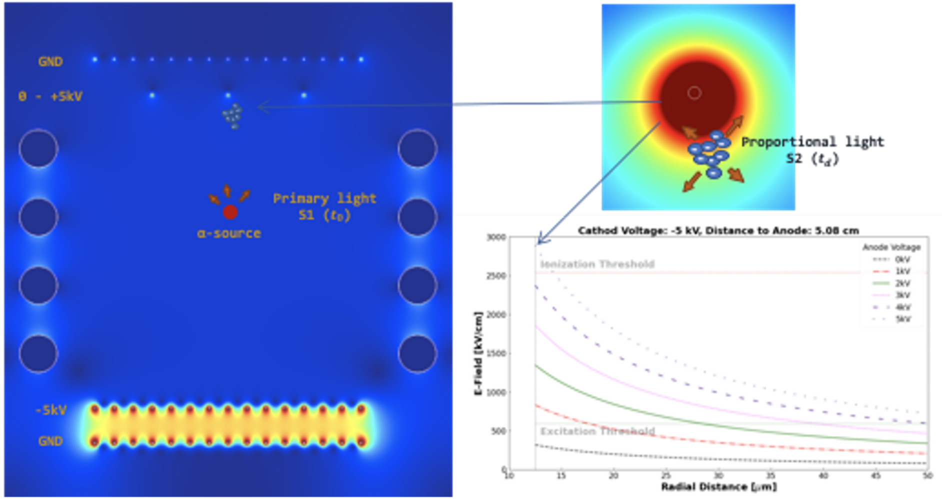
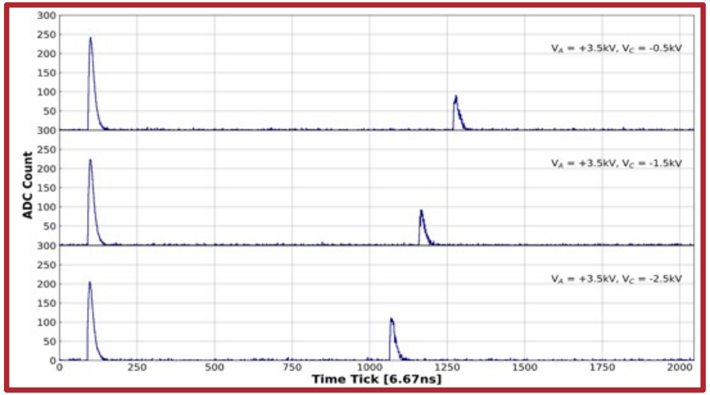
Proportional scintillation light in LAr

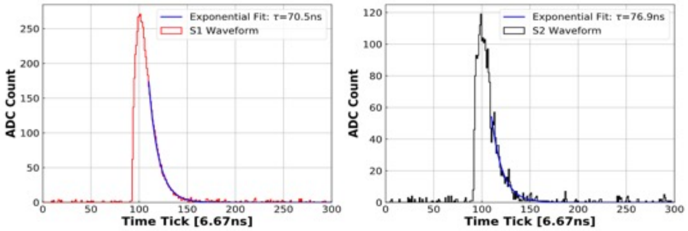
Courtesy of W. Mu (FNAL)

- Ongoing R&D at Fermilab to detect proportional secondary scintillation that could occur in similar ranges of local electric field.
- Proportional scintillation ~30 photons/electron observed at 1.8 MV/cm. Avalanches detected > 2 MV/cm.
- Possible improvement with Xe doping (quenching).

Anode kV	Cathode kV	Max Field kV/cm	Drift Field kV/cm	Drift Velocity cm/μs	Drift Time μs
2.0	0.0	1028.4	0.4	0.11	10.6
3.0	0.0	1542.6	0.6	0.14	8.6
3.5	0.5	1831.5	0.8	0.16	7.6
3.5	1.5	1895.2	1.0	0.18	6.9
3.5	2.5	1958.9	1.2	0.19	6.4



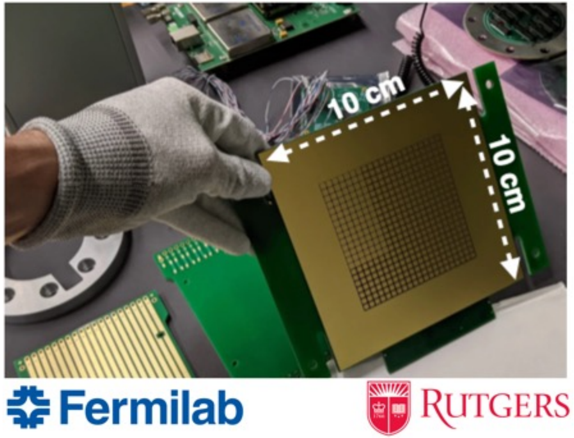




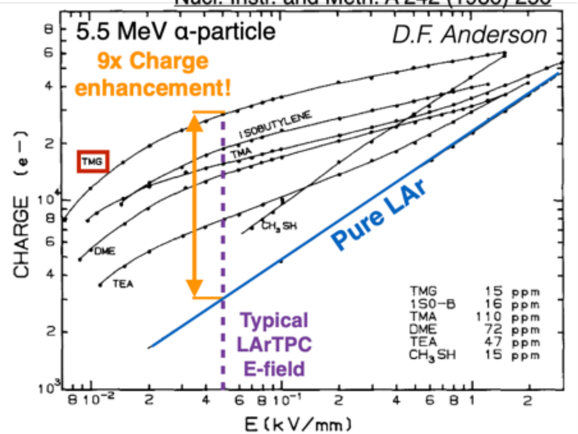
Photosensitive dopants

Courtesy of A. Mastbaum (Rutgers University), F. Psihas, J. Zennamo (FNAL)

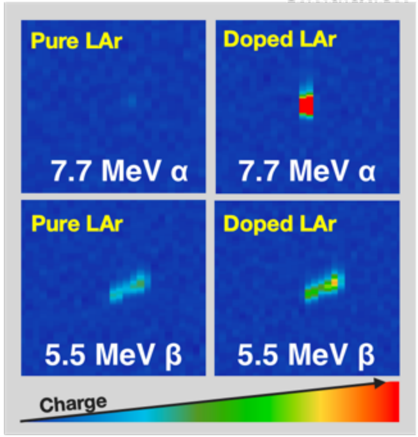
- Photosensitive dopants could convert scintillation light into charge.
  - Past R&D: +30% muon charge signals, increased detector linearity, and 250+ days of stable running demonstrated on ICARUS in a 3-ton prototype. Nucl. Instrum. Methods. Phys. Res. B 355, 660 (1995)
- More linearity, lower threshold, better energy resolution: 1% at 2 MeV (simulation), could enable searches for 0νββ [A. Mastbaum, F. Psihas, J. Zennamo arXiv:2203.14700 Submitted to PRD]
- Ongoing R&D to measure energy resolution of pixelated LArTPC exposed to radioactive sources in different doping scenarios



Nucl. Instr. and Meth. A 242 (1986) 256



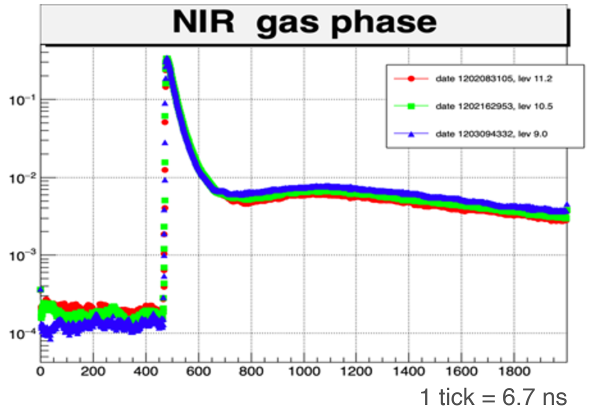
Simulation

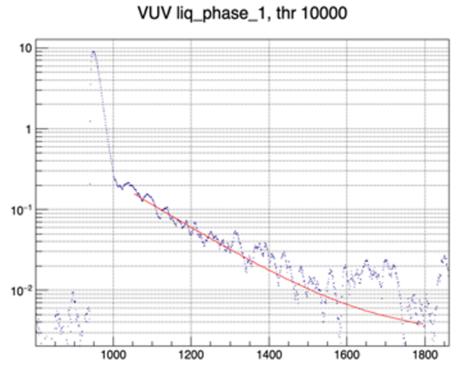


Near Infrared in liquid argon

Courtesy of C. Escobar, A. Para and P. Rubinov (FNAL)

- Possibility of emission on scintillation light in the near infrared (NIR) region of the spectrum interesting in addition or as an alternative to the VUV light. Main spectral feature 1.27 eV.
- Experimental setup at Fermilab.
  - 1 NIR and 1 VUV SiPM (no WLS) “looking” into an ^{241}Am source.
  - Data taking both in gas and in liquid with different contents of N_2 contamination.
- Puzzling slow component in the gas phase seen by the NIR SiPM at 3 μs and two slow components at τ ~ 300 ns and τ ~ 1170 ns seen by the VUV.
- Need NIR detector that could reach beyond 900 nm. Candidate detectors: InGaAs SPADs from Princeton Light Waves in the US and MPD in Italy.

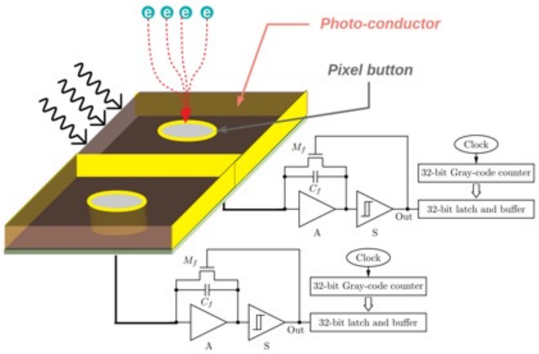


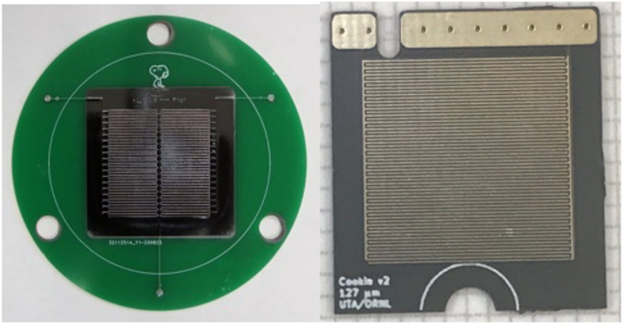


Courtesy of J. Asaadi (UTA)

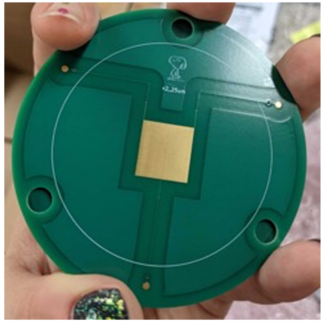
Combined light&charge readout with pixel detectors

- Integrated charge and light (L) sensor capable of directly sensing VUV photons with the same device would be a major breakthrough: effective instrumented area becomes enormous!
- Thin films of amorphous semiconductors and dopant cocktails. R&D underway at UTA, ORNL, UCSC and FNAL to find compatible photoconductor.
- Synergy with Q-Pix as enabling technology.

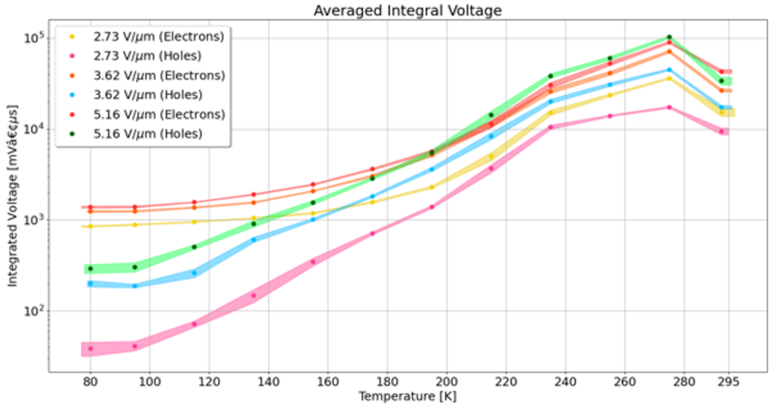




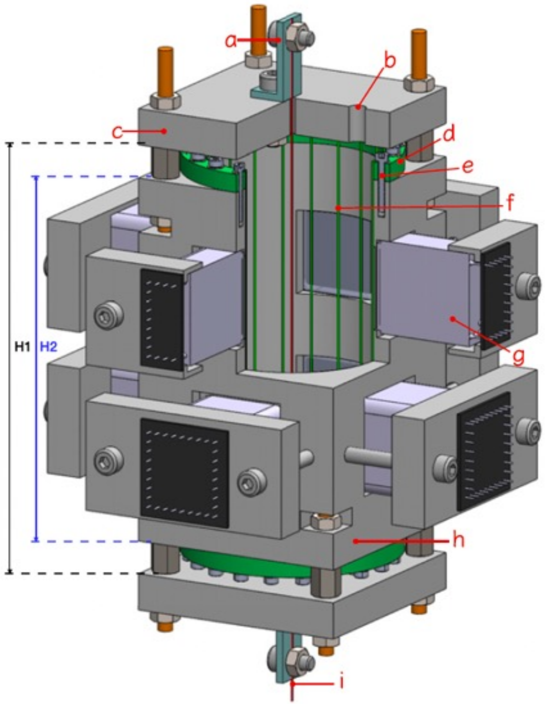
Commercial PCB 127 μm (right: cold electronics). Max field 5 V/μm



Custom PCB 25 μm
Target field 40 V/μm



Novel detector designs



- Radial geometry for the TPC explored with liquid xenon, with the intent of creating and detecting electroluminescence [Y. Wei et al., JINST 17 C02002 (2022)].
  - advantage: simplifies design and operation with single wire in the axial center
  - showstoppers: non-uniform electric field deteriorates the energy and position resolution, and amplification factor limited by light emissions increasing with the electric field and preventing the detection of single photoelectrons from physical activity.

- Dual readout TPCs, i.e. collecting charge from both the negatively charged carrier (electrons or ions) at the anode and the positive ions at the cathode.
  - pixelated anode plane would allow a “coarse” (mm to cm) event reconstruction to be mapped onto a small cathode region of interest where the local tracking in the tens of micron region is performed.
  - use of positive ions (which remain thermal during their drift) greatly reduces diffusion

Thank you!