

# Advancements in Photon Detection for DUNE Phase II: Enhancing Neutrino Physics Through Optimized Vertical Drift with APEX Systems

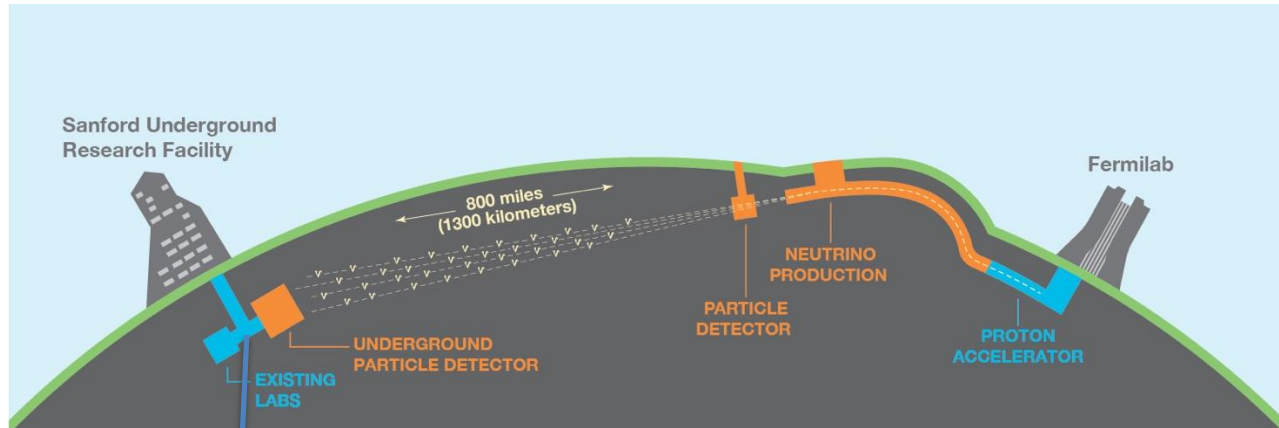
Ajib Paudel (Fermilab)

On behalf of the DUNE collaboration

CPAD Workshop 2024 (Nov 18-22) University of Tennessee, Knoxville

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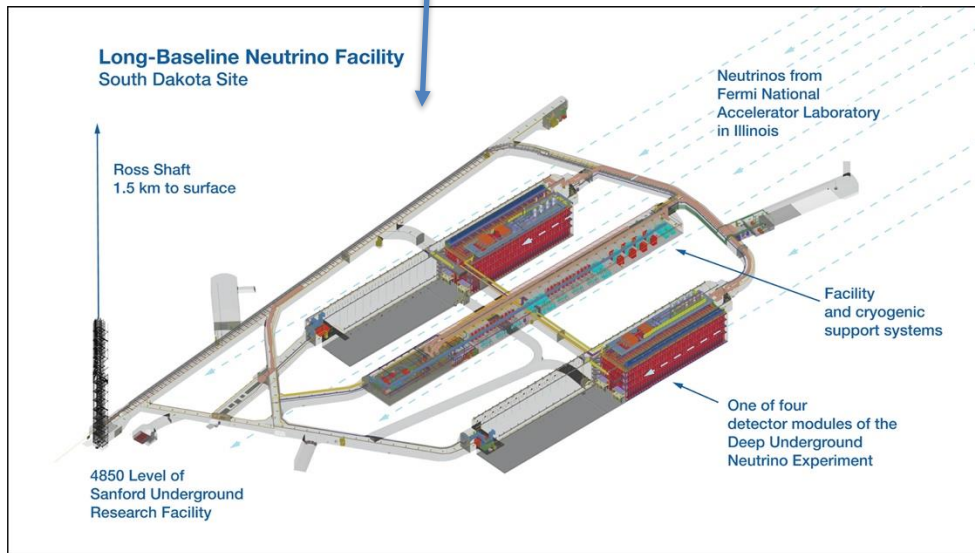
# Deep Underground Neutrino Experiment (DUNE)



**Physics goals:** neutrino oscillations, CP violation, proton decay, supernova neutrinos.

DUNE far detectors:

- (2 + 2) 17kt modules
- 1300 km away
- 1.5 km underground
- Designs for the 1<sup>st</sup> and 2<sup>nd</sup> far detector modules finalized
- 3<sup>rd</sup> and 4<sup>th</sup> modules to be built in Phase II (P5 recommendation), proposals and R&D ongoing



Planery talk by Sowjanya Gollapinni (Nov 21, 4:25 pm): DUNE Phase-II Detector R&D Status and Planning

# LArTPC operational principle (vertical drift design)

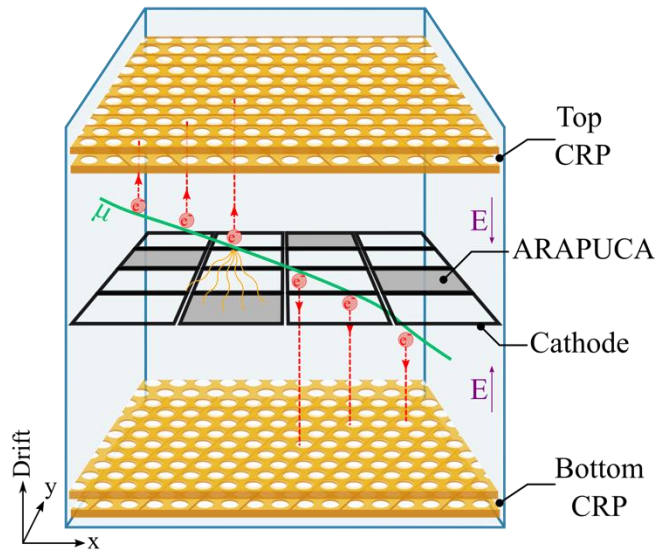


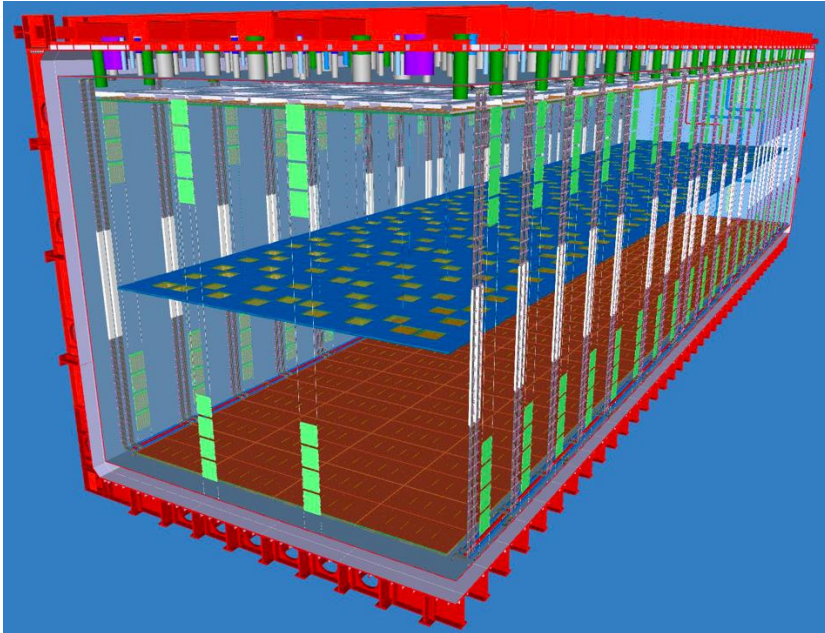
Fig: LArTPC operational principle  
Vertical drift

Uniform electric field:

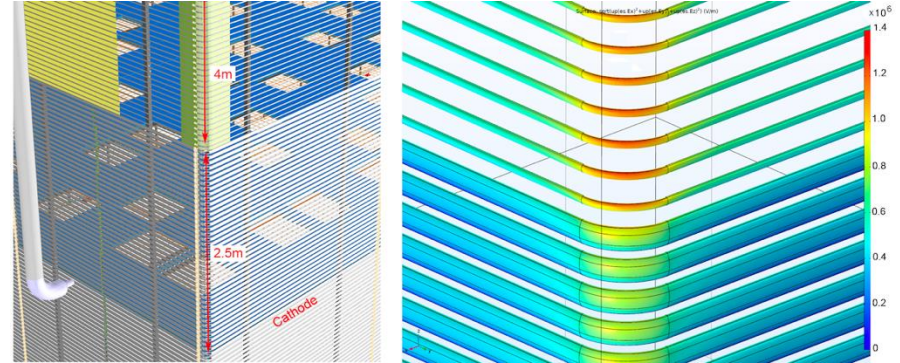
- The cathode operates at a high voltage of 300 kV.
- A uniform electric field is established between the cathode and the anode (CRP) using a field cage arrangement.
- The field cage consists of aluminum profile electrodes aligned from cathode to anode delimiting the liquid argon active volume of the TPC.

Major components: high-voltage cathode surface, PCB-based charge readout plane (anode), field cage, and X-ARAPUCA technology PDS on the cathode and behind the field cage.

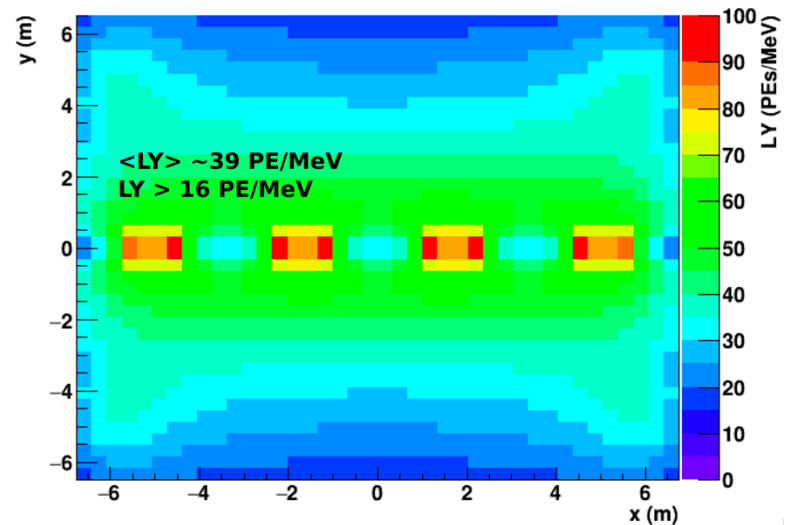
# DUNE vertical drift design (DUNE Phase I)



Active volume dimensions:  $60 \times 12 \times 13 \text{ m}^3$



Field Cage design

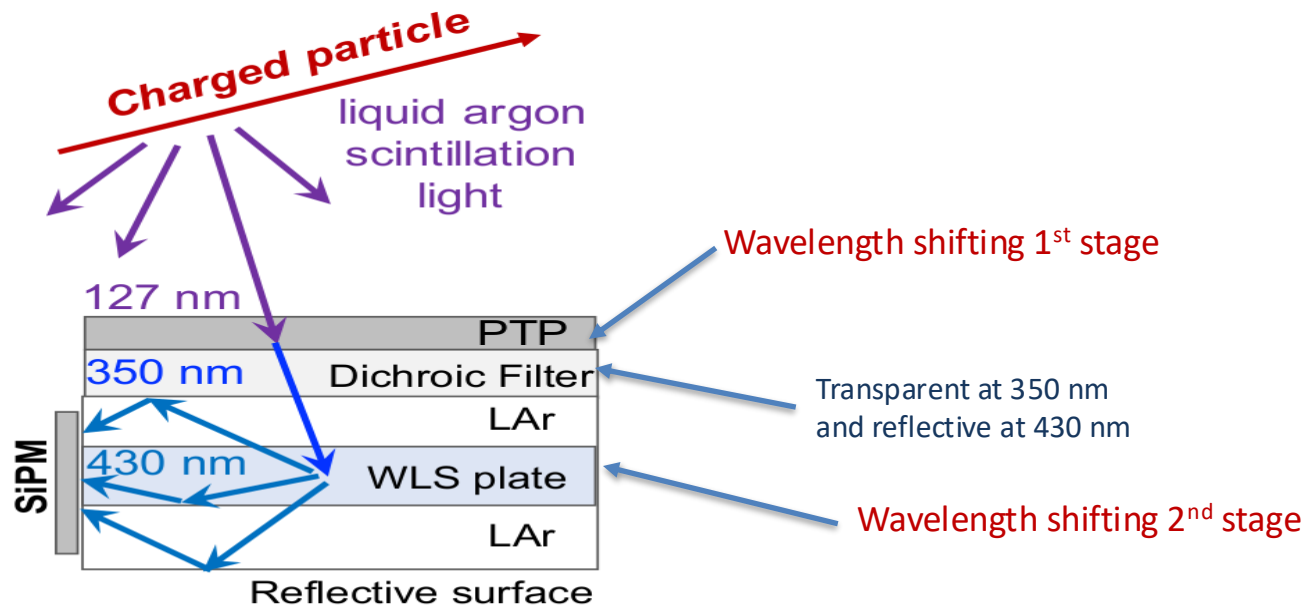


Light Yield map

A. Abed Abud et al JINST 19 T08004 (2024)

# DUNE Photon Detection System Technology

DUNE FD1 and FD2 will be using light trap technology (X-ARAPUCA) for the photon detection system:



*Not to scale.*

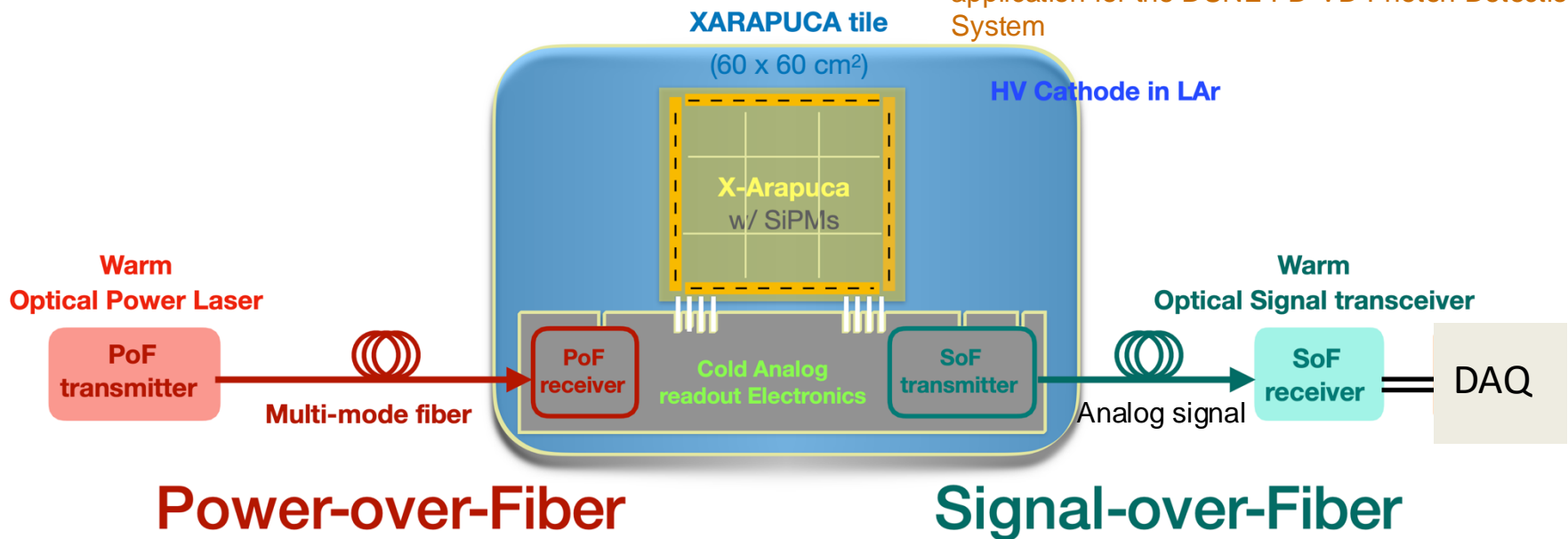
- The PDS is essential for providing the event time ( $t_0$ ) for non-beam events
- PDS can also provide trigger for non-beam events
- New advancements in Photon detection system technology and detector coverage, makes PDS capable of providing deposited energy reconstruction through scintillation light collection. Especially useful at low energy ( $>5$  MeV) where capability of TPC becomes limited.

# Innovative technologies for power reception and signal transmission

PDS on HV surface brings up challenges; solutions are PoF and SoF:  
→ provides voltage isolation in both power reception and signal transmission.

→ While PoF and SoF are well-established technologies, their extensive use in cryogenic detectors is novel.

Talk by Jairo Rondon (RDC 02, Nov 20): R&D of Power Over Fiber in harsh environments and its novel application for the DUNE FD-VD Photon Detection System

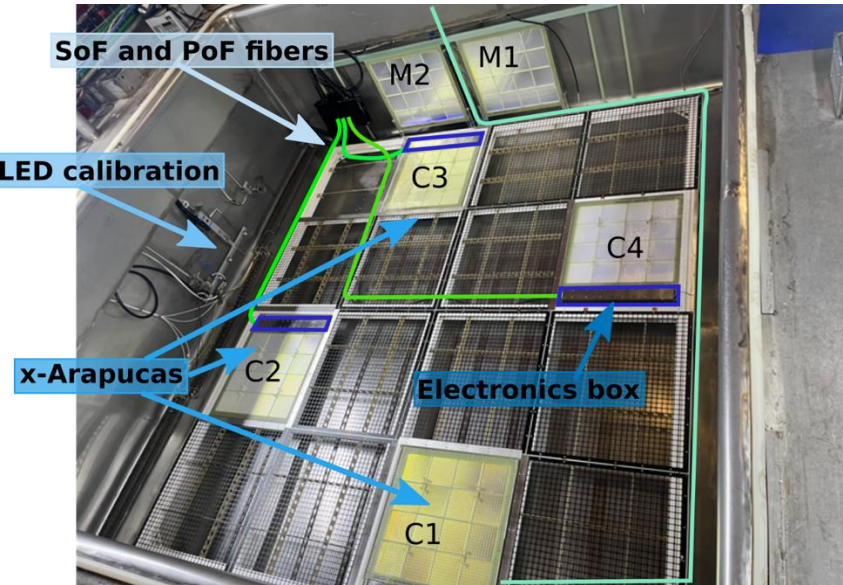


**Power-over-Fiber**

**Signal-over-Fiber**

Working principle of PoF and SoF solution

# Prototyping and testing of DUNE VD PDS system



Full scale prototype of DUNE-VD PDS system tested at the CERN Neutrino Platform.

Active volume: 0.21 m (drift) X 3 m X 3 m

A larger sized Prototype (ProtoDUNE-VD) ready to be operated in early 2025.

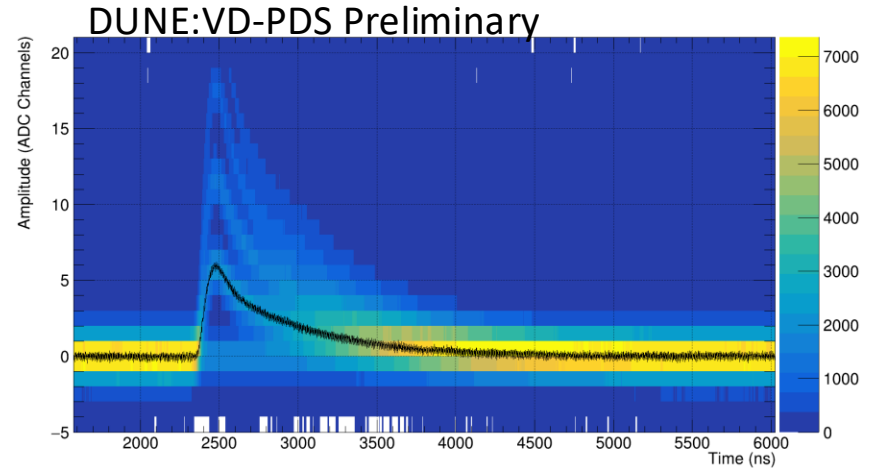


Fig: Signals recorded from an LED calibration run

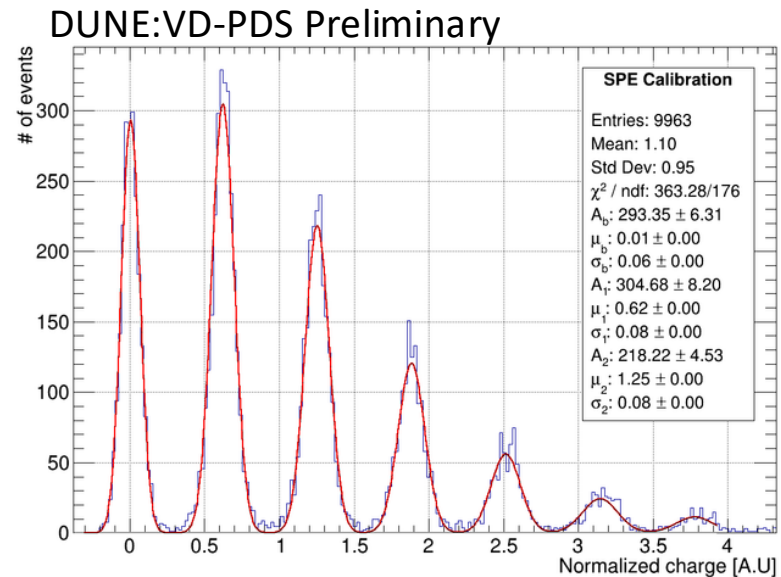
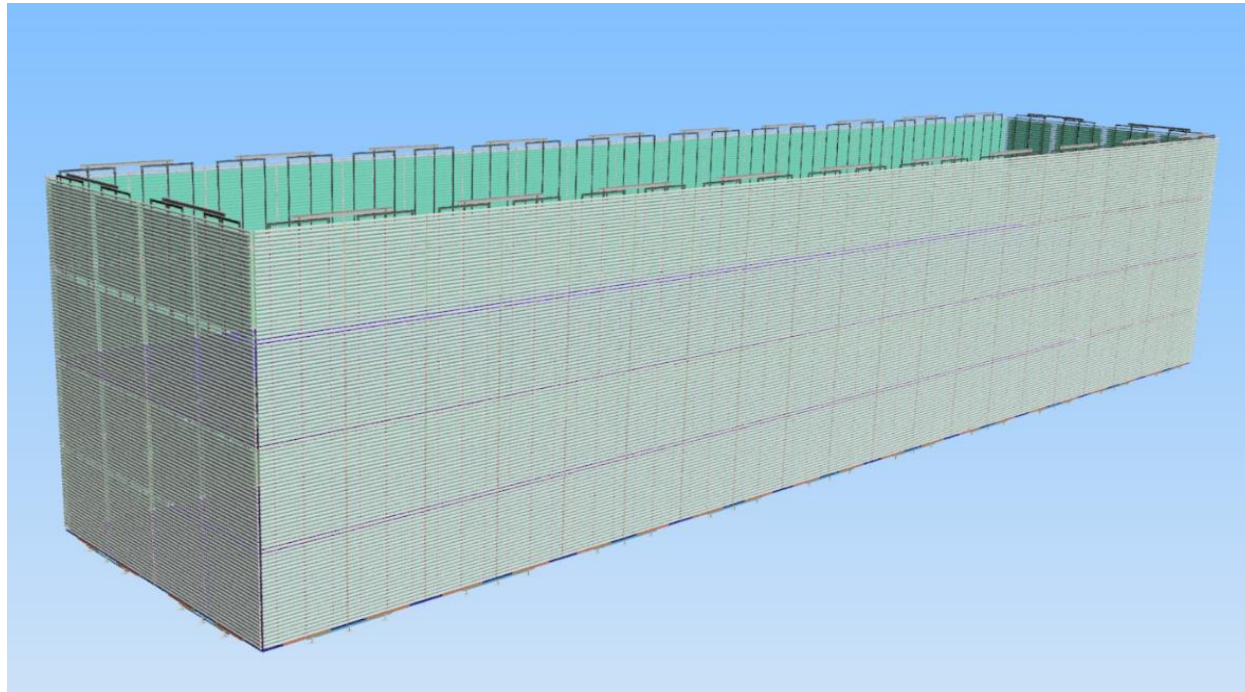


Fig: integral of LED calibration signals

# APEX: A proposal for DUNE Phase II Far Detectors Photon Detection System



Ref: <https://doi.org/10.48550/arXiv.2408.12725>

# APEX technology

**Mature Technology:** The innovative Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) technology for operating the Photon Detection System (PDS) on the High Voltage (HV) surface has been developed through extensive R&D for DUNE Vertical Drift (VD).

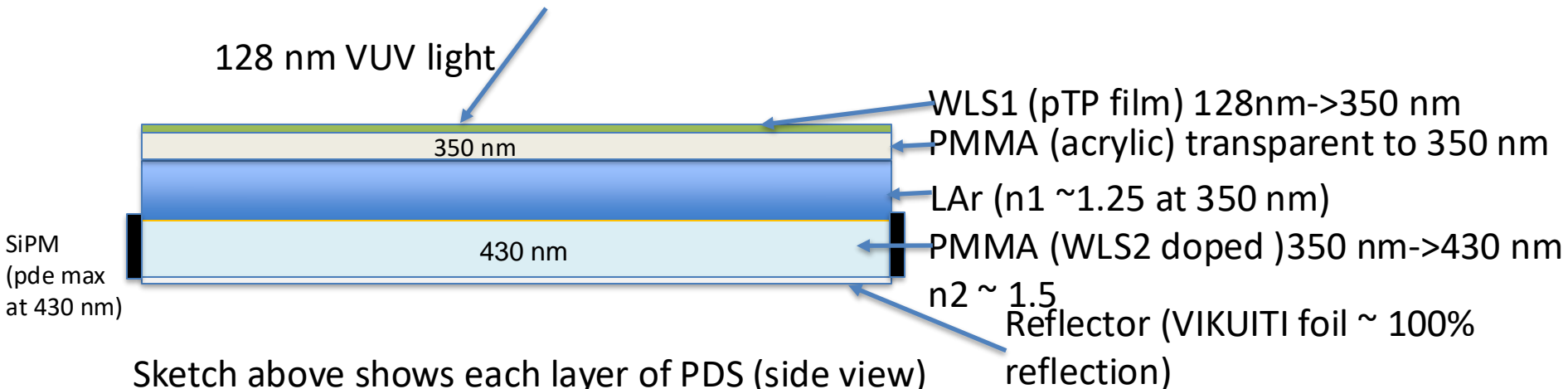
**APEX Proposal:** Utilizing advanced PoF and SoF technology, the APEX proposal places the PDS on to the HV field cage surface.

**Comprehensive Coverage:** Up to 100% coverage can be achieved on all four sides of the detector for scintillation light readout, excluding the top and bottom anode surfaces (CRP, for charge readout). Overall light detector coverage of up to 60% can be achieved.

**Higher Light Yield and uniformity:** Improved detector coverage enhances light yield and uniformity, enabling lower detection thresholds and higher resolution in calorimetric energy reconstruction.

# APEX Photon Detection System:

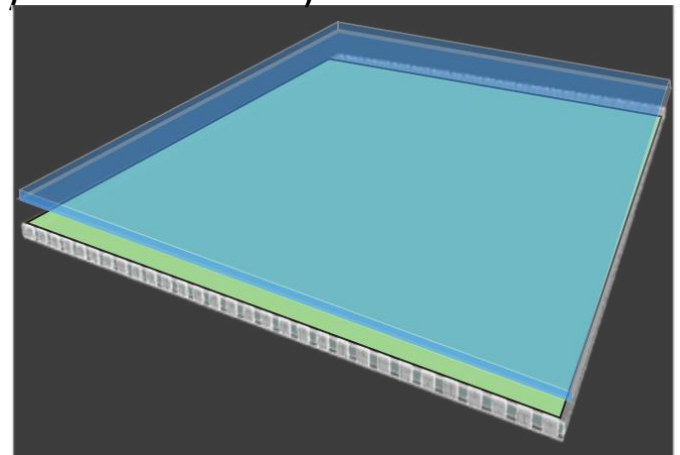
Proposed PDS is a maximally simplified application of the light trap concept of FD1 and FD2.



Sketch above shows each layer of PDS (side view)

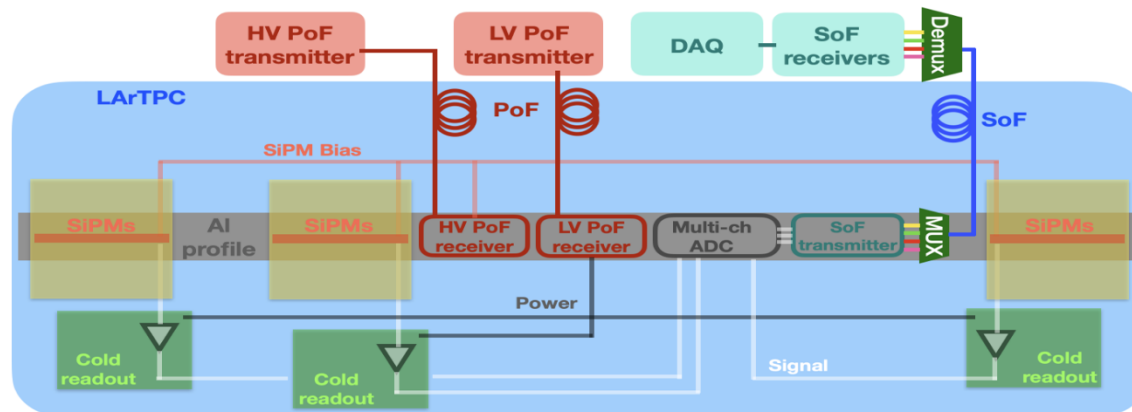
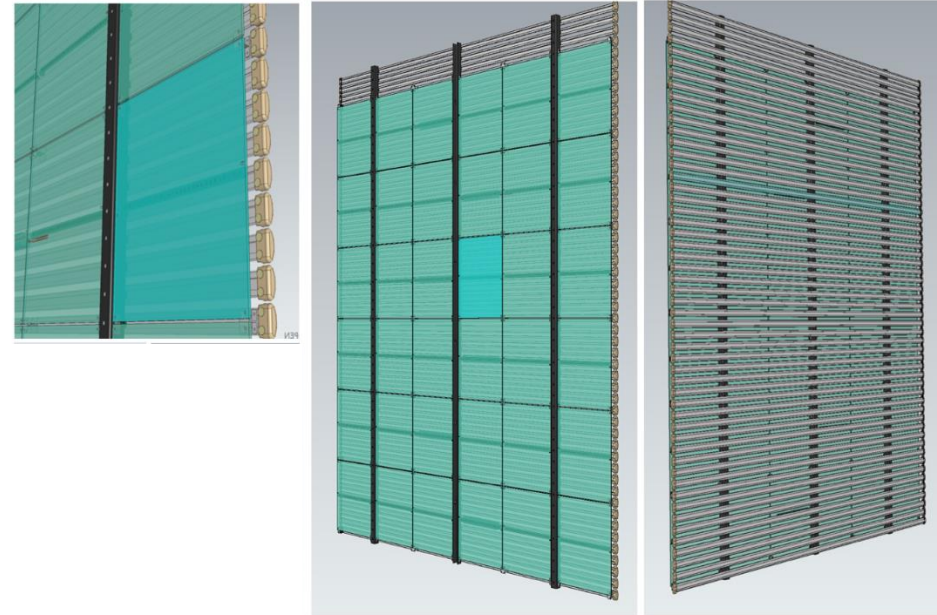
The size of each PDS module is 50 cm X 50 cm

Note: Total internal reflection mechanism is applied for light trapping.



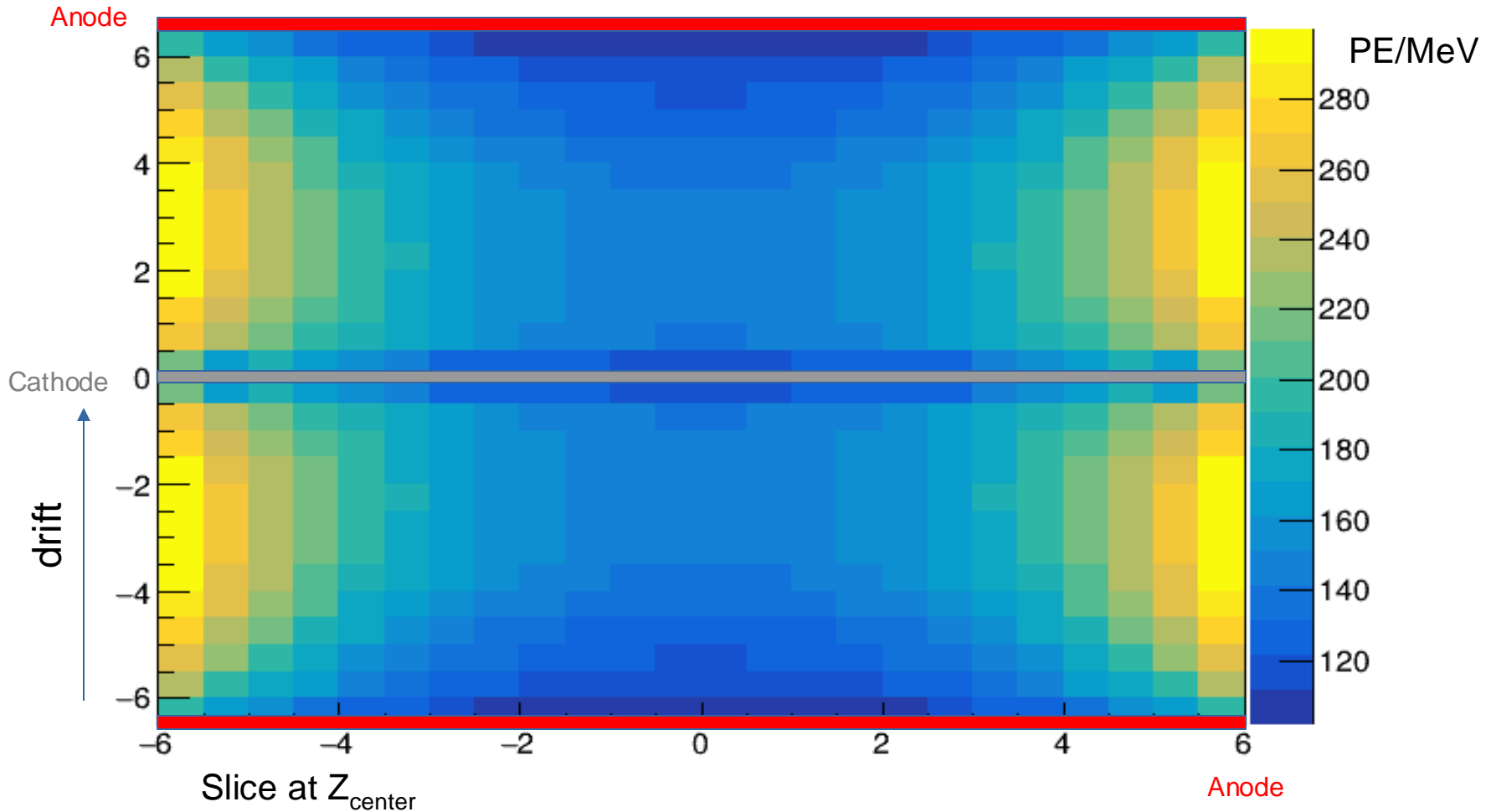
# APEX

- Each row of 6 PD modules in an APEX panel is a electrically isolated system
- 1 PD module/9 profiles
  - 5<sup>th</sup> profile: mechanical fastening and electrical reference
    - C-shaped profile: Faraday cage shielding for CE readout boards for the 6 module on horizontal row
  - PoF transmitter and SoF receivers (driver and laser diode) to the PDs via fibers
  - Digital signals are sent via SoF as opposed to analog signal in DUNE VD



arXiv:2312.03130

# APEX: Light Yield map



100% optical coverage on the 4 sides of the detector assumed

$LY_{\text{average}} \geq 180 \text{ PE/MeV}$   
 $LY_{\text{minimum}} \geq 109 \text{ PE/MeV}$

Compared to DUNE VD,  
LY average and minimum  
scales  $\sim 5$  and  $\sim 7$  times.

arXiv:2312.03130

# Prototyping APEX:

First round @CERN 2023:

→ Impact on drift field uniformity due to insulating material between FC electrodes.

Ton-scale TPC prototype @CERN (2024/25):

→ Up to eight full-size PD modules, for mechanical and cryogenic tests.

→ PD module with electronic chain: constructed and fully tested before integration.

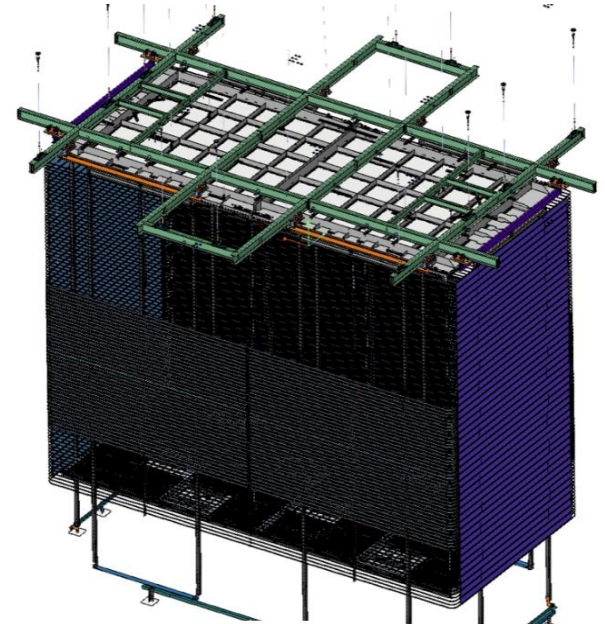
A larger-sized demonstrator with ~100 P(S)oF in/out fibers (@Fermilab)

Full-sized APEX PD-instrumented field cage to be deployed in VD ProtoDUNE cryostat (@CERN 2025/26)

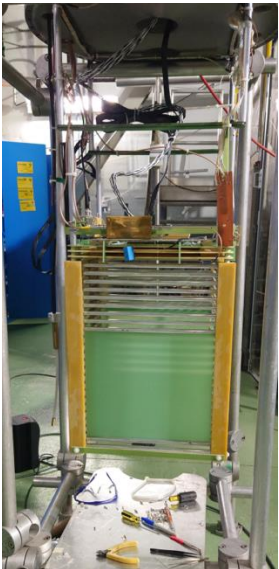
TON Scale prototype CERN 2024-2025



Kiloton-scale prototype at CERN (2026-2027)



CERN 50L TPC 2023



# Summary

- LArTPC photon detectors for DUNE have been rapidly evolving, enhancing the light yield and uniformity.
- Leveraging on the now well-established technologies of PoF and SoF in FD2, APEX proposal has been put forward for the DUNE Phase II FD3/4 photon detectors.
- APEX PDS system provides a detector coverage of around 60%. The average and minimum light yield is scaled 5 and 7 times respectively, compared to DUNE VD enabling higher energy resolution and lower detection threshold.