VD Technology and APEX Design for DUNE FD3

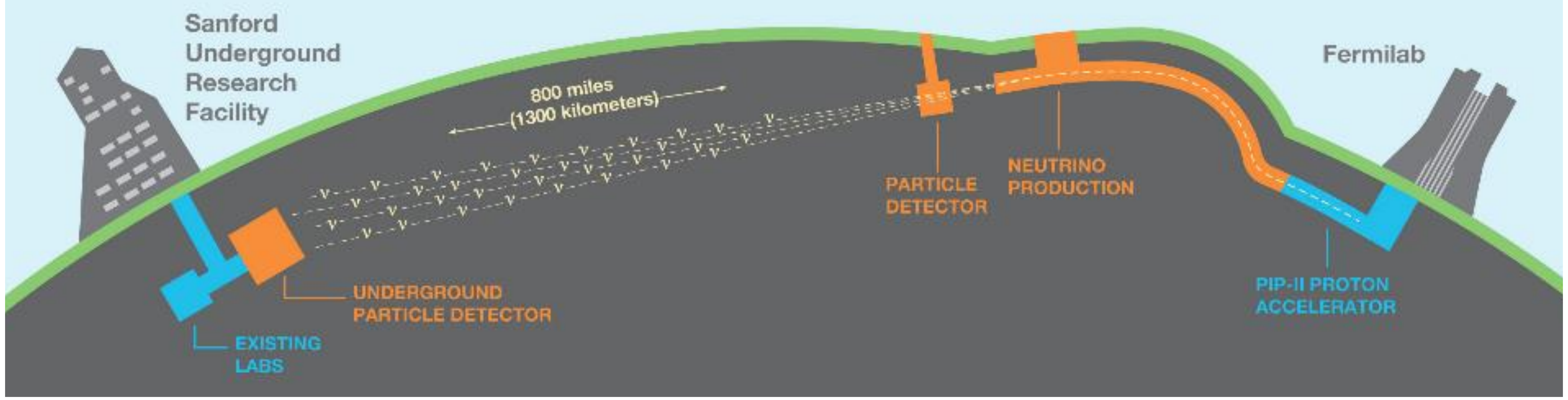
CoSSURF 2024
May 14
South Dakota Mines, Rapid City

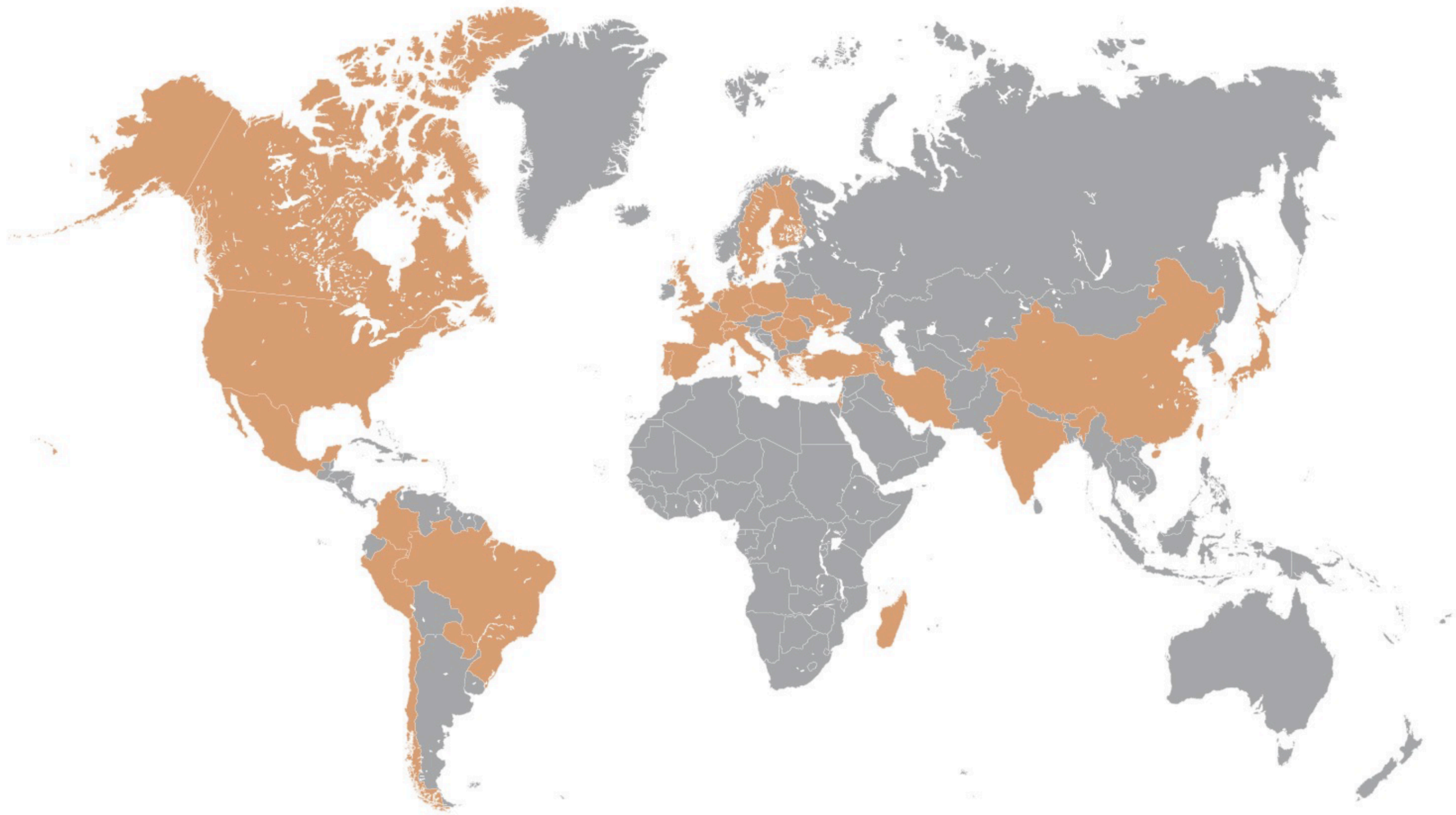
Wei Shi
on behalf of the APEX working group

Stony Brook University

DUNE Collaboration

1,450 collaborators
215 institutes, including CERN
35 countries

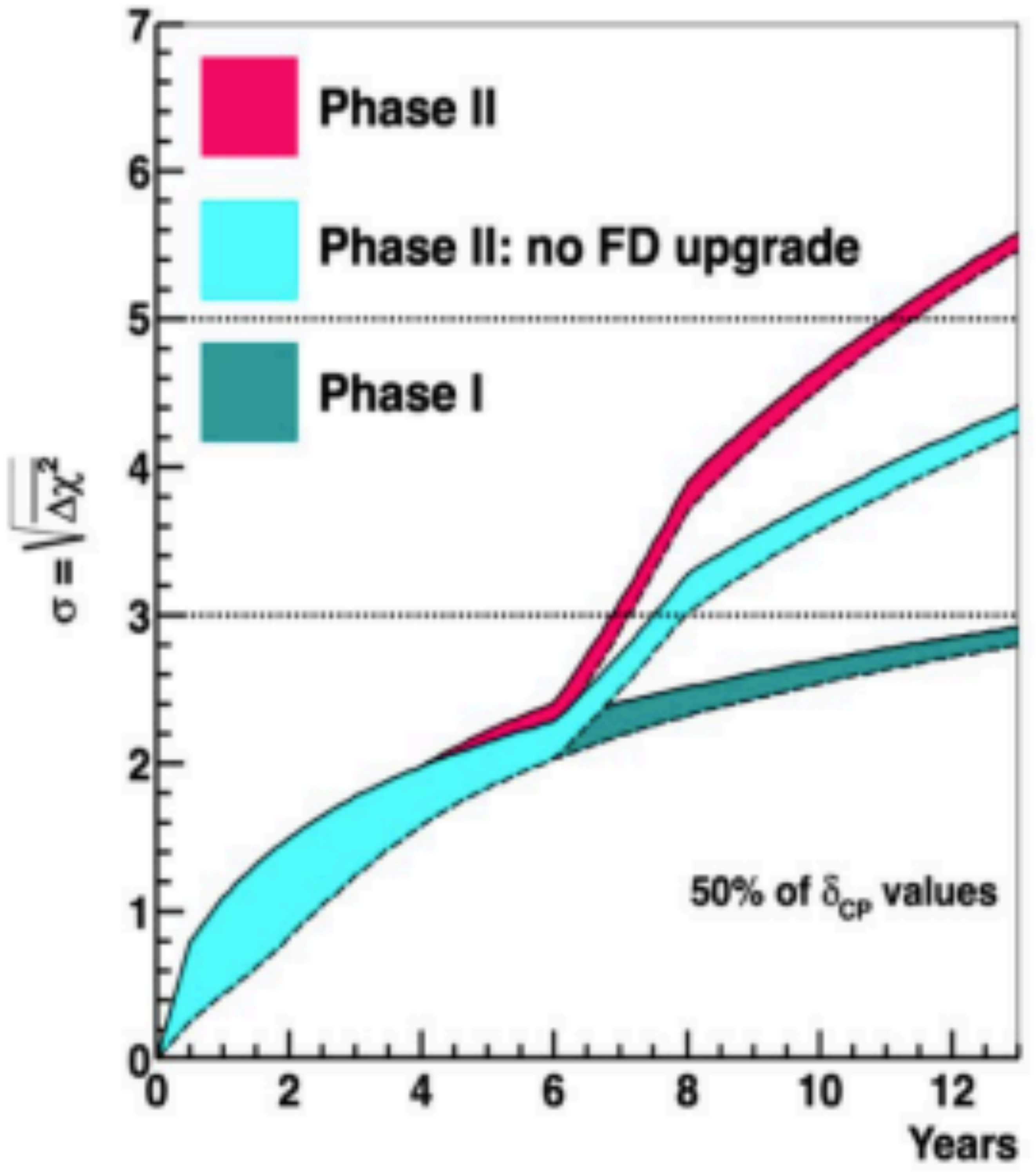




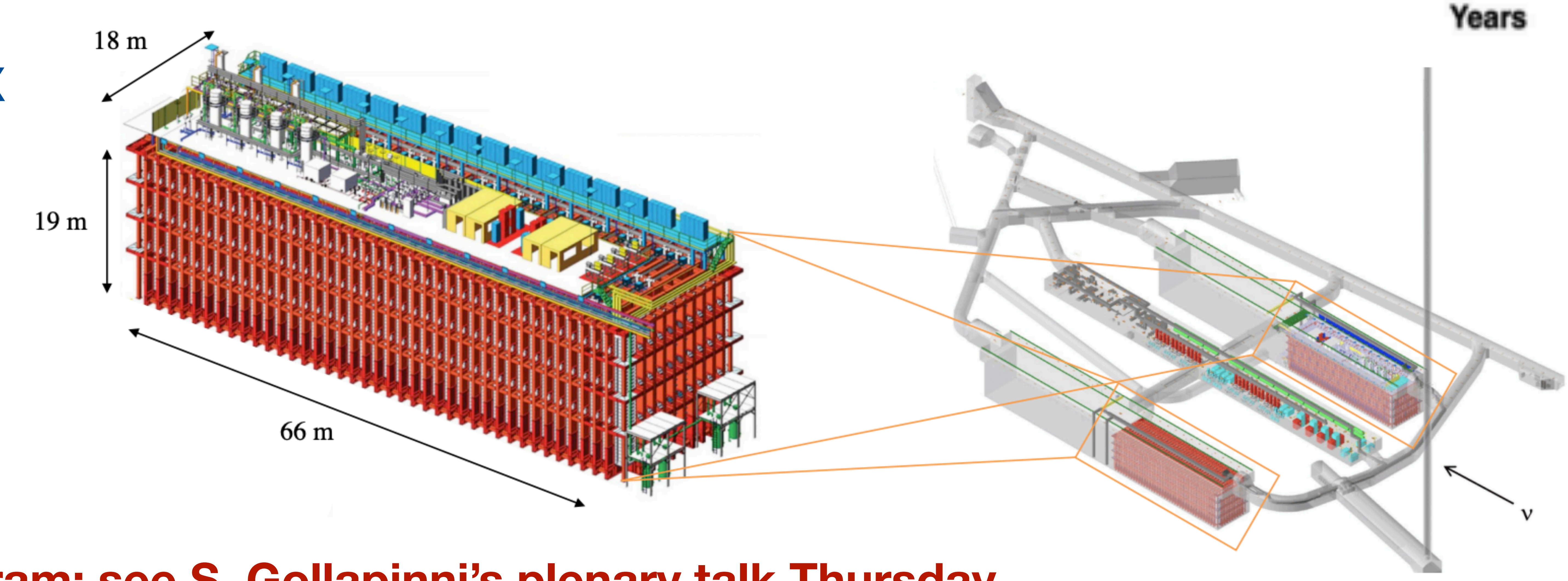
DUNE Phase II and FD3

Phase I (day 1)
- FD (approved): two 17 kt (total) LAr TPCs - FD1 (Horizontal Drift), FD2 (Vertical Drift)
- ND (baseline TBC and approve by 2025): NDLAr with TMS; DUNE-PRISM; SAND on-axis

Phase II - open to new (non-DUNE) collaborators!
- **Two additional 17 kt FD modules: FD3 and FD4**
- More Capable Near Detector (MCND) including ND-GAr
- > 2MW beam
- All necessary to complete the core CPV program of DUNE and more



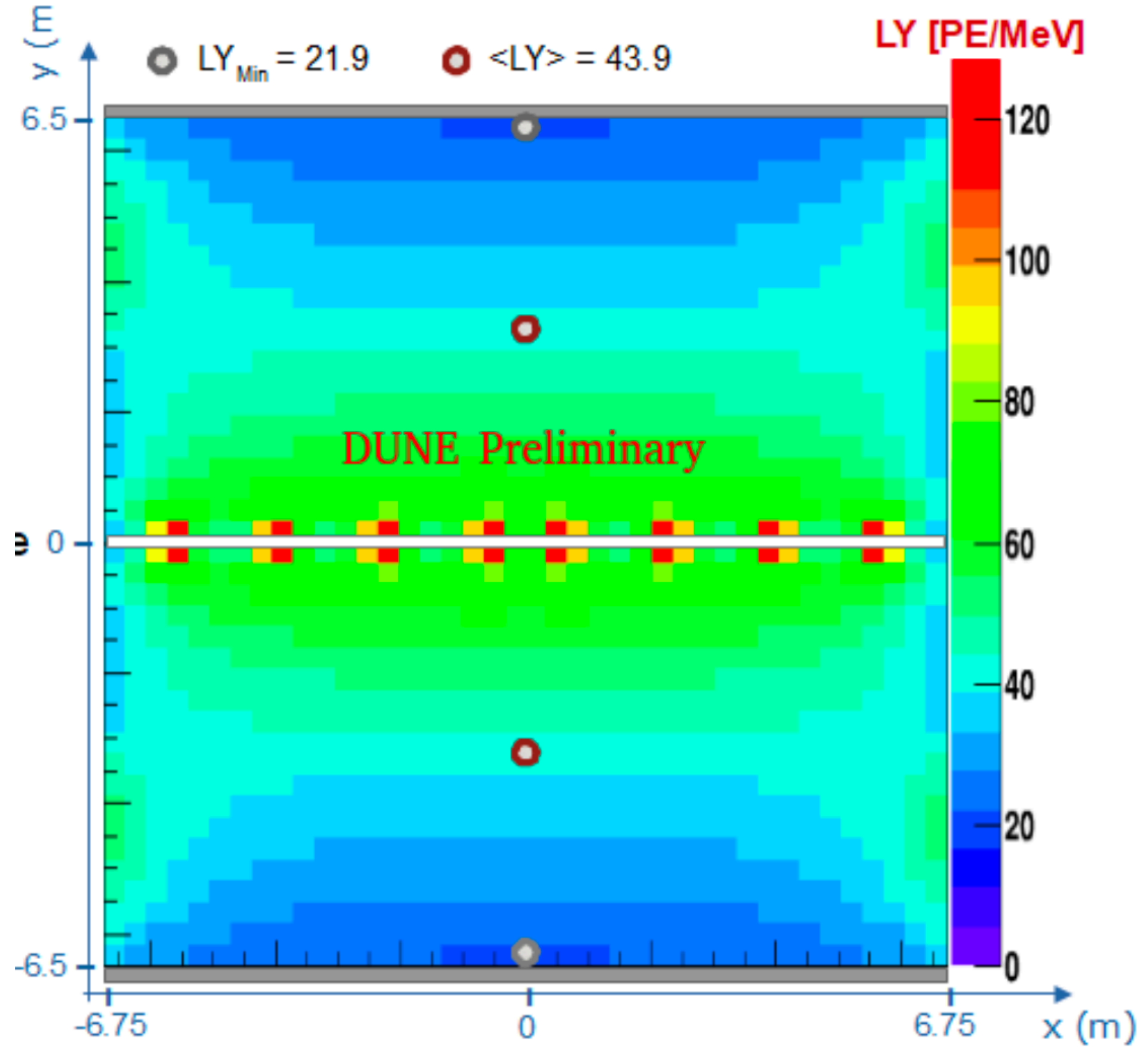
DUNE FD3 vision
- Similar in concept to FD2 - optimized VD
- Proposed upgrades: ★ **(This talk)**
  - **Major upgrade: light detection system - APEX**
  - Xe-doping
  - Modest optimization on charge readout
  - Incremental background control
- **Construction fully endorsed by the 2023 P5**
- FD technically limited schedule
  - **Earliest installation (completion):** 2029 (2034)



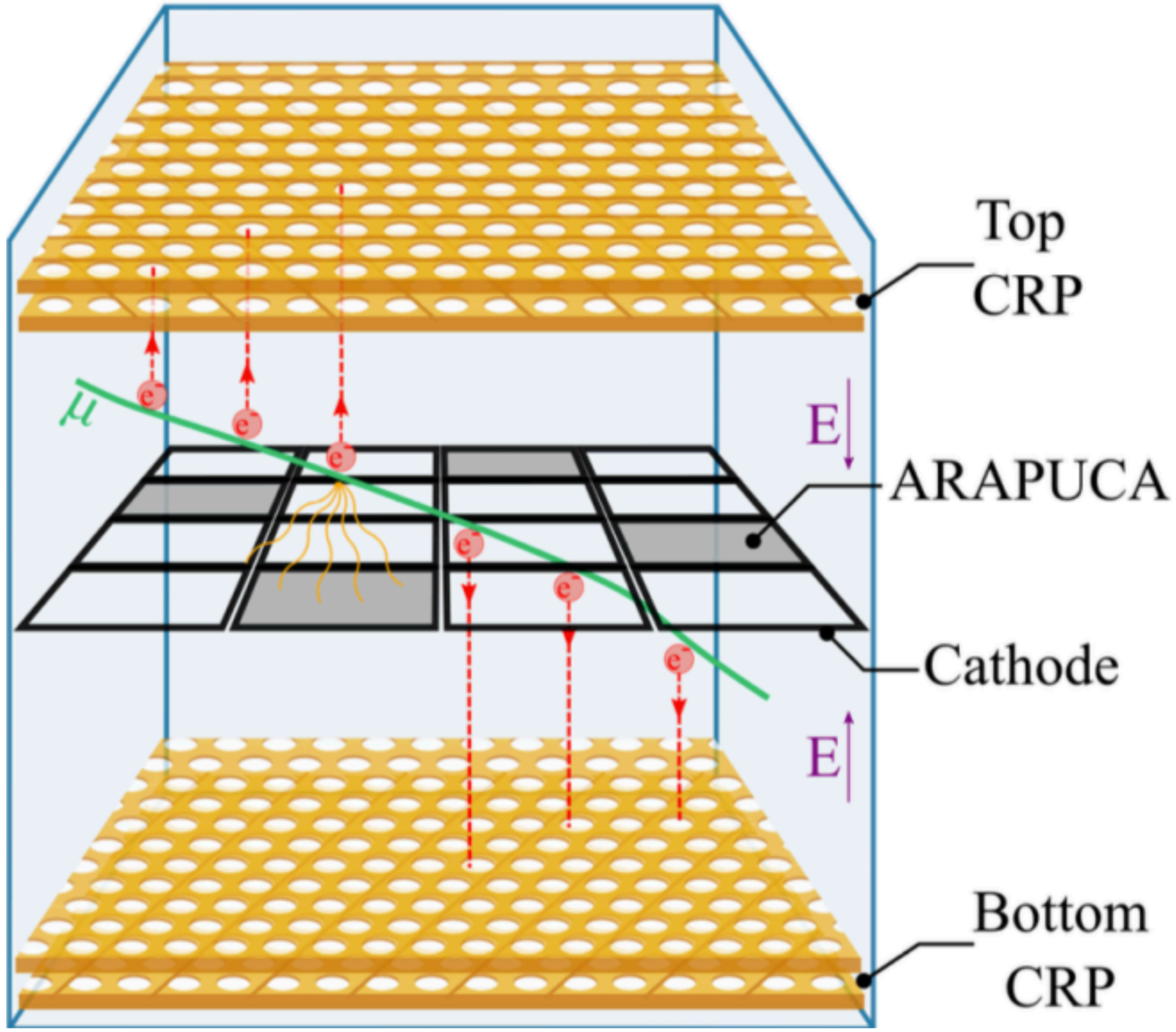
More on DUNE Phase II program: see S. Gollapinni's plenary talk Thursday

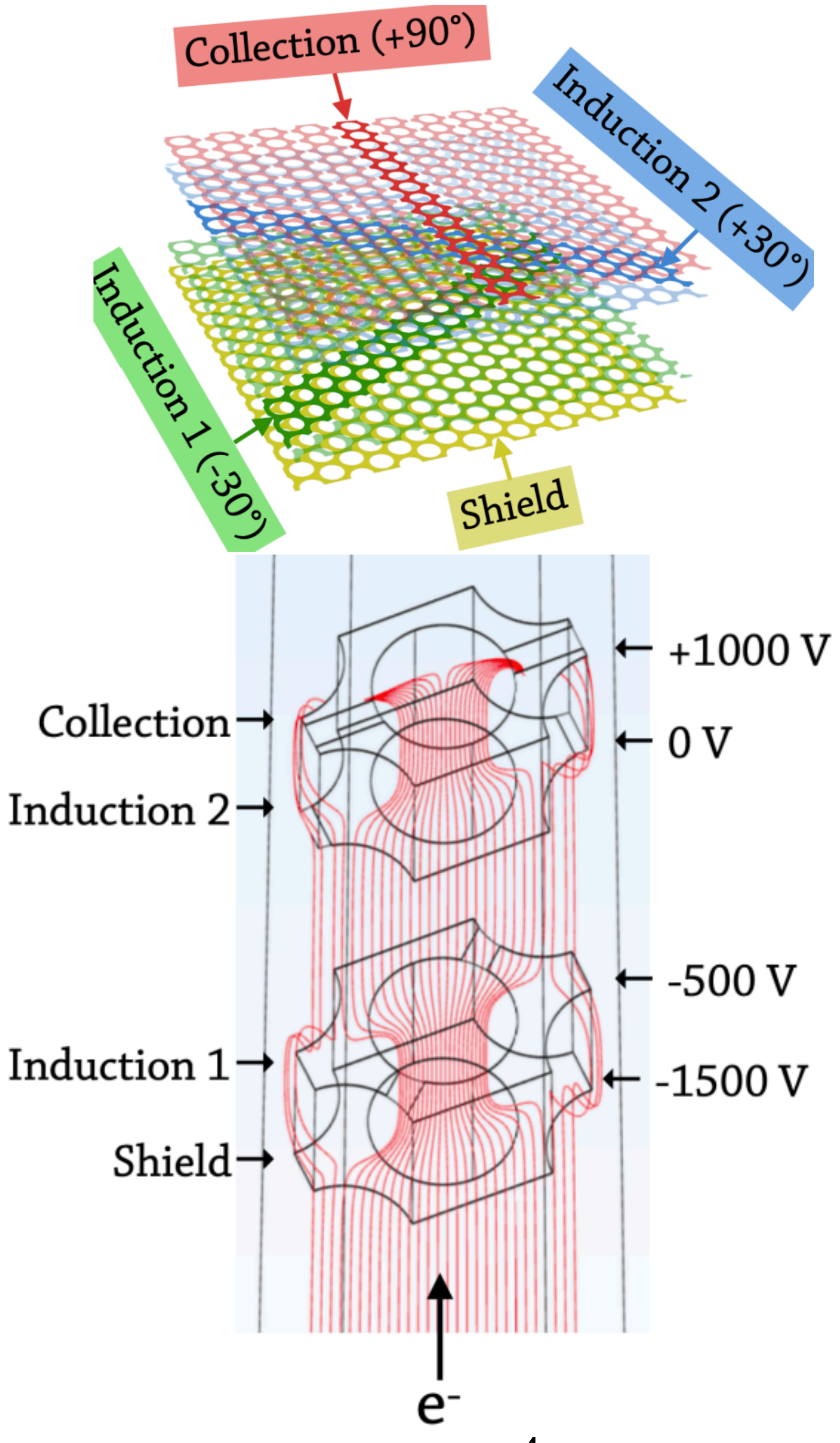
DUNE FD2 (VD)

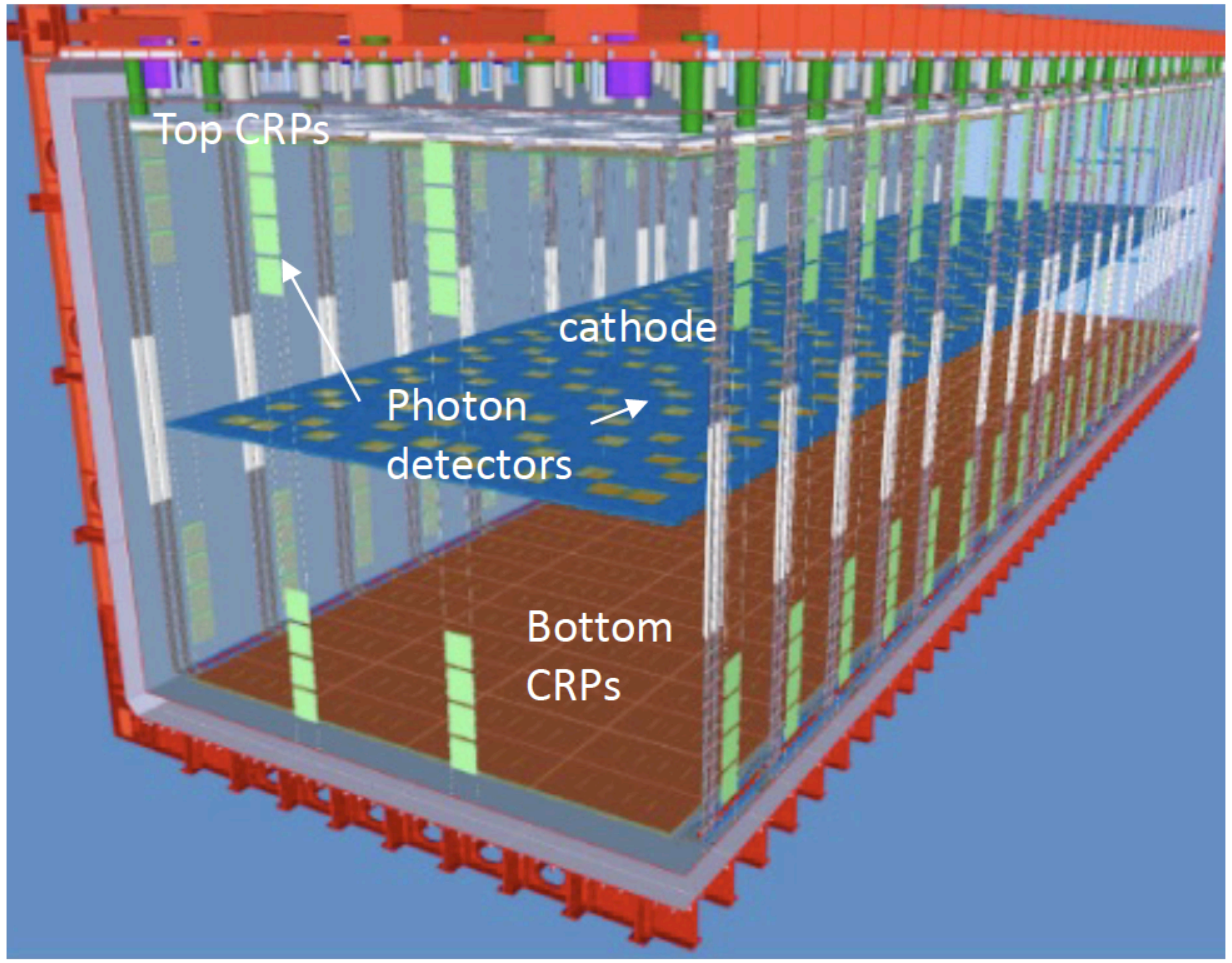
- The **state-of-the-art**: **6.5 m vertical drift distance**, maximized active volume 14,190 ton
- Simplified charge readout plane (CRP) perforated PCB, reducing overall costs to FD1
- **Power-over-Fiber (PoF)** technology enables **320 photodetectors** (X-Arapuca) deployed on **300 kV** high voltage surface **in LAr**
  - Noise immunity, voltage isolation and spark free
  - **First-ever** realization in cryogenics and particle physics - Paper soon on arXiv



FD2 PDS Light Yield



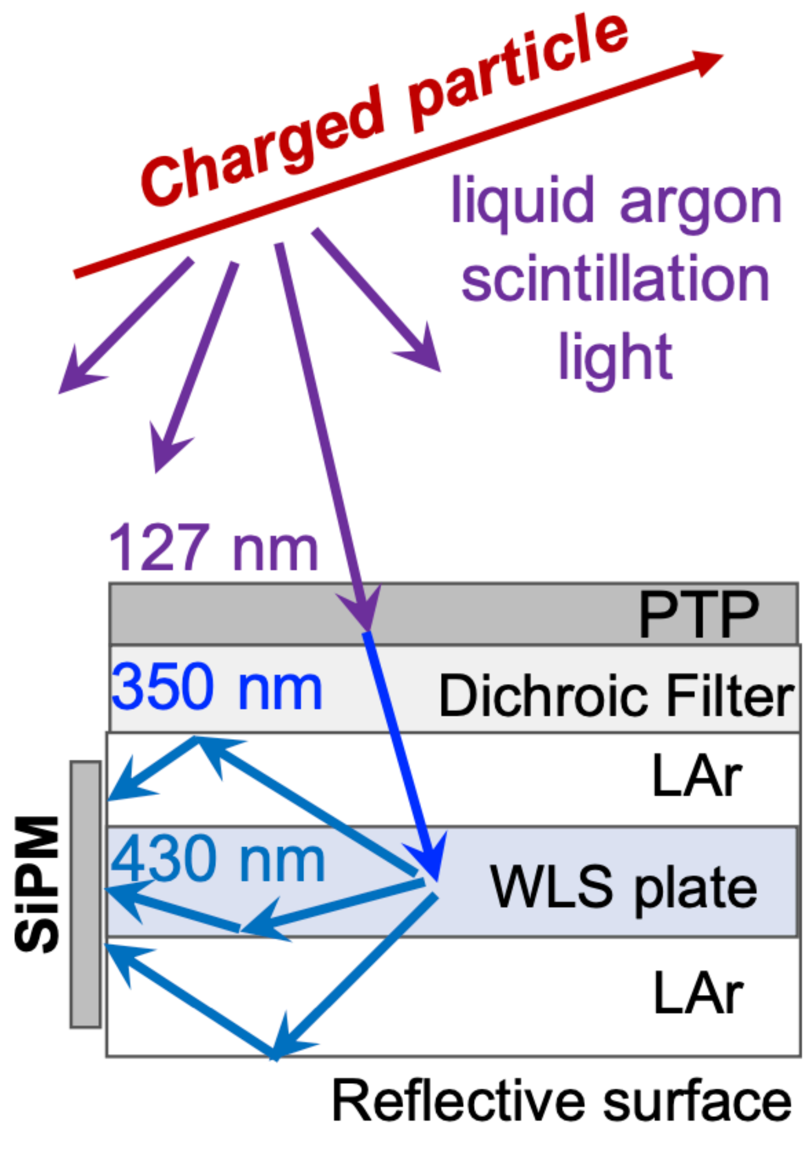




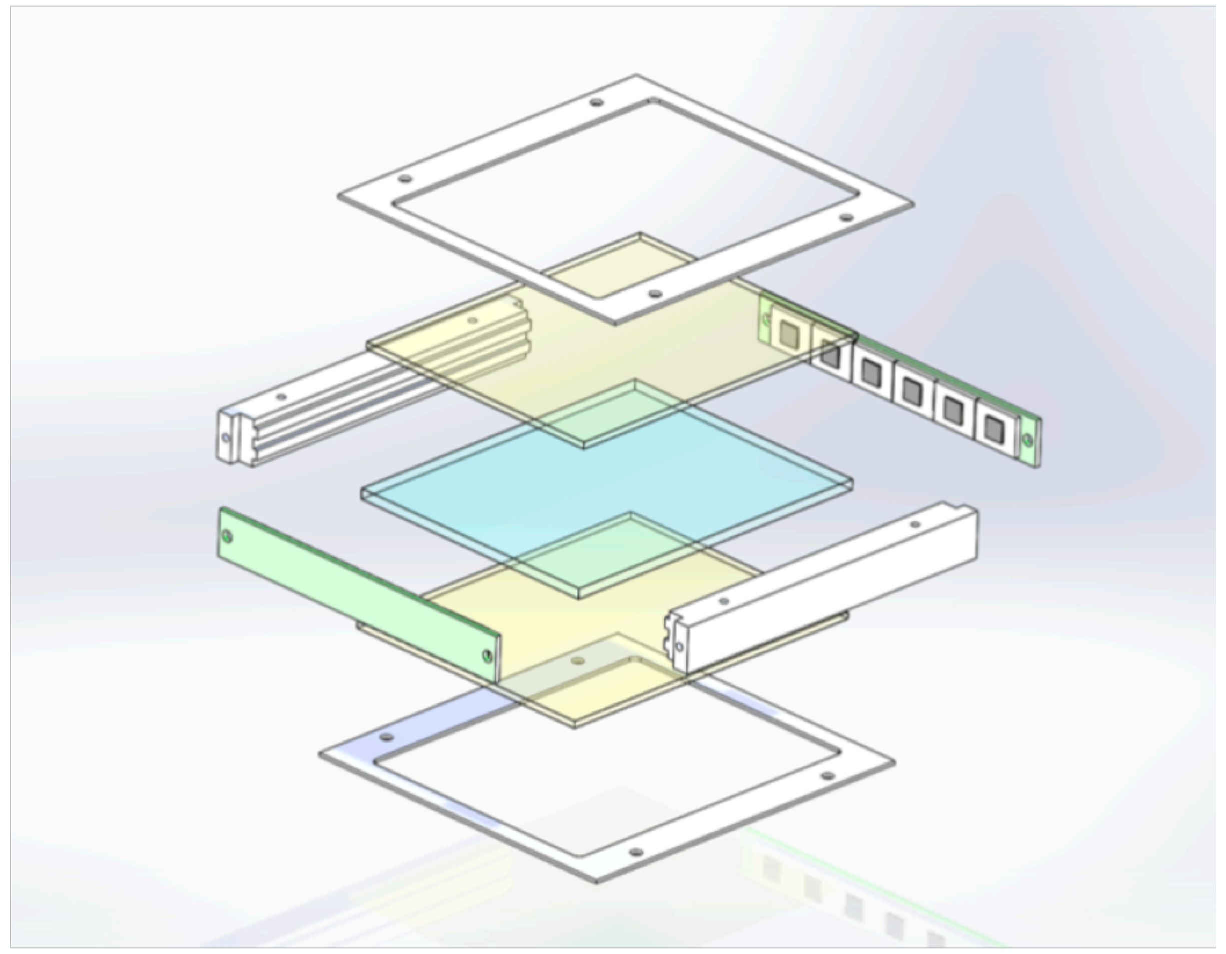
X-arapuca Photodetector in VD

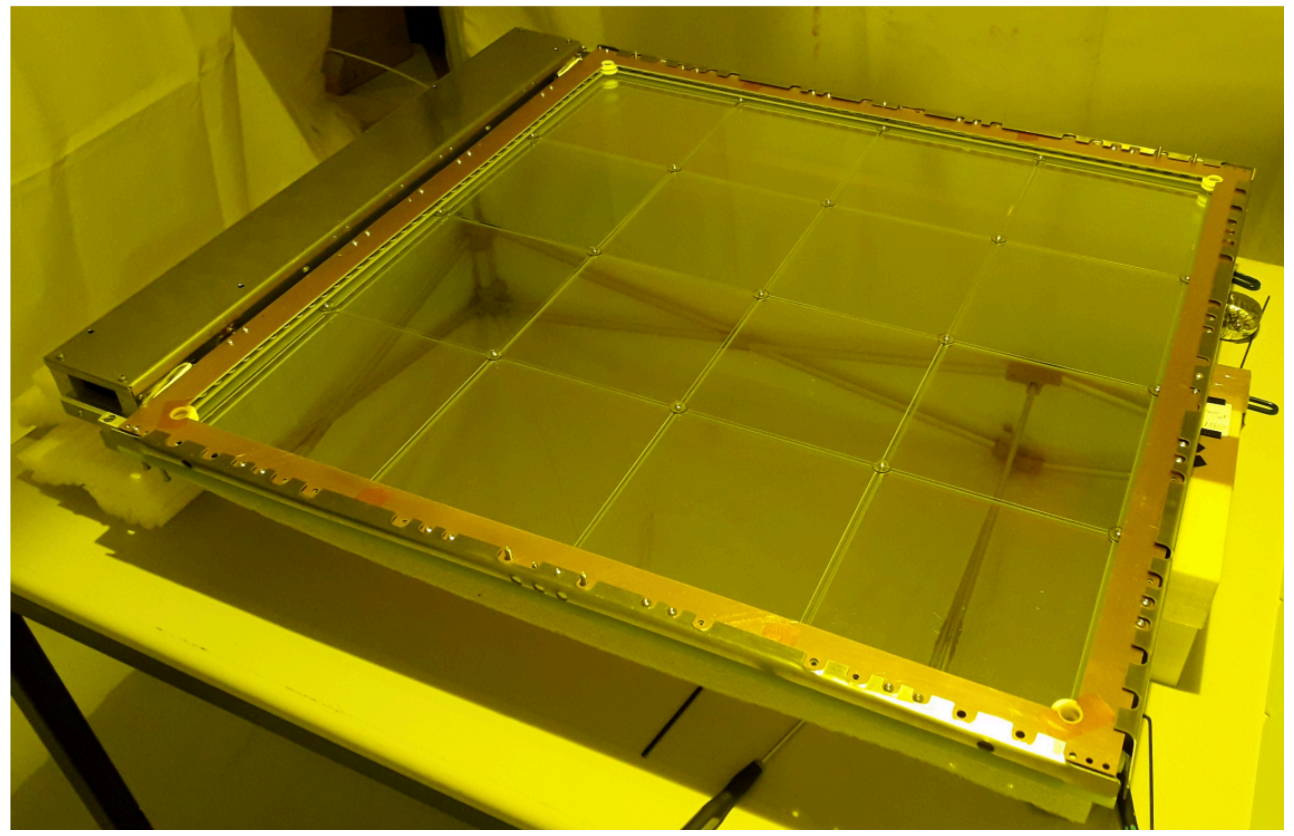
- **X-arapuca is a light trap**
  - pTP (**1st** wavelength shifting) and dichroic coating deposited on glass
  - Bulk material is acrylic (PMMA) plate doped with chromophore (**2nd** wavelength shifting)

- Widely used in LArTPC: MicroBooNE, ProtoDUNE-SP, SBND, DUNE FD1 & FD2
  - Average detector efficiency is **2-3%**
  - **Easy to scale up** for large area coverage
  - **Compact**: save space for more fiducial volume

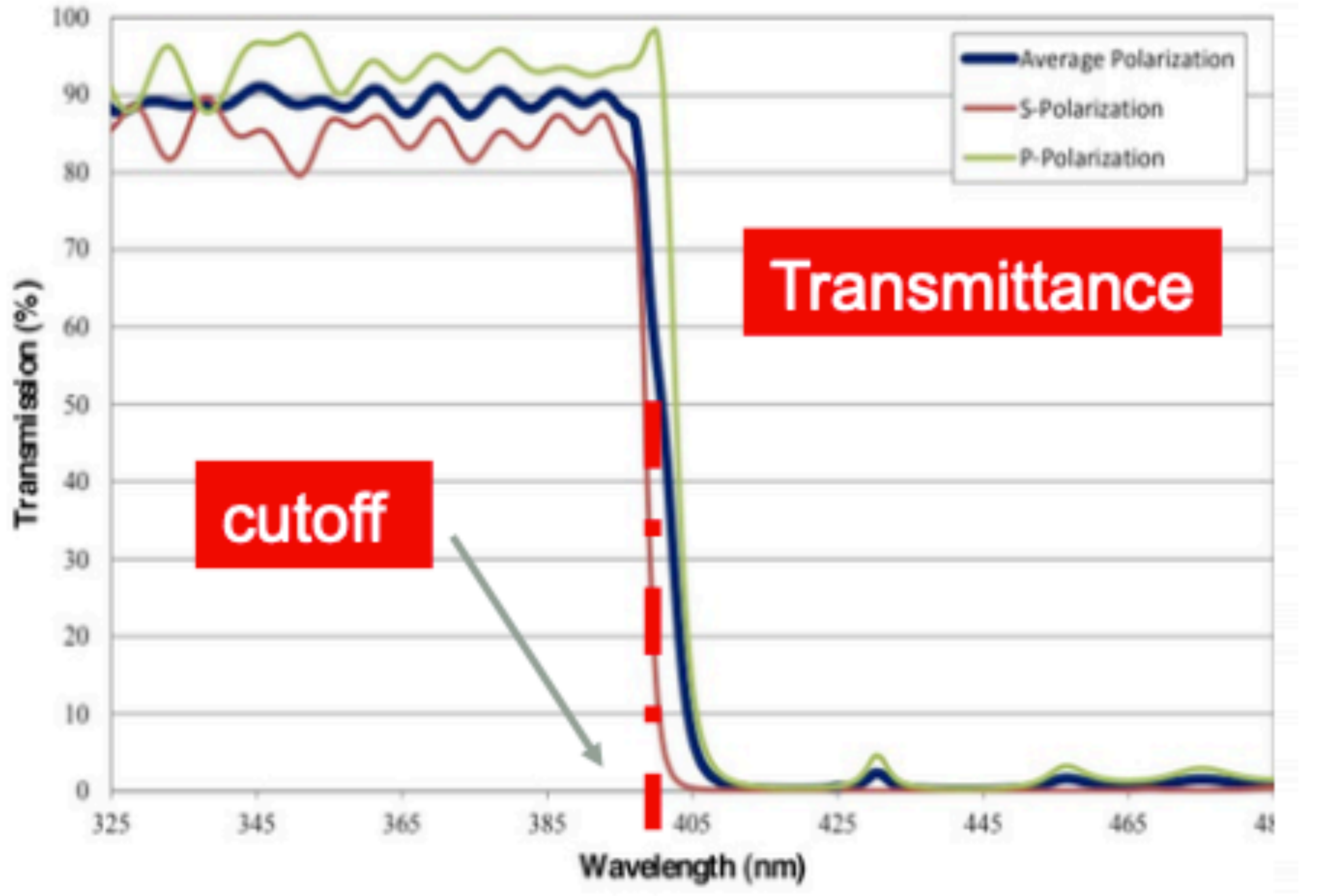


Not to scale.

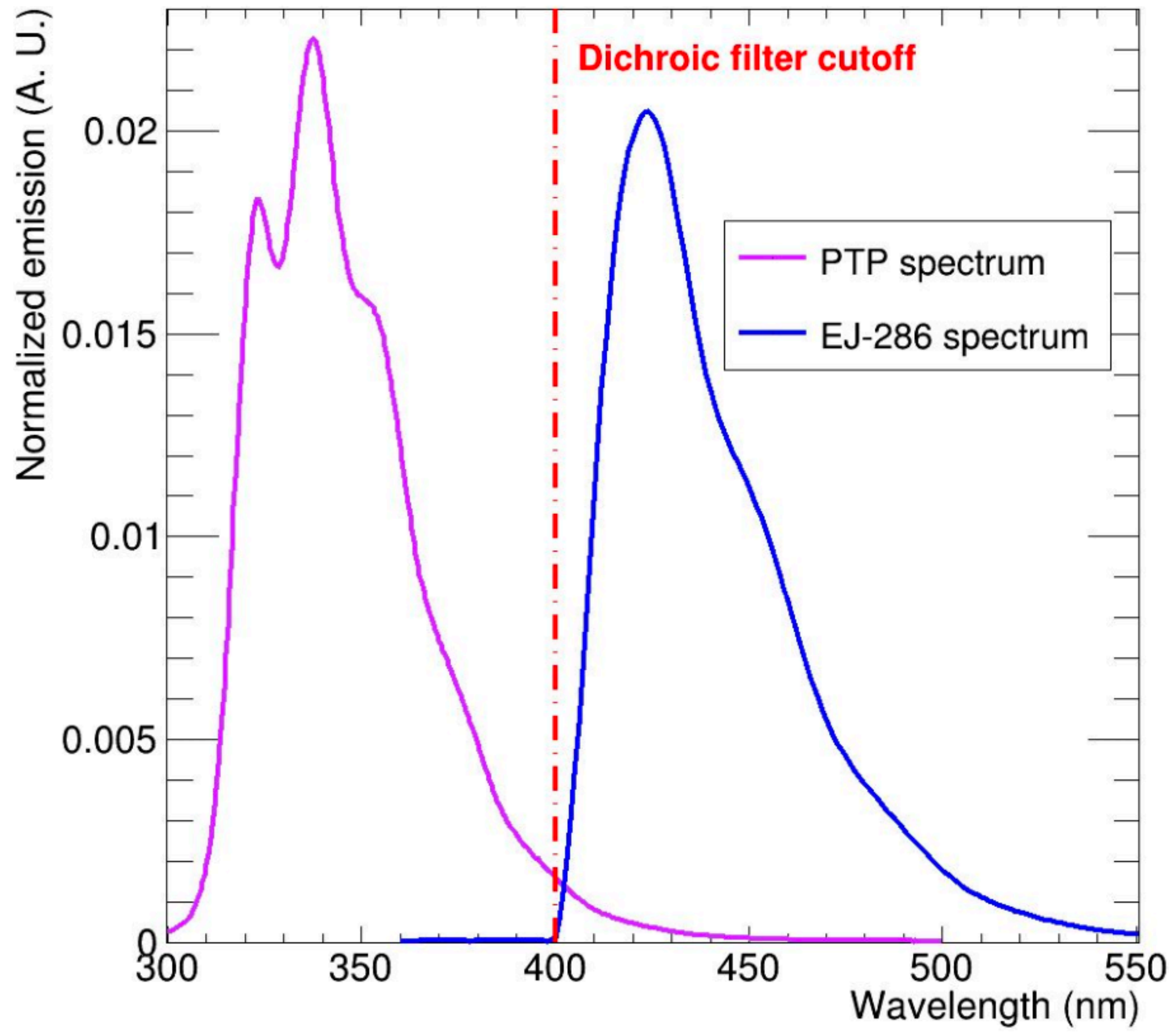


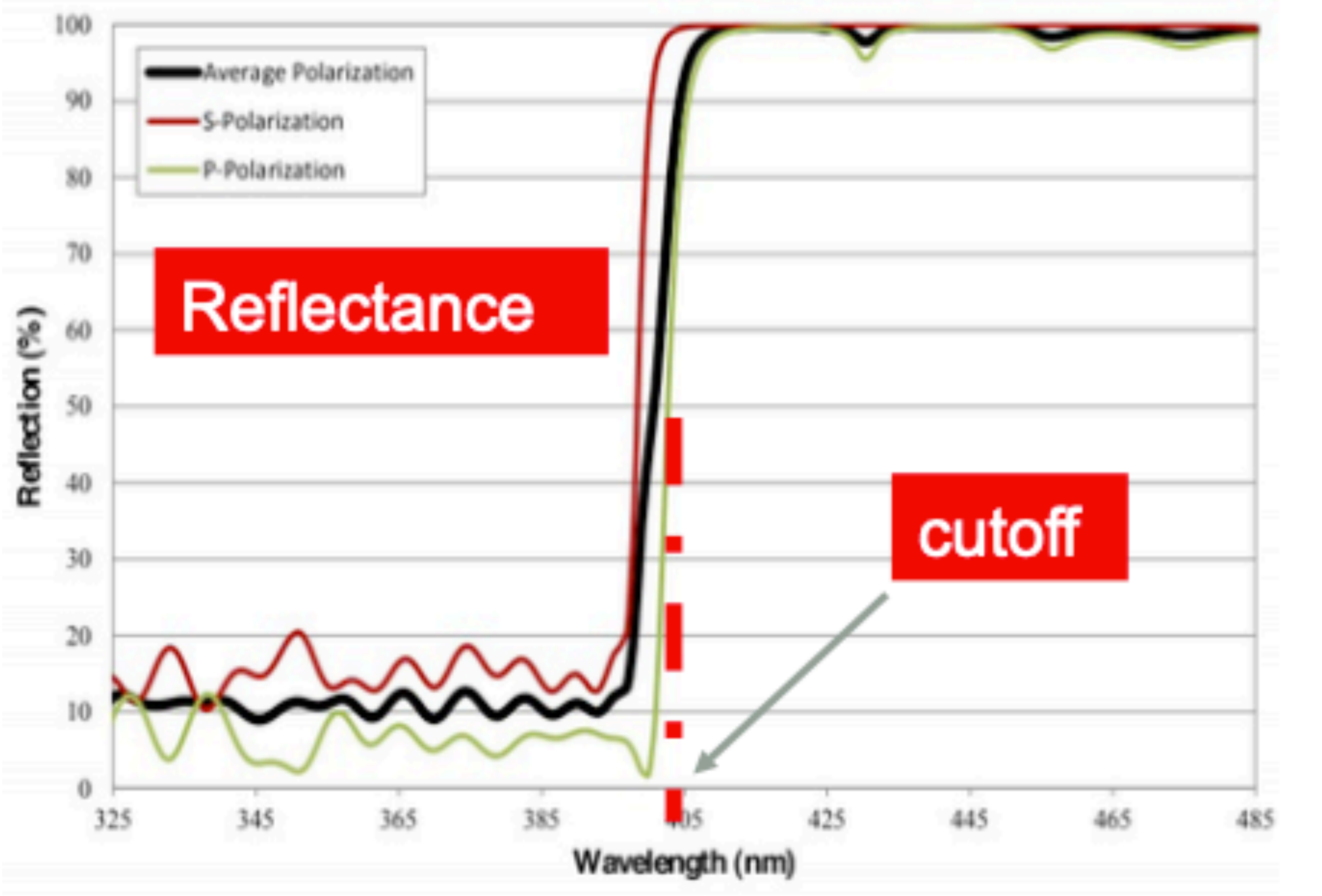


X-arapuca for ProtoDUNE-VD



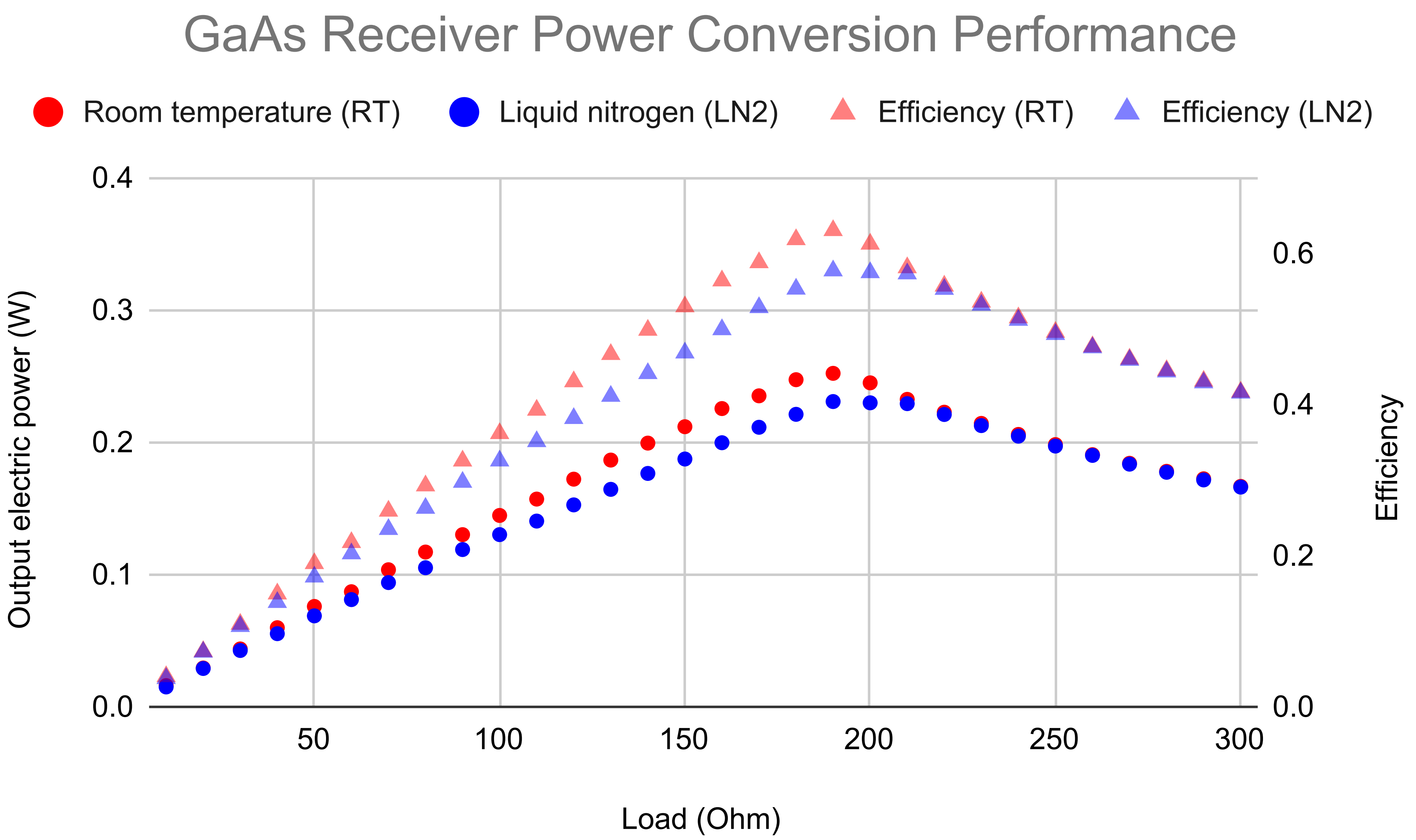
Dichroic filter spectrum



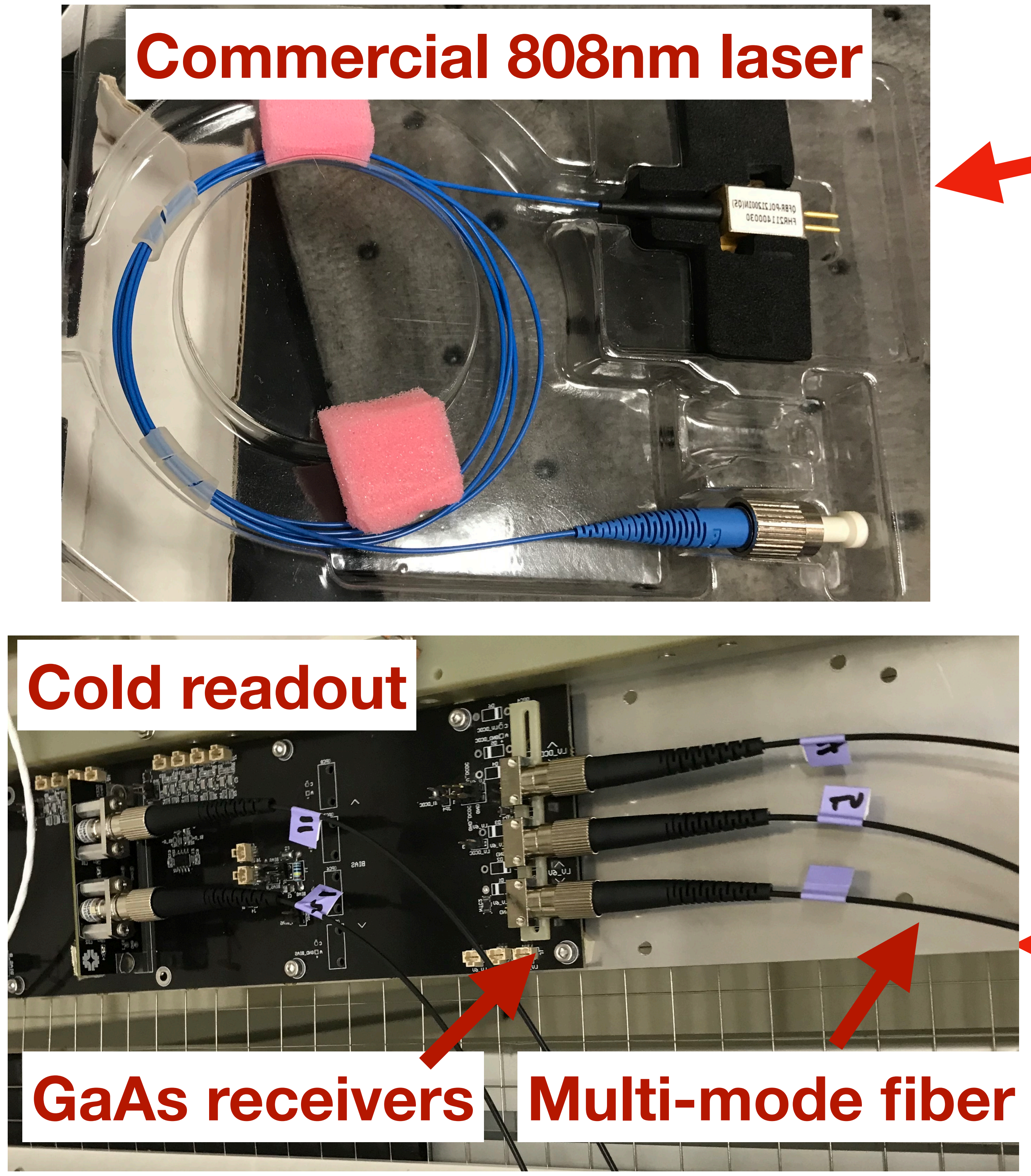


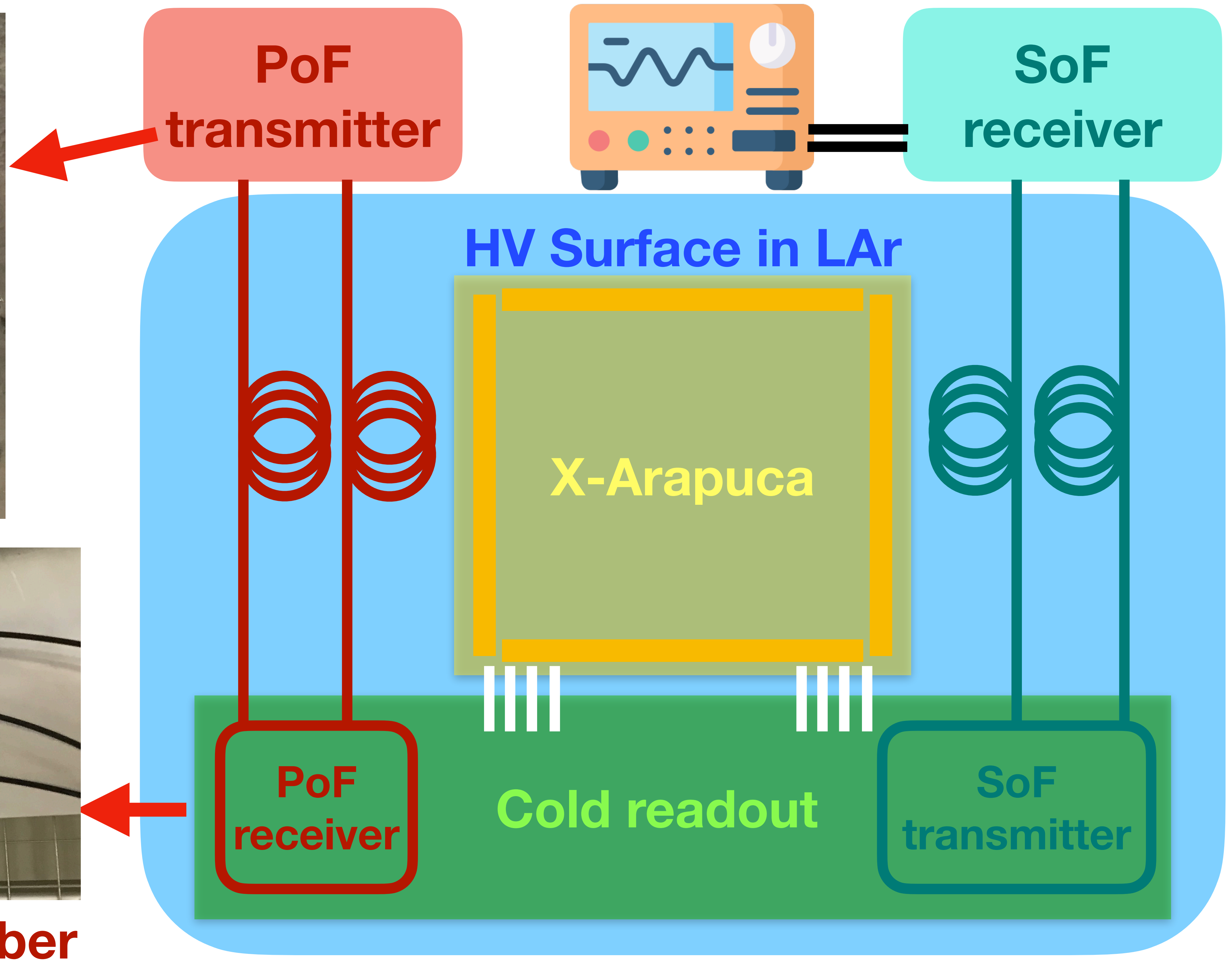
Solution for Detectors on HV Surface: Power over Fiber (PoF)

- Power can’t transmit via conductive cables due to discharge risks (field cage at HV)
- **PoF is a new technology to transmit power via optical fibers to detectors on HV surface, already applied in DUNE VD: developed over 3 years at Fermilab with industrial and university partners**
- Laser power is converted to electrical power: efficiency already at ~55%, could reach 75% in theory
- Light noise from PoF system well understood and mitigation solutions are developed



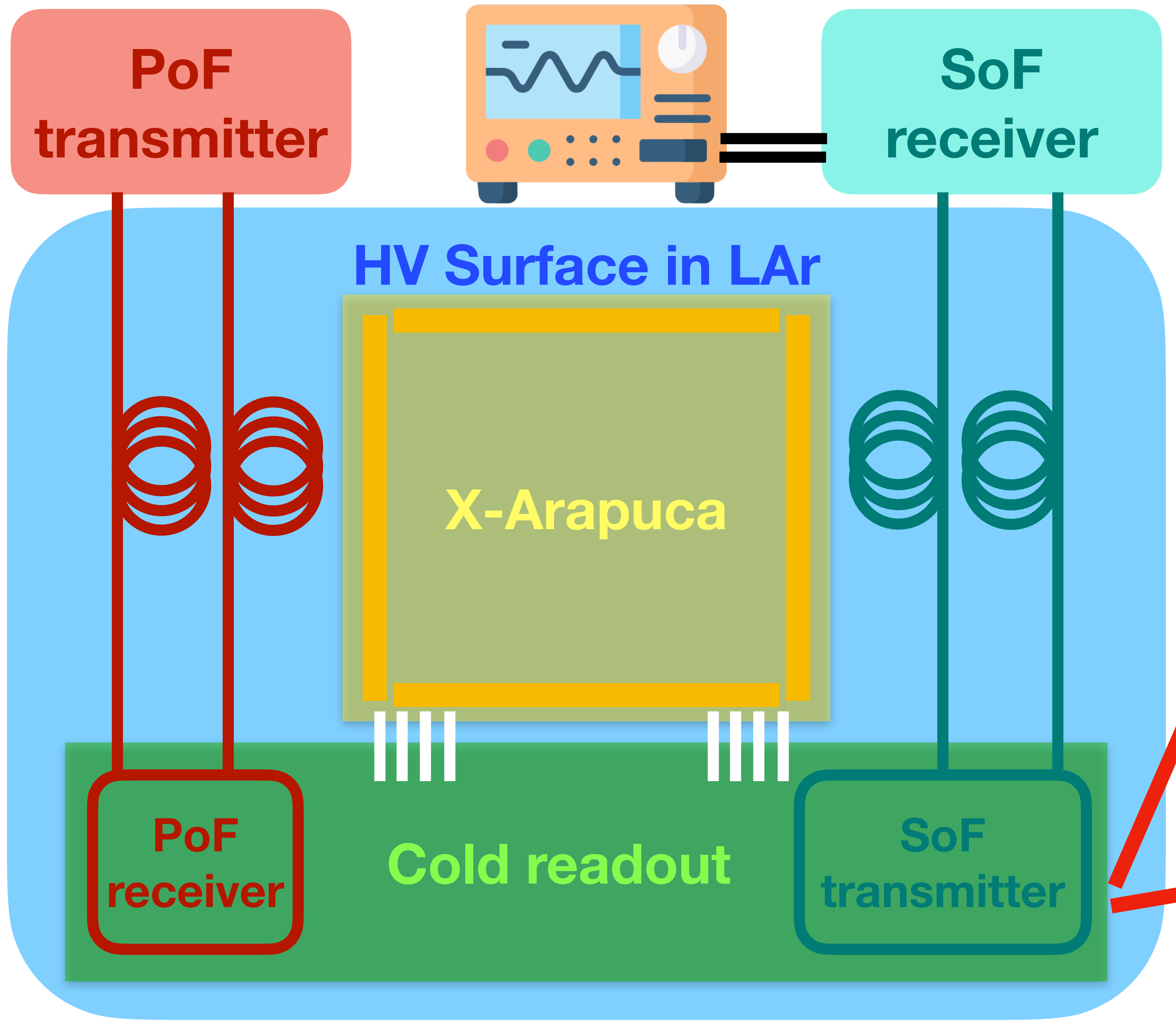
Input 808nm Laser@ 400mW

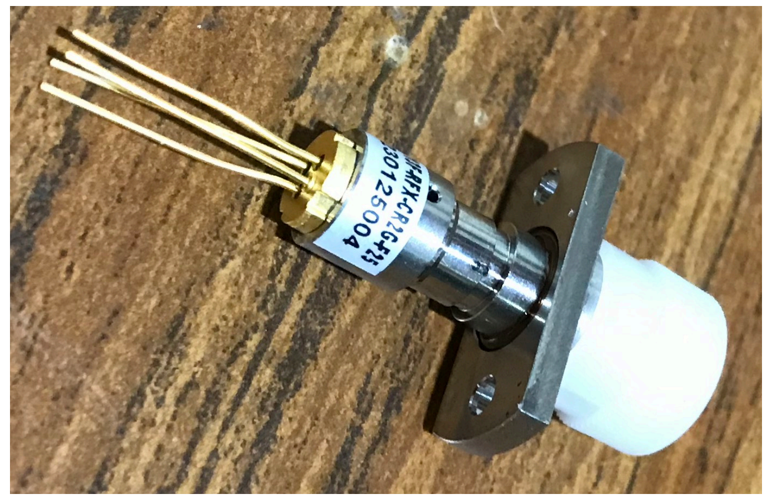


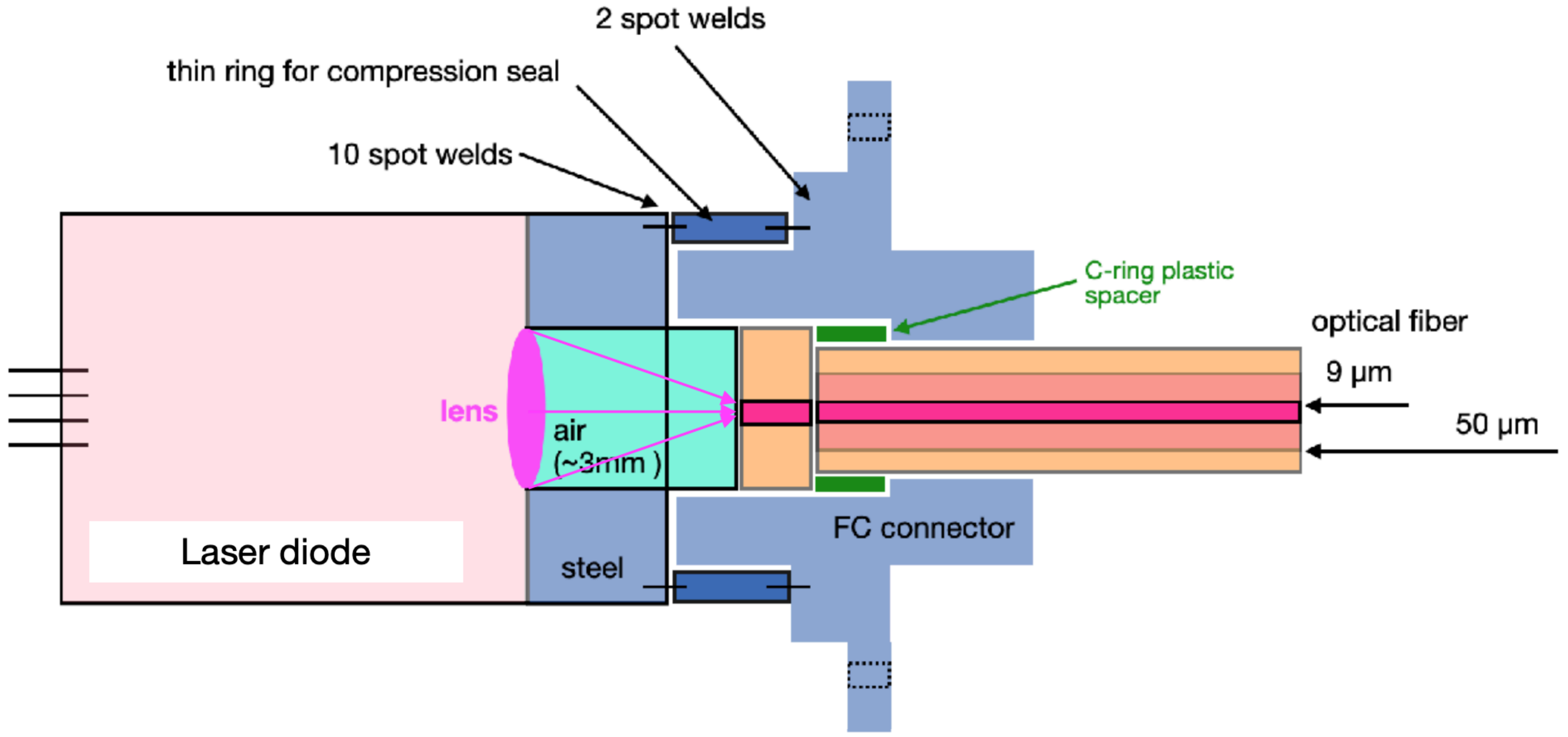


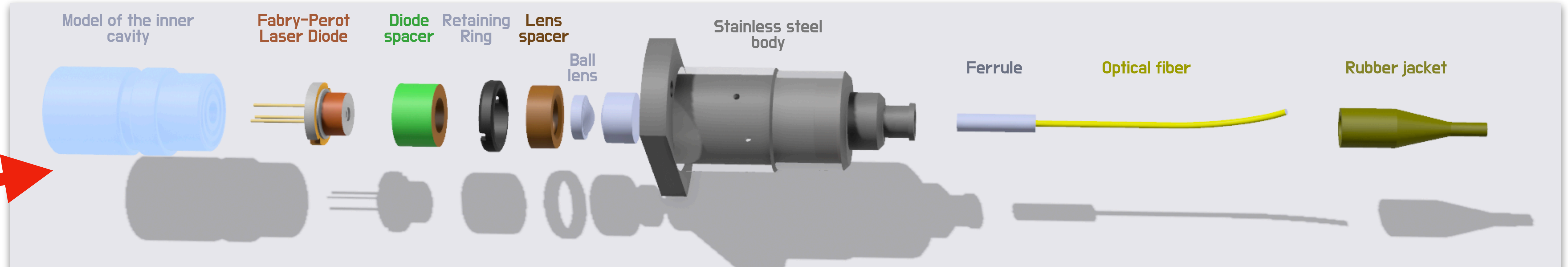
Solution for Detectors on HV Surface: Signal over Fiber (SoF)

- Use 1310 nm (room temperature) Fabry–Pérot laser diodes on front end cold electronics to convert SiPM electric signals to optical signals and transmit over fiber
- **A commercial laser diode with > 2 years of R&D to customize it for LAr application**
  - E.g.: customized defocused products solved power stability problem when immersed in >12” LAr
- Demonstrated long term stability above 6m LAr hydrostatic pressure (~12psig)







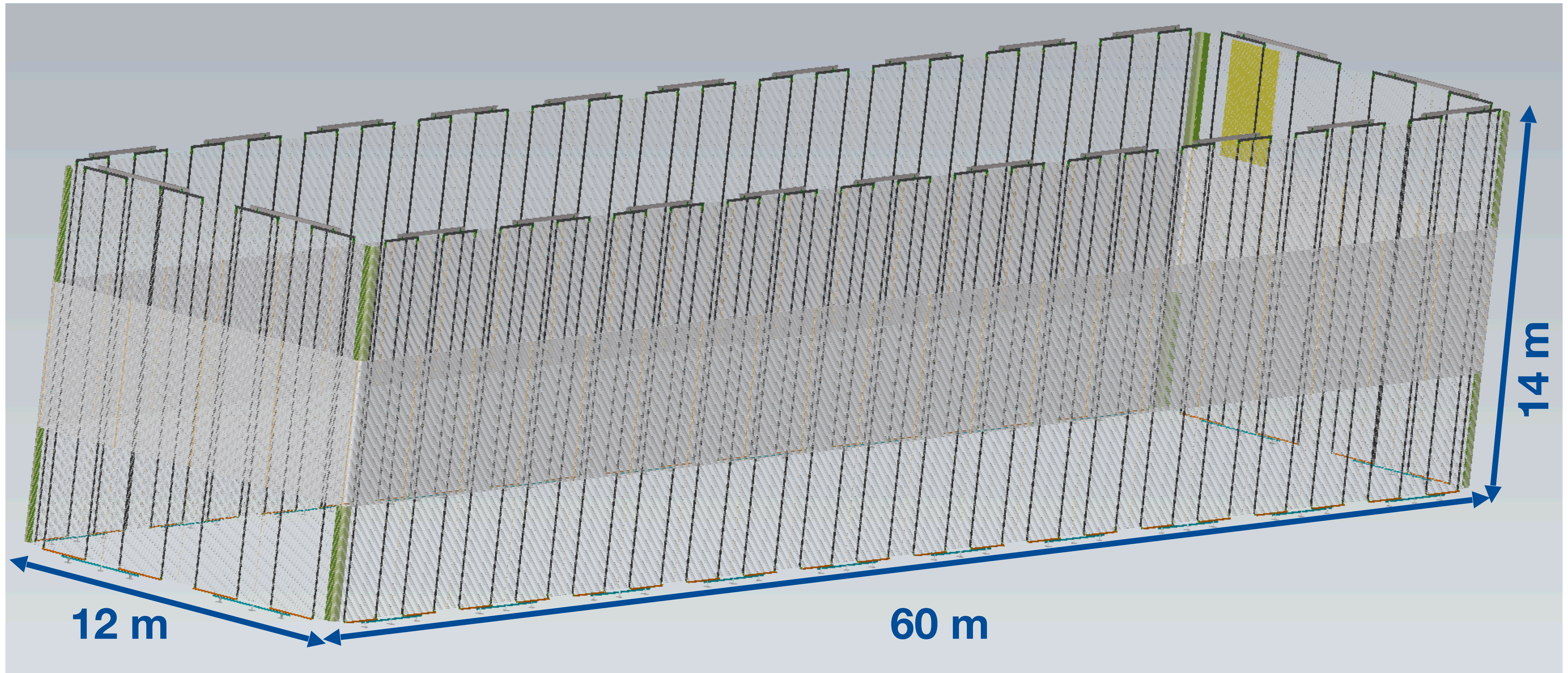


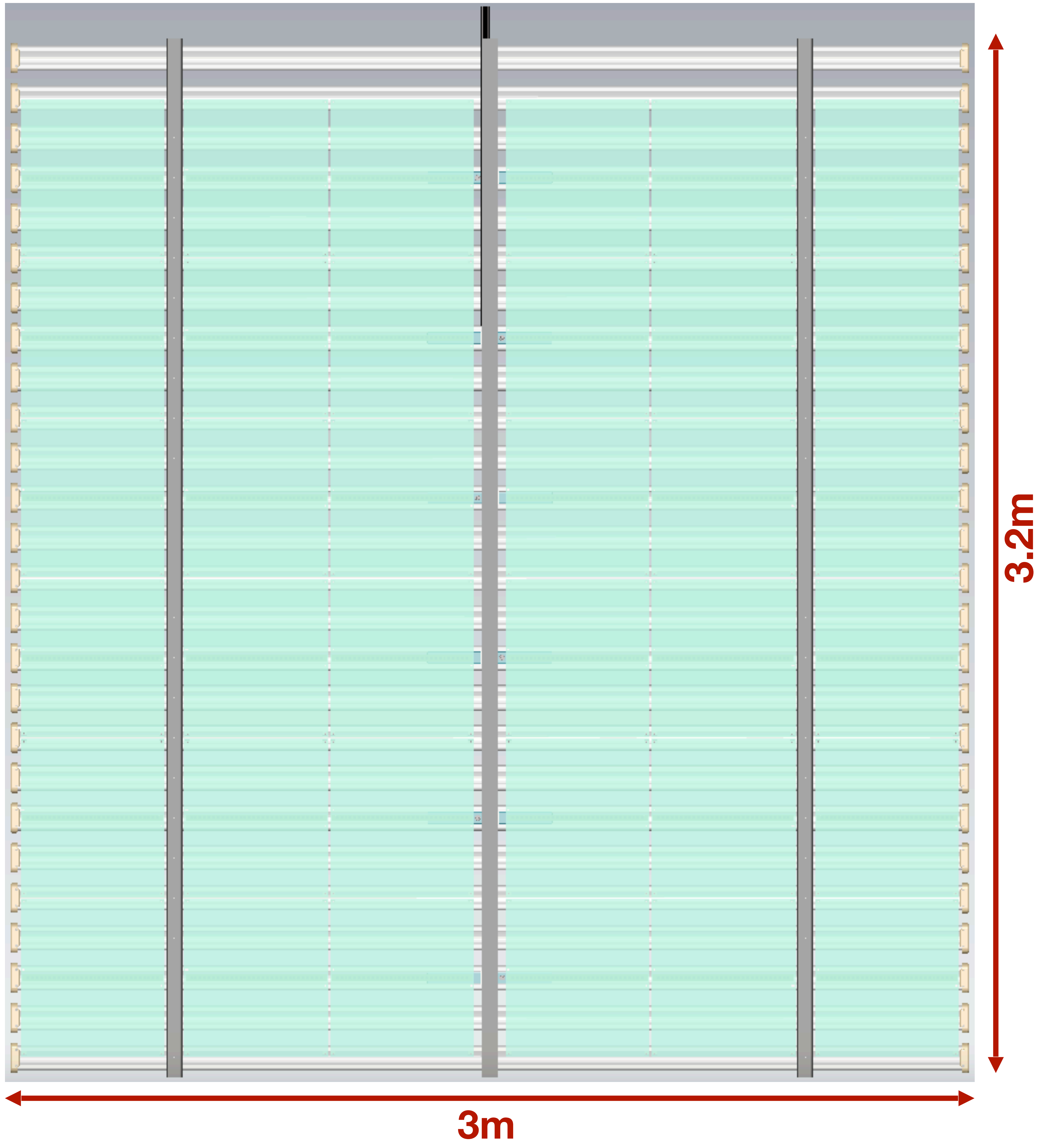
Customized laser diode

Convert LArTPC Field Cage Structure into a Fully Active Photon Detection System

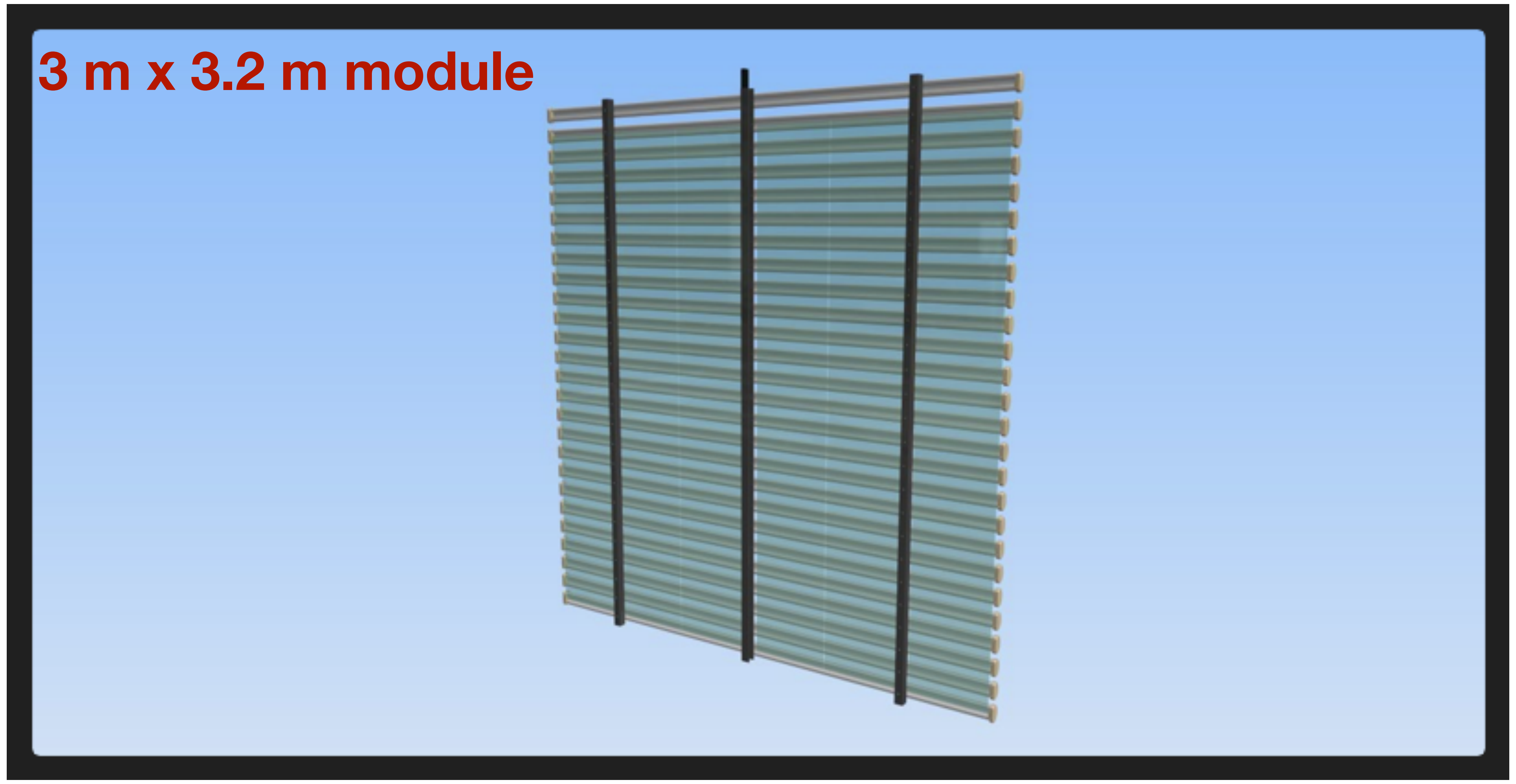
- **If X-arapuca photodetectors are on field cage walls of LArTPC active volume, would naturally expand optical coverage up to 2000m^2 (10x DUNE VD) ~ half of American football field!**

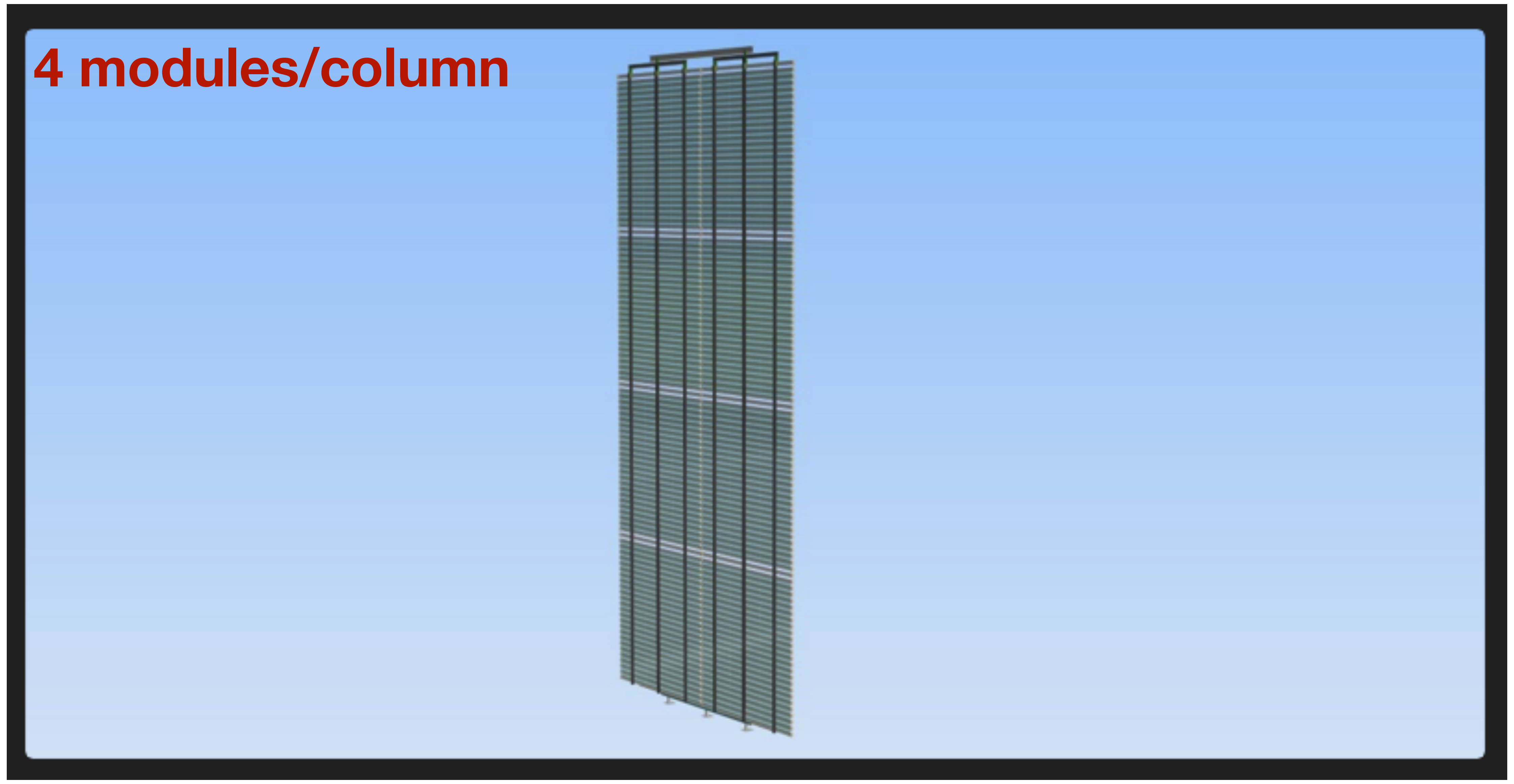
- Integrate to field cage modular unit - 3m x 3.2m panel
  - Operate X-arapuca on HV surface enabled by PoF & SoF
  - 0.5m x 0.5m X-arapuca directly facing active volume, 6 modules per row share power and readout
  - Up to 6 FRP box beams as structural support

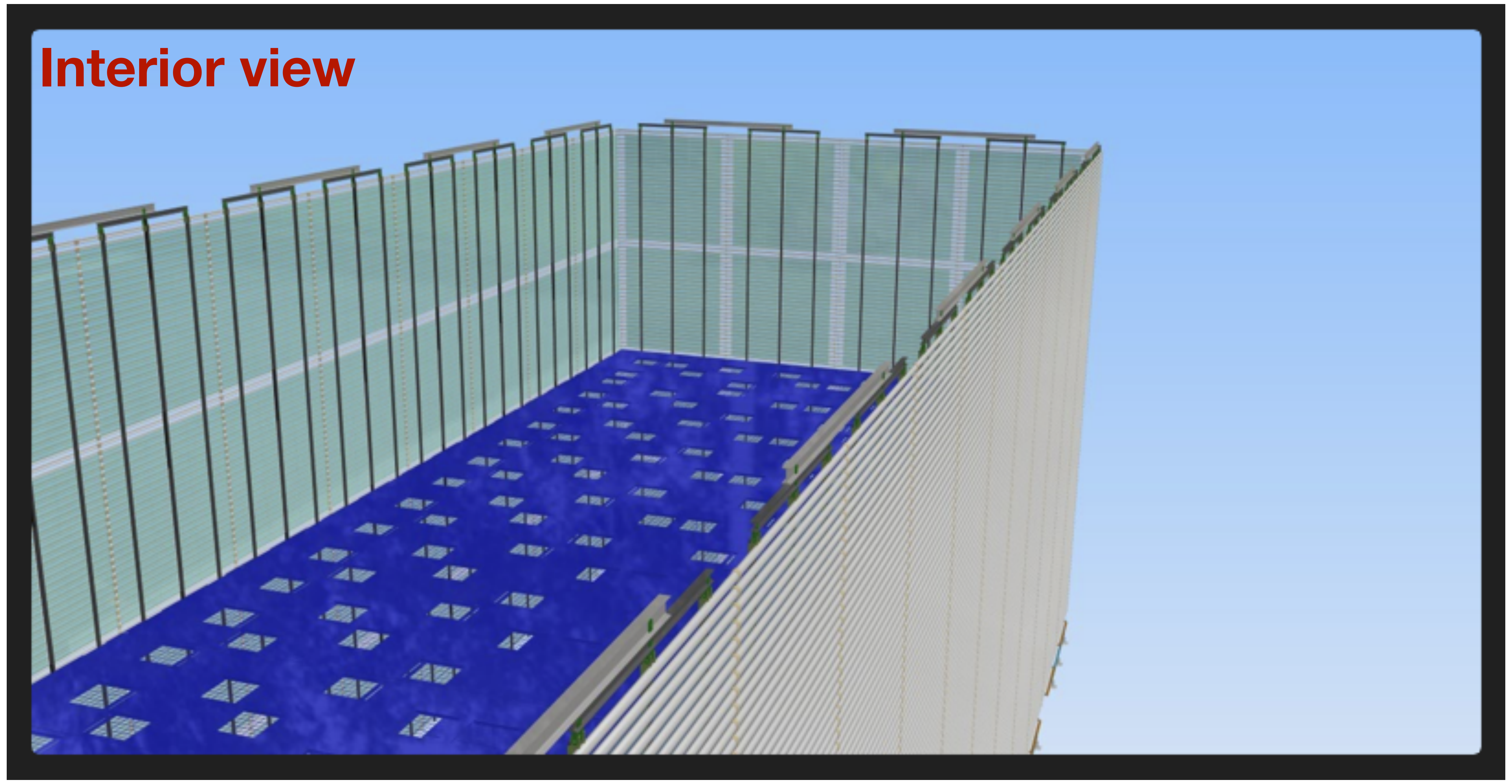


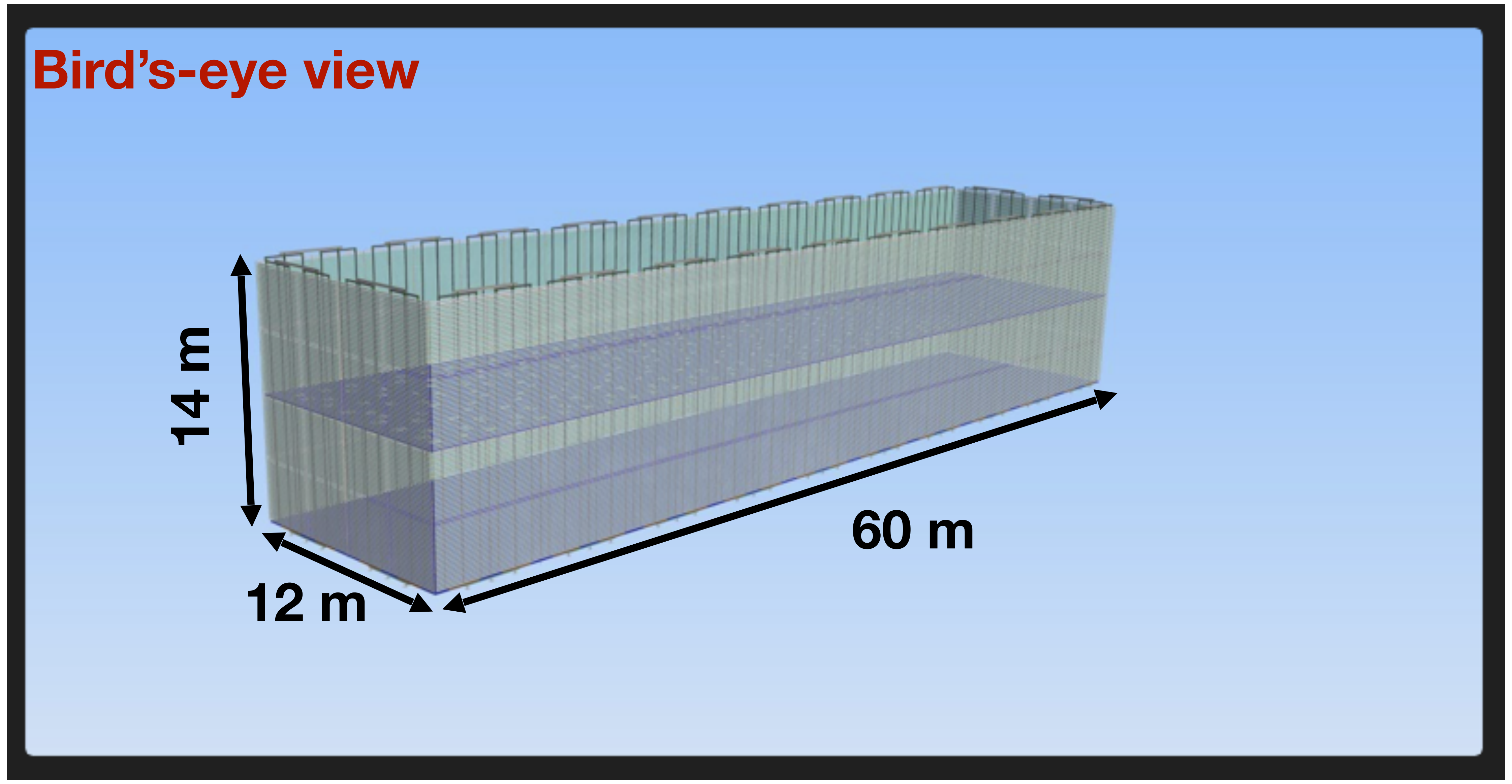


Views for DUNE FD3



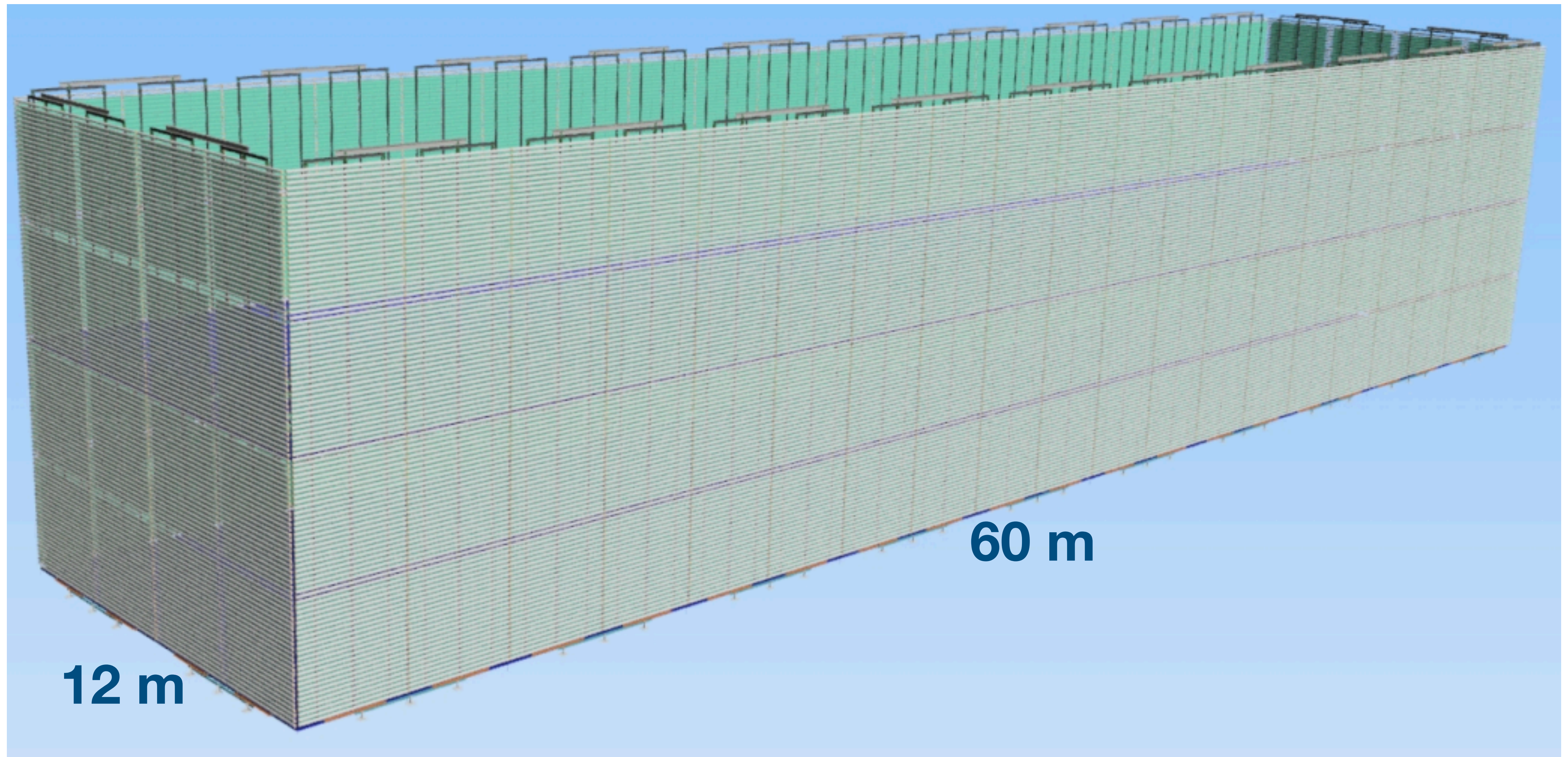




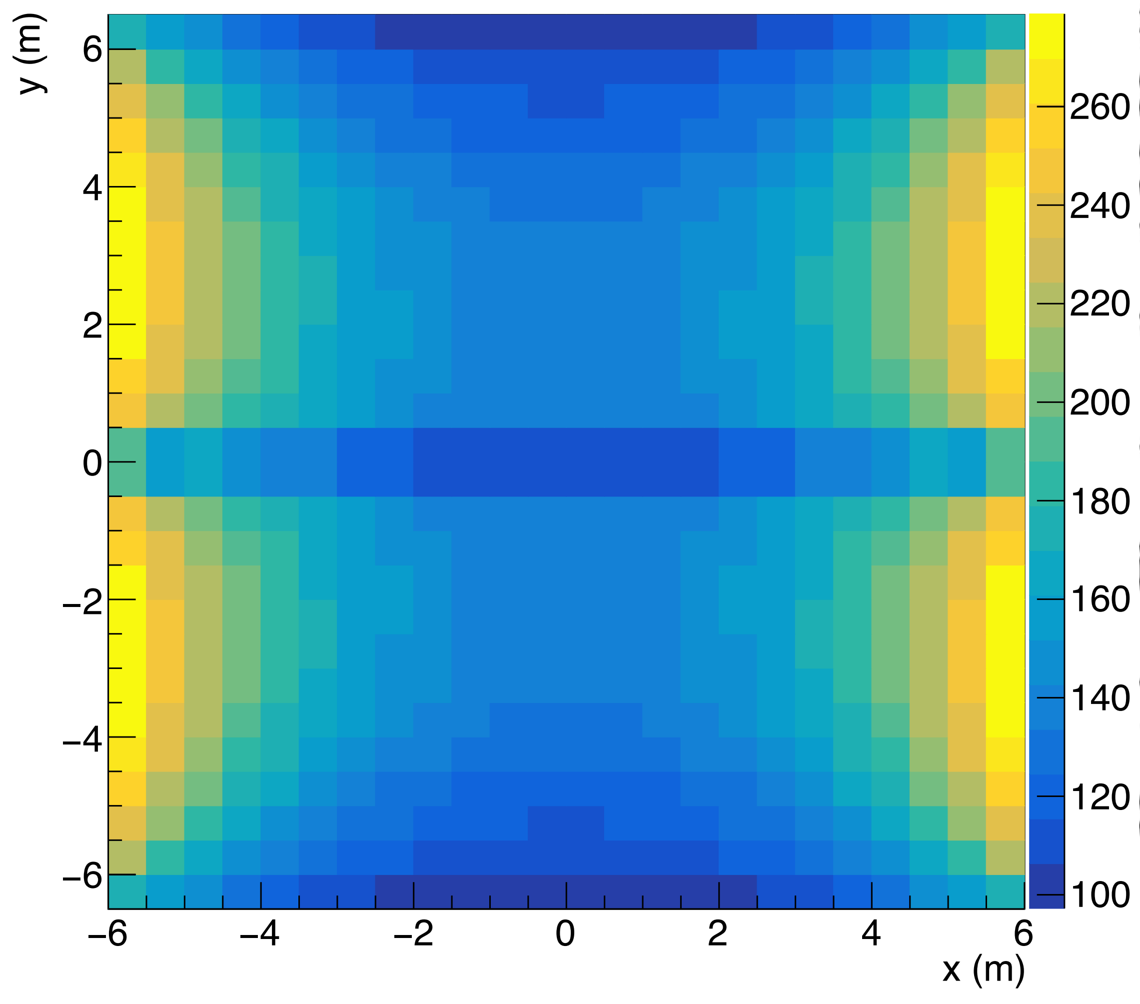


DUNE FD3 APEX (Aluminum Profiles with Embedded X-Arapucas): A fully integrated LArTPC field cage + photodetector system

- ~60% optical coverage of LAr (active) volume
- **Min** (avg.) **light yield** x**6** (x4) times higher wrt FD2, higher uniformity
- Lower detection thresholds, better timing and energy resolution extend frontiers of neutrino oscillation and low E astroparticle physics
  - Diffused supernova neutrino background
  - Separate CPV measurement in neutrino 2nd oscillation peak
  - Background tagging (e.g. neutron capture) and rejection
    - Enhance supernova & solar neutrinos sensitivity
  - Increase SNB trigger efficiency (to ~100%) in the range >=5 MeV deposited energy
  - BSM/dark matter

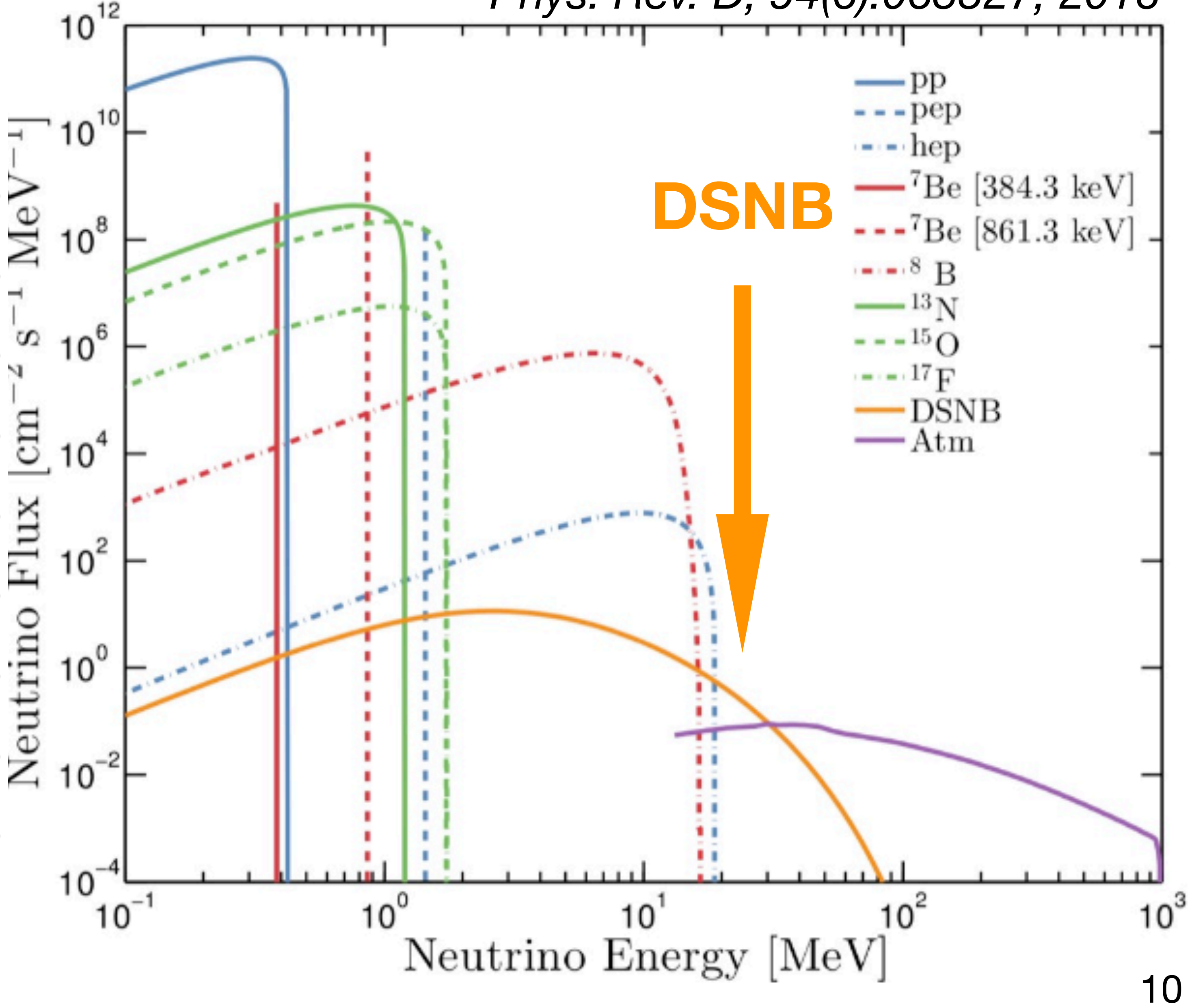


$LY_{mean} = 173.5\frac{PE}{MeV}, LY_{min} = 101.6\frac{PE}{MeV}$

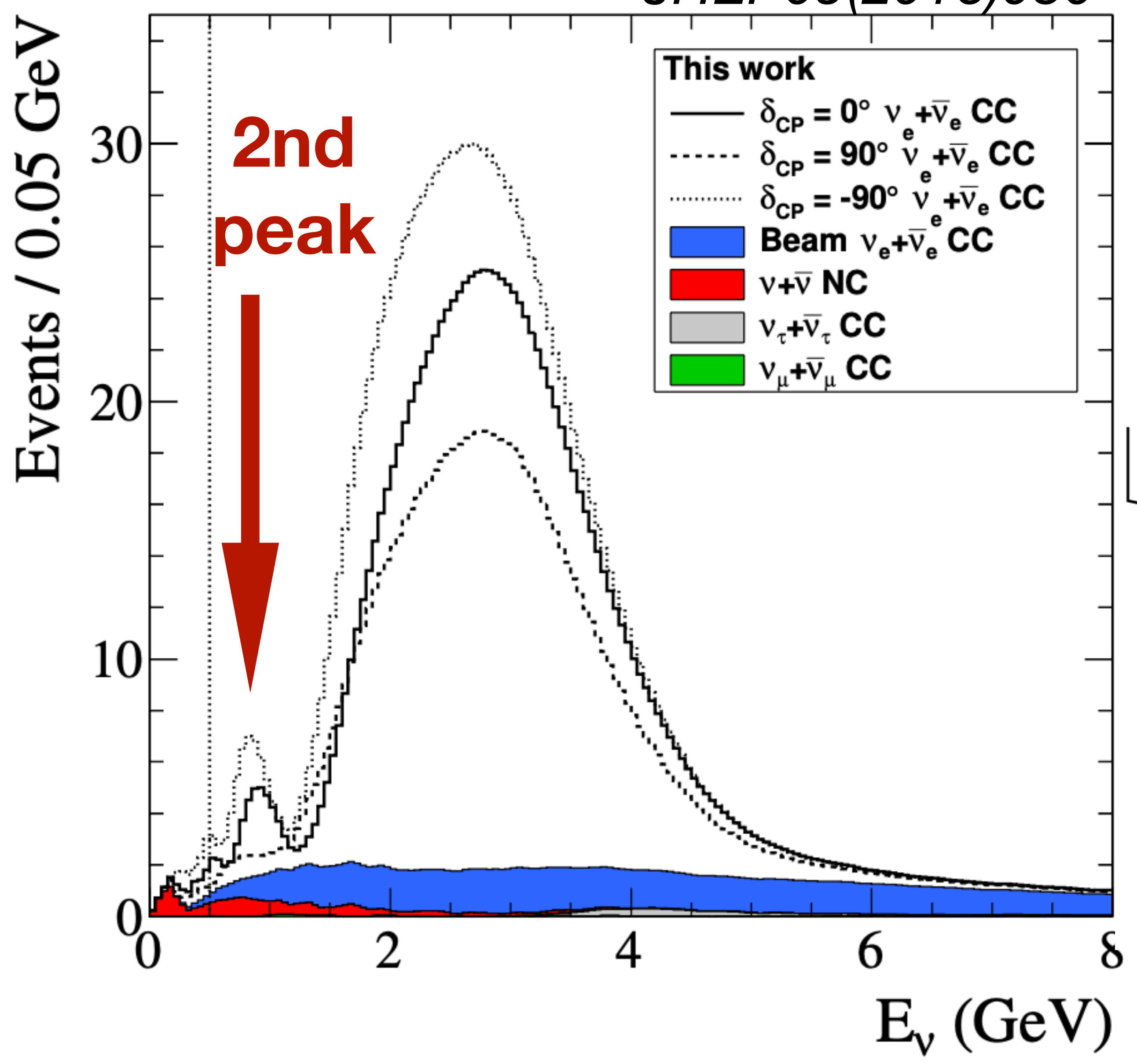


FD3 APEX

Phys. Rev. D, 94(6):063527, 2016



JHEP09(2016)030



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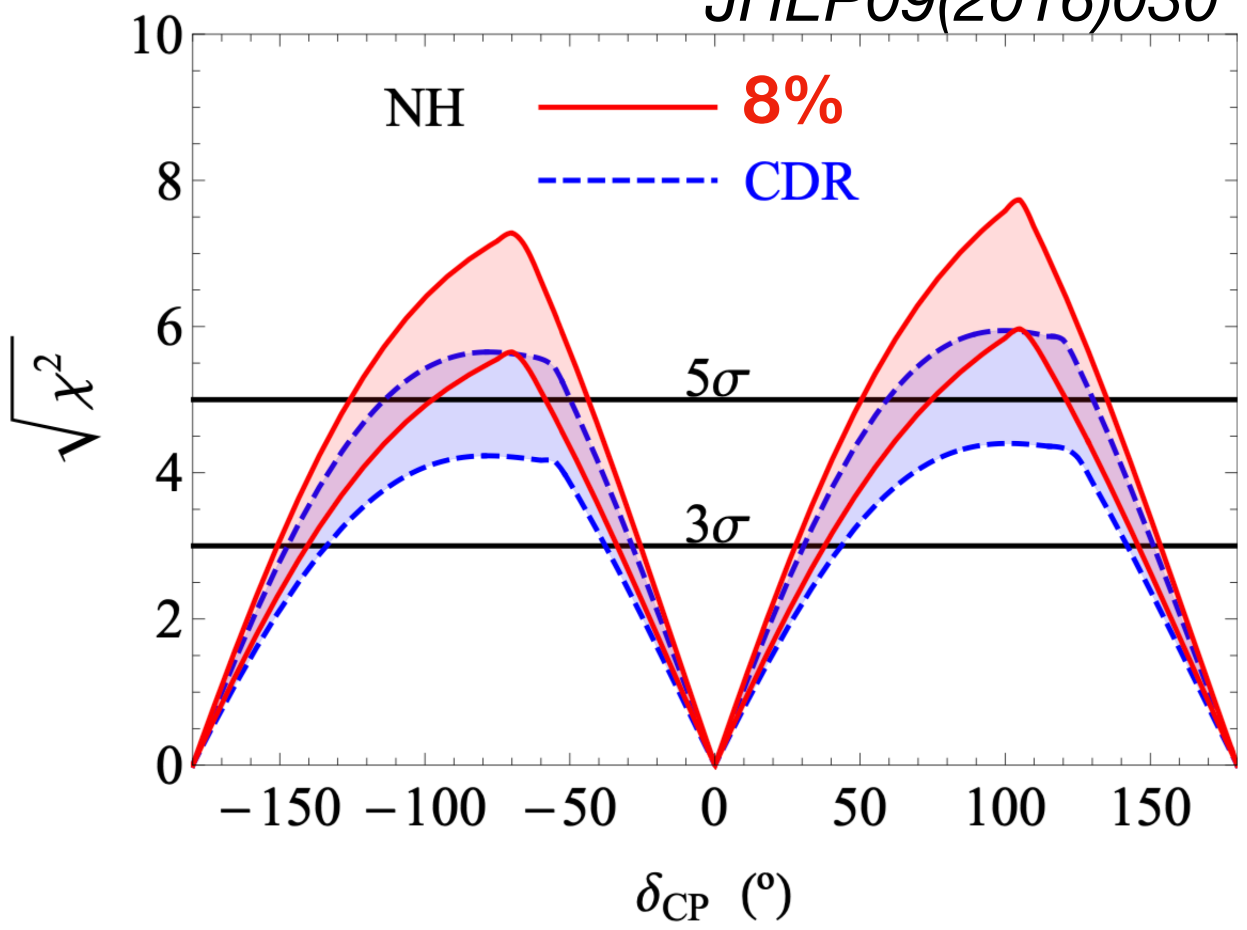
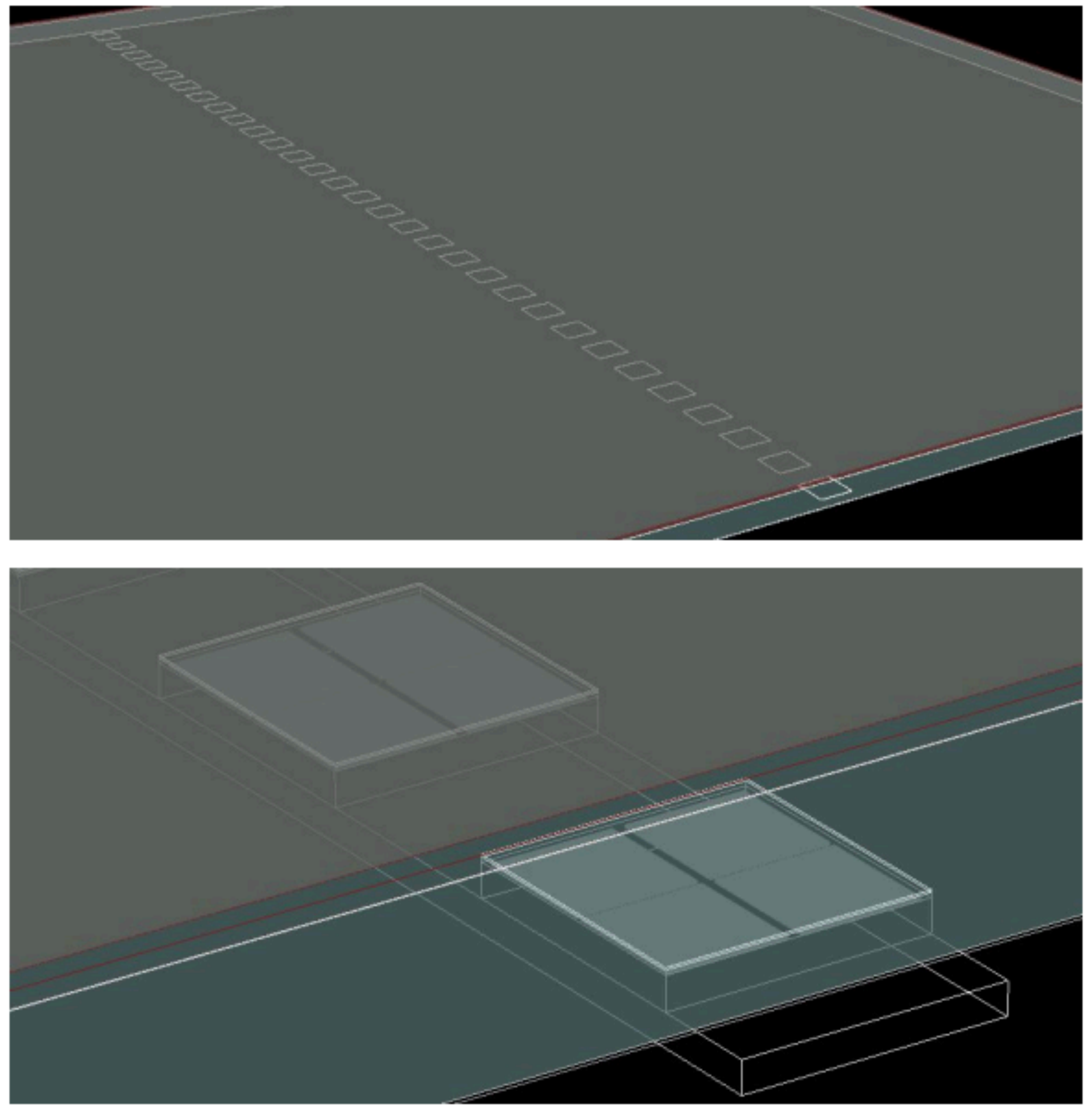


Optimize Photodetector Design

Simulation shows SiPM on edge doubles photon collection efficiency than glued at the center of acrylic

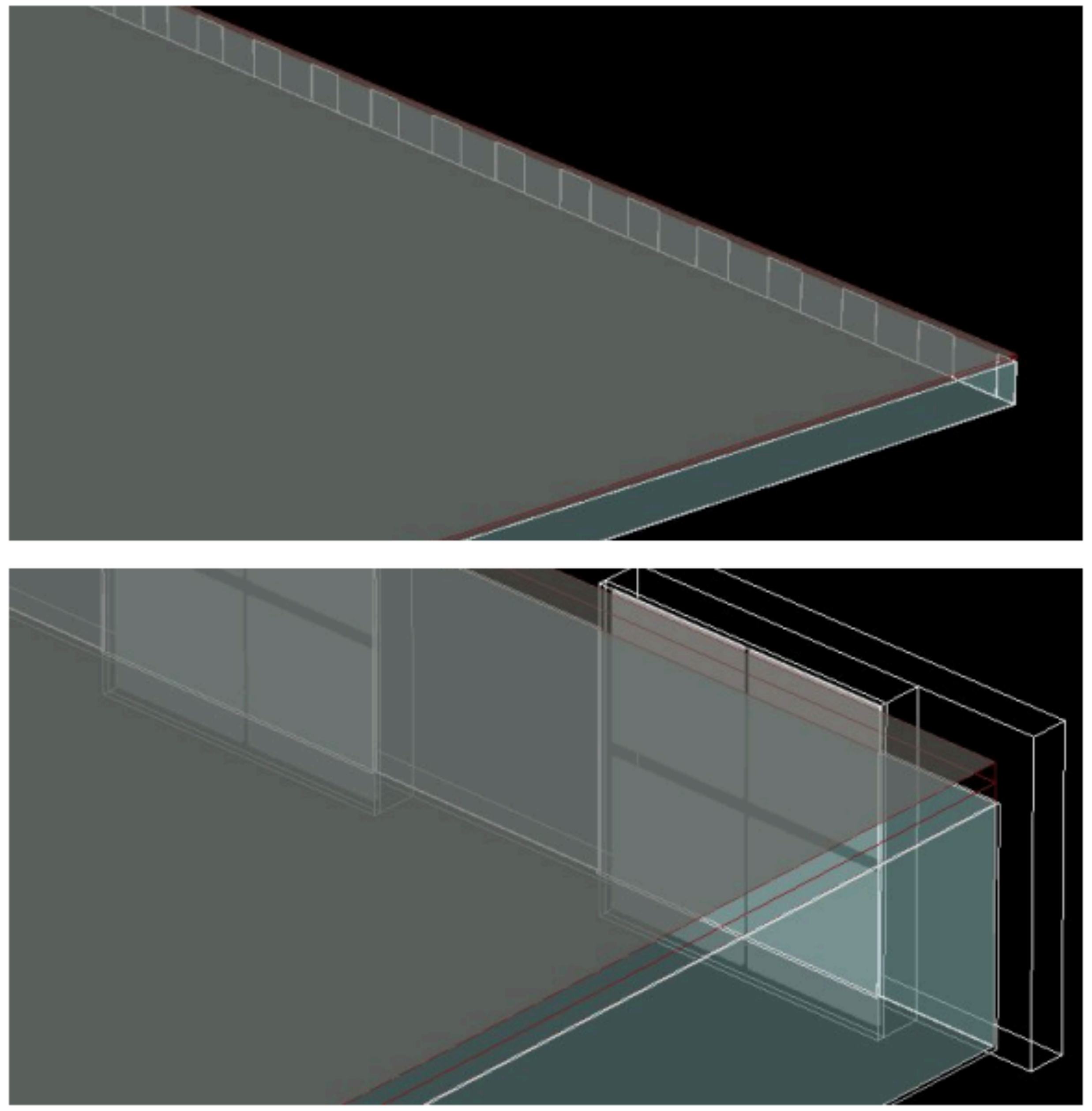
Results

Baseline



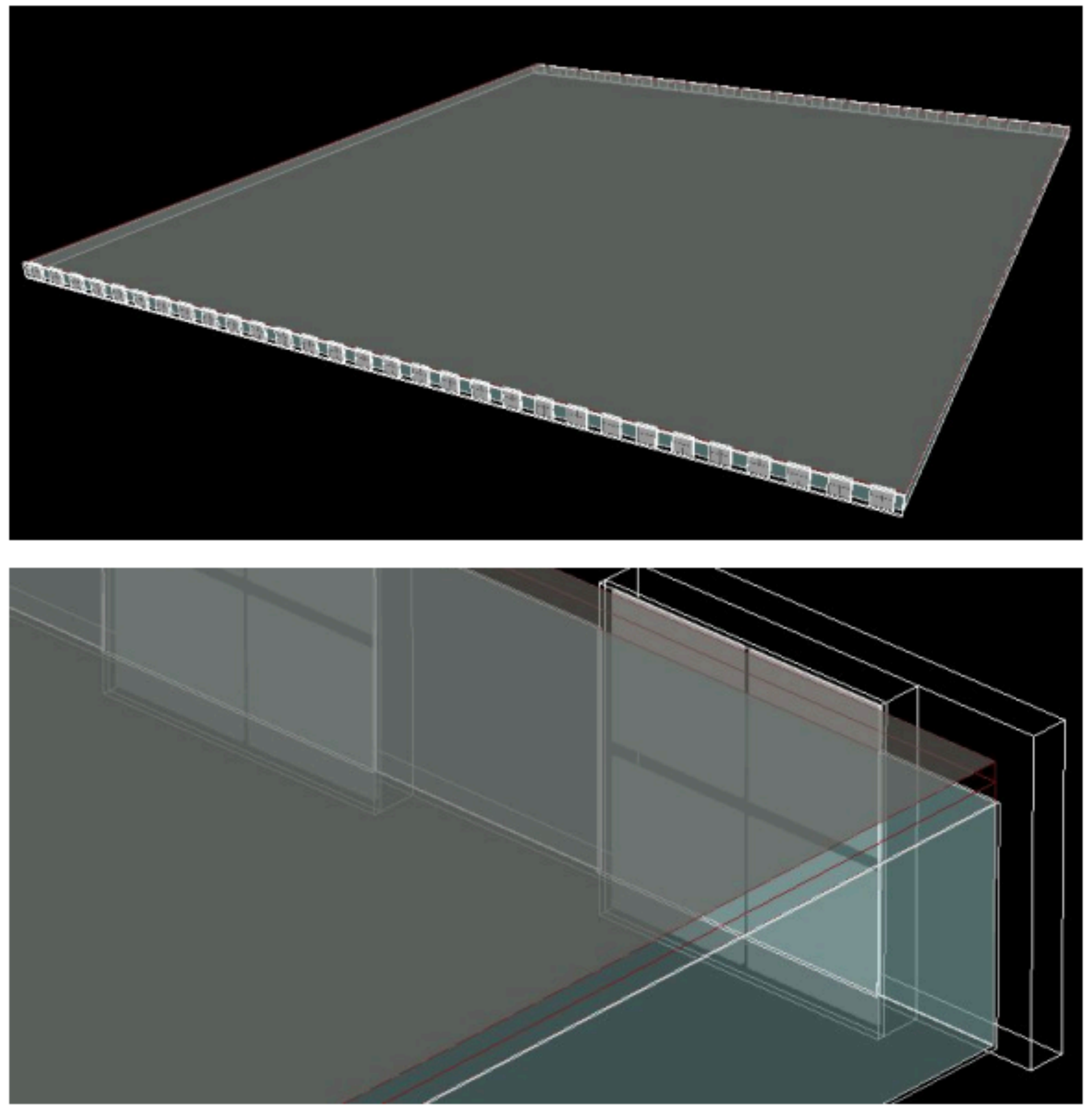
PCE ~ 0.63%

Side SiPMs



PCE ~ 1.23%

Side SiPMs (doubled)



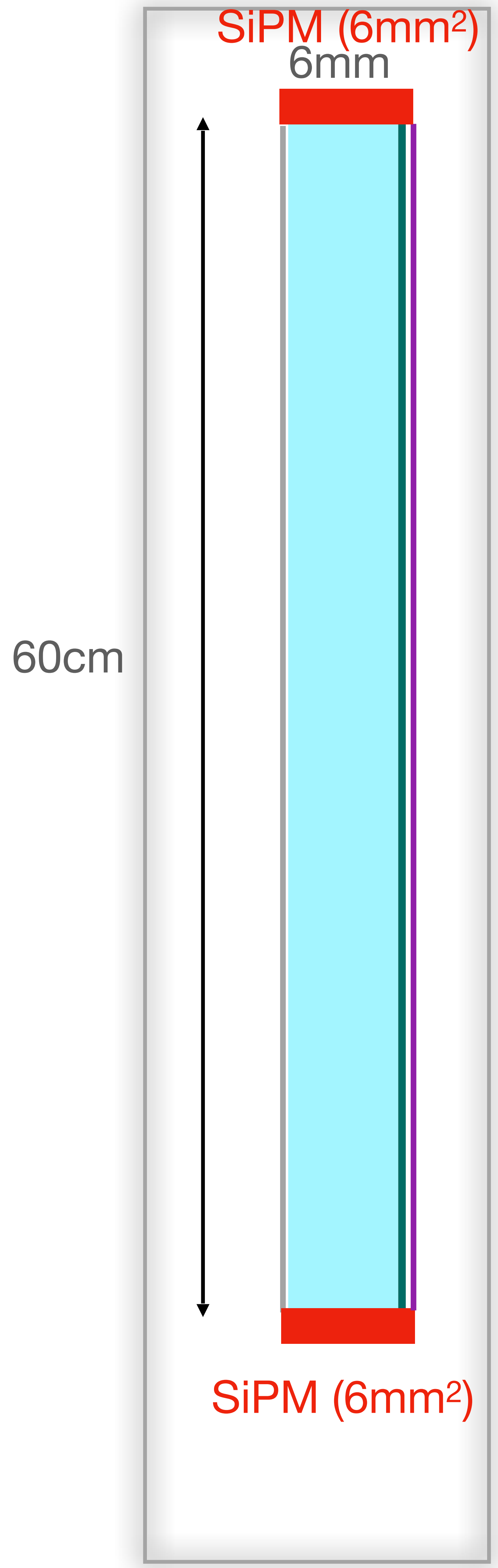
PCE ~ 2.27%

J. Urena

A Potential Two-acrylic-layer Design

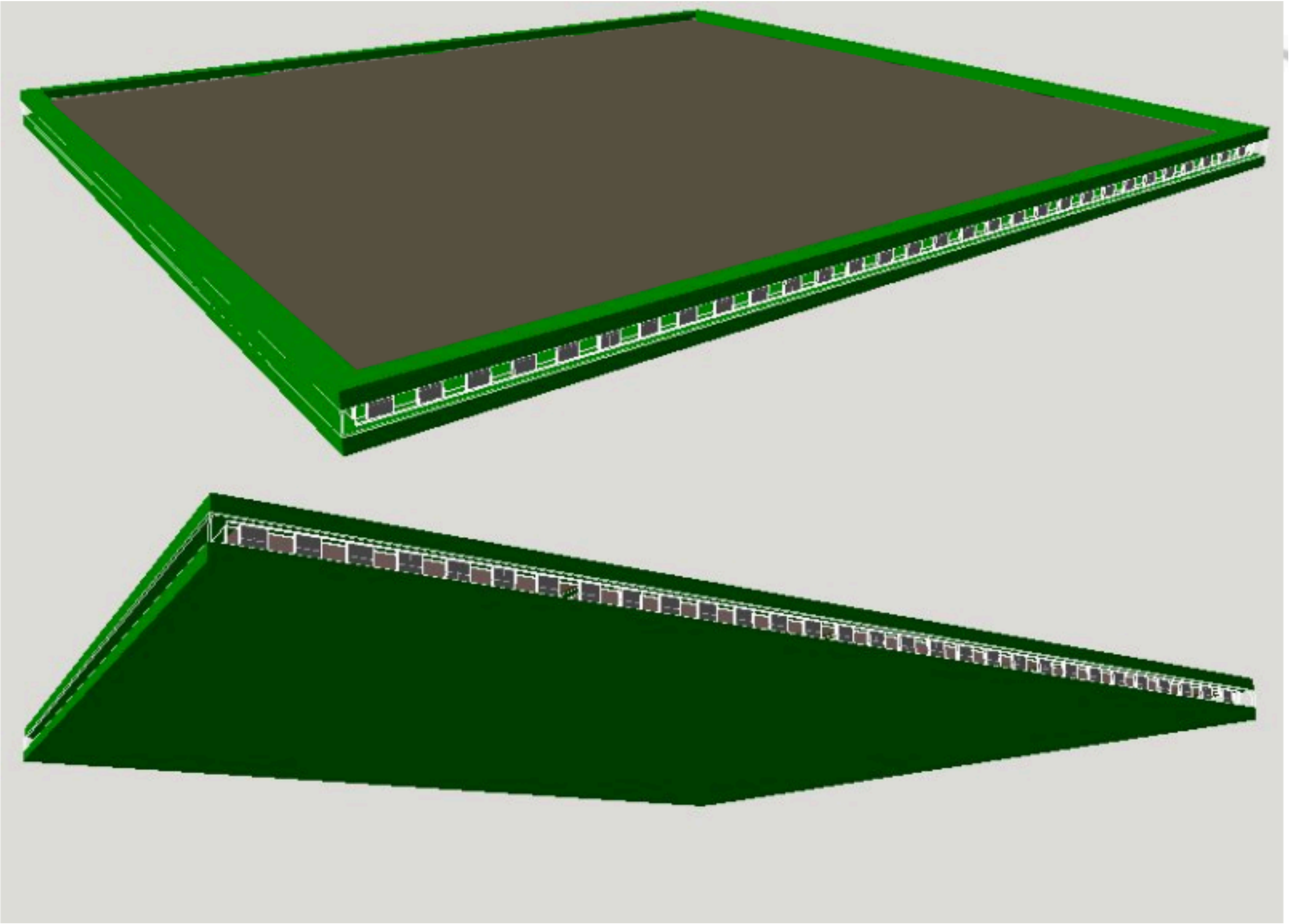
Baseline XA design

[Reflector - WLS2 - Dichroic - WLS1]
VIKUITI foil - PMMA - ALD - pTP film



Single sided SiPMs (PDE 1.23%)

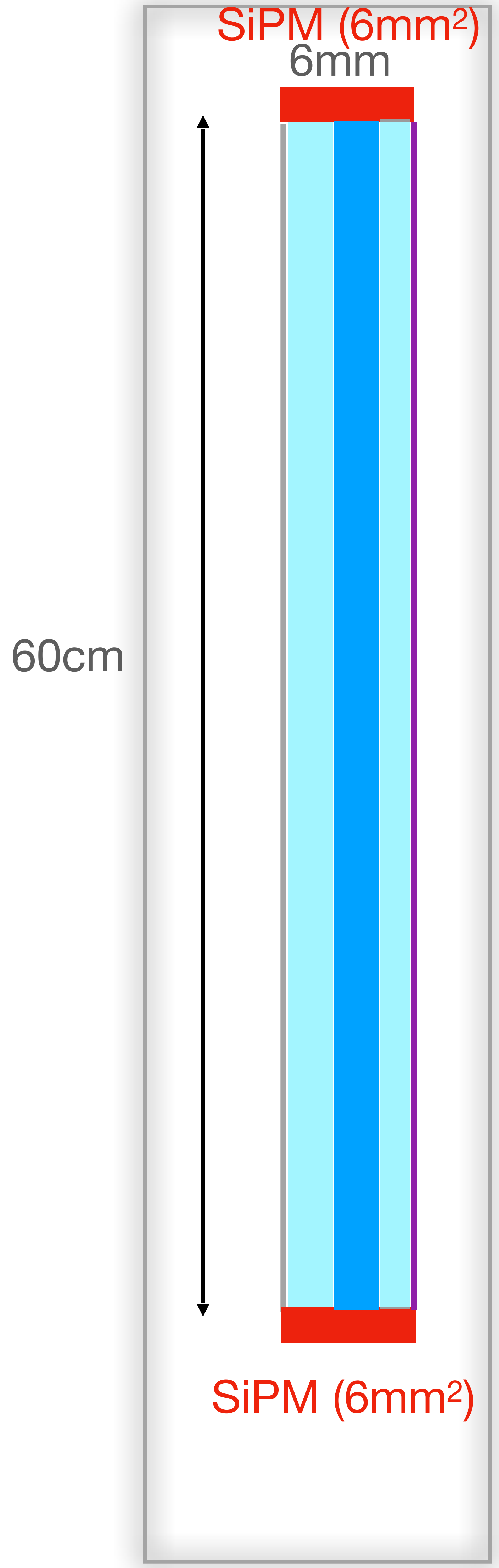
Detached acrylic plates
with LAr filled gap enable total reflection
PDE ~ 1.73% (40% higher)



Two-acrylic-layer design
for improved efficiency

Pending further simulation.

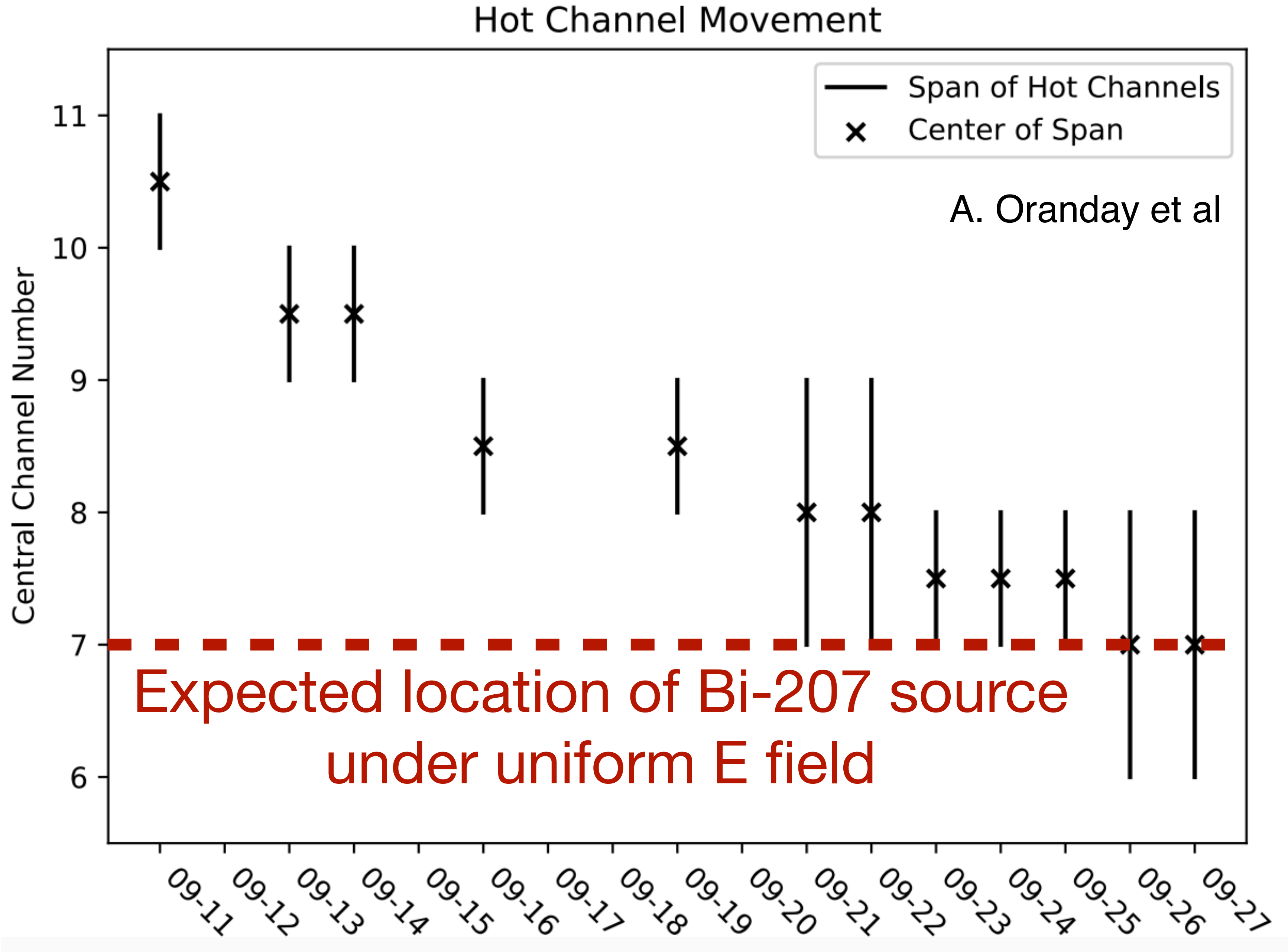
[Reflector - WLS2 - LAr - PMMA - WLS1]
VIKUITI foil - PMMA (doped) - LAr - PMMA - pTP film

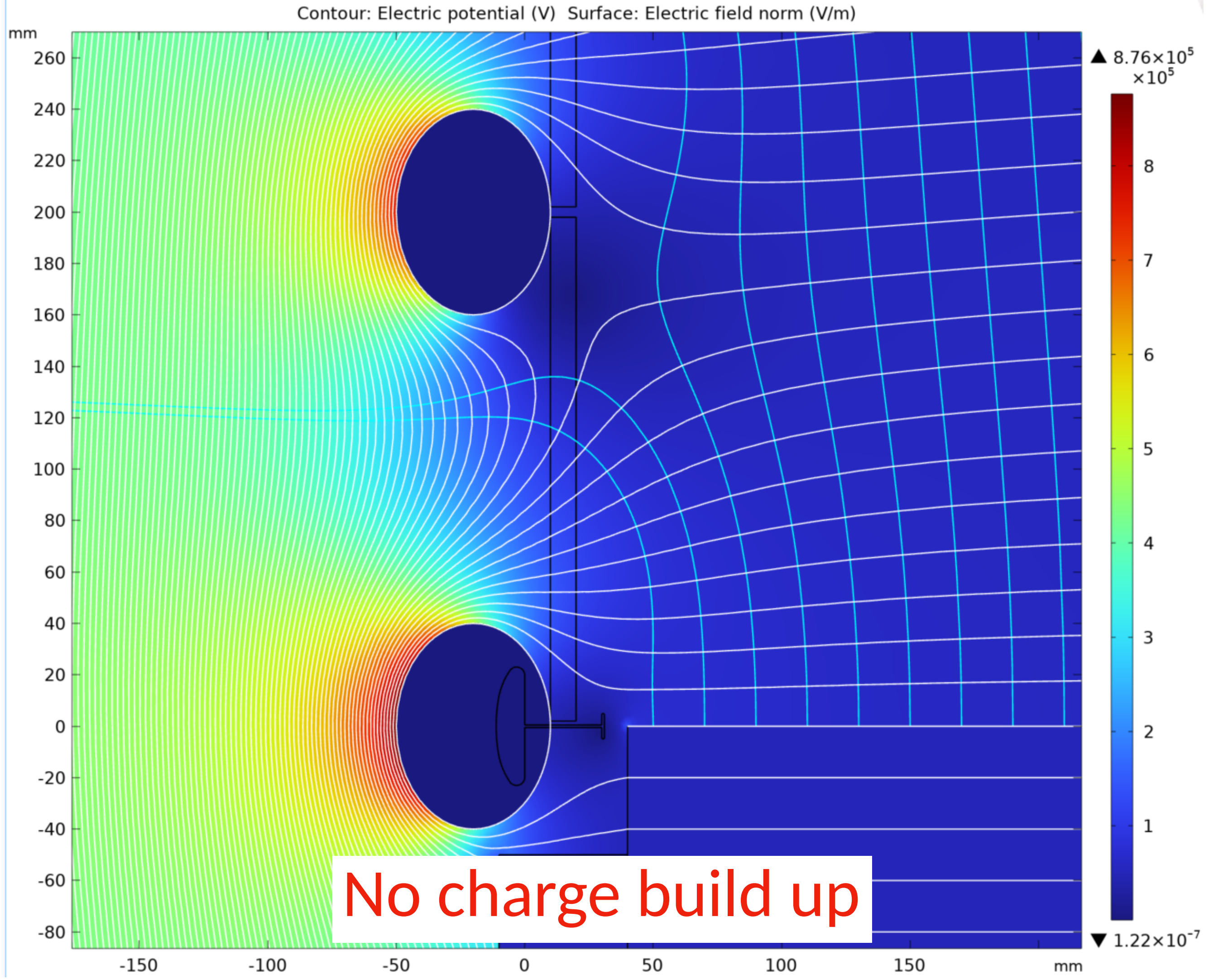


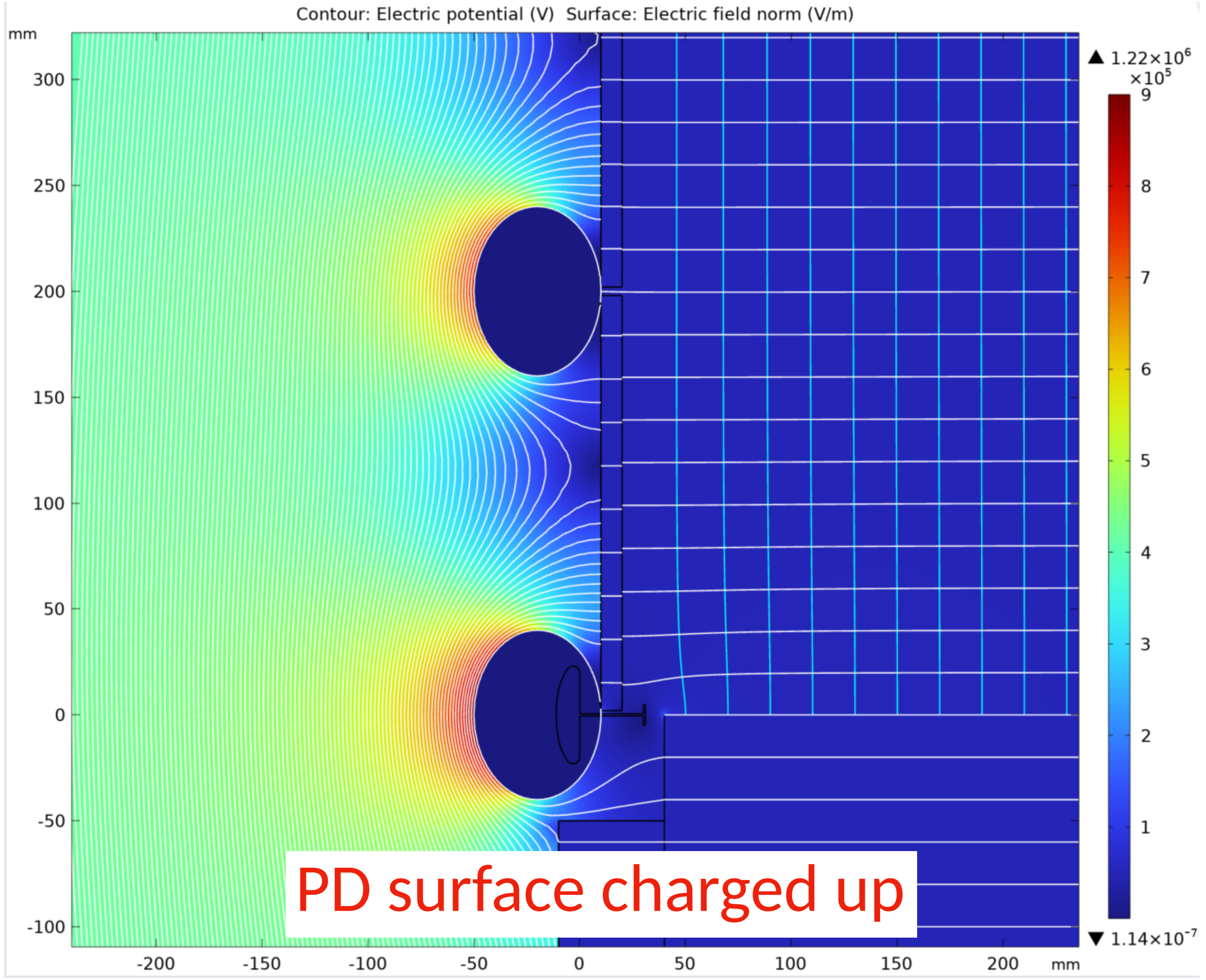
Charging up Test @ CERN 50L TPC

- A bulk G10 between FC metallic (conductive) profiles will charge up in **E** field
  - Interest to reduce the number of FC profiles if charging up time is short

- Test shows it's a slow process on surface: 2 weeks
  - **Extra FC profiles needed across PD**

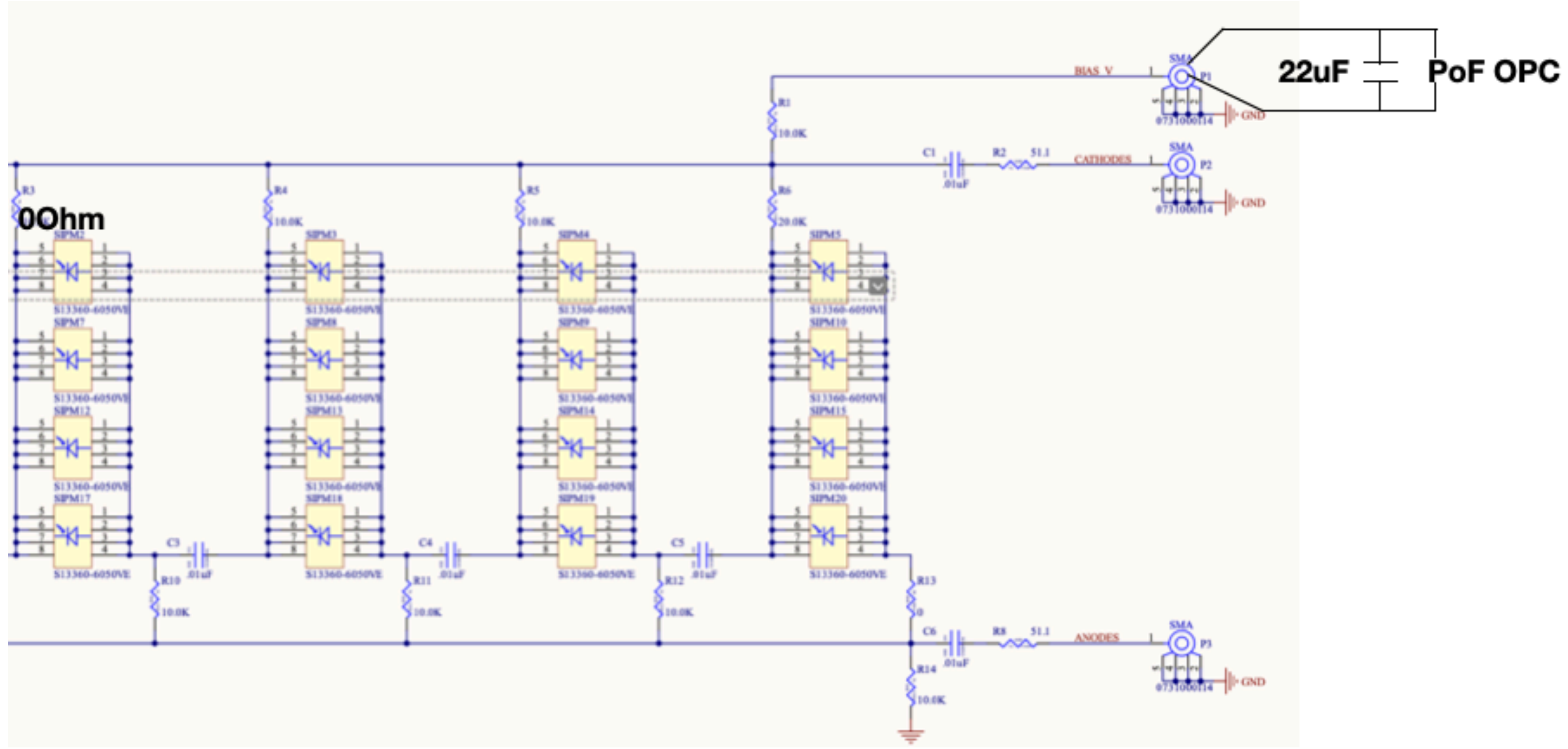


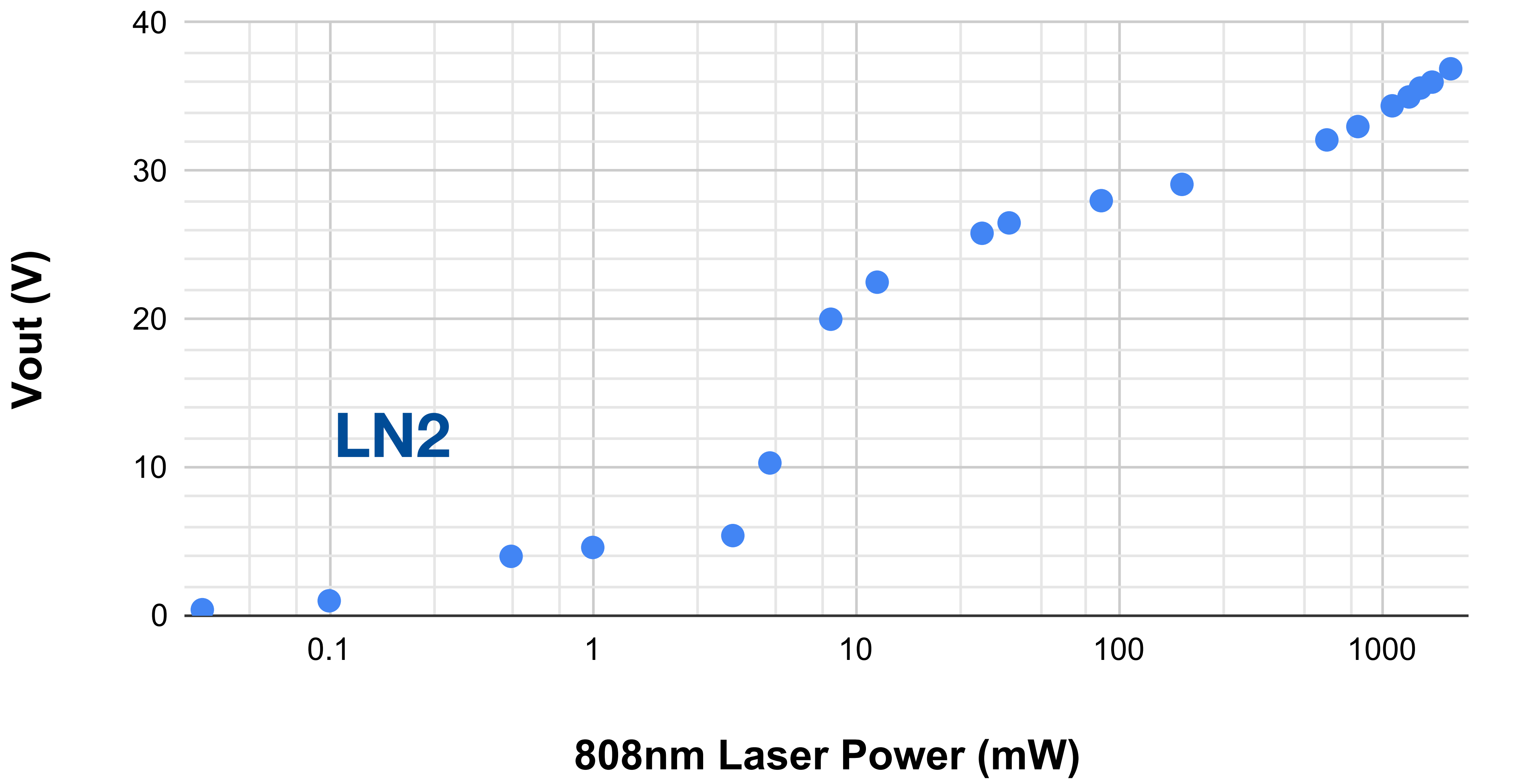




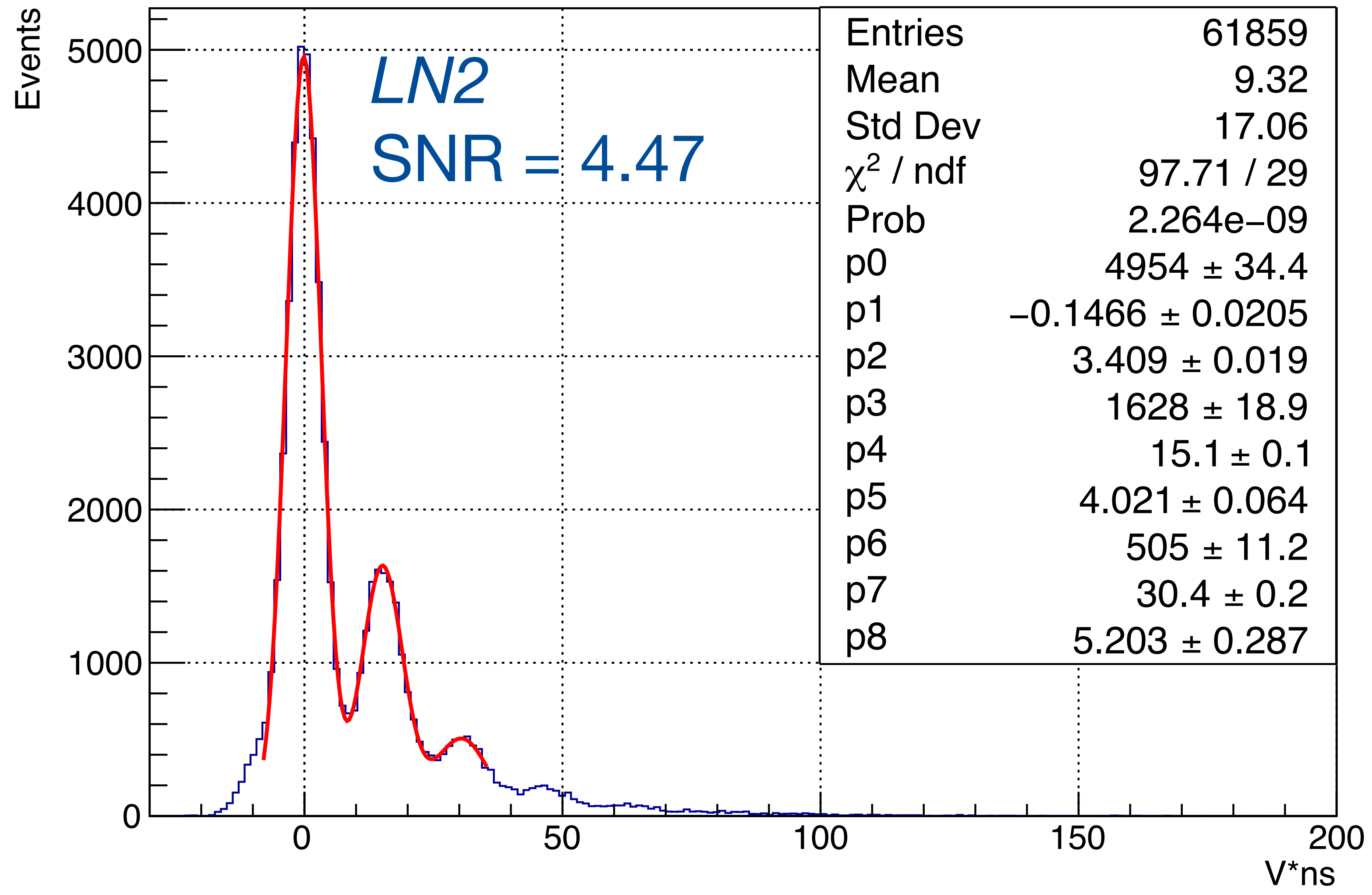
New Development for APEX: HV PoF for SiPM Bias

- PoF system for VD only outputs lower voltage (~7V)
    - VD adopted LDO + DC-DC stepup for SiPM bias
- Latest PoF HV product can provide bias up to 36.9V
    - Higher output possible by improving the receiver design
- **Demonstrated SiPM can be successfully biased from PoF and have good SNR**



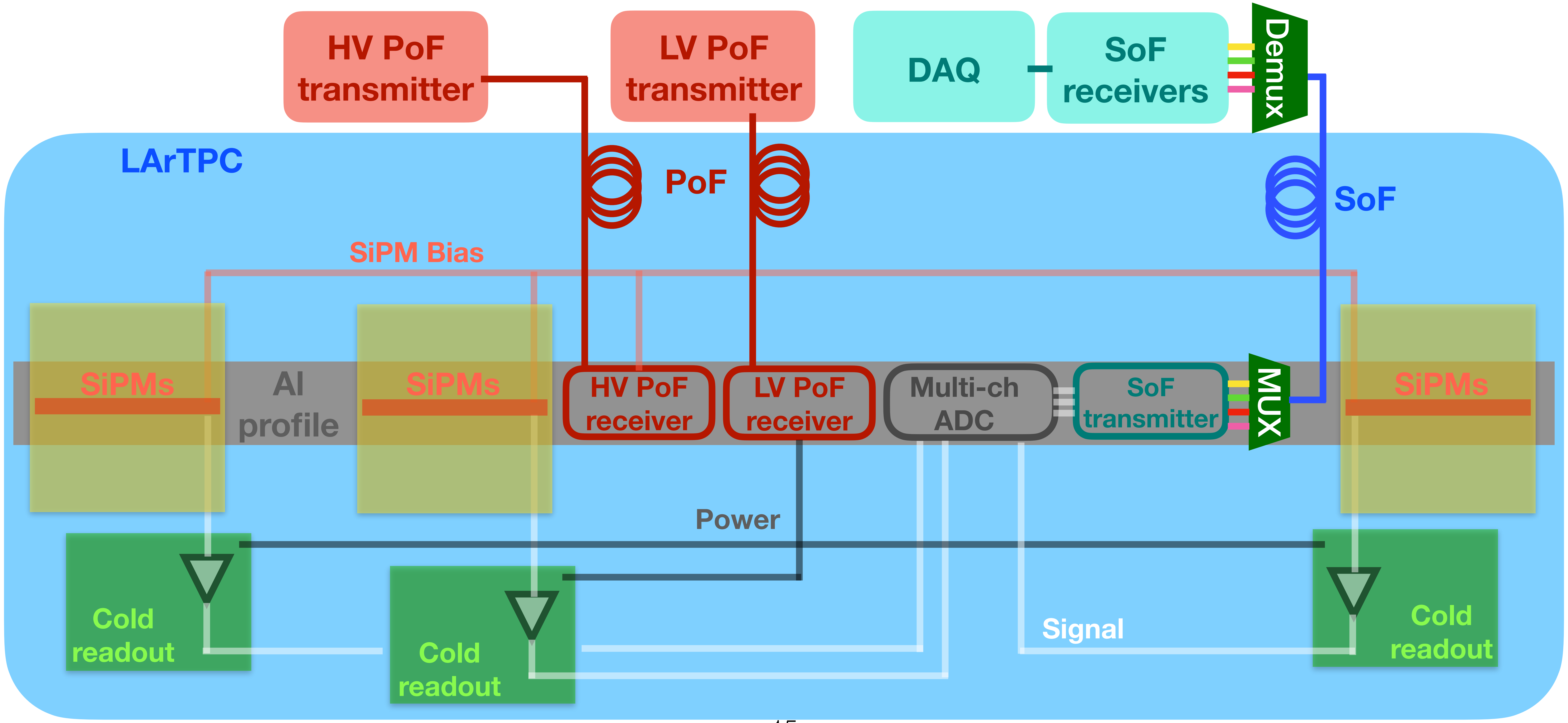


PoF bias=36.9V, 2μs integration time

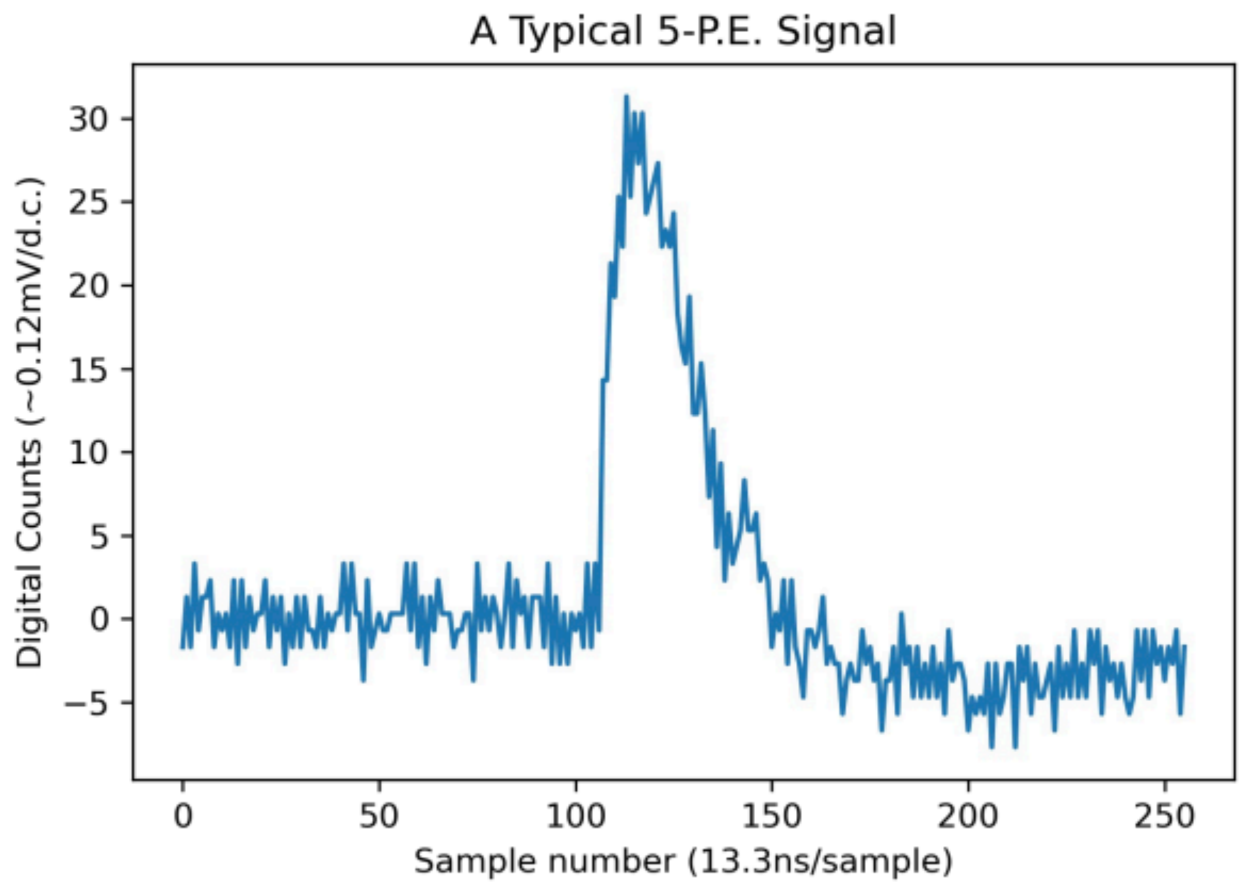


APEX Module Readout Concept with PoF and SoF

- LV PoF for powering cold readout electronics
- Each row of 6 PD modules share HV PoF to bias all SiPMs, share multi-channel ADC to SoF
- **Digital SoF is widely implemented in HEP experiments, the challenge is to make it work in LAr**
  - Wavelength division multiplexing for SoF can further reduce number of fibers (later slide shows some encouraging progress has been achieved already)

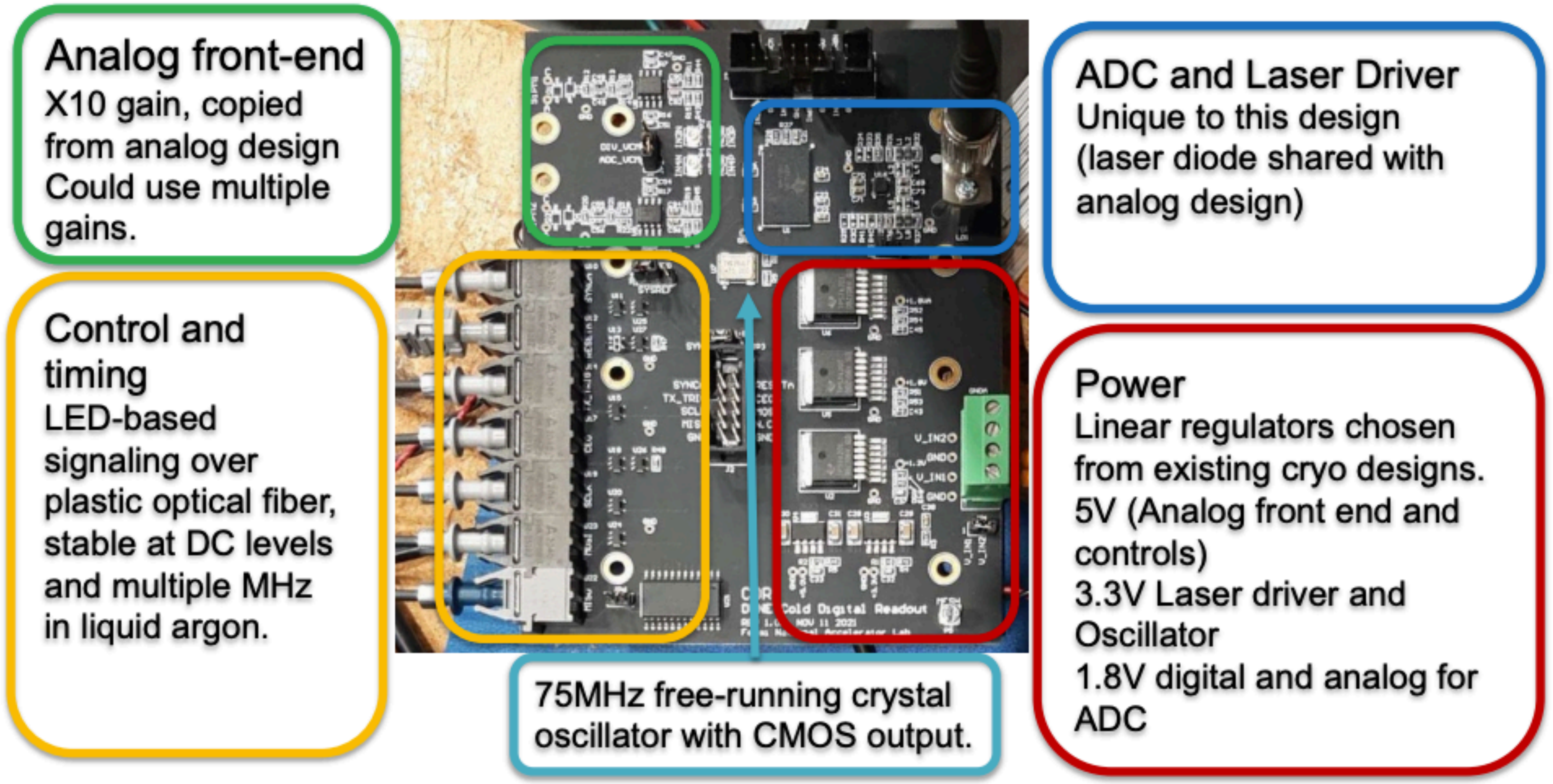


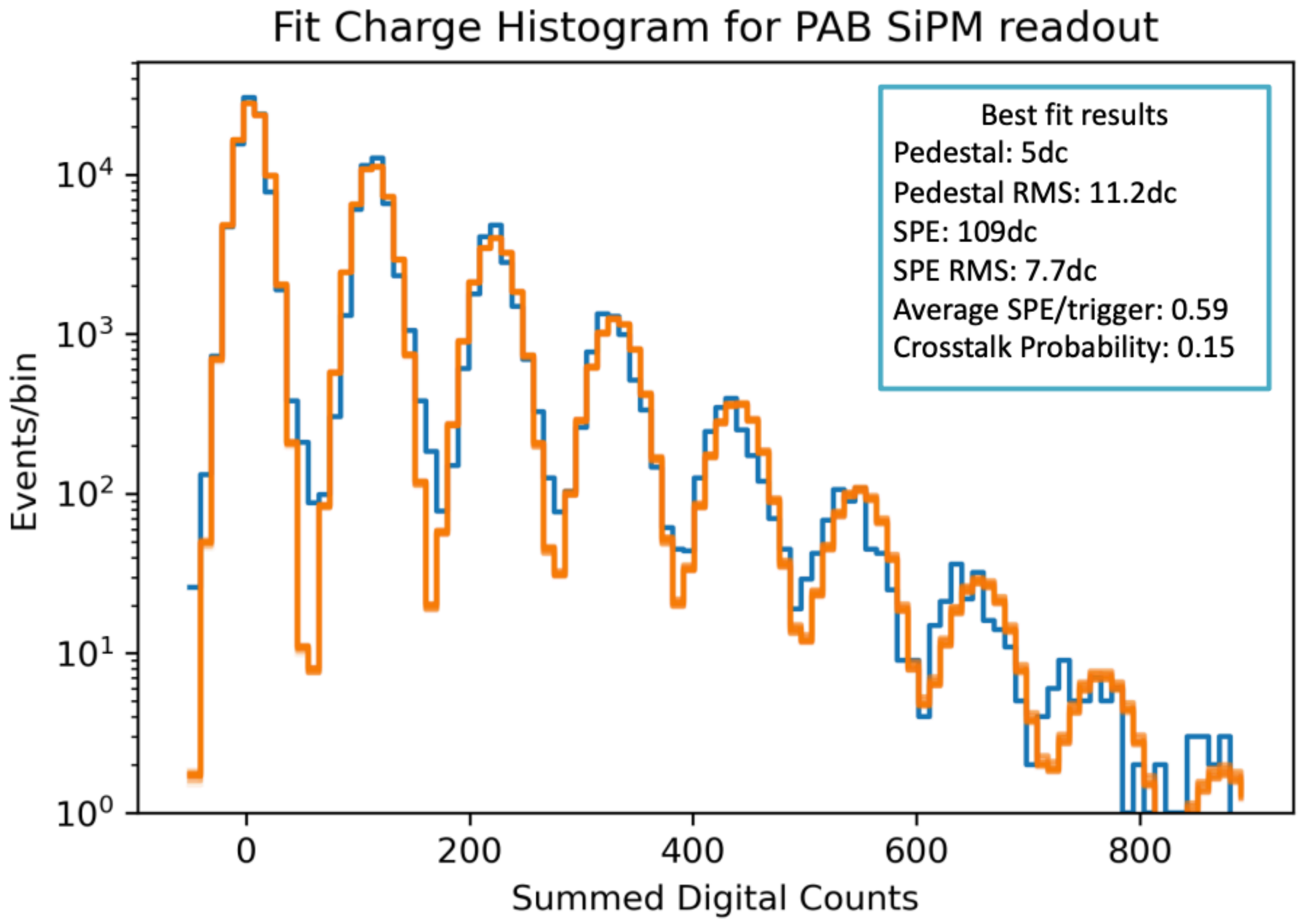
Signal Digitization and Transmission via Cryogenic Digital Optical Link
Baseline Solution



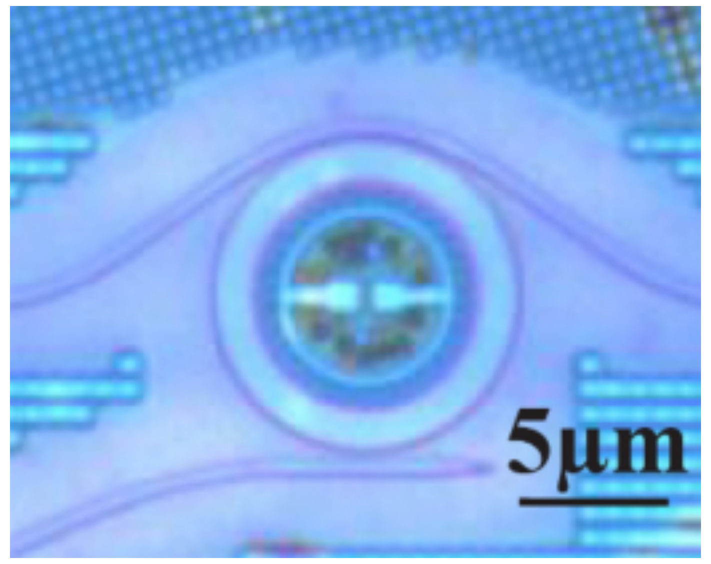
- Several prototypes at Fermilab
  - ADC chips: TI ADS52J90, ADI AD9656, TI ADS52J65 (to be tested)
    - Best efficiency when many channels can be utilized

- Slow control signals
  - Had issues with plastic optical fibers with LED transmitters
  - An onboard active controller device (ASIC, FPGA, Microcontroller) would greatly simplify the design, eliminating the need for most control

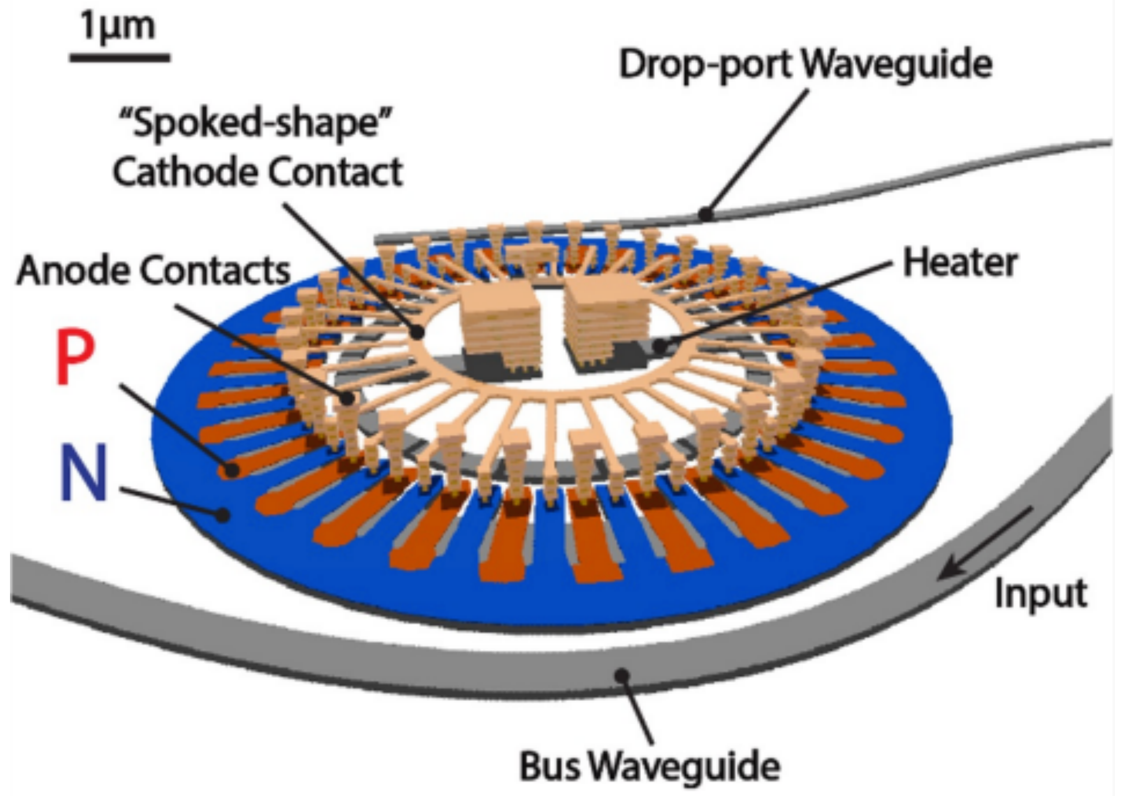




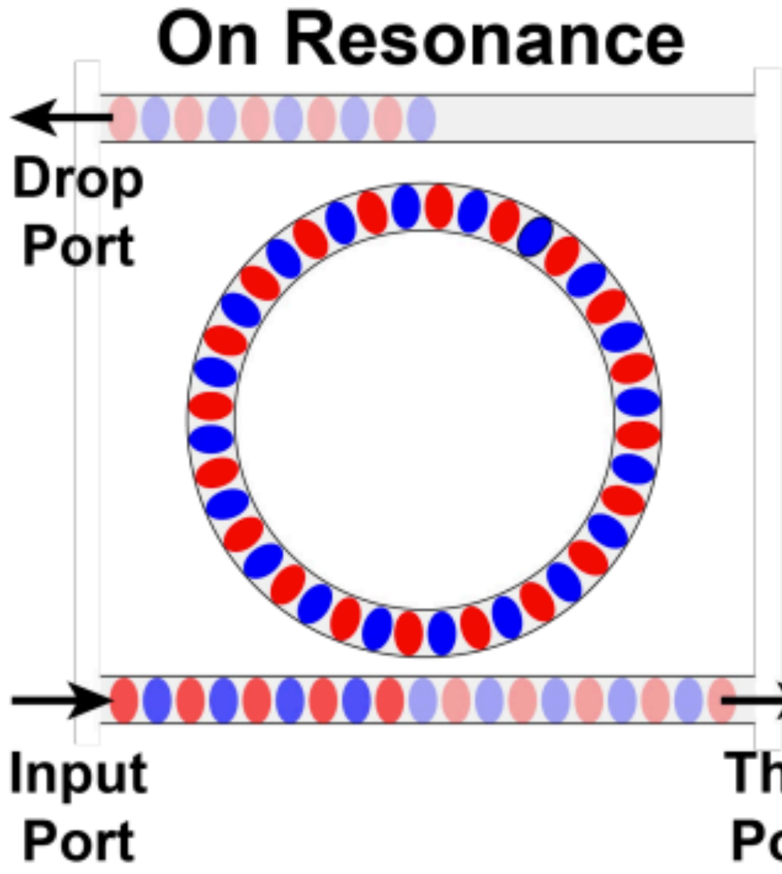
Advanced Solution:
Ring Resonator for SoF

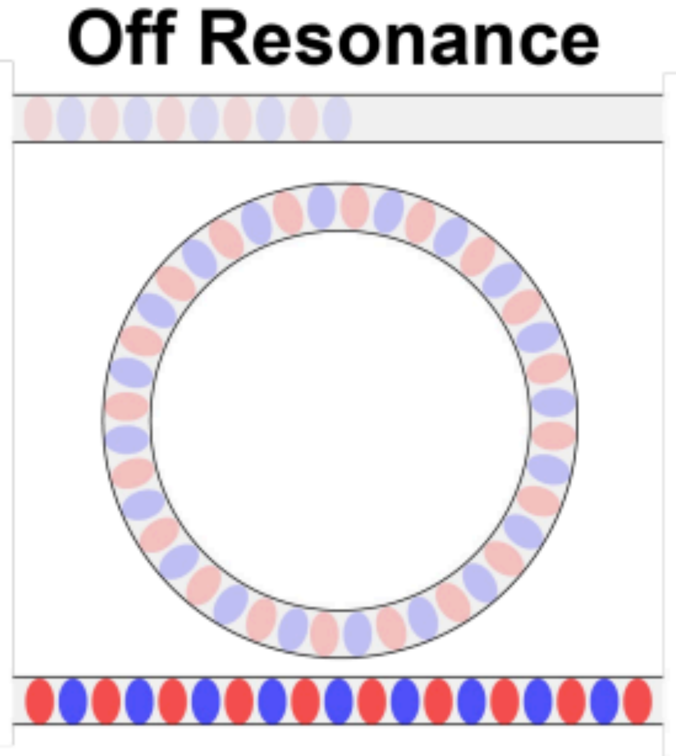


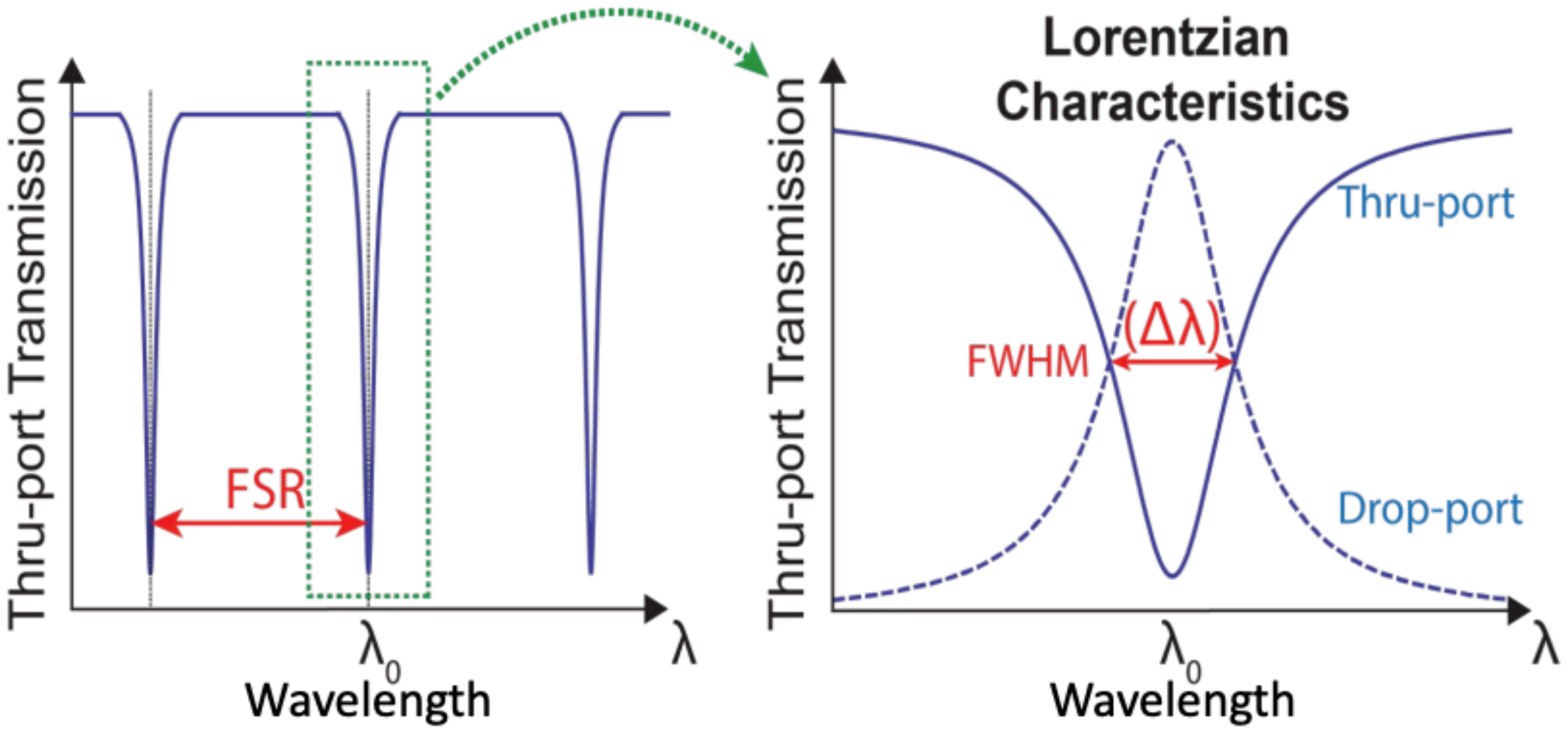
- Challenge of increasing readout channels and large bandwidth data transfer
  - 14(ADC-bits) x 67 MHz x 288 channel per FC ring x 24 rings ~ 6.5 **Tbit/sec**

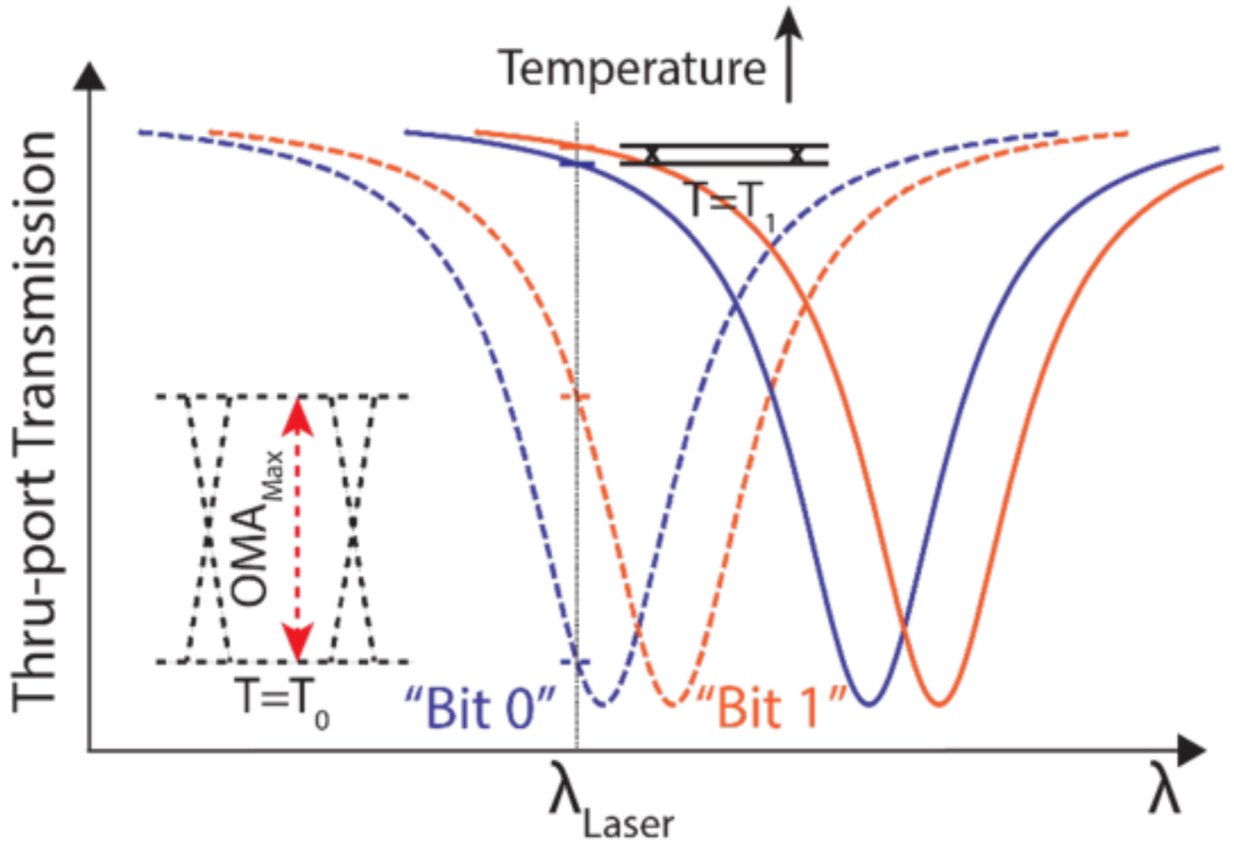


- **Micro-ring modulators (MRM)** offers low power, low heat load solution
  - < 1 pJ per bit@25Gb/s, translates to ~mW per FD3 XA
  - Signal bits modulates laser on and off
  - Wavelength division multiplexing can reduce number of fibers
- Already used in LHC experiments, but need to be customized for 87K application
  - MRM's tuning, optical packaging, integration with CMOS and detector
  - Have industry partners, R&D ongoing









Toward DUNE Phase II FD

DUNE FD3 Mini-Workshop Toward a Combined Photon Detection and Field Cage System

> 60 participants!

Jun 26 – 28, 2023
Stony Brook University Physics Building
US/Eastern timezone

- Kickoff workshop at Stony Brook
- Discussed items (detector & electronics) that can be further improved from VD
- Discussed synergies with other FD3 concepts (TPC charge readout)
- Made plans toward prototypes

June 26-28, 2023 @ Stony Brook

20+ Participating Institutions (US, South America, Europe)

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BERKELEY LAB Lawrence Berkeley National Laboratory

Stony Brook University

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

UNIVERSITY OF MINNESOTA

SOUTH DAKOTA MINES

UNIVERSITY OF CALIFORNIA SANTA BARBARA LET THERE BE LIGHT

INFN MILANO BICOCCA

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

CERN

Brookhaven National Laboratory

UTA THE UNIVERSITY OF TEXAS AT ARLINGTON

UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN

Yale

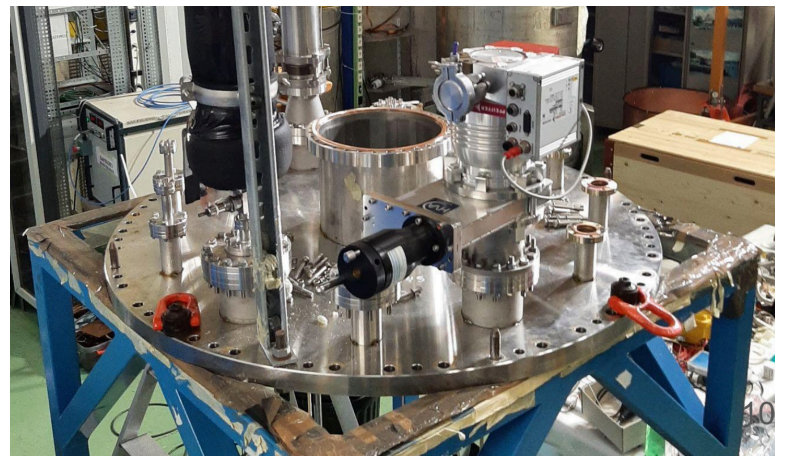
UNIVERSITY of WASHINGTON

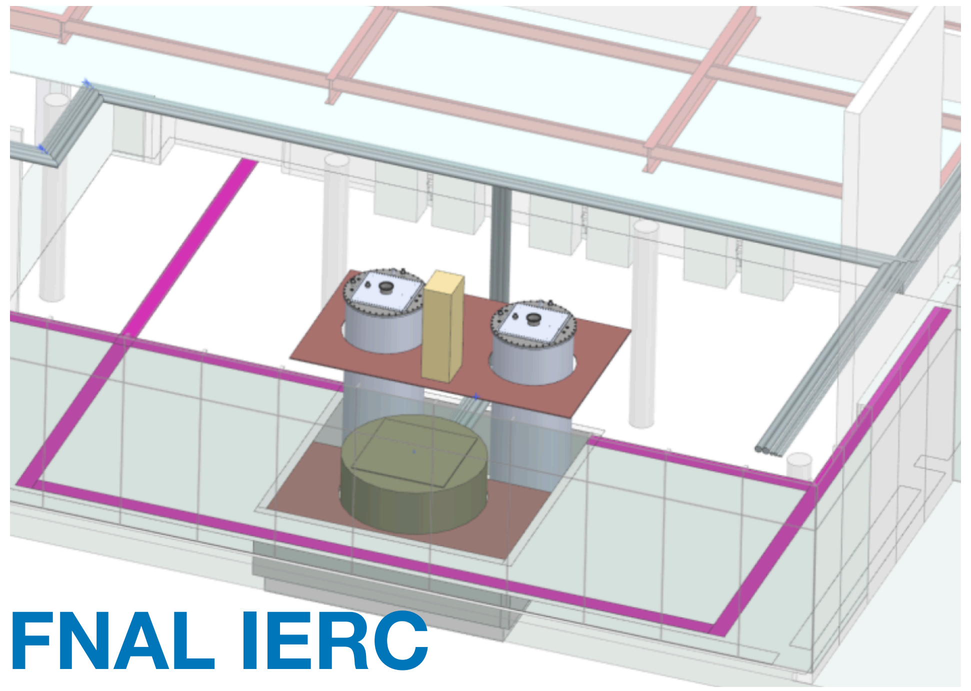
DUNE FD3 APEX Prototyping Stages

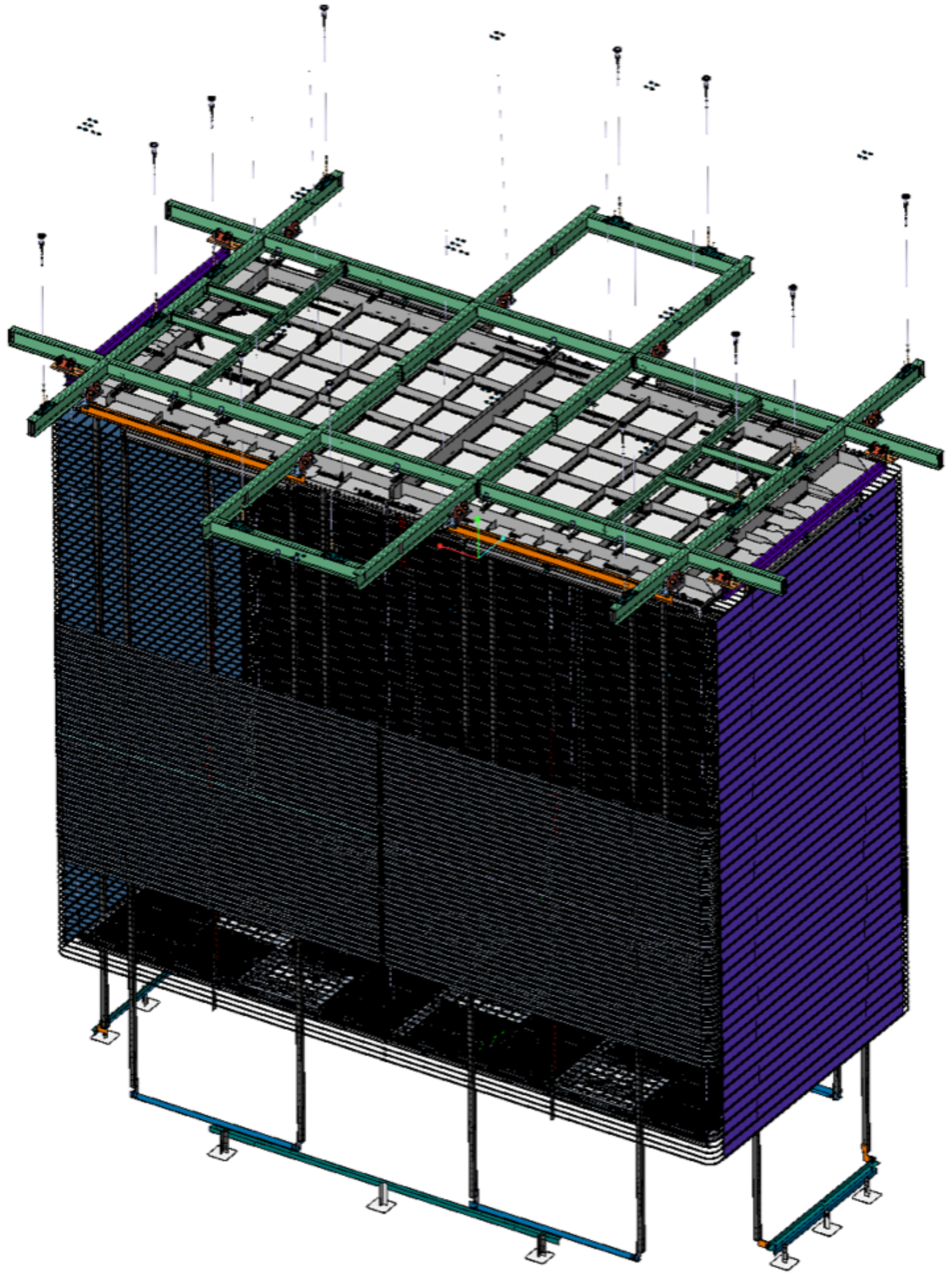
2023
Table-top
50L TPC

2024-2025
Ton-scale APEX
(CERN/Fermilab)

2025-2027
Kiloton-scale
ProtoDUNE/NP02
(CERN)

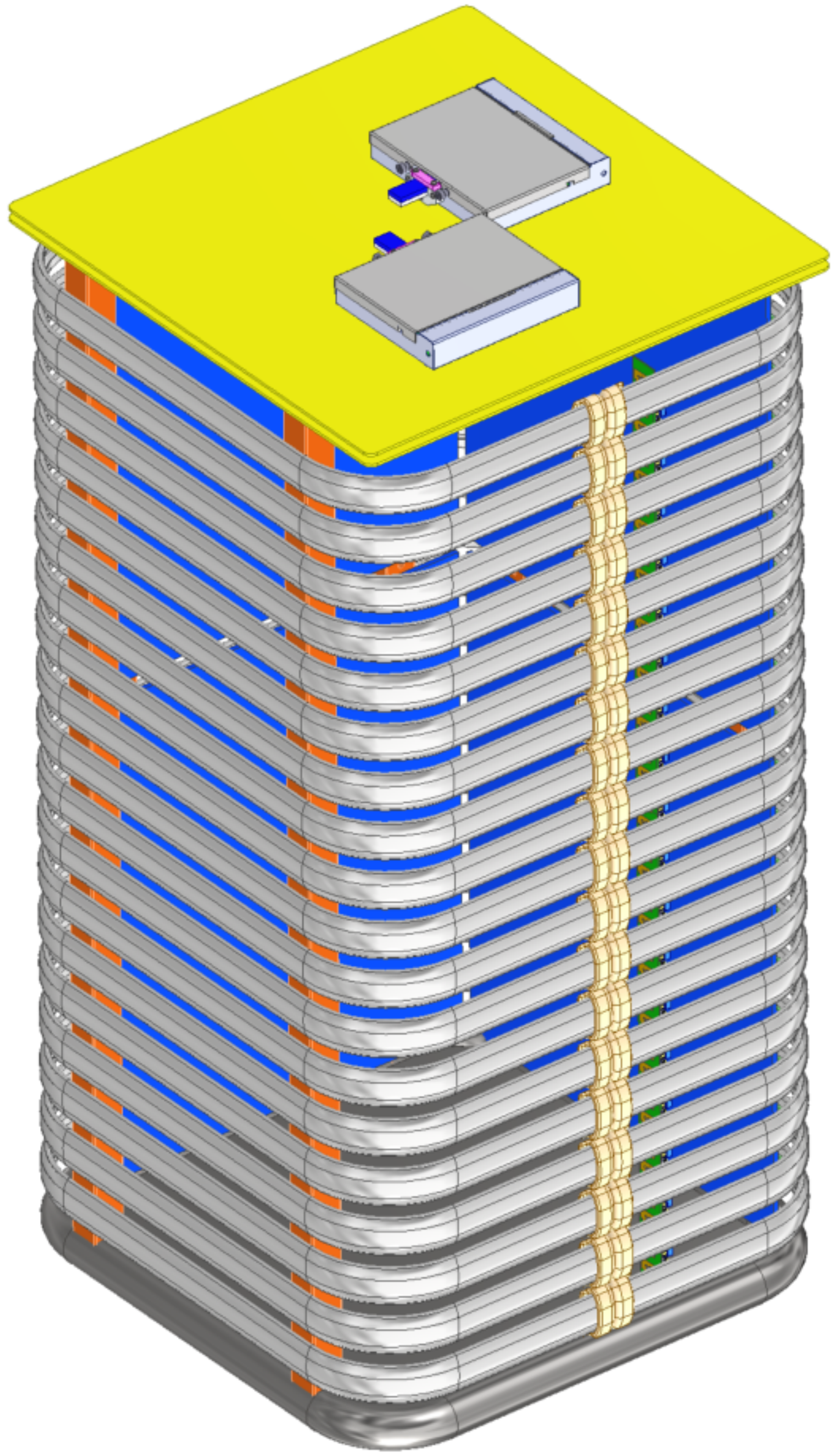


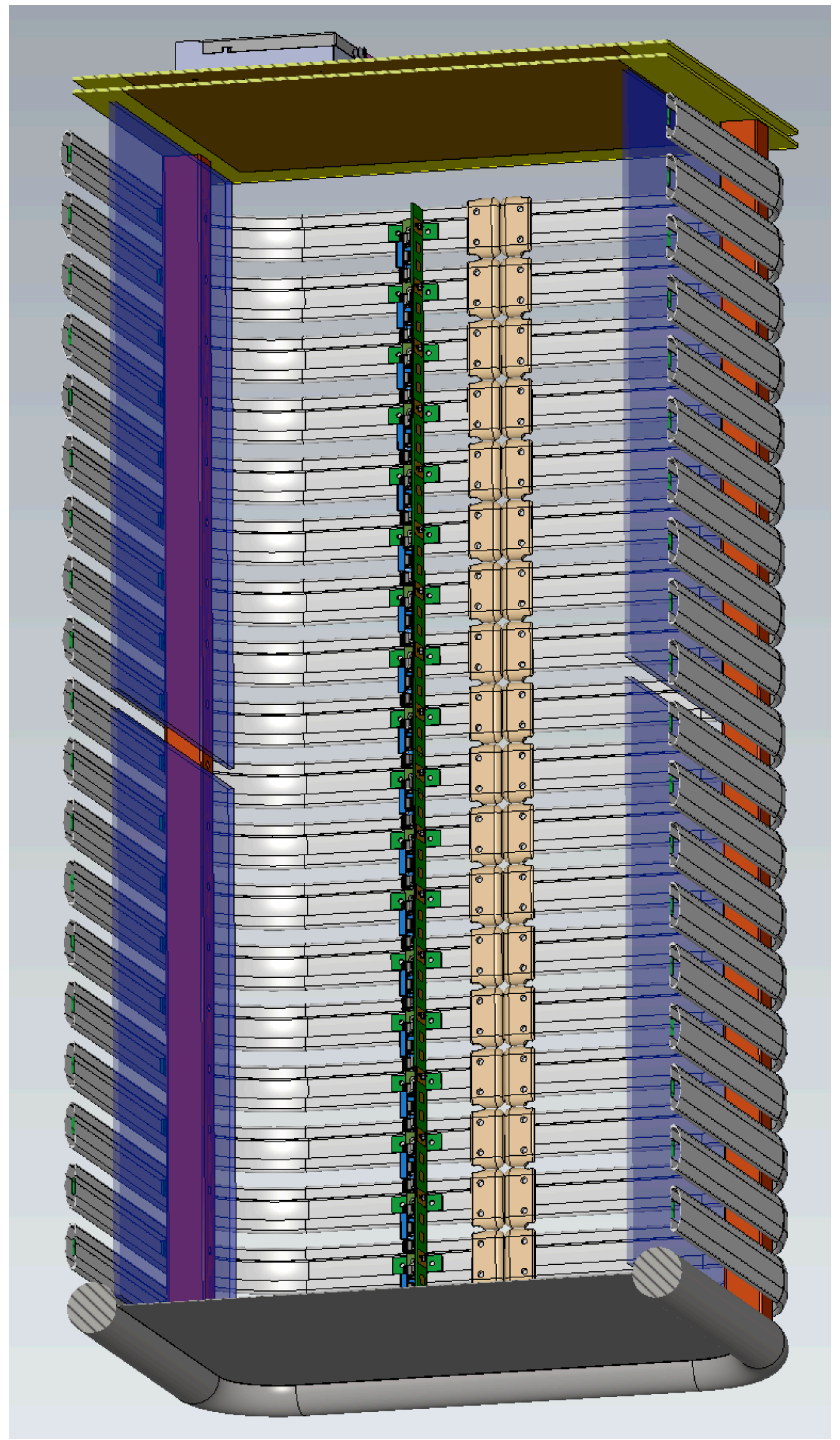


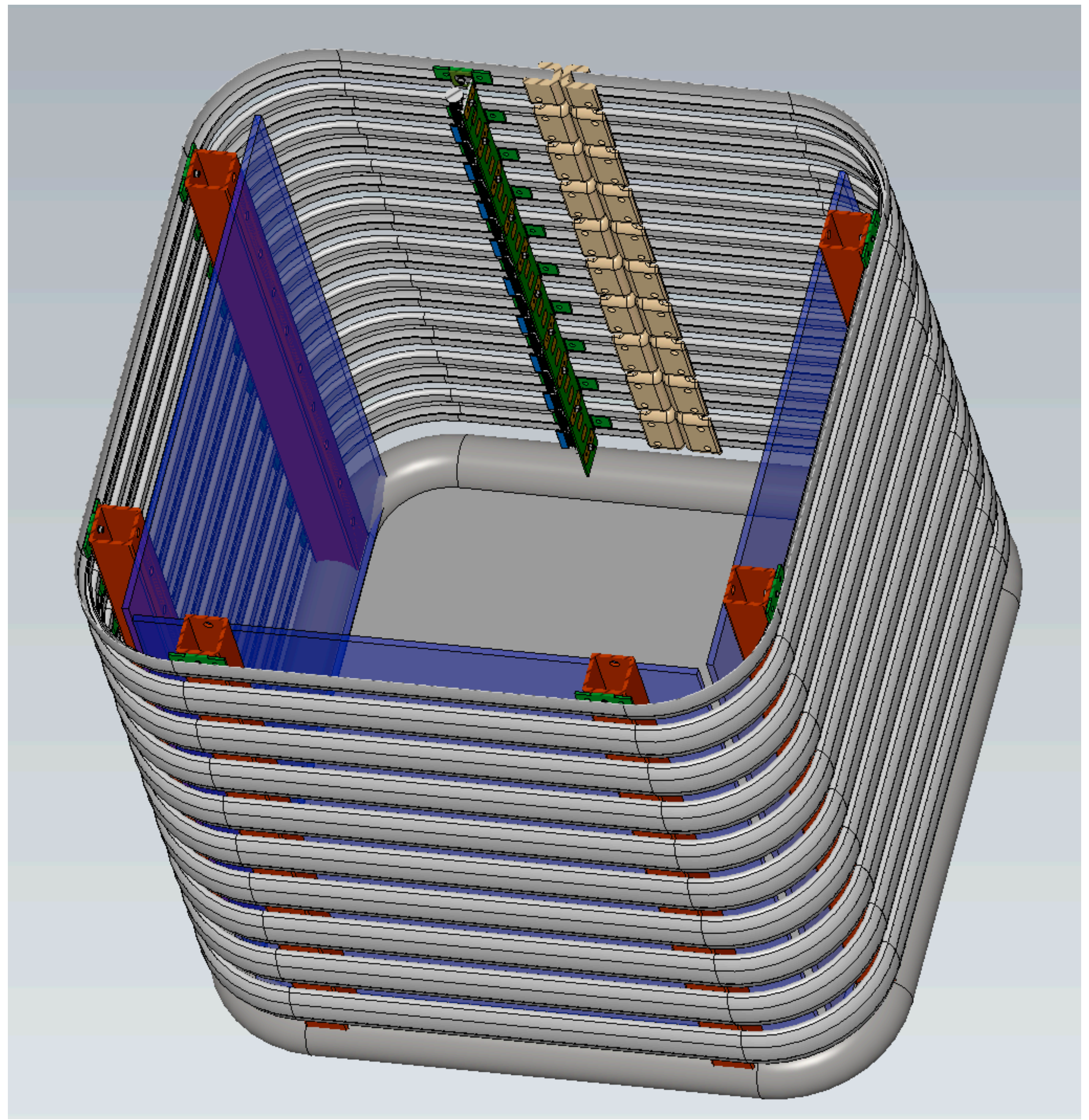


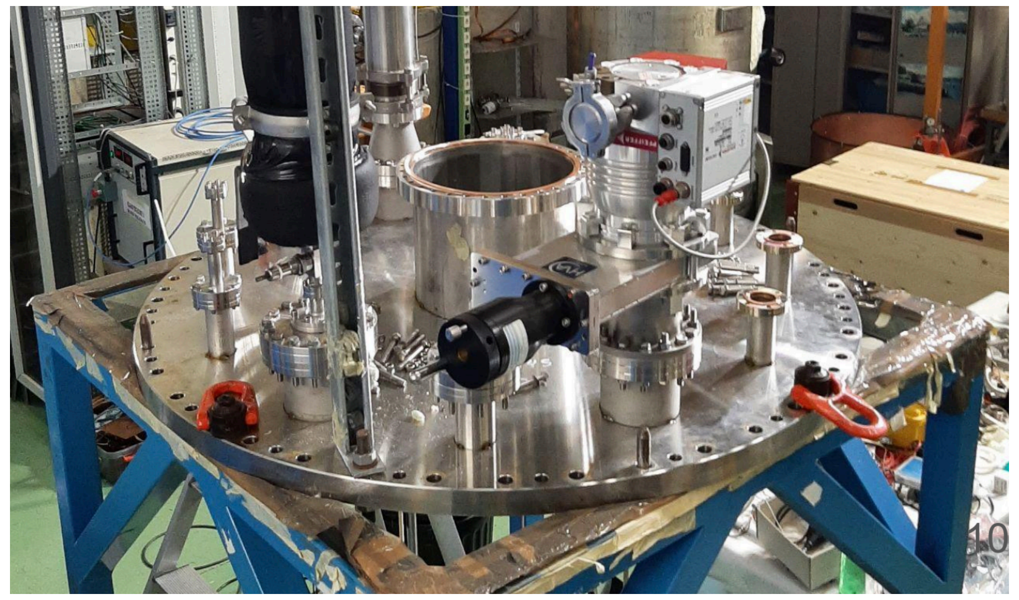
CERN 2t Prototype - Staged

- **1st prototype (summer 2024)**: pure acrylic + FC mechanical mockup only
  - Mechanical & cryogenic cool down stability tests
  - TPC/E field tests (charge up test…)
- **2nd prototype (end of 2024)**: Improved mockup with photodetector + SiPM + PoF/SoF readout
  - Electronics/fiber routing + signal readout tests
- Both prototypes could instrument up to 8 X-Arapuca modules









Summary

- APEX is a proposed solution to significantly expand the active optical coverage area to O(2000m^2) toward 4π light collection for DUNE Phase II FD
- Many new ideas developed from DUNE VD R&D
- Prospects of improving energy resolution at GeV and MeV region by leveraging dual calorimetry and PDS timing
- Challenging but exciting: integration of PDS to the LArTPC field cage, power delivery and cold readout via fiber, and reducing channel count
- Staged 2t prototypes expected to be built and tested this year