Photon Detection System for DUNE Phase II FD: Physics Prospects and Prototyping Status

NuFact 2024 - WG6: Detectors
Sep 20, 2024
Argonne National Lab

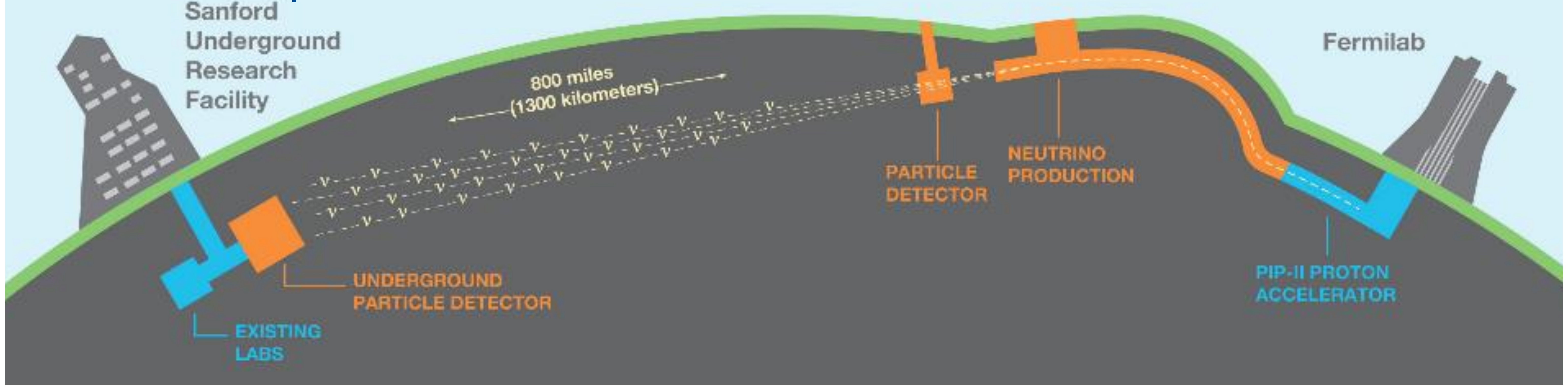
Wei Shi
on behalf of the DUNE Collaboration

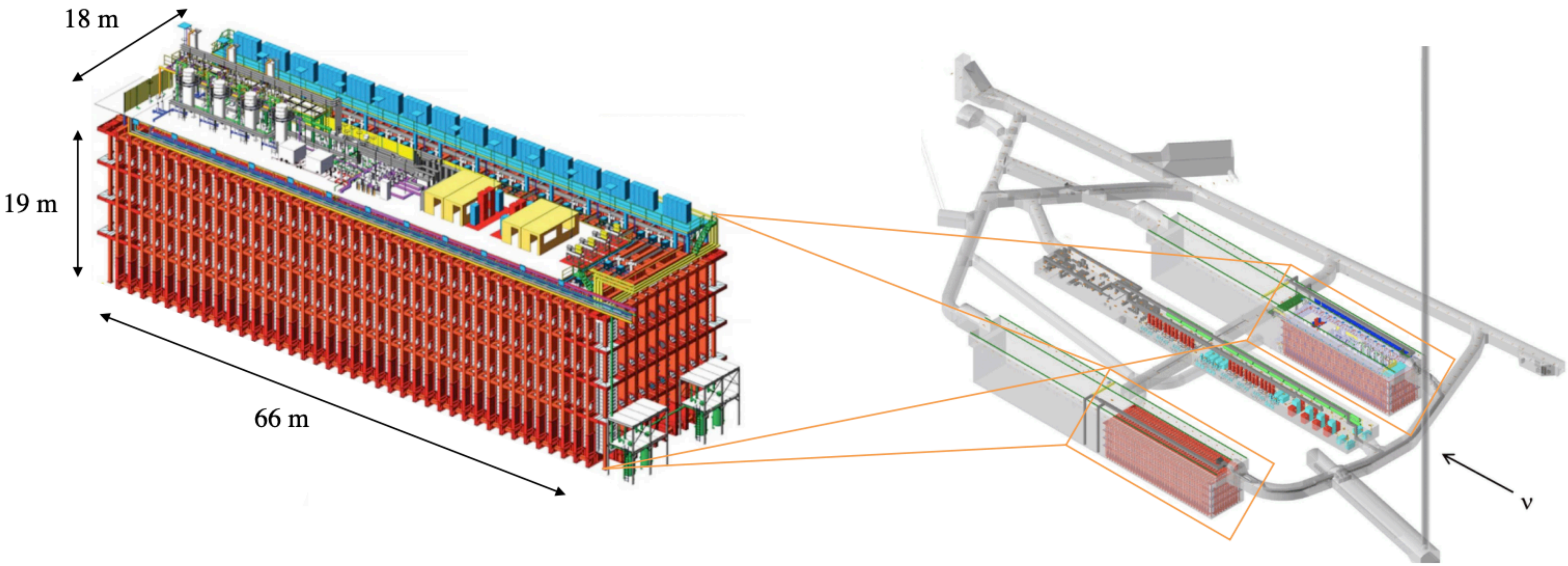
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

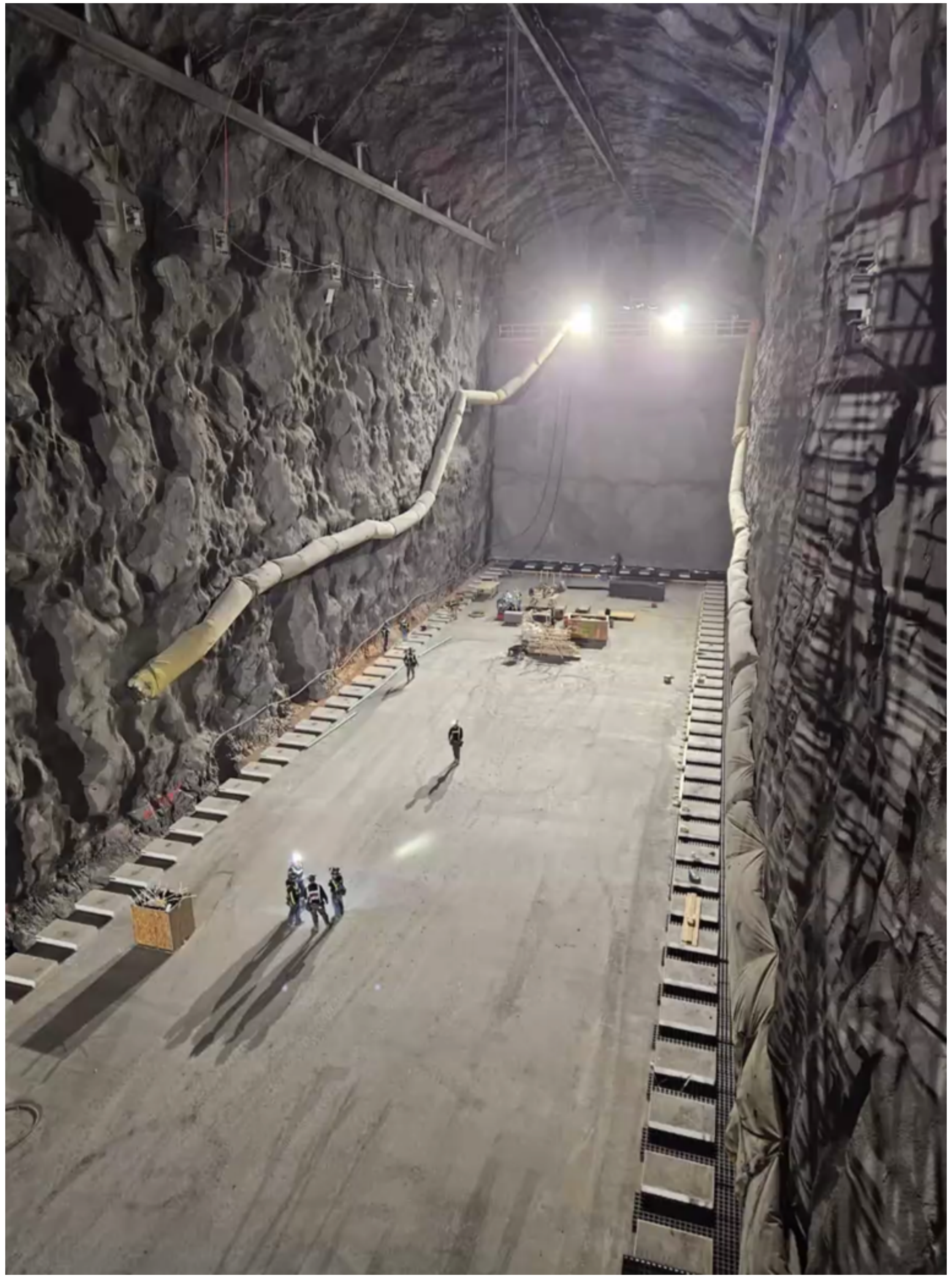
Stony Brook University

DUNE Far Site

SURF in Lead, South Dakota
Cavern excavation completed Feb 1, 2024 - outfitting & receive cryostats
4850 ft underground, 8 soccer fields, 800 ktons of rock
Could house up to four 17 kt LAr TPC far detector modules

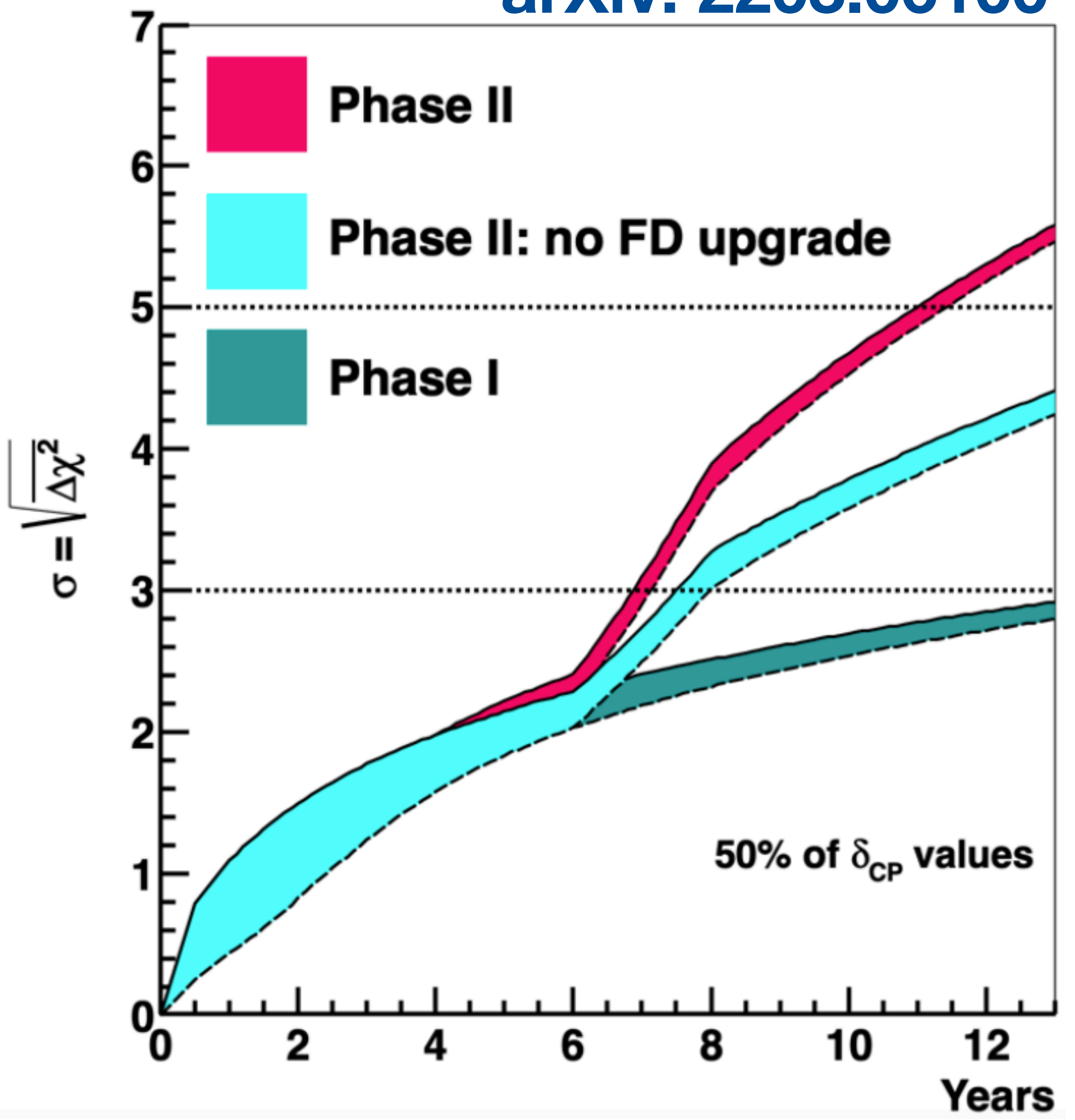






DUNE Phase II and FD3 APEX

DUNE Snowmass
arXiv: 2203.06100



Phase I (day 1)

- FD (approved): two 17 kt (total) LAr TPCs - FD1 (Horizontal Drift), FD2 (Vertical Drift)
- ND (aim to approve by 2025): NDLAr with TMS; DUNE-PRISM; SAND on-axis

Phase II is ramping up - 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
- **Major upgrade light detection system - APEX** ★ **(This talk)**
- **Reference design: APEX + CRP**
- Construction fully endorsed by the 2023 P5
- FD technically limited schedule
  - Earliest installation cryostat: 2029
  - Detector: 2031
  - Completion of LAr filling: 2034

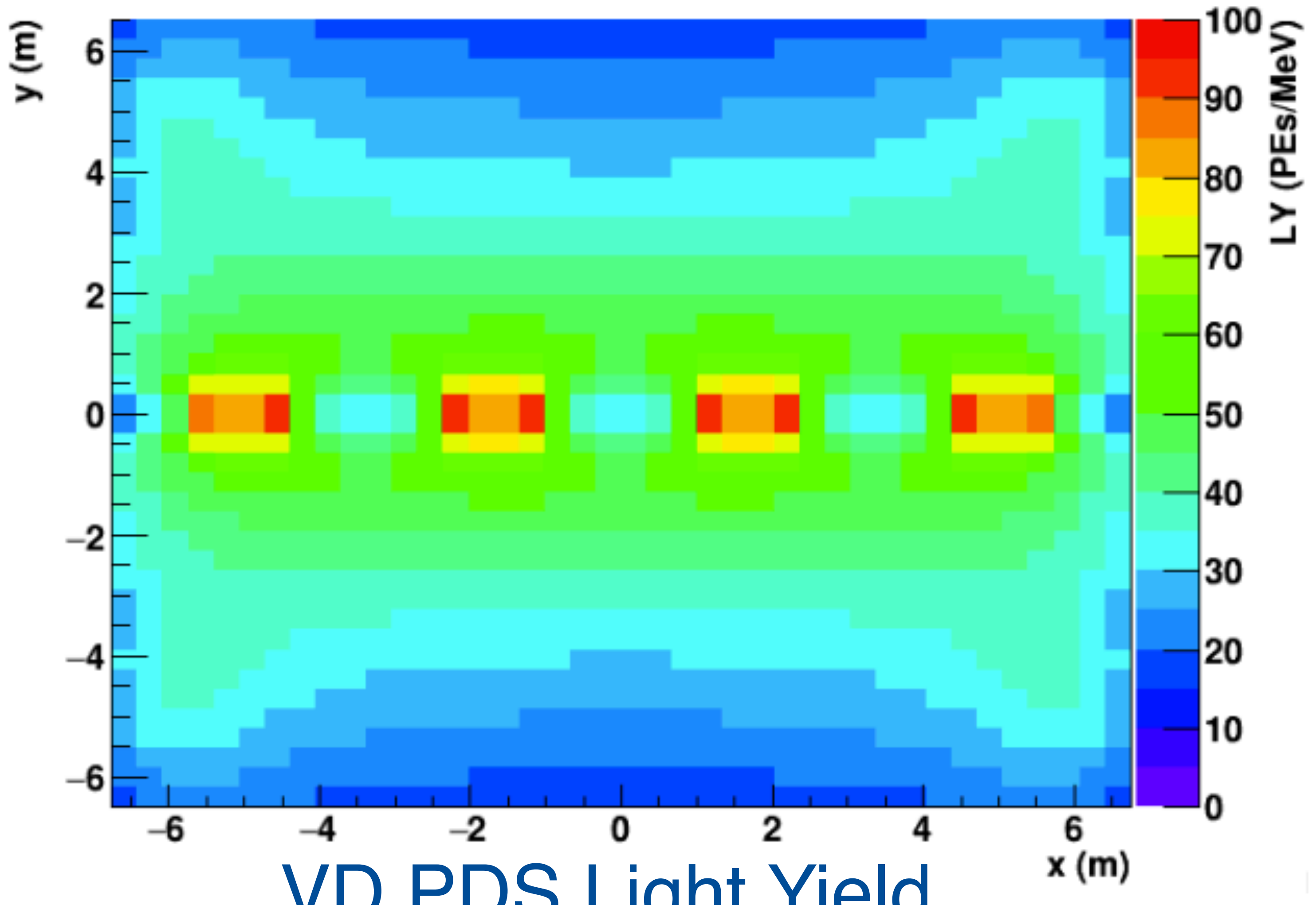
DUNE Phase II White Paper - arXiv: 2408.12725

Technology	Option for FD3	Option for FD4	Can integrate with
CRP (strip-based charge readout)	✓	✓	APEX
APEX (X-ARAPUCA light readout on field cage with SiPMs)	✓	✓	CRP, LArPix, Q-Pix, ARIADNE, SoLAr
LArPix, **LightPix** (pixel charge and light readout)		✓	APEX, SoLAr
Q-Pix, **Q-Pix-LILAr** (pixel charge and light readout)		✓	APEX, SoLAr
ARIADNE (dual-phase with optical readout of ionization signal)		✓	APEX
SoLAr (integrated charge and light pixel readout)		✓	APEX, LArPix, Q-Pix
Hybrid Cherenkov + scintillation		✓	N.A.

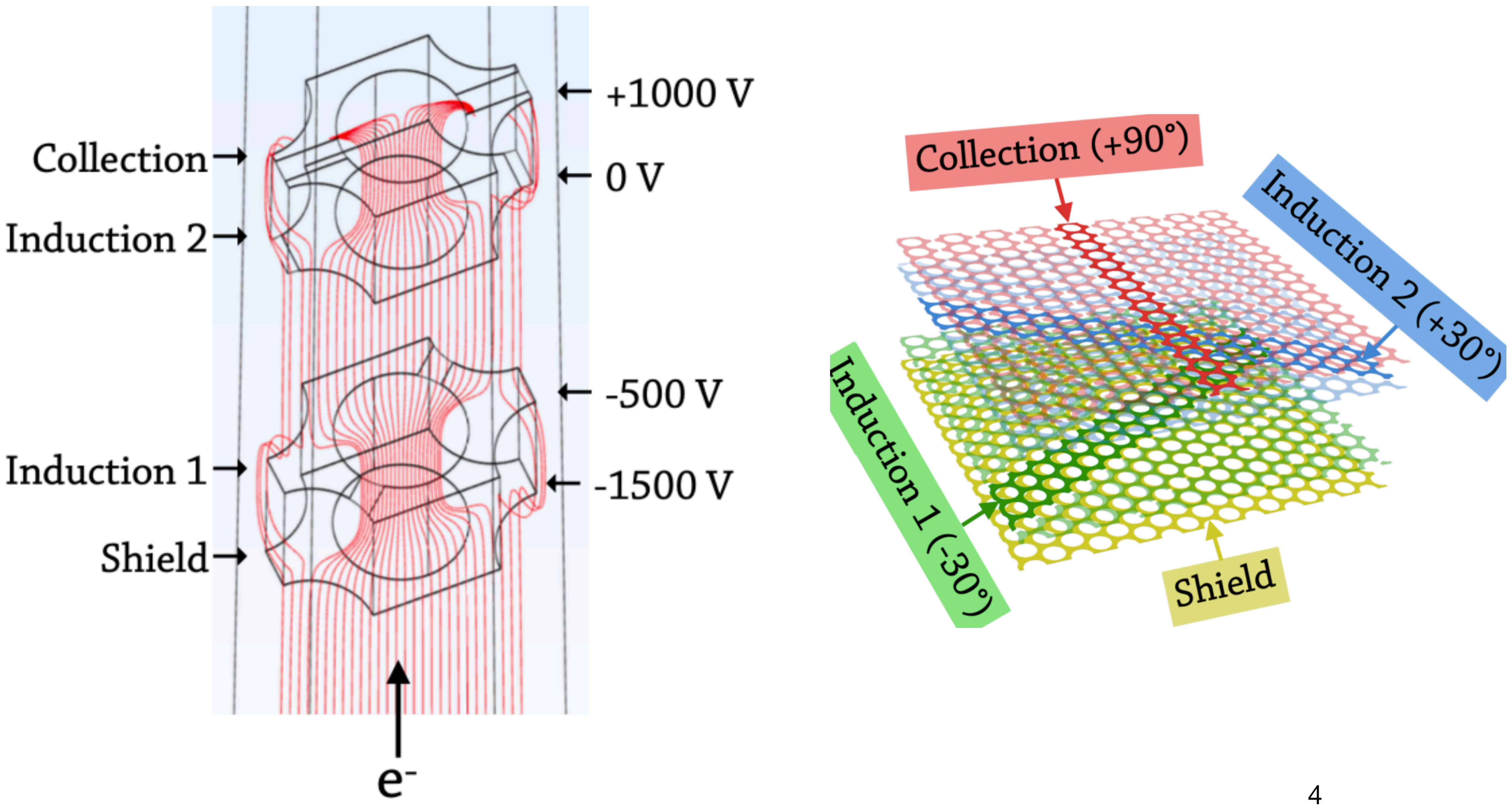
Table 4: LArTPC integration of the detector technologies currently being considered for the Phase II FD modules. Here, "FD3" refers to the FD3 reference design requiring only minimal modification to the FD2 vertical drift design. The "FD4" options could also become options for FD3 over time.

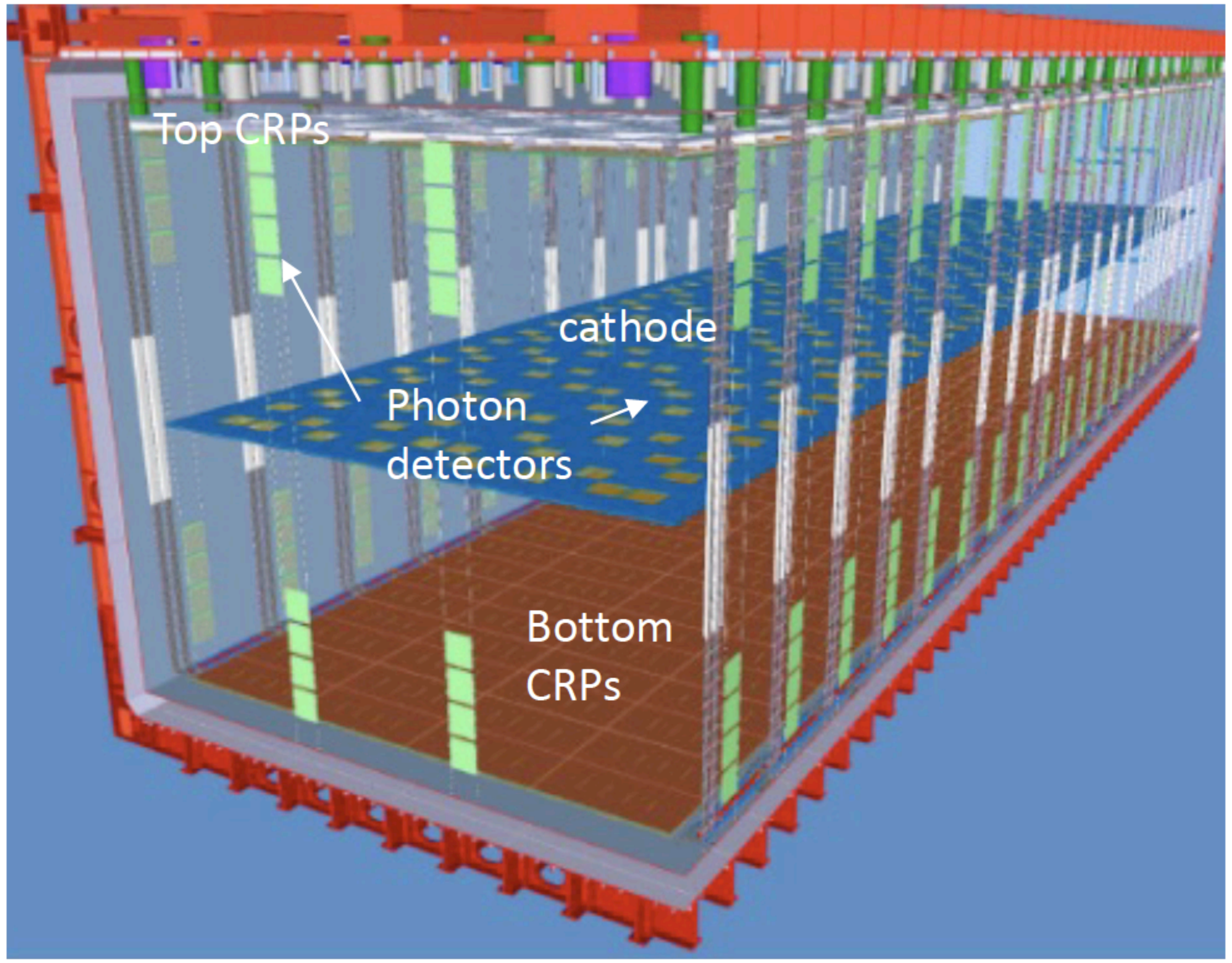
DUNE Vertical Drift FD

- **6.5 m vertical drift distance**, active volume 10,586 m^3 - 14,756 ton
- Charge readout: perforated PCB (reducing overall costs to HD)
- **Photodetectors**: X-Arapuca (60 cm x 60 cm)
  - **Power-over-Fiber (PoF)** technology enables **320** photodetectors deployed on **300 kV** high voltage surface **in LAr**
    - **First-ever** in cryogenics and particle physics - arXiv:2405.16816
  - Similar amount photodetectors on membrane
  - Average detector efficiency is **3-4%**
  - **VD: light yield mean ~ 39 PE/MeV (min 16 PE/MeV)**



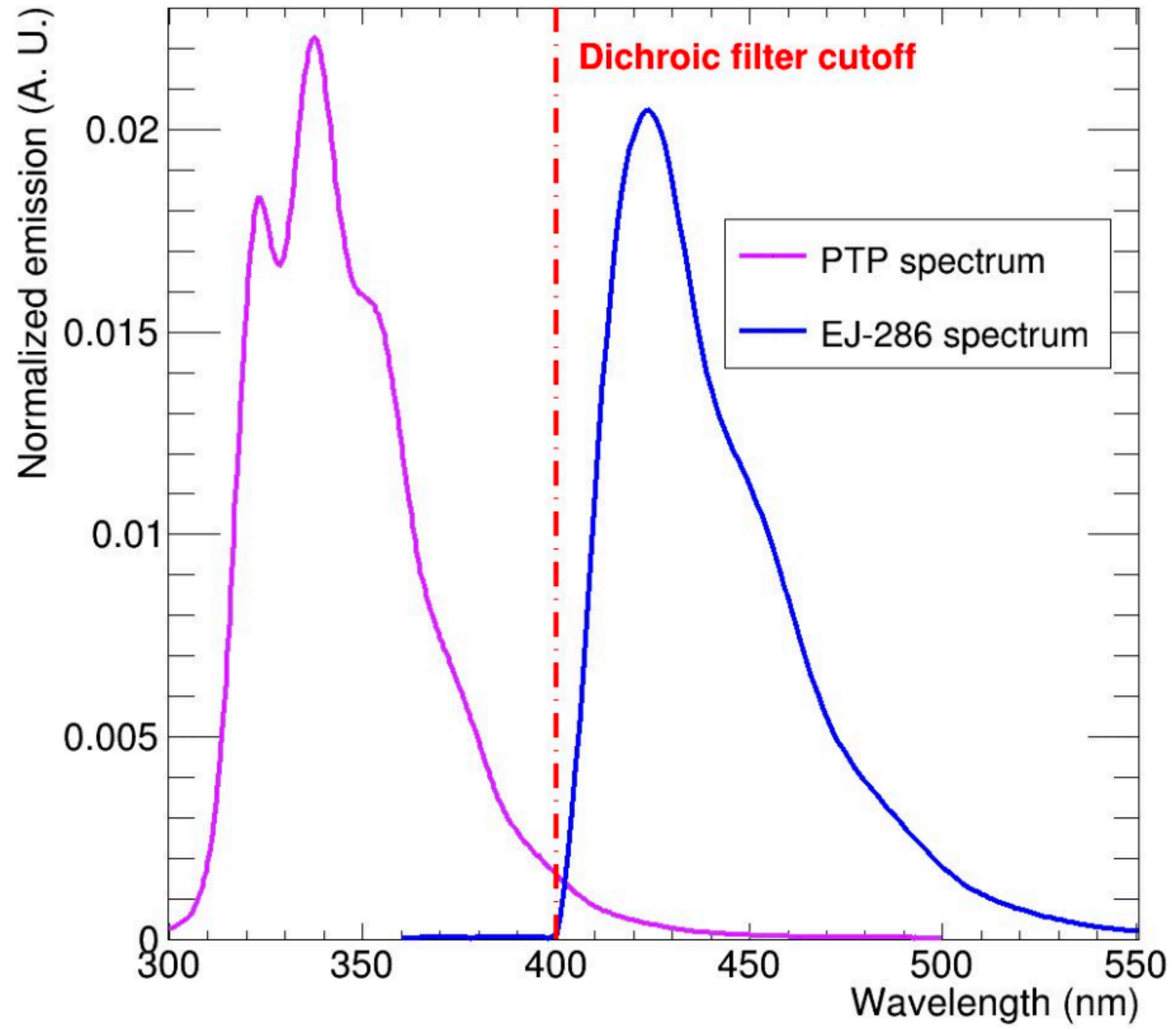
VD PDS Light Yield
(VD TDR arXiv: 2312.03130)

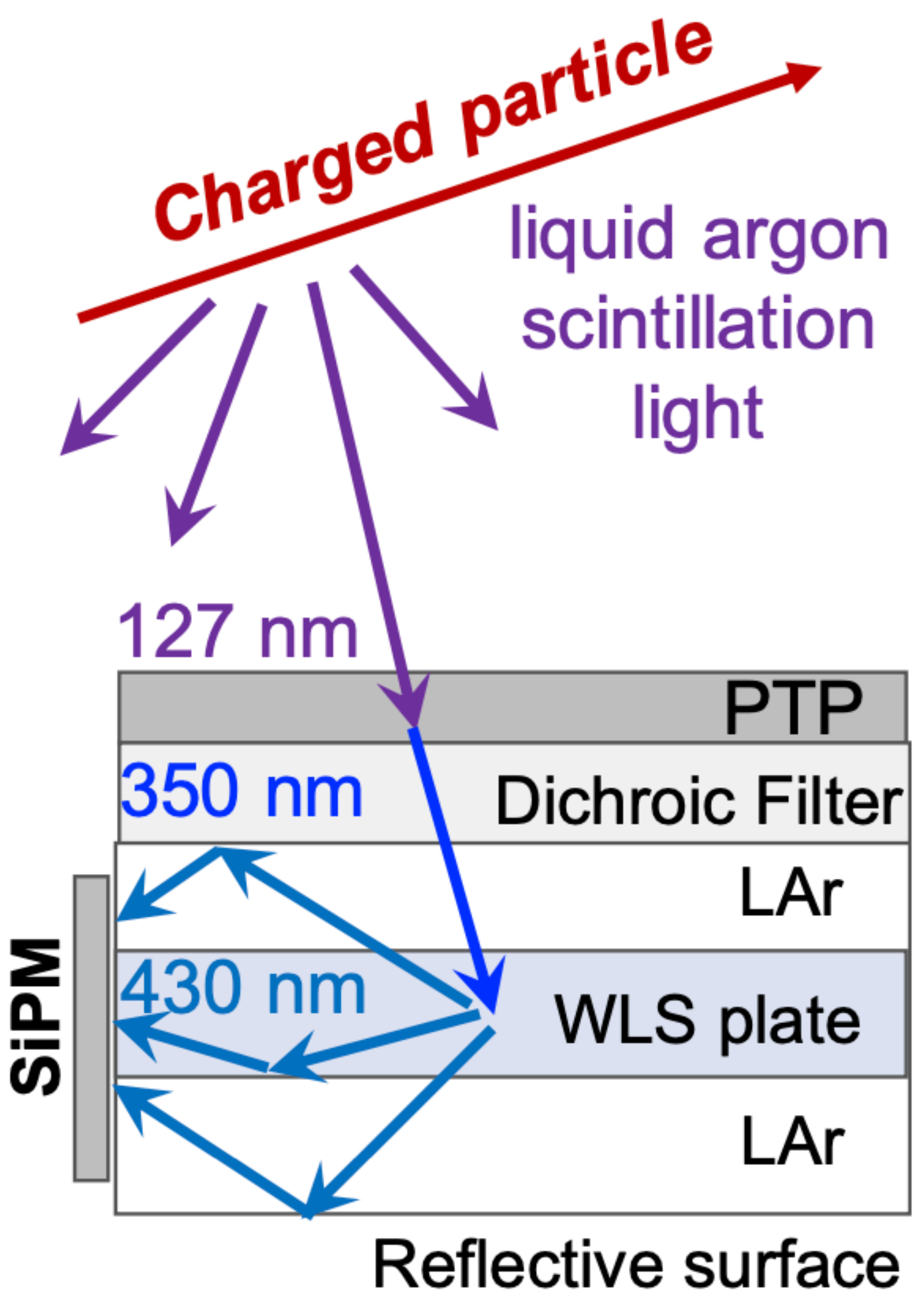




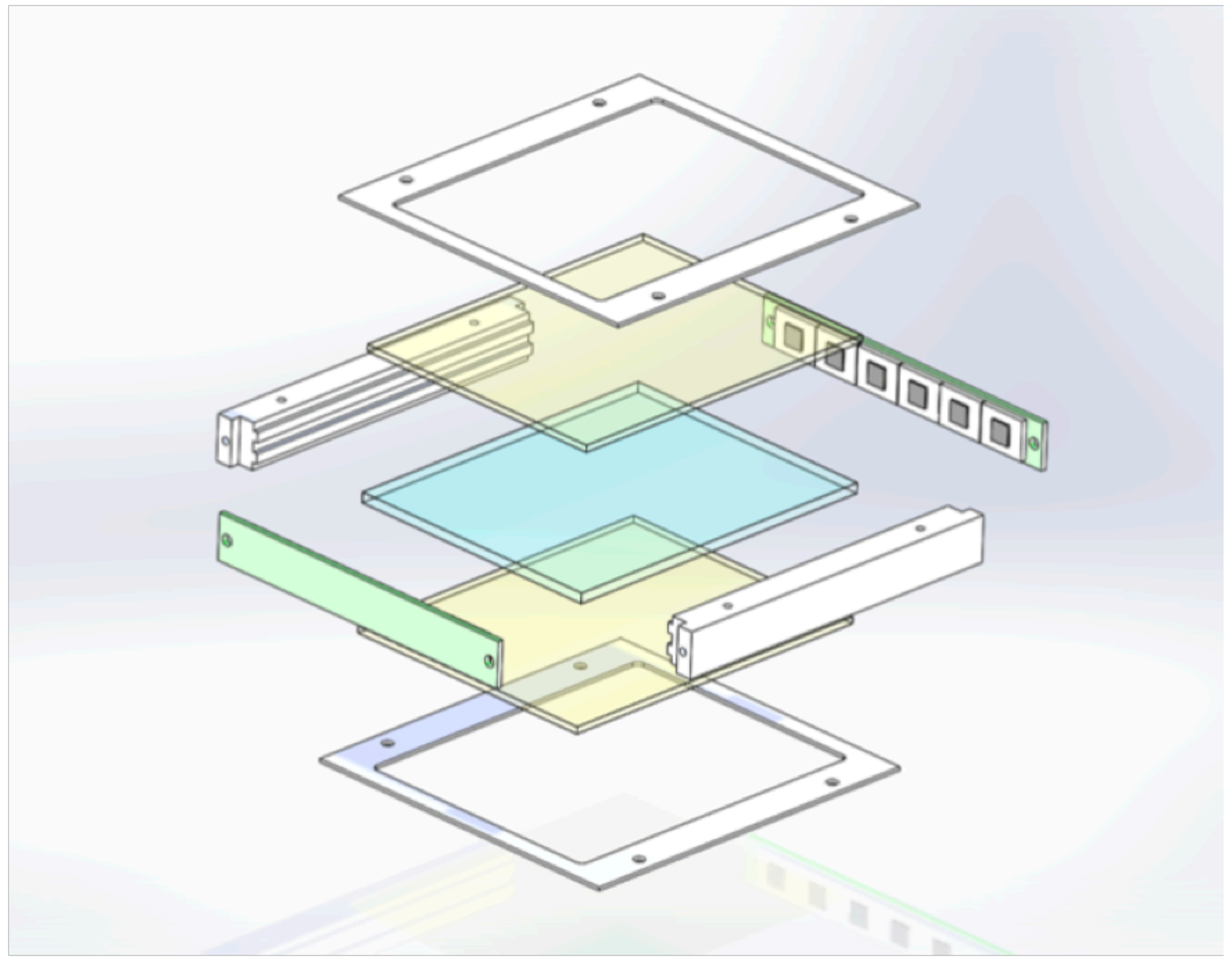
Photodetector as a Light Trap

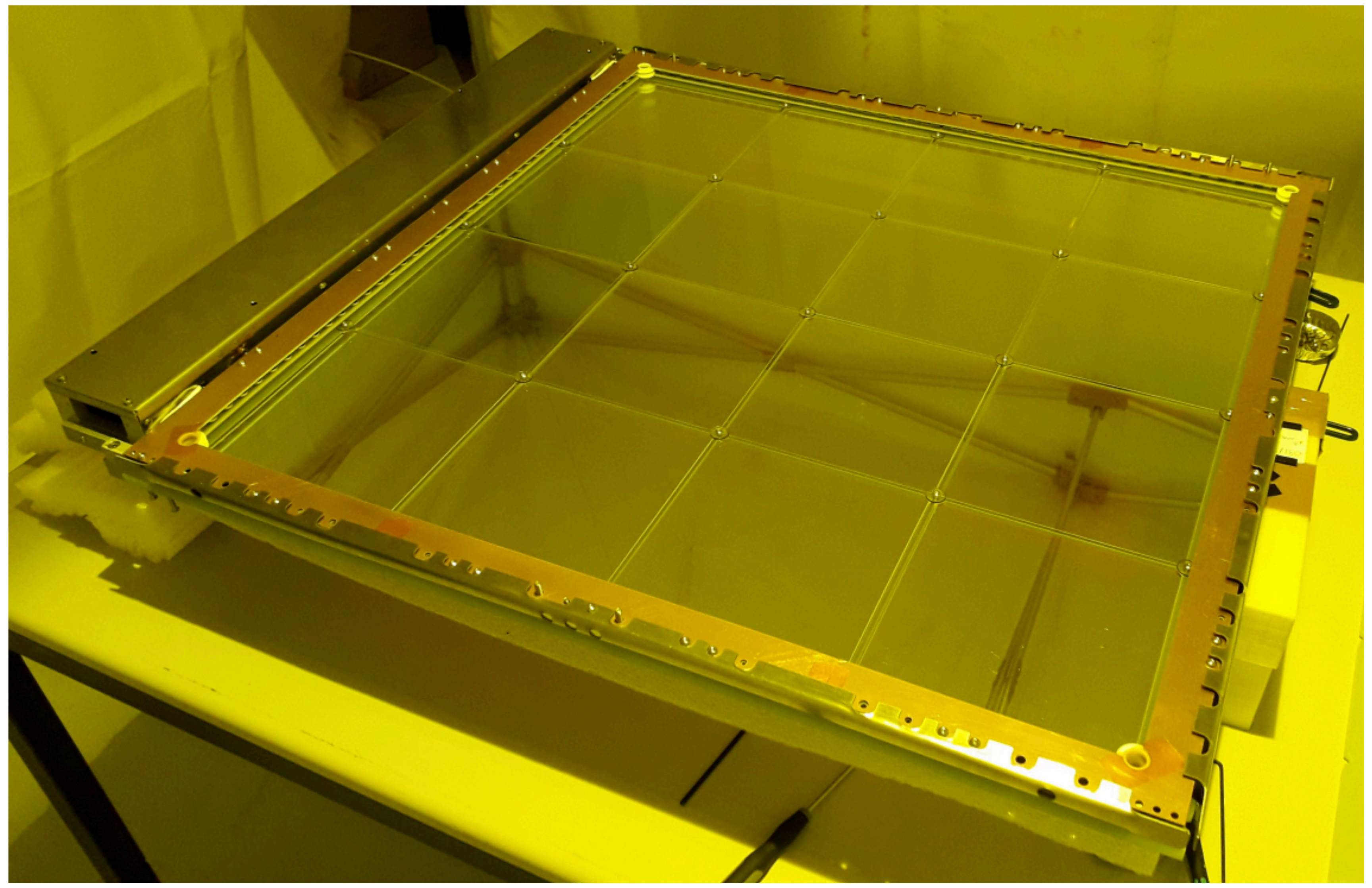
- Two-stage wavelength shifting + dichroic filter for light trapping
  - 127 nm → 350 nm → 430 nm
  - **Compact device**
    - Save space for more fiducial volume
    - Easy to scale up for large area coverage
- Widely used in LArTPCs: ProtoDUNEs, SBND, DUNE HD & VD





Not to scale.



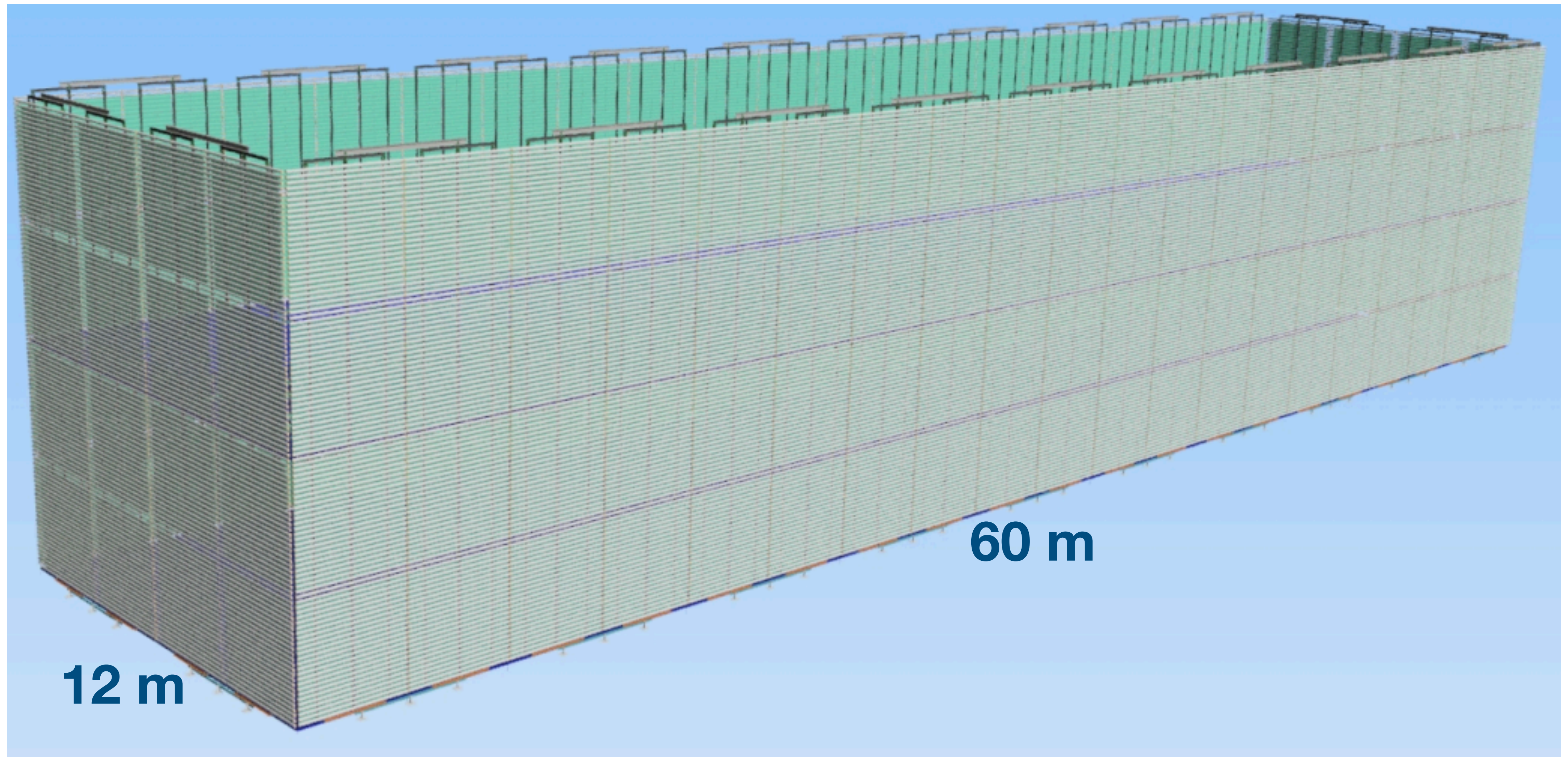


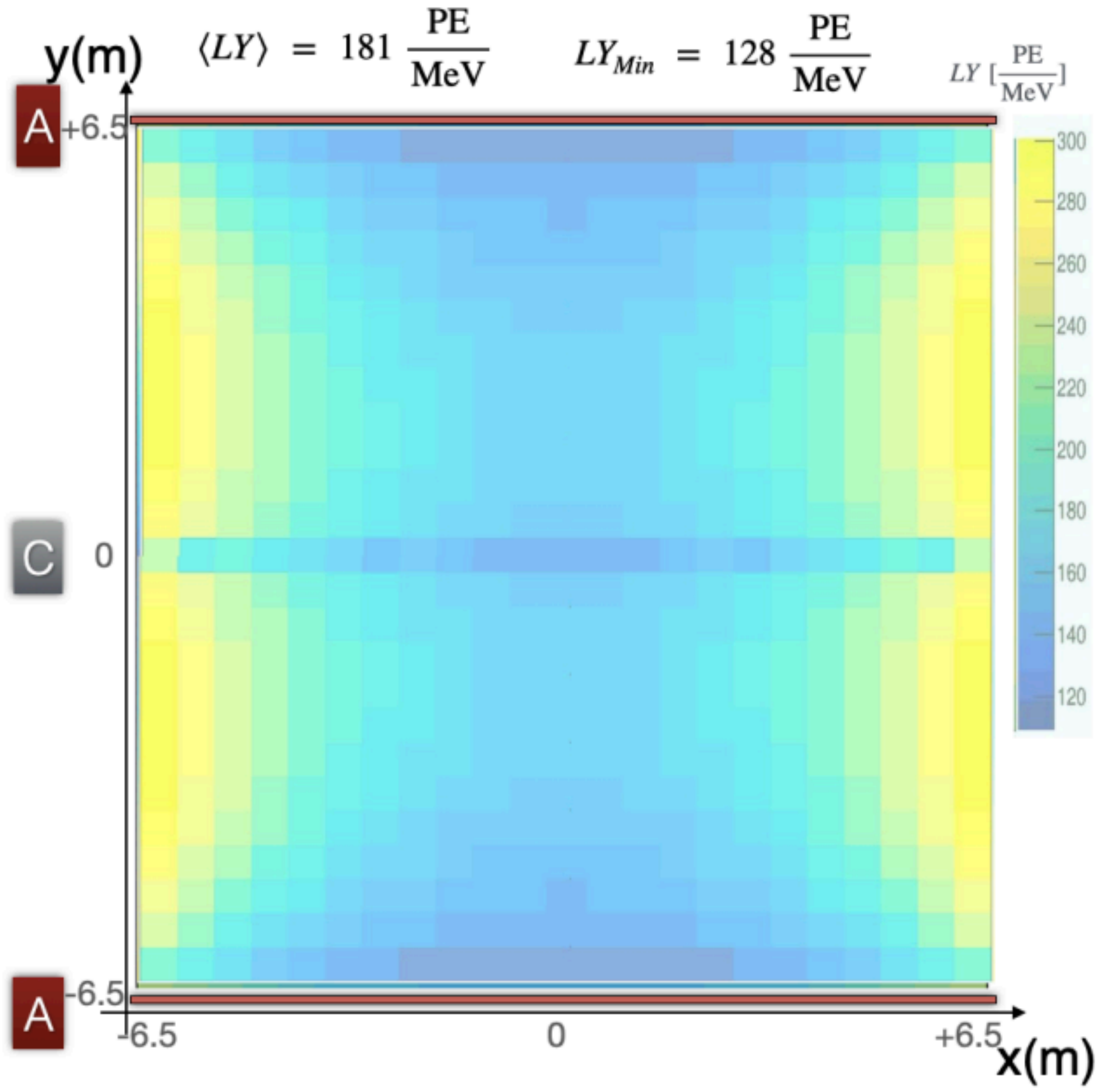
X-arapuca for ProtoDUNE-VD

FD3 APEX
(Aluminum Profiles with Embedded X-Arapucas)

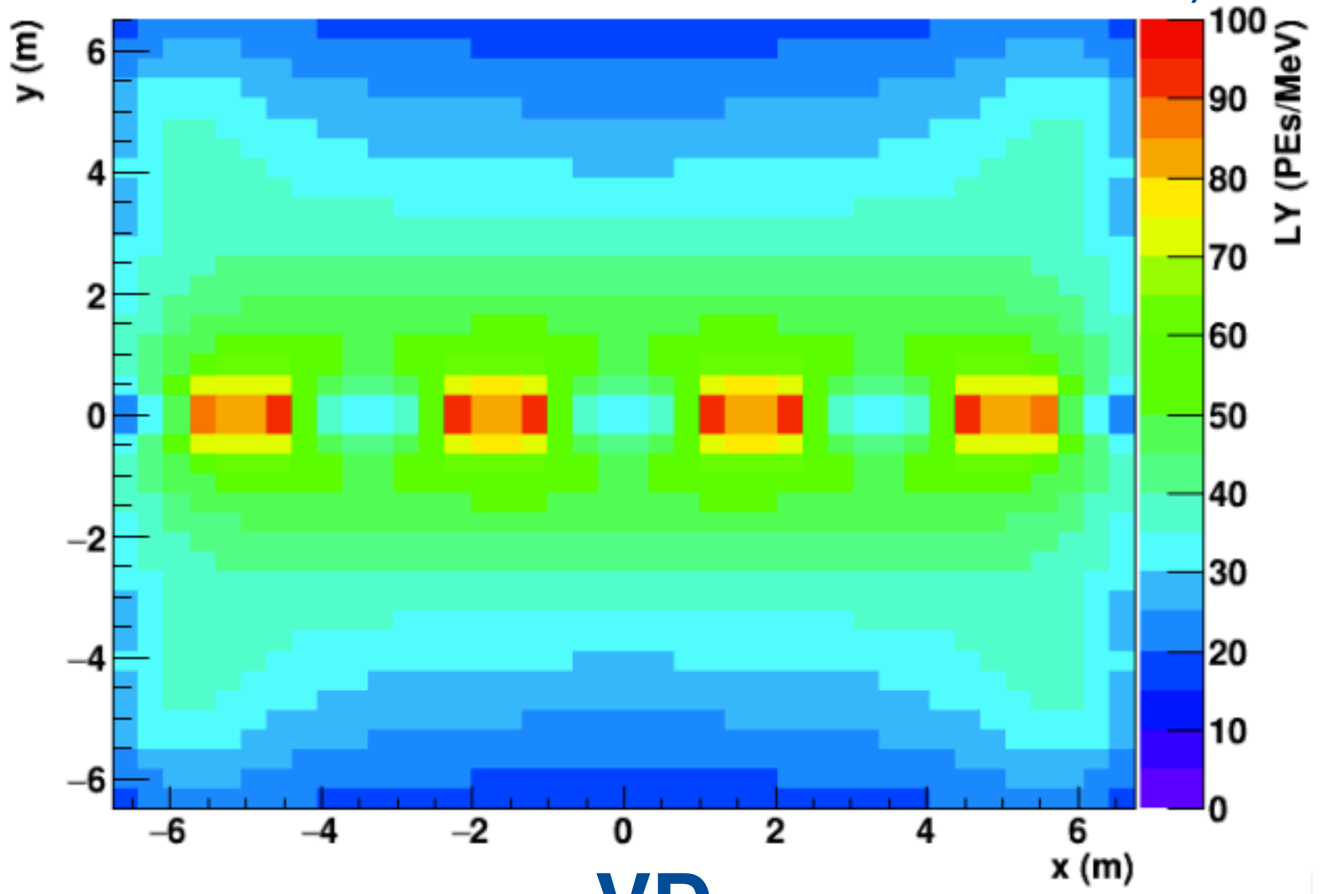
An ambitious detector building on the success of VD

- Up to 2000 m^2 optical coverage: 10 times of FD2
  - ~7000 large-size 50 cm x 50 cm photodetectors
  - Avg. light yield up to 220 PE/MeV, > 4 times VD, higher uniformity
- PoF/SoF for detector operation on HV & cryogenics
  - 9000+ fibers, total length 1000 km+
- Cold digitization, signal bandwidth > 6.5 Tbit/sec
- SNR ~ 10 (signal over fiber), dynamic range up to 2000 PE
- Lower detection thresholds to 5MeV (w. bkg control)

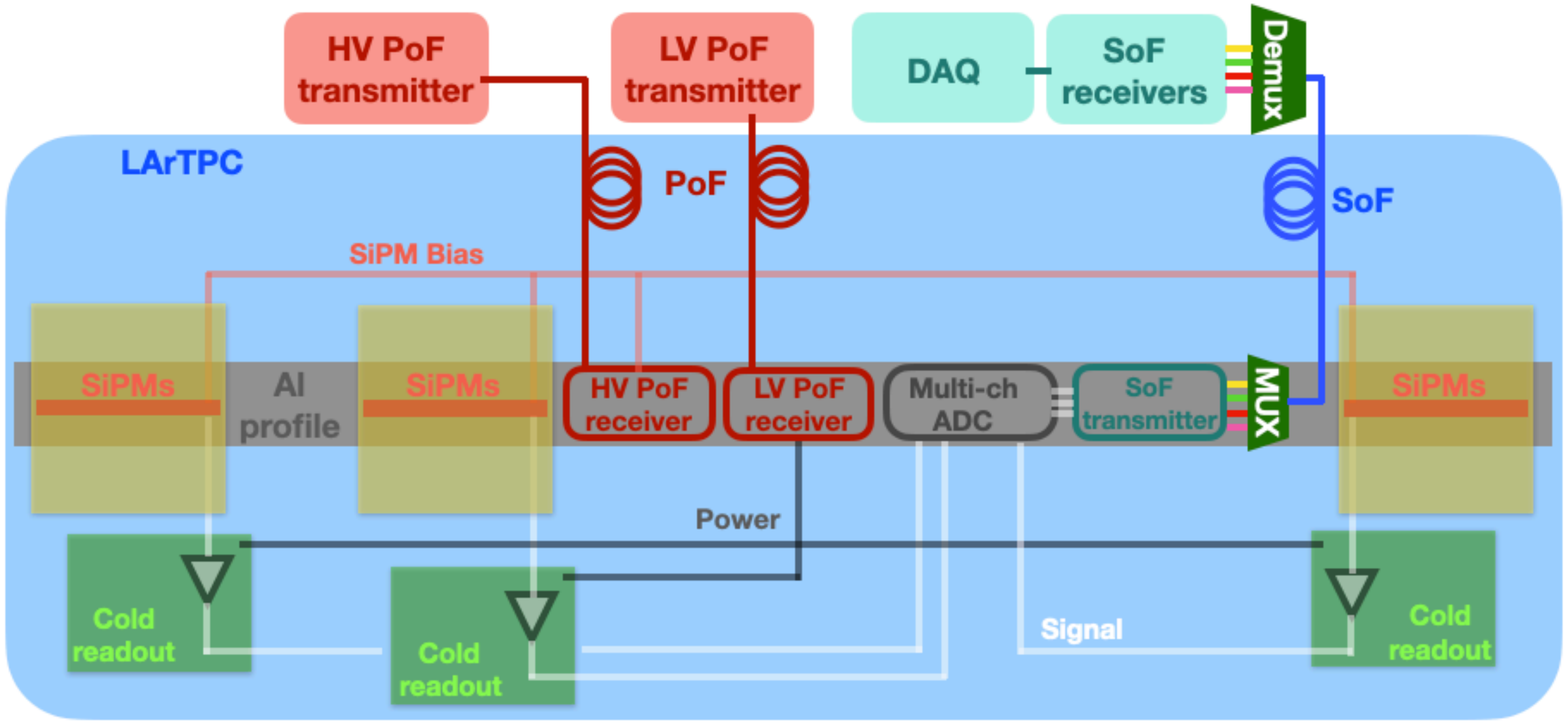




Mean LY ~ 39 PE/MeV, min 16 PE/MeV)



VD

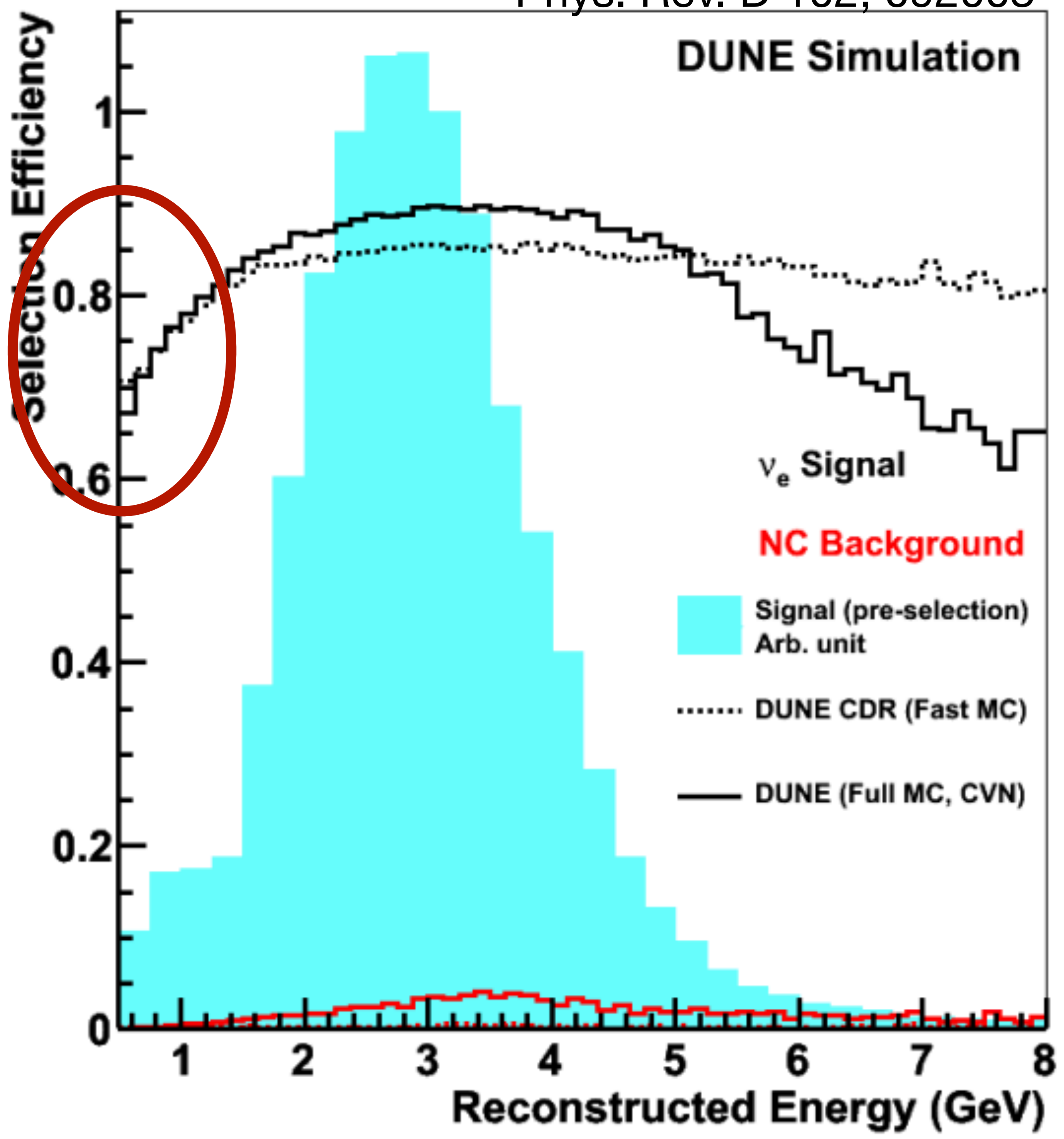


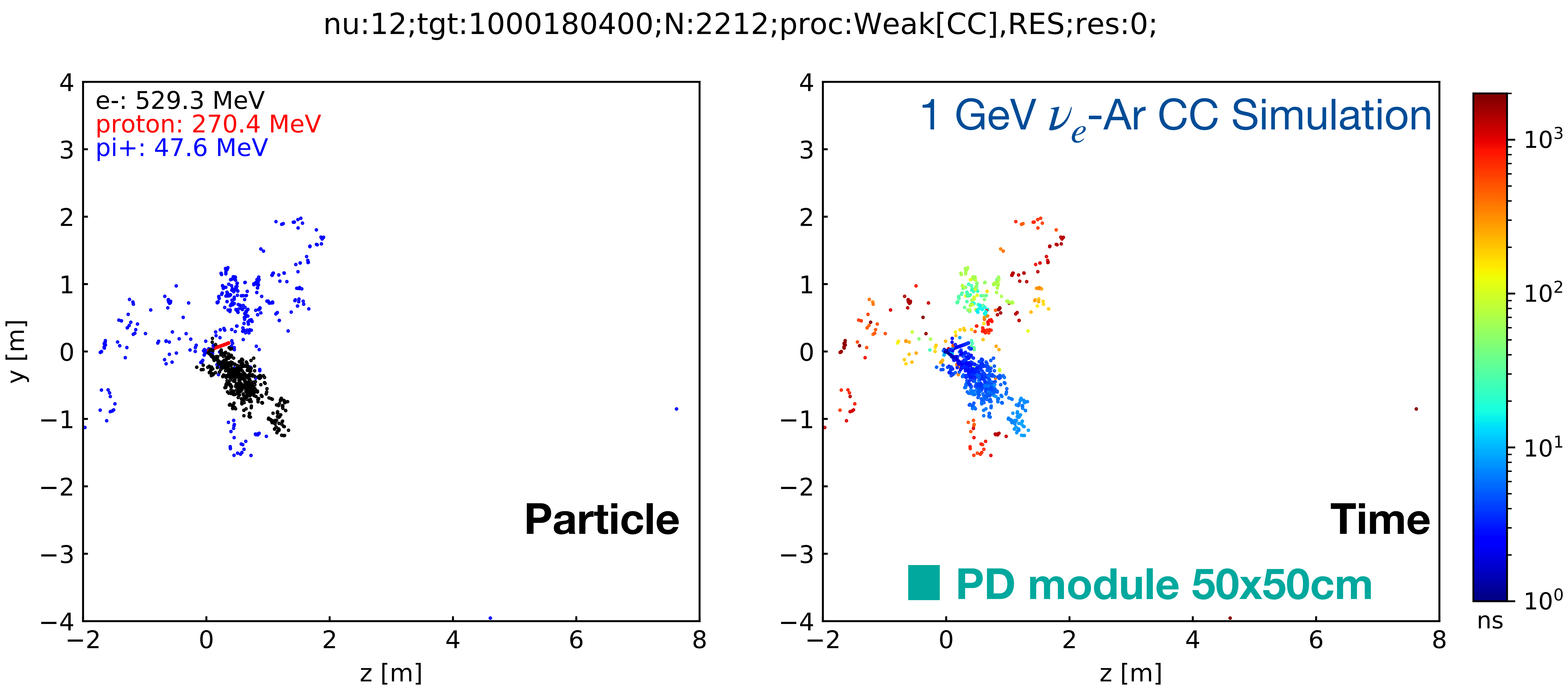
FD3 APEX: - arXiv: 2408.12725

Motivation for FD3 Enhanced Light Detection (I)

- **Enhanced light** info (**timing**, position, etc) expected to **boost charge-PID-based event selection** and **improve FD ν_e event selection efficiency**
  - Sharp drop in efficiency at lower energy due to sparse electron showers and similarity to charged pion track bkgs
  - **Example event display: excellent light timing and coverage expected to help tag delayed pion decay products when combined with charge info**
  - Improved ν_e-CC selection efficiency will recover statistics at 2nd osc peak

Eur. Phys. J. C 80, 978 (2020)
Phys. Rev. D 102, 092003



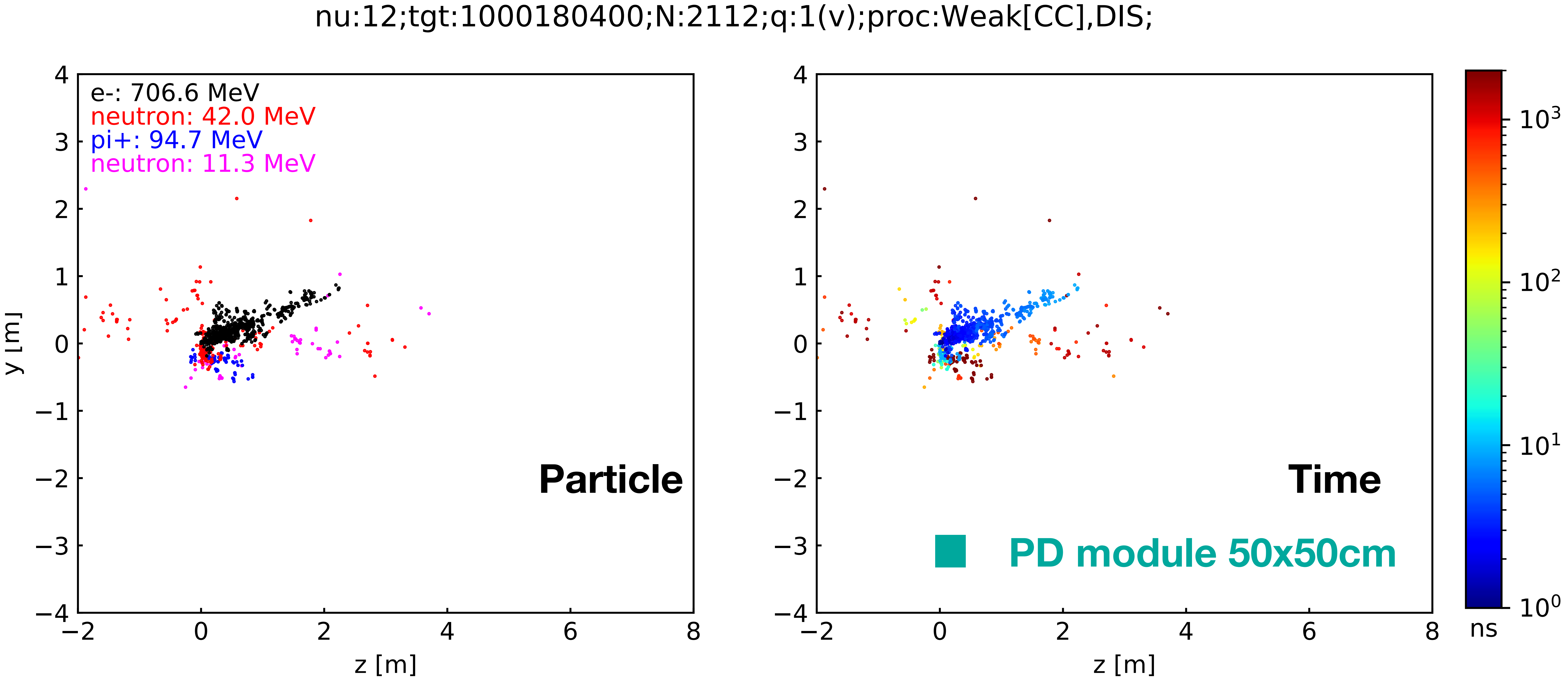


Motivation for FD3 Enhanced Light Detection (II)

- **Enhanced light** info (**timing**, position, etc) expected to **boost charge-PID-based reconstruction** and **improve charge calorimetry energy resolution than phase I FD**
  - **Identify μ/π decay/capture**
  - Tag **neutron** propagation with timing (up to μs), n-capture tagging with PDS + TPC
  - Reconstruct track/event **direction** for background rejection

Energy resolution in Phase I FD (DUNE VD TDR)

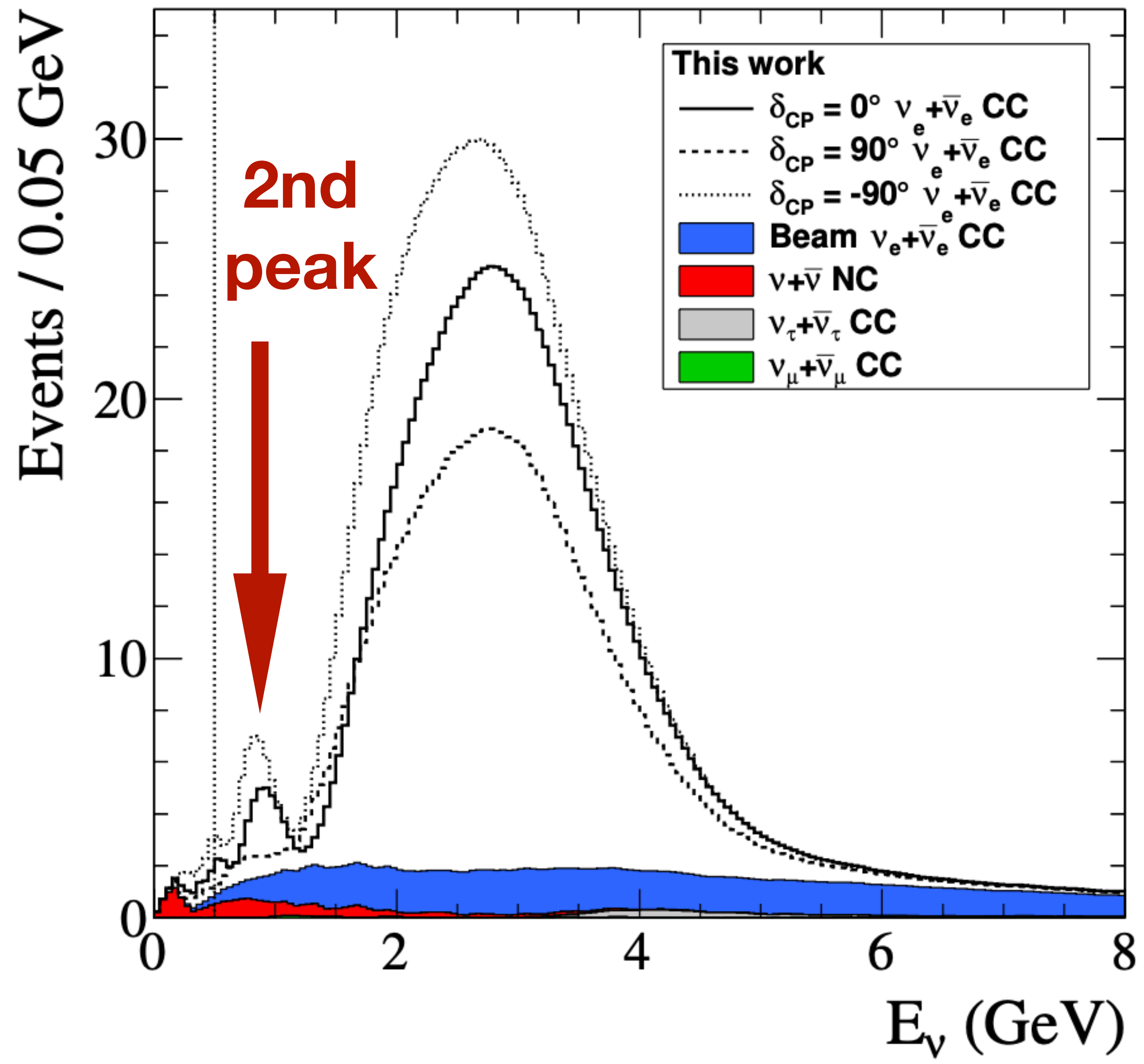
Event hypothesis	Vertical Drift	Horizontal Drift
ν_μ CC with contained μ track	21%	18%
ν_μ CC with exiting μ track	19%	20%
ν_e CC	14%	13%



How Light Helps CPV Measurement

- **Light calorimetry offers an independent energy reconstruction for all DUNE CPV measurement**
- **Light assisted PID helps improve charge based event reconstruction: energy resolution and efficiency**
  - **Better E resolution improve the sensitivity contribution from spectra shape**
  - **Better E resolution and selection efficiency will improve the CPV significance at 2nd oscillation peak**
    - DUNE wide-band beam offers possible access to the 2nd oscillation peak
    - Stronger CPV effect @2nd peak
    - Lower energy region: very different interaction processes and systematics
    - Measuring CP independently with two oscillation peaks is a unique capability of DUNE

JHEP09(2016)030



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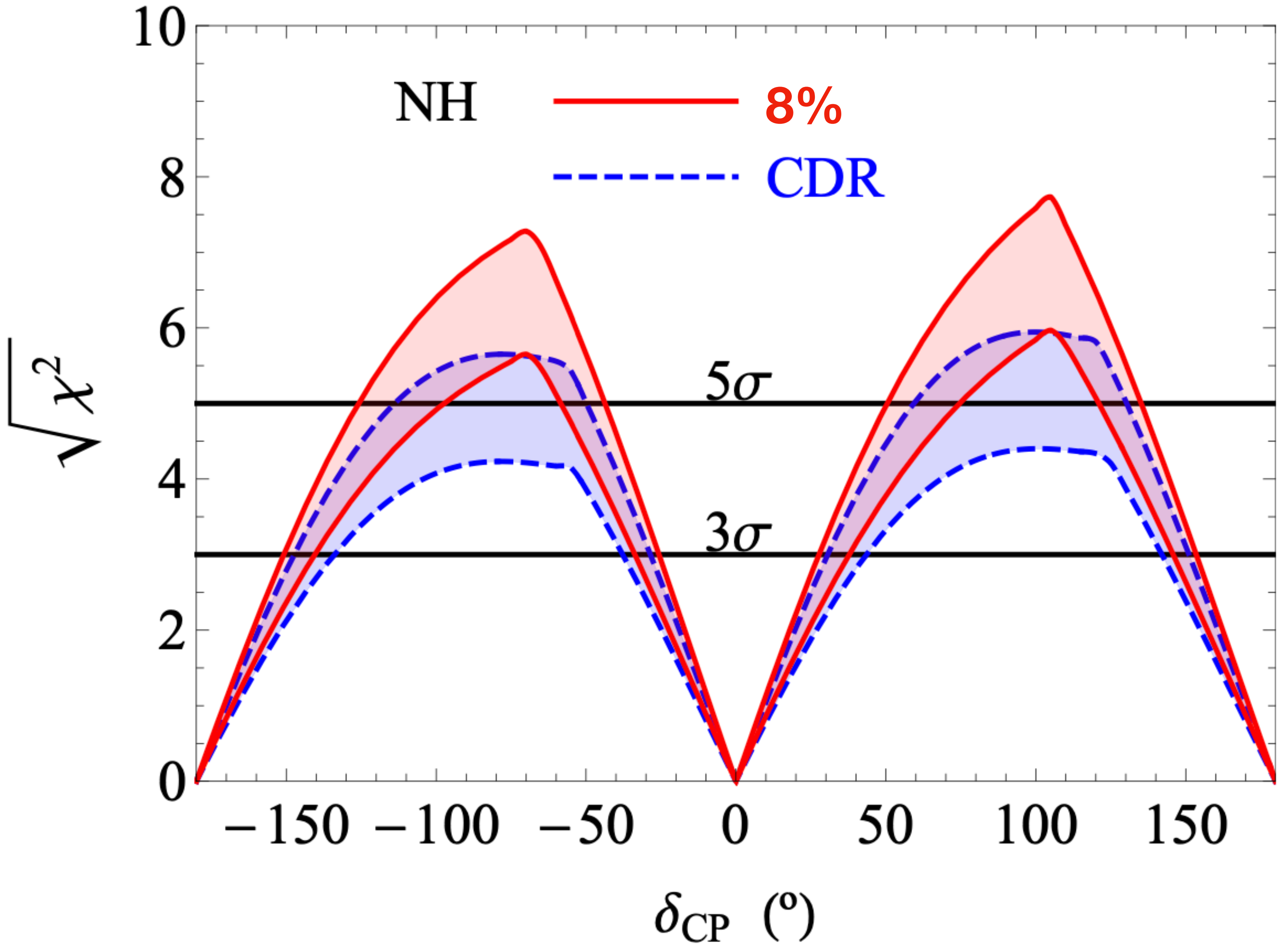
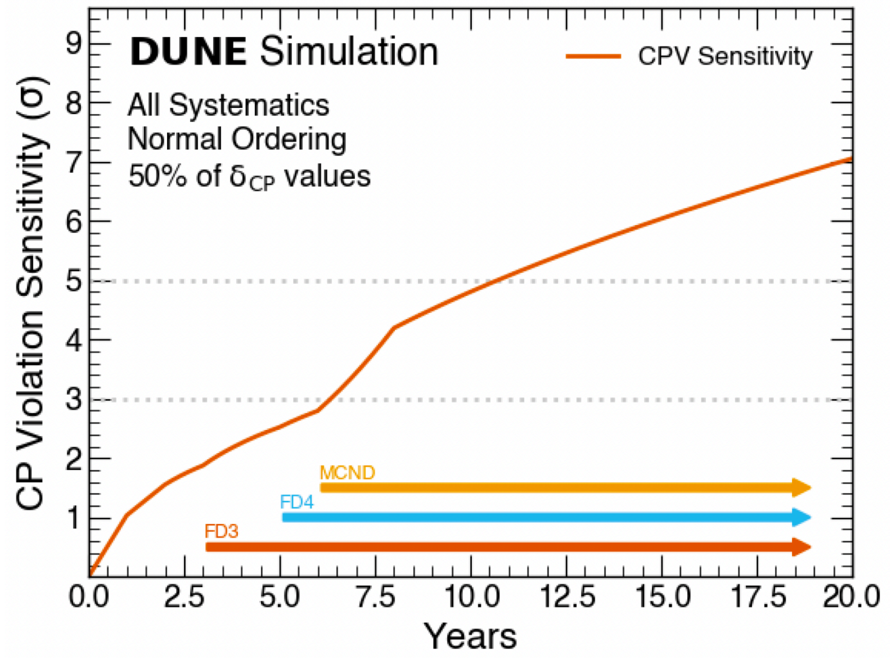
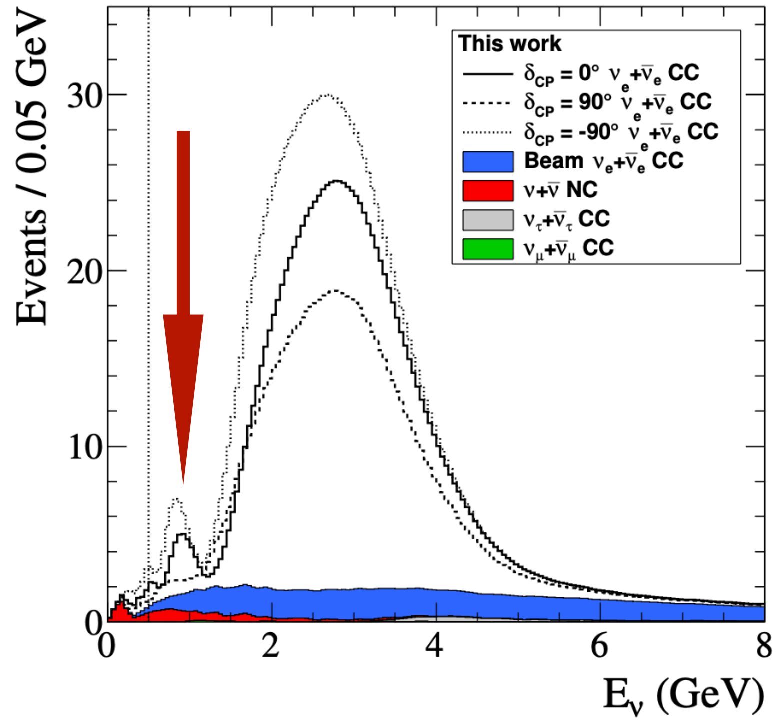


Enhanced Light Detection Opens New Windows into Neutrino CPV

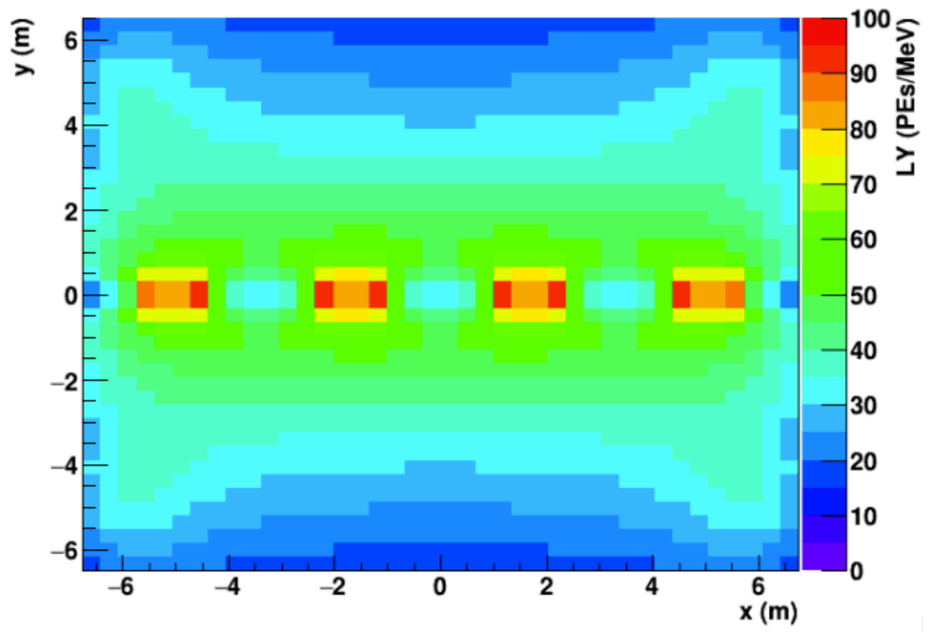


Standard oscillation analysis

Light assisted 2nd osc peak & shape analysis

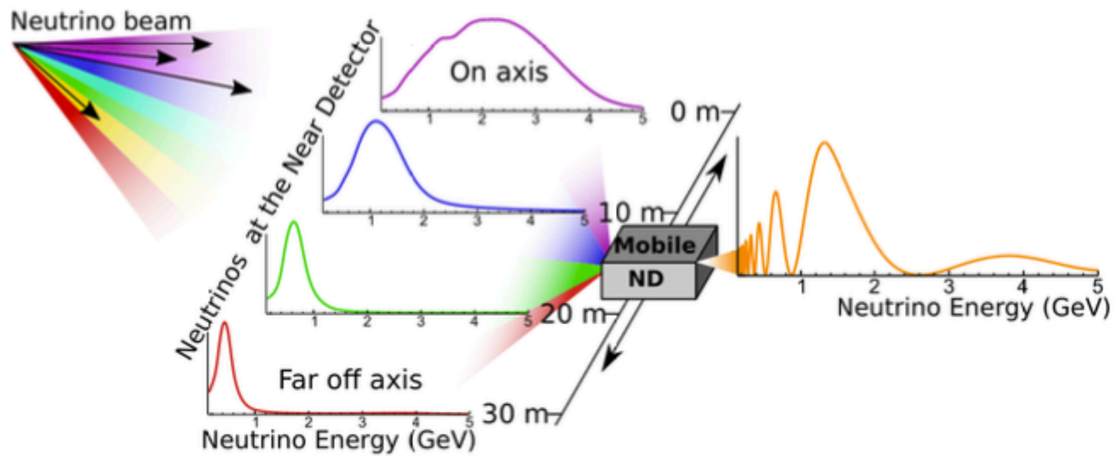


DUNE Neutrino CPV



Pure light calorimetry

Data-driven: DUNE-PRISM

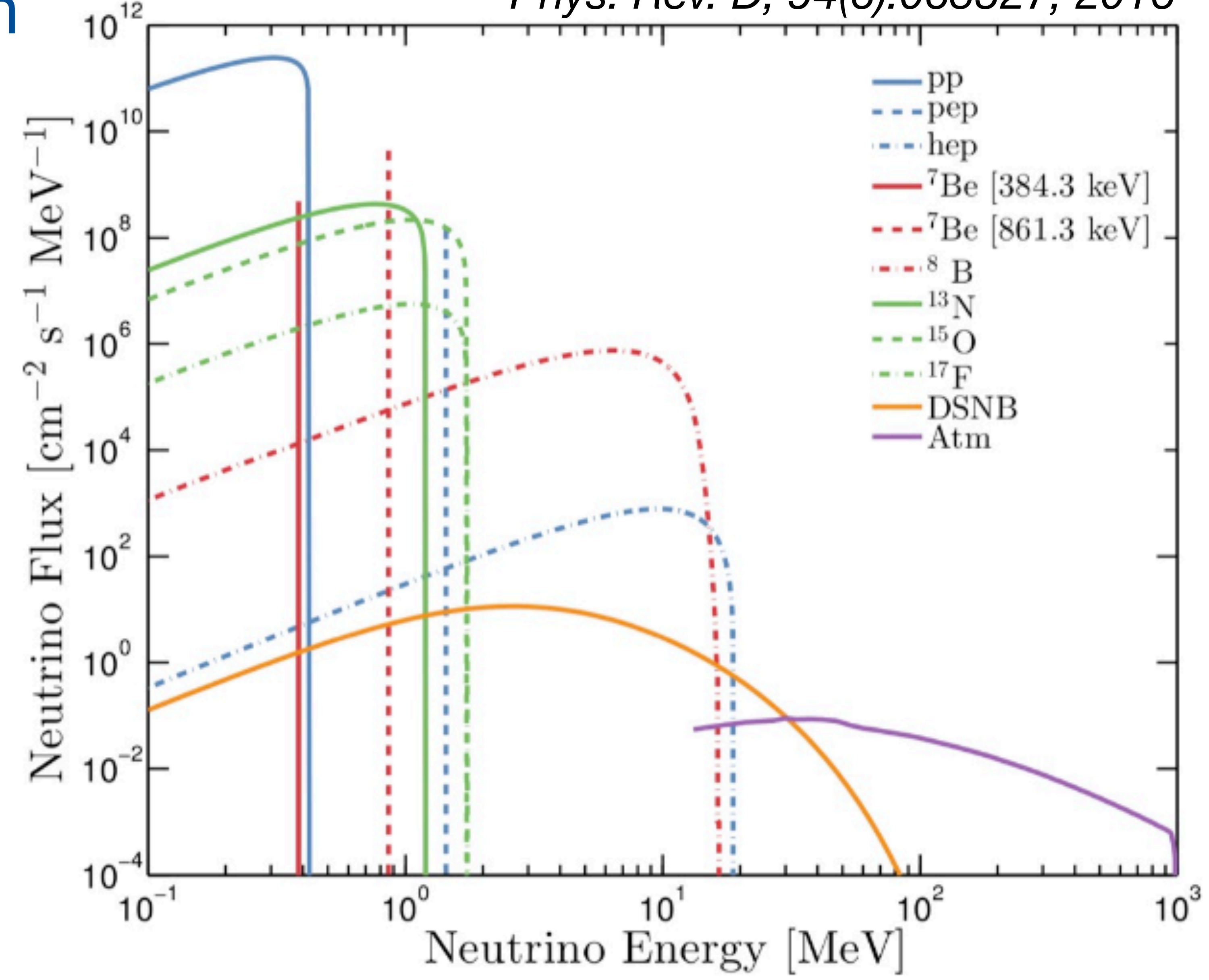


Enhanced Light Detection Motivation for tens-of-MeV ν_e CC Events

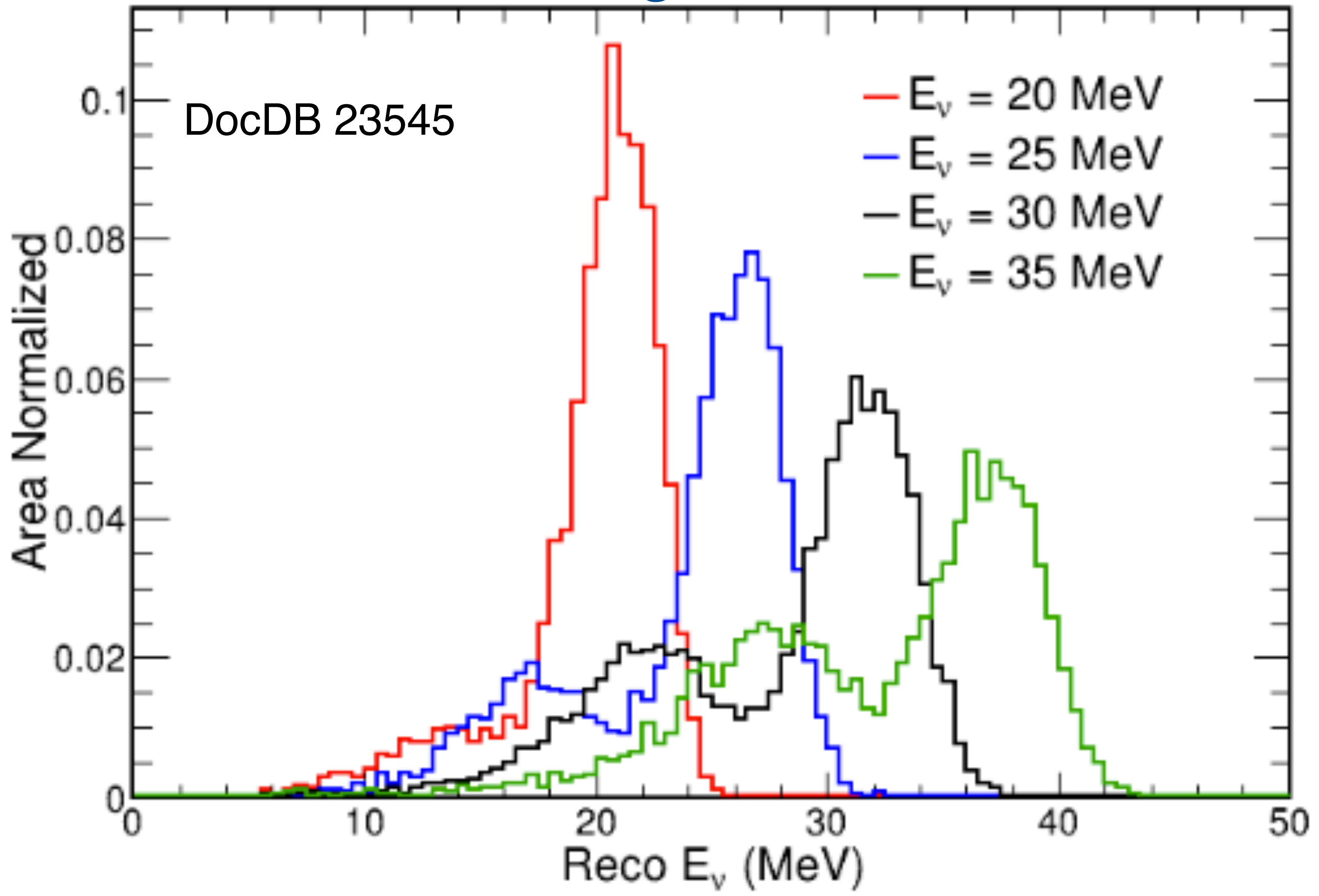
- Combined **light** and charge calorimetry expected to improve MeV energy resolution
- Enhanced light system expected to facilitate **nucleon** (**n**/alpha/p) multiplicity tagging
  - **Smearing to the secondary peak will be reduced**

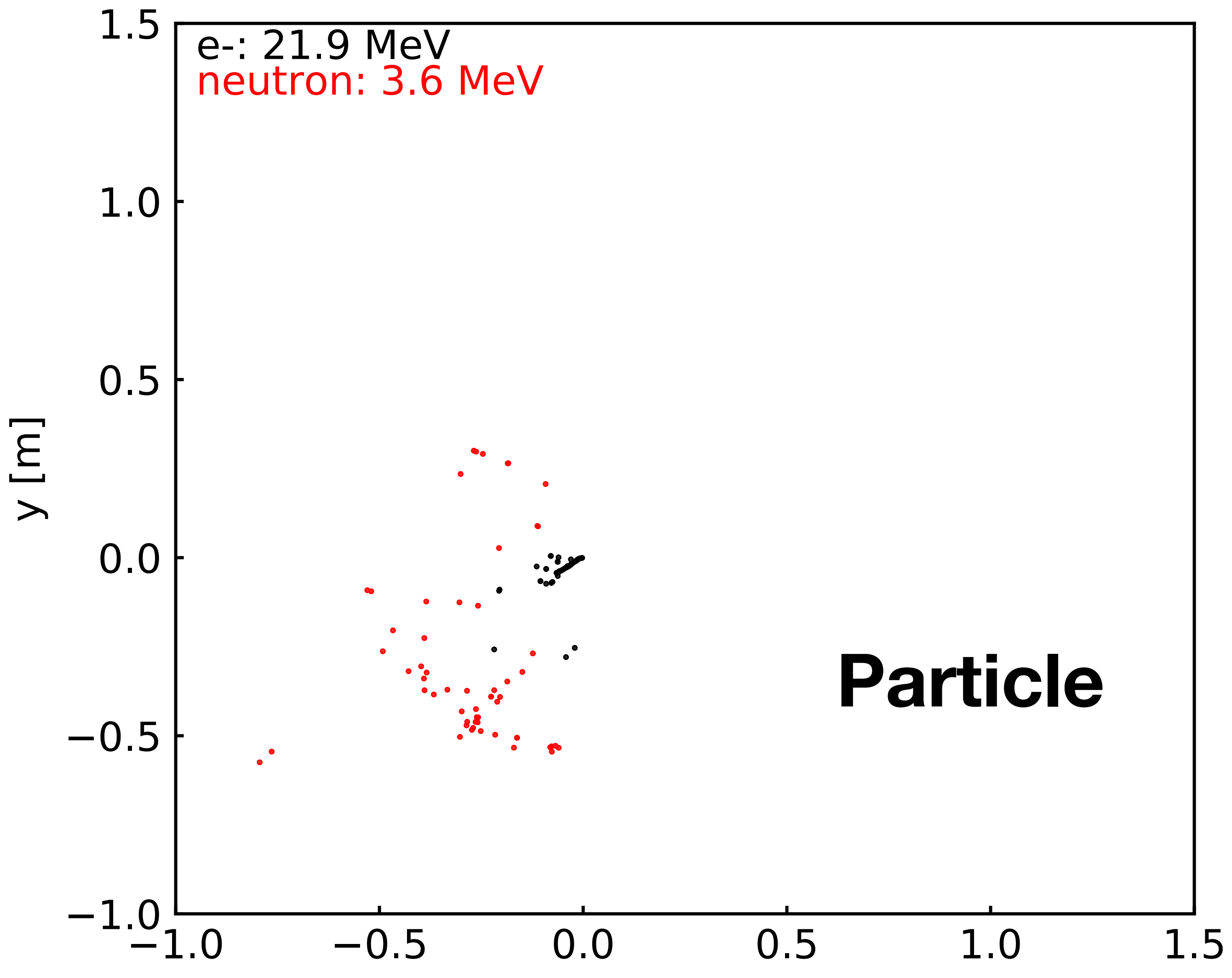
- **Expect to boost many DUNE low energy and other physics programs**
  - Improve search for diffused supernova neutrino background
  - Improve Δm^2_{21} sensitivity with solar neutrino day-night asymmetry
  - Observe CEvNS glow of a supernova neutrino burst
  - Increase supernova neutrino burst trigger efficiency
  - BSM/dark matter …

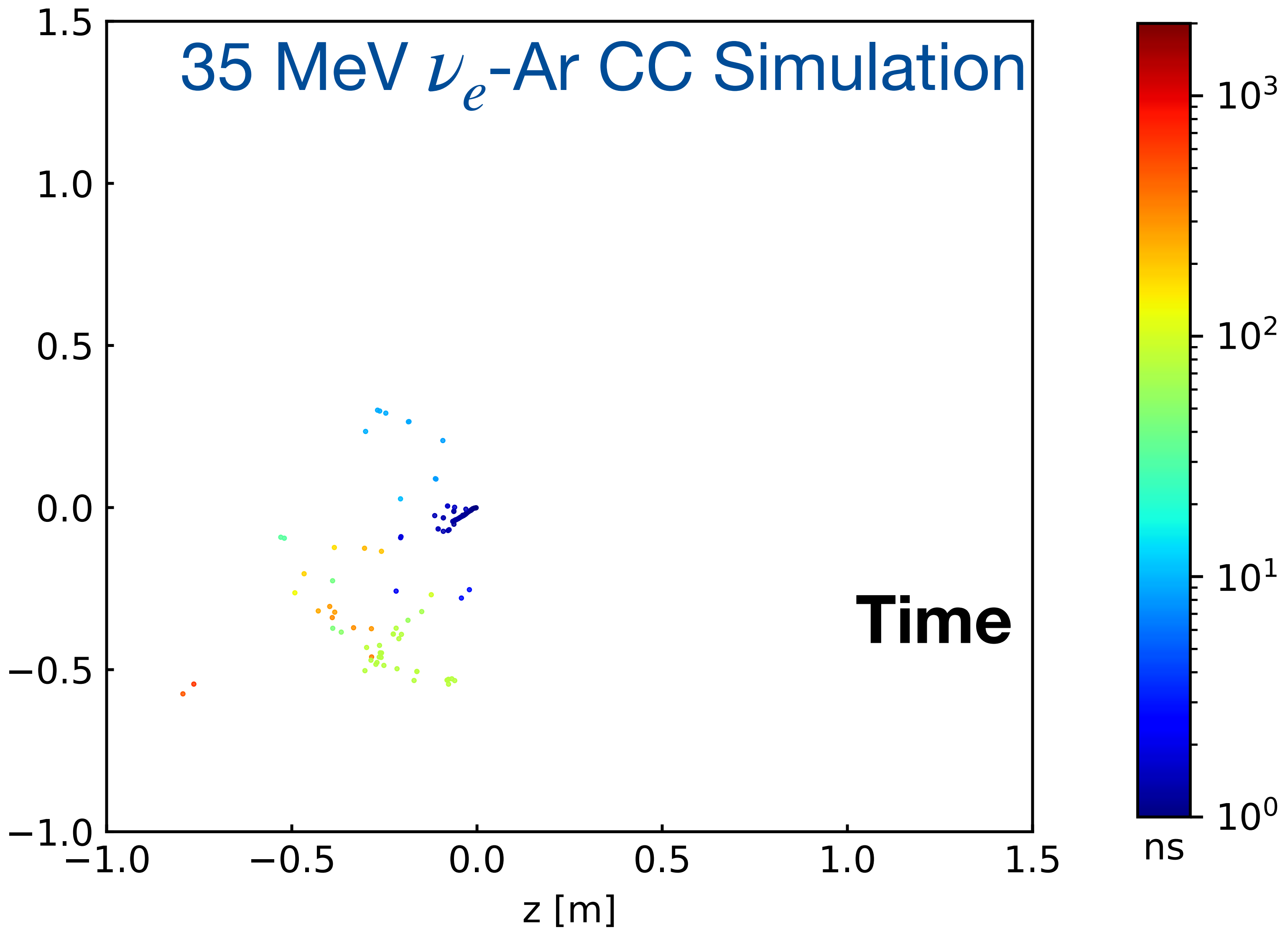
Phys. Rev. D, 94(6):063527, 2016



Phase I charge reconstruction



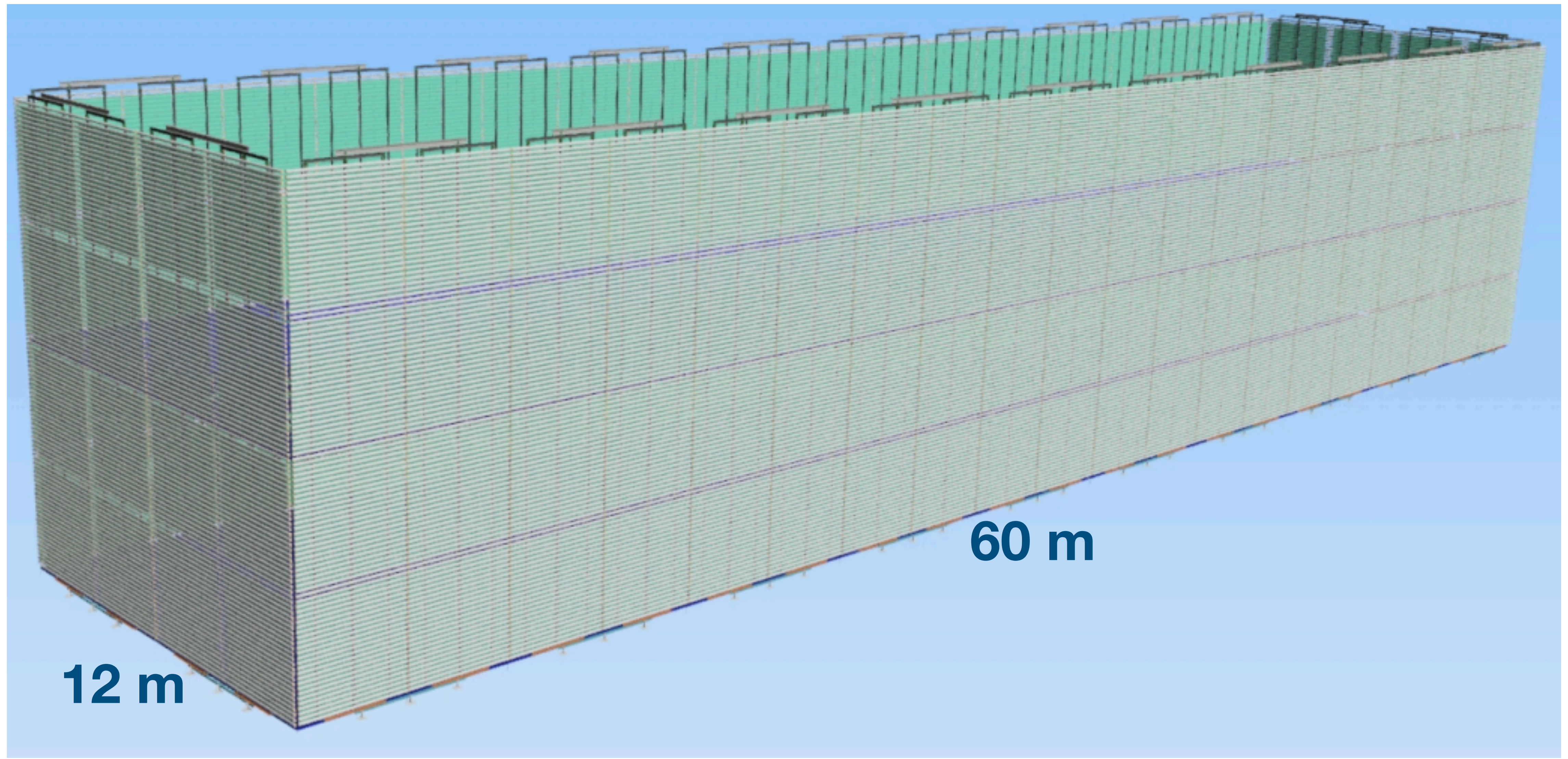


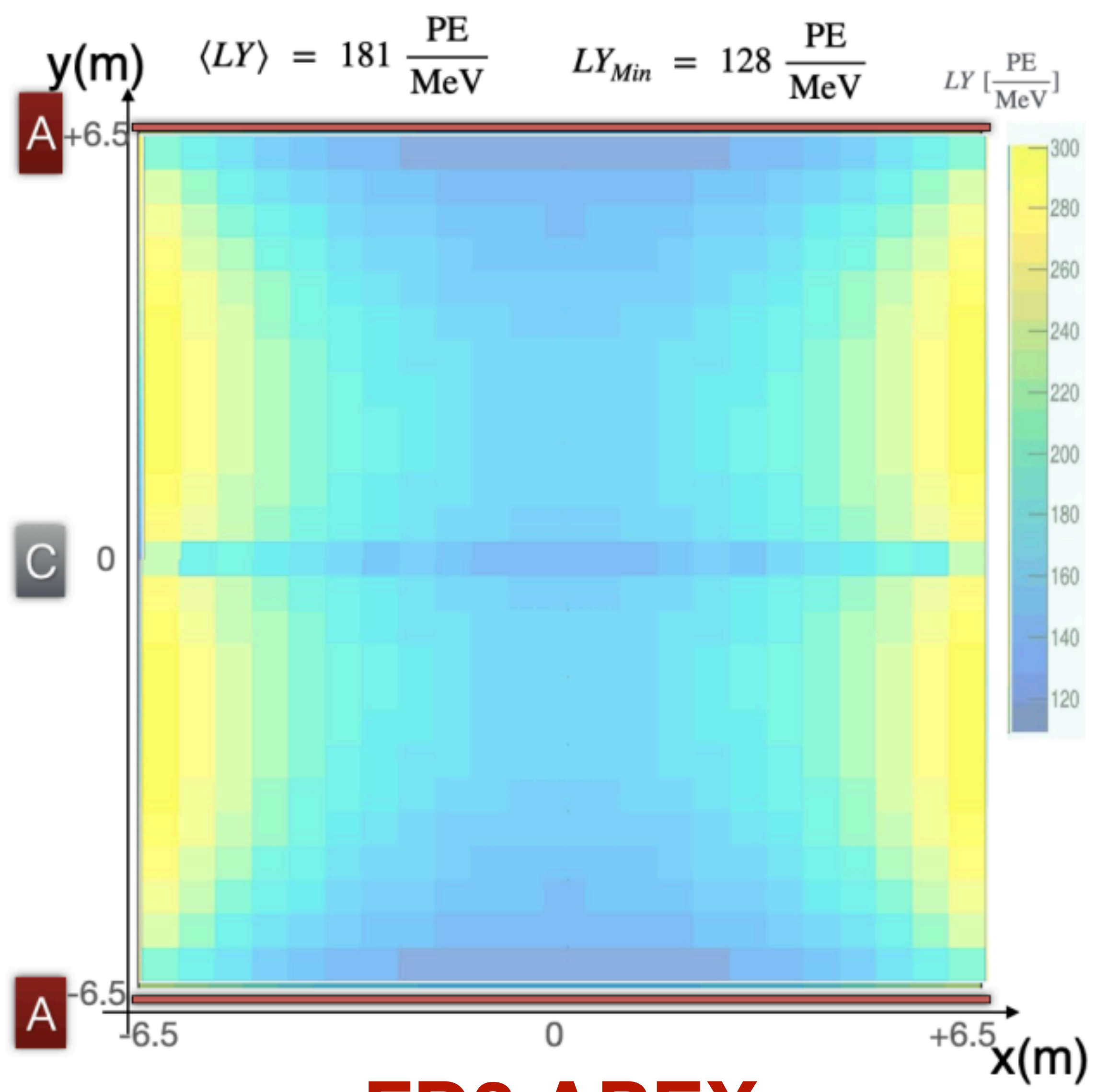


APEX (Aluminum Profiles with Embedded X-Arapucas): Designed to Deliver Aforementioned Physics for FD3

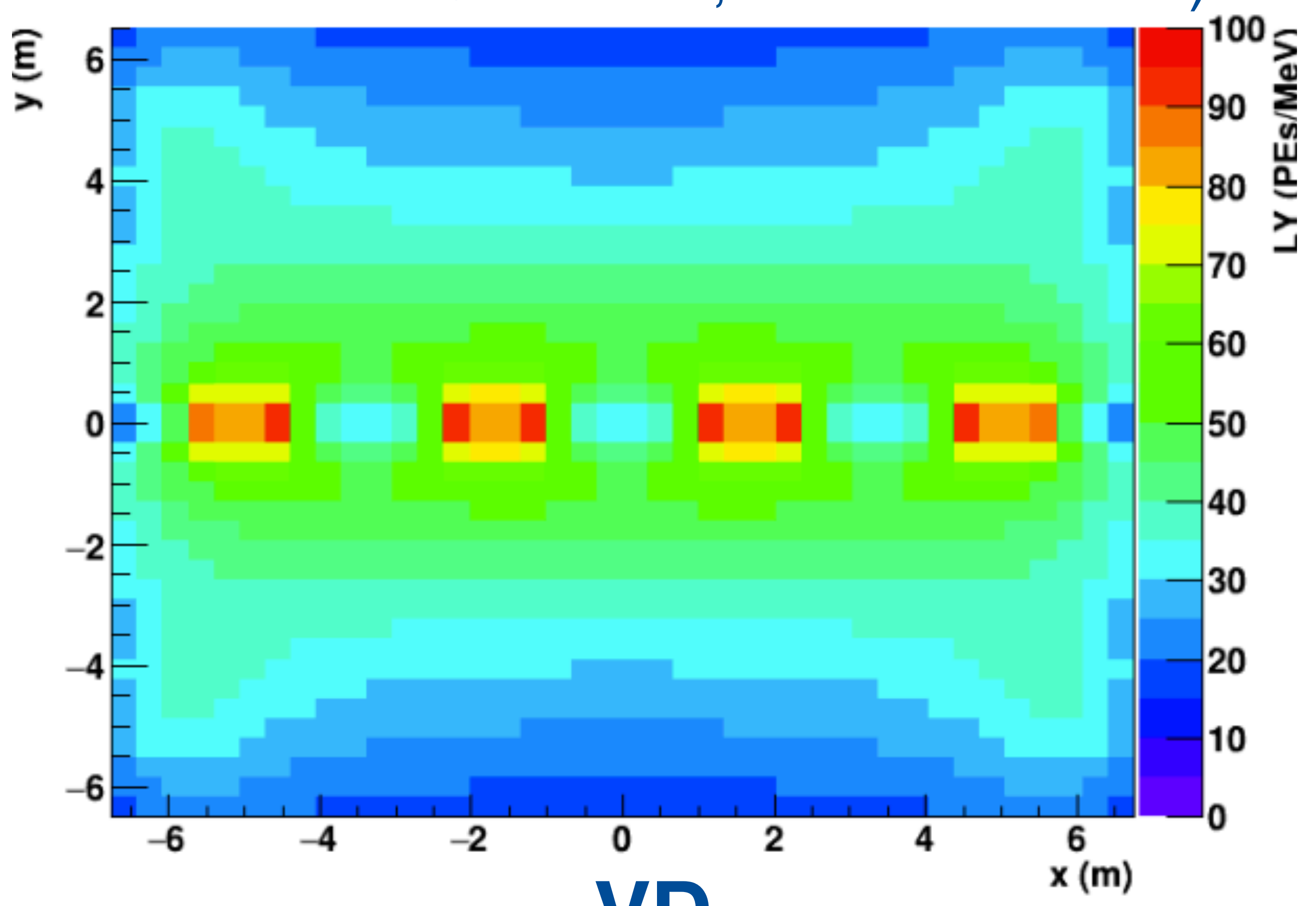
An ambitious detector building on the success of VD

- Up to 2000 m^2 optical coverage: 10 times of FD2
    - ~7000 large-size 50 cm x 50 cm photodetectors
    - Avg. light yield up to 220 PE/MeV, > 4 times VD, higher uniformity
- PoF/SoF for detector operation on HV & cryogenics
    - 9000+ fibers, total length 1000 km+
- Cold digitization, signal bandwidth > 6.5 Tbit/sec
- SNR ~ 10 (signal over fiber), dynamic range up to 2000 PE
- Lower detection thresholds to 5MeV (w. bkg control)

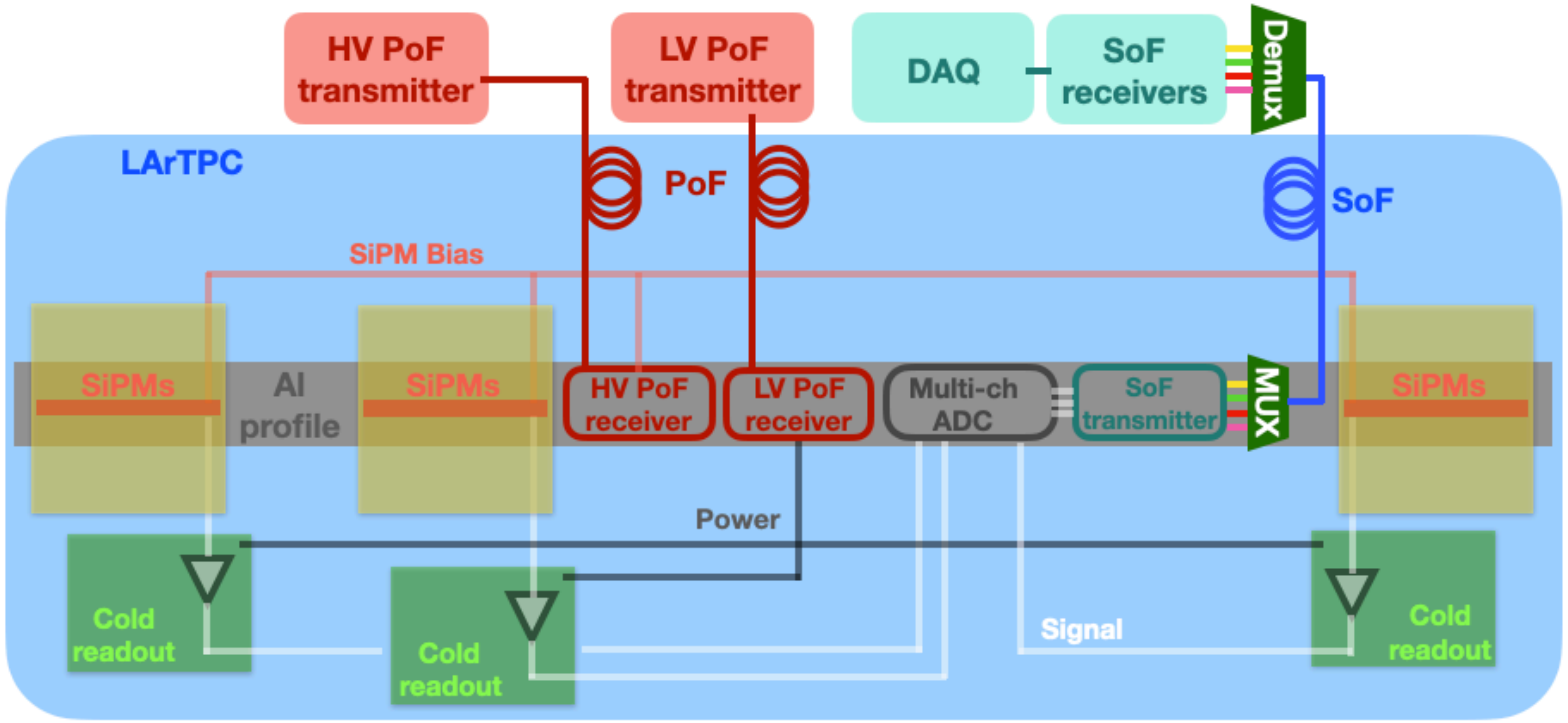




FD3 APEX

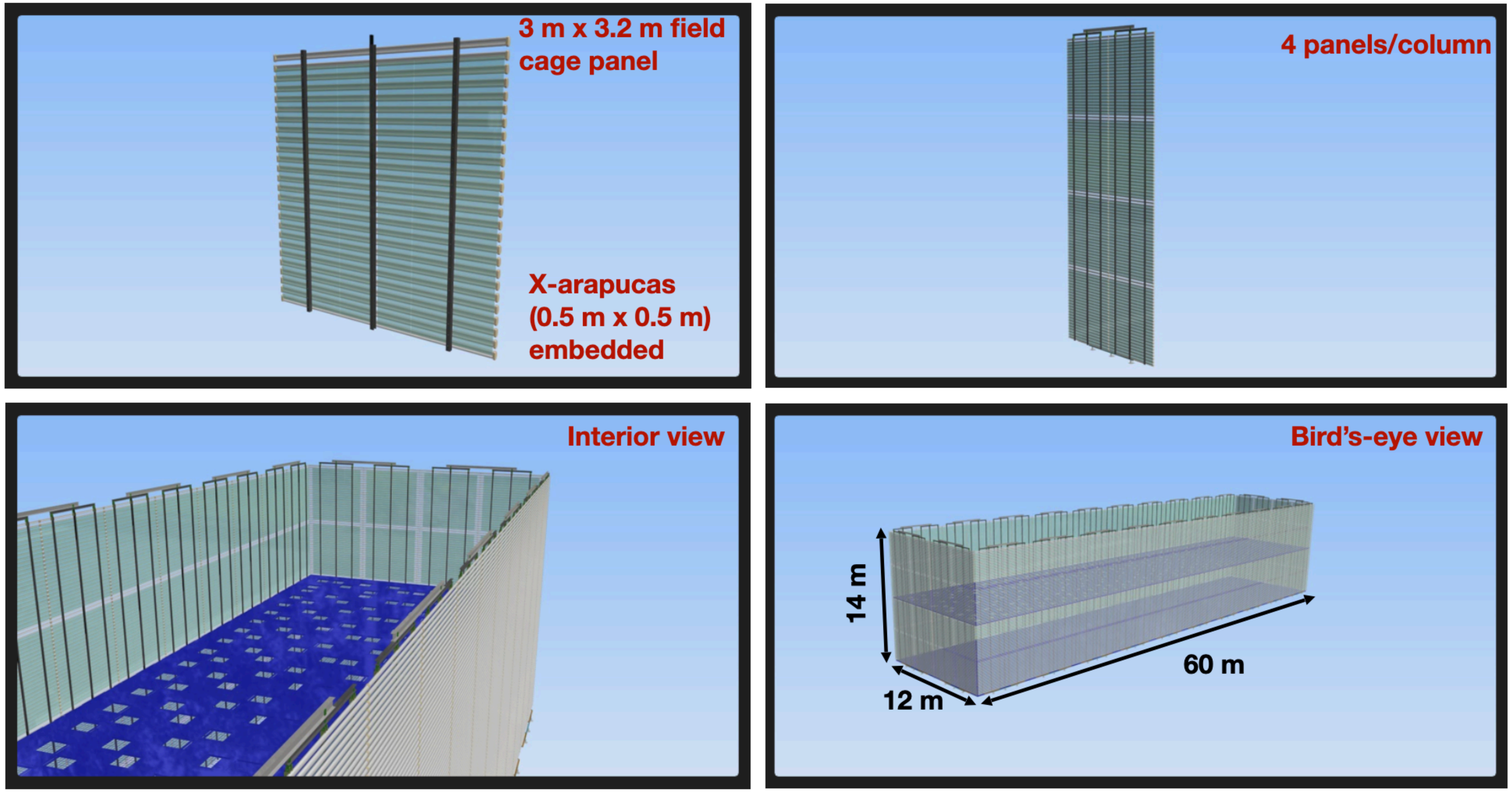


VD



APEX (Aluminum Profiles with Embedded X-Arapucas): Ongoing Development

- **System engineering and prototyping**
- Photo-collector R&D: new wavelength shifting coating
- Photosensor (SiPM) & optical coupling R&D
- Photodetector design, simulation, and prototyping
- **Large bandwidth SoF, High Voltage PoF**
- **LAr cold readout electronics (digital & digital SiPM)**
- Light propagation modeling
- Charge-light dual calorimetry event reconstruction
- Physics potentials across MeV-GeV



Inaugural APEX Workshop Toward DUNE Phase II FD

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

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

60+ participants!
20+ institutions (US, South America, Europe)

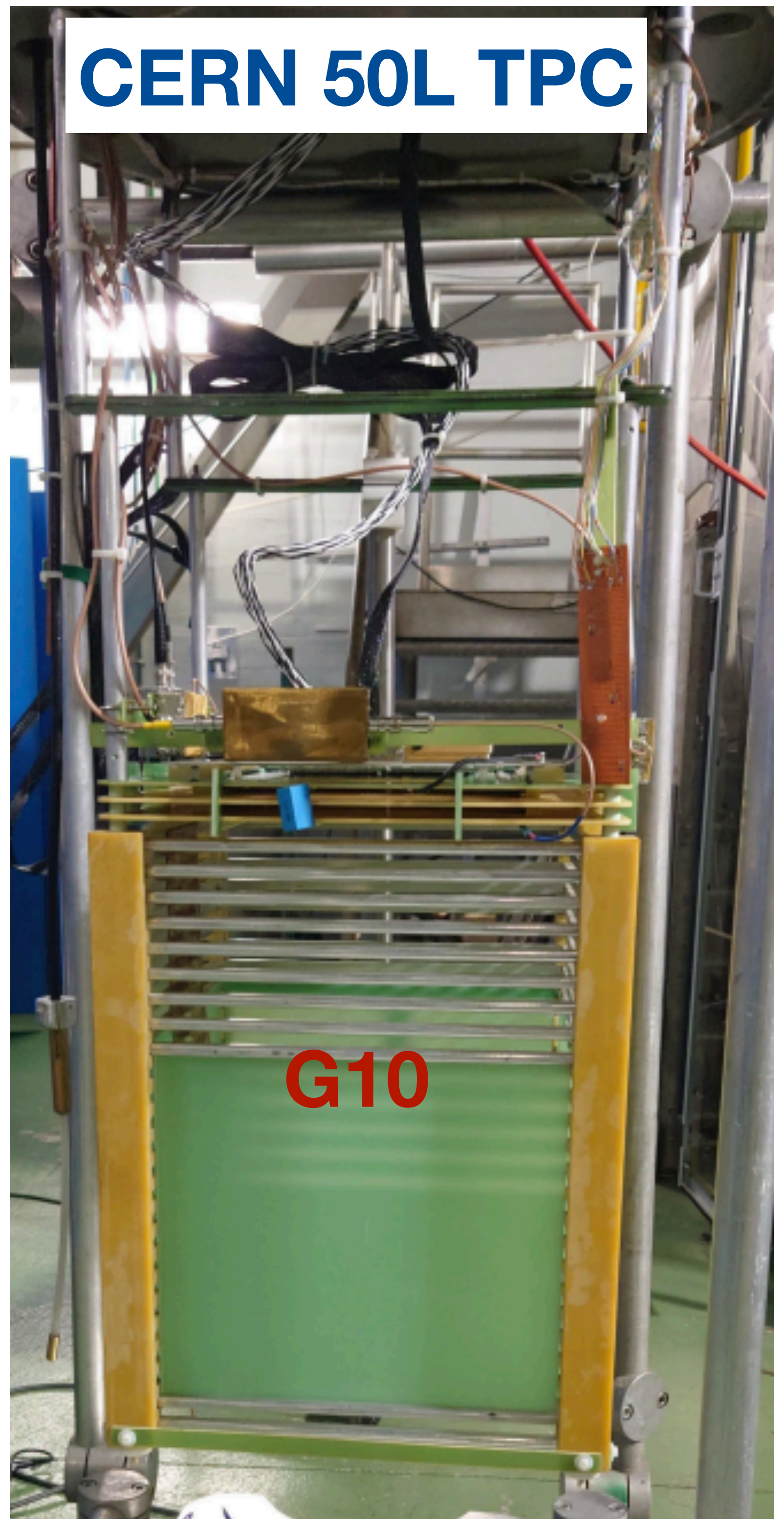
June 26-28, 2023 @ Stony Brook

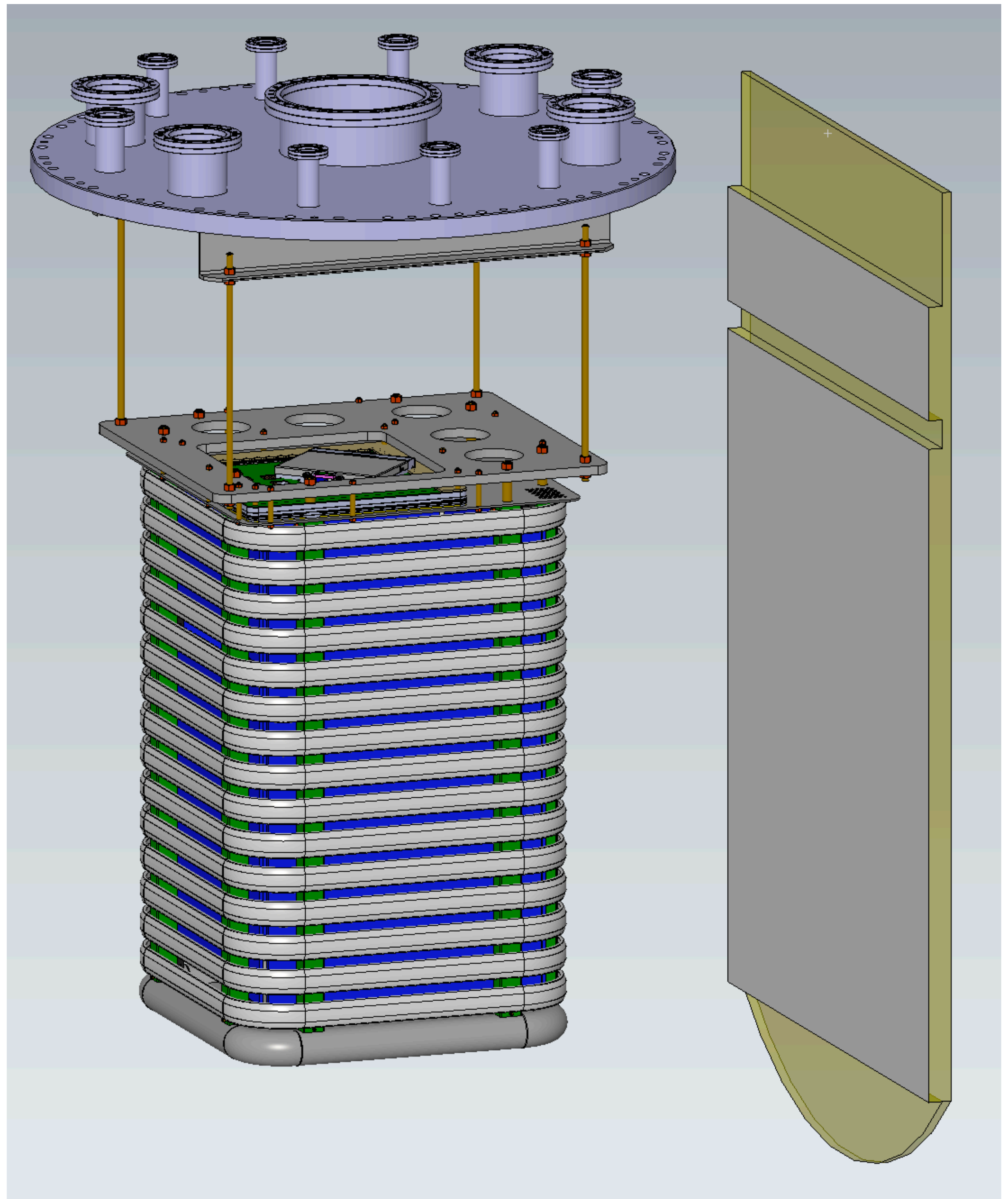
DUNE FD3 APEX Prototyping Phases

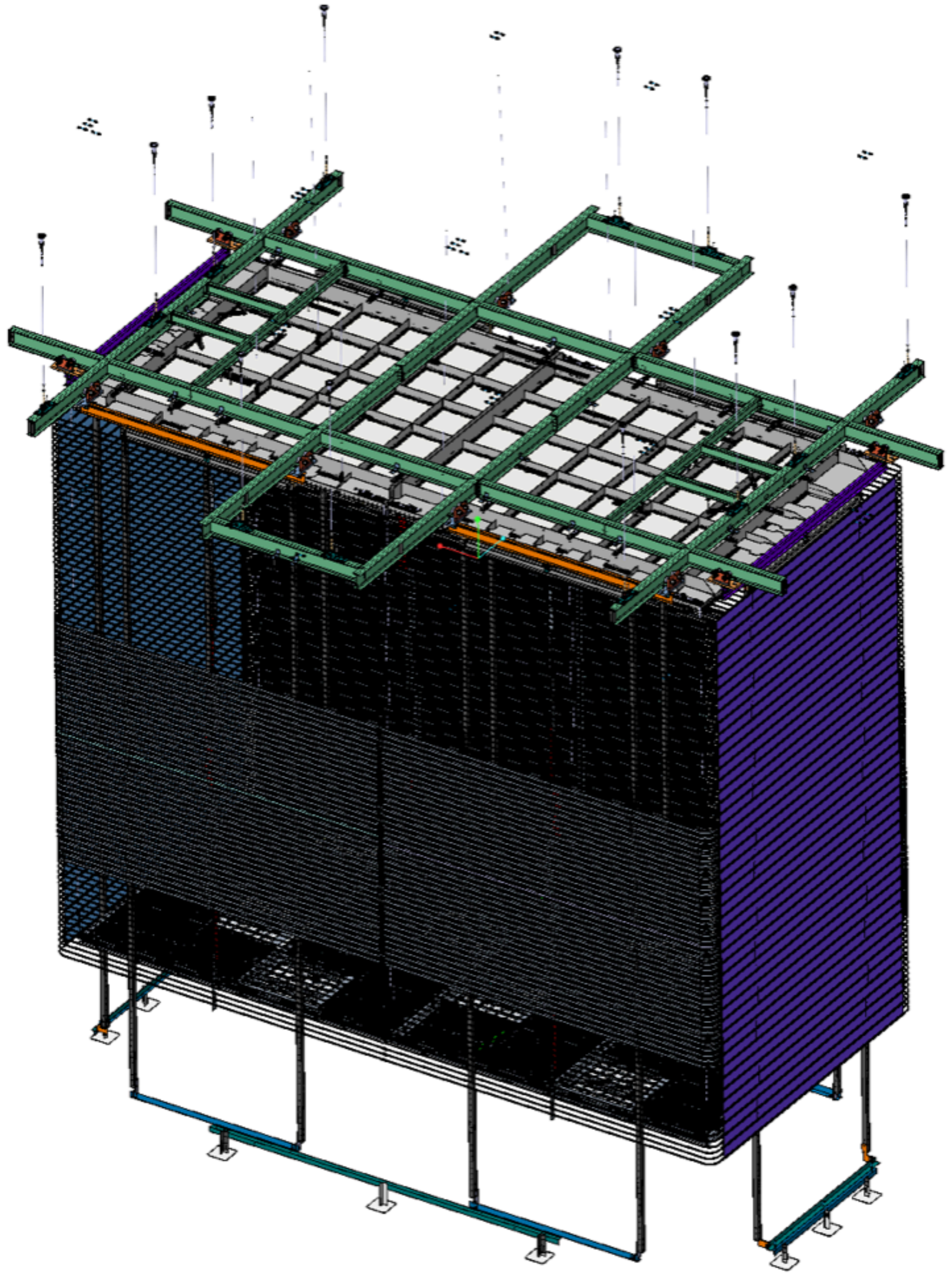
2023
Table-top
50L TPC

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

2025-2027
Kiloton-scale
ProtoDUNE-III @NP02
(CERN)

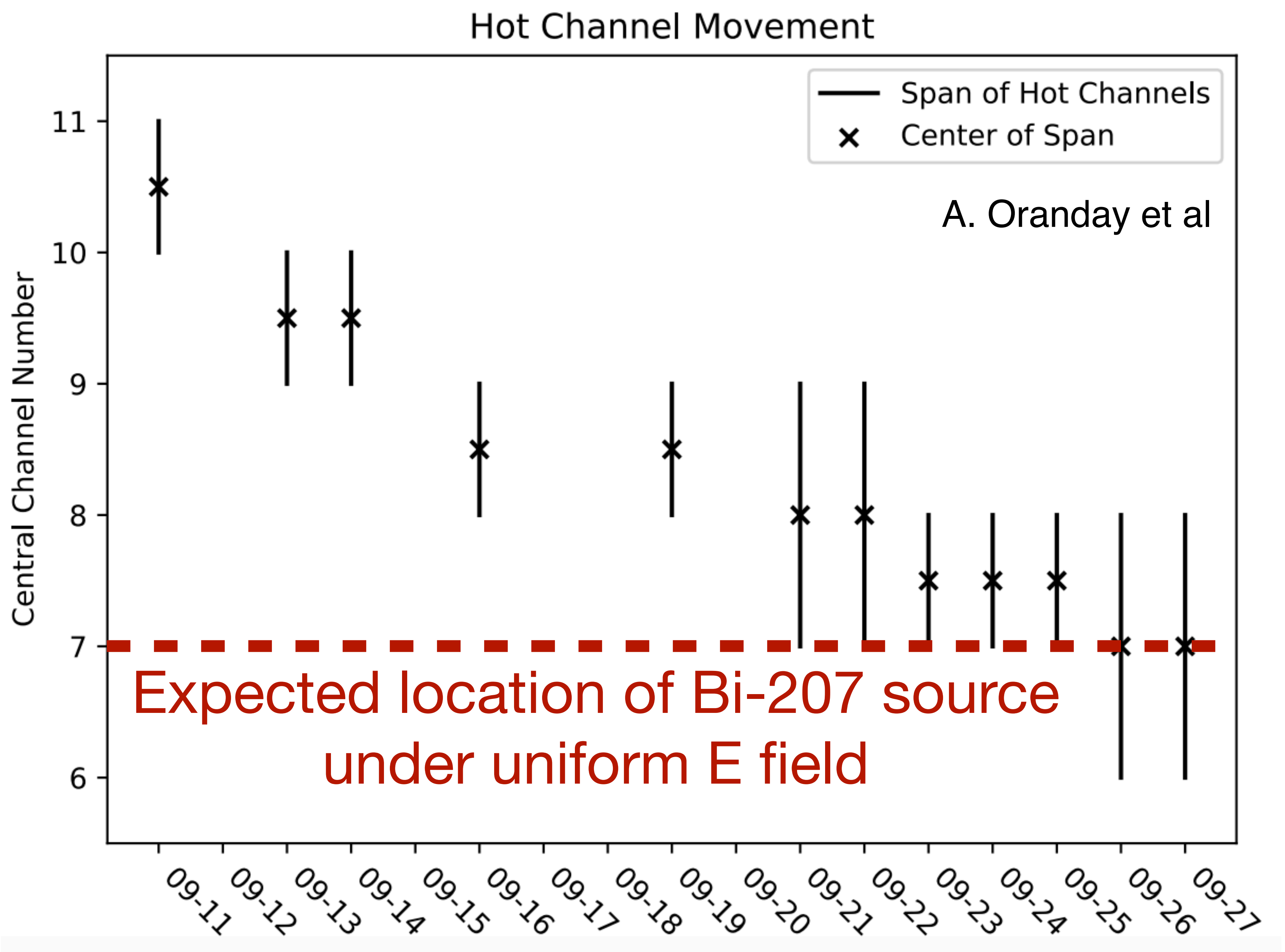


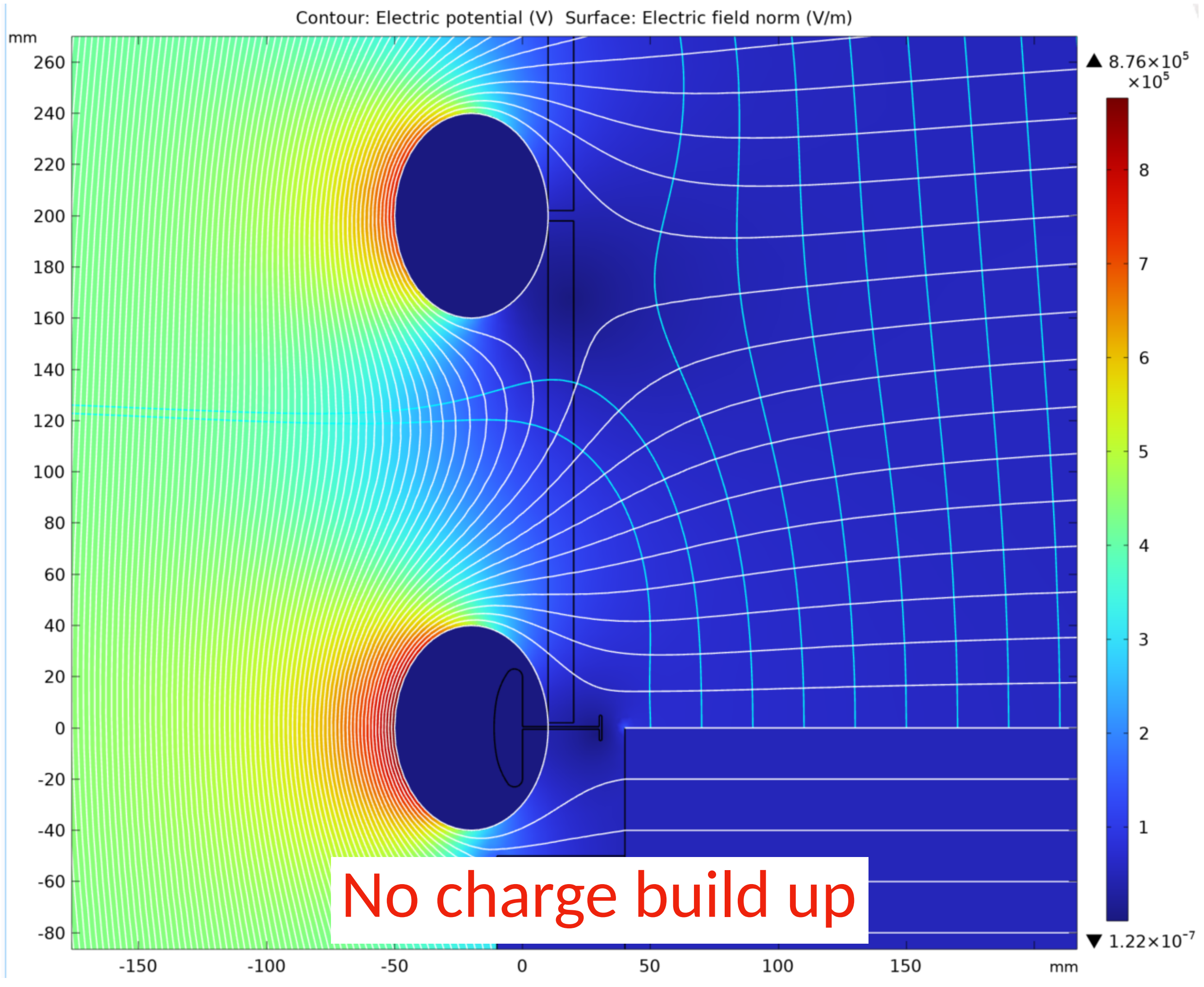


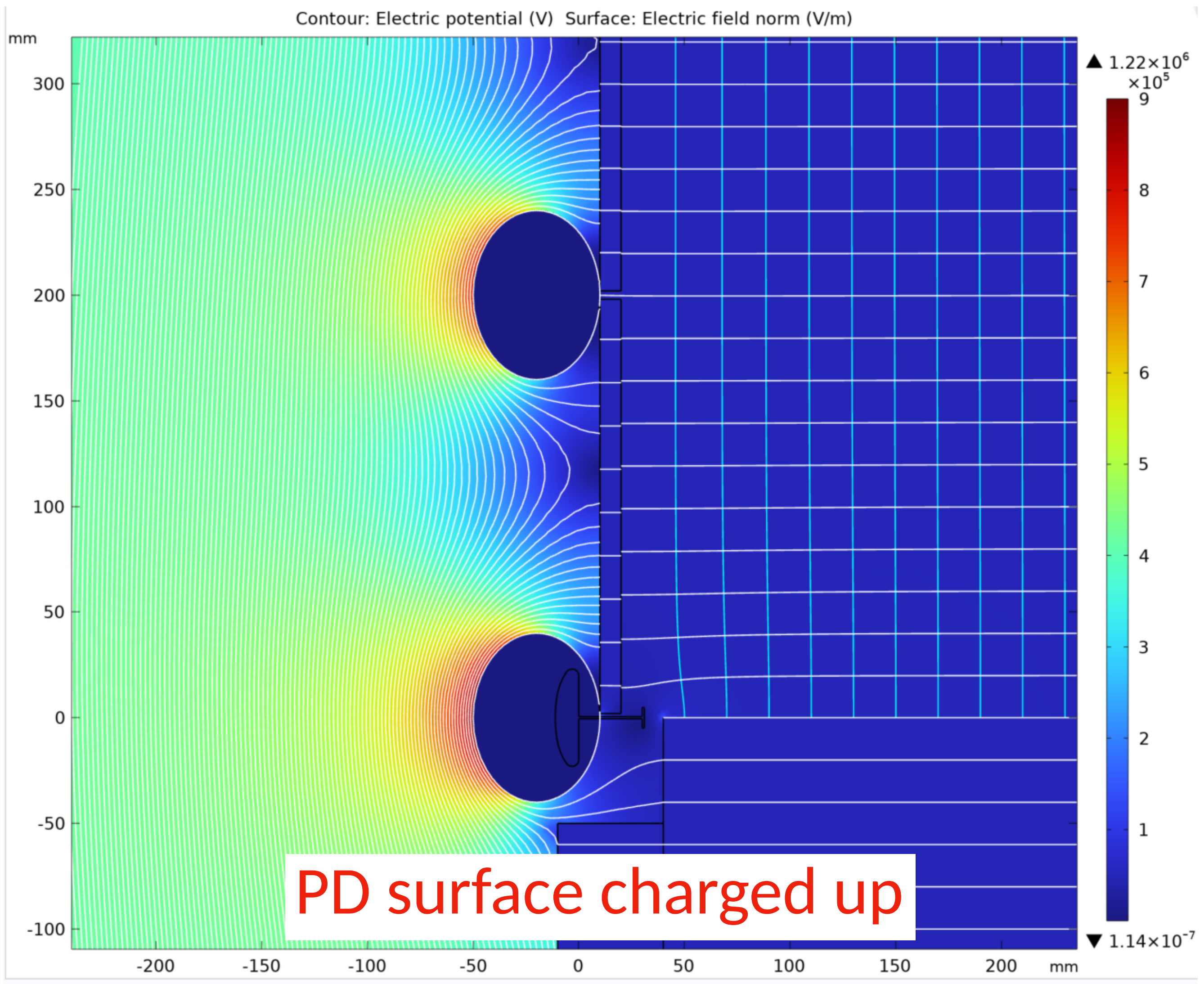


Charging up Test @ CERN 50L TPC

- 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
  - **Same number of field cage profiles as phase I FD is still needed to save charging up time**





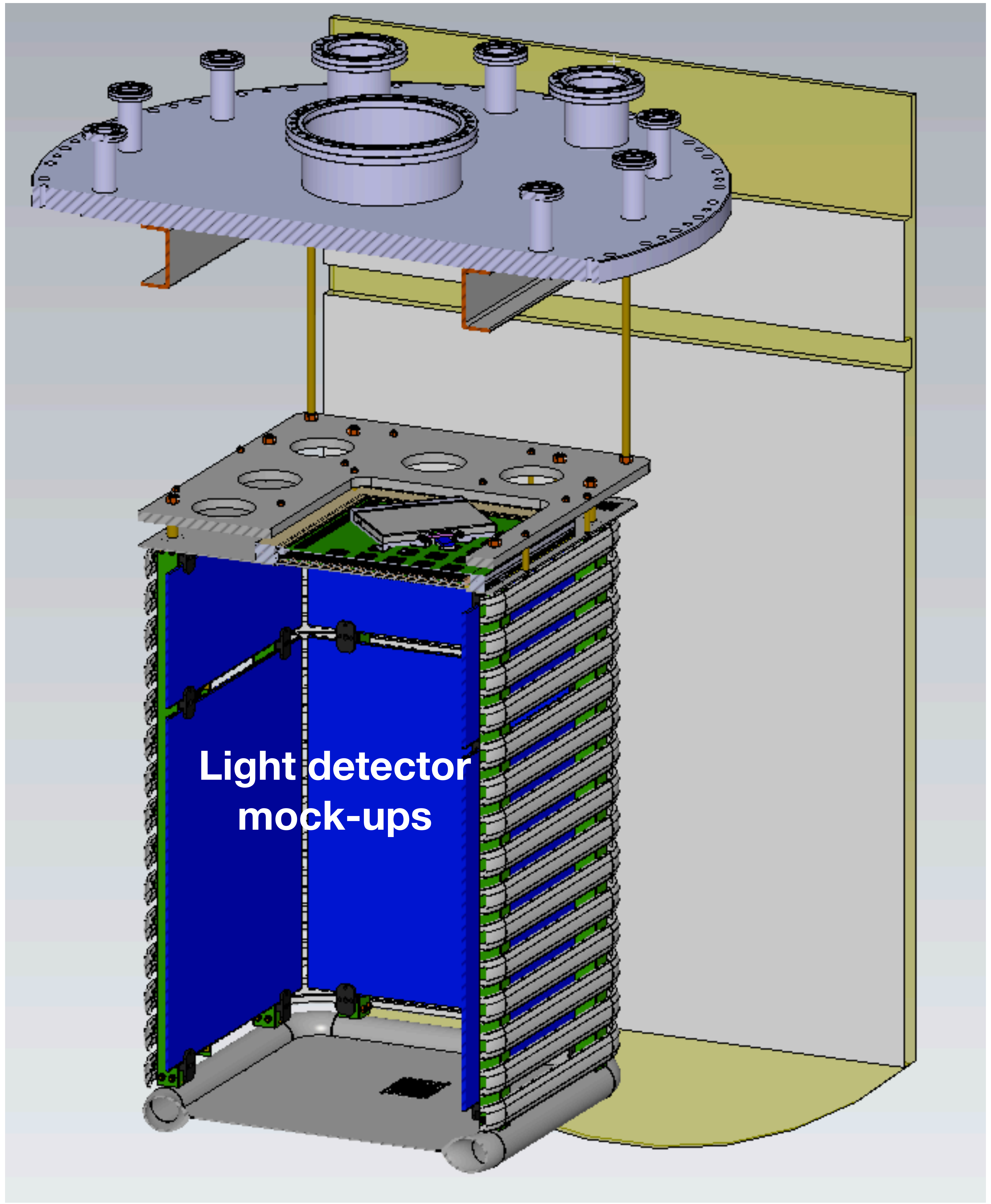


Staged APEX CERN-2ton Prototype

- **Run 1 - projected to run ~3 weeks in Nov 2024**
  - Pure acrylic (PD-side-mechanical mockup only) + field cage + active TPC readout (with purification/recirculation)
  - **Goals**
    1. **Define** detector assembly, installation, and mounting **procedures** (and generate **feedbacks**)
    2. **Demonstrate** stability and reliability of **each component** and the **full prototype** in **thermal cycle(s)**
    3. **Further demonstrate** safe operation on **HV**, improved field **uniformity from insulating material on FC**
  - Procurement and machining work ongoing

- **Run 2 - early 2025**: **IF** 1st prototype is successful, then **reuse** the same structure for the 2nd prototype
  - **Active photodetector** (with WLS functions, SiPM) + **PoF/SoF digital readout** + fiber routing
  - Prototype could be instrumented with **up to 8 photodetector** modules
    - R&D ongoing for further improve light trap photodetectors
    - Actively improving digital readout with PoF/SoF

Welcome new (non-DUNE) collaborators!



Summary

- APEX is a reference design for DUNE Phase II FD3 light detection system
- APEX significantly expands the active optical coverage area to O(2000m^2) toward 4π light collection
- APEX will open new windows to GeV oscillation physics and MeV energy physics by leveraging light calorimetry and all other light system information
- Staged 2ton APEX prototypes is being built at CERN and will be tested 2024-2025, followed by ProtoDUNE scale prototype