Tagging Neutron Capture on Argon for Light Calorimetry Calibration and MeV Physics

NuFact 2024 - WG 6
Sep 18, 2024
Argonne National Lab

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on behalf of the DUNE Collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Stony Brook University

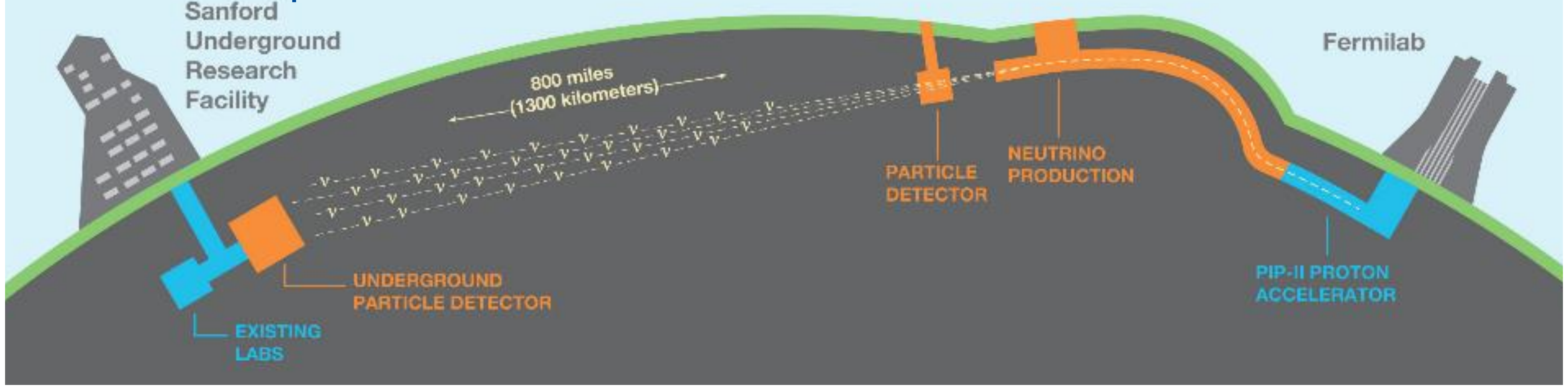
DUNE and Far Site

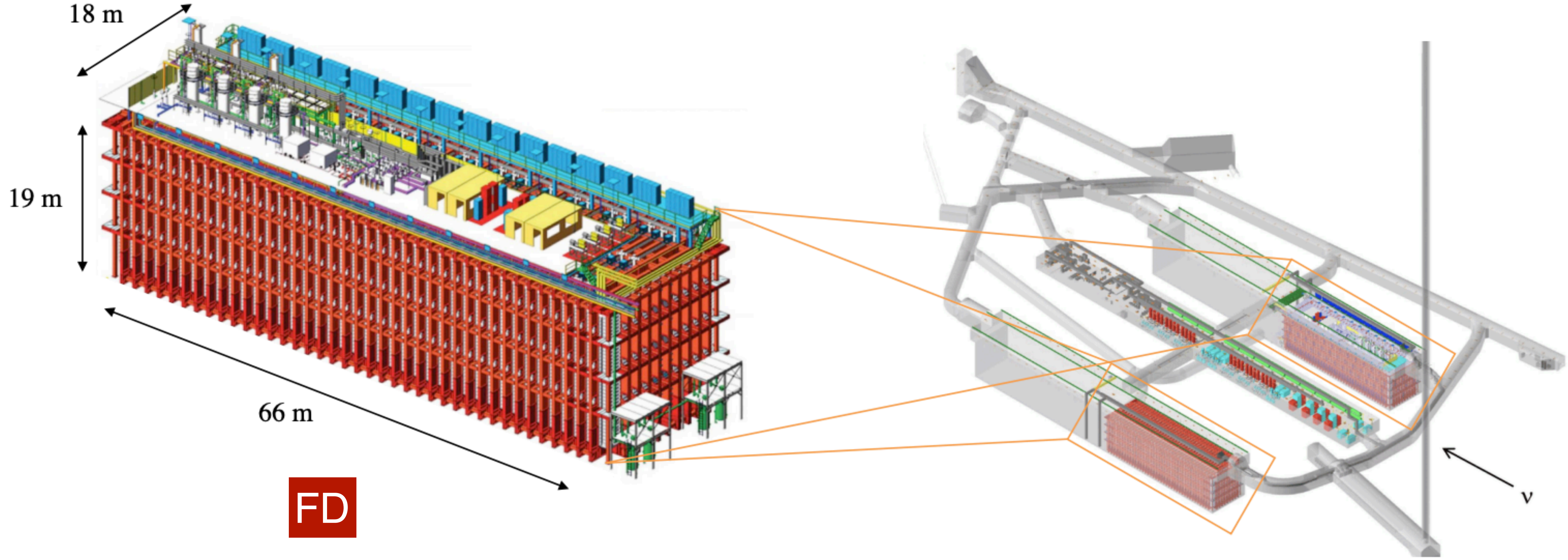
SURF in Lead, South Dakota

Cavern excavation completed Feb 1, 2024 - outfitting & receive cryostats

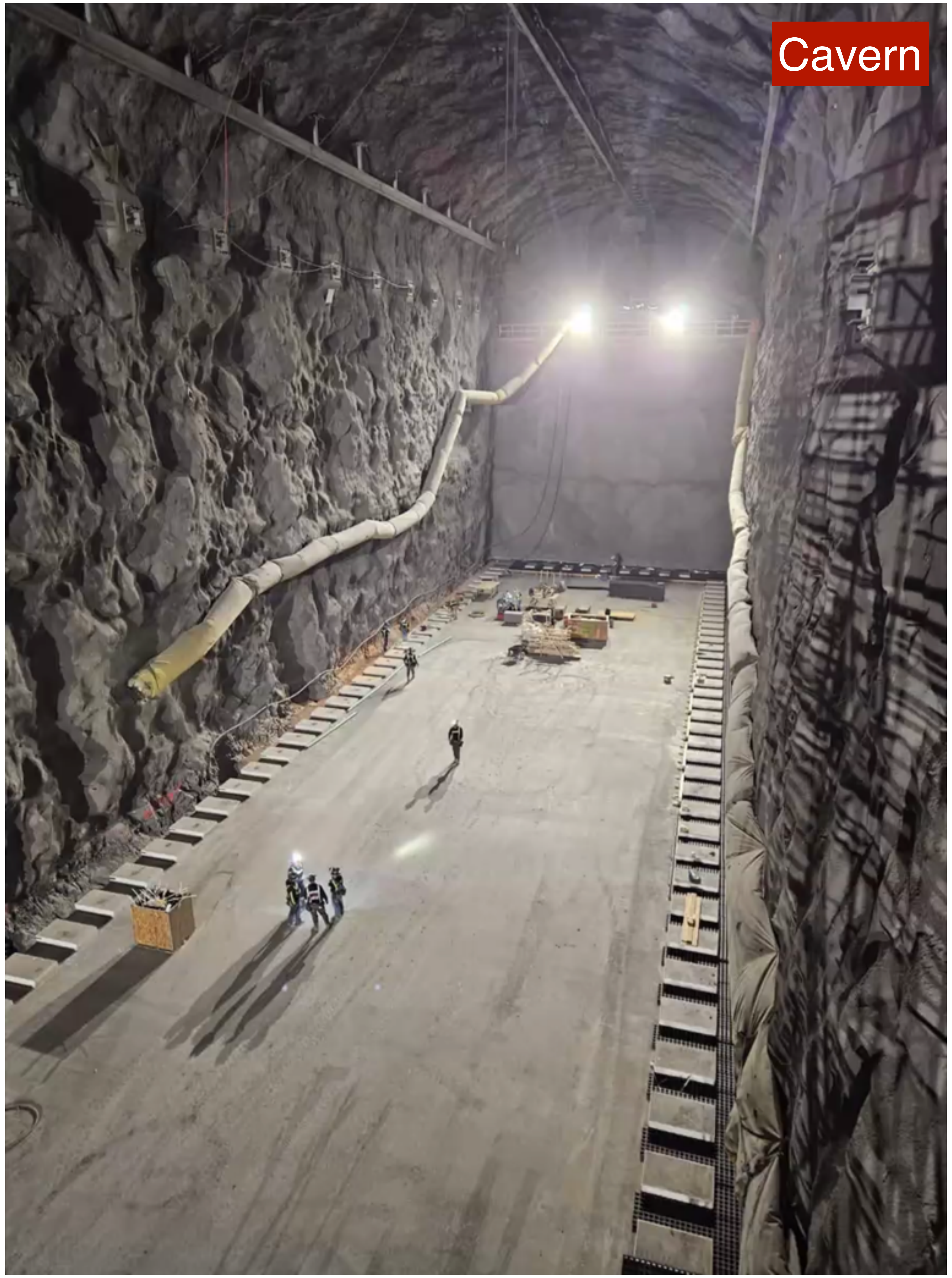
4850 ft underground, 8 soccer fields, 800 ktons of rock

Could house up to four 17 kt LAr TPC far detector modules





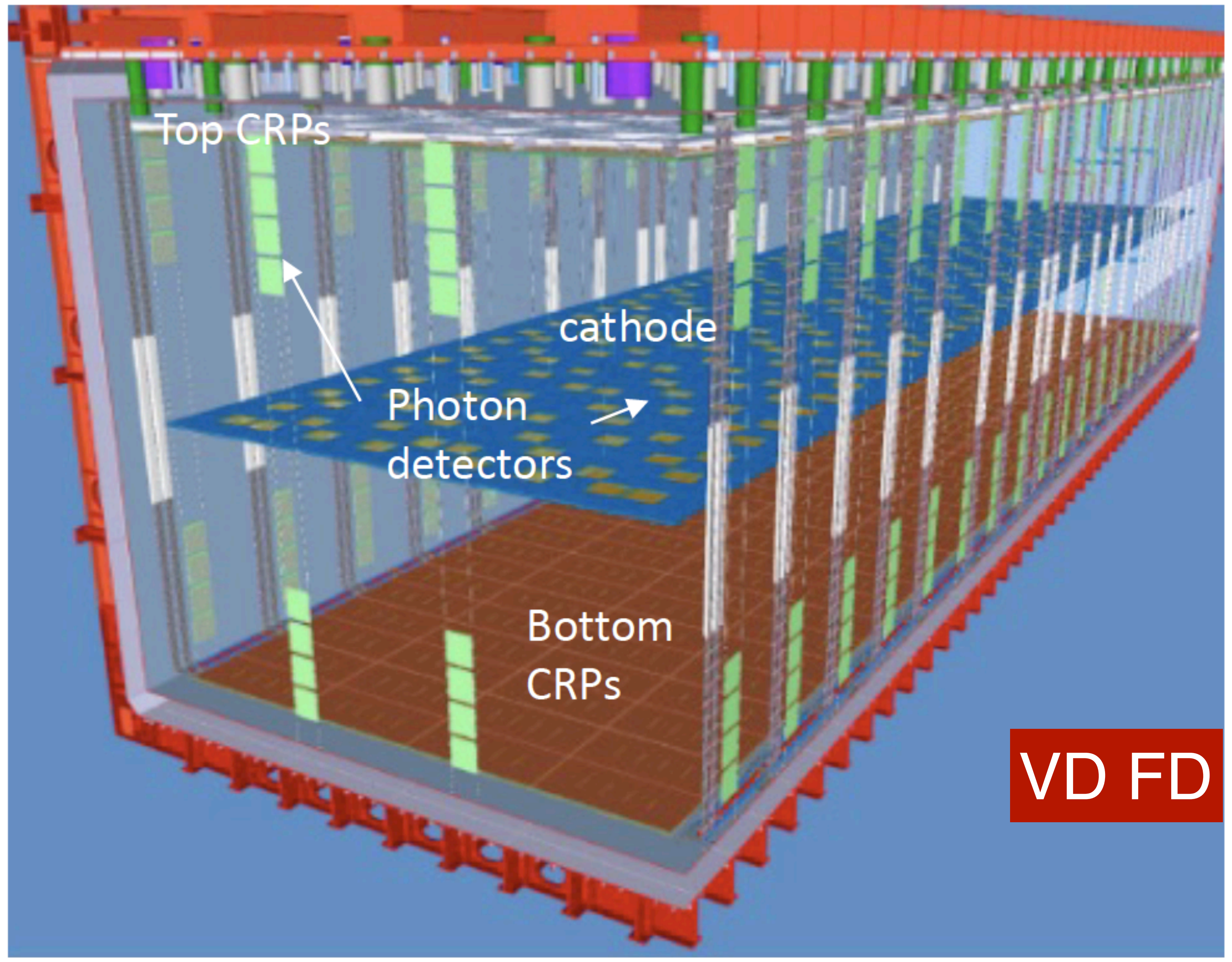
FD

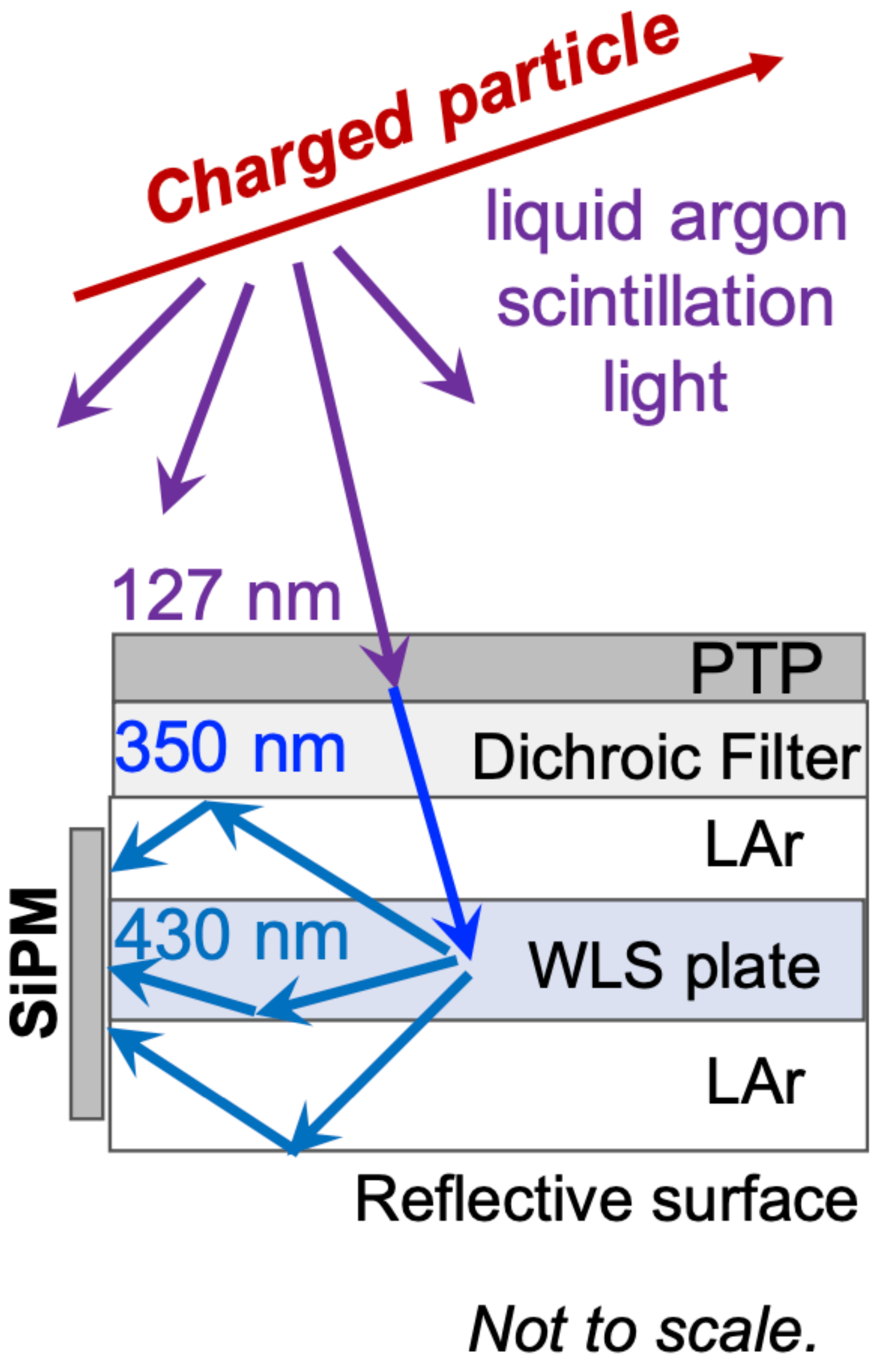


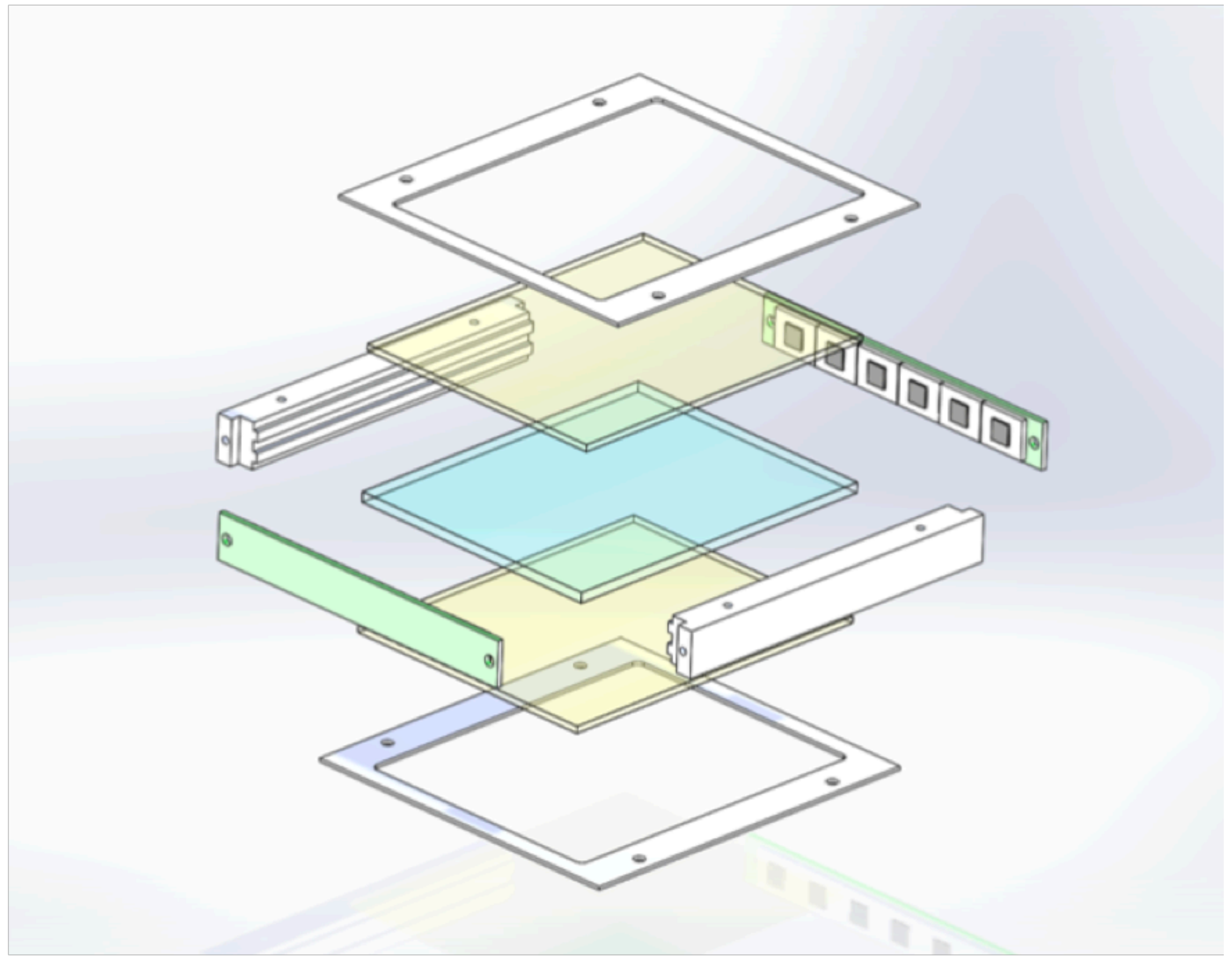
Cavern

Photon Detector System in Vertical Drift Far Detector

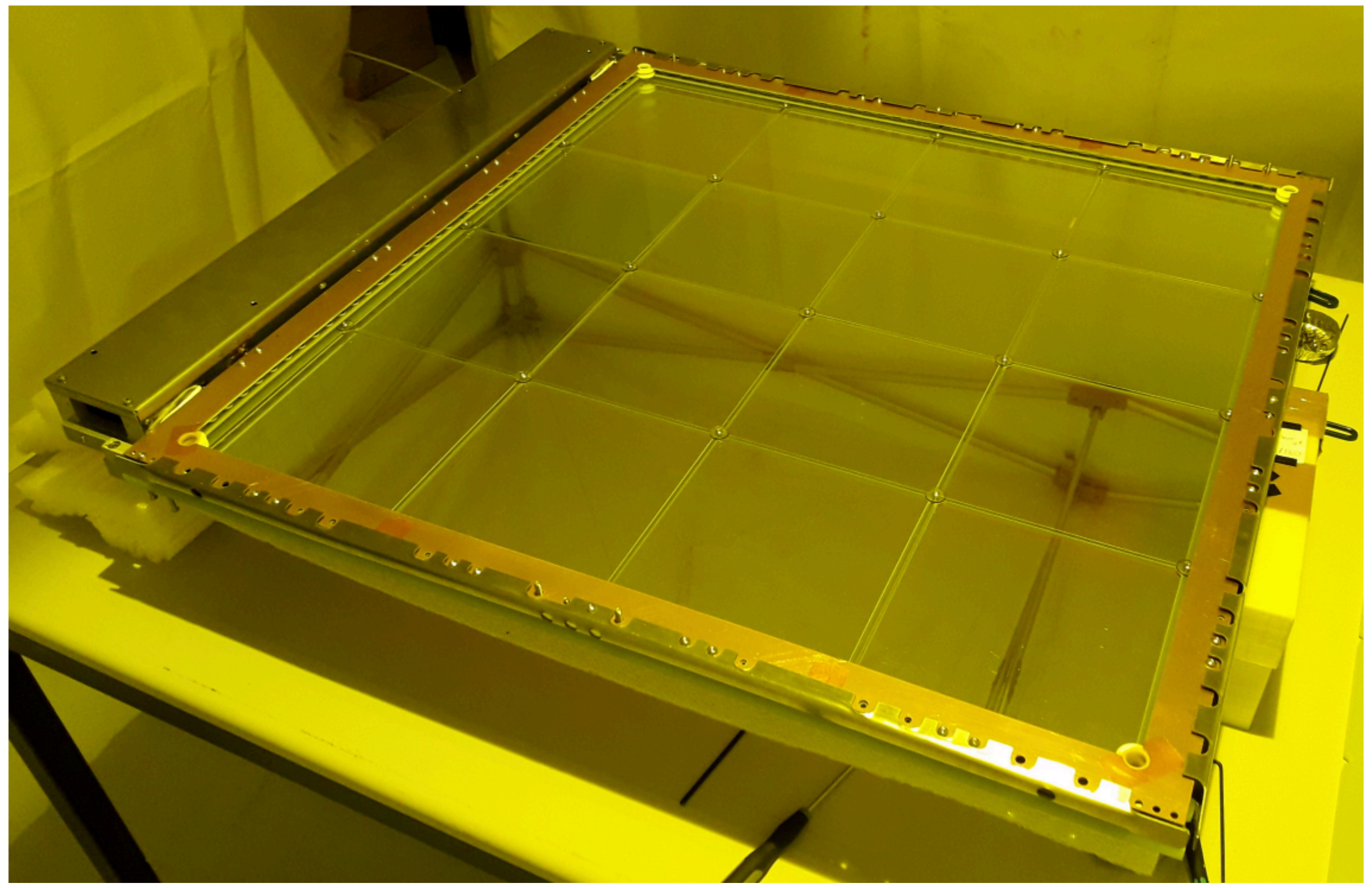
- Two drift volumes, ionized electrons drift vertically under E field (cathode → anode)
- **Photodetectors**: X-Arapuca (60 cm x 60 cm)
  - Two-stage wavelength shifting: 127 nm → 350 nm → 430 nm
  - Dichroic filter for light trapping
  - Compact detector **device,** avg. detector efficiency **3-4%**
- In VD, **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 VD membrane







Exploded view of X-Arapuca

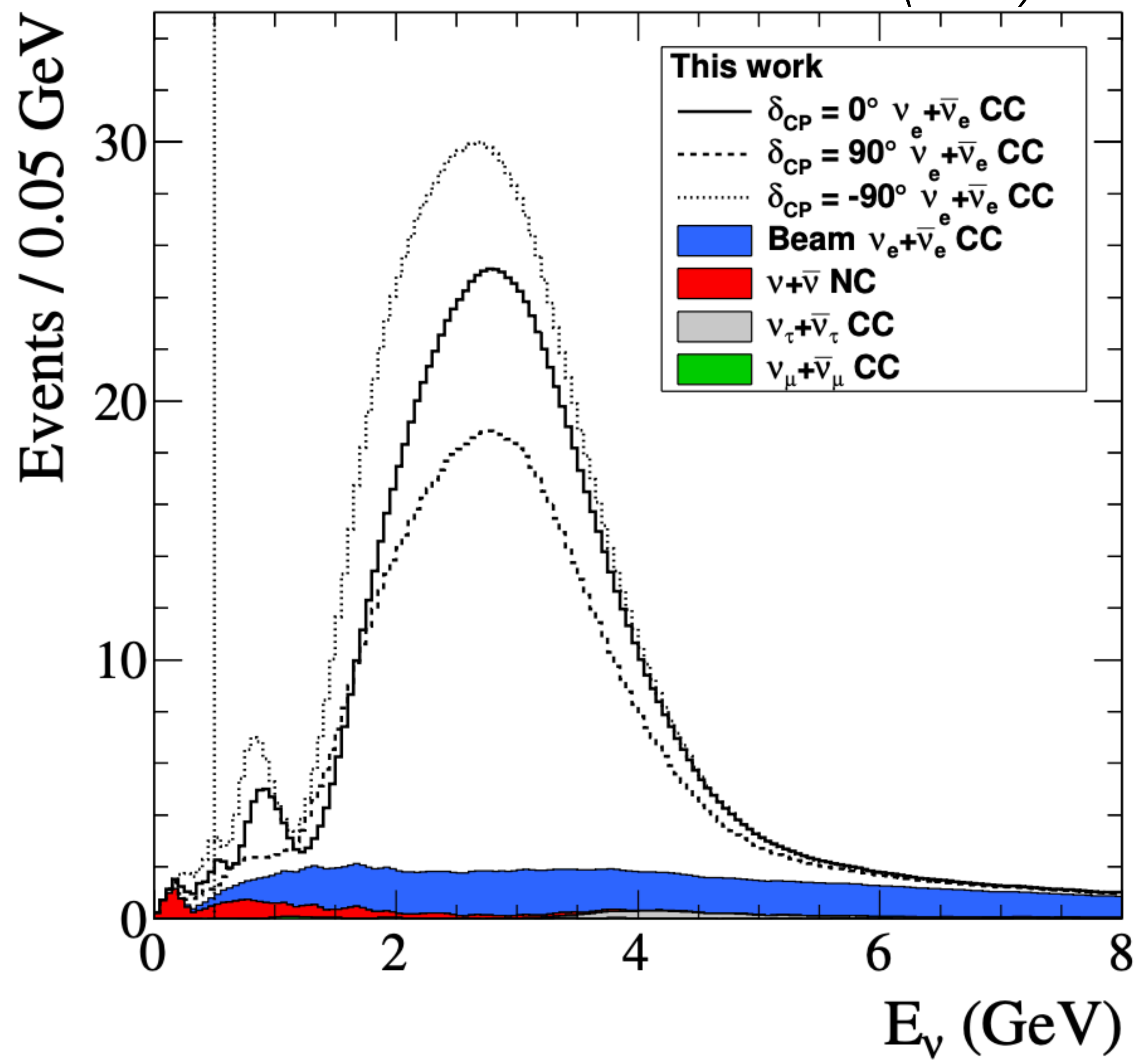


60cm x 60cm X-arapuca for ProtoDUNE-VD

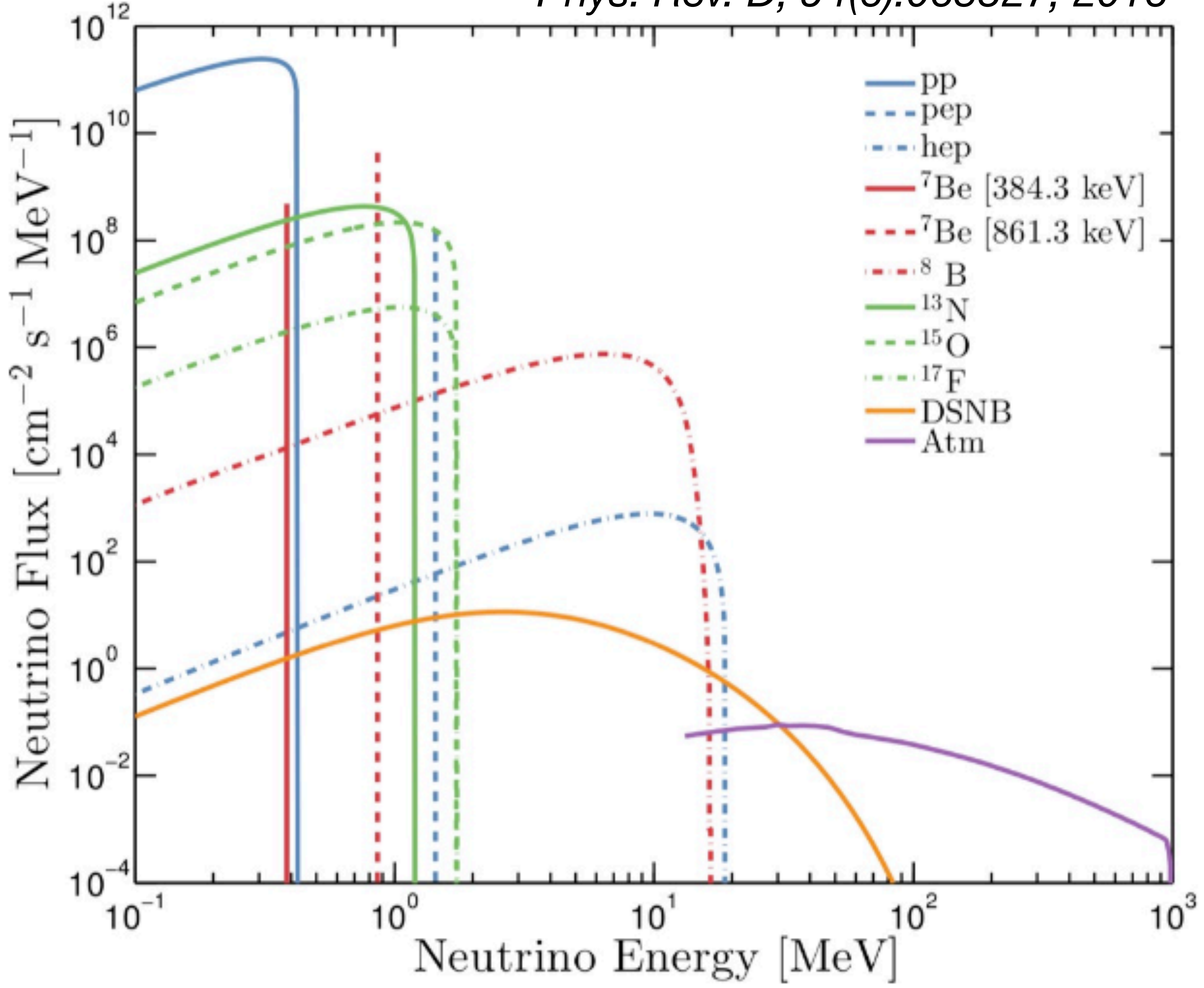
Light Calorimetry Important for DUNE physics

- **GeV**
  - Light offers an independent calorimetry aside from charge
    - **Light calorimetry based reconstructed energy can be used to probe neutrino oscillation**
- **MeV**
  - **Combined light and charge calorimetry expected to improve energy resolution at tens of MeV energy**

JHEP09(2016)030



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



Energy Resolution

- Light calorimetry calibration in simulation
  - **Constant term** p_0 (right example: dominate@ >12.8MeV)
    - Many contributions: **energy calibration,** source energy spread, energy loss fluctuations
  - Stochastic term p_1
    - Intrinsic statistical spread in the number of detected photons given by Poisson statistics (higher light yield helps: improve detector)
  - Noise term p_2 (right example: dominate@ $<$ 12.8MeV)
    - Cumulative electronic noise (high signal-noise-ratio helps: improve readout)

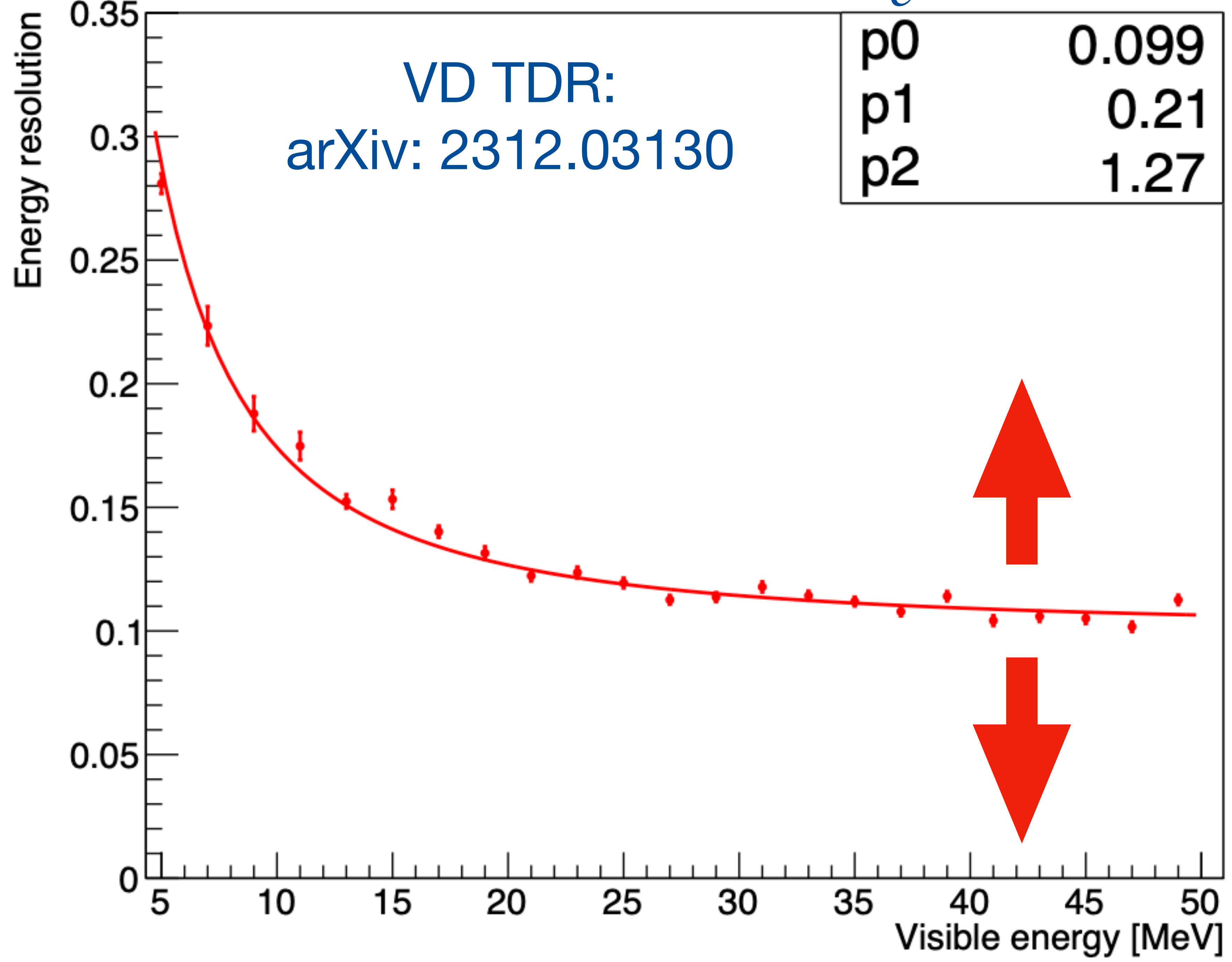
- Calibration uncertainty contributes to energy resolution

- Need to calibrate PDS light yield with a "standard candle" and gauge simulations
  - First time demonstrate MeV energy calibration for PDS in ColdBox

$$(\frac{\sigma_E}{E})^2 = p_0^2 + (\frac{p_1}{\sqrt{E}})^2 + (\frac{p_2}{E})^2$$

Simulated VD PDS

energy resolution on ν_e events

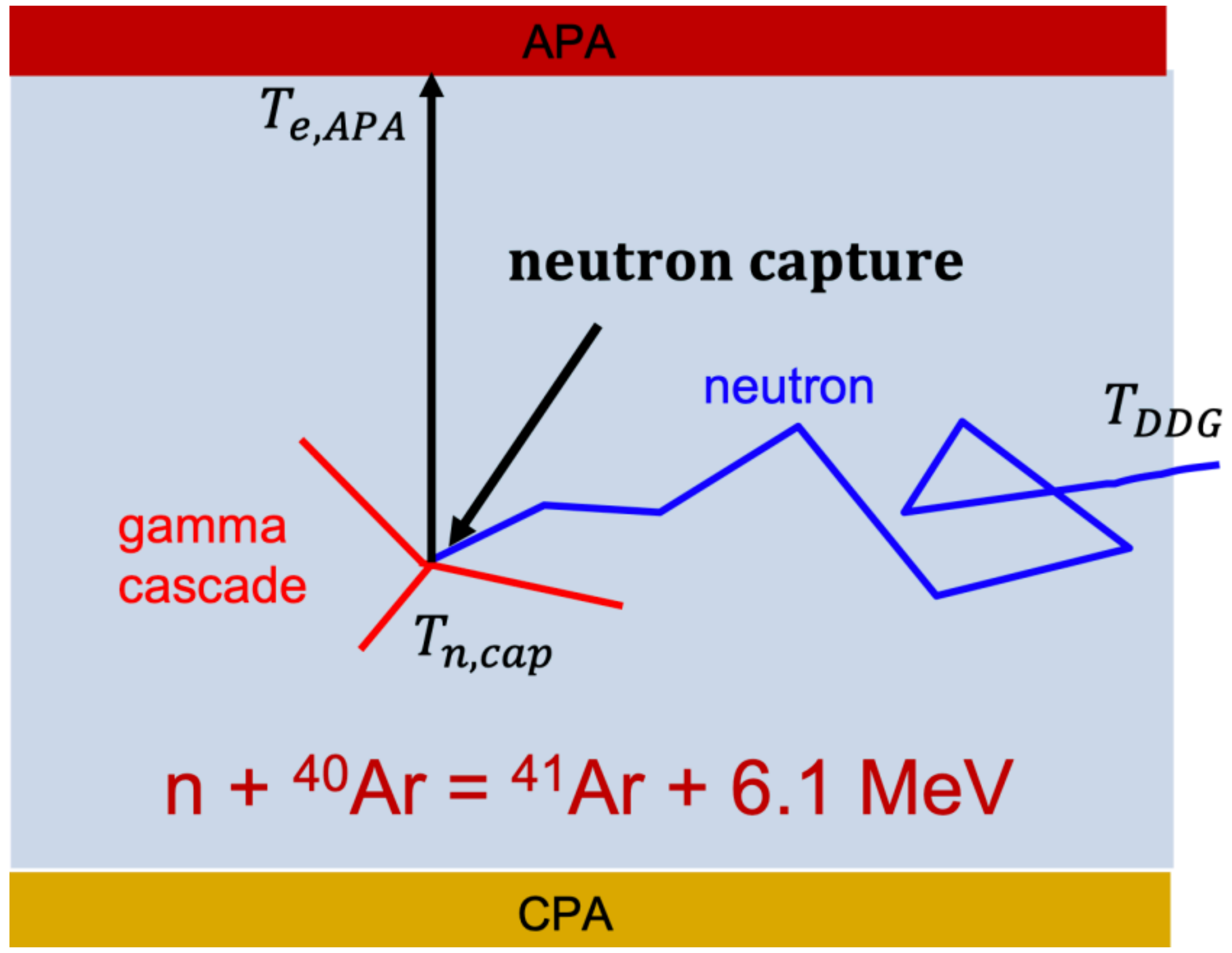


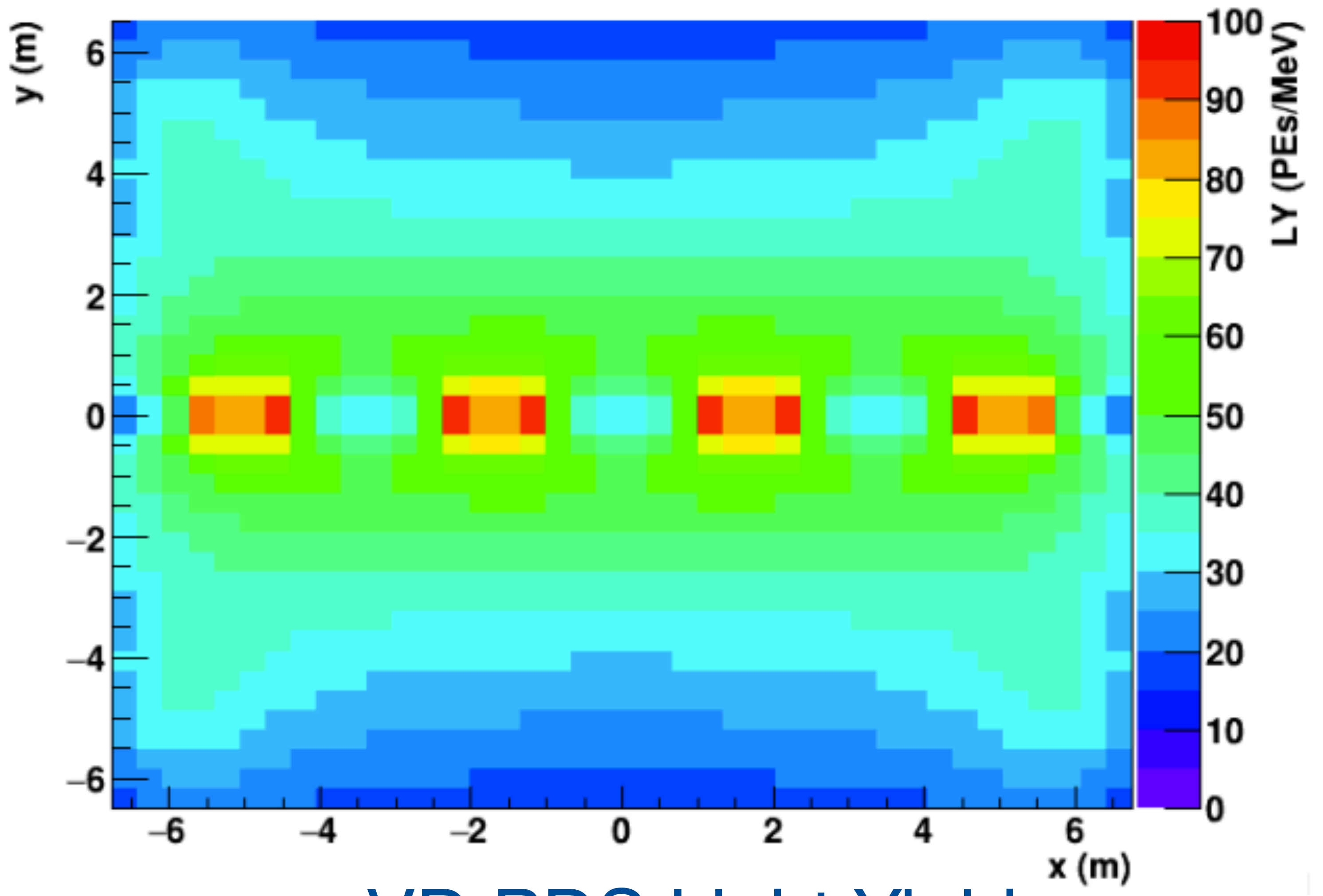
Light Calorimetry Calibration with Neutrons

- Neutron as a calibration source
  - Can sample the large FD with its **long interaction lengths** in LAr
    - ~30m @57keV (ARTIE: arXiv:2212.05448)
  - Provides a **“standard candle”**
    - Neutron capture on ^{40}Ar produces fixed energy **6.1 MeV γ cascade**
    - Most common mode: **4.7 MeV γ, 1.2 MeV γ, 167 keV γ**

- Light calorimetry energy reconstruction relies on light yield map

- **Light yield map**: average # of detected PEs per MeV as a function of position/voxels
  - Voxel sizes vary depending on interested physics
  - **Energy calibration for MeV physics**: look for highly localized energy deposits **(~tens of cm)** n-capture events





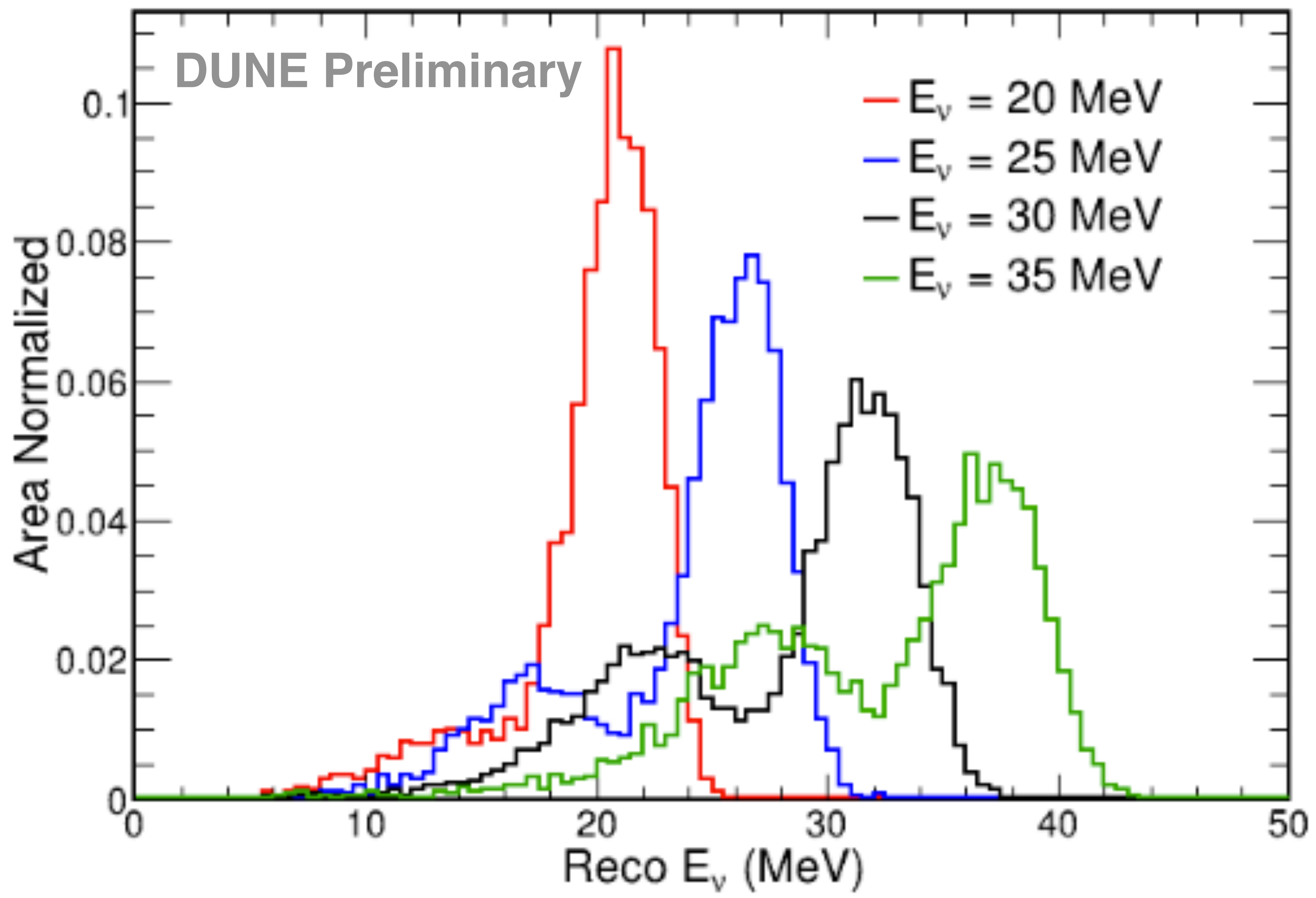
VD PDS Light Yield
(VD TDR arXiv: 2312.03130)

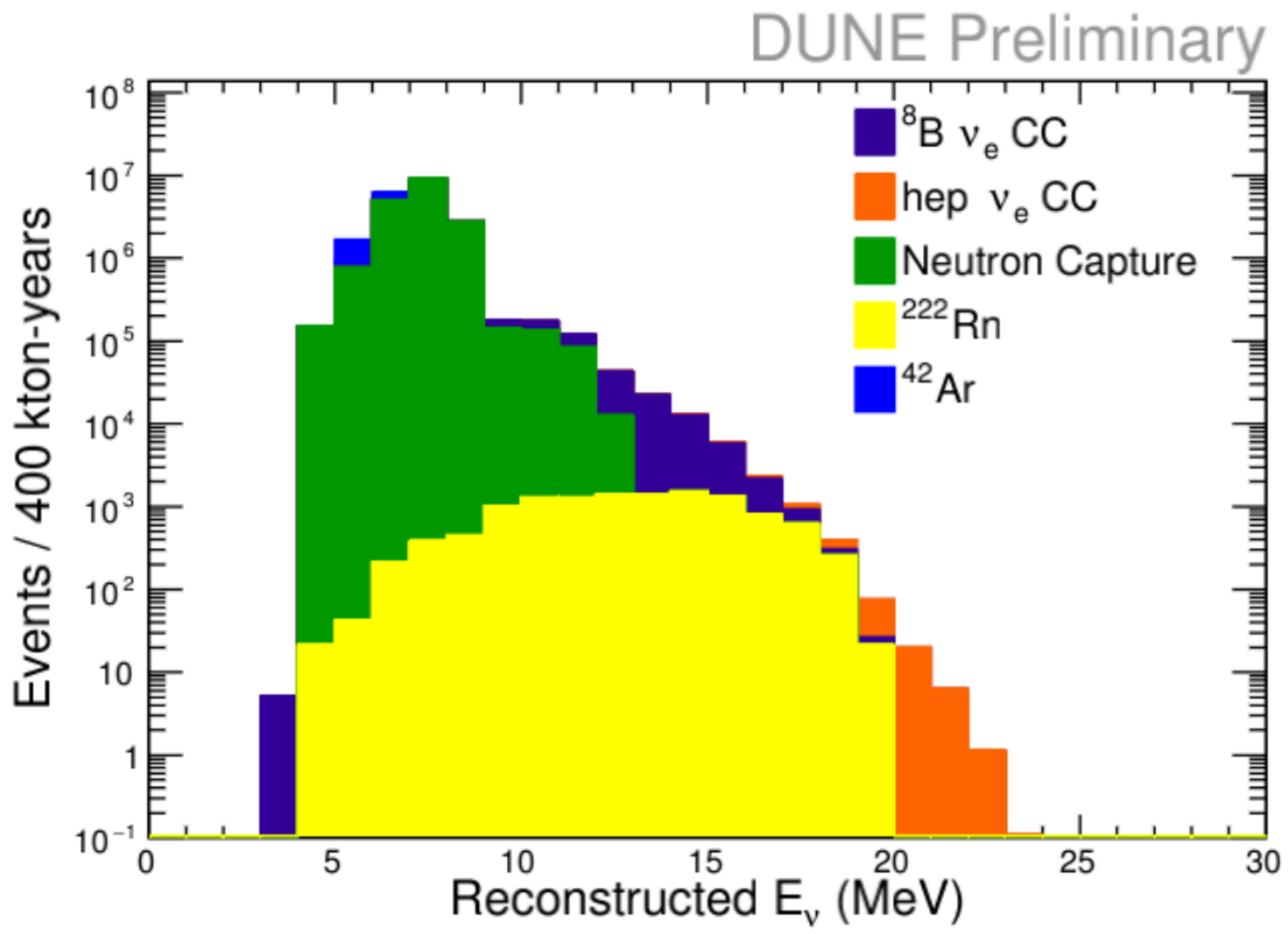
Tagging Neutrons Also Important for MeV Physics

- Above ~10MeV, **signal ν_e can knock out nucleons** from Ar nucleus
  - Neutron is the primary outcoming nucleon
    - Energy smearing from binding energy loss (~7.9 MeV)
    - Neutron capture on ^{40}Ar over deposits 6.1 MeV
  - One of the main reason for huge feed down observed in energy reconstruction

- Neutron is also the most **dominant cavern background** for solar ^{8}B neutrino measurement at DUNE FD

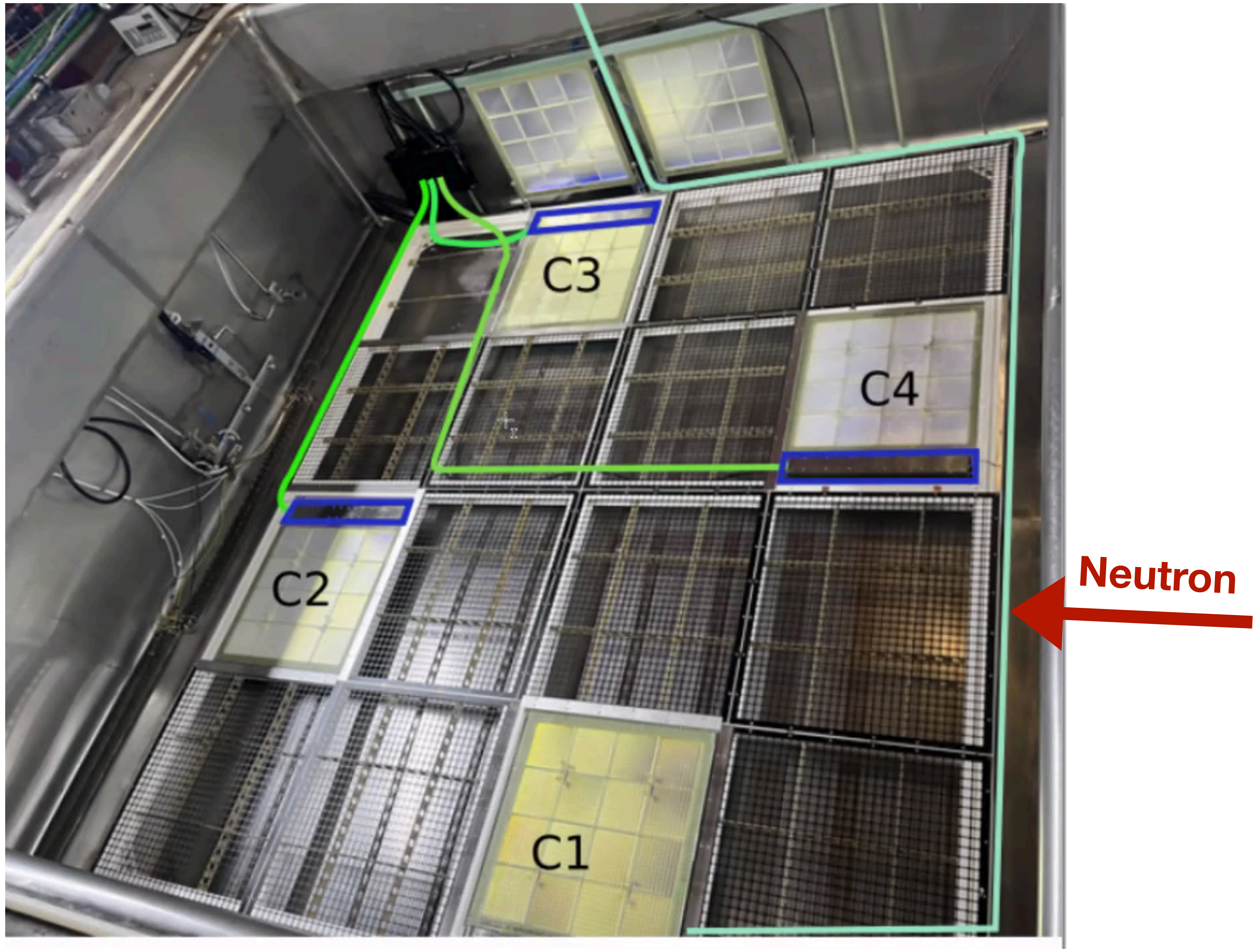
- If captured neutrons are tagged, we can at least improve energy resolution and background rejection for MeV physics

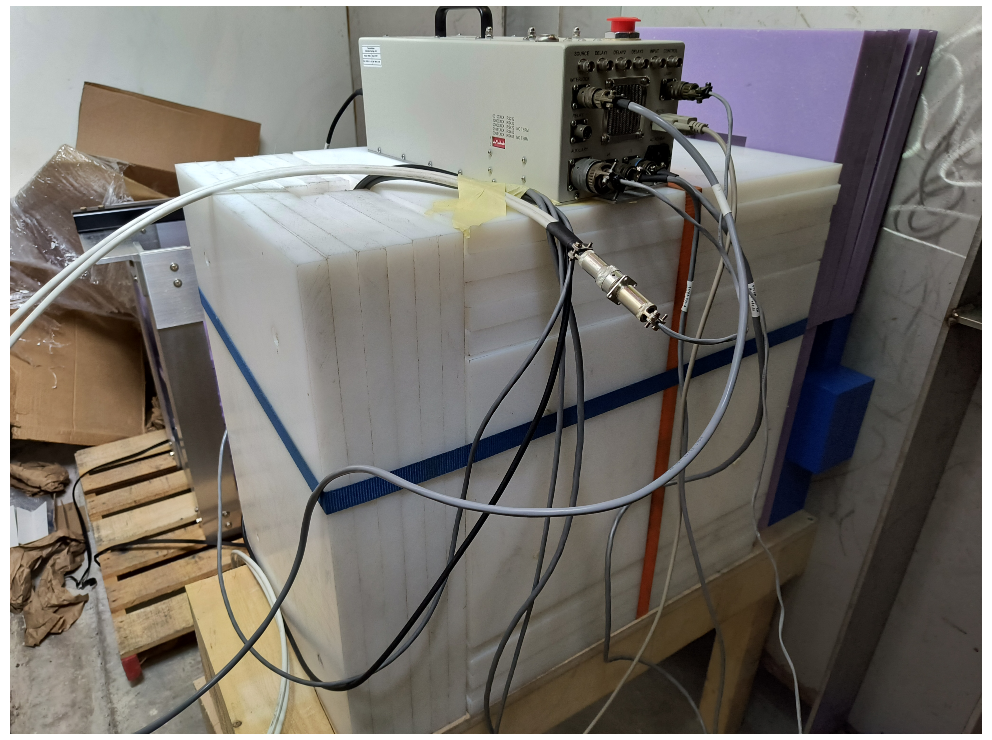




Demonstrate Calibration at CERN VD ColdBox with Pulsed Neutron Source (PNS) Generator

- ColdBox - 3m x 3m x 1m LAr test facility: ~22cm vertical drift @ 10kV (E field: 454 V/cm, **140 μs** drift time)
  - 4 X-arapuca photodetectors on cathode
- A deuterium-deuterium generator (DDG) produce ~1 million/s mono-energetic KE = 2.5 MeV neutrons
  - Deployed at side of VD ColdBox

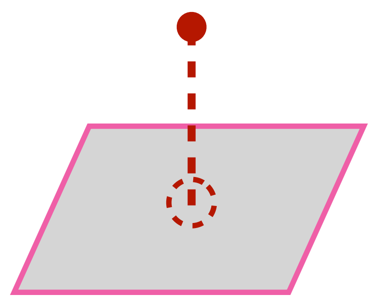




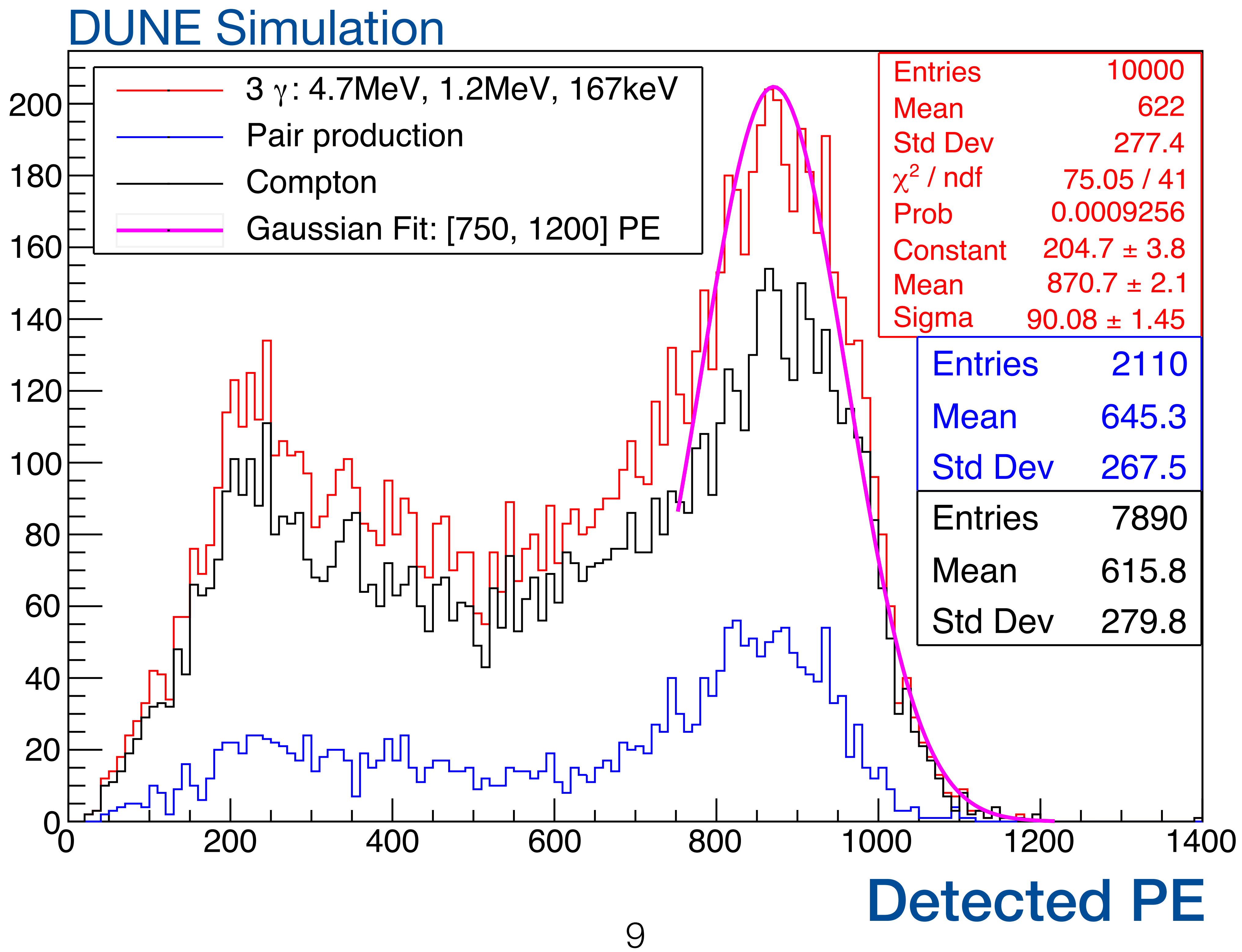
MeV γ Light Signal Simulation in ColdBox

- Focus on n-capture right on top of any of the 4 XAs on cathode
  - Simulated γ **point sources @ ~15 cm above XA**
  - Bigger PD signal compared to captures far away from XA

d=15cm (drift direction)



- Energy calibration looks for characteristic peak in detected photoelectrons (>500 PE) from the cascade γs

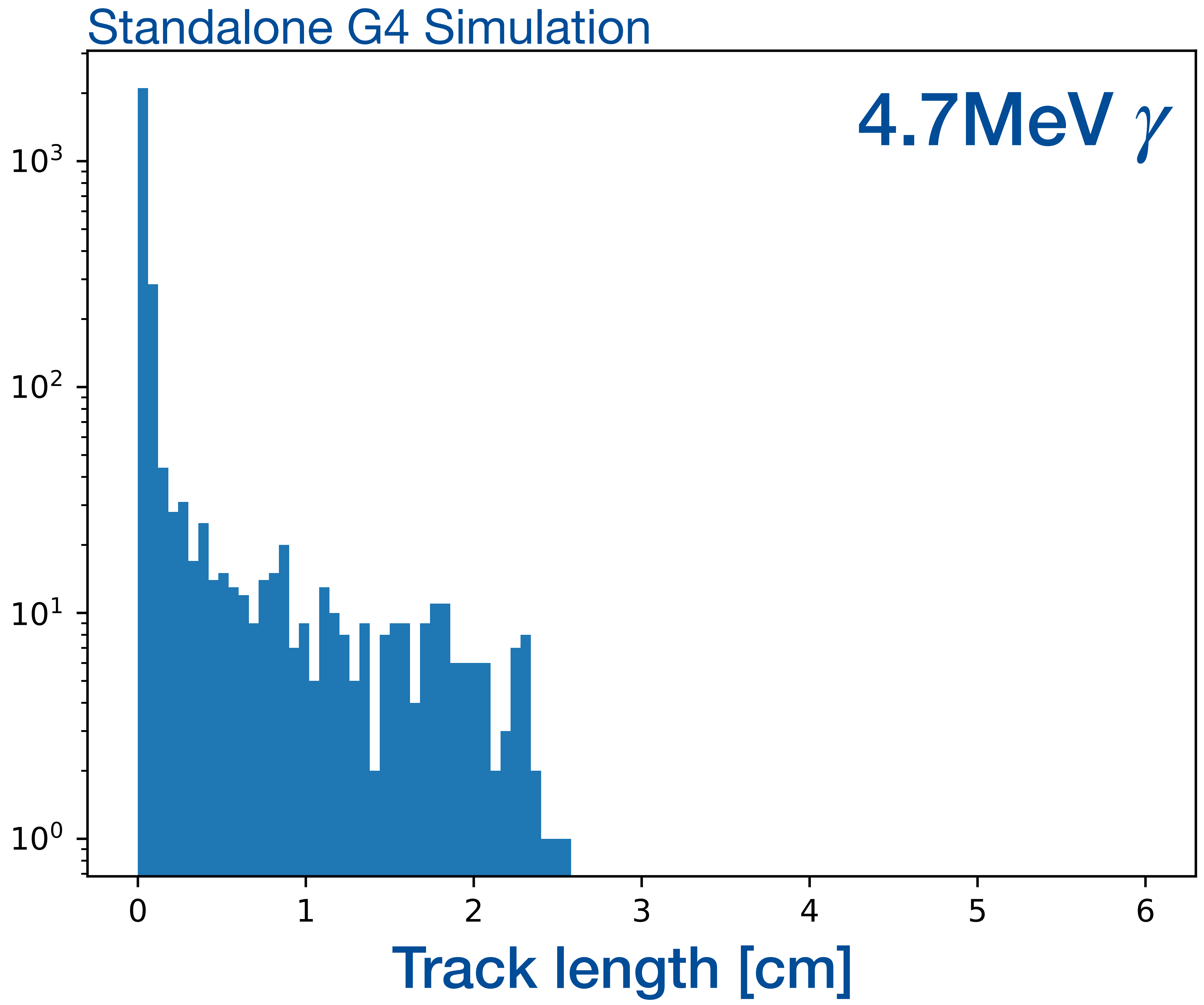


Example calibration uncertainty:
$\sigma_{PE}/\overline{PE}$ = 10.3% @15cm

MeV γ charge signal in simulation - blip like object

- Simulated MeV γ in an infinite LAr Bath (200m x 200m x 200m)
  - **Expected signal track length should be < 2.5cm**
- Standard reconstructed track: 2.5 cm

- Neutron capture signals are blip-like object

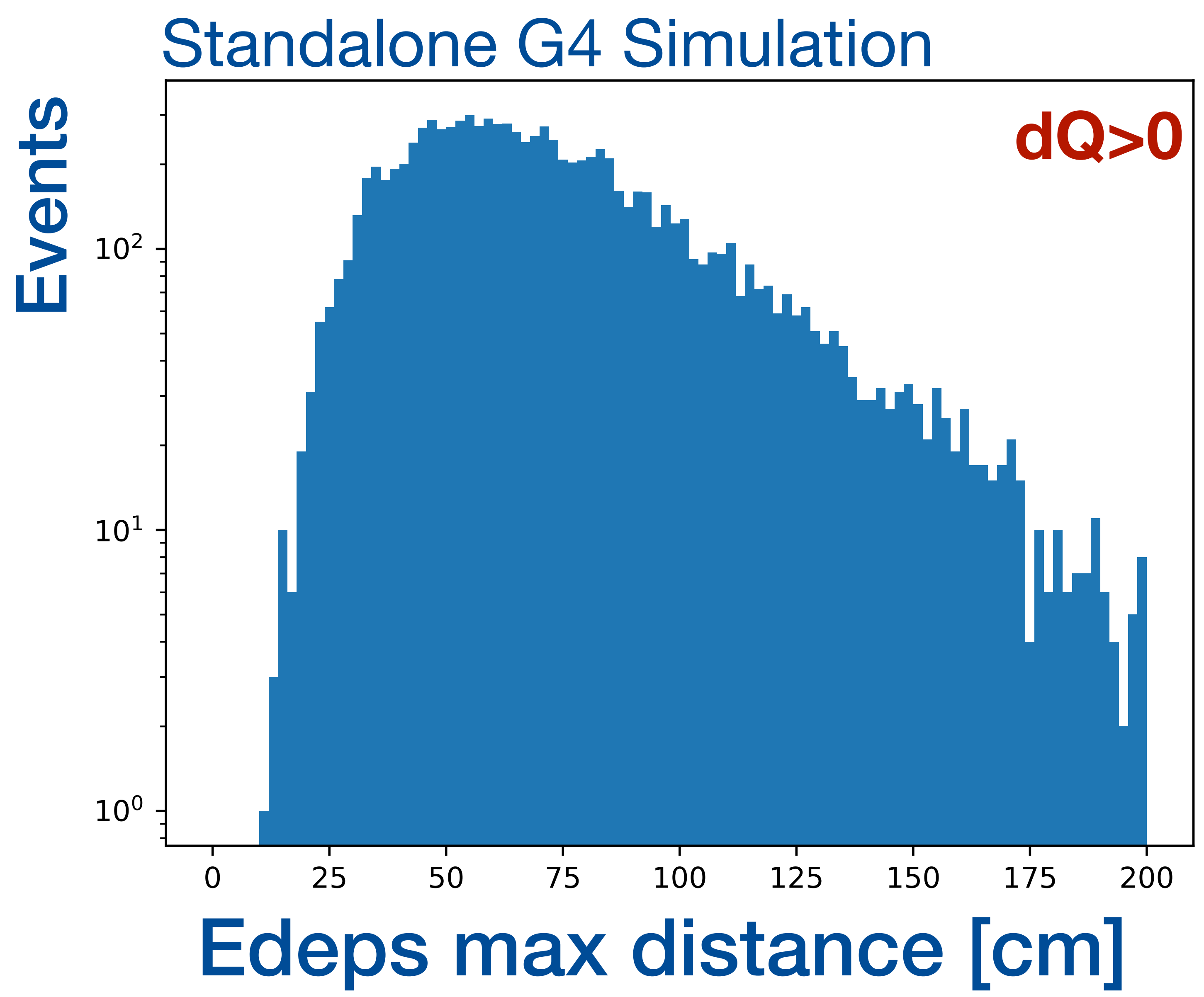


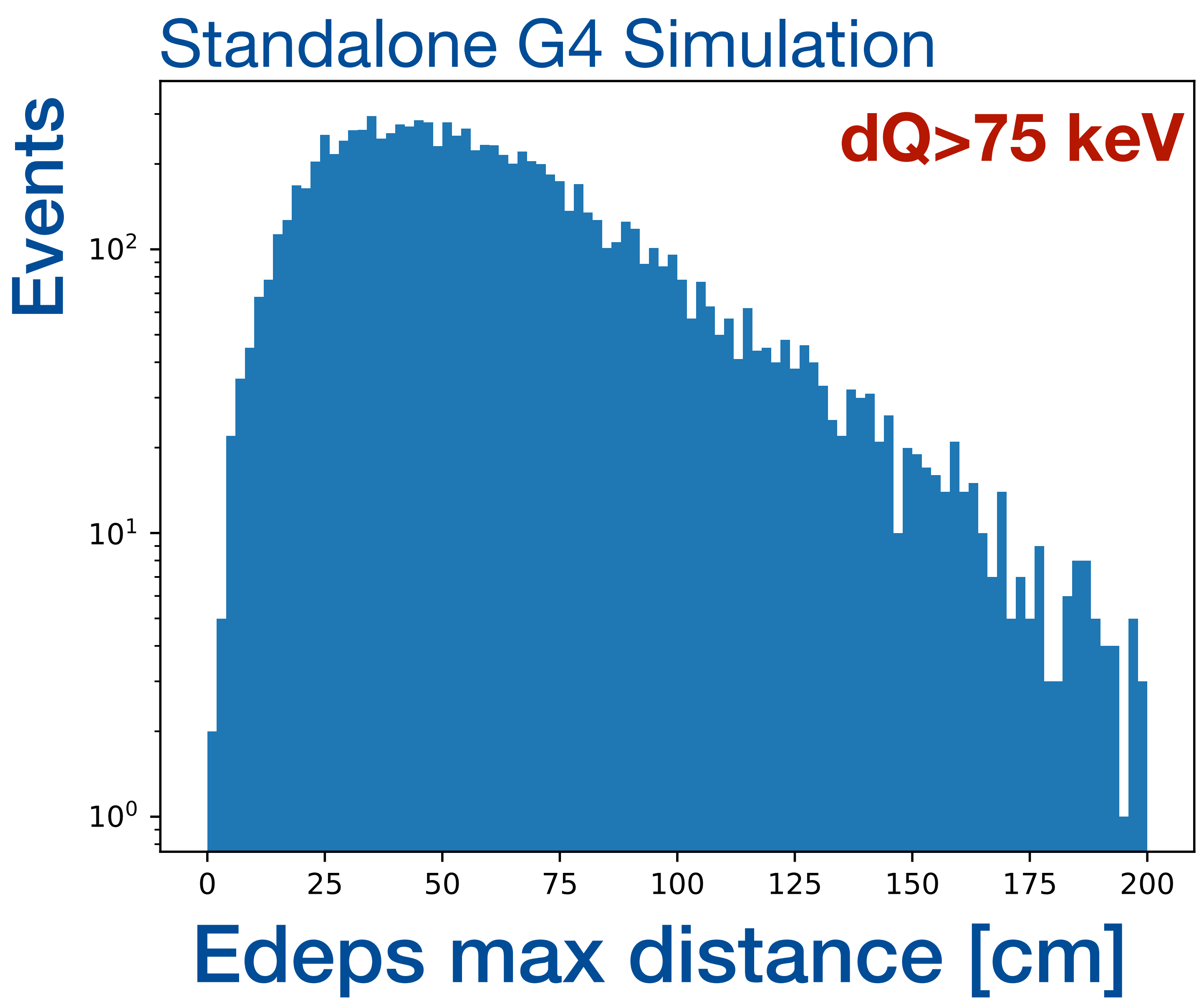
MeV γ charge signal in simulation - a few blips

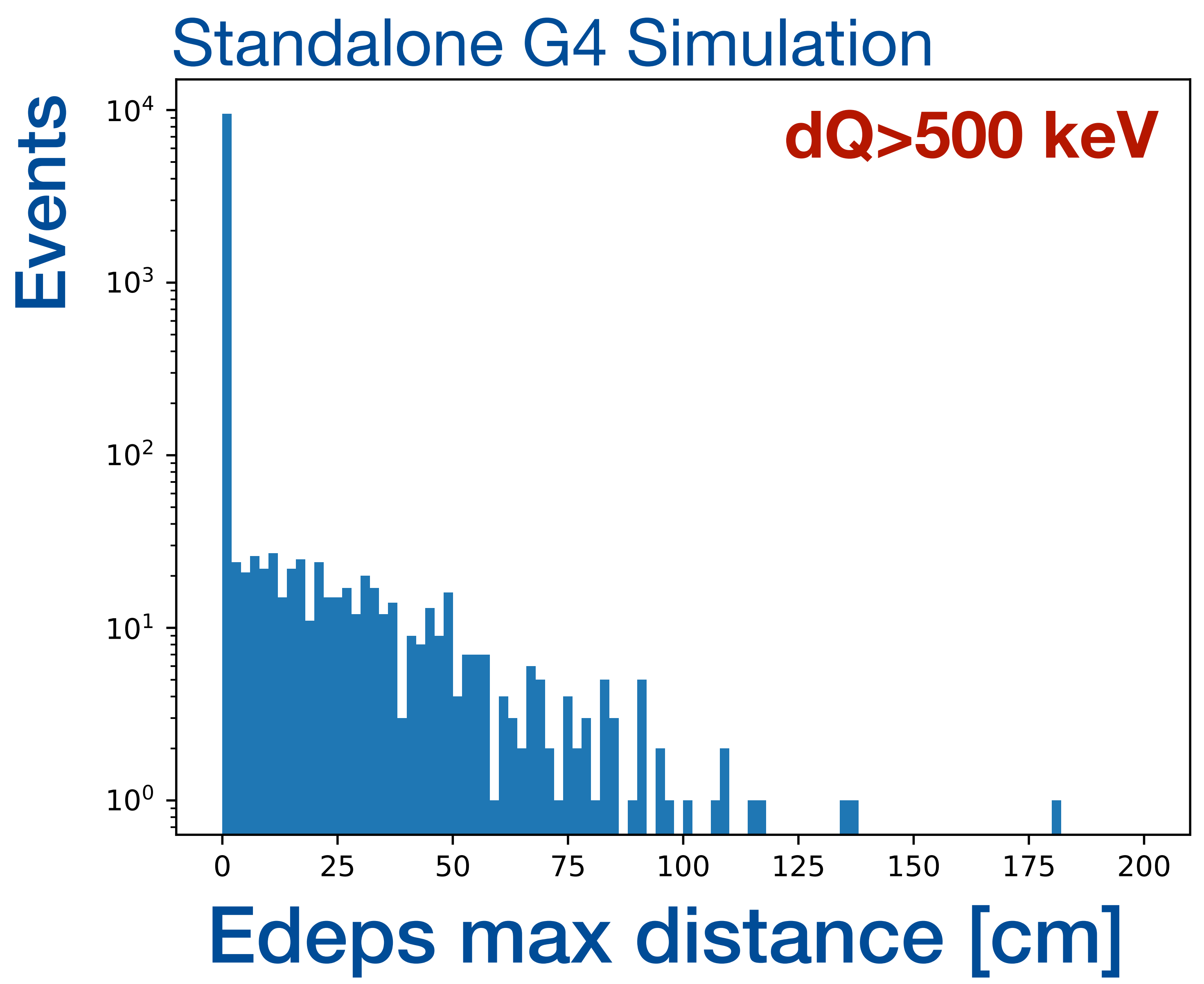
- Charge detection thresholds:
  - 75 keV is a very ideal threshold
  - 500 keV is a conservative estimate of noise RMS of ColdBox
- Expect to observe only a few blips under realistic detection threshold
  - Example event is a 4.7 MeV γ goes through pair production
    - Very likely we can't see the 510 keV γ from pair prod events in ColdBox
    - Similar number of blips expected for Compton events

MeV γ charge signal in simulation - event size

- Max distance among energy deposits under various charge detection threshold for **4.7 MeV γ, 1.2 MeV γ, 167 keV γ**
  - Expected capture signal event size below 1m under realistic charge detection threshold

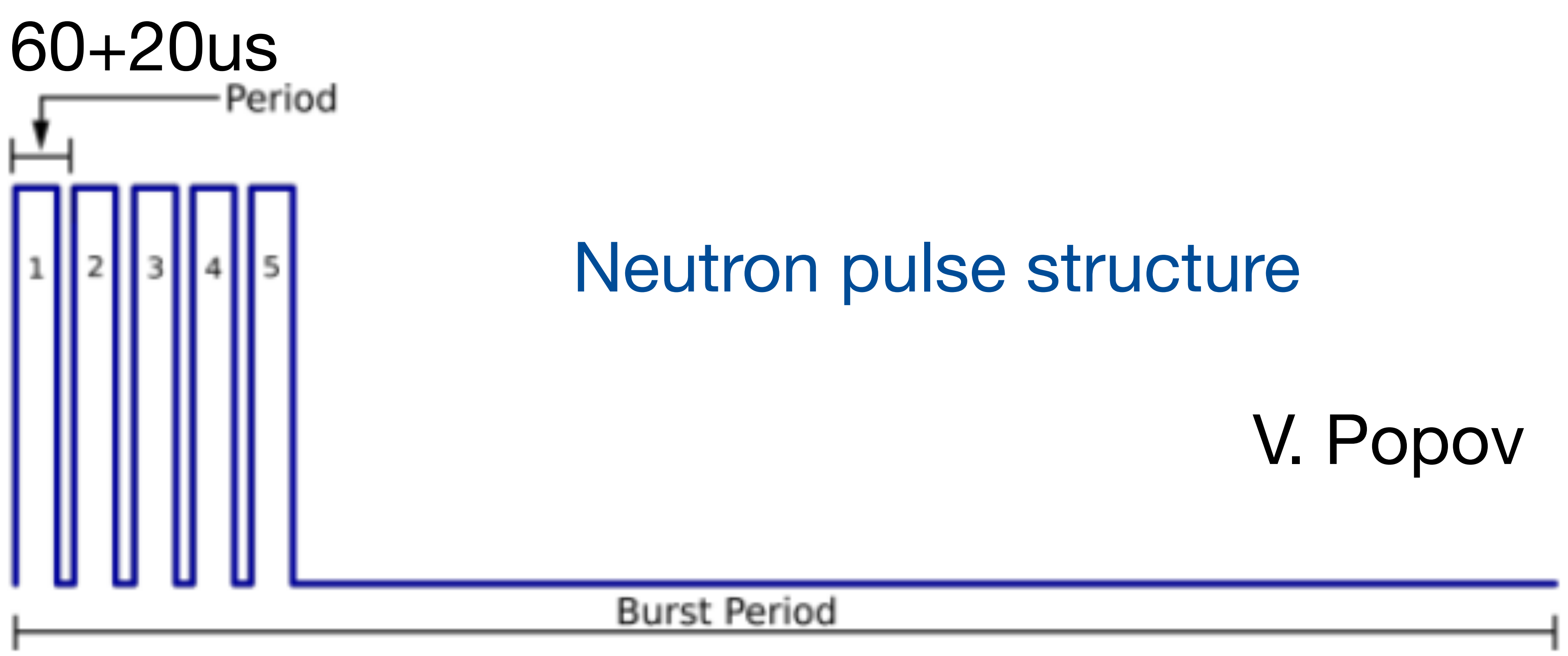






First PNS ColdBox run in April

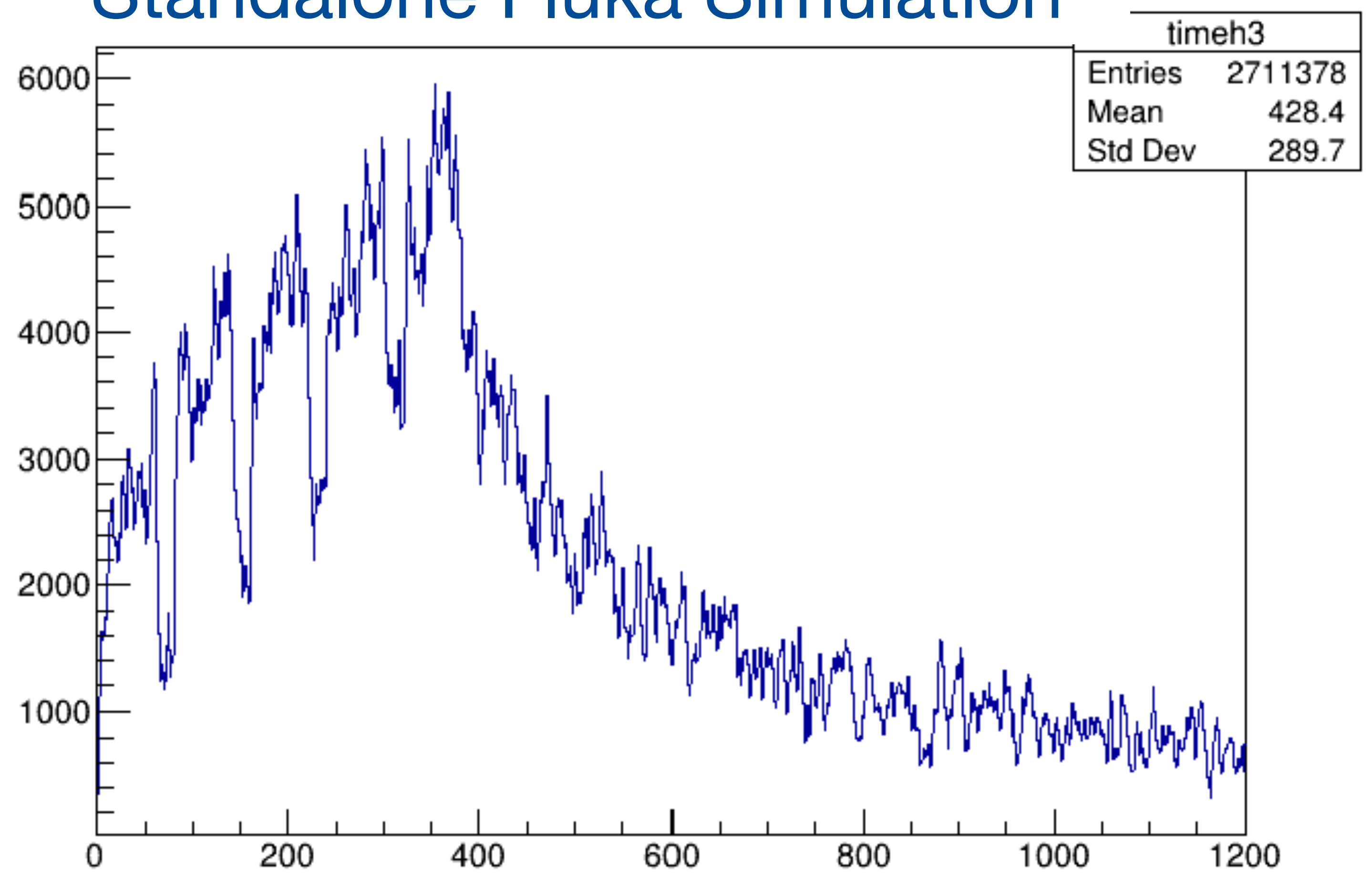
- ~250k PNS events (1ms read out window)
- Neutron beam time structure observed in photodetector peak timing distribution



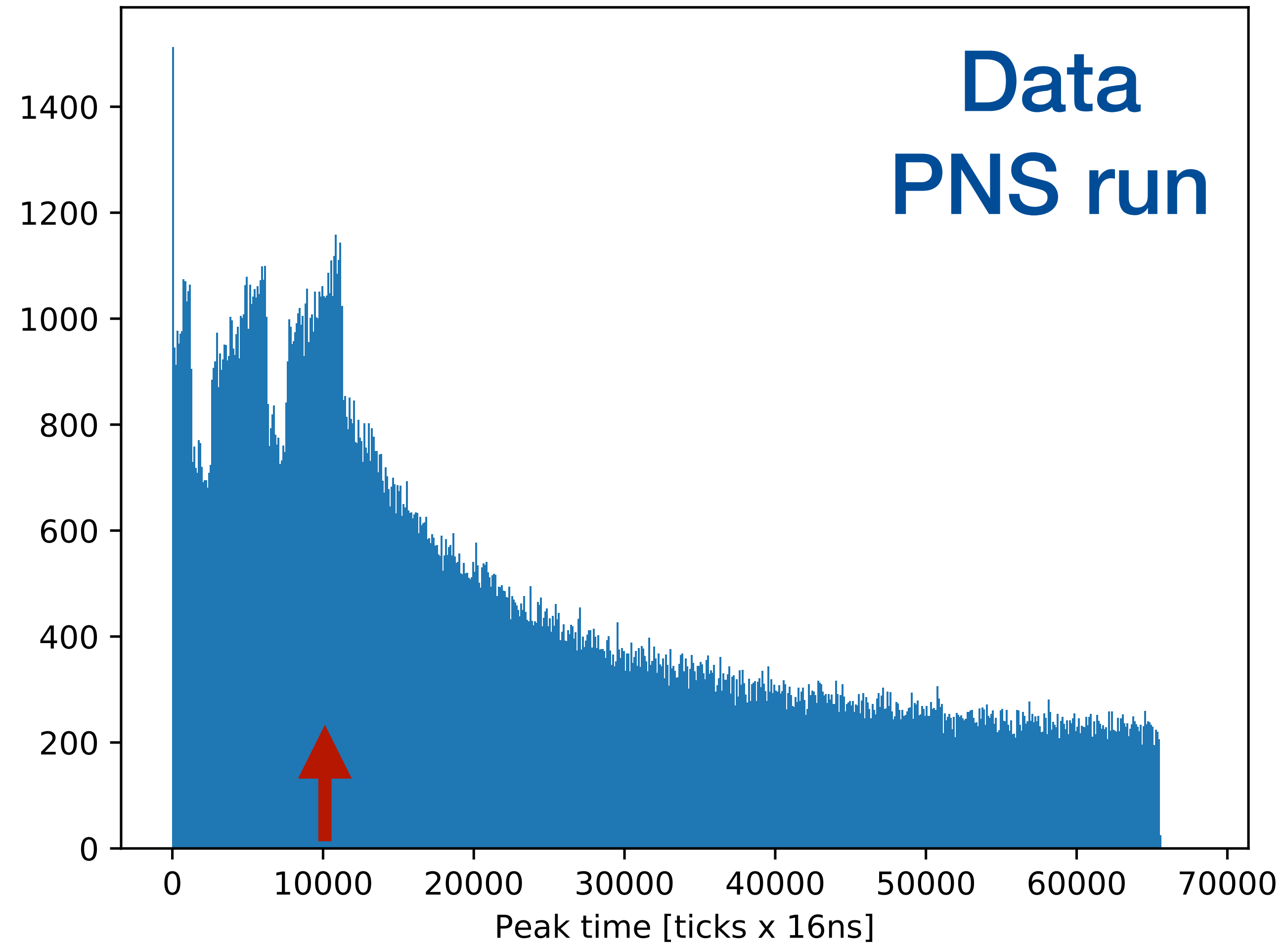
Neutron pulse structure

V. Popov

Standalone Fluka Simulation

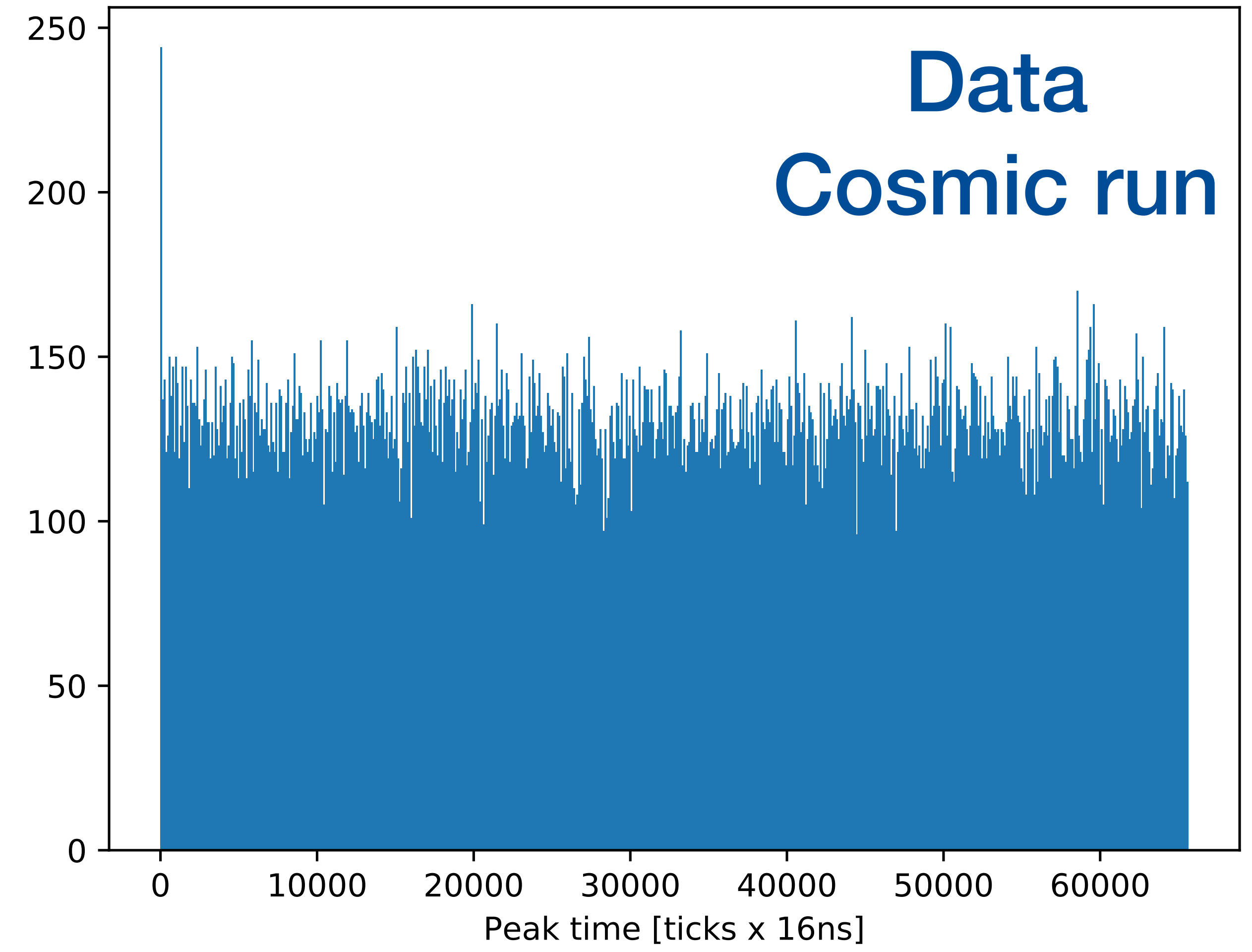


DUNE work in progress



160us

DUNE work in progress

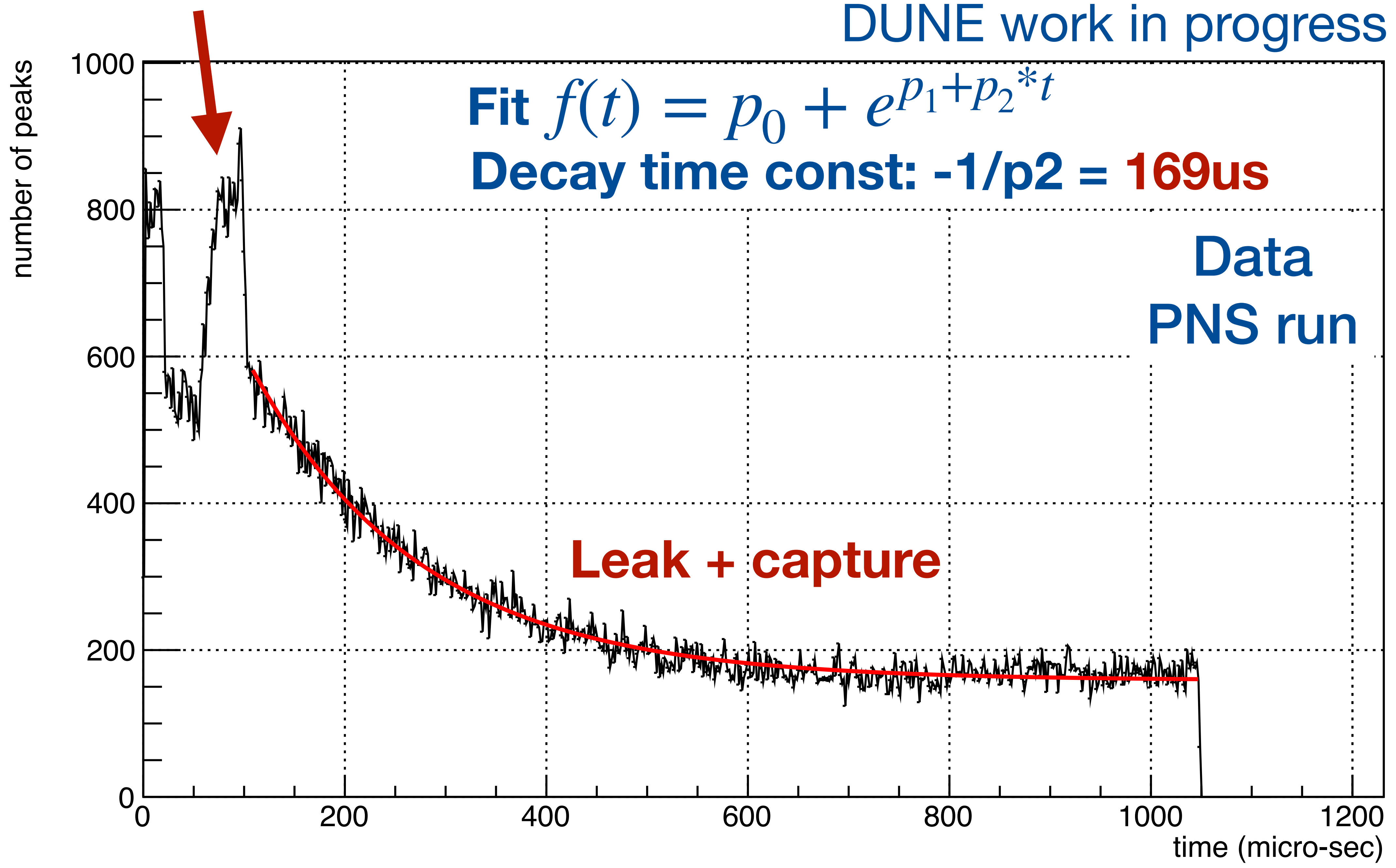


A possible by-product: measuring neutron related time constants

Expect these relevant processes:

+ n **inelastic** scattering: 2-2.5MeV neutron σ ~0.7b, KE reduced to (sub)MeV in ~one interaction, sub-μs → **0-3 MeV γs**
+ n **elastic** scattering (MeV/sub MeV, a few μs) ⇢ **CRP can't detect Ar recoil, negligible light**
+ n **leakage** small detector (no signal, need input from sim)
+ n-**capture** γ (O(100)μs) → **γs in total 6.1MeV**
+ flat bkg (cosmic, others)

Inelastic + elastic + leak + capture

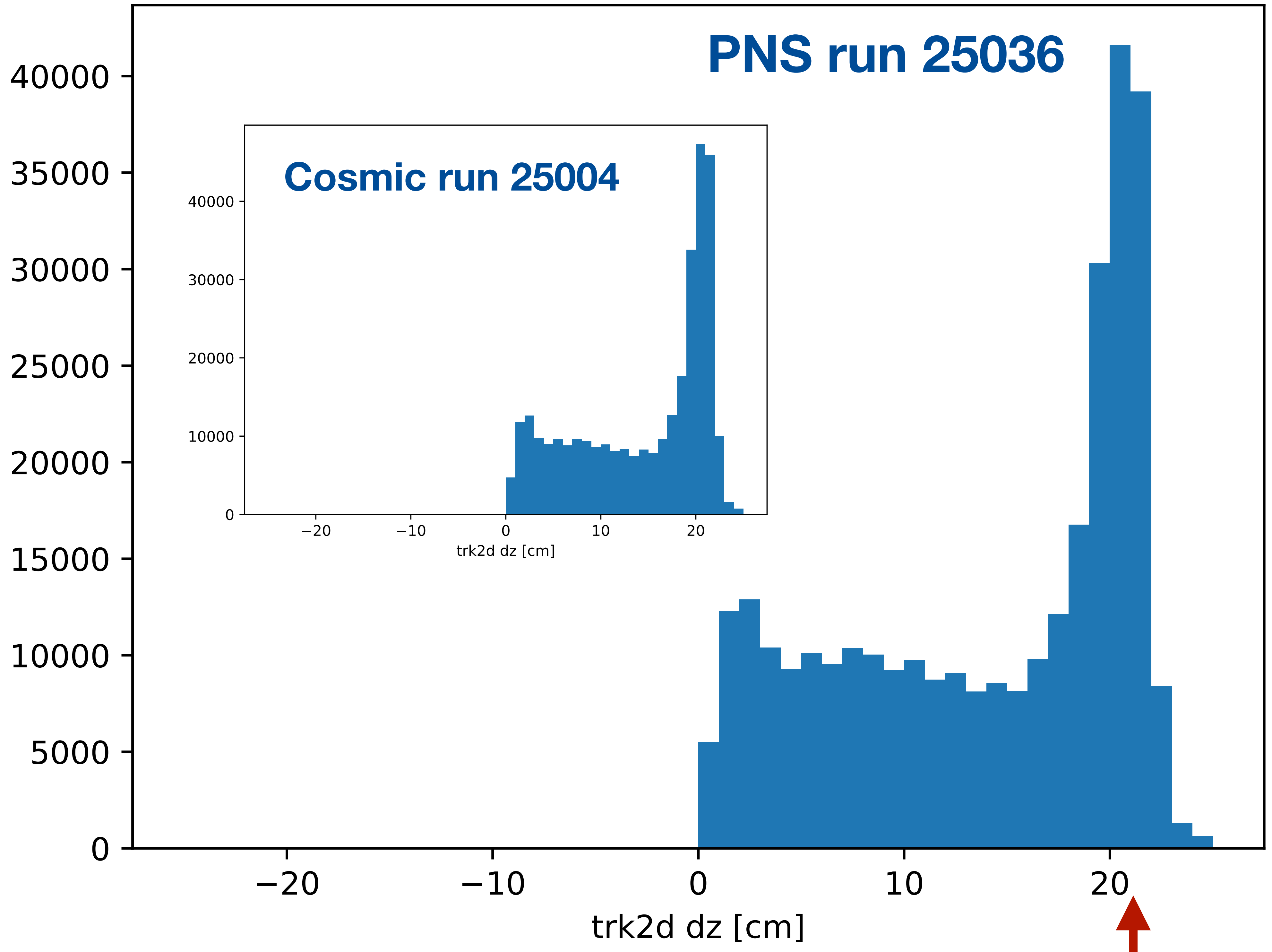


Detailed simulation study ongoing to compare with data

Backgrounds

- Expected bkg sources that create light signals
  - **Cosmics**: close to 50% anode-cathode crossing cosmics, the rest are cosmics entering from the side → better @VD
  - **Captures @ inactive region**: buffer LAr (no instrument CRP/cathode), cryostat structure, etc
  - **Gammas from beam neutron inelastic scattering**: only look after beam stops
  - **Ar39** radiological beta decay background (0.565 MeV) → irreducible bkg

DUNE work in progress

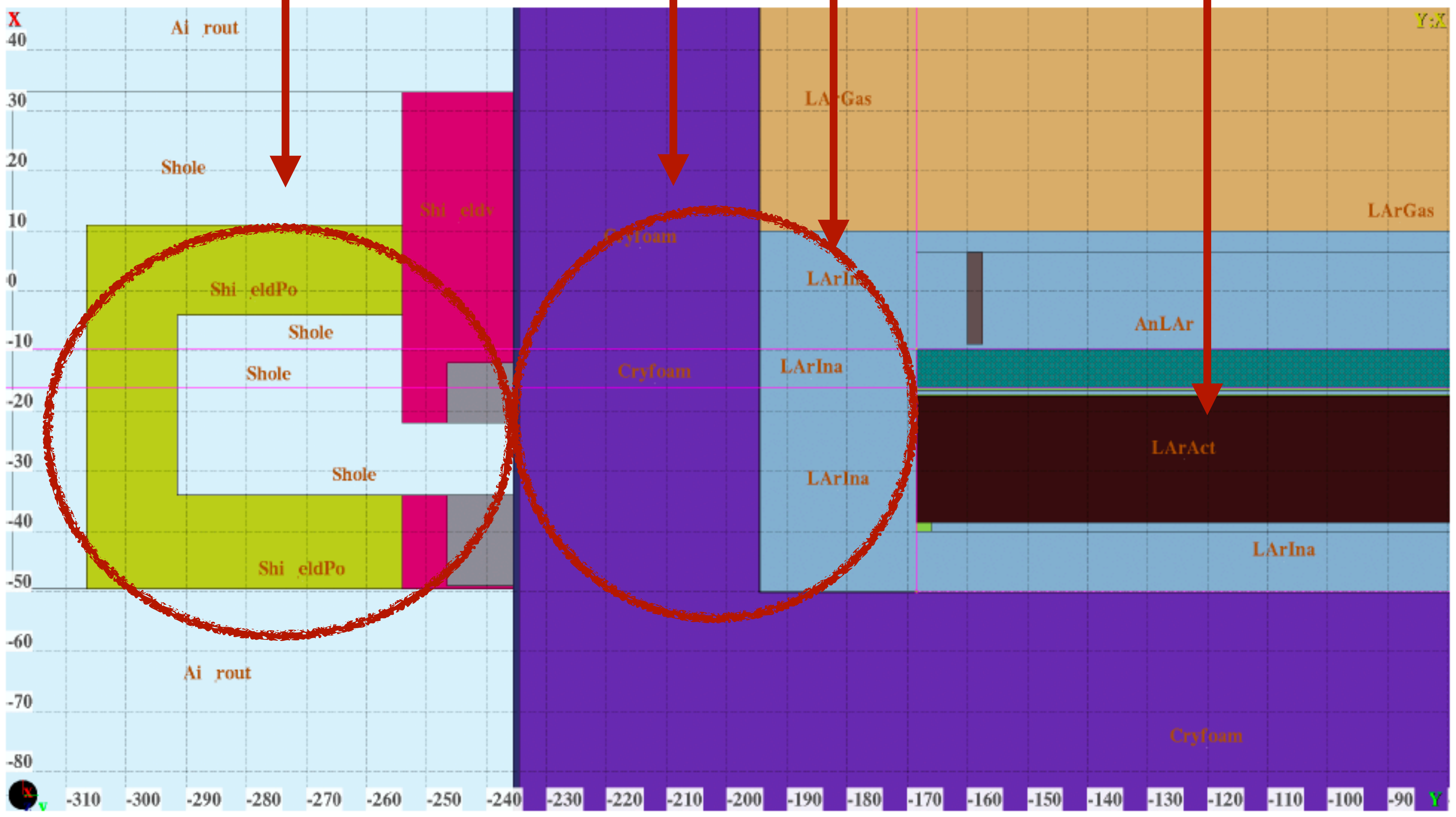


Crossing cosmics have full 22cm drift

PNS

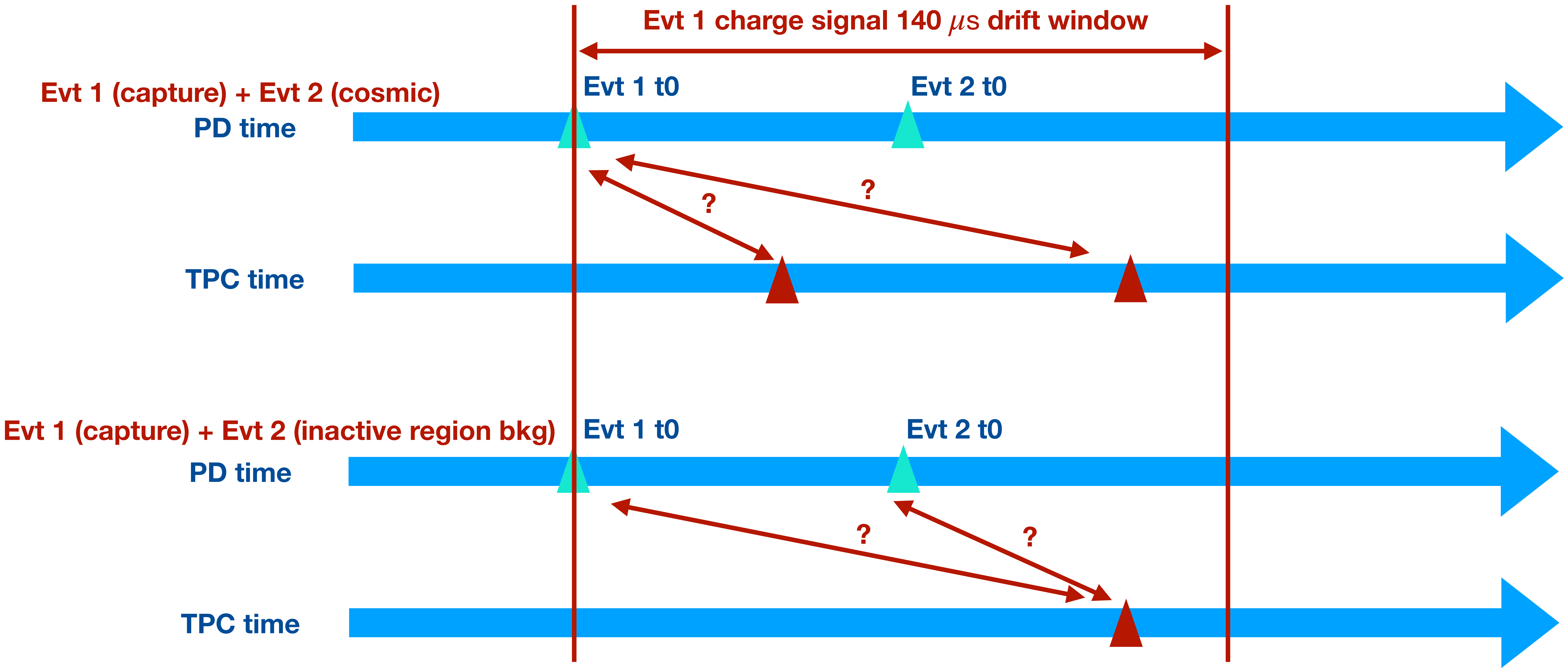
Inactive region (cryostat + LAr)

Active LArTPC



Find the Capture Light Signal

- Match TPC reconstructed blips to PD signals on top of each X-arapuca photodetector
  - Data analysis ongoing to resolve **charge light matching ambiguity**



Summary

- **Light calorimetry is important for DUNE physics**
  - Offers independent energy reconstruction for all neutrino oscillation measurement
  - Boosts energy resolution when combined with charge at MeV region

- **Unique interaction of neutron with argon can calibrate FD light yield map**
  - Standard candle - capture
  - Can sample large FD

- **First pulsed neutron source physics run at VD ColdBox**
  - Simulation and reconstruction of signal well understood
  - Look for a characteristic peak from a 3-γ cascade mode in photodetector signal
  - Prospect to understand timing associated with different neutron interactions
  - Ongoing charge - light matching expects to improve backgrounds rejection