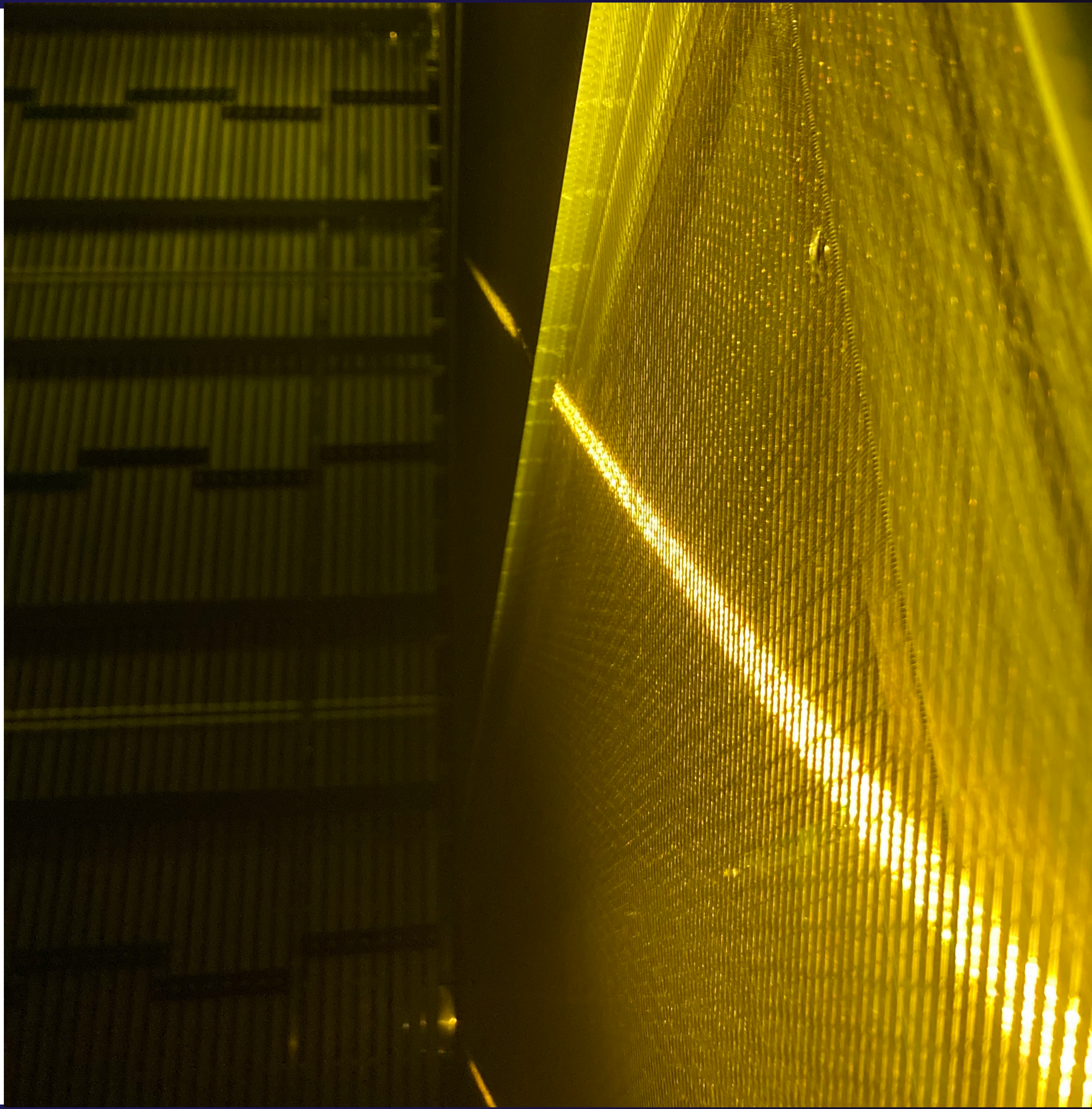
The Deep Underground Neutrino Experiment

Mattia Fanì
Los Alamos National Laboratory

On behalf of the DUNE Collaboration

Outline

- The Deep Underground Neutrino Experiment (DUNE)
- Main detection technique
- DUNE Beam & Detectors
- ProtoDUNE at CERN
- The DUNE physics and performances
  - Low-energy events in DUNE



Detail of an Anode Plane Assembly in ProtoDUNE-HD at CERN

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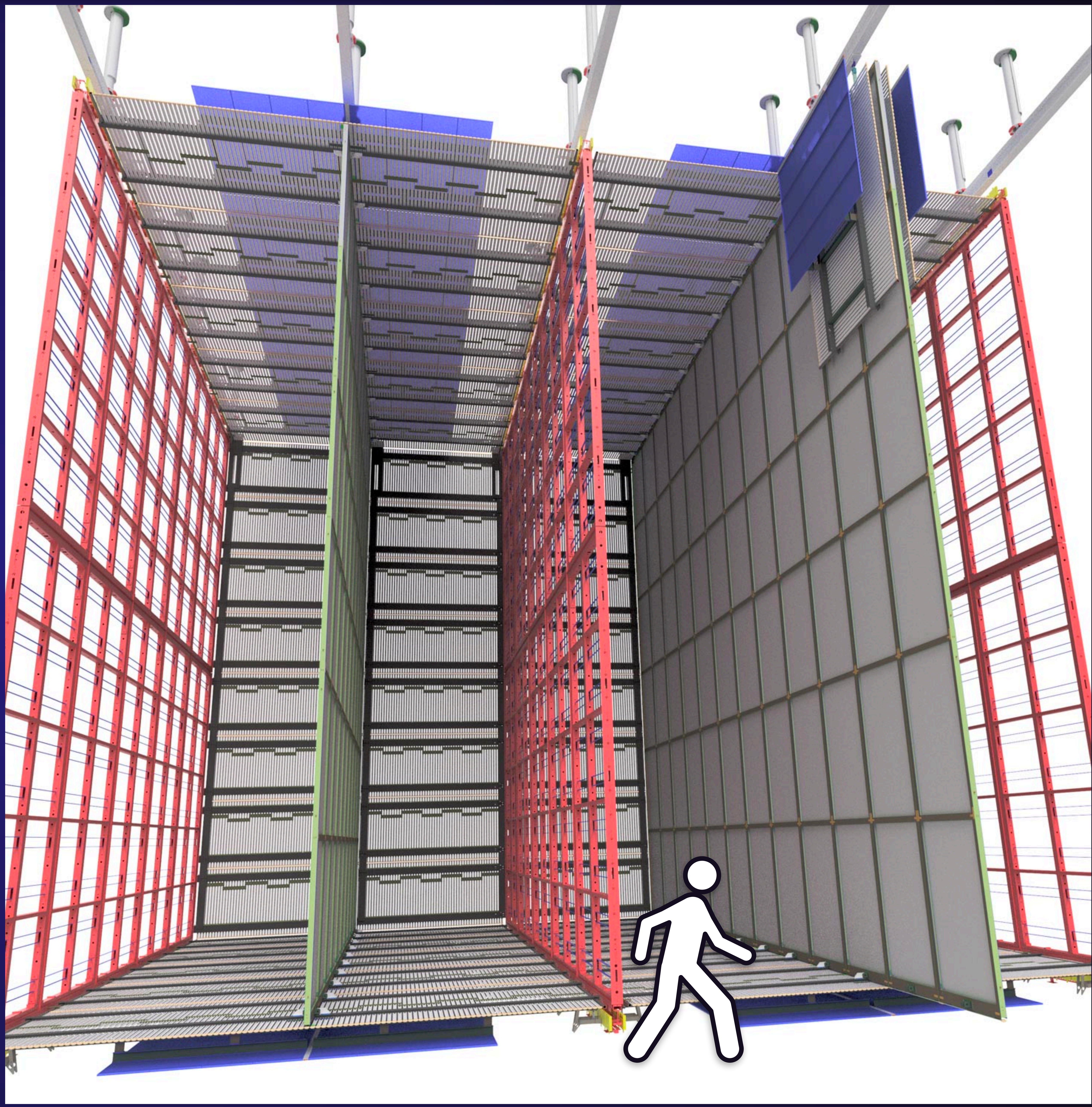
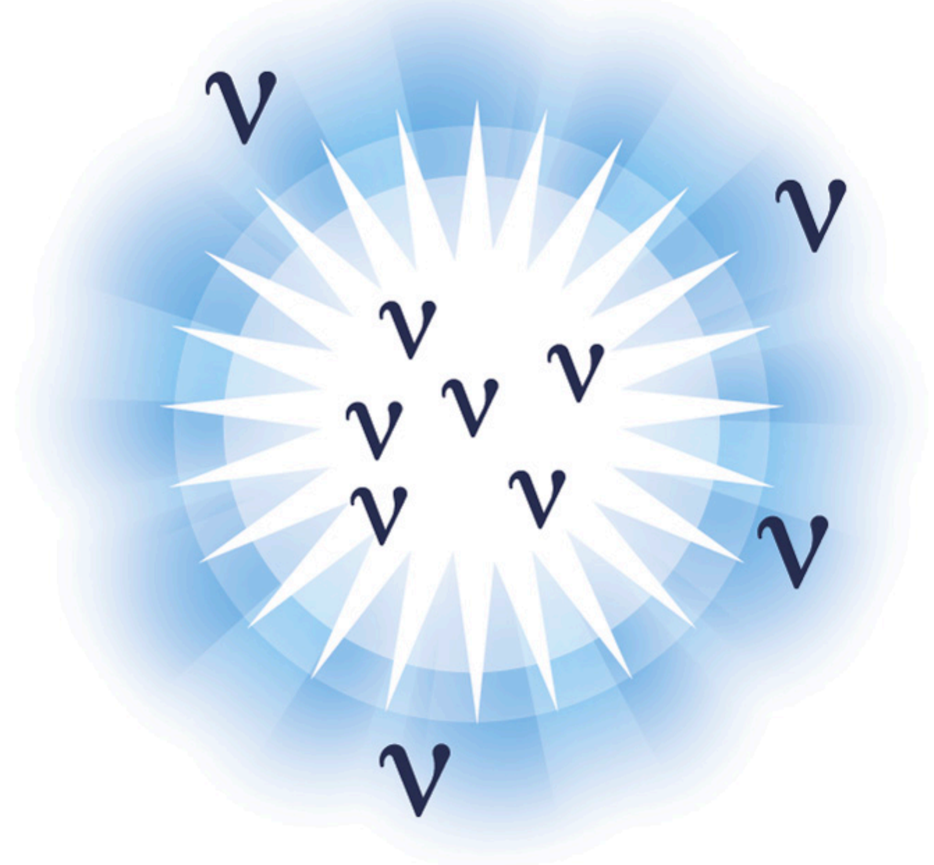


Schematic of DUNE design
DUNE-TDR arXiv:1807.10334

The Deep Underground Neutrino Experiment

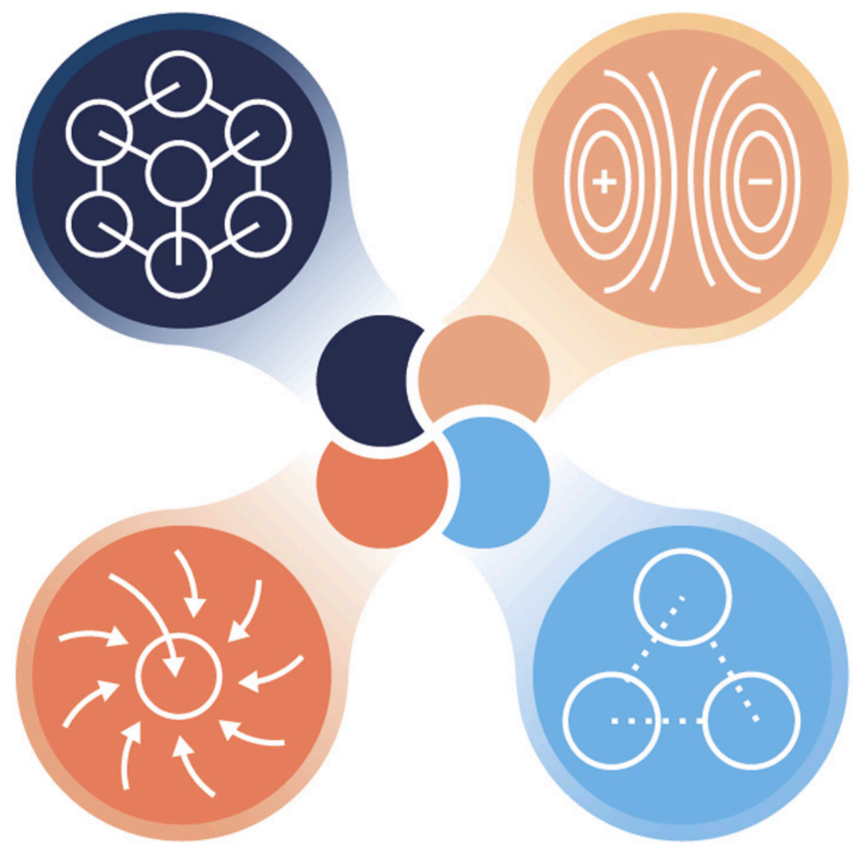
- A worldwide Collaboration: **1400+ people**, **200+ institutions**, **37 countries w/ CERN**
- Long baseline experiment: 1300 km from Fermilab to SURF, 4300 m water equivalent depth
- The most intense neutrino beam ever: **1.2 MW**, upgradable to **2.4 MW**
- Two detectors, Near/Far, the largest liquid argon neutrino detector in the world (**70 kt**) - **2 phases**
- Detector prototypes (ProtoDUNE) already operational at CERN

Science goals



- **Constrain flavor and mass models, search for the origin of matter, testing the three-flavors paradigm:**
  - Precise neutrino oscillation parameters for $\nu_e/\bar{\nu}_e$ appearance, $\nu_\mu/\bar{\nu}_\mu$ disappearance searches, CP violation, mass hierarchy in the ν sector

- **Learn about supernovae, neutron stars and black holes**
  - DUNE alone would detect > 3x as many ν as all active detectors did for SN1987A



- **Shed light on Grand Unified Theories (GUT), physics beyond the Standard Model:**
  - Proton decay, baryon number violation, sterile neutrinos, non-standard interactions and more

[DUNE TDR Vol. 2: https://arxiv.org/pdf/2002.03005.pdf]

Image credit: Fermilab

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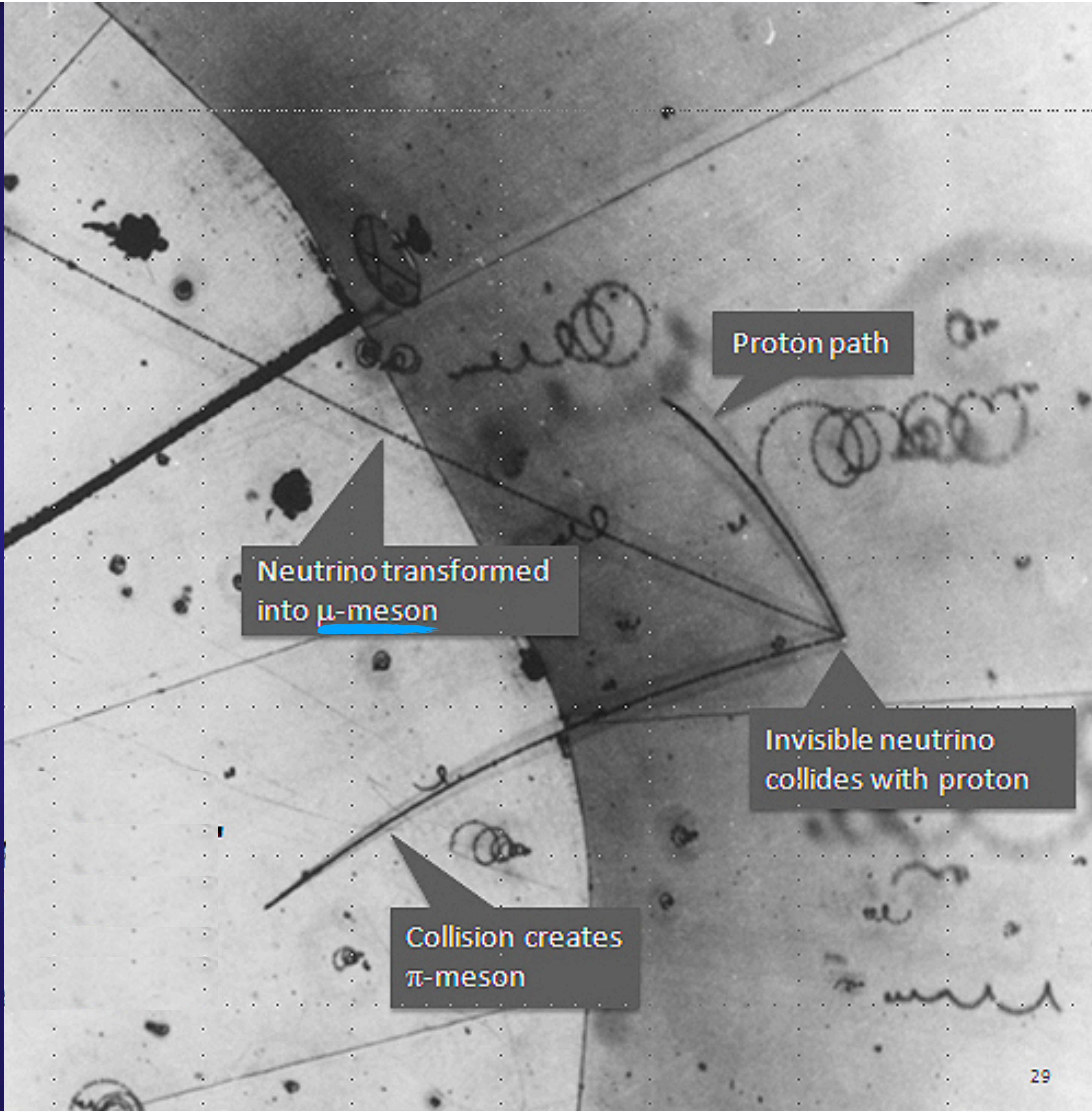
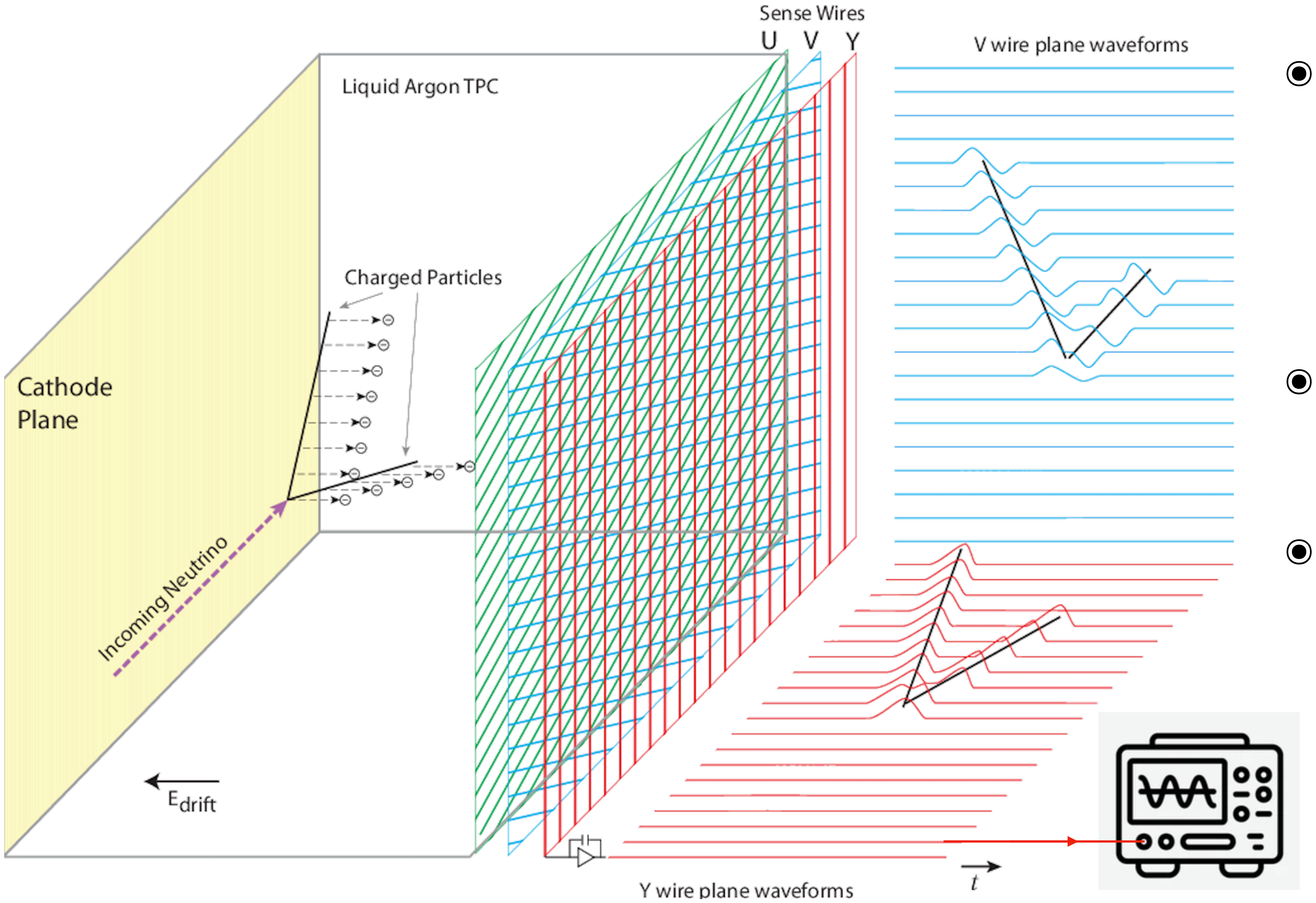


First detection of a neutrino event with a bubble chamber, 1970
Image credit: Argonne National Laboratory

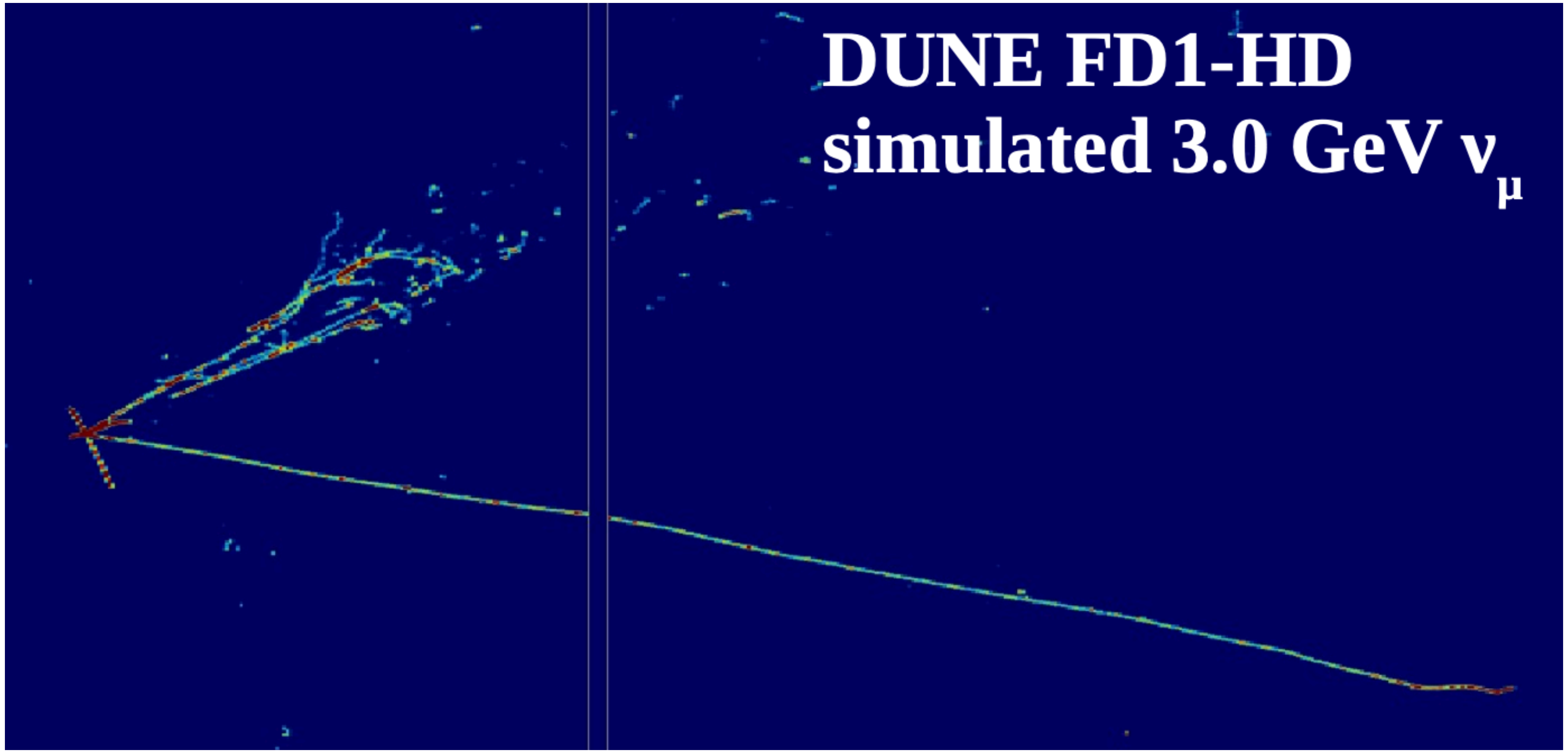
Liquid Argon Time Projection Chamber (LArTPC)

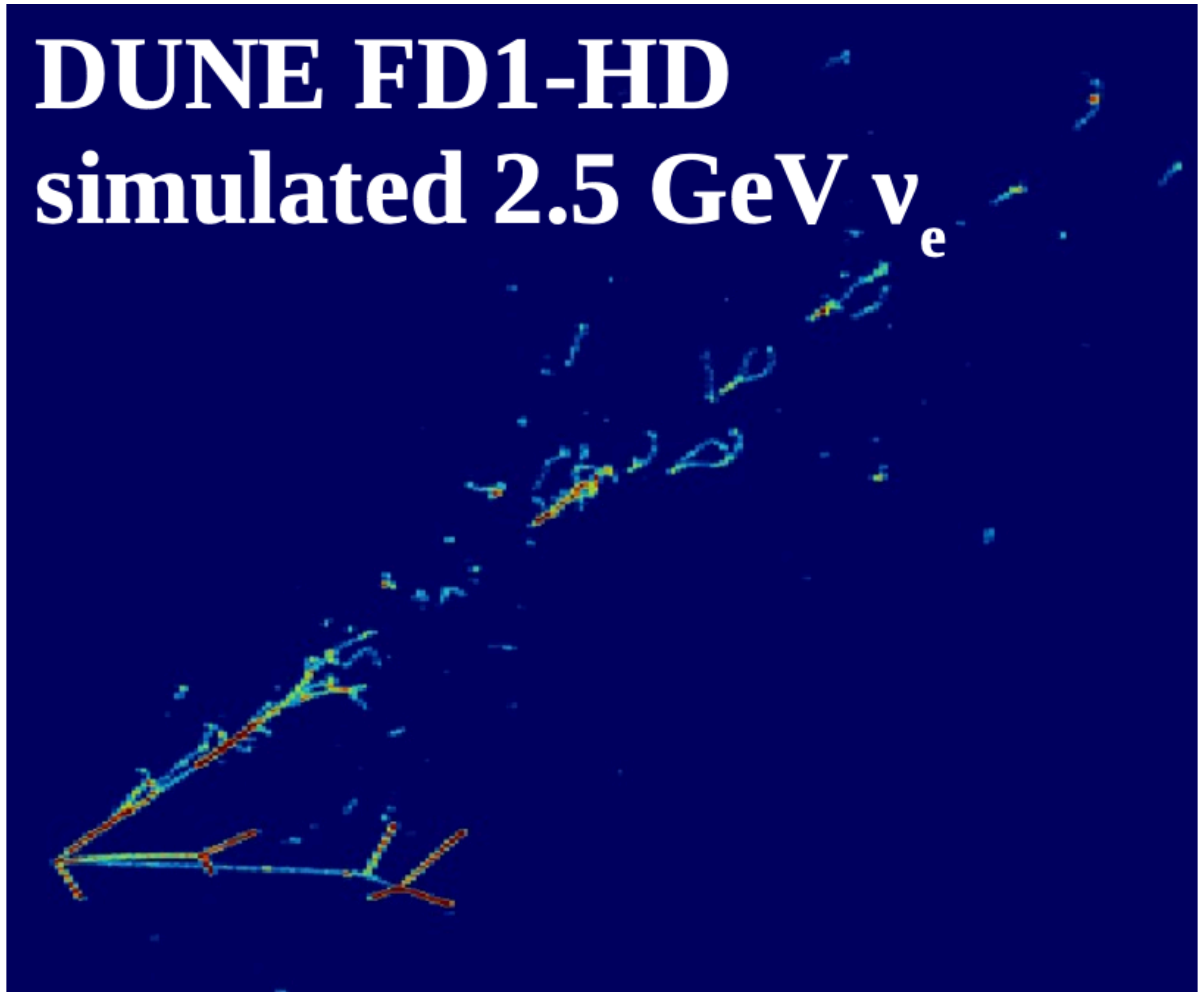


- Rapid development over the last two decades
  - ICARUS, WA105, MicroBooNE, LArIat, ArgonCube, SBND, ProtoDUNE
- Charge from drifted electrons collected by wires; information on interaction time and triggering from LAr scintillation time
- Two possible working principles
  - Different e$^-$ drift direction and detection technologies
    - Horizontal Drift (HD)
    - Vertical Drift (VD)

[DUNE TDR Vol 1: https://cds.cern.ch/record/2709272/files/pdf.pdf]

DUNE Imaging & Reconstruction





- Excellent track reconstruction: mm-resolution
- Clean separation of ν_μ and ν_e charged-currents

Low detection thresholds for charged particles
→ precise reconstruction of lepton and hadronic energy
→ E_ν reconstruction over broad energy range

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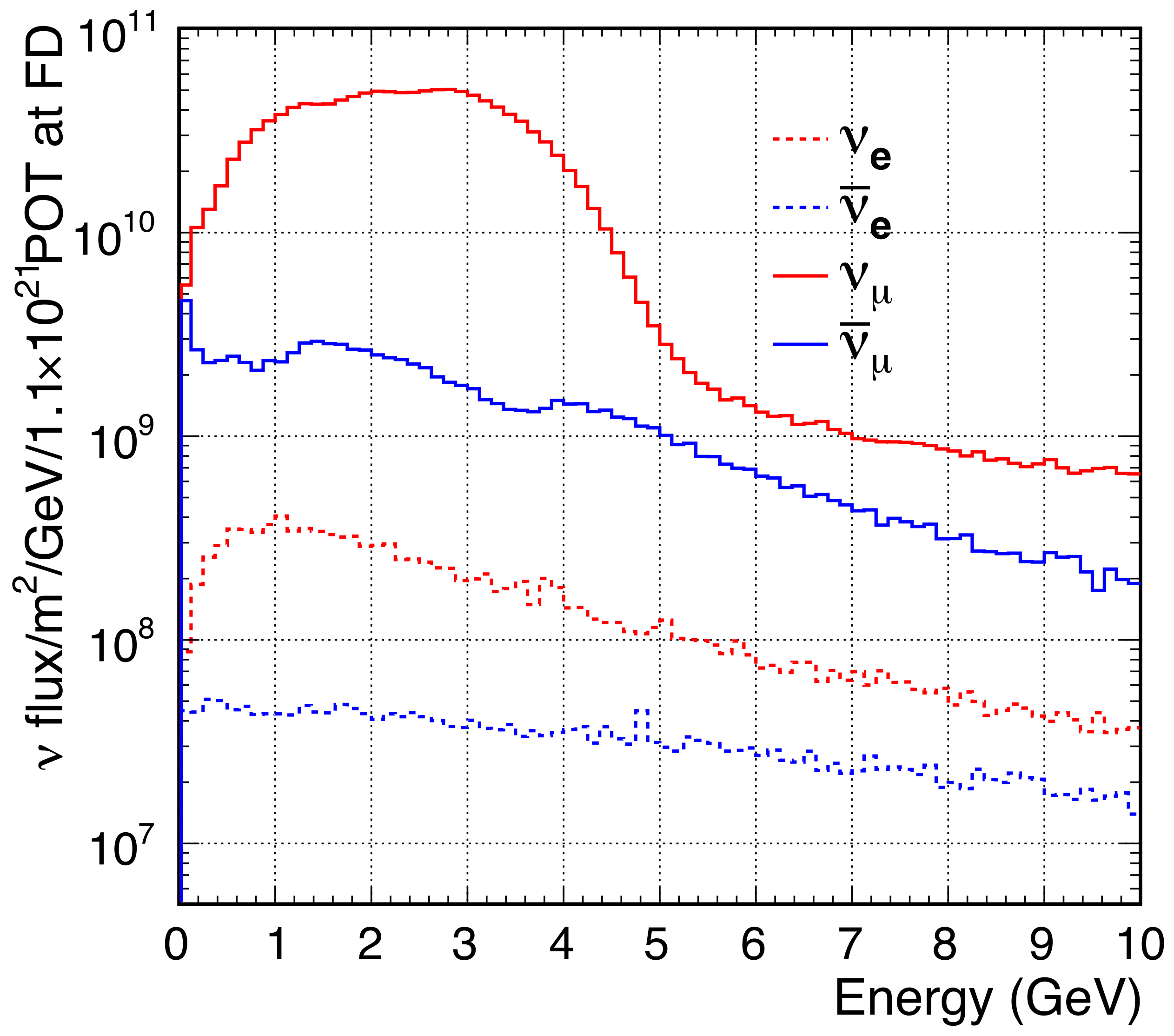
LBNF/DUNE excavation work
Photo credit: Fermilab

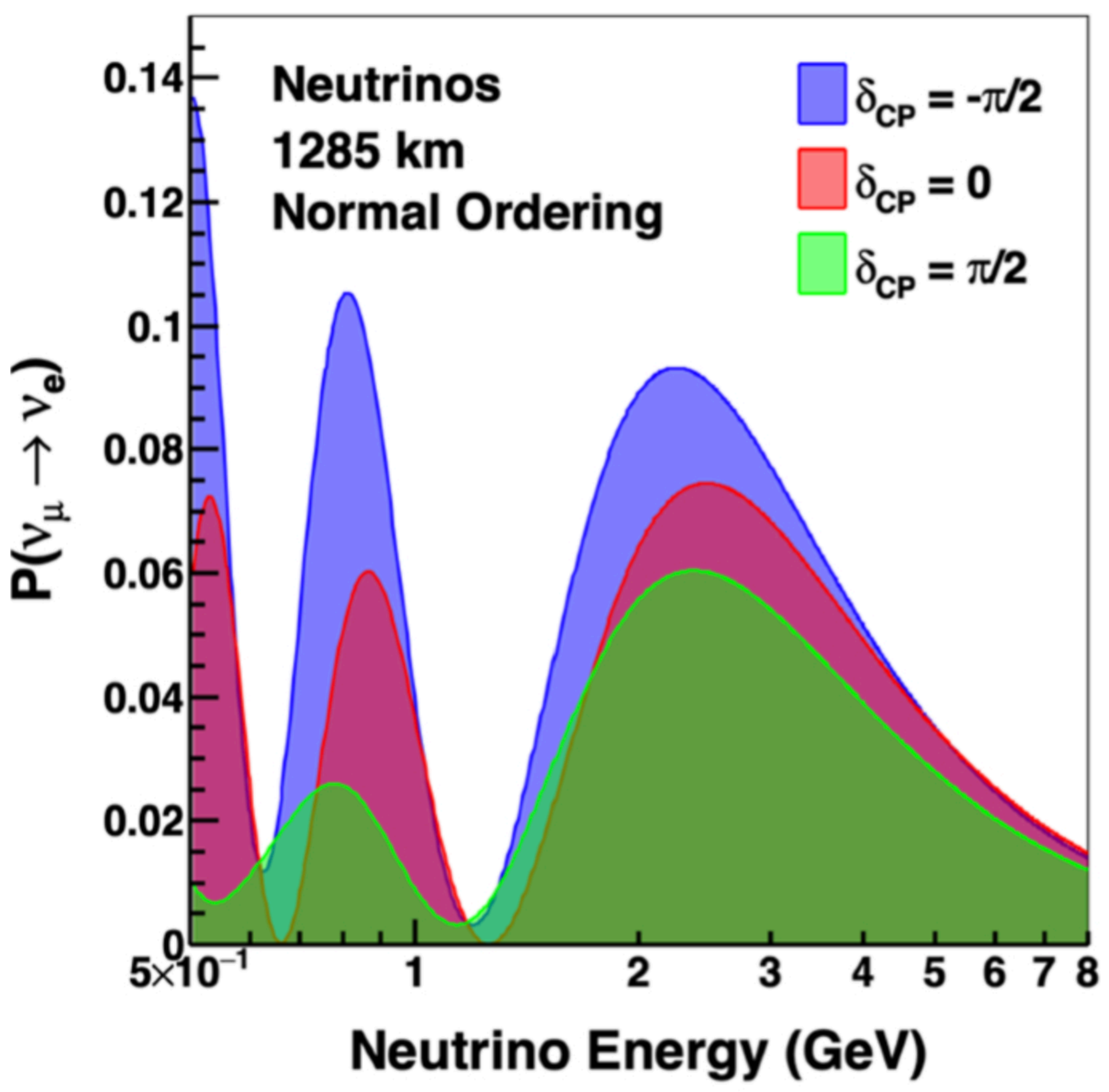
The DUNE beam

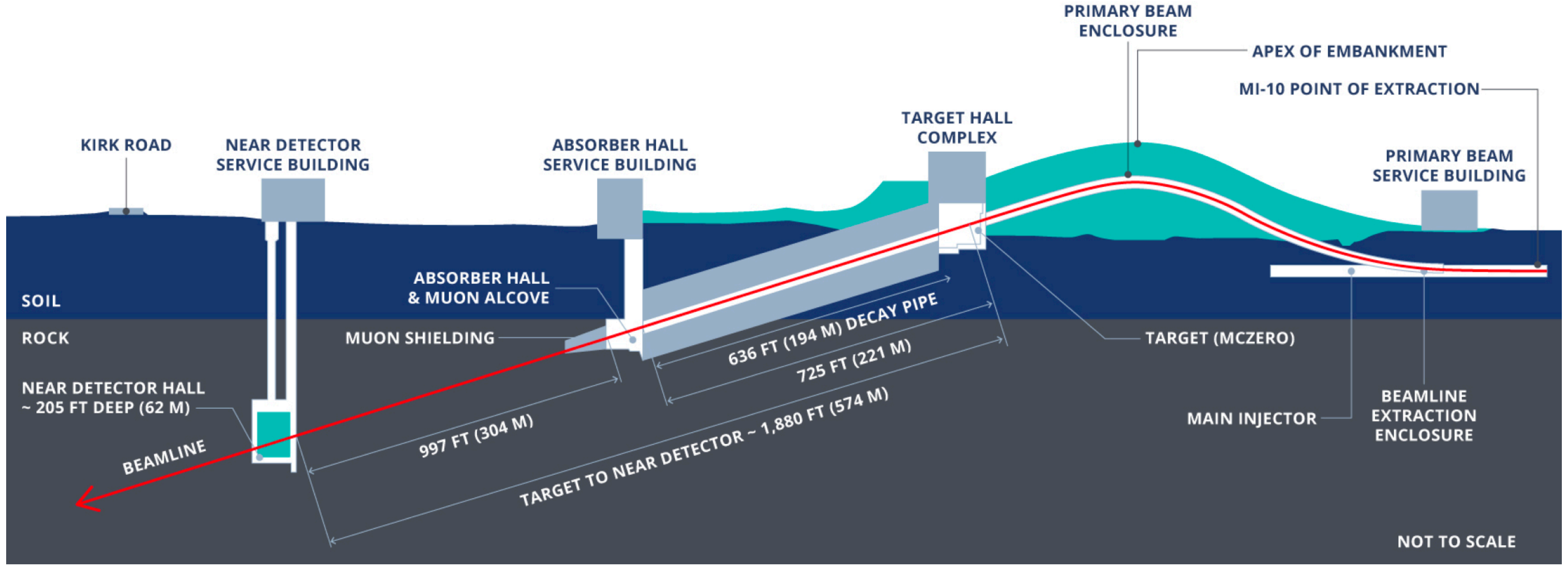
- **Proton beam line**
  - Produce neutrino beam by focusing charged pions and allowing them to decay
  - Can operate in neutrino and antineutrino modes
- **Proton Improvement Plan-II (PIP-II)**
  - Proton beam: 1.2 MW (phase-1), 2.4 MW (phase-2)
  - Accelerated to 60-120 GeV by FNAL accelerator complex
  - Bent down at 5.8° to reach Sanford
  - Horns/beam line designed to maximize CP violation sensitivity
- **Expected neutrino fluxes available**:
  - Neutrino-enhanced, Forward Horn Current (FHC),
  - Antineutrino-enhanced, Reverse Horn Current (RHC)

<u>On-axis wide band beam covering main oscillation features</u>

[Eur. Phys. J. C 80 (2020) 10, 978]



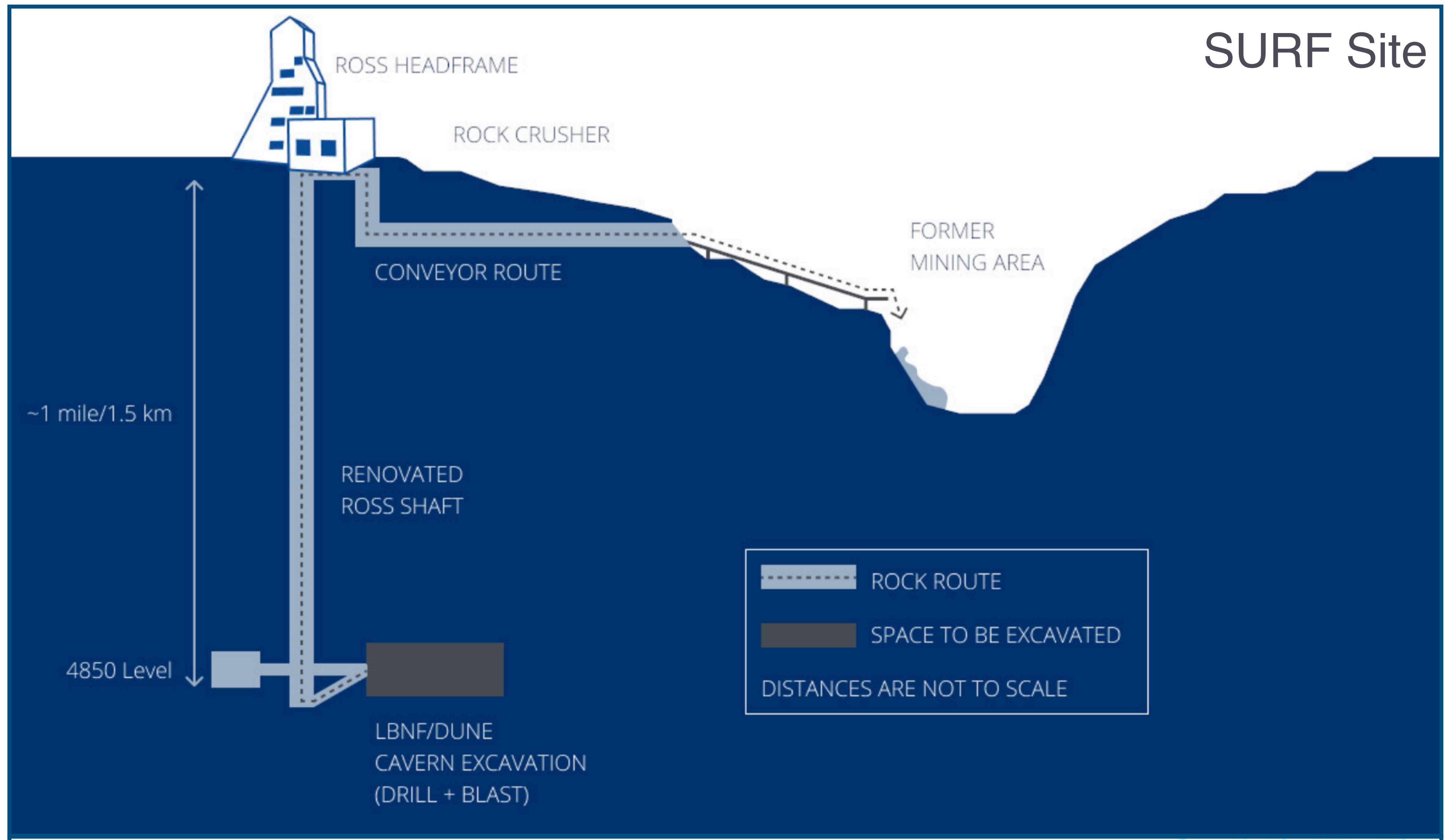


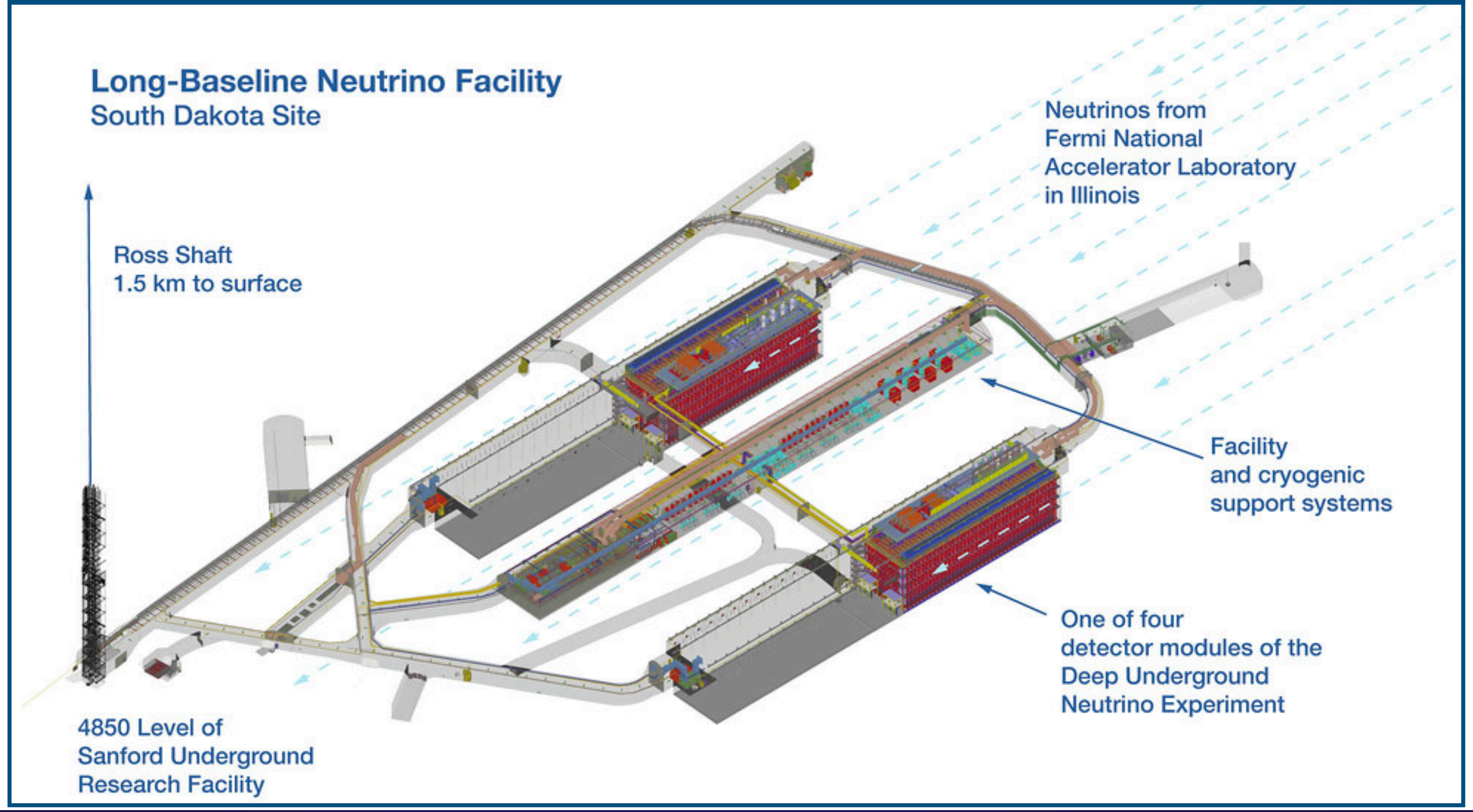


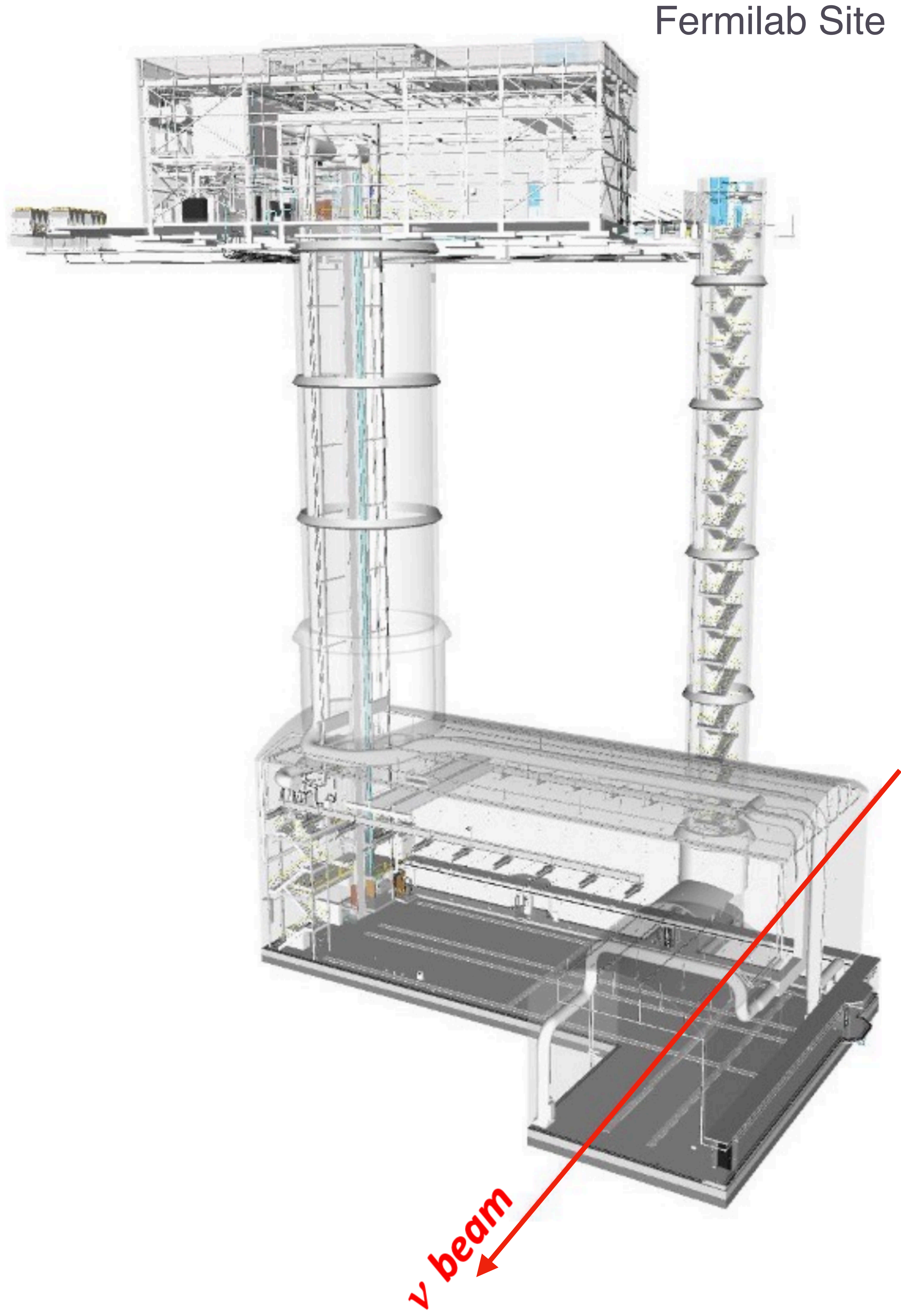
DUNE Near/Far site facility status

- **Far Detector (FD) site at SURF**
  - Deepest laboratory in the US: 1.5 km underground
  - Excavation work: 64.3% of in-situ rock volume removed as of 15 May 2023
  - Three main caverns:
    - 4 detector halls in 2 caverns
    - 1 utility cavern
- **Near Detector (ND) site at Fermilab**
  - 60 m underground, 574 m away from the neutrino source
  - Near Detector Conceptual Design Report (CDR) now finalized and recently published

[https://arxiv.org/abs/2103.13910]

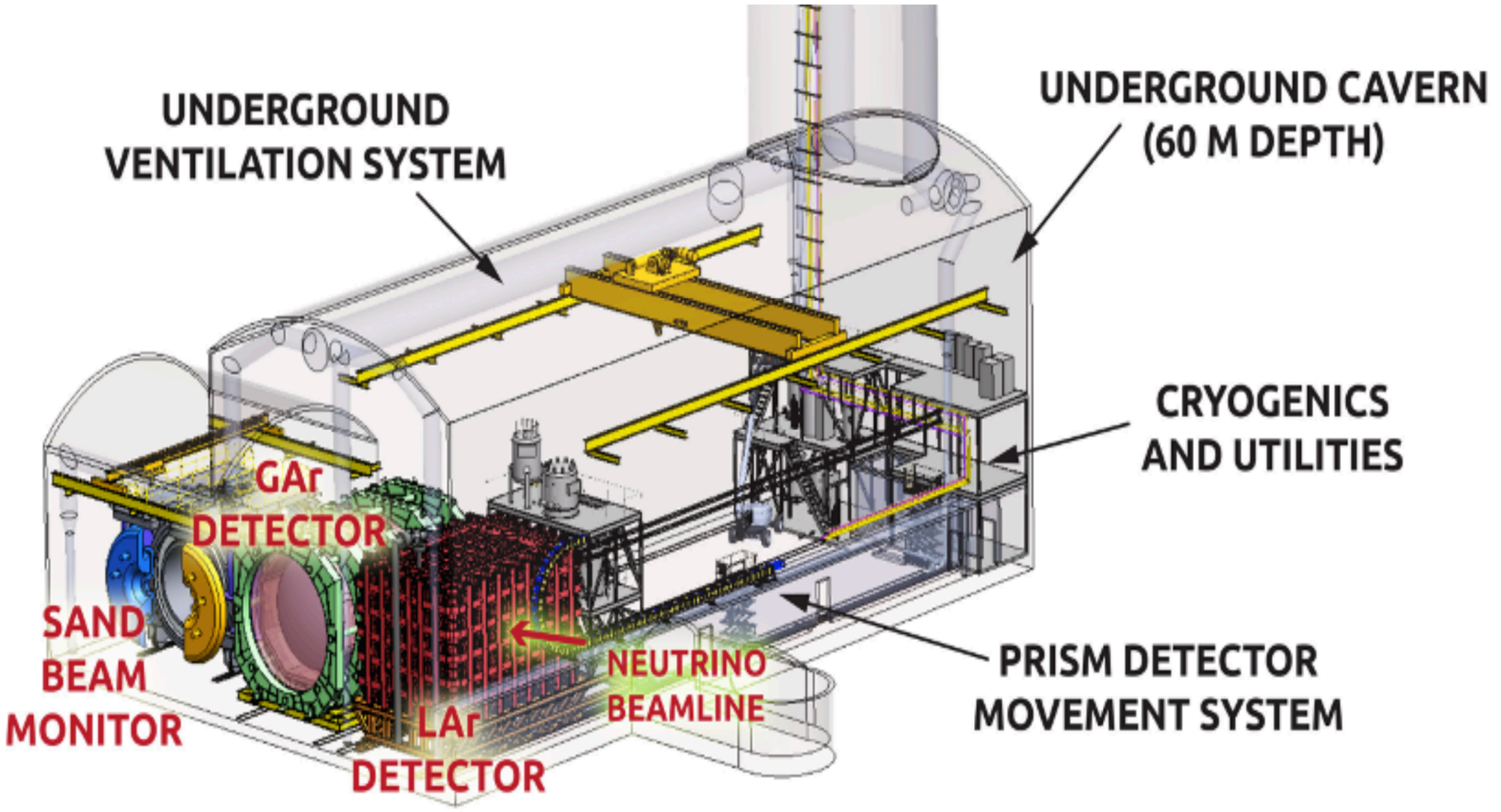






The DUNE Near Detector (ND)

- Independently constrain the cross section, flux, energy response, detector systematics
- Broad physics program
- Multiple complementary systems:
  - **ND-LAr** - Liquid Argon TPC
    - Modular, pixel read-out
  - **ND-GAr** - High Pressure Gas TPC
    - TMS - The Muon Spectrometer
    - HP GAr TPC surrounded by ECal+magnet (Phase-2)
  - **SAND** - on-axis beam monitor
    - Inner tracker surrounded by 100 t ECal, SC magnet (0.6 T)
    - On-axis beam monitor for beam spectrum/stability



- **PRISM**
  - ND-LAr and ND-GAr move up to 30 m off-axis
  - Beam characterization dependent on the off-axis angle to minimize flux and cross section systematics

The DUNE Far Detector (FD)

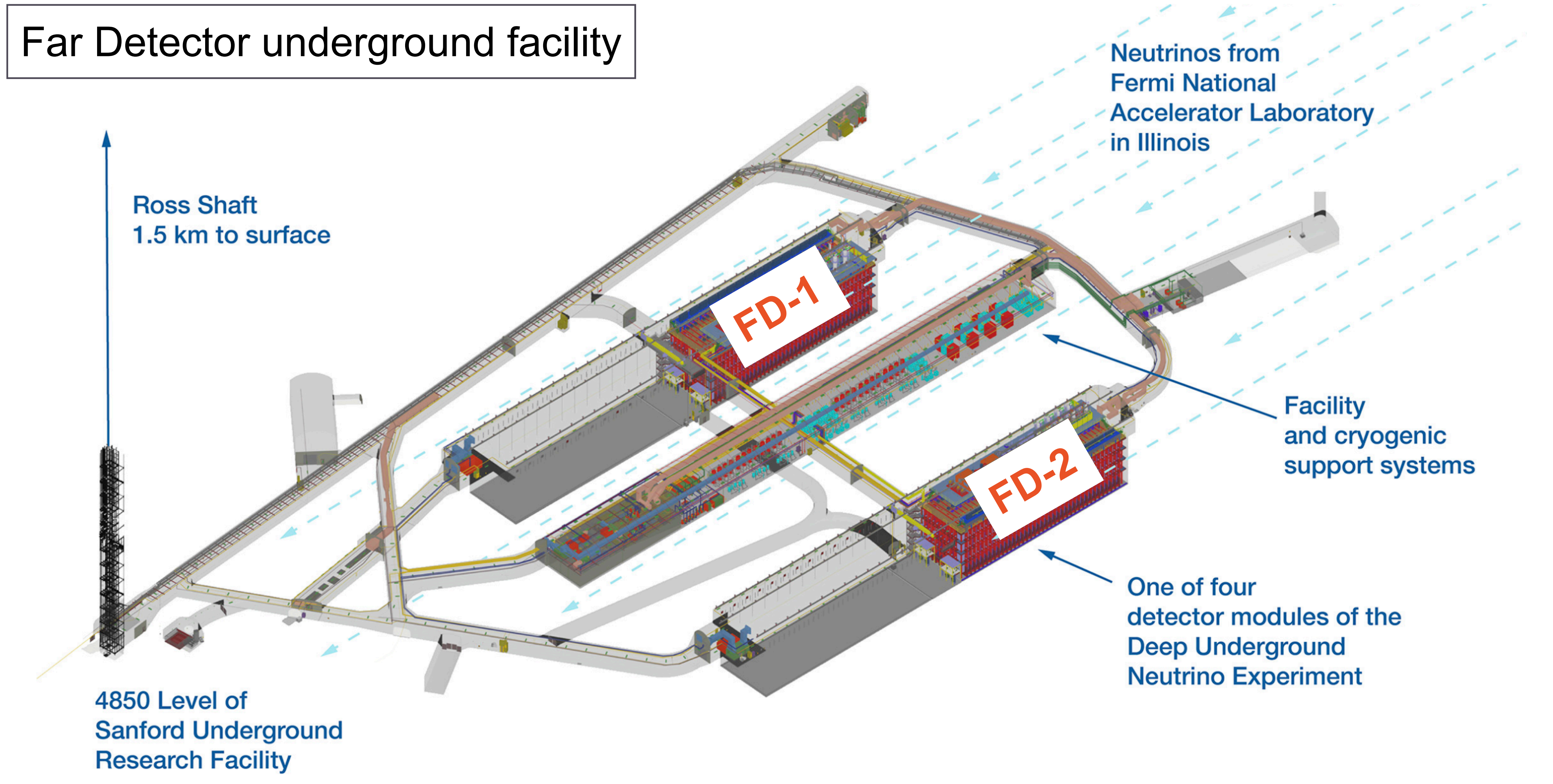
- 4 Detector modules, ~17 kt each
- Single phase (SP) Liquid Argon Time Projection Chambers (LArTPC) - main detector technology

Phase-1
- **FD #1**: SP LArTPC, Horizontal Drift (HD)
- **FD #2**: SP LAr-TPC, Vertical Drift (VD)

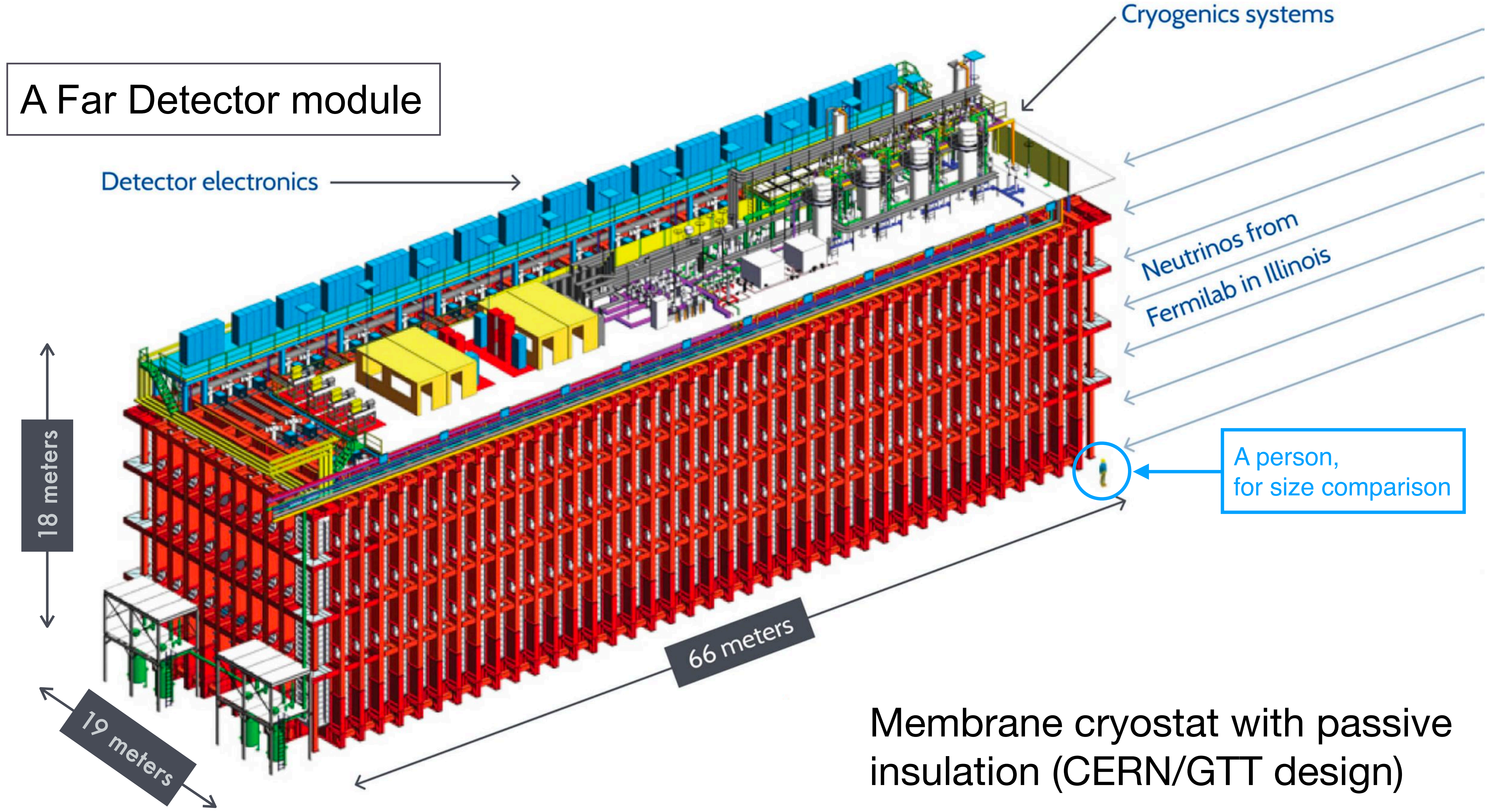
  - Cryostat installation starts mid-2020s
  - Expected to be operational end of 2020s → **DUNE science begins**

Phase-2
- **FD #3**: SP LAr-TPC enhanced VD concept - TBC
- **FD #4**: Ongoing R&D for Module of Opportunity

Far Detector underground facility



A Far Detector module

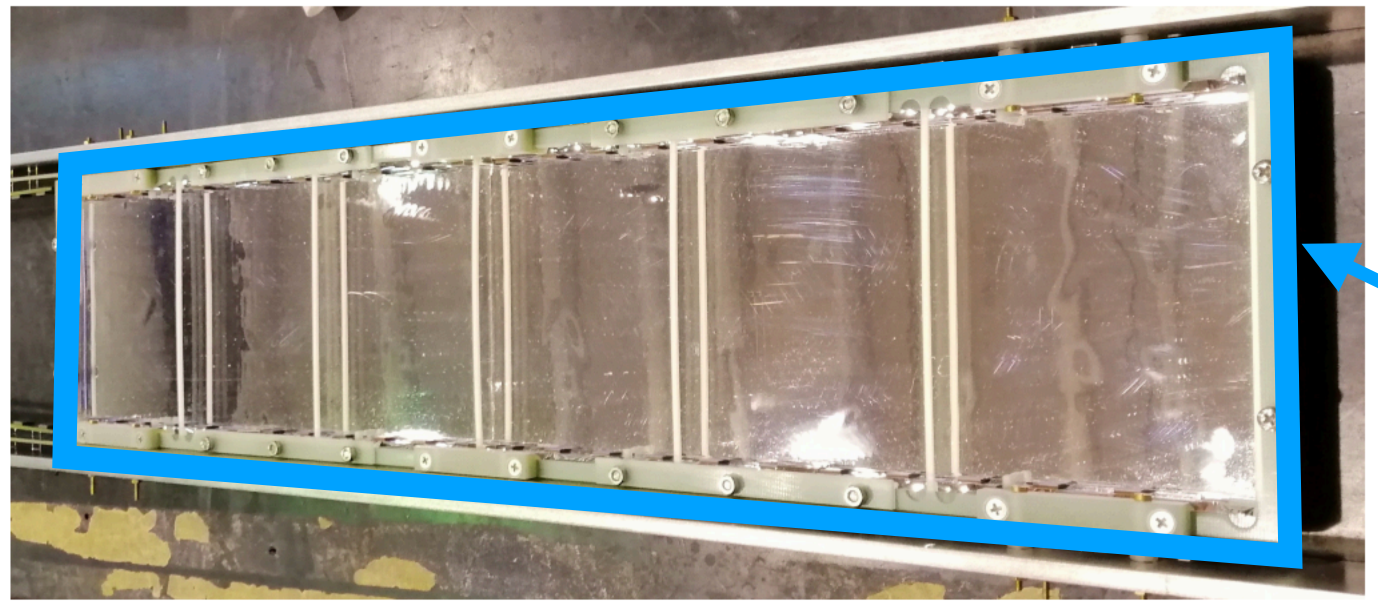


Membrane cryostat with passive insulation (CERN/GTT design)

FD#1 - LAr-TPC Horizontal Drift Technology

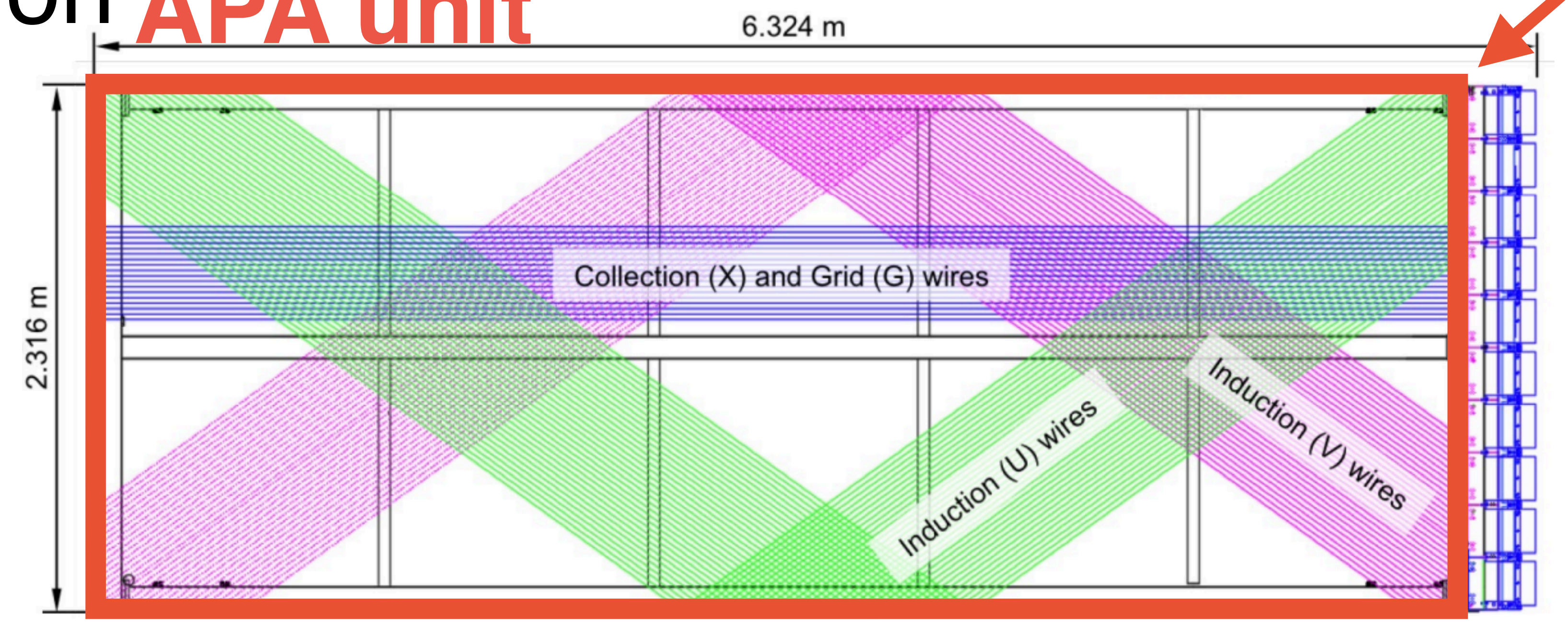
- Alternated APA/CPA
  Anode and Cathode Plane Assemblies
  - Segmented: 4 drift volumes,
    Drift distance: 3.6 m
  - Electric field = 500 V/cm
    (HV = -180 kV)
  - Anode: 150 APAs
    4 wire planes each
    Grid, 2x Induction, Collection
  - High-resistivity CPAs
    to prevent fast discharge
- **Photon Detectors**:
  X-ARAPUCA light traps

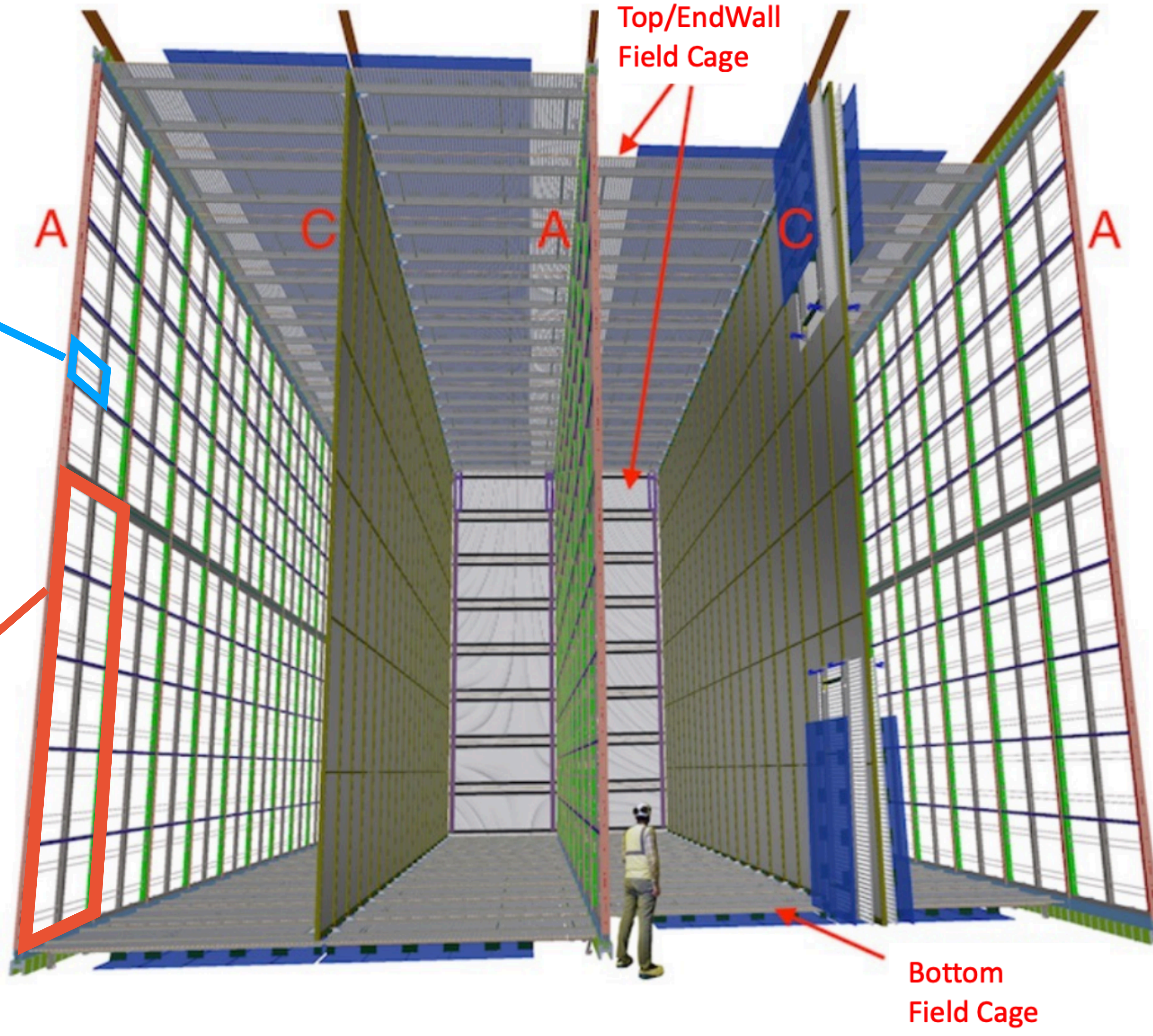
X-ARAPUCA module



1 SuperCell = ¼ PDS module -- SiPM readout
High-reflectivity inner surfaces
Wavelength-shifting + dichroic filter for light trapping

APA unit

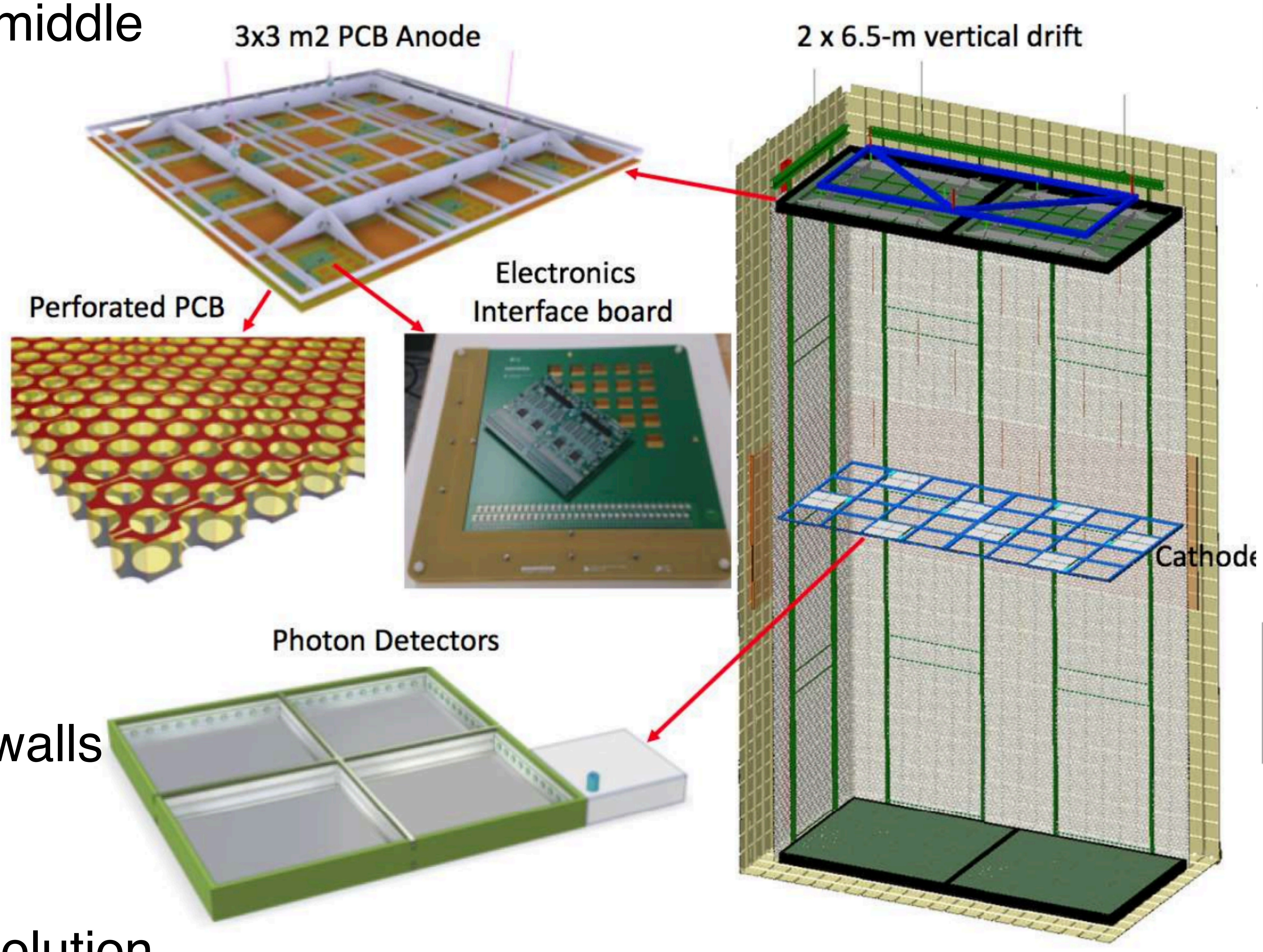


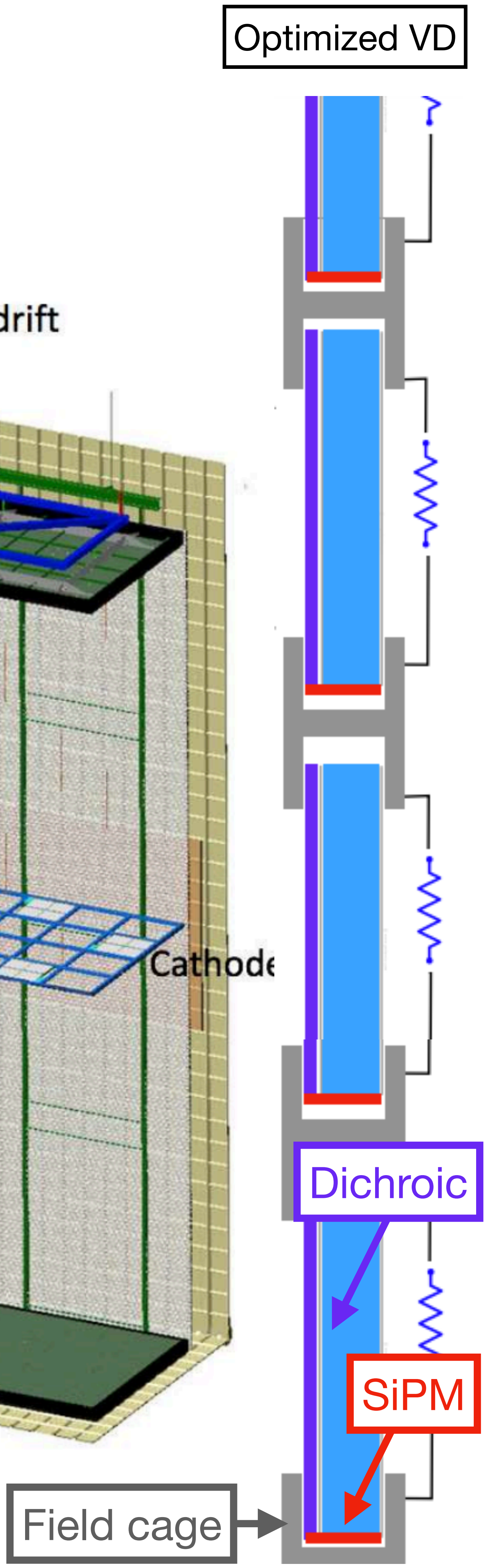


[DUNE TDR, B. Abi *et al* 2020 *JINST* **15** T08010]

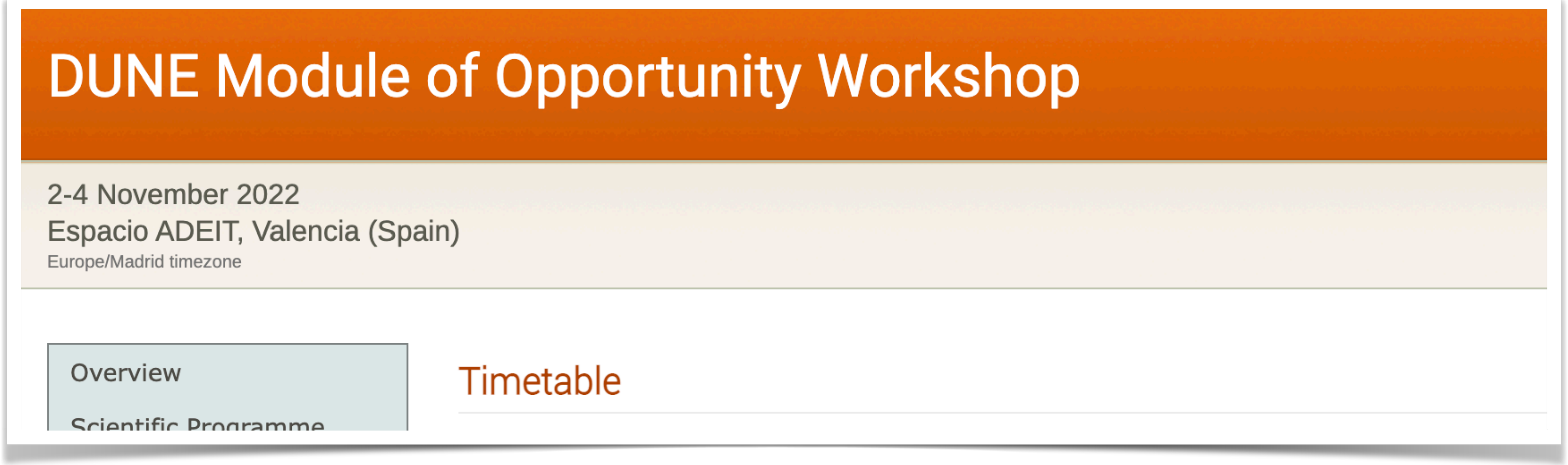
FD#2 - LAr-TPC Vertical Drift Technology

- **Charge readout**:
  - Drift along vertical direction and cathode plane in the middle
  - Readout on strips etched on PCBs
  - Two induction and one collection readout
  - Cathode at -300 kV, drift field of 450 V/cm
- **Photon Detection System (PDS)**
  - Based on X-ARAPUCA – “4π” reference design
  - SiPM and electronics partially on Cathode: @ 300 kV
  - PoF & SoF demonstrated in ProtoDUNE
- **Optimized VD** FD#3: more enhanced concepts
  - X-ARAPUCA bars can be installed inside Field Cage walls
  - PDS full FC optical coverage
    -> potentially no need for cathode PDS
  - Dual calorimetry (charge ⊕ light): improve energy resolution
  - Extend sensitivity for low-energy physics: SNB, solar, BSM

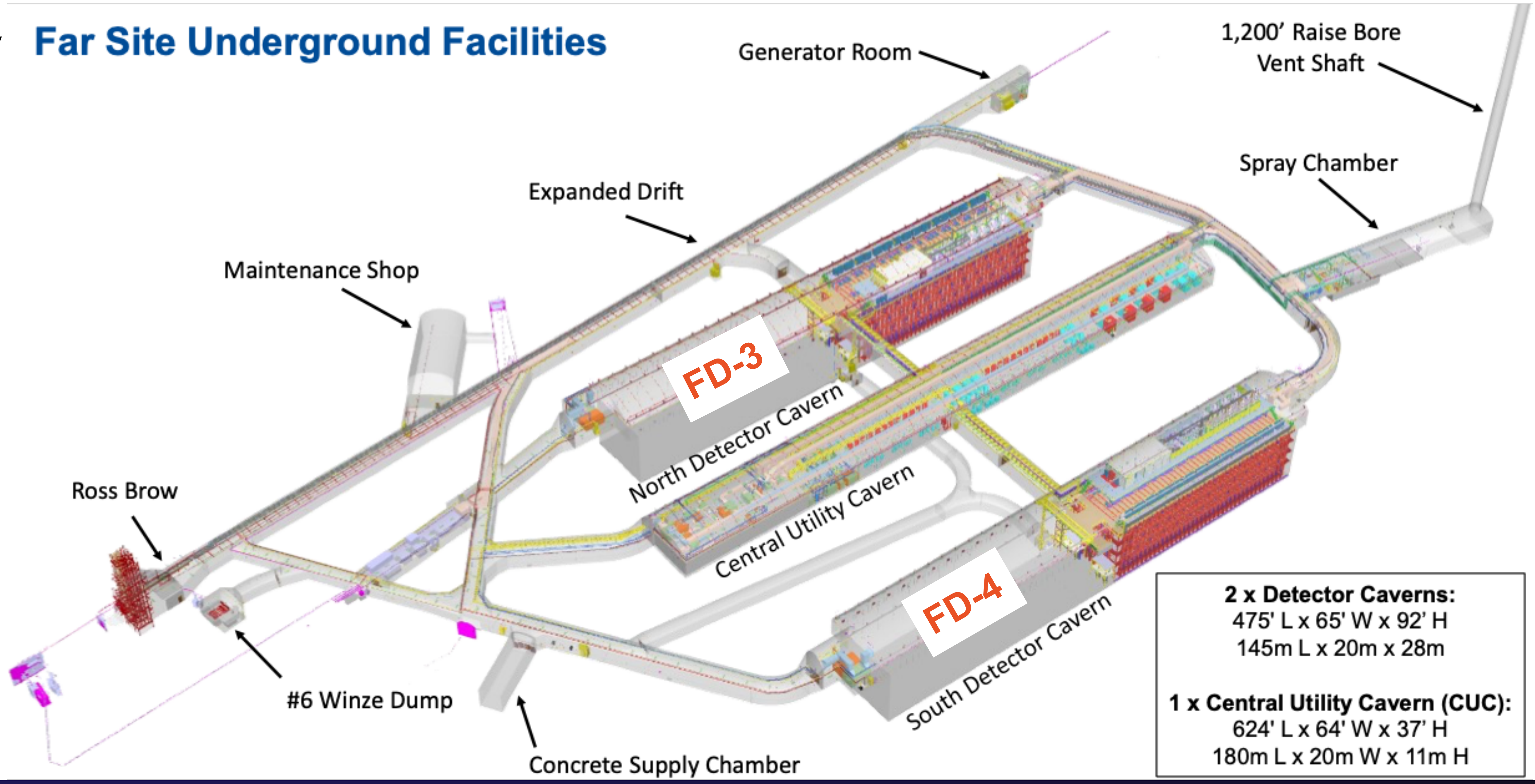




FD#4 Module of Opportunity



- Detector concepts
  - **Optimized VD** for FD#3,4: optimized r/o CE (digital) & SoF (large bandwidth) for higher ch count
  - **SLoMo** concept: A SURF Low Background Module
  - **SoLAr** concept: novel pixelated charge readout
  - **Xe-doped** LArTPC neutrinoless double beta decay concept
  - **Theia** concept: A hybrid Cherenkov/scintillation detector module for DUNE
  - **LiquidO** concept: Opaque Liquid Scintillator for Neutrino Detection
- Several R&D presented
  - **Q-Pix**, **LArPix**, and many more



[https://indico.ific.uv.es/event/6722/]

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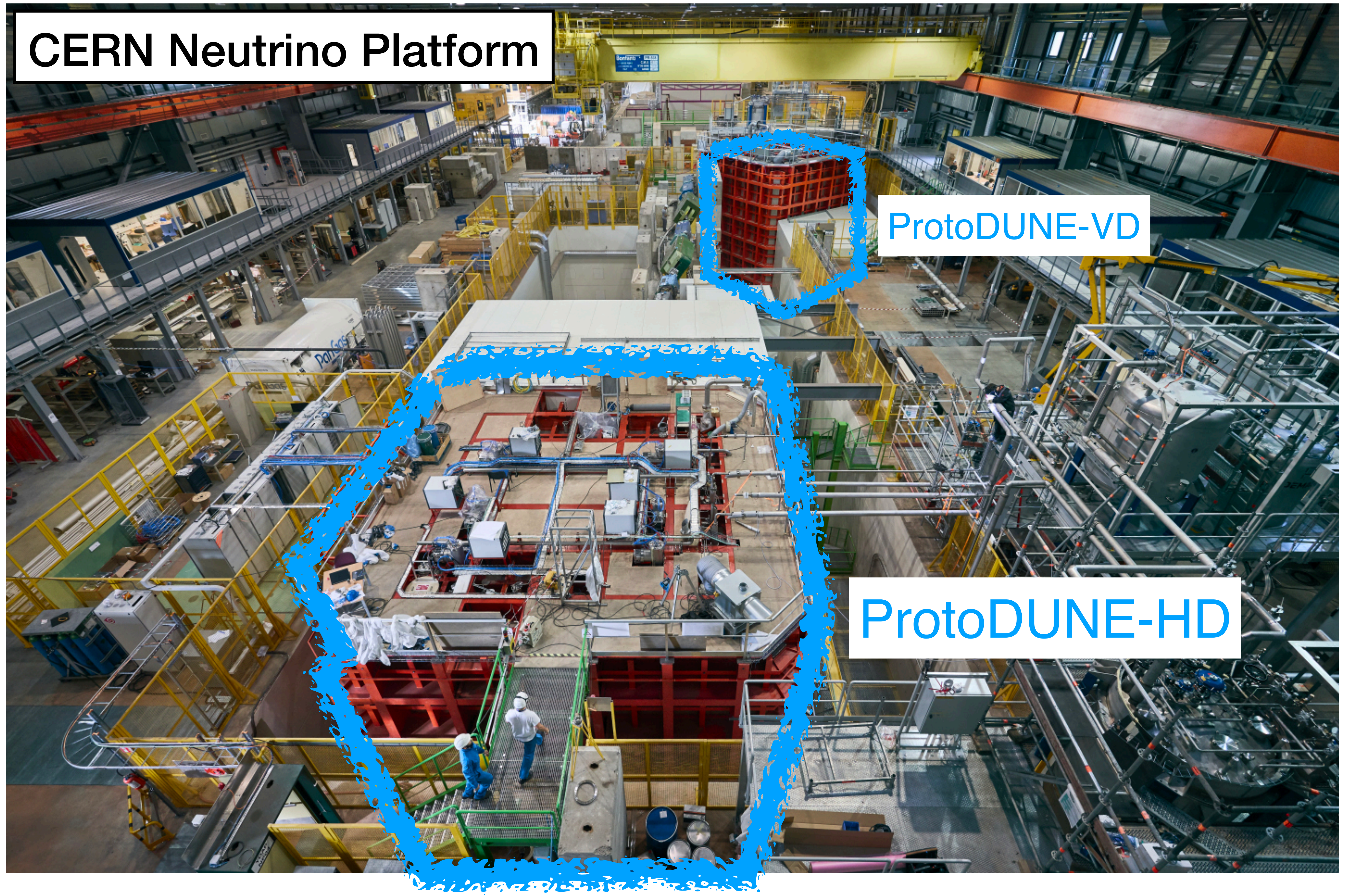
The ProtoDUNE cryostat
Photo credit: CERN

ProtoDUNE at CERN

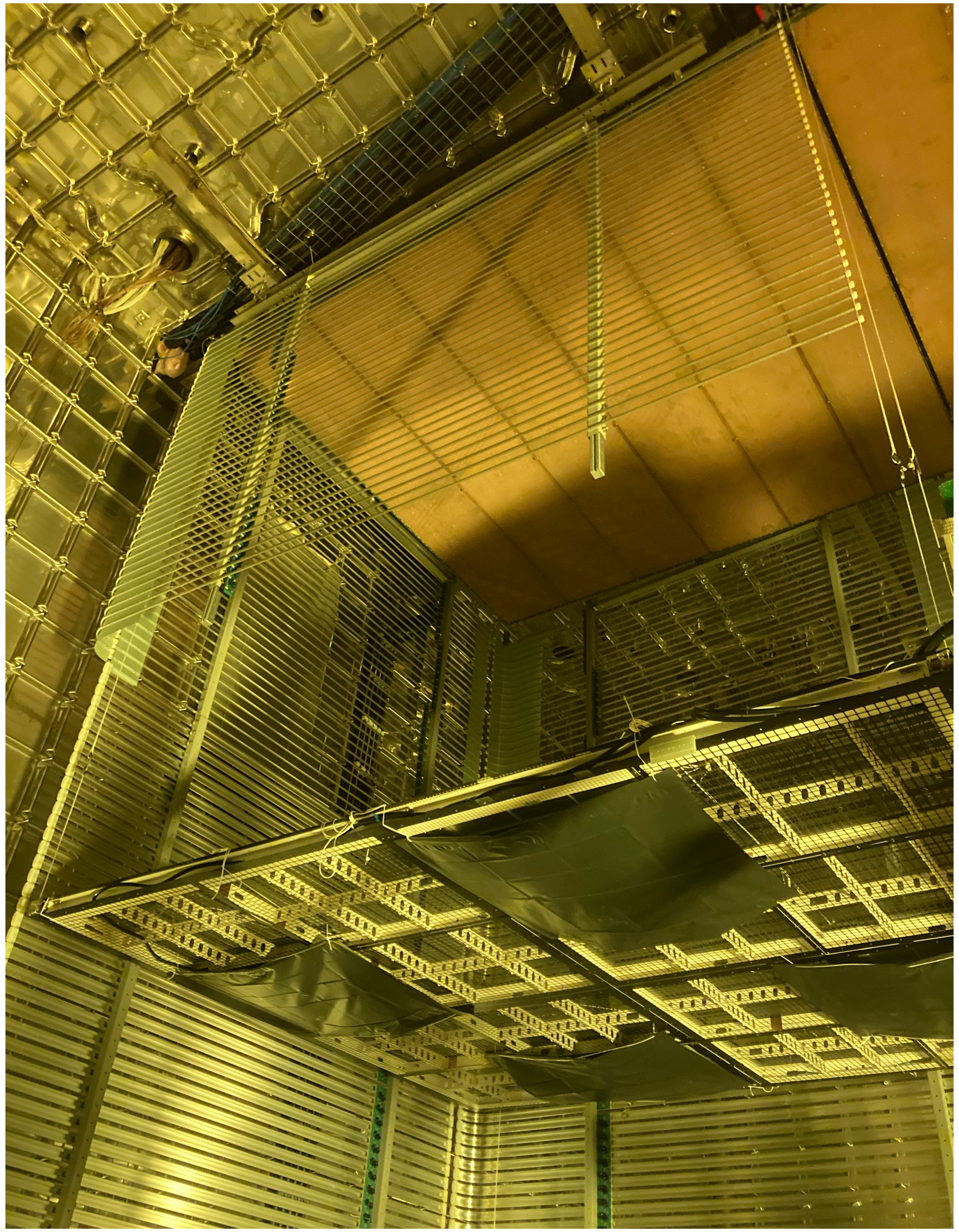
Each DUNE-FD module will be **20 times larger** than one ProtoDUNE detector

the largest LAr-TPC detectors ever built

- **Two 750 t prototypes 7.2 x 6.1 x 7.0 m**
  - Design validation of all components, at full scale
  - **Single-phase Horizontal Drift (HD)**
    - Charged particle beam + cosmic rays
    - Event reconstruction, full analysis
    - Calibration systems, Xe doping, HV tests
  - **Single-phase Vertical Drift (VD)**
    - Different approach to LArTPC principle
    - Significantly simplified implementation



A drift volume of ProtoDUNE-HD

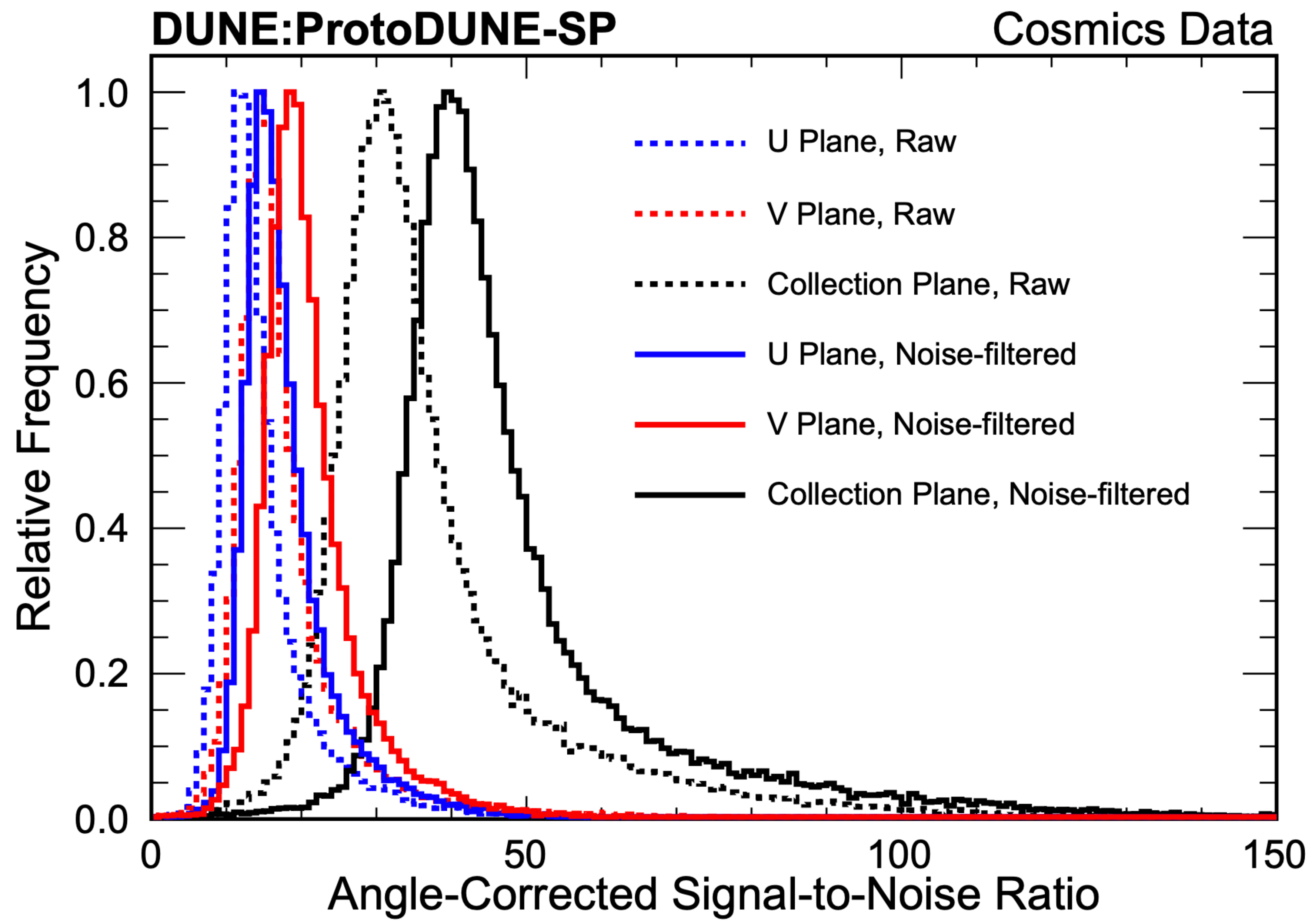


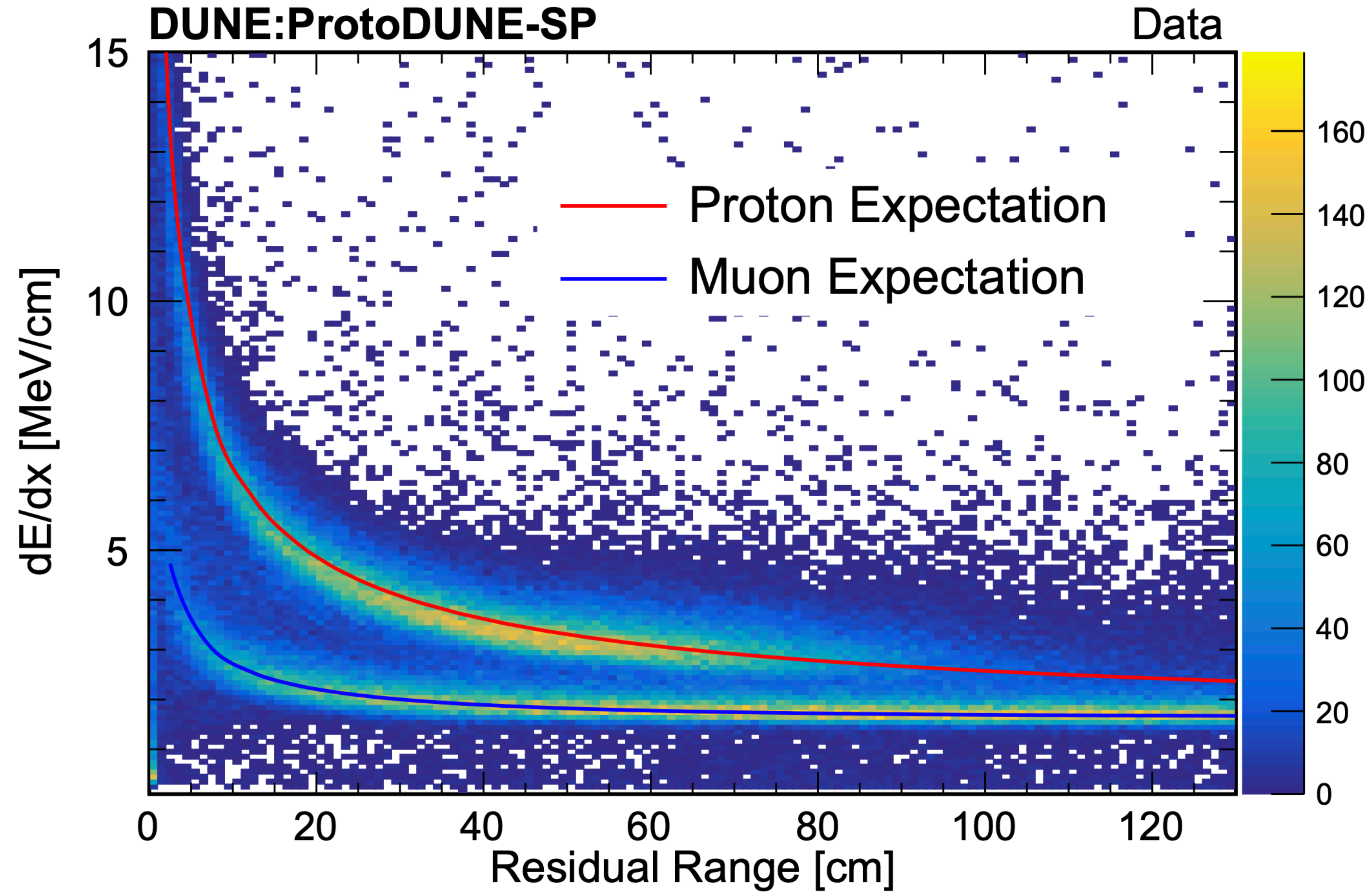
A drift volume of ProtoDUNE-VD (under construction)

ProtoDUNE-SP Performance

- **Detector performance validation**
  with cosmic rays, beam charged particles;
  photon detector demonstration
- **Stable operation**
  - > 99.5% of HV uptime for cosmic rays and beam data taking
  - High purity, well above requirements
    (> 30 ms e-lifetime most runs, > 20 ms all runs)
  - > 99% of TPC channels (wires) active
- **Low noise in all readout channels**
  - S/N > 10 - induction wires
  - S/N > 40 - collection wires
- **Test of full analysis chain**
  - Hit clustering, track reconstruction, particle ID
  - Simulation tuning - detailed paper

[Phys. Rev. D 102, 092003 (2020)]





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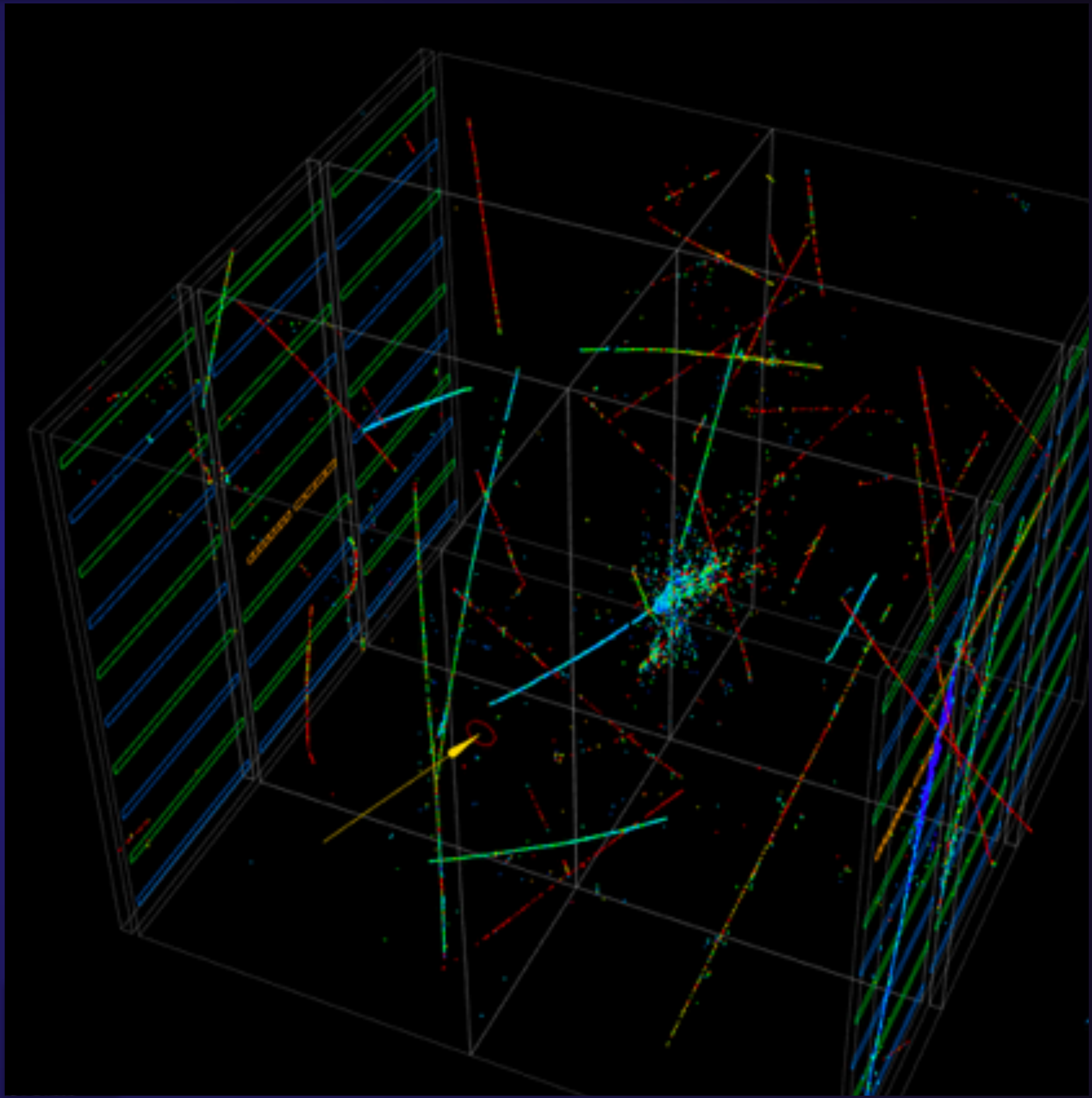


A reconstructed test beam π^+ interacting in ProtoDUNE-SP recorded with a number of cosmic rays

DUNE Neutrino Oscillations

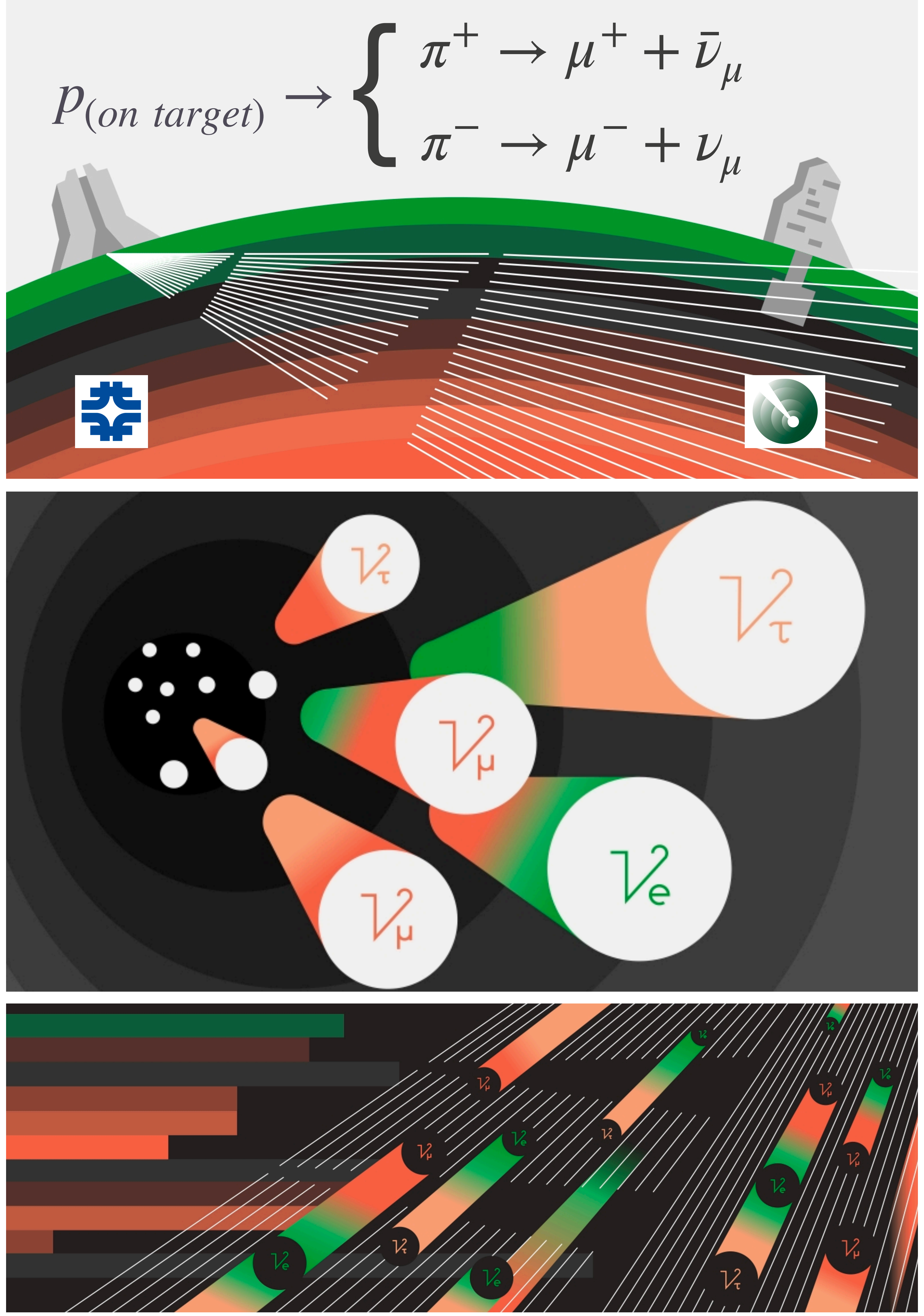


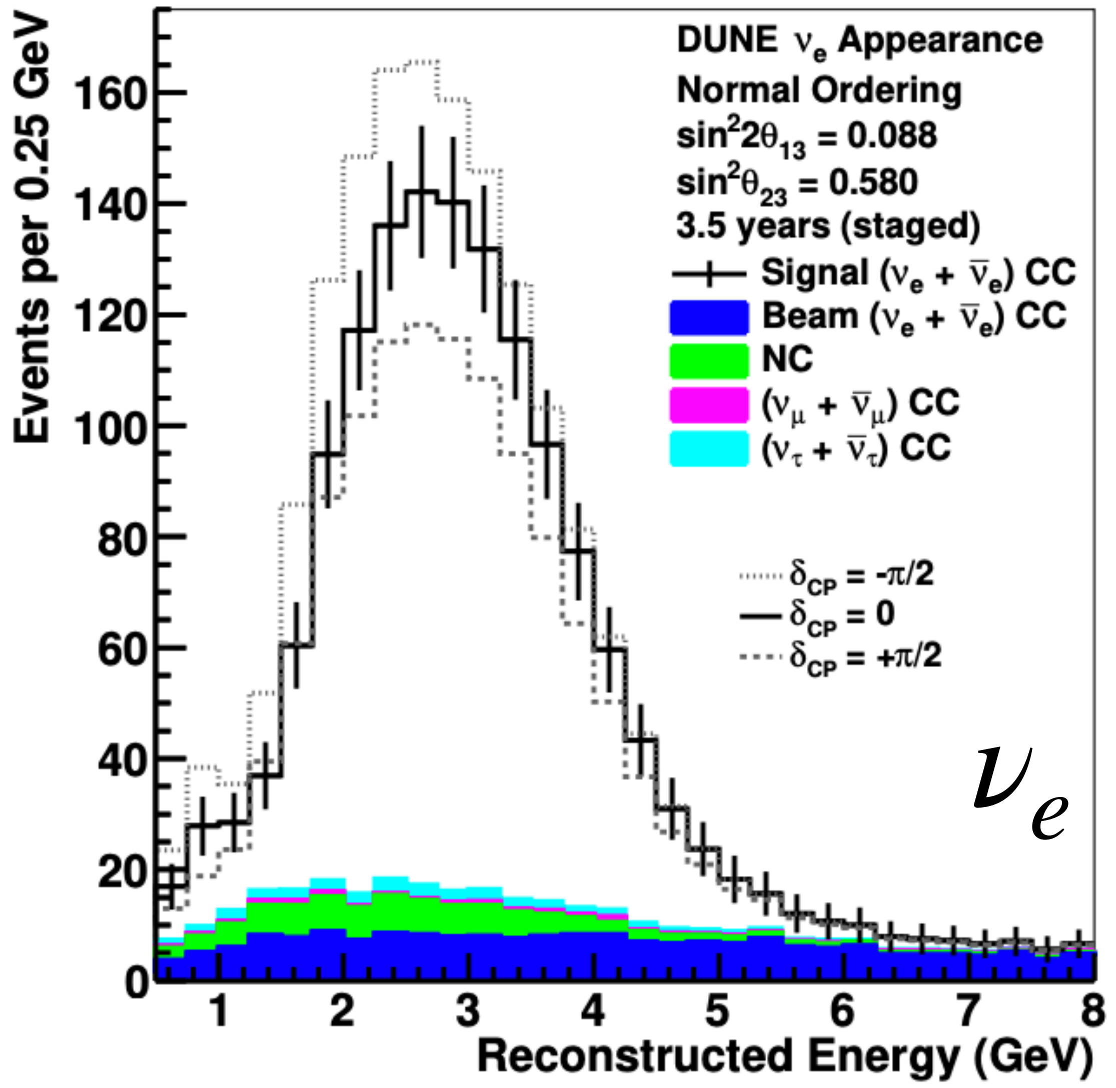
Image credit: SURF

- Projected results for $\nu_e/\bar{\nu}_e$ **appearance**, $\nu_\mu/\bar{\nu}_\mu$ **disappearance**, assuming Normal ordering
- **Reconstructed spectra** of selected Charged Current events
- **Sensitivity assessment** includes full FD systematics treatment (flux, cross-section, and detector) and ND constraints
  - ~1000 ν_e appearance events
  - ~10,000 ν_μ disappearance events

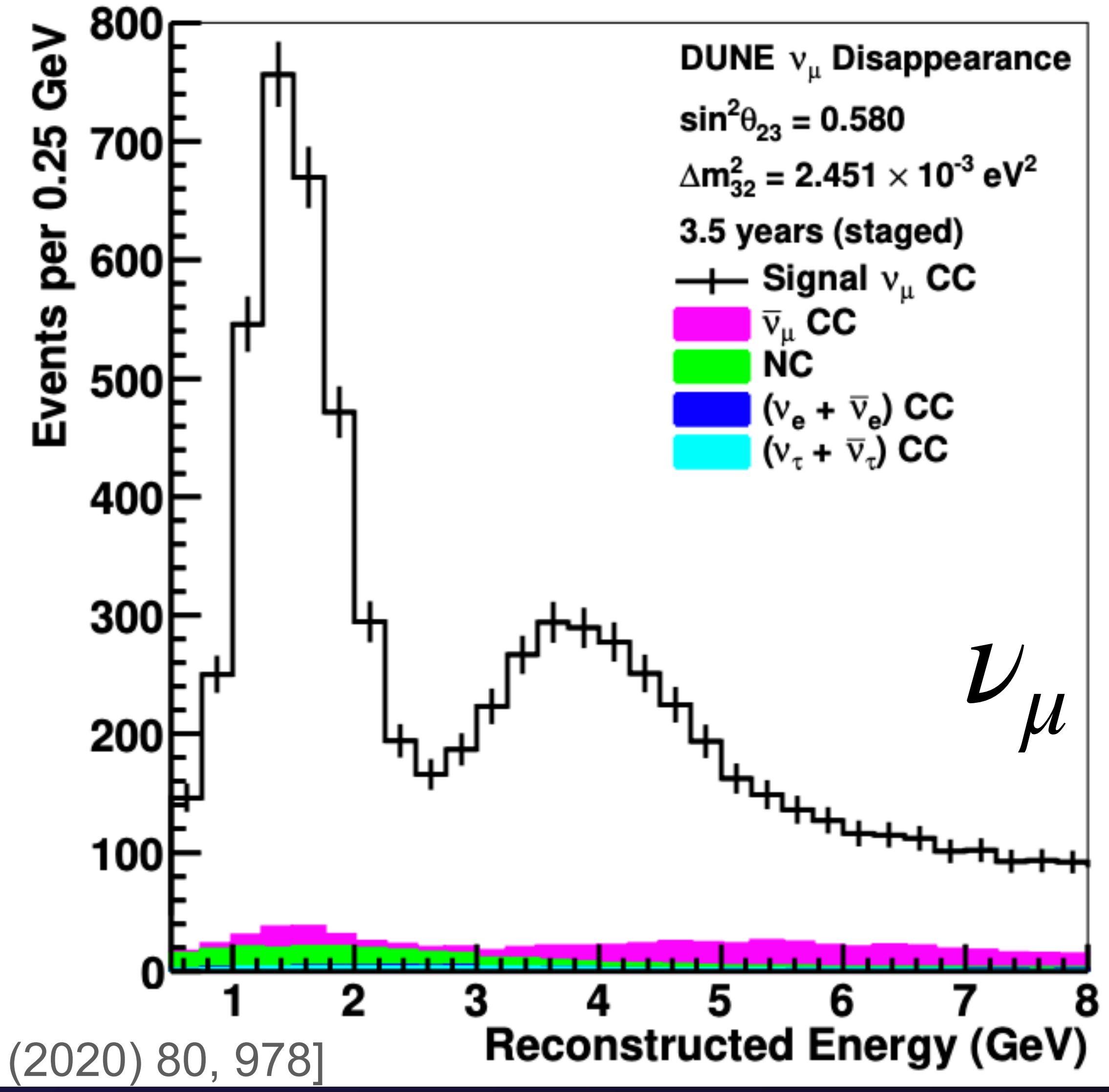
Variation with mass ordering, δ_{CP}

Neutrino Mode

appearance



disappearance

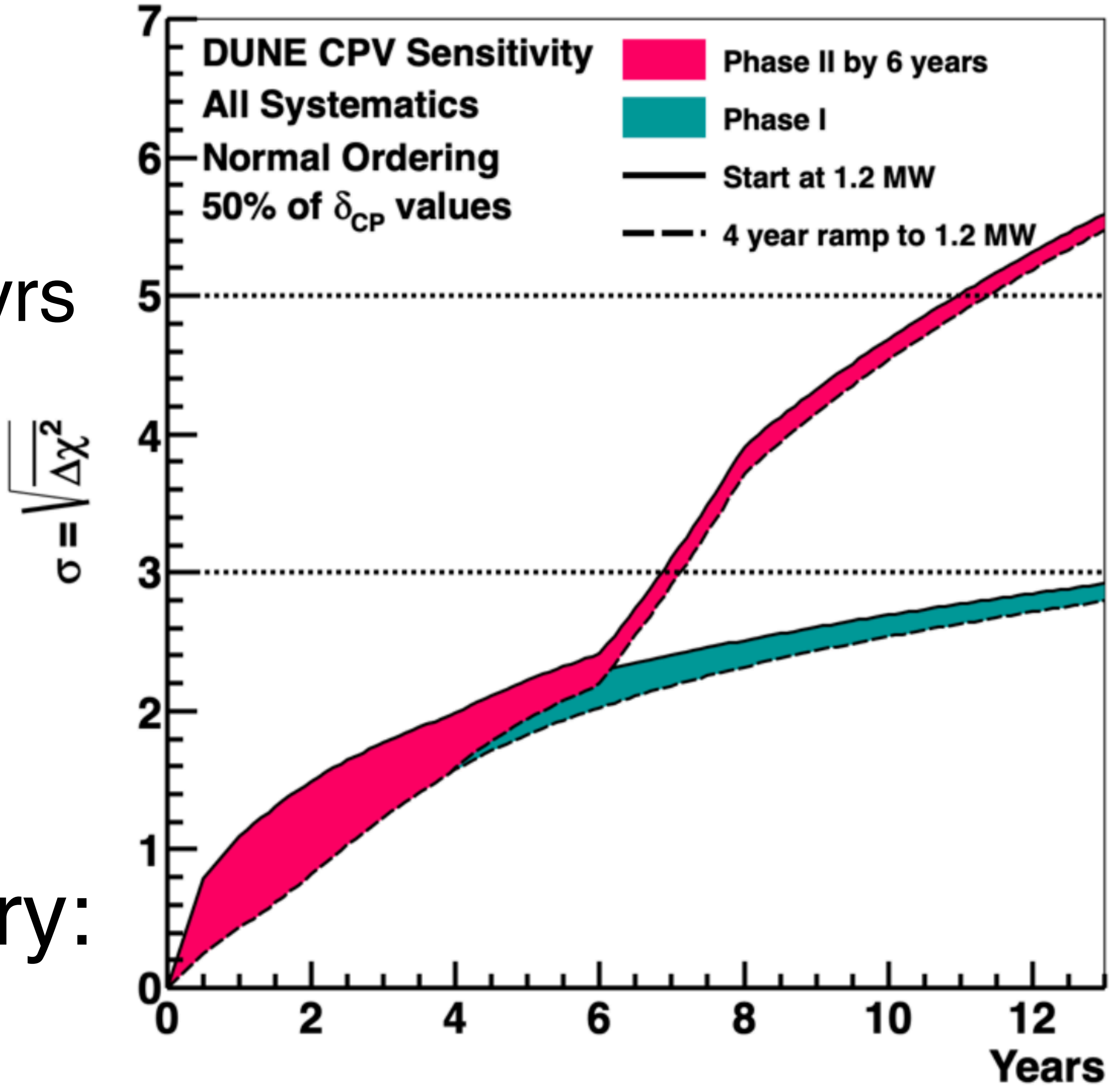


[EPJC (2020) 80, 978]

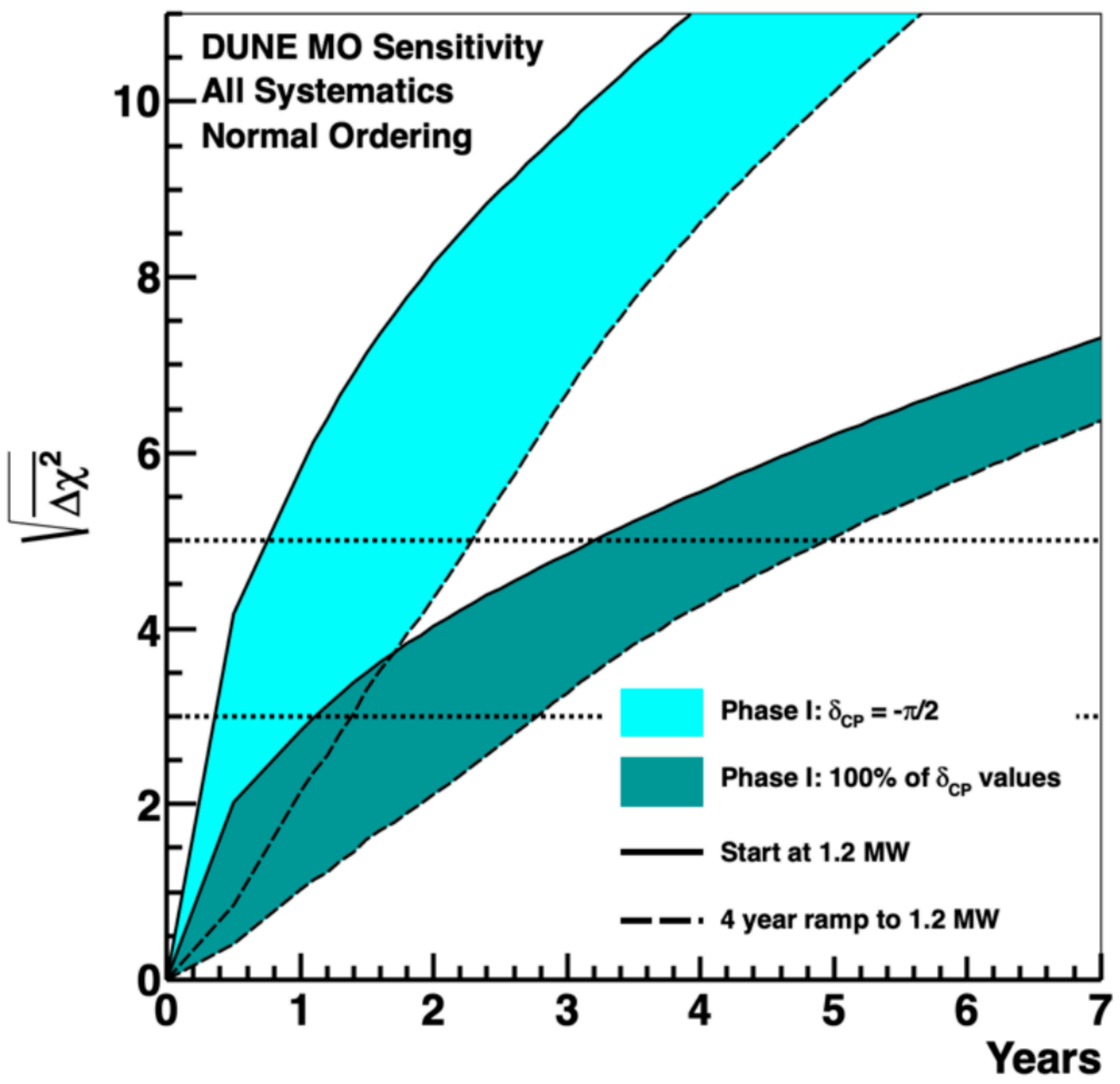
DUNE CP violation and mass ordering

- Assumed **staged running**
  - ν-beam / $\bar{\nu}$-beam mode
  - Full PIP-2, Full ND-GAr, FD#3,4 in 4-6 yrs
- Mass ordering (Phase-1):
  - 1 year if $\delta_{CP} = -\frac{1}{2}$,
  - 4 years for all δ_{CP} values
- Potential of **CP violation** discovery:
  - Requires Phase-1 + Phase-2

CP violation



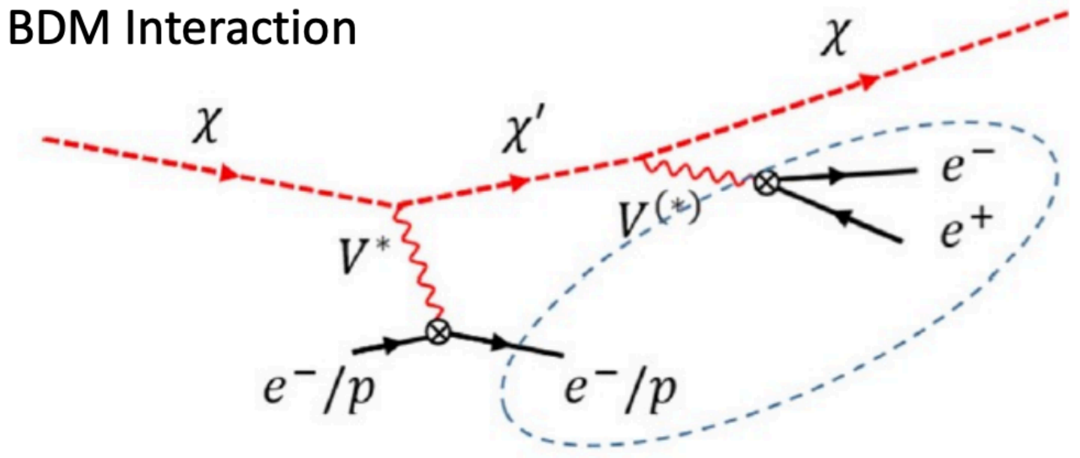
Mass hierarchy



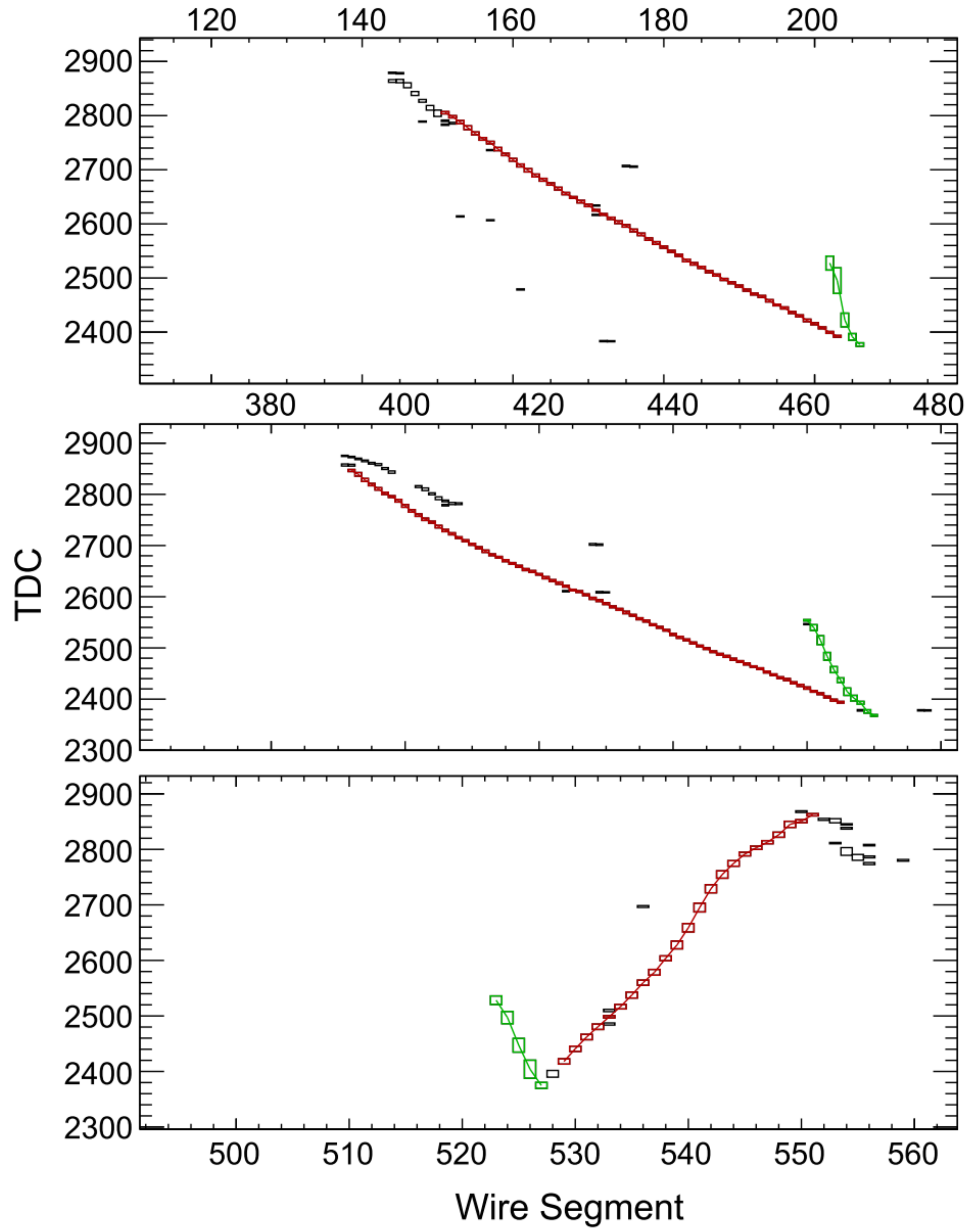
[https://arxiv.org/pdf/2203.06100.pdf]

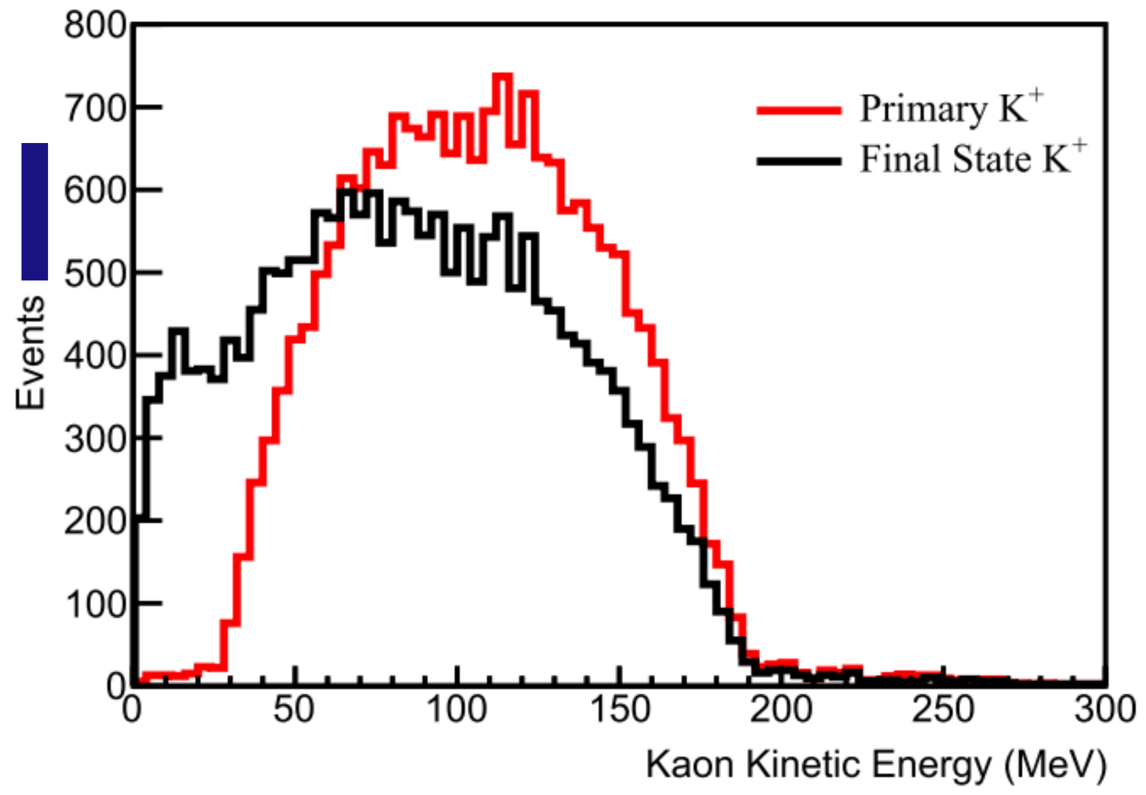
DUNE physics Beyond the Standard Model

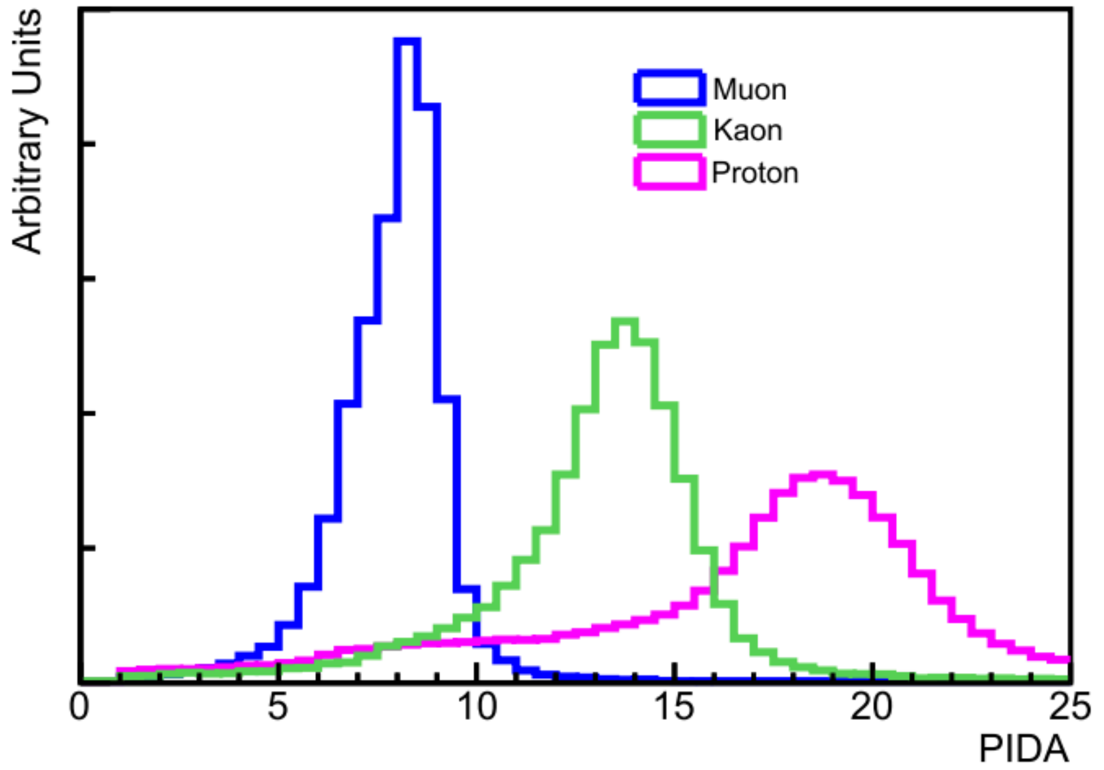
- Non-standard short-baseline and long-baseline oscillation phenomena:
  - Sterile neutrino mixing,
  - Non-standard neutrino interactions,
  - Non-unitarity
  - CPT violation
- Searches at the FD:
  - Baryon number violation
  - Inelastic boosted dark matter
- Searches at the ND:
  - Trident interactions
  - Heavy neutral leptons
  - Low-mass dark matter

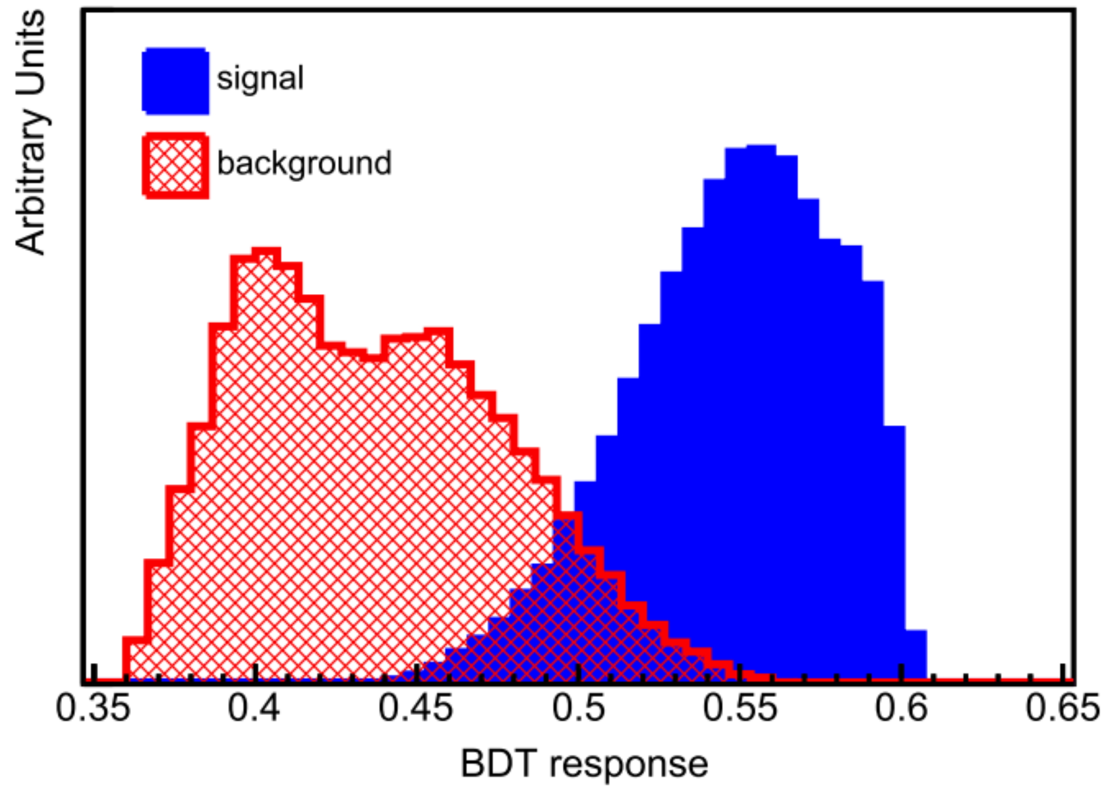


Atmospheric ν interaction $\nu_\mu + n \to \mu + p$
selected in the $p \to K^+ + \bar{\nu}$ sample
if p misidentified as a K









[EPJC (2021) 81, 322]

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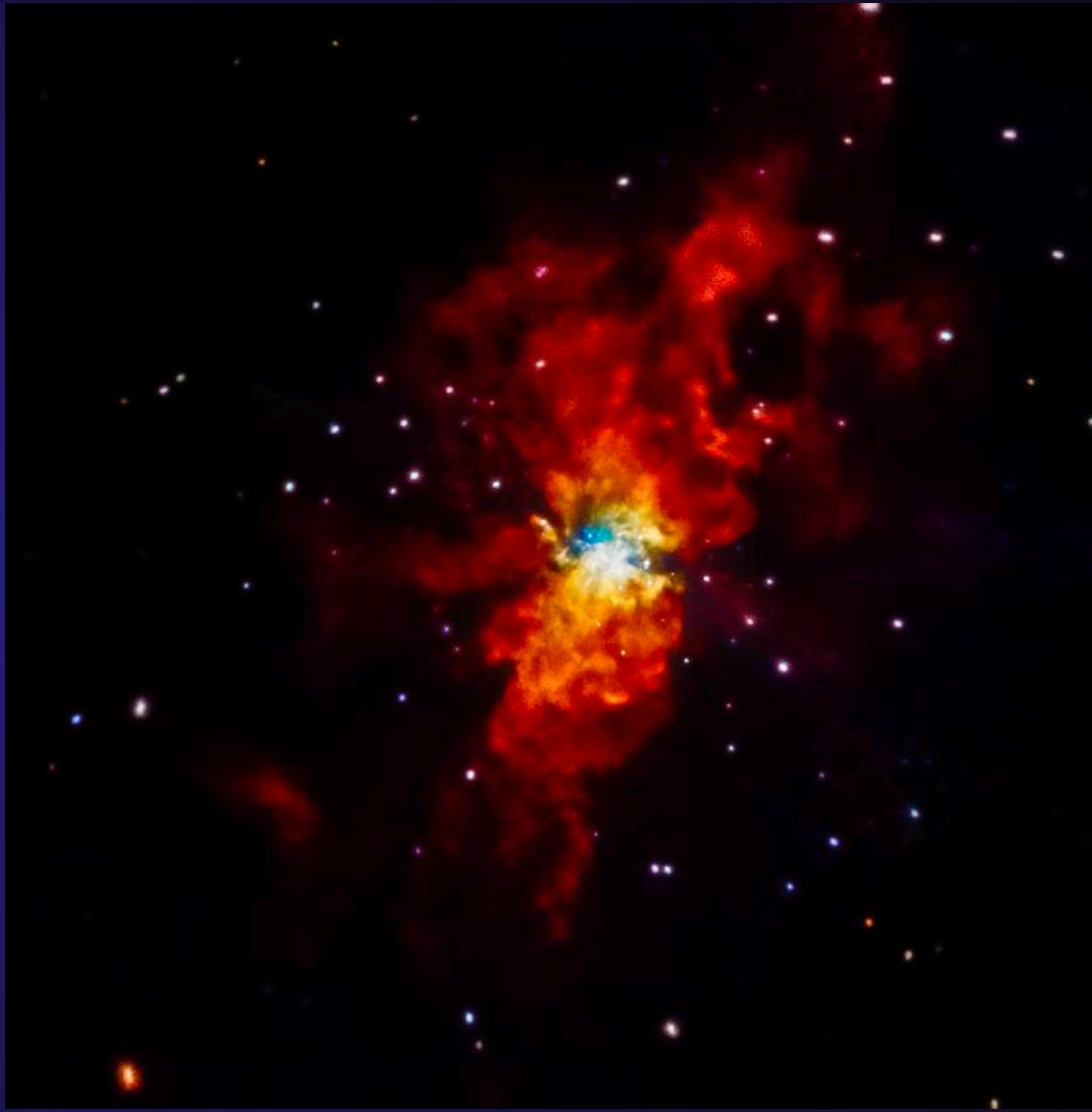


X-ray image of M82 galaxy's SN 2014J
as recorded by Chandra on Jan 21, 2014
Photo credit: NASA

Supernova neutrino signal in LAr

Interaction channels in argon

- Charged-current (CC) interaction on Ar

$$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$$

$$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$$

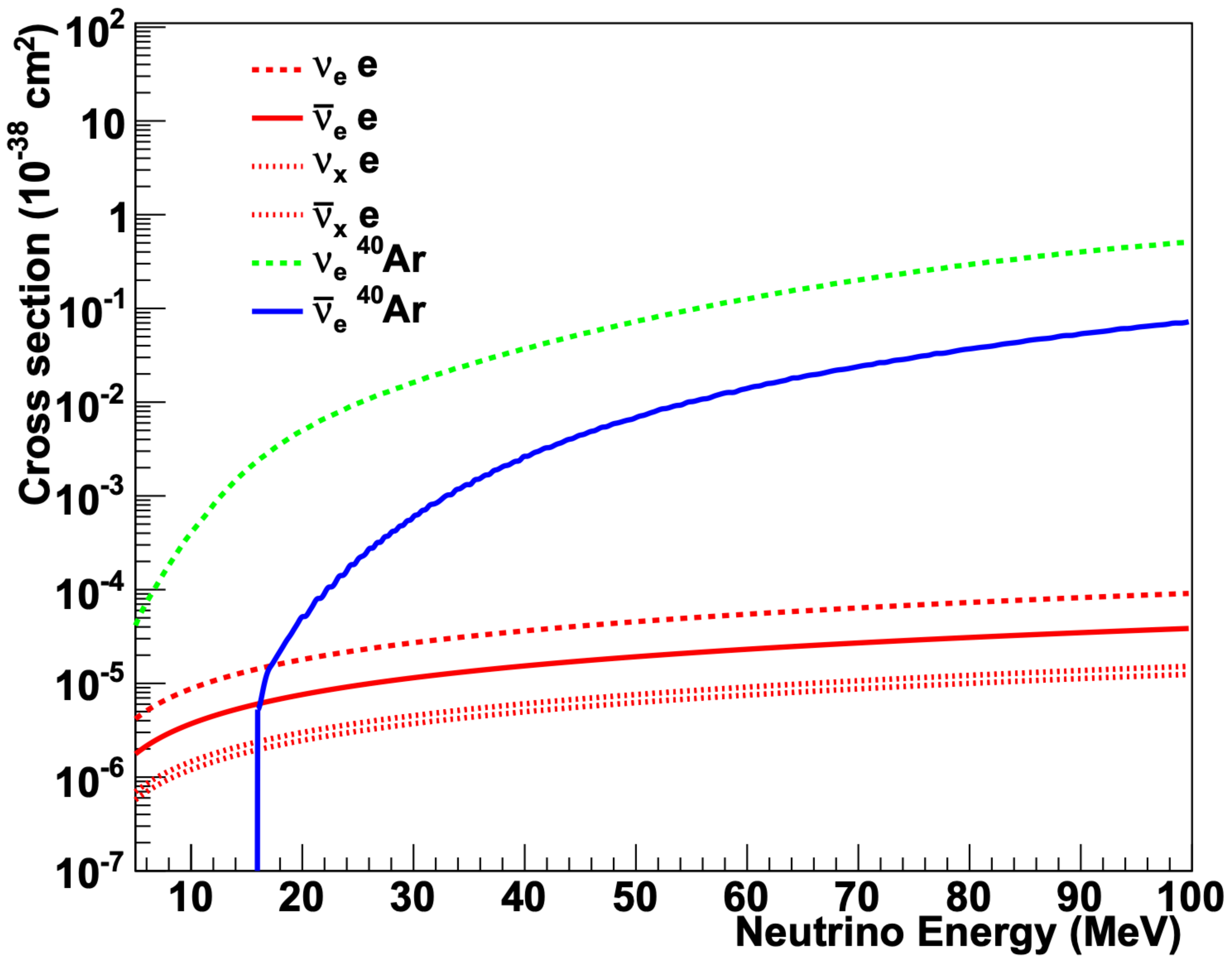
Dominant interaction due to LAr sensitivity to ν_e

- Elastic scattering on electrons (ES)

$$\nu_x + e^- \rightarrow \nu_x + e^-$$

- Neutral current (NC) interactions on Ar

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$



- Further separation possible by K*, Cl*, Ar* de-excitation, ejected nucleons
- Event-by-event categorization by interaction type is also possible for DUNE's sub-cm spatial resolution

arXiv:2008.06647

SN Event simulation and reconstruction in DUNE

SNν events:

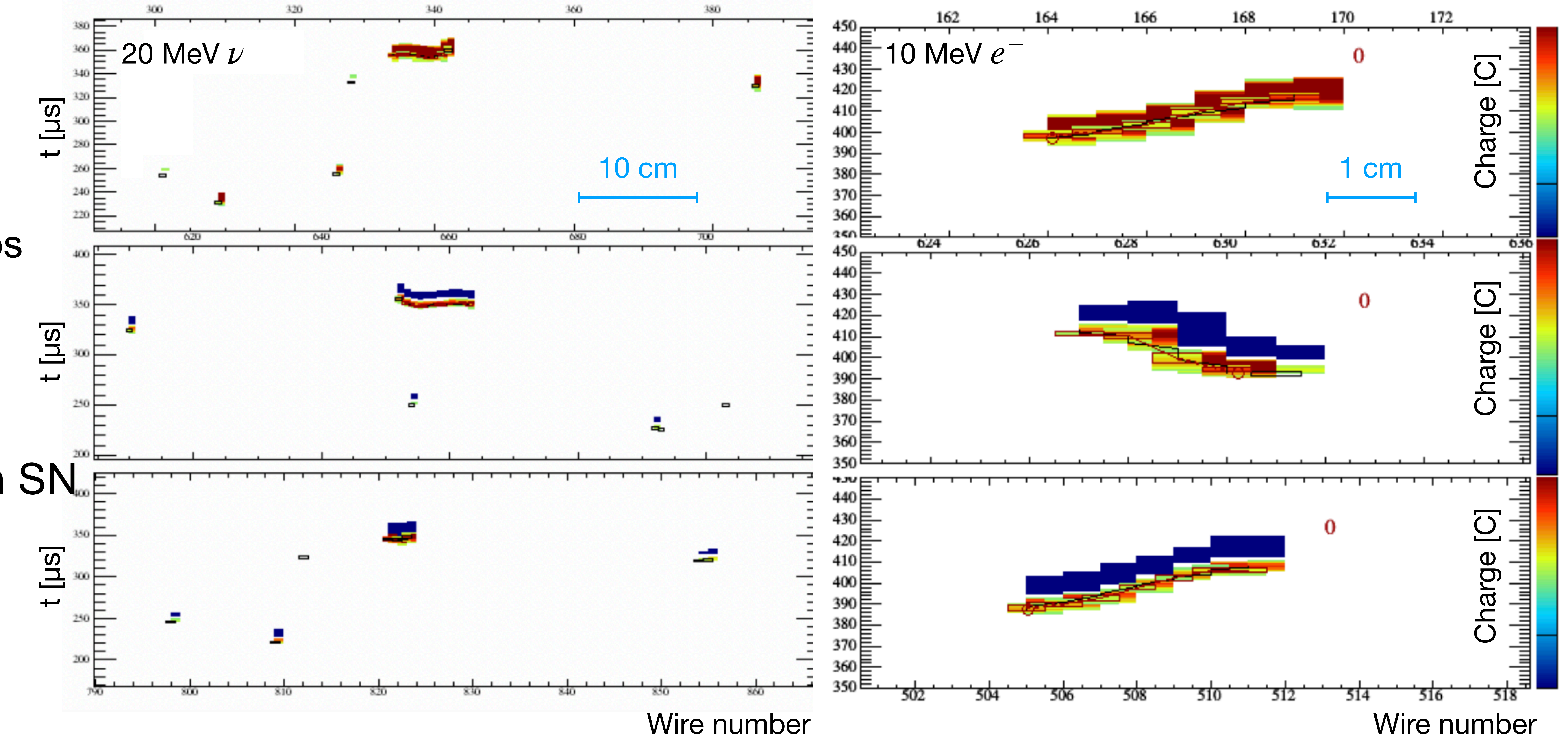
- Low deposited energy
- Small $e^{-/+}$ stub-like tracks

Reconstructed tracks:

- $\nu_e CC$: cloud of de-excitation γ blips
  - γ (Compton, bremsstrahlung)
  - Nucleons (missing reco KE)
    - Inelastic scattering on Ar
- ES: lone e^- pointing away from SN
  - Single scattered e^- tracks
- NC: e^- in de-excitation clouds
  - γ rays (single or cascade)

ν_e CC event $\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$

ν-e ES event $\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$

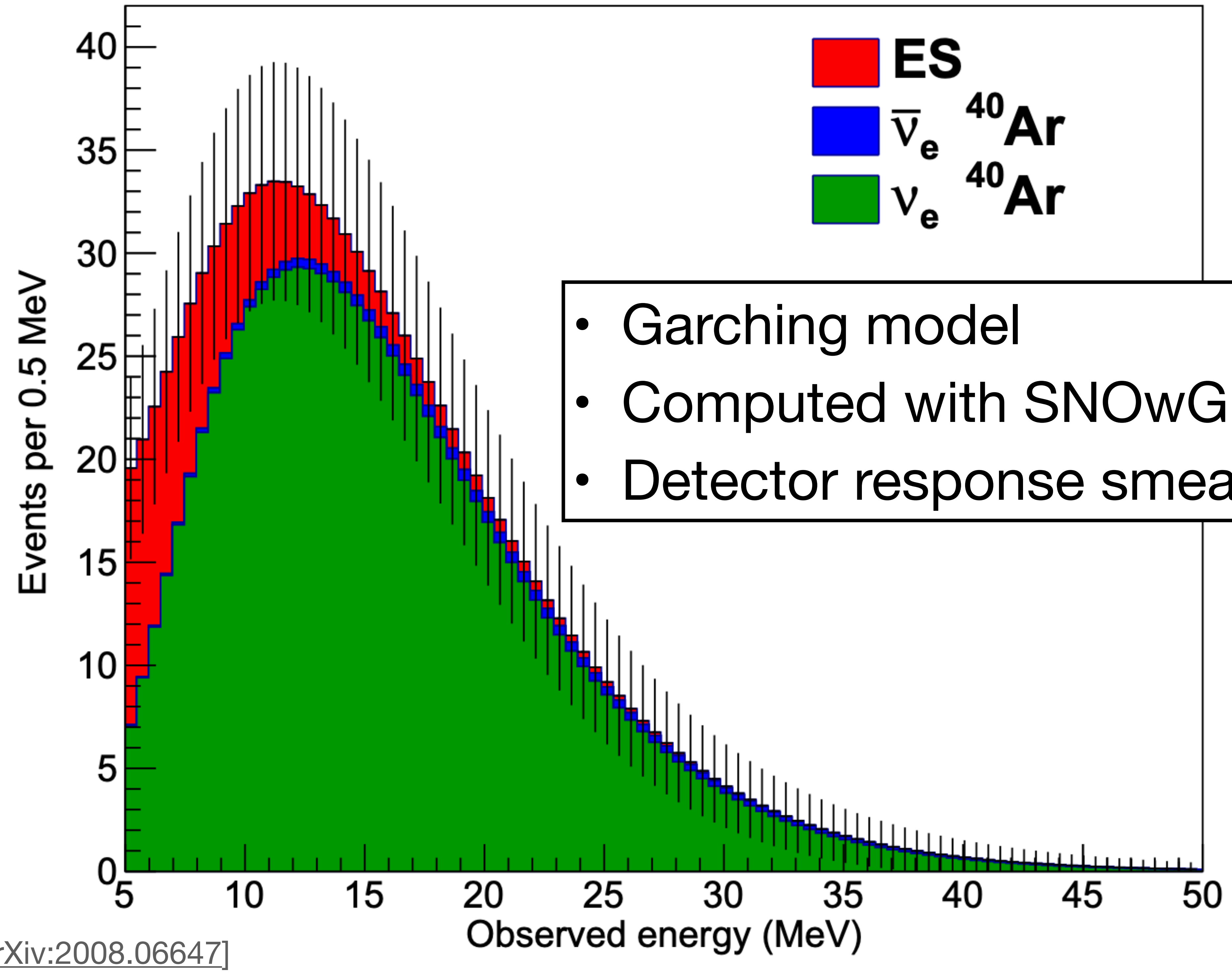


Events simulated using MARLEY, Reconstructed in LArSoft

[DUNE TDR, B. Abi *et al* 2020 *JINST* **15** T08010]

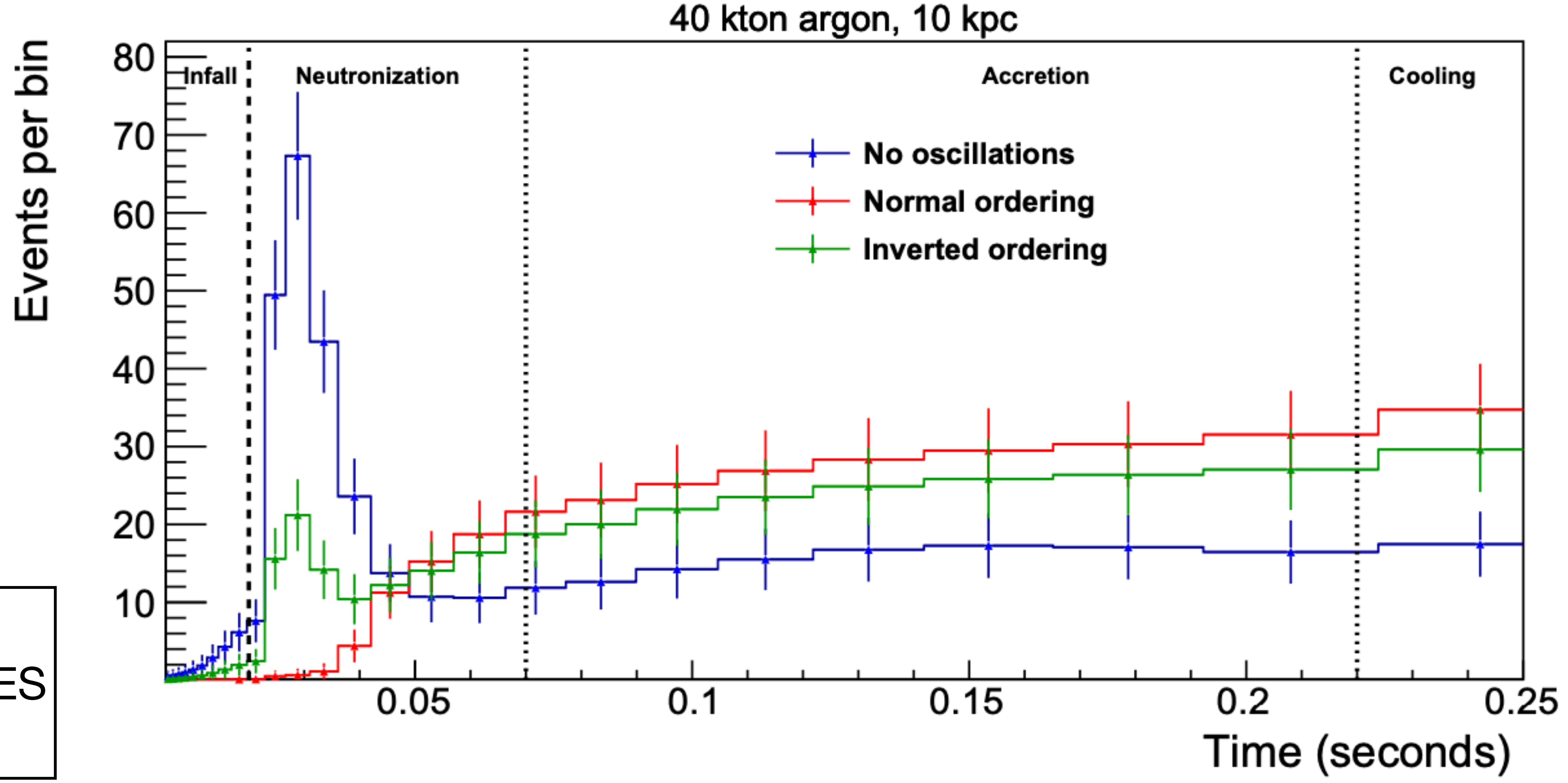
Distributions of expected observed events

- Electron-capture model
- 40 kton of liquid argon
- Statistical error



- Garching model
- Computed with SNOwGLoBES
- Detector response smearing

[arXiv:2008.06647]



- DUNE is most sensitive to $\nu_e CC$ events but will also observe others
- Unique to DUNE - other detectors largely sensitive to $\bar{\nu}_e$
- SN direction can be determined exploiting directionality and Bragg peak at the stopping end of $\nu - e$ ES events (See K. Scholberg's talk)

Number of expected observed events

DUNE has unique sensitivity to low-energy ν_e from a galactic supernova burst

- 100s to 1000s from galactic SNB
- 10s from LMC, O(1) from Andromeda
- Large uncertainty due to SN model
- 5° resolution on the SN direction

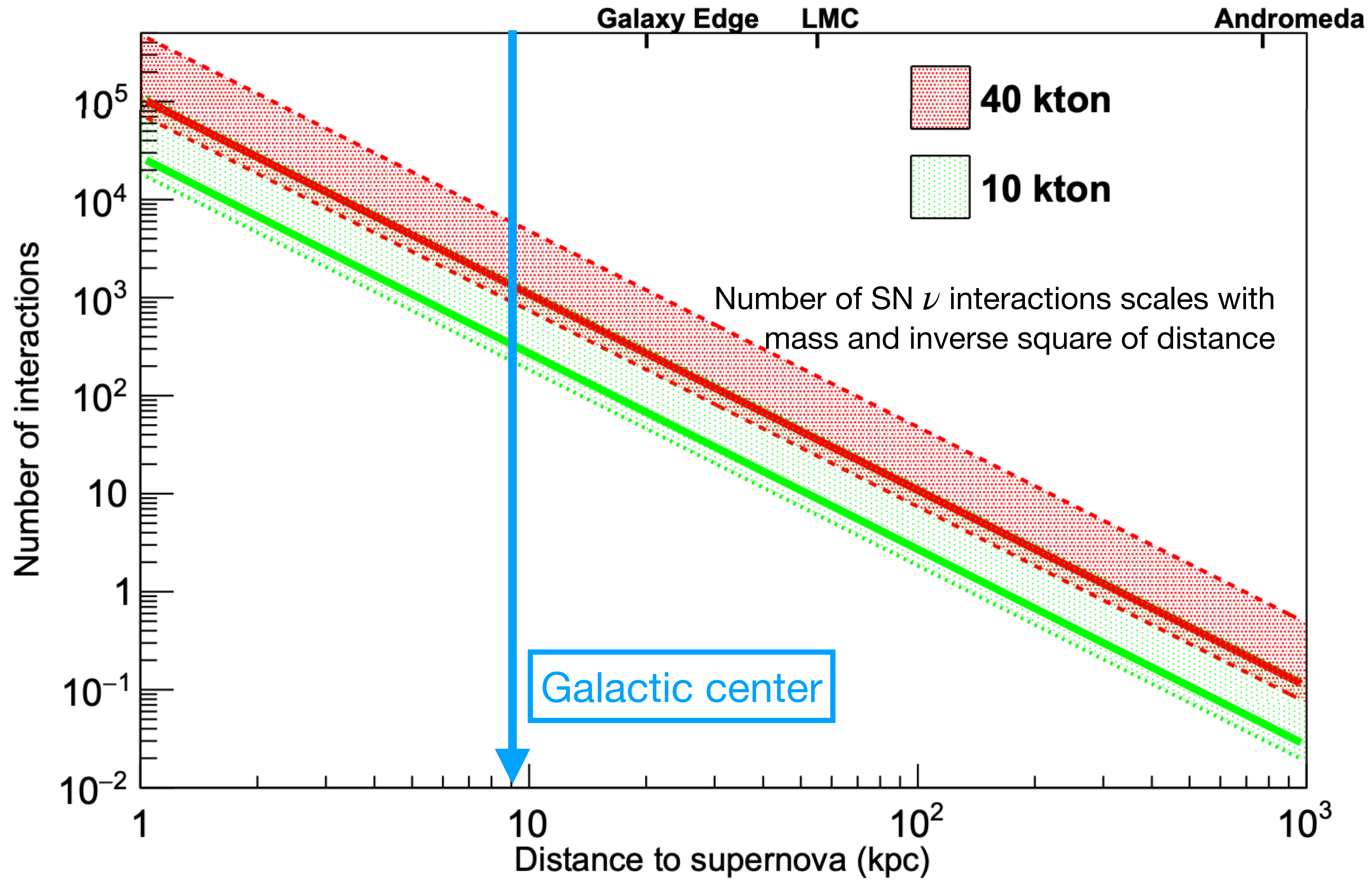
Several unknown:

➡Neutrino mass ordering

➡Collective oscillations from ν-ν scattering

➡Underlying model

➡Physics uncertainties in core collapse



Channel	Liver-more	GKVM	Garching
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2648	3295	882
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

arXiv:2008.06647

Conclusions

- DUNE will measure neutrino oscillations providing insights on matter/antimatter imbalance in the Universe and other open questions in physics
- Unique sensitivity to low-energy ν_e from a galactic supernova burst
- Prototyping efforts underway at CERN with test beam runs planned in 2024
- Excellent performance in ProtoDUNE-SP-I with many exciting physics results coming out
- First DUNE far detector installation in mid-2020s with beginning of science program in late 2020s

Thank you for your attention