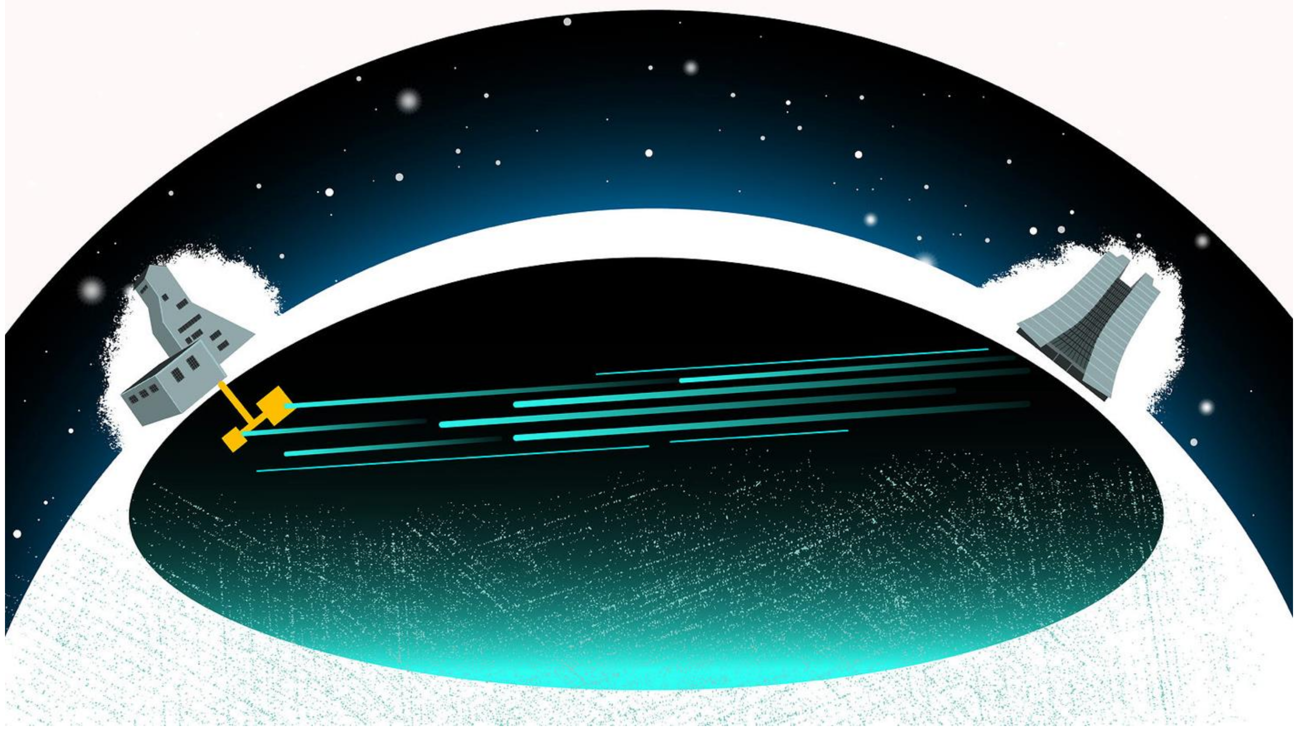
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Inés Gil-Botella

CIEMAT

Fermilab Italian 2024 Summer Students School

22 July 2024

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

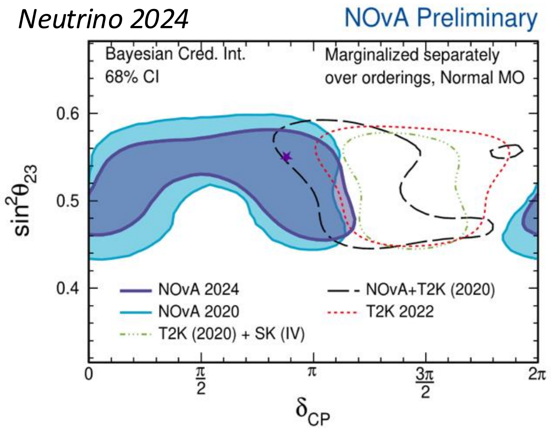
Outline

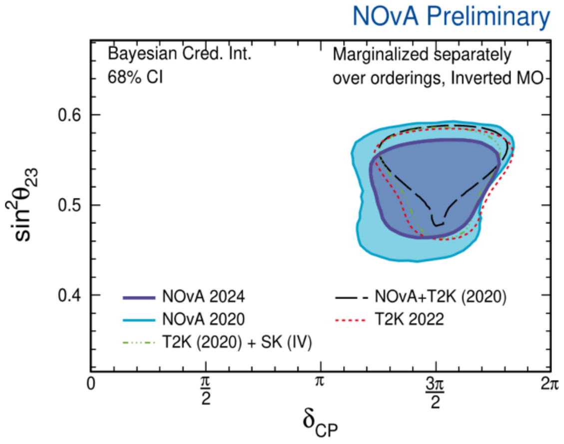
- Neutrino oscillations in long-baseline neutrino experiments
- **DUNE project**
  - Physics program
  - Long-Baseline Neutrino Facility (LBNF)
- **DUNE Detectors**
  - LArTPC Far Detector technologies
  - Near Detectors
- **DUNE Prototypes**
  - ProtoDUNEs at CERN
  - ND demonstrator at Fermilab
- Conclusions

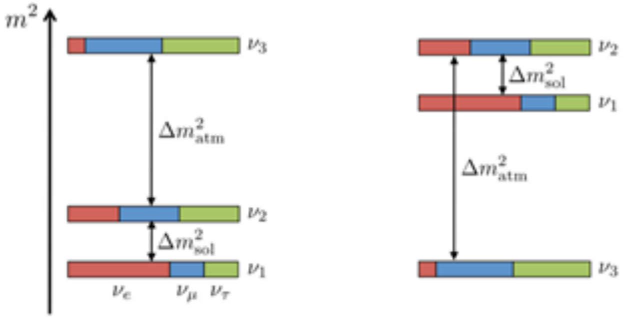
Discovery opportunities in LBL experiments

- **CP violation**
  - Discrepancies between T2K and NOvA in CPV preferred regions for normal ordering
  - To reach discovery and precise measurement, **larger detectors** and (upgraded or new) **beams** are needed
- **Neutrino mass ordering**
  - Slight preference for normal ordering
- **Octant of θ_{23}**
  - Maximal? $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?
- **Neutrino anomalies:** sterile neutrinos?
- **Supernova neutrino burst and solar neutrino detection**
- **Beyond the Standard Model searches:** nucleon-decay, testing the 3-neutrino flavor paradigm, dark matter, etc.

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\text{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\text{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

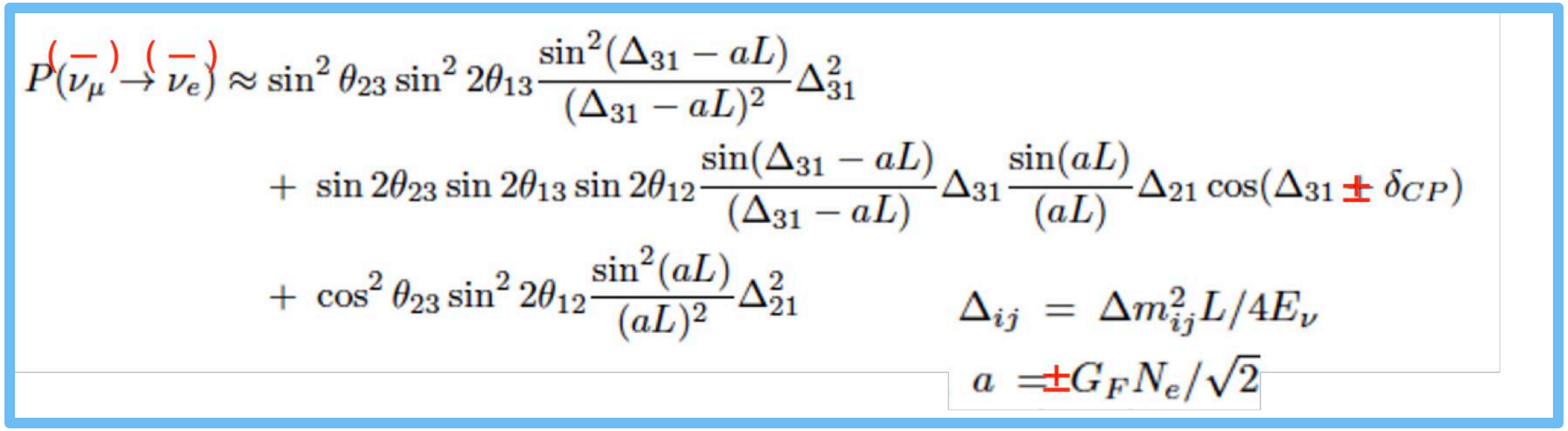






Long-baseline neutrino oscillations

- Neutrino oscillation probability in matter



$$
\begin{aligned}
P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx\ & \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 \\
& + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP}) \\
& + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2
\end{aligned}
$$

$$\Delta_{ij} = \Delta m^2_{ij} L/4E_\nu$$

$$a = \pm G_F N_e/\sqrt{2}$$

  - Depends on δ_{CP}, θ_{13}, θ_{23}, Δm^2_{32} in a complicated way
- If the mass ordering is normal (inverted), ν_e appearance is enhanced (suppressed)
- If δ_{CP} is $-\pi/2$ ($+\pi/2$), ν_e appearance is enhanced (suppressed)
- For antineutrinos, the mass ordering and δ_{CP} effects both go in the opposite direction
- To access all of these parameters, we need to measure these probabilities precisely as a function of neutrino energy

Long-baseline neutrino experiments

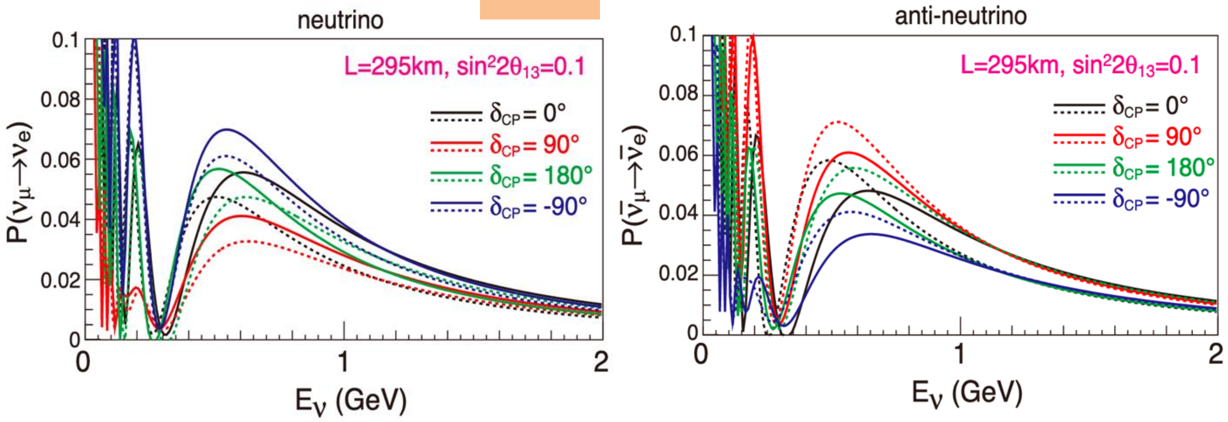
- **T2HK (Tokai to HyperK) approach (L=295km)**: Minimize matter effects and maximize statistics to focus on CPV discovery (MO and other parameters must be known by other means)

Narrow-band beam (~0.6 GeV; 500 kW → 1.3 MW) and Water-Cerenkov detector (180 kt fiducial)

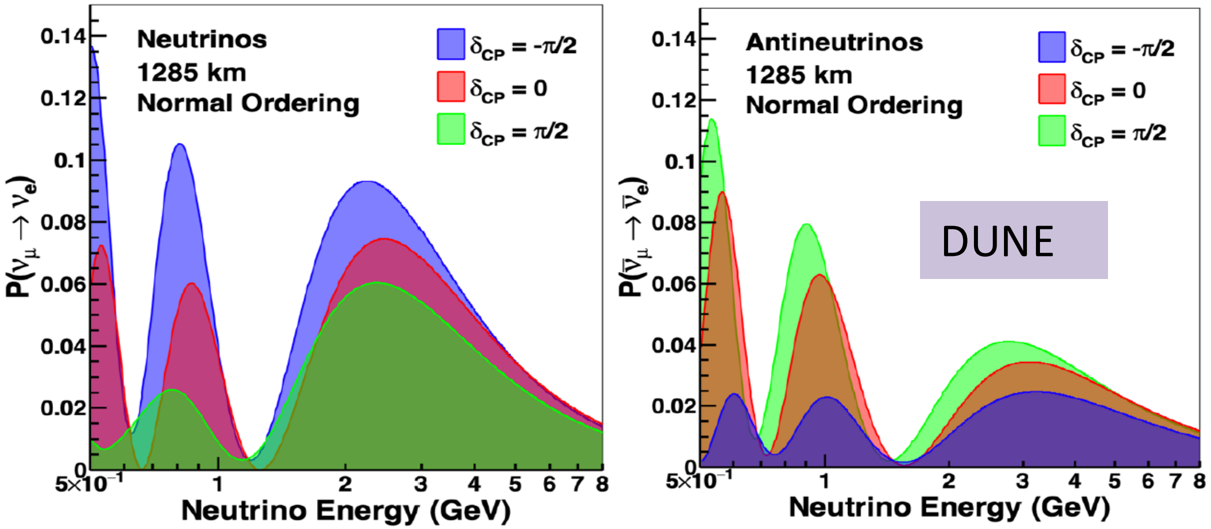
- **DUNE (FNAL to SURF) approach (L=1285km)**: measure first and second oscillation maxima to disentangle CPV and matter effects and access to all neutrino oscillation parameters

Wide-band beam (0.5-5 GeV; 1.2 → >2 MW) and liquid Argon TPC (>40 kt fiducial)

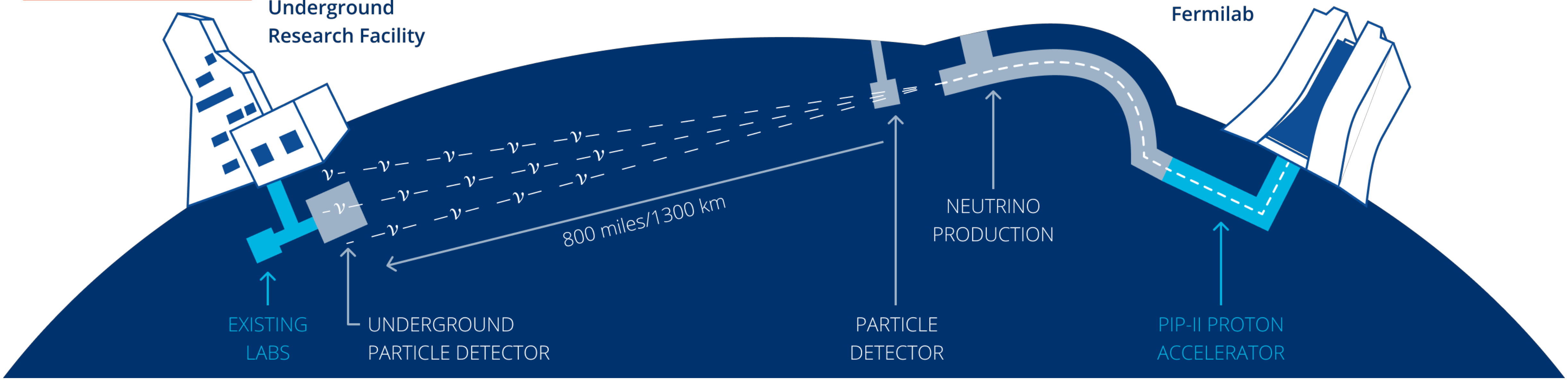
HK



DUNE



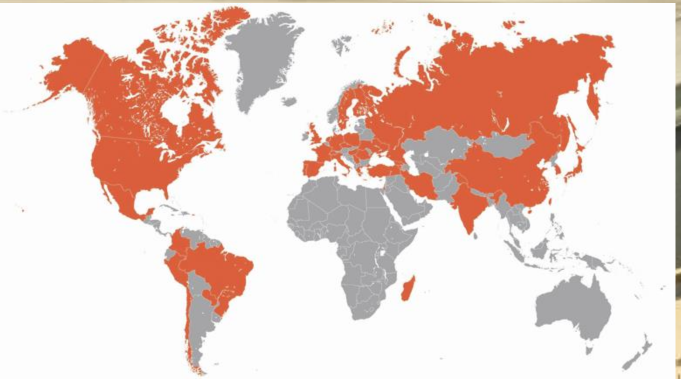
DUNE TDR (Volumes: JINST 15 (2020) 08, T08008, T08009, T08010, Vol II arxiv:2002.03005, 2312.03130)
ND CDR (arXiv:2103.13910)



- The most powerful **neutrino beam** in the world (>2 MW) will be sent from **Fermilab** (Chicago) to **SURF** (South Dakota) along **1300 km** distance to be detected by four liquid argon far modules (**70 kton LAr**) at 1.5 km deep underground and a **near detector complex** at 560 m from the neutrino source
    - The **long baseline** enables an unambiguous measurement of the neutrino **mass ordering**
    - The **wide-band** energy spectrum of neutrinos enables detailed fitting of the **oscillation** parameters
    - **LAr technology** enables precise **reconstruction** of the neutrino interactions
    - The FD **underground location** enables **astrophysical** measurements
    - The **ND** complex enables unprecedented control of **systematic** uncertainties

DUNE collaboration

- International collaboration
  - Over 1400 collaborators, over 240 institutions
  - 38 countries + CERN
- Huge endeavor!

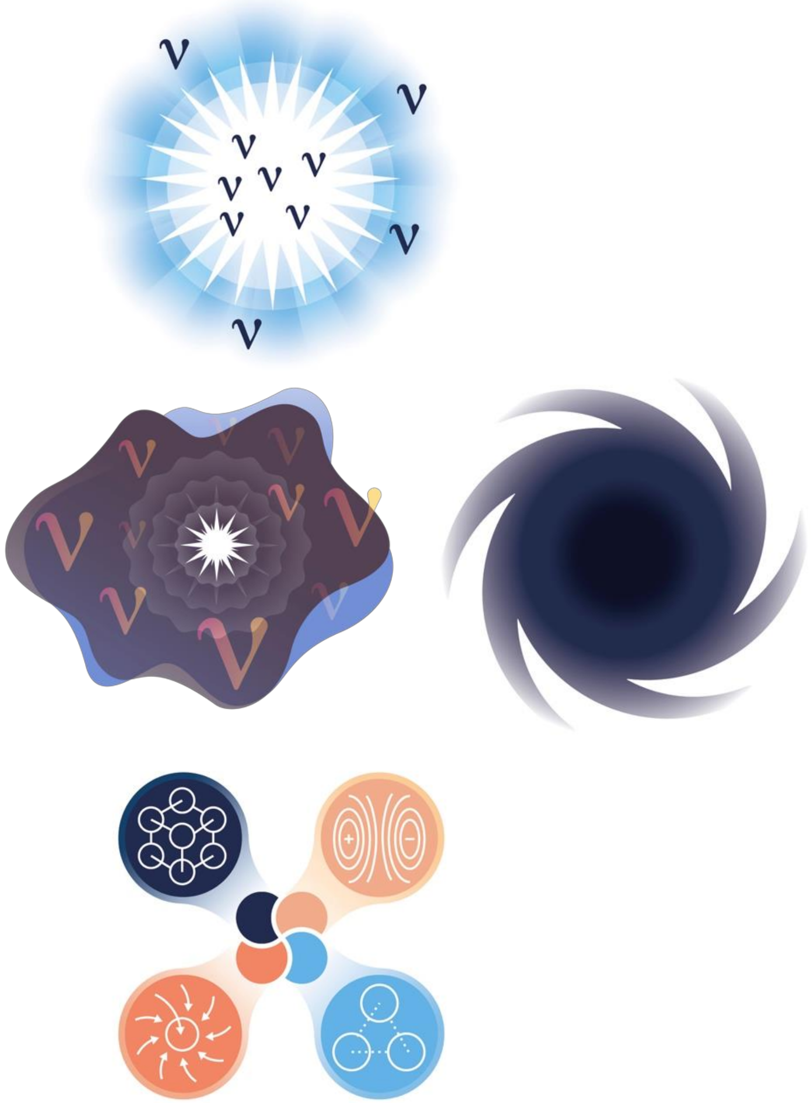


DUNE physics program

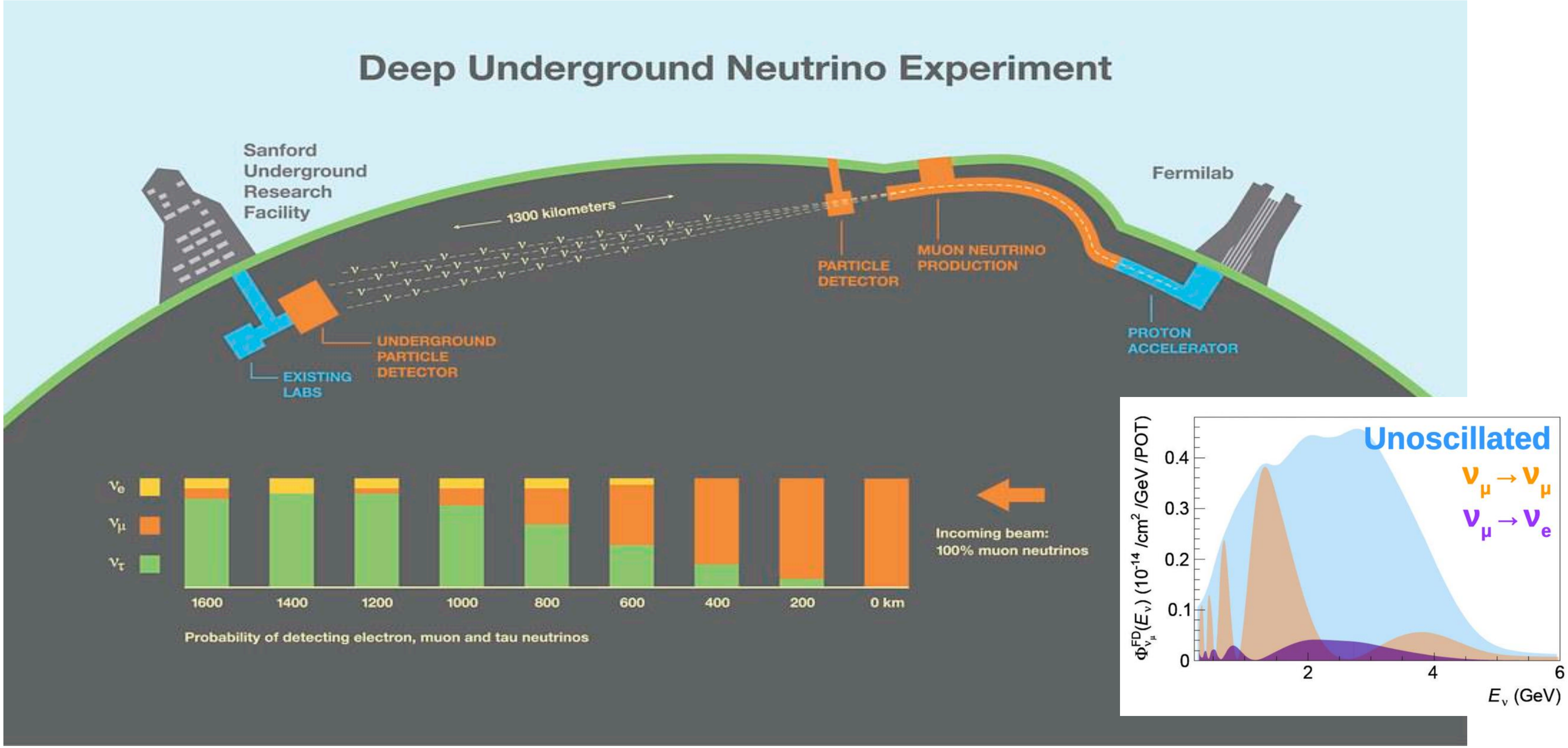
- Unambiguous, high precision measurement of **neutrino oscillations** (mass ordering, differences between neutrinos and antineutrinos - CP violation…) **in a single experiment**

- Detection of low-energy neutrinos: **supernova neutrinos, solar neutrinos**

- **Beyond the Standard Model** searches (proton decay, sterile neutrinos, non-standard interactions, dark matter…)

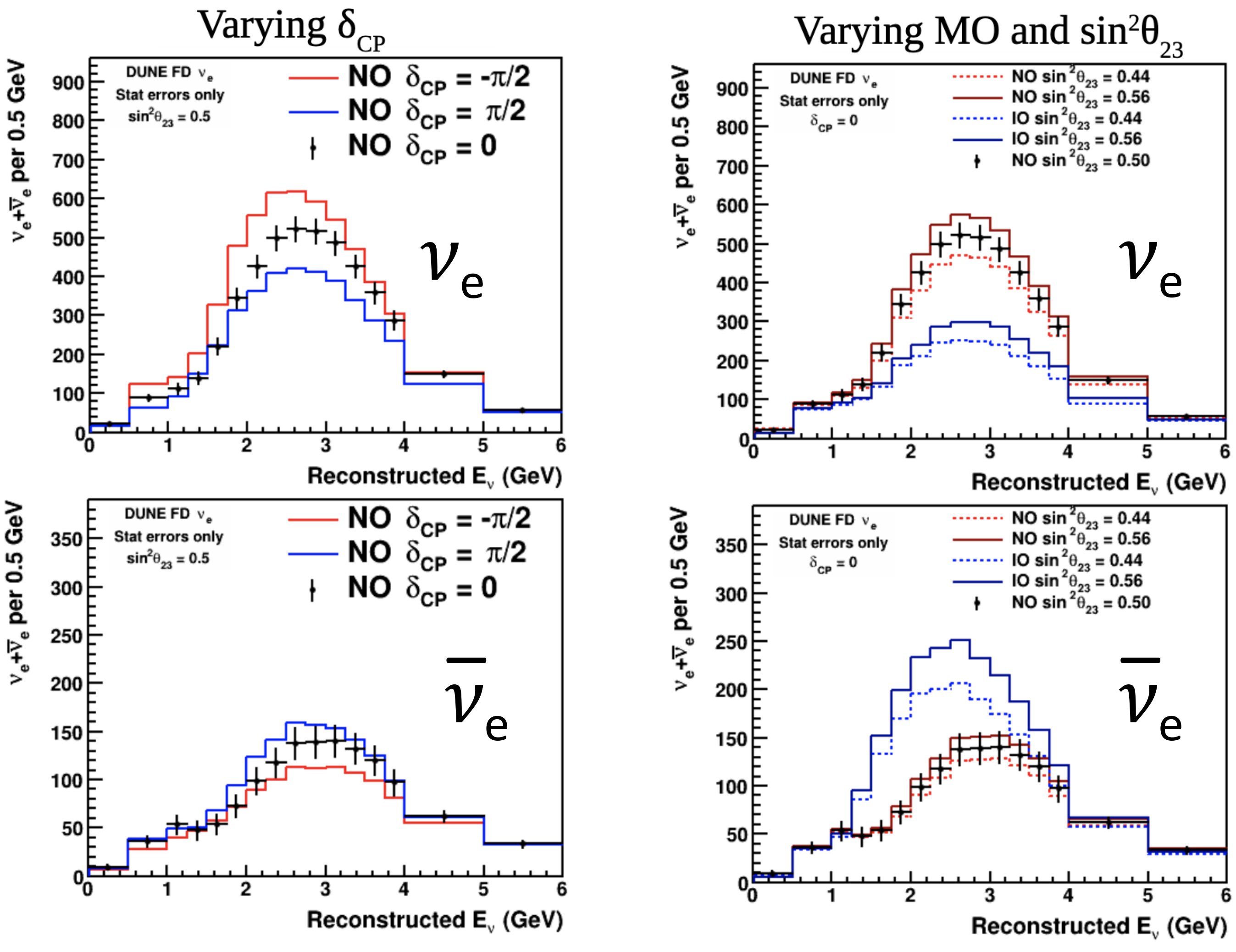


DUNE neutrino oscillations



Neutrino energy spectra at the Far Detector

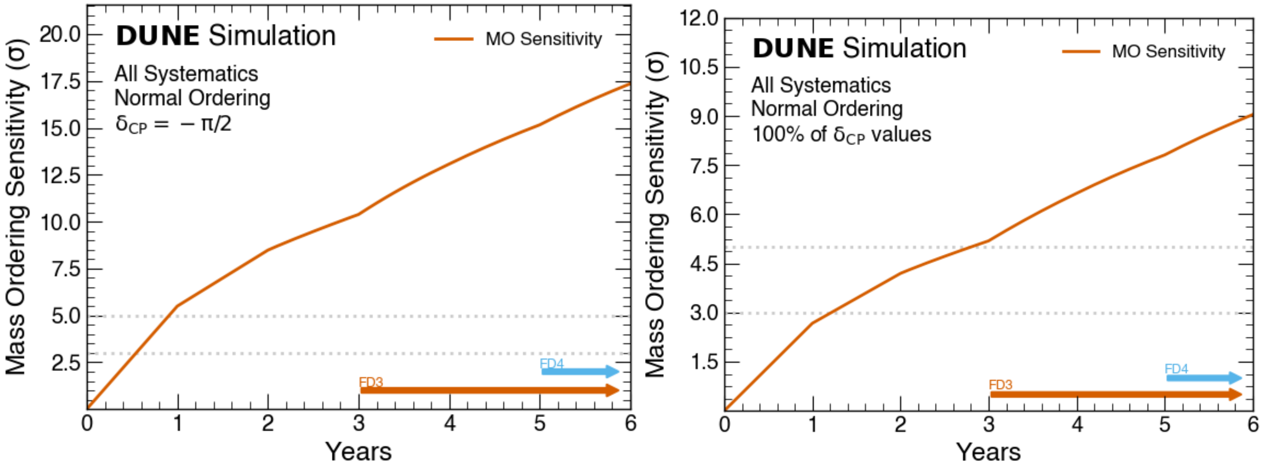
- Sensitivity to $\boldsymbol{\delta_{CP}}$
  - If $\delta_{CP} \sim -\pi/2$, DUNE will measure an enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- Sensitivity to mass ordering (**MO**)
  - If MO is normal, DUNE will measure a much larger enhancement in electron neutrino appearance, and a reduction in electron antineutrino appearance
- MO, δ_{CP}, and θ_{23} all affect spectra with different shape → additional handle on resolving degeneracies



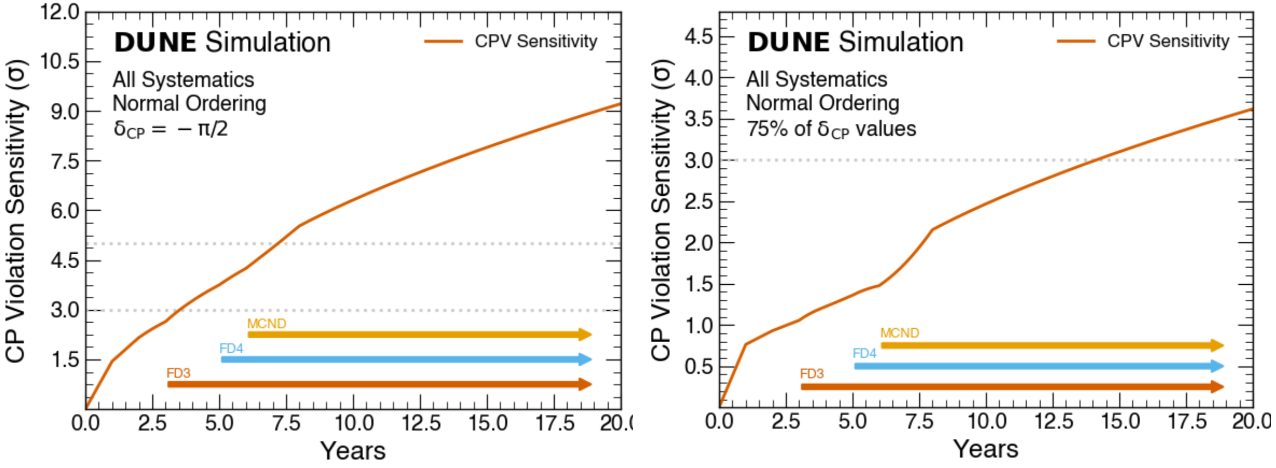
DUNE sensitivity

Neutrino mass ordering

Eur. Phys. J. C 80, 978 (2020)



CP violation sensitivity



- For best-case oscillation scenarios, DUNE has

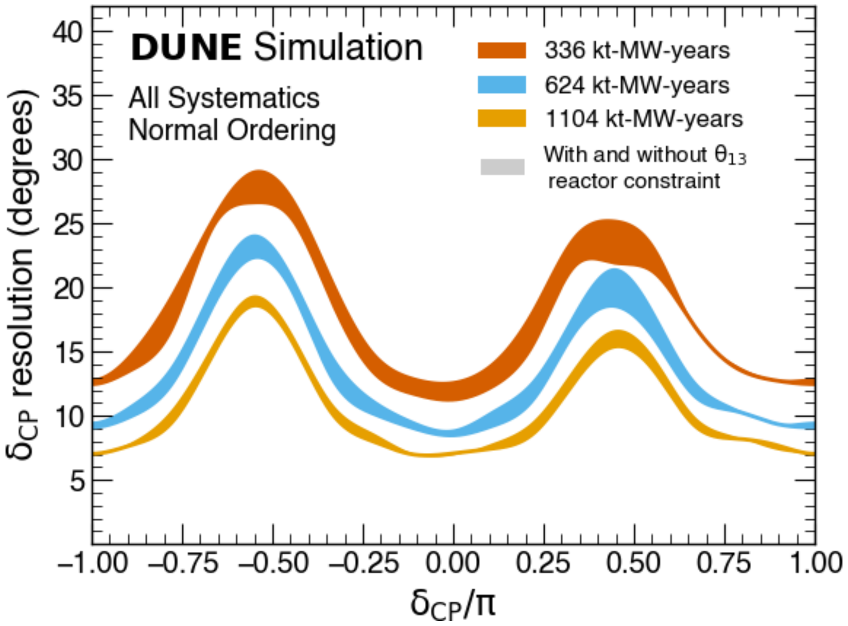
  >5σ mass ordering sensitivity in 1 year
  >3σ CPV sensitivity in 3.5 years

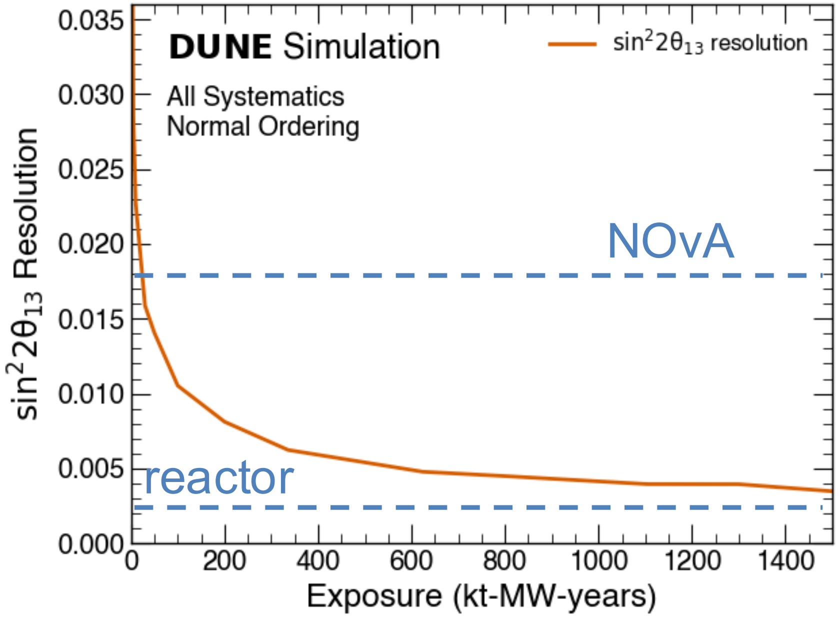
- For worst-case oscillation scenarios, DUNE has >5σ mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ

DUNE precise measurements

- Ultimate precision 6-16° in $\boldsymbol{\delta_{CP}}$
- World-leading precision (for long-baseline experiment) in $\boldsymbol{\theta_{13}}$ → comparisons with reactor measurements are sensitive to new physics

δ_{CP}



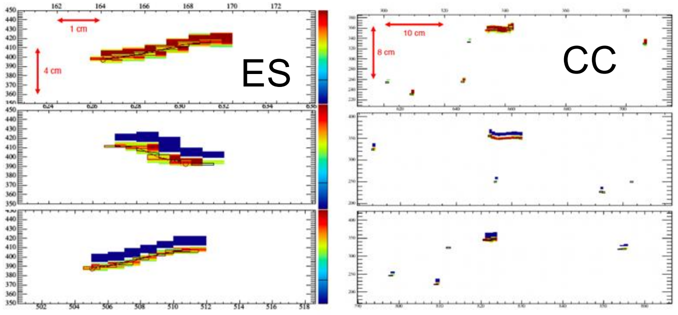


θ_{13}

Astrophysical neutrinos in DUNE

Unique sensitivity to MeV electron neutrinos: CC $\nu_e + \mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$ *(main channel)*

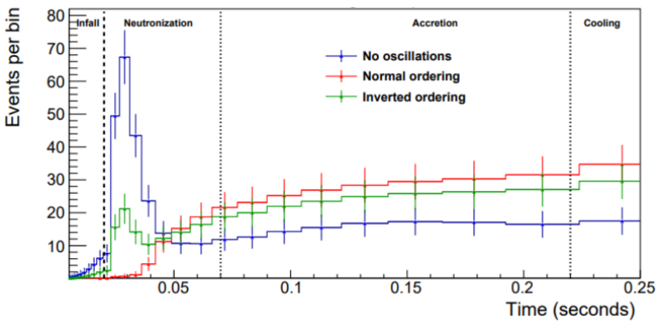
ES $\nu_x + e^- \rightarrow \nu_x + e^-$ *(pointing)*



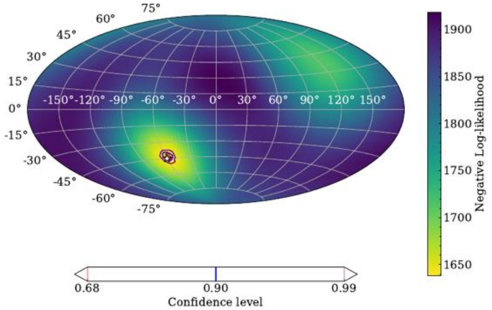
Neutrinos from core-collapse supernovae

- **Neutronization** burst measurements → mass ordering measurement

Eur. Phys. J. C 81 (2021) 5, 423
Phys.Rev.D 107 (2023) 11, 112012



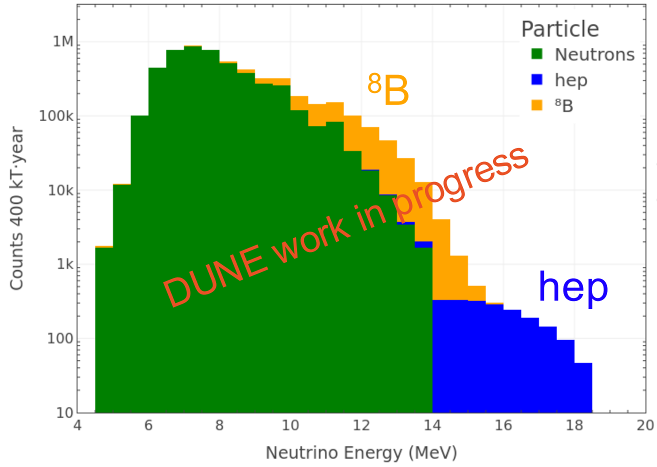
- **Pointing** capabilities: ES channel ~5° pointing resolution



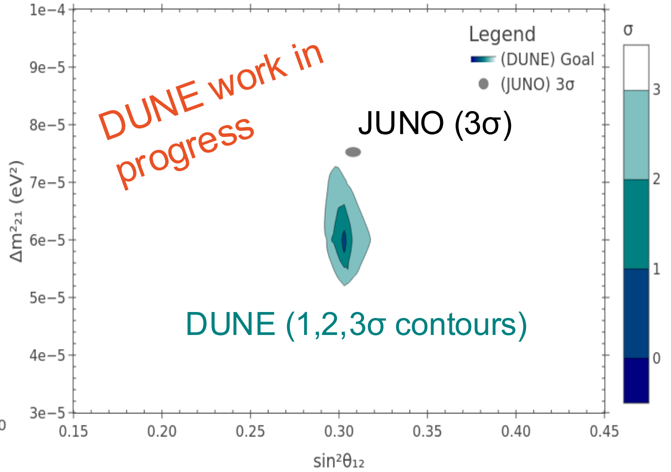
Neutrinos from the Sun

- DUNE has excellent sensitivity to **^{8}B solar neutrinos** above ~10 MeV, and discovery sensitivity to the **hep solar flux**
- DUNE can improve upon existing solar oscillation measurements via **day-night asymmetry** induced by matter effects → comparison with JUNO

Reco solar ν_e spectrum in DUNE



DUNE goal contours for solar best-fit

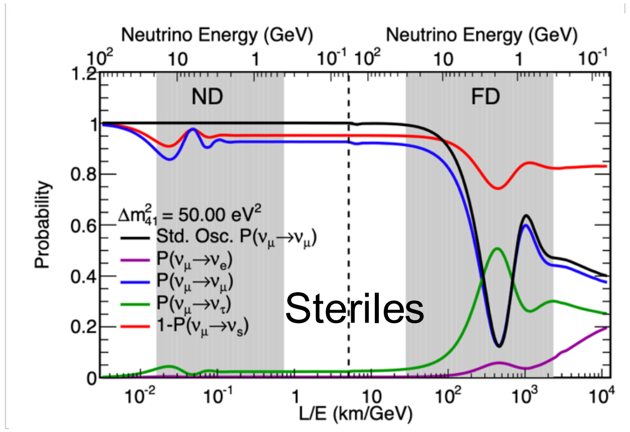


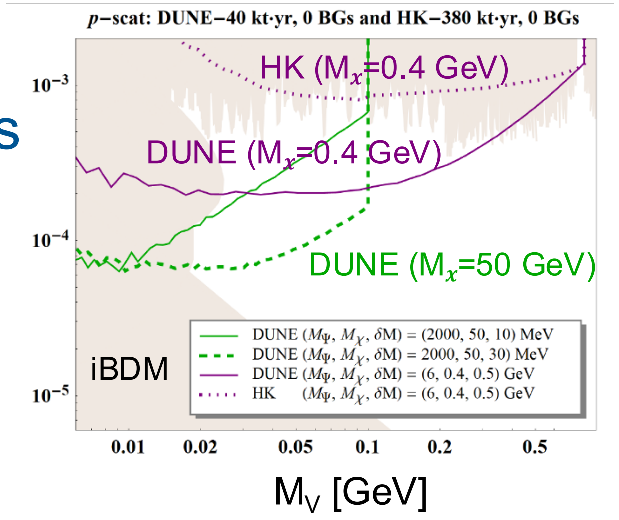
DUNE Beyond of Standard Model searches

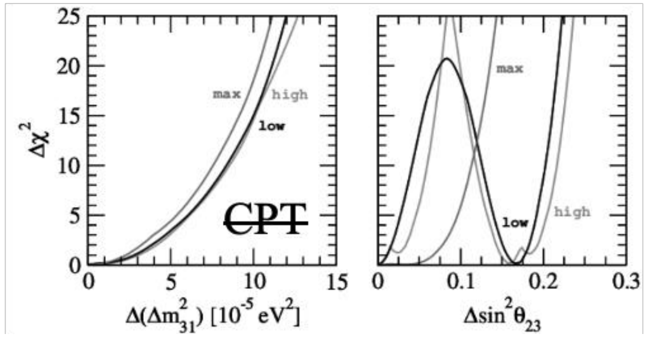
- **New physics in neutrino oscillations**: If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrino mixing, CPT violation, Non Standard Interactions (NSI)…
  - DUNE covers a very broad range of L/E at both the ND and FD
  - High statistics in ν & $\bar{\nu}$ measurements → search for CPT violation
  - DUNE has unique sensitivity to NSI matter effects due to long baseline

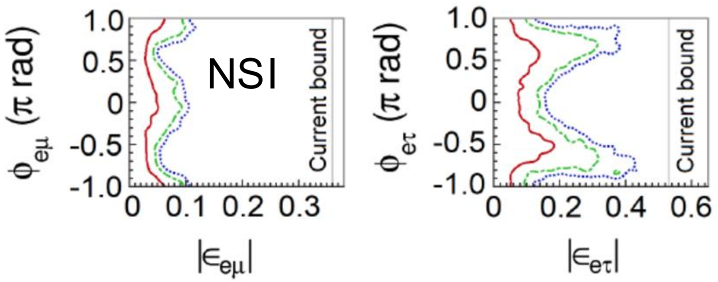
- Other **BSM** in Far and Near Detectors
  - Dark matter at FD & ND, nucleon decay, n-$\bar{\text{n}}$ oscillations, heavy-neutral leptons, neutrino tridents, ...

Eur. Phys. J. C (2021) 81:322

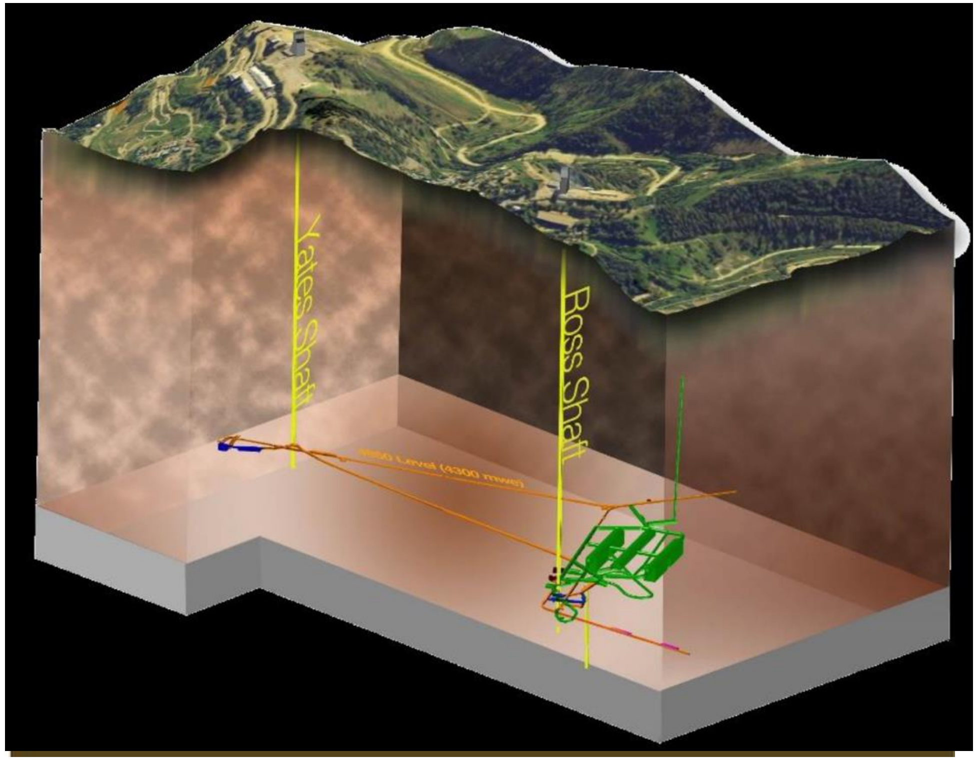






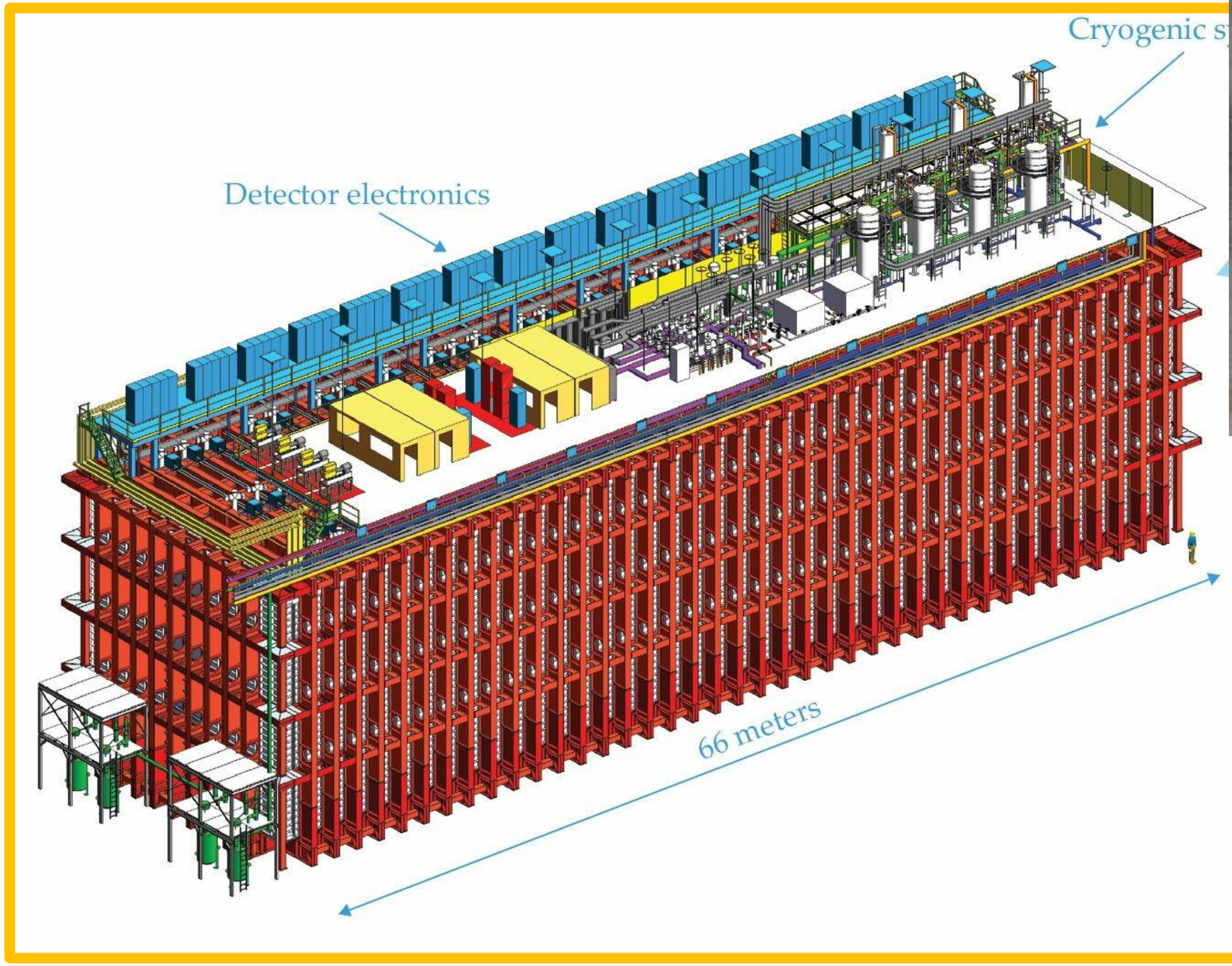


LBNF Far Site at SURF (South Dakota)




SURF caverns completed in February 2024

LBNF Far Site at SURF (South Dakota)

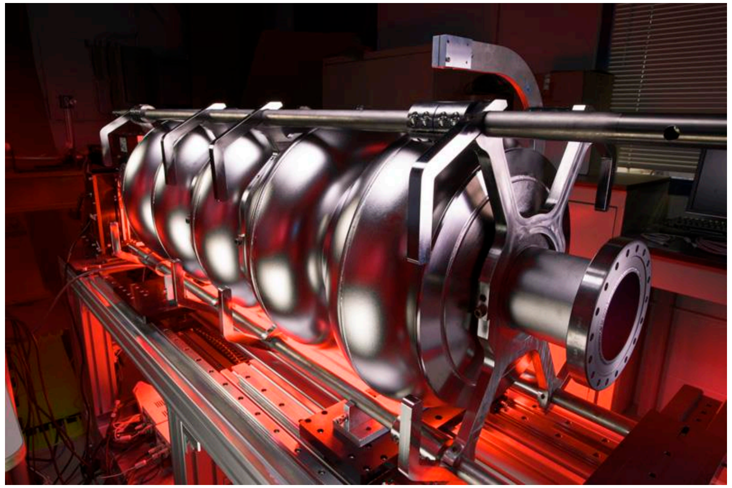



Transport to A Coruña harbour: April

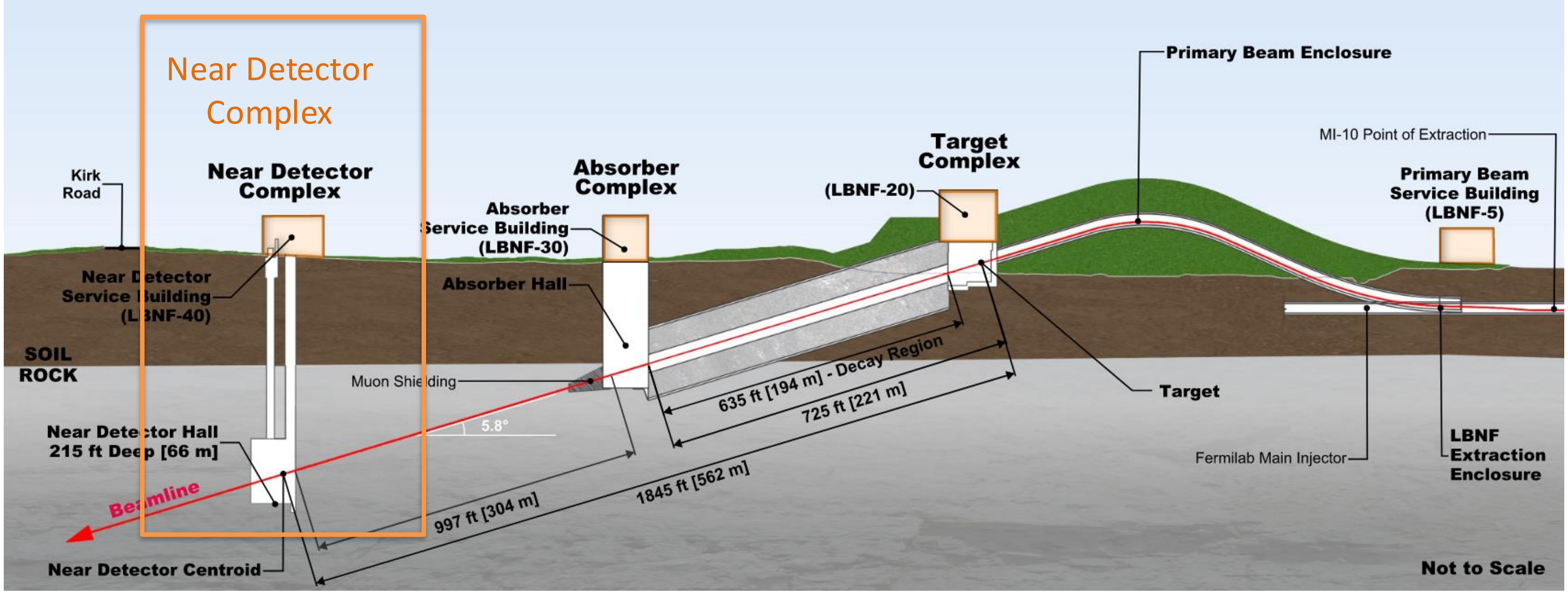

Loaded on vessel ~mid May

LBNF at Fermilab

PIP-II construction



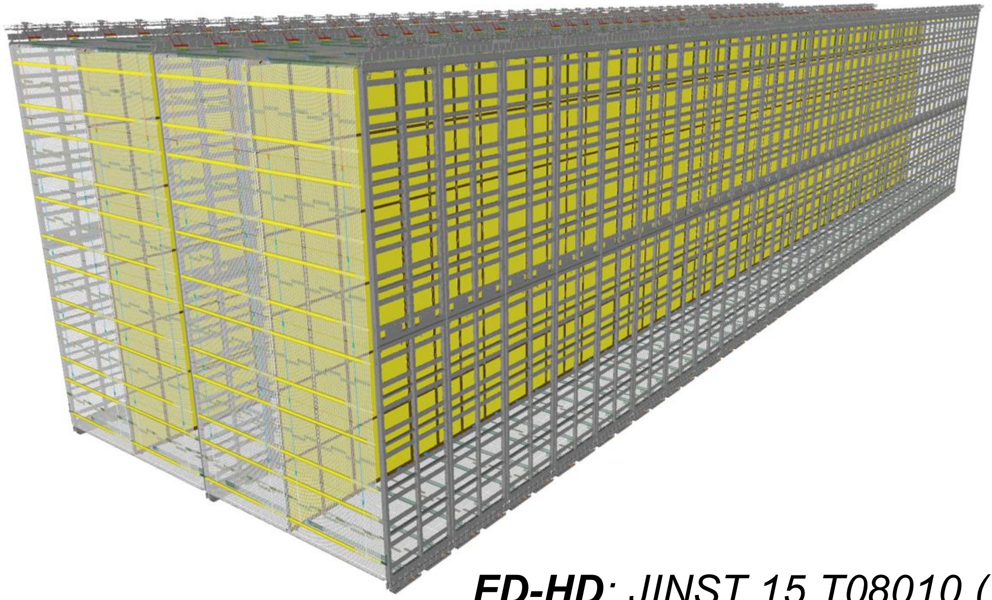
LBNF Near Detector Complex



- **Where?** ND hall is located 560 m from proton target, 65 m deep, on-site at Fermilab
- **Why?** Purpose of the ND is to measure the rate & spectrum of neutrinos before they make their journey west and to the FD. The ND measures the neutrinos before oscillations.

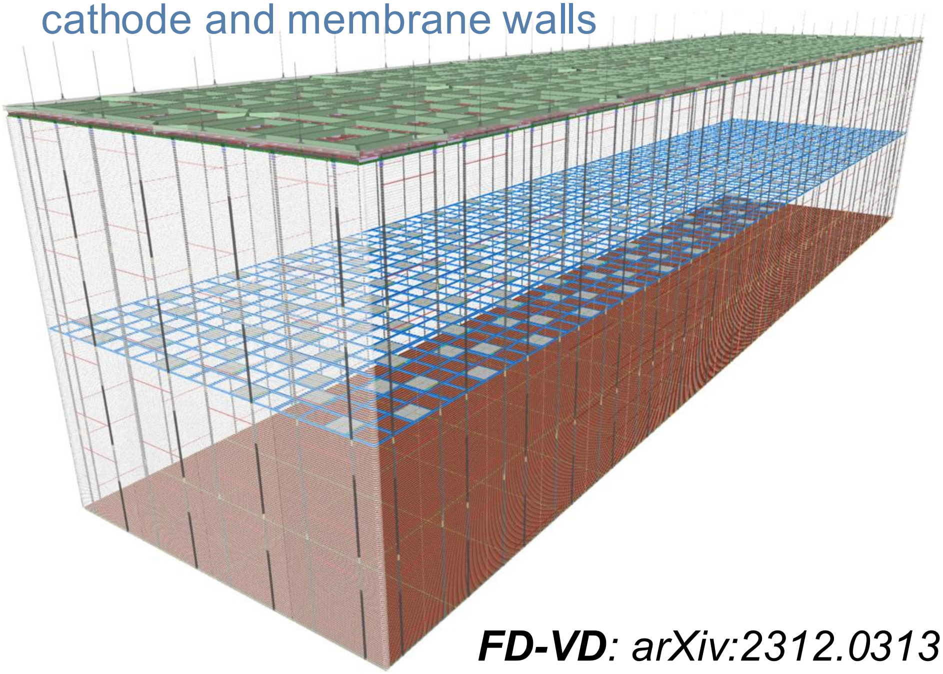
DUNE Far Detectors - Two Technologies

- **FD-HD: Horizontal Drift**
  - 3.6 m horizontal drift
  - Vertical anode wire planes
  - Vertical resistive cathode
  - Photon detectors (X-ARAPUCA light traps) inserted behind the wire planes



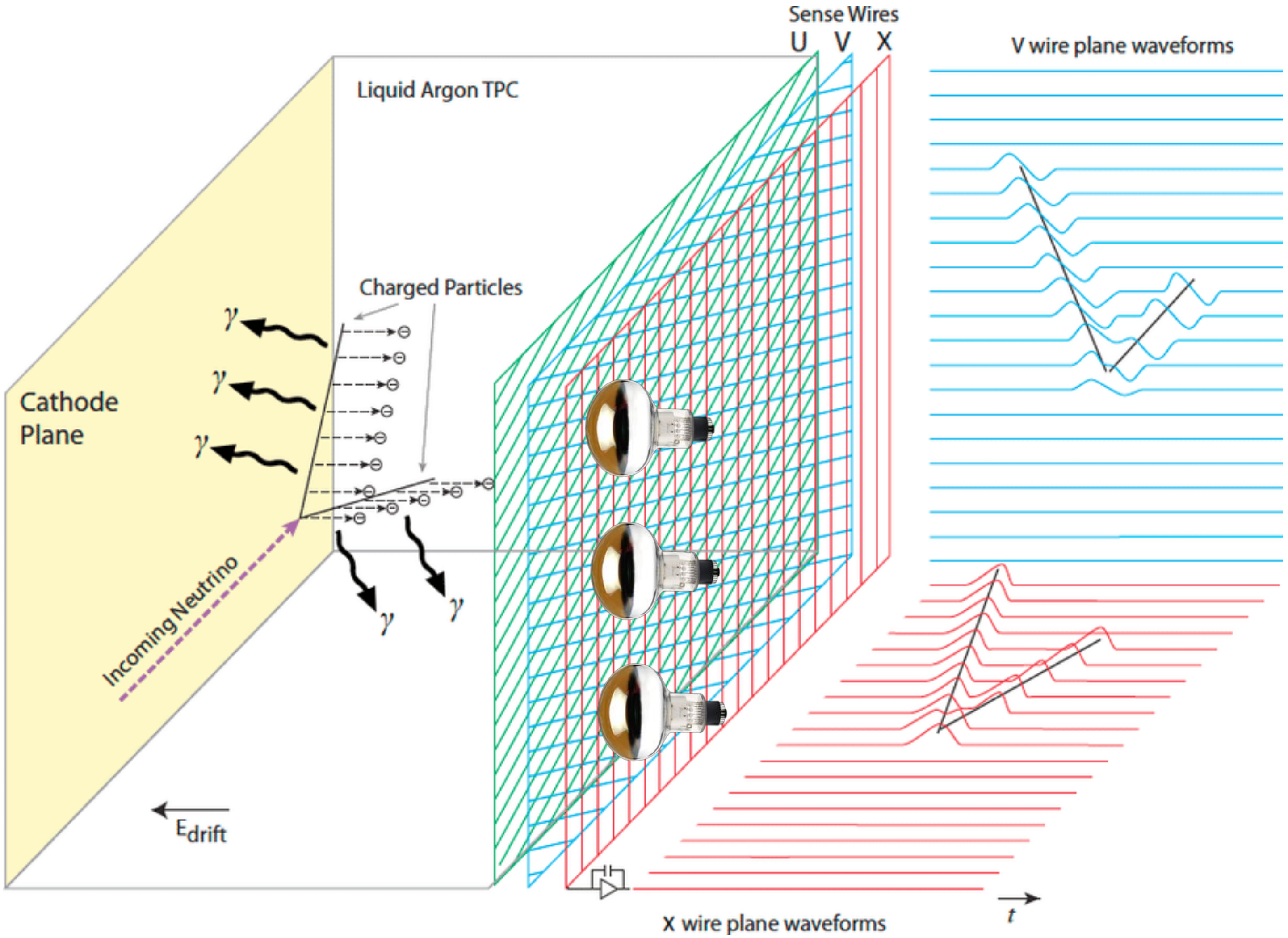
***FD-HD**: JINST 15 T08010 (2020)*

- **FD-VD: Vertical Drift**
  - 6.5 m vertical drift
  - Horizontal PCB anode readout
  - Horizontal grid cathode
  - Photon detectors (X-ARAPUCA light traps) on cathode and membrane walls



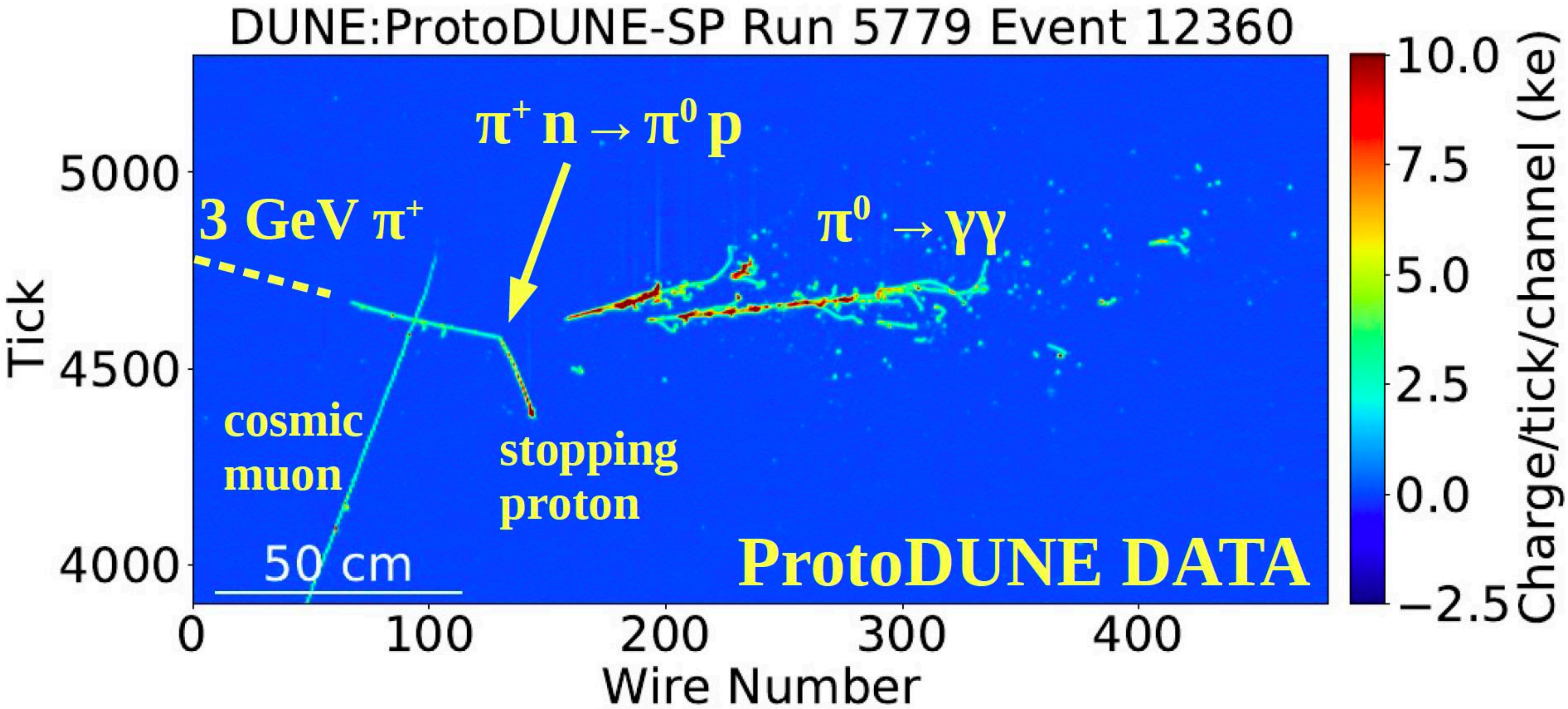
***FD-VD**: arXiv:2312.03130 (2023)*

DUNE FD: LAr TPCs

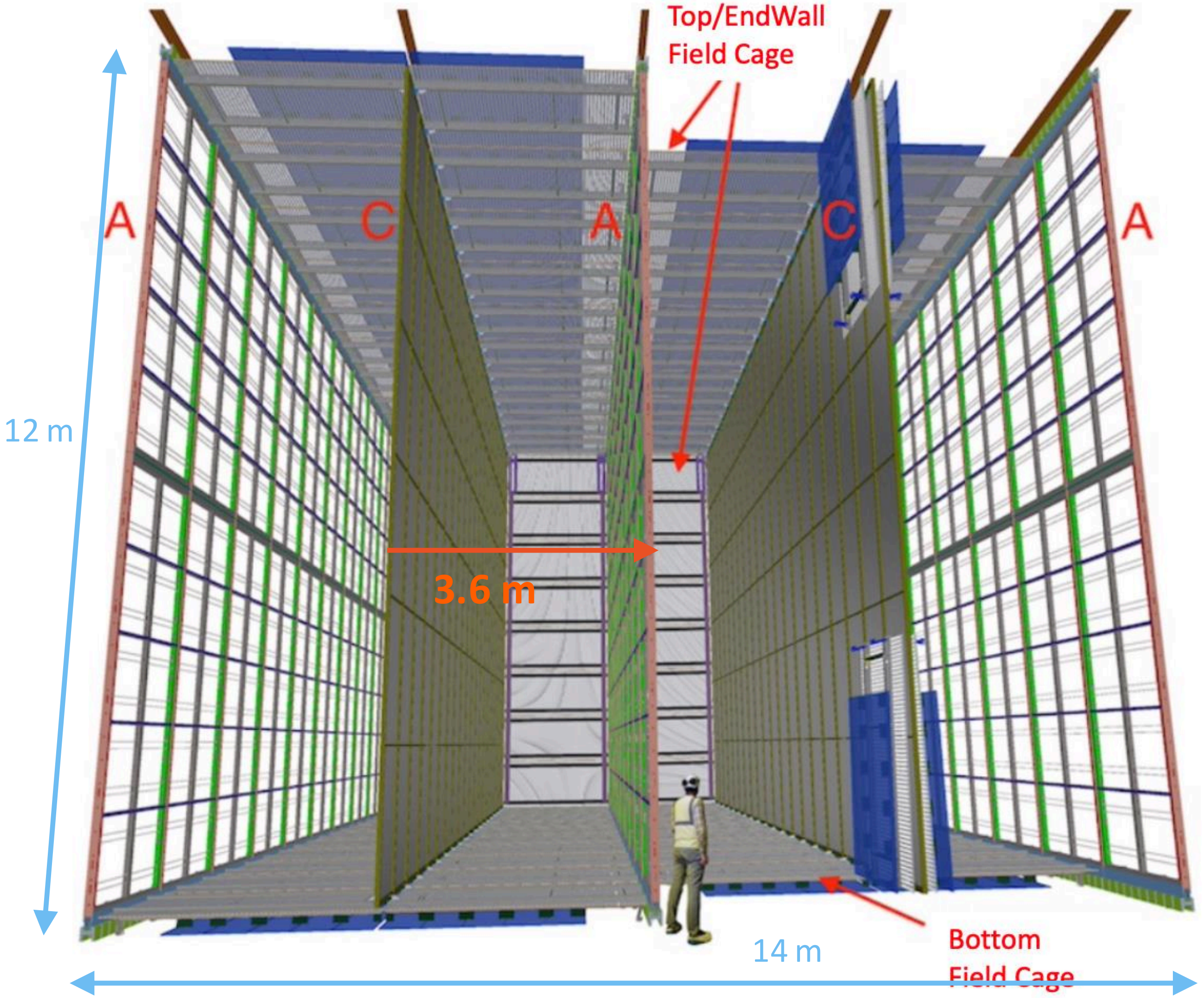


- A charge particle interacting in LAr creates:
  - **Ionization electrons** (~42k ion-electron pairs/MeV) drifted to the anode readout thanks to an electric field and then collected and readout by wires/pixels
  - Fast **scintillation signals** (~40k γ/MeV) collected by photodetectors
- 3D reconstruction of interactions
- Challenges:
  - Cryogenic infrastructure
  - LAr purity
  - Uniform HV drift field over long distances

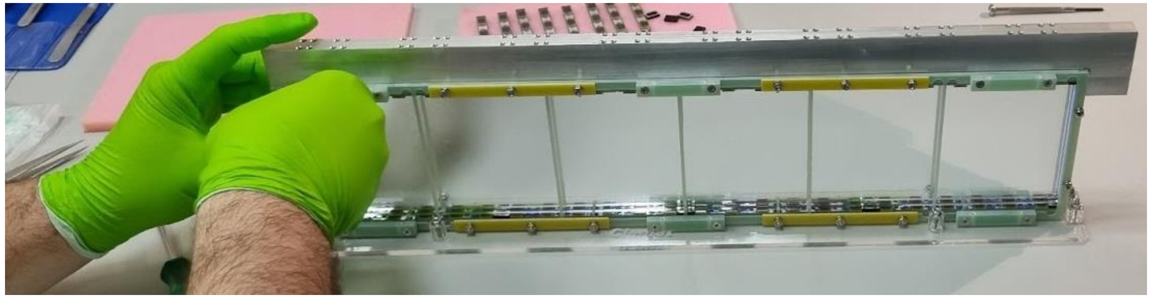
LArTPC events



FD-HD Horizontal Drift

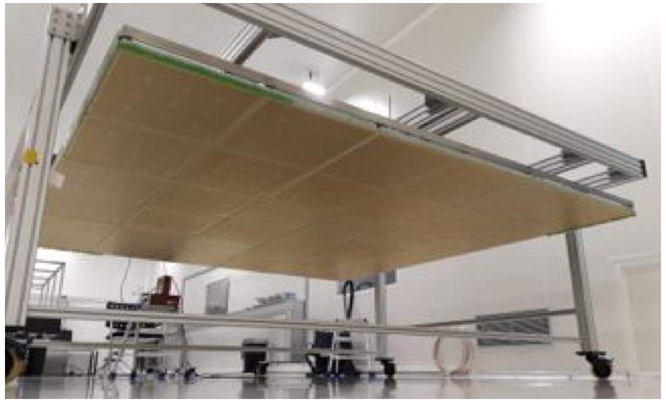


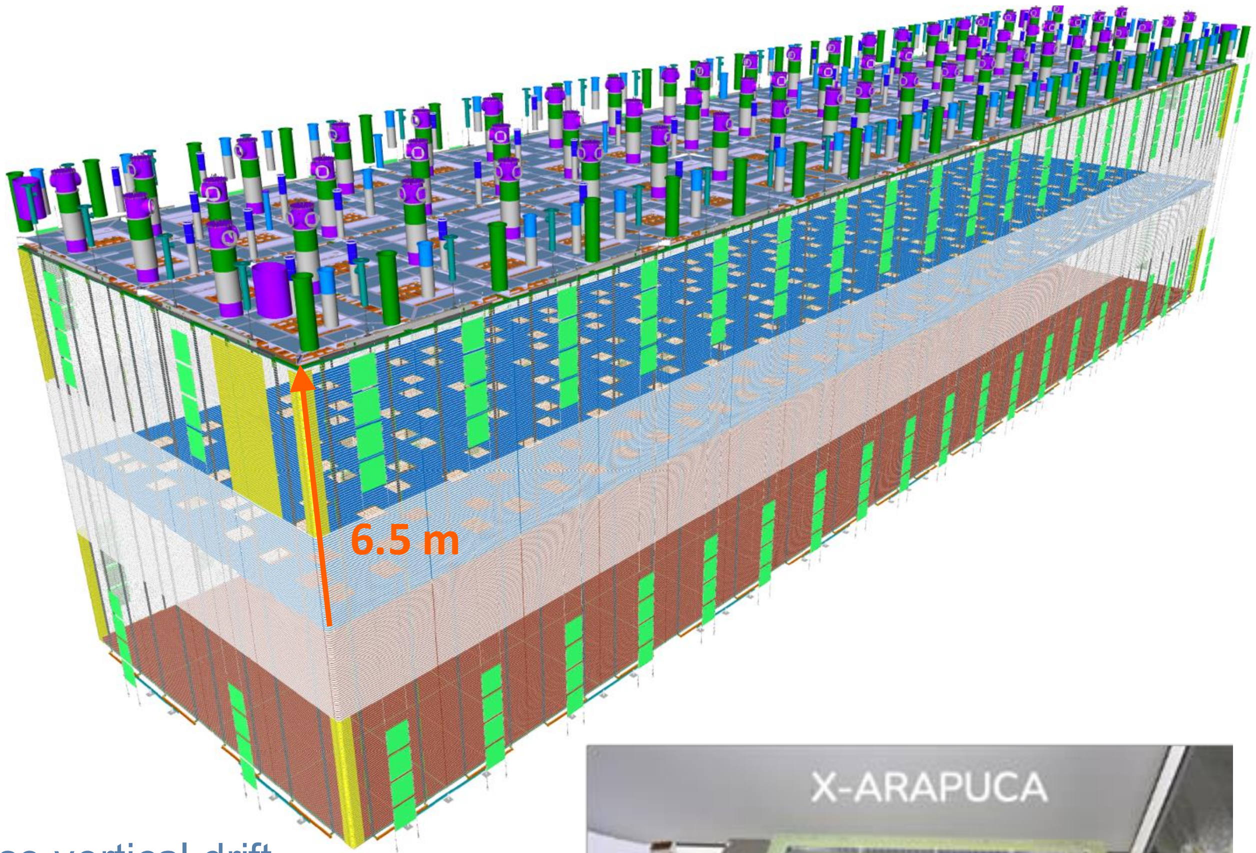
- Alternating Anode (APA) and Cathode (CPA) Plane Assemblies
- 4 drift volumes (3.6 m drift distance x 12 m x 60 m)
- Electric field E = 500 V/cm
- Cathode HV = -175 kV
- APA with wire plane readout
- Photon detectors integrated in the cathode: X-ARAPUCA light traps

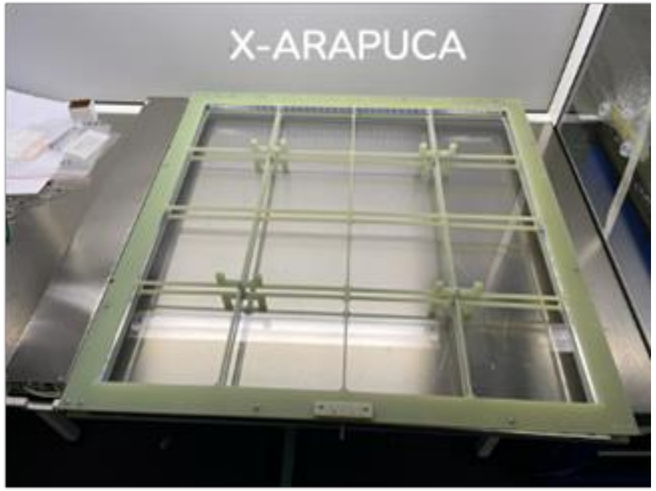


FD-VD Vertical Drift

Charge Readout Plane (CRP)





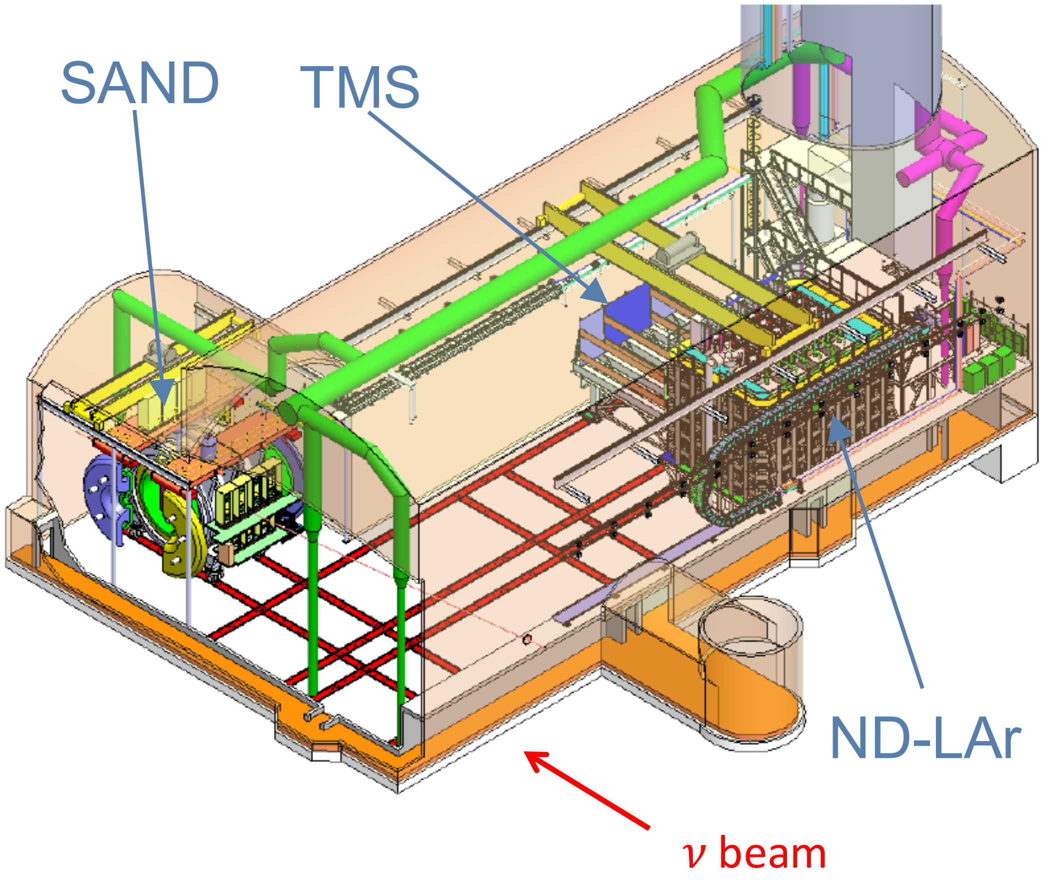


- Simpler design: 1 cathode + 2 anode planes
  - Simpler to install → first DUNE FD module will use vertical drift
  - VD is baseline design for FD modules 3 and 4
- 2 drift volumes (6.5 m drift distance x 13.5 m x 60 m)
- Same drift field → Cathode HV = -300 kV
- 320 CRP units with perforated PCB's with segmented electrodes (strips)
- Photon Detectors (X-ARAPUCAs): 640 XAs (60 x 60 cm² each)

DUNE Near Detectors

- Near Detector Complex: prediction of the far detector spectrum, systematic uncertainties constraints and beam monitoring
- Movable detector system: **ND-LAr** (liquid argon TPC near detector) + **TMS** (The Muon Spectrometer)
  - Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
  - Same target, same technology → inform predictions of reconstructed E_ν in Far Detector
- **SAND** (System for on-Axis Neutrino Detector): on-axis magnetized detector; monitoring beam stability and measurement of neutrino interactions

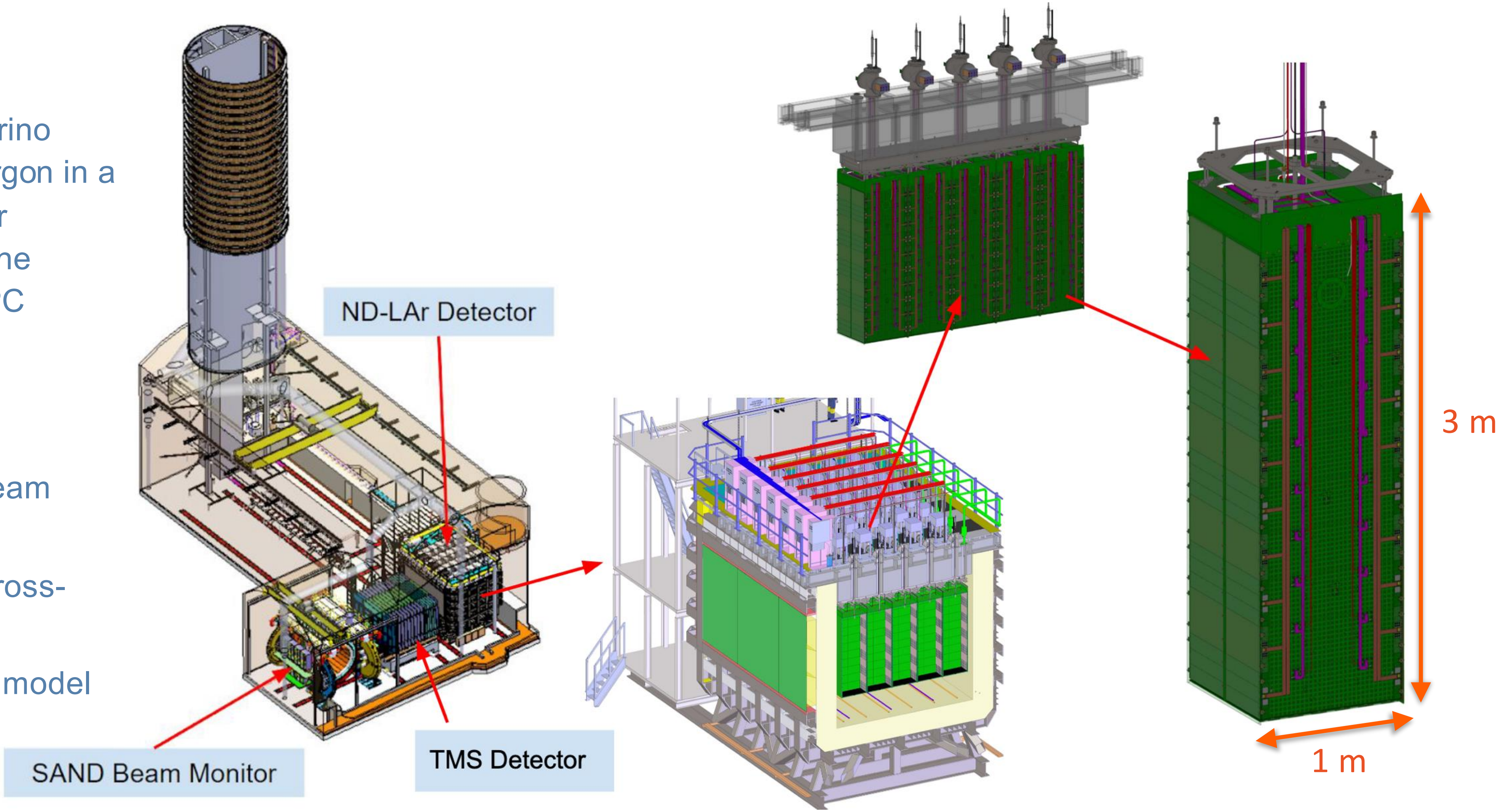
CDR: Instruments 5 (2021) 4, 31



ND: ND-LAr

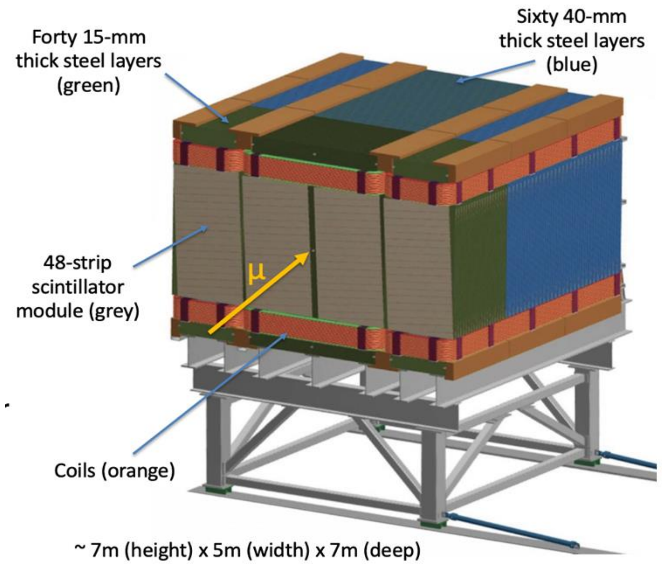
Modular/independent TPC regions with **pixelated charge readout** and high-performance **light readout** (high rate environment: ~55 int/spill)

- Measures:
  - LBNF beam neutrino interactions on argon in a detector of similar performance as the DUNE Far LArTPC detectors
- Constrains:
  - LBNF neutrino beam model
  - Neutrino-argon cross-section
  - LArTPC detector model

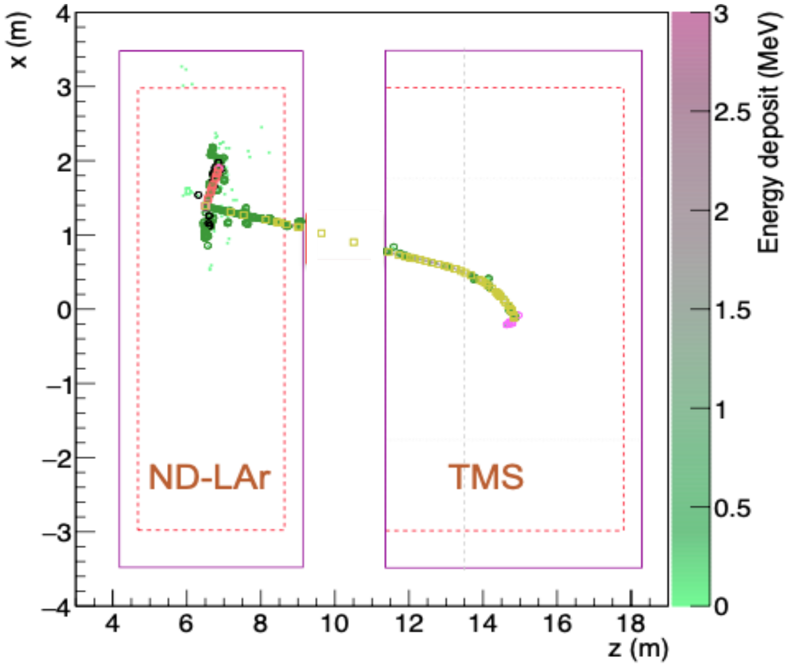


35 TPC modules, arranged in 7 banks each of 5 modules

ND: TMS



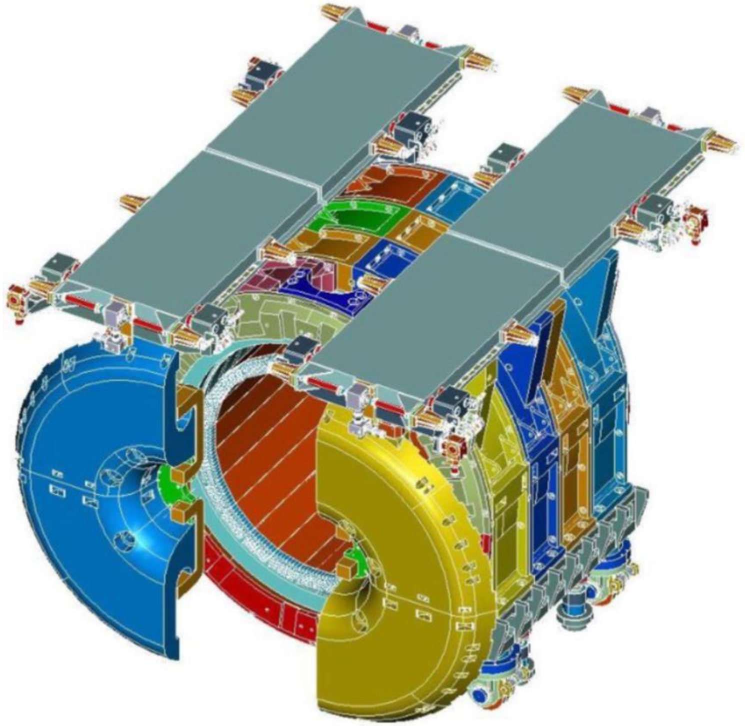
~ 7m (height) x 5m (width) x 7m (deep)

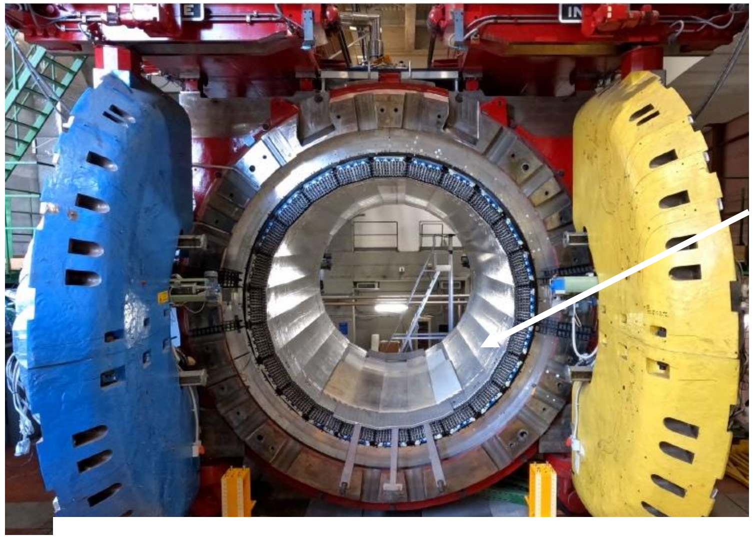


- Primary role
  - muon catcher for the LAr TPC so that the ND can match FD performance
  - sign selection (μ^+, μ^-)
- Secondary role
  - Day 1 beam monitor
  - gets a beam monitor in place in support of the FD as quickly as possible after beam turns on which allows us to get neutrino beam physics started

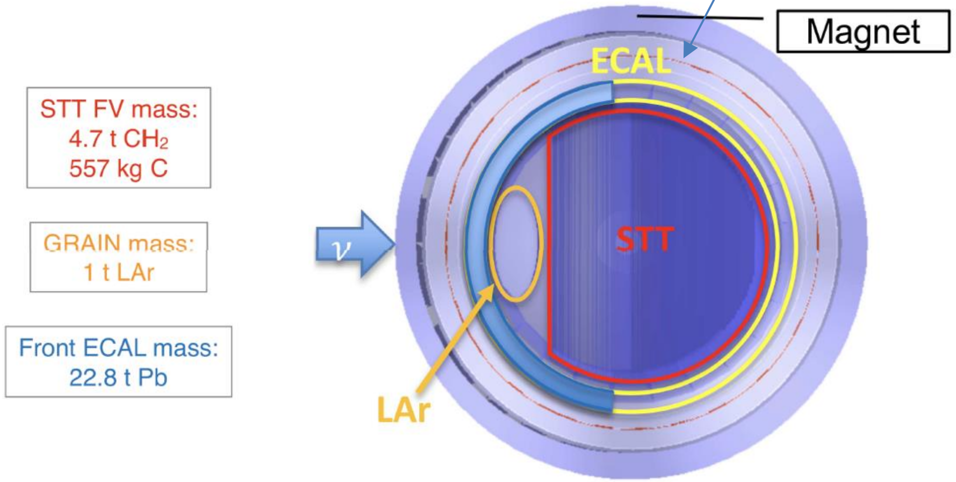
ND: SAND

SAND is a multipurpose detector with highly performant ECAL, light-targeted tracker, LAr target, all of them in a magnetic field (neutrino measurements and beam monitoring)





Electromagnetic Calorimeter (ECAL) (Covering the surface of the magnetized volume - 4π)



STT FV mass:
4.7 t CH_2
557 kg C

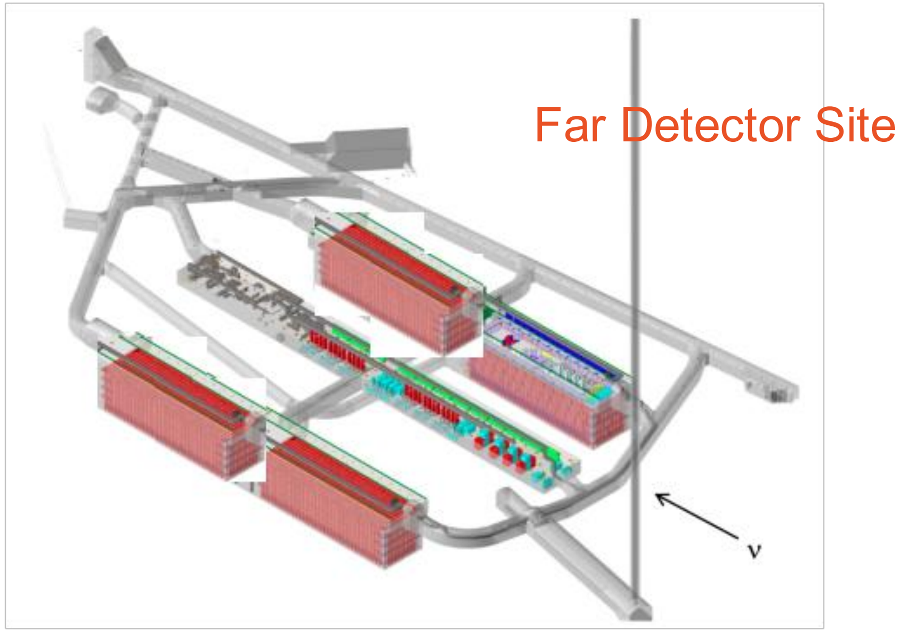
GRAIN mass:
1 t LAr

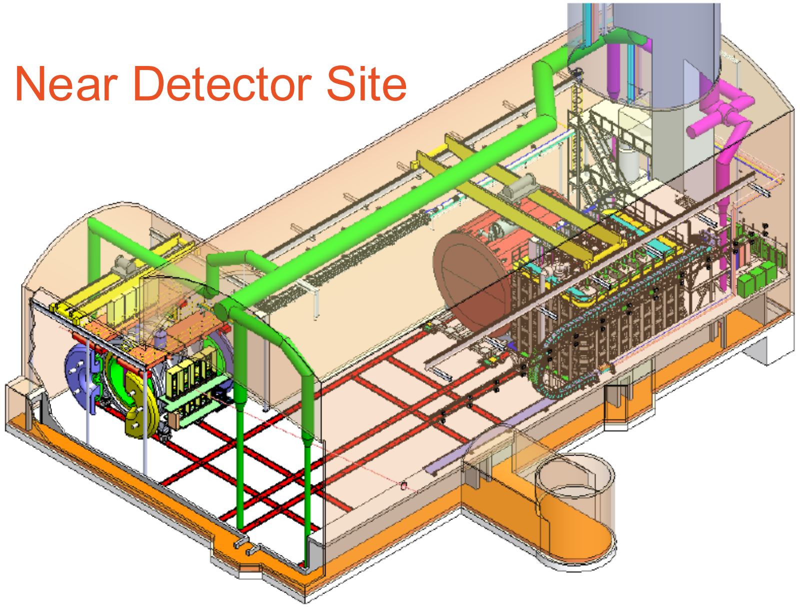
Front ECAL mass:
22.8 t Pb

- The superconducting magnet (0.6 T) and the ECAL are repurposed from the KLOE detector.
- The STT (with CH_2, C targets) and GRAIN (1t LAr) are new detectors, being designed and prototyped

DUNE Phases

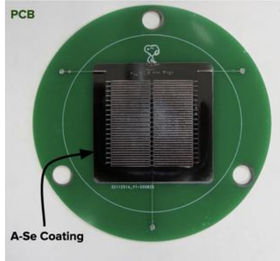
- **DUNE Phase I** (2026 start detector installation; 2029 physics; 2031 beam + ND)
  - Full near + far site facility and infrastructure
  - Two 17 kt LArTPC modules
  - Upgradeable 1.2 MW neutrino beamline
  - Movable LArTPC near detector with muon catcher
  - On-axis near detector
- **DUNE Phase II**:
  - Two additional FD modules (≥40 kt fiducial in total)
  - Beamline upgrade to >2 MW (ACE-MIRT)
  - More capable Near Detector (ND-GAr)

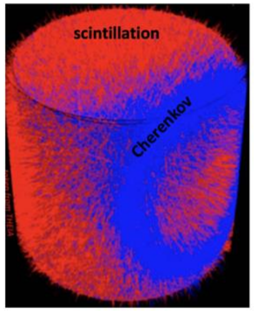


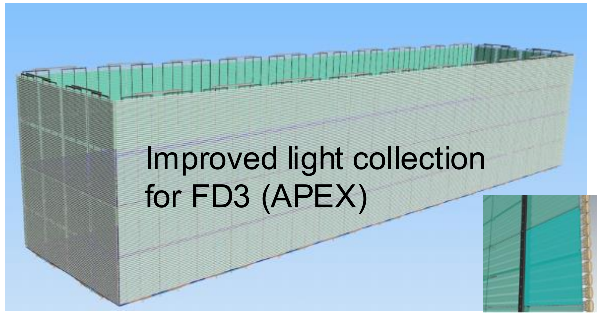


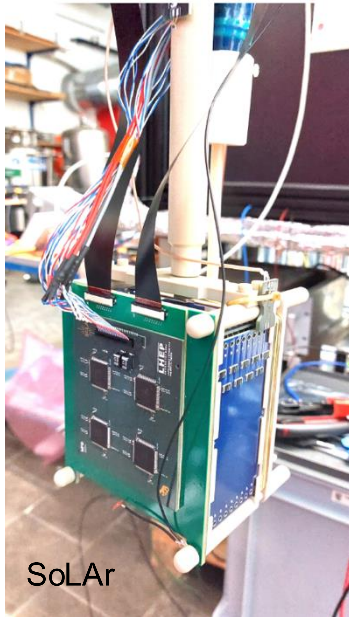
More opportunities for Phase II DUNE FD

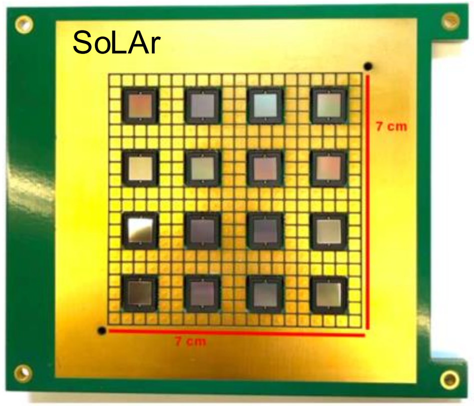
- Vertical Drift module is the baseline design for Phase II FD modules
- Pursuing improvements to light collection for FD3, including Aluminum Profiles with Embedded X-ARAPUCA (APEX)
- The phased construction program allows the development of the technology to expand the DUNE physics scope (solar, supernova neutrinos, $0\nu\beta\beta$, dark matter…)
- FD4 is the "Module of Opportunity", and more ambitious designs are being considered, including pixel readout, integrated charge-light readout, low background modules, and non-LAr technologies



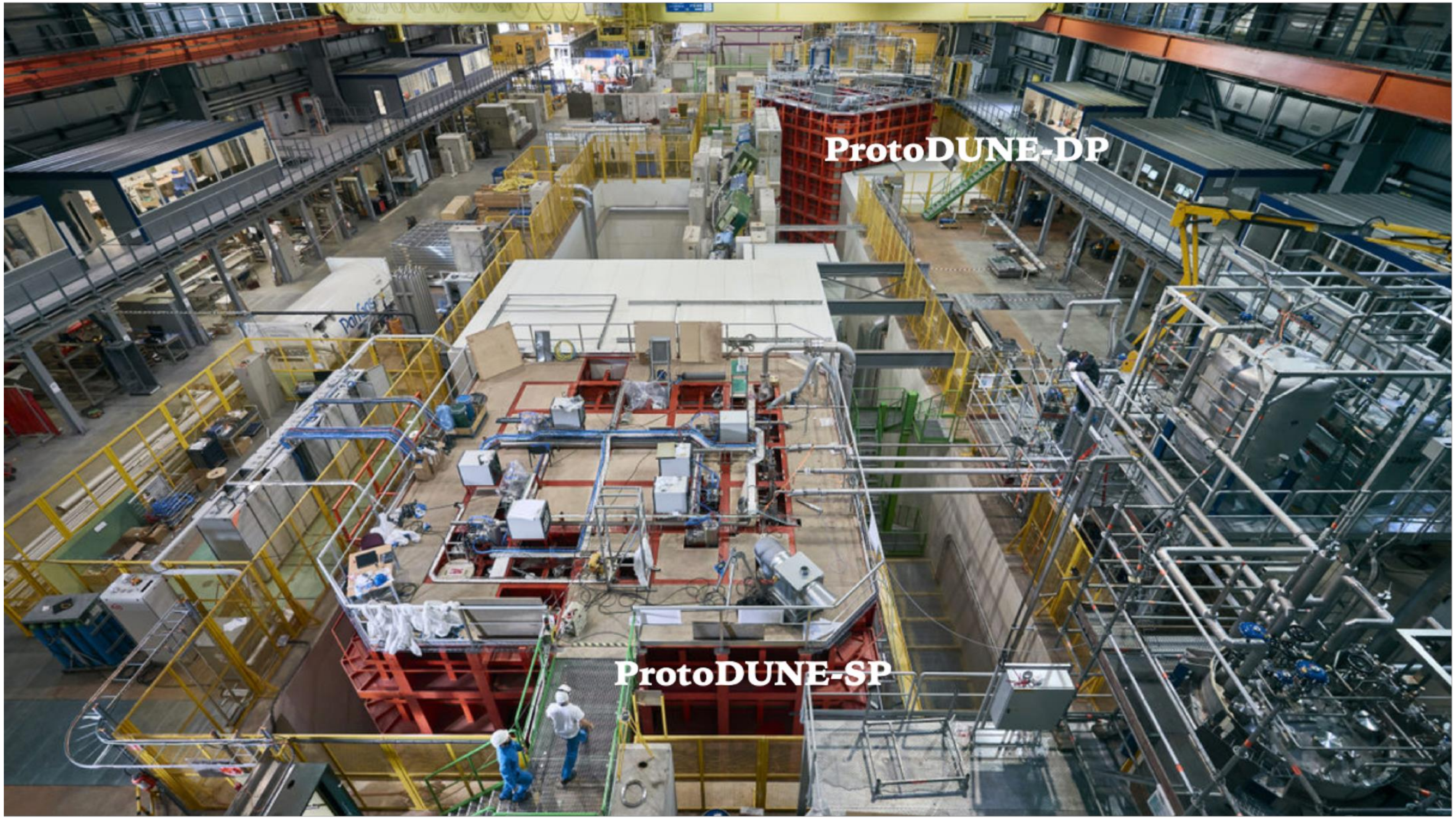



Improved light collection for FD3 (APEX)


SoLAr

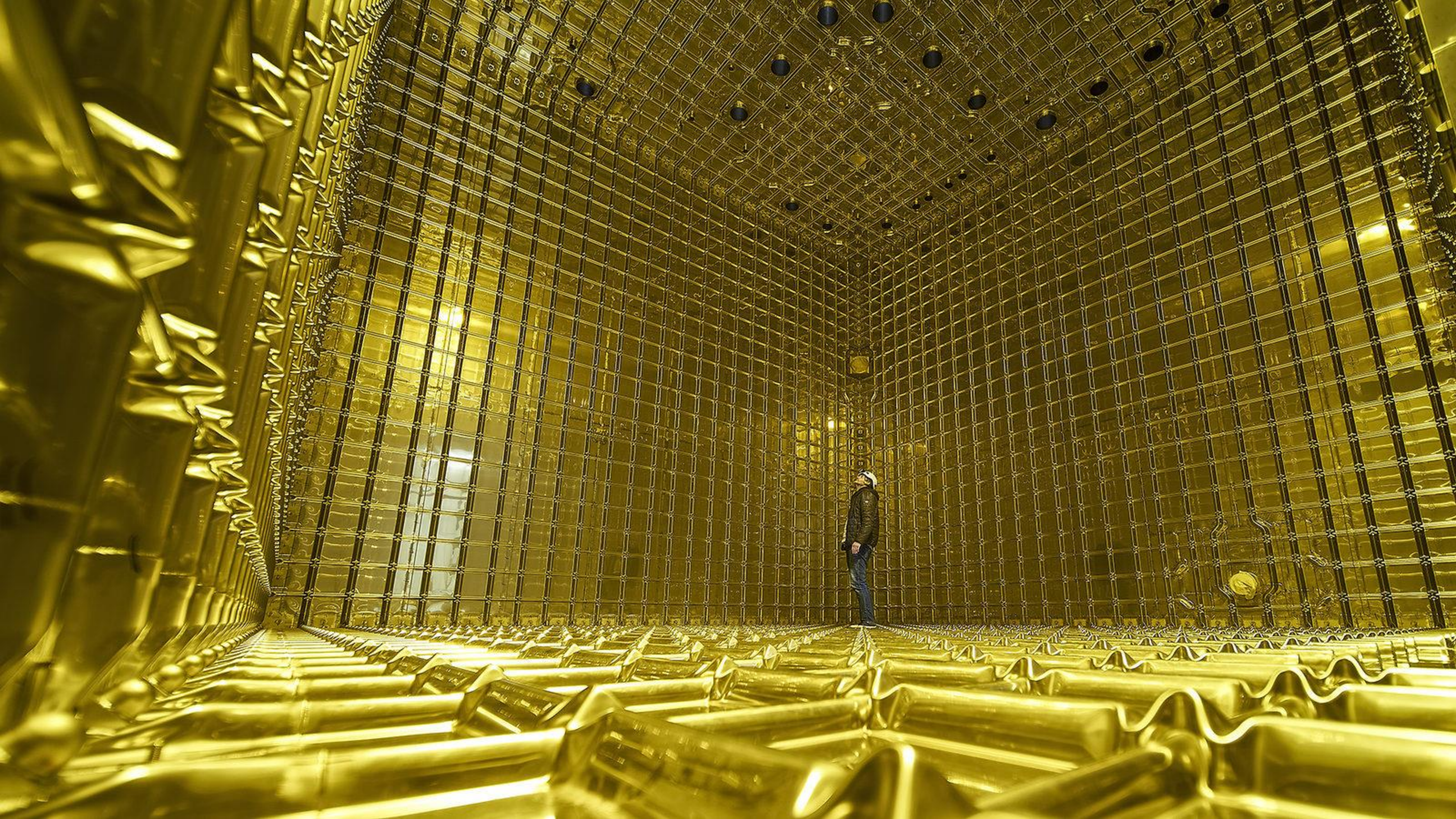

SoLAr

DUNE Prototypes - ProtoDUNEs at CERN



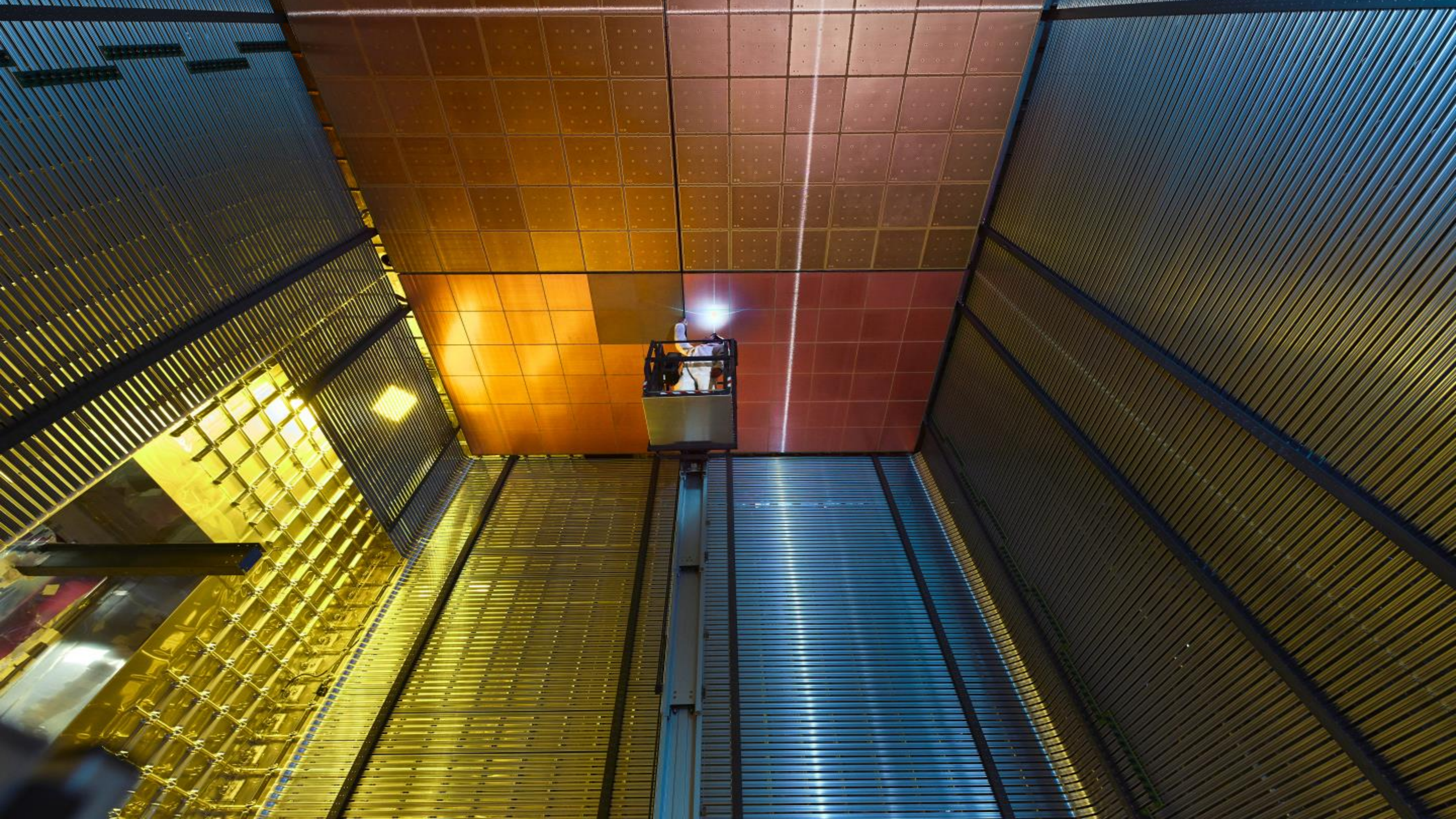
ProtoDUNE/DUNE
~1:20

Full scale DUNE
TPC components



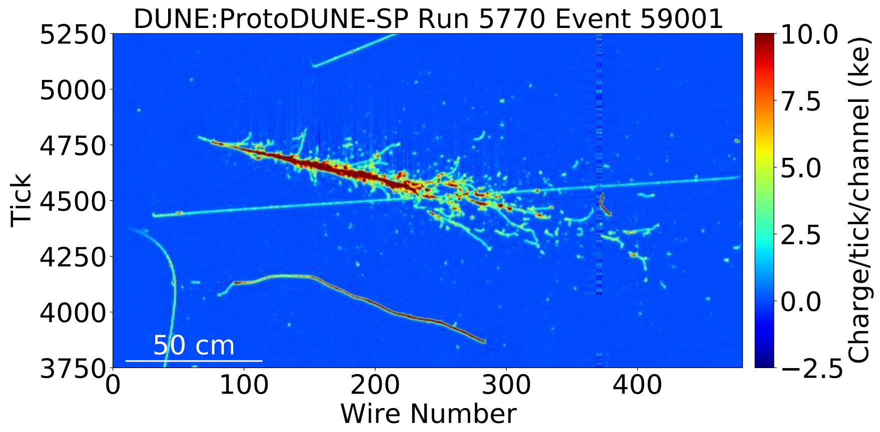

Genie
Genie
Genie AWP-20S

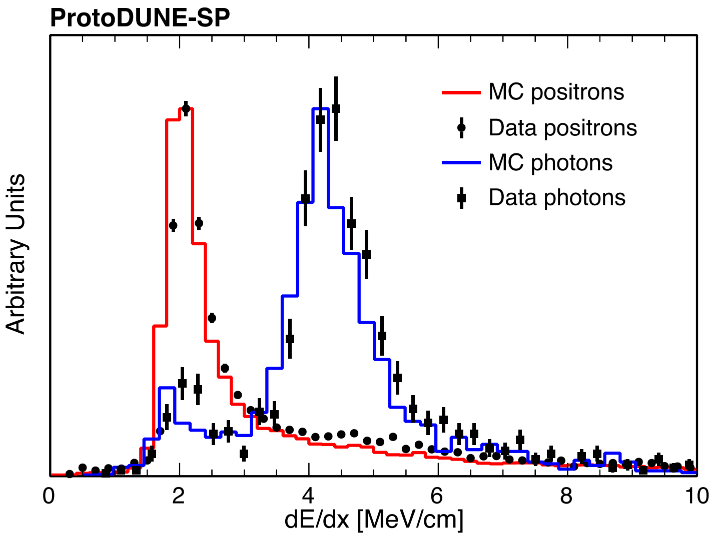

20MVL

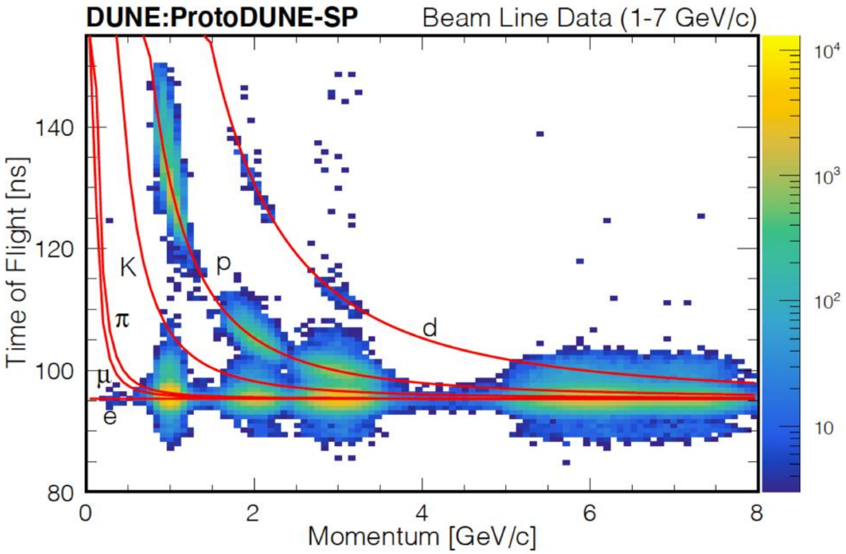


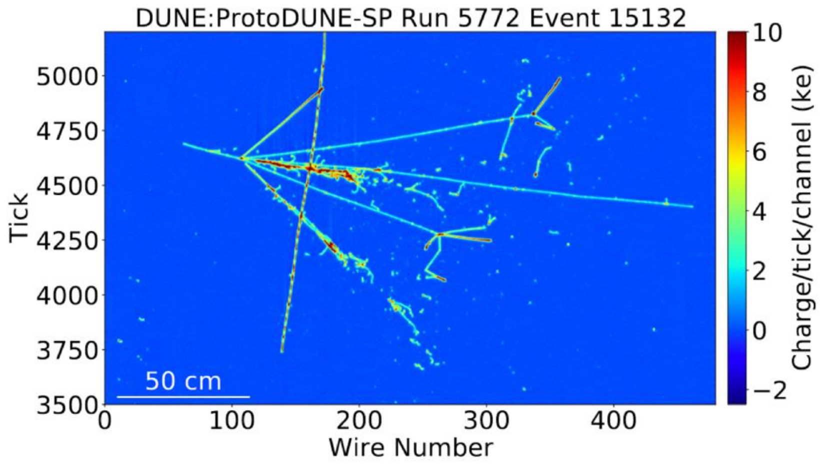
FD: ProtoDUNEs at CERN (1st Phase)

- **1st Phase of ProtoDUNEs**
  - Construction and operation of ProtoDUNEs at CERN (2018-2020)
  - Successful demonstration of the DUNE LAr TPC performance
  - Several ongoing analyses (hadron-Ar cross sections…)









FD: ProtoDUNEs at CERN (2nd phase)

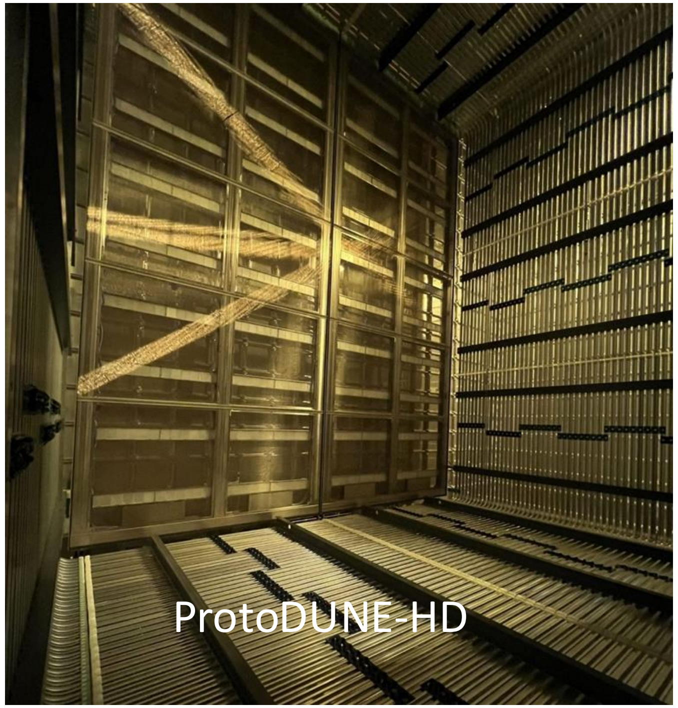
- **2nd Phase of ProtoDUNEs (2020-2023 construction + operation ≥2024)**

ProtoDUNE-HD

- Final technical solutions for all FD-HD subdetectors
- Detector filled and currently taking data with charged-particle test-beam and cosmic muons at CERN

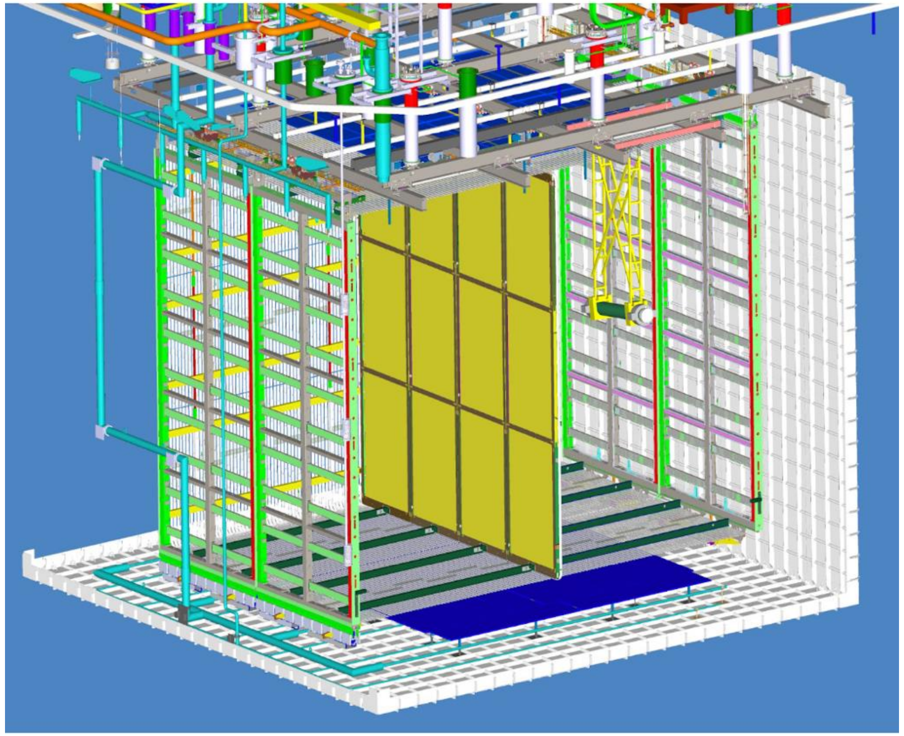
ProtoDUNE-VD

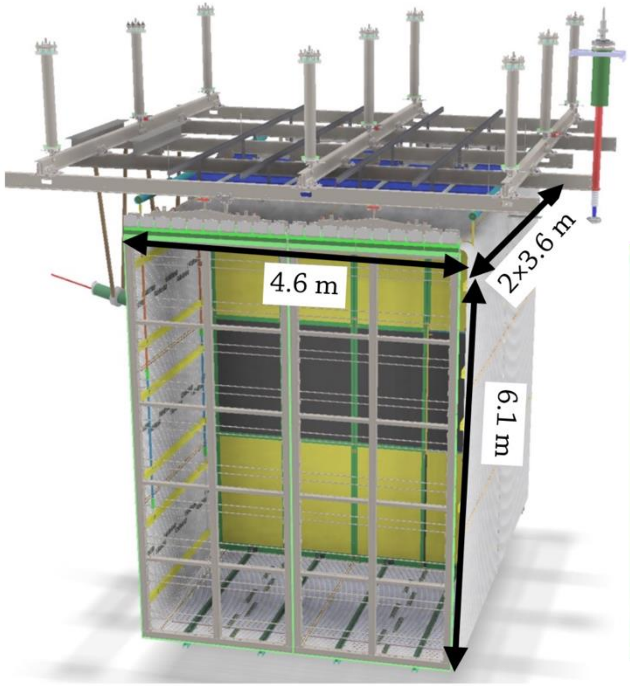
- Realization of a Module-0 detector in 2022-2023
- LAr will be transferred to ProtoDUNE-VD in October for running starting in early 2025


ProtoDUNE-HD

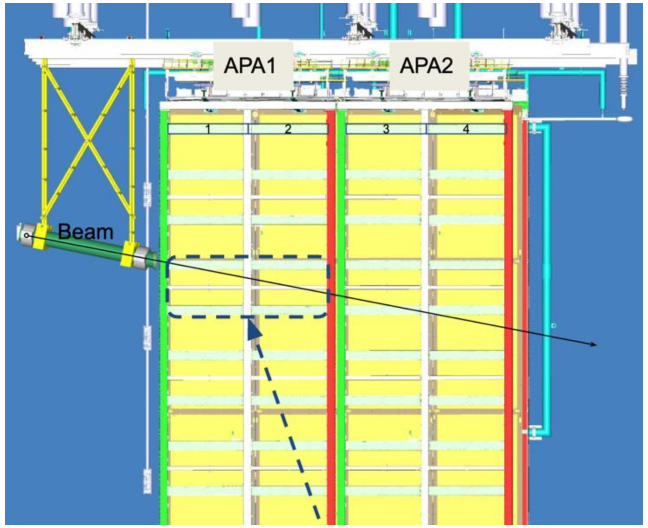

ProtoDUNE-VD

ProtoDUNE-HD



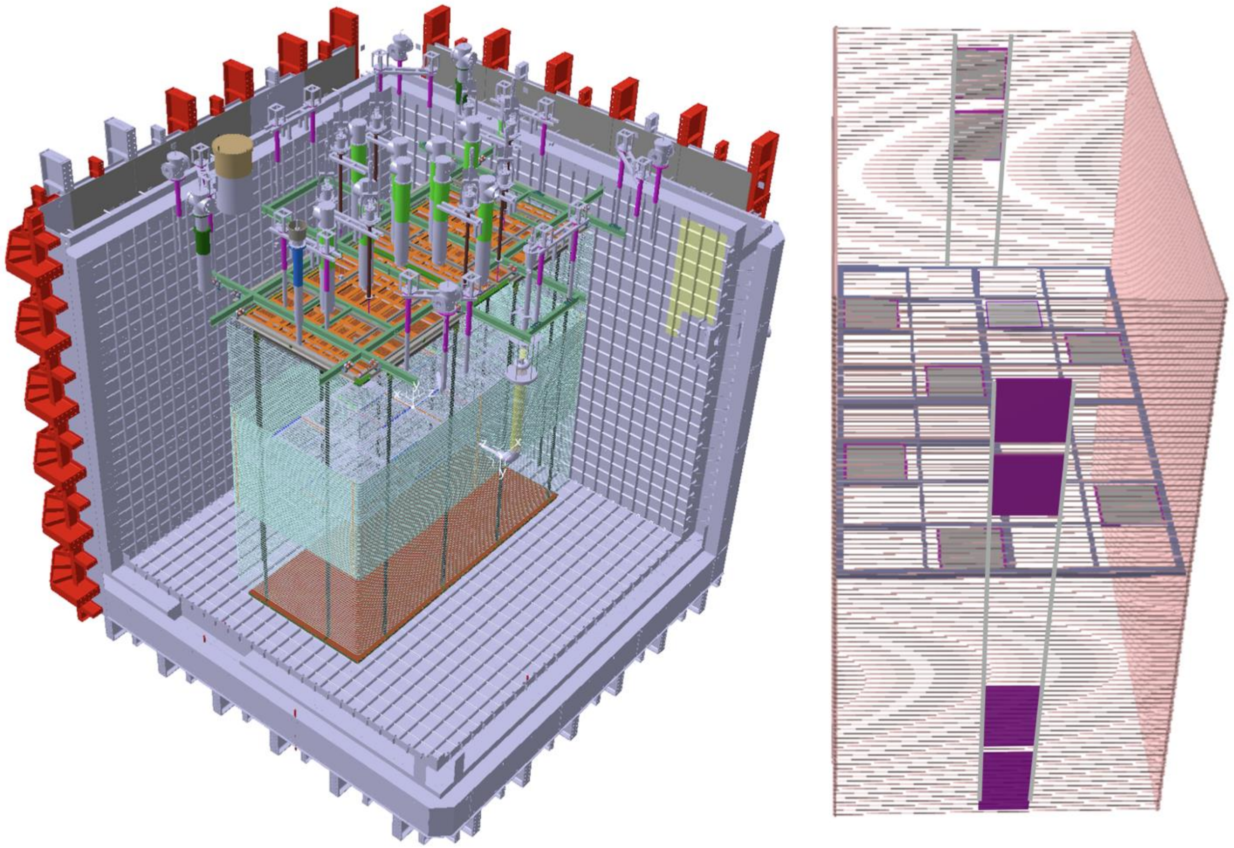


- 2 APAs (instead of 3) per wall
- Drift volume further from the cryostat (longer beam pipe)
- New calibration systems (laser, neutron source)



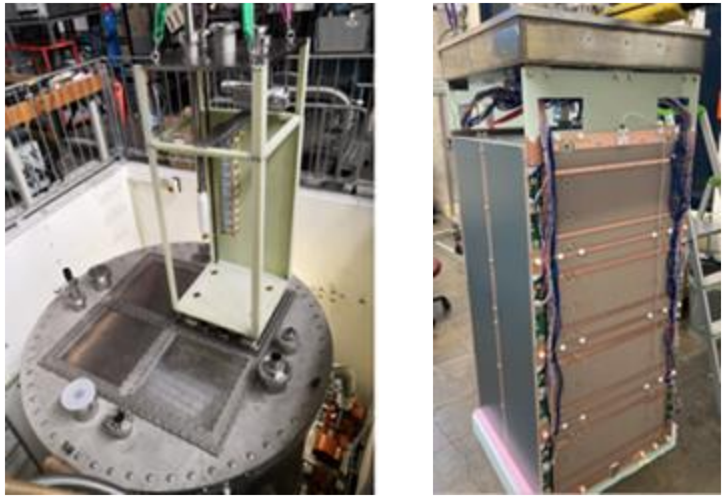
ProtoDUNE-VD

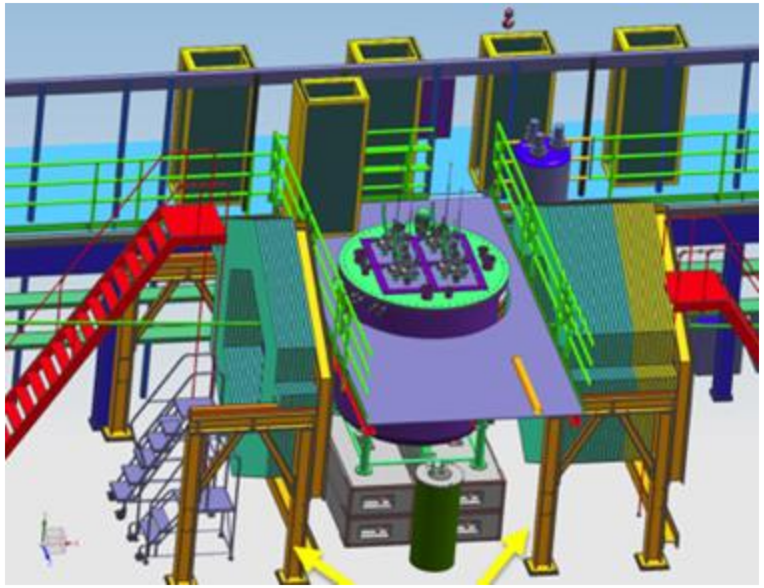
- 2 top CRPs + 2 bottom CRPs
- Cathode in the middle hanging from the top CRPs
- Field cages hanging independently from the cryostat roof
- ~3.2 m long drift, 300 kV capable HV system
- 8 Photon Detection modules on the cathode and 8 modules on the walls



DUNE Prototypes: 2x2 ND-LAr demo at Fermilab

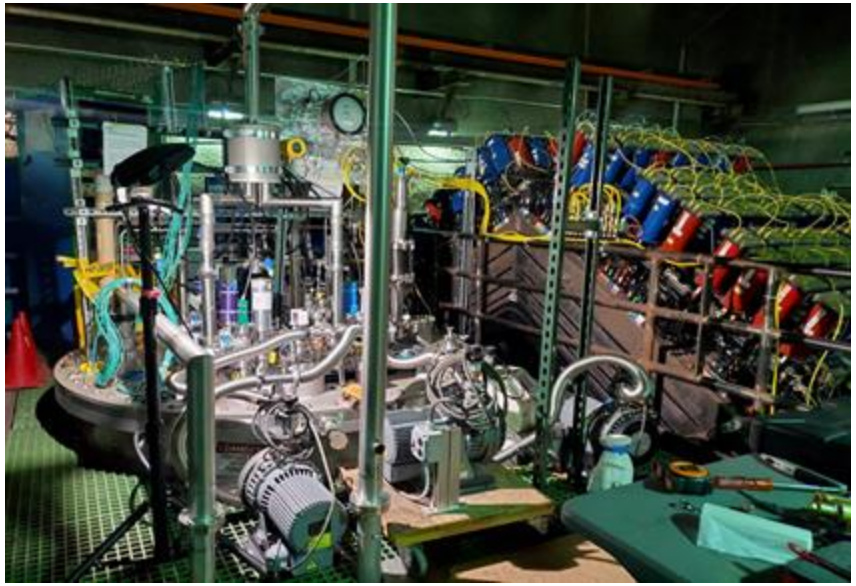
- **ND challenge**: neutrino pile-up (several dozens of neutrinos per spill)
  - Very high rate at near site motivates pixelated readout and optical modularity
- **Four LArTPC modules** built and operated in LAr in Bern with a total of ~330k pixel channels
- Operation of **2x2 ND-LAr in NuMI Neutrino Beam**
  - Four TPC modules installed in former location of MINOS-ND
  - Includes upstream/downstream trackers, repurposed from MINERvA
- **Goals**: Demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to DUNE

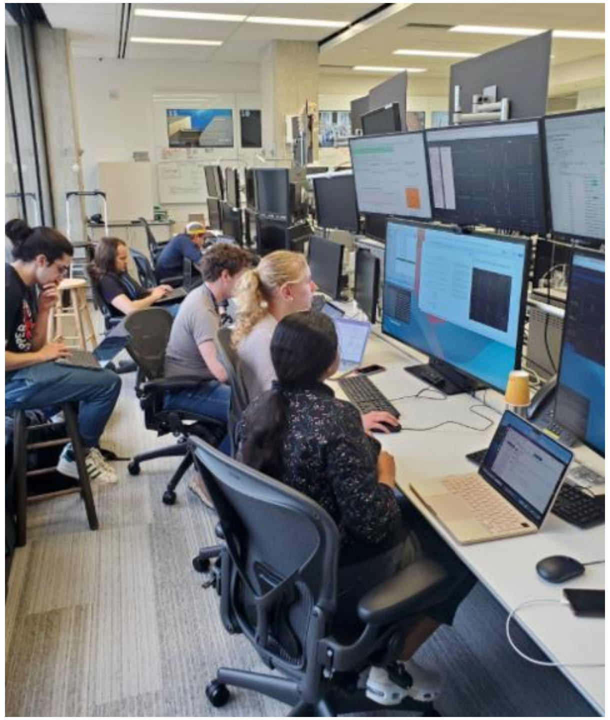




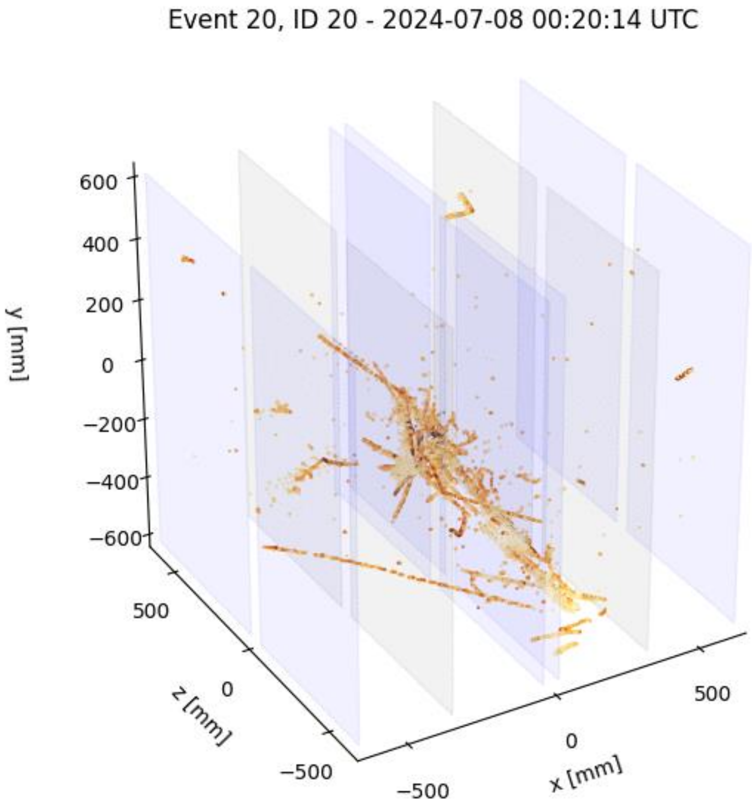
2x2 ND-LAr demonstrator at Fermilab

- Cooldown and argon filling finished May 31
- 24/7 shifts since early June
- Operating since July 8 at NuMI





First DUNE Near Detector 2x2 Demonstrator neutrino events (July 2024)



Conclusions

- DUNE is the **best-in-class long-baseline neutrino experiment** for **precise oscillation measurements** and possible **discoveries** in neutrino physics
- DUNE is **unique** in its approach to making these measurements, with its key features being the long-baseline, wide-band beam, underground location and liquid argon detector technology
- A very active **prototyping program** at large scale is **underway at CERN and Fermilab** together with an **ongoing R&D program** for DUNE Phase II detectors
- DUNE provides a **full exciting physics and technology program for the next decades starting this decade**

Join us!!

Grazie!
Thanks!