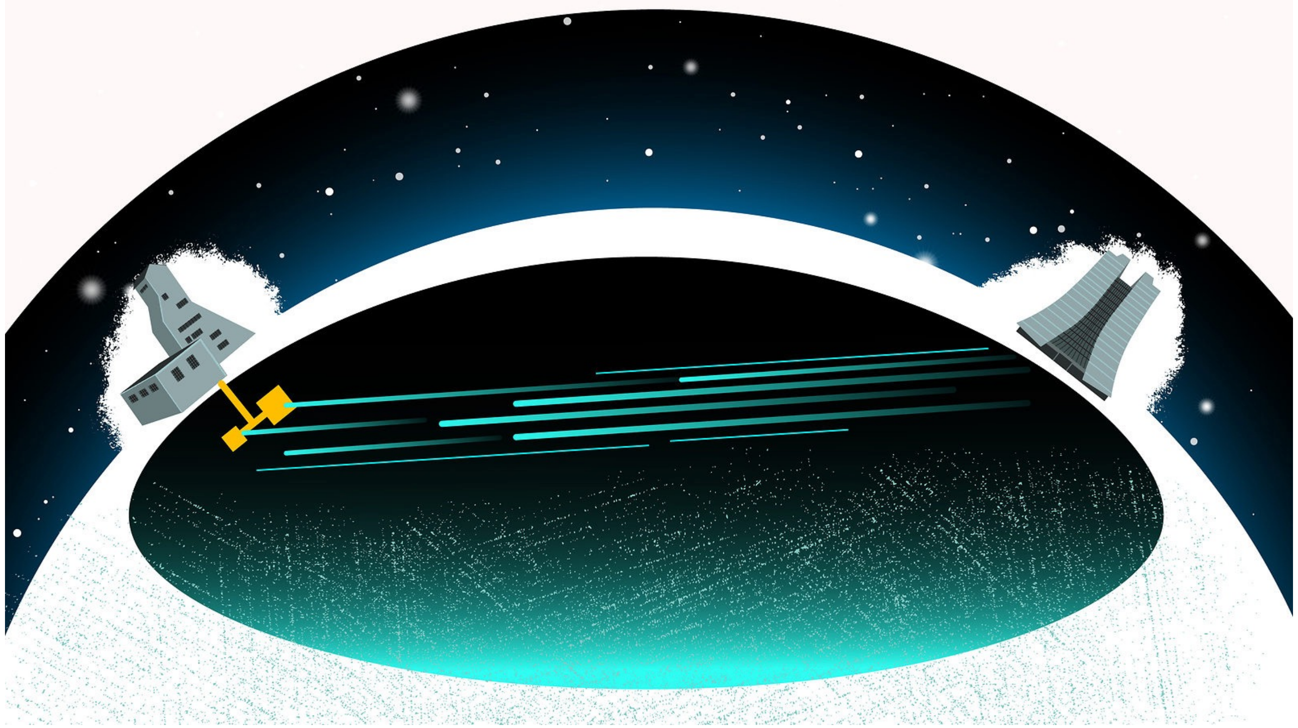
DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT



Inés Gil-Botella

CIEMAT

Fermilab Italian Summer School

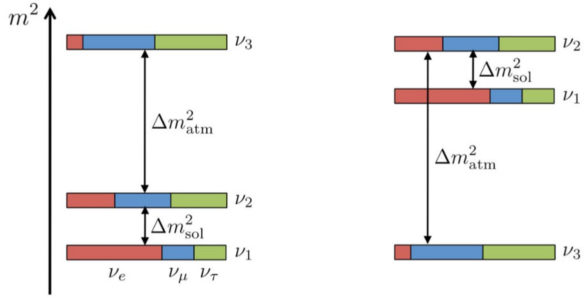
18 July 2022

Outline

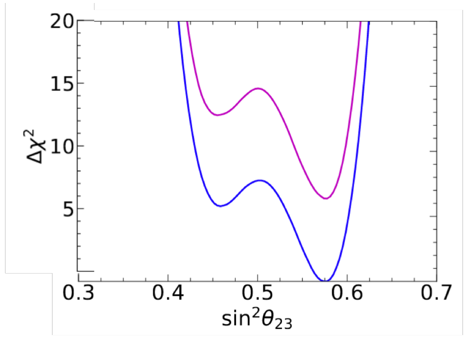
- Neutrino oscillations in long-baseline neutrino experiments
- **DUNE**
  - Physics program
  - Long-Baseline Neutrino Facility (LBNF)
- The **Far Detectors**
  - LAr TPC technologies
  - ProtoDUNEs at CERN
- The **Near Detectors**
  - Prototyping at Fermilab
- Conclusions

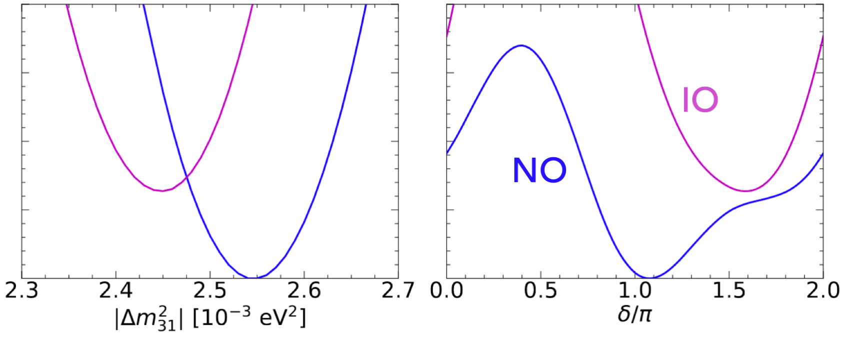
Discovery opportunities in LBL experiments

- **CP violation**
  - T2K and NOvA could reach 3σ sensitivity to CPV over the next years
  - To reach discovery and precise measurement, **larger detectors** and (upgraded or new) **beams** are needed
- **Neutrino mass ordering**
  - Almost complete degeneracy in present data
- **Octant of θ_{23}**
  - Maximal? $\nu_\mu \leftrightarrow \nu_\tau$ mixing symmetric? If so, why?
- **Neutrino anomalies:** sterile neutrinos?
- **Supernova neutrino burst and Diffuse SN Neutrino Background**
- **Solar neutrinos**
- **Beyond the Standard Model:** nucleon-decay, testing the 3-neutrino flavor paradigm, dark matter, etc.



Mariam Tórtola et al., JHEP 02 (2021) 071





Long-baseline neutrino oscillations

- Neutrino oscillation probability in matter

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{CP})$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2$$

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

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

  - 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

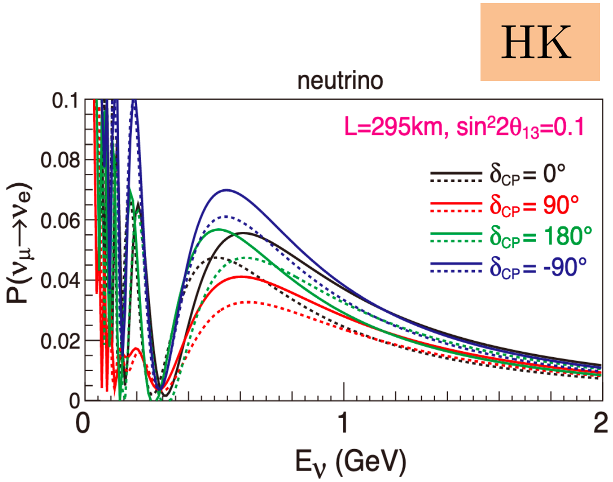
Long-baseline neutrino experiments

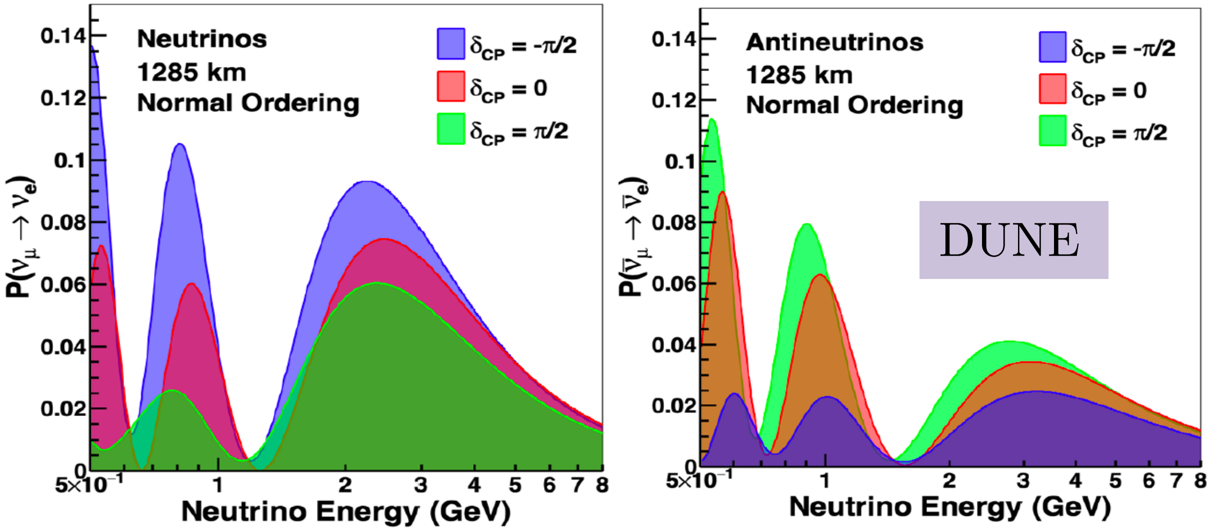
- **T2HK (Tokai to HyperK) approach (L=295km)**: Minimize matter effects and maximize statistics to focus on CPV discovery (MO and other parameters must be known by other means)

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

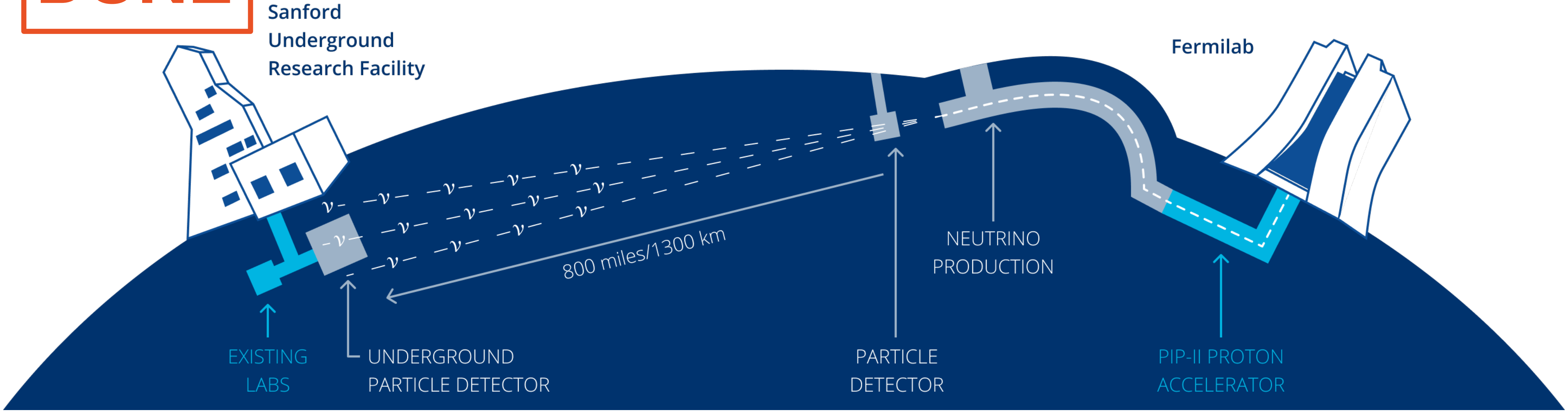
Wide-band beam (0.5-5 GeV; 1.2 → 2.4 MW) and liquid Argon TPC (>40 kt fiducial)





DUNE

__DUNE TDR__ (Vol I,III,IV https://iopscience.iop.org/journal/1748-0221/page/extraproc95, Vol II arxiv:2002.03005)
__ND CDR__ (arXiv:2103.13910)

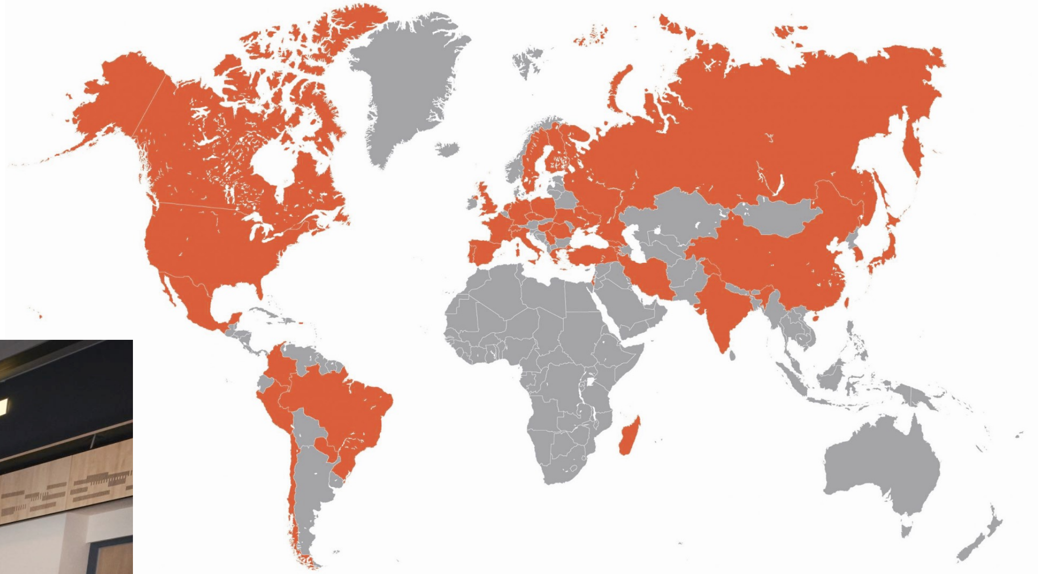


- The most powerful **neutrino beam** in the world (1.2 MW upgradeable to 2.4 MW) will be sent from **Fermilab** (Chicago) to **SURF** (South Dakota) along **1300 km** distance to be detected by four liquid argon far modules (**70 kton LAr**) at 1.5 km deep underground and a **near detector complex** 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

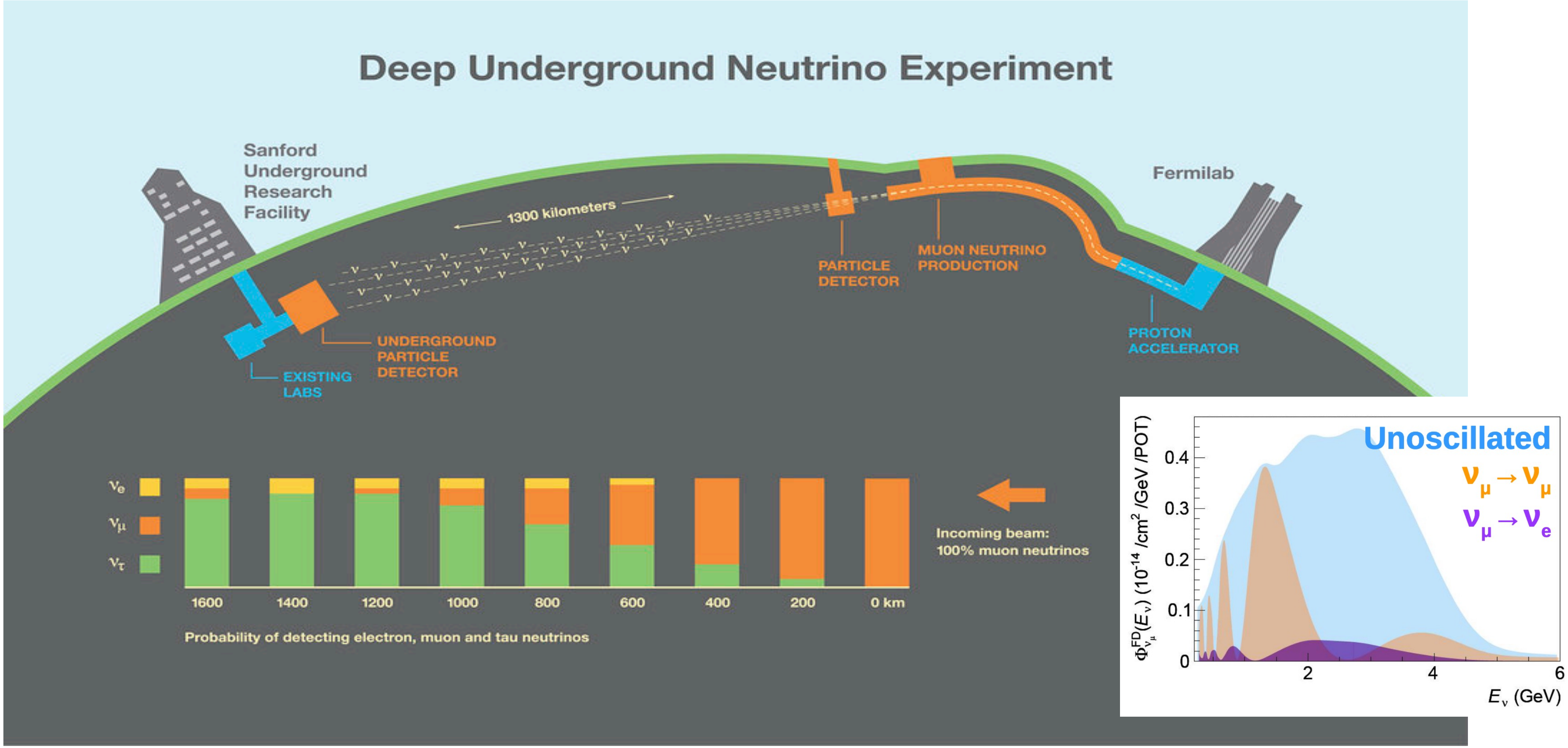
DUNE collaboration

DEEP UNDERGROUND NEUTRINO EXPERIMENT

- International collaboration
  - Over 1400 collaborators
  - Over 210 institutions
  - 37 countries + CERN
- Huge endeavor!

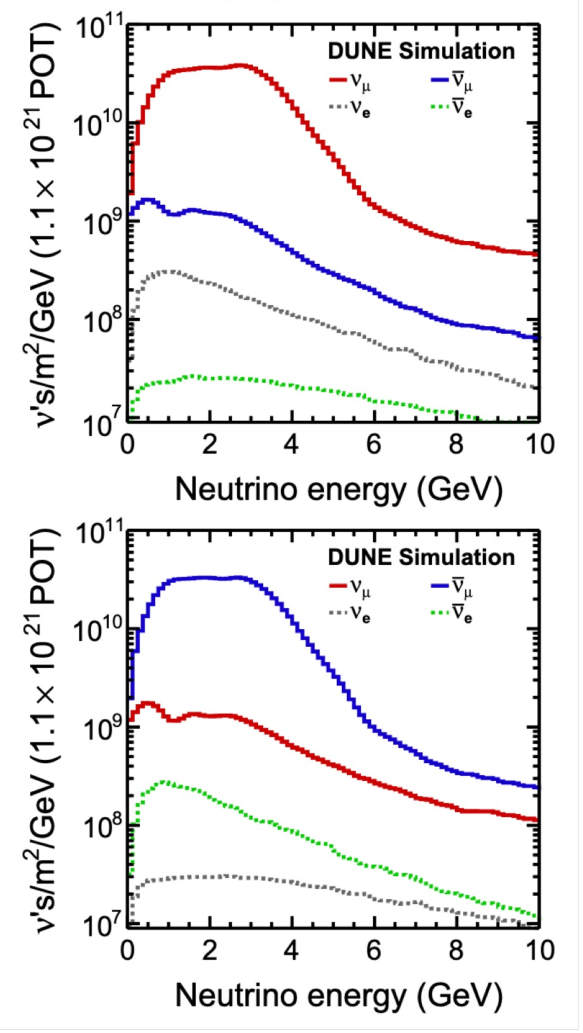


DUNE neutrino oscillations



DUNE reconstructed neutrino spectra

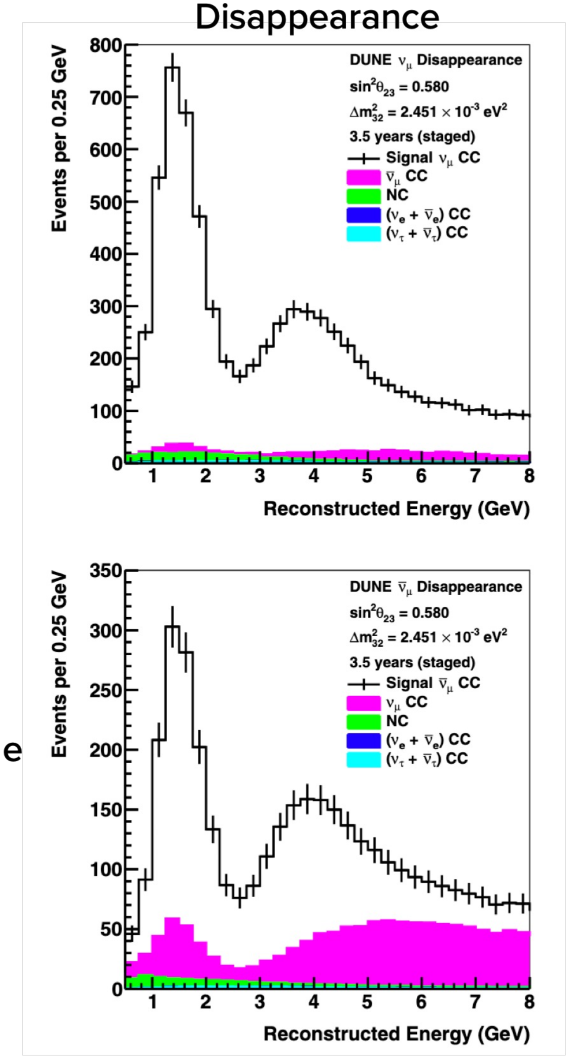
Neutrino beam



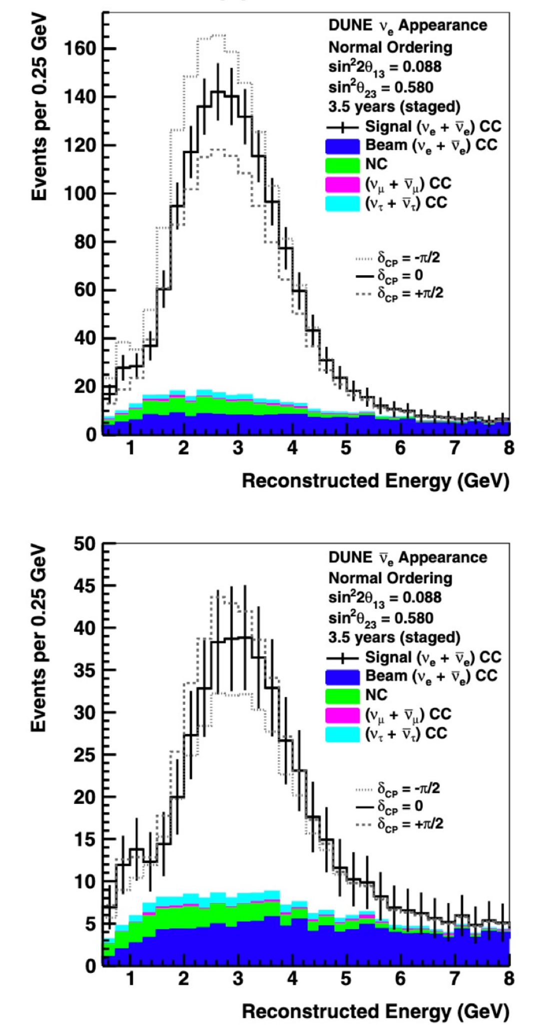
Neutrino mode

Antineutrino mode

Disappearance



Appearance



DUNE LBL oscillation measurements

$$\boxed{P(\nu_\mu \to \nu_e) = \frac{\Phi_e^{FD}(E_\nu)}{\Phi_\mu^{ND}(E_\nu)}}$$

flux cross-section detector acceptance and efficiency

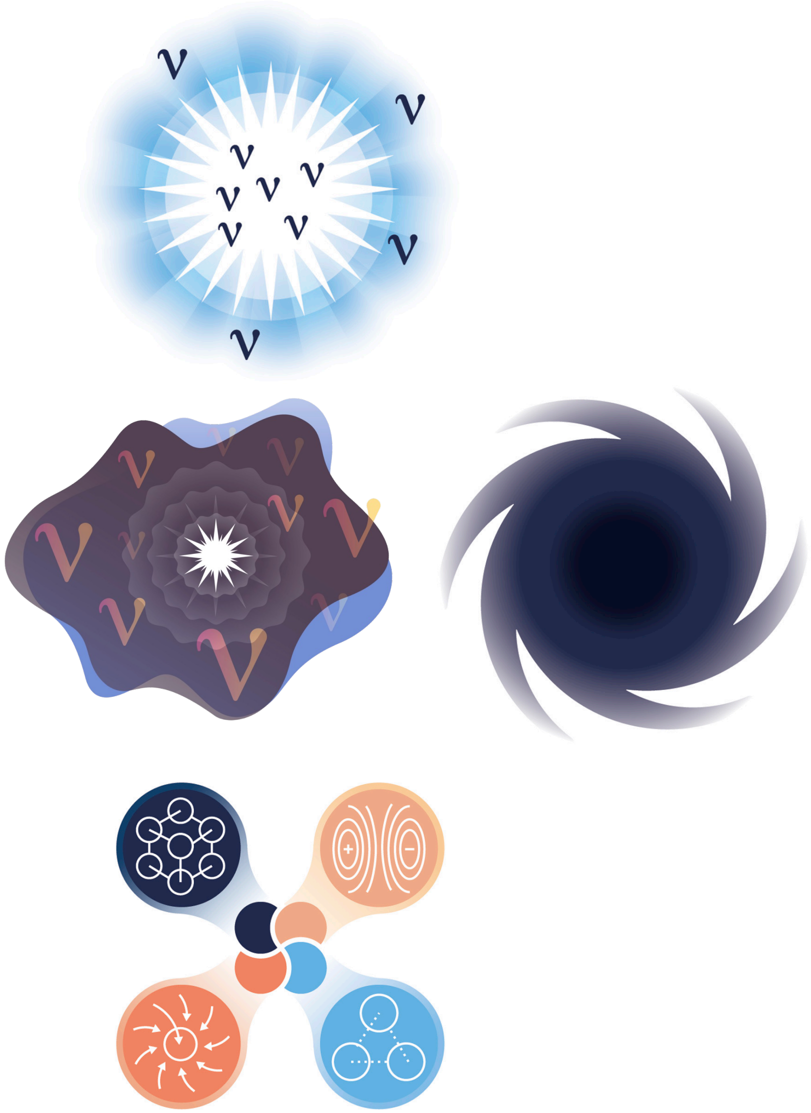
$$\boxed{N(E_{rec}) = \Phi(E_\nu) \times \sigma(E_\nu) \times \epsilon(E_\nu) \times \mathbf{D}(E_\nu \to E_{rec})}$$

$$\frac{N_e^{FD}(E_{rec})}{N_\mu^{ND}(E_{rec})} = \frac{\int dE_\nu \mathbf{D}^{FD}(E_\nu \to E_{rec})\Phi_e^{FD}(E_\nu) \times \sigma_e(E_\nu) \times \epsilon_e^{FD}(E_\nu)}{\int dE_\nu \mathbf{D}^{ND}(E_\nu \to E_{rec})\Phi_\mu^{ND}(E_\nu) \times \sigma_\mu(E_\nu) \times \epsilon_\mu^{ND}(E_\nu)}$$

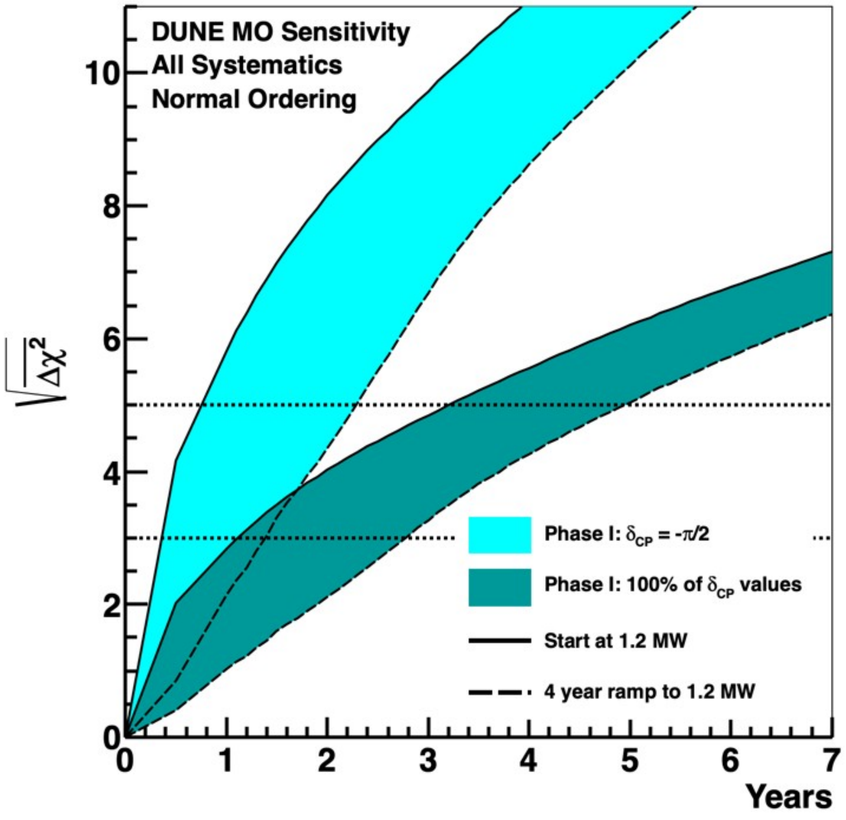
- What we see in the FD is the **reconstructed neutrino energy**
- This distribution depends on the flux, the ν-Ar cross section, the reconstruction efficiency, and the true → reco smearing
- We use models to **predict** this distribution in the FD, but this introduces **systematic uncertainties**
- **ND** can reduce systematic uncertainties in the flux, neutrino interactions on Ar, and detector response

DUNE physics program

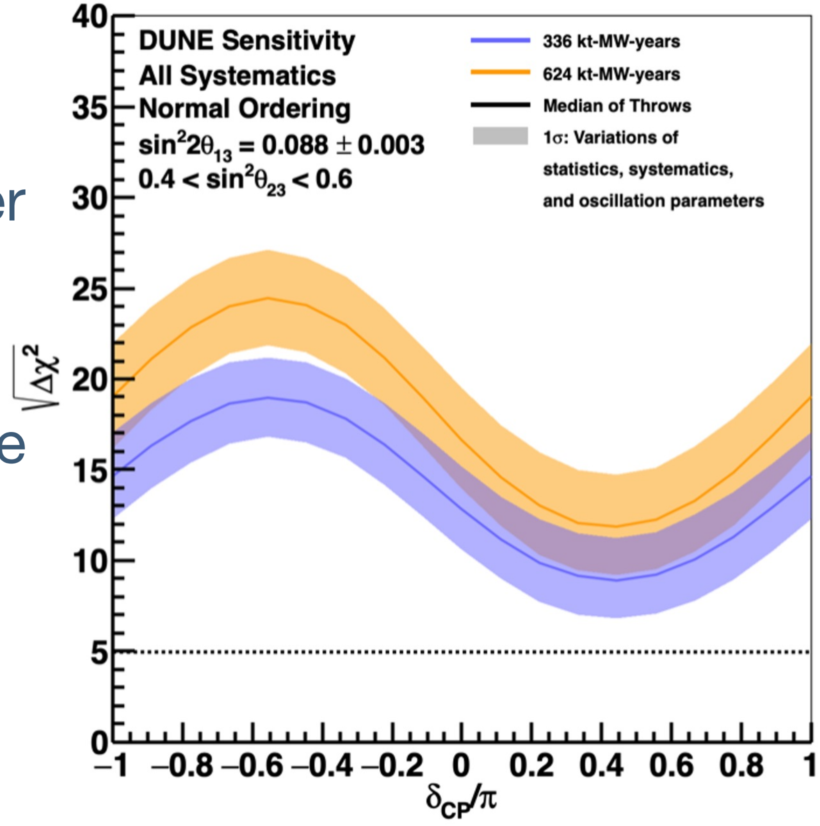
- Unambiguous, high precision measurement of **neutrino oscillations** (mass ordering, differences between neutrinos and antineutrinos - CP violation…) **in a single experiment**
- Detection of low-energy neutrinos: **supernova neutrinos, solar neutrinos**
- **Beyond the Standard Model** searches (proton decay, sterile neutrinos, non-standard interactions, dark matter…)



DUNE Neutrino mass ordering

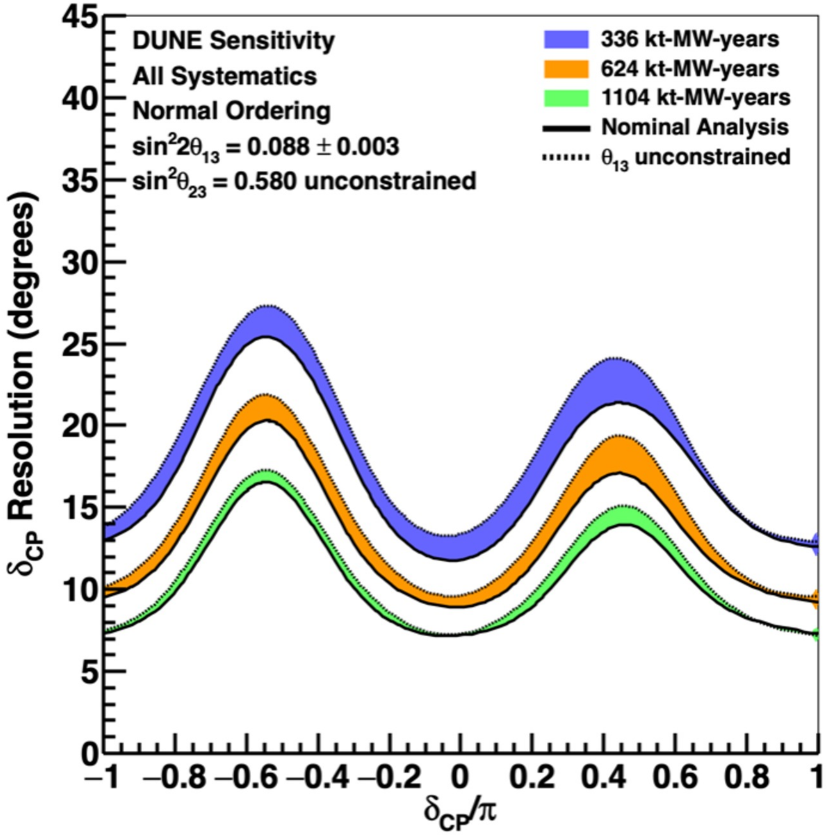


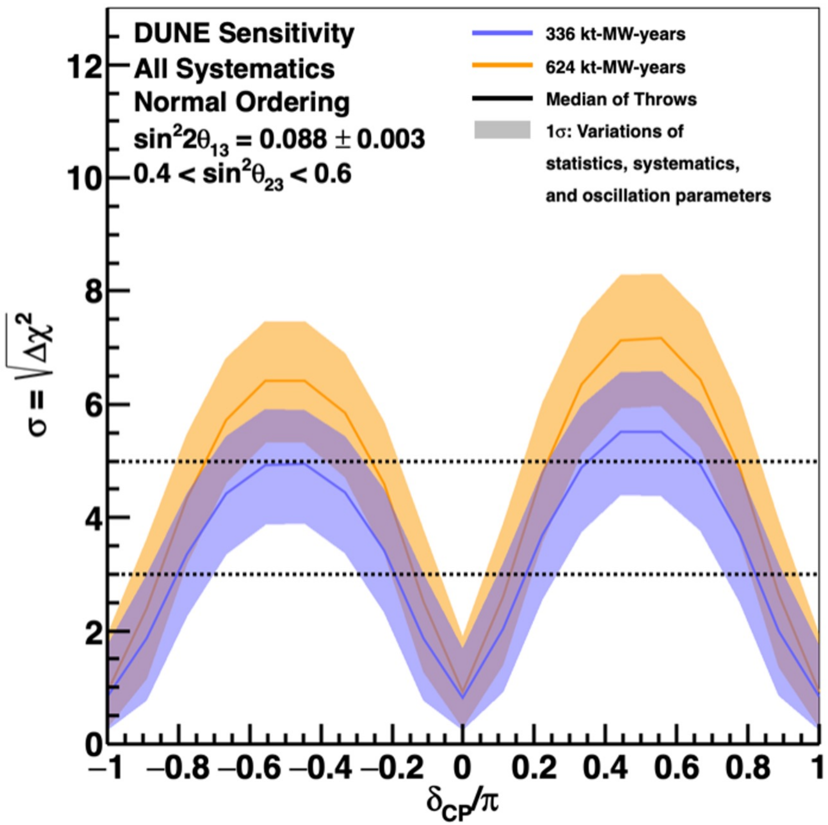
- DUNE has unprecedented and unrivaled ability to definitively resolve the mass ordering independent of other experiments
- 4 years of running with 2 FD modules in most conservative beam ramp to 1.2 MW provides clear discovery potential
- More than 5σ sensitivity for 100% δ_{CP} in few years of data



DUNE CP violation

- 5σ discovery potential for CP violation over >50% of δ_{CP} values
- 7-16° resolution to δ_{CP} with external input for only solar parameters





DUNE Low-energy neutrinos

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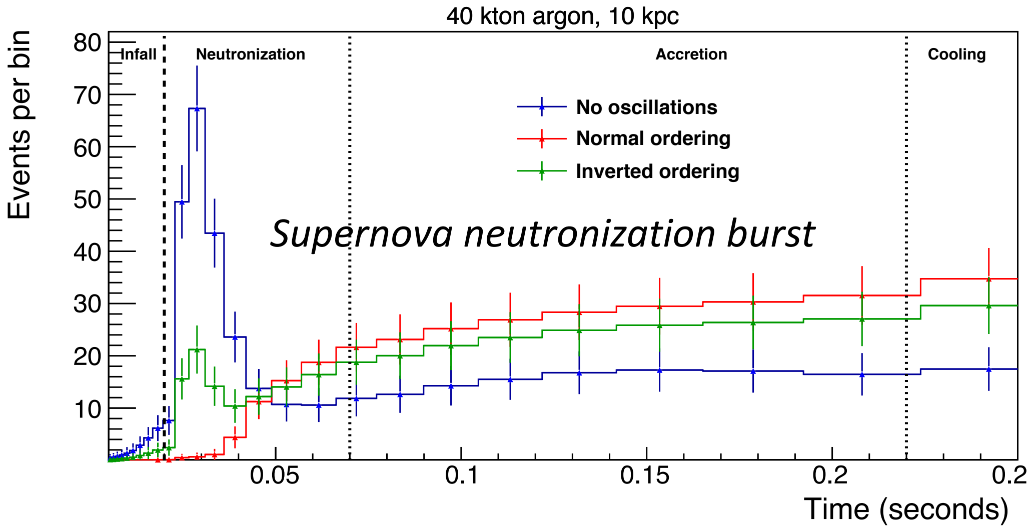
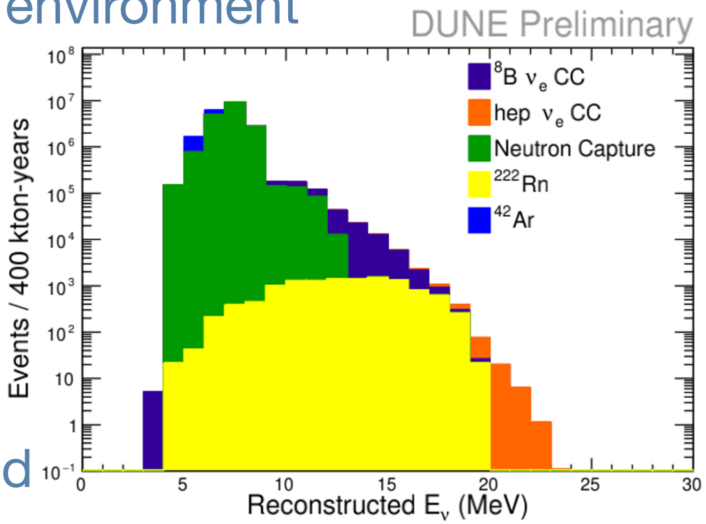
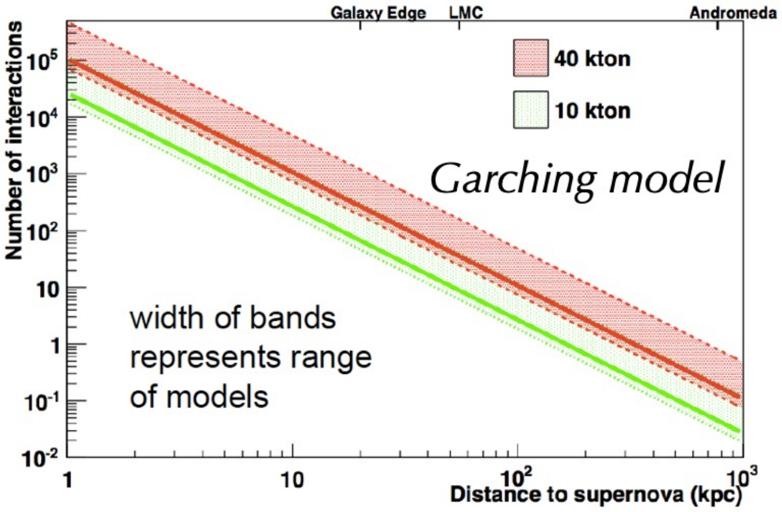
- The DUNE underground location allows for astrophysical neutrino measurements
- DUNE expects to detect several thousand events from a **galactic supernova burst** to learn about
  - Core-collapse mechanism
  - Black hole formation
  - Neutrino oscillations in extreme environment
  - Neutrino mass ordering
  - Absolute neutrino mass
  - …
- Sensitivity to **solar neutrinos**
  - ^{8}B and yet-unobserved hep solar neutrinos can be measured



Supernova neutronization burst





Garching model

width of bands represents range of models

DUNE Beyond the Standard Model searches

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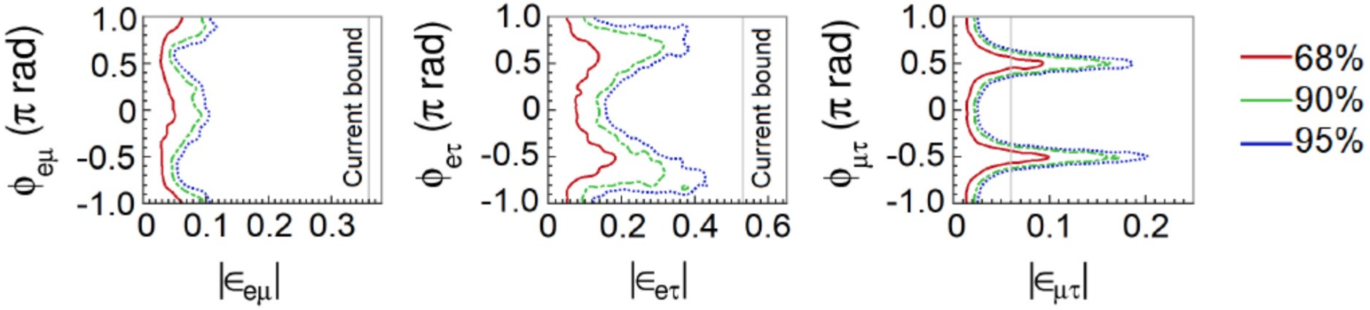
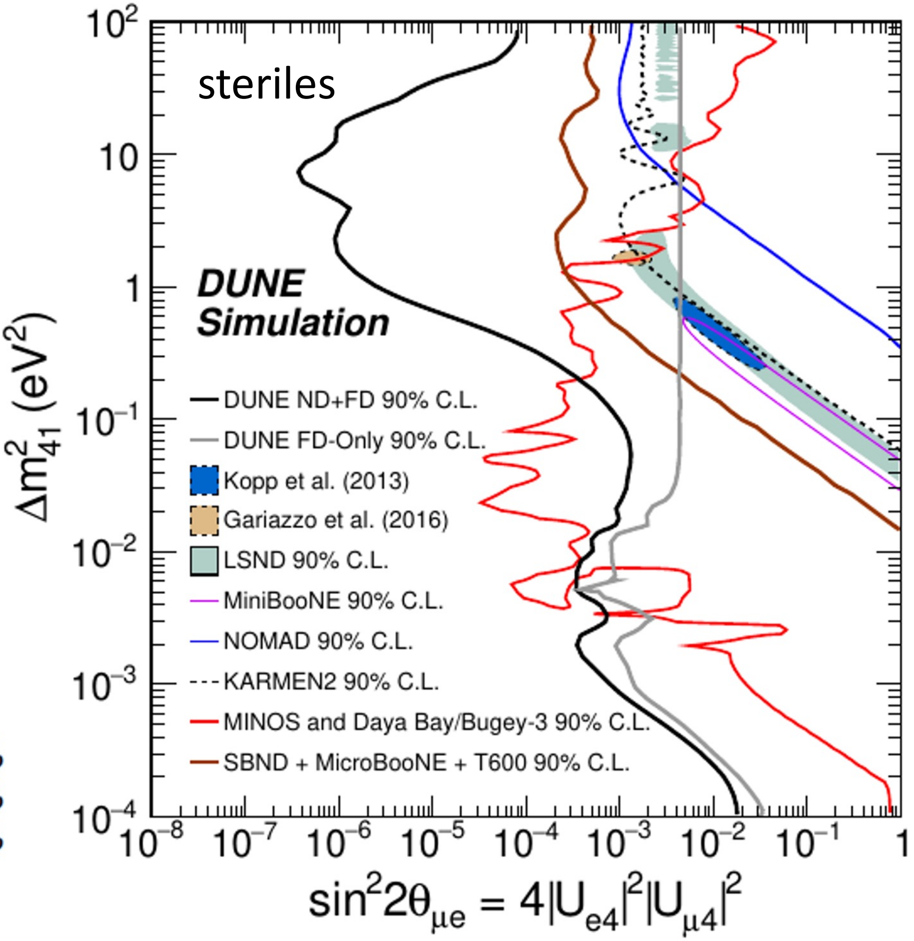
- Search for non-standard interactions
- CPT violation
- Sterile neutrinos
- Heavy-Neutral Leptons
- Dark Matter
- …

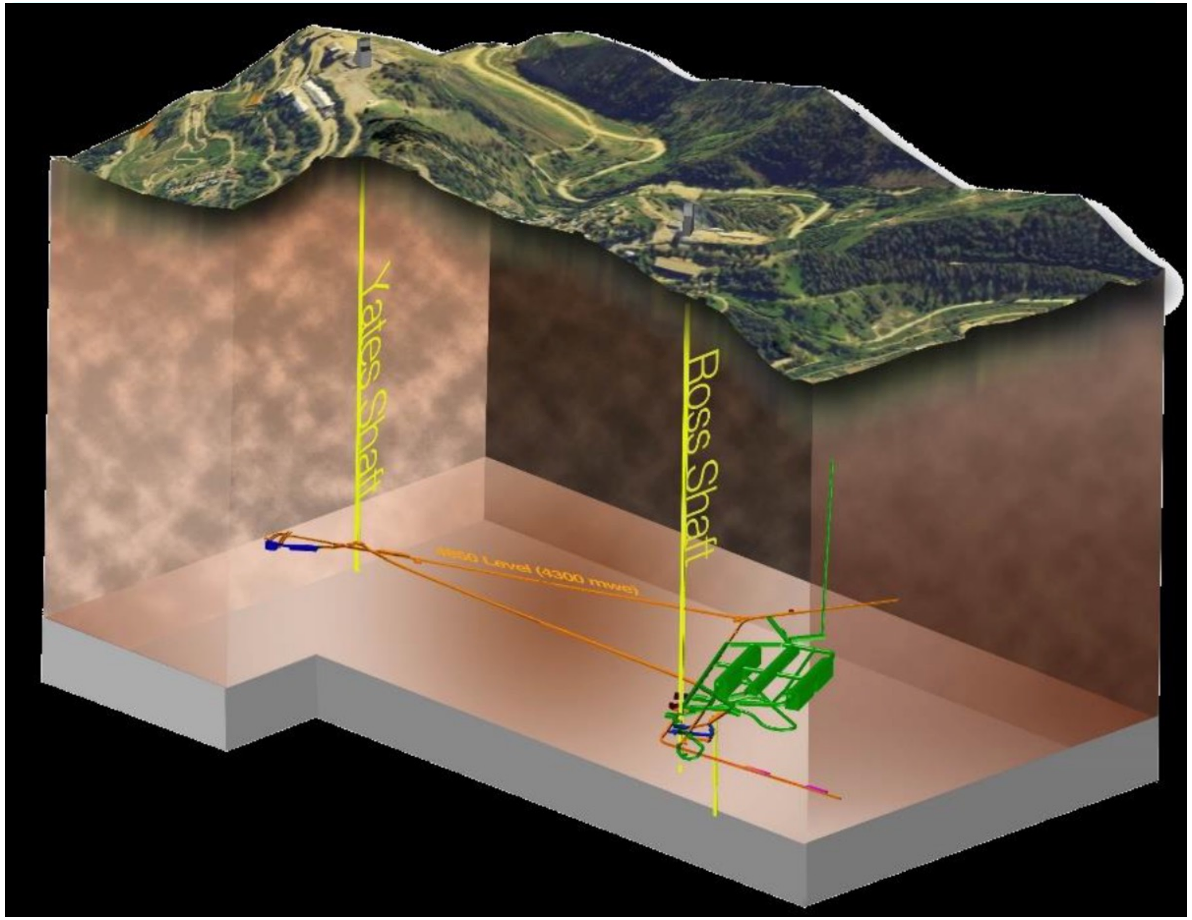
NSI



ν_e CC appearance



LBNF Far Site at SURF (South Dakota)



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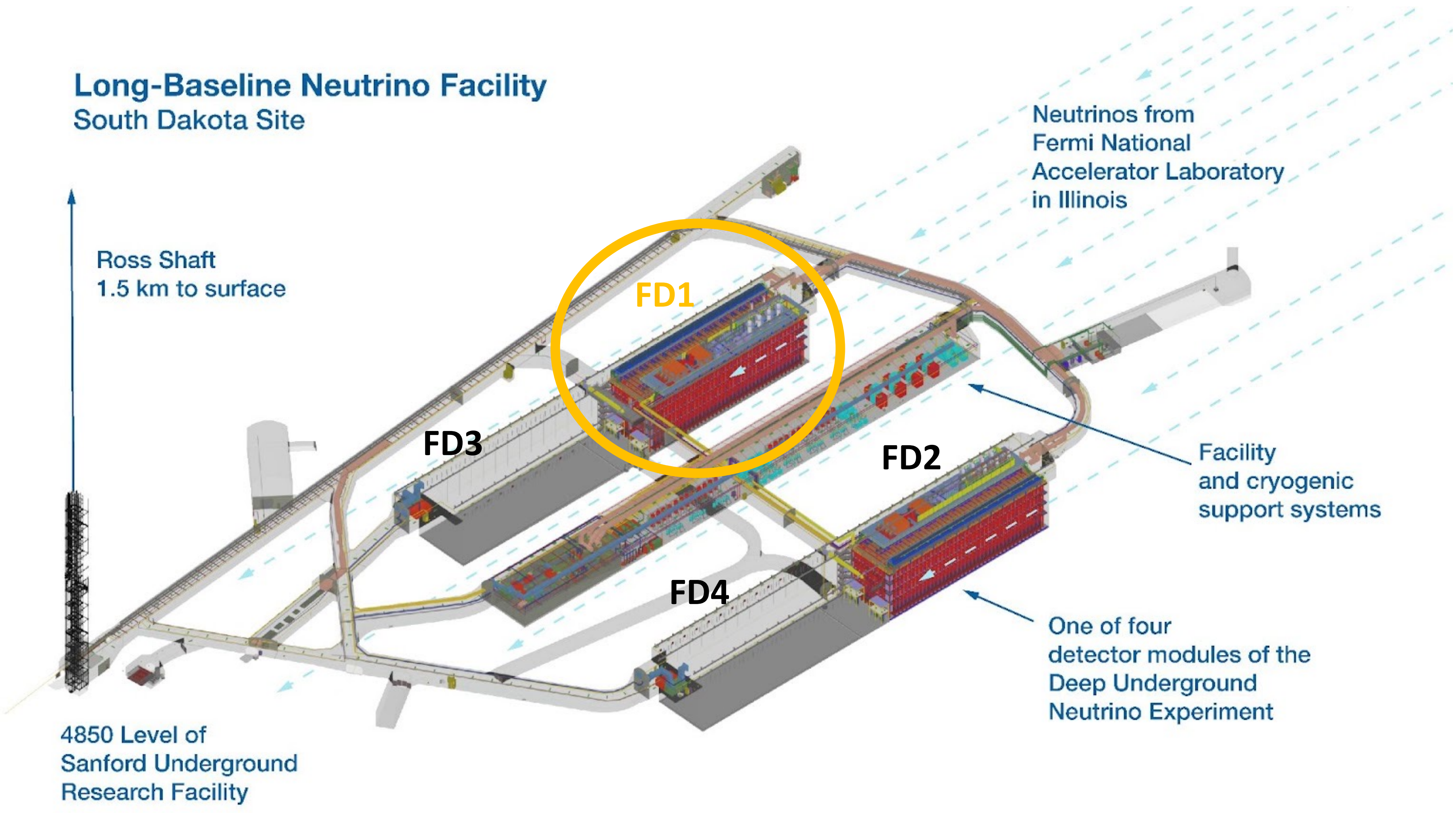
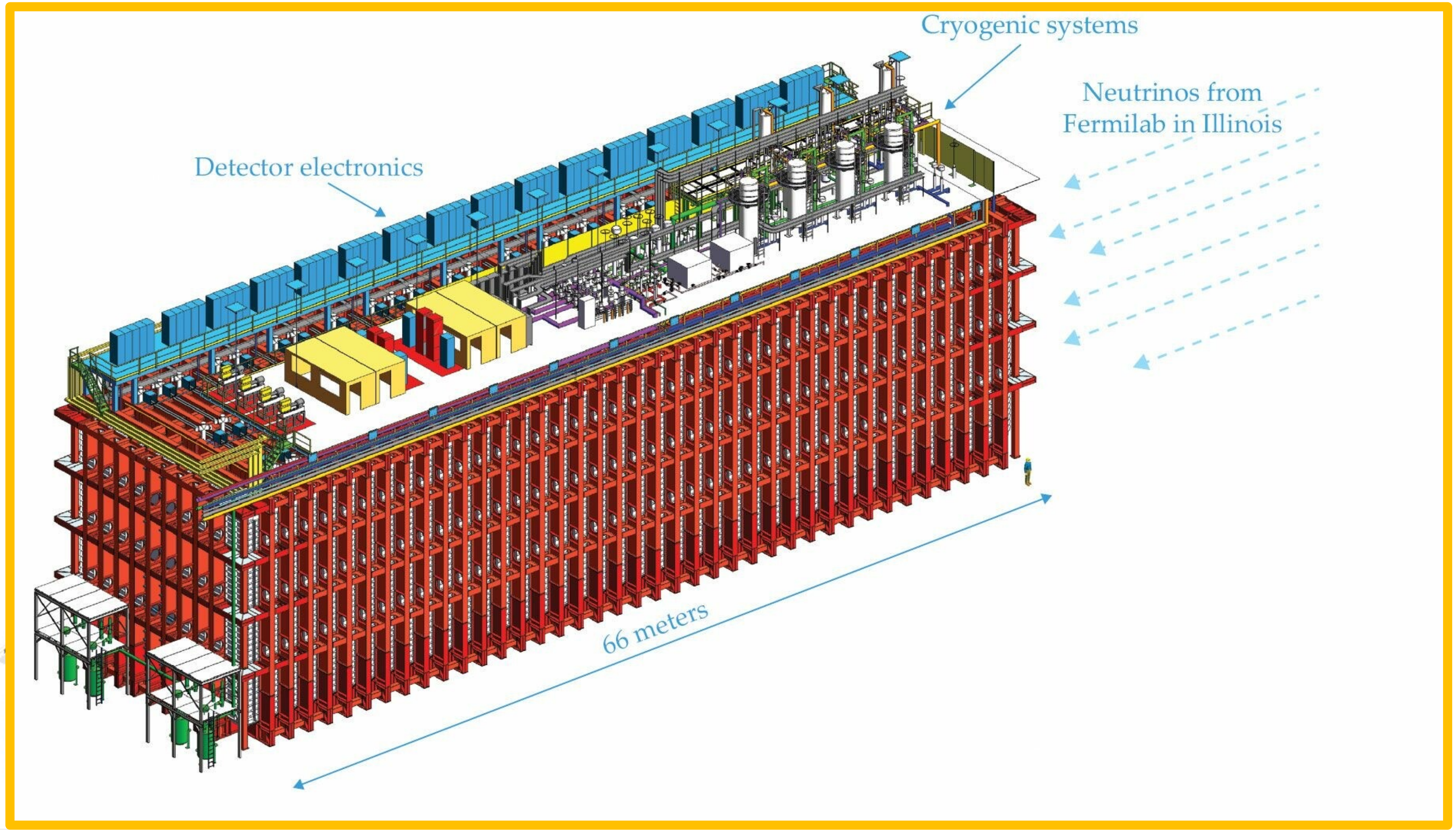


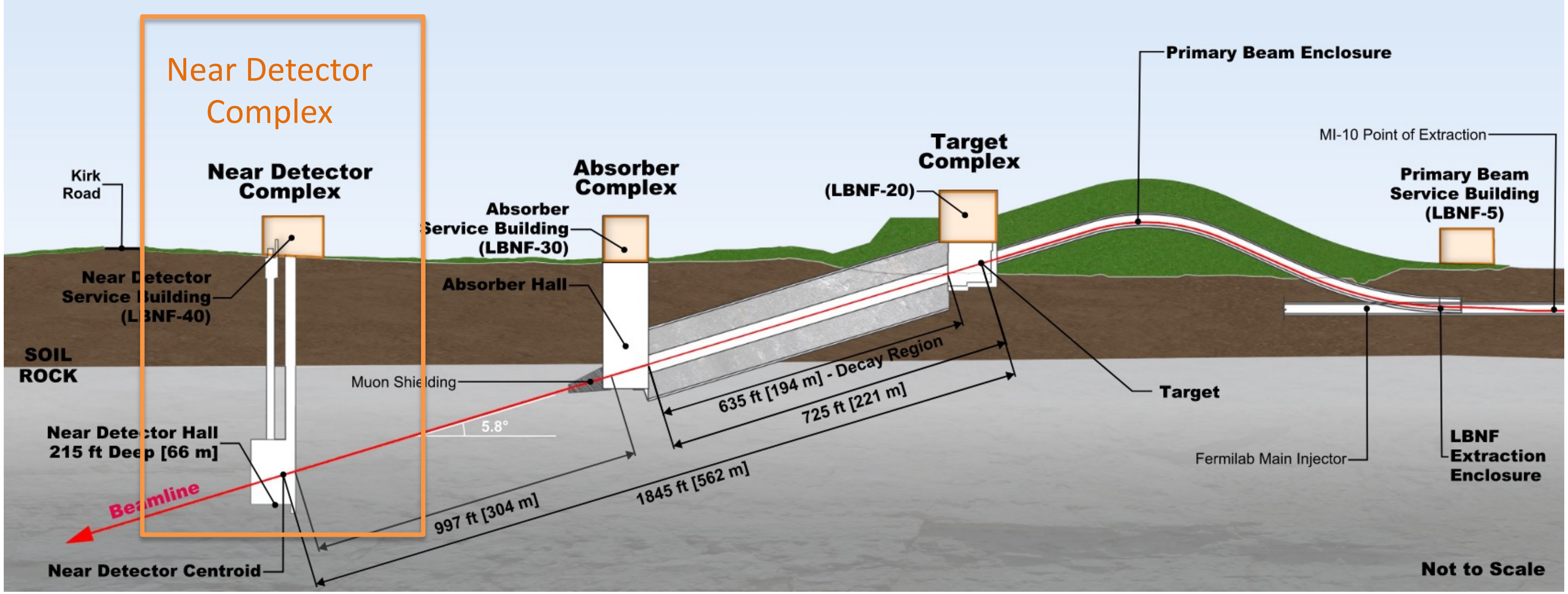
LBNF Far Site at SURF (South Dakota)



LBNF at Fermilab

PIP-II construction May 2022

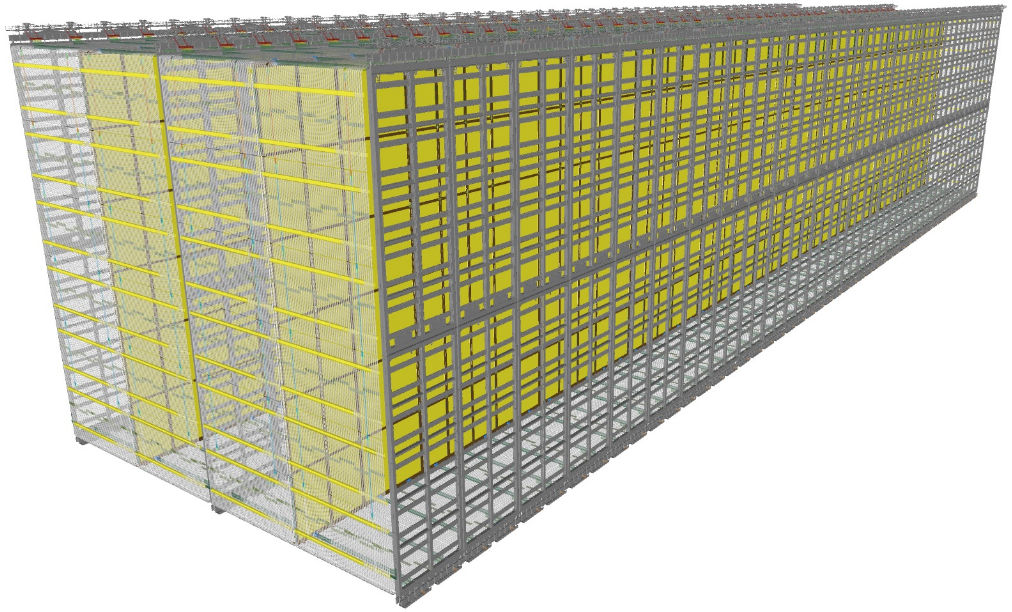
LBNF Near Detector Complex



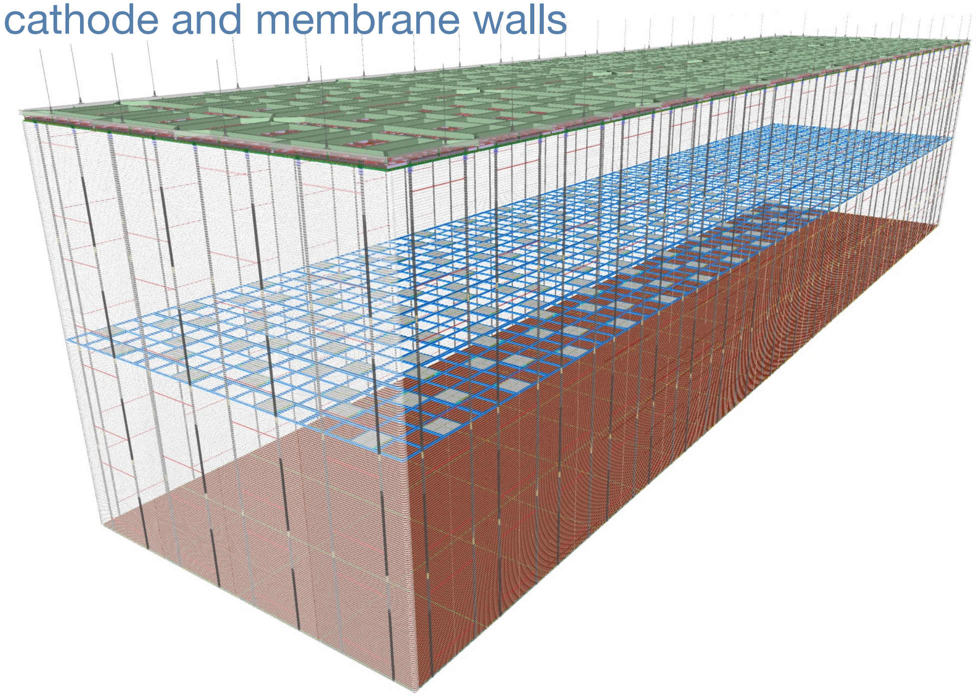
- **Where?** ND hall is located 560 m from proton target, 65 m deep, on-site at Fermilab
- **Why?** Purpose of the ND is to measure the rate & spectrum of neutrinos before they make their journey west and to the FD. The ND measures the neutrinos before oscillations.

DUNE Far Detectors

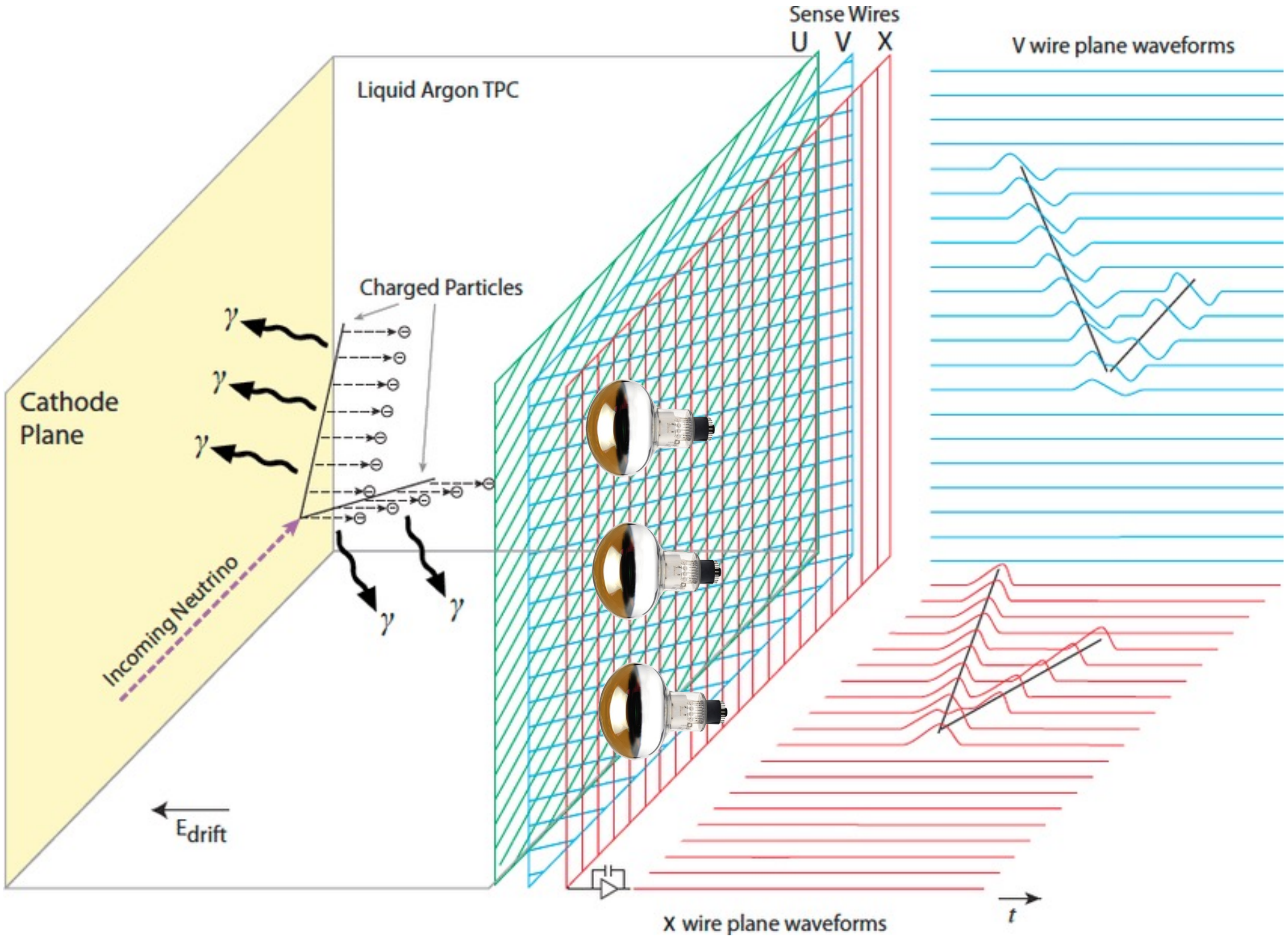
- **FD1: Horizontal Drift**
  - 3.6 m horizontal drift
  - Vertical anode wire planes
  - Vertical resistive cathode
  - Photon detectors (X-ARAPUCA light traps) inserted behind the wire planes



- **FD2: 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

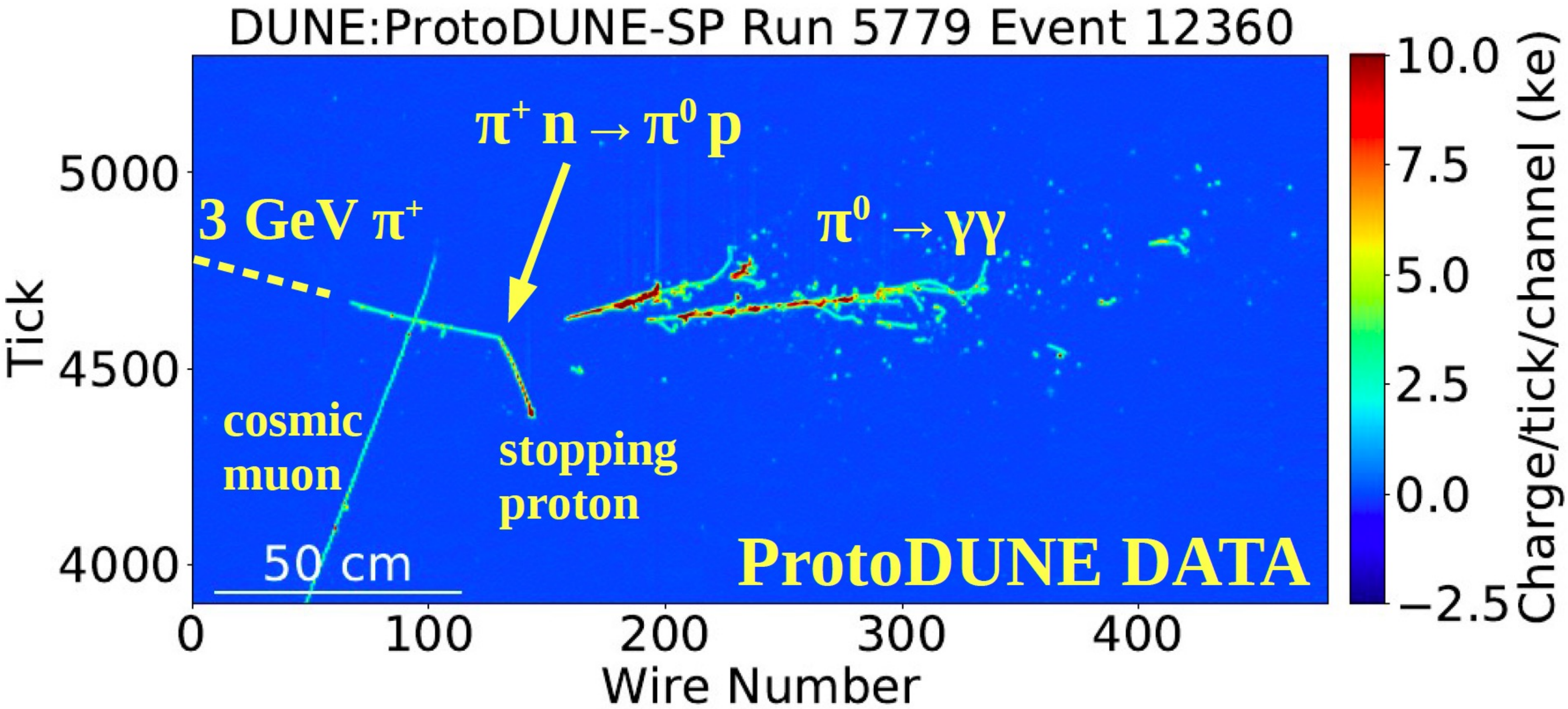


DUNE FD: LAr TPCs

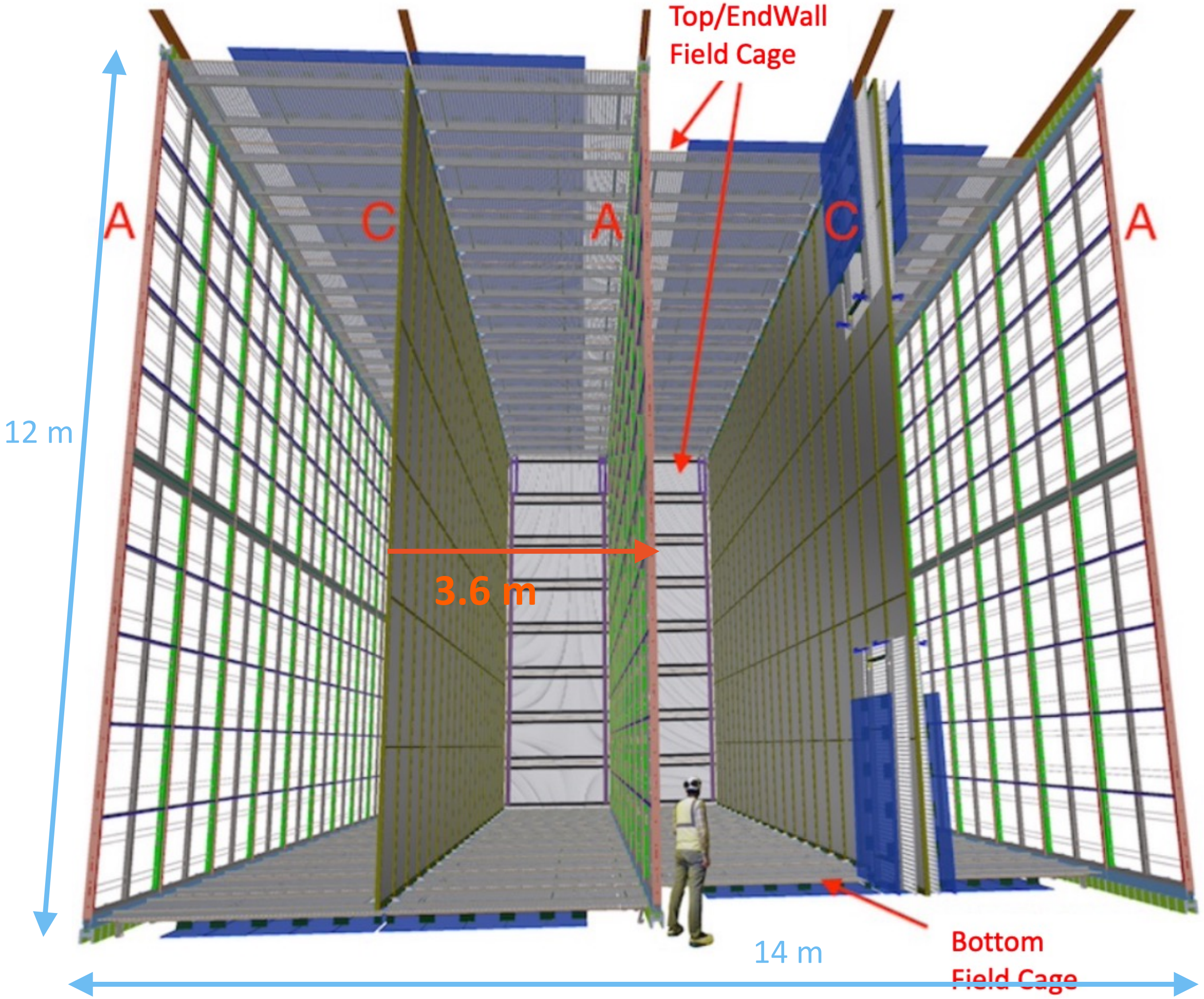


- A charge particle interacting in LAr creates:
  - **Ionization electrons** (~42k ion-electron pairs/MeV) drifted to the anode readout thanks to an electric field and then collected and readout by wires/pixels
  - Fast **scintillation signals** (~40k γ/MeV) collected by photodetectors
- 3D reconstruction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

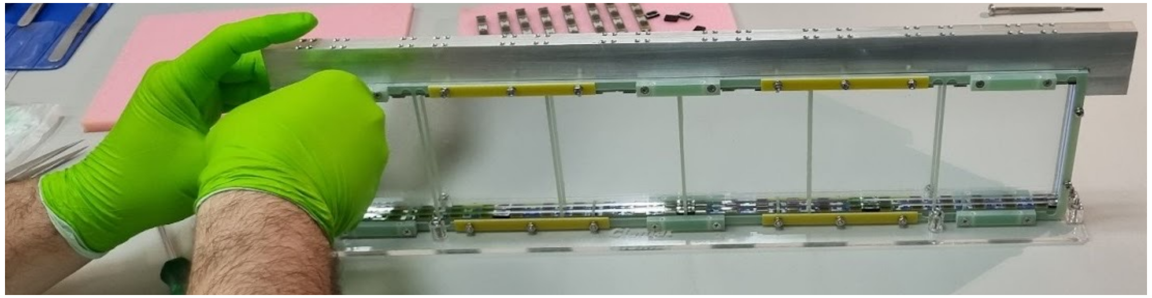
LArTPC events



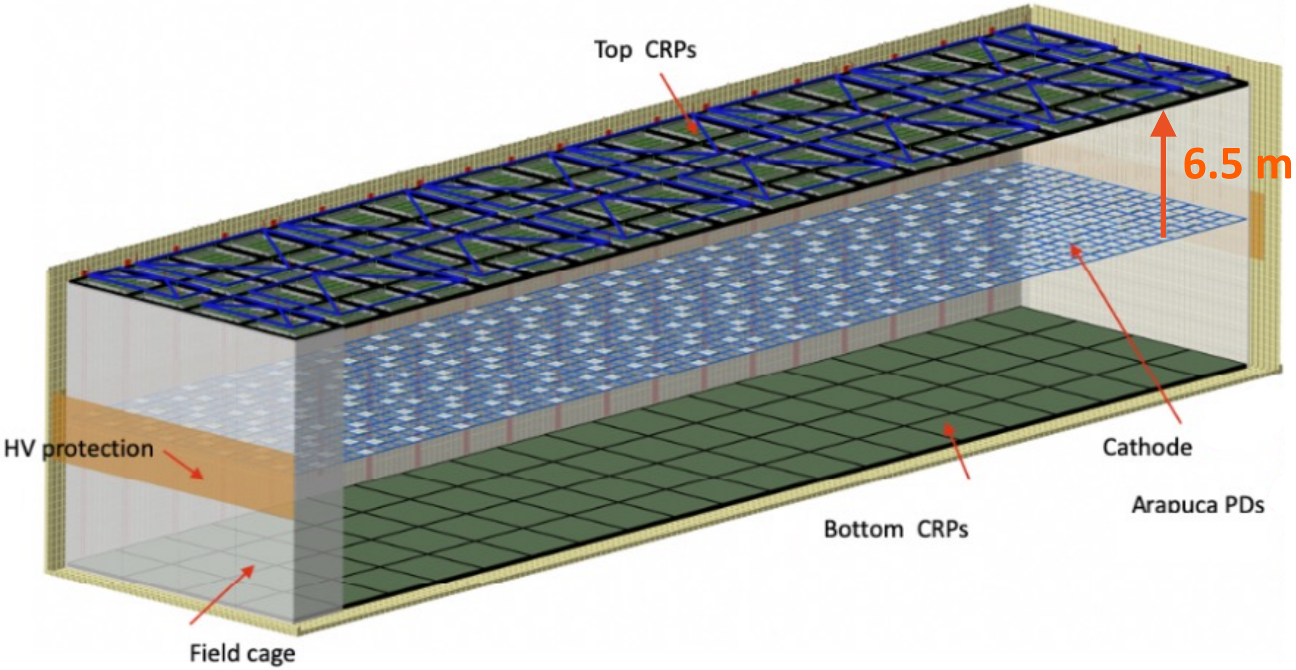
FD1 Horizontal Drift



- 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

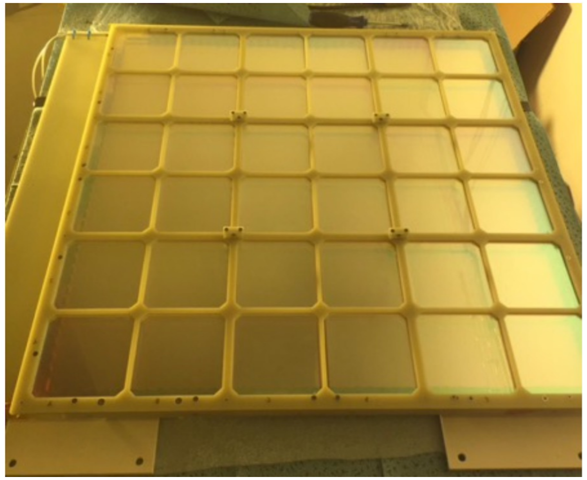


FD2 Vertical Drift



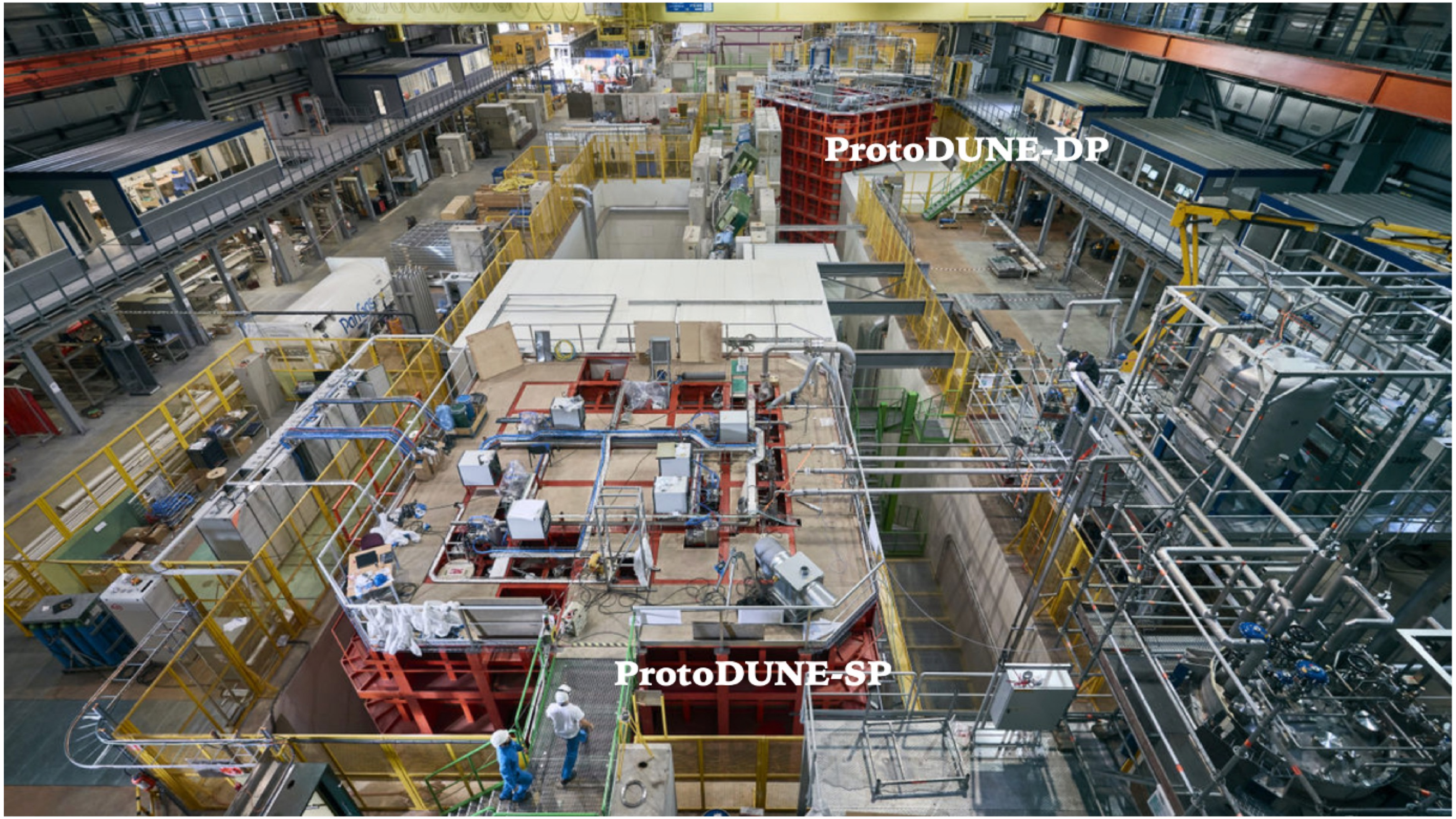
Charge Readout Plane (CRP)

X-ARAPUCA tile (PDS)



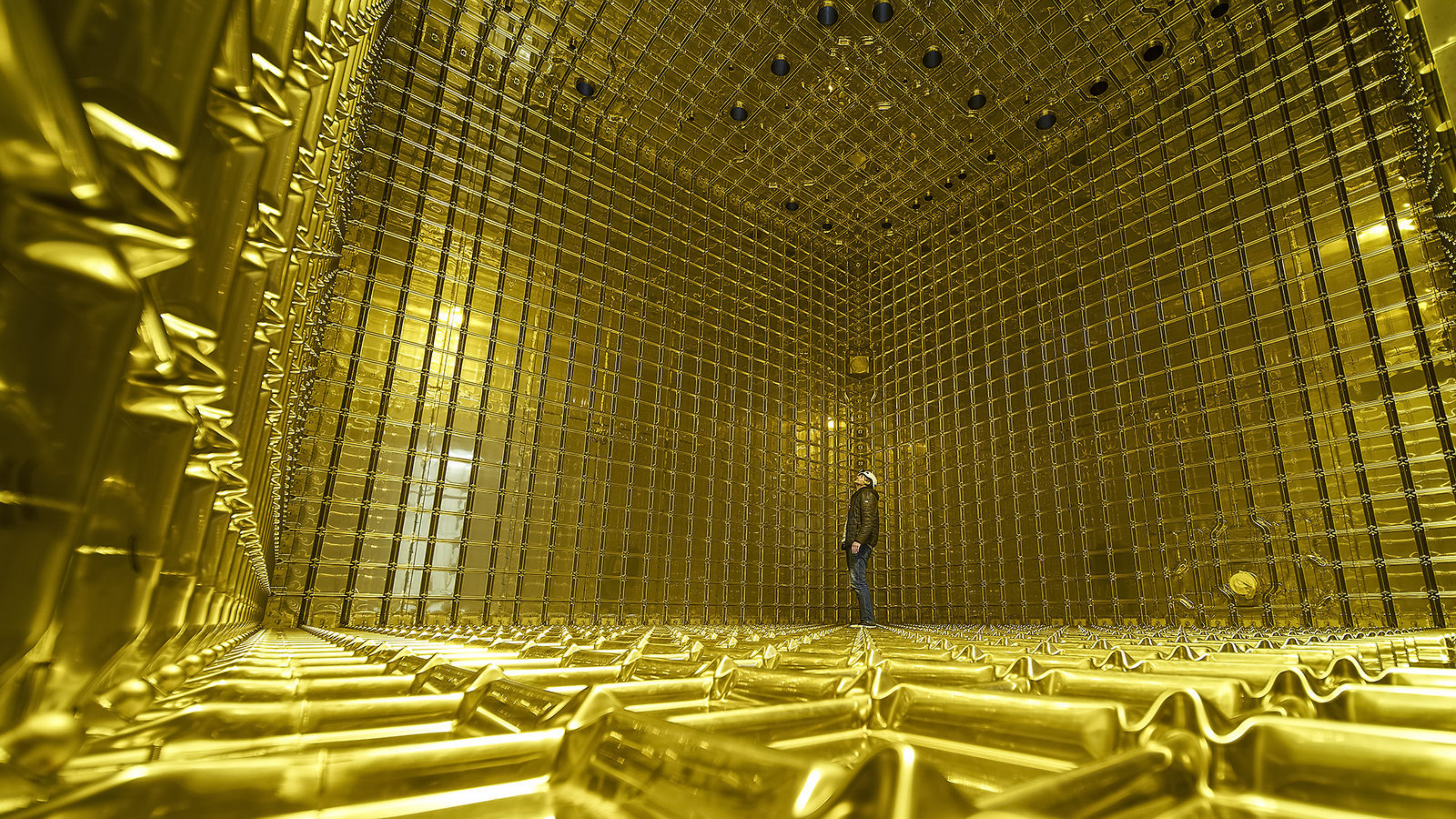
- Simpler design: 1 cathode + 2 anode planes
- 2 drift volumes (6.5 m drift distance x 13.5 m x 60 m)
- Same drift field → Cathode HV = -300 kV
- 320 CRP units with perforated PCB's with segmented electrodes (strips)
- Photon Detectors: 640 XAs (60 x 60 cm^2 each)

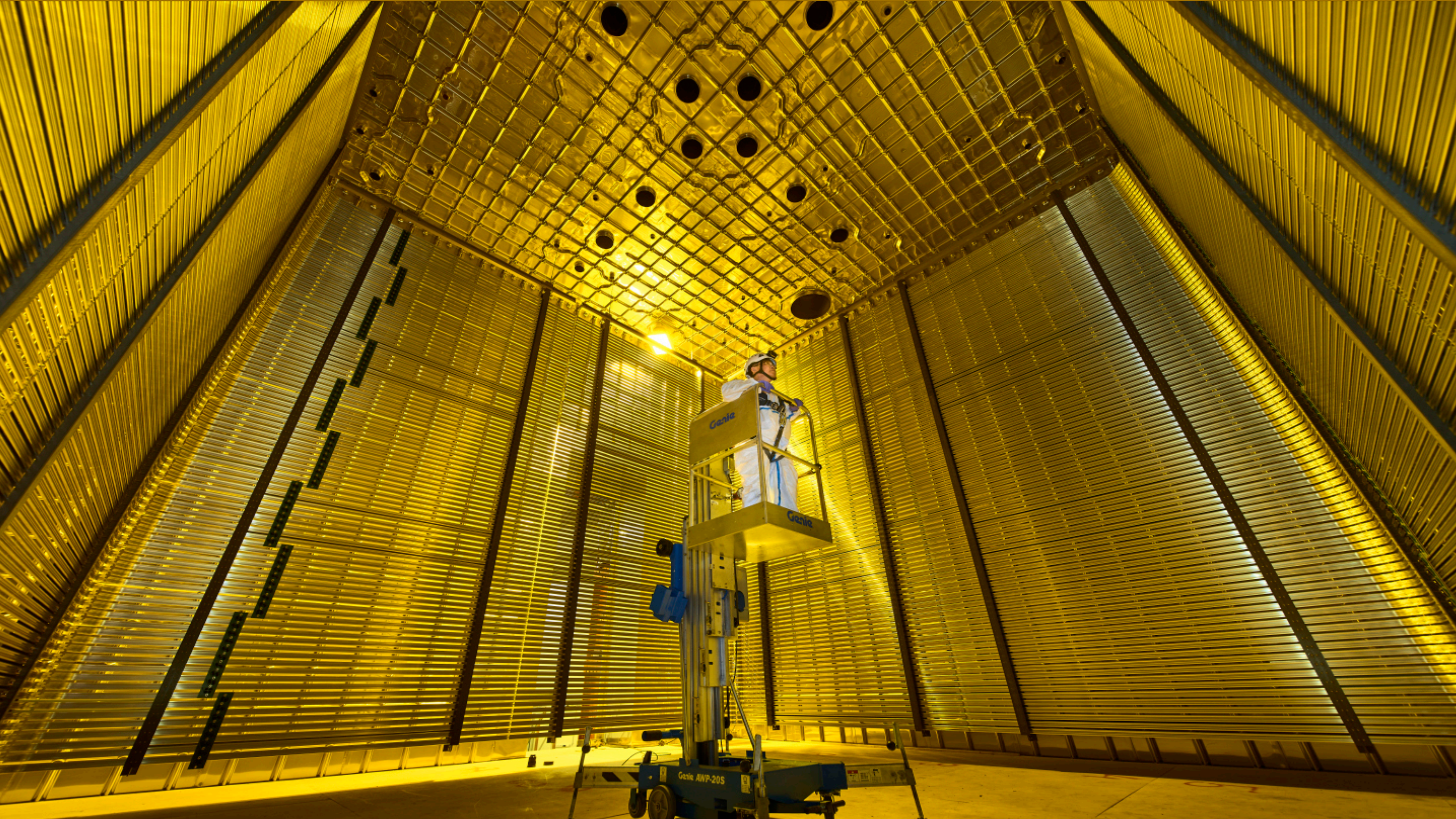
ProtoDUNEs at CERN (2017-2020)



ProtoDUNE/DUNE
~1:20

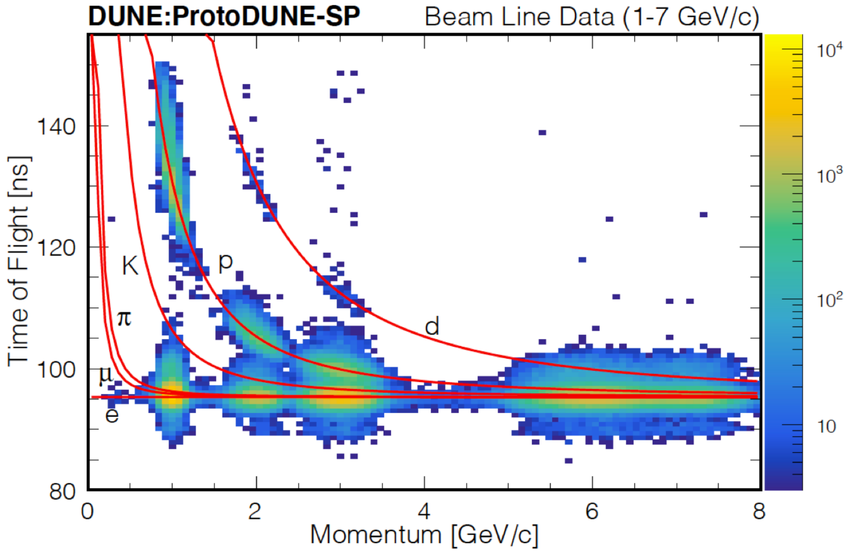
Full scale DUNE
TPC components

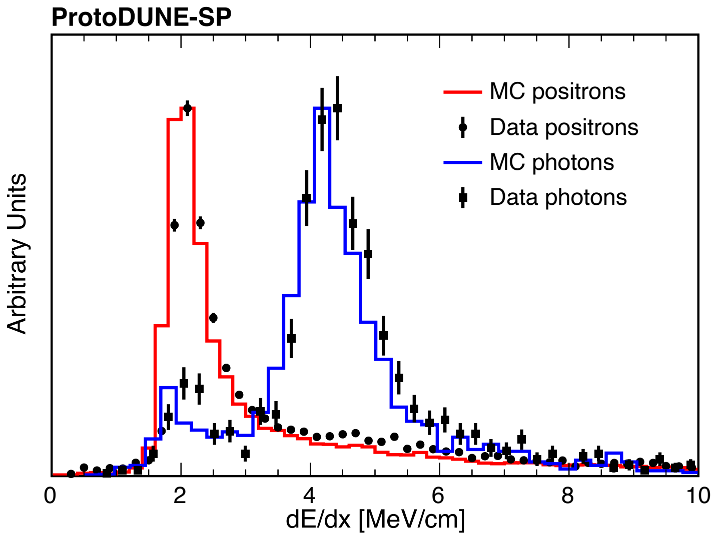


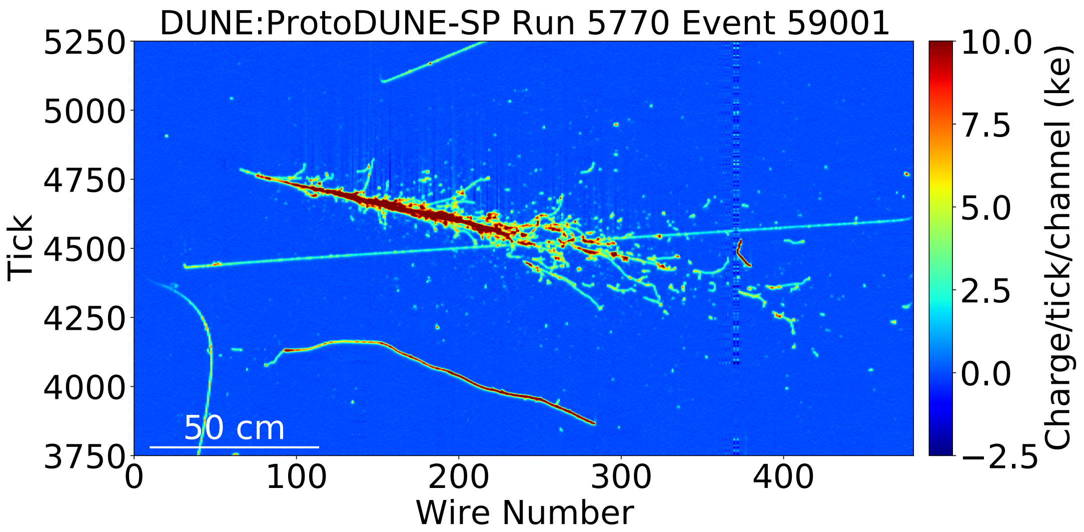

Genie
Genie
Genie AWP-20S

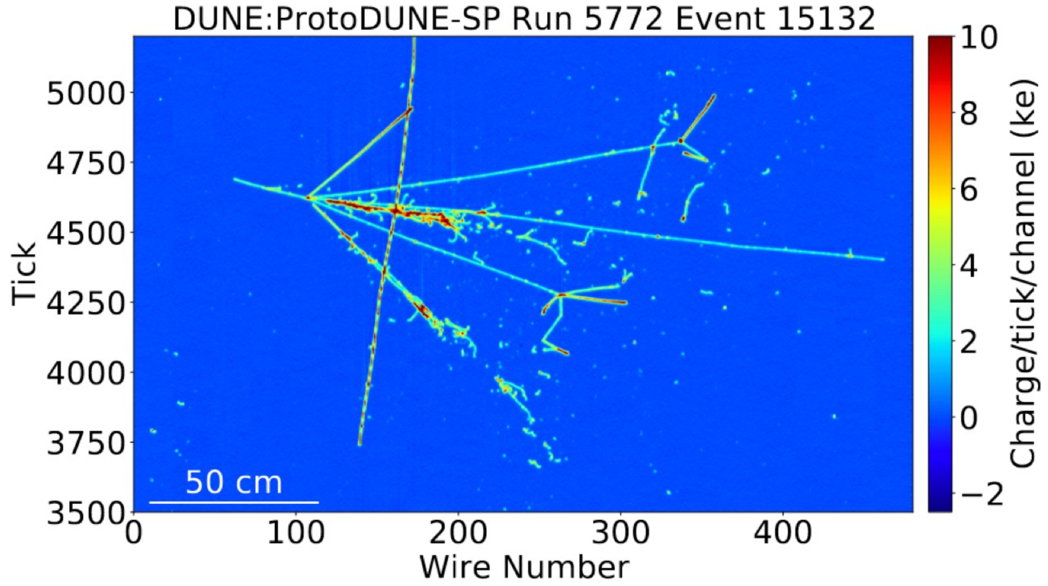

JLG
20MVL

ProtoDUNEs at CERN





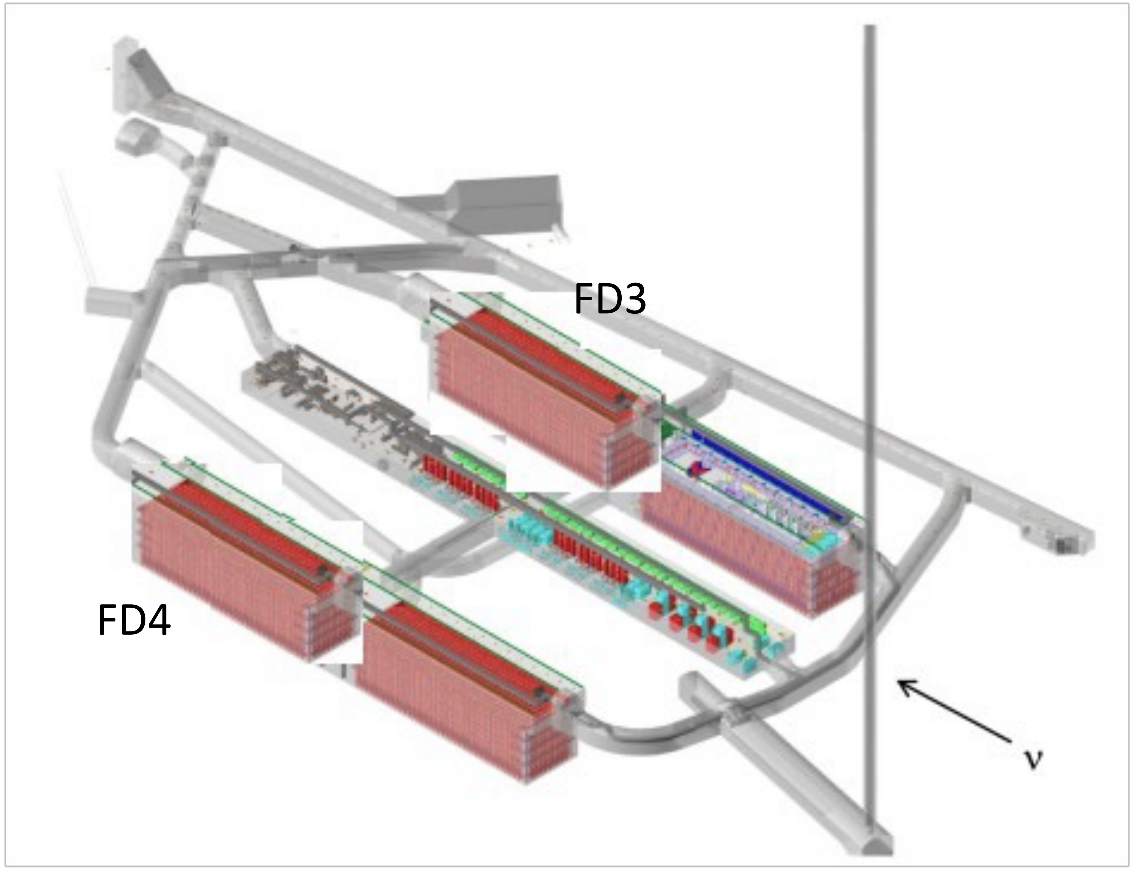




ProtoDUNEs at CERN

- Dual-Phase has evolved towards a single-phase vertical (VD) drift technology for FD2
  - Charge Readout Planes immersed in LAr
  - Same photon detection system as for ProtoDUNE-SP
- **ProtoDUNE-II HD (2022-2024):**
  - Final technical solutions for all FD1 subdetectors
  - ProtoDUNE-II installation and data taking in 2022-2023 with test-beam and cosmic muons
- **ProtoDUNE-VD (2022-2024):**
  - Realization of a Module-0 detector in 2022-2023 and data taking in 2023-2024

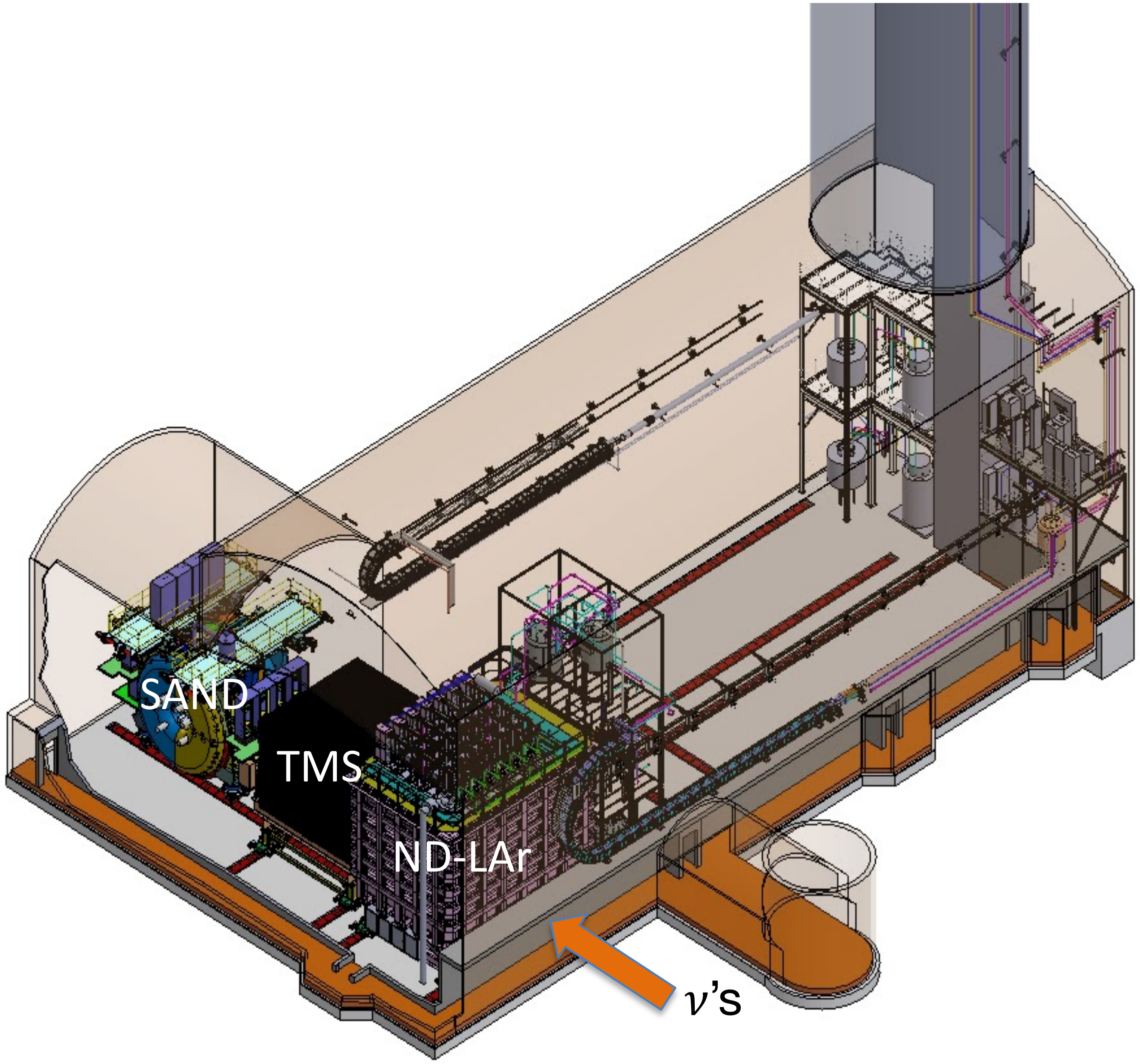
FD Modules of opportunity to enhance physics



- DUNE requires 4 FD modules (at least 40 kt fiducial mass) to achieve the physics goals
- 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…)
  - Lower energies
  - Lower backgrounds
- Many ideas being discussed
  - Qpix/LArPix and light collection
  - photosensitive dopants to convert light to ionization, Xe-doping
  - background reduction with shields, purification, low radioactive Ar, etc.

DUNE Near Detectors

CDR: Instruments 5 (2021) 4, 31

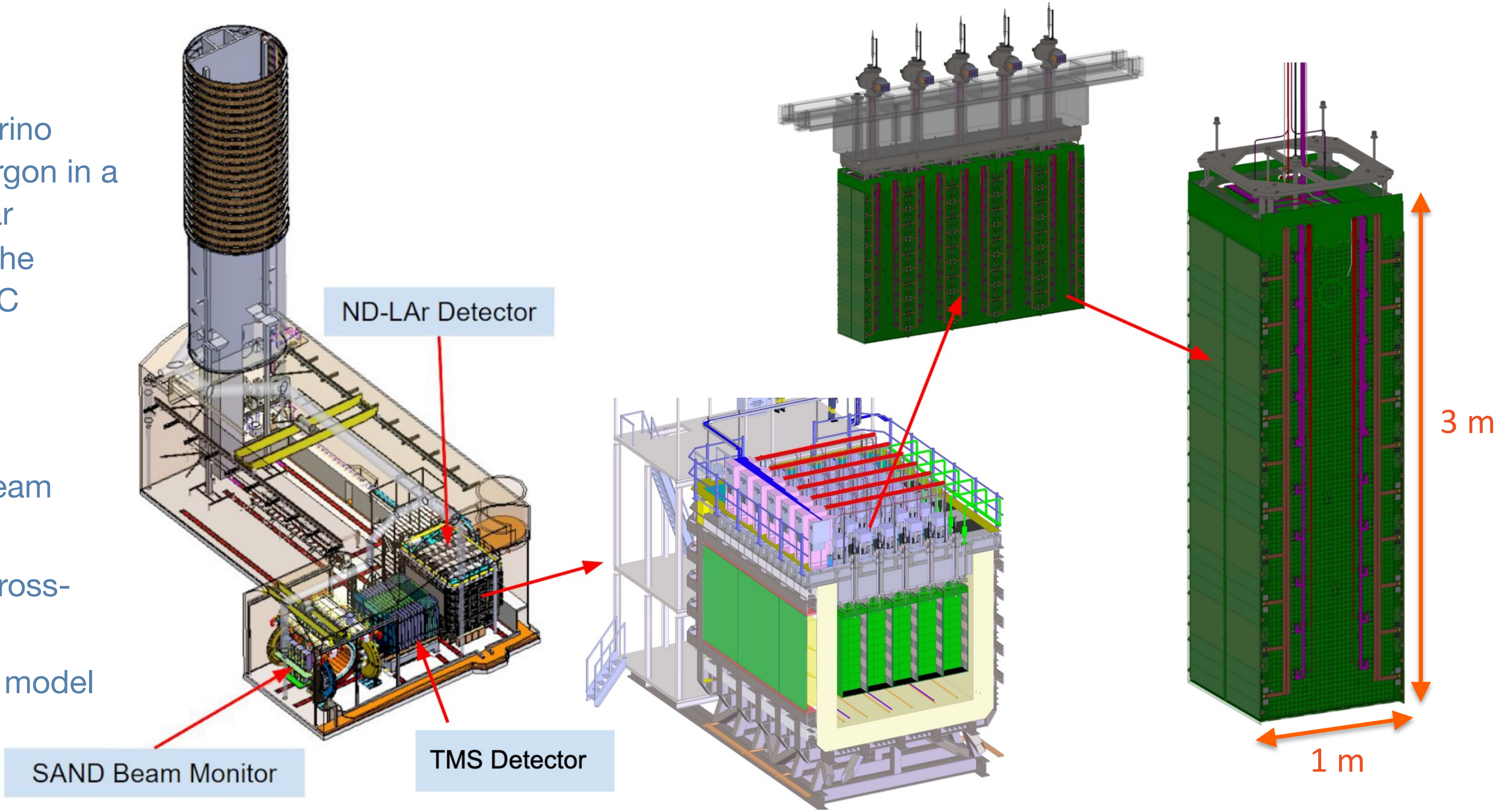


- Near Detector Complex: prediction of the far detector spectrum, systematic uncertainties constraints and beam monitoring
  - **ND-LAr** (liquid argon TPC near detector) + **TMS** (The Muon Spectrometer): can be moved off-axis (**PRISM**)
  - **SAND** (System for on-Axis Neutrino Detector): on-axis detector; monitoring beam stability and measurement of neutrino interactions

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

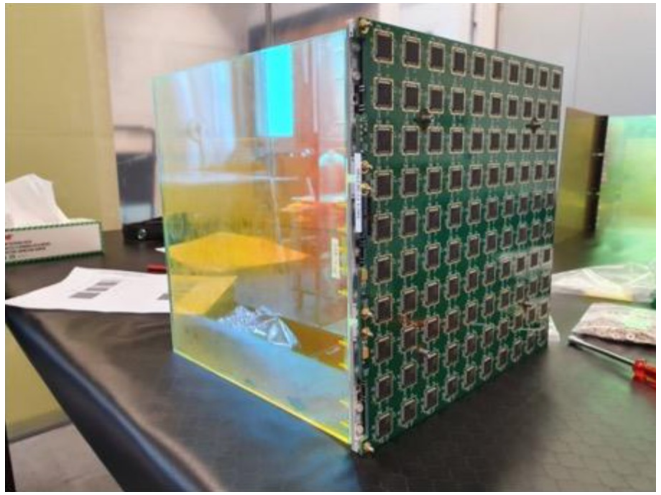


35 TPC modules, arranged in 7 banks each of 5 modules

ND: ND-LAr prototype at FNAL

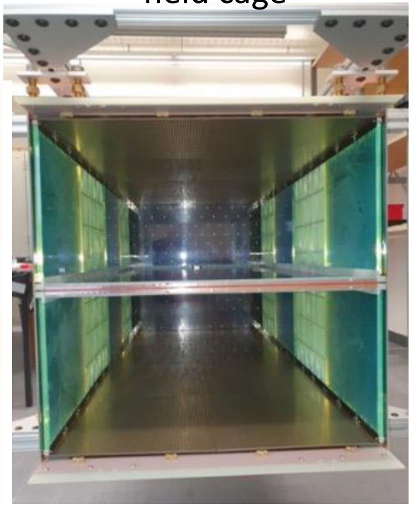
- Four ton-scale prototype TPC modules: **ArgonCube 2x2** LArTPCs at FNAL
- Each TPC Module:
  - Active Size: 0.7m x 0.7m x 1.25m
  - 16 pixel tiles, with ~80 k pixel channels total
  - 16 light collection modules, with 96 light sensors (SiPMs)
  - Resistive-film-on-fiberglass field cage
- 2x2 NuMI Test Beam Facility (FNAL) in progress of construction
- 2x2 Operation in NuMI Neutrino Beam: 2022-2025

Single pixel tile & light module assembly

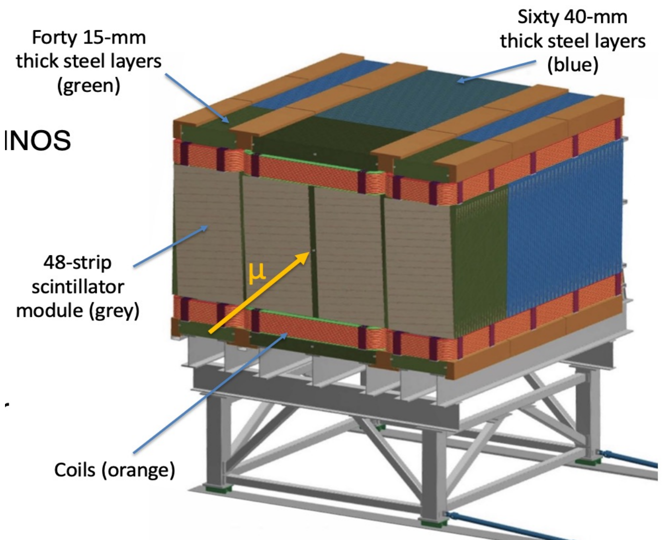


One anode full assembled

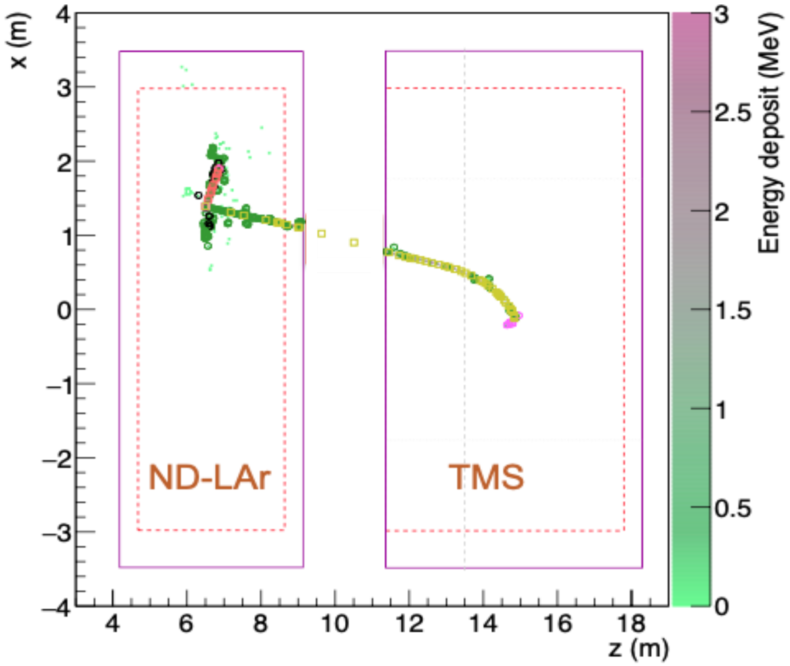
Two anodes inside the field cage



ND: TMS



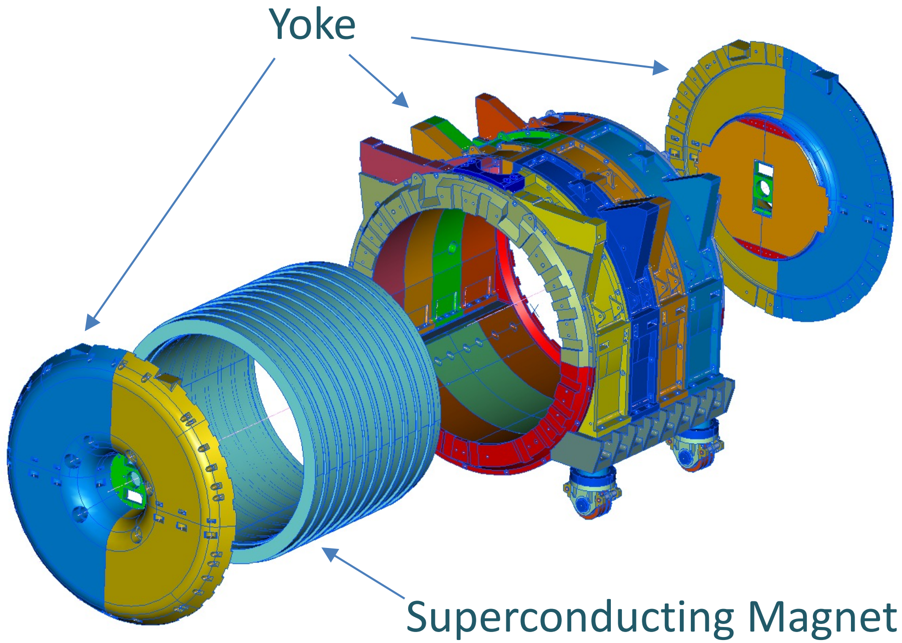
~ 7m (height) x 5m (width) x 7m (deep)

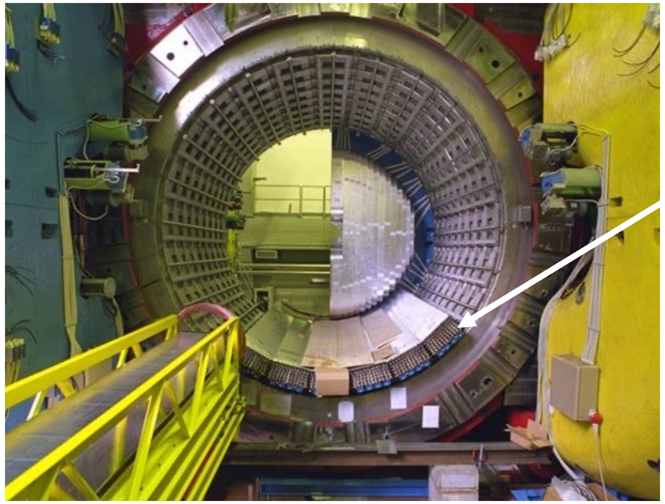


- Primary role
  - muon catcher for the LAr TPC so that the ND can match FD performance
  - sign selection (μ^+, μ^-)
- Secondary role
  - Day 1 beam monitor
  - gets a beam monitor in place in support of the FD as quickly as possible after beam turns on which allows us to get neutrino beam physics started

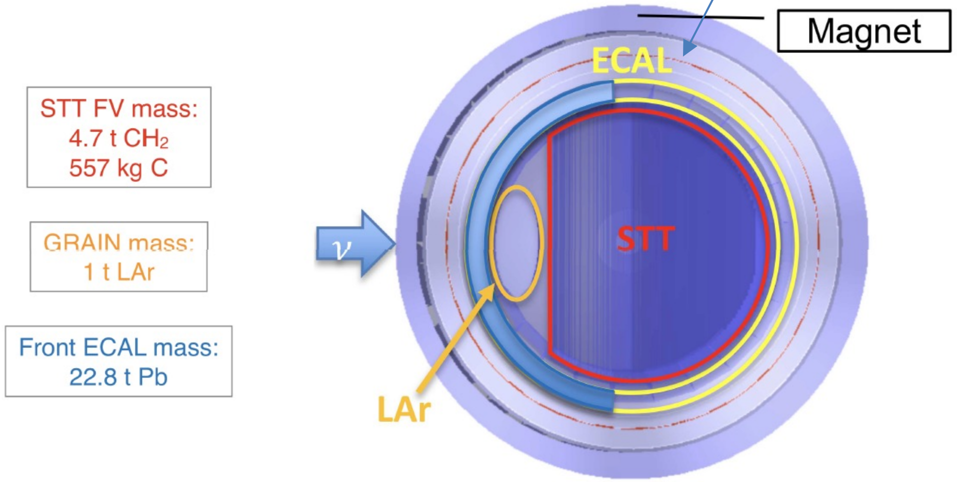
ND: SAND

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)



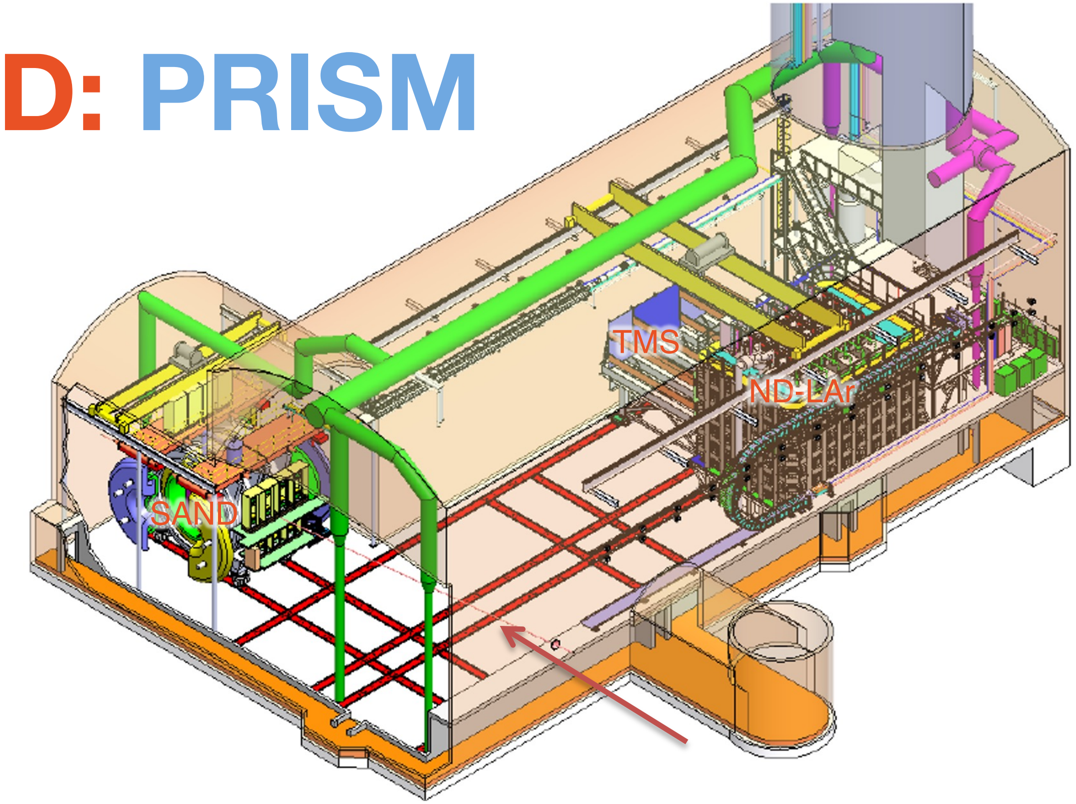
STT FV mass: 4.7 t CH_2 557 kg C

GRAIN mass: 1 t LAr

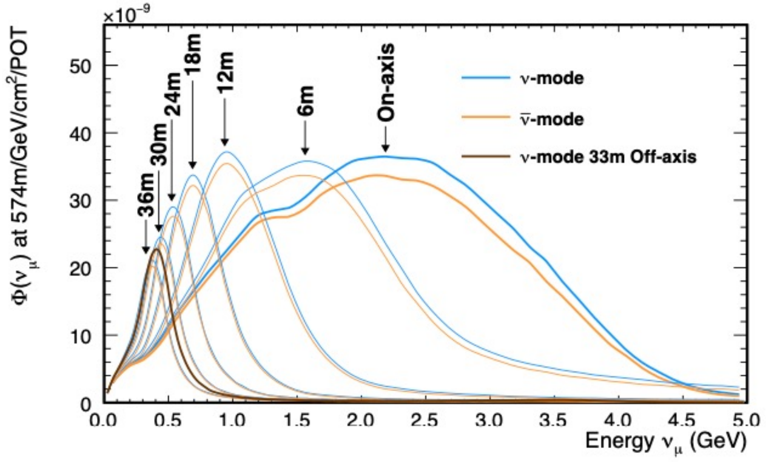
Front ECAL mass: 22.8 t Pb

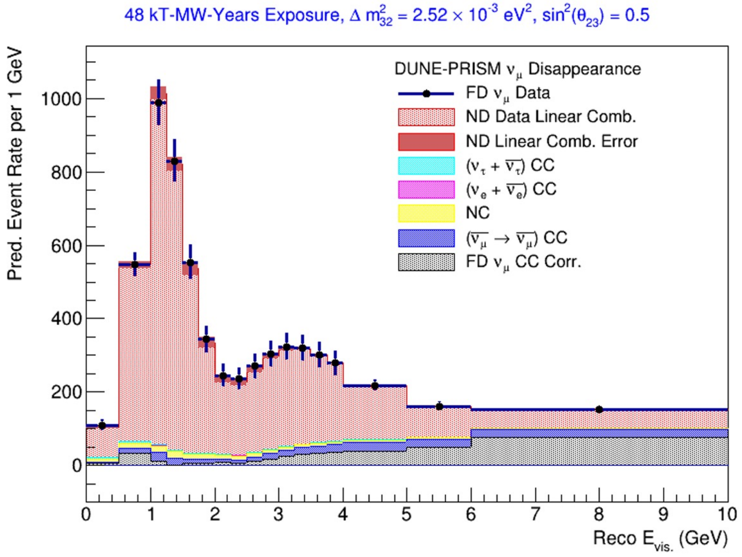
- The yoke, the magnet and the ECAL are repurposed from the KLOE detector.
- The STT and GRAIN are new detectors, to be engineered and built.

ND: PRISM



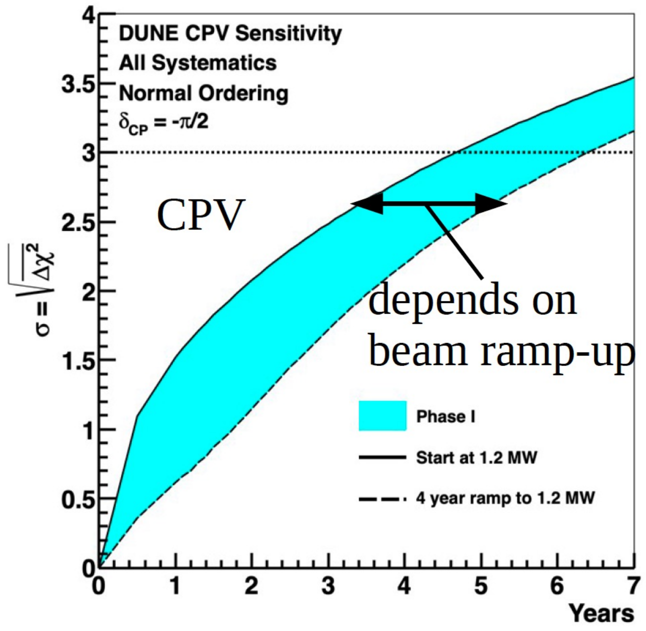
- ND-LAr + Spectrometer can be moved off-axis to enhance flux at lower energies
- These samples allow one to build a linear combination to match FD *oscillated* spectra and build analysis with minimal interaction modeling





DUNE phases

- **Phase I:**
  - FD1 (2024-2026): start of installation; FD2 one year later
  - **Start science with 2 FDs in 2029**
  - Start **oscillation physics** with 1.2 MW beam in **2031** + ND complex (ND-LAr, TMS, SAND, PRISM) in 2031
    - 5σ mass ordering sensitivity in ~1-4 years (depending on the true value of δ_{CP}) and 3σ observation of maximal CP violation
- **Phase II** (ultimate science capabilities):
  - FD3/4 + upgrades ND (TMS → ND-GAr) + 2.4 MW beam
    - 5σ CPV for 50% of δ_{CP} and precision δ_{CP}, Δm^2_{32}, θ_{23}, θ_{13}



Conclusions

- DUNE is the **best-in-class neutrino experiment** for **precise 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
- DUNE provides a **full exciting physics and technology program for the next decades**

Join us!!

Grazie!
Thanks!