The Road to DUNE

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SLAC Summer Institute

23 August 2017

THE UNIVERSITY OF CHICAGO

DUNE

First DUNE Collaboration Meeting

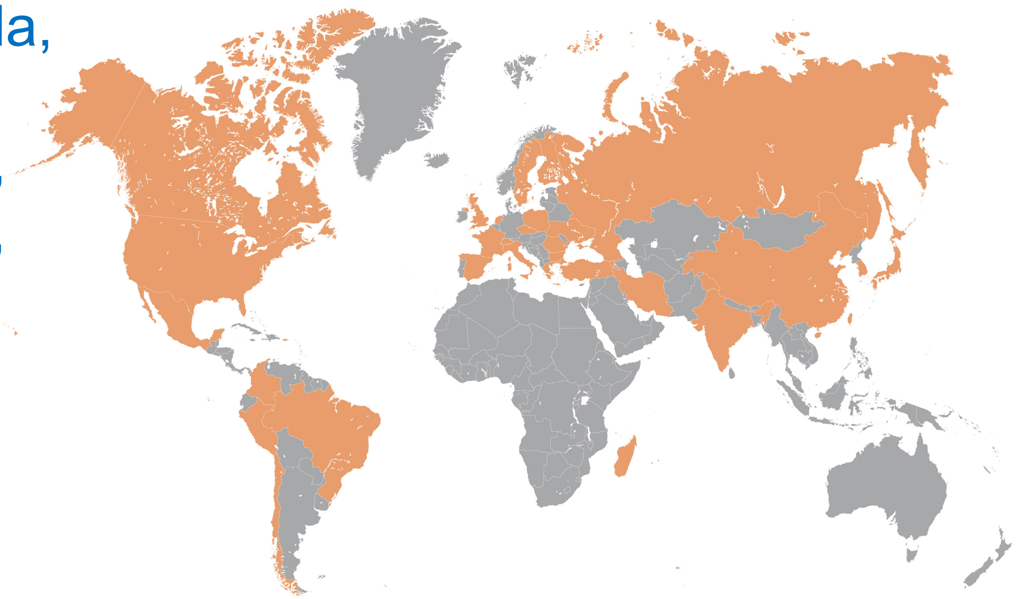
The DUNE Collaboration

As of today:

60 % non-US

1056 collaborators from 175 institutions in 31 nations

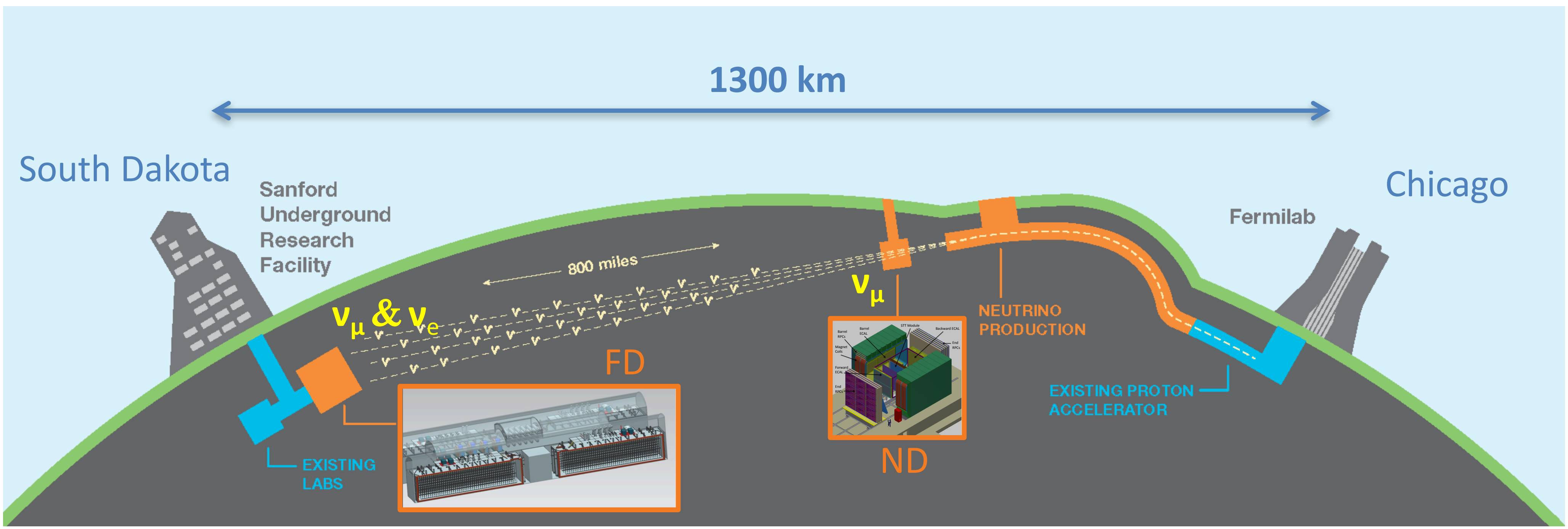
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, France, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA



DUNE: a fully international science collaboration
LBNF (Long Baseline Neutrino Facility): US(DOE)-hosted project with international contributions

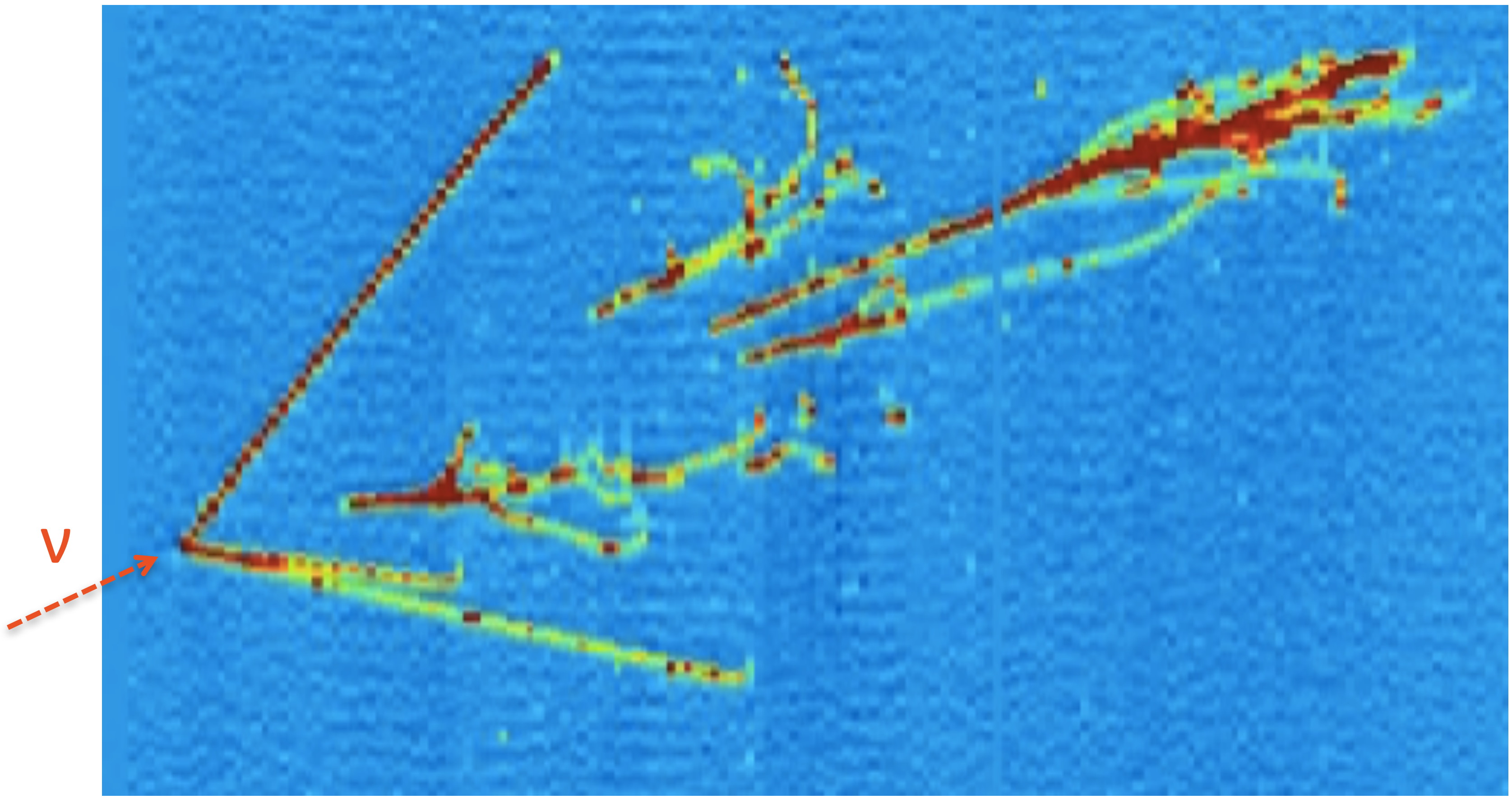
LBNF/DUNE Overview

- Muon neutrinos/antineutrinos from high-power proton beam
  - **1.2 MW** from day one; upgradeable to 2.4 MW
- Massive underground Liquid Argon Time Projection Chambers
  - **4 x 17 kton** fiducial mass of > 40 kton
- Near detector to characterize the beam (100s of millions of neutrino interactions)



DUNE Science

Combination of world's most intense neutrino beam, a deep underground site, and massive LAr detectors enables broad science program addressing some of the most fundamental questions in particle physics.



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DUNE Science Program

- Neutrino Oscillation Physics
  - **Search for leptonic (neutrino) CP Violation**
  - Resolve the mass hierarchy ($m_3 > m_{1,2}$ or $m_{1,2} > m_3$)
  - Precision oscillation physics
    - Parameter measurements, θ_{23} octant
    - **Testing the current 3-neutrino model, non-standard interactions, …**
- Nucleon Decay
  - Particularly sensitive to $p \rightarrow K^+ \overline{\nu}$ (SUSY motivated)
- Supernova burst physics and astrophysics
  - 3000 ν_e events in 10 sec from SN at 10 kpc

+ many other topics (ν interaction physics with near detector, atmospheric neutrinos, sterile neutrinos, WIMP searches, Lorentz invariance tests, etc.)

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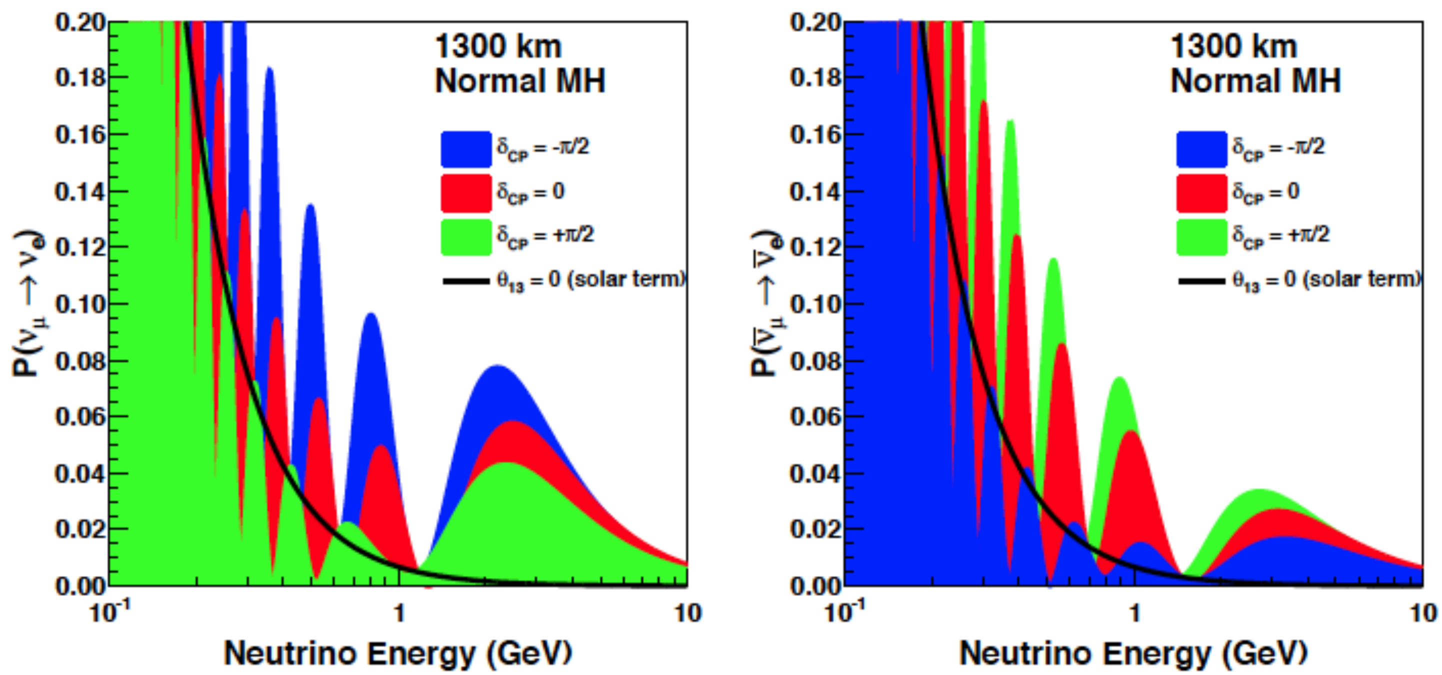
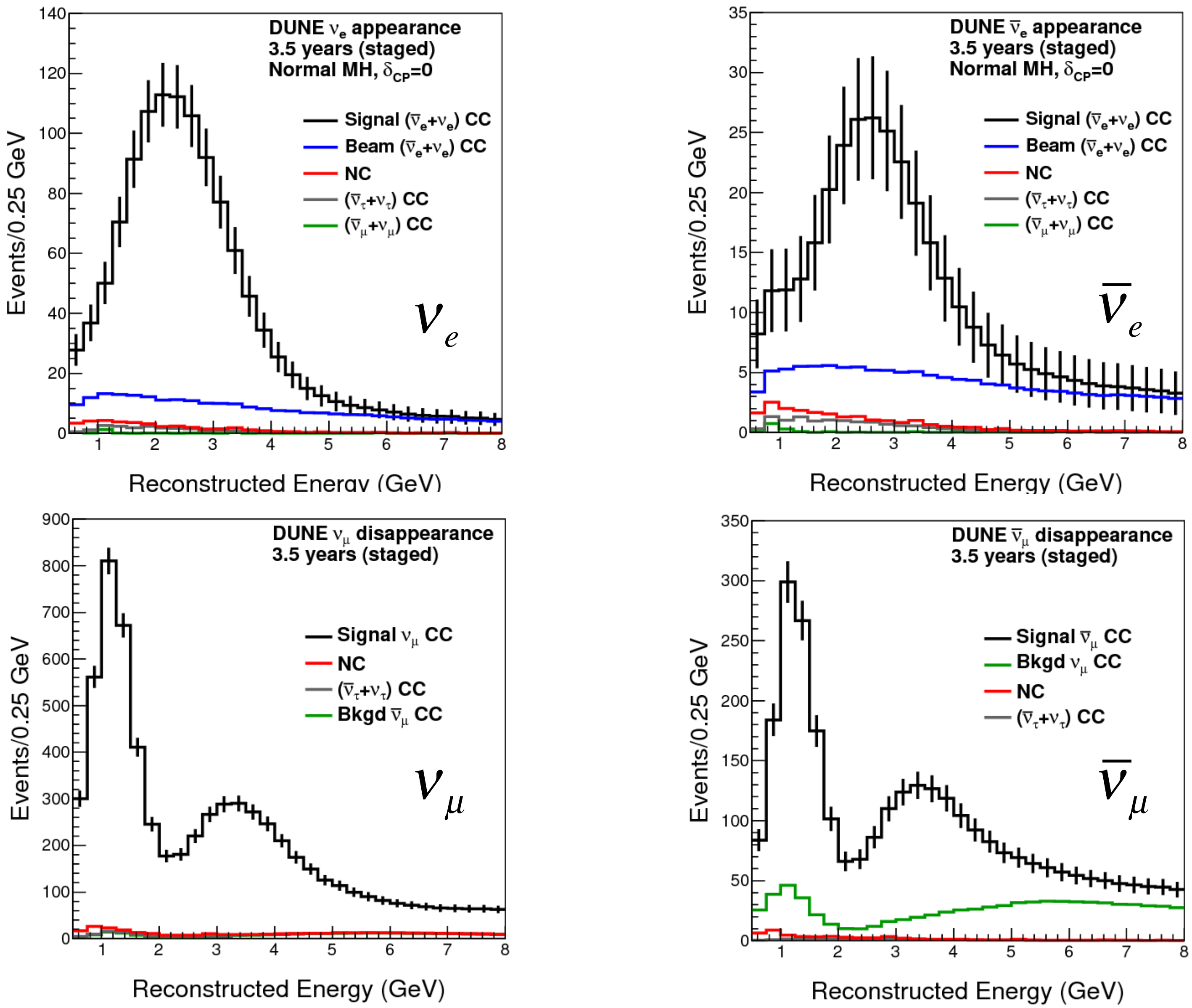
DUNE Neutrino Oscillation Strategy

Measure neutrino spectra at 1300 km in a wide-band beam



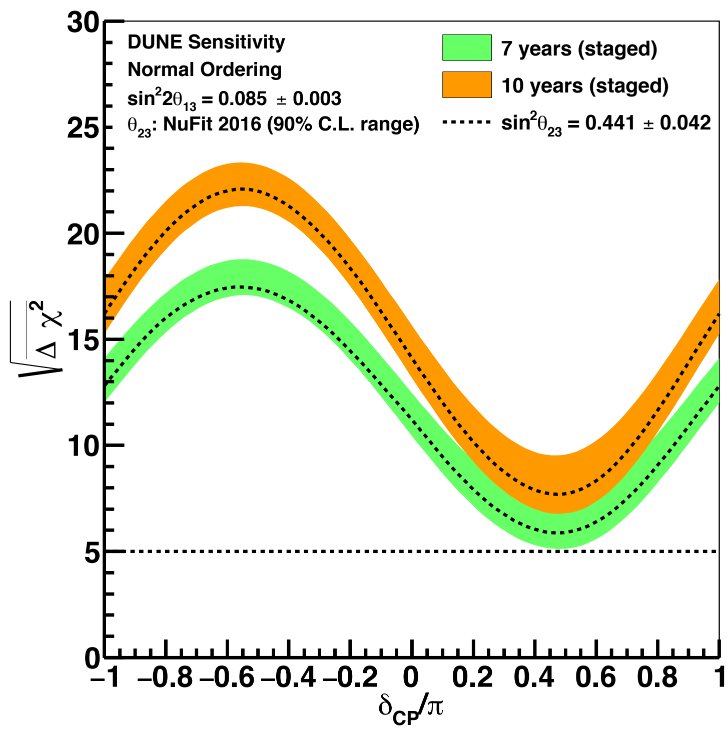
- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects. All four can be measured in a single experiment.
- Wide-band beam and long baseline break the degeneracy between CP violation and matter effects.

Appearance and disappearance spectra

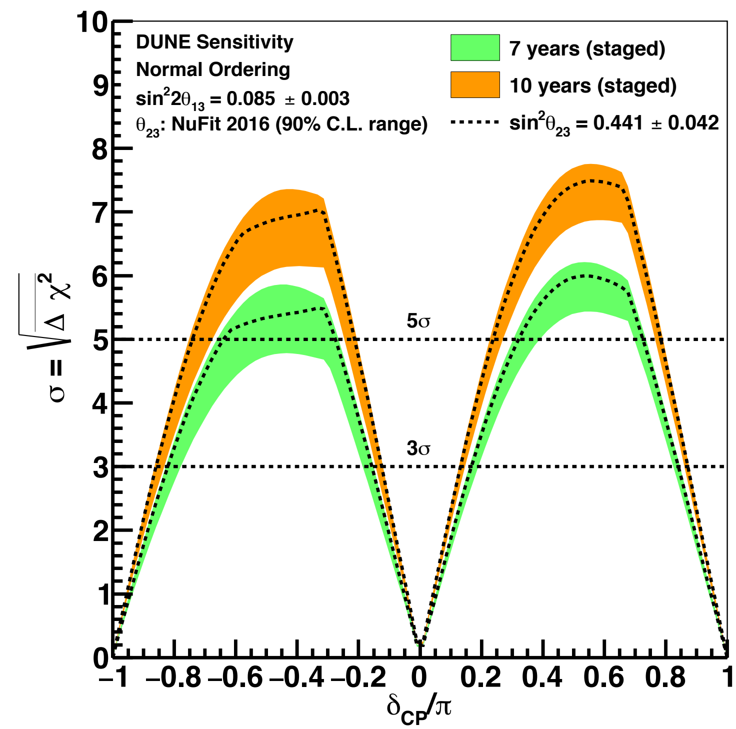


Mass Hierarchy and CP Violation

Mass Hierarchy Sensitivity



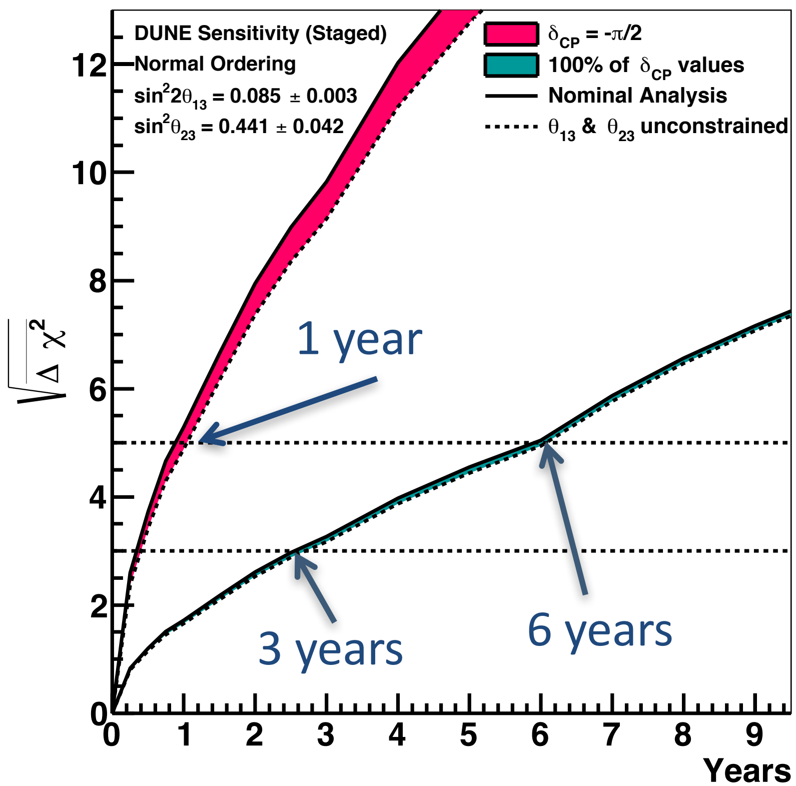
CP Violation Sensitivity

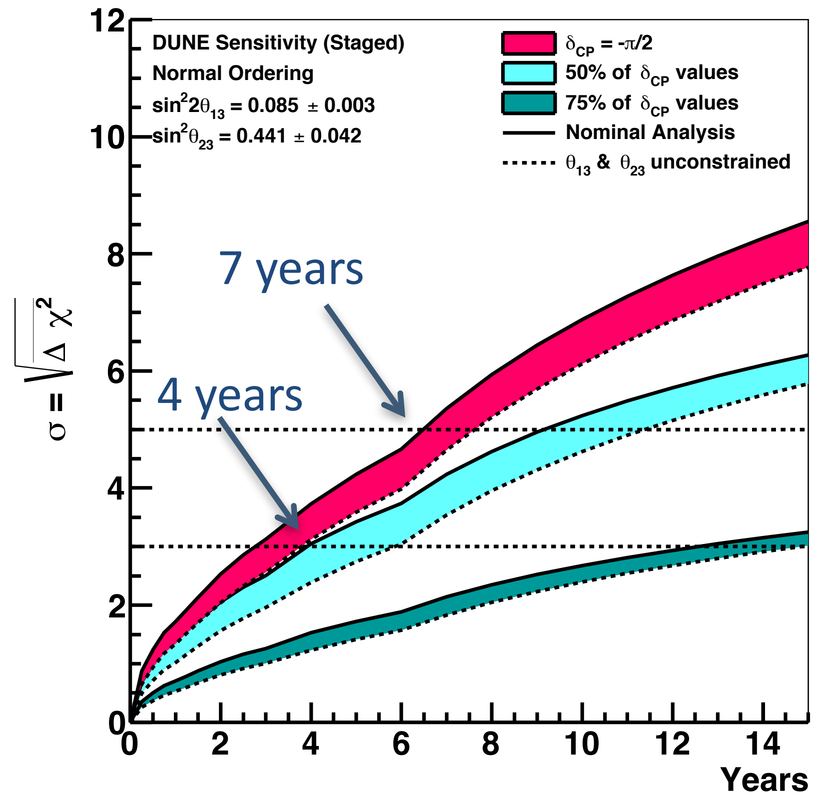


After 7 years (staged):

- CP Violation: 5σ if δ_{CP} near $-\pi/2$; 3σ over 65% of δ_{CP} range
- Mass hierarchy determination: $> 5\sigma$ for all parameter values

Sensitivity vs. time

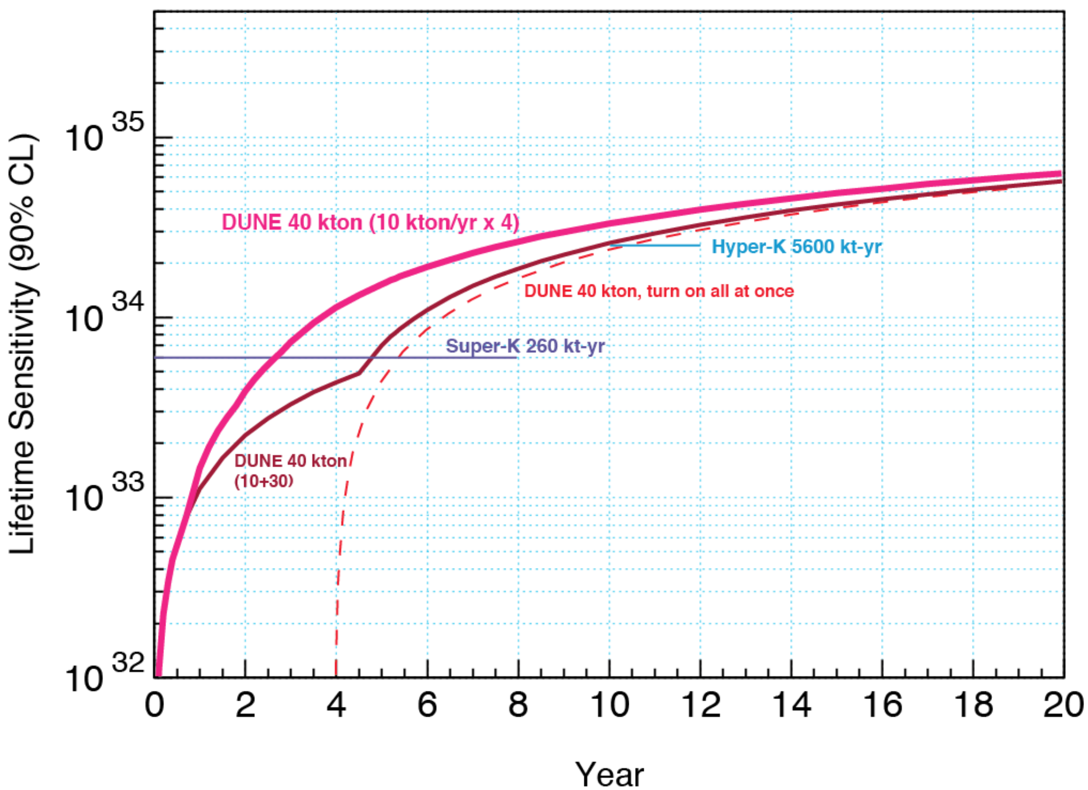




Important sensitivity milestones throughout beam physics program

Expected DUNE Sensitivity to $p \rightarrow K^+ \bar{\nu}$

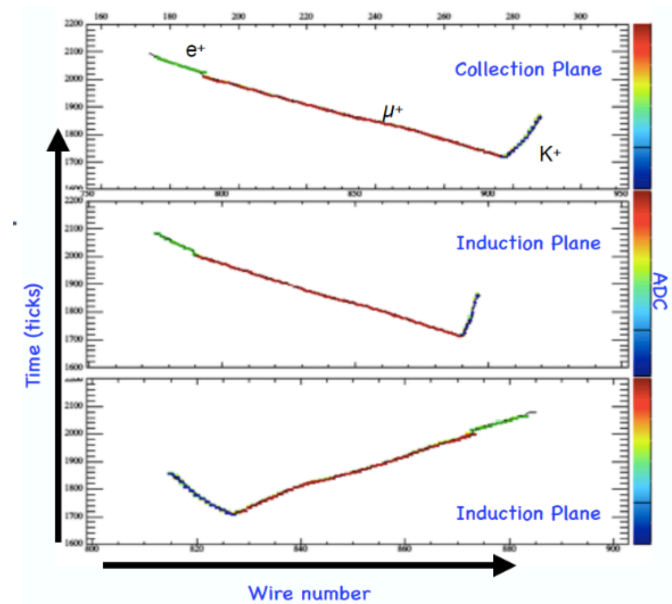
- Very low-background mode with high detection efficiency
- Clear identification of kaons with dE/dx and decay chain in LAr TPC



$p \rightarrow K^+ \bar{\nu}$

$K^+ \rightarrow \mu^+ \bar{\nu}_\mu$

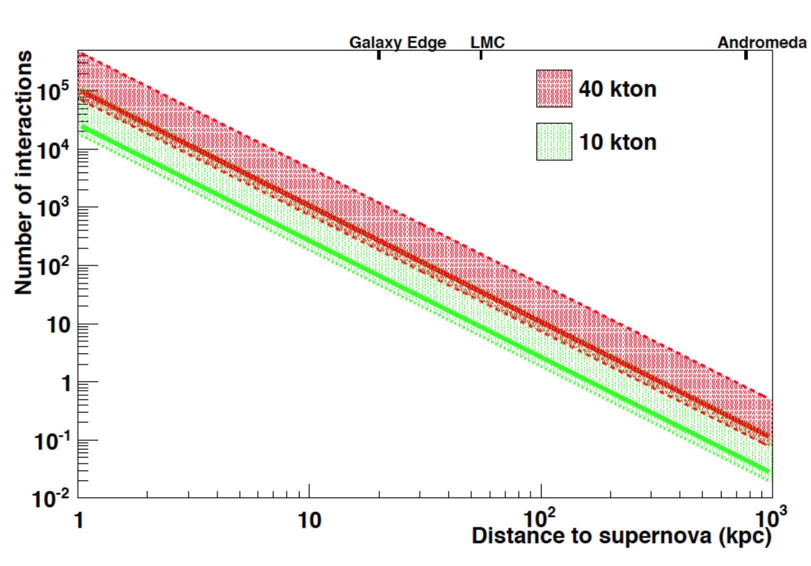
$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$

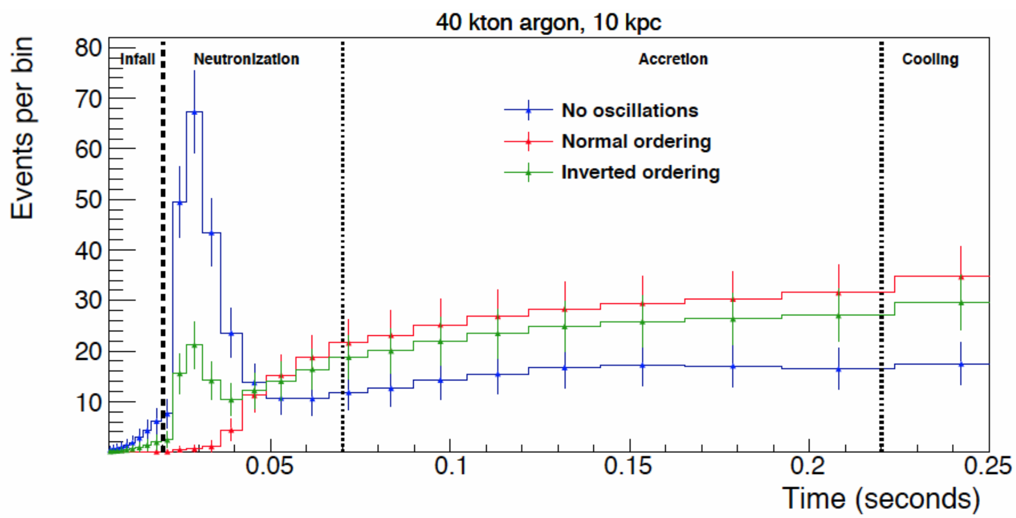


Simulation and reconstruction of proton decay at DUNE

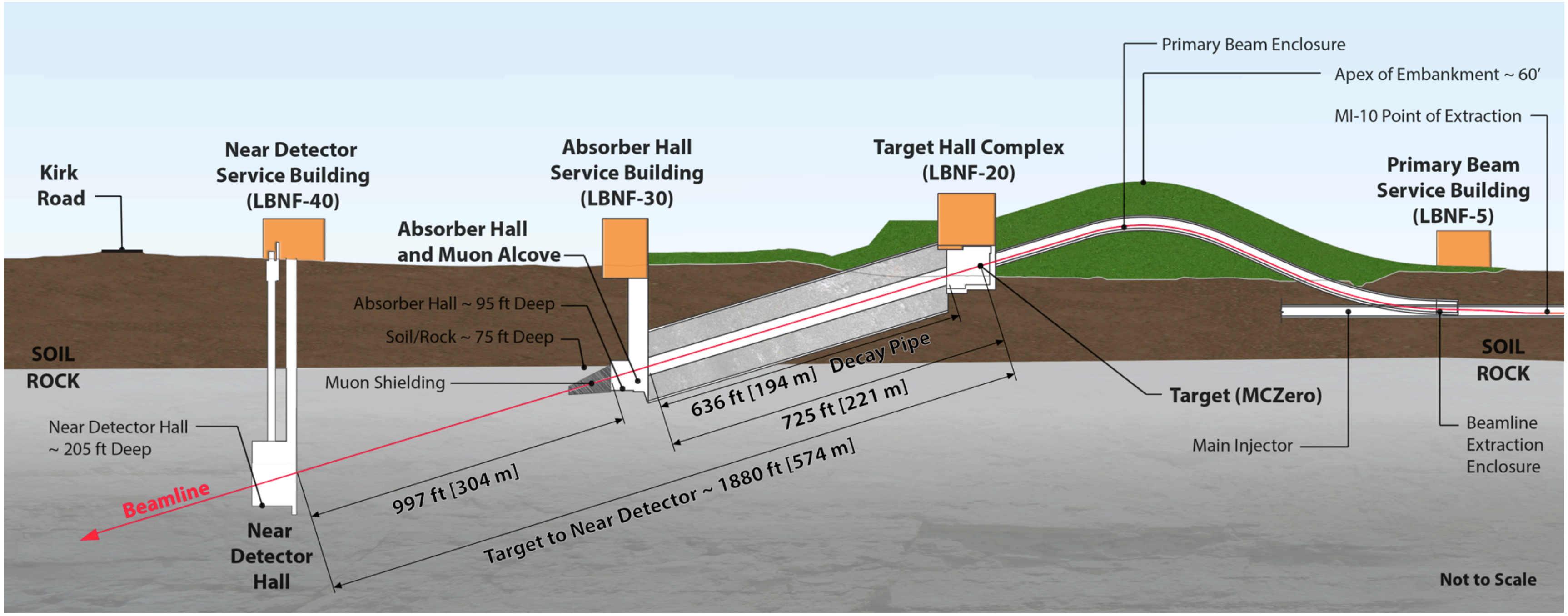
SN Neutrinos in DUNE

- LAr provides unique sensitivity to ν_e: $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$
- About 3000 ν_e events in 10 sec from SN at 10 kpc
- The time structure of the SN signal during the first few tens of ms after the core bounce can provide a clear indication if the ν_e burst is present, and makes it possible to distinguish between different mixing scenarios





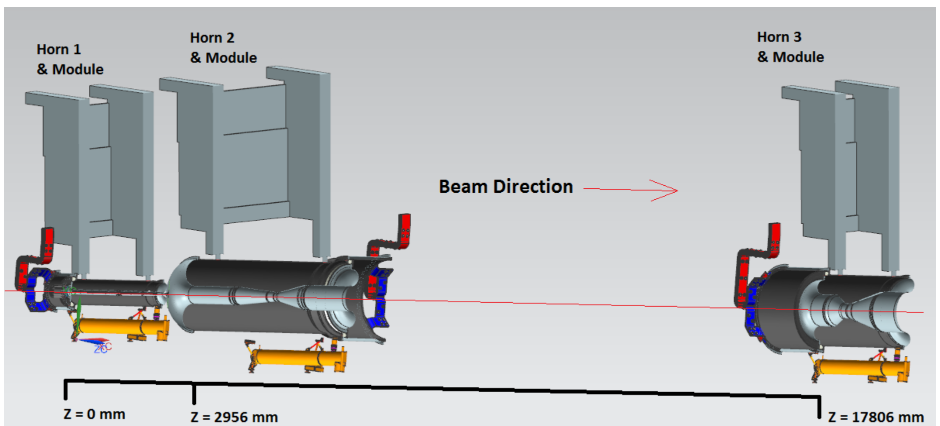
Beam and Near Detector

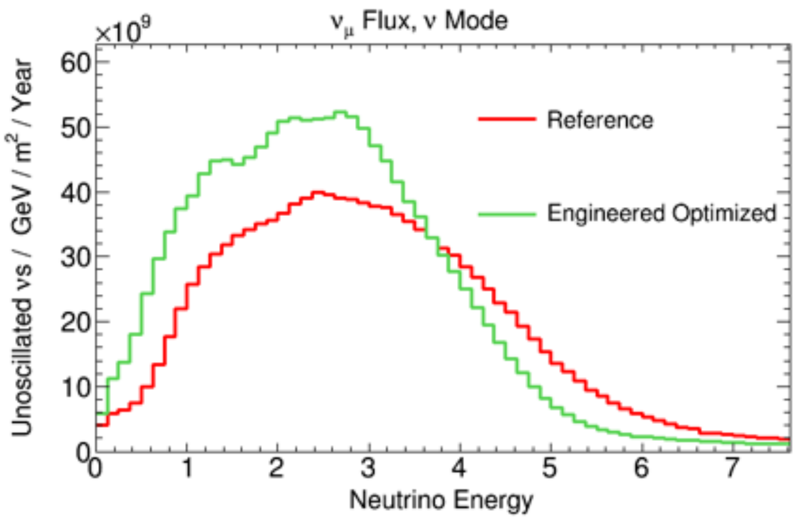


- Primary proton beam @ 60-120GeV extracted from Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- DUNE Near Detector
  - Precisely measure beam neutrino fluxes
  - Constrain systematic uncertainties for oscillation measurements
  - Multiple designs under consideration

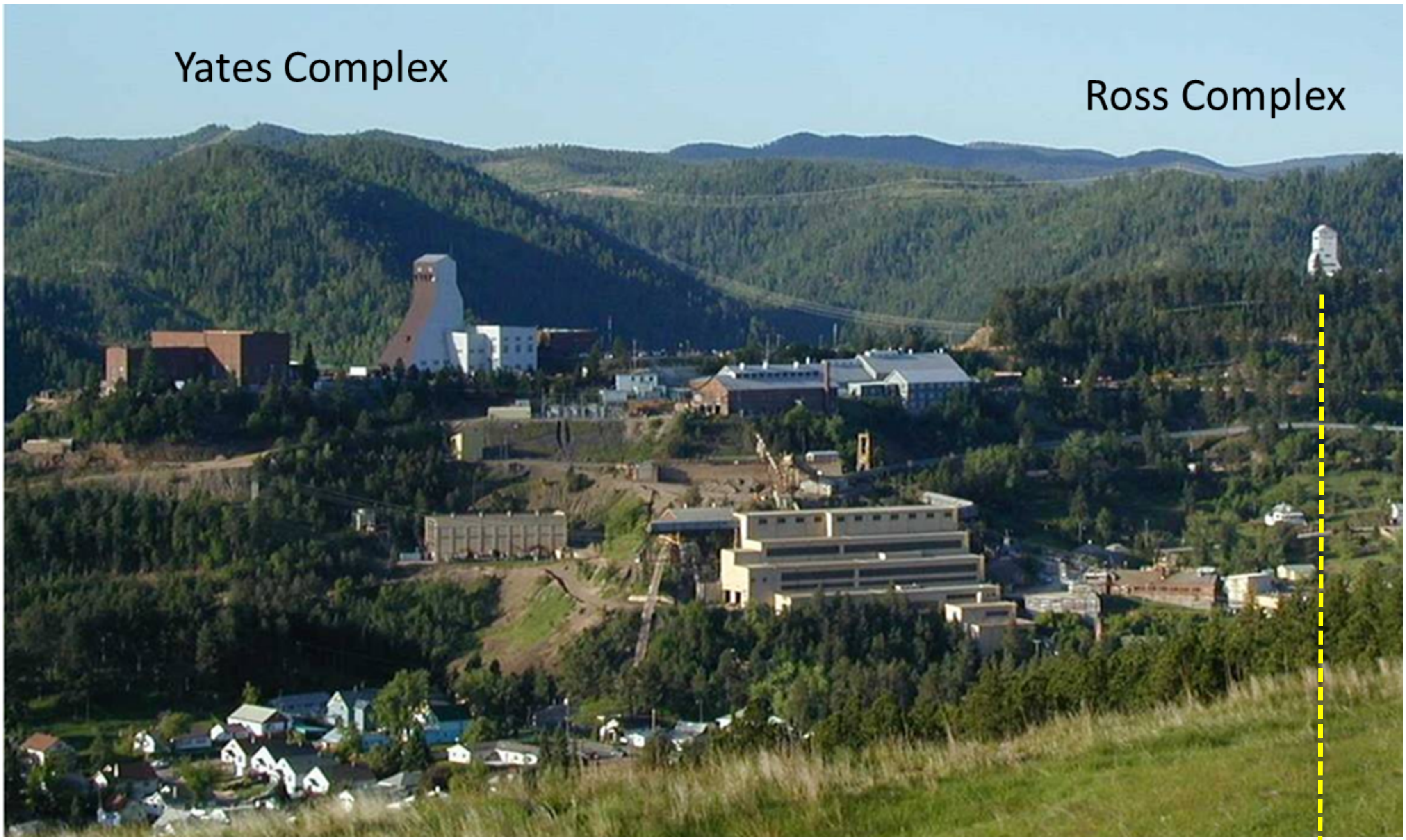
Optimization of neutrino beamline

- Significant effort to optimize target and horn system for better sensitivity to CP violation
- Currently, evaluating technical and cost impact of design with 4 interaction-length target and 3 horns.



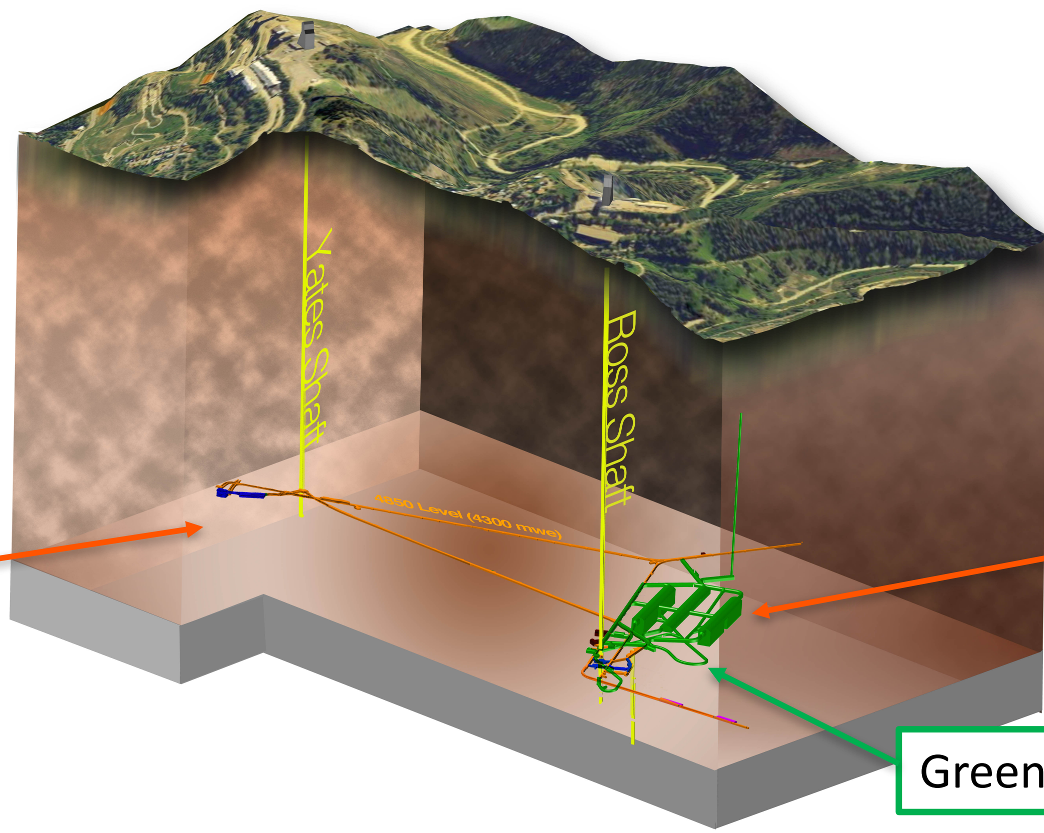


DUNE/LBNF Far Site



DUNE Far Site

Ross Campus of 4850 ft level of Sanford Underground Research Facility



Davis Campus:
- LUX
- Majorana demo.
- …
- **LZ**

Ross Campus:
- CASPAR
- …
- **DUNE**

Green = new construction

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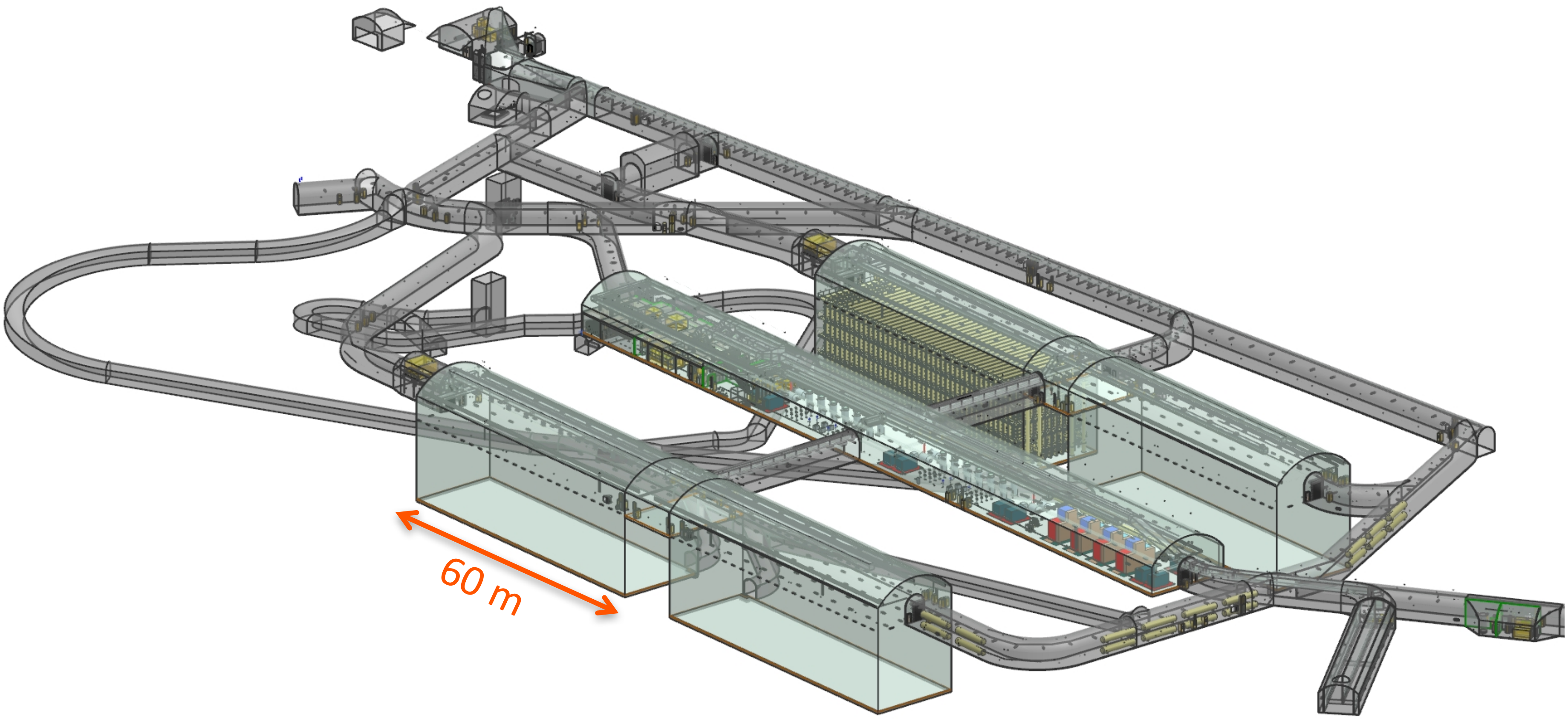
LBNF/DUNE Groundbreaking, July 21, 2017

Participants underground and on the surface at SURF

and at Fermilab.

DUNE Far Detector

- **70-kt LAr-TPC = 4 x 17 kt (4 x 10 kt fiducial) detectors**



- **4 chambers, each hosting a 10 kt fiducial module**
- **Modules will be similar, but likely not identical**
- **Requires excavation of 875,000 tons of rock**

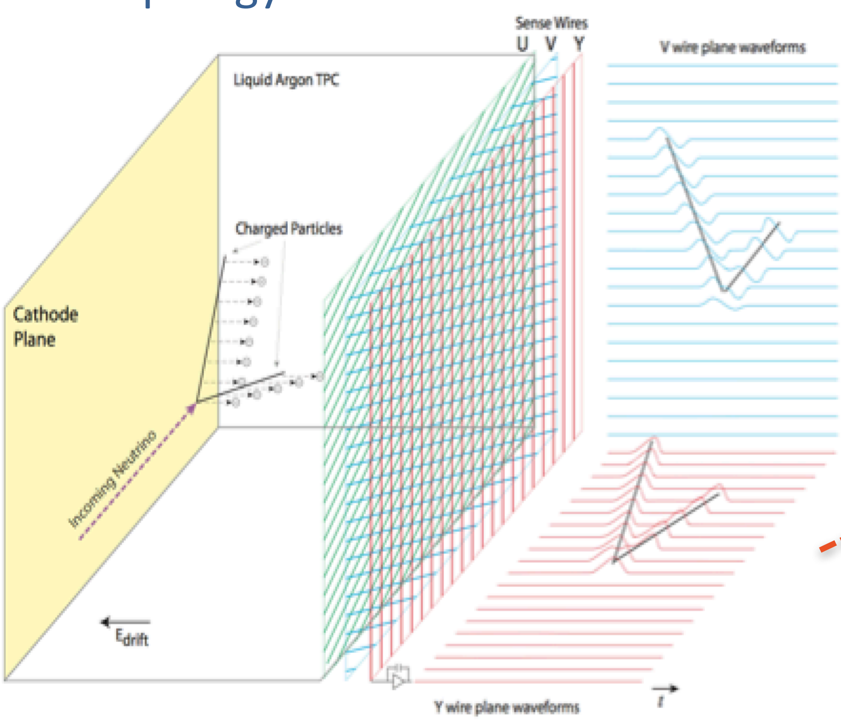
DUNE Far Detector: LAr TPCs

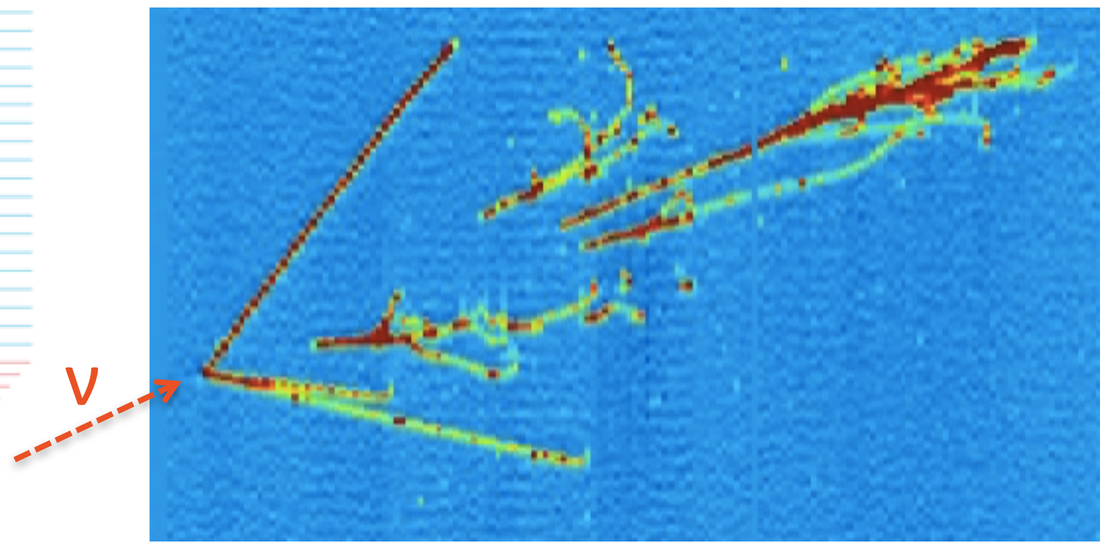
LAr TPC provides:

- Excellent 3D imaging
  - few mm resolution over large volume
- Excellent energy measurement
  - Fully active calorimeter
- Allows particle ID by dE/dx, range, event topology

Major (and exciting) challenges

- Scaling technology to very large detector volumes
- Event reconstruction and classification





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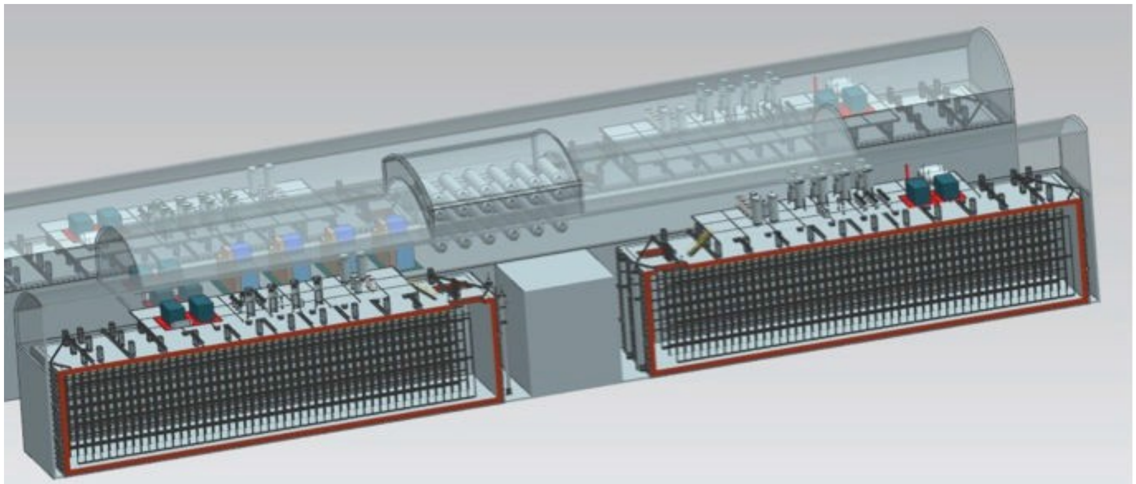
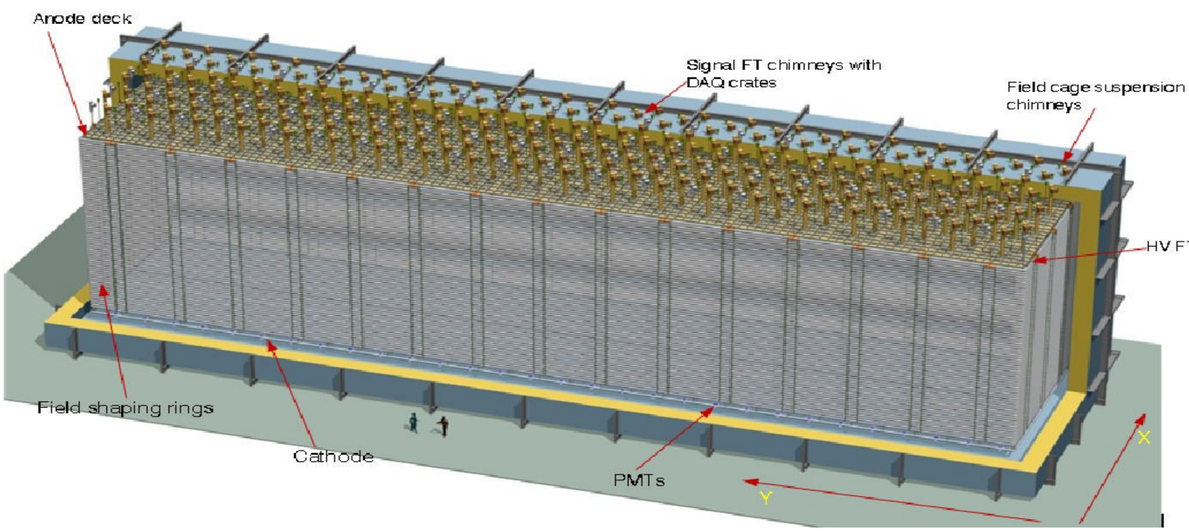
DUNE Far Detector Technologies

Collaboration is considering (and prototyping) two liquid argon readout technologies:





Single Phase

- drift electrons detected in the liquid
- Readout technology of ICARUS, ArgoNeuT, MicroBooNE, SBND
- 3.5 m max drift

Dual Phase

- amplification of electron signal in gas phase
- Pioneered at large scale by WA105.
- 12 m max drift

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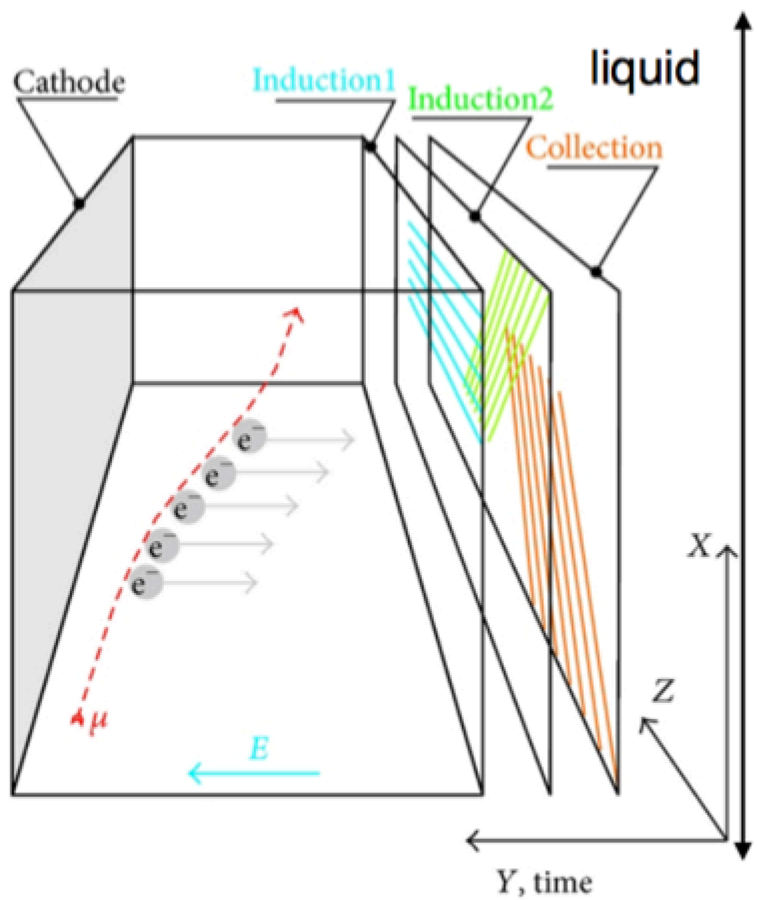
Liquid argon TPC: Single and dual phase

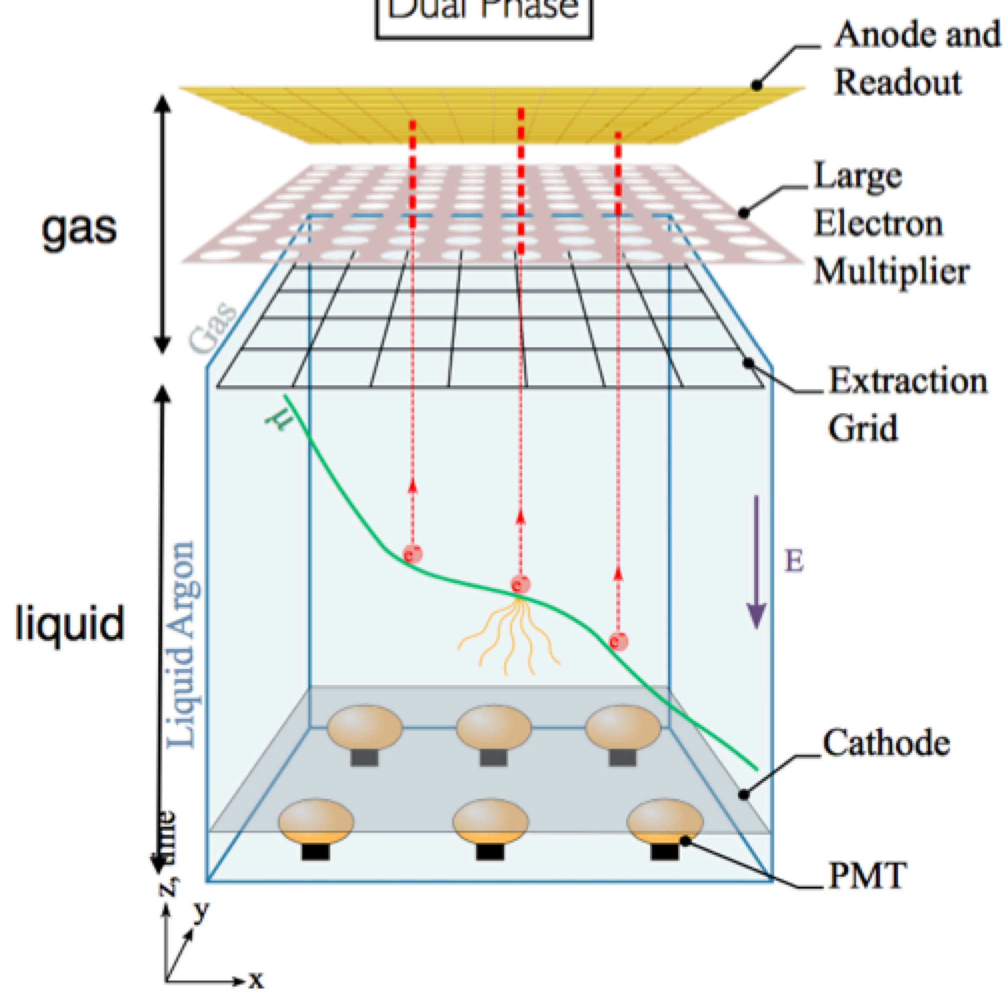
- Ionization charges drift horizontally and are read out with wires
- No signal amplification in liquid

- Ionization charges drift vertically and are read out on PCB anode
- Amplification of signal in gas phase by LEM

Single Phase



Dual Phase



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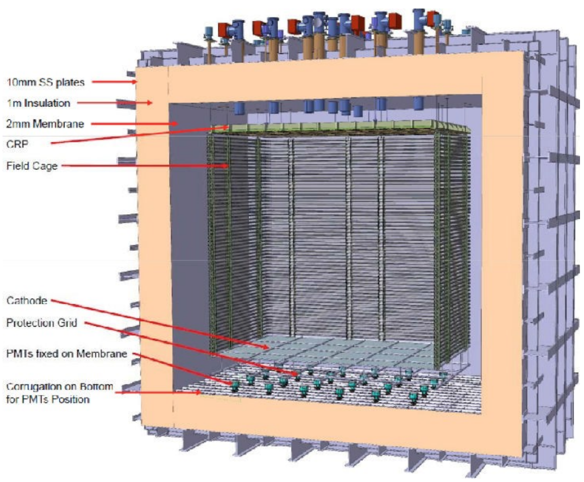
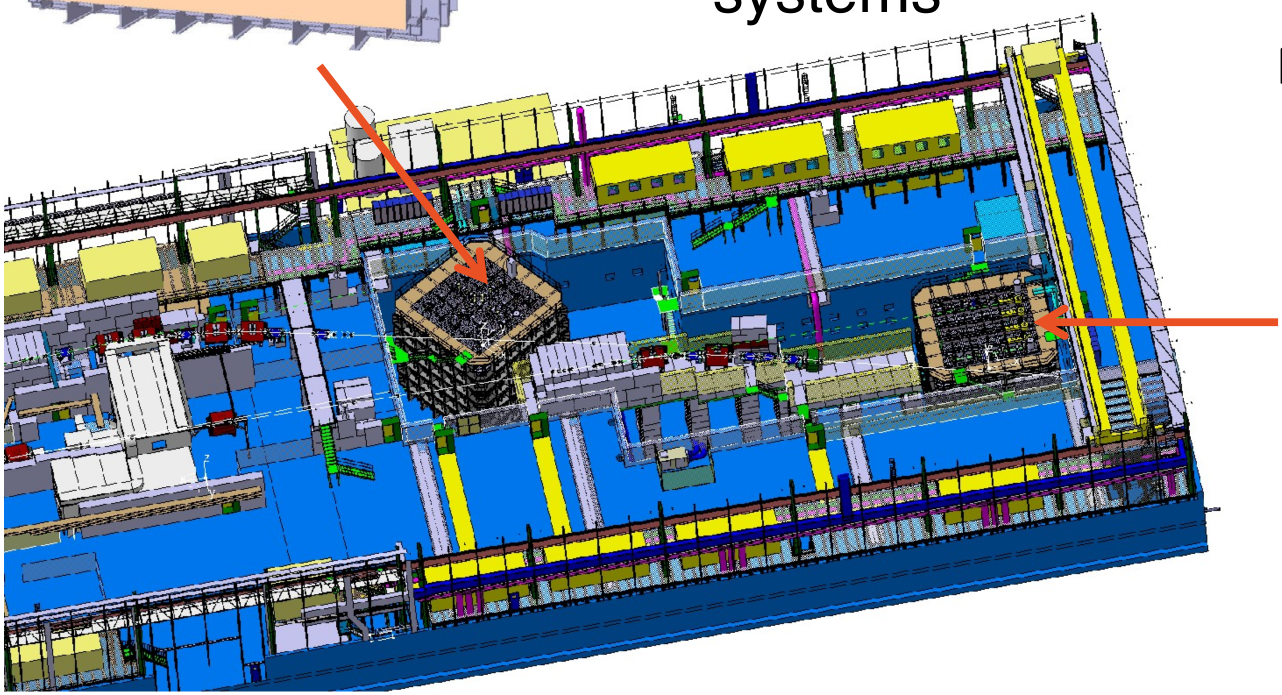
Prototypes at CERN Neutrino Platform

ProtoDUNE Dual Phase

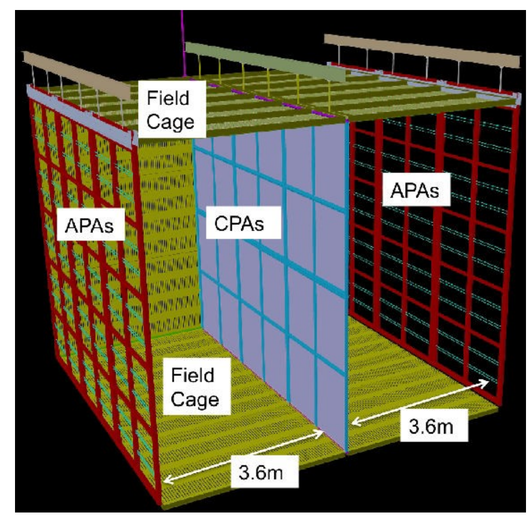


Major CERN investment to support DUNE

- EHN1 extension in the North area
- Two tertiary charged-particle beam lines
- Two 8m×8m×8m cryostats & cryogenic systems



ProtoDUNE Single Phase



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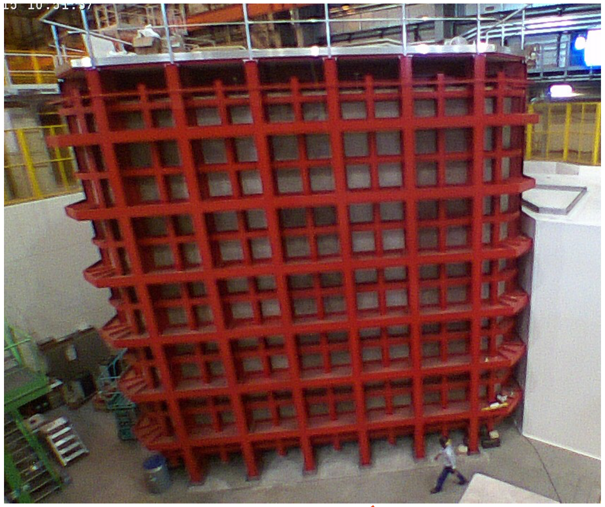
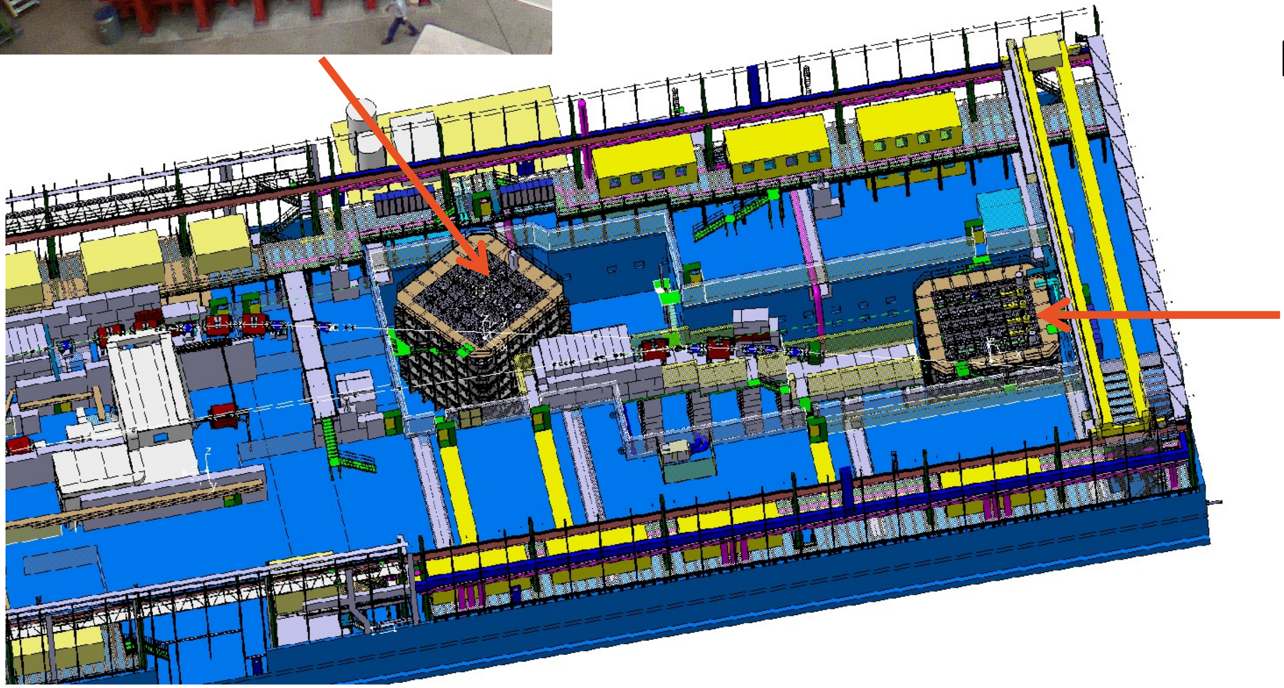
Prototypes at CERN Neutrino Platform

ProtoDUNE Dual Phase



Both ProtoDUNEs aim to begin data taking in mid 2018.

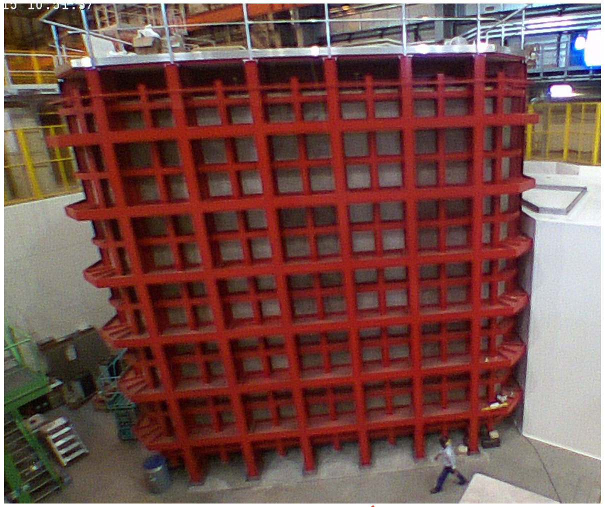
EHN1 Webcams: http://cenf-ehn1-np.web.cern.ch/images/np04-webcam-neutrino-platform-hall-ehn1



ProtoDUNE Single Phase

Prototypes at CERN Neutrino Platform

ProtoDUNE Dual Phase



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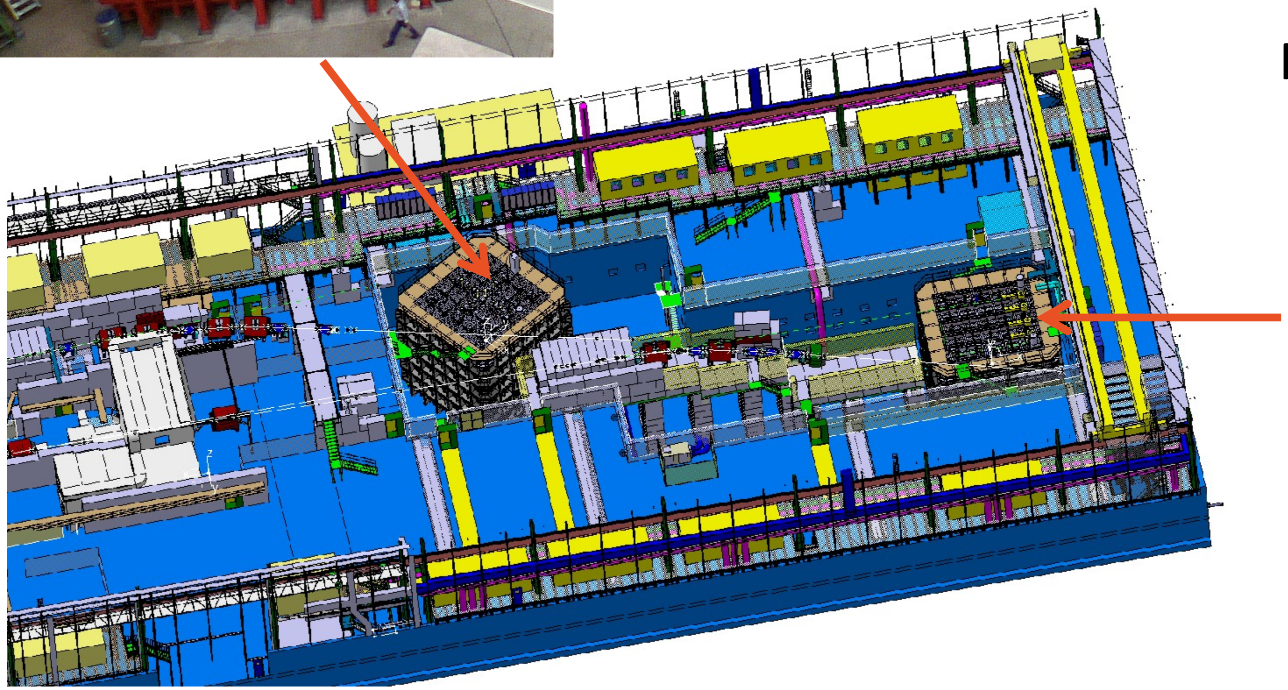
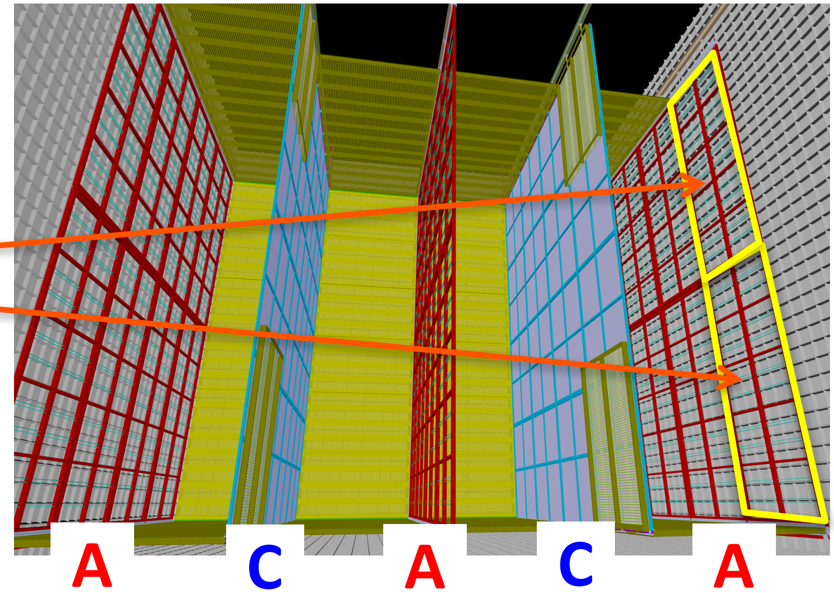


ProtoDUNE Single Phase

DUNE → ProtoDUNE-SP

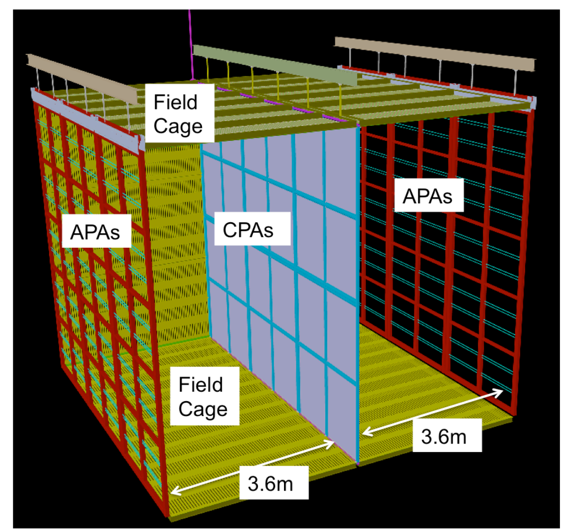
DUNE Far Detector

- Active volume: **12m x 14m x 58m**
- 150 Anode Plane Assemblies
  - 6m high x 2.3m wide
- 200 Cathode Plane Assemblies
  - Cathode @ -180 kV for 3.5m drift

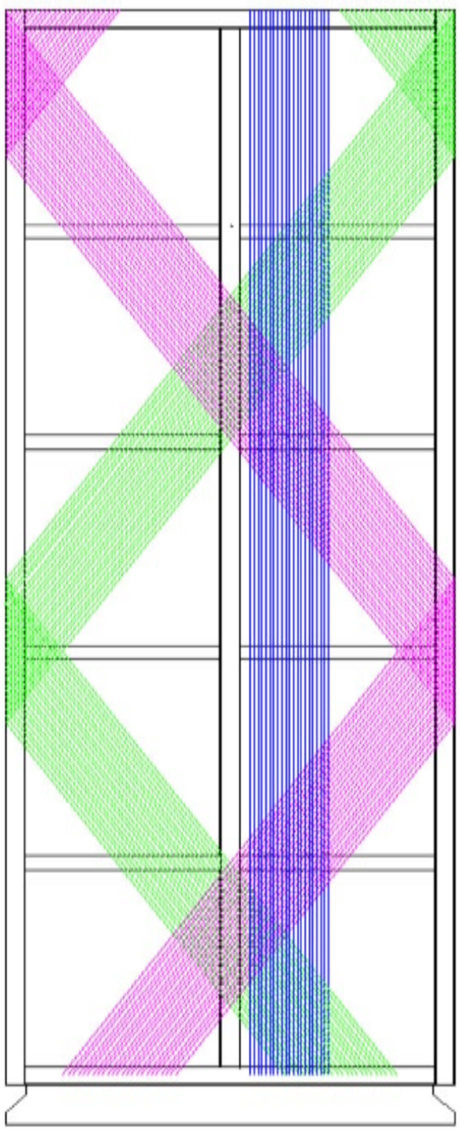


ProtoDUNE-SP

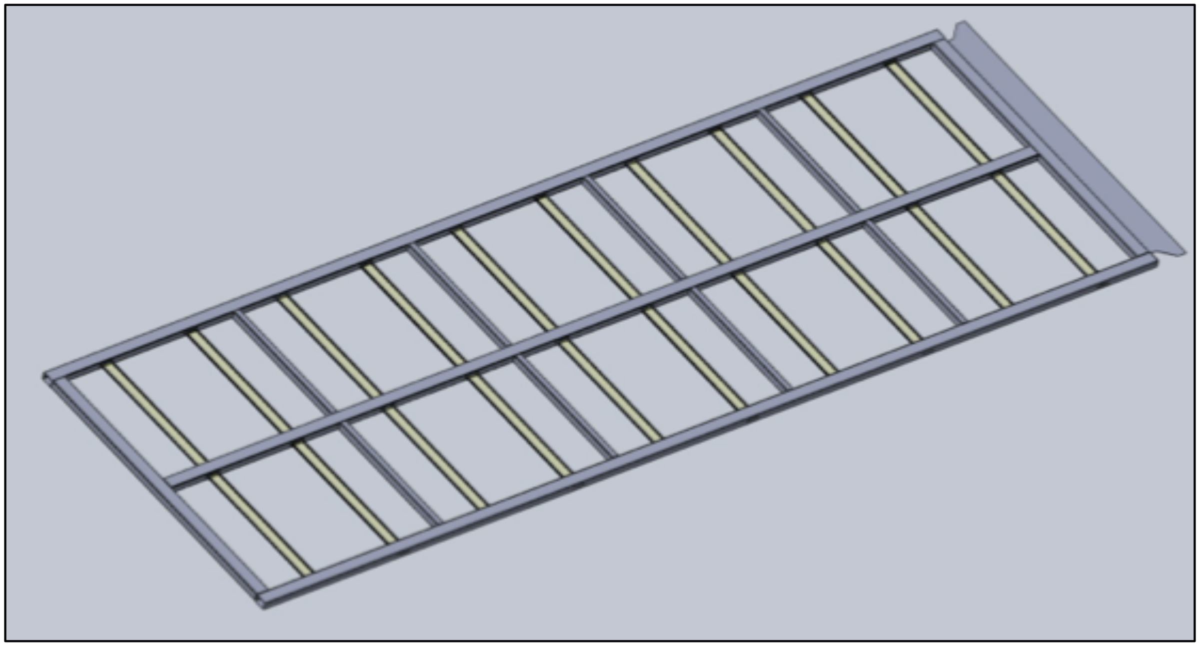
- 1/25 of full DUNE far detector
- 6 full-sized drift cells (150 in far detector)



Anode Plane Assemblies for ProtoDUNE-SP

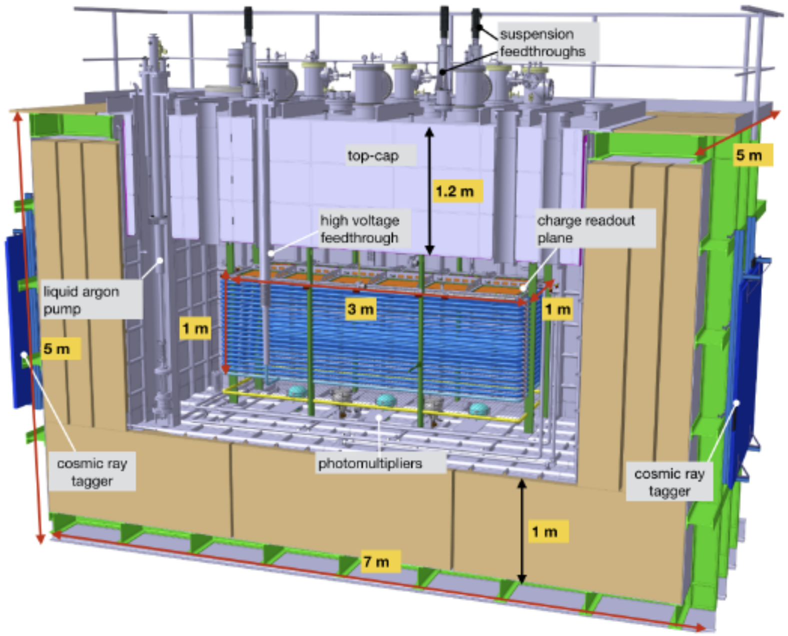


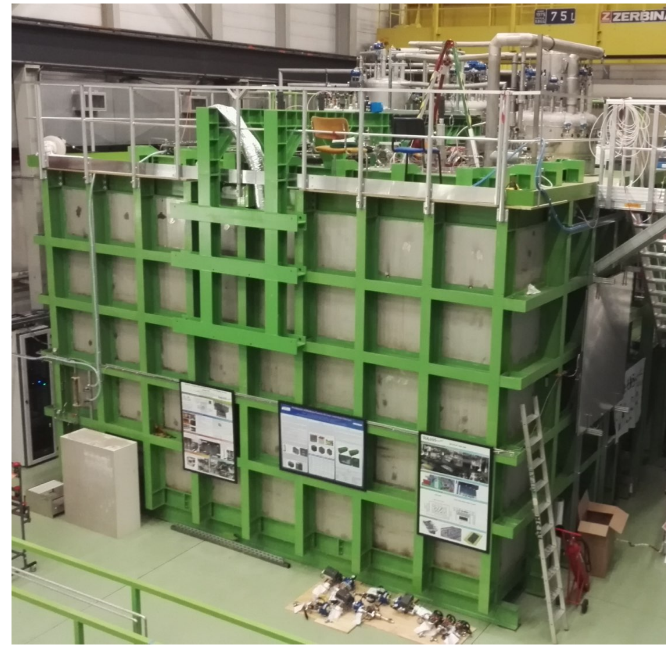
ProtoDUNE-SP Photon Detector System

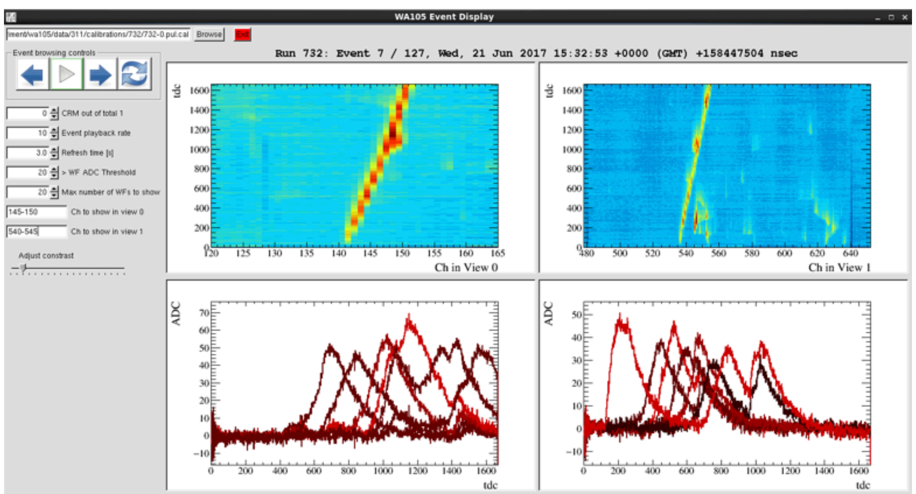


- 10 photon detector system bars per anode plane assembly
- 3 designs being tested in ProtoDUNE-SP
  - Radiator/WLS Bar
  - Dip-coated bars
  - ARAPUCA Arrays

Pre ProtoDUNE-DP: 1m × 1m × 3m

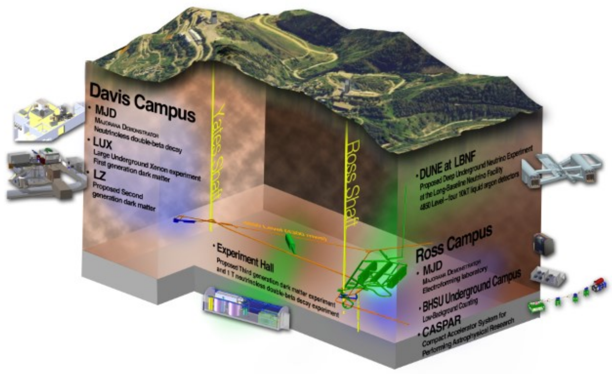


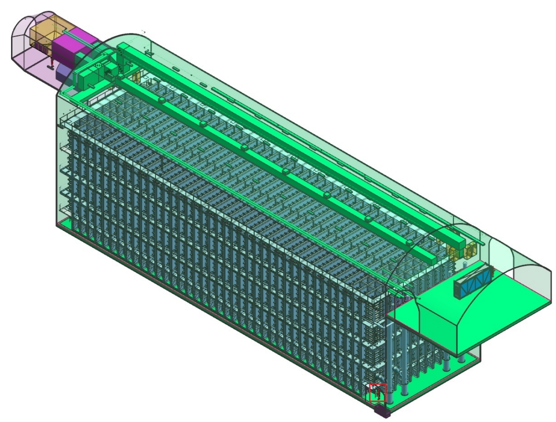


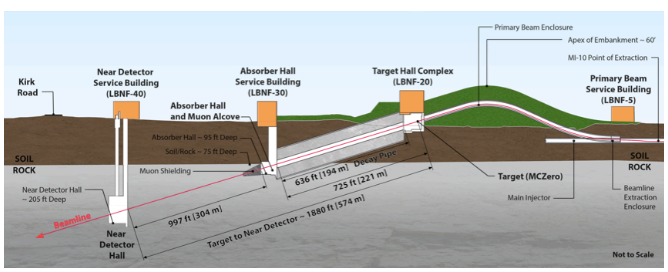


- First tracks observed in 1×1×3m in June 2017
- Assembly of first charge readout planes for protoDUNE-DP (6×6×6m) will begin this fall

DUNE Timeline







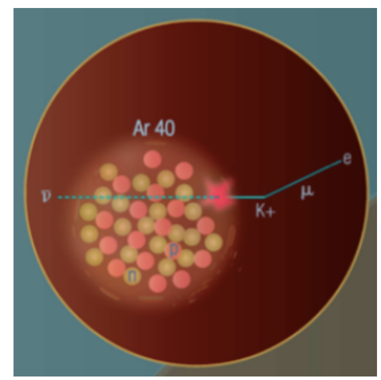
2017: Far Site Construction Begins

2018: protoDUNEs at CERN

2021: Far Detector Installation Begins

2024: Physics Data Begins

2026: Neutrino Beam Available



40 kton + 2 MW beam to follow in subsequent years

Summary

- DUNE will use a broadband beam and long baseline (1300 km) to make precise, simultaneous measurements of the mass ordering, the CP-violation phase, and the neutrino mixing angles
- The large mass, high granularity, and deep underground location of the DUNE far detector provide good sensitivity to baryon non-conservation and supernova burst neutrinos
- Groundbreaking at SURF took place on July 21, 2017.
- On track to operate ProtoDUNE-SP and ProtoDUNE-DP at CERN in summer 2018
- We look forward to start operation of first far detector module in 2024, and first data with beam, near detector, and first two far detector modules in 2026!

We hope DUNE will have a bright future!

Review of DUNE cryostat at SURF, 21 August 2017

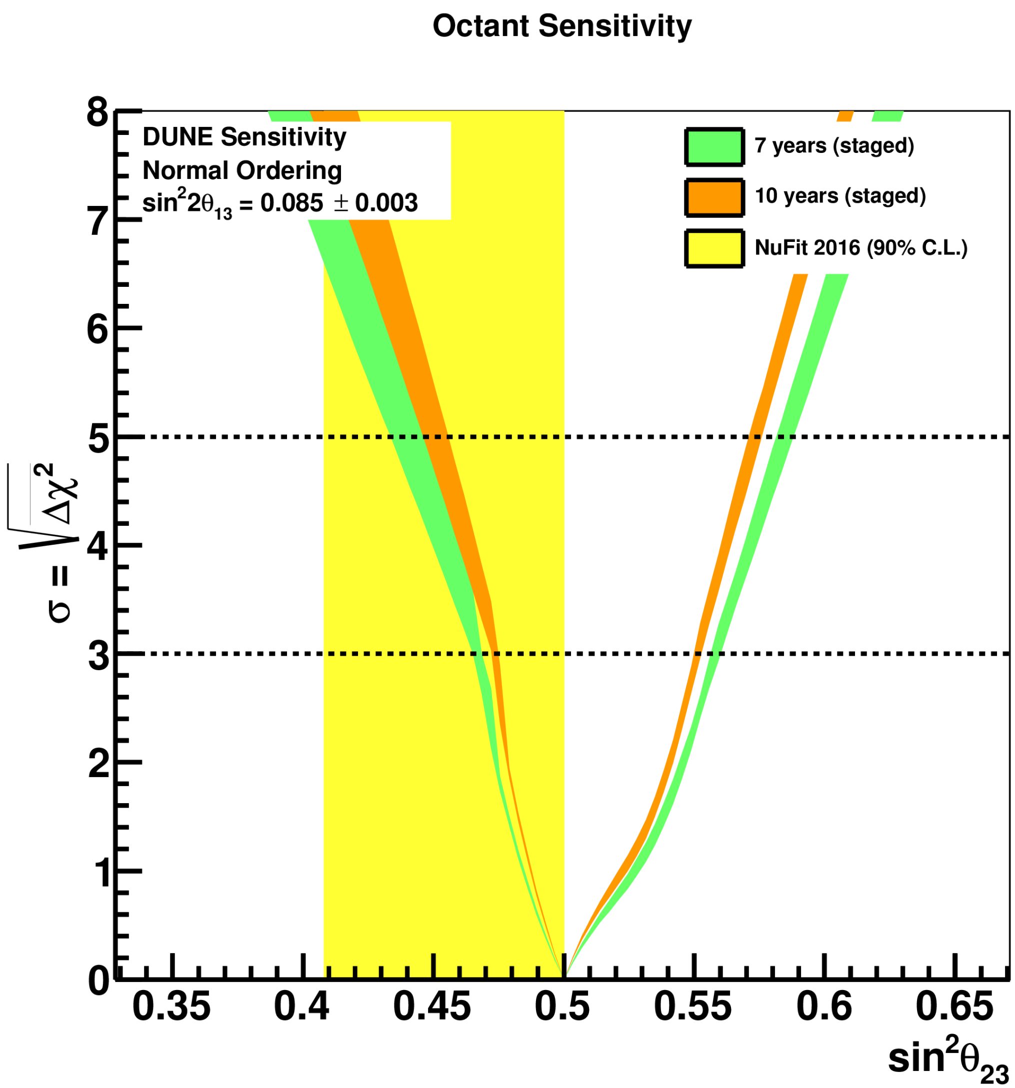
Backup

Staging assumptions

- Year 1 (2026): 20-kt FD with 1.07 MW (80-GeV) beam and initial ND constraints
- Year 2 (2027): 30-kt FD
- Year 4 (2029): 40-kt FD and improved ND constraints
- Year 7 (2032): upgrade to 2.14 MW (80-GeV) beam (technically limited schedule)

Exposure (kt-MW-years)	Exposure (Years)
171	5
300	7
556	10
984	15

DUNE Sensitivity to θ_{23} Octant



SN neutrinos in DUNE

Event rates in DUNE (40 kt LAr) for a core-collapse SN at 10 kpc

Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

no oscillations *collective effects*

- Unique sensitivity to electron neutrinos
- Width of bands represents range of models
- Solid: Garching model
  PRL104 (2010) 251101