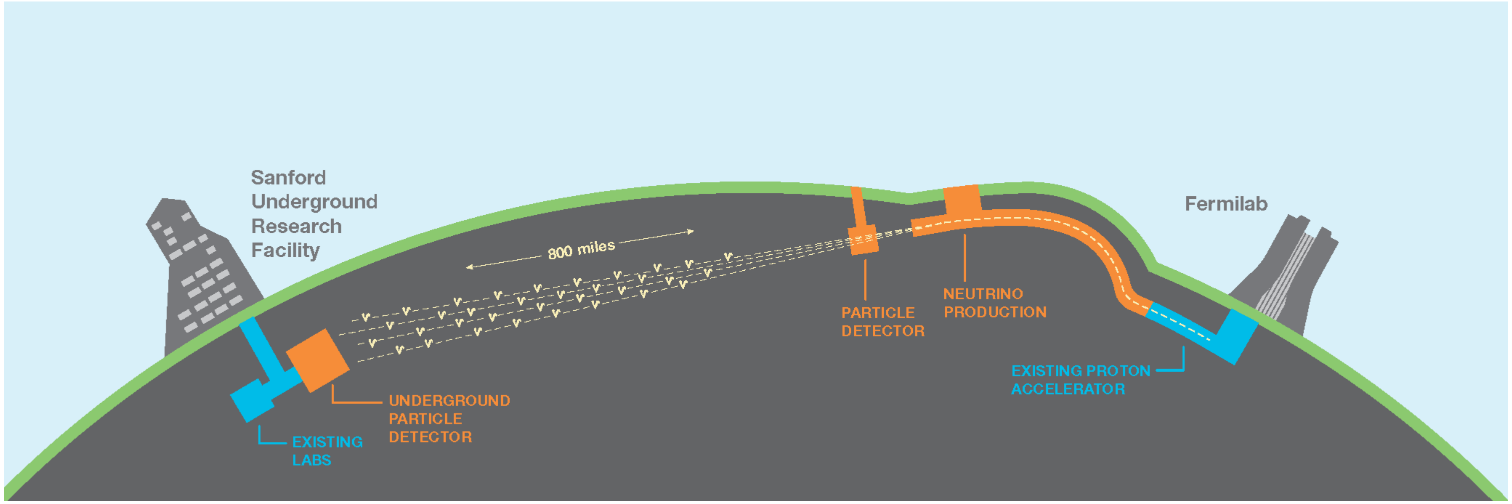


DUNE: The Deep Underground Neutrino Experiment

Ed Blucher

Journée DUNE France, 22 January 2018

THE UNIVERSITY OF CHICAGO

DUNE

First DUNE Collaboration Meeting

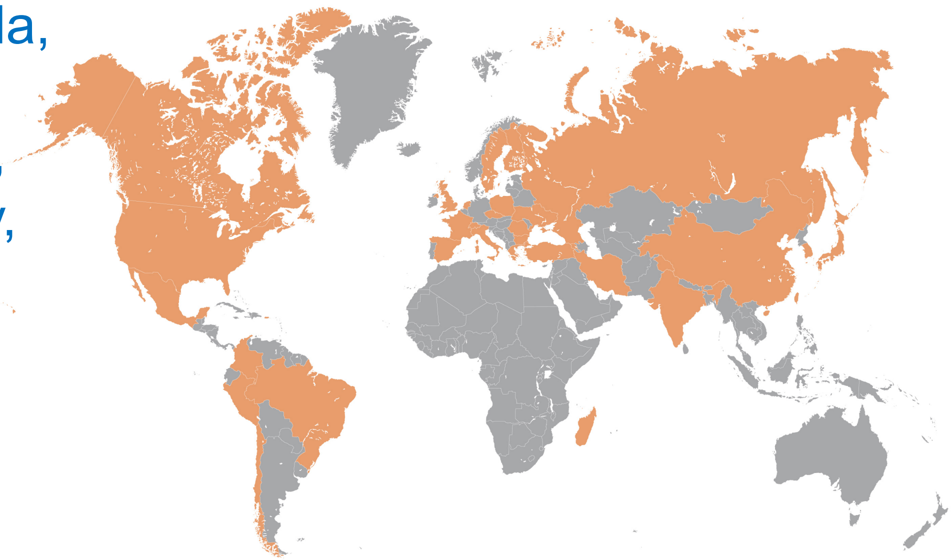
The DUNE Collaboration

As of today:

60 % non-US

1061 collaborators from 175 institutions in 31 nations

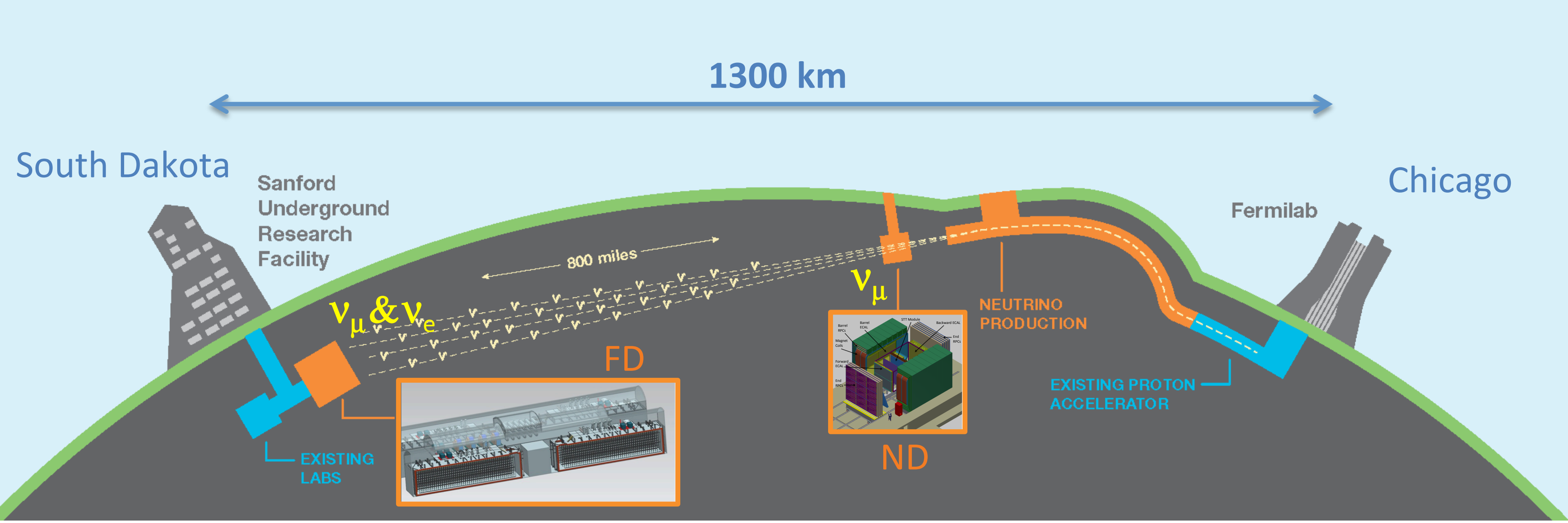
Armenia, Brazil, Bulgaria, Canada, CERN, Chile, China, Colombia, Czech Republic, Spain, Finland, **France**, Greece, India, Iran, Italy, Japan, Madagascar, Mexico, Netherlands, Paraguay, Peru, Poland, Romania, Russia, South Korea, Sweden, Switzerland, Turkey, UK, Ukraine, USA



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

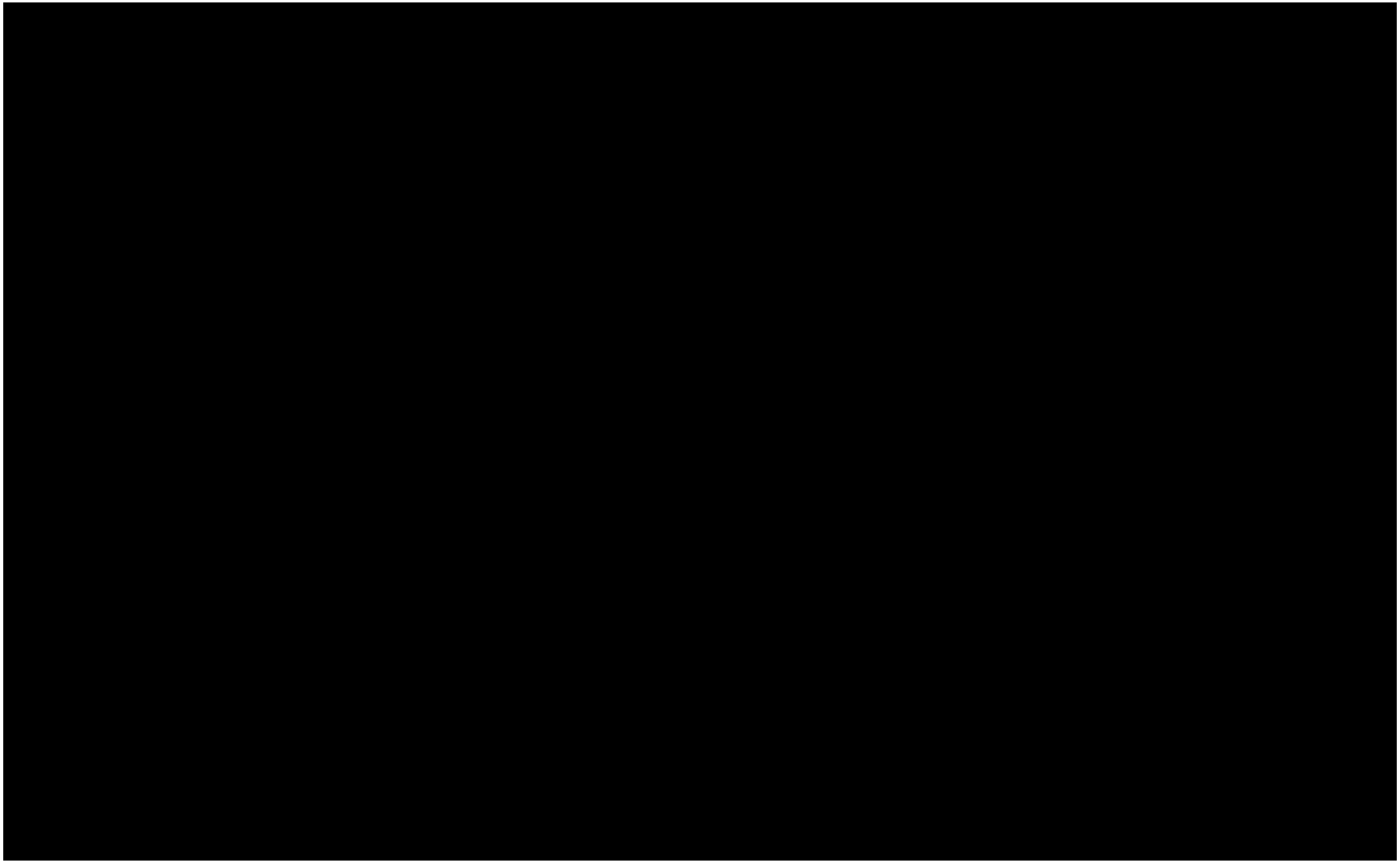
LBNF/DUNE Overview

- 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)



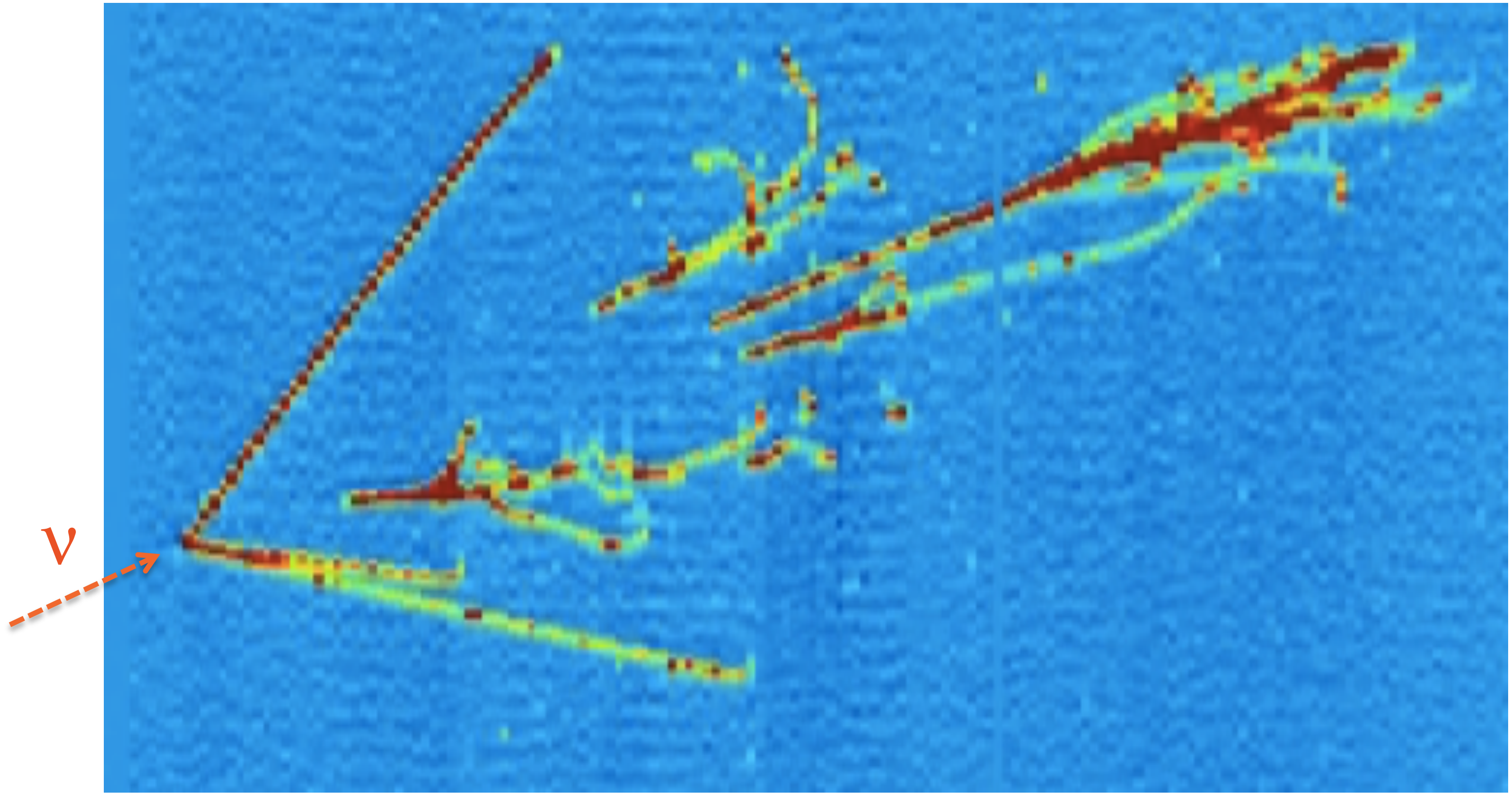
LBNF/DUNE Overview

LBNF/DUNE Overview



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.



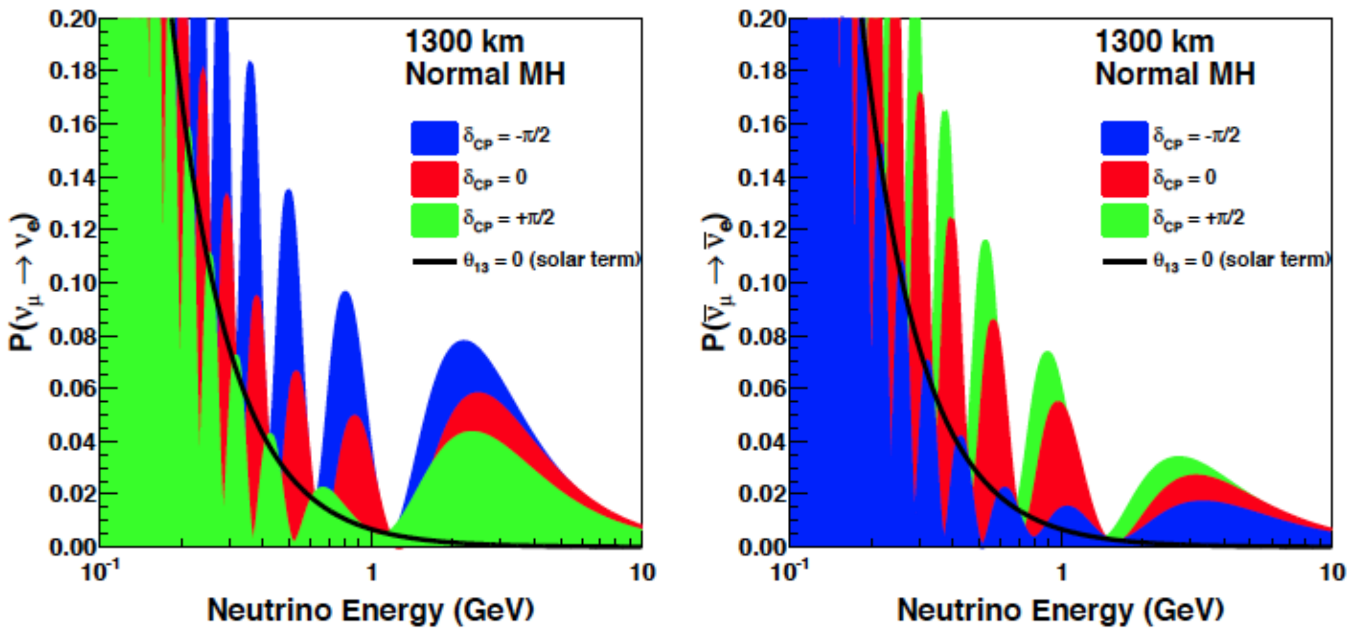
DUNE Science Program

- Neutrino Oscillation Physics
  - **Search for leptonic (neutrino) CP Violation**
  - Resolve the mass ordering ($m_3 > m_{1,2}$ 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.)

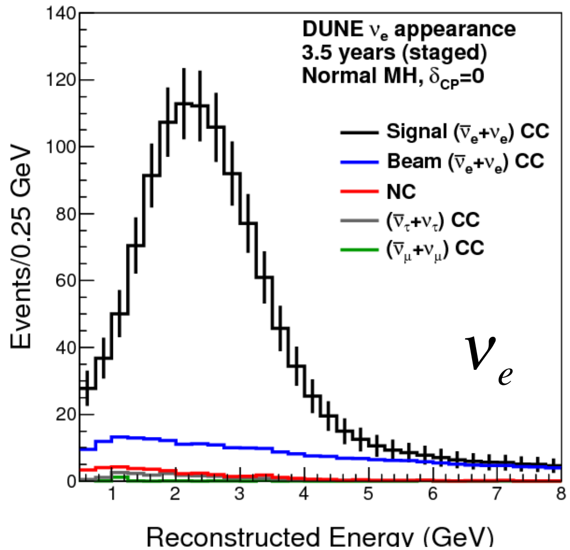
DUNE Neutrino Oscillation Strategy

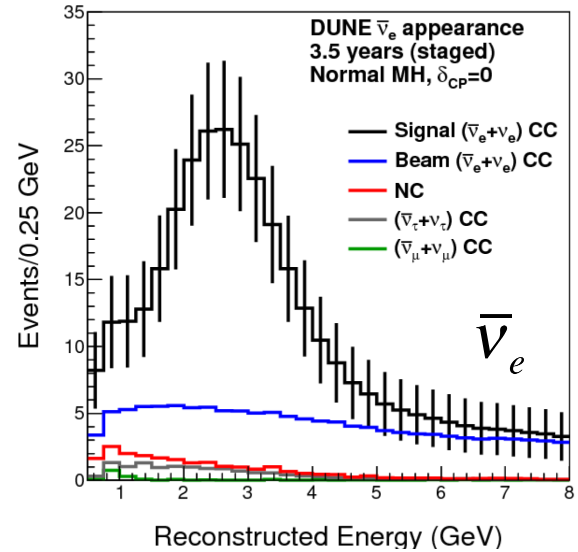
Measure neutrino spectra at 1300 km in a wide-band beam

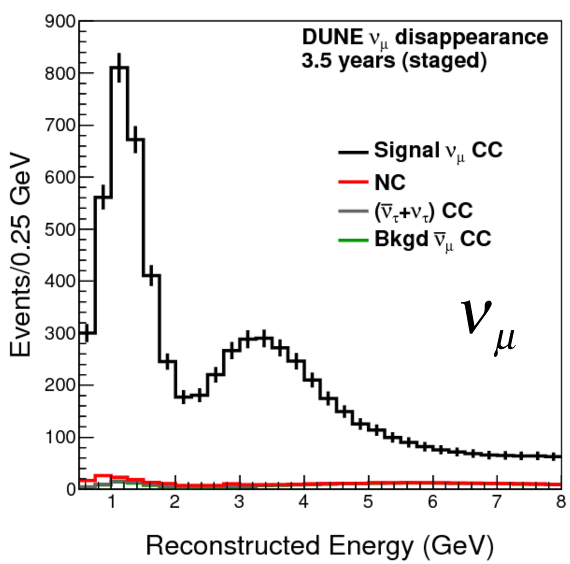


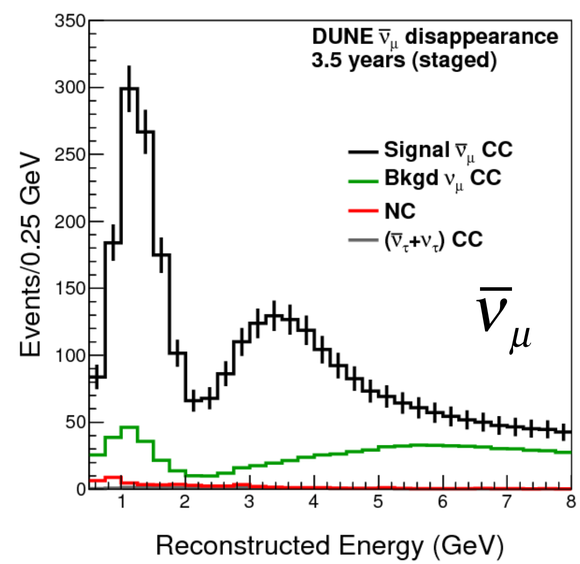
- ν_e appearance probability depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects. All four can be measured in a single experiment.
- Wide-band beam and long baseline break the degeneracy between CP violation and matter effects.

Appearance and disappearance spectra



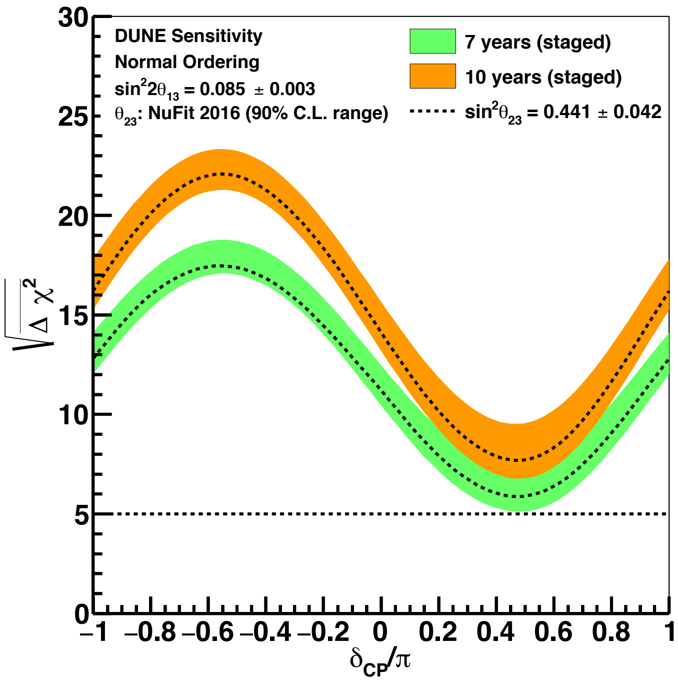




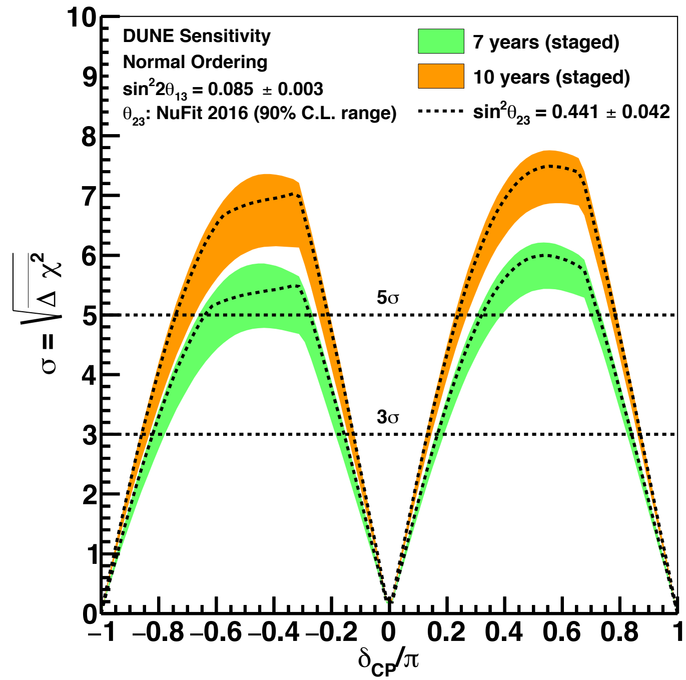


Mass Hierarchy and CP Violation

Mass Hierarchy Sensitivity



CP Violation Sensitivity

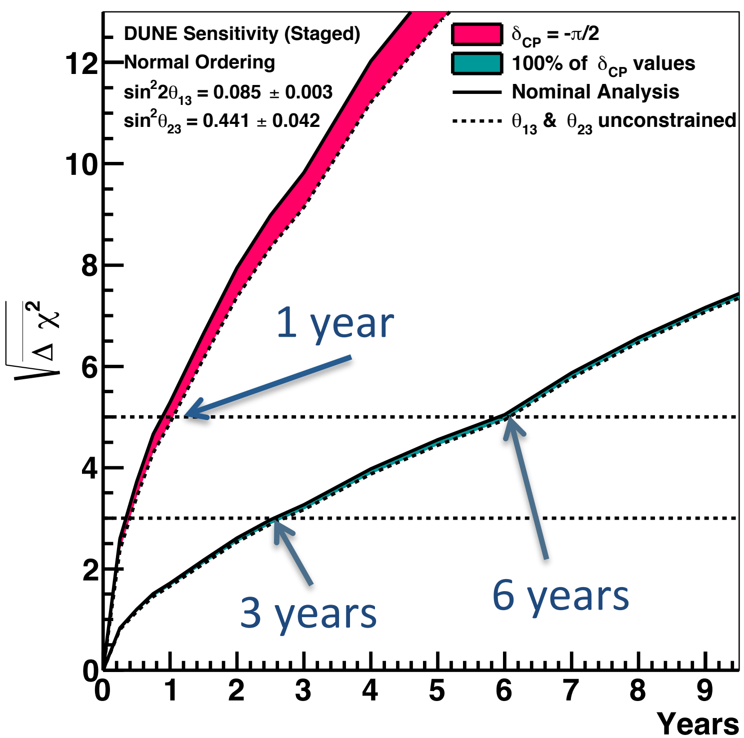


After 7 years (staged):

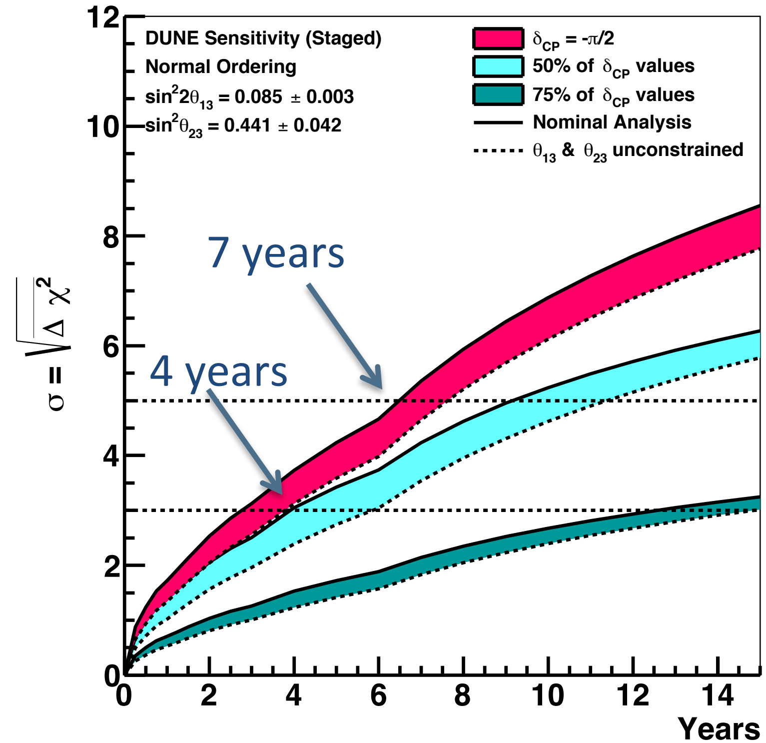
- CP Violation: 5σ if δ_{CP} near $-\pi/2$; 3σ over 65% of δ_{CP} range
- Mass hierarchy determination: > 5σ for all parameter values

Sensitivity vs. time

Mass Hierarchy Sensitivity



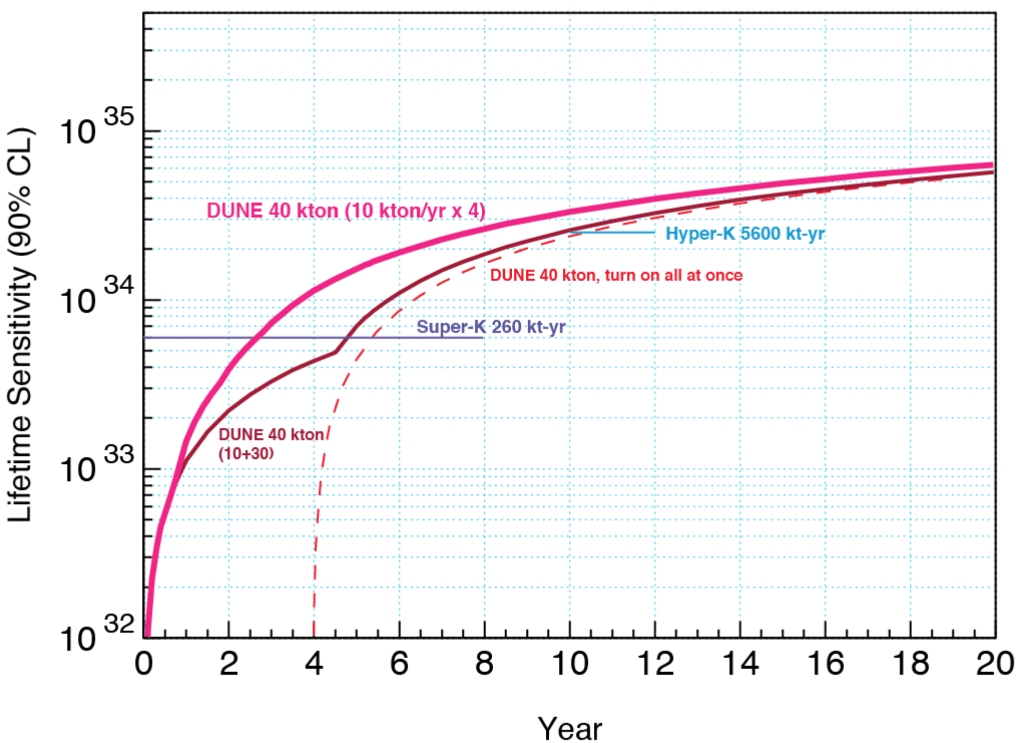
CP Violation Sensitivity



Important sensitivity milestones throughout beam physics program

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

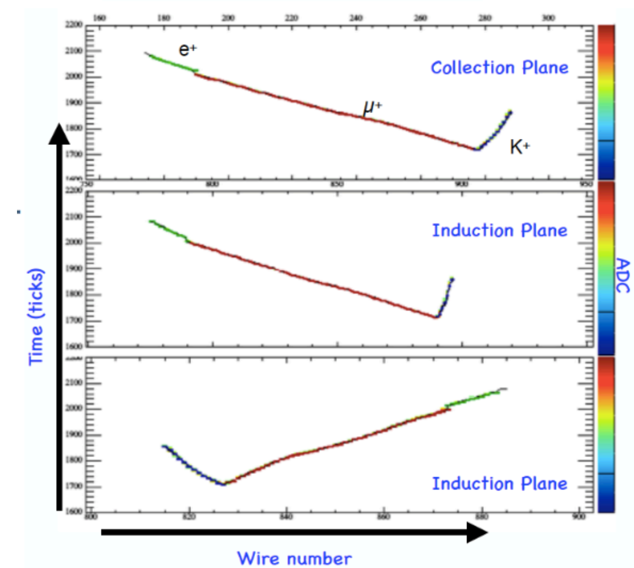
- Very low-background mode with high detection efficiency
- Clear identification of kaons with dE/dx and decay chain in LAr TPC



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

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

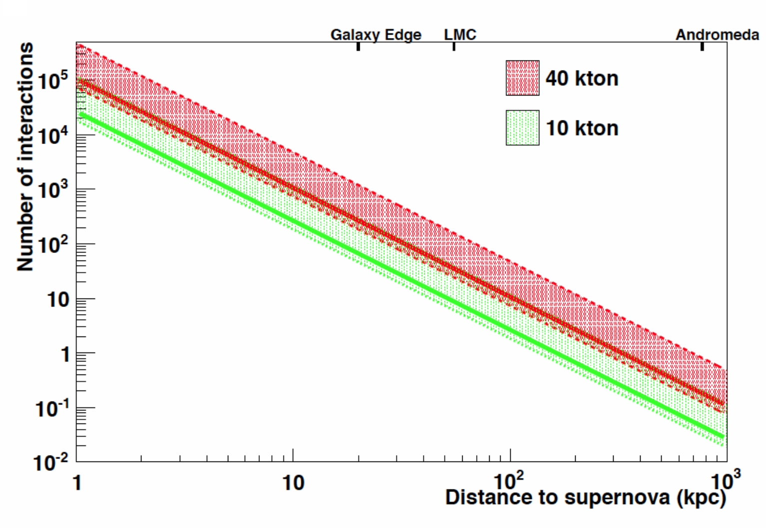
$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$

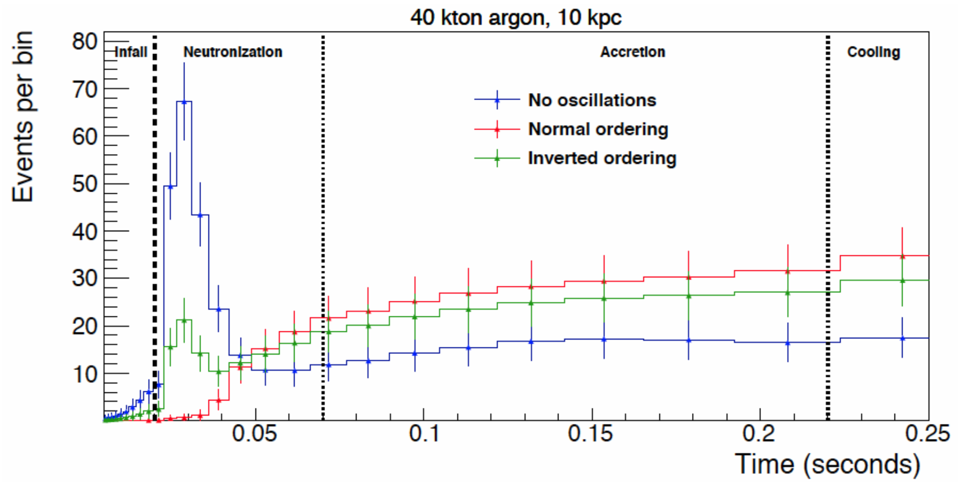


Simulation and reconstruction of proton decay at DUNE

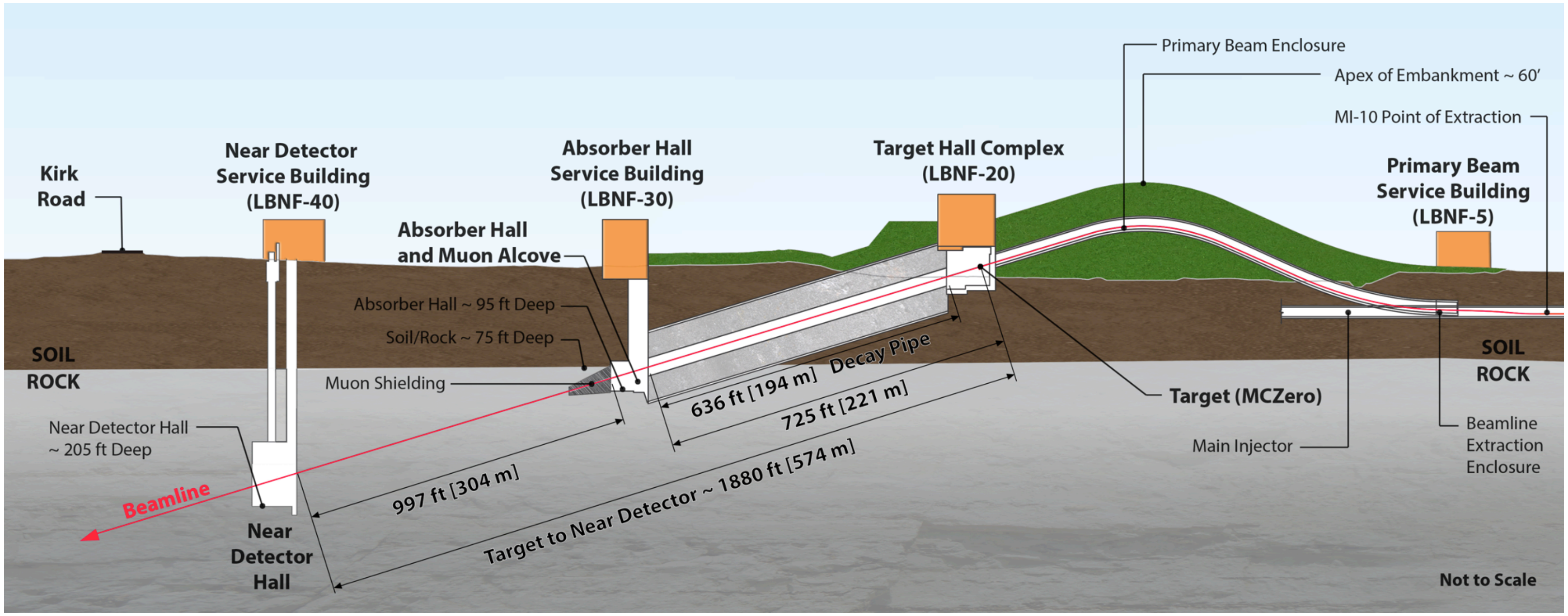
SN Neutrinos in DUNE

- 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





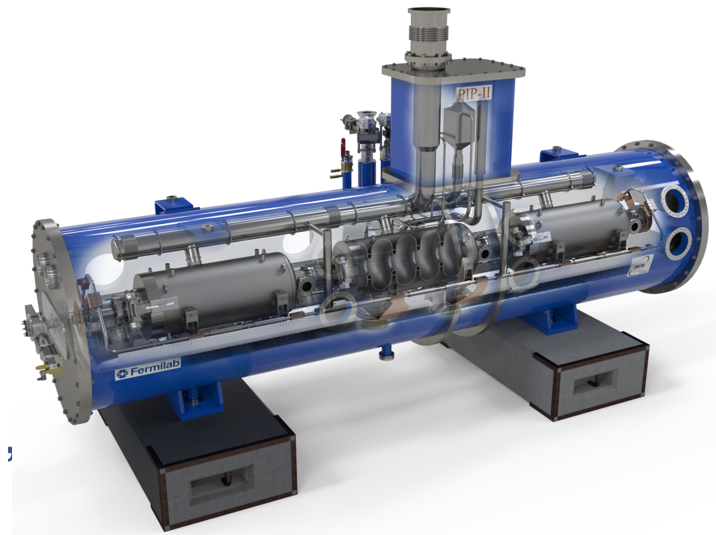
Beam and Near Detector

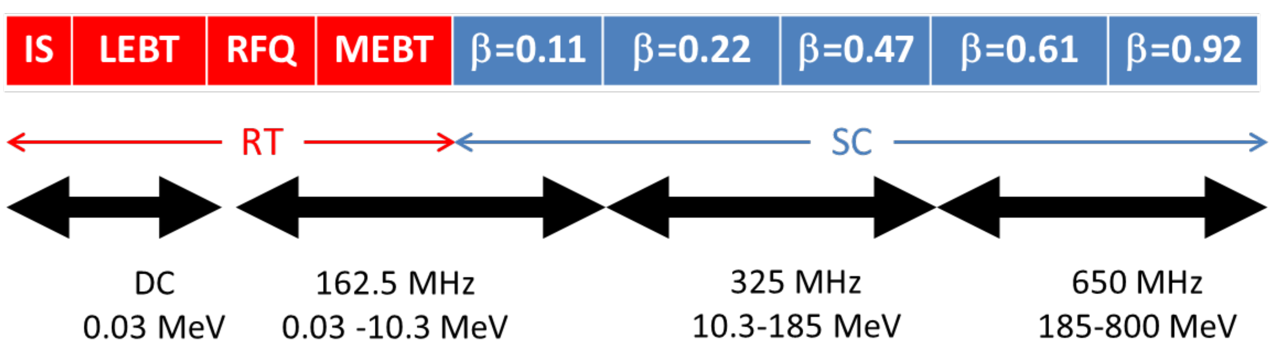


- Primary proton beam @ 60-120GeV extracted from Main Injector
- Initial 1.2 MW beam power, upgradable to 2.4 MW
- DUNE Near Detector: non-magnetized LAr-TPC + magnetized “multi-purpose tracker"
  - Precisely measure beam neutrino fluxes
  - Constrain systematic uncertainties for oscillation measurements
  - Goal is to settle on near detector concept by May 2018

PIP-II

- Goal: Deliver world-leading beam power to the U.S. neutrino program while providing a flexible platform for the future
  – 1.2 MW to LBNF over 60-120 GeV; upgradable to 2.4 MW
- Scope
  – 800-MeV SC Linac
  – Modifications to Booster, Recycler, Main Injector
- Current and Prospective Partners
  – Fermilab, ANL, LBNL
  – France (CEA & IN2P3), India (DAE), Italy (INFN), UK (STFC)





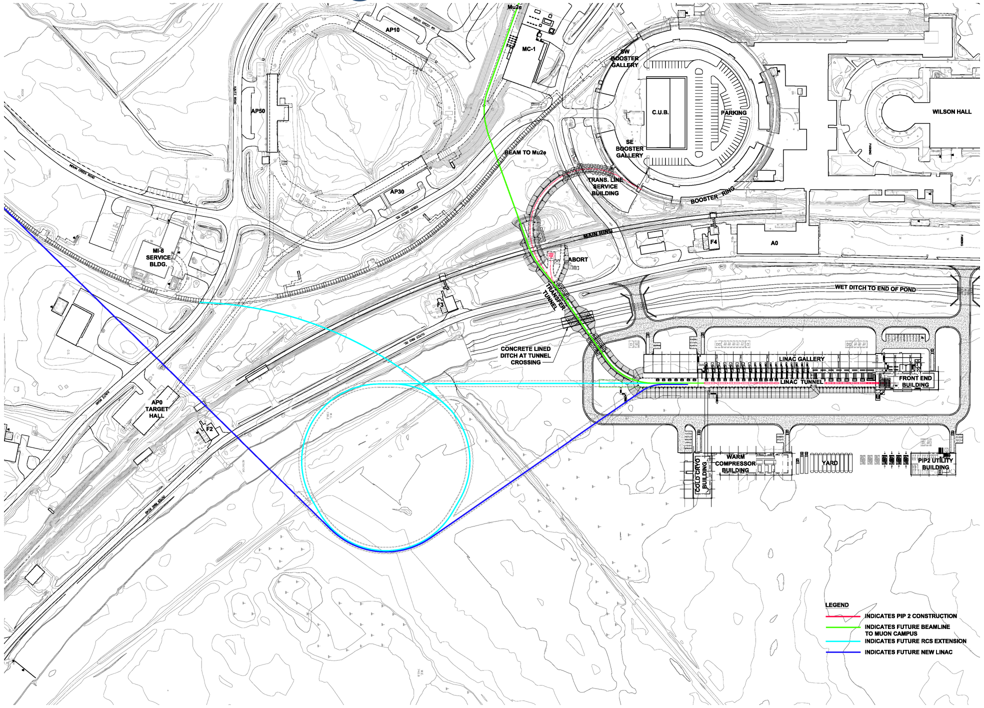
PIP-II Status

- R&D and conceptual development underway for many years
  - Builds upon major investment in superconducting radio frequency (SRF) technologies over the last decade+
- Conceptual Design Report released

  http://pip2-docdb.fnal.gov/cgi-bin/ShowDocument?docid=113
- Planned project completion: 2026
- Discussions with French laboratories
  - Both CEA and IN2P3 have experience directly relevant to the PIP-II linac based on their participation in European XFEL and ESS
  - Timing of PIP-II relative to ESS completion is good
  - Discussions at technical level have been extended to the agency level

2+ MW @ 60-120 GeV

- Concepts exist for upgrade of the Fermilab complex to 2.4 MW
  - 1.5×10^{14} protons from Main Injector every 1.2 s @ 120 GeV
  - Every 0.6 sec @ 60 GeV
- Will require replacement of the existing 8-GeV Booster with either an 8-GeV pulsed linac or a new 8-GeV rapid cycling synchrotron



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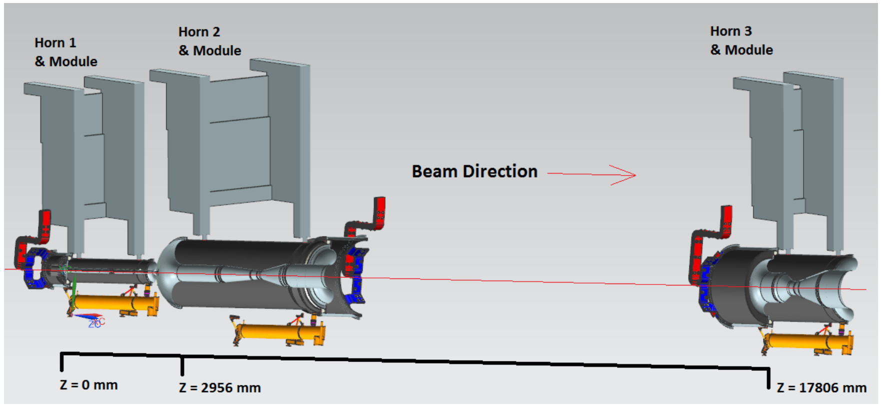
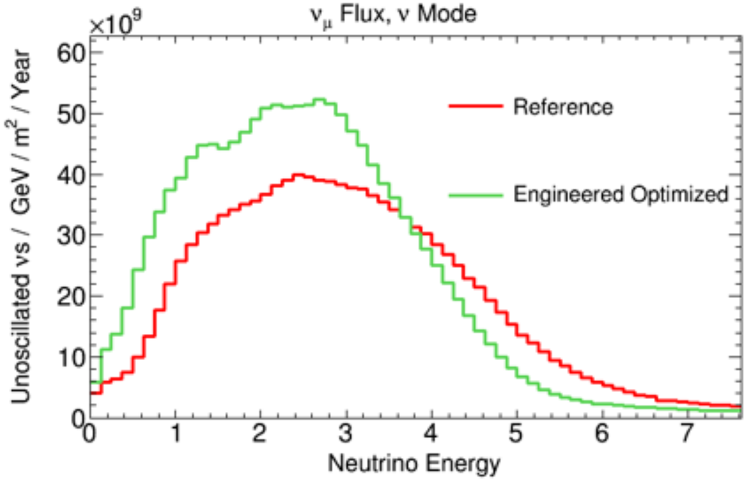
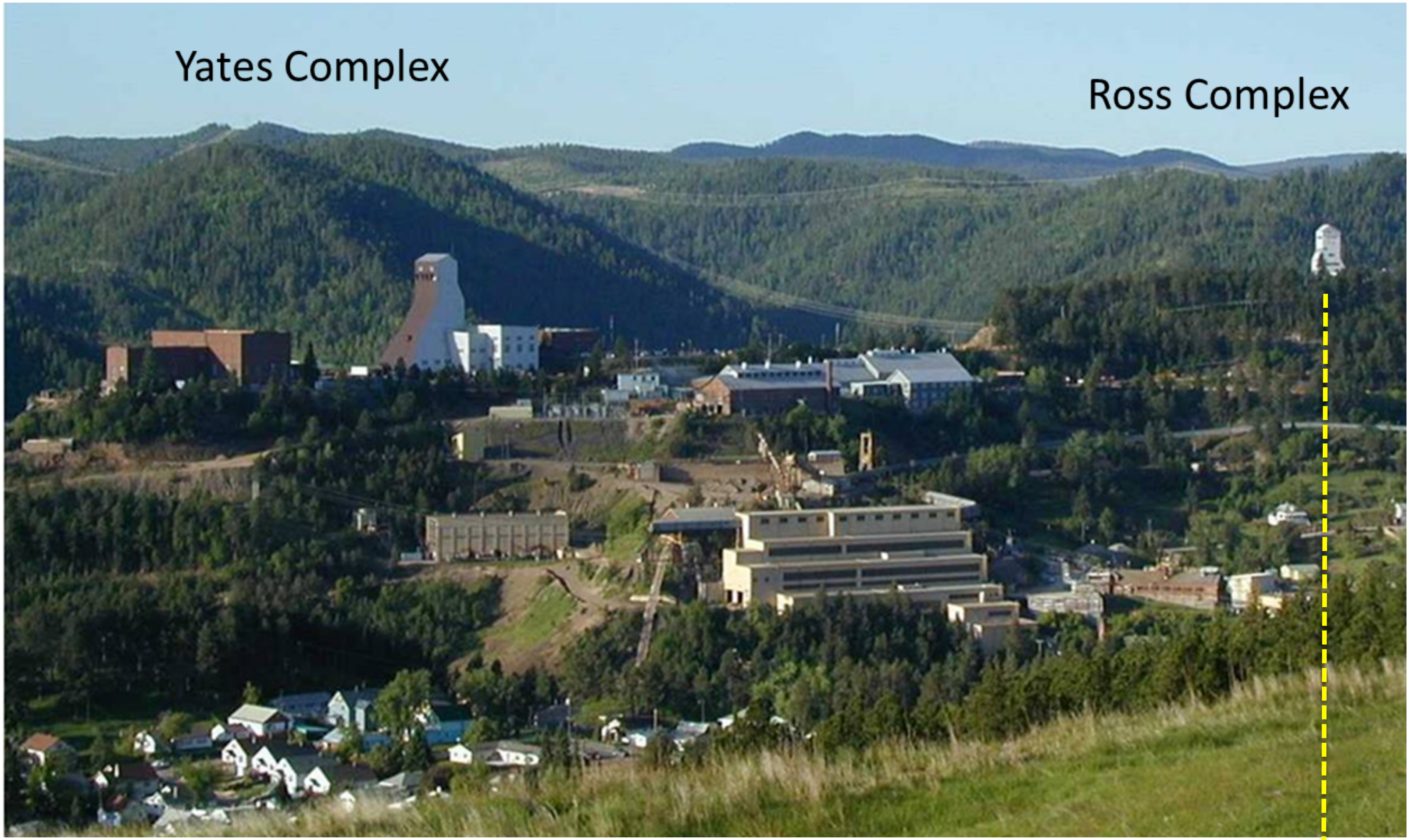
Optimization of neutrino beamline

- Significant effort to optimize target and horn system for better sensitivity to CP violation
- LBNF has adopted optimized design with 4 interaction-length target and 3 horns.





DUNE/LBNF Far Site



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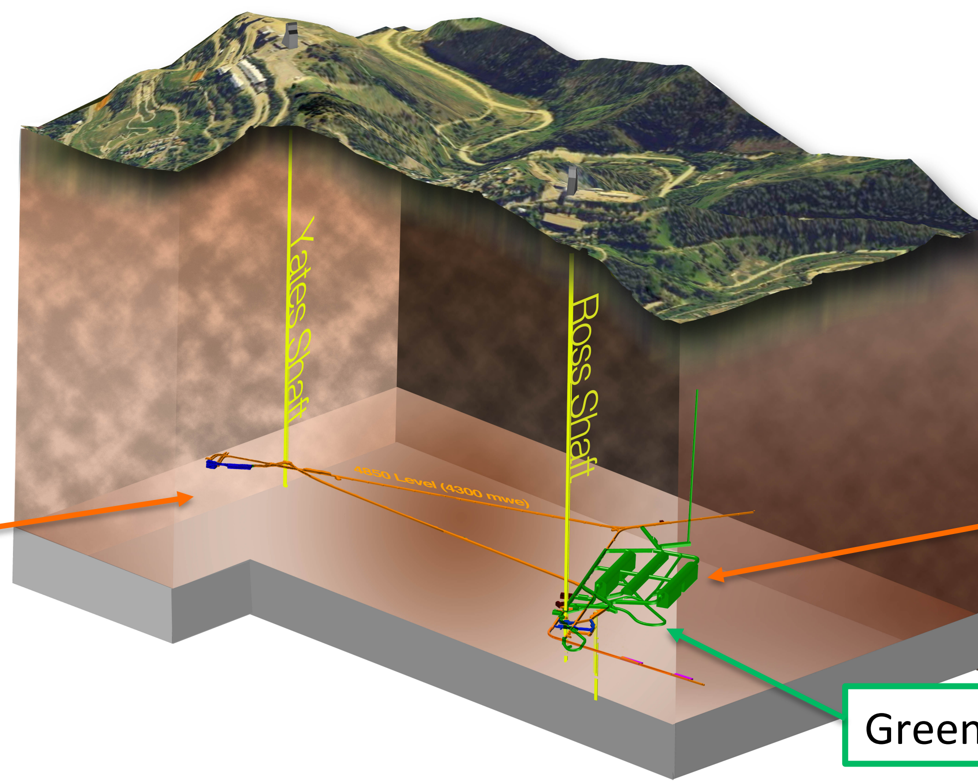
DUNE Far Site

Ross Campus of 4850 ft level of Sanford Underground Research Facility



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

Ross Campus:
- CASPAR
- …
- **DUNE**

Green = new construction

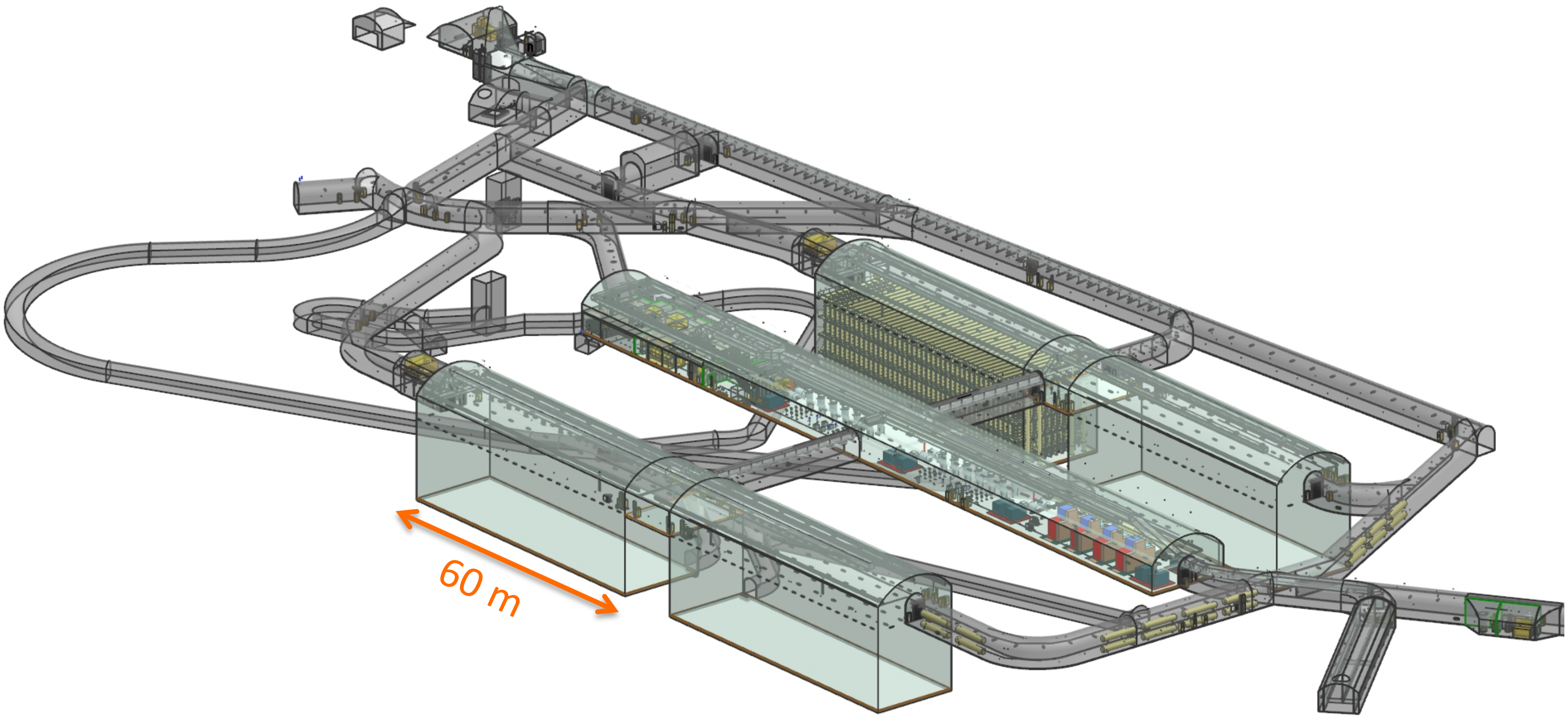
LBNF/DUNE Groundbreaking, 21 July 2017

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 not identical**
- **Requires excavation of 875,000 tons of rock**

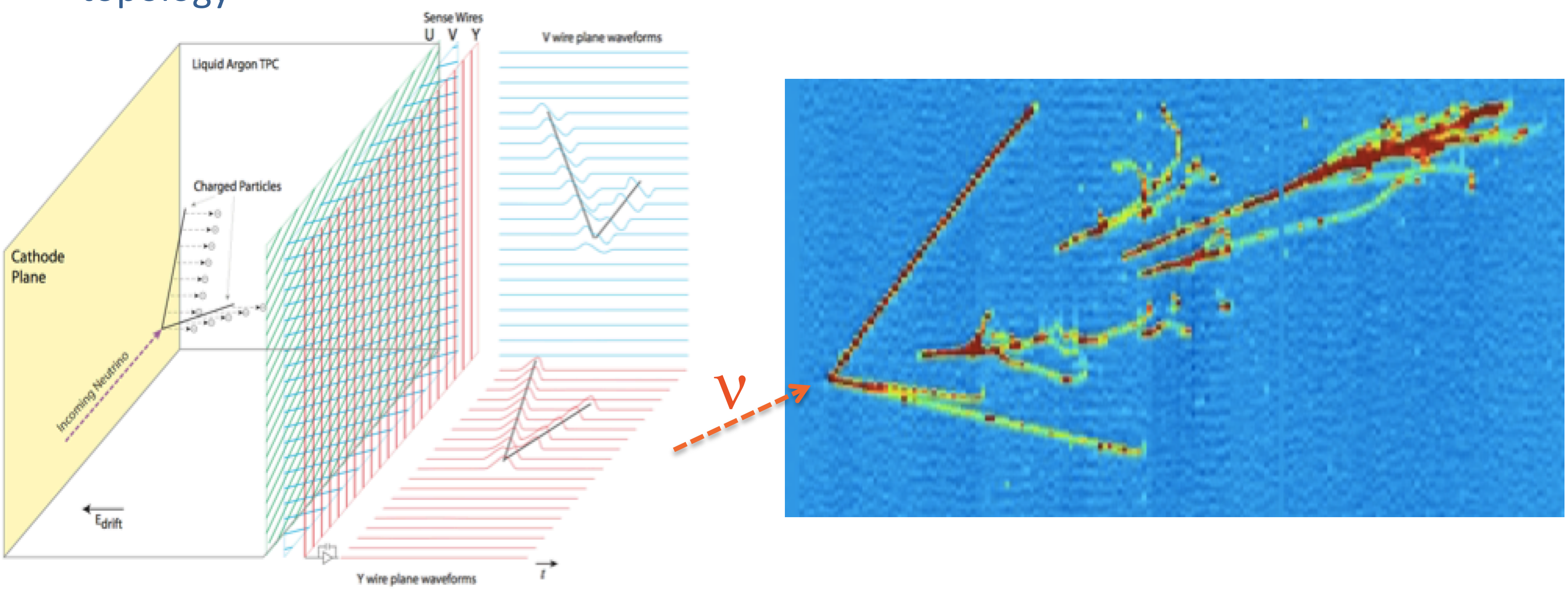
DUNE Far Detector: LAr TPCs

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

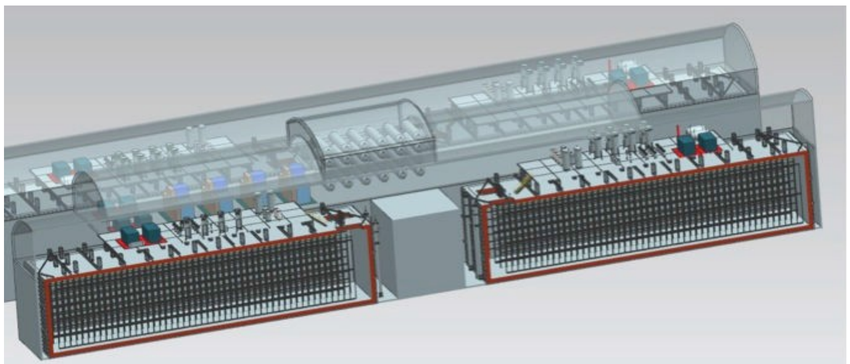
Major (and exciting) challenges

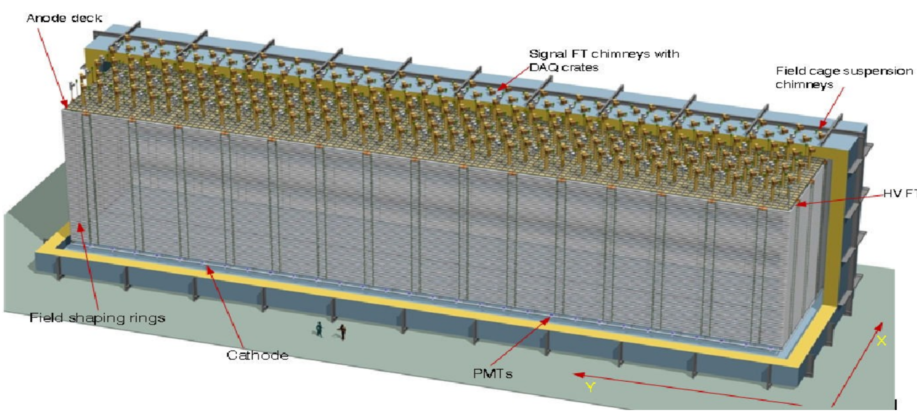
- Scaling technology to very large detector volumes
- Event reconstruction and classification



DUNE Far Detector Technologies

Collaboration is planning to employ (and is prototyping) two liquid argon readout technologies:





Single Phase

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

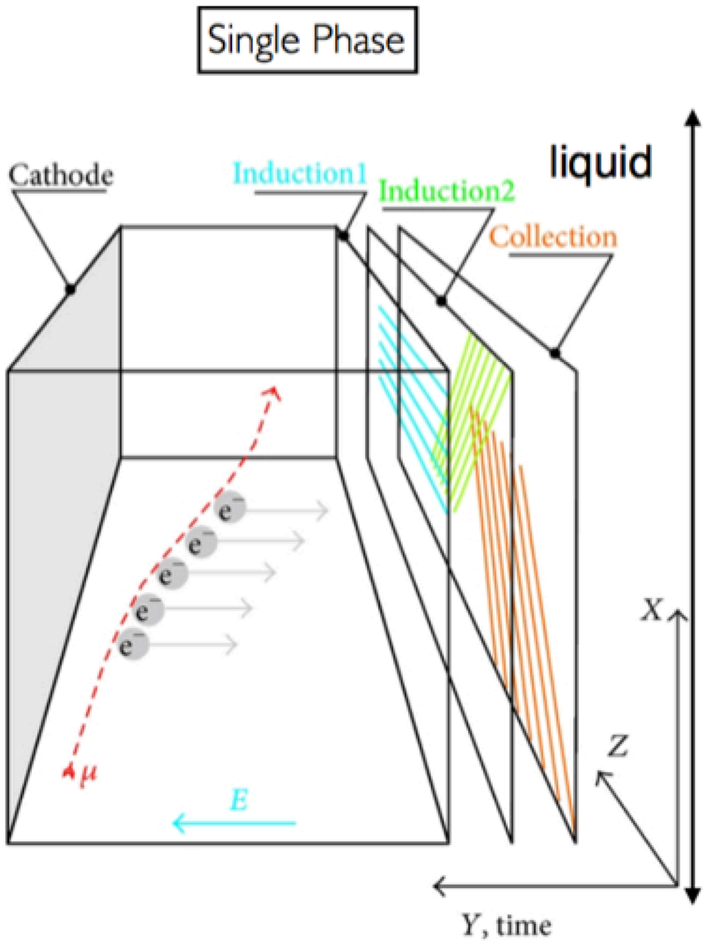
Dual Phase

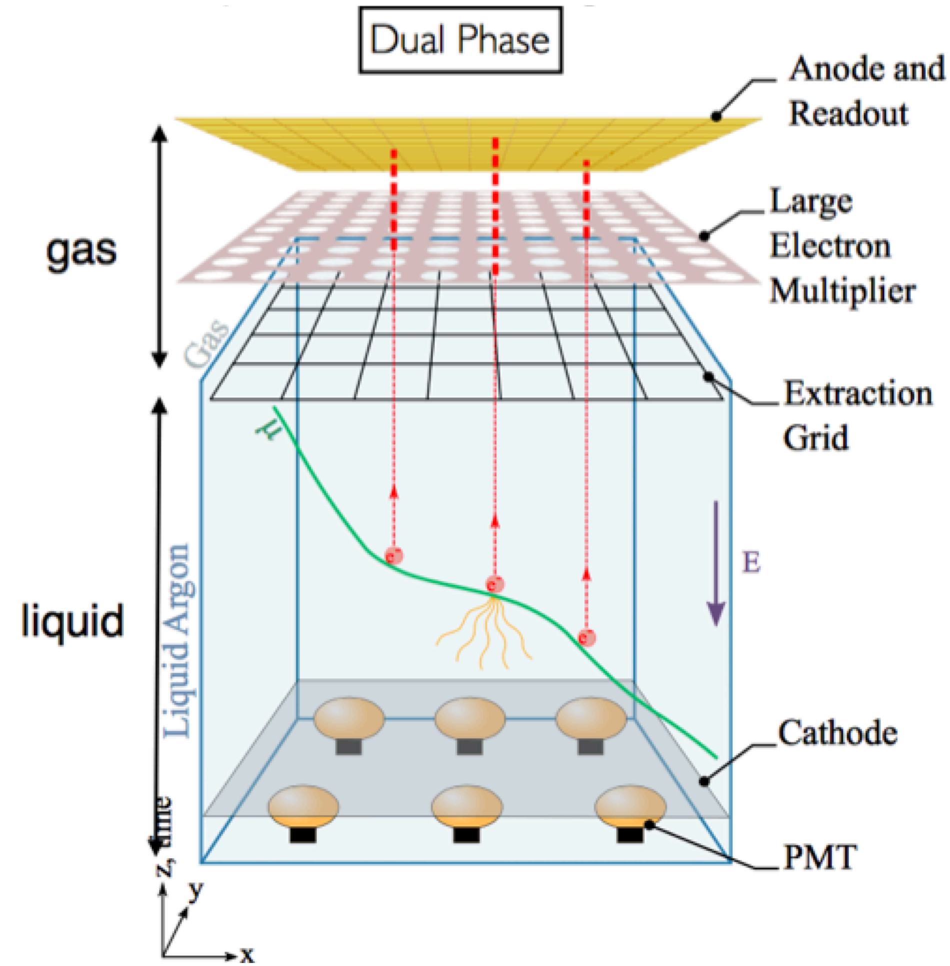
- amplification of electron signal in gas phase
- Pioneered at large scale by WA105
- 12 m maximum drift

Liquid argon TPC: Single and dual phase

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

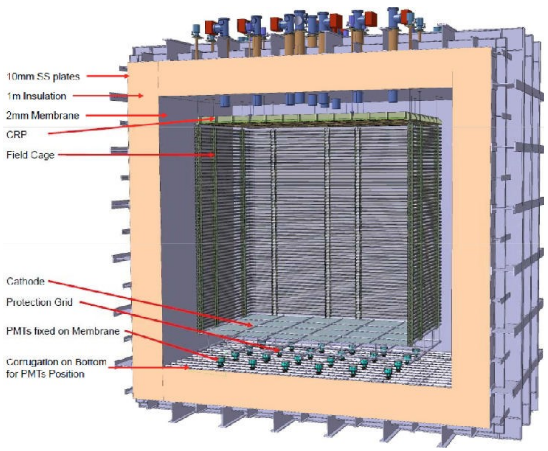
- Ionization charges drift vertically and are read out on PCB anode
- Amplification of signal in gas phase by LEM





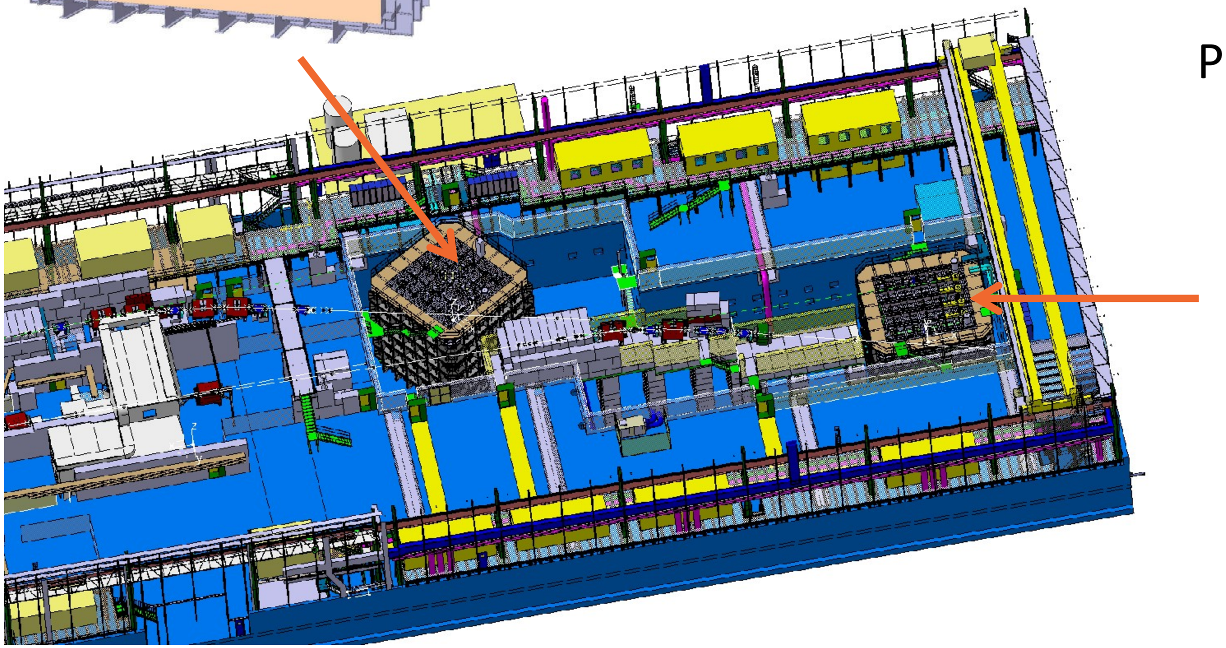
Prototypes at CERN Neutrino Platform

ProtoDUNE Dual Phase

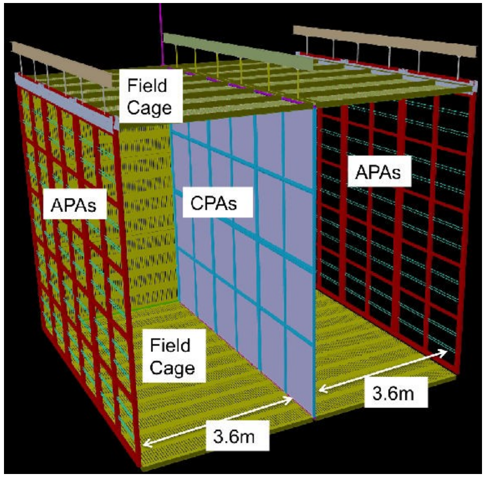


Major CERN investment to support DUNE

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



ProtoDUNE Single Phase



Prototypes at CERN Neutrino Platform

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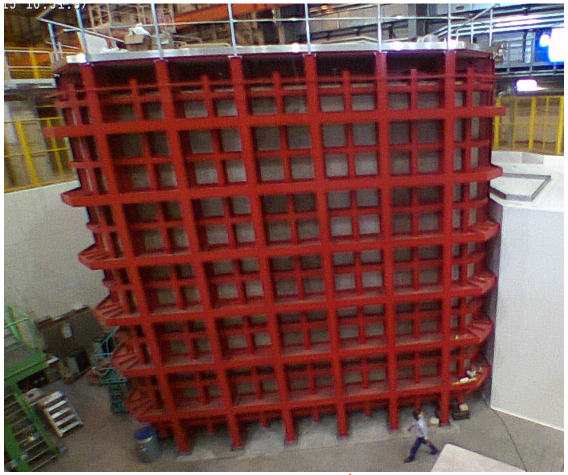
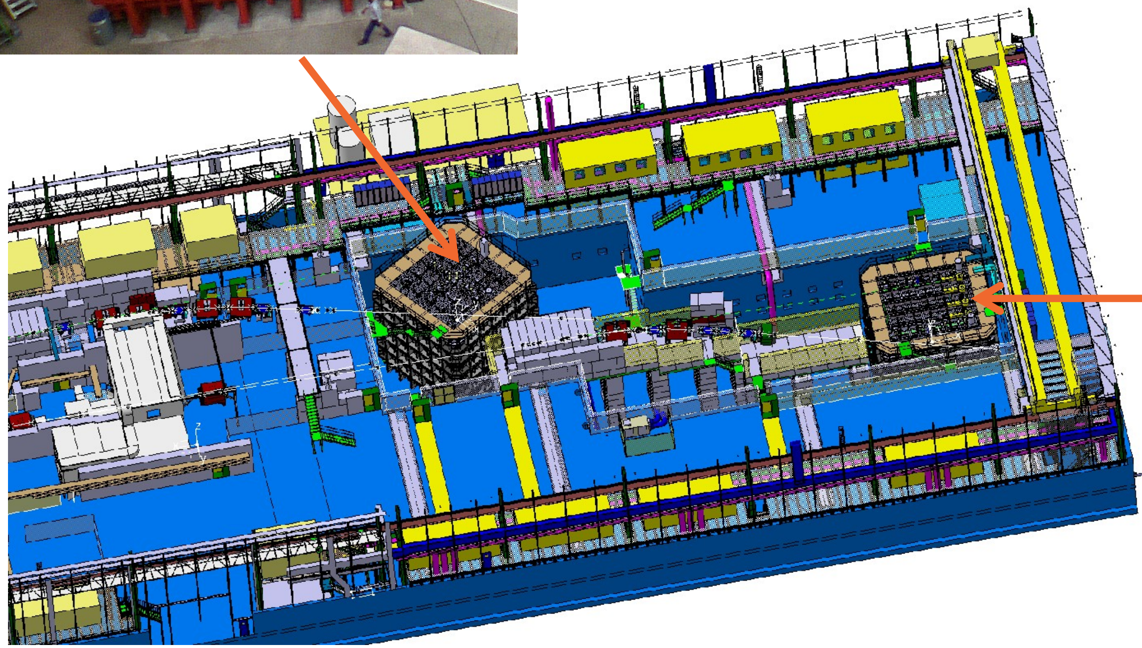


Both ProtoDUNEs aim to begin data taking in mid 2018.

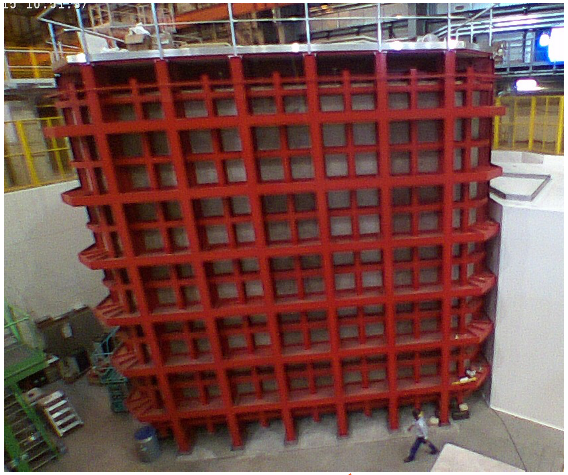
EHN1 Webcams:
http://cenf-ehn1-np.web.cern.ch/images/np04-webcam-neutrino-platform-hall-ehn1



ProtoDUNE Single Phase

Prototypes at CERN Neutrino Platform

ProtoDUNE Dual Phase



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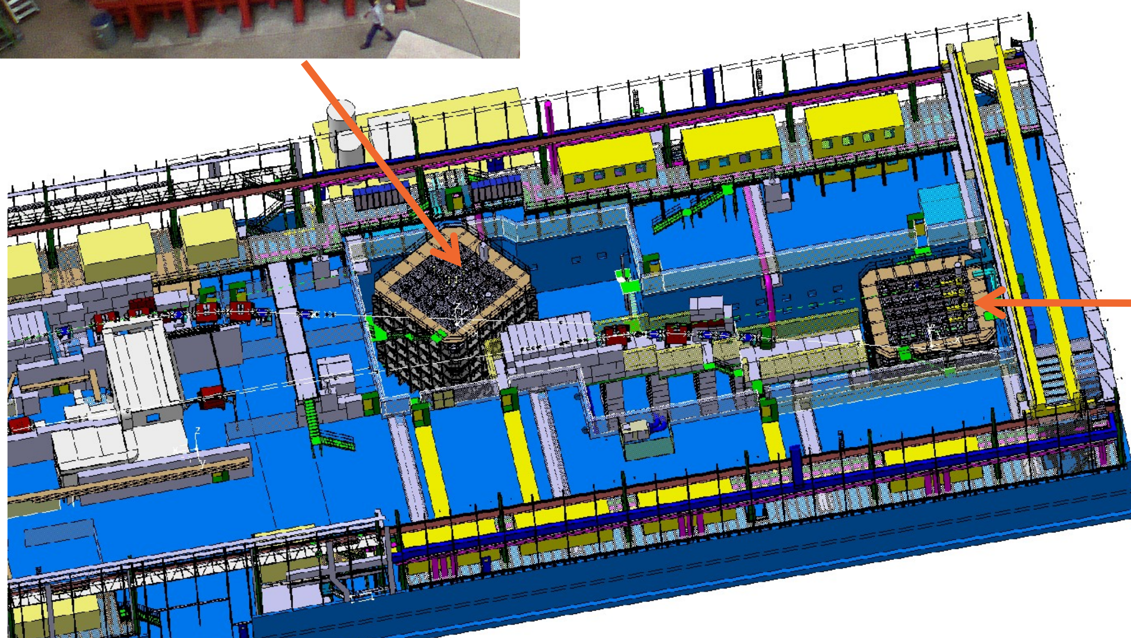
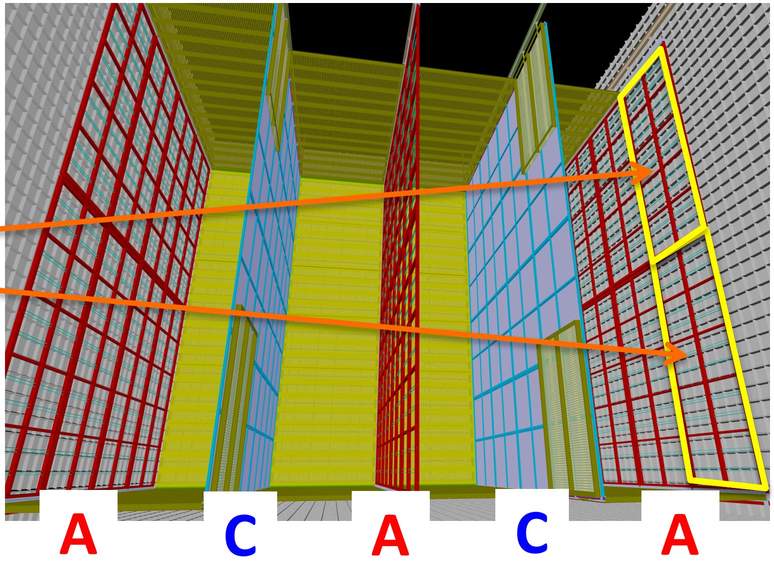


ProtoDUNE Single Phase

DUNE → ProtoDUNE-SP

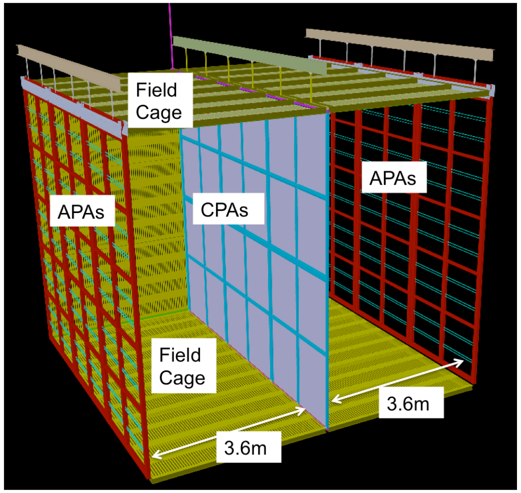
DUNE Far Detector

- 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 3.6m drift



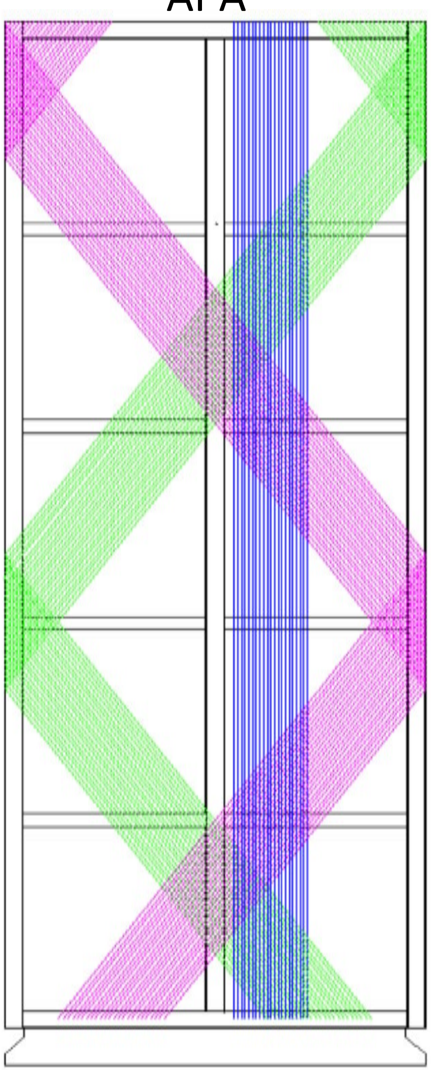
ProtoDUNE-SP

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



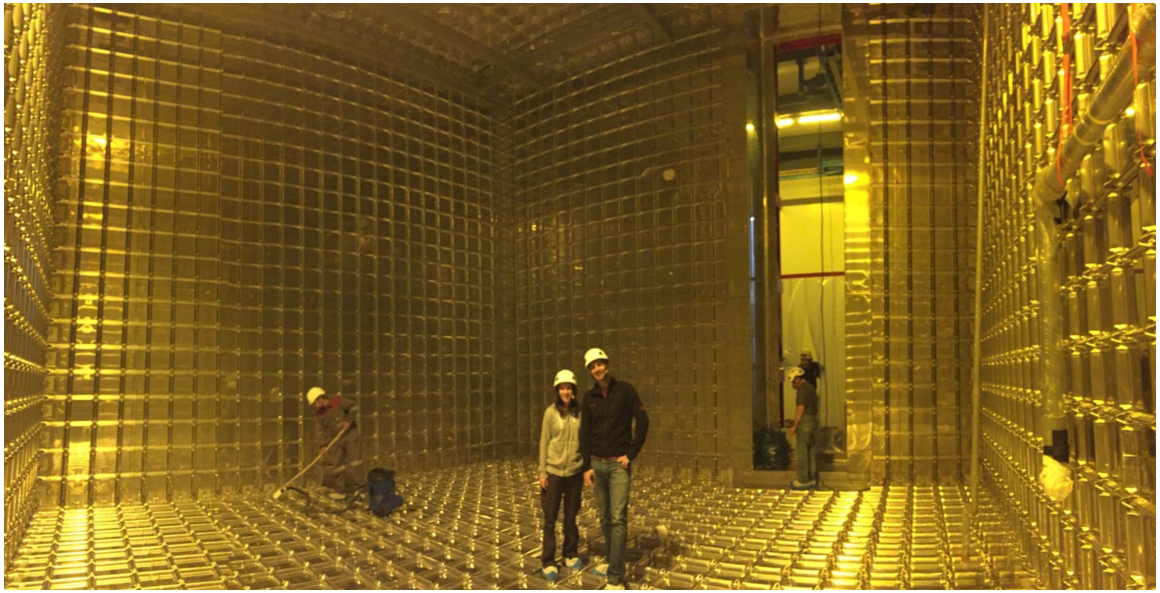
ProtoDUNE-SP

APA

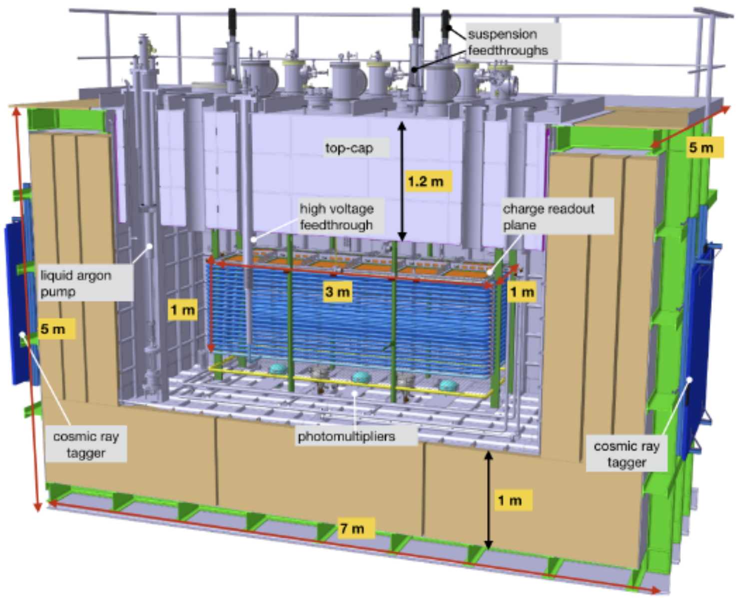


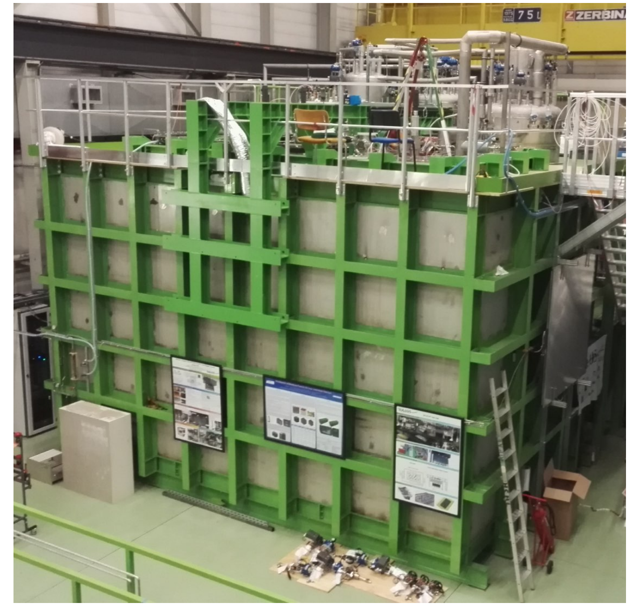
APA #1 in clean room

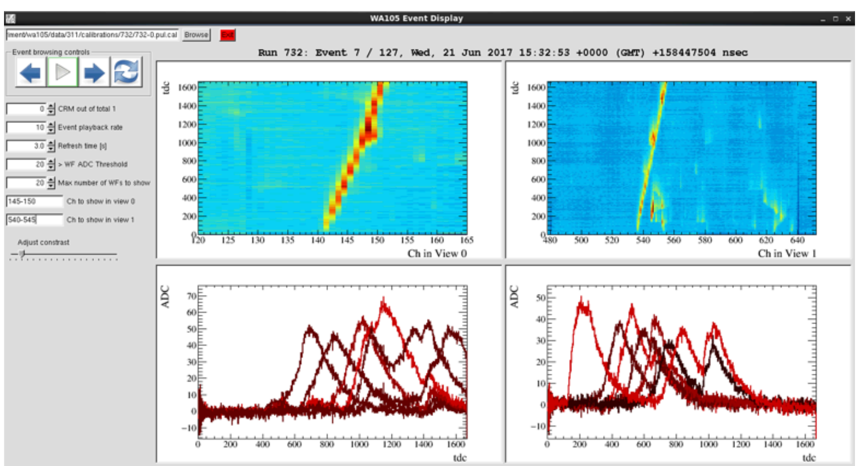
APA in cold box



Pre ProtoDUNE-DP: 1m × 1m × 3m

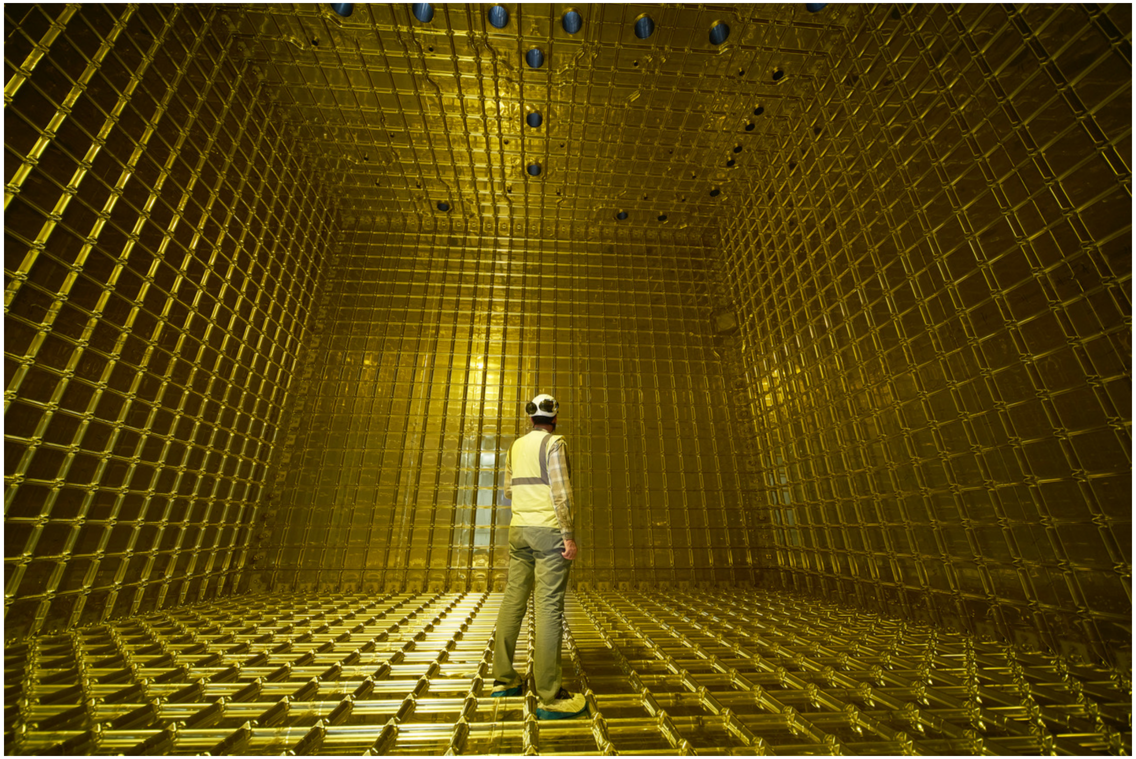


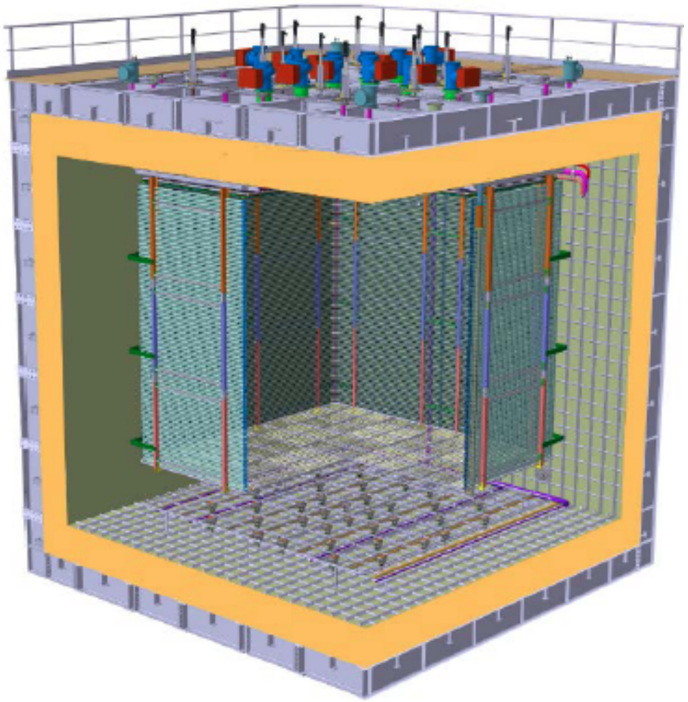




- First tracks observed in 1×1×3m in June 2017
- Revealed some technical issues still under investigation

ProtoDUNE-DP

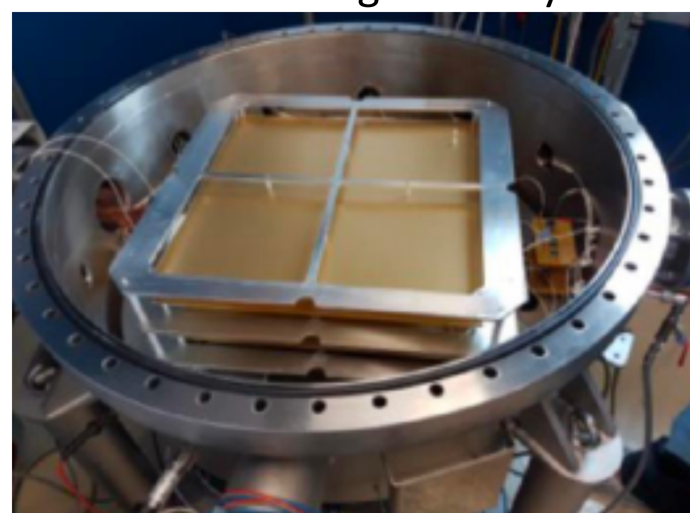


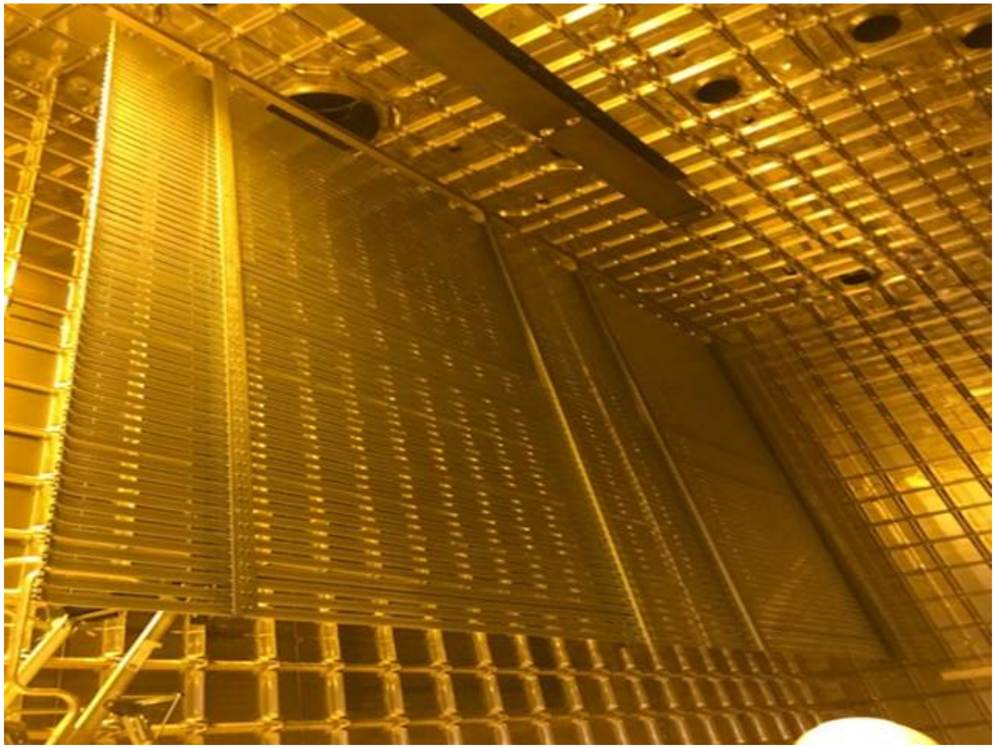


ProtoDUNE-DP

Full-sized engineering model for CRP frame

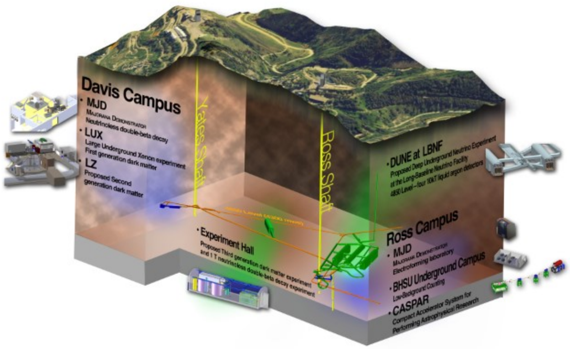
LEM Testing at Saclay

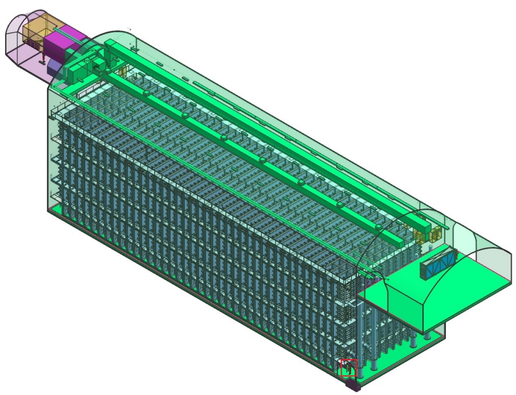




First field cage panels installed
19 December 2017

DUNE Timeline





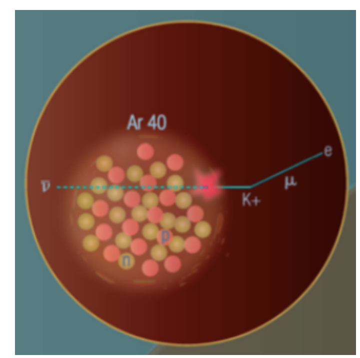
2018: protoDUNEs at CERN

2019: Far detector excavation begins

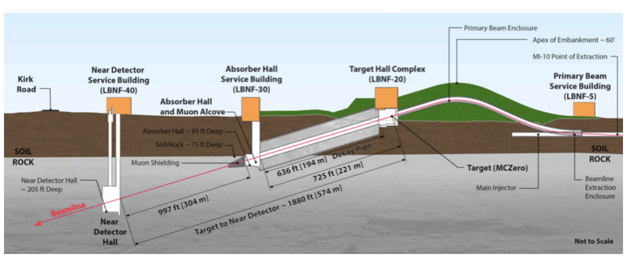
2022: Start Detector #1 Installation

2024: Physics Data Begins

2026: Beam on with 2 detectors



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 21 July 2017.
- On track to operate ProtoDUNE-SP and ProtoDUNE-DP in 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

International Project Milestones	Date
Start Main Cavern Excavation	2019
Start Detector #1 Installation	2022
Beam on with two detectors	2026

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