DUNE

Stefan Söldner-Rembold

Users Meeting

21 June 2018

Fermilab

DUNE is growing

- 1132 collaborators from 179 institutions in 32 countries
- 624 faculty/scientists, 188 postdocs, 106 engineers, 214 PhD students
- Growing at a rate of about 100 collaborators/year

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.

Recently joined: Portugal

U.S., India sign agreement providing for neutrino physics collaboration at Fermilab and in India

April 16, 2018

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This release was originally issued today by the U.S. Department of Energy.

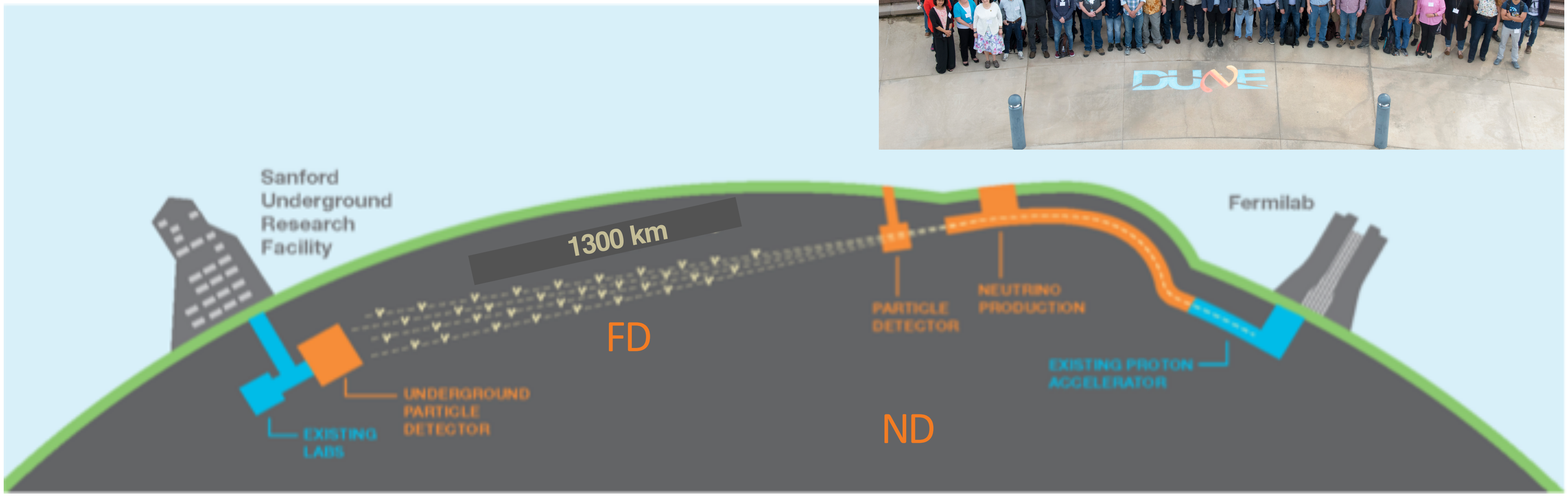
Earlier today, April 16, 2018, U.S. Secretary of Energy Rick Perry and India's Atomic Energy Secretary Dr. Sekhar Basu signed an agreement in New Delhi to expand the two countries' collaboration on world-leading science and technology projects. It opens the way for jointly advancing cutting-edge neutrino science projects under way in both countries: the Long-Baseline Neutrino Facility (LBNF) with the international Deep Underground Neutrino Experiment (DUNE) hosted at the U.S. Department of Energy's Fermilab and the India-based Neutrino Observatory (INO).

LBNF/DUNE brings together scientists from around the world to discover the role that tiny particles known as neutrinos play in the universe. More than 1,000 scientists from over 170 institutions in 31 countries work on LBNF/DUNE and celebrated its groundbreaking in July 2017. The project will use Fermilab's powerful particle accelerators to send the world's most intense beam of high-energy neutrinos to massive neutrino detectors that will explore their interactions with matter.

INO scientists will observe neutrinos that are produced in Earth's atmosphere to answer questions about the properties of these elusive particles. Scientists from more than 20 institutions are working on INO.

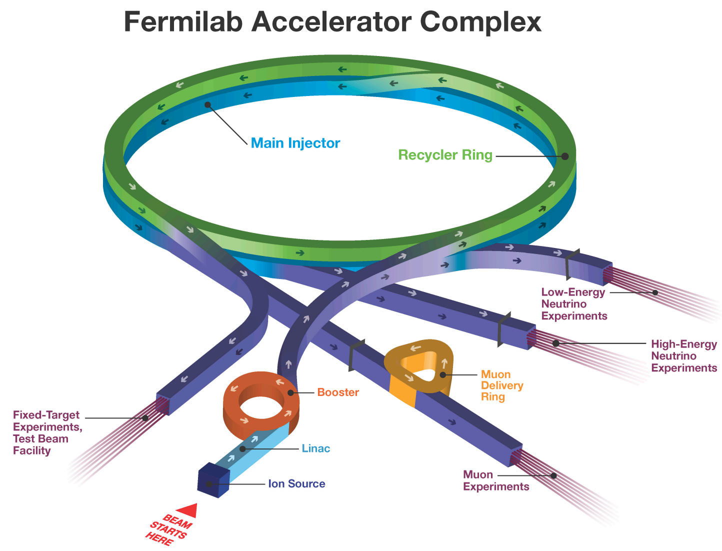
U.S. Secretary of Energy Rick Perry, left, and Indian Atomic Energy Secretary Sekhar Basu, right, signed an agreement on Monday in New Delhi, opening the door for continued cooperation on neutrino research in both countries. In attendance were Hema Ramamoorthi, chief of staff of the U.S. DOE's Fermi National Accelerator Laboratory, and U.S. Ambassador to India Kenneth Juster. Photo courtesy of Fermilab

DUNE

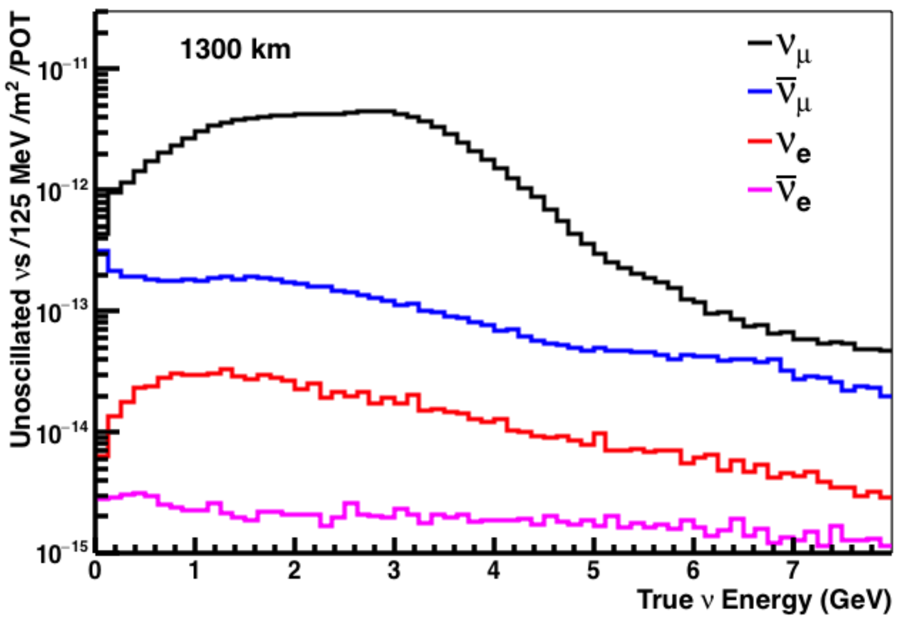


- Approximately 40 kt fiducial mass liquid-argon Far Detector.
- Located at SURF's 1478 m level with 1300 km baseline.
- Near Detector located approximately 575 m from neutrino source.
- Wide-band neutrino beam (~ GeV range).
- Flagship physics topics: CPV, supernova neutrinos, proton decay.

The LBNF Beam



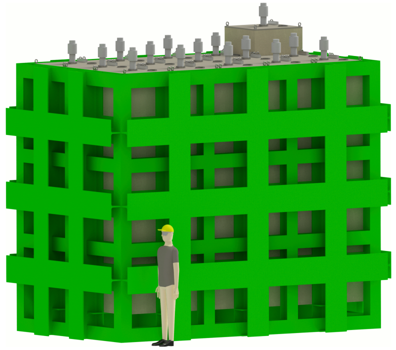
Neutrino Flux at 1300 km
(CDR Optimized Beam)



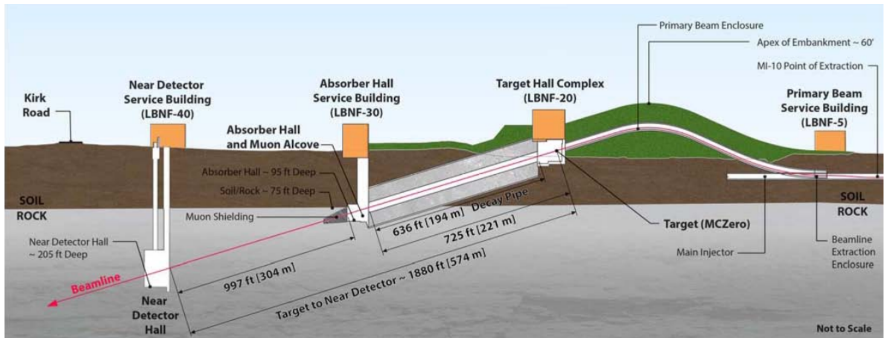
- 60-120 GeV proton beam at 1.2 MW, upgradeable to 2.4 MW
- Horn-focused neutrino beam line optimized for CP violation sensitivity using genetic algorithm
- Engineering design of 3-horn focusing system based on optimized parameters in progress
- Neutrino (FHC) and antineutrino (RHC) modes

The DUNE Near Detector

- Constrain systematic uncertainties for long-baseline oscillation analysis
  - flux, cross-section, and detector
- DUNE ND design concept near final
  - Active ND Design Group
  - ND Conceptual Design Report (CDR) planned for 2019



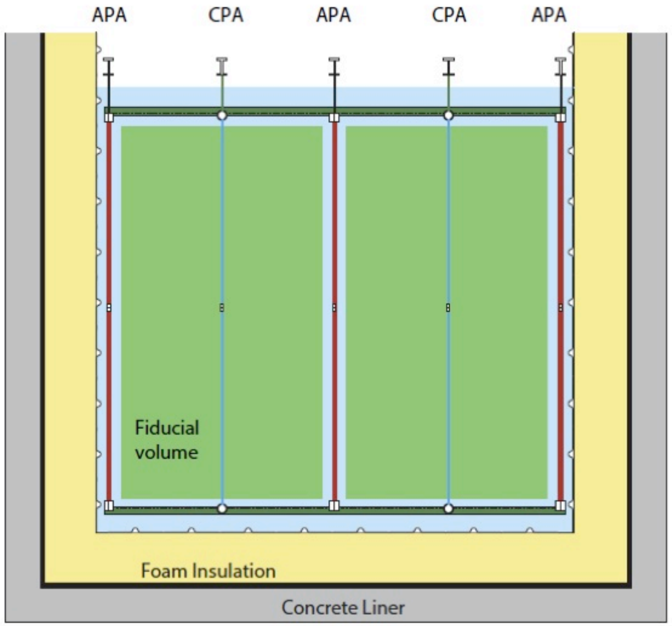
- DUNE ND design concept is an integrated system composed of multiple detectors:
  - Highly segmented LArTPC
  - Magnetized multi-purpose tracker
  - Electromagnetic calorimeter
  - Muon chambers

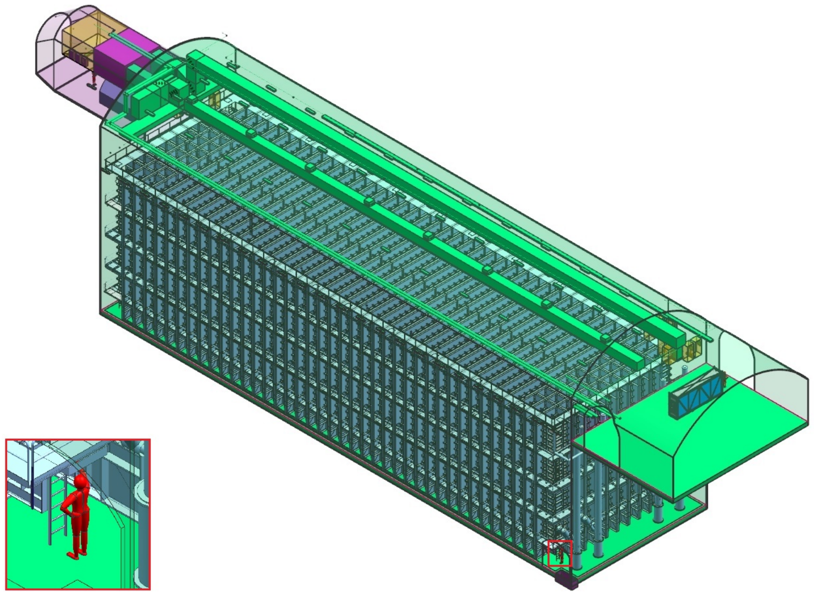


- Conceptual design will preserve option to move ND for off-axis measurements
- >100 million interactions will also enable a rich non-oscillation physics programme

DUNE Far Detector

- Four 10-kt (fiducial) liquid argon TPC modules
- Single and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection (need wavelength shifting to visible)
- Modules will not be identical





384,000 readout wires

150 “APAs” (2.3 m x 6 m)

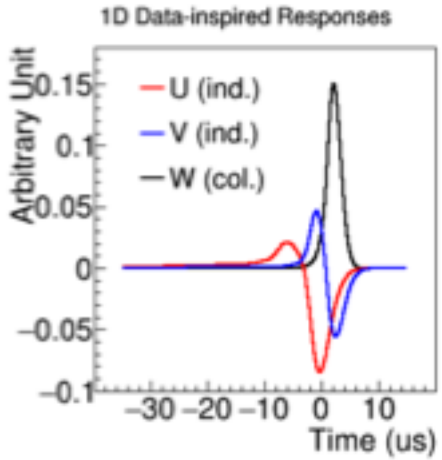
12 m high

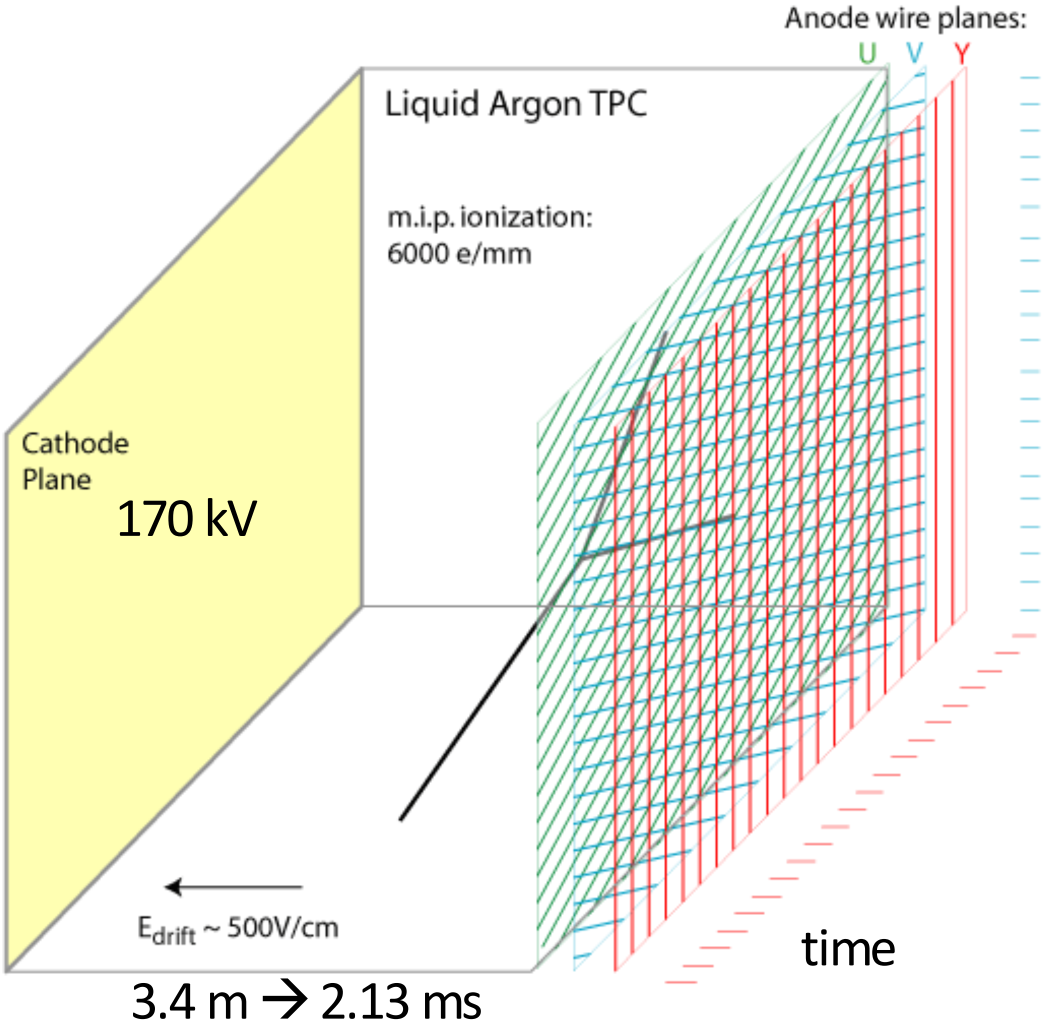
15.5 m wide

58 m long

Single-phase: charge drifts to wire planes (APAs)

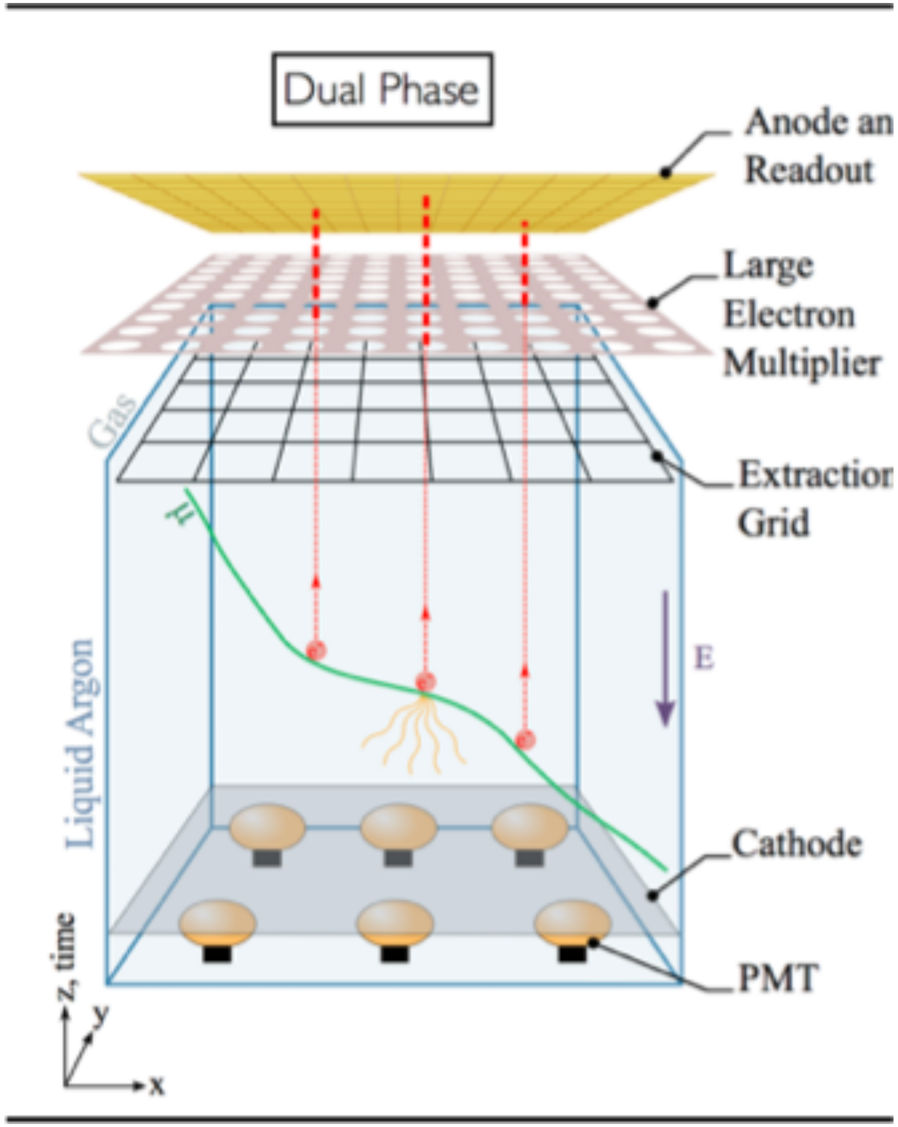
Single Phase Concept



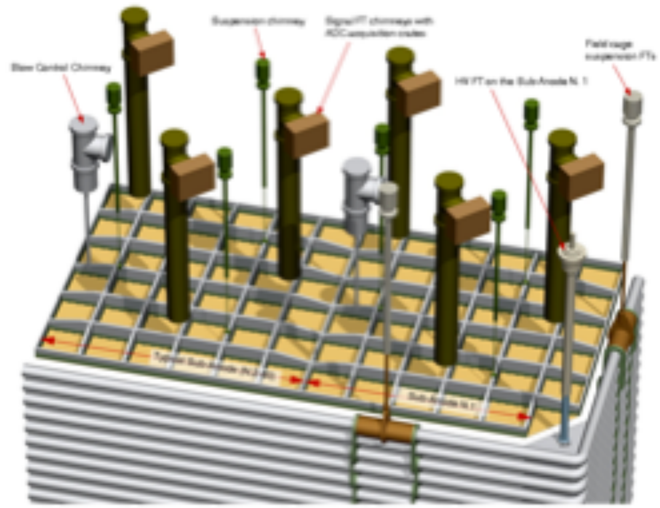


time →

Dual Phase TPC



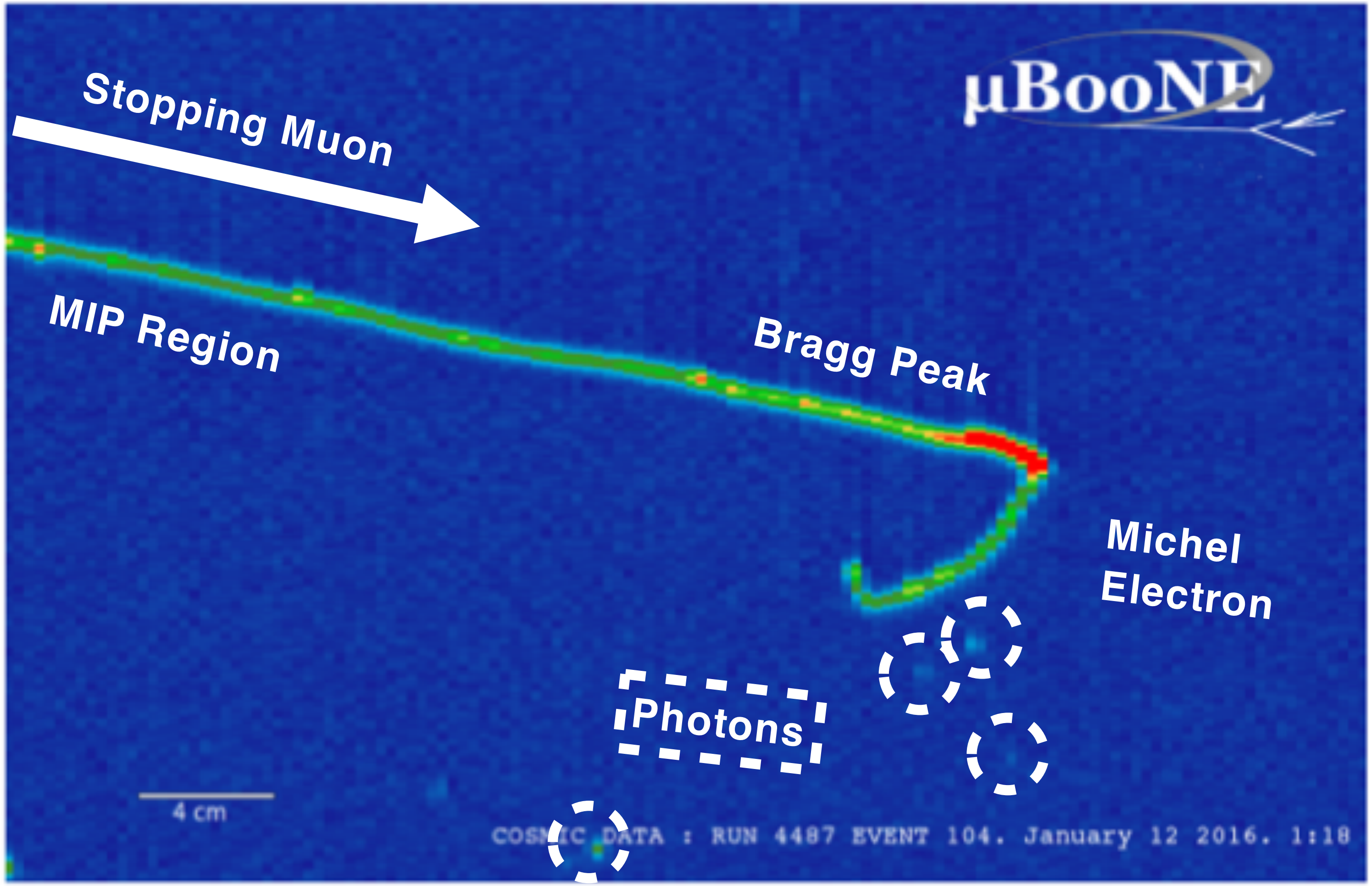
- Larger drift distance (12 m) – higher fields
- Potentially better signal to noise
- Readout/HV access through chimneys on top.



153,600 channels

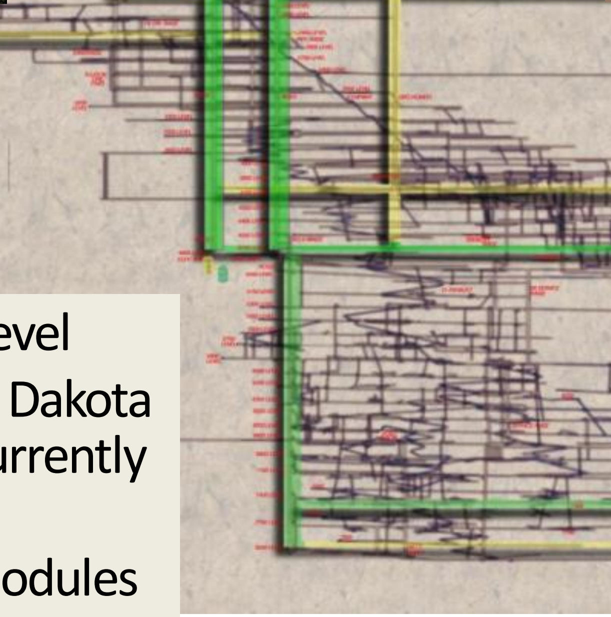
80 3x3 m² Charge Readout Planes

A powerful imaging technology



Textbook plot…

Sanford Underground Research Facility (SURF)



- Experimental facilities at a level of 1478 m, located in South Dakota
- Two vertical access shafts currently being refurbished
- Large excavation for 40 kt modules

Testing the standard "three-flavour" paradigm

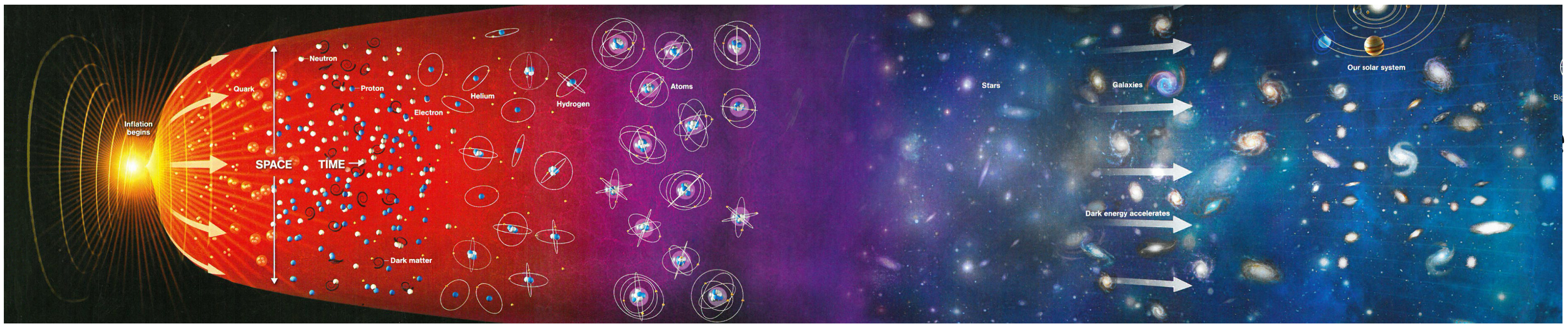
complex phase

$$U_{\text{PMNS}} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

CP Violation in the lepton sector might provide support for *Leptogenesis* as mechanism to generate the Universe's matter-antimatter asymmetry.

CP Violation: $\delta \neq \{0, \pi\}$

$s_{ij} = \sin\theta_{ij}\ ;\ c_{ij} = \cos\theta_{ij}$



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CP Violation: $\delta \neq \{0, \pi\}$ $\quad s_{ij} = \sin\theta_{ij} \; ; \; c_{ij} = \cos\theta_{ij}$

Caveat:

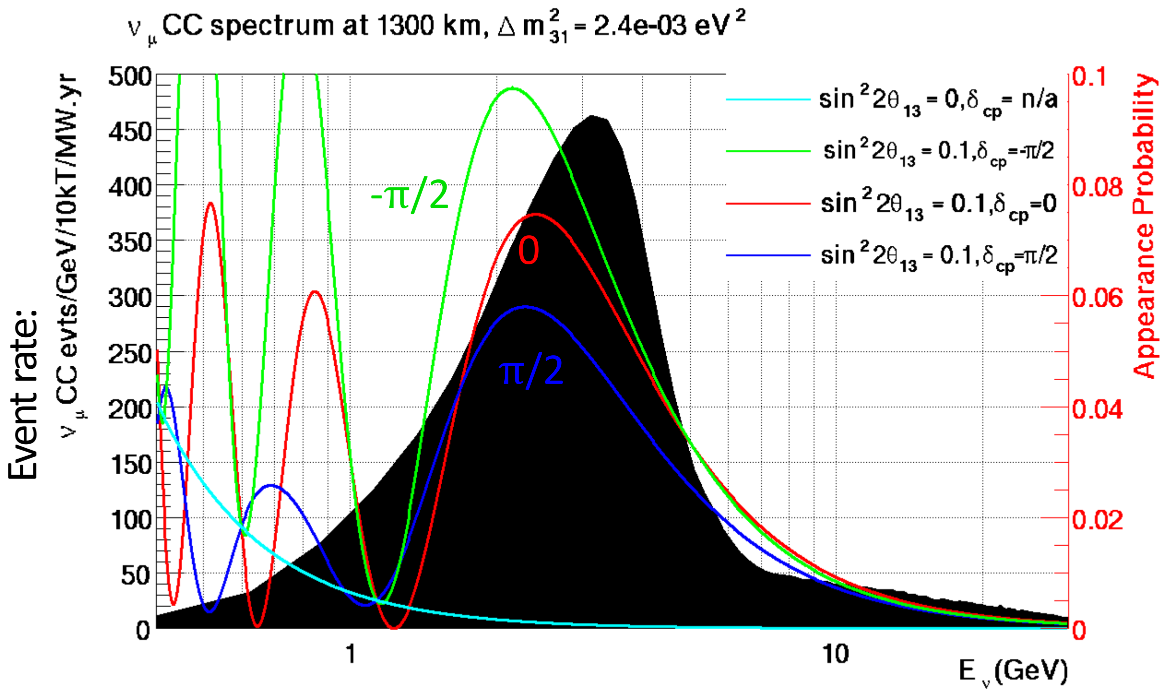
No direct evidence for *Leptogenesis*, since a model is needed to connect the low-scale CPV observed here to high-scale CPV for heavy neutrinos that lead to *Leptogenesis*.

DUNE Oscillation Strategy

$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

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

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

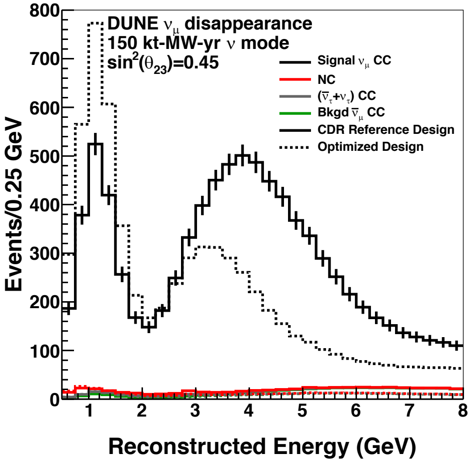


- ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and matter effects – measurements of all four possible in a single experiment
- Large value of $\sin^2(2\theta_{13})$ allows significant ν_e appearance sample

DUNE Oscillation Strategy

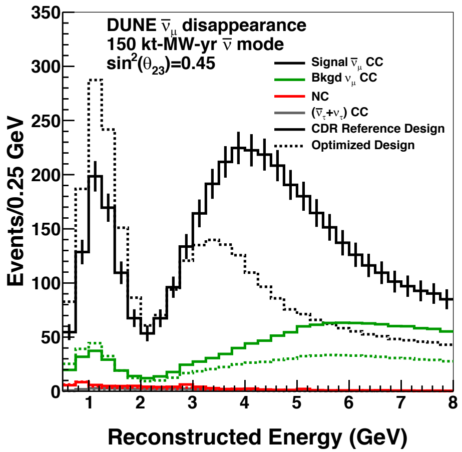
- Measure ν_e appearance and ν_μ disappearance over range of energies
- Disentangle mass ordering and CP violation effects

muon-neutrino disappearance

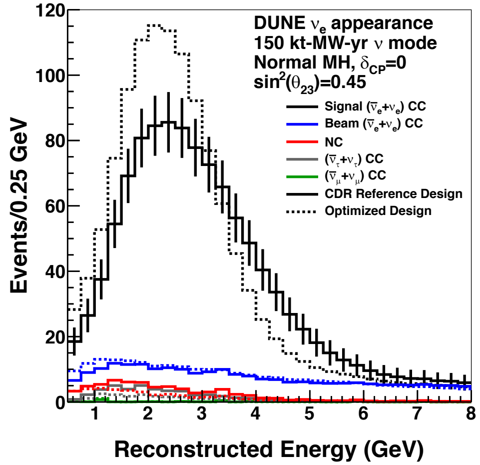


ν_μ

$\bar{\nu}_\mu$



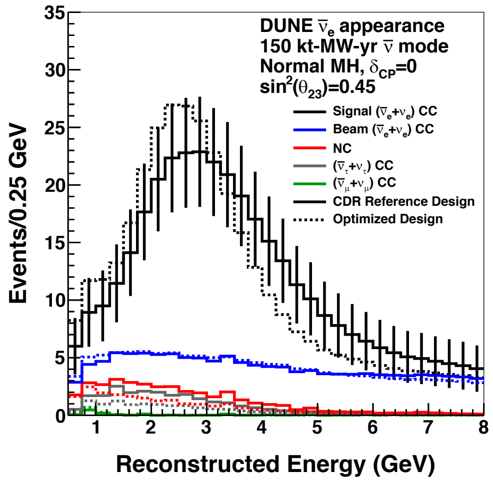
electron-neutrino appearance



ν_e

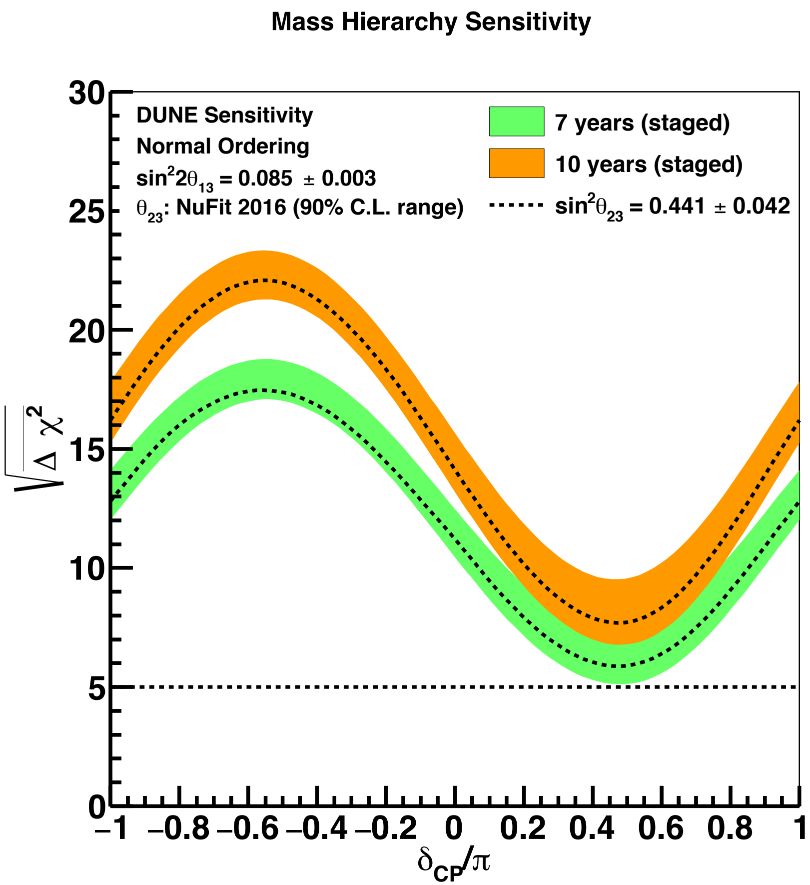
7 years of data

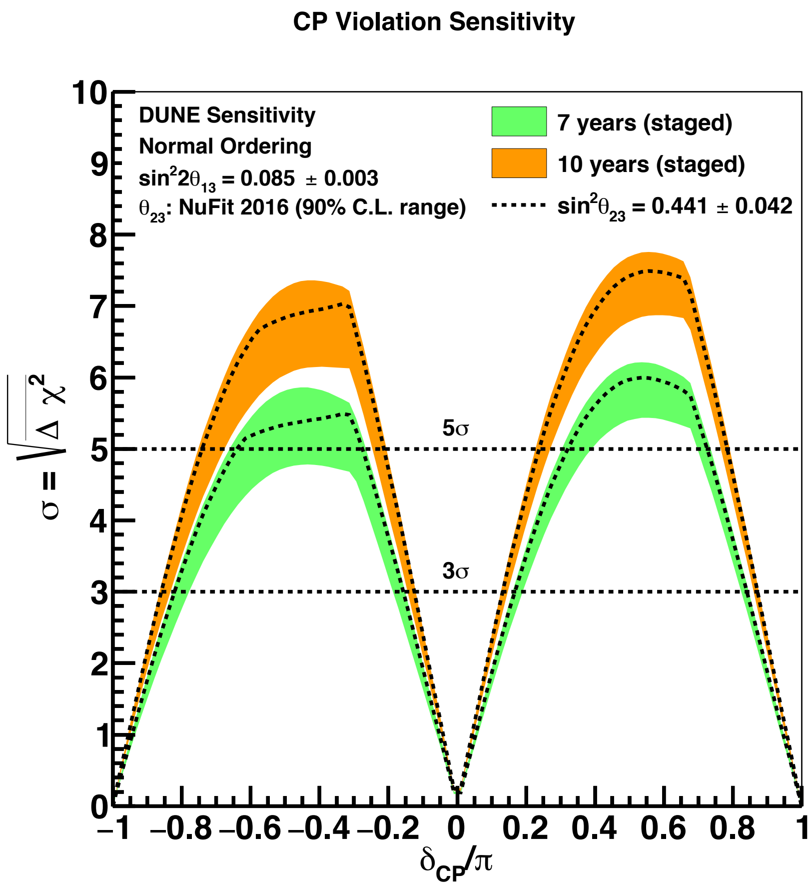
$\bar{\nu}_e$



DUNE CDR, arXiv:1512.06148

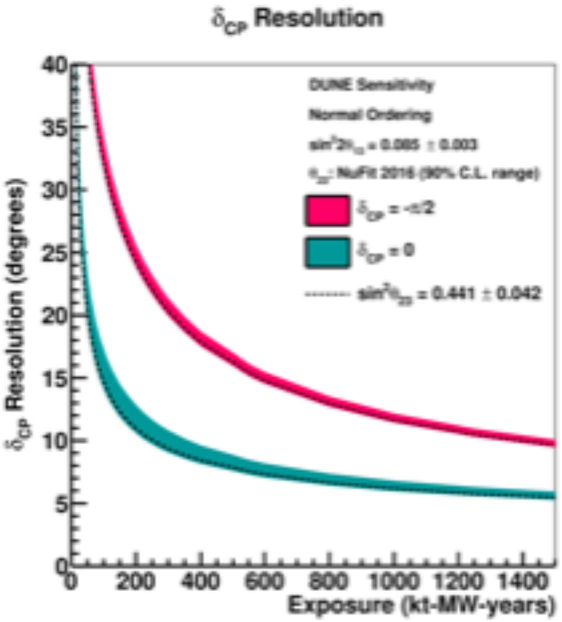
Mass Ordering and CPV

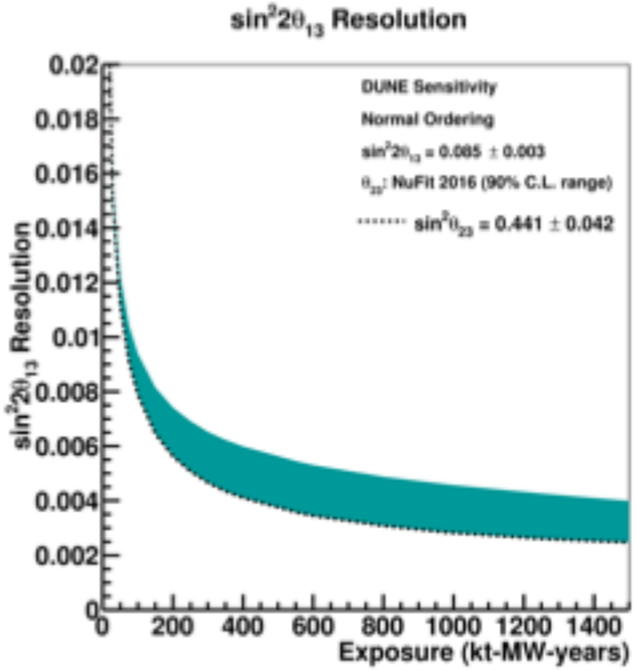


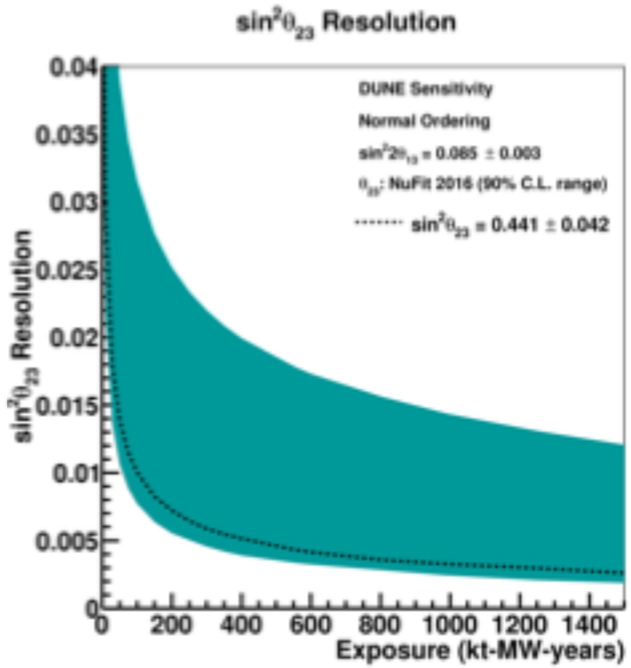


- Sensitivities in DUNE CDR based on GLoBES calculations, with approximated systematics
- Width of the bands represents the range of sensitivities for 90% C.L. range in ϑ_{23}

Oscillation Parameter Sensitivity







DUNE CDR

Monte Carlo Analysis

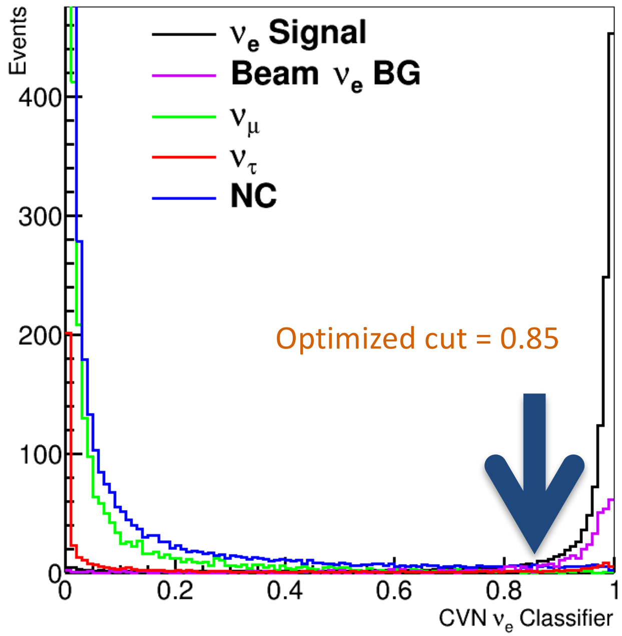
NEUTRINO 2018 Heidelberg 4-9 June

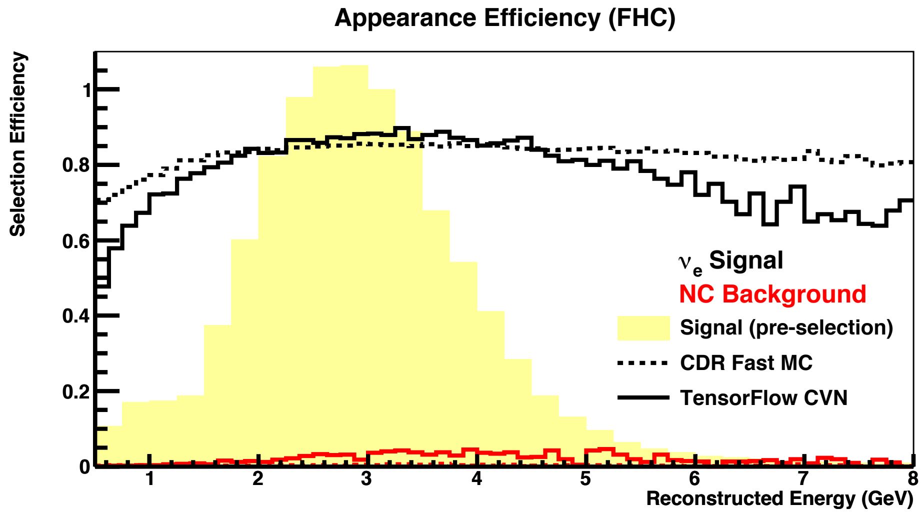
NEW!

- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
  - Shared framework among many LArTPC experiments
  - GENIE event generator and GEANT4 particle propagation
  - Detector readout simulation including realistic waveforms and white noise
- Automated signal processing and hit finding
- Automated energy reconstruction
  - Muon momentum from range (contained) or multiple Coulomb scattering (exiting)
  - Electron and hadron energy from calorimetry
- Event selection using Convolutional Visual Network (CVN)
- Oscillation analysis using CAFAna fitting framework (shared with NOvA)
- CDR-style systematics analysis (update coming in 2019)
- Results are for single phase; dual phase analysis in progress

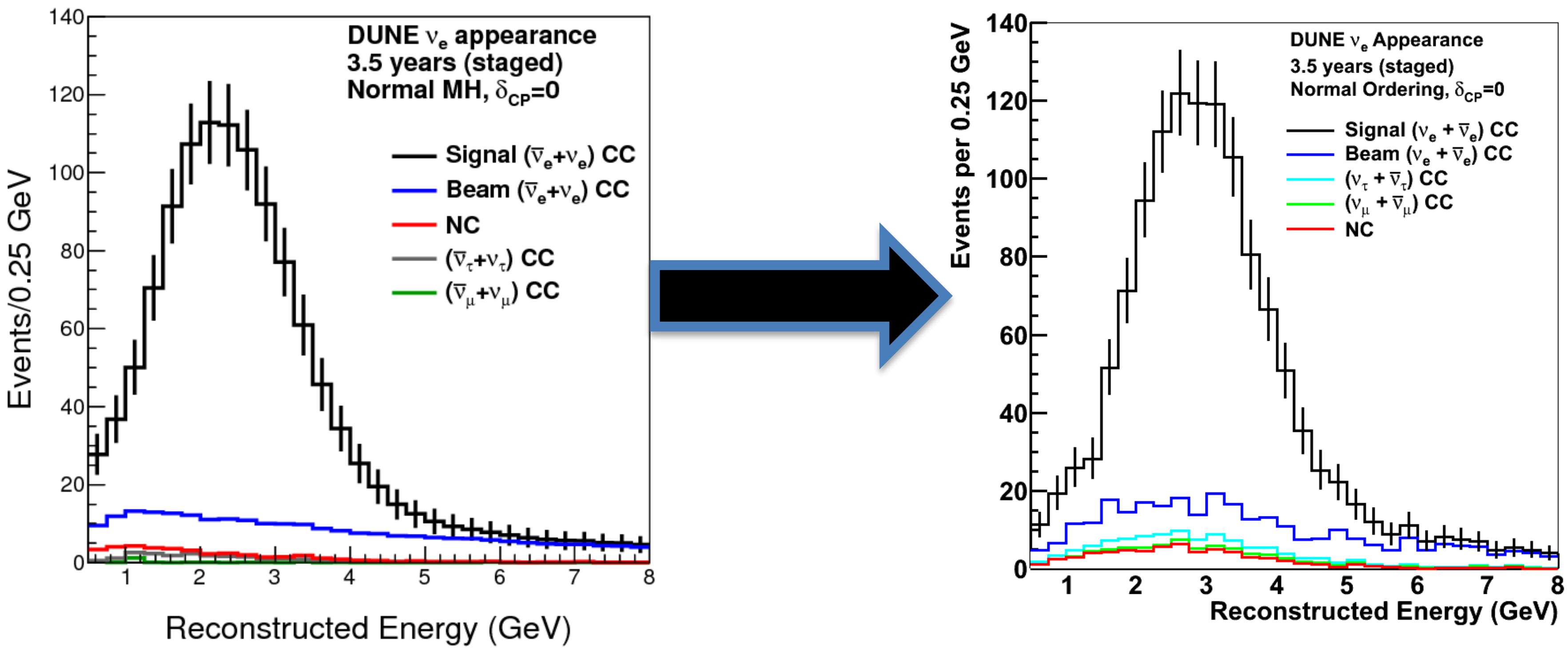
CVN Event Selection

- ResNet architecture implemented in TensorFlow
- Training performed on sets of 500 x 500 DUNE MC images
- DUNE MC images classified into categories
  - ν_e^{CC}, ν_μ^{CC}, ν_τ^{CC}, NC
- Event selection by applying cuts on ν_e^{CC}-like and ν_μ^{CC}-like CVN classifiers
  - ν_e^{CC}-like cut chosen by optimizing CPV sensitivity





Results of improved MC analysis

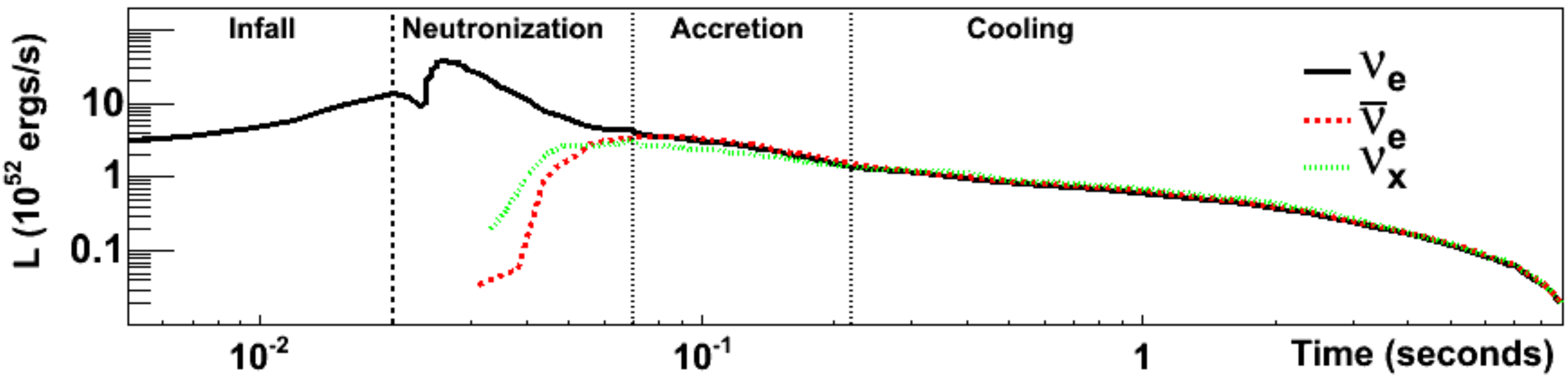


- Sensitivity from MC-based analysis with automated reconstruction and event selection exceeds CDR sensitivity
- Full update planned for TDR in 2019

Supernova Neutrinos

In LArTPC, SNB signal dominated by electron neutrinos:

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



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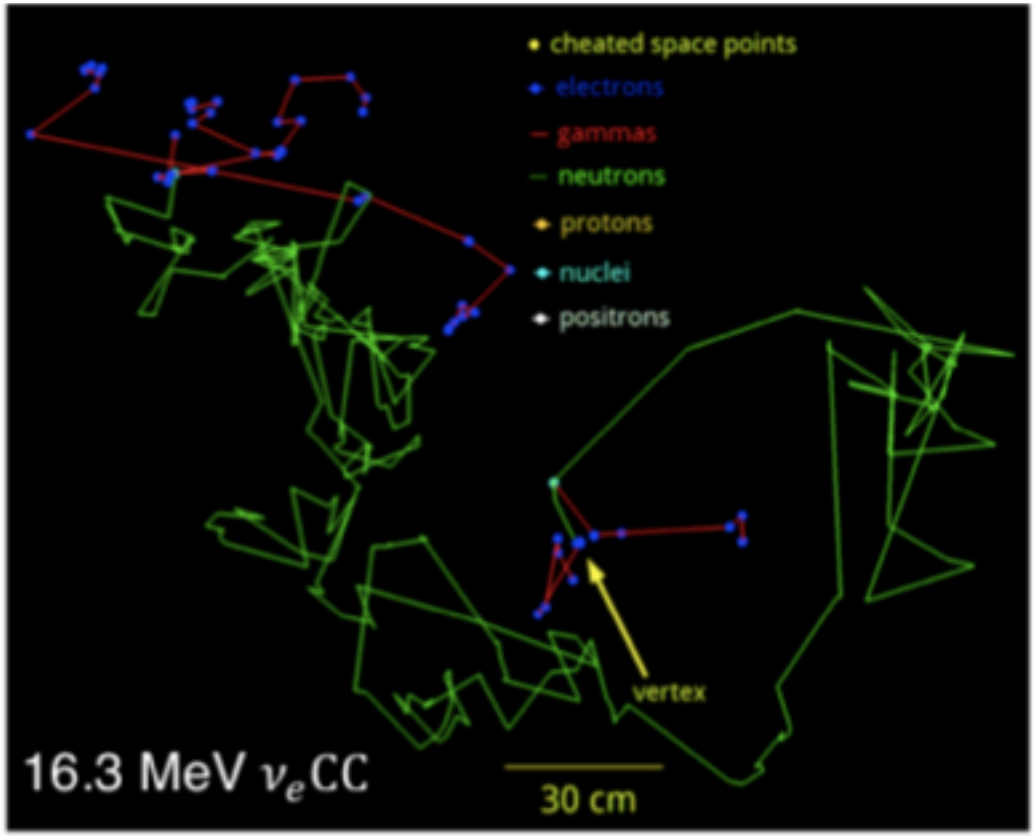
MARLEY event generator: marleygen.org



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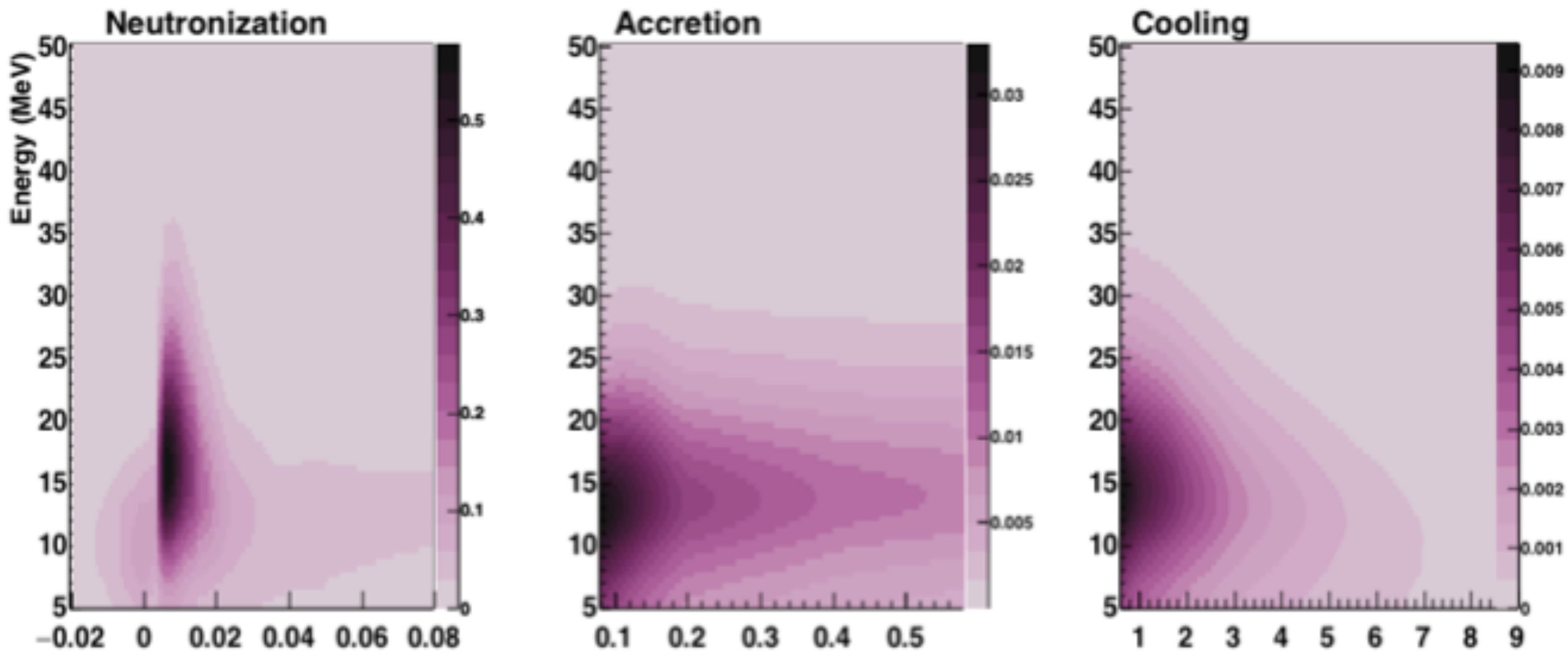

Events per 0.5 MeV per ms, 40 kton @10 kpc

MANCHESTER 1824
DUNE

Supernova Neutrinos

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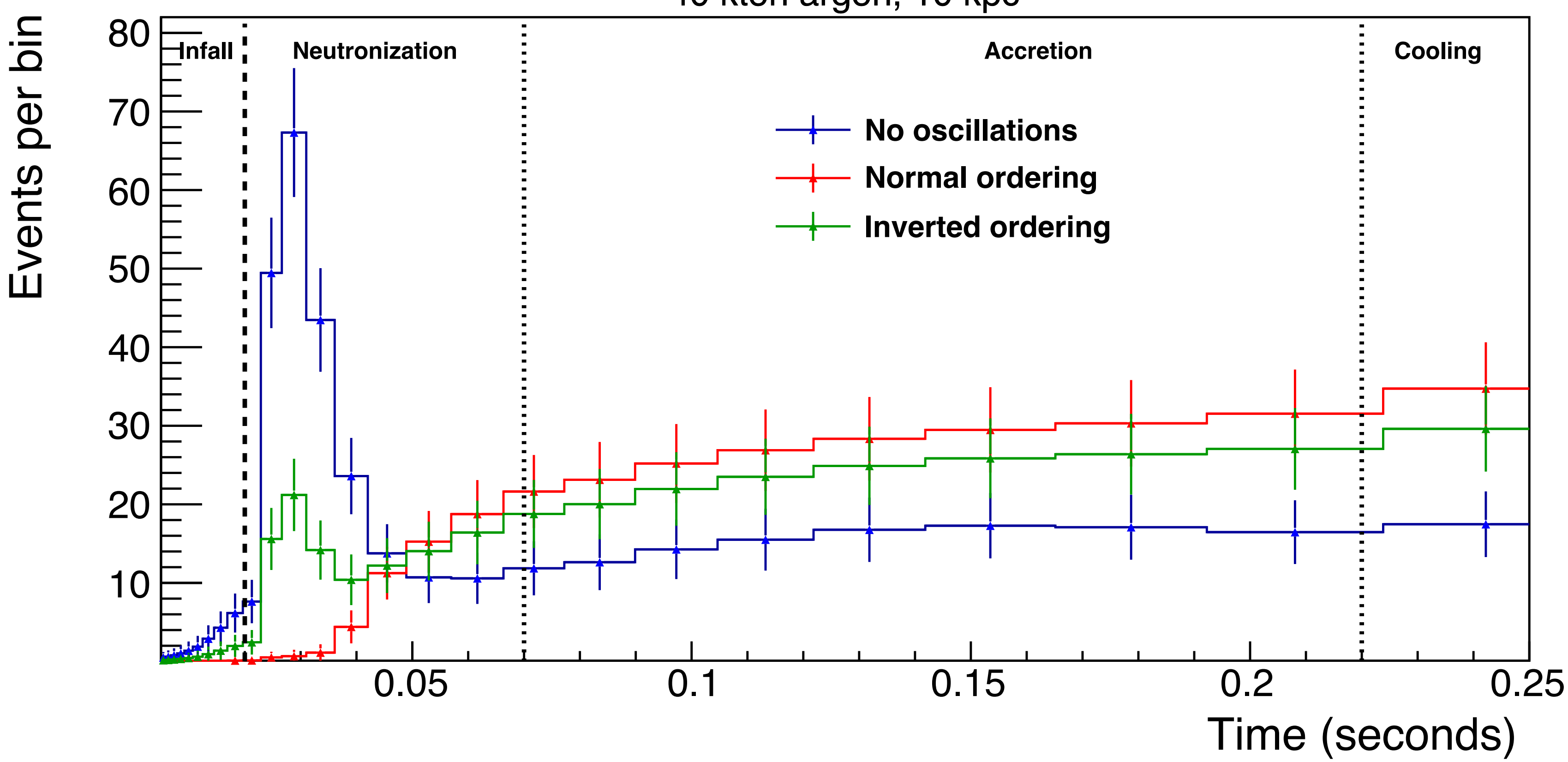
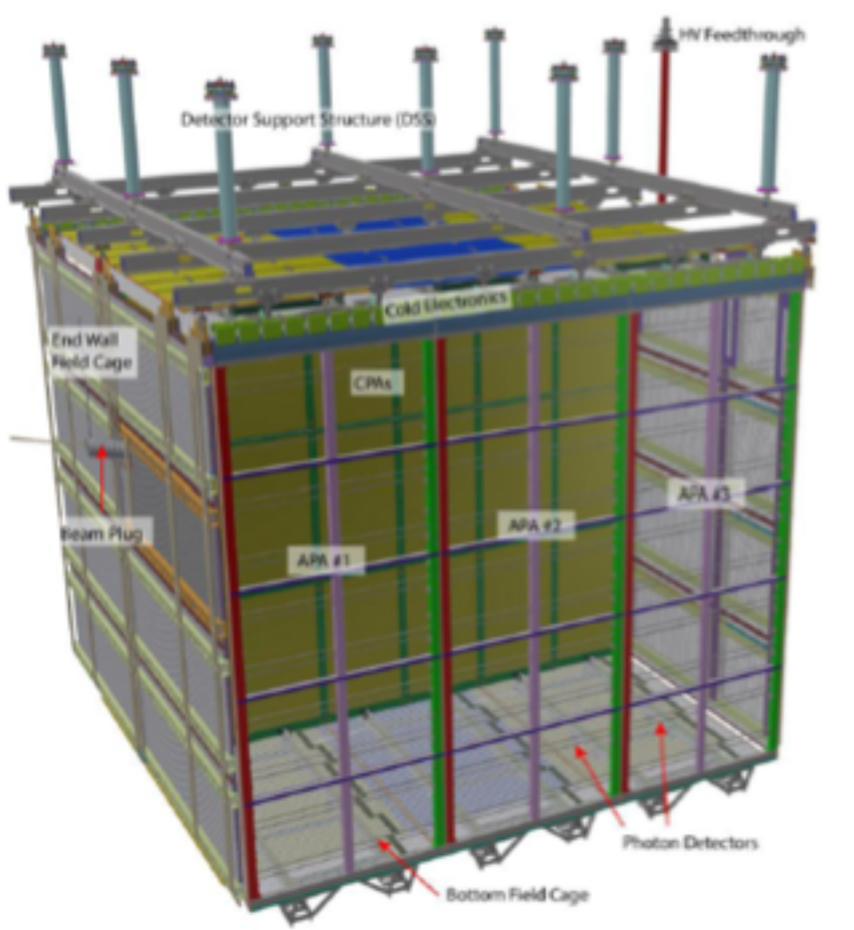


Measurement at early times tests mass ordering and SNB model

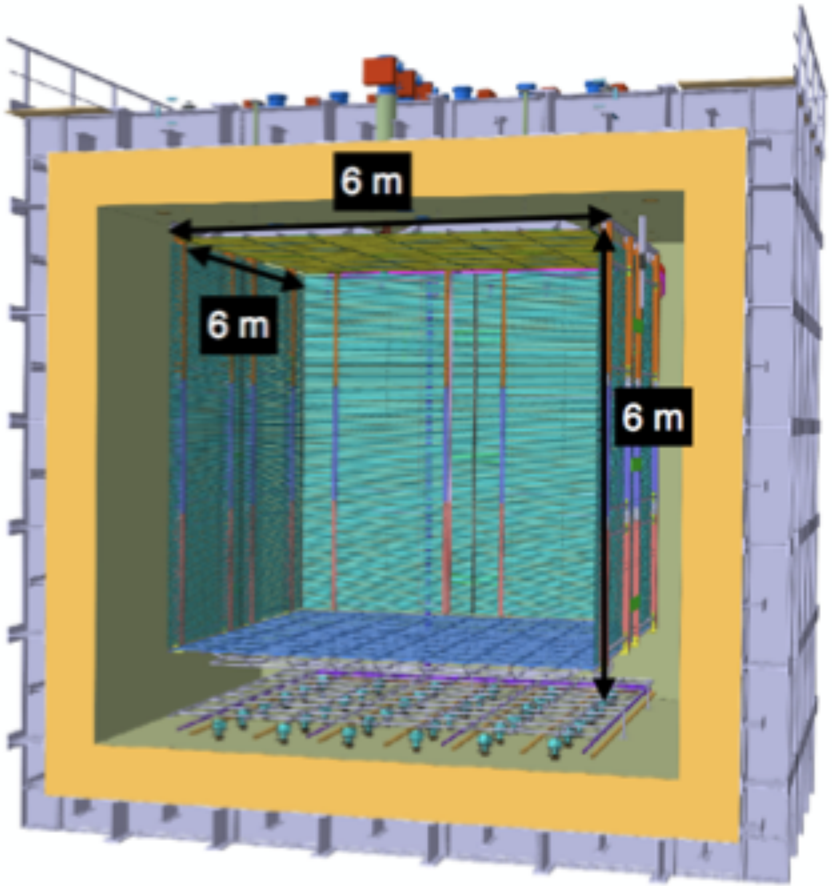
ProtoDUNE(s)

Single Phase



Active volume 6.9 x 7.2 x 6 m^3

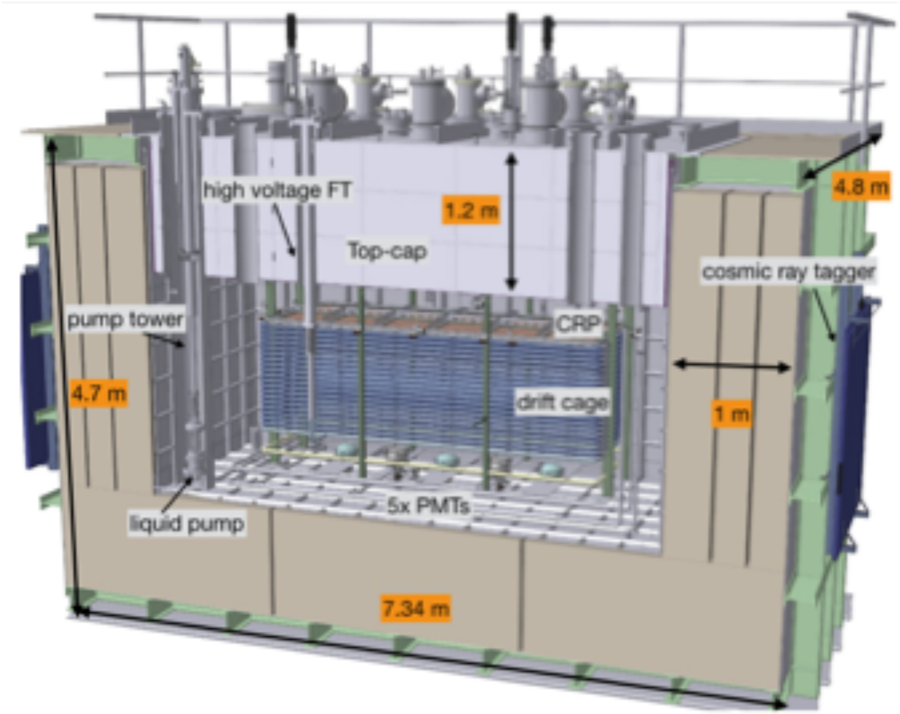
Dual Phase



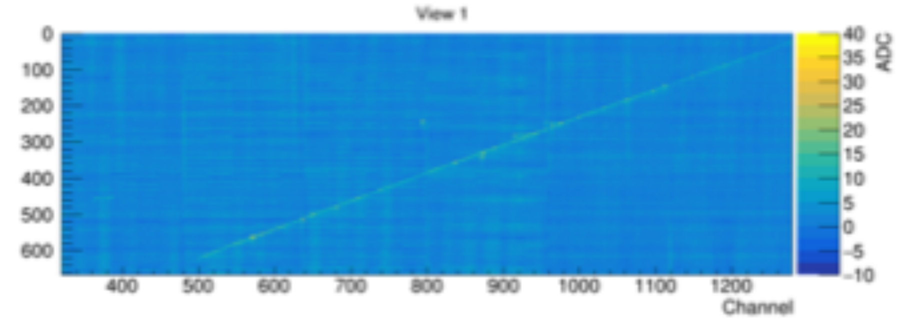
Active volume 6 x 6 x 6 m^3

CERN North Area

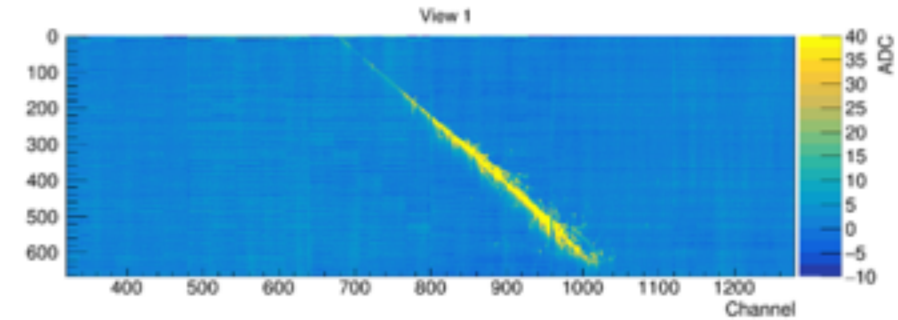
3x1x1 Dual Phase Prototype



Muon



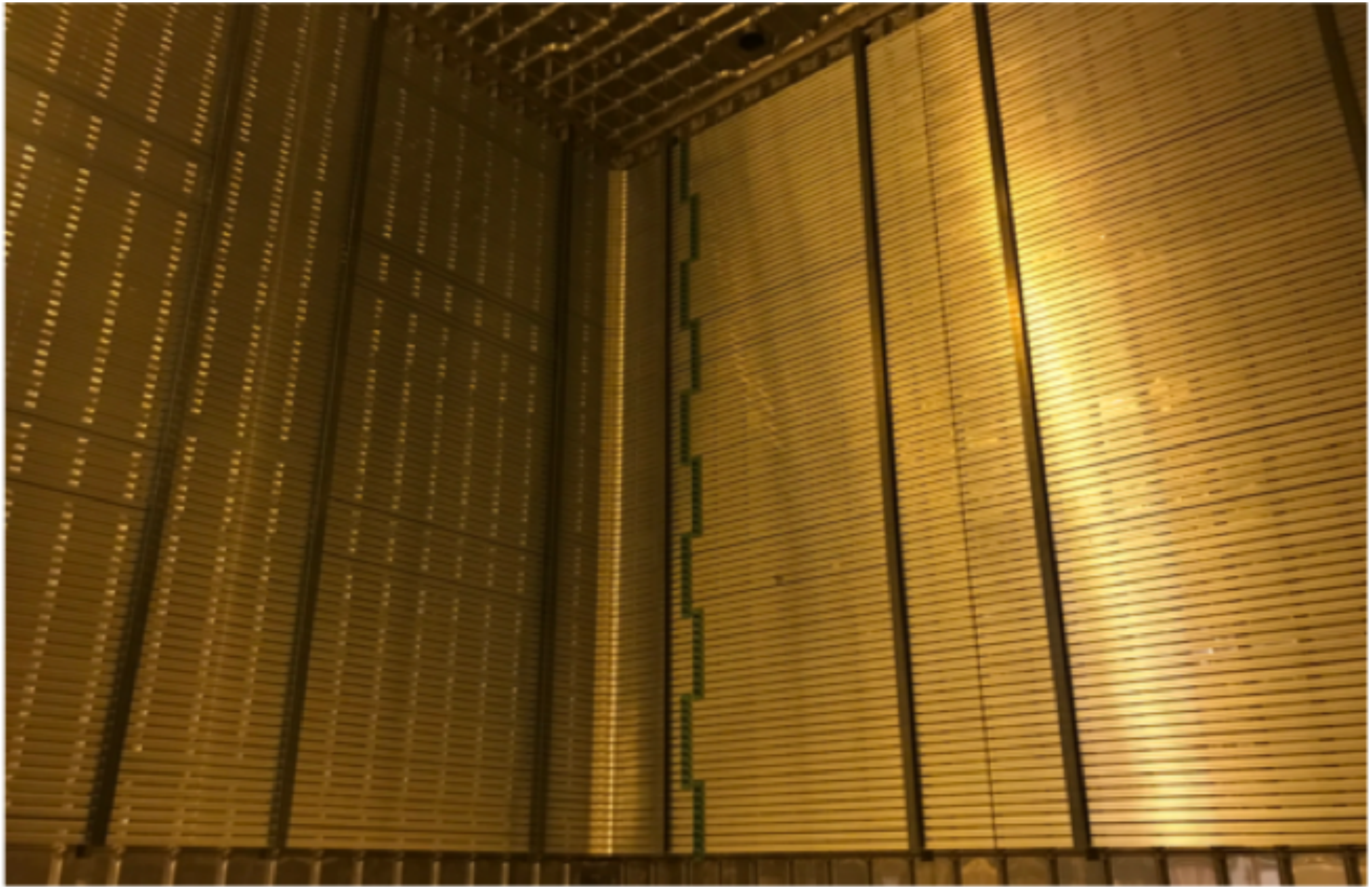
EM Shower



- 3x1x1 prototype ran from June to November 2017
- Successful demonstration of dual phase LArTPC concept
- ENC <1800 e^- (S/N ≈ 100 for a MIP)
- Led to improved designs for protoDUNE dual phase

arXiv:1806.03317

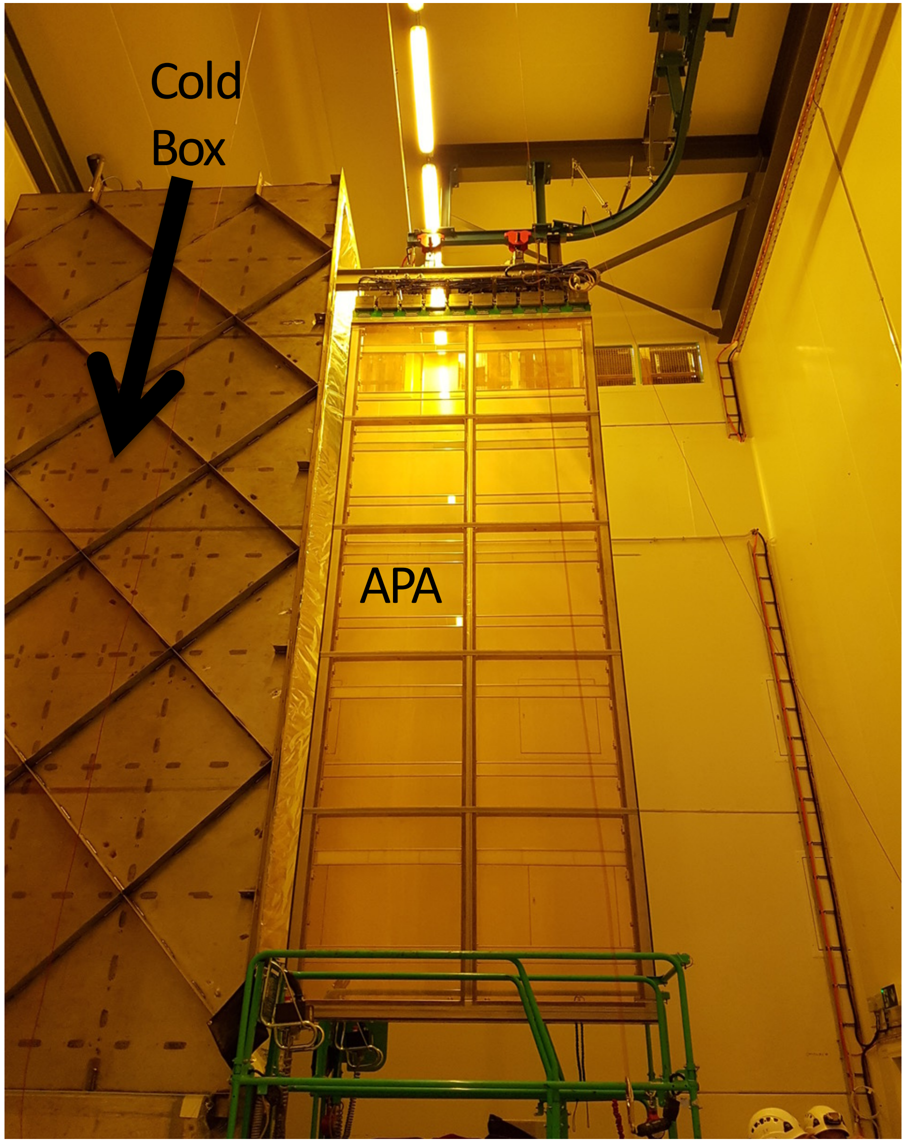
ProtoDUNE DP Field Cage



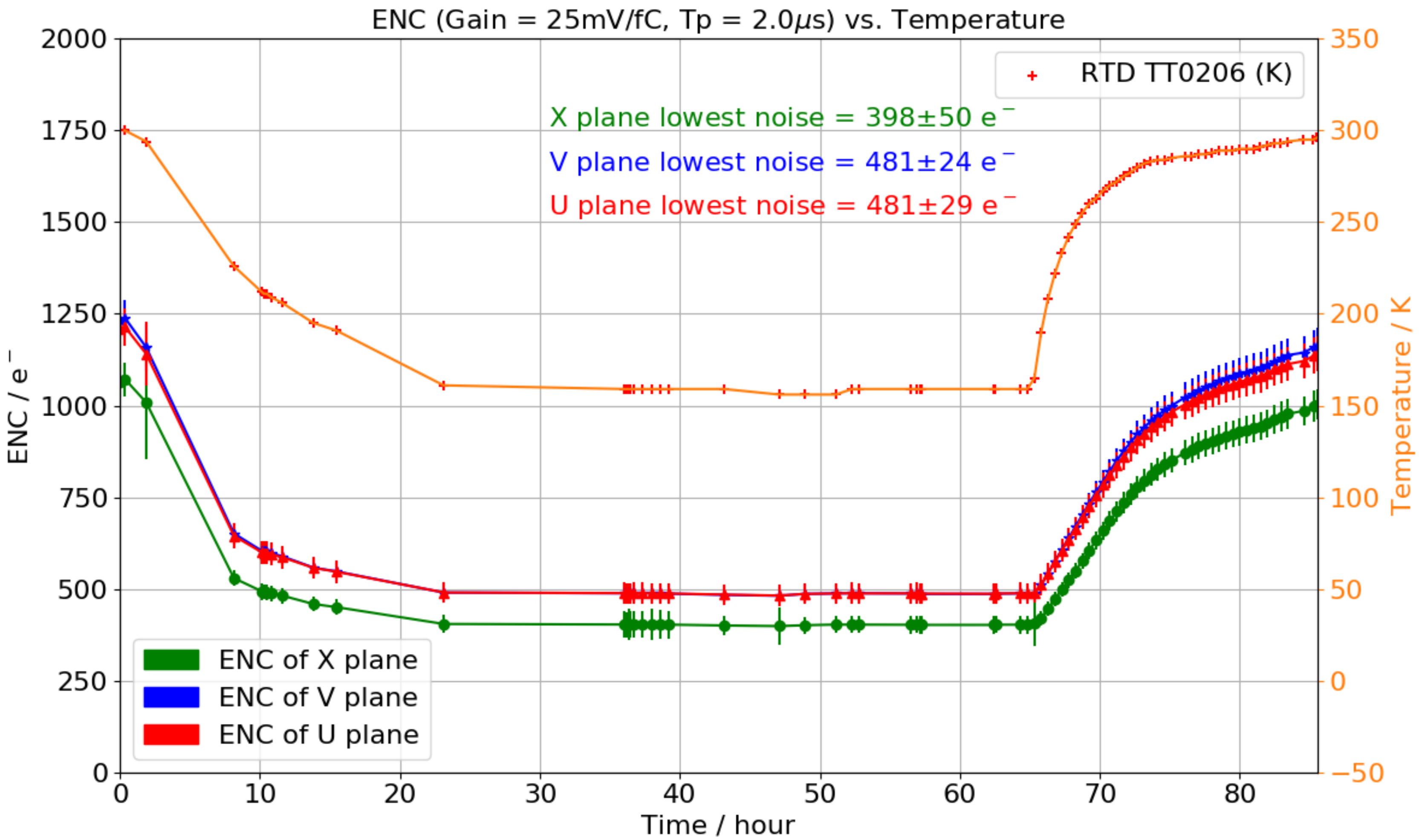
ProtoDUNE DP Field Cage

ProtoDUNE SP Cold Box

- Allows testing of assembled APA and electronics before installation in protoDUNE
- Incorporates feed-through, cabling, and readout system identical to protoDUNE
- Filled with cold nitrogen gas for testing at "cool" temperature (~160 K)
- Successful demonstration of required noise levels at cryogenic temperature



ProtoDUNE SP Cold Box



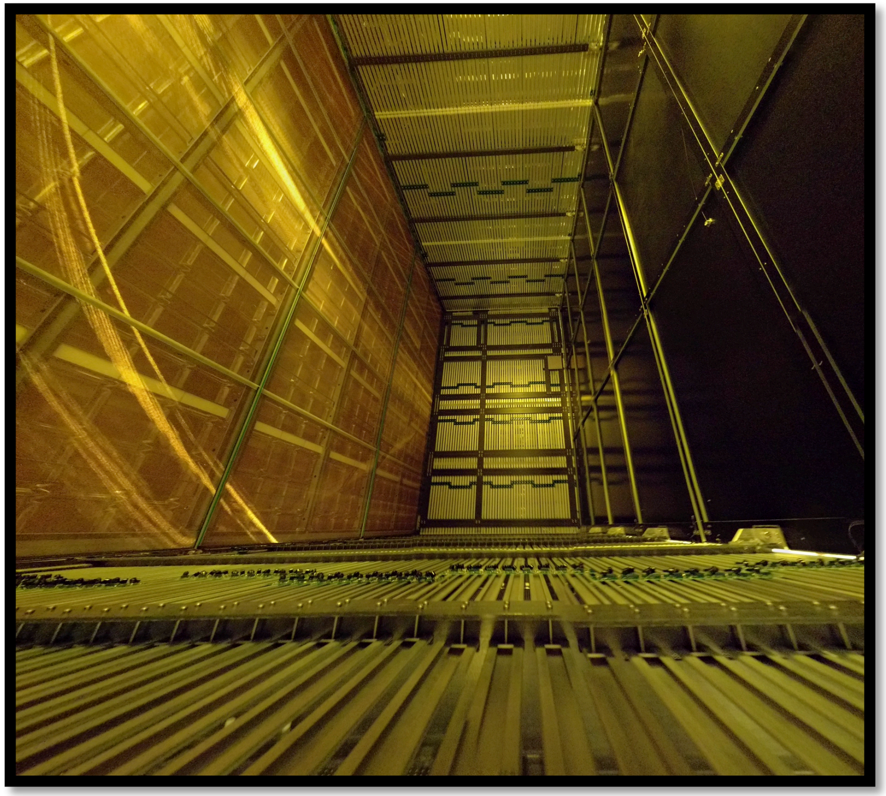
ProtoDUNE Schedule

Single Phase Installation Complete: May 2018

Single Phase Cooldown: July 2018

Single Phase Beam: August-November 2018

Dual Phase Installation Complete: Fall 2018



Far Detector Interim Design Report

- Three Volumes (Executive Summary, Single Phase, Dual Phase), about 600 pages
- Describes the first two FD modules (DP,SP)
- Not yet a detailed technical document, no costing
- Important milestone on the way to the TDR in 2019
- Will be made public within ~ 1 month

DUNE Progress

- now: Decision on conceptual design of ND
- now: Far Detector Interim Design Report
- July 2018: Completion of DUNE prototypes at CERN
- April 2019: DUNE TDR submitted
- Oct 2019: CD2/3b Review of LBNF, US DUNE scope

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