DUNE: Status and Prospects

Jelena Maricic, University of Hawaii at Manoa, for DUNE Collaboration

Double Beta Decay and Underground Science

November 10, 2016

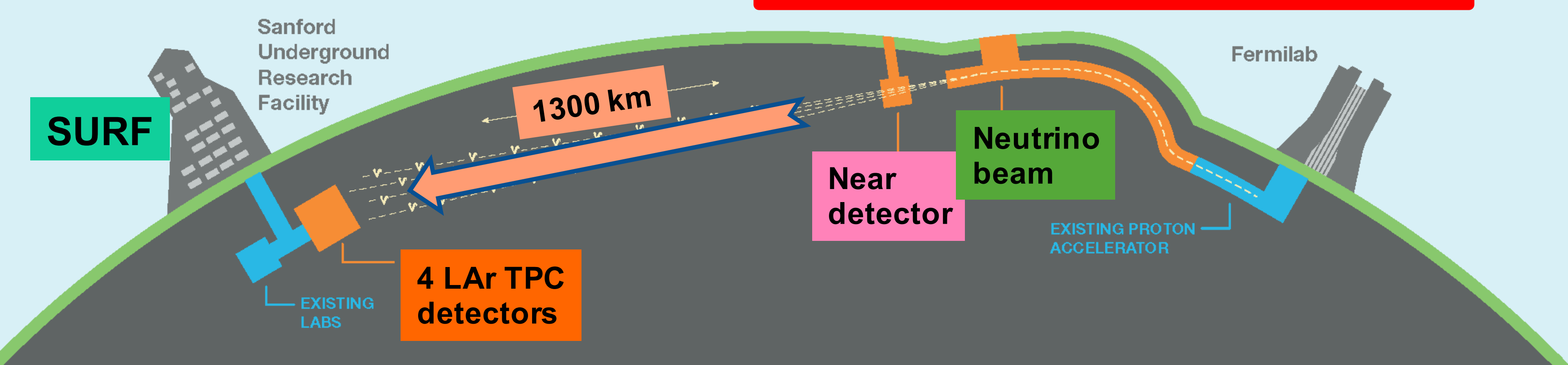
DUNE and LBNF

LBNF (LBN Facility) - **wide-band, on-axis neutrino beam** for DUNE.
Unprecedented beam power:

1.2 MW → 2.4 MW
(2026) (II phase)

DUNE consists of:
- Far Detector (FD):
  4 LAr TPC at SURF
- 40 kton (fiducial)
  at 1.5 km depth (4300 mwe)
- Near Detector (ND)
- International science collaboration

$\nu_\mu/\bar{\nu}_\mu$ beam: FNAL → FD
1300 km Long Baseline

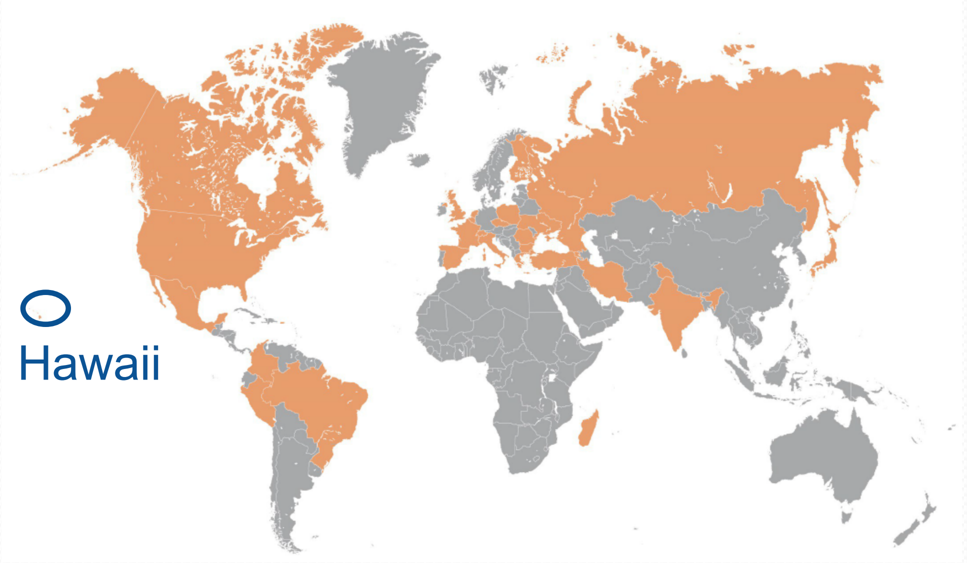


DUNE Science Program

- Several opportunities for major scientific discoveries:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - δ_{CP} violation phase
    - MO (mass ordering) of neutrino masses
    - θ_{23} octant, precision test of 3-flavor neutrino model
  - Nucleon decay
  - Detection of galactic-core supernovae neutrinos
  - Tests of neutrino NSI (Non-Standard Interactions) and measure cross-sections for particle interactions on argon.

DUNE Collaboration

- Strong, international collaboration (from 2014):
- 950 collaborators
- 161 institutions
- 30 countries
- Welcomes theorists and welcomes you



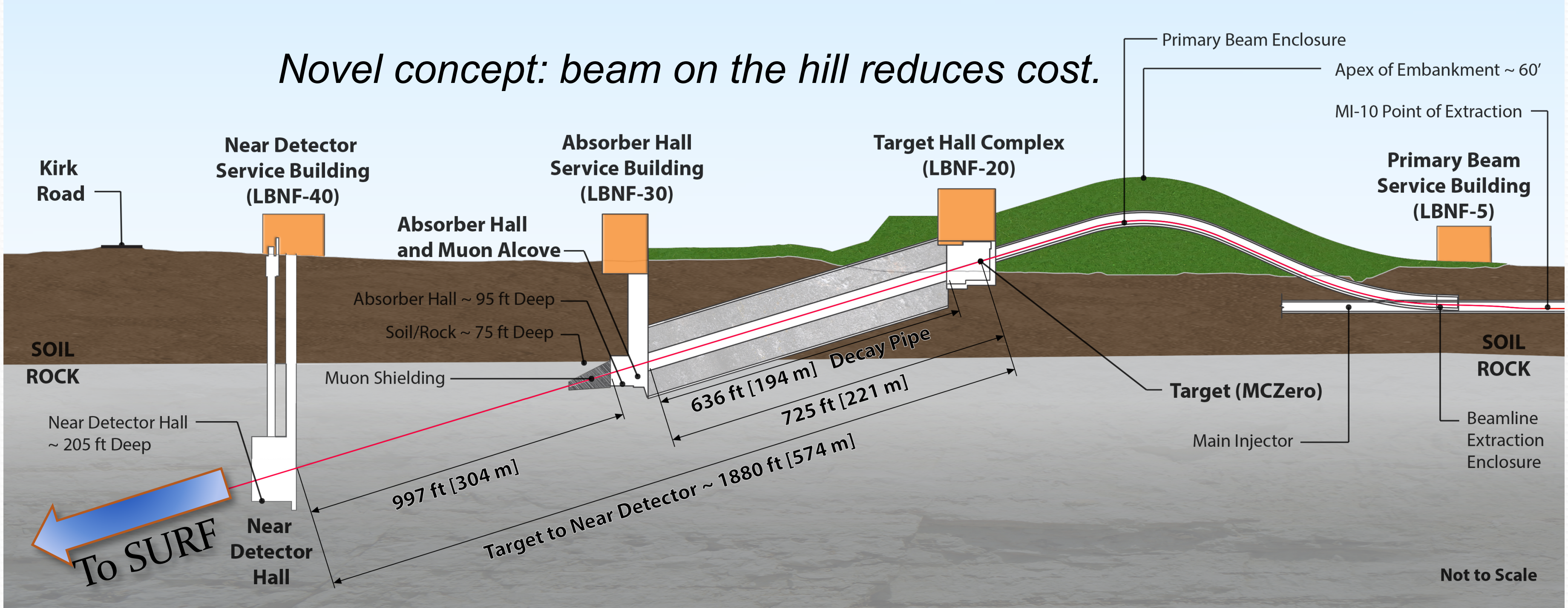
DUNE/LBNF: Technical Elements

LBNF IS MORE THAN JUST A BEAM

- What does it take for LBNF to support DUNE's elaborate program?
  - Major partners: **FNAL, CERN** and **SURF**
  - Construction and maintenance of underground and surface facilities at SURF, capable of hosting a 4-module LAr TPCs with over 70 kton LAr.
  - Cryostats, refrigeration and purification systems to operate all detectors
  - A high-power, wide-band, tunable, neutrino beam at FNAL
  - Underground and surface facilities at FNAL hosting near detector and potentially other neutrino experiments

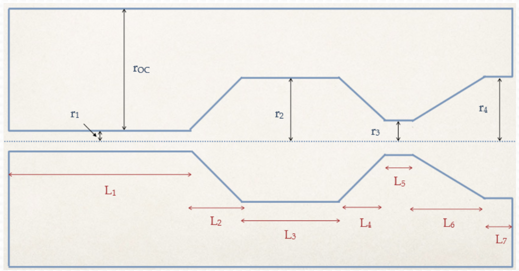
The LBNF Beamline

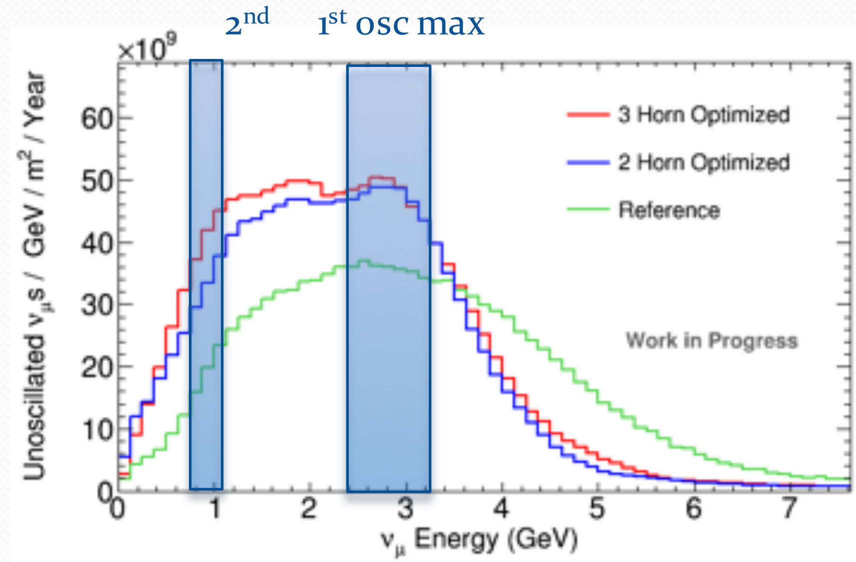
- Conventional horn-focused Beam Line
  - Extracts 60 - 120 GeV protons from FNAL Main Injector.
  - 101 mrad pitch to get to FD in S. Dakota
  - ~200 m Decay pipe
  - ND hall at boundary of FNAL site
  - Critical contributions from international partners (UK, CERN)



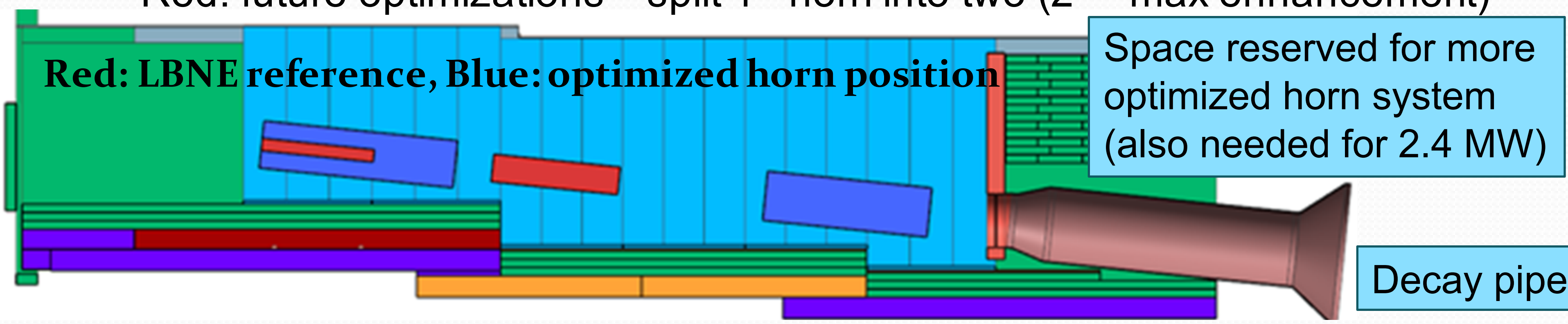
Optimizing the Focusing System

- Based on genetic algorithm developed for LBNO.
- Vary: proton energy 60-120 GeV, horn shape/size/current/position, target size/shape/position/materials, decay pipe length/diameter.





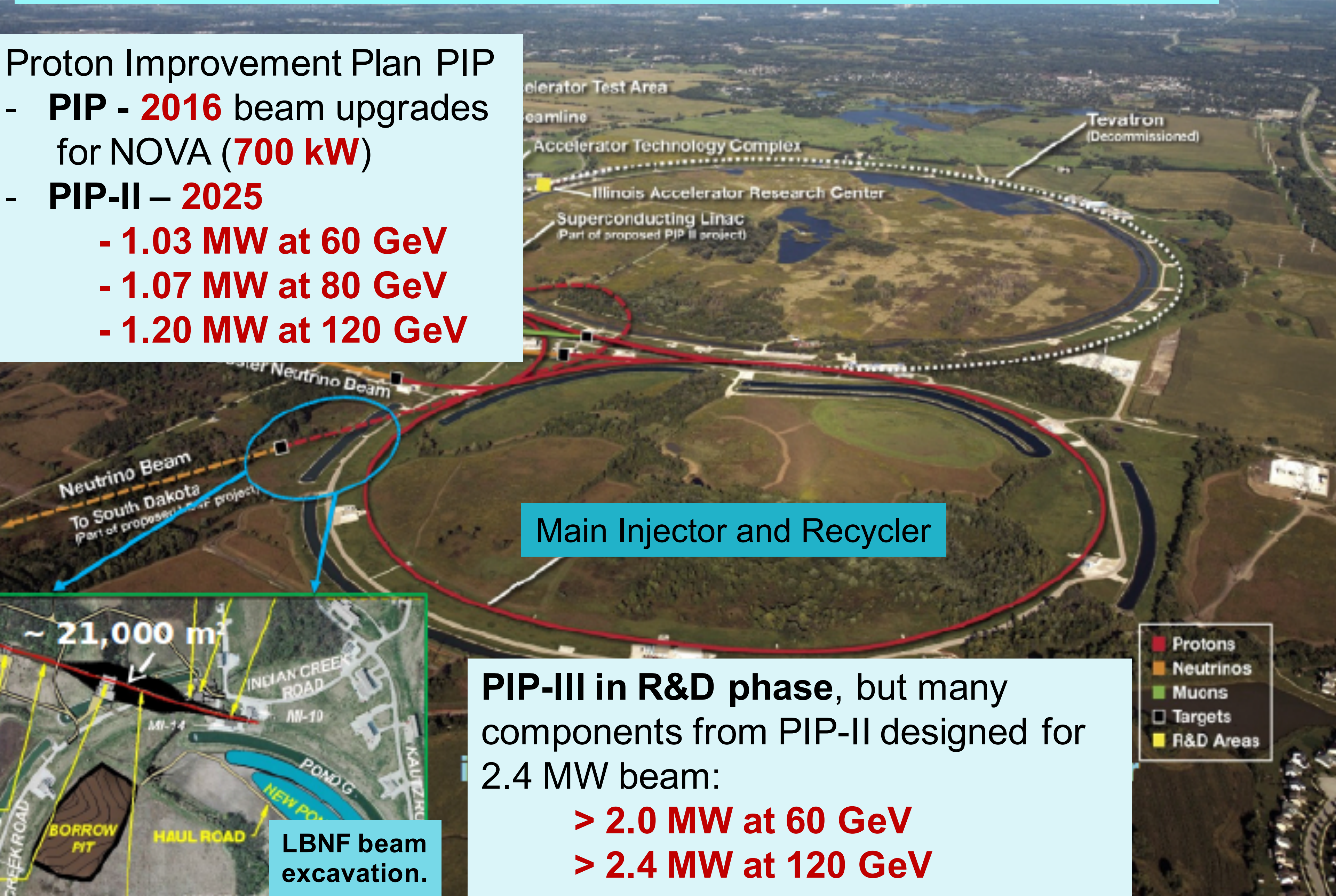
- Green: LBNE reference
- Blue: DUNE optimized –
  - longer target ($2\lambda \rightarrow 5\lambda$) + longer 1st horn
  - larger (radially) 2nd horn
- Red: future optimizations – split 1st horn into two (2nd max enhancement)



Major Upgrades to FNAL Accelerator Complex

Proton Improvement Plan PIP

- **PIP - 2016** beam upgrades for NOVA (**700 kW**)
- **PIP-II – 2025**
  - **- 1.03 MW at 60 GeV**
  - **- 1.07 MW at 80 GeV**
  - **- 1.20 MW at 120 GeV**



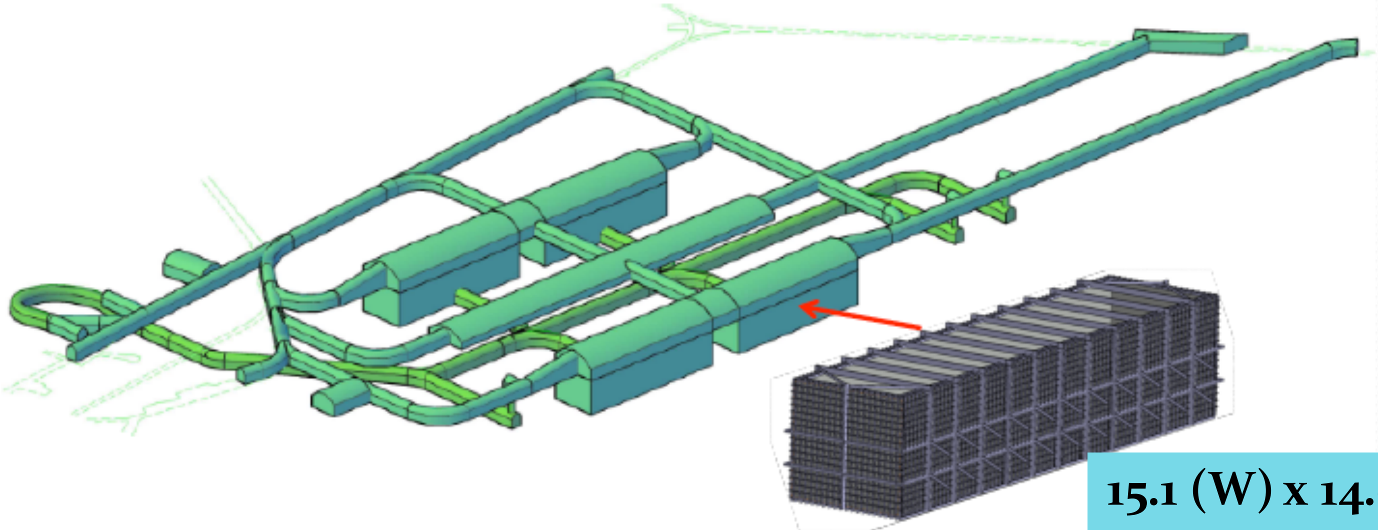
LBNF beam excavation.

PIP-III in R&D phase, but many components from PIP-II designed for 2.4 MW beam:

- **> 2.0 MW at 60 GeV**
- **> 2.4 MW at 120 GeV**

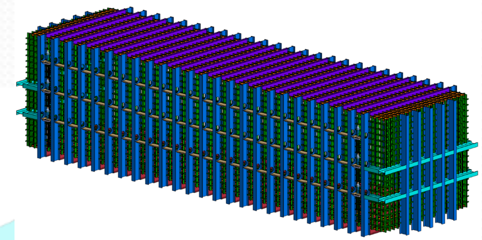
Sanford Underground Research Facility South Dakota

- Attractive deep site: 4300 mwe
- Hosted Homestake neutrino experiment
- Accommodates 4 detector chambers and accompanying utilities
- Built-in flexibility to accommodate all detector needs, independent of design (single or dual phase LAr TPC).
- Extensive preparatory work for LBNF/DUNE already done – rock sampling, test blast vibration study (03/16), shafts refurbishment, detailed cost estimate
- ***DOE approval pending: to begin excavation & surface building***



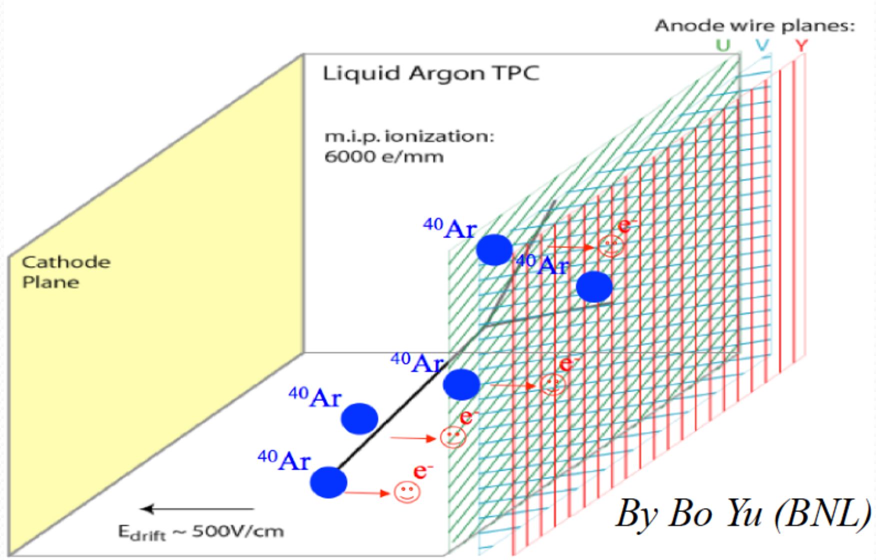
15.1 (W) x 14.0 (H) x 62 (L) m^3

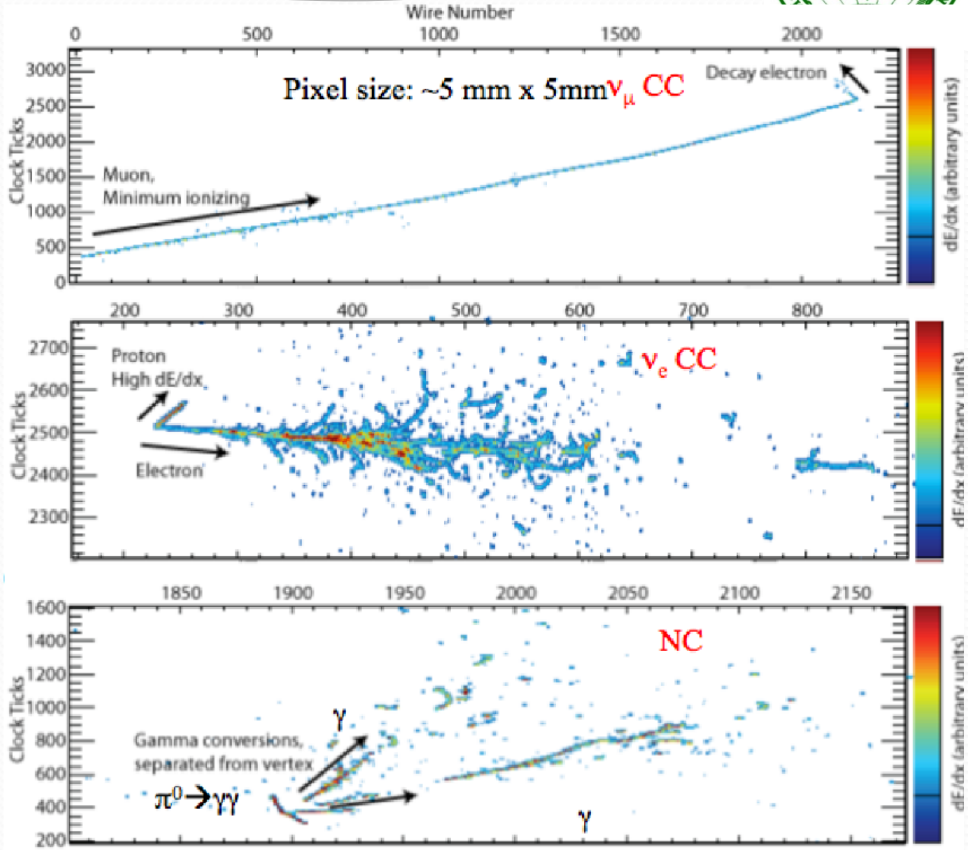
Scale of a single cryostat housing 17.5 kton LAr TPC



7 story
building 156 at CERN

FD technology – Liquid Argon Time Projection Chamber



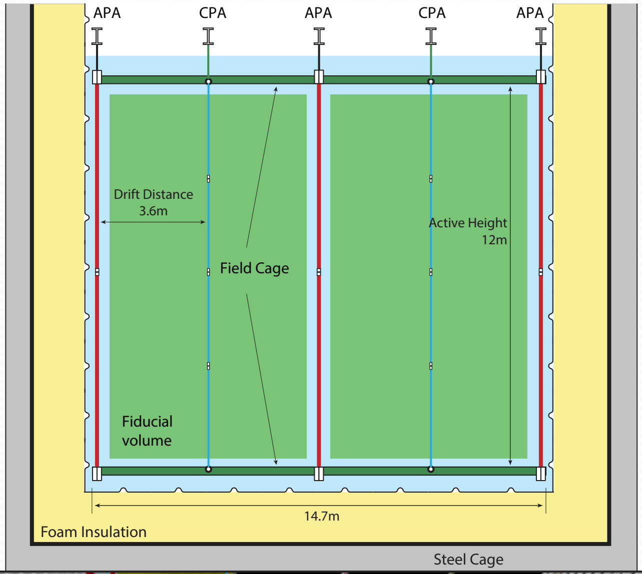


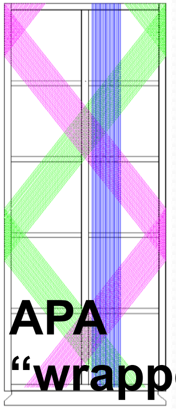
Event display in LArTPC (MicroBooNE MC)

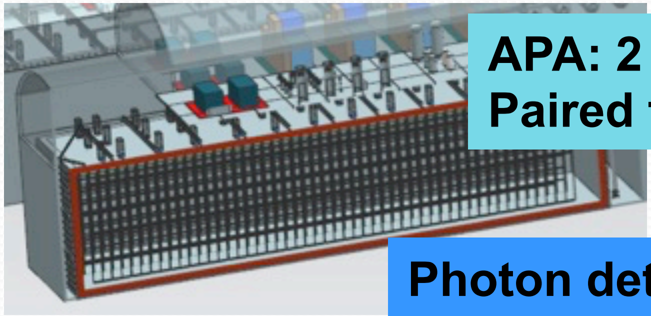
- LAr TPC: excellent tracking and calorimetry
- Suitable for very large detectors – high signal eff. and bkg. discrimination
- High resolution 3D reconstruction – charged particles ionize Ar; electrons drift to anode wires (~ms) for xy coordinate; drift time – z coordinate
- Ar scintillation light (~ns) detected by photon detectors – provides t_0

FD design: Single Phase LAr TPC

- Design fixed for the first 10 kton module – based on LBNE modular drift cell design
- APA (anode) and CPA (cathode) suspended from ceiling like curtains
- APA with "wrapped" induction planes
- Photon detectors detect Ar scintillation with light guides and SiPMs at the end for readout

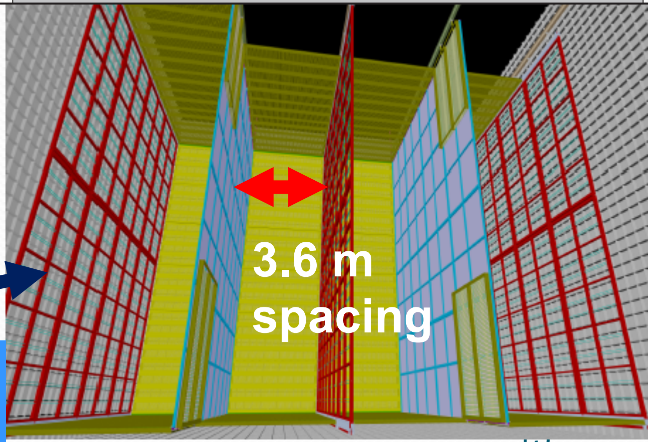






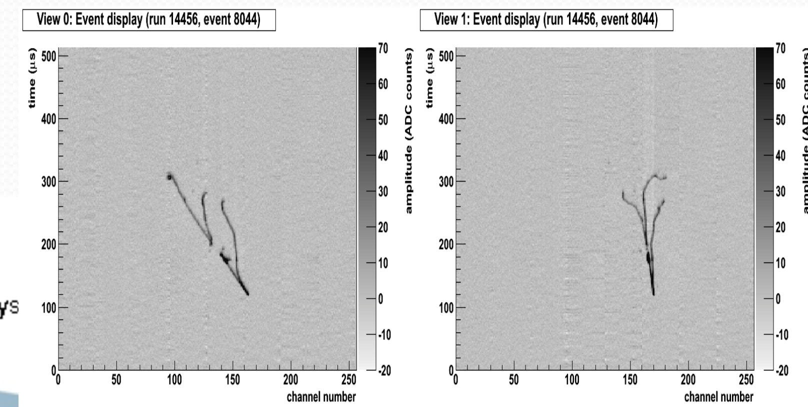
APA: 2 x 6 x 2.3 m
Paired top to bottom

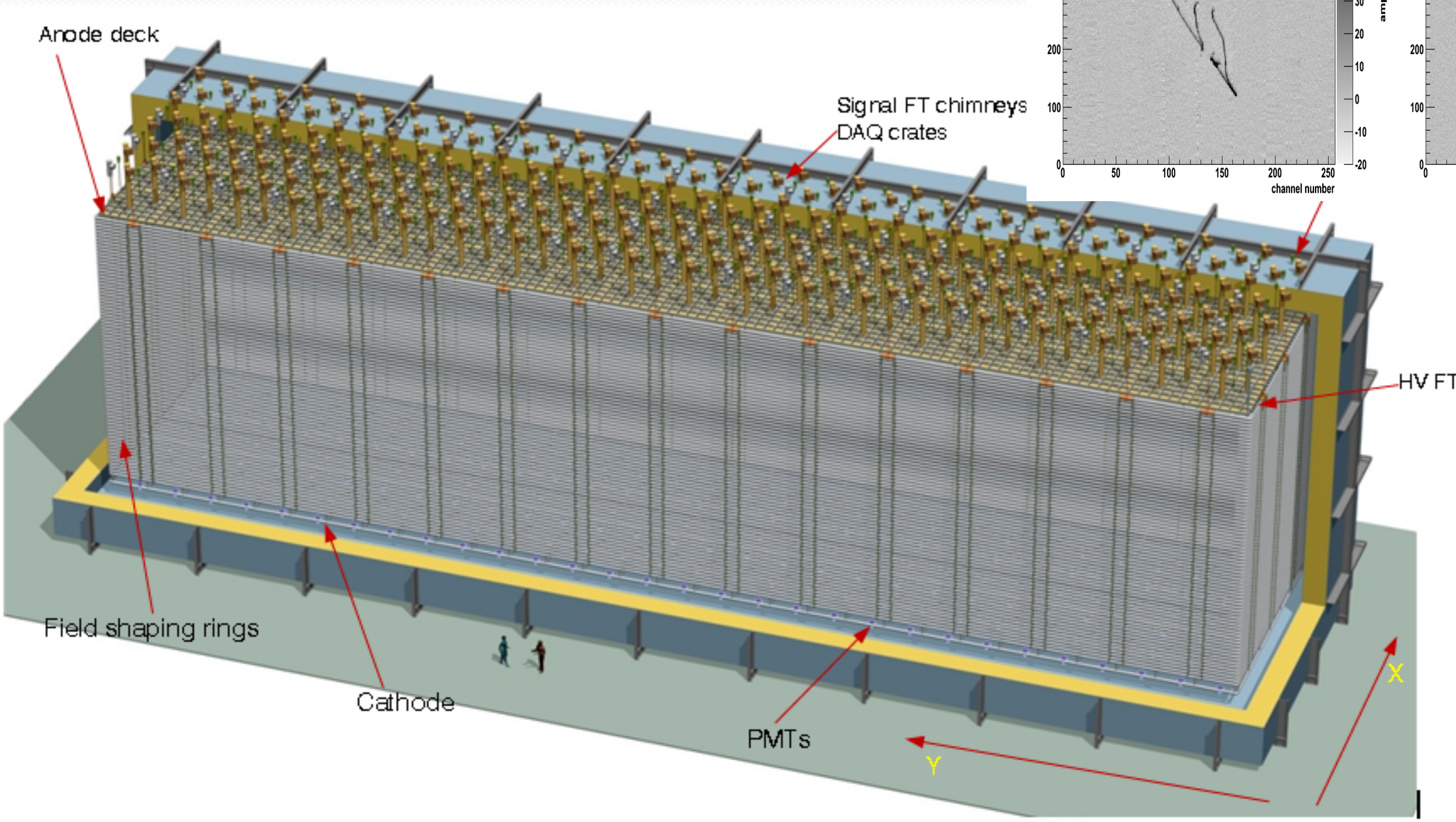
Photon detectors embedded in APA planes



DUNE Dual-Phase LArTPC FD Design

- Single TPC volume with Amplification in gas phase (LBNO design):
  - 12m max drift (vertical), LEM (Large Electron Multiplier) read-out
  - Features excellent S/N: ~100/1
  - Scintillation via PMT's below cathode





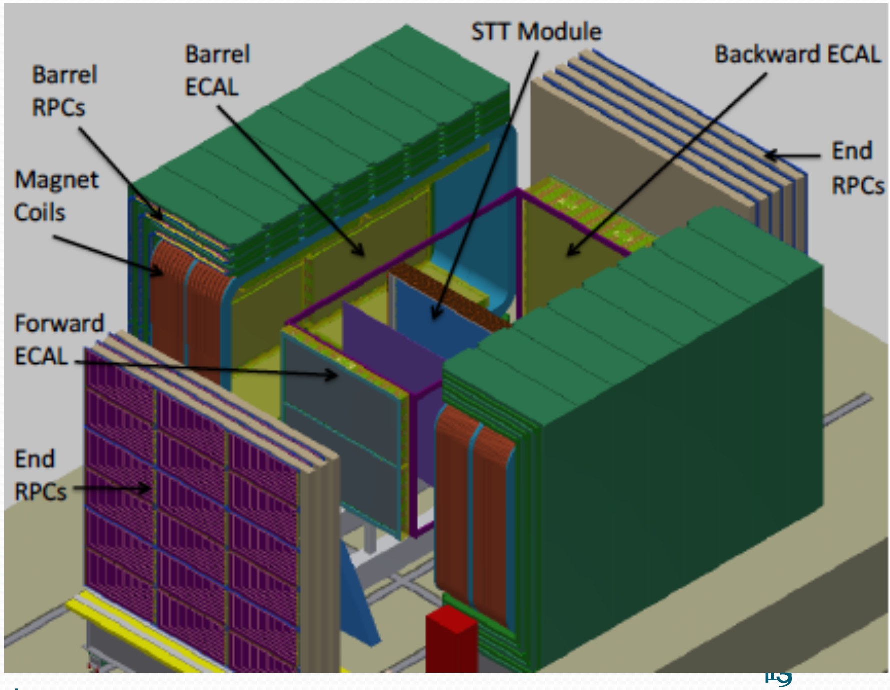
Near detector

- Monitors initial neutrino beam
- Fine grain tracker magnetized neutrino detector (design based on success of NOMAD and T2K ND).

- Includes muon detectors in absorber hall.

- ND design alternatives/additions:
  - LAr TPC
  - high pressure gas Ar TPC

  for direct comparison with FD.



DUNE: Science Program

DUNE Physics Program Core

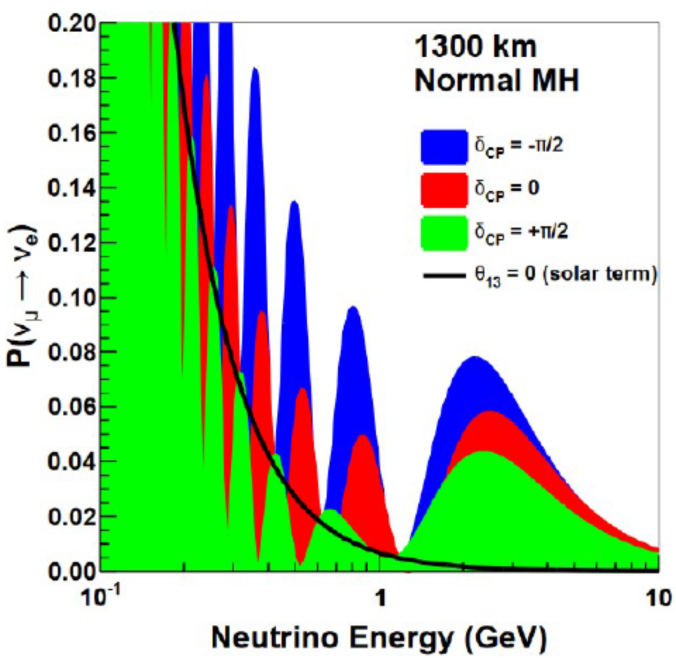
$$P(\nu_\mu \rightarrow \nu_e) \approx \boxed{\sin^2\Theta_{23}\,\sin^2 2\Theta_{13}}\,\frac{\sin^2(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})^2}\,\Delta_{31}^{\ 2}$$
$$+\boxed{\sin 2\Theta_{23}\,\sin 2\Theta_{13}}\,\sin 2\Theta_{12}\,\frac{\sin(\Delta_{31}-\boxed{aL})}{(\Delta_{31}-\boxed{aL})}\,\Delta_{13}\,\frac{\sin(\boxed{aL})}{(\boxed{aL})}\,\Delta_{21}\cos(\Delta_{31}+\delta_{CP})$$
$$+\boxed{\cos^2\Theta_{23}}\,\sin^2 2\Theta_{12}\,\frac{\sin^2(\boxed{aL})}{(\boxed{aL})}\,\Delta_{21}^{\ 2}$$

$\Delta_{ij} = \Delta m_{ij}^2\ L/4E_\nu$
$a = G_F N_e/2^{1/2}$

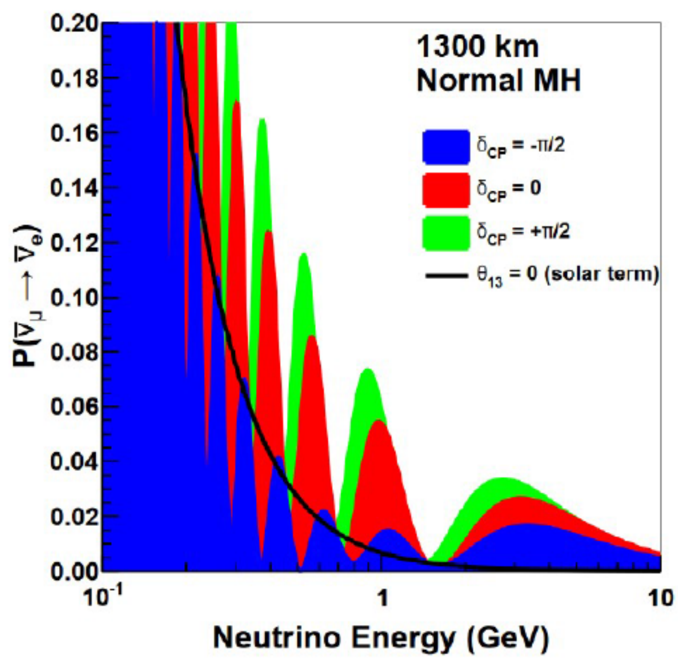
- $\mathrm{Sin}^2(2\theta_{13})$ – size of event sample
- δ_{CP} – amplitude of oscillations
- Δm^2's – frequency of oscillations
- MO – both amplitude and frequency

- Oscillations in wide band beam effective for simultaneous measurement of MO, δ_{CP} and ν mixing angles.

Neutrinos



Antineutrinos



Expected event rates for measurements: δ_{CP}, MO and Oscillations

- Measurements (δ_{CP}, MO, θ_{23}, θ_{13}) rely on analysis of 4 combined samples (optimized beam, 56% LBNF uptime, $\delta = 0$,

ν mode / 150 kt-MW-yr	ν_e appearance	ν_μ disappearance
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam ν_e background	204	–
NC background	17	76
Other background	22	29

Anti-ν mode / 150 kt-MW-yr	ν_e appearance	ν_μ disappearance
Signal events (NH / IH)	**168 (438)**	**2639**
Wrong-sign signal (NH /IH)	47 (28)	1525
Beam ν_e background	105	–
NC background	9	41
Other background	13	18

40 kt · 1.1 MW · 3.5 yr = 150 kt-MW-yr

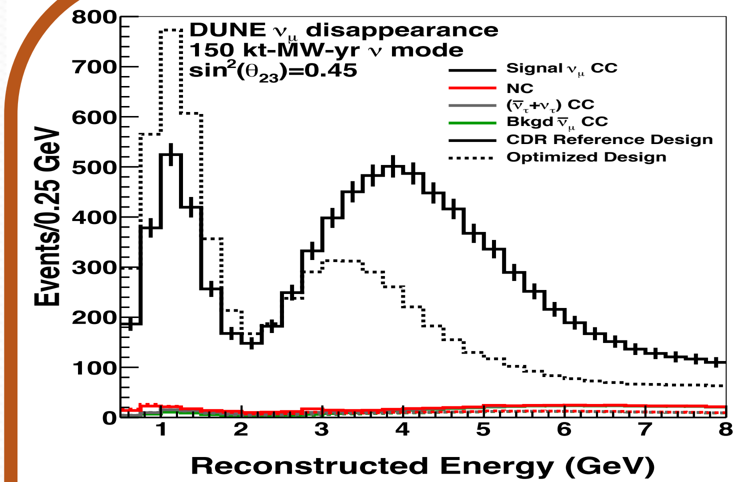
Neutrino spectra in DUNE

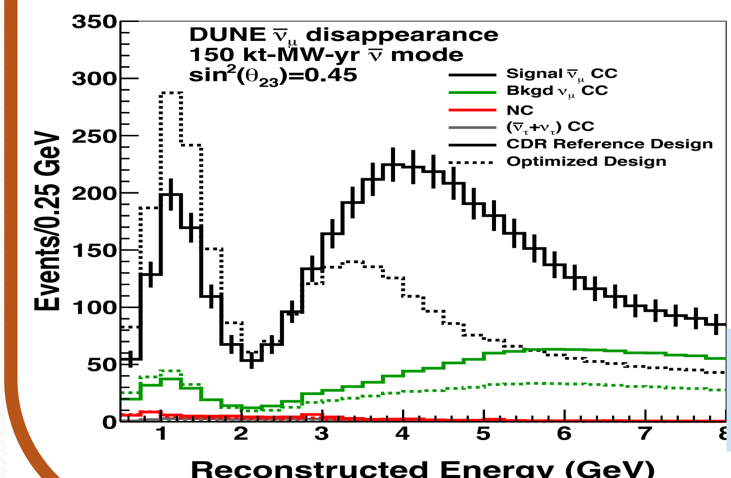
Long baseline: Matter effects are large ~ 40%

Wide-band beam: Measure ν_e appearance and ν_μ disappearance over range of energies

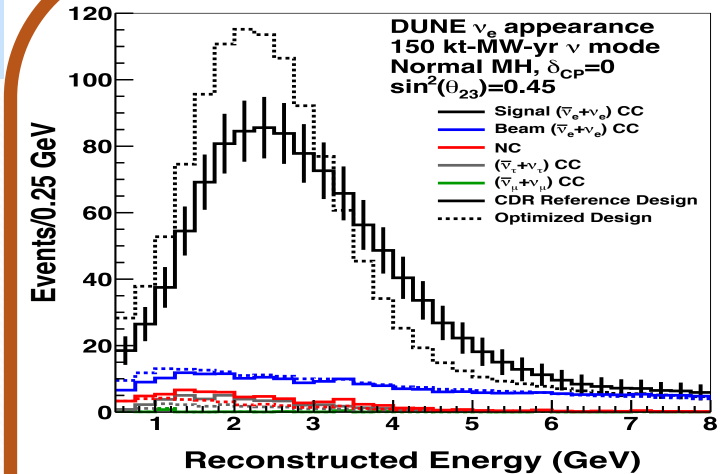
MO & CPV effects are separable

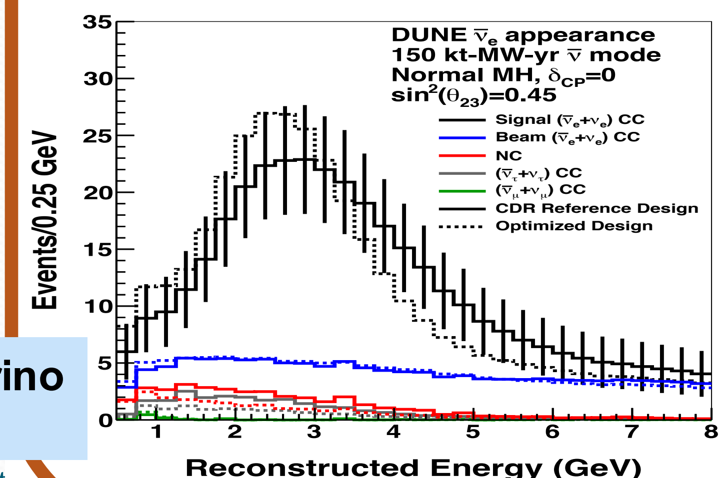
Neutrino mode





ν_μ / $\bar{\nu}_\mu$ disappearance





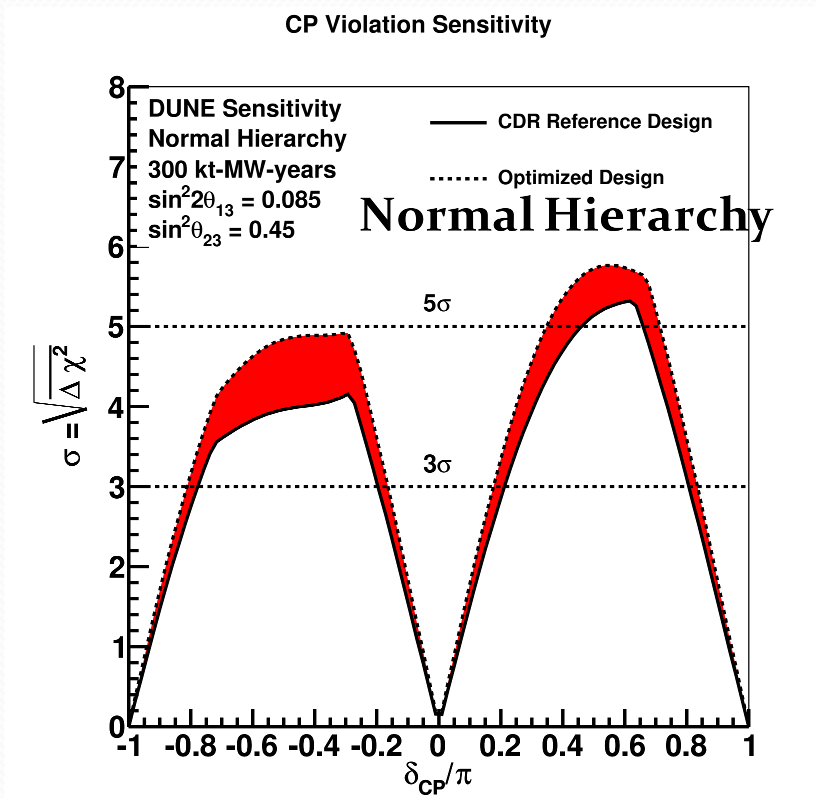
ν_e / $\bar{\nu}_e$ appearance

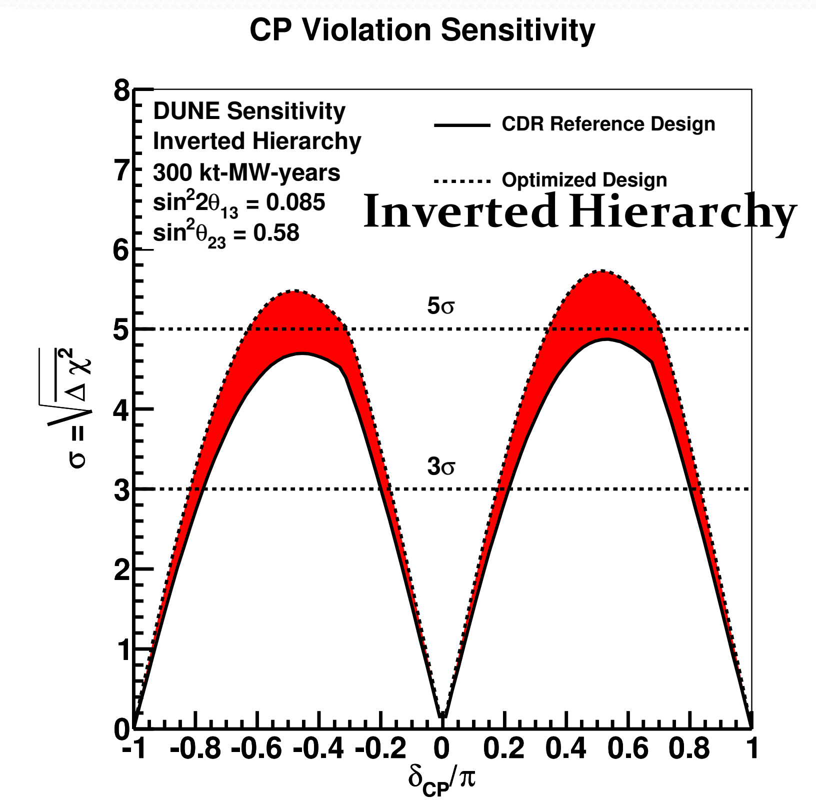
Anti-Neutrino mode

Dependence of CP Violation on MO

- Sensitivity to CPV after 300 kt-MW-yrs
- Software configuration available on arXiV: 1606.09550

- *Bands represent range of beam configurations*

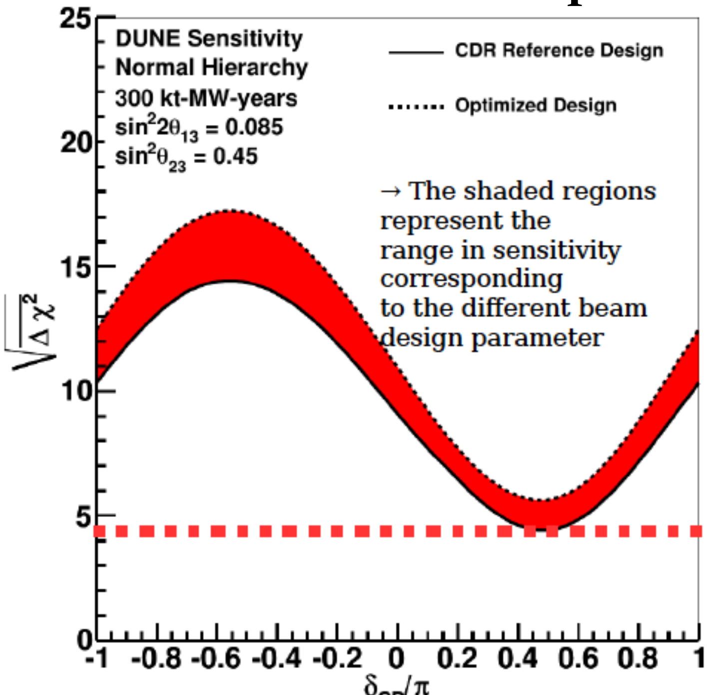


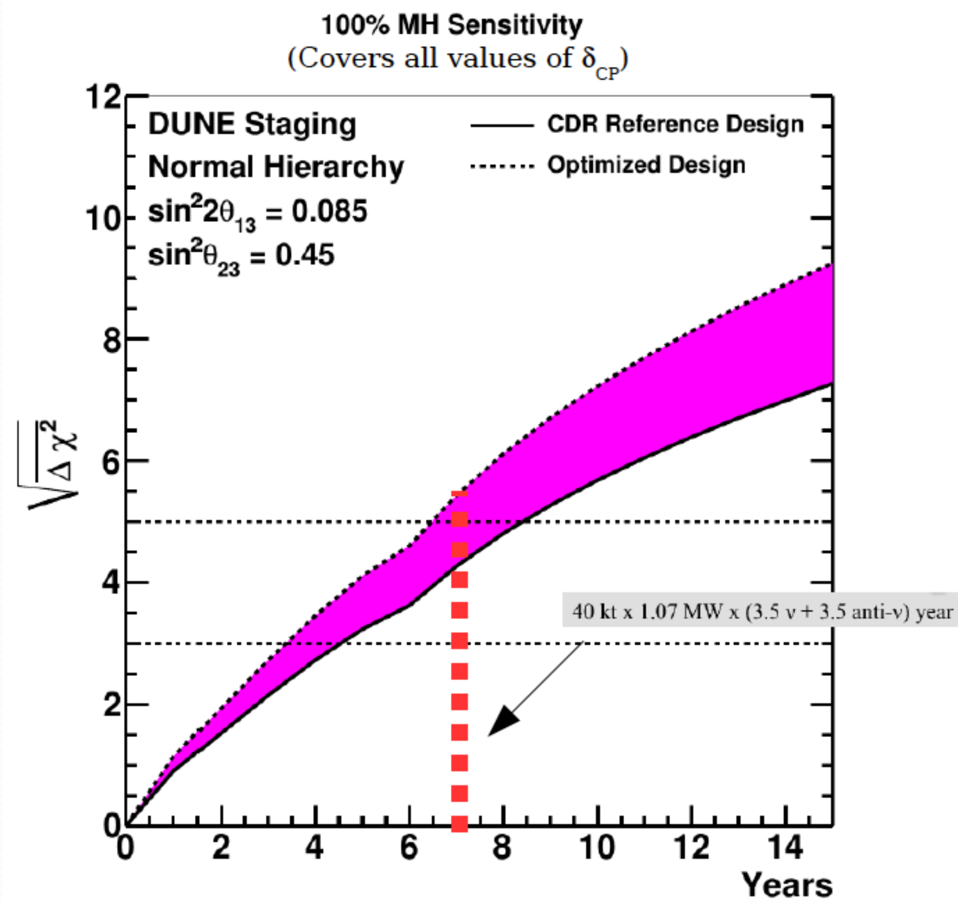


DUNE: CPV and MO sensitivity

- Sensitivity to MO as:
  - function of exposure in kton-MW-yrs and
  - Fraction of δ_{CP} values with given sensitivity or greater.

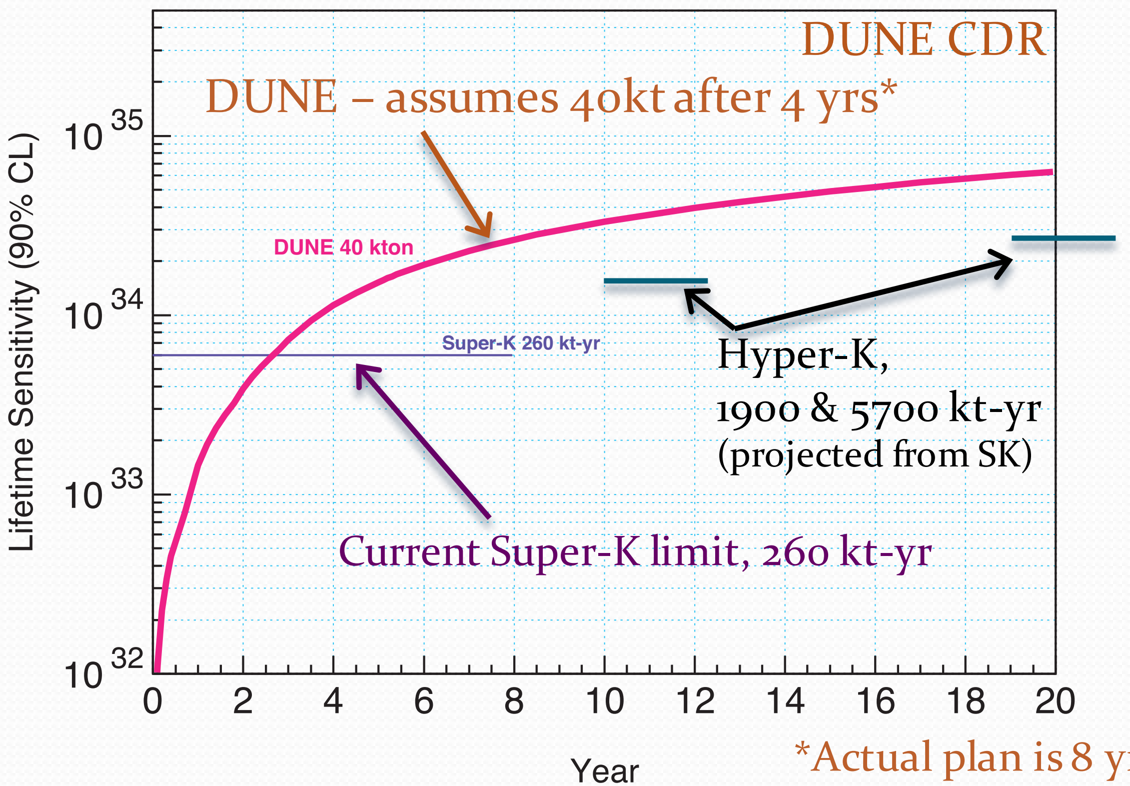
MO for all values of CPV phase

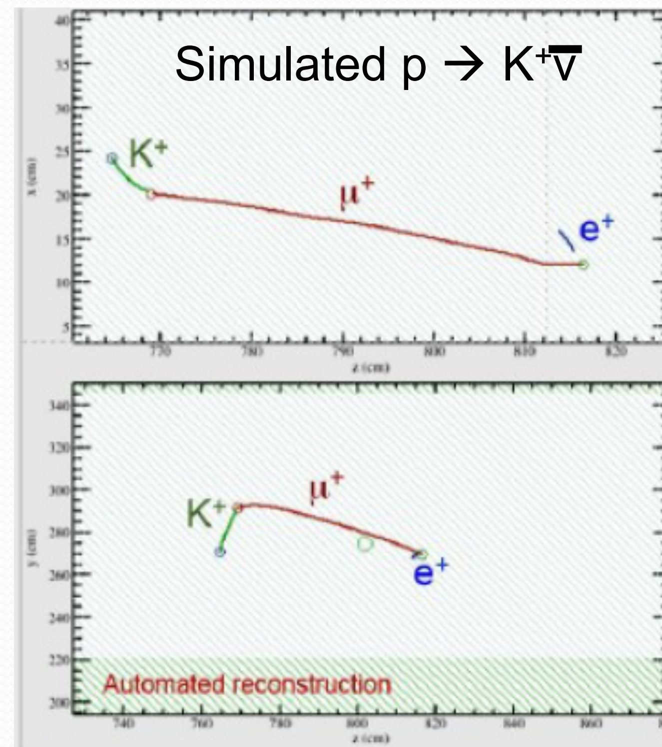




Nucleon Decay Sensitivity

- ✓ Proton decay – test of baryon number conversation.
- ✓ May explain matter-antimatter asymmetry.
- ✓ Many accessible modes, including SUSY favored: $p \rightarrow K^+ \bar{\nu}$
- ✓ Sensitive, bkg. free searches thanks to imaging, dE/dx and calorimetry in LAr TPC.





*Actual plan is 8 yrs to reach 40kt;

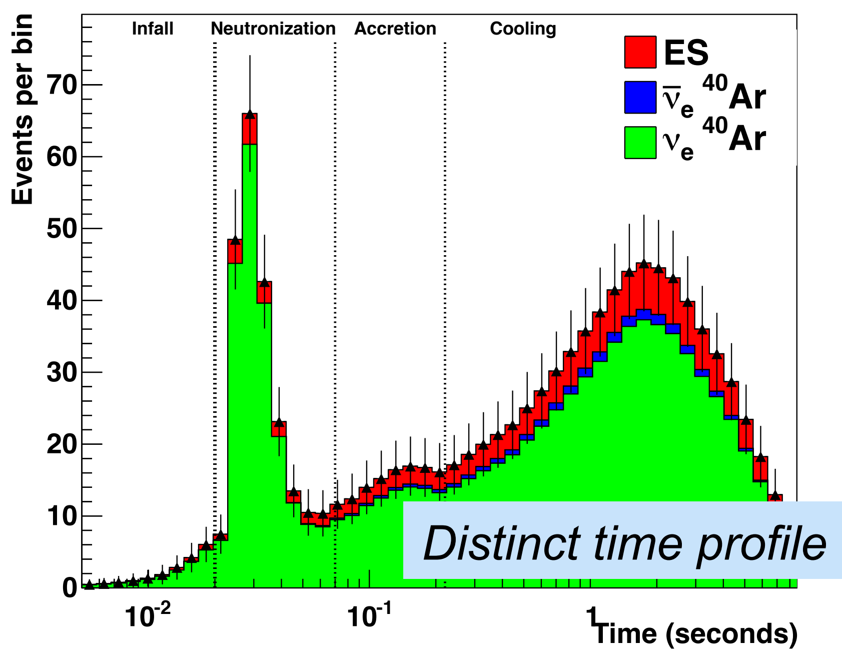
Super-nova neutrino burst detection

- About 99% of the gravitational binding energy of the proto-neutron star goes into neutrinos → few thousand events expected for galactic SN
- Dominant process: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

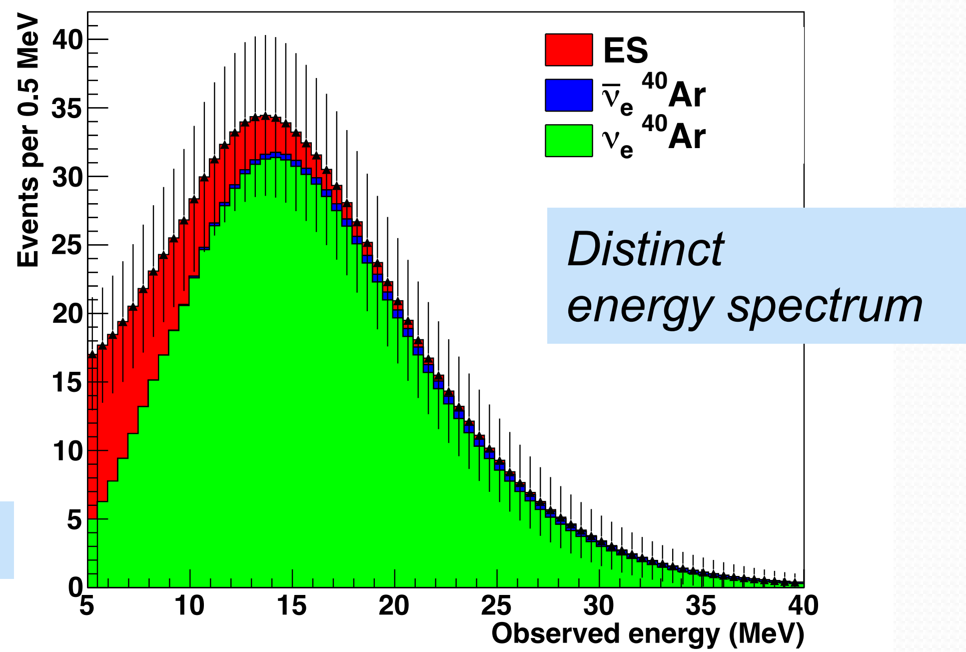
**Contrary to water/LS Detectors – antinu dominate*

- LAr uniquely sensitive to neutronization process at ~30ms.
- Elastic event – may give directionality.
- Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3500 neutrinos in 40kt DUNE for SN@

DUNE CDR



Distinct time profile



Distinct energy spectrum

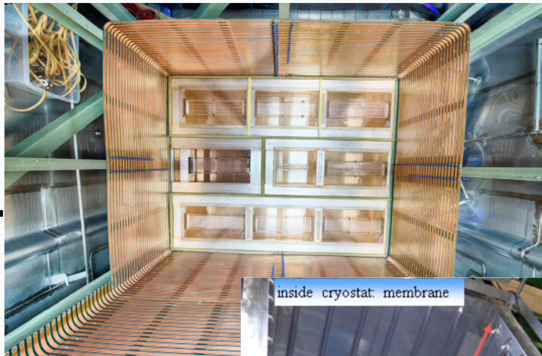
DUNE:
Large Scale Prototypes

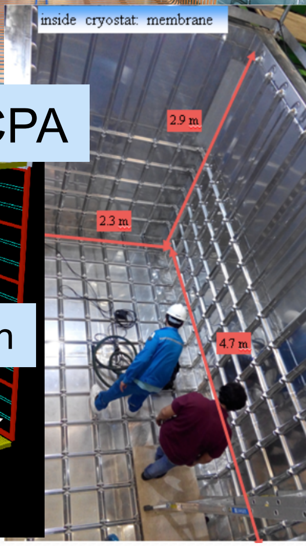
R&D toward 10 kton LAr TPC

- Scaling up to 10 kton: ~0.5-1 kton prototypes necessary to test all critical technical aspects for single and dual phase design
- Experience needed for building, maintaining, operation & data analysis of large LAr TPCs.
- R&D schedule
  - 35-ton s-phase TPC at FNAL (completed)
  - 3x1x1 m^3 d-phase TPC at CERN (2016)
  - S-p and d-p protoDUNE at CERN (2018)

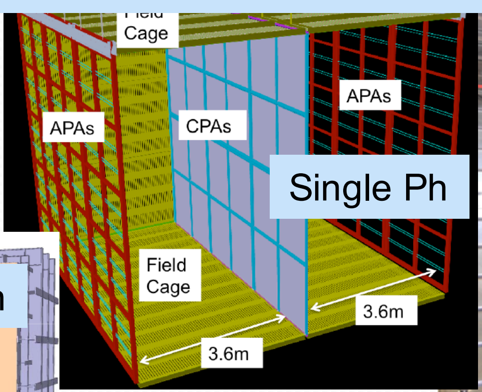
  in the beam and

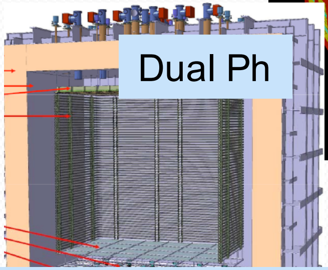
  with physics program





4 full size APA & 1 CPA





Full size readout plane, cathode, light collection, ½ drift distance (6 m)

DUNE:
Path Forward

DUNE Schedule

- 2017 Cavern excavation
- 2018 ProtoDUNEs (SP & DP) operational at CERN

- 2019 Technical Design Review (DOE & international Agencies)
- 2020 Cryostat construction

- 2022 Far detector installation (1st module)
- 2023 Far detector installation (2nd module)

- 2024 20 kton operational – start for taking non-beam physics

- 2026 First beam operations at 1.2 MW

Summary

- DUNE is going forward with a strong scientific program:
  - CPV phase, MO, nucleon decay, supernovae ν, cross-sections…
- DUNE/LBNF project: 40 kt LAr TPC FD, fine grained ND and 1.2 MW wide-band neutrino beam 1300 km away
- DUNE/LBNF enjoys strong international support:
  - FNAL – DUNE/LBNF is the lab's priority + synergy with SBN
  - US Government – DOE approved LBNF FY 2017 budget ($45M - $55M)
  - CERN – neutrino platform for ProtoDUNEs at CERN, key roles in LBNF and SBN program

Exciting time for neutrino physics and DUNE!

Thank you!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