Deep Underground Neutrino Experiment: Status and Prospects (for the DUNE Collaboration)

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Argonne National Laboratory

New Trends in High-Energy Physics, October 2-8, 2016.

Plan of the Talk

- Neutrino Oscillation Status
- The Goals of DUNE Experiment
- DUNE Experiment Collaboration and Organization
- Status of Neutrino Beam, Near and Far Detectors
- DUNE Physics Measurements
- Liquid Argon TPC Development Path to LBNF/DUNE
- DUNE Timeline
- Summary

Neutrino Oscillation: Quick Reminder

- The three neutrino mixing:

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} Big & Big & Small \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix}$$

$$= \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

θ_{12} measured from $P(\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_x)$ by reactor $\bar{\nu}_e$ and solar ν_e.

θ_{13} measured from $P(\bar{\nu}_e \to \bar{\nu}_e)$ by reactor $\bar{\nu}_e$.
θ_{13} and δ measured from $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e)$ by accelerator ν_μ.

θ_{23} measured from $P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu)$ by atmospheric ν_μ and accelerator ν_μ.

- Neutrino oscillation parameters:

PMNS matrix:	3 mixing angles: θ_{12}, θ_{23}, θ_{13}
	1 phase: δ => CP-violation in ν-sector
Mass differences:	2 mass difference scales: Δm^2_{12}, Δm^2_{23}.

Neutrino Oscillation Results

- Current understanding

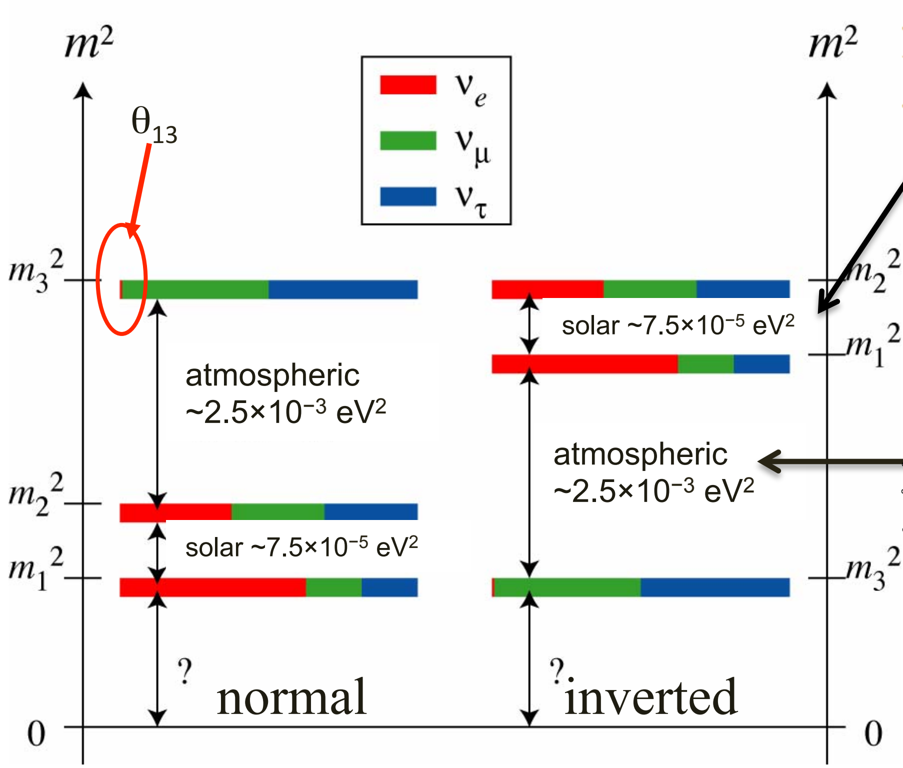
-Mass squared differences:

$\Delta m^2_{21} \approx 7.5 \times 10^{-5} eV^2$
$|\Delta m^2_{32}| \approx 2.5 \times 10^{-3} eV^2$

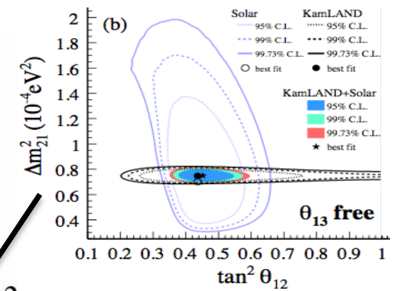
-Mixing angles:

$\sin^2\theta_{12} \approx 0.31$
$\sin^2\theta_{23} \approx 0.45 - 0.55$
$\sin^2\theta_{13} \approx 0.02$

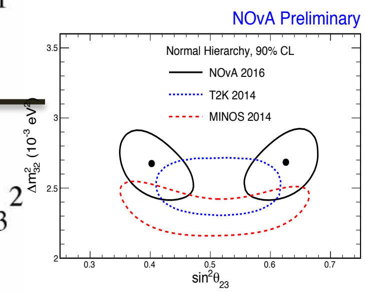
-Absolute mass scale is unknown.



KamLAND+solar



NOvA/T2K/MINOS

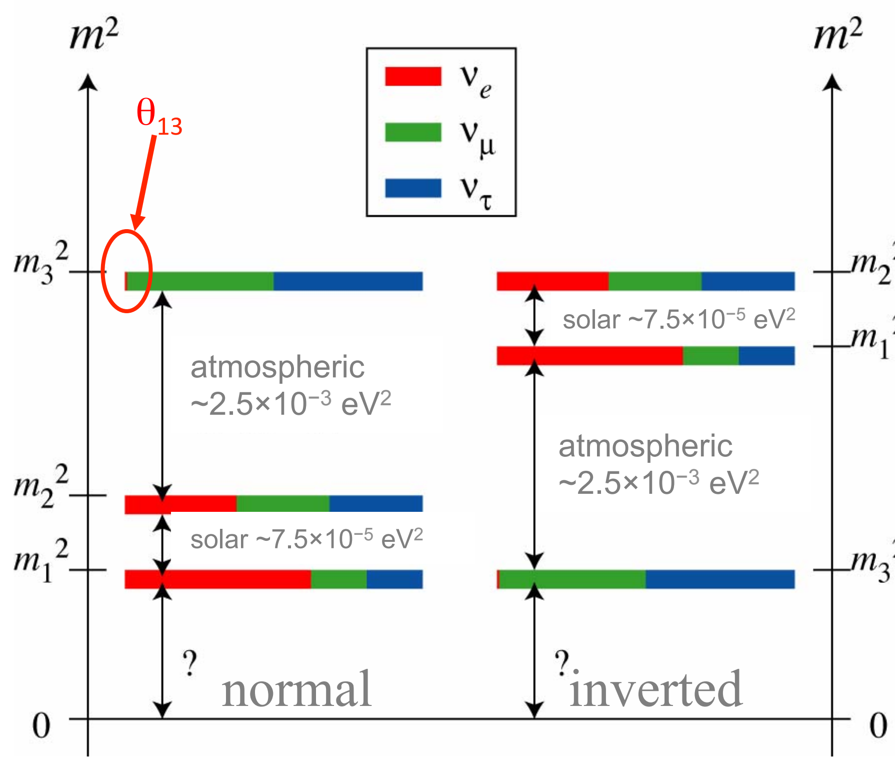


Please see related talks:
-V. Pantuev's Tritium β-decay talk
-A. Babic's 0ν2β-decay talk

Please see related talks:
-Z. Djurcic's NOvA talk
-V. Paolone's T2K talk
-T. Yano's Super-K talk
-D. Naumov's Daya Bay talk

Neutrino Oscillation Questions

Recently measured what is ν_e component in the ν_3 mass eigenstate, i.e. θ_{13}.



Missing information in 3x3 mixing scheme:

1. Is the μ - τ mixing maximal?
   -Only know $\sin^2\theta_{23} \approx 0.45 - 0.55$
2. What is the mass hierarchy?
   -Normal or inverted?
3. Do neutrinos exhibit CP violation, i.e. is $\delta_{CP} \neq 0$?

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E}L\right) \sin\left(\frac{\Delta m_{13}^2}{4E}L\right) \sin\left(\frac{\Delta m_{23}^2}{4E}L\right)$$

4. Why are quark and neutrino mixing matrices so different?

Please see S. Bilenky's talk on "Neutrino in the Standard Model and Beyond"

$$U_{MNSP} \sim \begin{pmatrix} Big & Big & Small \\ Big & Big & Big \\ Big & Big & Big \end{pmatrix} \quad \text{vs.} \quad V_{CKM} \sim \begin{pmatrix} 1 & Small & Small \\ Small & 1 & Small \\ Small & Small & 1 \end{pmatrix}$$

The Goals of DUNE Experiment

- Primary focus of the DUNE science program is on fundamental open questions in particle physics and astro-particle physics:

  1) Neutrino Oscillation Physics

     -CPV in the leptonic sector

       "Our best bet for explaining why there is matter in the universe"

     -Mass Hierarchy

     -Precision Oscillation Physics & testing the 3-flavor paradigm

  2) Nucleon Decay

     -Predicted in beyond the Standard Model theories [but not yet seen]

       e.g. the SUSY-favored mode, $p \rightarrow K^{+}\overline{\nu}$

  3) Supernova burst physics & astrophysics

     -Galactic core collapse supernova, sensitivity to ν_e

       Time information on neutron star or even black-hole formation

Any would be a major discovery

- DUNE Ancillary Science Program

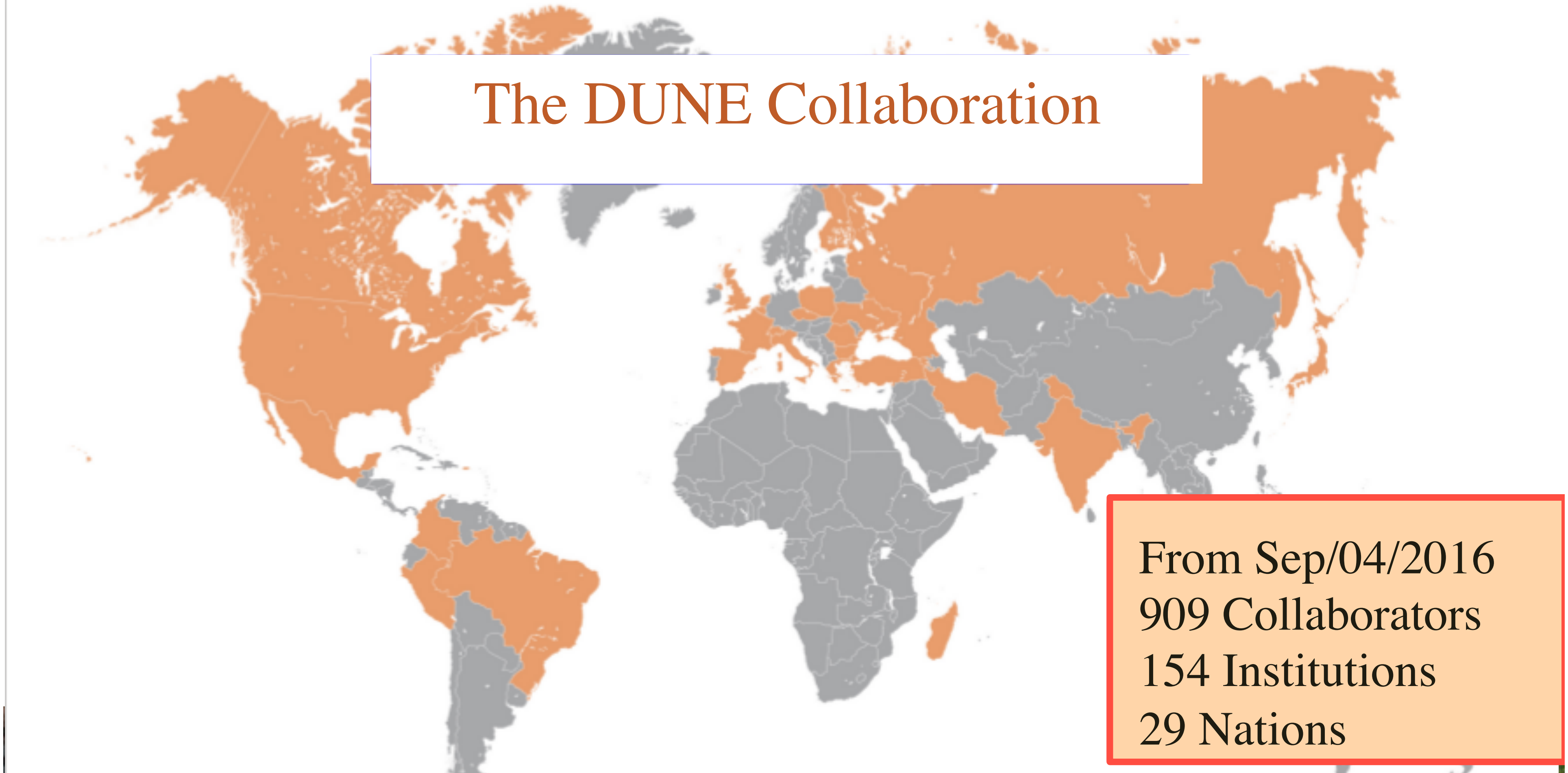
  -Other LBL oscillation physics with BSM sensitivity

  -Oscillation physics with atmospheric neutrinos

  -Neutrino Physics in the near detector

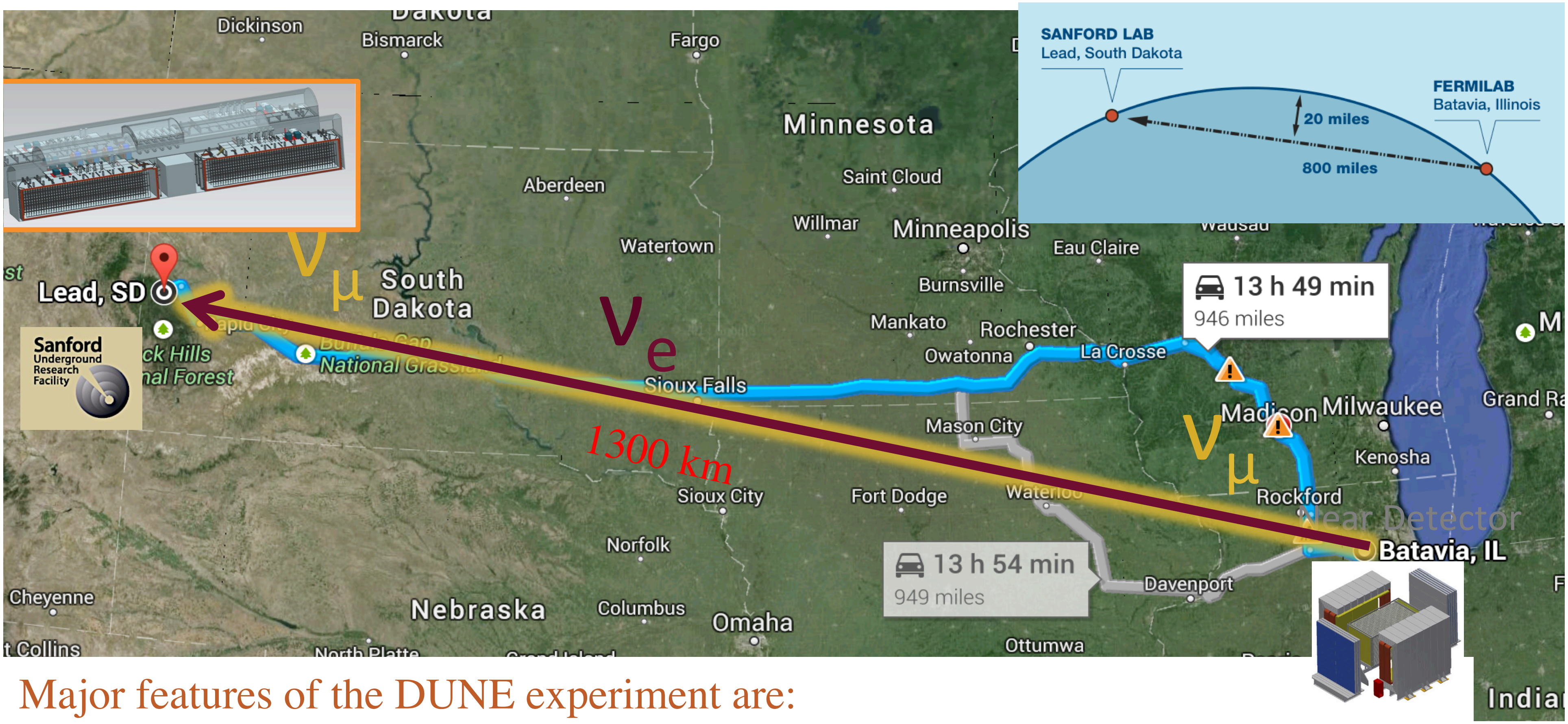
  -Search for signatures of Dark Matter

The DUNE Collaboration



From Sep/04/2016
909 Collaborators
154 Institutions
29 Nations

Deep Underground Neutrino Experiment (DUNE)



Major features of the DUNE experiment are:

- A high-intensity wide-band neutrino beam originating at FNAL
  - -1.2 MW proton beam upgradable to 2.4 MW
- A highly capable near detector to measure the neutrino flux
- A ~40 kt fiducial mass liquid argon far detector
  - -Located 1300 km baseline at SURF's 1.5 km underground level (2300 mwe)
  - -Staged construction of four ~10 kt detector modules. First module to be installed starting in 2021.

Deep Underground Neutrino Experiment (DUNE)

DUNE/LBNF Conceptual Design Report (CDR):
Volume 1: The LBNF and DUNE Projects, arXiv:1601.05471
Volume 2: The Physics Program for DUNE at LBNF, arXiv:1512.06148
Volume 4: The DUNE Detectors at LBNF, arXiv: 1601.02984

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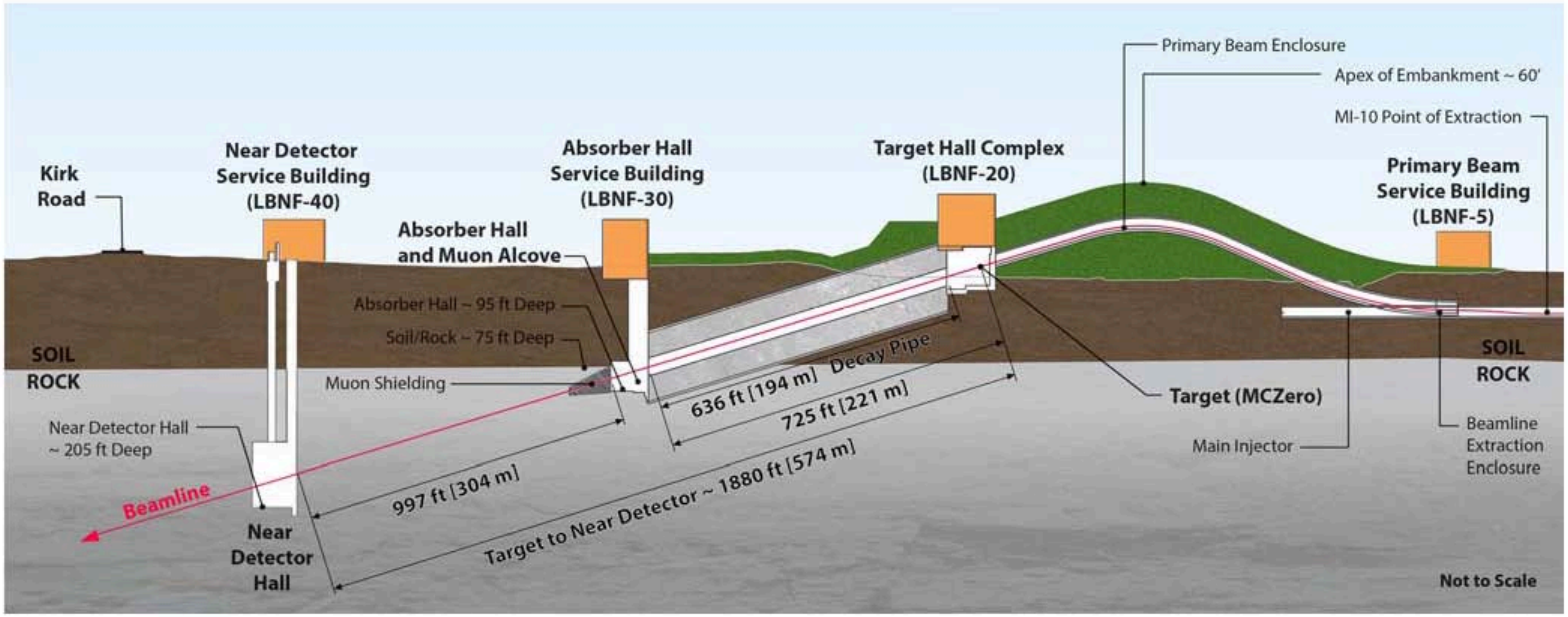
Project Organization: DUNE – LBNF Relationship

- Detectors and Science Collaboration will be managed separately from the neutrino facility and infrastructure

- LBNF (Long Baseline Neutrino Facility): DOE/Fermilab hosted project with international participation
  -LBNF houses, and delivers beam (i.e. beamline) to detectors built by the DUNE collaboration
  -LBNF responsibilities are:
    - ✓ Neutrino beamline
    - ✓ Near detector conventional facilities
    - ✓ Far detector cavern and conventional facilities

- DUNE (Deep Underground Neutrino Experiment) is responsible for
  -Far and Near Detectors
  -Scientific Research Program

LBNF/DUNE Neutrino Beam

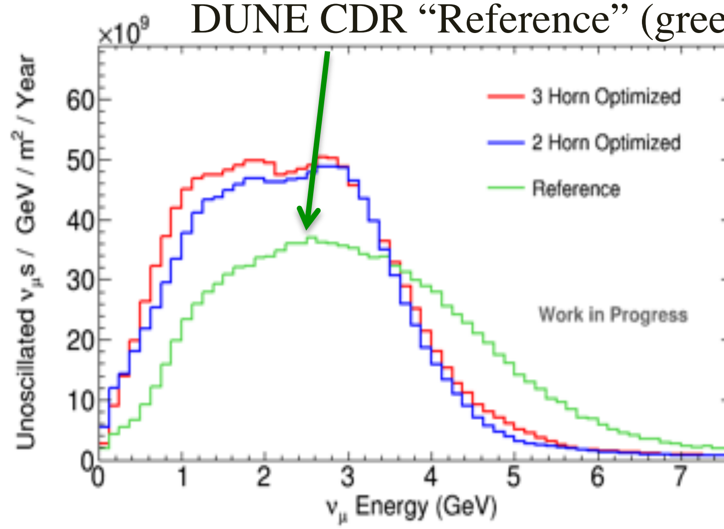


- 60 - 120 GeV Proton beam energy
- Initial power 1.2 MW upgradable to 2.4 MW

  -PIP II complete before start of data taking

- Up to 10^{21} protons on target per year
- Good coverage 1 to 5 GeV

DUNE CDR "Reference" (green)

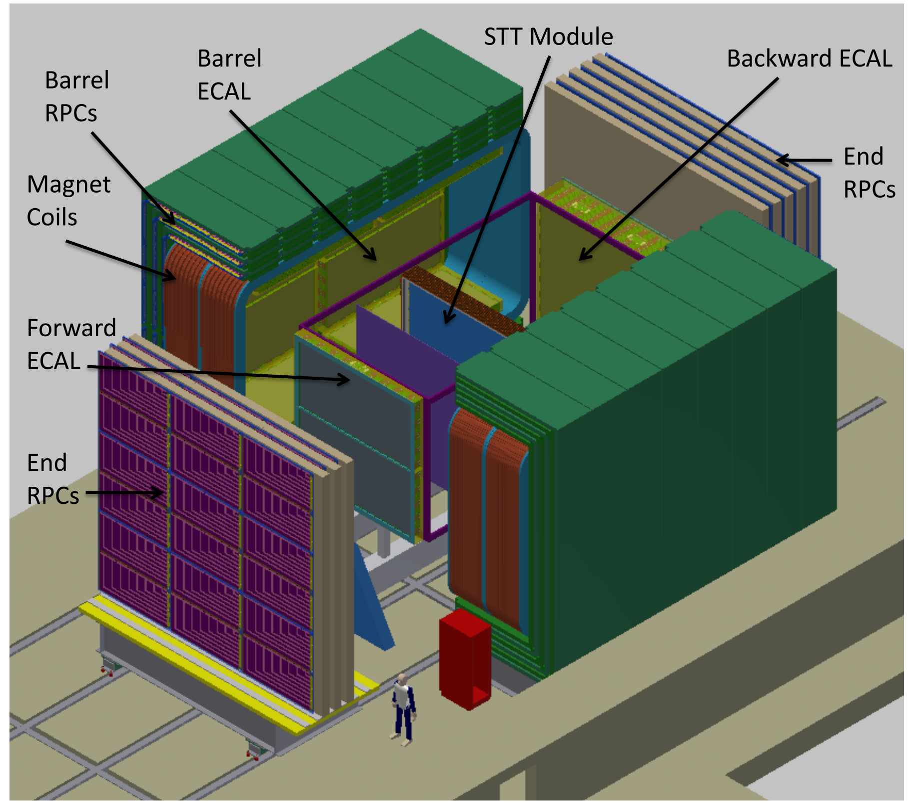


DUNE Near Detector current reference design

- Goal is to precisely measure the neutrino fluxes ν_e , $\overline{\nu}_e$, ν_μ , and $\overline{\nu}_\mu$
  -Percent level neutrino flux determination
  -Precision neutrino cross section measurements

- NOMAD-inspired Fine-Grained Tracker (FGT), consisting of:
  -Central straw-tube tracking system (215,040 channels)
  -Lead-scintillator sampling ECAL
  -RPC-based muon tracking systems
  -Magnetic Spectrometer (0.4 T)

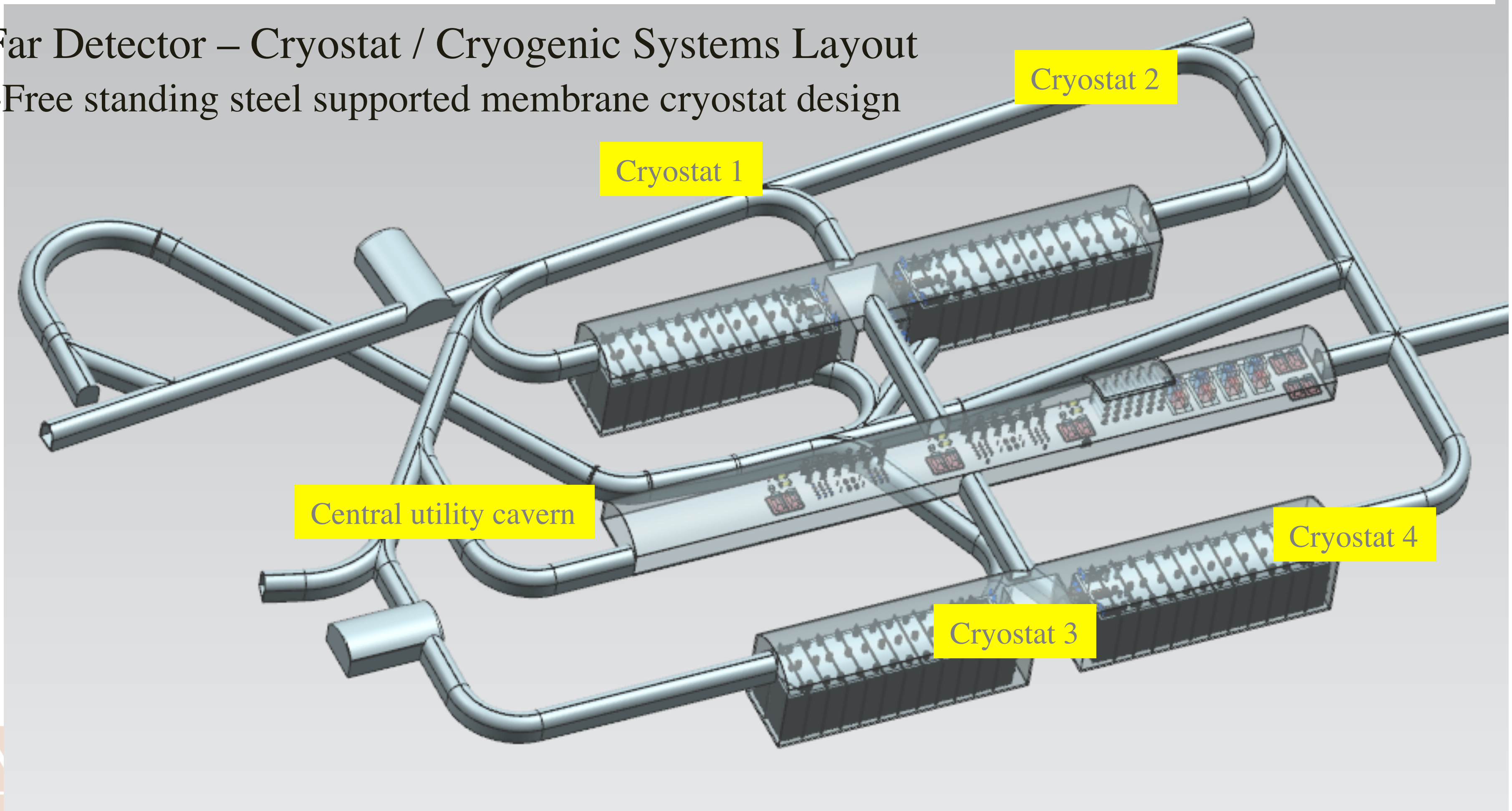
- Integrated nuclear targets: Ar, $(C_3H_6)_n$, Ca, C, Fe, etc.
  -Sufficient for 10 times the un-oscillated far detector neutrino rate from the high pressure argon targets



- Design still being optimized
  -Quantifying the benefits of augmenting the ref. design with a LArTPC or high-pressure gaseous argon TPC.

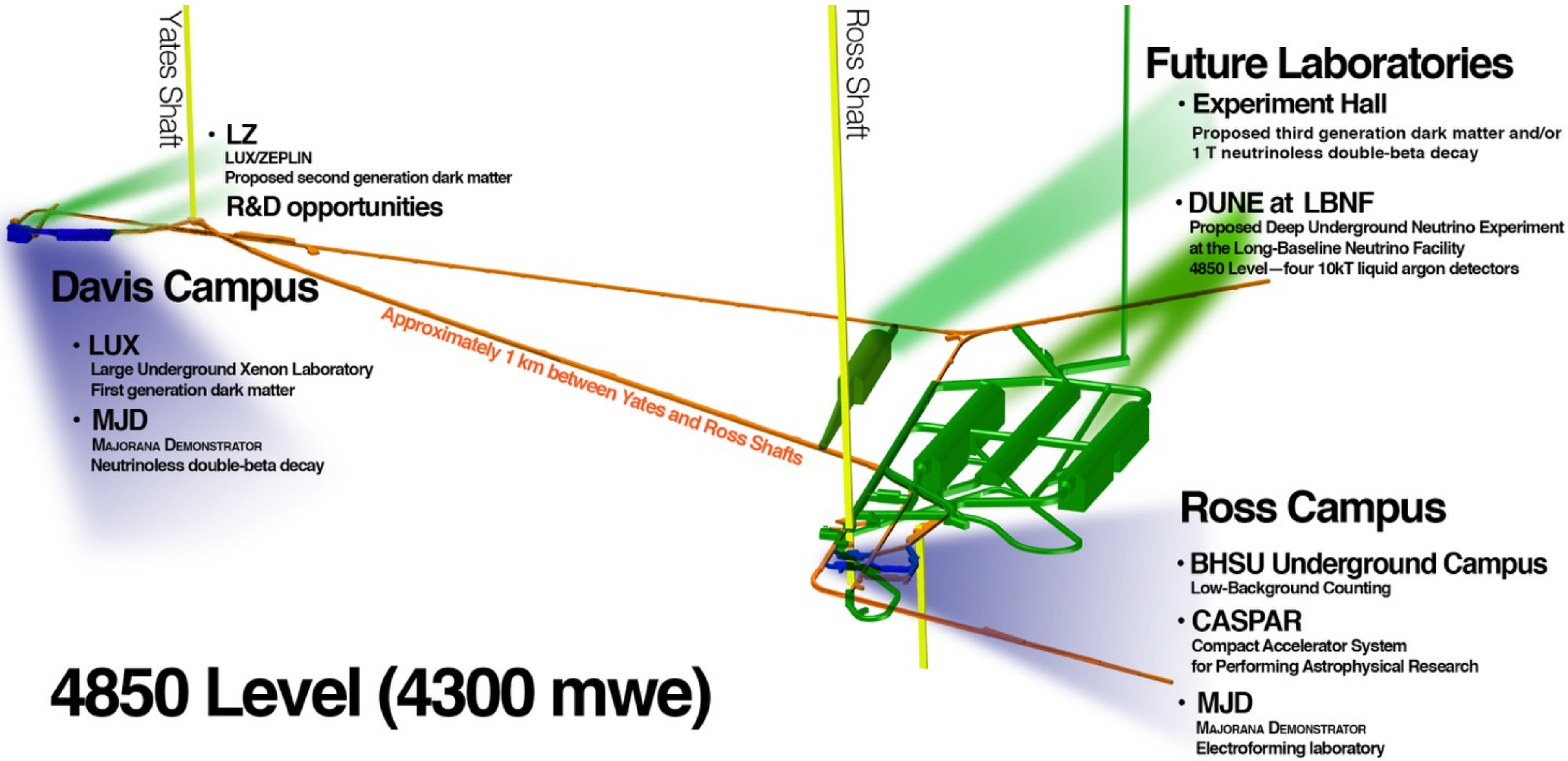
DUNE Far Detector Staged Approach

- Four-Cavern Layout at the Sanford Underground Research Facility (SURF) at the 4850 foot Level (4300 m.w.e.)
  - -Four independent 10-kt (fiducial mass) Far Detector liquid argon TPC modules
  - -Allows for staged construction of the Far Detector
  - -Gives flexibility for evolution of liquid argon (LAr) TPC technology design
- Far Detector – Cryostat / Cryogenic Systems Layout
  - -Free standing steel supported membrane cryostat design



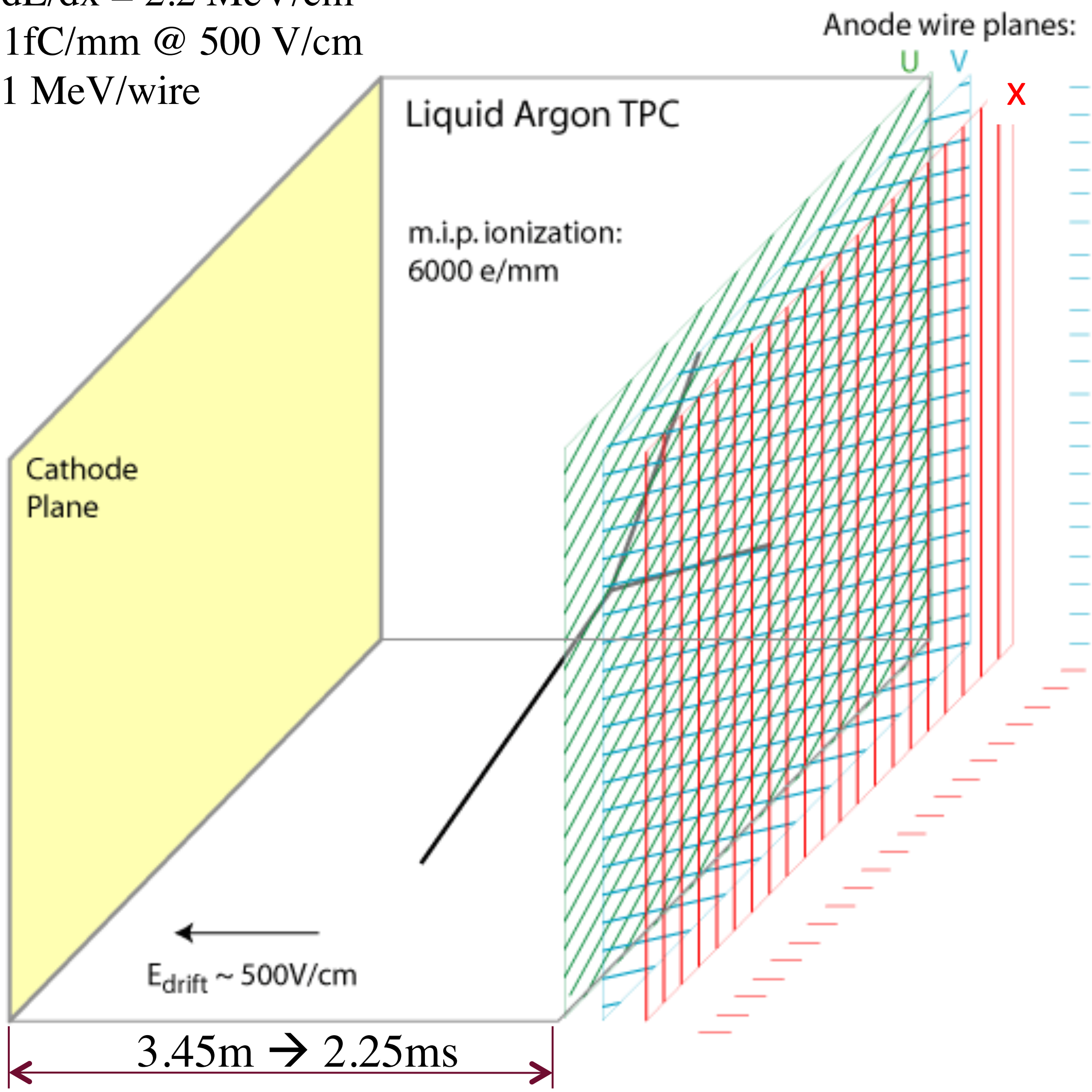
Sanford Underground Research Facility, Lead, S. Dakota

- Site has long & storied history as home to neutrino experiments
- LBNF scope: 4 detector chambers, utility cavern, connecting drifts
- Extensive preparatory work for LBNF/DUNE already done
- DOE approval pending to begin excavation & surface building construction

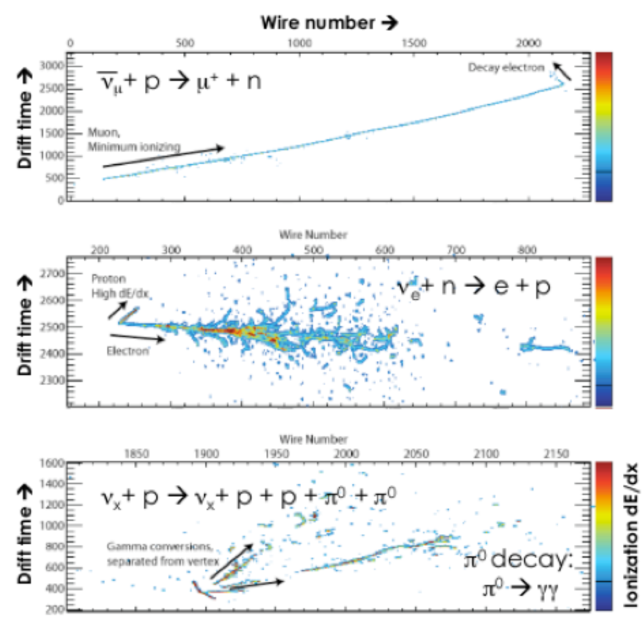


Liquid Argon Time Projection Chamber (TPC) Operation

MIP dE/dx = 2.2 MeV/cm
→ ~ 1fC/mm @ 500 V/cm
→ ~1 MeV/wire

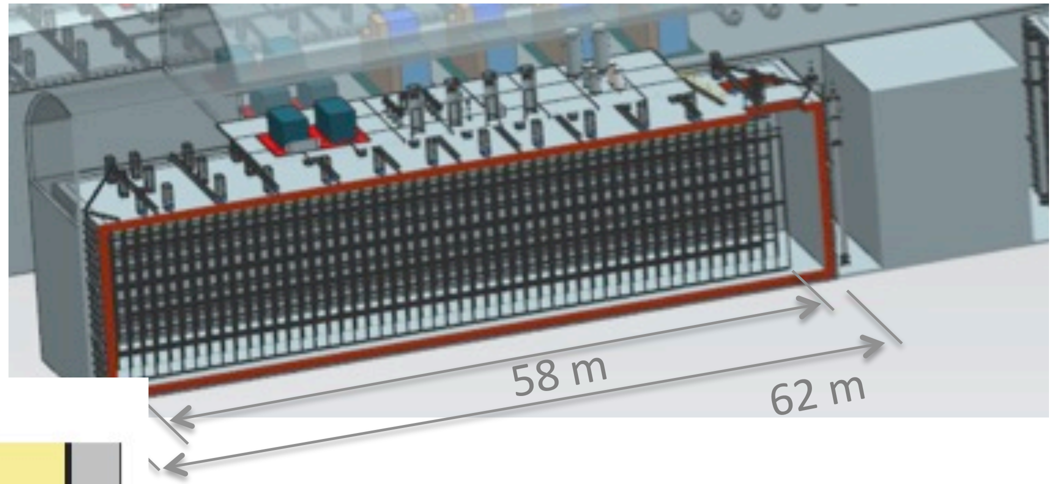


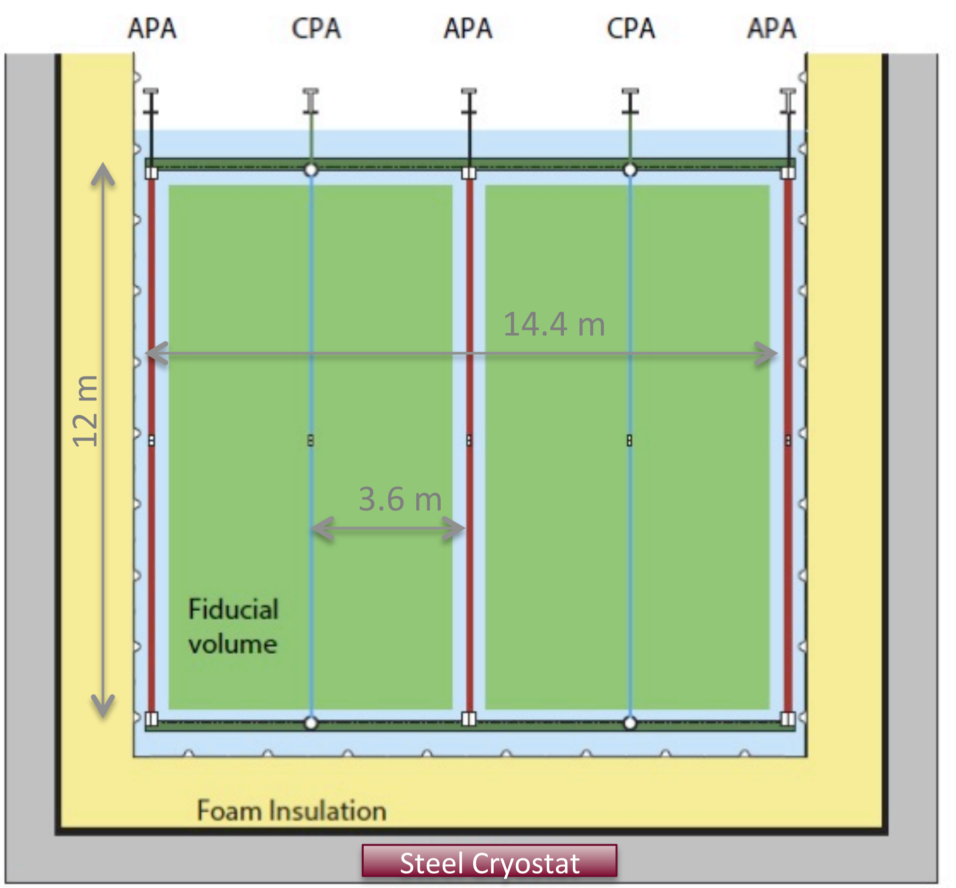
- Ionization charge drifts to finely segmented collection planes.
  - -high resolution data
  - - high event selection efficiency and efficient background rejection
- Scintillator light detected to determine interaction time.



Far Detector Reference Design: Single-phase LAr TPC

- Liquid Argon Time projection chamber with both charge and optical readout.
- First 10kt detector will be single phase





- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - -Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - -3.6 m drift length
- Photon detection for event interaction time determination for underground physics

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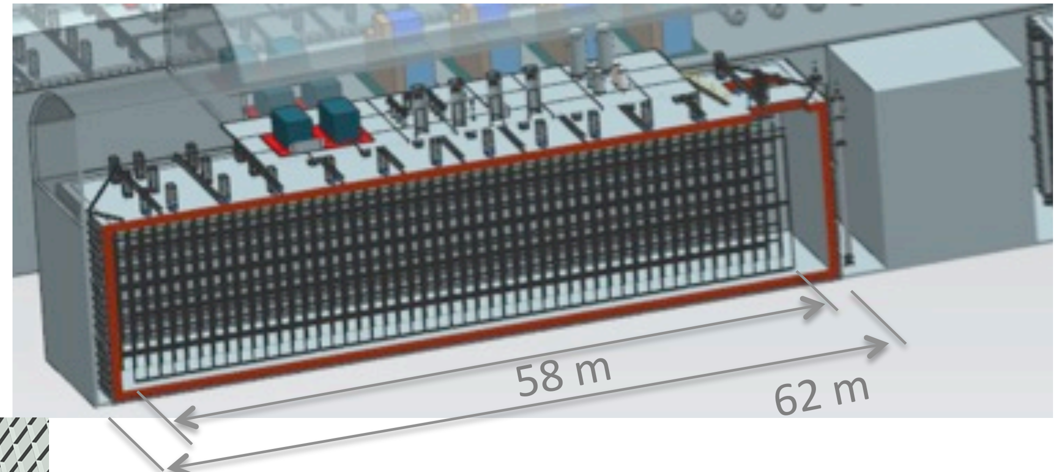
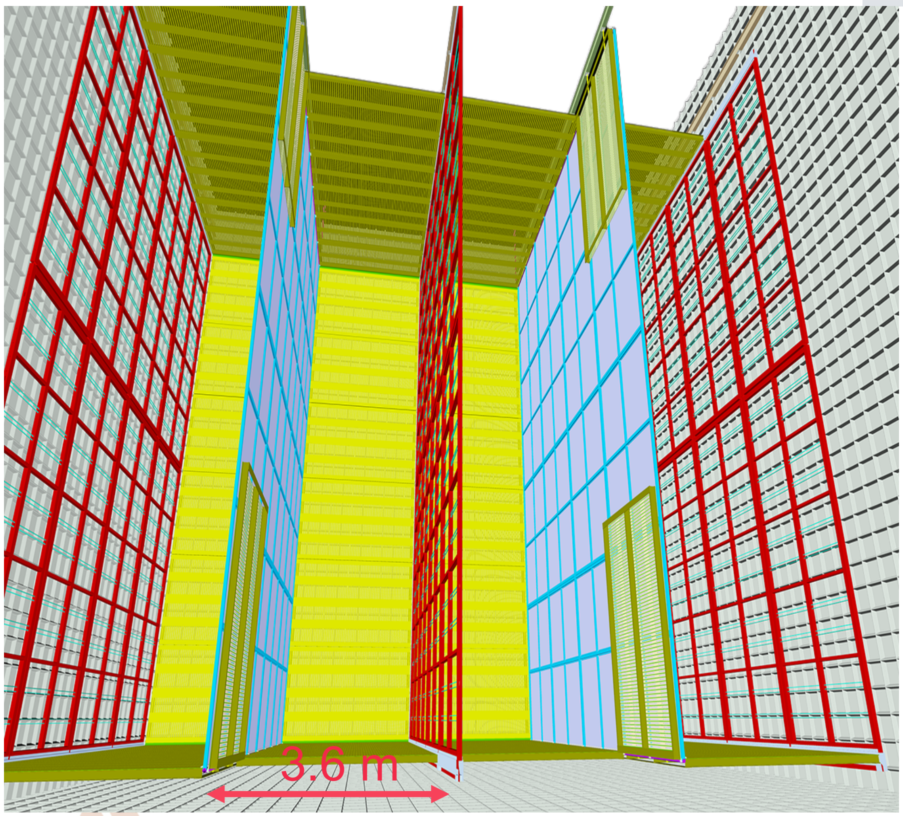
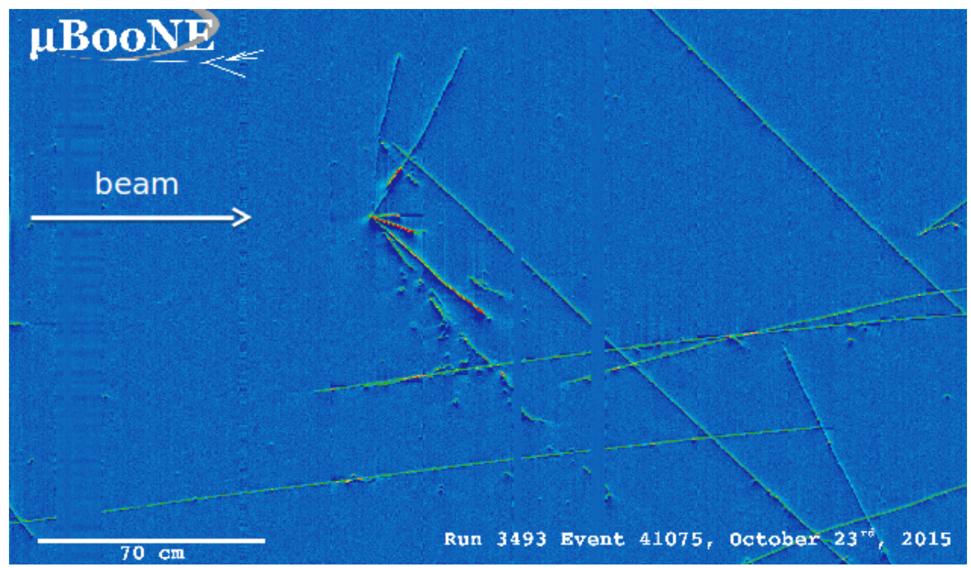




- MicroBooNE example: mm spatial resolution



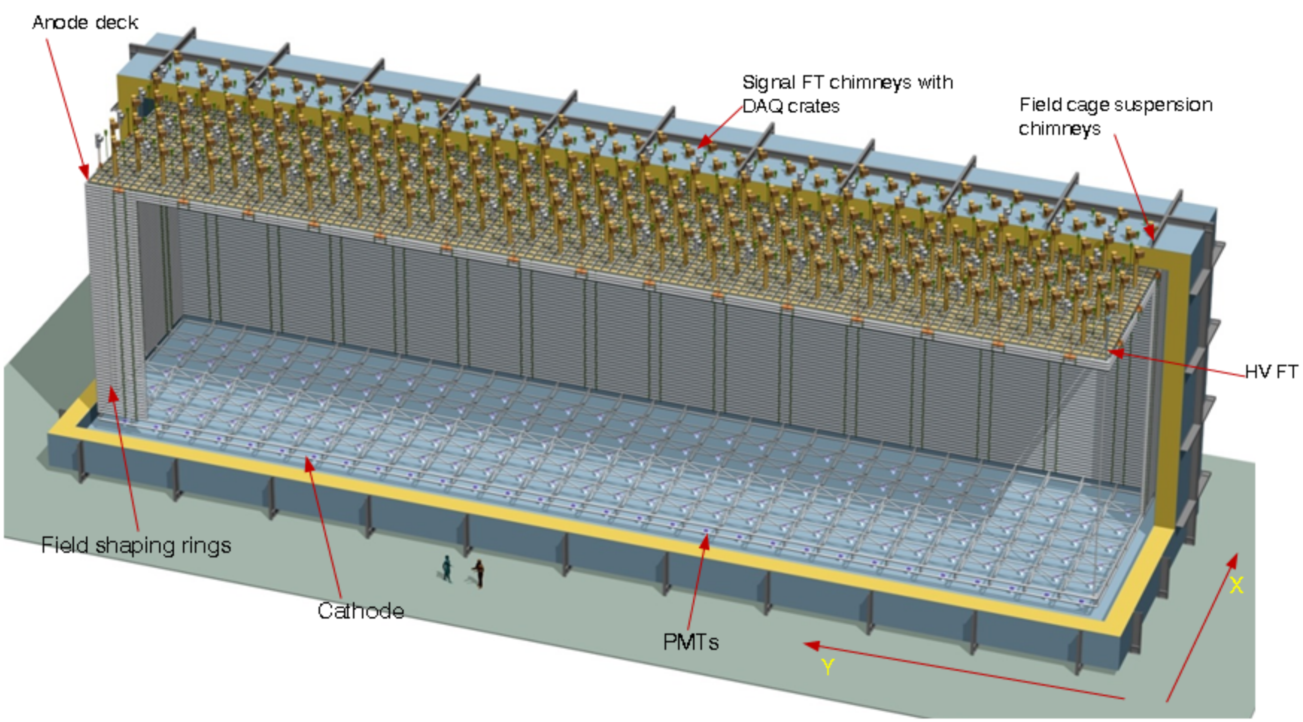
Alternative Far Detector Design: Dual-phase LAr TPC

- DUNE collaboration recognizes the potential of the dual-phase technology

  -A dual-phase implementation of the DUNE far detector is presented as an alternative design in the CDR (Conceptual Design Report).

  -DUNE strongly supports the WA105 development program at the CERN neutrino platform

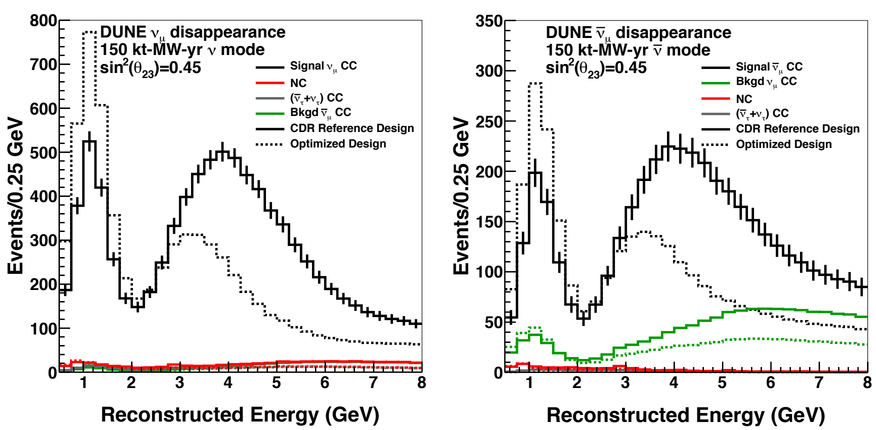
  -If demonstrated, could form basis of second or subsequent 10-kt far detector modules



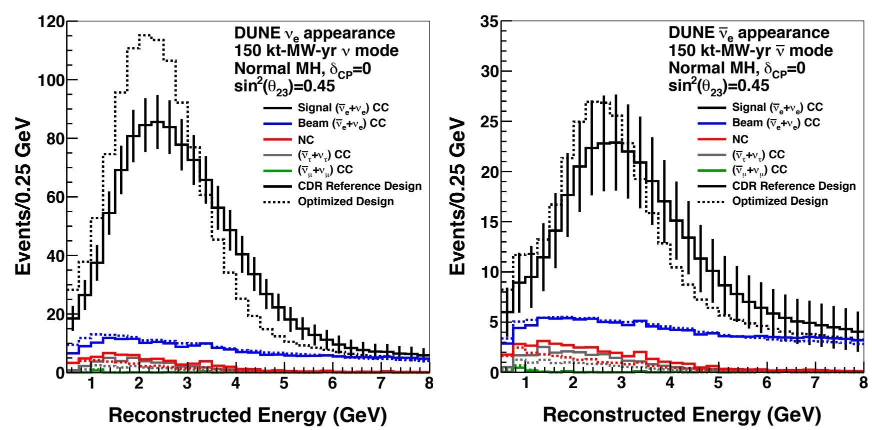
Neutrino Oscillation Strategy

- Measure neutrino spectra at 1300 km in a wide-band beam
  -Determine MH and θ_{23} octant, probe CPV, test 3-flavor paradigm and search for neutrino NSI in a <u>single experiment</u>
- Long baseline:
  Matter effects are large ~ 40%
- Wide-band beam:
  Measure ν_e appearance and ν_μ disappearance over range of energies
  MH & CPV effects are separable

ν_μ / $\bar{\nu}_\mu$ disappearance



ν_e / $\bar{\nu}_e$ appearance



Neutrino Oscillation Strategy (cont.)

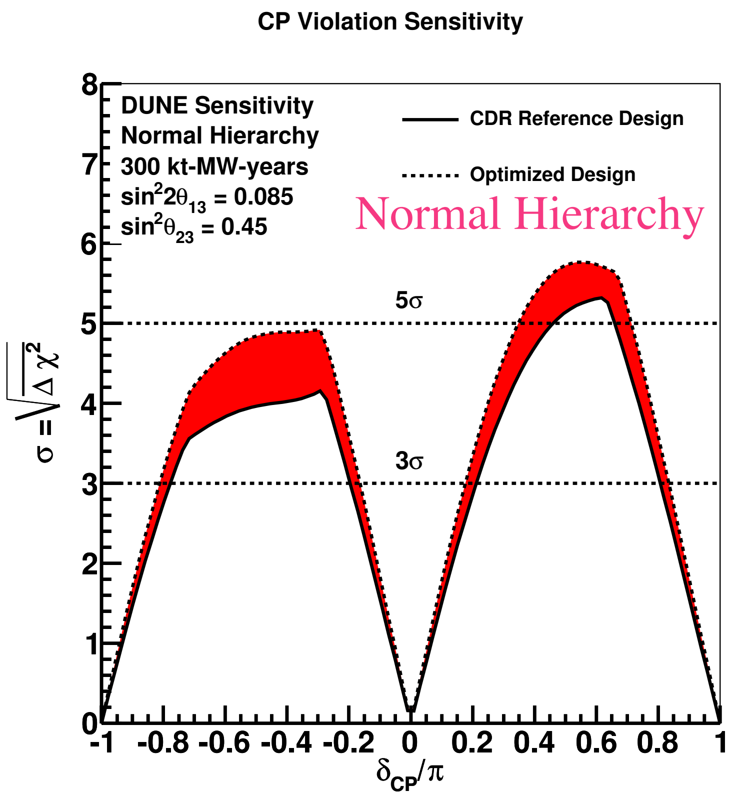
- Physics (MH, θ_{23}, θ_{13}, δ) extracted from combined analysis of 4 samples:
  - -CDR estimates, assuming: CDR optimized beam, 56% LBNF uptime, FastMC detector response
  - -Physics inputs: δ **= 0,** $\boldsymbol{\theta_{23}}$ **= 45°**, others from NuFIT: Gonzalez-Garcia, Maltoni, Schwetz, JHEP 1411 (2014)

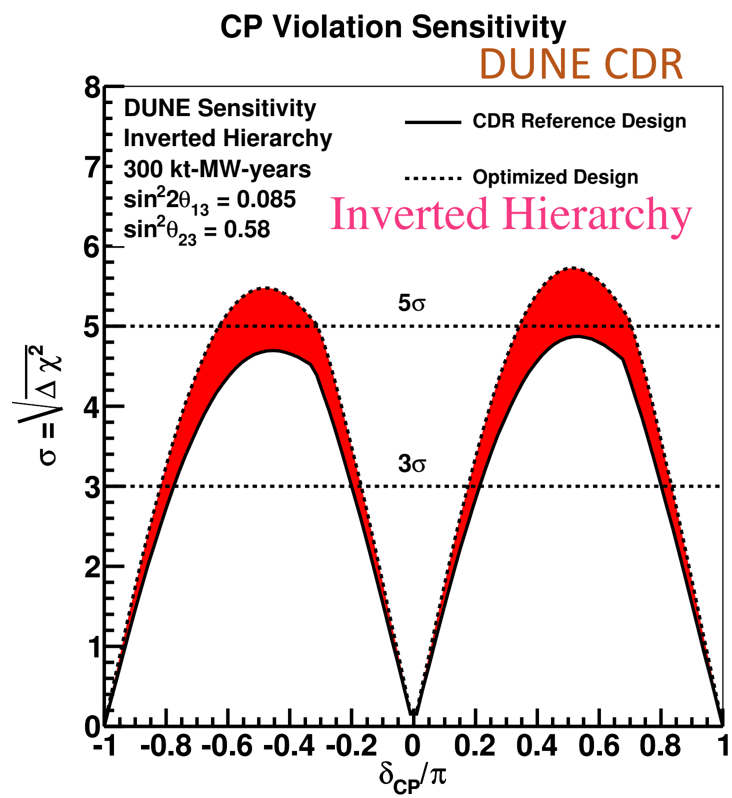
ν mode / 150 kt-MW-yr	ν_e appearance	ν_μ disappearance
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam ν_e background	204	–
NC background	17	76
Other background	22	29

Anti-ν mode / 150 kt-MW-yr	$\bar{\nu}_e$ appearance	$\bar{\nu}_\mu$ 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

DUNE Sensitivity to CP Violation

- Sensitivity to CP Violation, after 300 kt-MW-yrs (3.5 + 3.5 yrs x 40kt @ 1.07 MW)





(Bands represent range of beam configurations)

- Experimental configuration (geometry, flux, detector response) used for sensitivity calculations shown here is published in **arXiV:1606.09550**

DUNE Sensitivity to CP Violation (vs Exposure)

- Sensitivities shown as function of exposure in kt-MW-yr's.

  40-kt x 10 yrs x 1.2 MW
  ~ 500 kt-MW-yr

  Other factors:

  -Efficiency / Background Rejection

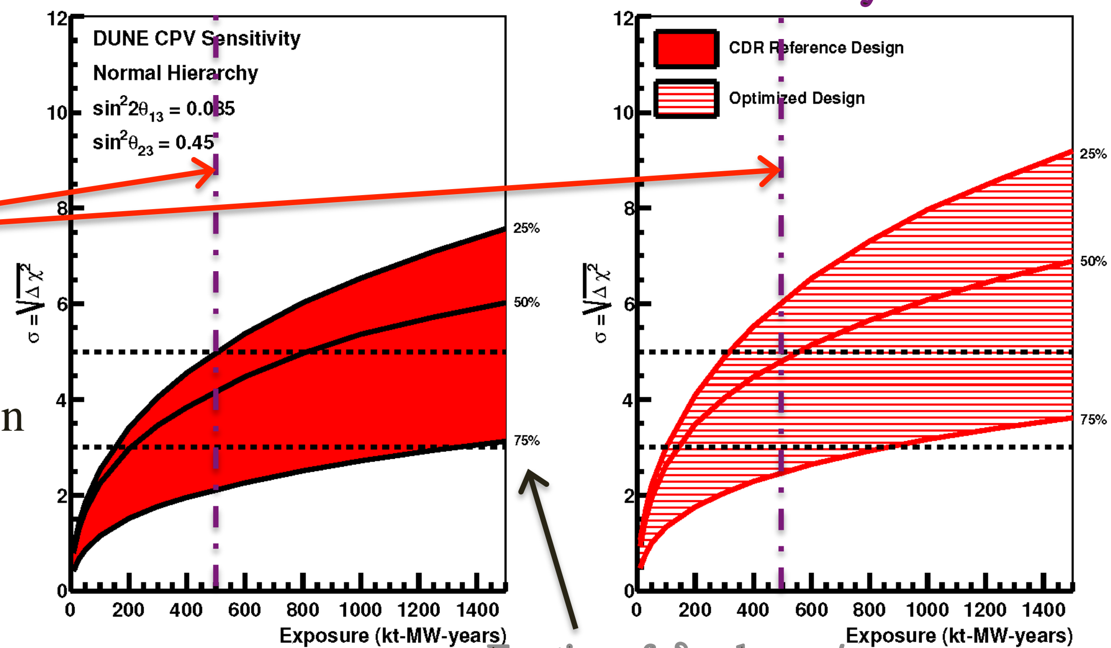
  -Neutrino beam flux

  -Physics: MH, θ_{23}, θ_{13}, δ_{CP}

  -Systematic Errors

  -Complications from BSM physics?

DUNE CDR **CP Violation Sensitivity**



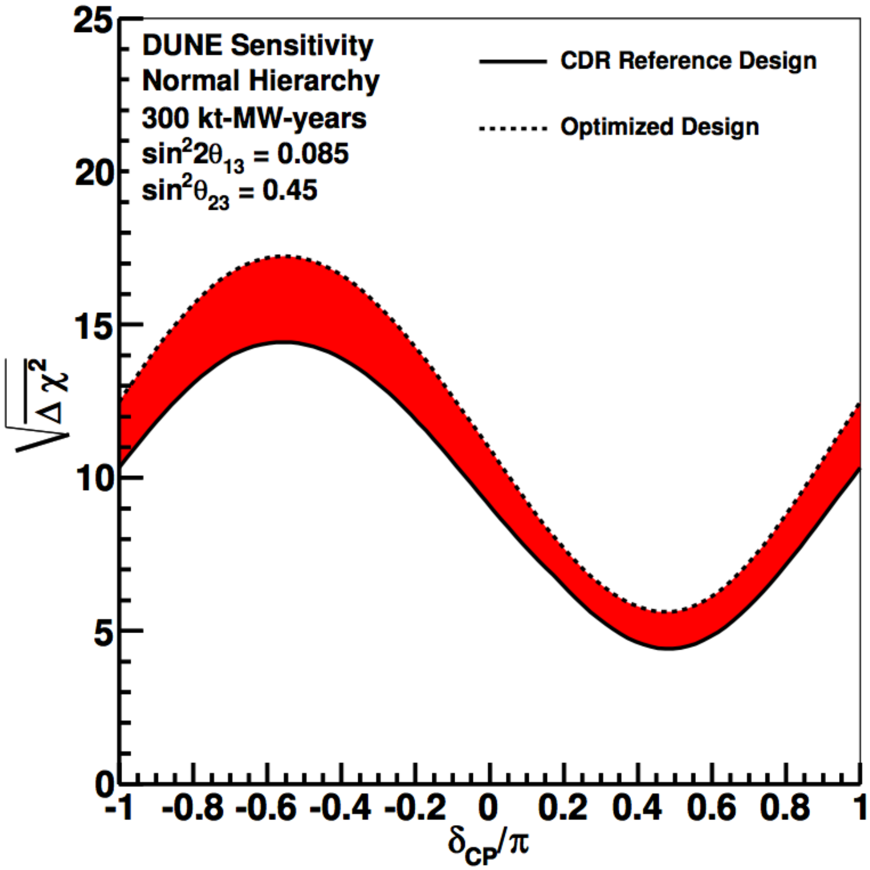
Fraction of δ values w/ this sensitivity or greater

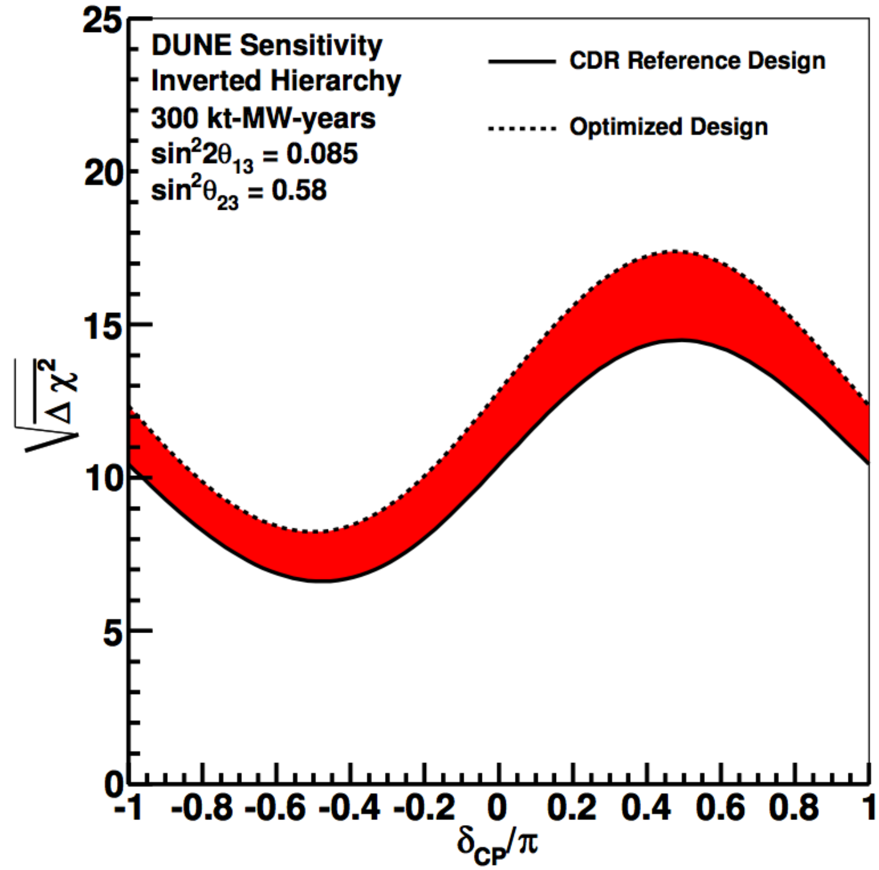
Significance with which the CP violation can be determined for **25%, 50%, 75% of δ_{CP}**

- DUNE Strengths: LArTPC technology, flexible wide-band beam, Near Detector, direction resolution for atmospheric neutrinos

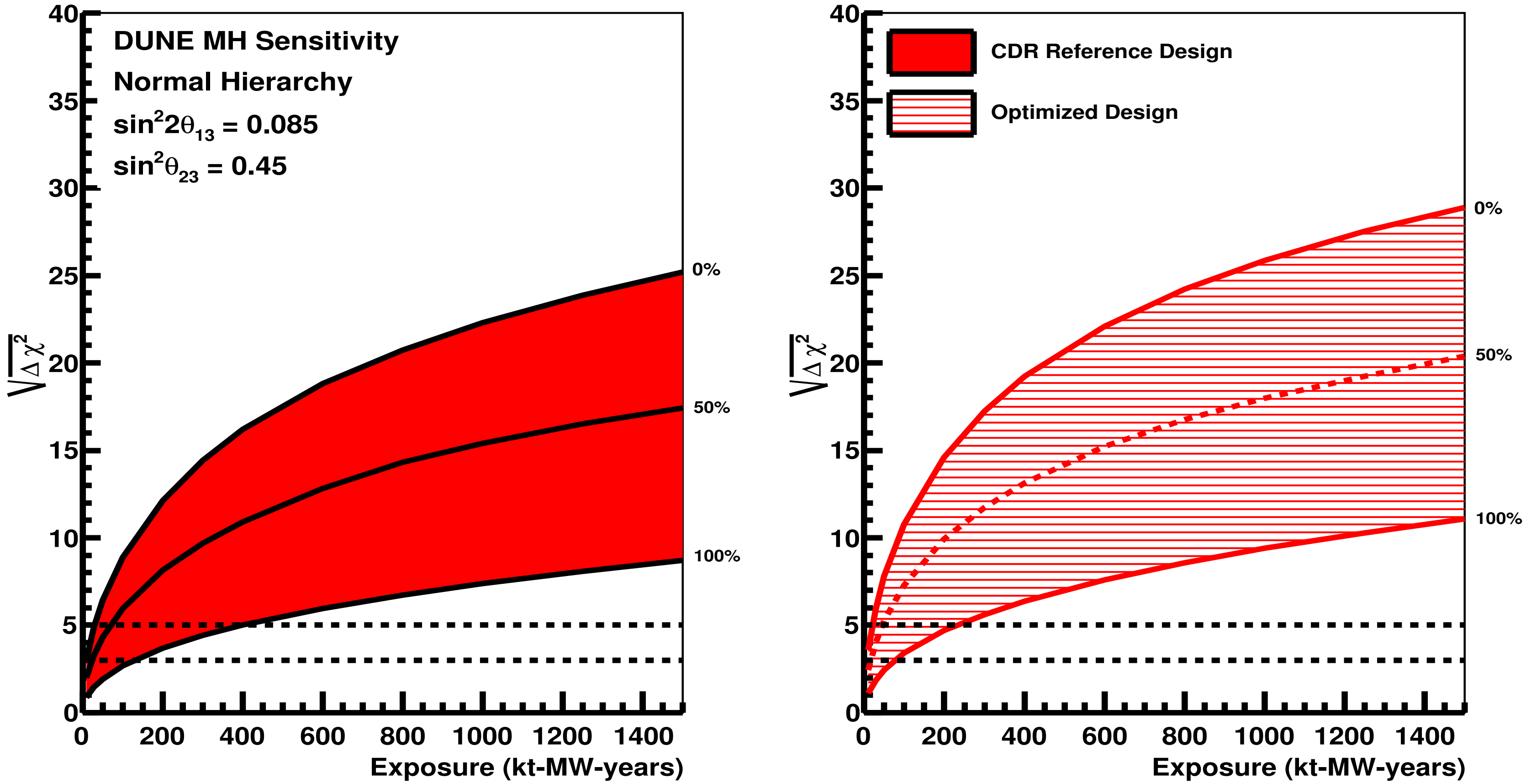
DUNE Mass Hierarchy Sensitivity

- Significance with which the mass hierarchy can be determined as a function of the value of δ_{CP} for an exposure of 300 kt · MW (3.5 + 3.5 yrs x 40kt @ 1.07 MW)





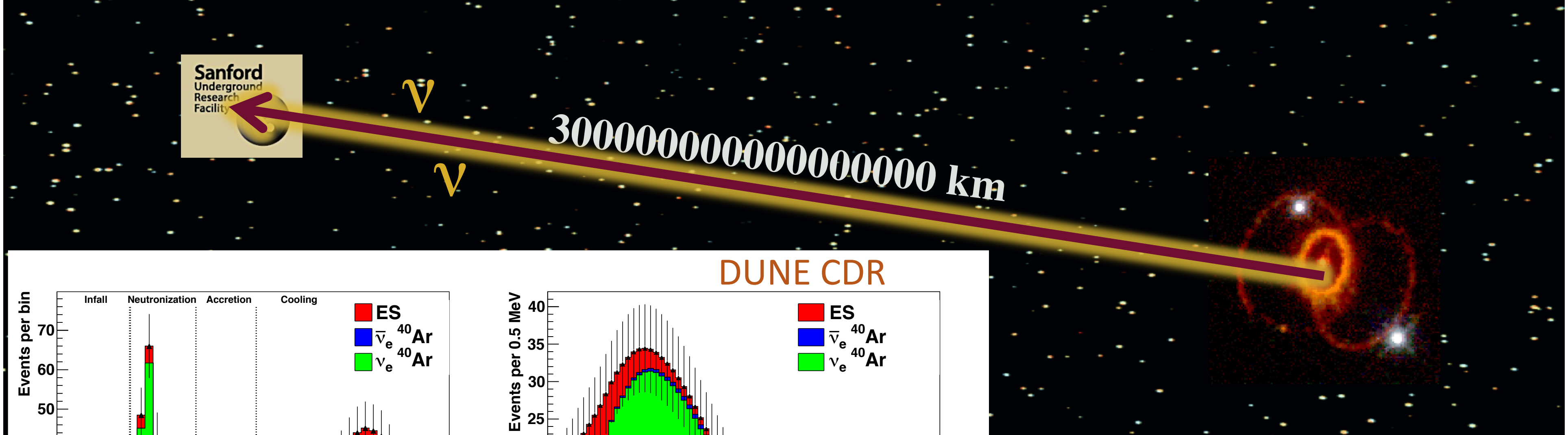
DUNE Mass Hierarchy Sensitivity (vs Exposure)



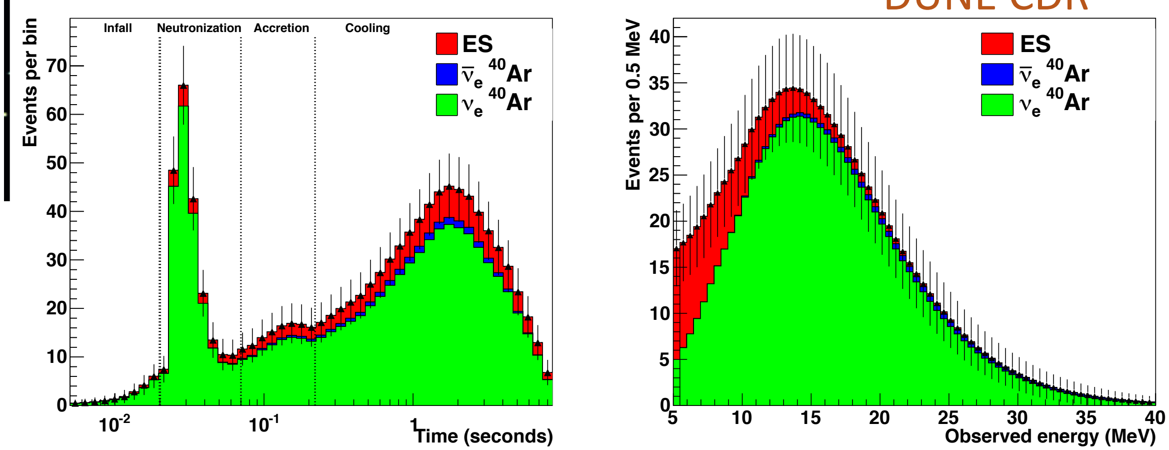
- DUNE can definitively determine the neutrino mass hierarchy
- For a favorable CP phase this could be achieved in a few years!
- Improvements in beam design can greatly improve the sensitivity thus reducing the time needed for a definitive measurement

Neutrinos from Supernovae

- About 99% of the gravitational binding energy of the proto-neutron star goes into neutrinos.
- Expect 2-3 core-collapse supernovae in the Milky Way per century ≈ 3000 neutrinos in 34kt LBNE for SN@10 kpc
- Unique sensitivity through $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$



DUNE CDR



-Note distinct features in time (left plot) and energy (right plot) spectra

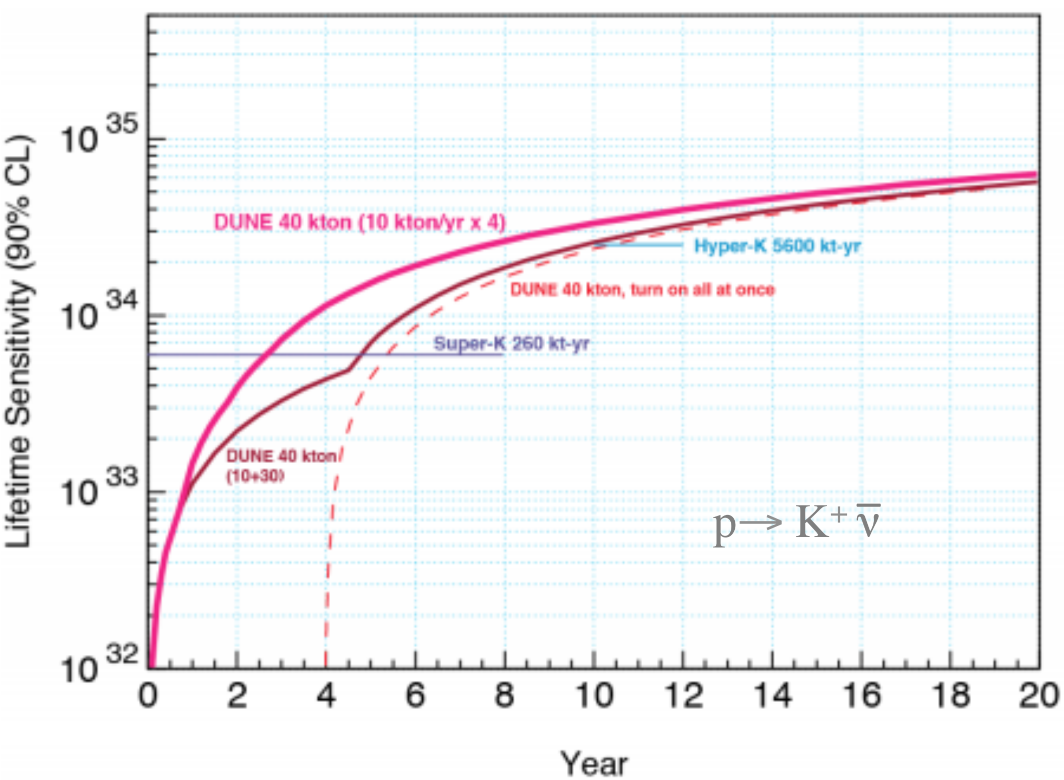
-A large theory effort is underway to understand neutrino related dynamics of the supernova. Both oscillations, mass, and self-interactions have large effects on observables e.g. mass hierarchy could have very distinct effects on the spectrum.

Nucleon Decay

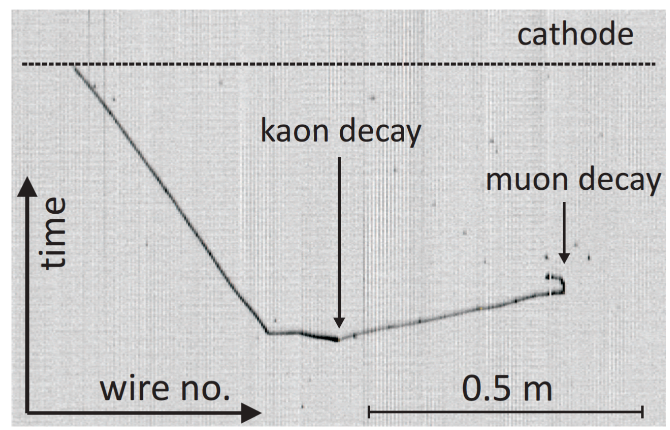
- Imaging, dE/dx, calorimetric capabilities of LArTPC enable sensitive, background-free searches
- Many modes accessible, superior detection efficiency for K production modes:

  SUSY-favored p → $K^+ \bar{\nu}$

Decay Mode	Water Cherenkov		Liquid Argon TPC	
	Efficiency	Background	Efficiency	Background
$p \to K^+\overline{\nu}$	19%	4	97%	1
$p \to K^0\mu^+$	10%	8	47%	< 2
$p \to K^+\mu^-\pi^+$			97%	1
$n \to K^+e^-$	10%	3	96%	< 2
$n \to e^+\pi^-$	19%	2	44%	0.8



Kaon observed entering ICARUS TPC in CNGS run



Technical Design & Large-scale Prototypes

Please see J. Kisiel's talk on ICARUS

- DUNE 10-kt LArTPC Modules represent O(50x) scale-up w.r.t. largest LArTPC modules to date (ICARUS), 100x scale-up w.r.t. MicroBooNE

- Operation of large-scale prototypes an important ingredient of DUNE program
  - -Need understand production as well as operational issues
  - -Provides opportunities for Test Beam data
    - ✓ Direct Link to DUNE Science Program

- **Key Steps/Milestones include operation of large-scale prototypes**
  - **-Two ProtoDUNE Detectors** (Single-Phase & Dual-Phase) operational at CERN in 2018
    - ✓ Provides key risk mitigation opportunity for Far Detector modules
  - **-DUNE Technical Design Report** to be reviewed in 2019
    - ✓ Done in context of both US DOE process and international organizations

LArTPC Development Path to LBNF/DUNE

Fermilab and CERN neutrino platforms provide a strong LArTPC development and prototyping program.

Single-Phase LArTPCs

ICARUS@LNGS

ArgoNeut
LArIAT

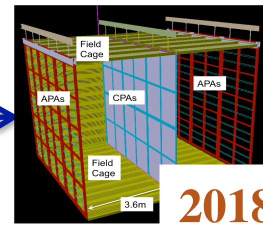
2015

DUNE 35t Prototype

Completed!

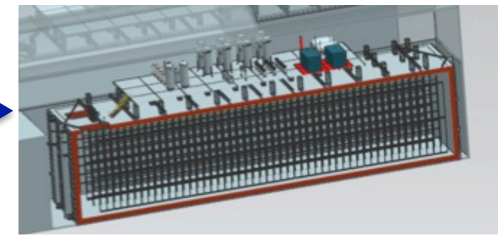
2015

protoDUNE @ CERN



2018

DUNE Reference Design

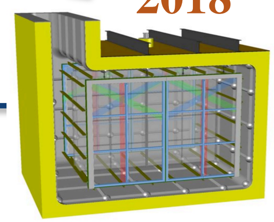


SBN

2015

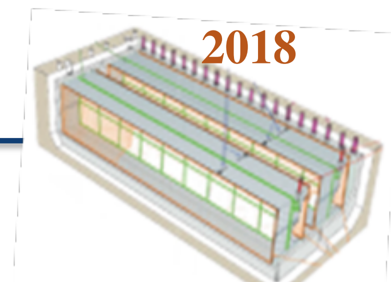
MicroBooNE

2018



SBND

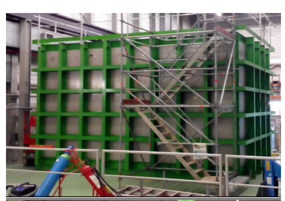
2018



ICARUS@SBN

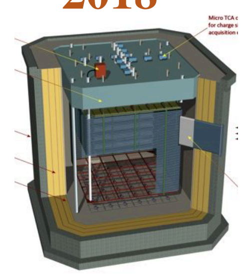
Dual-Phase LArTPCs

2016



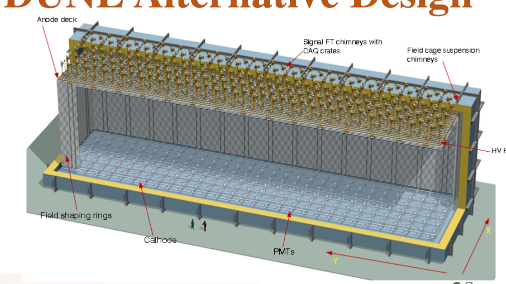
WA105: 1x1x3 m^3

2018



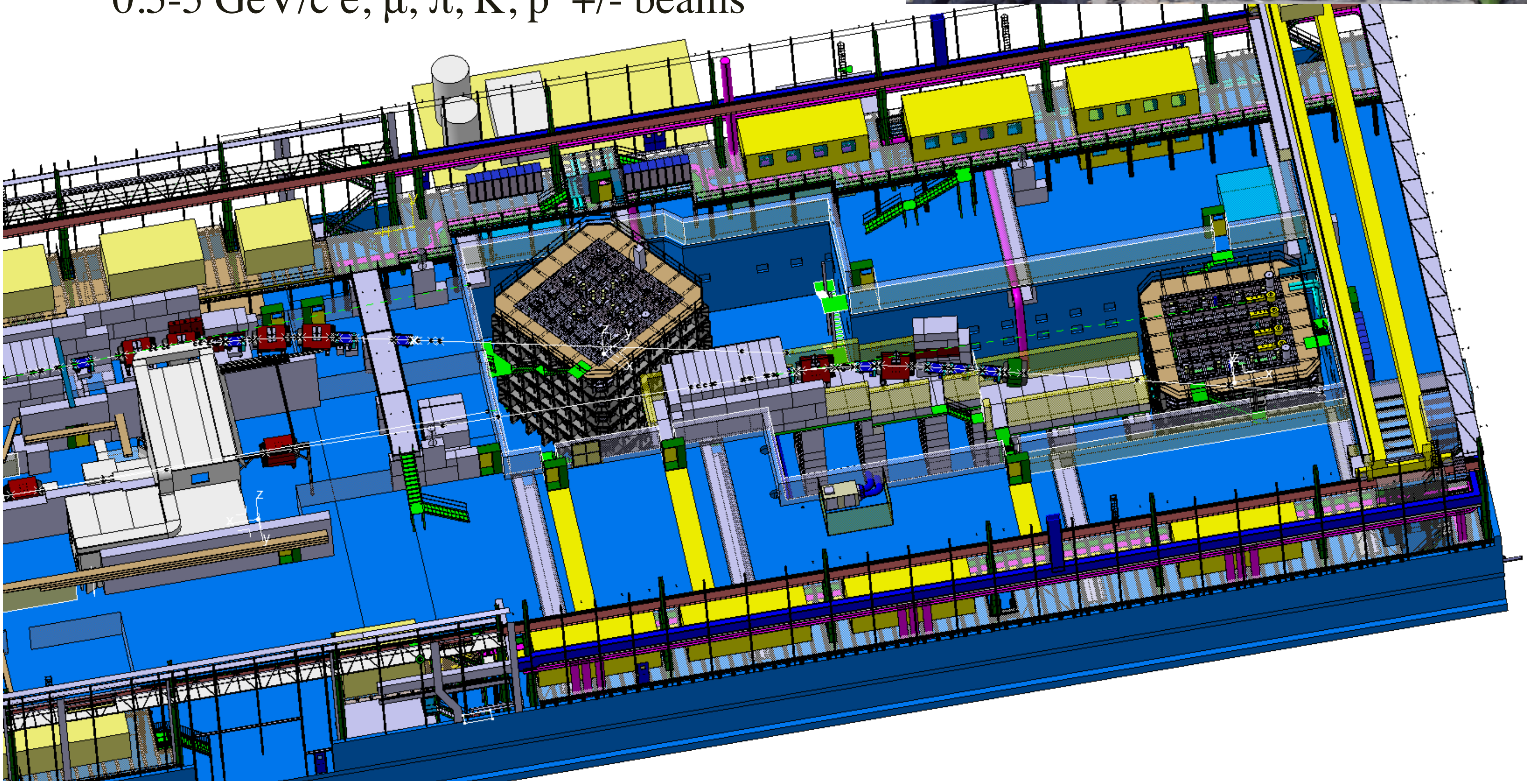
WA105

DUNE Alternative Design



ProtoDUNE Detector Status

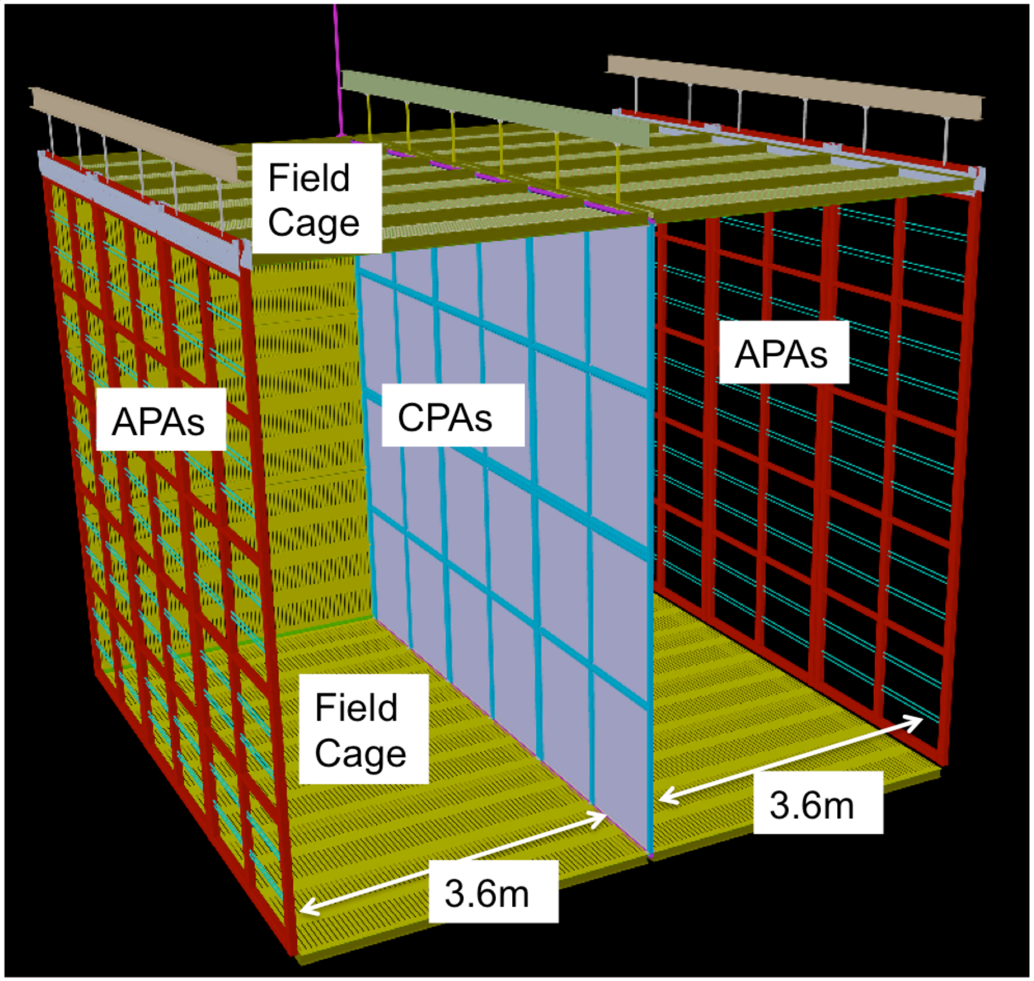
- EHN1 Extension now in construction
- Beneficial Occupancy, Sept. '16
- Cryostats complete, April '17
- Test-Beam Operations in 2018
- H2/H4 tertiary beam lines:
  0.5-5 GeV/c e, μ, π, K, p +/- beams



ProtoDUNE-SP

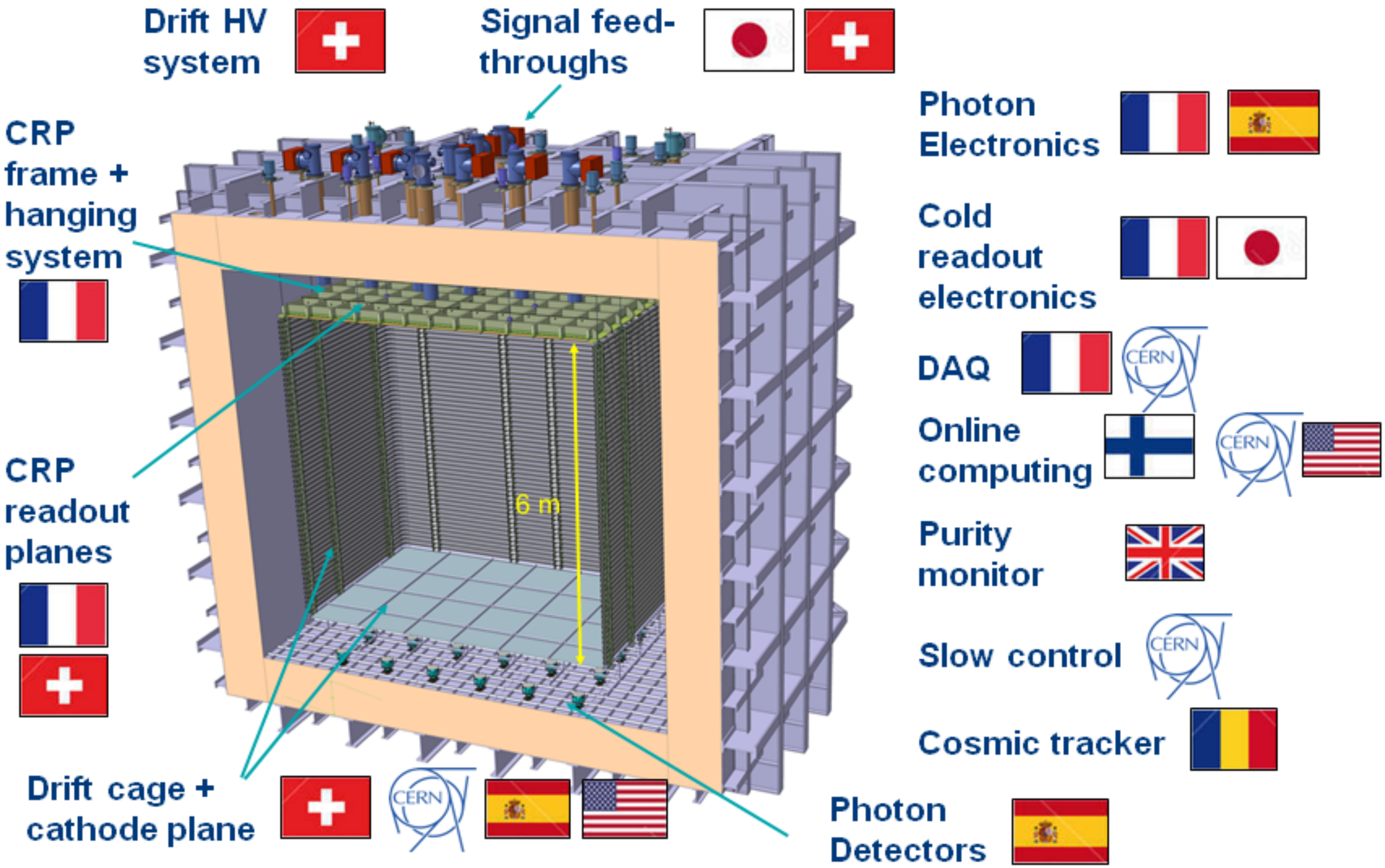
- Single-phase TPC prototype
  - Will sit in H4 beam line @ CERN
  - Will consist of 4 full-size APA's plus CPA's → 2 x 3.6m drift regions
  - Will install photon detectors of different fabrication methods
  - Plan for operation in 2018

- Will be a key test of:
  - DUNE Detector components
  - Construction methods
  - Installation procedures
  - Commissioning
  - Detector response to particles



Dual phase protoDUNE - WA105 6x6x6m^3

(US contributions under discussion)



DUNE/LBNF Timeline

- July 2015 “CD-1 Refresh” review. Conceptual design review.
- Dec. 2015 CD-3a CF Far Site. Needed to authorize far site conventional facilities work including underground excavation and outfitting.
- 2017 Ongoing shaft renovation at SURF complete.
- 2017 Start of far site conventional facilities.
- 2018 Testing of “full-scale” far detector elements at CERN.
- 2019 Technical Design review.
- 2021 Ready for start of installation of the first far detector module.
- 2024 start of physics with one detector module.

  Additional far detector modules every ~2 years.
- 2026 Beam available.
- 2026 Near detector available.
- 2028 DUNE construction finished.
- Reach an exposure of 120 kt-MW-yr by 2035.

Summary DUNE Status and Prospects

- The DUNE collaboration has formed and is managed as other international HEP collaborations (LHC model).
  -The scope of DUNE is a high power beam, high precision near detector, and four far liquid argon detectors each with over 10 kt fiducial mass.
  -The baseline will be 1,300 km and the detector will be at SURF 4850 ft.
- Capability of making major discoveries in
  -Long-baseline oscillation physics
  -Nucleon decay
  -Neutrino astrophysics
  -Other areas
- Expect to start far site construction in 2017.
- Will be testing "full-scale" detector elements at CERN in 2018.
- Start of physics in 2024 with first 10 kton detector (beam available in 2026).
- Many opportunities for early discoveries

Backup Slides

Neutrino Oscillation

- Neutrinos produced in weak decays are linear combinations of mass eigenstates

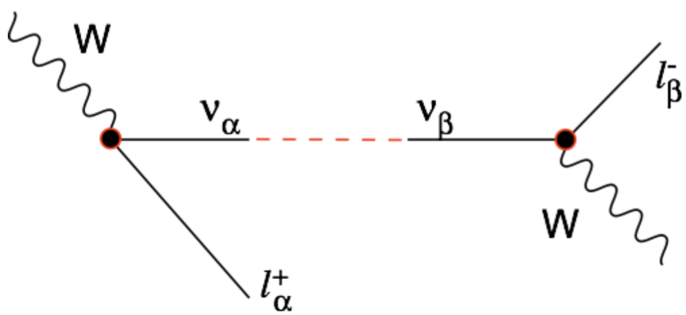
$$|\nu_\alpha> = \Sigma\, U^*_{\alpha i}\, |\nu_i>$$

Neutrino of flavor
α = e, μ, or τ

Leptonic Mixing Matrix

Neutrino of definite mass m_i

- Neutrino flavor content evolves in time with L/E i.e. "oscillates"



$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \mathrm{Re}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \mathrm{Im}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

- Neutrino oscillation described by
  - -amplitude, determined by mixing matrix U_{ij}
  - -wavelength, determined by $(mass)_{ij}^2$ differences
  - -matter effects

Neutrino Mixing

- Three neutrino mixing
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1/2} & 0 \\ 0 & 0 & e^{i\alpha_2/2} \end{pmatrix}$$

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

δ = CP-violating phase

$\Delta_{ij} = \Delta m^2_{ij} L / 4E_v$

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

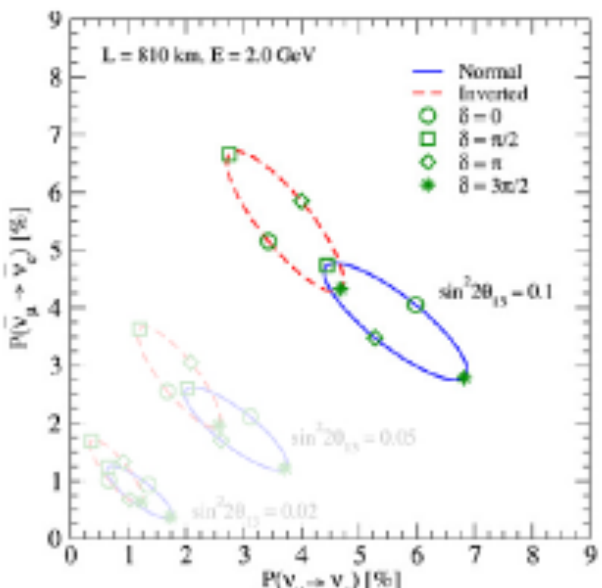
- Electron neutrino appearance example:

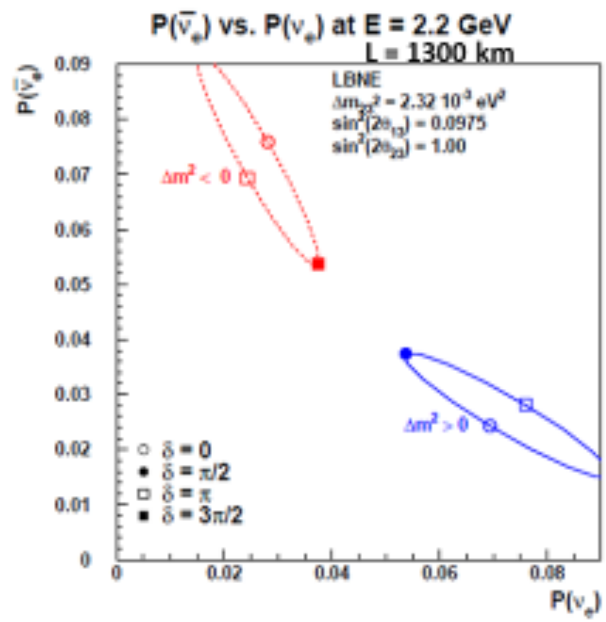
$$\begin{aligned} P(\nu_\mu \to \nu_e) \simeq\; & \sin^2\theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2 \\ & + \sin 2\theta_{23} \sin 2\theta_{13} \sin 2\theta_{12} \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \frac{\sin(aL)}{(aL)}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

-ν_e appearance amplitude depends on θ_{13}, θ_{23}, δ_{CP}, and mass hierarchy (sign Δm_{31}^2).
-Large value of $\sin^2 2\theta_{13}$ allows significant ν_e appearance sample.
-δ_{CP} and the term a switch signs in going from the $\nu_\mu \to \nu_e$ to the $\bar{\nu}_\mu \to \bar{\nu}_e$

Bi-Probability Plots

- These are older unofficial bi-probability plots
  -show interplay of $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ vs mass-hierarchy option and δ_{CP}-values.





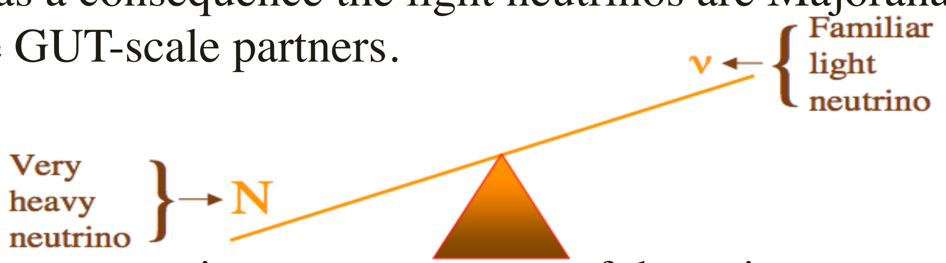
Comparison of 800 km to 1300 km

Why is CP-violation (i.e. $\delta_{CP} \neq 0$) with neutrinos so important?

-Striking feature of the Universe: only matter, virtually no anti-matter!

-Observation of CP-violation would make it more likely that the baryon-antibaryon asymmetry of the universe arose through leptogenesis.

-The theory of leptogenesis is linked to the see-saw theory and as a consequence the light neutrinos are Majorana and have GUT-scale partners.

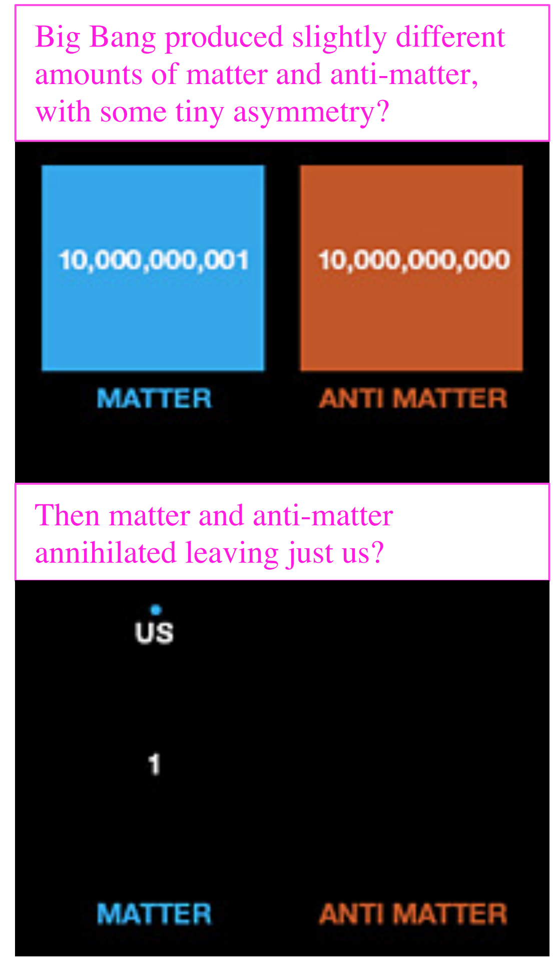


-The matter-antimatter asymmetry of the universe may be explained through CP-violating decays of the heavy partners, producing a state with unequal numbers of Standard Model leptons and antileptons.

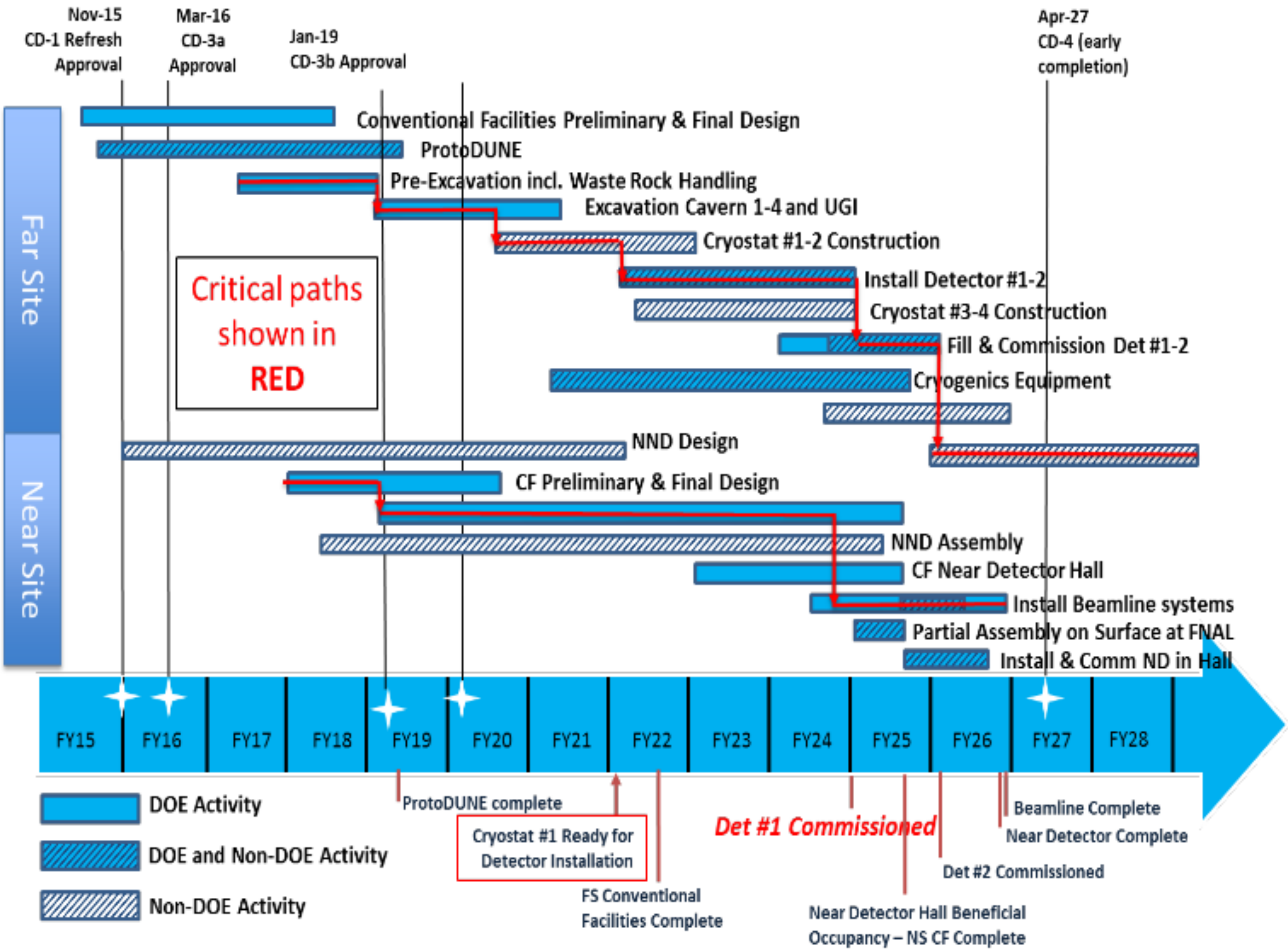
$N \rightarrow L^- + \varphi^+$ and $N \rightarrow L^+ + \varphi^-$ (φ^+, φ^- - Standard-Model Higgs)

-The Standard Model processes convert such a state into the world around us with an unequal number of baryons and antibaryons.

-It is thought that CP-violation would be very unlikely to appear in the heavy sector without happening in light neutrinos.



Timeline



Nov-15
CD-1 Refresh
Approval
Mar-16
CD-3a
Approval
Jan-19
CD-3b Approval
Apr-27
CD-4 (early
completion)
Far Site
Near Site
Conventional Facilities Preliminary & Final Design
ProtoDUNE
Pre-Excavation incl. Waste Rock Handling
Excavation Cavern 1-4 and UGI
Cryostat #1-2 Construction
Install Detector #1-2
Cryostat #3-4 Construction
Fill & Commission Det #1-2
Cryogenics Equipment
Critical paths
shown in
RED
NND Design
CF Preliminary & Final Design
NND Assembly
CF Near Detector Hall
Install Beamline systems
Partial Assembly on Surface at FNAL
Install & Comm ND in Hall
FY15
FY16
FY17
FY18
FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
DOE Activity
DOE and Non-DOE Activity
Non-DOE Activity
ProtoDUNE complete
Cryostat #1 Ready for
Detector Installation
FS Conventional
Facilities Complete
Det #1 Commissioned
Near Detector Hall Beneficial
Occupancy – NS CF Complete
Det #2 Commissioned
Beamline Complete
Near Detector Complete

DUNE Oscillation Physics Milestones

- Rapidly reach scientifically interesting sensitivities:

  e.g. in best-case scenario for CPV ($\delta_{CP} = +\pi/2$) :

  with 60 – 70 kt.MW.year reach 3σ CPV sensitivity

  e.g. in best-case scenario for MH :

  with 20 – 30 kt.MW.year reach 5σ MH sensitivity

Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42°$)	70	45
CPV at 3σ ($\delta_{CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{CP} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{CP} = 0$)	450	290
CPV at 5σ ($\delta_{CP} = -\pi/2$)	525	320
CPV at 5σ 50% of δ_{CP}	810	550
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	1200	850
CPV at 3σ 75% of δ_{CP}	1320	850

P5 Goal

- There is genuine potential for early physics results

DUNE 35-ton Single-Phase Prototype

- Phase-II of program w/ membrane cryostat
  - ✓ First phase established Ar purity capability
  - ✓ 2nd phase – install, operate LBNE style TPC
  - ✓ operations Feb-Mar 2016
  - ✓ Purity → Success!
  - ✓ TPC / Scint Det. Ops → Success!

    -Incl. operation @ 250 V/cm

  - ➢ Not everything worked well:

    -Noise environment not good

    -Early end due to mechanical failure leading to LAr contamination