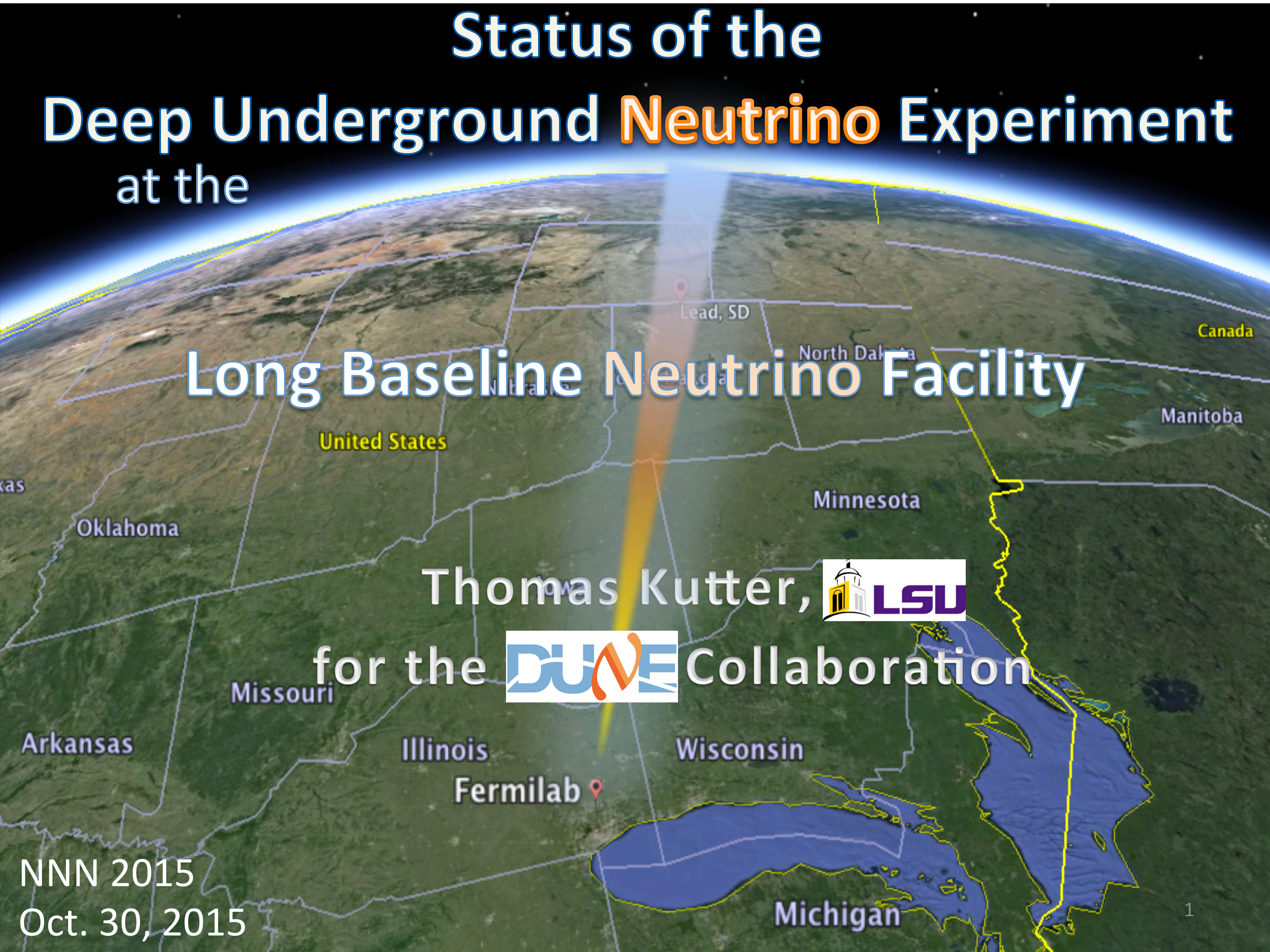
Status of the
Deep Underground Neutrino Experiment
at the
Long Baseline Neutrino Facility



Thomas Kutter, LSU
for the DUNE Collaboration

NNN 2015
Oct. 30, 2015

Outline

- Introduction
- Scientific Program
- DUNE Strategy
- Overview of LBNF and DUNE Experiment
- Physics Sensitivities
- Timeline + Summary

Neutrino mixing

Neutrinos change flavor while propagating in vacuum/matter

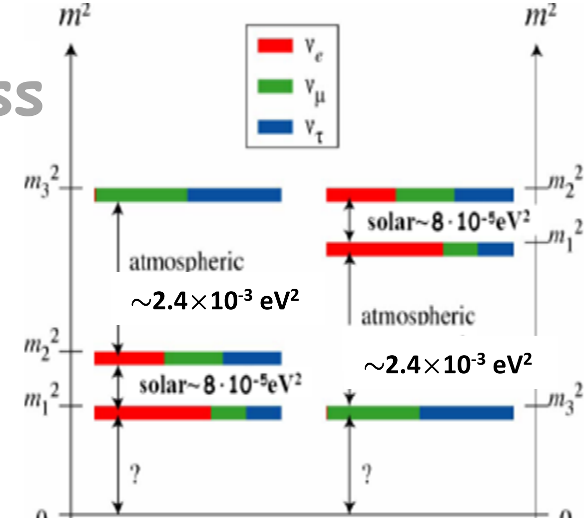
➔ Neutrinos have mass = evidence for physics beyond the standard model

PMNS (Pontecorvo, Maki, Nakagawa, Sakata) – matrix describes mixing between flavor and mass eigenstates in analogy to CKM (Cabibbo,Kobayashi, Maskawa) –matrix for quarks

Flavor $\qquad s_{ij} = \sin\theta_{ij}\,;\quad c_{ij} = \cos\theta_{ij}$ $\qquad$ **Mass**

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

atmospheric & accelerator | reactor & accelerator | solar & reactor



normal $\qquad$ inverted

hierarchy

Mixing	Neutrinos	Quarks
θ_{12}	$(33.5 \pm 1)^o$	$(13.04 \pm 0.05)^o$
θ_{23}	$(45 \pm 3)^o$	$(2.38 \pm 0.06)^o$
θ_{13}	$(8.5 \pm 0.3)^o$	$(0.201 \pm 0.011)^o$
Δm^2_{21}	$(7.53 \pm 0.18)\times 10^{-5}$ eV^2	
$\lvert\Delta M^2\rvert$	$(2.44 \pm 0.06)\times 10^{-3}$ eV^2	
δ_{CP}	$(-90^{+115}_{-122})^o$	$(67\pm 5)^o$

DUNE Primary Physics Program

1) Neutrino Oscillation Physics

- Search for neutrino CP properties :

  What is the value of the phase δ ?

- Measure neutrino mass hierarchy
- Perform precision measurements of neutrino (mixing) parameters :

  Test the 3 flavor paradigm

  Measure symmetry between 2nd and 3rd generation :

  how close is θ_{23} to $\pi/4$?

  Measure neutrino cross sections

2) Nucleon Decay

Target SUSY-favored mode: $p \rightarrow K^{+}\overline{\nu}$

3) Supernova burst and astro-physics

Galactic core collapse supernova, best sensitivity to ν_e

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Target SUSY-favored mode: $p \rightarrow K^{+}\overline{\nu}$

High precision measurements to look for the unexpected

3) Supernova burst and astro-physics

Galactic core collapse supernova, best sensitivity to ν_e

Measurement Strategy

Use high intensity ν_μ (and $\overline{\nu}_\mu$) beam

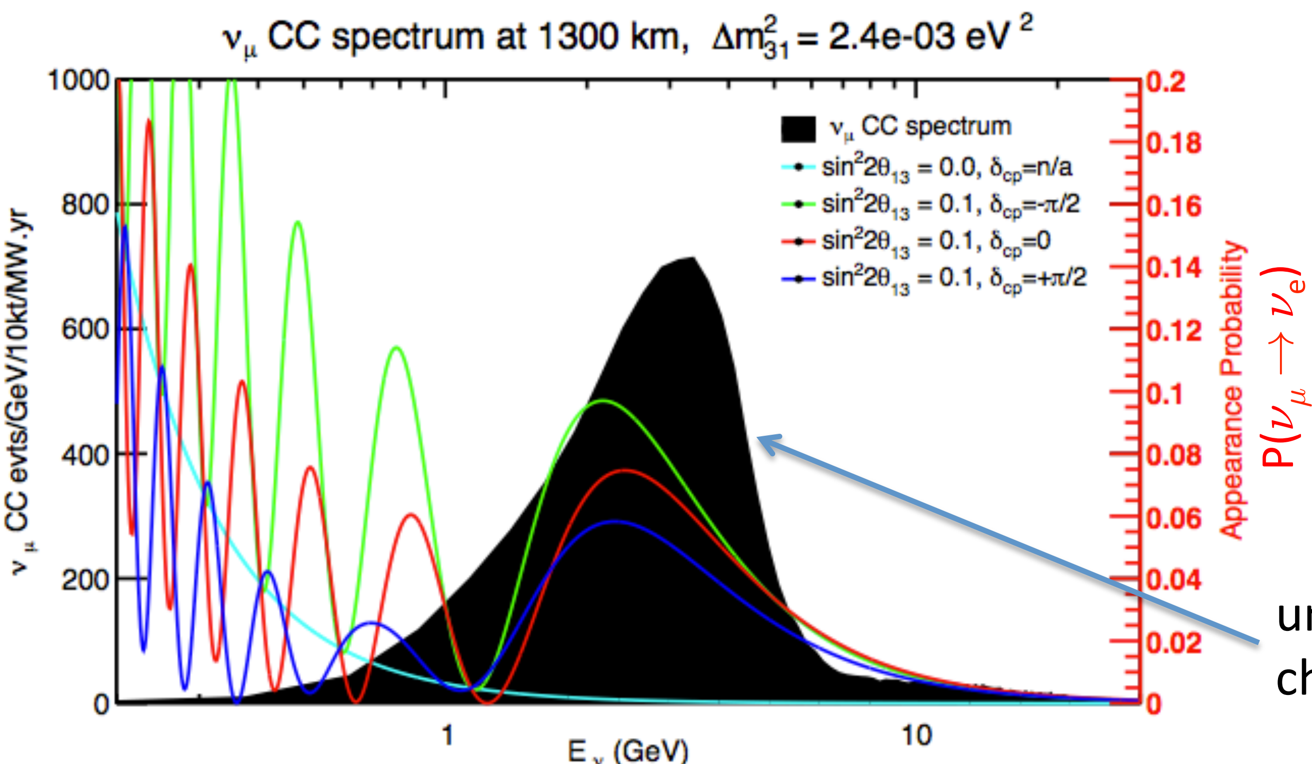
→ measure $\overset{(-)}{\nu}_e$ appearance and $\overset{(-)}{\nu}_\mu$ disappearance

Choose long baseline

→ large matter effects ~40% (at L=1300 km)

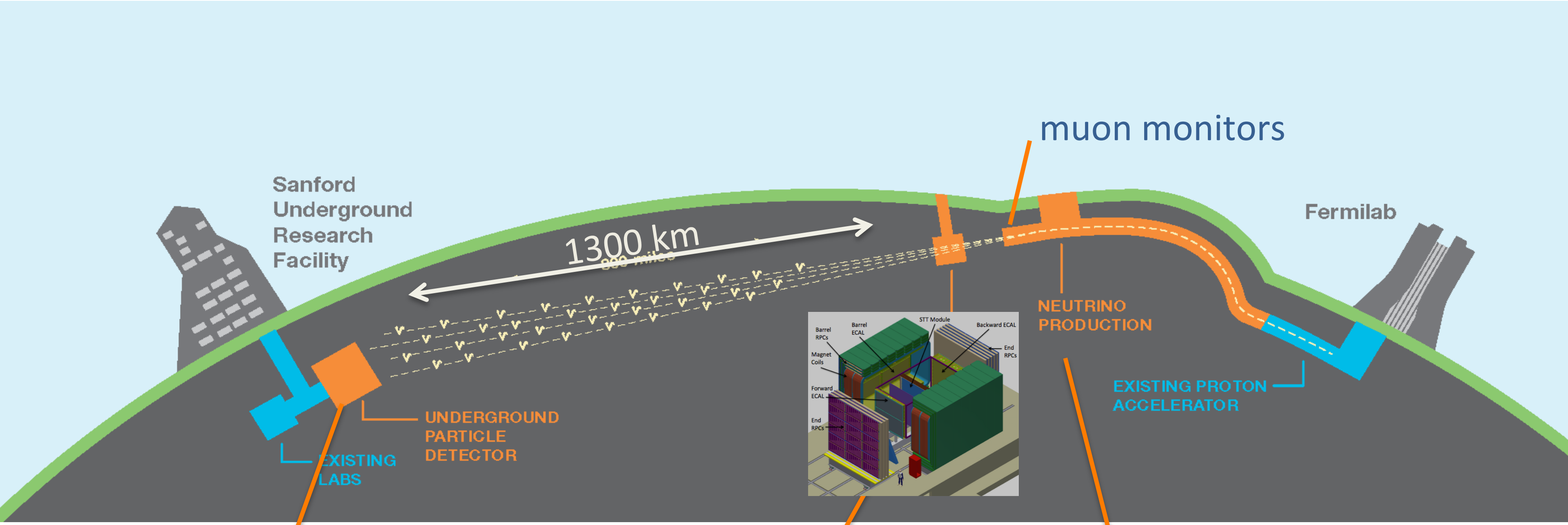
Match E_ν to oscillation maxima over broad energy range

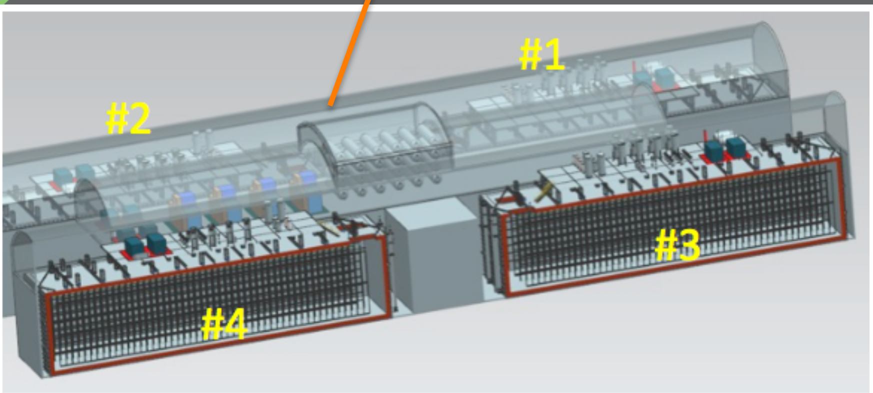
→ disentangle CP and mass hierarchy



Suitable large detector: good E_ν reconstruction and particle identification

DUNE Overview



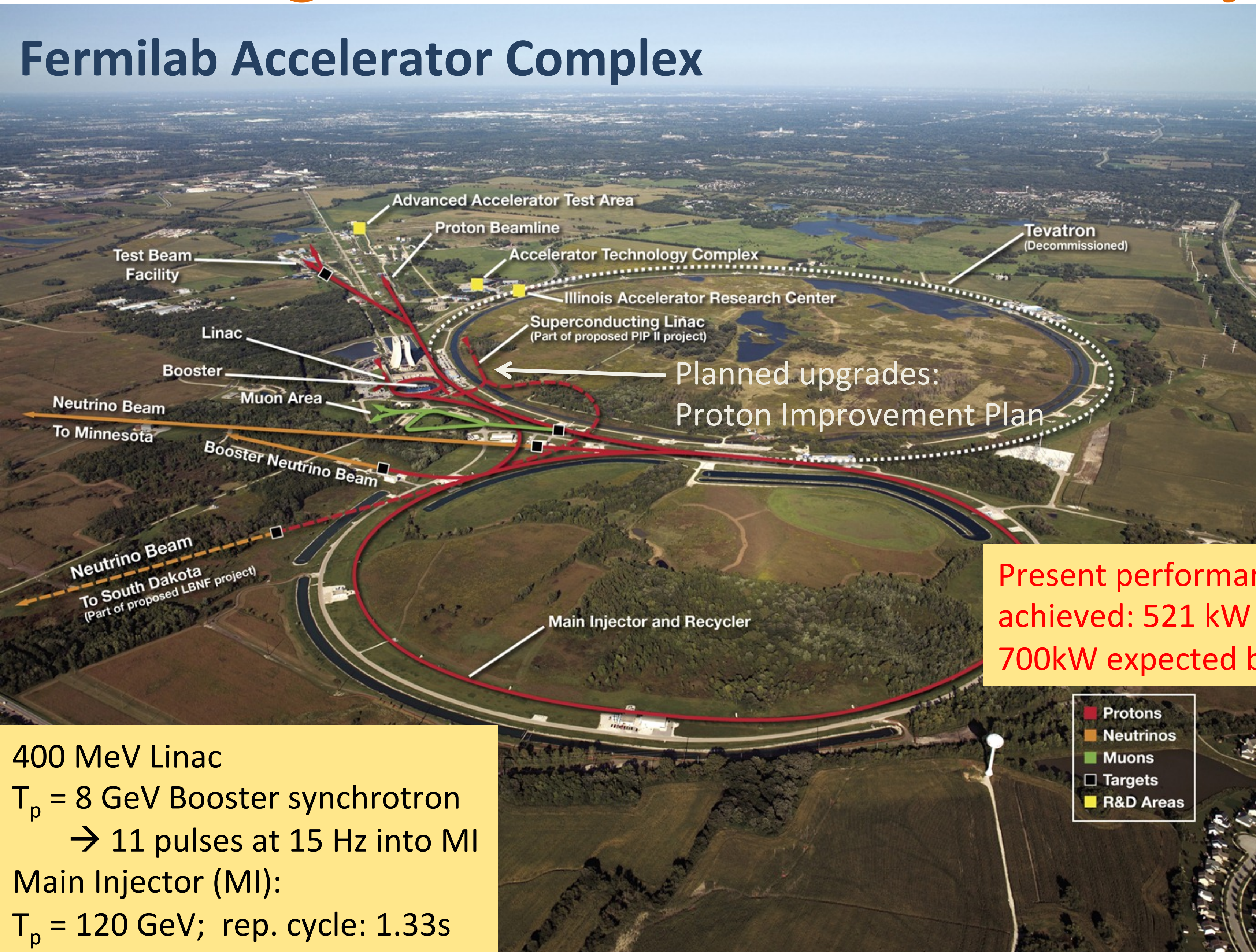


high precision near detector at 574m

Wide band, high purity ν_μ beam with peak flux at 2.5 GeV operating at $\sim$1.2 MW and upgradeable

- four identical cryostats deep underground
- staged approach to four independent 10 kt LAr detector modules
- Single-phase and dual-phase readout under consideration

Long Baseline Neutrino Facility



Present performance:
achieved: 521 kW
700kW expected by 2/2016

400 MeV Linac

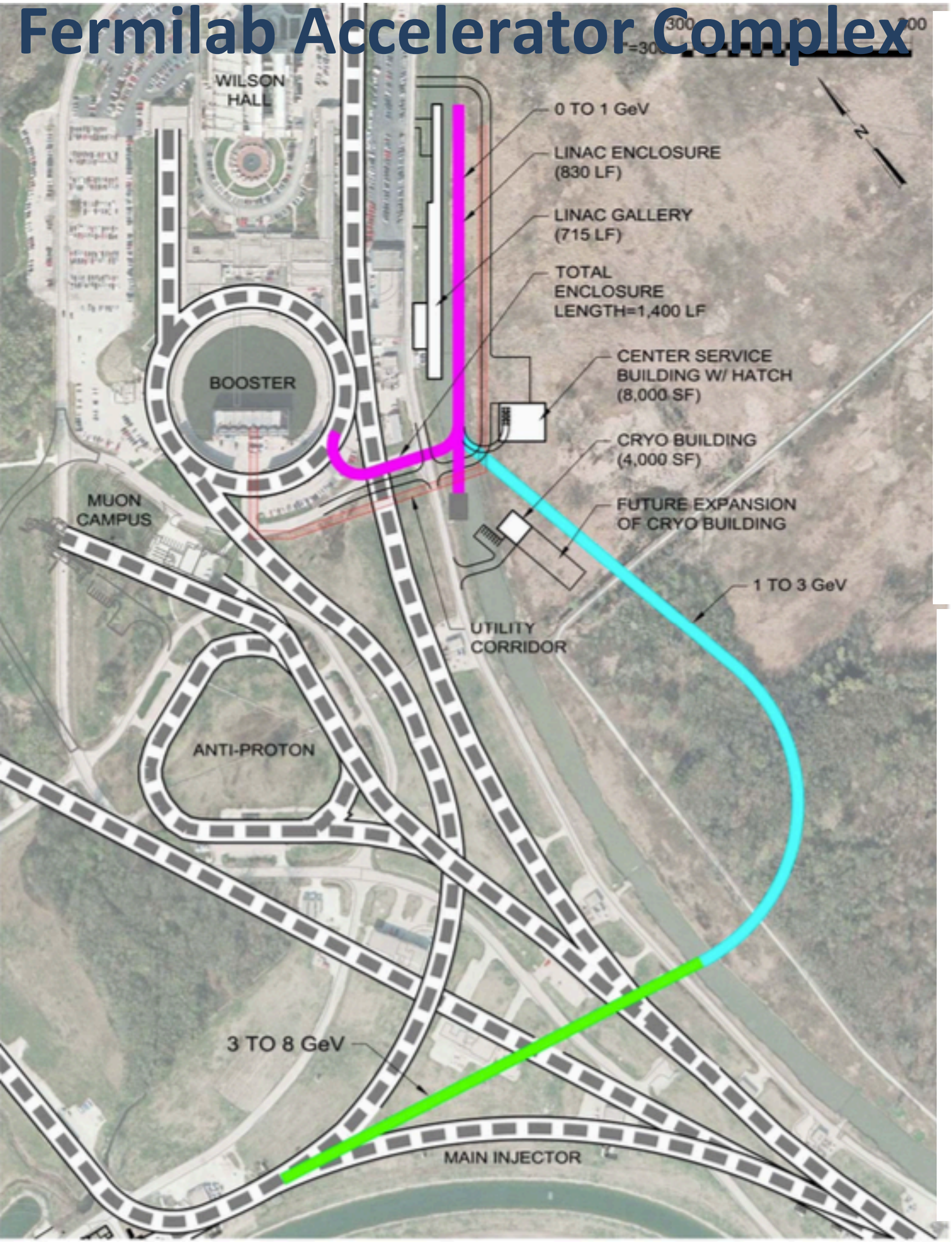
T_p = 8 GeV Booster synchrotron

→ 11 pulses at 15 Hz into MI

Main Injector (MI):

T_p = 120 GeV; rep. cycle: 1.33s

Proton Improvement Plan II and III



Upgrades to increase proton yield

PIP II : (ready by ~2025)

MI beam power → **1.2 MW**

- upgrade to superconducting (SC) 800 MeV linac
- Booster rep. rate: 15 → 20 Hz
- MI rep. cycle: 1.33 →1.2 s

PIP III : (> 2025)

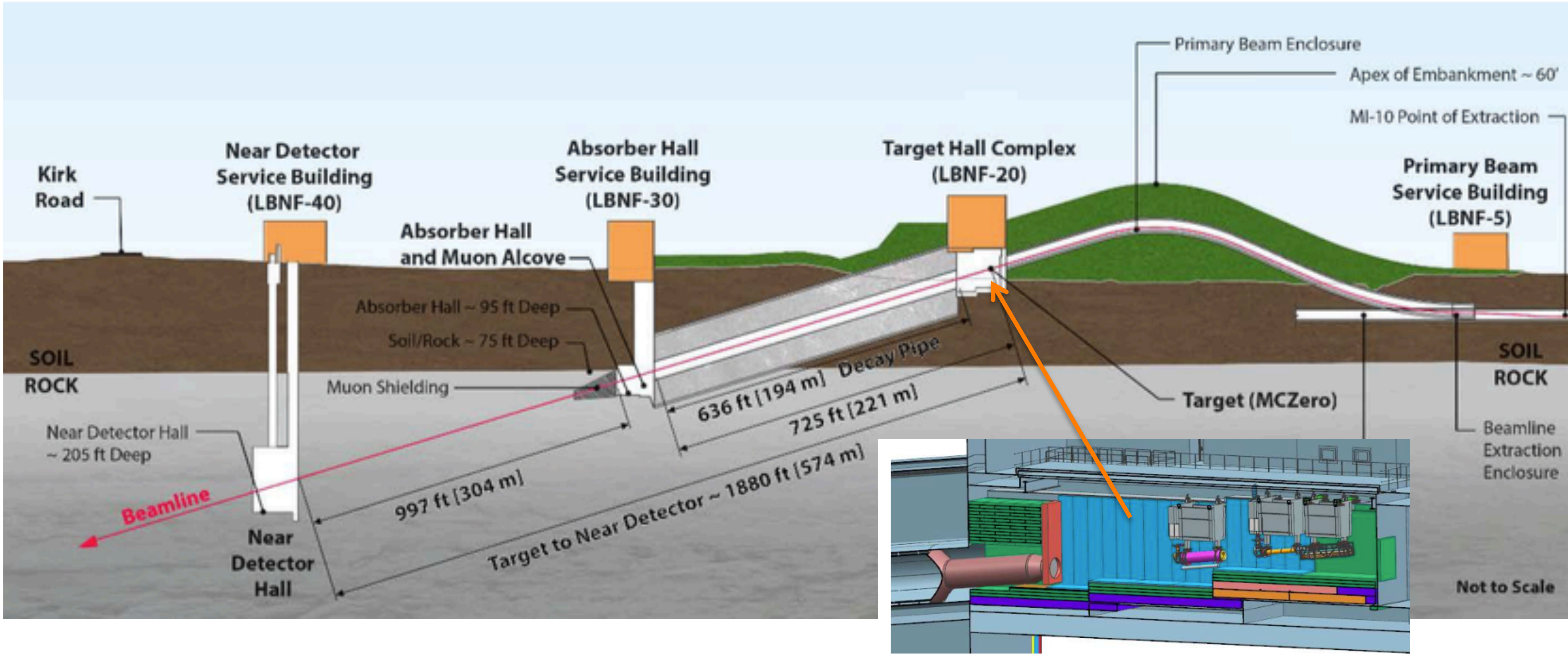
MI beam power → **2.3 MW**

- Upgrade to 8 GeV SC linac

OR

- Upgrade to 2 GeV SC linac and
- Replace booster with 8 GeV rapid cycling synchrotron (RCS)

LBNF Beamline



Extract 60 – 120 GeV primary proton beam onto 95cm graphite target

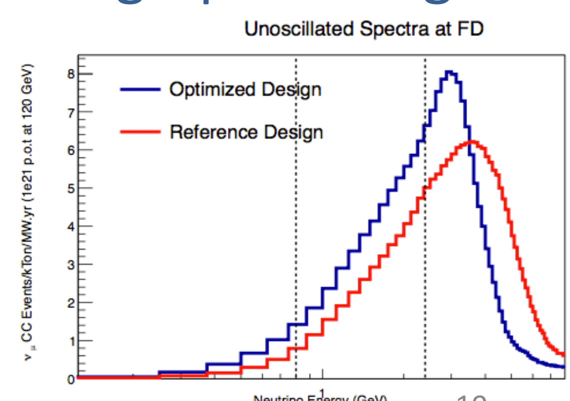
→ (1.1 – 1.9) $\times 10^{21}$ protons on target/yr

Focusing horns

1) NuMI like horn (reference design) NNN15: L. Fields

2) optimized focusing design (genetic algorithm)

Decay pipe: 4m diameter ~200m long; He filled



DUNE Near Detector

Measure :

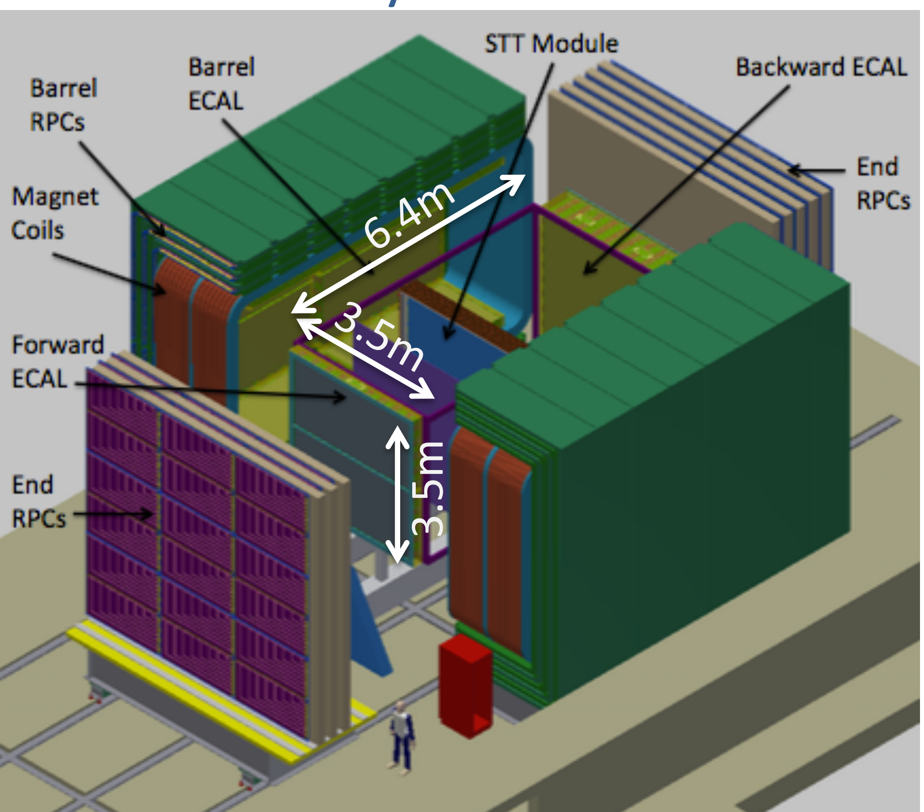
- CC ν_μ events (normalization, spectrum)
- CC ν_e , NC π^0 events (backgrounds)
- Neutrino interaction properties

$\sim 10^7$ interactions/yr → high precision

Reference design:

Fine Grained Tracker inside 0.4 T magnetic field : straw-tube tracker

Surrounded by lead-scintillator ECal and RPC muon tracker



Multiple nuclear targets:

Ar, C, Ca, Fe, ...

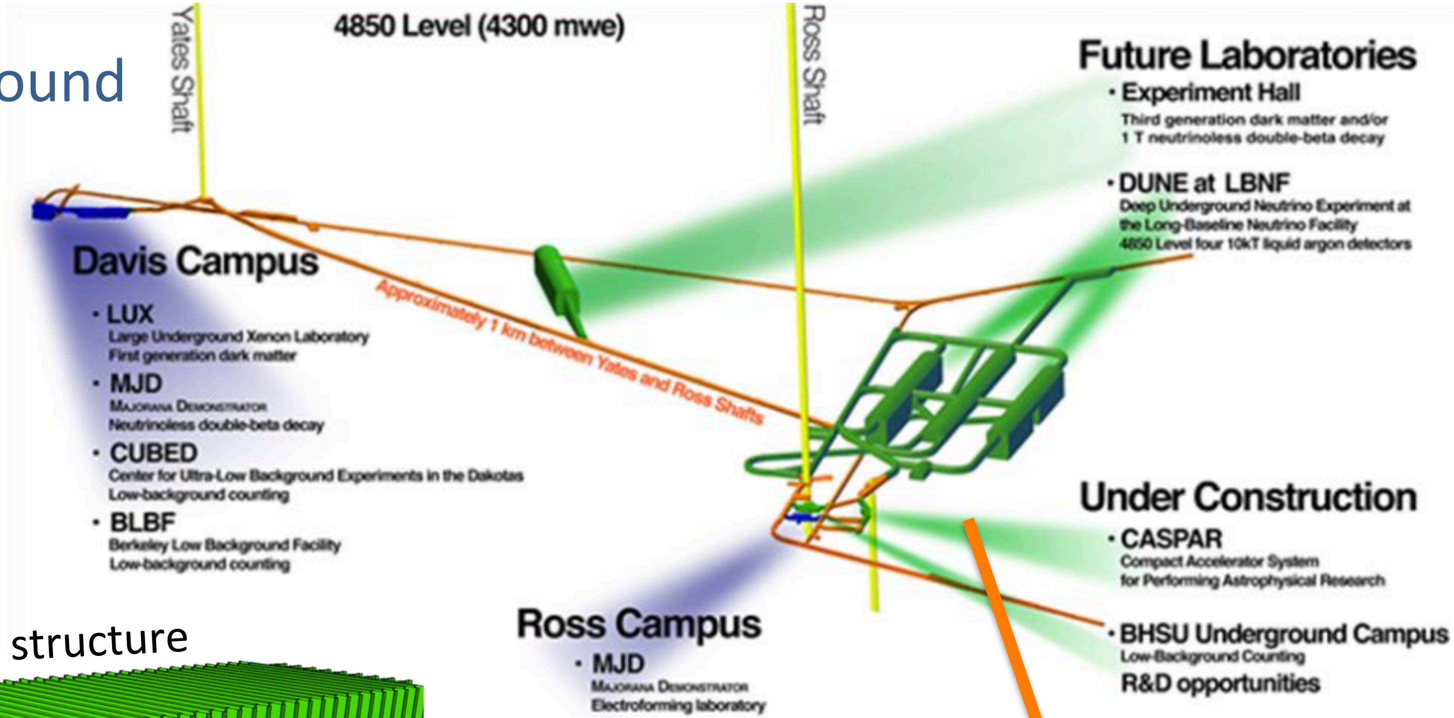
Other designs under consideration:

- Magnetized LAr TPC
- High-pressure GAr TPC

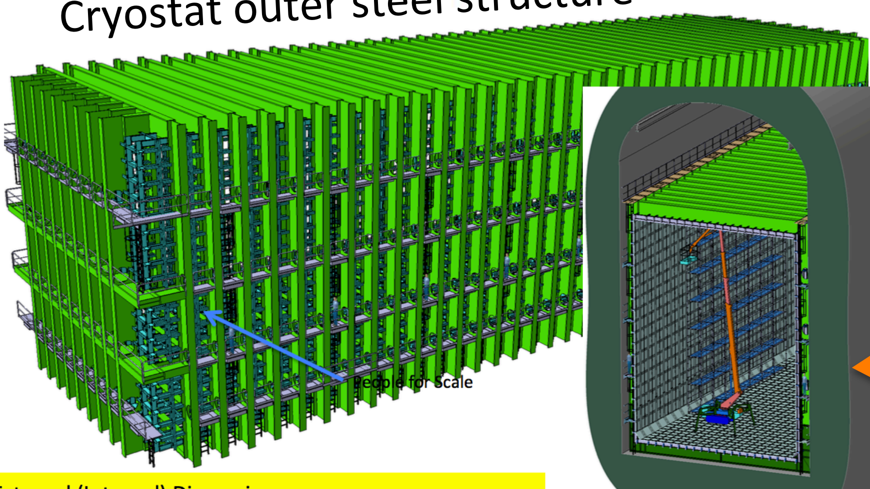
DUNE Far Detector at SURF

Location:

Sanford Underground Research Facility

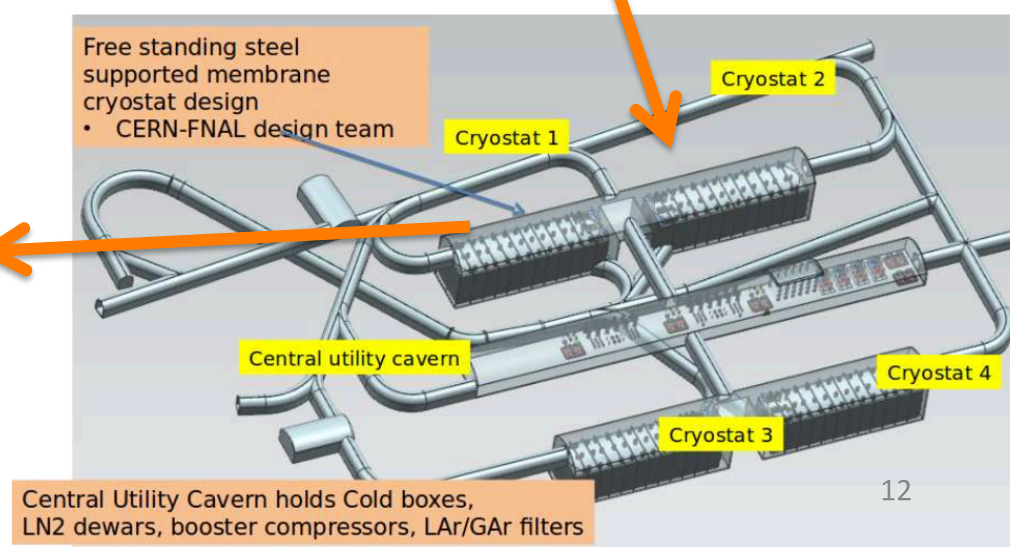


Cryostat outer steel structure



External (Internal) Dimensions
19.1m (16.9m) W x 18.0m (15.8m) H x 66.0m (63.8m) L

Can accommodate single and dual-phase LAr detectors

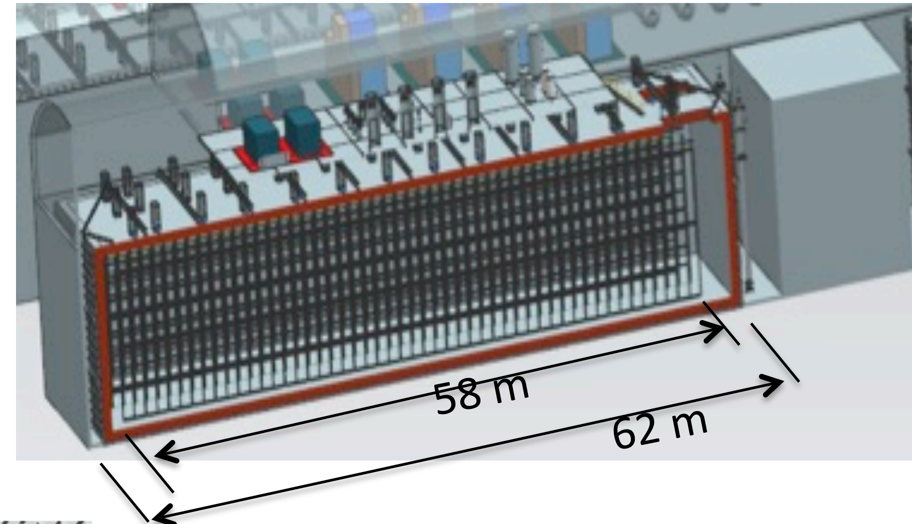


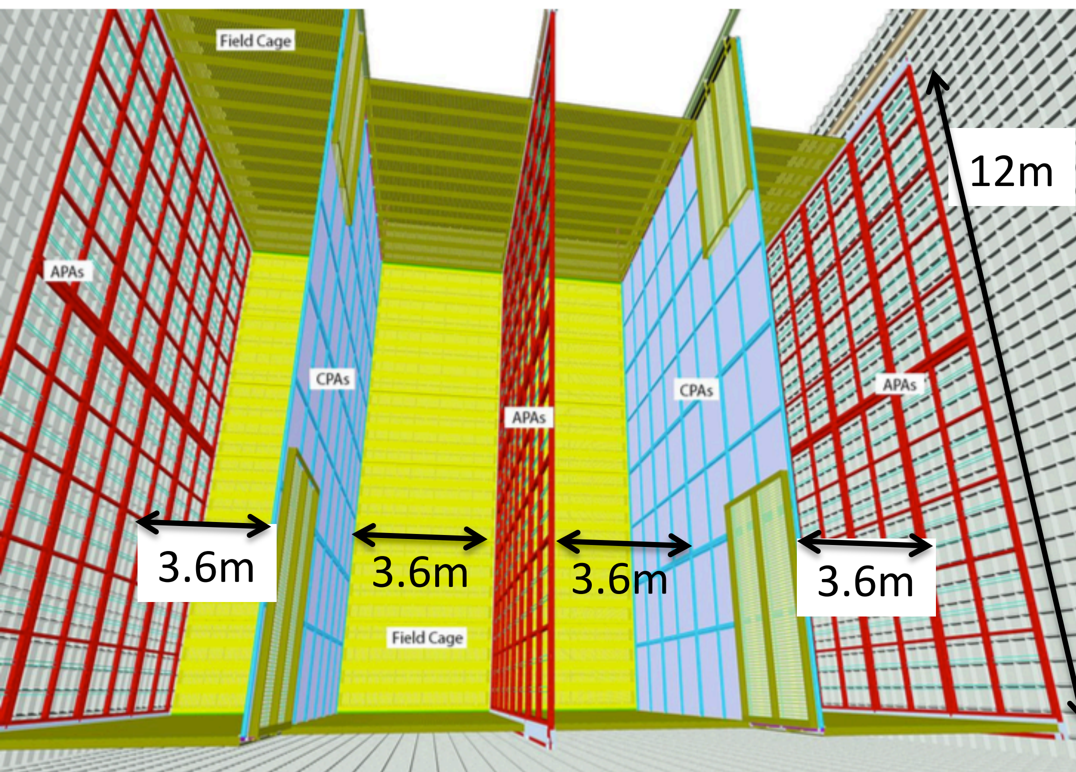
Single-Phase LAr Detector

Readout of

- Ionization charge and
- scintillation light

Detector mass [kt]	
total	17.1
active	13.8
fiducial	11.6





Time Projection Chamber:

3 wire Anode Planes (APAs)

[induction + collection wires]

2 cathode planes at -180 kV

4 drift regions: 3.6m drift each

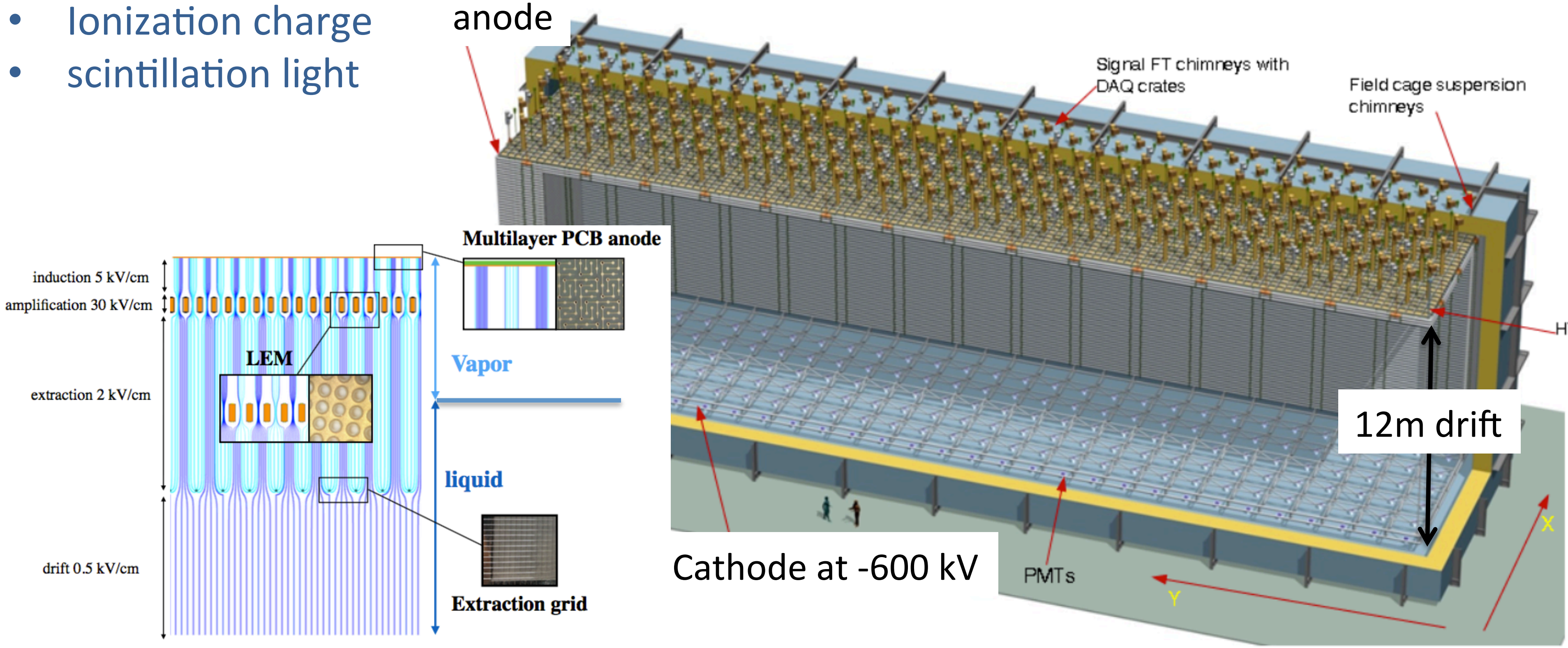
Photon Detection System

integrated in APAS to measure non-beam event timing

Dual-Phase LAr Detector

Readout of

- Ionization charge
- scintillation light

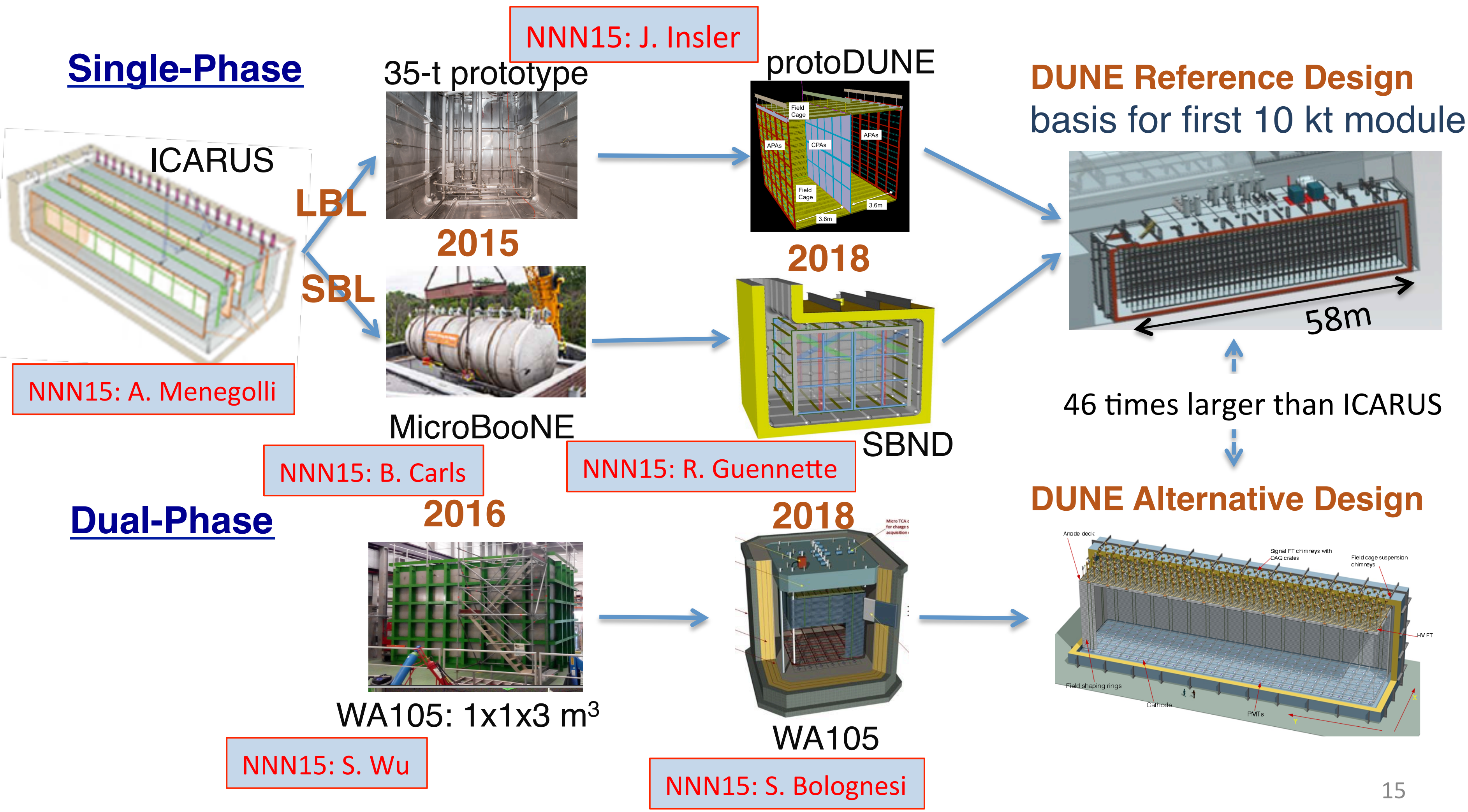


Ionization charge extracted into Ar gas phase
charge amplification via large electron multipliers (LEM) before readout
[2 dimensional charge collection]

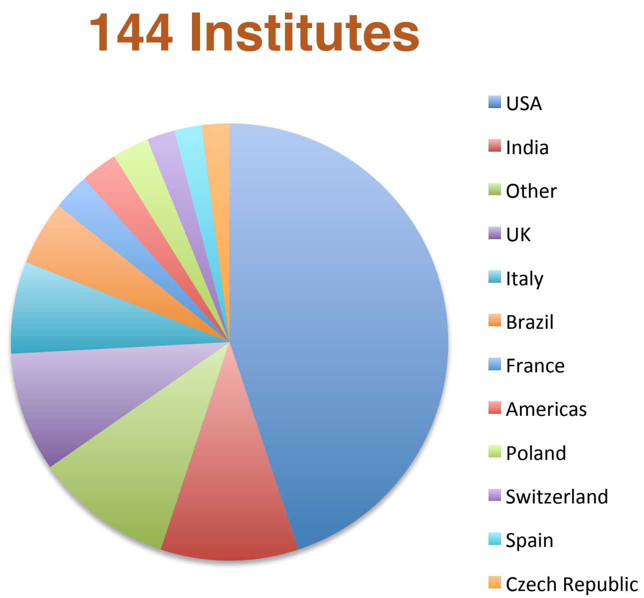
→ If demonstrated, could be used as alternative design for 2nd or subsequent 10 kt far detector modules

LArTPC Development Path

Fermilab SBN and CERN neutrino platform provide a strong LArTPC development and prototyping program



DUNE Collaboration

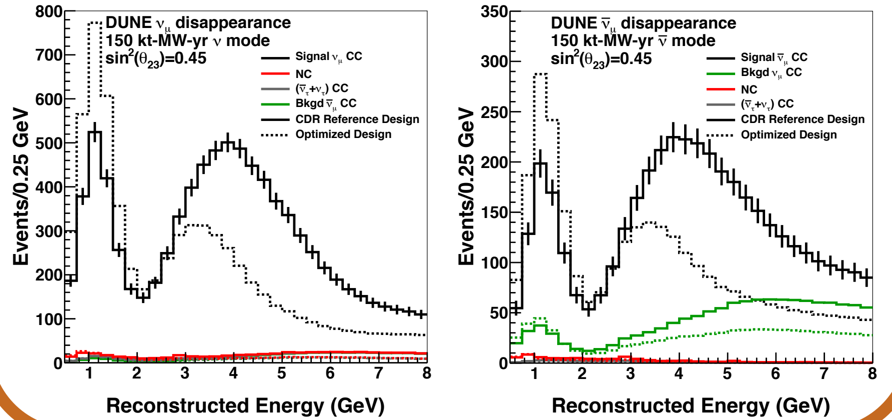


Neutrino Oscillation Prospects

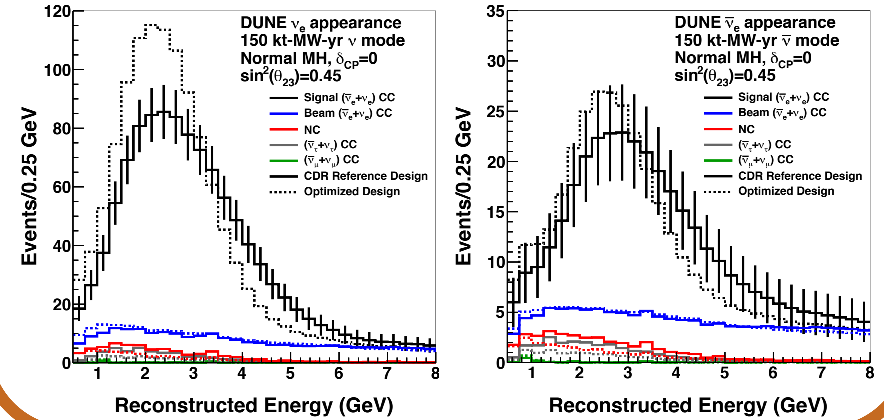
Exposure: 150 kt MW yr

Assumes: $\sin^2 2\theta_{13} = 0.084$, $\sin^2\theta_{23} = 0.45$, $\Delta m^2_{31} = 2.47\times10^{-3}$, $\delta_{CP} = 0$

ν_μ / $\overline{\nu}_\mu$ disappearance



ν_e / $\overline{\nu}_e$ appearance



→ Simultaneous fit to all 4 samples to determine oscillation parameters

Integrated events 0.5 – 20 GeV

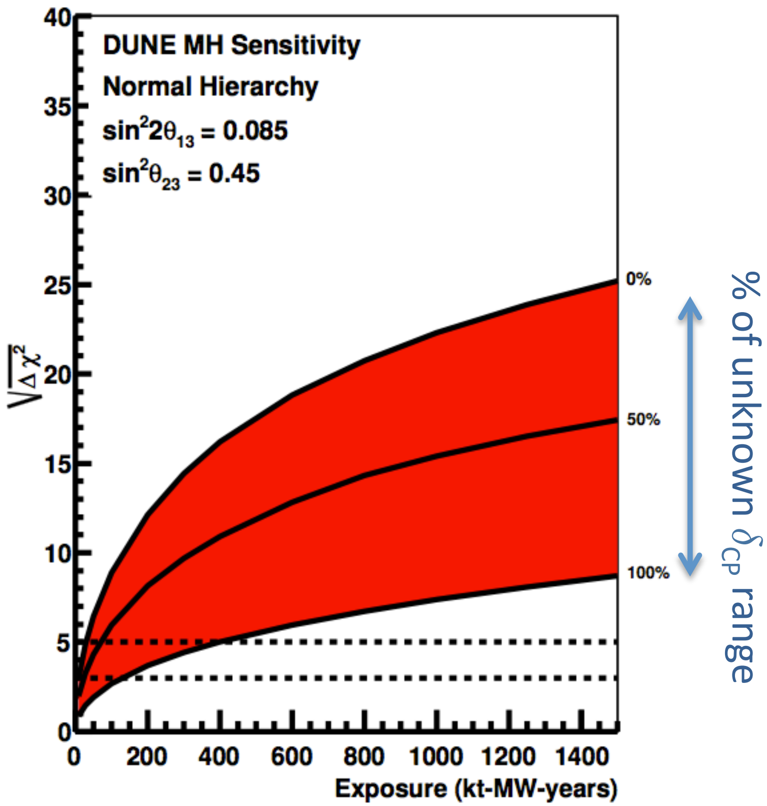
	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_μ Signal	10842	7929
$\bar{\nu}_\mu$ CC Bkgd	958	511
NC Bkgd	88	76
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	63	29
$\bar{\nu}$ mode (150 kt · MW · year)		
$\bar{\nu}_\mu$ Signal	3754	2639
ν_μ CC Bkgd	2598	1525
NC Bkgd	50	41
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	39	18

	CDR Reference Design	Optimized Design
ν mode (150 kt · MW · year)		
ν_e Signal NH (IH)	861 (495)	945 (521)
$\bar{\nu}_e$ Signal NH (IH)	13 (26)	10 (22)
Total Signal NH (IH)	874 (521)	955 (543)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	159	204
NC Bkgd	22	17
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	42	19
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	3	3
Total Bkgd	226	243
$\bar{\nu}$ mode 150 kt · MW · year)		
ν_e Signal NH (IH)	61 (37)	47 (28)
$\bar{\nu}_e$ Signal NH (IH)	167 (378)	168 (436)
Total Signal NH (IH)	228 (415)	215 (464)
Beam $\nu_e + \bar{\nu}_e$ CC Bkgd	89	105
NC Bkgd	12	9
$\nu_\tau + \bar{\nu}_\tau$ CC Bkgd	23	11
$\nu_\mu + \bar{\nu}_\mu$ CC Bkgd	2	2
Total Bkgd	126	127

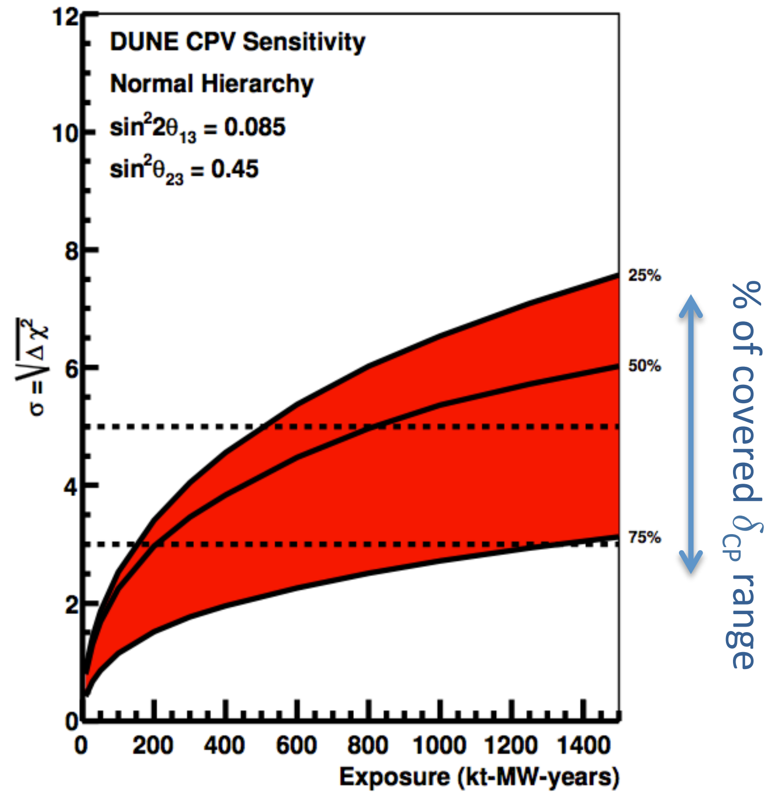
Projected Performance vs Exposure

Assuming reference beam design

Mass hierarchy sensitivity



CP violation sensitivity



→ DUNE will make

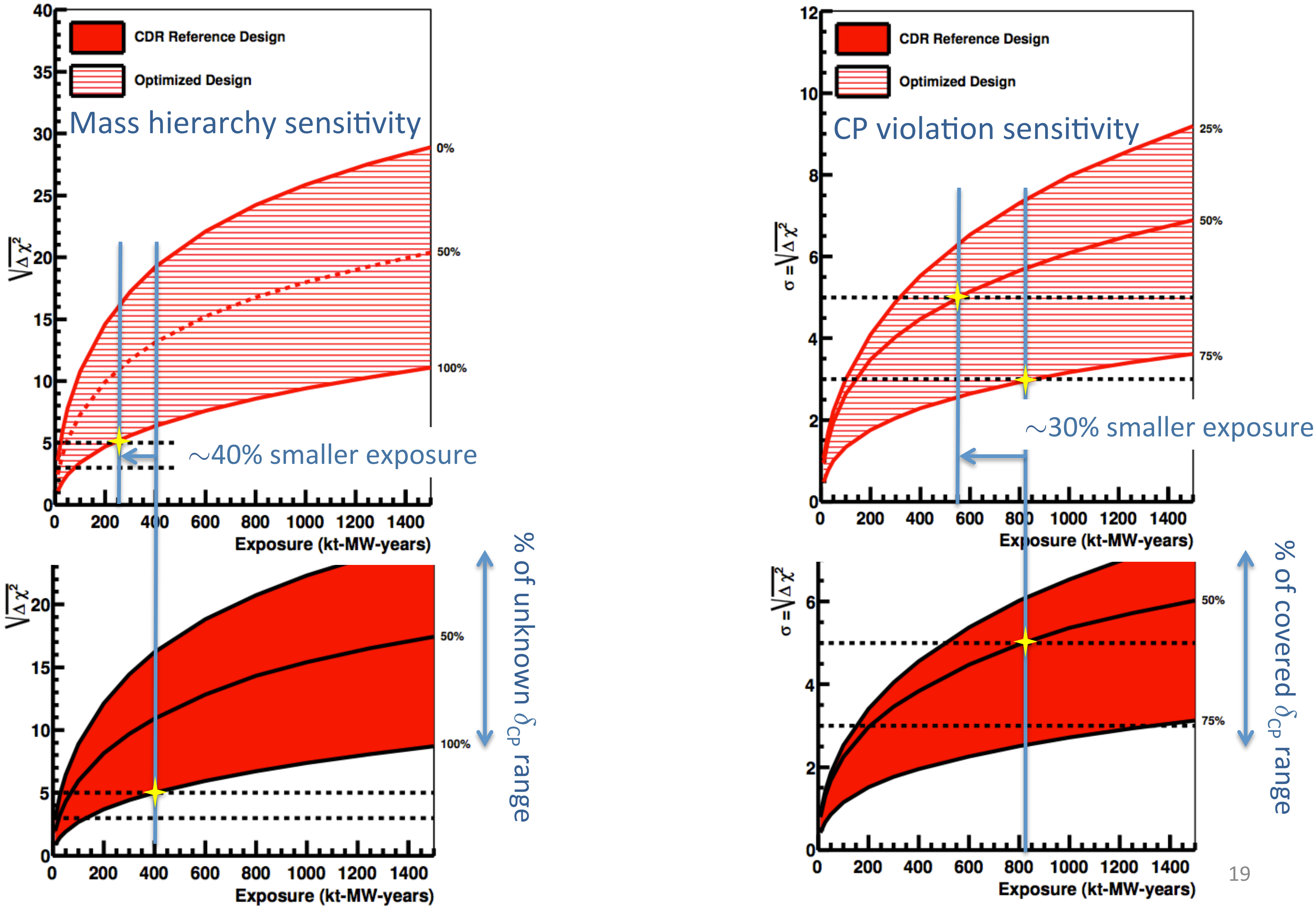
→ definitive determination of neutrino mass hierarchy

→ 5 σ measurement of CP violation for 50% of all possible values of δ_{CP}

Systematic uncertainty on $\nu_\mu \oplus \nu_e = 5 \oplus 2$ %

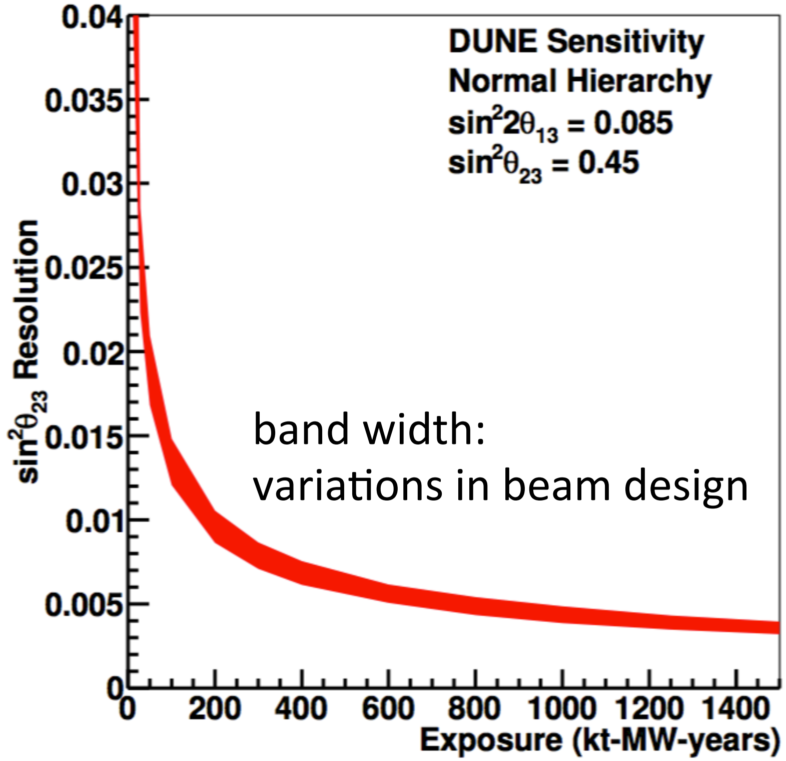
NNN15: E. Worcester

Projected Performance vs Exposure

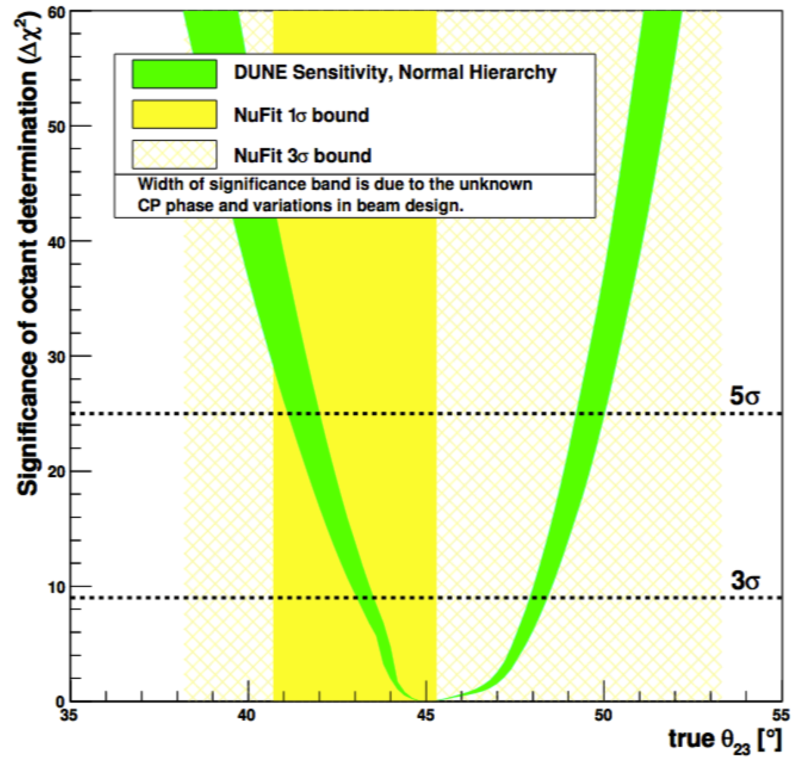


θ_{23} Resolution and Octant Sensitivity

$\sin^2\theta_{23}$ resolution



Octant sensitivity



→ Information on potential symmetry between 2nd and 3rd generation ?
(e.g. equal contribution of ν_μ and ν_τ to ν_3)

Global fit indicates:
global minimum at θ_{23} = $(42.2^{+3.0}_{-1.6})^o$ for NH
2nd local minimum at θ_{23} = $(49.5^{+1.5}_{-2.1})^o$ for IH

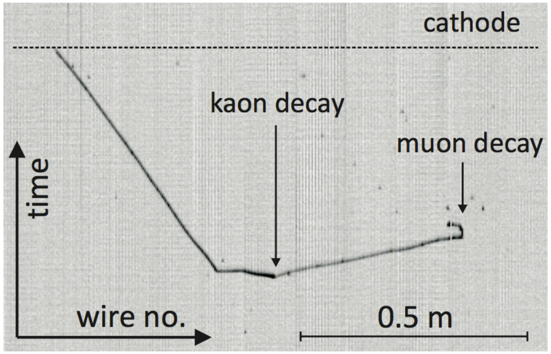
Nucleon Decay

Large LAr detectors offer enhanced capabilities to detect some predicted/hypothesized nucleon decay modes

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

events per Mt yr

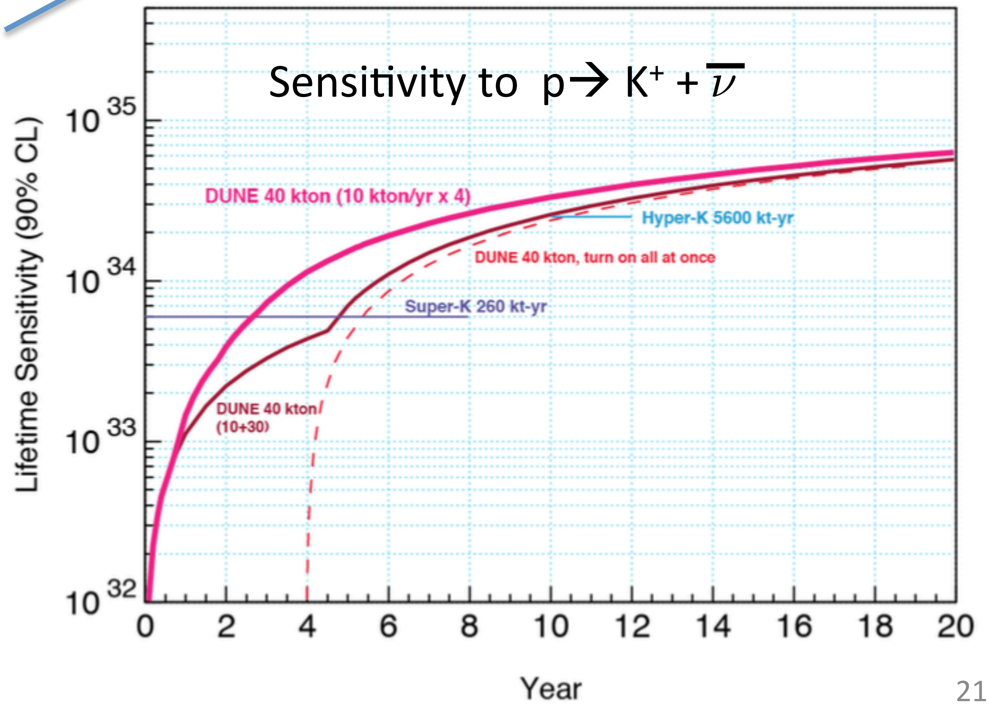
ICARUS T600 event



Antonello et al.,
Adv. HE Phys. (2013) 260820

Strengths of LAr:

- Low threshold (no Cherenkov thresh.)
- Good event reconstruction and PID
- Low backgrounds
  - Cosmogenic K^0 production followed by charge exchange



Supernova Neutrinos

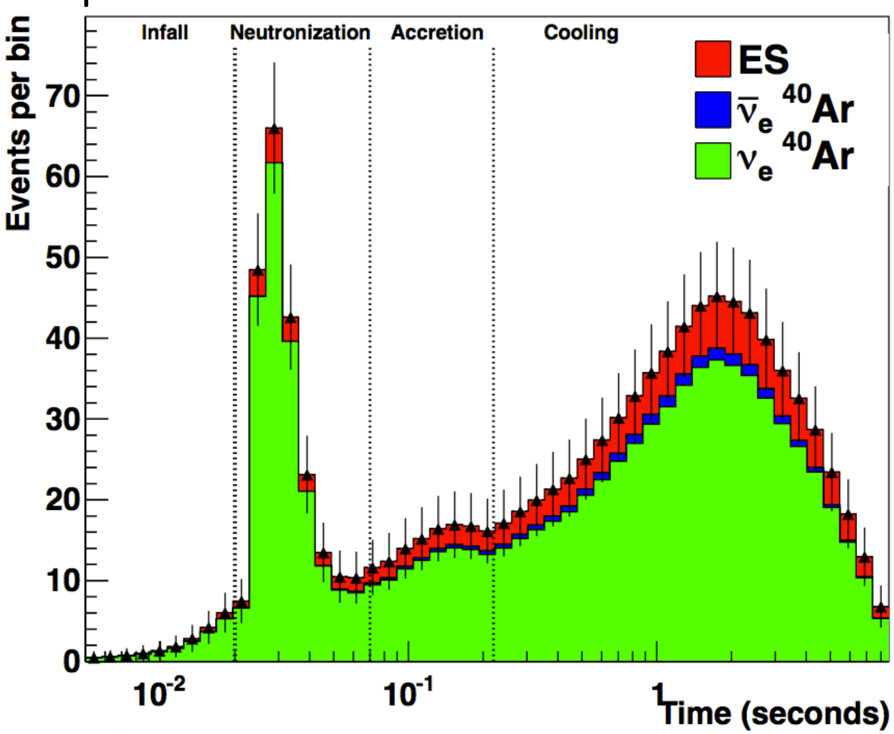
LAr detectors are predominantly sensitive to ν_e: $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

→ sensitivity to neutronization burst: flux primarily composed of ν_e

→ sensitivity to neutrino mass hierarchy (imprint on E spectrum)

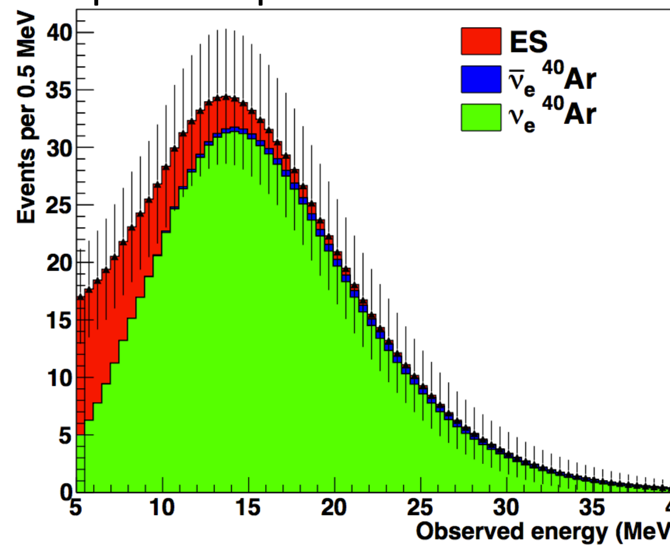
→ complementary to water Cherenkov and liquid scintillator experiments ($\overline{\nu}_e$ sensitivity)

Expected events in 40kt of LAr for SN at 10 kpc



total burst duration: ~10 s

Expected spectrum in 40kt of LAr

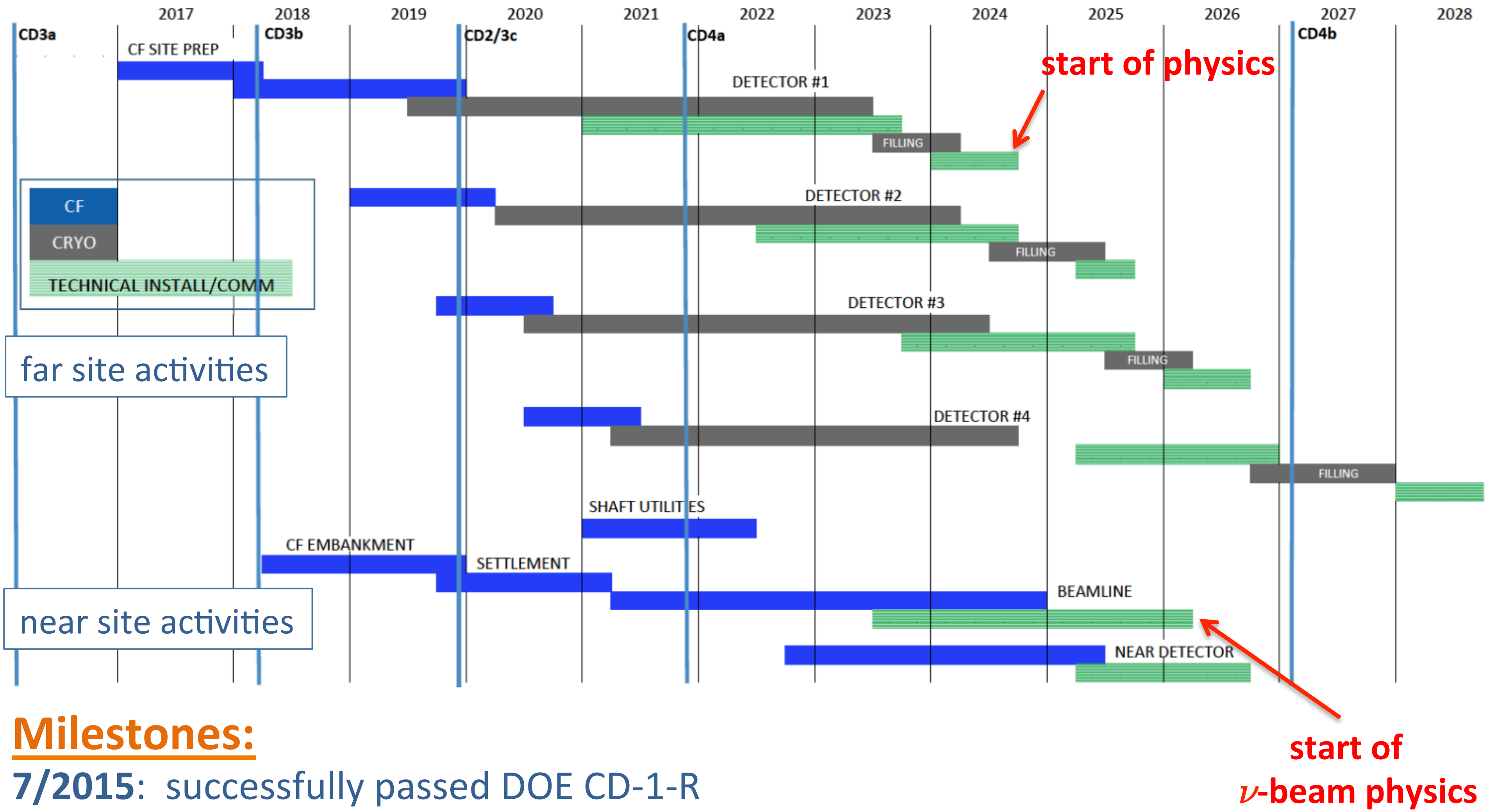


Channel	Events "Livermore" model	Events "GKVM" model
$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$	2720	3350
$\overline{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$	230	160
$\nu_x + e^- \rightarrow \nu_x + e^-$	350	260
Total	3300	3770

Event nos. assume NO neutrino oscillations

Signal: Burst of events with energies of tens of MeV

LBNF/DUNE Timeline



Milestones:

7/2015: successfully passed DOE CD-1-R

10/2015: protoDUNE approved at CERN

12/2015: DOE CD-3a review → approval means start of construction (far site excavation starting in 2017))

Summary

- DUNE science program addresses fundamental questions in particle physics
    1. Neutrino Oscillations: CP violation, Mass hierarchy, precision measurements of neutrino oscillation parameters and neutrino interactions
    2. Nucleon decay
    3. SNe burst and astro-physics

- LBNF/DUNE will employ a 1.2 MW (and upgradable) neutrino beam, near detector and a modular 40kt LAr far detector at Fermilab and SURF

- International DUNE collaboration has formed and welcomes new members to help define, build and further improve the experimental program

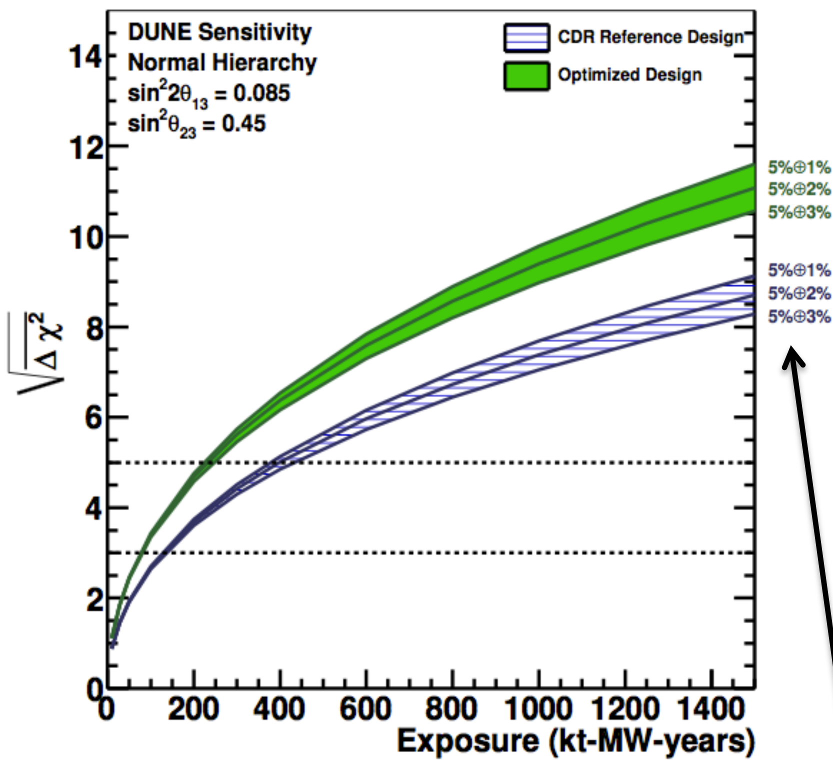
Backup slides

Physics Milestones

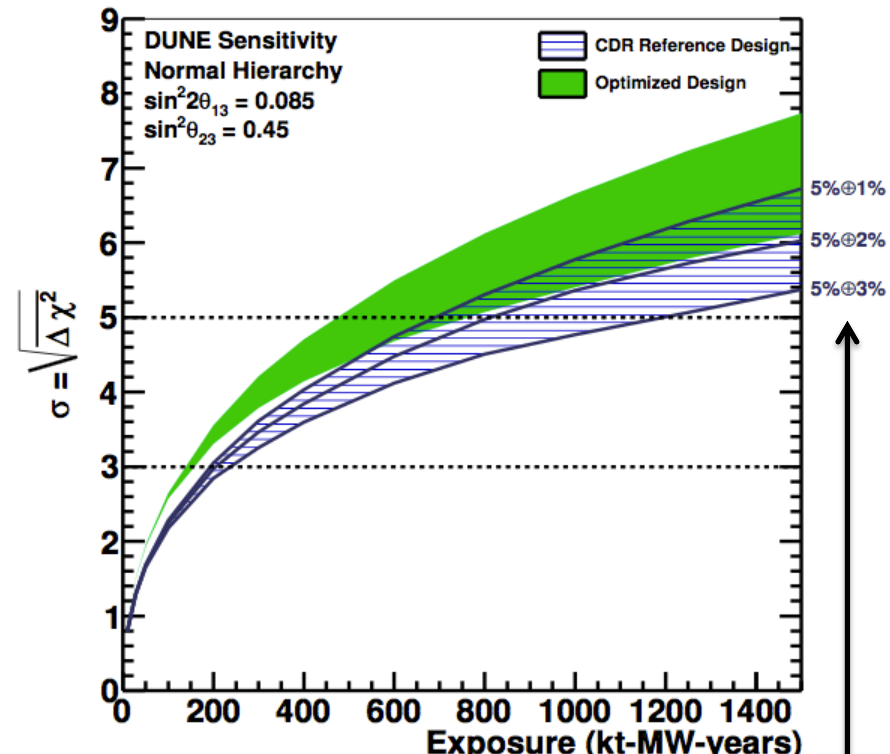
Physics milestone	Exposure kt · MW · year (reference beam)	Exposure kt · MW · year (optimized beam)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	70	45
CPV at 3σ ($\delta_{\rm CP} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\rm CP} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\rm CP} = +\pi/2$)	280	210
MH at 5σ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

Effect of Systematic Uncertainties

Mass hierarchy sensitivity
(100% of δ_{CP} coverage)



CP violation sensitivity
(50% of δ_{CP} coverage)



Systematic uncertainty
on $\nu_\mu \oplus \nu_e$

→ Systematic uncertainty < 3% important after $\sim$200 kt MW yr

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