The Deep Underground Neutrino Experiment

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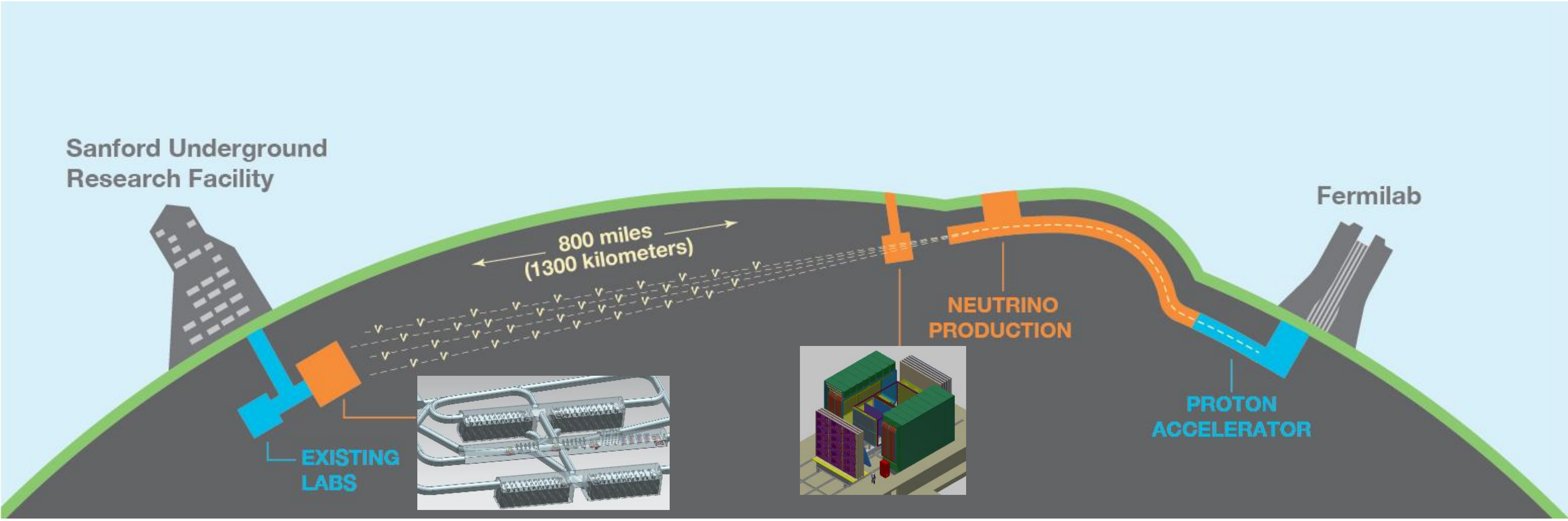
On behalf of the DUNE Collaboration

Rencontres du Vietnam 2017

July 16-22, 2017

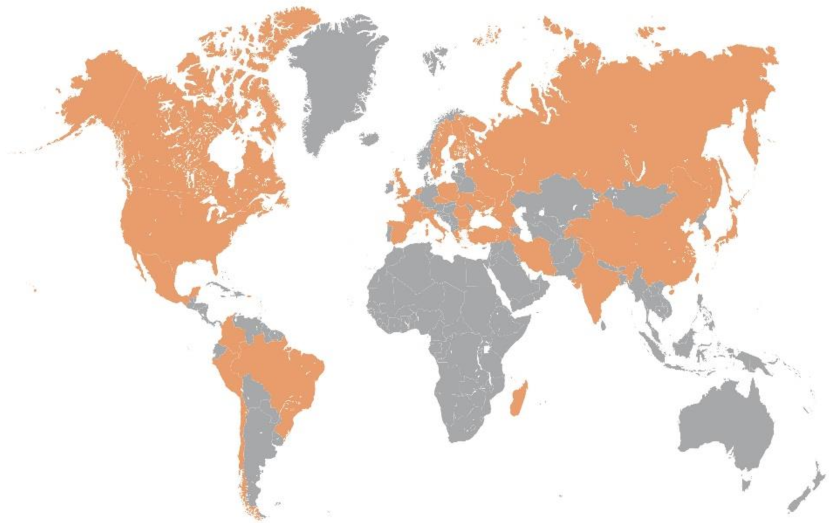
DUNE Overview



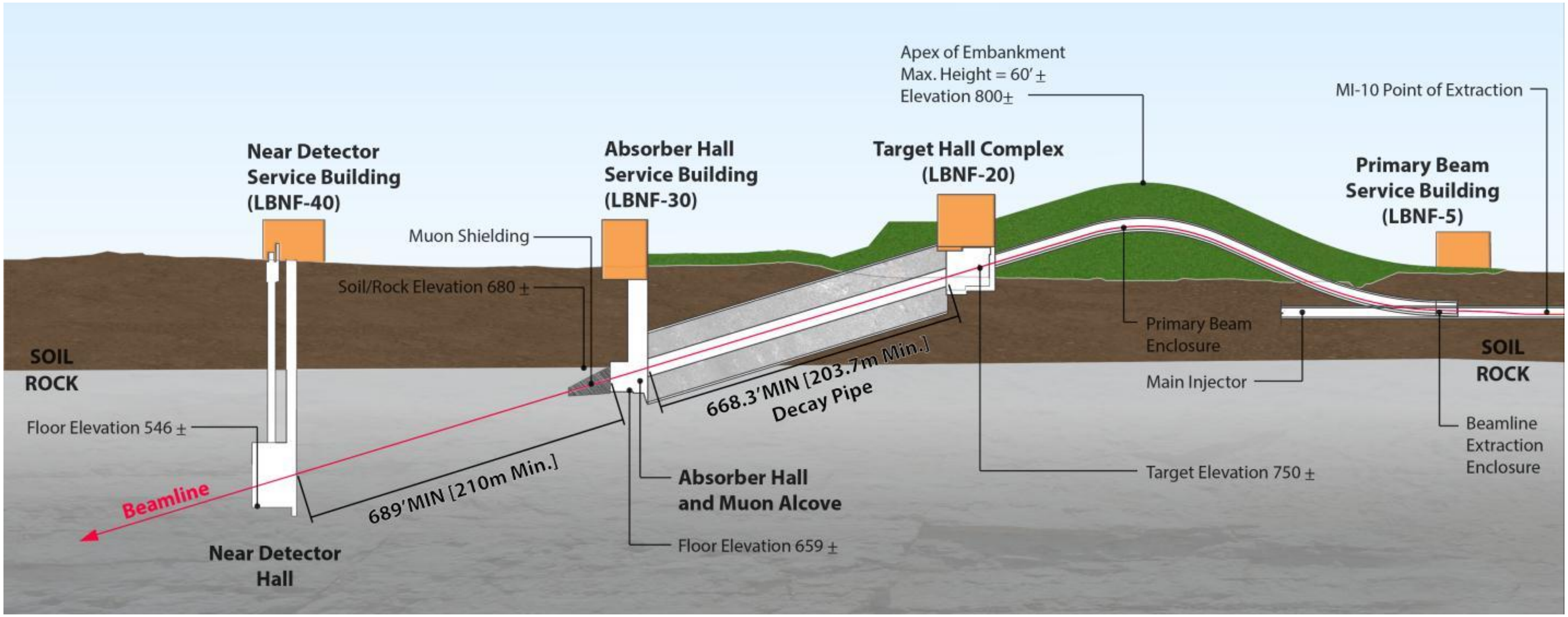
- Measure ν_e appearance and ν_μ disappearance in a wide band ν beam at a 1300 km baseline
- Measure CP violation, mass hierarchy (MH), and neutrino mixing parameters in a single experiment
- Large detector, deep underground gives access to nucleon decay, supernova neutrinos, etc.

DUNE Collaboration

Global collaboration
- 964 collaborators
- 164 institutions
- 30 countries



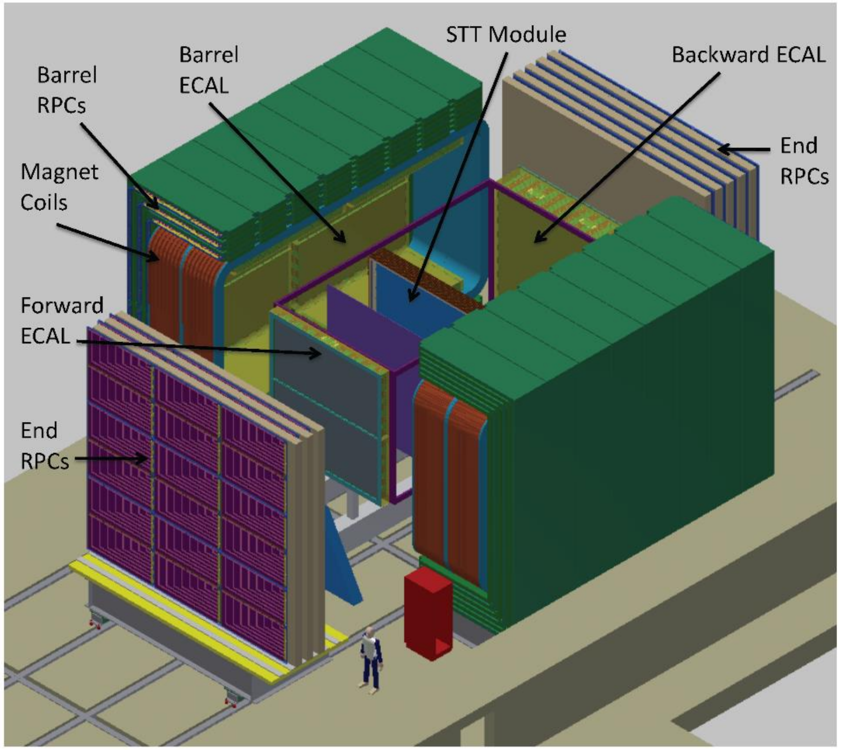
Long Baseline Neutrino Facility Beamline



- Horn-focused beam line similar to NuMI beam line
- 60-120 GeV protons from Fermilab Main Injector
- Initial power: 1.2 MW (@120 GeV); plan to upgrade to 2.4 MW
- 200 m decay pipe at ~5.8^{o} pitch, angled at the far detector

Near Detector (ND)

- Primary purpose: constrain systematic errors for FD oscillation measurements
- High-precision cross-section and short baseline measurements

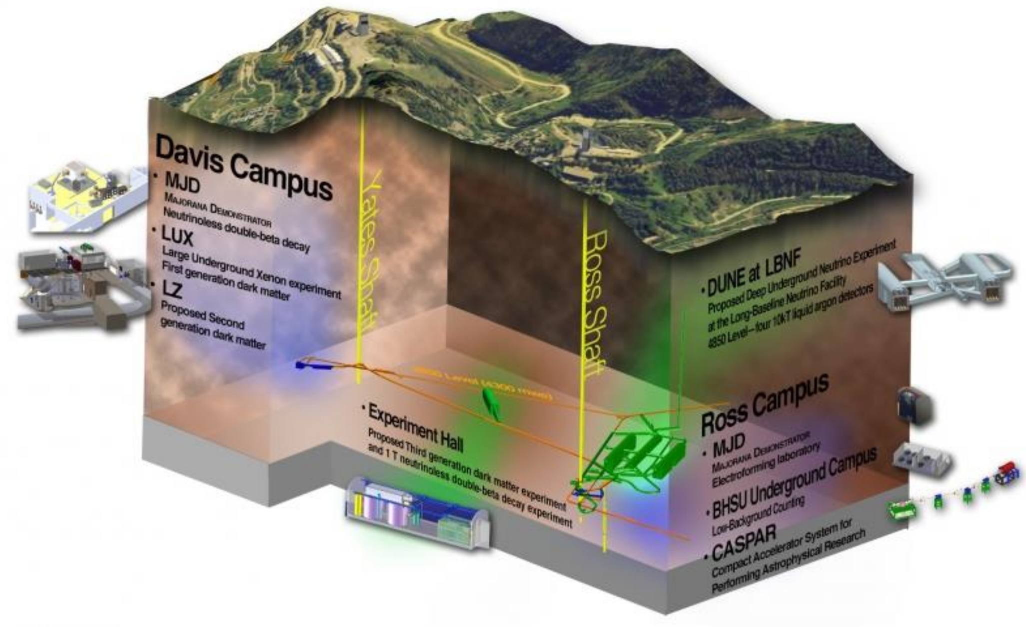


- Fine-grained tracker
  - DUNE reference design
  - Excellent resolution
    - 0.1 mm vertex
    - 2 mrad angular
    - 5% momentum
- Straw tube tracker (SST)
- Lead-scintillator ECAL
- RPC muon trackers

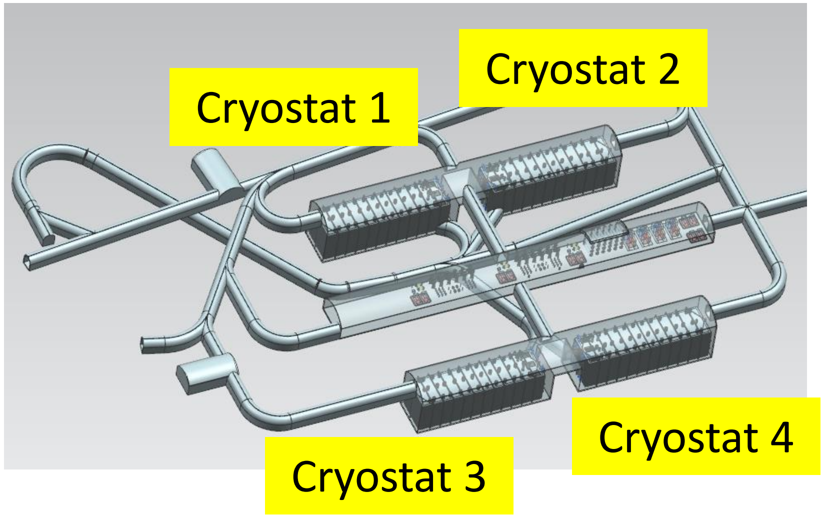
Far Detector (FD) at SURF

- Two FD designs of Liquid Argon Time Projection Chamber (LArTPC) are considered: single phase (only LAr) and dual phase (LAr + GAr)
- Four 10-kt (fiducial) modules, totally 40-kt (fiducial) LAr at 4850ft level

Sanford Underground Research Facility

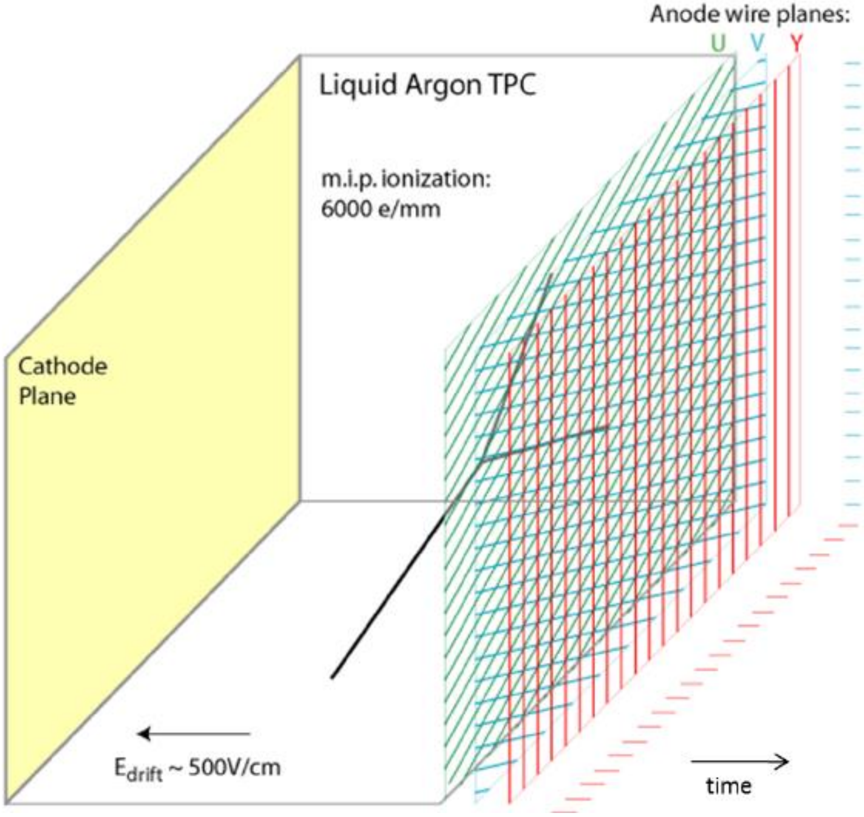


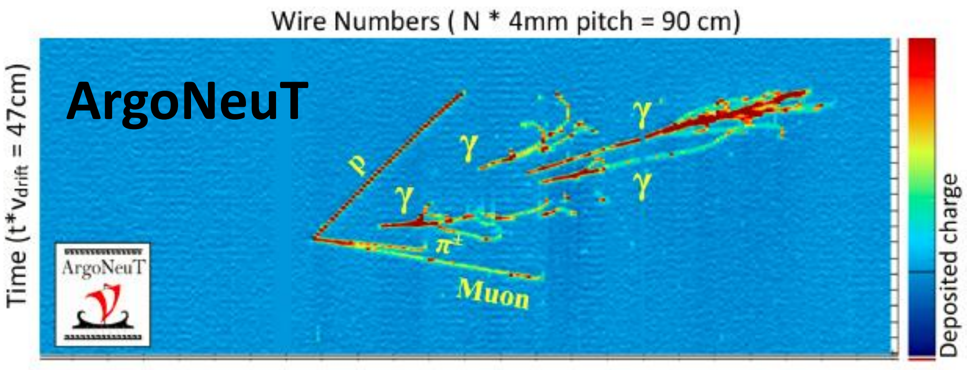
FD: 4 modules



Liquid Argon Time Projection Chamber (LArTPC)

Singles Phase LArTPC illustrated

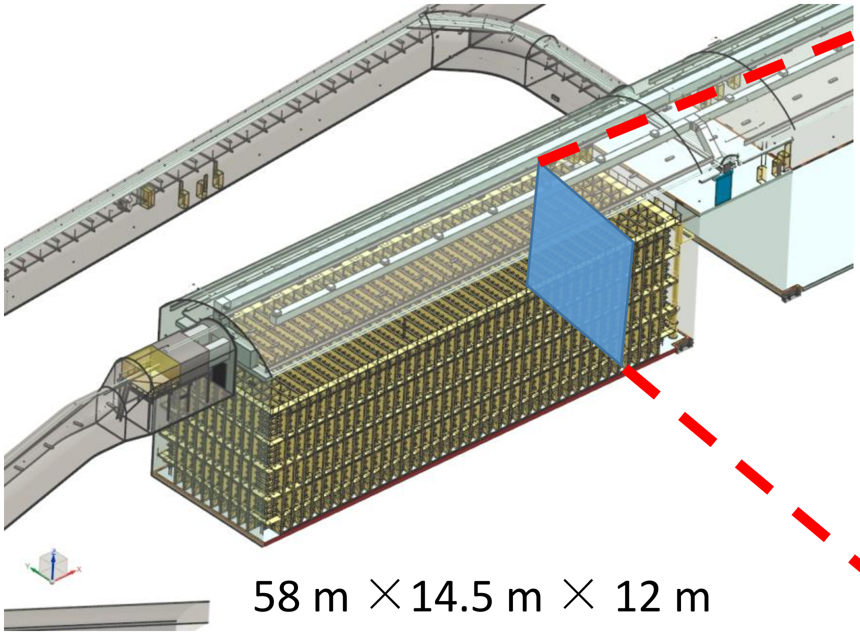




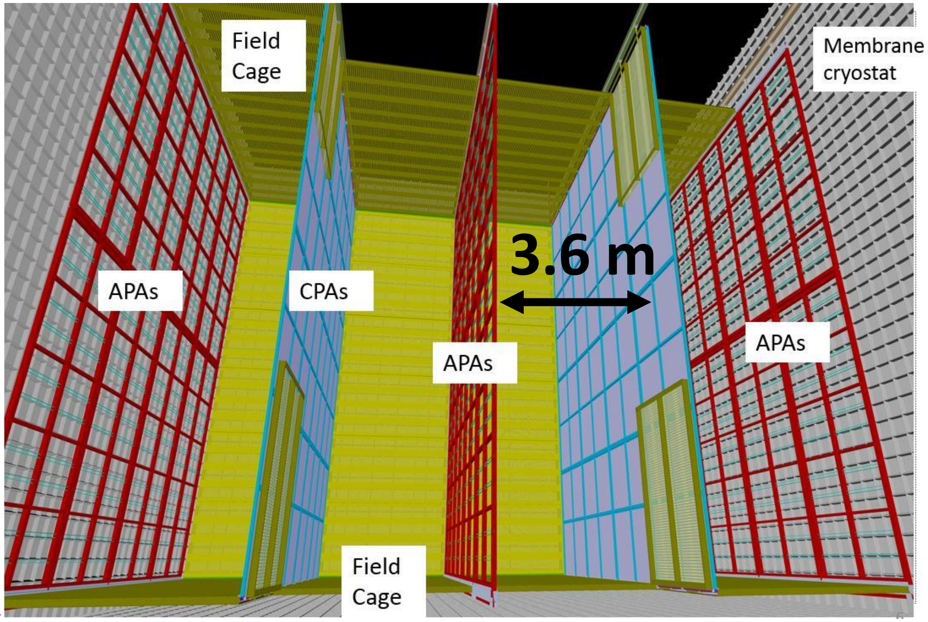
- Energetic, charged particles ionize liquid argon along their paths
- Electric filed drift the ionization electrons to wire planes that record information of time, geometry and charge
- LArTPC features: unique e/γ separation, and precision 3D imaging capability

Far Detector: Single Phase

- Liquid Argon TPC
- Four drift regions across detector
  - 3.6 m drift each
  - 500 V/cm drift filed
  - Anode and Cathode Plane Assemblies (APA, CPA) suspended from ceiling
- APA planes are composed of three wire planes:
  - 2 induction and 1 collection planes
  - Charge collection and readout
- Photon detectors (SiPM) are embedded in APAs

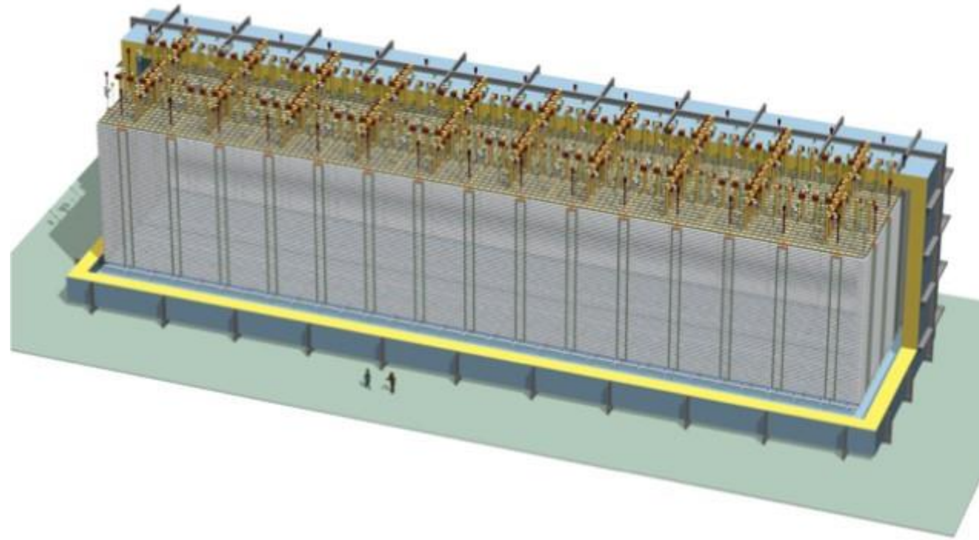


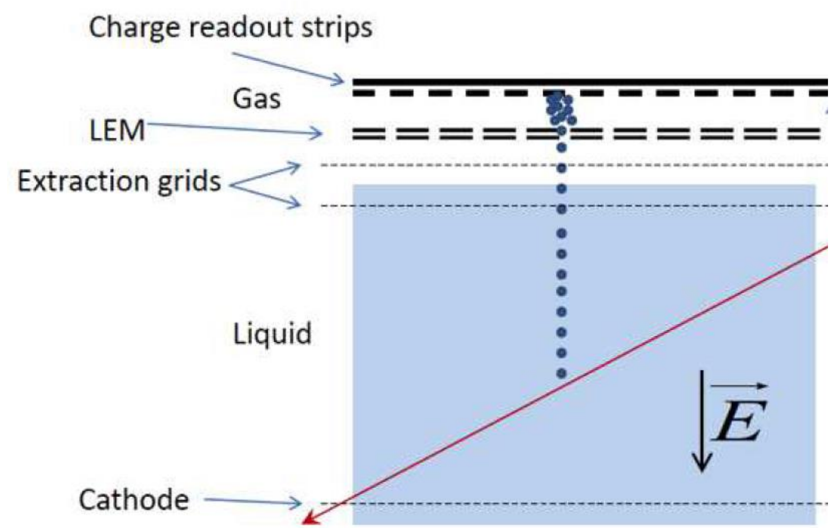
58 m × 14.5 m × 12 m



Far Detector: Dual Phase

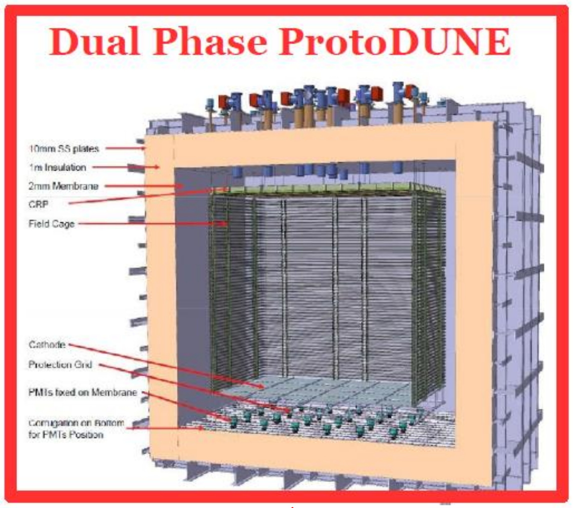
- Liquid + Gas Argon detector
  - LAr target
  - GAr amplification and readout
- Single drift region in LAr
  - 12 m vertical drift
  - 500 V/cm drift filed
- Ionization charge extracted from liquid into gas layer
- Amplification via Large Electron Multiplier (LEM)
- Charge readout strips
- Scintillation via PMT's below cathode

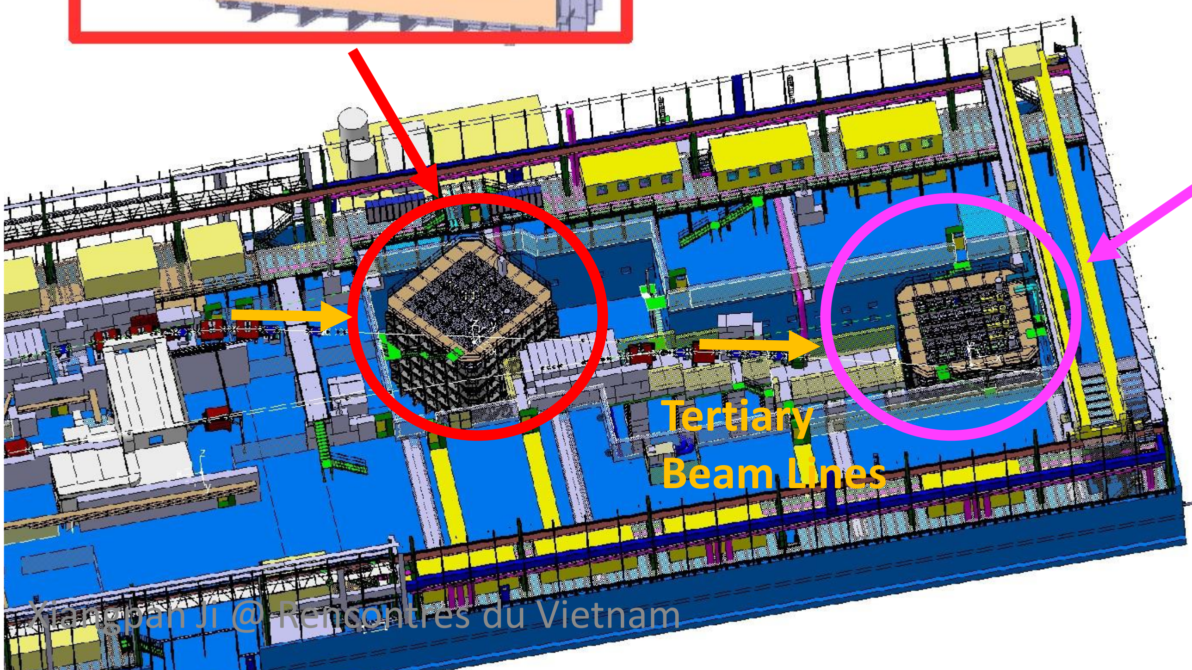


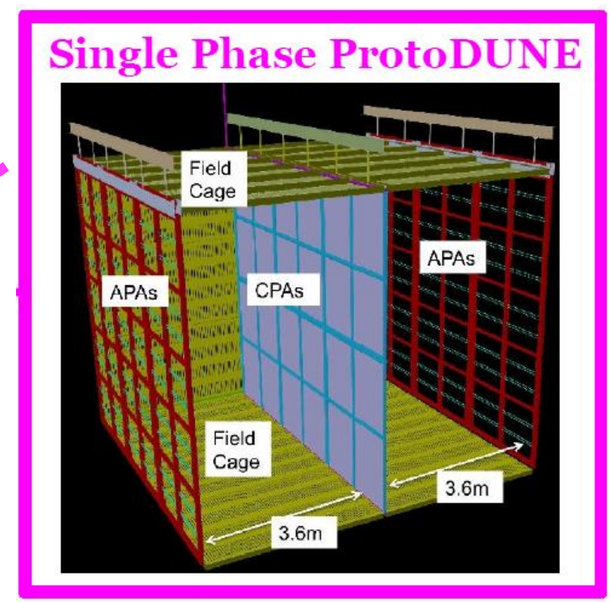


ProtoDUNEs at the CERN Neutrino Platform

- Two FD prototypes being built at CERN
- CERN Neutrino Platform in construction
- Provided valuable insight into detector design, operations, and data analysis
- Test-Beam operations in 2018: 0.4-12GeV, e,μ,π,K,p

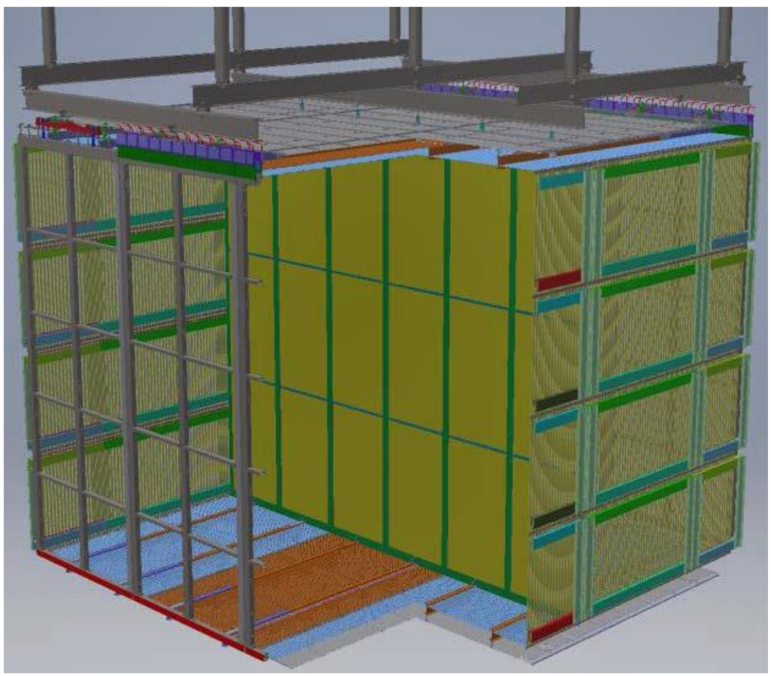


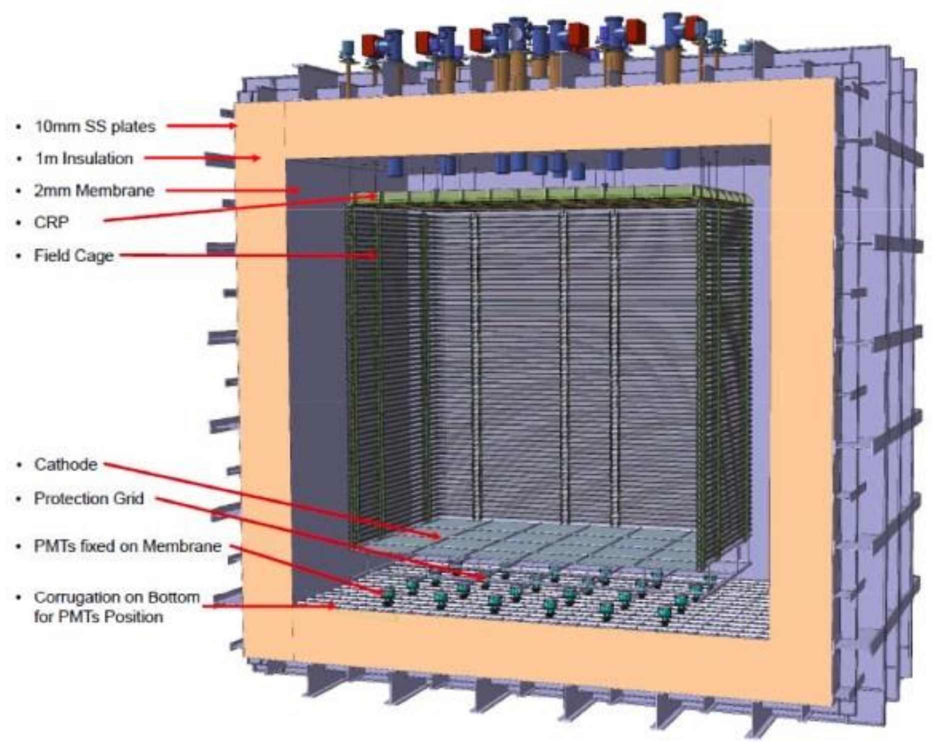




ProtoDUNEs Construction

- Single-phase ProtoDUNE:
  - Full-sized APA-CPA
  - full drift distances (3.6m)
  - 6 m ×6 m×6 m
- Dual-phase ProtoDUNE:
  - Full-sized readout planes
  - half of final drift distance
  - 6 m ×6 m×6 m





DUNE Timeline

- **2017: Far Site Construction Beings**
- 2018: Two ProtoDUNEs operational at CERN
- 2021: Start of 1st FD module (single phase) installation
- 2023: Start of 2nd FD module installation
- 2024: First 20-kt Far Detector operational
- **2026: Beam operation begins**

Physics Research

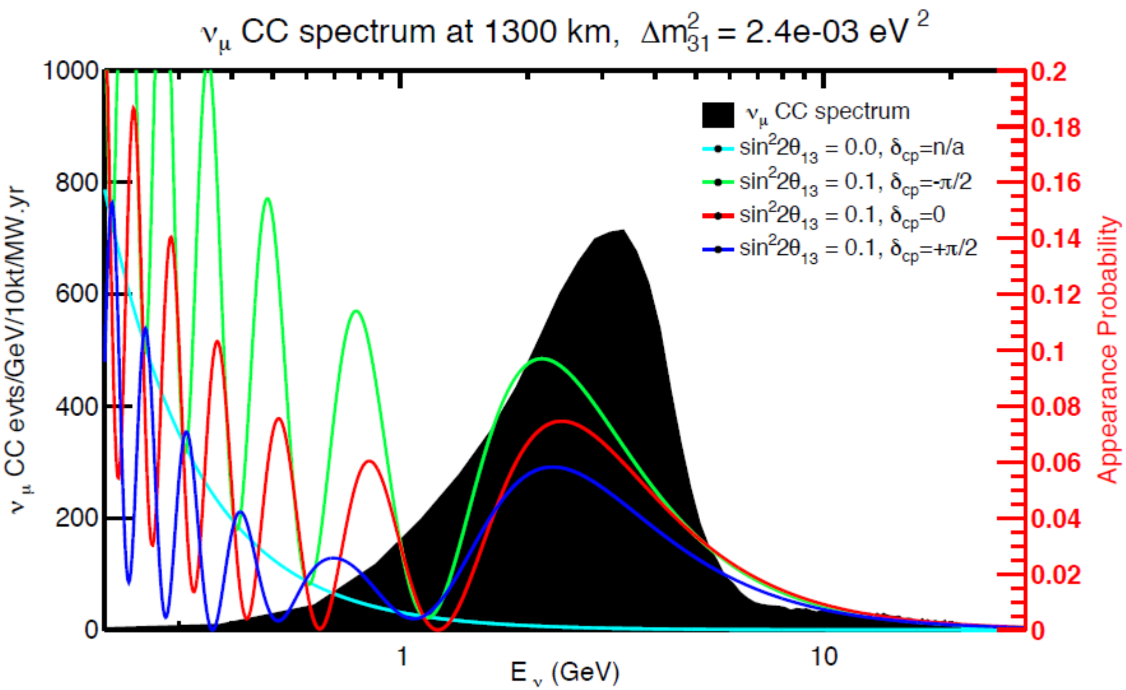
- Long baseline oscillation physics
- Nucleon decay
- Supernova neutrinos
- Other physics topics

$\nu_\mu \rightarrow \nu_e$ Appearance

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

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

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



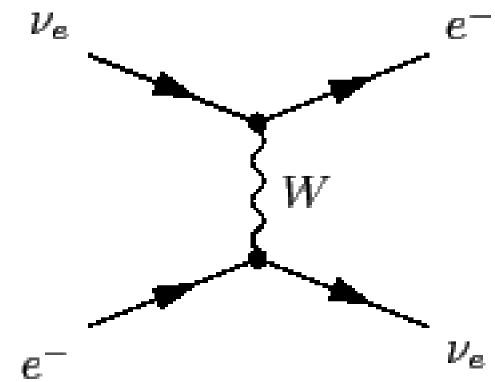
- ν_e appearance amplitude depends on: θ_{23}, θ_{13}, δ_{CP}, matter effect
- Large value of $\sin^2 2\theta_{13}$ allows significant ν_e appearance sample

Matter Asymmetry

- Electrons are present in matter while positrons and other leptons are not.

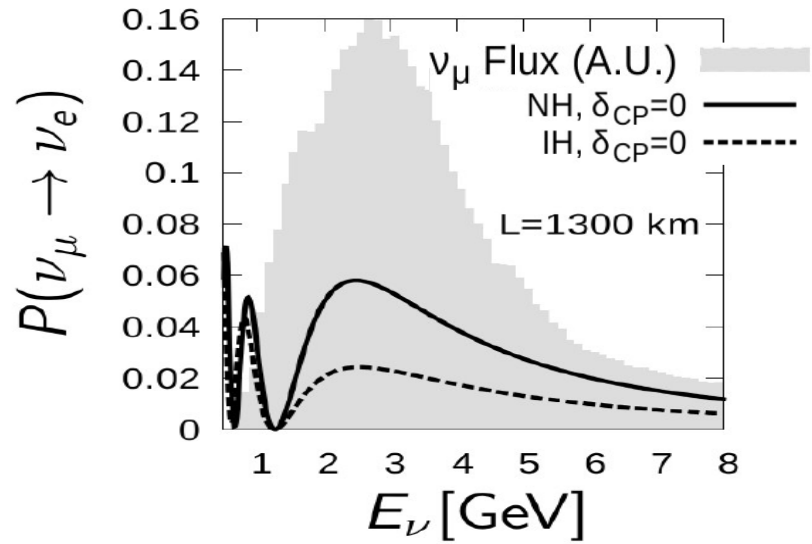
- CC matter effects occur for ν_e and $\bar{\nu}_e$, ν_μ and ν_τ have only NC matter effect interactions

- Normal hierarchy: matter effect enhances ν_e appearance probability and suppresses $\bar{\nu}_e$ appearance probability (opposite for inverted hierarchy).

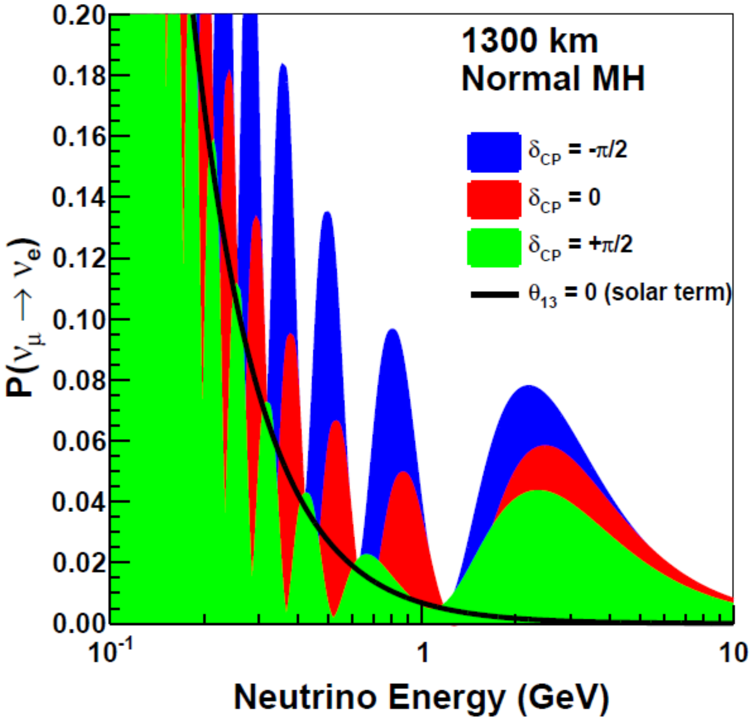


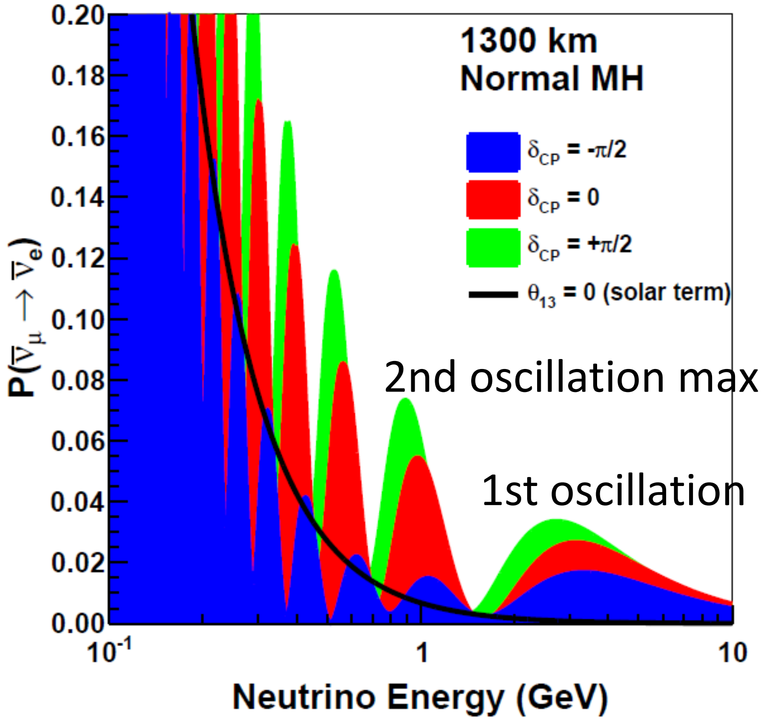
Charged-Current Coherent Forward Scattering on Electrons

(ν_e CC process illustrated)



Neutrino Oscillation at DUNE

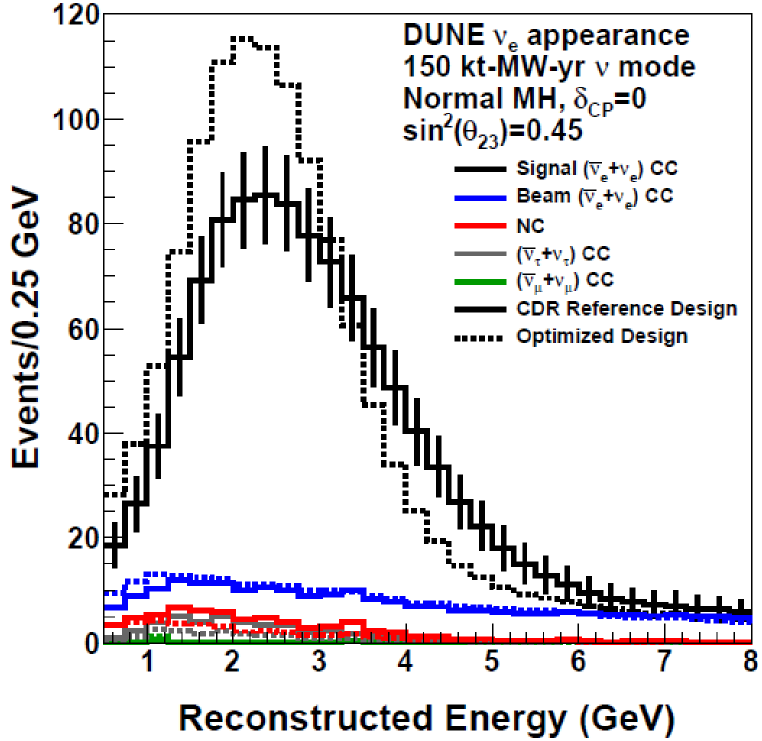




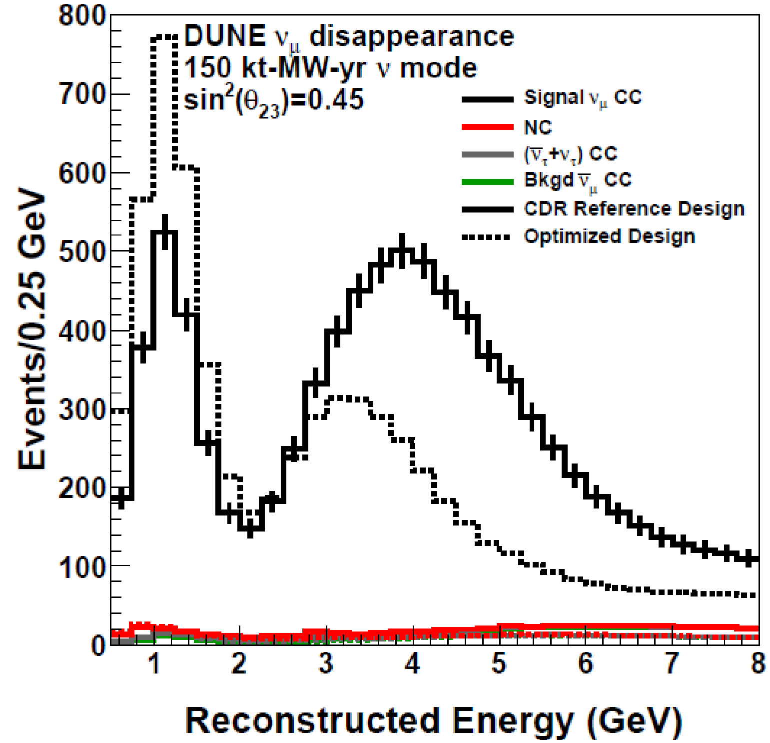
- Measure $\nu_e(\nu_\mu)$ (dis)appearance probability with ν_μ and anti-ν_μ beam
- Measure CP violation, MH, and oscillation parameters
- 1300 km baseline: large matter effect to solve MH
- Wide band beam covers 1st and 2nd oscillation maxima

Oscillation Sensitivity Calculations

ν_e appearance

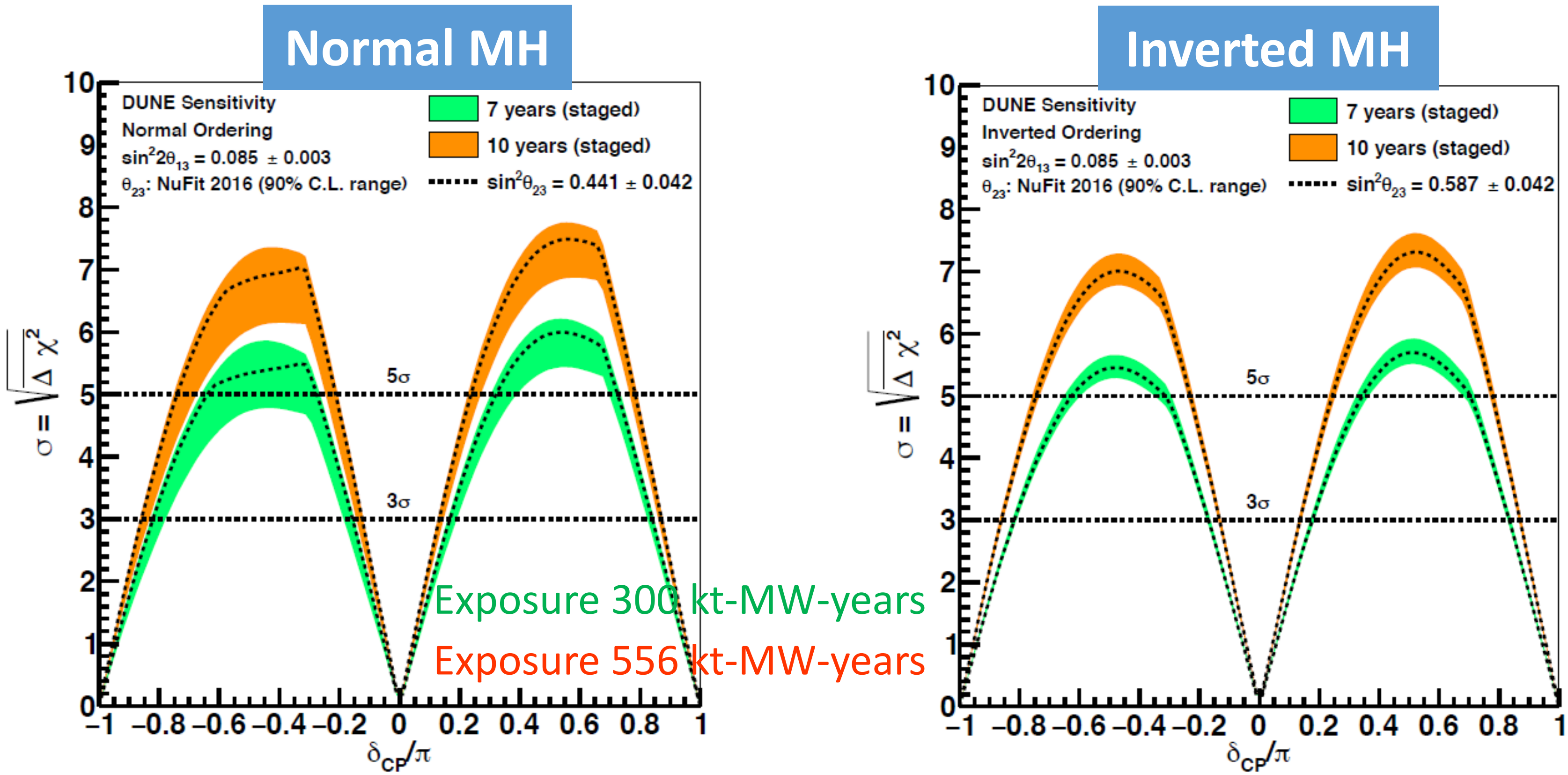


ν_μ disappearance



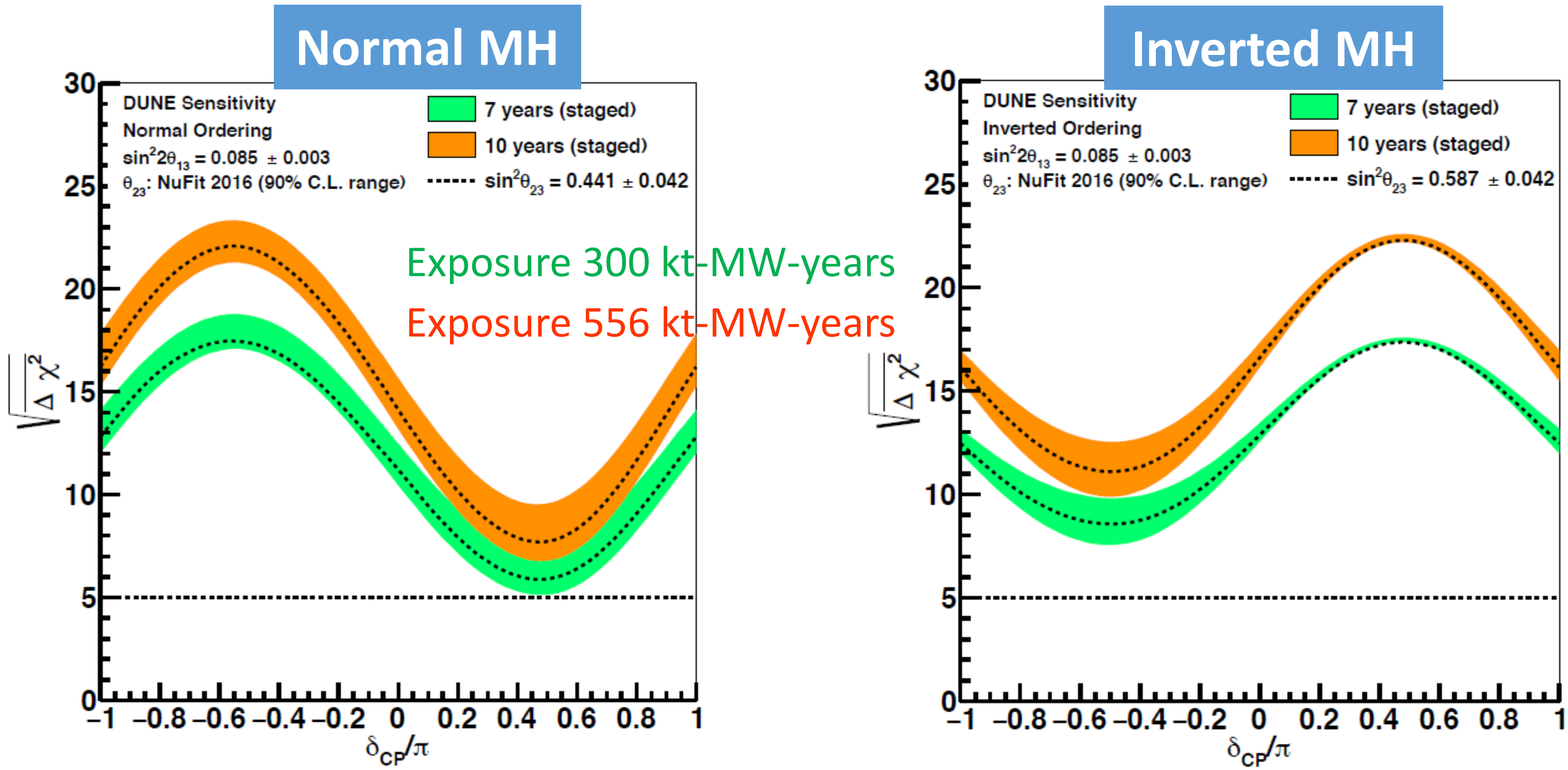
- GLoBES-based fit to four samples in FD: $\nu_e/\bar{\nu}_e$ $(\nu_\mu/\bar{\nu}_\mu)$ (dis)appearance (GLoBES configurations in arXiv:1606.09550)
- Shape information helps to pin down oscillation parameters

CP Violation Sensitivity



- **Width of band** corresponds to 90% C.L. variations in value of θ_{23} based on NuFit 2016 fit values
- **Equal running time** in neutrino and anti-neutrino modes

Mass Hierarchy Sensitivity



- **Width of band** corresponds to 90% C.L. variations in value of θ_{23} based on NuFit 2016 fit values
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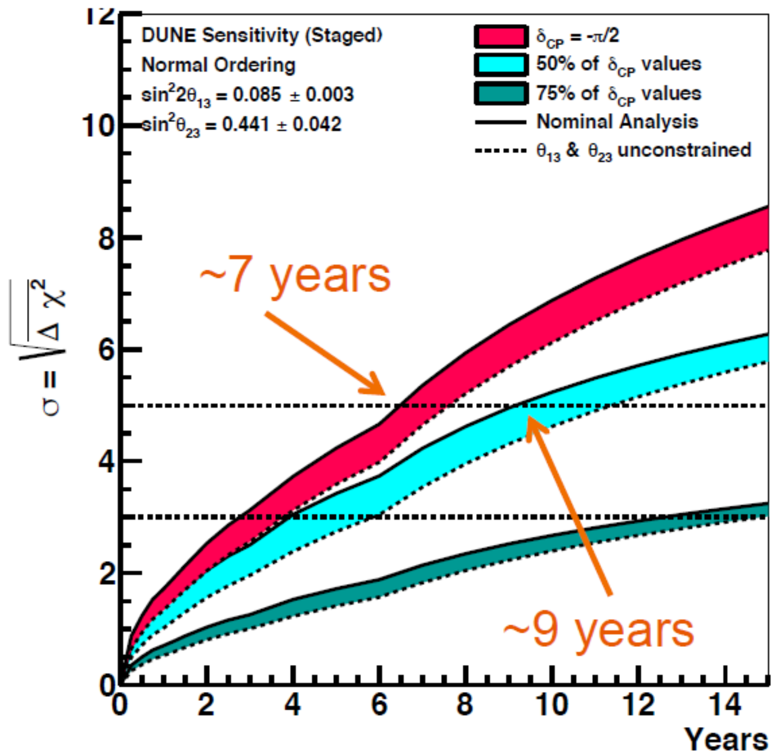
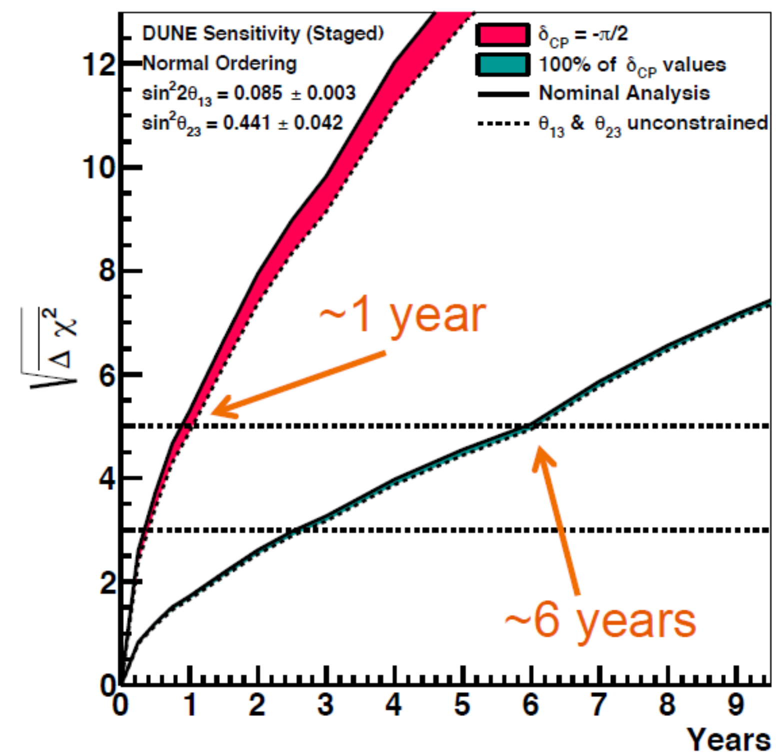
CPV and MH Sensitivity Over Time

CP Violation Sensitivity



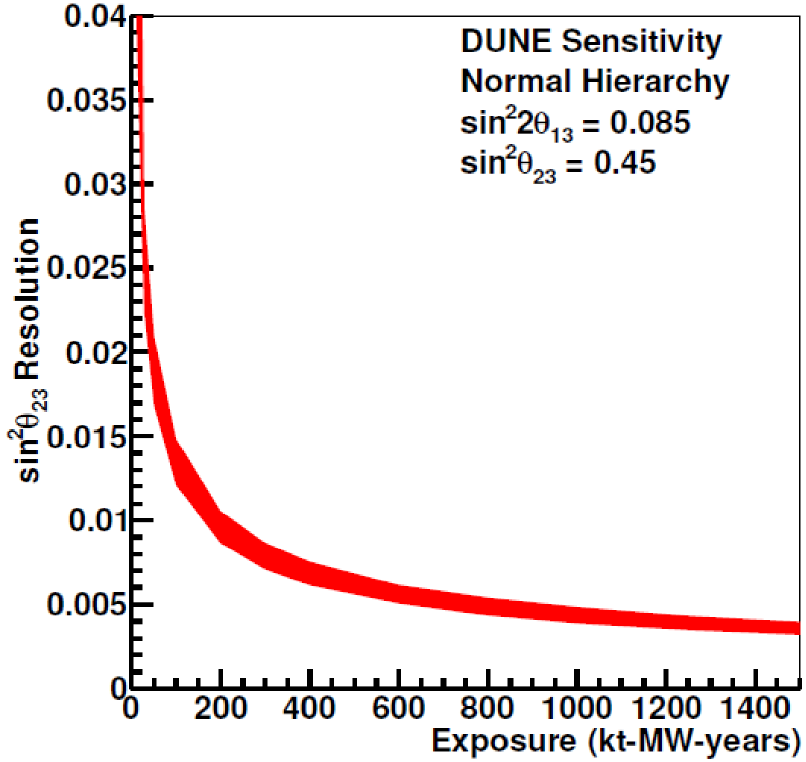
Mass Hierarchy Sensitivity



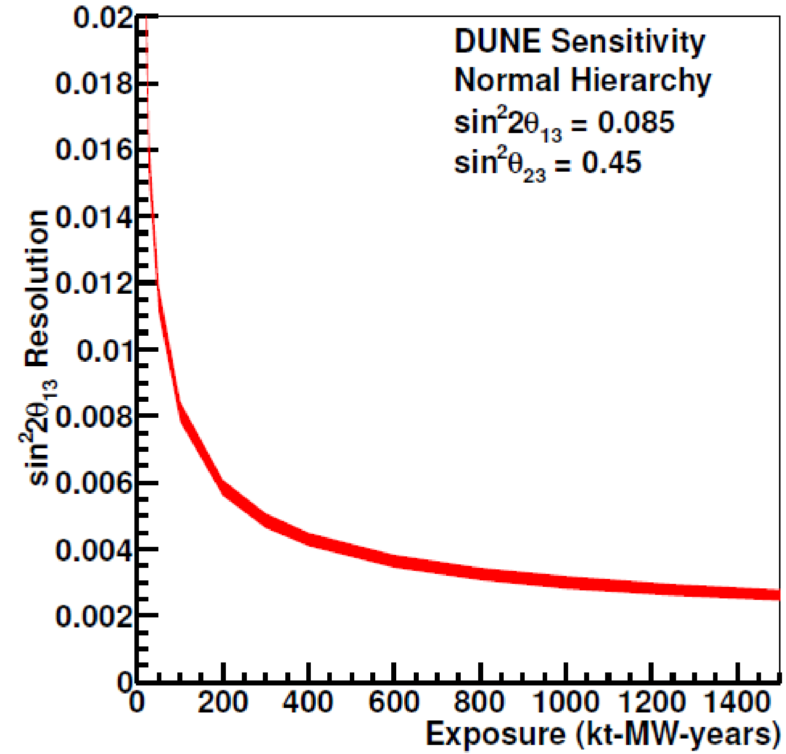
- **Equal running time** in neutrino and anti-neutrino modes

Oscillation Parameter Sensitivity

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



$\sin^2 2\theta_{13}$ Resolution

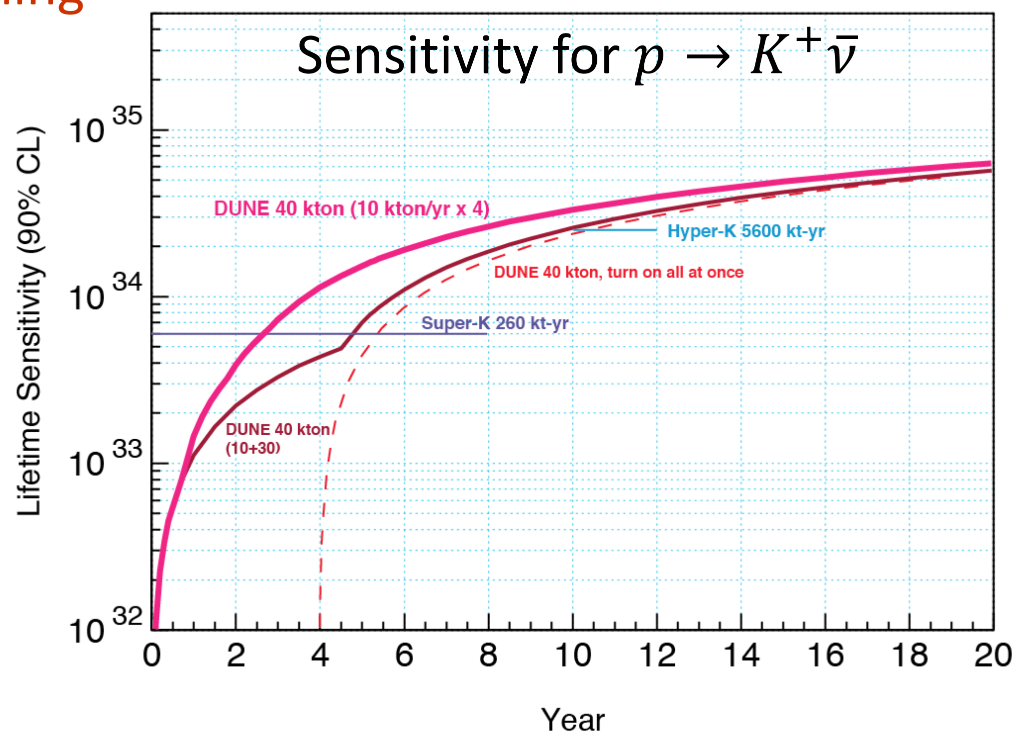


- Long-baseline experiments will approach the resolution of reactor experiments in the measurement of the mixing angles.

Proton Decay

- Test of fundamental symmetries, e.g. baryon number conservation
- Grand Unified Theories (GUTs) make specific predictions for decay modes, lifetimes, branching ratios

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



- Features DUNE FD:
  Low background rate
  (deep underground location)
  High signal efficiency
  (precision tracking in LArTPC)
  Large exposure
  (40 kt, running 20+ years)

Supernova Neutrino Burst (SNB)

- Core-collapse supernova are a huge source of neutrinos of all flavors
  - 99% of energy taken by neutrinos
  - 1% of energy, the exploding matter
  - 0.01% light
- Expected SNs in our Galaxy (d ≈ 10 kpc): 1-3 SN/century
- **SN1987a** observation yielded insights, but many details left to be understood
- High-statistics observation of SNB neutrinos, with sensitivity to flavor components, interesting for **astrophysics** and **neutrino physics**

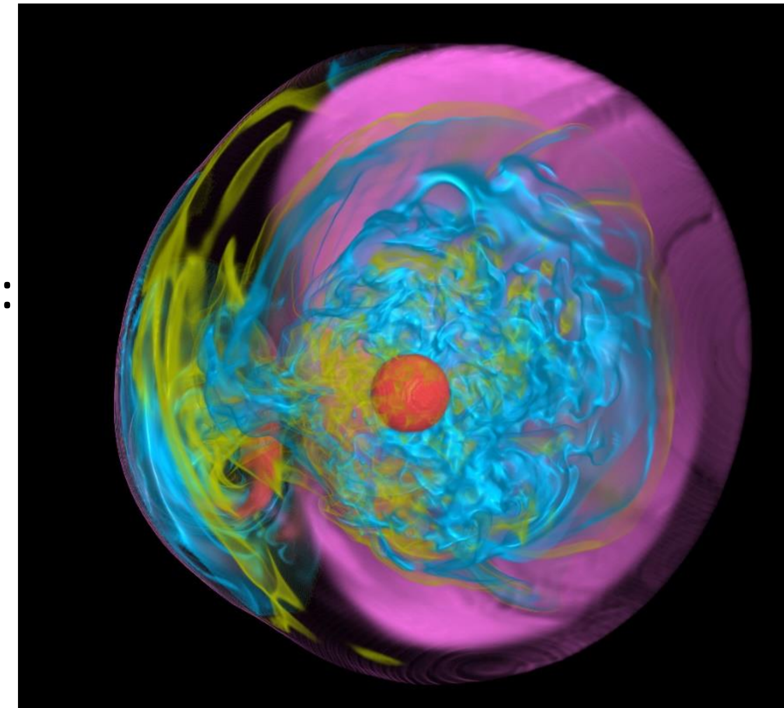


Image credit: A. Mezzacappa

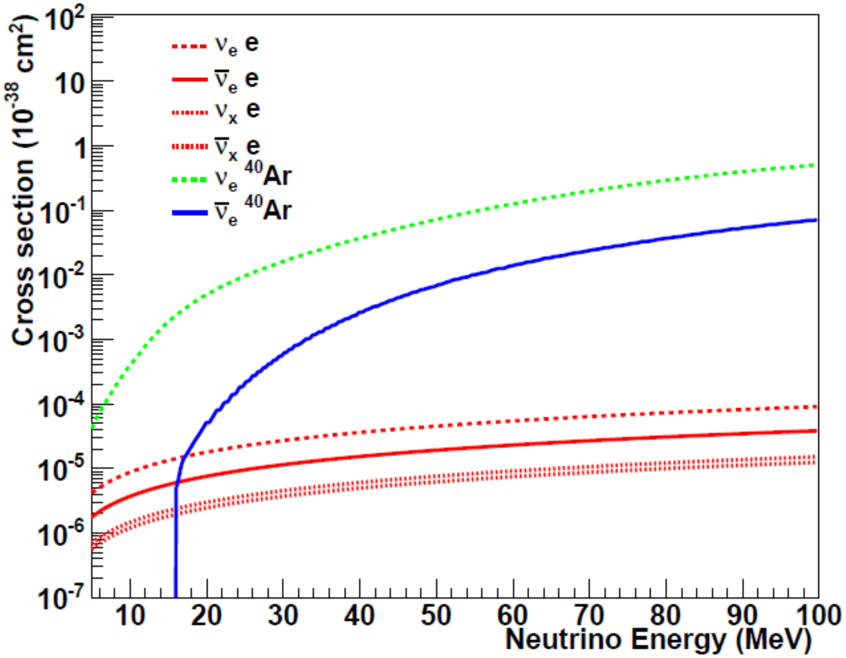
Supernova neutrinos in DUNE

- Elastic scattering (ES) on electrons

$$\nu + e^- \rightarrow \nu + e^-$$
$$\bar{\nu} + e^- \rightarrow \bar{\nu} + e^-$$

- Charged-current (CC) interactions on Ar

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$
$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^*$$



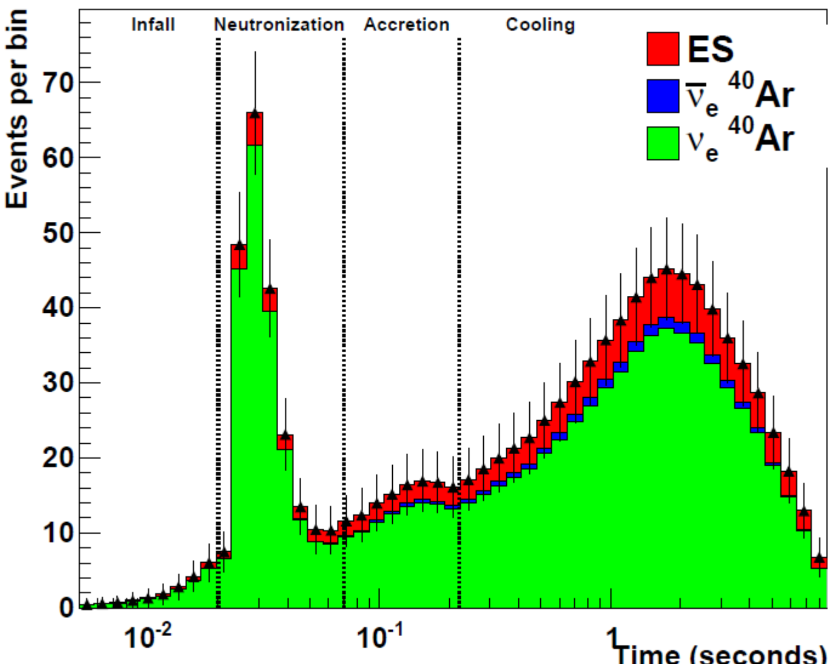
- Event rates in DUNE (40 kt LAr) for a core-collapse SN at 10 kpc

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

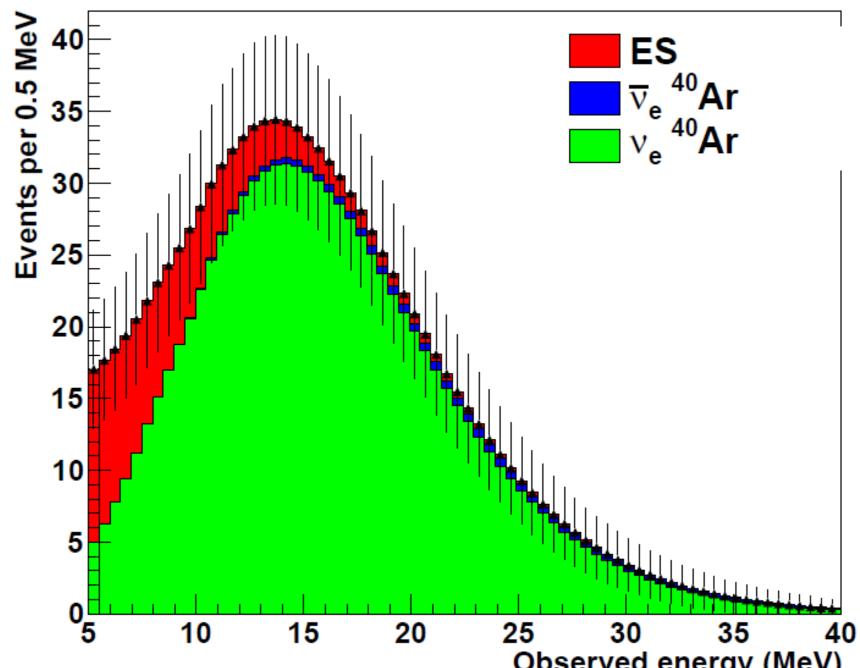
no oscillation collective effects

Supernova neutrino spectra in DUNE

- Required energy resolution < 10%
- Energy threshold ~ 5 MeV
- SN at 10 kpc in DUNE (40 kt LAr)



Flavor composition
as a function of time



Expected energy spectra
integrated over time

* Garching model

Other Physics Topics

DUNE has many other physics topics:

- Atmospheric neutrinos
- ν_τ appearance
- Non-standard interactions (NSI)
- Long-range interactions
- Sterile neutrinos
- Large extra dimensions
- Lorentz/CPT violation
- Light dark matter

Summary

- ◊ DUNE physics program will produce results at each stage of 20+ year operation

- ◊ DUNE has a broad physics program
  - Measure the CP Violation and determine the Mass Hierarchy
  - Precision oscillation parameter measurements
  - Search for Nucleon Decay and Supernova Burst ν
  - Also include: Atmospheric ν, NSI, Sterile ν, …

- ◊ Far site construction and prototypes are underway this year

Thanks

Backup

Single Phase FD Performance

Parameter	Reference Performance	Achieved Elsewhere	Expected Performance
Signal/Noise Ratio[1]	9:1	10:1 [6, 7][2]	9:1
Electron Lifetime	3 ms	$>$ 15 ms [7]	$>$ 3 ms
Uncertainty on Charge Loss due to Lifetime	$< 1\%$	$< 1\%$ [7]	$< 1\%$
Dynamic Range of Hit Charge Measurement	15 MIP		15 MIP
Vertex Position Resolution[3]	(2.5,2.5,2.5) cm		(1.1,1.4,1.7) cm [8, 9]
$e-\gamma$ separation ϵ_e	0.9		0.9
$e-\gamma$ separation γ rejection	0.99		0.99
Multiple Scattering Resolution on muon momentum[4]	~18%	~18% [10, 11]	~18%
Electron Energy Scale Uncertainty	5%	2.2%[12]	From LArIAT and CERN Prototype
Electron Energy Resolution	$0.15/\sqrt{E(\mathrm{MeV})}$ $\oplus 1\%$	$0.33/\sqrt{E(\mathrm{MeV})}$ [12] $+1\%$	From LArIAT and CERN Prototype
Energy Resolution for Stopping Hadrons	1–5%		From LArIAT and CERN Prototype
Stub-Finding Efficiency[5]	90%		$> 90\%$

Dual Phase FD Performance

Table 5.1: Performance parameters specific to the dual-phase far detector design

Parameter	Requirement	Achieved Elsewhere	Expected Performance
Gas phase gain	20	200	20-100
Electron Lifetime	3 ms	> 3 ms 35-t prototype	> 5 ms
Minimal S/N after 12 m drift	9:1	$> 100{:}1$	12:1-60:1

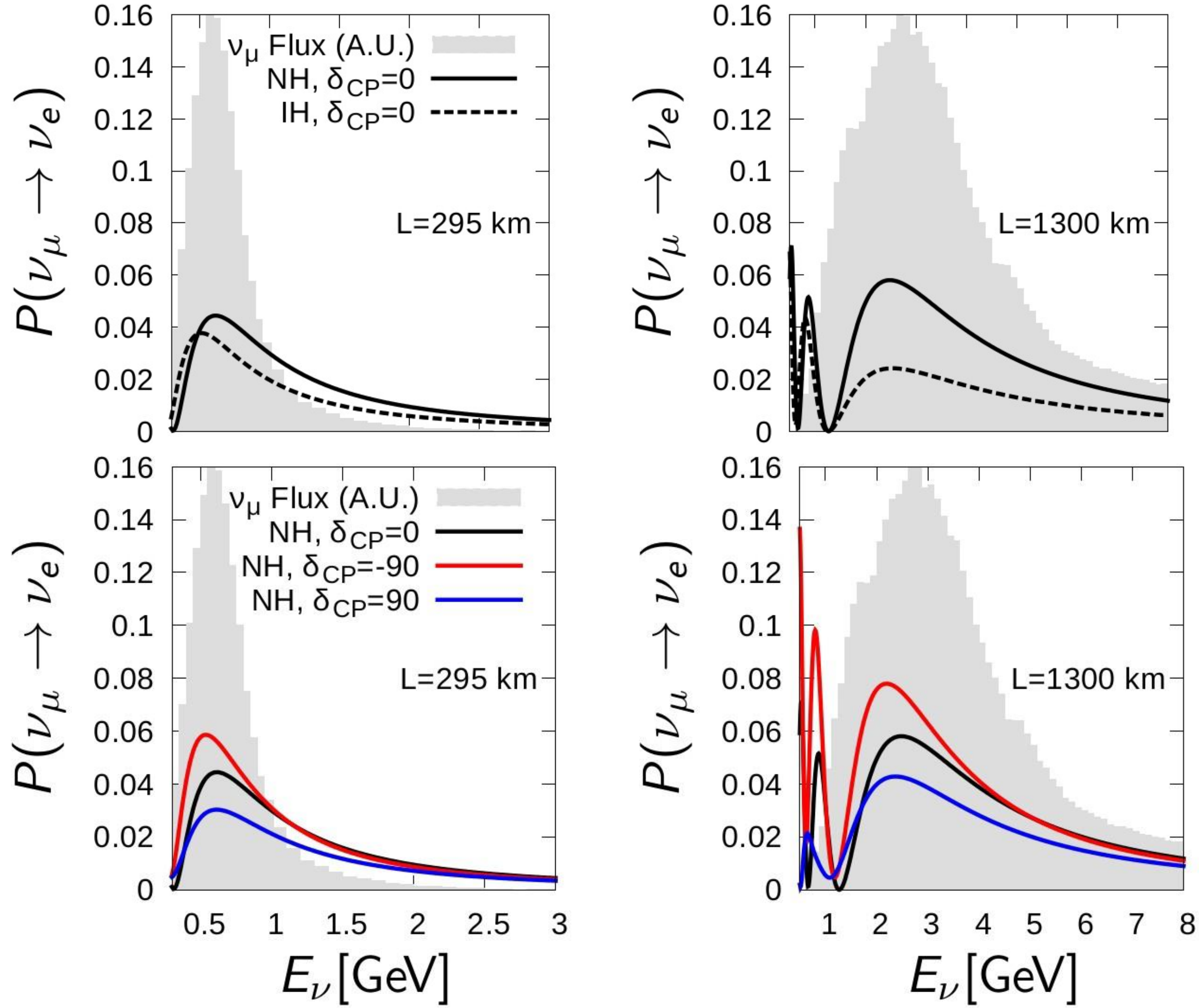
Table 5.2: Sizes and Dimensions for the 12-kt (15-kt) dual-phase LArTPC

Item	Value(s)	
Active volume width and length	W = 12 m	L = 60 m
Active volume height	H = 12 m (H = 15 m)	
Active volume/LAr mass	8,640 (10,800) m^3	12,096 (15,120) metric ton
Field ring vertical spacing	200 mm	
Field ring tube diameter	140 mm	
Anode plane size	W = 12 m	L = 60 m
CRP unit size	W = 3 m	L = 3 m
HV for vertical drift	600–900 kV	
Resistor value	100 MΩ	

Baseline Comparison

MH

δ_{CP}



Sensitivity Benchmarks

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 ($\delta_{\mathrm{CP}} = +\pi/2$)	70	60
CPV at 3σ ($\delta_{\mathrm{CP}} = -\pi/2$)	160	100
CPV at 5σ ($\delta_{\mathrm{CP}} = +\pi/2$)	280	210
MH at 5σ (worst point)	400	230
10° resolution ($\delta_{\mathrm{CP}} = 0$)	450	290
CPV at 5σ ($\delta_{\mathrm{CP}} = -\pi/2$)	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