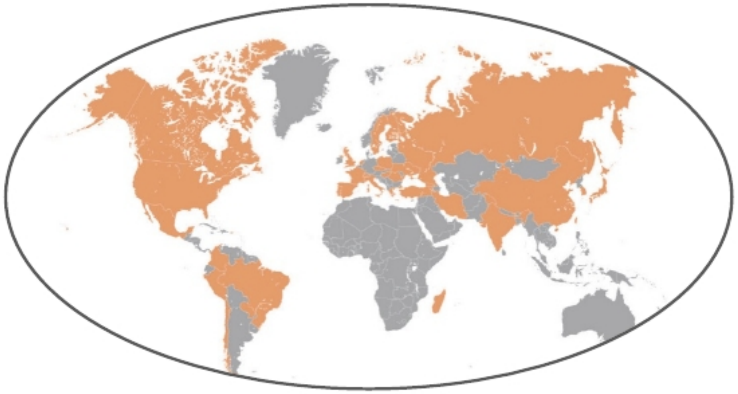
DUNE

Jaime Dawson on behalf of the DUNE collaboration
Laboratoire AstroParticule et Cosmologie, Paris

DUNE: international collaboration

1400+ collaborators
200+ institutions
37 countries (including CERN)



Neutrino Oscillation

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

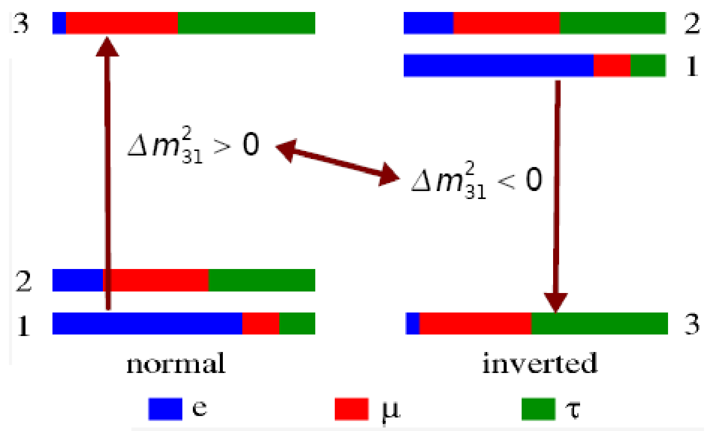
Pontecorvo – Maki – Nakagawa – Sakata (PMNS) matrix

- 3 mixing angles
- 1 CP phase

- Oscillation also governed by 2 mass splittings Δm^2_{ij}

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$\theta_{23} \sim 45^o$ $\theta_{13} \sim 9^o$ $\theta_{12} \sim 33^o$



Still to discover

- Mass ordering (sign of Δm^2_{31})
- CP violation ($\delta_{cp} \neq 0$ or π)
- Octant θ_{23} ($\theta_{23}=45^o$?)

Precision measurements

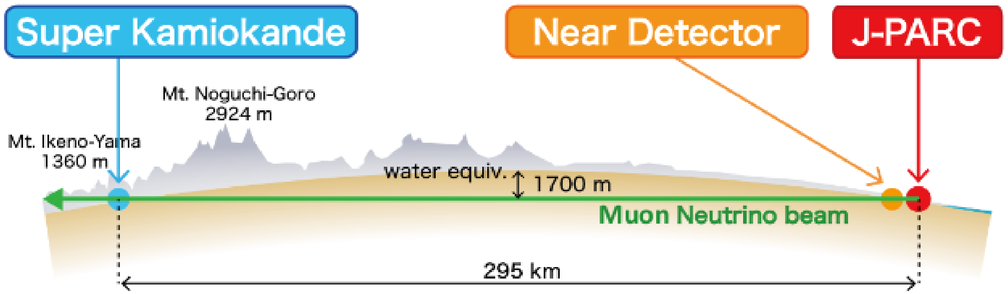
Complete picture of neutrino oscillation

3 flavour mixing

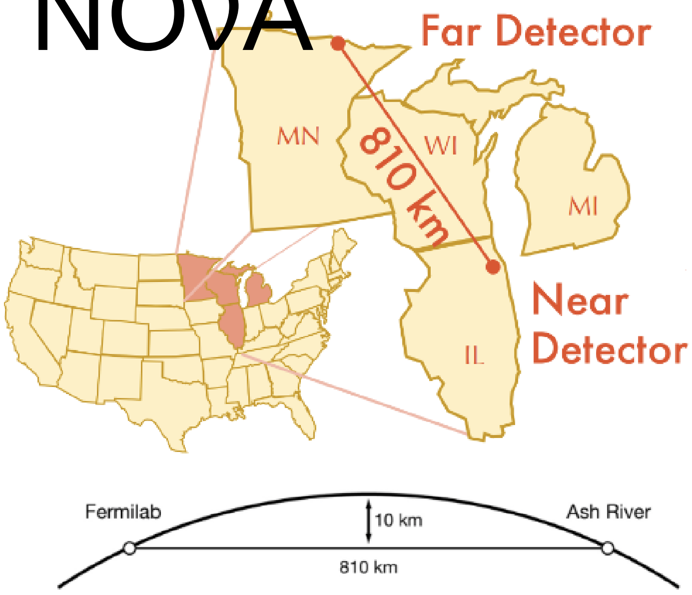
PMNS unitarity

Long Baseline Experiments – State of the Art

T2K



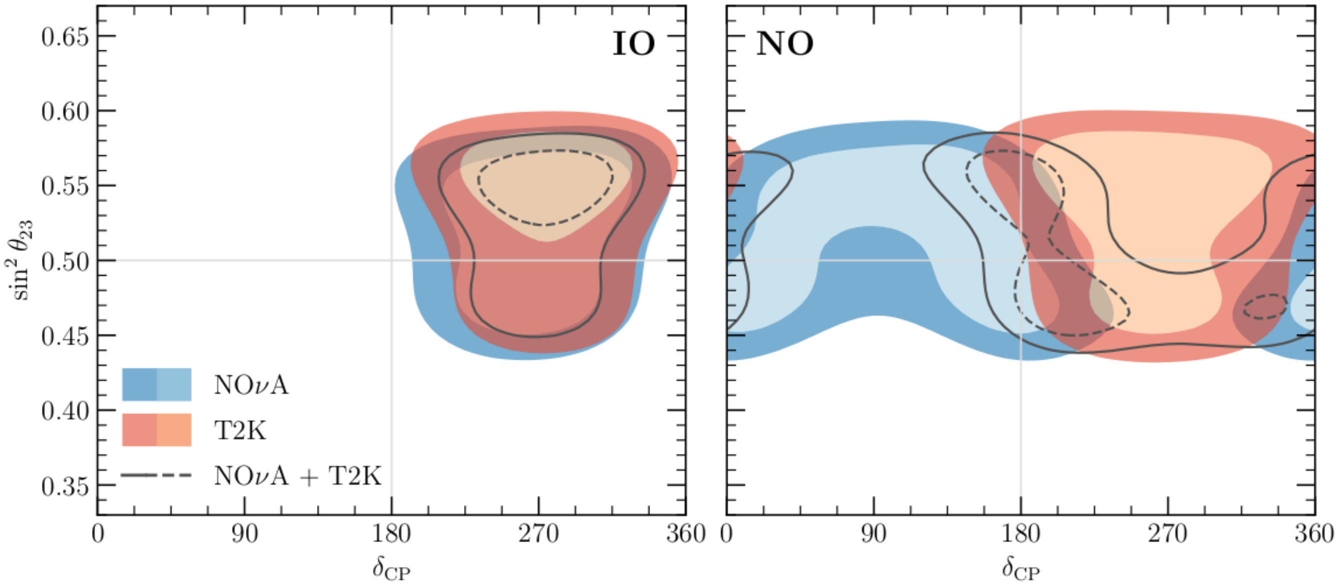
NOνA



T2K Far Detector is Water Cherenkov (SuperK 50 ktons)
Baseline is 295 km
Narrow-band beams (off-axis) peaked at 0.6 GeV
Most events are CC Quasi-Elastic

NOVA has functionally identical Near and Far detectors (finely grained liquid scintillator; 14kton far)
Baseline is 810km
Narrow band beam (off-axis) peaked at 1.9 GeV
Higher neutrino energy
Deep Inelastic Scattering occurs

Long Baseline Experiments – State of the Art



arXiv: 2410.0538410.0
NuFIT 6.0 (2024), www.nu-fit.org

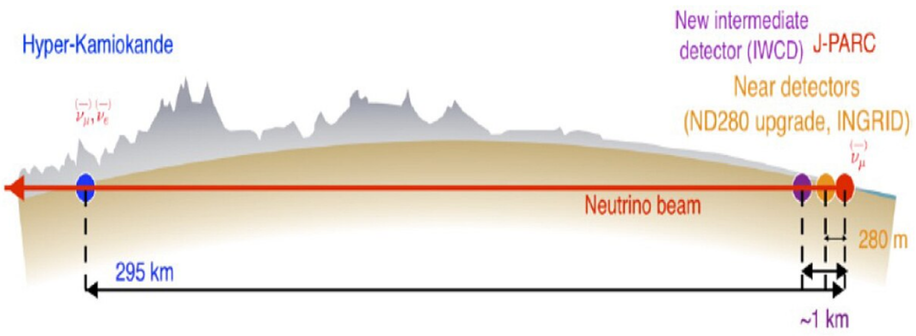
- NOνA , T2K mild preference for Normal Ordering
- For Normal Ordering - NOνA and T2K prefer different regions for δCP
- For Inverted Ordering – contours overlap

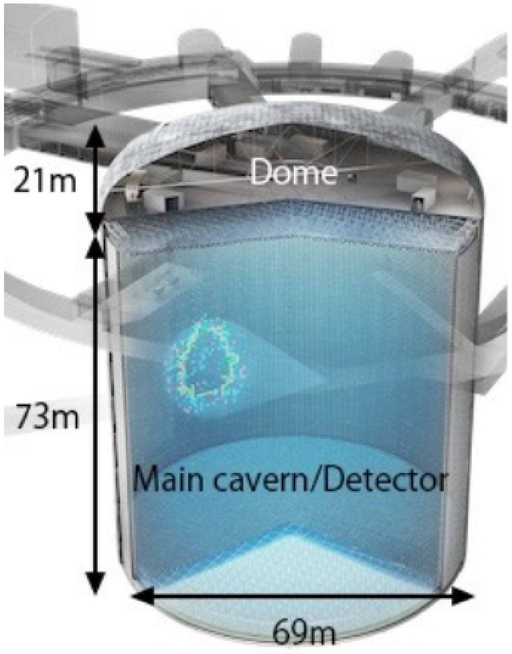
NOνA and T2K joint fit

- Preference for Inverted Ordering

Long Baseline Experiments – Future

HyperK

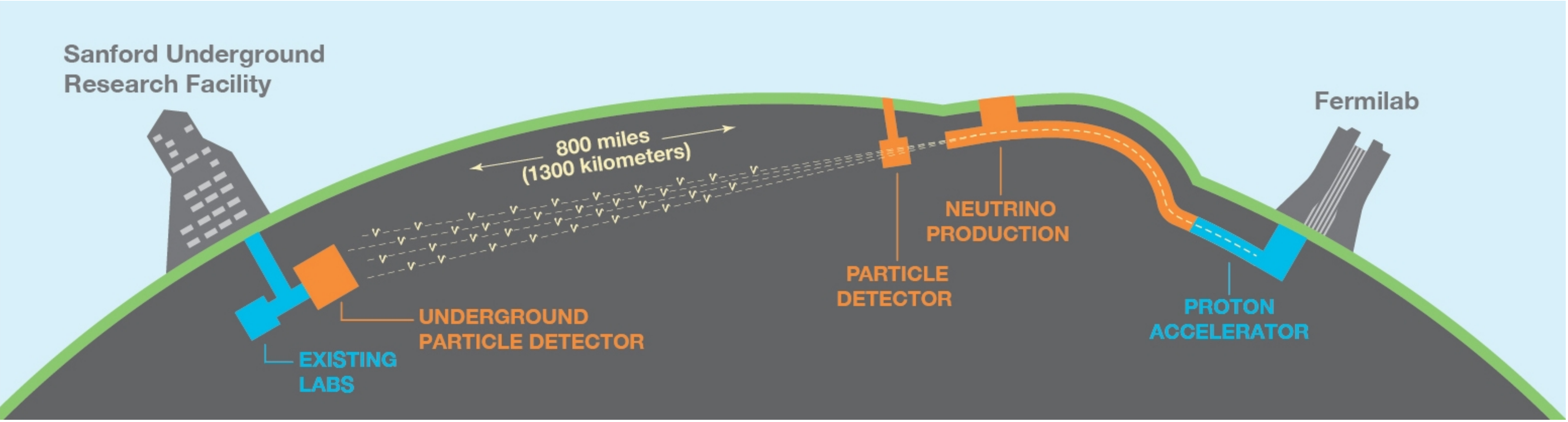




Same baseline (295km) and off-axis (2.5^0) as T2K
Increased beam power (1.3 MW)
8.4 times larger than SK (187 kton fiducial volume) – Water Cherenkov
Upgraded T2K Near Detectors
Construction now, expected start in 2028

and DUNE ...

DUNE is next generation neutrino oscillation experiment



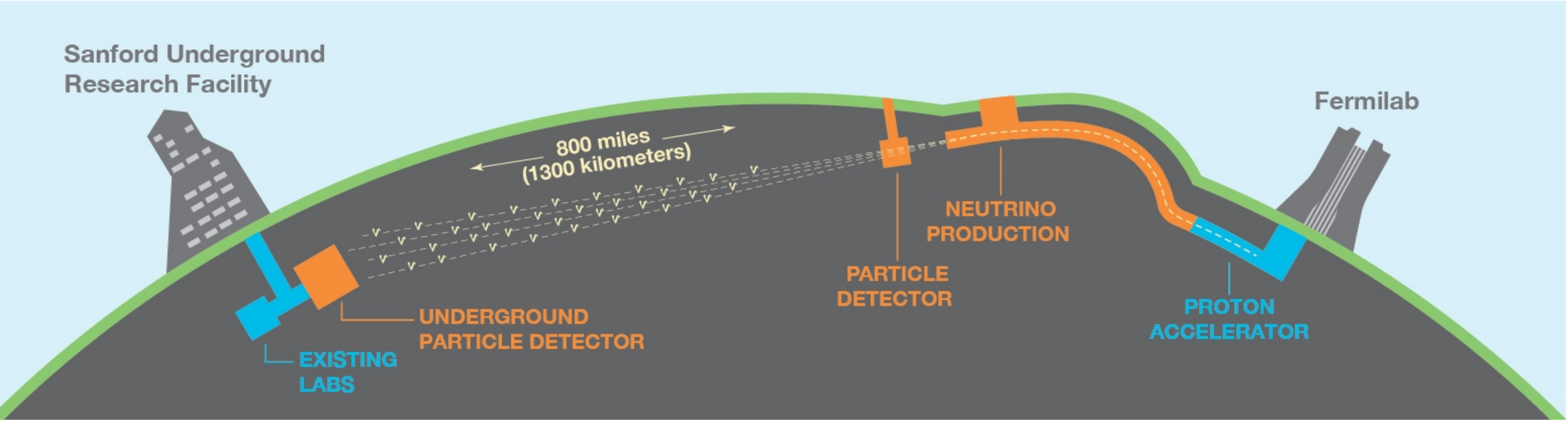
Far detectors at SURF:
4 x 17 kt Liquid Argon TPCs
1.5 km underground

Long baseline: 1300km

1.2 MW wide-band beam from Fermilab (upgradable to 2.4 MW)

Near Detector to measure initial composition

Physics Goals

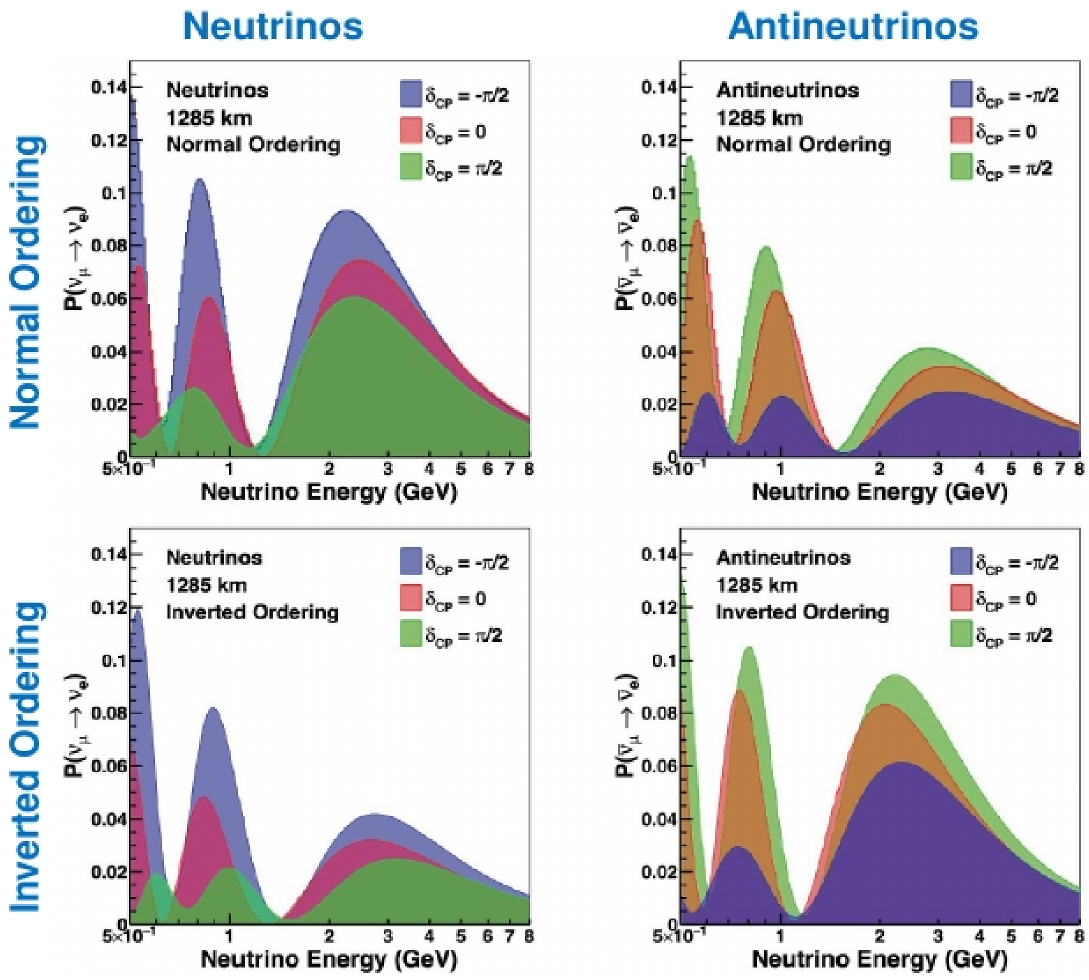


Neutrino oscillations : measure ν_μ disappearance + ν_e and ν_τ appearance (both neutrino and anti-neutrino modes)
Mass Ordering, leptonic CP Violation discovery, θ_{23} octant and more in a single experiment + physics beyond the Standard Model
Large underground detectors : Nucleon Decay searches, SuperNovae core collapse etc

DUNE

Long baseline (completely disentangle mass ordering and CP violation)
High power beam and gigantic far detectors (more stats)

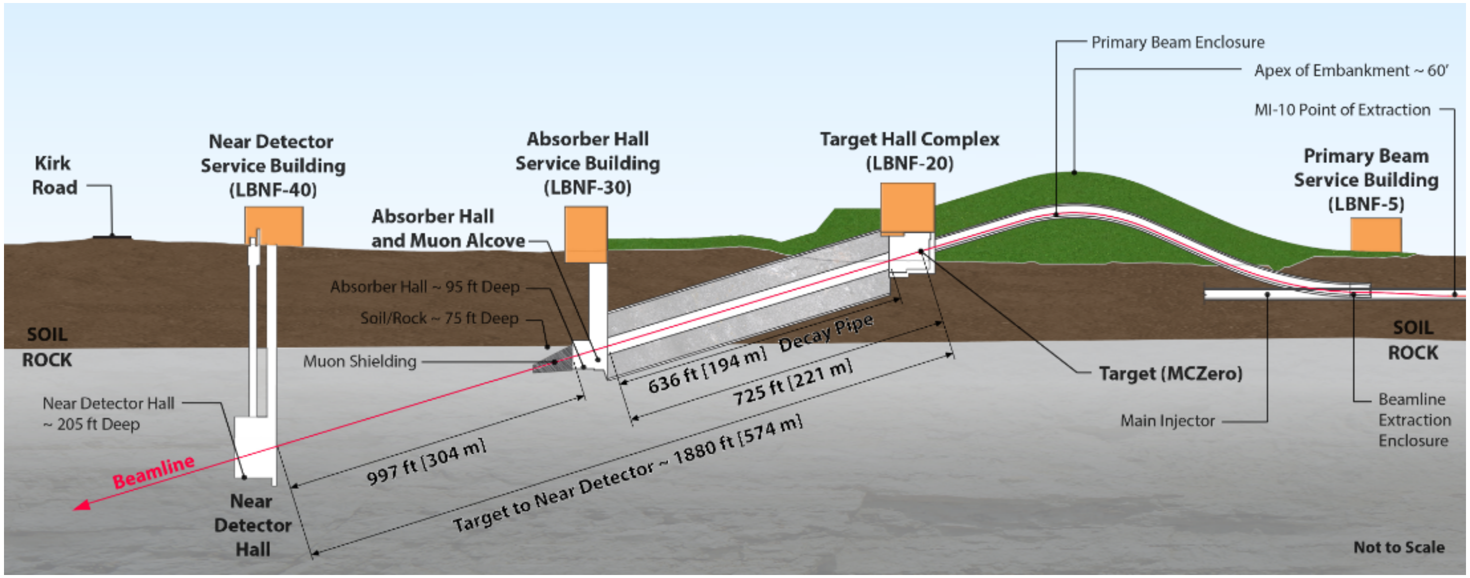
Make a spectral measurement
use a wide band beam
(neutrino/anti-neutrino mode)



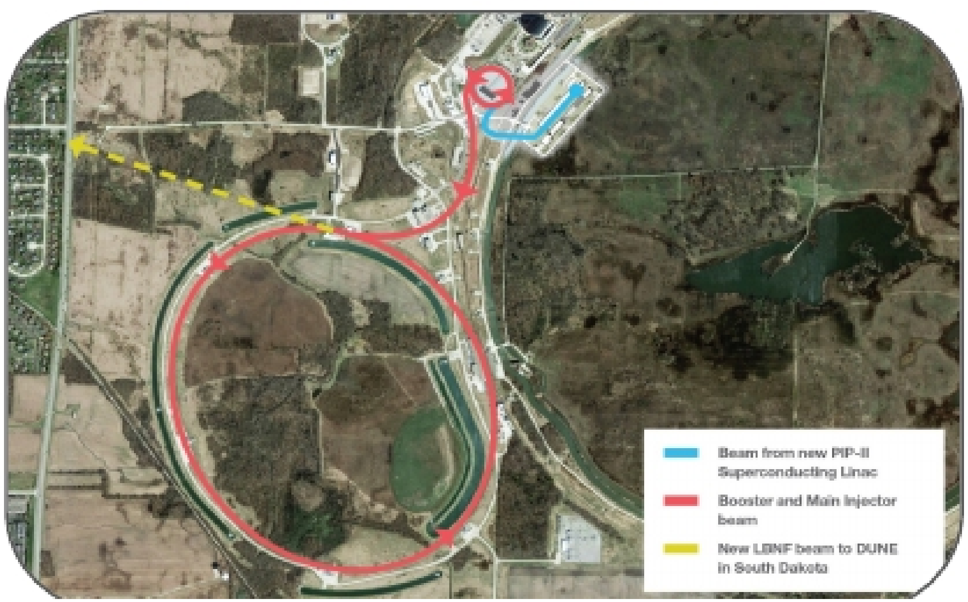
Measurement range spans 2 oscillation peaks

Gain additional power on deltaCP

Neutrino Beam



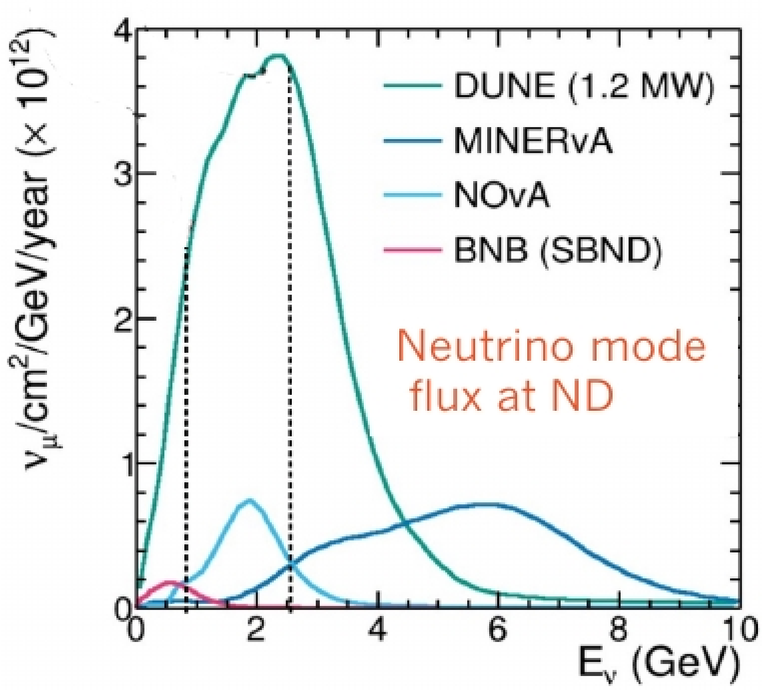
World's most intense neutrino (anti-neutrino) beam

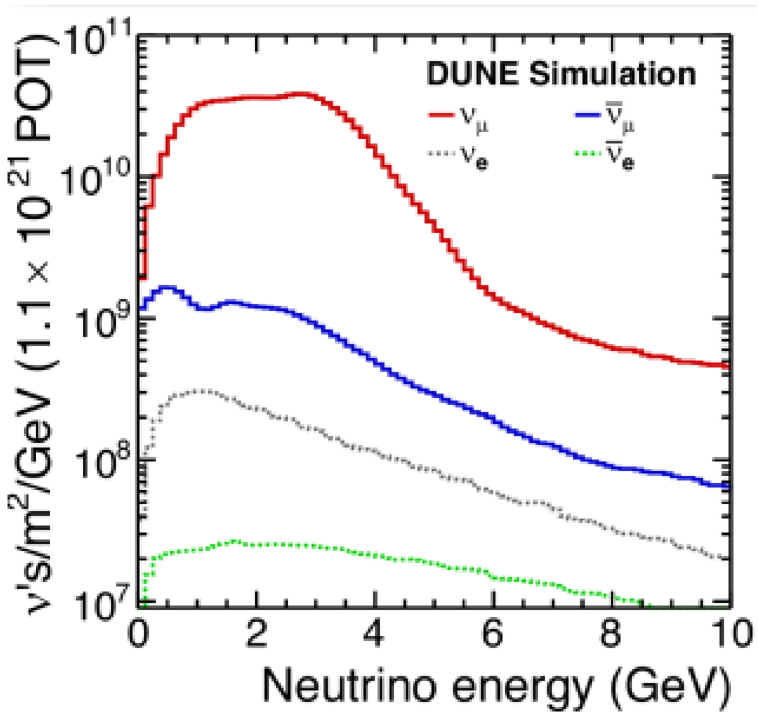


PIP-II construction
- first beam 2031
- reach 1.2 MW end of 2032

Phase-2
- upgrade to deliver 2.1 MW

Neutrino beam

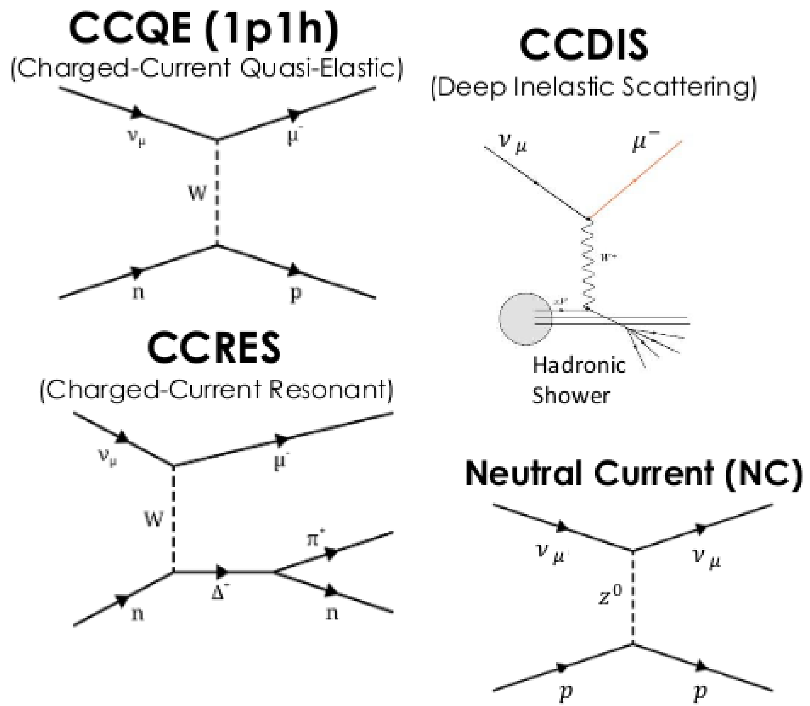




Wide band beam
2 oscillation maxima

Neutrino Signal

Neutrino interactions can be quite complex (multiple products and showers)

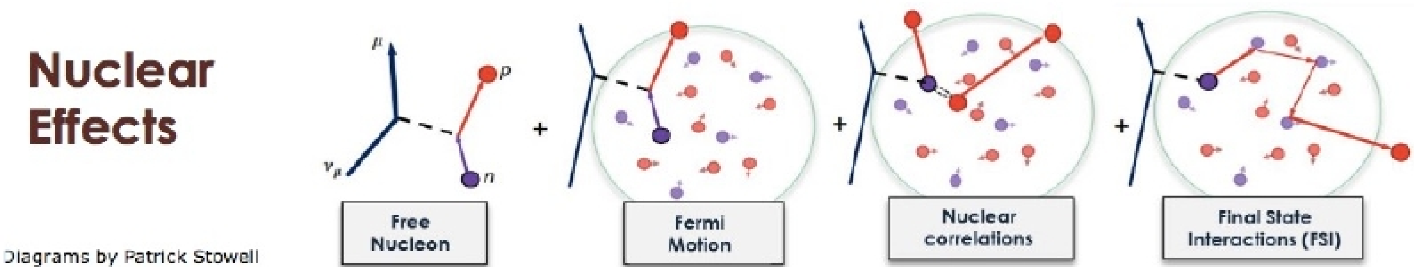


Neutrino flavour determined by outgoing lepton

Neutrino Energy Reconstruction dependent on Interaction Model

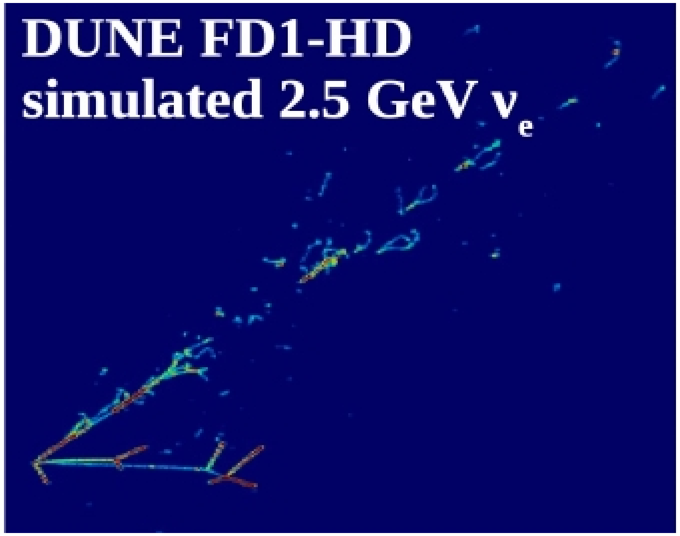
Not all products may be visible (neutrons)

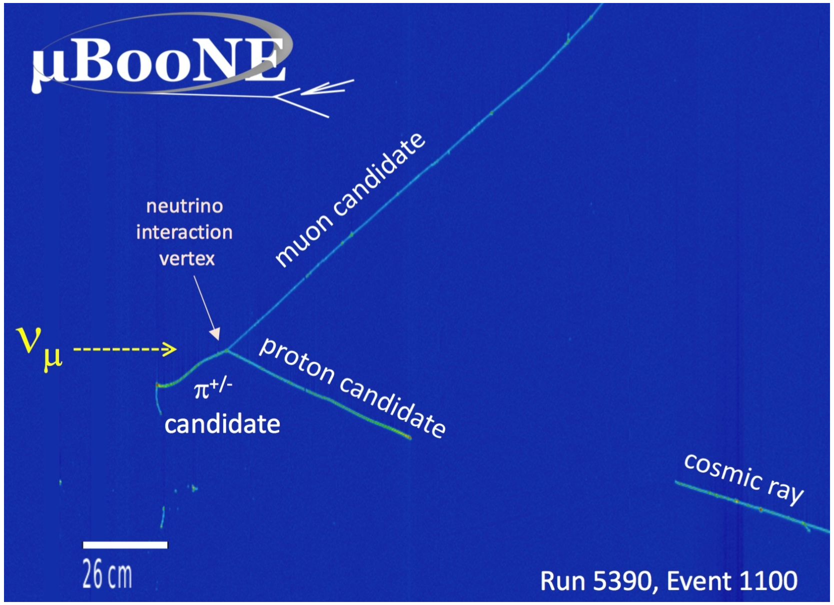
Need highly performing Near and Far detectors!

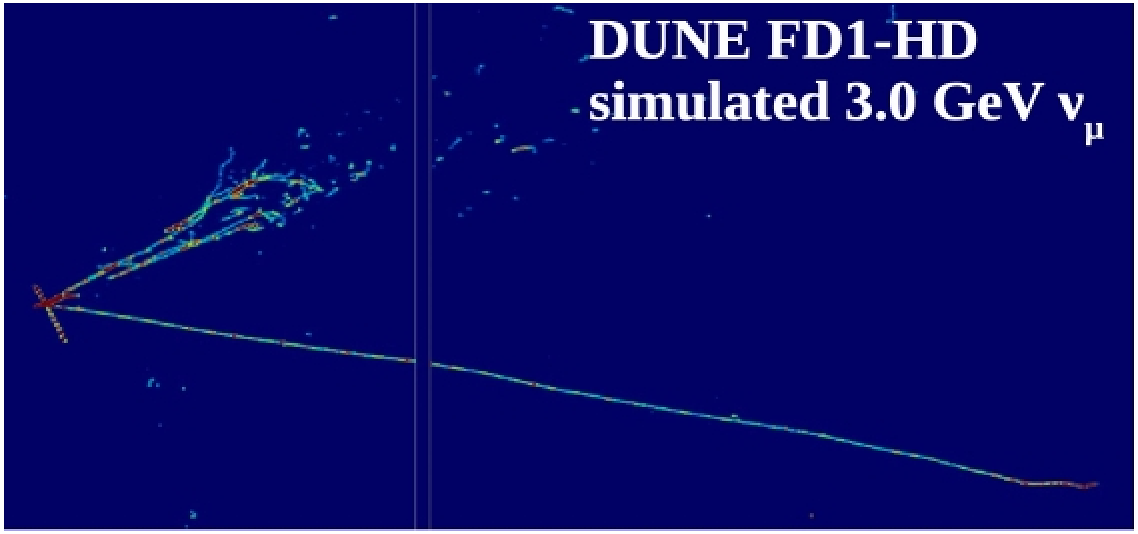


LAr TPCs

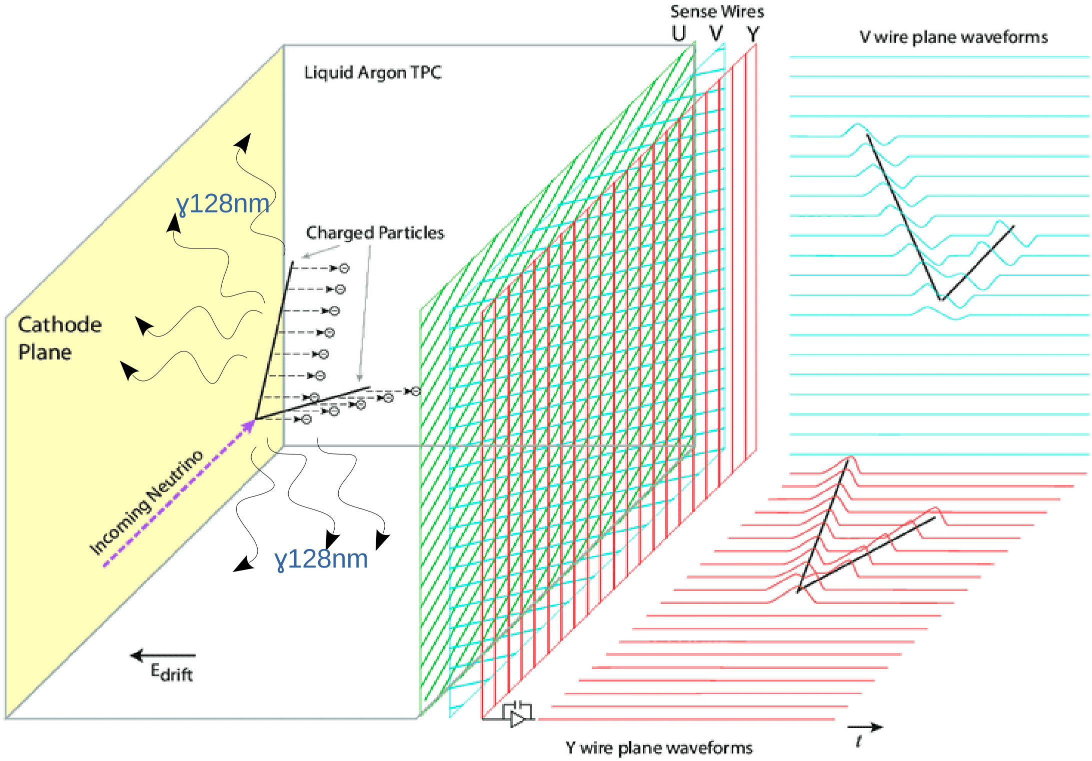
- Massive detectors (17 ktons Far Detectors)
- Fine-grain ‘images’ of neutrino interactions
- Separation ν_μ/ν_e
- Good energy reconstruction
- Low energy threshold







LAr TPC



- Prompt Scintillation signal (LAr 128nm)
  - Detected with PMTs/SiPMs (wavelength shifting)
  - Gives time-stamp of interaction (T0)
- Electric Field ~0.5kV/cm
- Drifts electrons towards anodes (mm/us)
  - Induces signals on wires
- Read out wires (strips)
- 3D Interaction Position
  - Drift time = Δ Arrival time (Charge - Light)

Near detector system

Predict the neutrino spectrum at the FD

Measure interactions on Ar

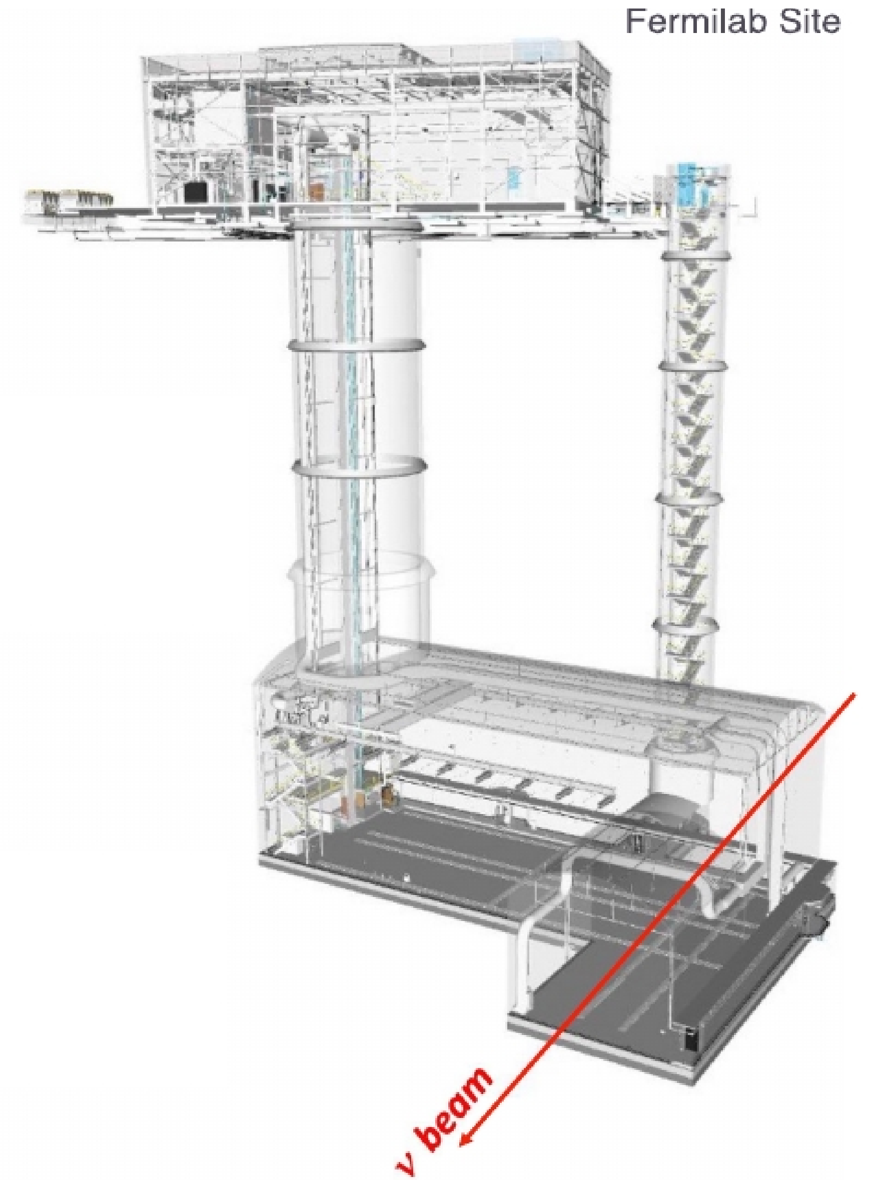
Measure neutrino energy

Constrain x-section model

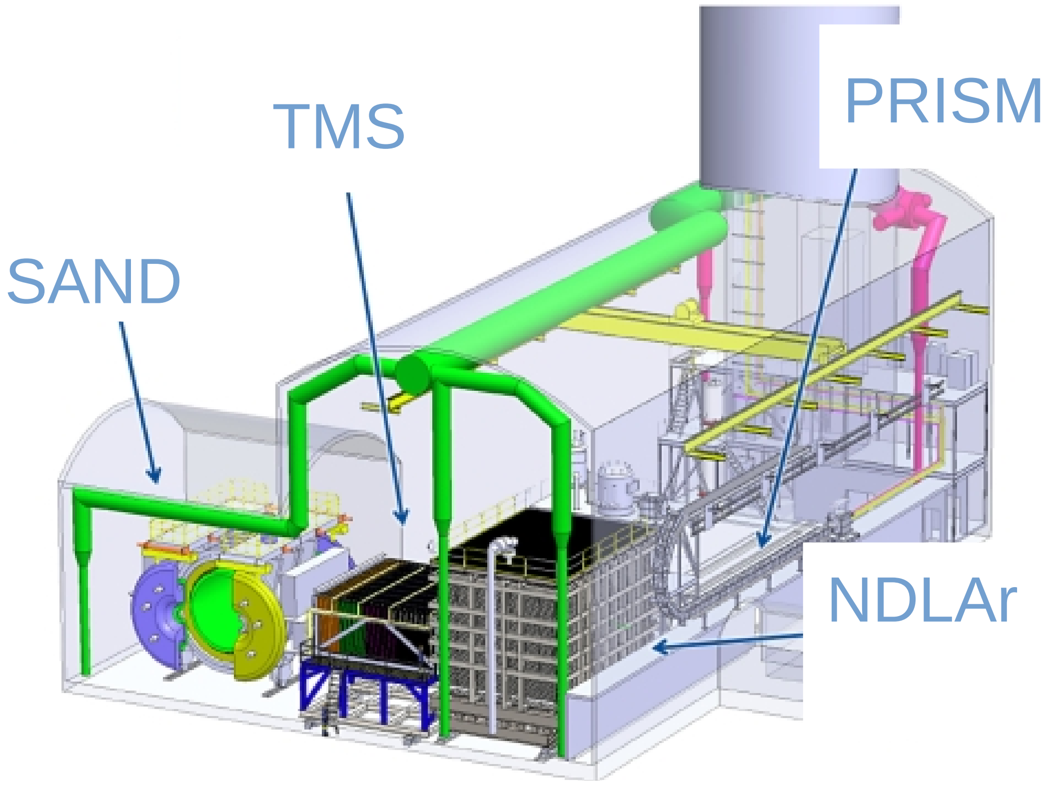
Measure neutrino flux

Obtain data with different fluxes

Monitor the neutrino beam



Near detector system



Suite of high performance detectors

NDLAr – 150t liquid argon TPC

The Muon Spectrometer – magnetised steel range stack
- measures sign and momenta of escaping μ

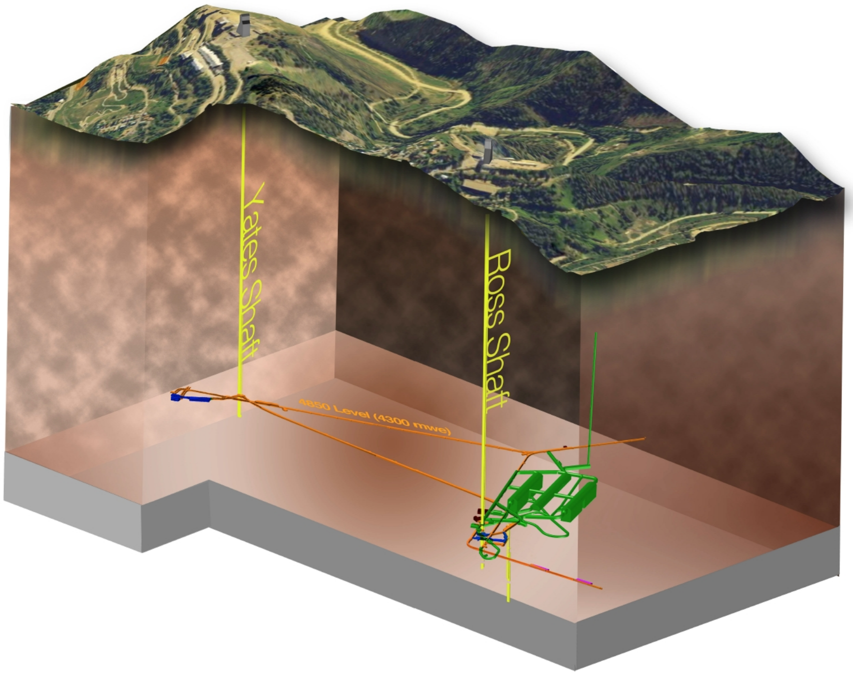
SAND – magnetized LAr Target (GRAIN), tracking (STT) and calorimeter (ECAL)
- Fixed On-axis beam monitor

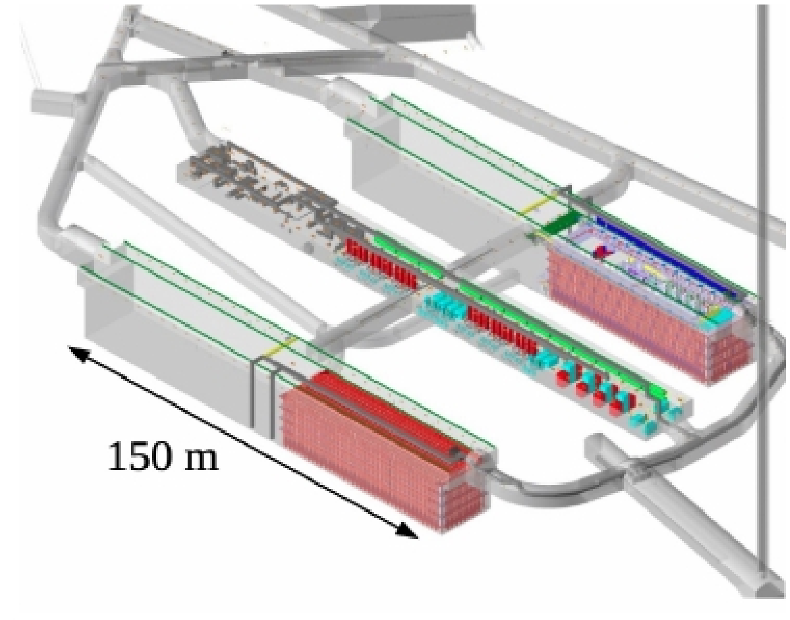
PRISM – Moveable component - NDLAr + TMS

Construction of Near site facilities starts 2025

Phase-2
- Upgrade TMS with Gas-Ar TPC (NDGar)

Far detector at SURF



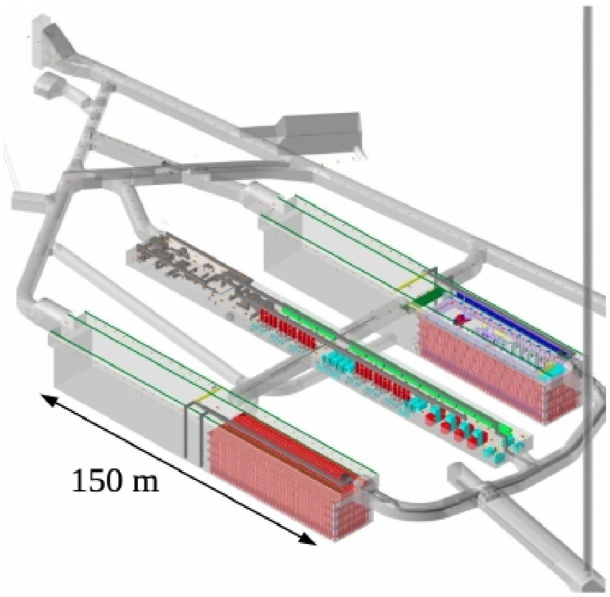


- Sanford Underground Research Facility in Lead, South Dakota
- Four 17-kt LAr TPC modules, located 1.48 km underground
- Excavation complete 2024
- FD1 – Horizontal Drift LArTPC
- FD2 – Vertical Drift LArTPC

Phase-2
- FD3 (decision 2027)
- FD4 module of opportunity (decision 2028)

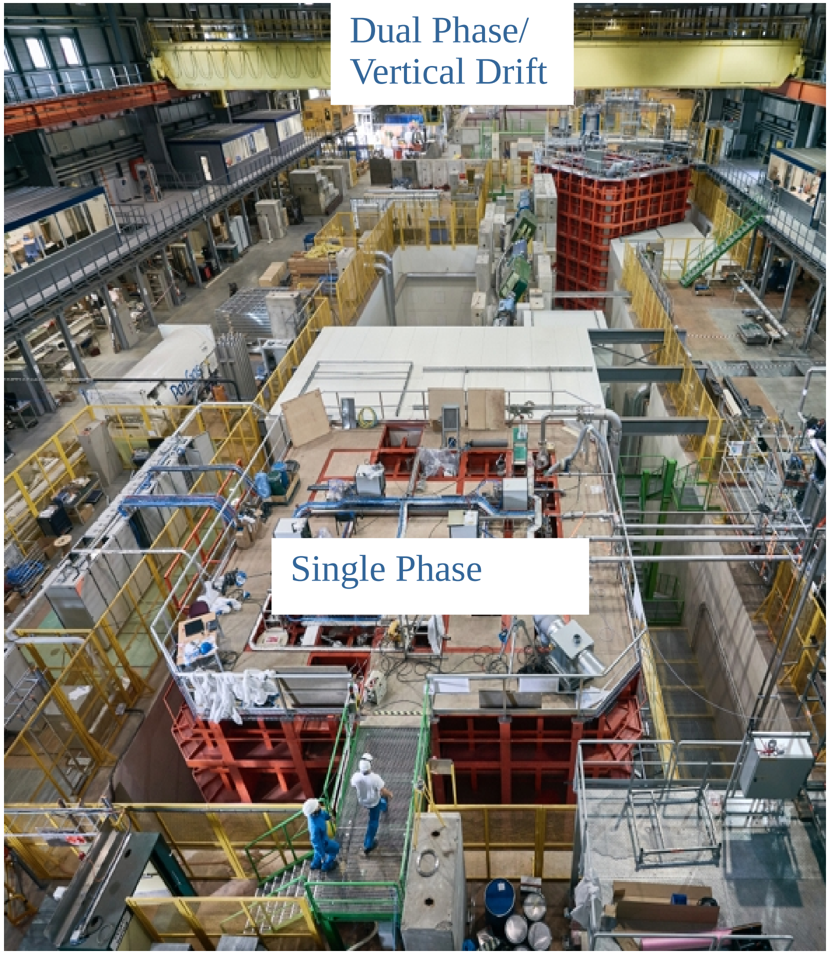
Far detector at SURF

- Sanford Underground Research Facility in Lead, South Dakota
- Excavation complete 2024
- Cavern infrastructure being installed now



ProtoDUNEs

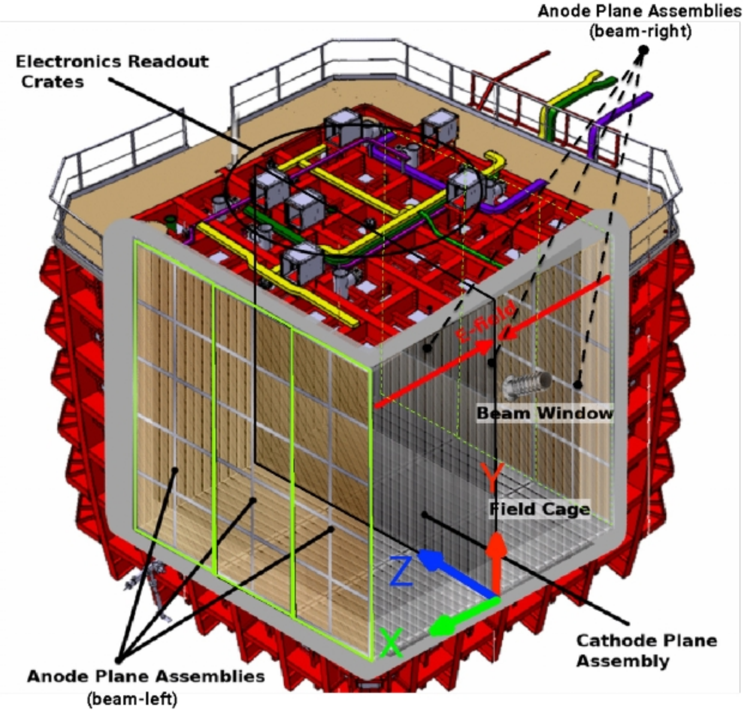
- TPC technologies tested with full-size components at the CERN neutrino platform – protoDUNEs
- Each cryostat holds 720 tons LAr
- Single Phase success (now Horizontal Drift)
- Experience with ProtoDUNE Dual Phase led to Vertical Drift
- Charged particle test beams to characterise detector response over the energy range of interest for DUNE (~0.5 GeV to 8 GeV)



CERN Neutrino platform

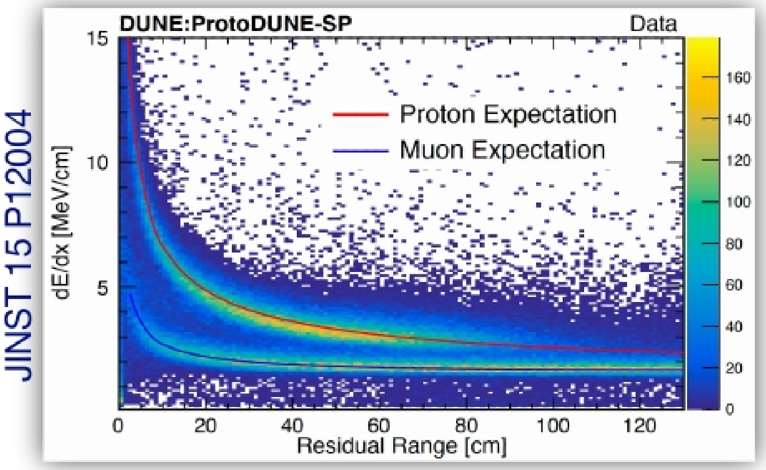
ProtoDUNE Single-Phase

- LArTPC (770 tons) in a charged-particle test beam
- Operated from August 2018 – July 2020
- Instrumented Beamline
- Known incident particle momentum - 300 MeV/c to 7 GeV/c
- First results paper: JINST 15 P12004



Detector Parameter	Specification	Goal	ProtoDUNE Performance
Electric Drift Field	> 250 V/cm	500 V/cm	500 V/cm *
Electron Lifetime *Impurity Concentration*	> 3 ms *(<100 ppt [O_2-equiv])*	10 ms *(<30 ppt [O_2-equiv])*	> ~30 ms in TPC ** *< 10 ppt*
TPC Electronics Noise	< 1000 e ENC	ALARA	550-650 e ENC (raw) 450-560 e ENC (cnr)***
TPC dead channels	< 1%	ALARA	0.2 % (of ~15,360 channels over 1.5 yr operation)
PhotoDetector Light Yield	> 0.5 Ph/MeV (at cathode plane - 3.6 m distance)		1.9 Ph/MeV ++ (at 3.3 m distance)
PhotoDetector Time Resolution	< 1μs	< 100 ns	14 ns ^^

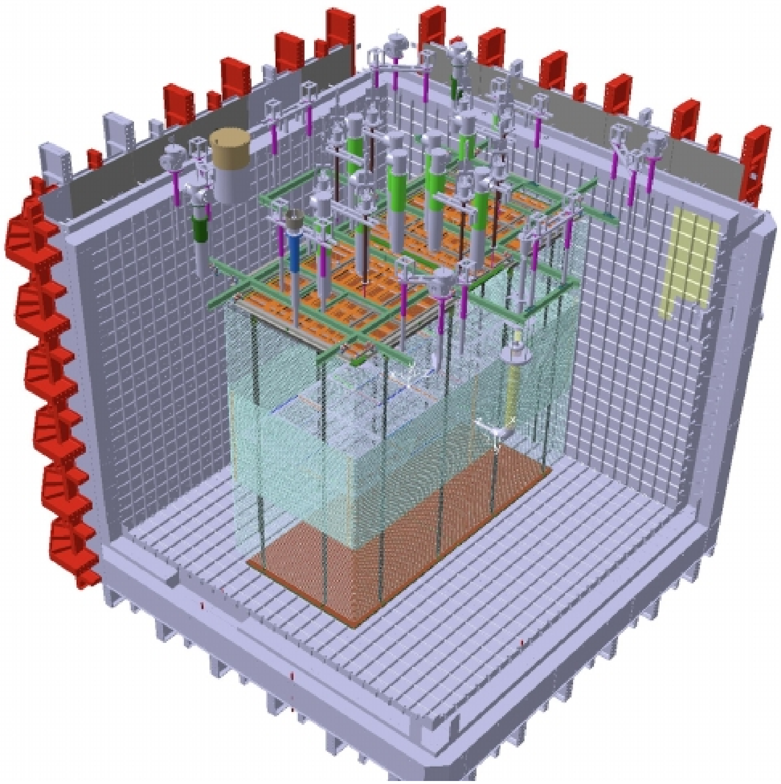
* 99.5% uptime. ** in TPC EF=500 V/cm, in PurMon EF=20 V/cm - (< 10 ppt [O_2-equiv] during beam run).
*** coherent noise removed. ++ from extrapolation based on actual ARAPUCA data. ^^ two pulse separation.



Stopping muon and proton dE/dx vs. residual range in ProtoDUNE-SP.

ProtoDUNE Vertical-Drift

- Large-scale test of the Vertical Drift design in the NP02 cryostat in the Neutrino Platform at CERN
- Active volume: 3 × 6.8 × 7 m2
  - 2 CRPs top
  - 2 CRPs bottom
  - 2 Cathode modules
- Operated at -175 kV



Top volume

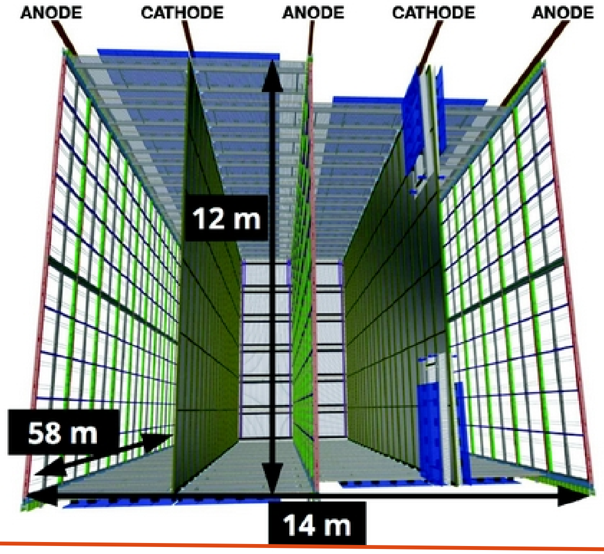
Bottom volume

Operating at CERN now!

Far detector at SURF

Horizontal Drift

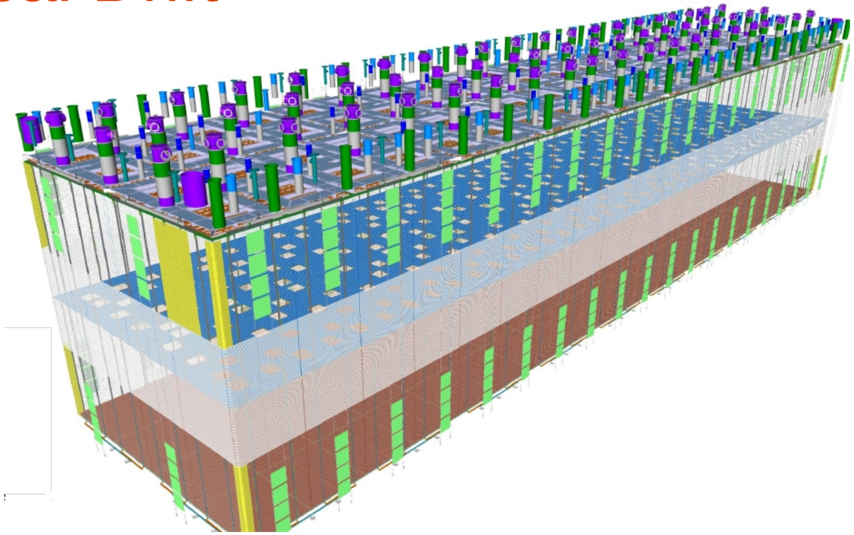
FD1



- Modular design
  - 500 V/cm horizontal-drift (HD) field
  - 3.5-meter drift length
- Wire plane charge read-out
- Photodetectors (Arapuca) embedded in Anode Plane Assemblies

Vertical Drift

FD2



- Two volumes
  - 500 V/cm vertical-drift (VD) field
  - 6-meter drift length
- PCB charge read-out
- Top electronics replaceable
- Xe-doping
- Photodetectors (Arapuca) embedded in HV Cathode and on membrane

Neutrino Oscillations

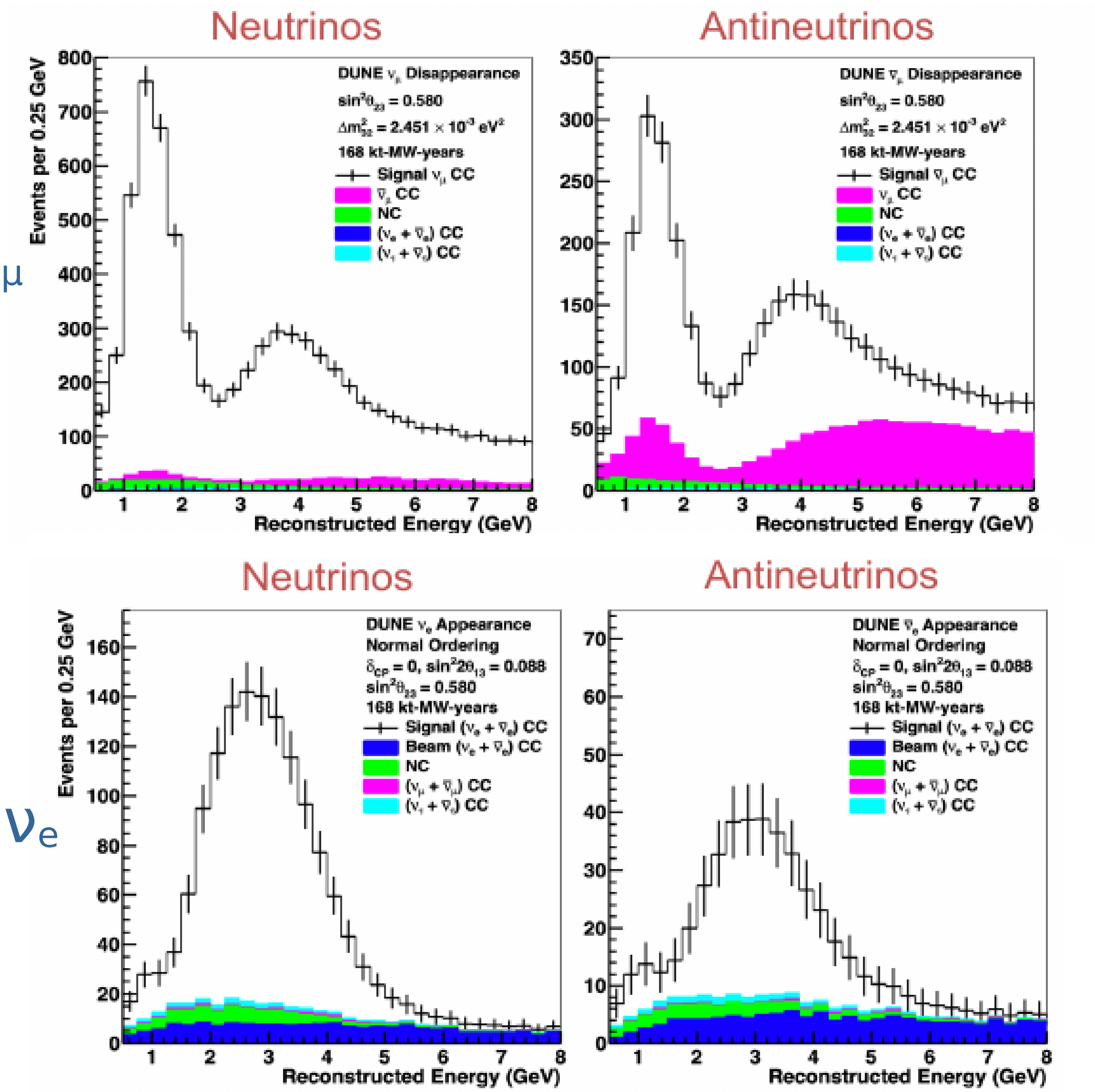
~7 years running

Measure appearance and disappearance for both neutrino and anti-neutrinos

Order of 10,000 ν_μ and 1,000 ν_e

ν_μ

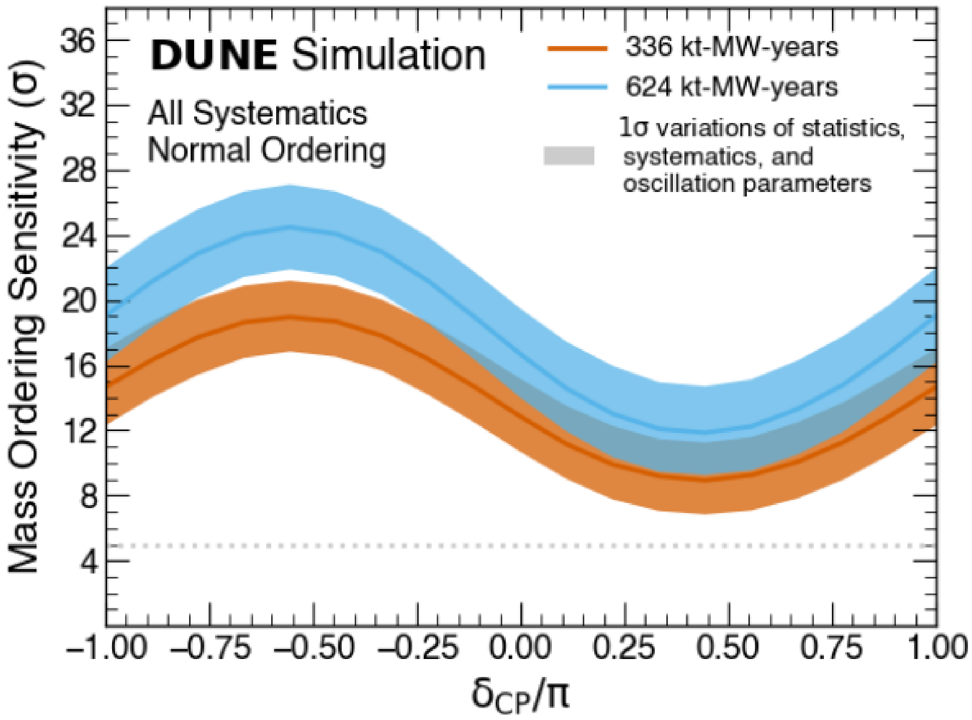
ν_e

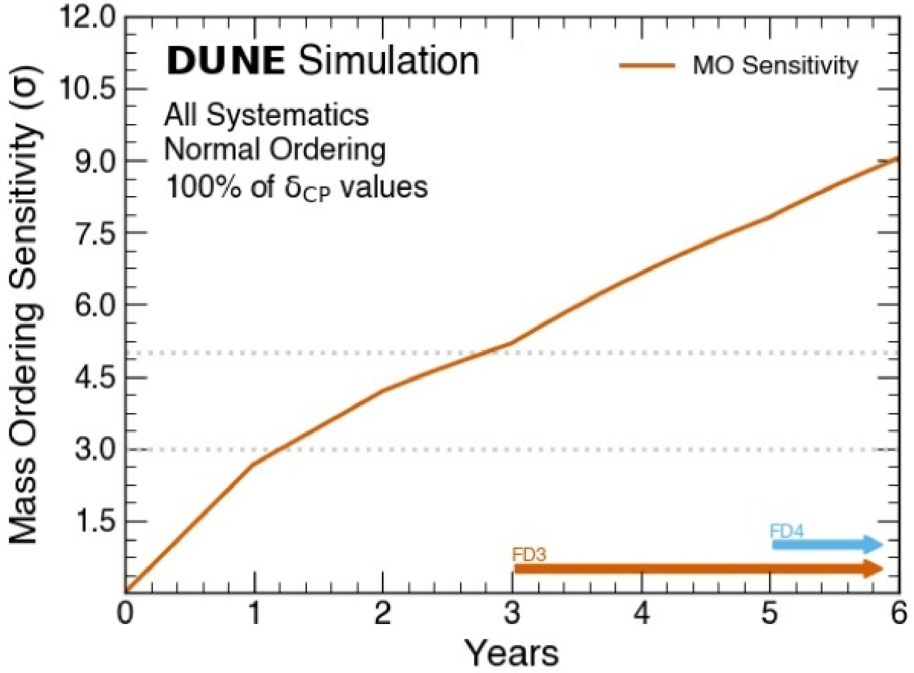


DUNE Technical Design Report (TDR) arXiv:2002.03005

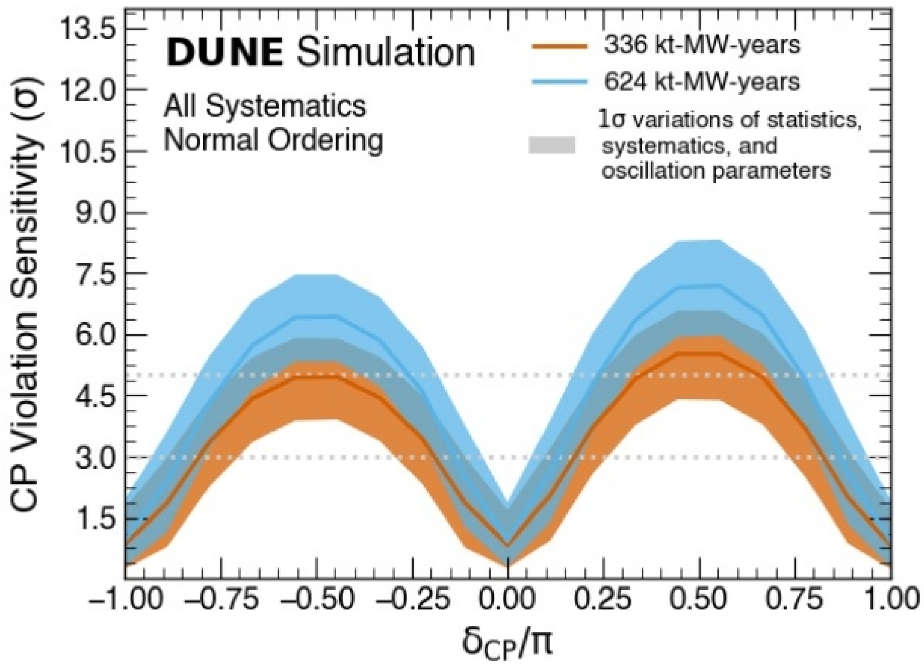
Sensitivity – Mass Ordering

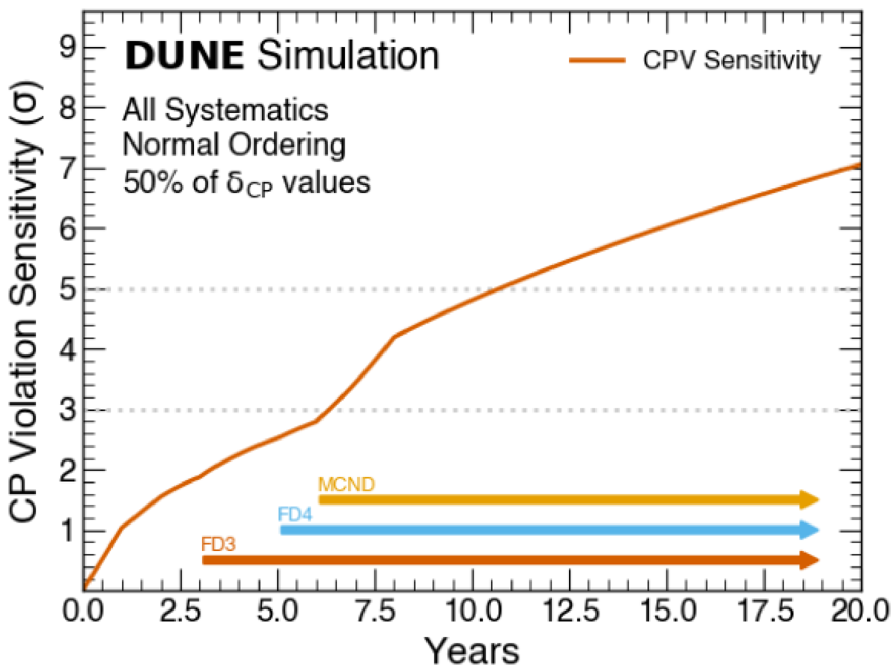
Determine neutrino mass ordering at 3σ (5σ) with 66 (100) kt-MW-yr exposure



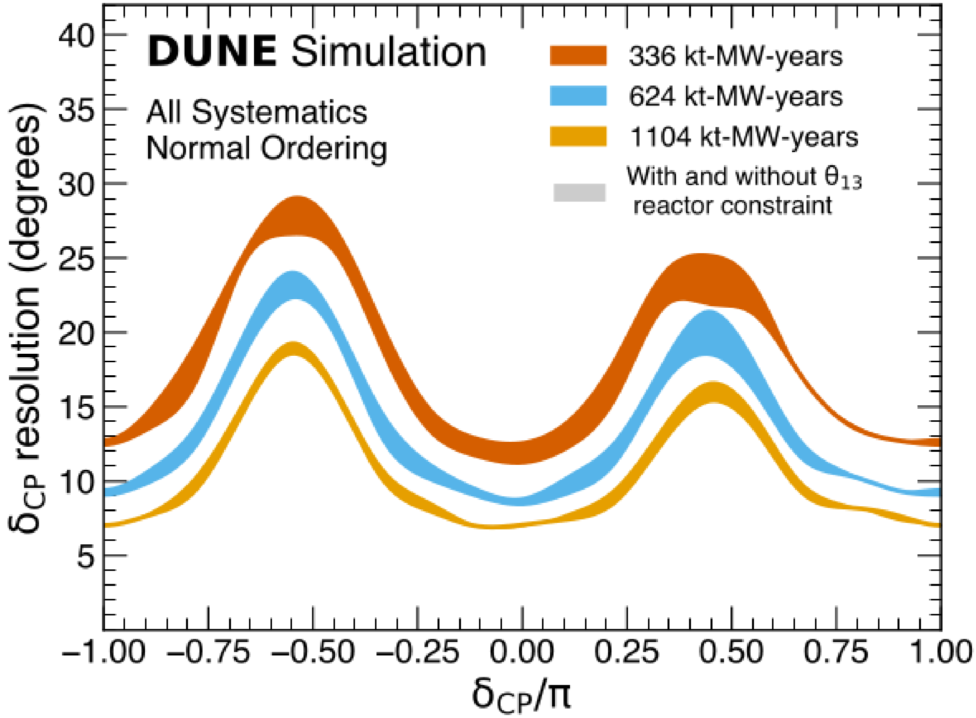


Sensitivity – CP violation

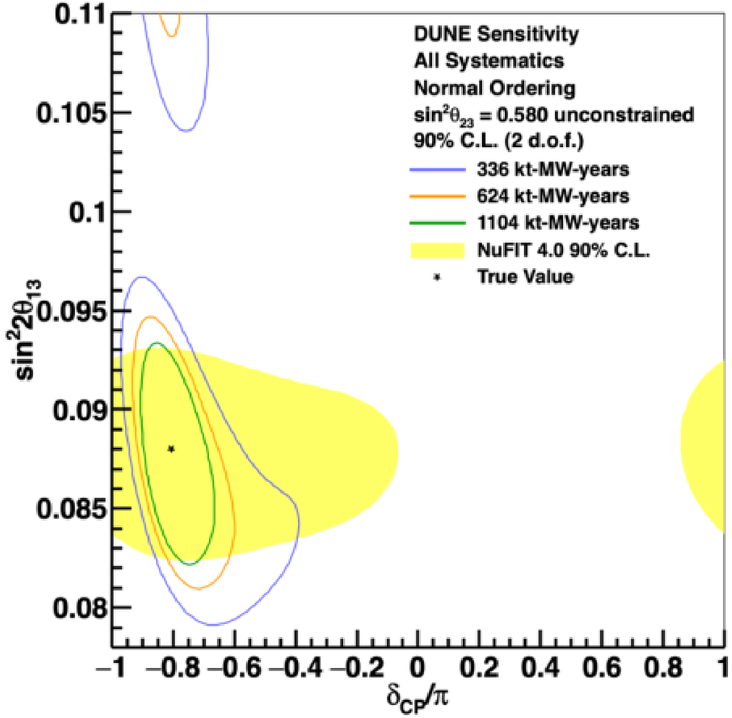




Precision Measurements



Oscillation parameters:
Δm^2_{32}, δ_{CP}, θ_{23}, θ_{13}



Off-beam program

Astrophysical Neutrinos
Galactic supernova
Solar

Atmospheric Neutrinos

BSM physics (at Near and Far)

Deviations from 3-flavour oscillation (sterile ν, NSI, PMNS non-unitarity, CPT violation etc)

Other new physics: Neutrino trident rate, dark matter, baryon number violation

and more !

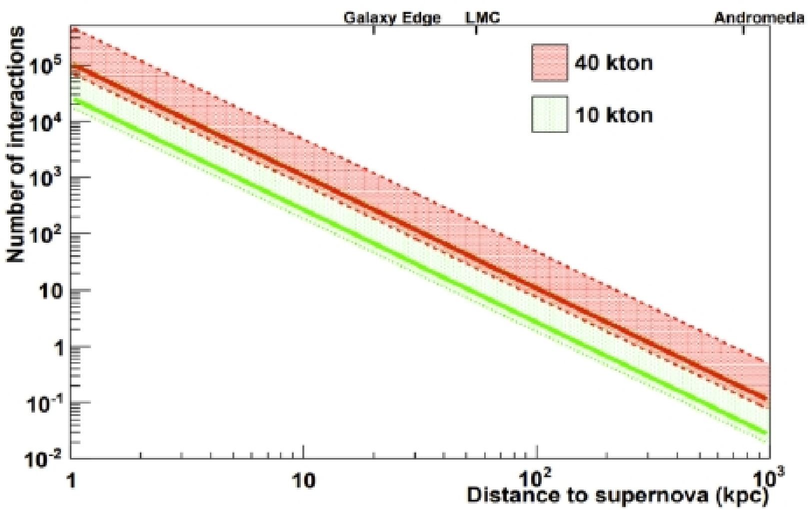
Galactic SuperNova

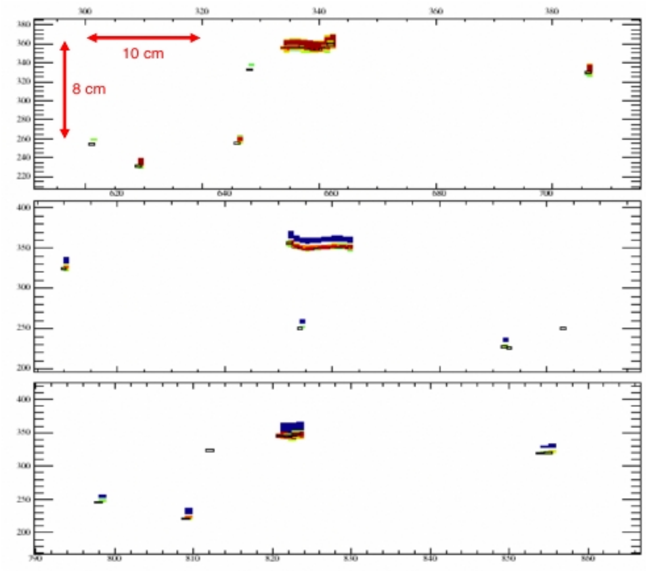
Uniquely DUNE is sensitive to ν_e

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

Also elastic-scattering

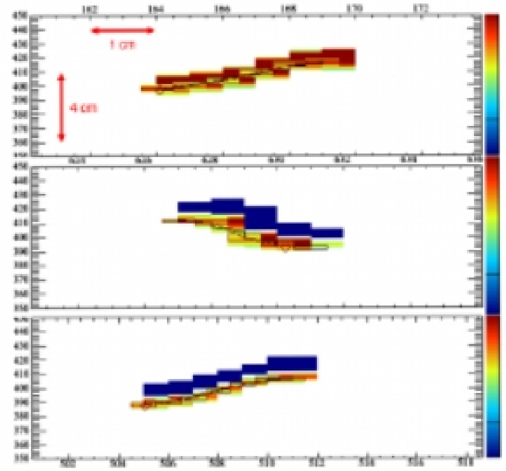
5-50 MeV signals





20.25 MeV νeCC

10 MeV electron
(Simulation+Reconstruction)



10.25 MeV νES

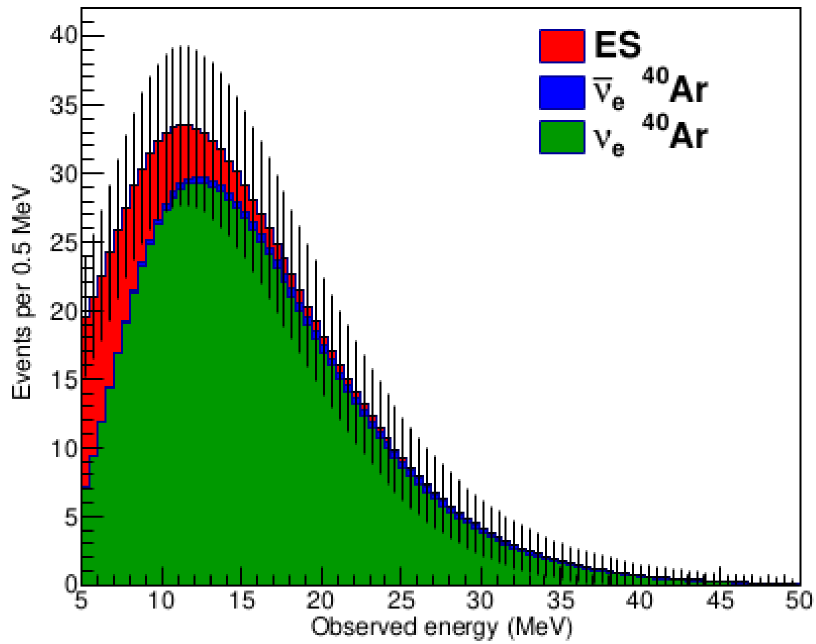
2008.06647

Galactic SuperNova

SN trigger – (Light and Charge signals)
Continuous data-taking, all waveforms stored for 100s (with 10s pre-trigger)

Light signal provides:
- SN signal arrival times
  - Global triangulation (SuperNova Early Warning System)
- Position in drift direction needed to correct of electron drift loss (Energy estimate)

ES short tracks – forward scattering allows direction estimate



'Garching' model SN as seen by 40 ktons DUNE (inc detector response)

2008.06647

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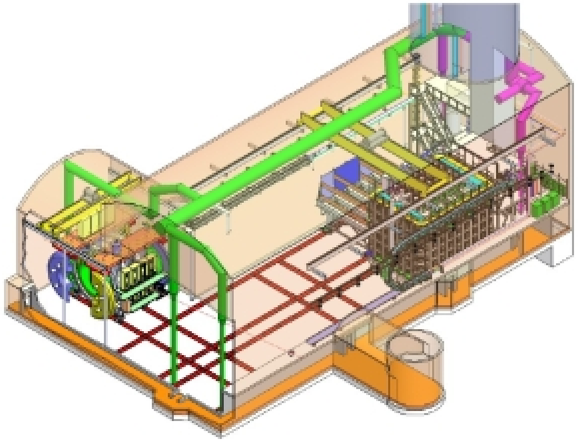
Schedule

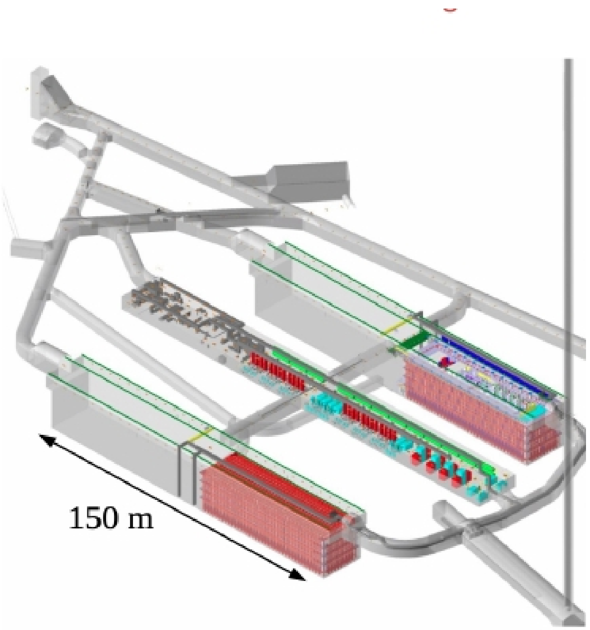
Phase 1

- Excavation complete 2024
- Far Detector
  - FD1 installation begins 2026
  - Running by 2028
  - FD2 installation begins 2029
- New neutrino beam 2031
- Near Detector System 2031
  - Moveable NDLAr + TMS
  - On-axis Near detector (SAND)

Phase 2

- Far Detector
  - +FD3 FD4
    - Increased physics scope
  - Neutrino beam upgrade (2.4 MW)
- Near Detector upgrade





Summary

- Next generation long baseline neutrino experiments will obtain thousands of events
  - Unambiguous determination of the mass hierarchy
  - Achieve 5-sigma level sensitivity to CP violation
  - Precisely measure neutrino oscillation parameters

- DUNE will meet the challenge
  - High power broadband beam
  - Long baseline
  - Fine imaging neutrino events with LarTPCs

- DUNE has a wide physics program
  - Physics beyond the Standard Model
  - Large underground detectors: preparation for a galactic SuperNova