Vulcano Workshop 2024 - Frontier Objects in Astrophysics and Particle Physics

The DUNE Experiment

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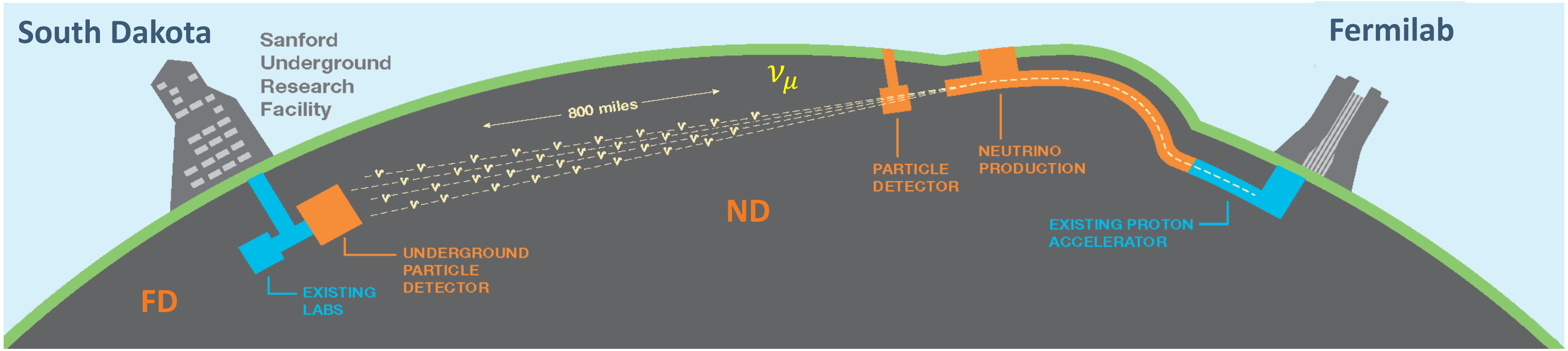
for the DUNE Collaboration

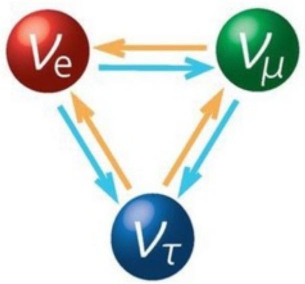
The Deep Underground Neutrino Experiment (DUNE) and the Long Baseline Neutrino Facility (LBNF)

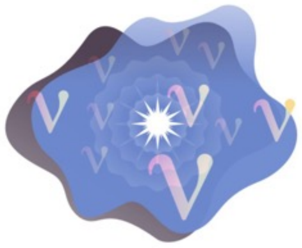


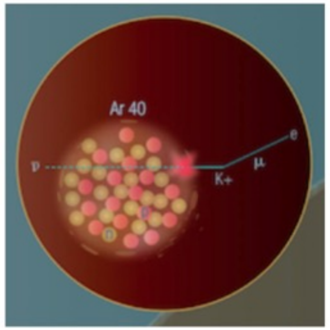
A new generation long baseline neutrino oscillation experiment based on:

- $\nu/\bar{\nu}$ **beam** wide band **~ 1-10 GeV** - high intensity: **1.2 MW** upgradeable **to 2.4MW** produced at FNAL
- **Near Detector** complex at Fermilab, **576 m** from the neutrino source
- **Far Detector**
  - **1300 km** away from neutrino source
  - **1.5 km underground** at the Sanford Underground Neutrino Facility (SURF)
  - **4 modules 17 kt each** Liquid Argon Time Projection Chambers (LArTPCs)

DUNE: Physics Program







- Long- baseline wide-band neutrino beam
  - Measurement of CP violation phase and determination of the neutrino mass ordering in a single experiment with spectral information
- Underground location → access to astrophysical neutrinos
  - Supernova neutrino burst detection – sensitive to the ν_e component
  - Atmospheric neutrino – capability of ν_τ identification
  - Solar neutrinos – potential for detection of hep flux
- Massive detectors with excellent tracking and calorimetric information
  - Search for baryon number violating processes – $p \rightarrow \nu K+$, $n\,\bar{n}$
- Long baseline + higher energy neutrino beam
  - ν_τ appearance, NSI searches
- Capable Near Detector Complex
  - Precise neutrino physics
  - BSM searches

Neutrino oscillations: impressive progress since 1998

PMNS* neutrino mixing matrix

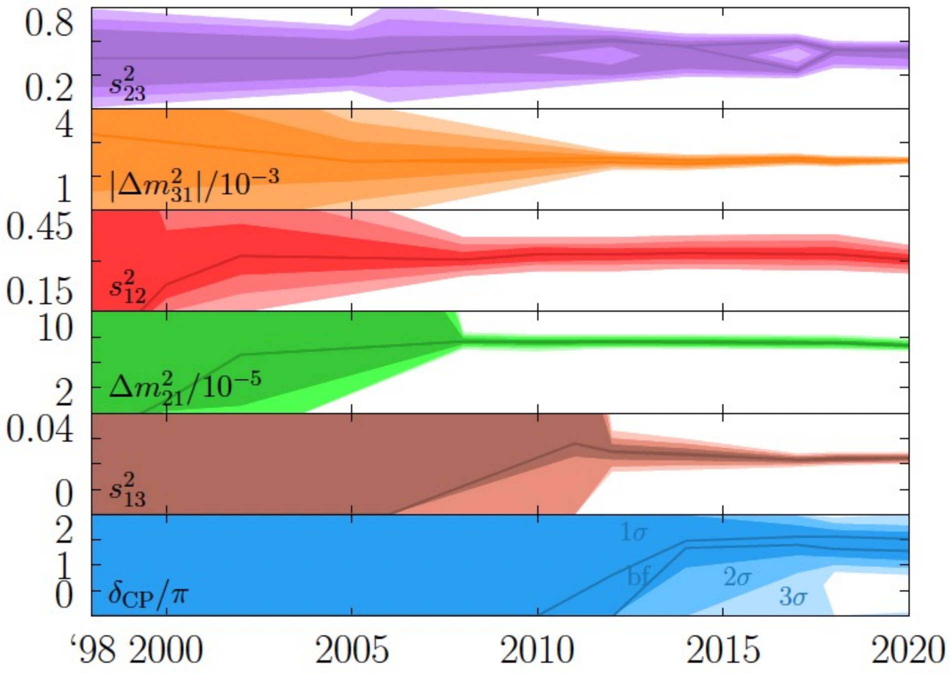
*Pontecorvo Maki Nakagawa Sakata

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

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix}$$

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

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

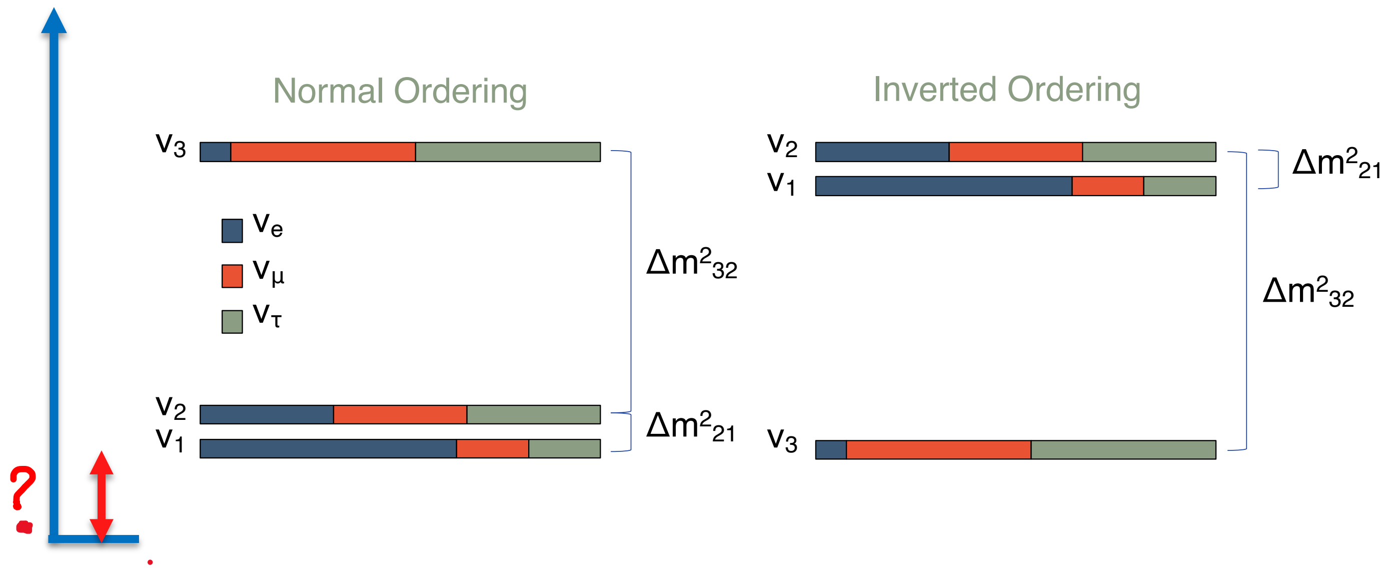


arXiv:2212.00809

	θ_{23}	θ_{13}	θ_{12}	δ
Leptons *	49	8.5°	34°	140°-370° (3σ range)
Quarks	2.4°	0.20°	13°	68°

*NO/PDG2022

Open Questions and Unknowns

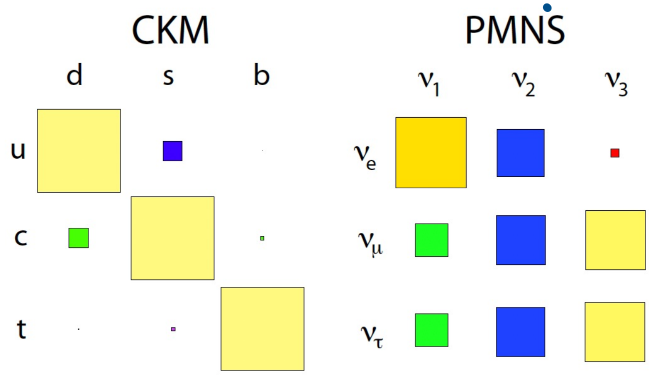


- What is the neutrino mass ordering? (Is Δm^2_{32} positive or negative?)
- Is there leptonic CP violation?
- Is θ_{23} mixing maximal?
- Is the PMNS matrix unitary?

- What is the neutrino absolute mass scale?
- Are neutrinos Majorana particles?
- Can neutrinos explain the matter-antimatter asymmetry in the Universe?

	θ_{23}	θ_{13}	θ_{12}	δ
Leptons	$\sim 45°$	$8.5°$	$34°$	?
Quarks	$2.4°$	$0.20°$	$13°$	$69°$

Is the θ_{23} mixing maximal?
$\theta_{23} = 45° \rightarrow |U_{\mu 3}| = |U_{\tau 3}|$



LBL Oscillation Probabilities in the 3-neutrino framework

ν_e appearance : mass ordering, δ_{CP} , octant of θ_{23}

$$P_{\nu_\mu\to\nu_e,(\bar\nu_\mu\to\bar\nu_e)} \approx 4\,\sin^2\theta_{13}\,\sin^2\theta_{23}\frac{\sin^2\Delta}{(1-A)^2} + \alpha^2\sin^2 2\theta_{12}\,\cos^2\theta_{23}\frac{\sin^2 A\Delta}{A^2} + 8\,\alpha\,J_{\rm CP}^{\rm max}\cos(\Delta\pm\delta_{\rm CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{1-A}$$

$$J_{\rm CP}^{\rm max} = \cos\theta_{12}\sin\theta_{12}\cos\theta_{23}\sin\theta_{23}\cos^2\theta_{13}\sin\theta_{13}$$

$$\Delta \equiv \frac{\Delta m^2_{31}L}{4E_\nu} \qquad A \equiv \frac{2E_\nu V}{\Delta m^2_{31}} \qquad \alpha \equiv \Delta m^2_{21}/\Delta m^2_{31} \qquad V_C = \sqrt{2}G_F n_e\,.$$

for $\bar\nu$
- «minus» sign
- V→ -V

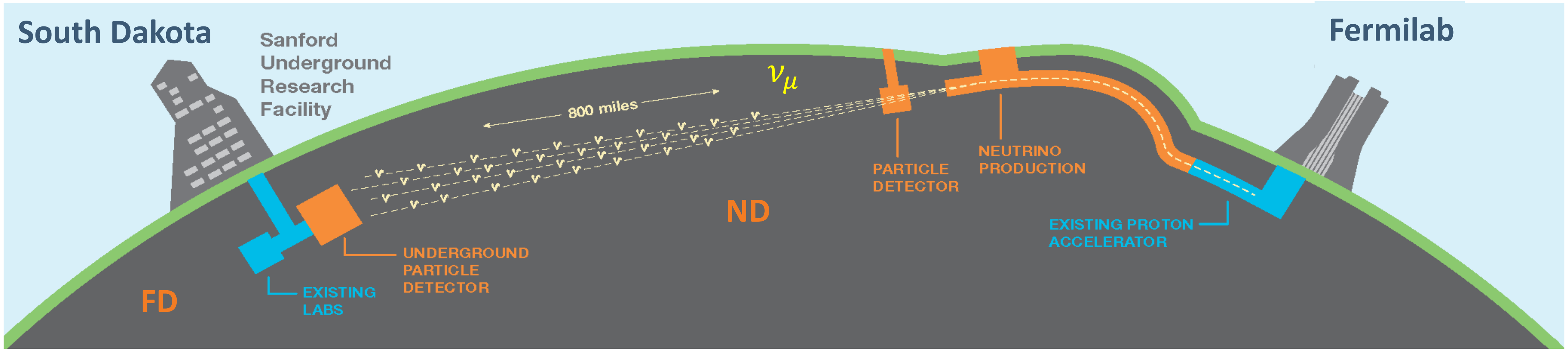
α, Δ , A are sensitive to the sign of Δm^2_{31}

ν_μ disappearance: $|\Delta m^2_{32}|, \sin\vartheta^2_{23}$, constrain octant

$$P_{\nu_\mu\to\nu_\mu} \approx 1-\sin^2 2\theta_{\mu\mu}\sin^2\frac{\Delta m^2_{\mu\mu}L}{4E_\nu} \approx 1-\cos^2\theta_{13}\sin^2(2\theta_{23})\sin^2\frac{\Delta m^2_{32}L}{4E_\nu} + \mathcal{O}(\alpha, s^2_{13})$$

$$\begin{aligned}\sin^2\theta_{\mu\mu} &= \cos^2\theta_{13}\sin^2\theta_{23}\,,\\ \Delta m^2_{\mu\mu} &= \sin^2\theta_{12}\Delta m^2_{31} + \cos^2\theta_{12}\Delta m^2_{32}\\ &\quad + \cos\delta_{\rm CP}\sin\theta_{13}\sin 2\theta_{12}\tan\theta_{23}\Delta m^2_{21}\end{aligned}$$

DUNE's way to Mass Ordering and δ_{CP}



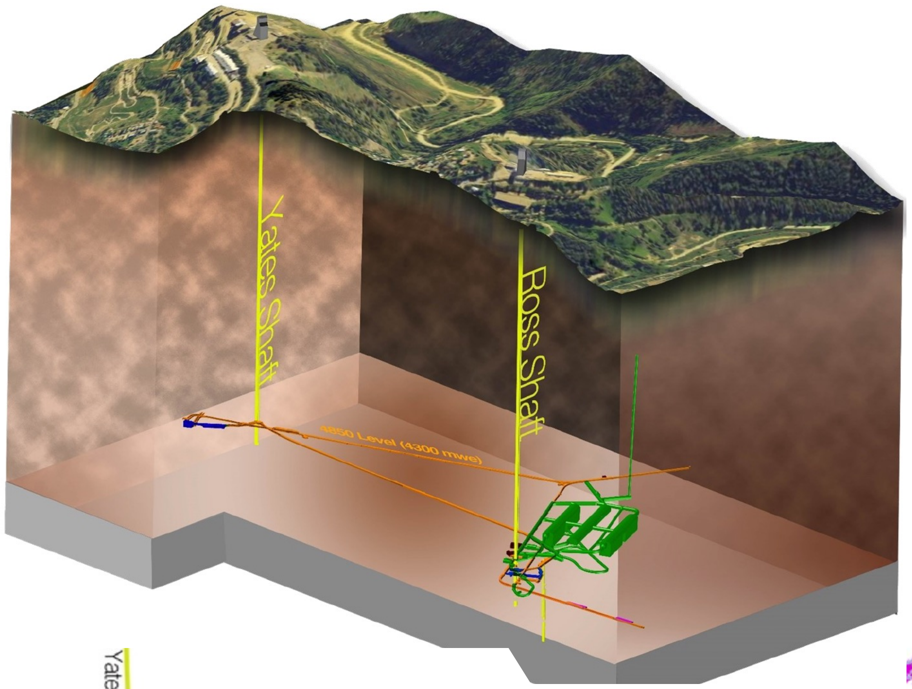
measurement of ν_μ **unoscillated beam** at the **Near Detector** :

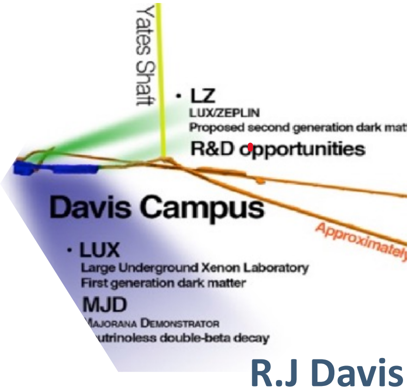
measurement of **oscillated ν_μ & ν_e spectra** at the **Far Detector** :

Then repeat for antineutrinos – and compare oscillations of neutrinos and antineutrinos

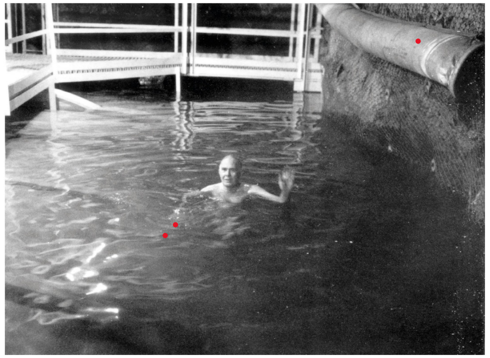
Sanford Underground Research Facility - SURF

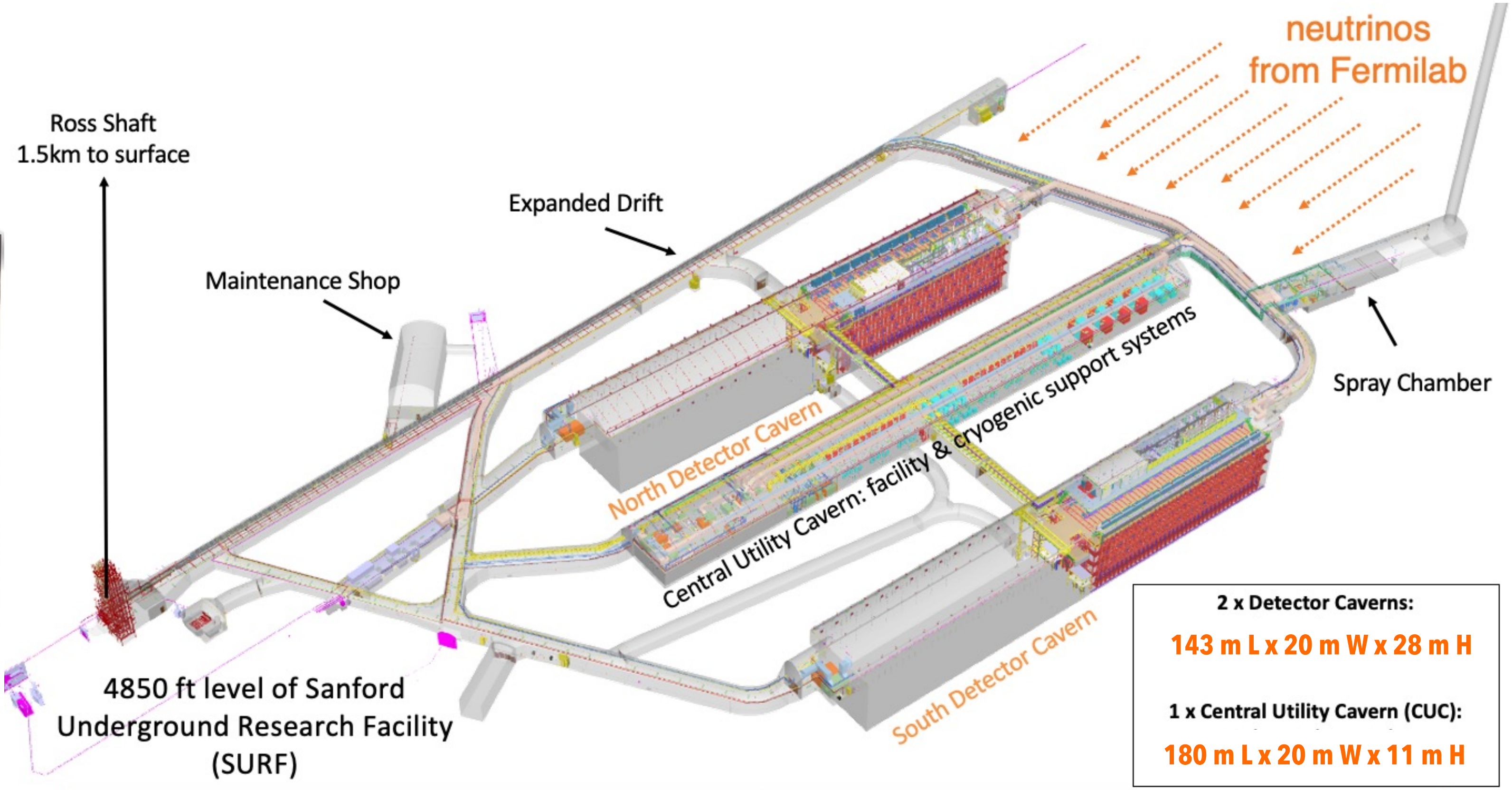
Previously known as the Homestake (gold)
Mine in the Black Hills in South Dakota





R.J Davis

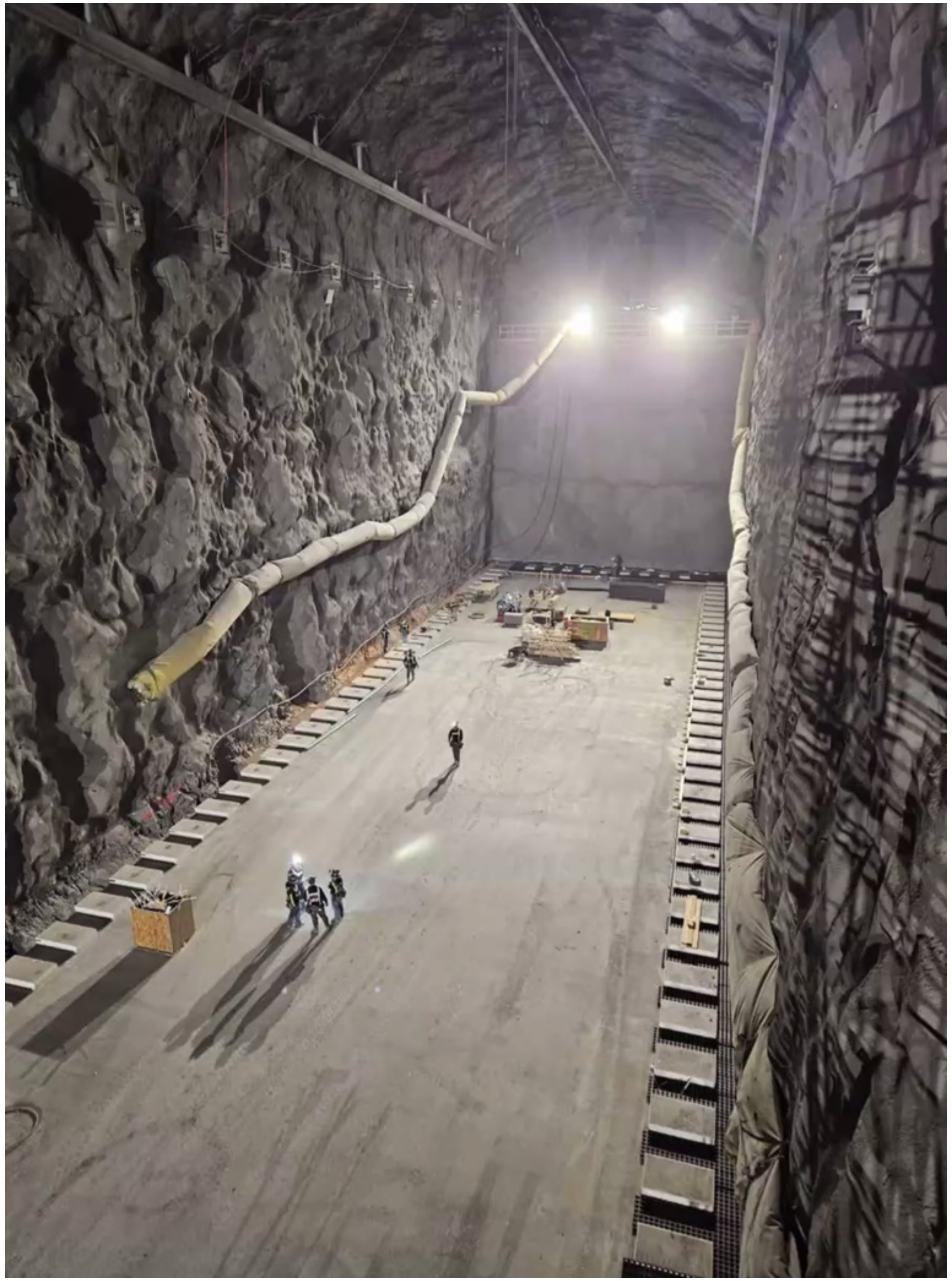




2 x Detector Caverns:
143 m L x 20 m W x 28 m H

1 x Central Utility Cavern (CUC):
180 m L x 20 m W x 11 m H

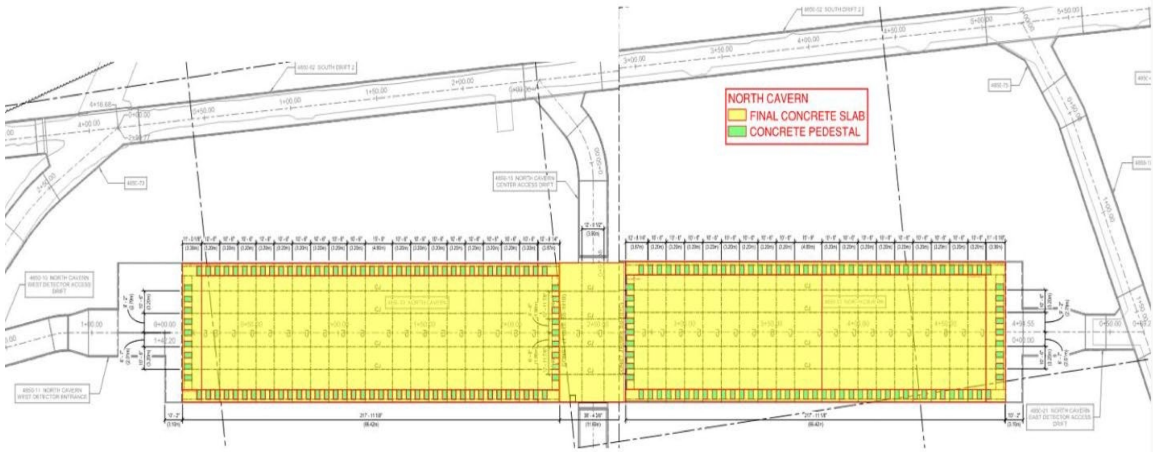
Excavations at SURF completed



North /South Caverns 145 m L x 20 m Wx 28 m H

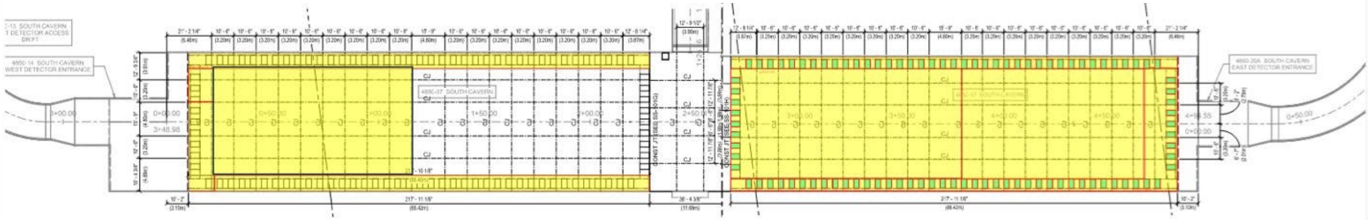
Outfitting of North Cavern, South Cavern & Central Utility Cavern

North Cavern Concrete



South Cavern Concrete

SOUTH CAVERN
FINAL CONCRETE SLAB
CONCRETE PEDESTAL

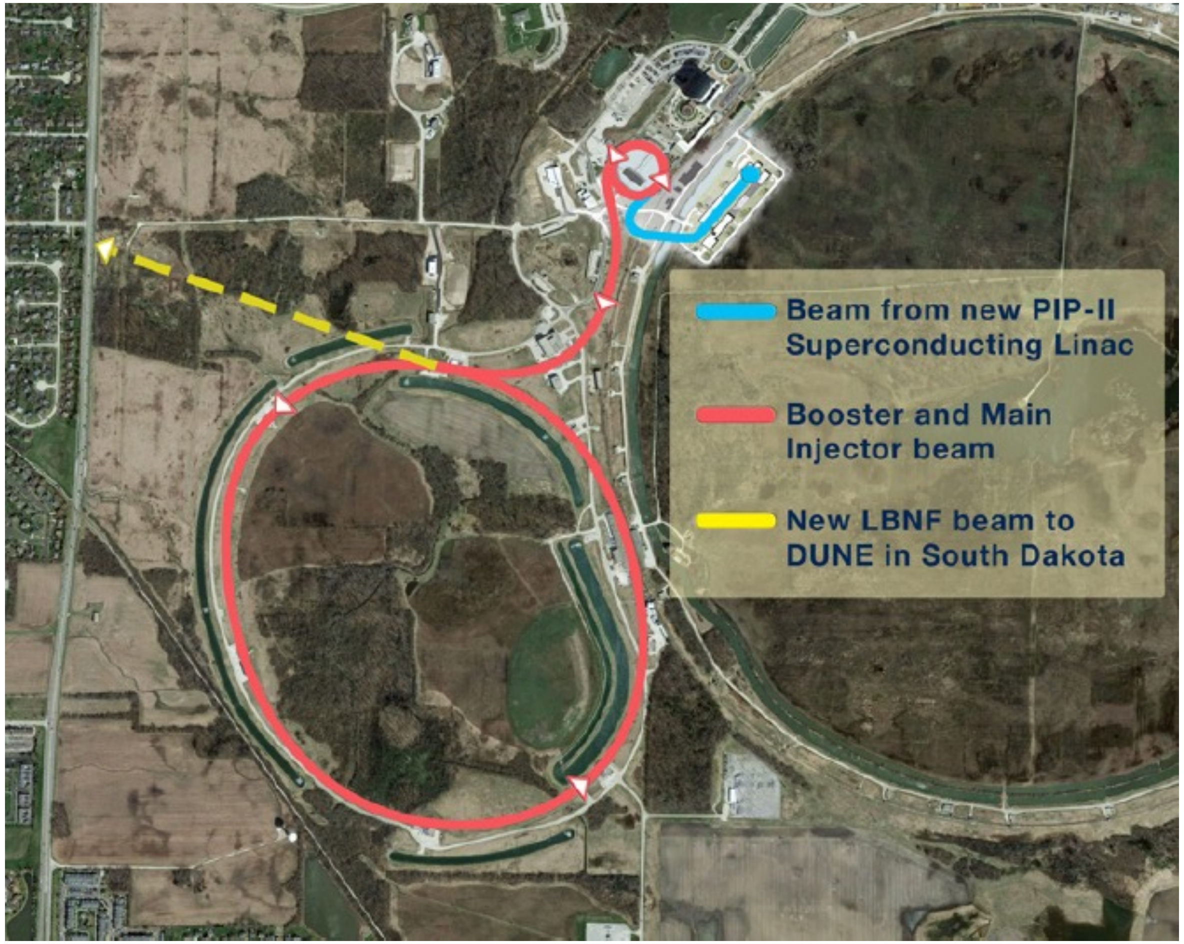


145 m L x 20 m W x 28 m H

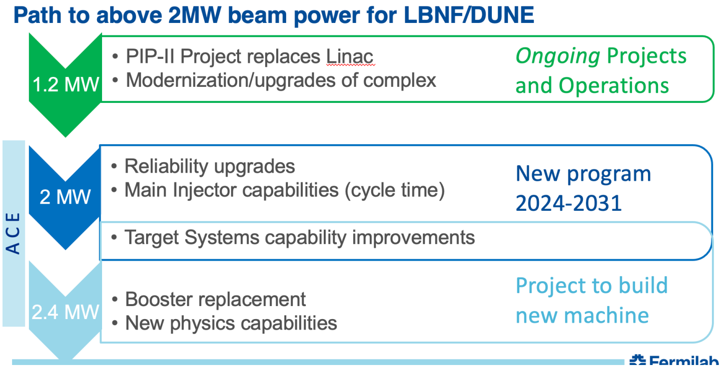
LBNF Beamline

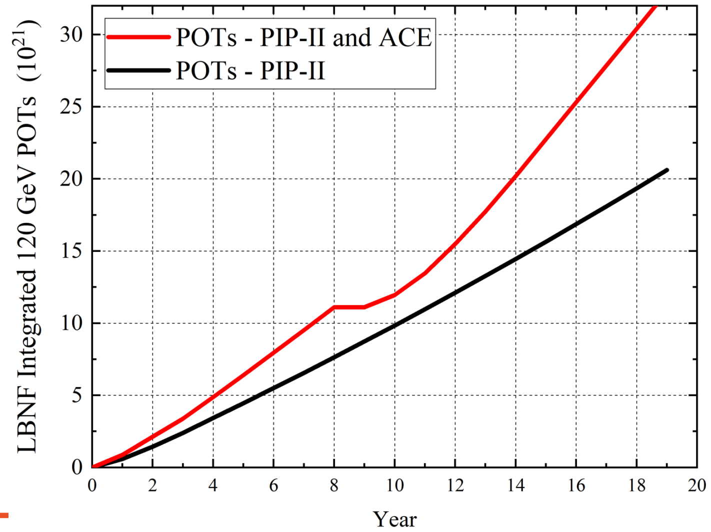
120 GeV protons from the Main Injector at FNAL

from 0.7 MW to 1.2 MW LINAC upgrade →
Proton Improvement Plan - PIP-II



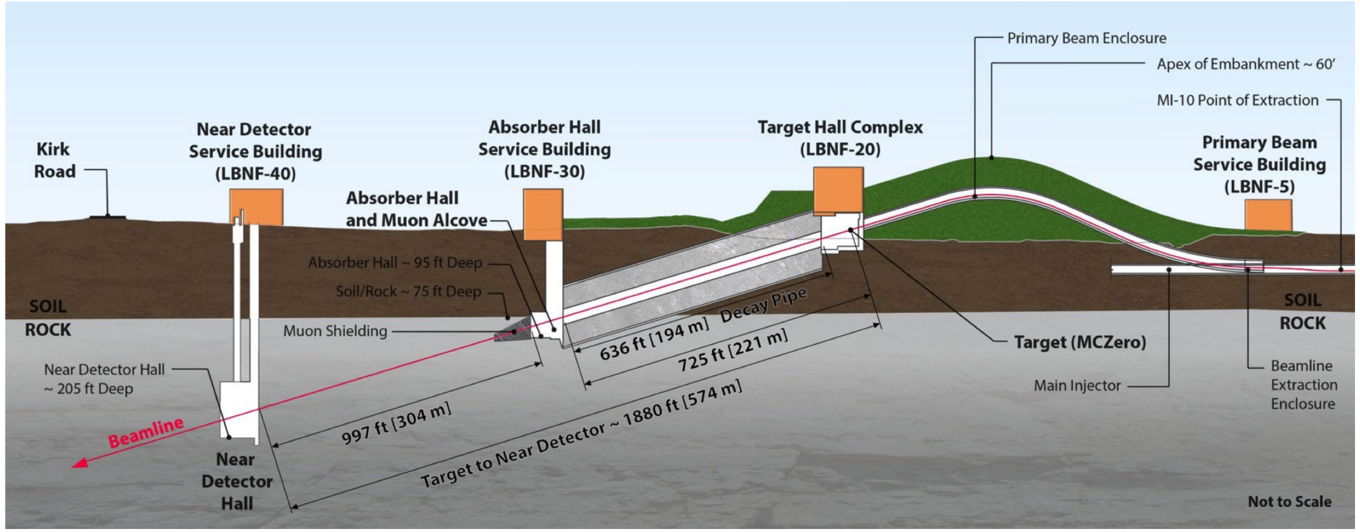
- **Accelerator Complex Evolution (ACE) > 2 MW** beam power
  - Main Injector Cycle time shortening
  - Target System upgrade



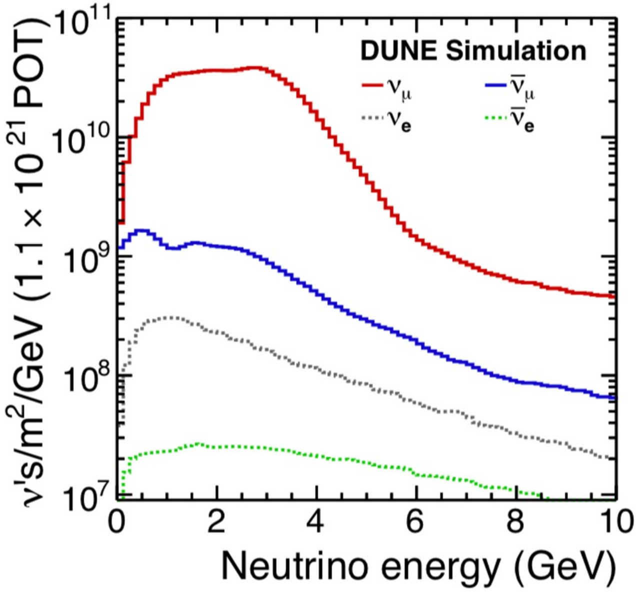


INFN DUNE

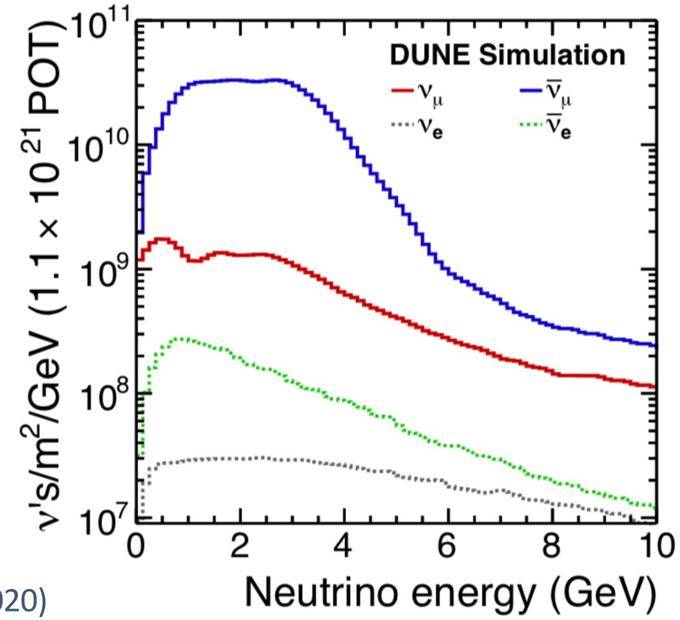
LBNF neutrino beam



- beamline at a slope of 5.8°
- 120 GeV proton beam onto a graphite target
- pulse duration: 10 µs
- 3 horn focusing system, water cooled, peak current of 300 kA
- Forward /Reverse Horn Current
- He filled decay pipe, 194 m long, 4 m Ø
- wide band beam
- design optimized to CP violation sensitivity



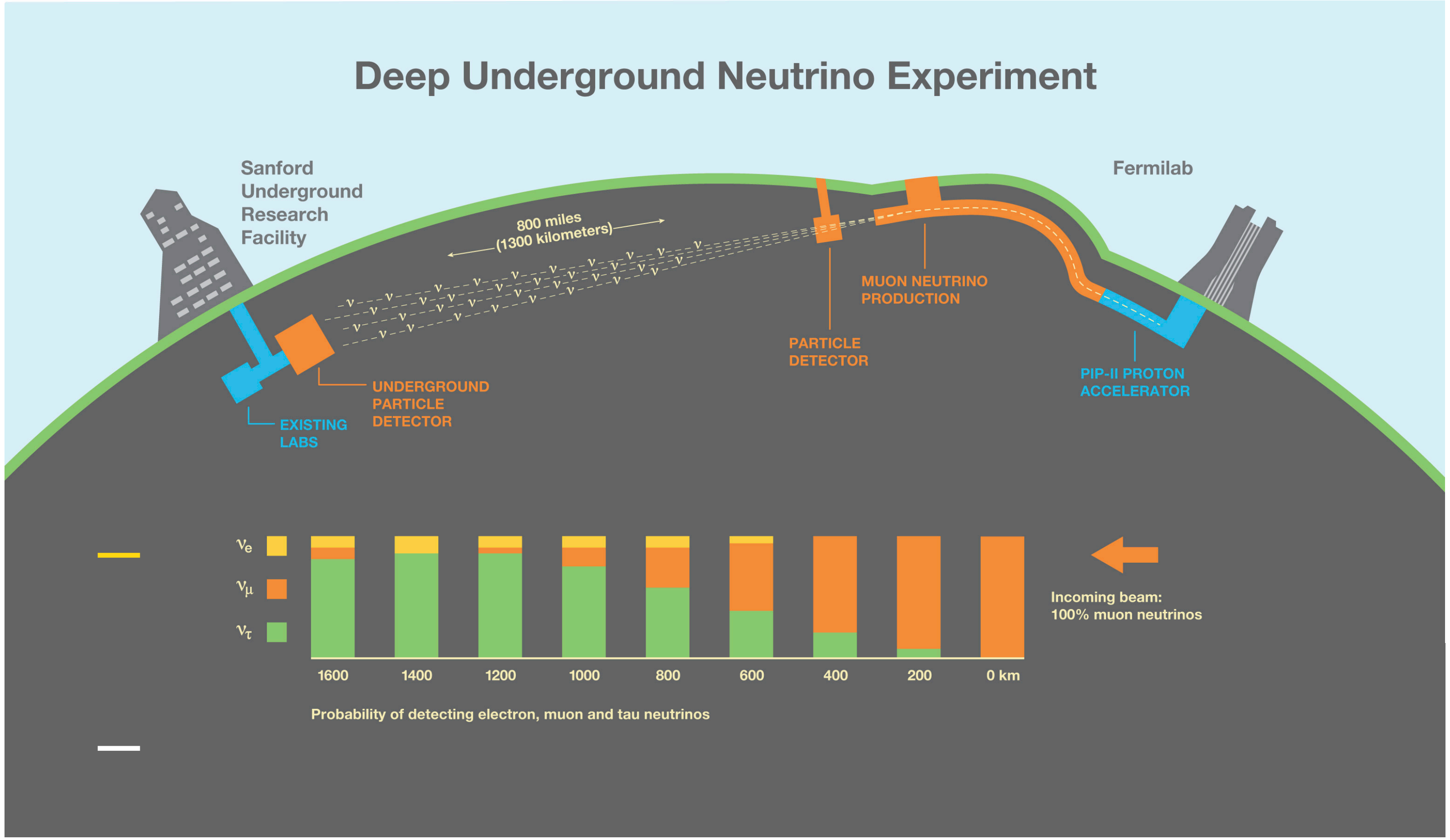
FHC
(ν-mode)

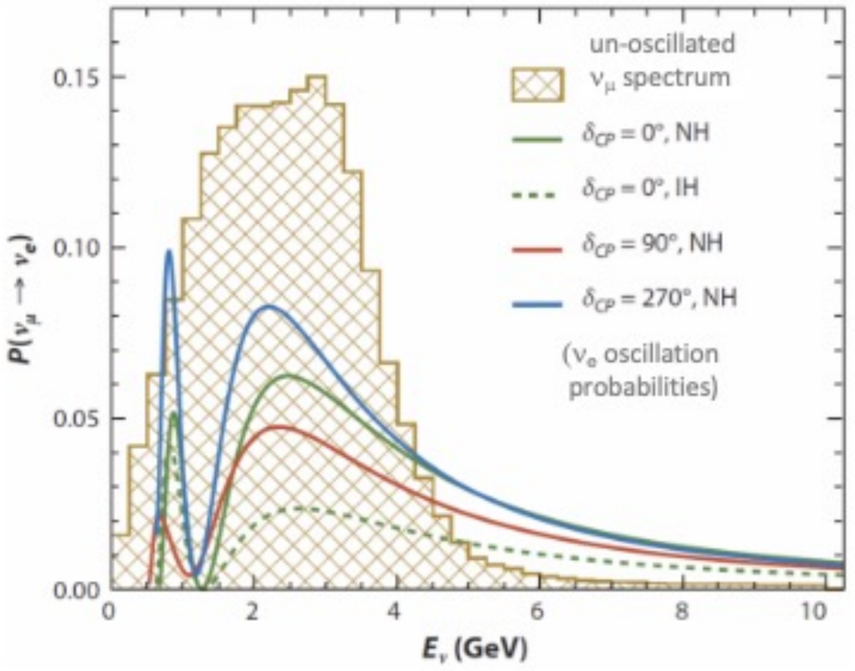


RHC
($\bar{\nu}$-mode)

Eur. Phys. J. C **80** 10, 978 (2020)

Neutrino Oscillations in DUNE





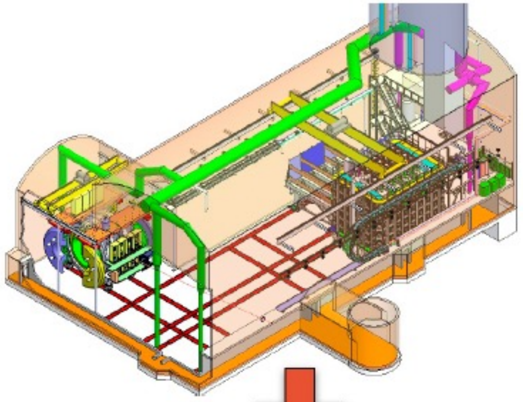
beam spectrum covers the full neutrino oscillation curve

not simply a counting experiment

DUNE Phased Construction

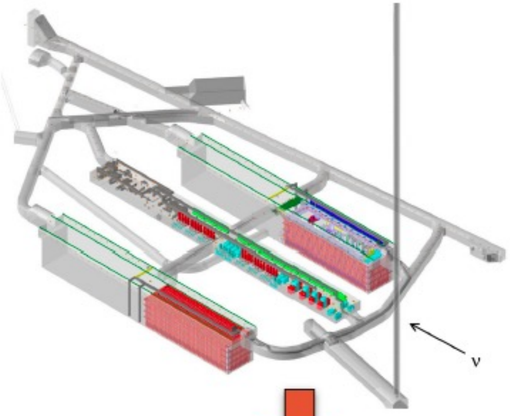
Near Detector (ND)

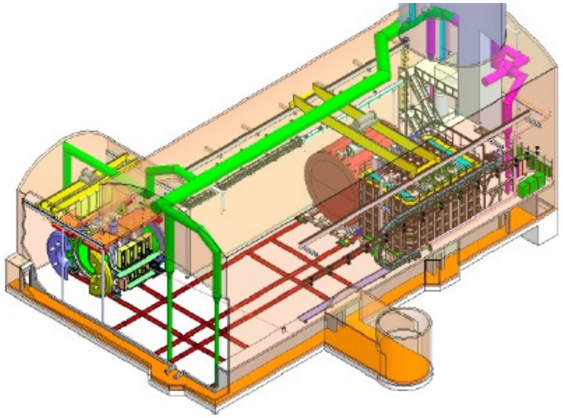
Far Detector (FD)



Phase I

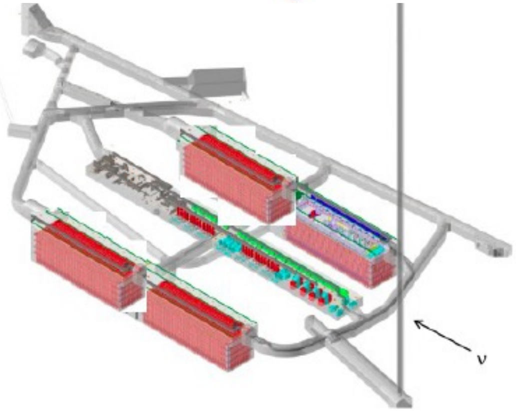
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)





Phase II

- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (ACE Upgrades)



Parameter	Phase-I	Phase-II	Impact
FD mass	20 kt fiducial	40 kt fiducial	FD statistics
Beam power	up to 1.2 MW	>2 MW	FD statistics
ND configuration	ND-LAr, TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

options other than LAr for ND , FD Phase-II detectors being considered, not listed here

Far Detectors (FD)

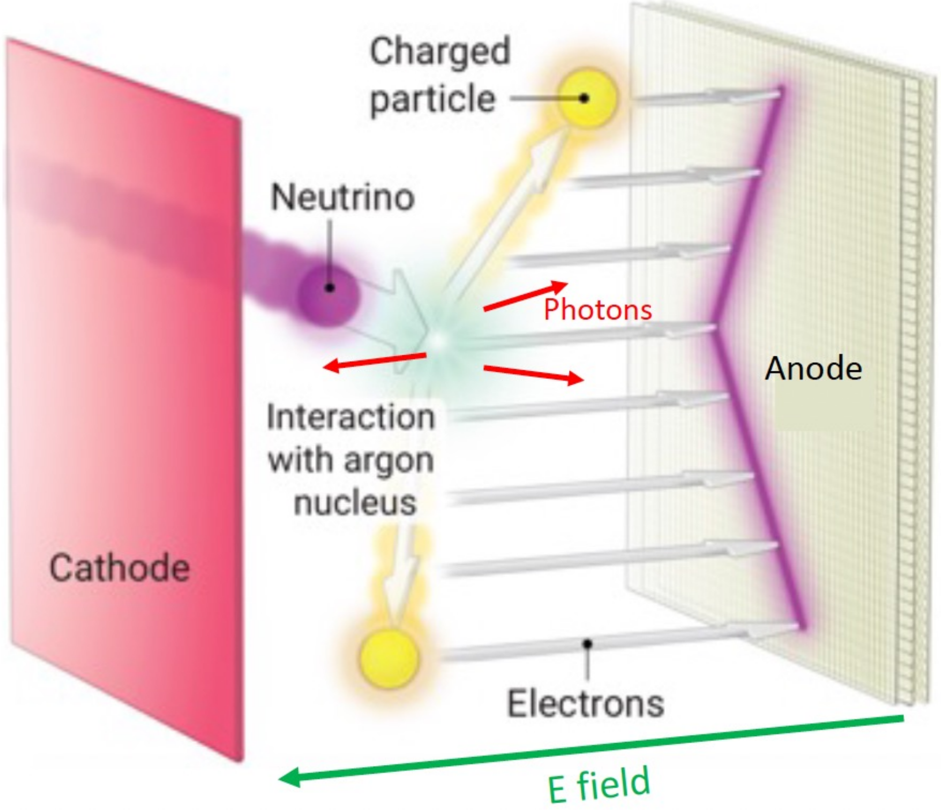
2 (max 4) LAr TPCs, each 17 kt LAr (10 kt fiducial)

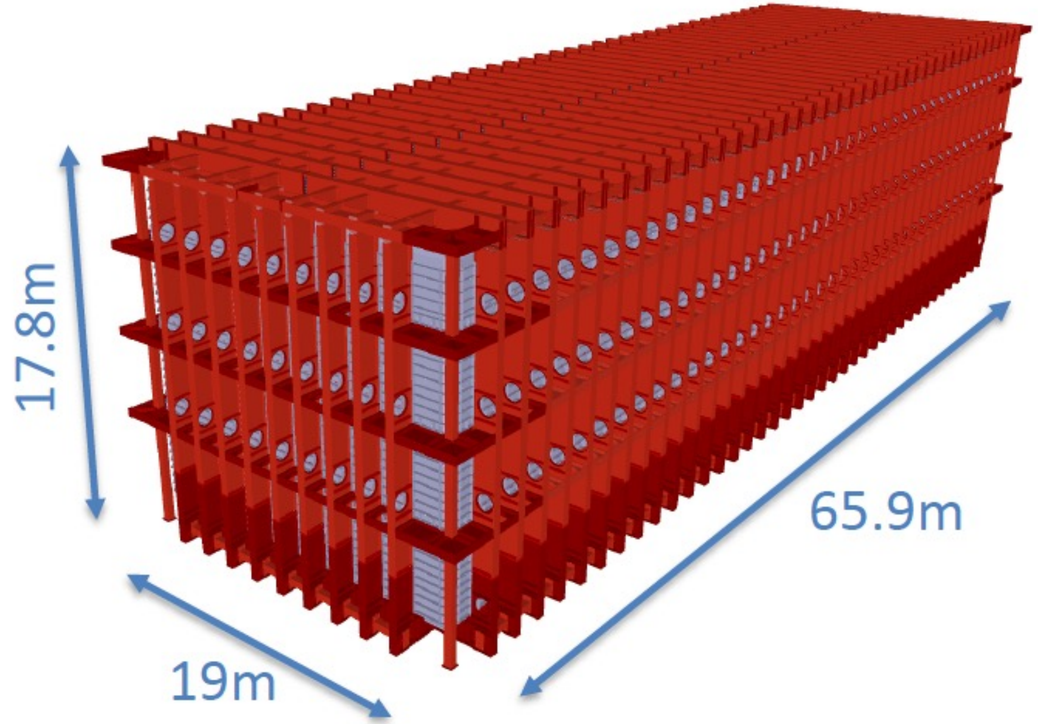
FD Horizontal (charge) **Drift**

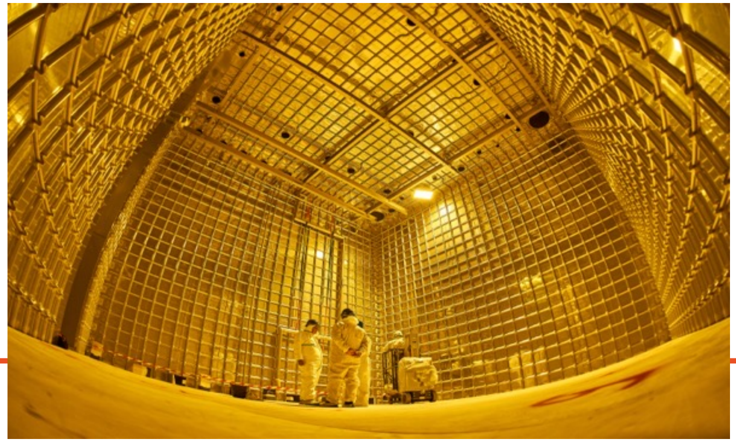
FD Vertical (charge) **Drift**

Membrane cryostat with passive insulation

Internal volume ~28'500 m^3 ~17.5 kt LAr

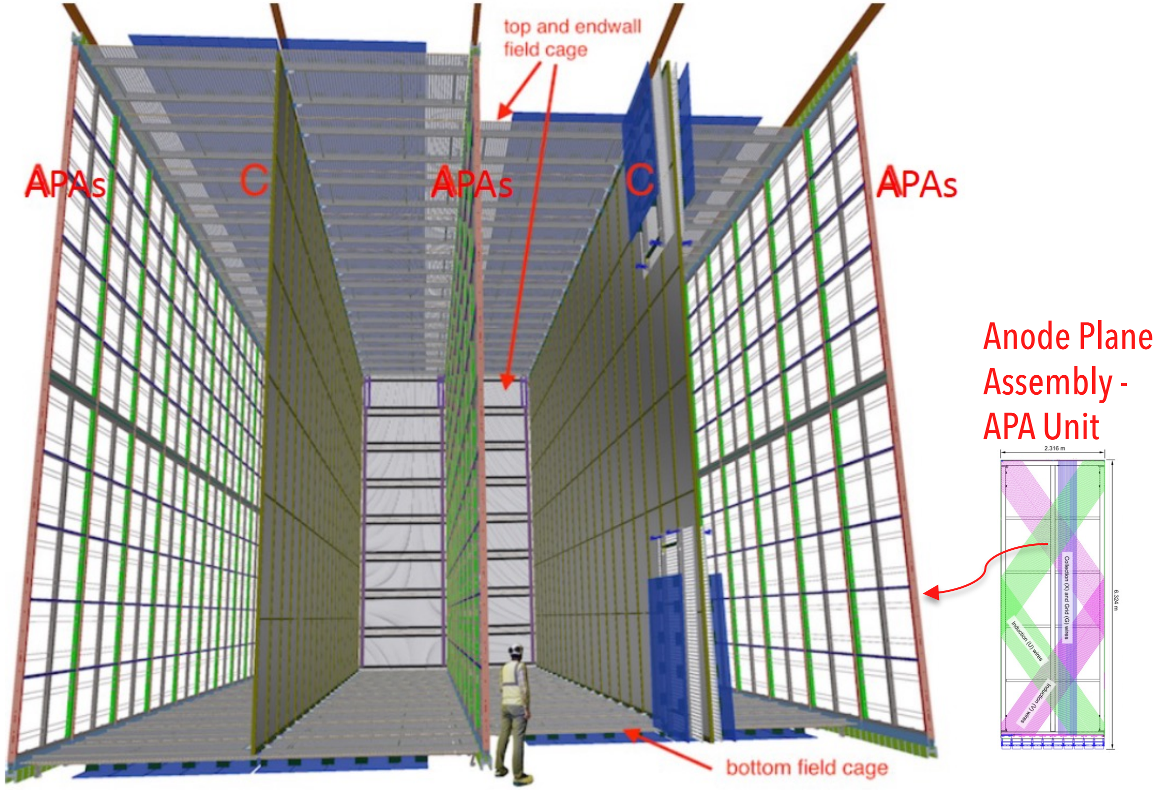






similar cryostats already constructed (protoDUNE, SBND)

Horizontal Drift

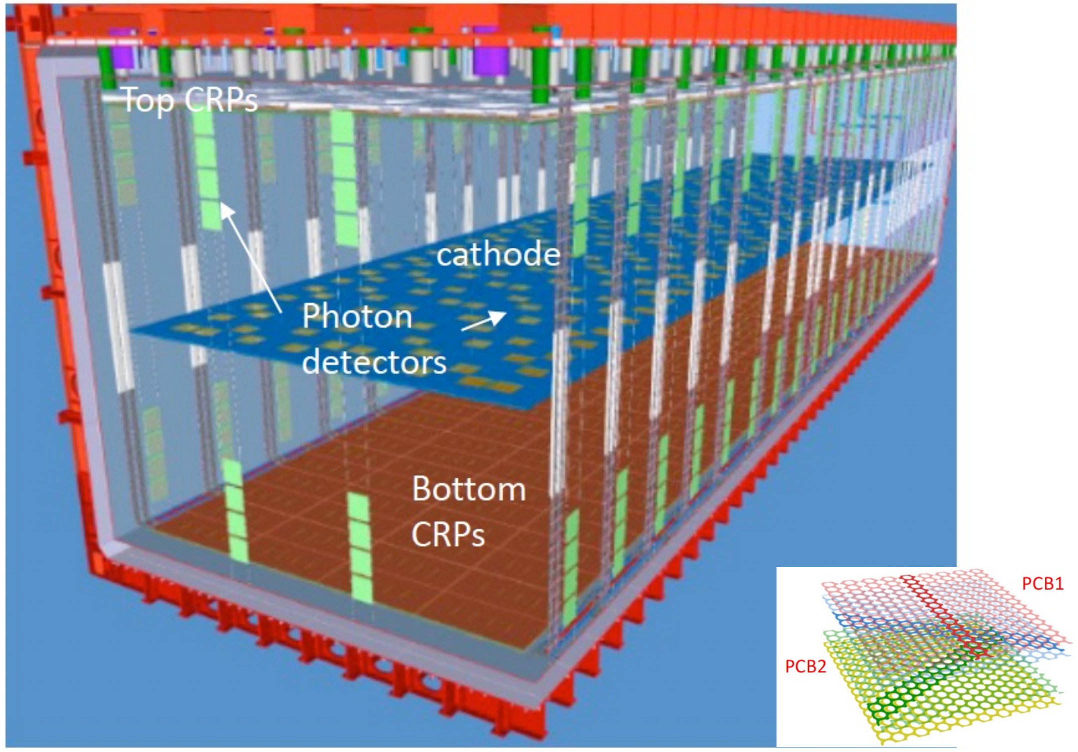


Drift length ~ 350 cm → 180 kV on cathode

- 150 Anode Plane Assemblies (APAs)
- 384,000 readout wires

Photon detection: X-Arapuca modules (SiPM based light traps) embedded in APAs- **300,000 SiPMs**

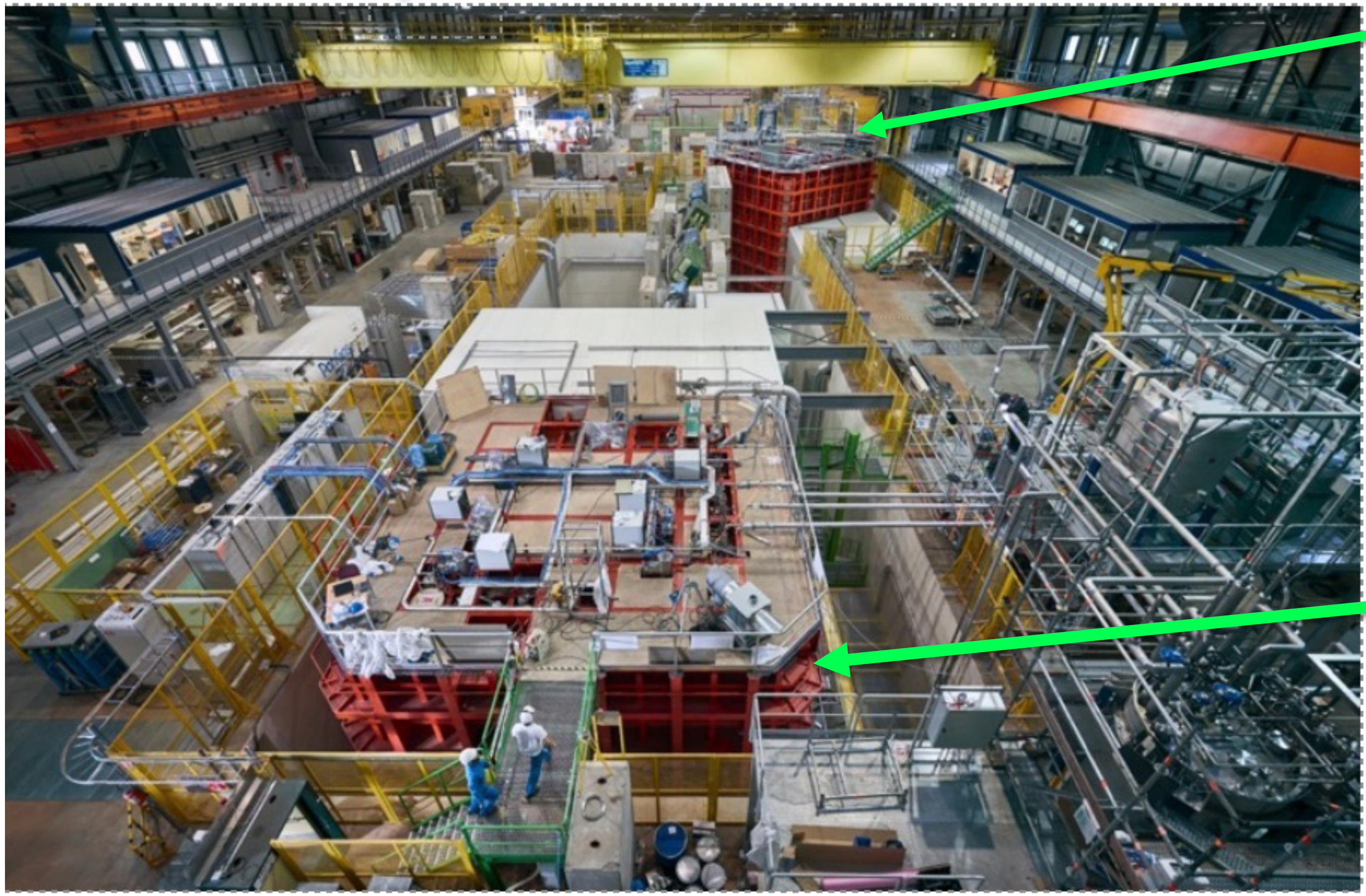
Vertical Drift



- Drift length ~ 640 cm -> ~ 300 kV on cathode
- Charge Readout Planes -CRP: perforated PCB's
- Photon detectors on the field cage walls and on the cathode @ 300 KV; decoupling from HV, achieved with optical fibres for signal and power transmission

ProtoDUNE's @ the CERN Neutrino Platform (NP)

The Neutrino Platform provides unique test beam infrastructure for the neutrino community



NP02 : Single Phase Vertical Drift

Cosmic Ray run in 2024

NP04 : Single Phase Horizontal Drift

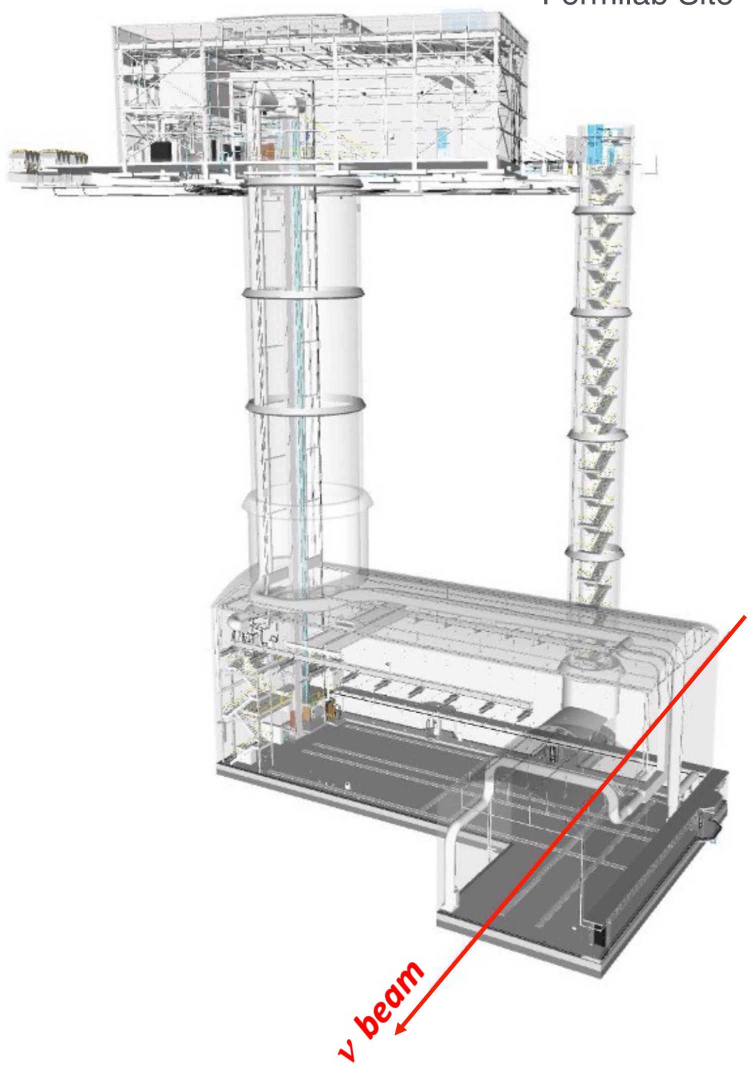
2018-2020 runs: charged particle beams + CRs

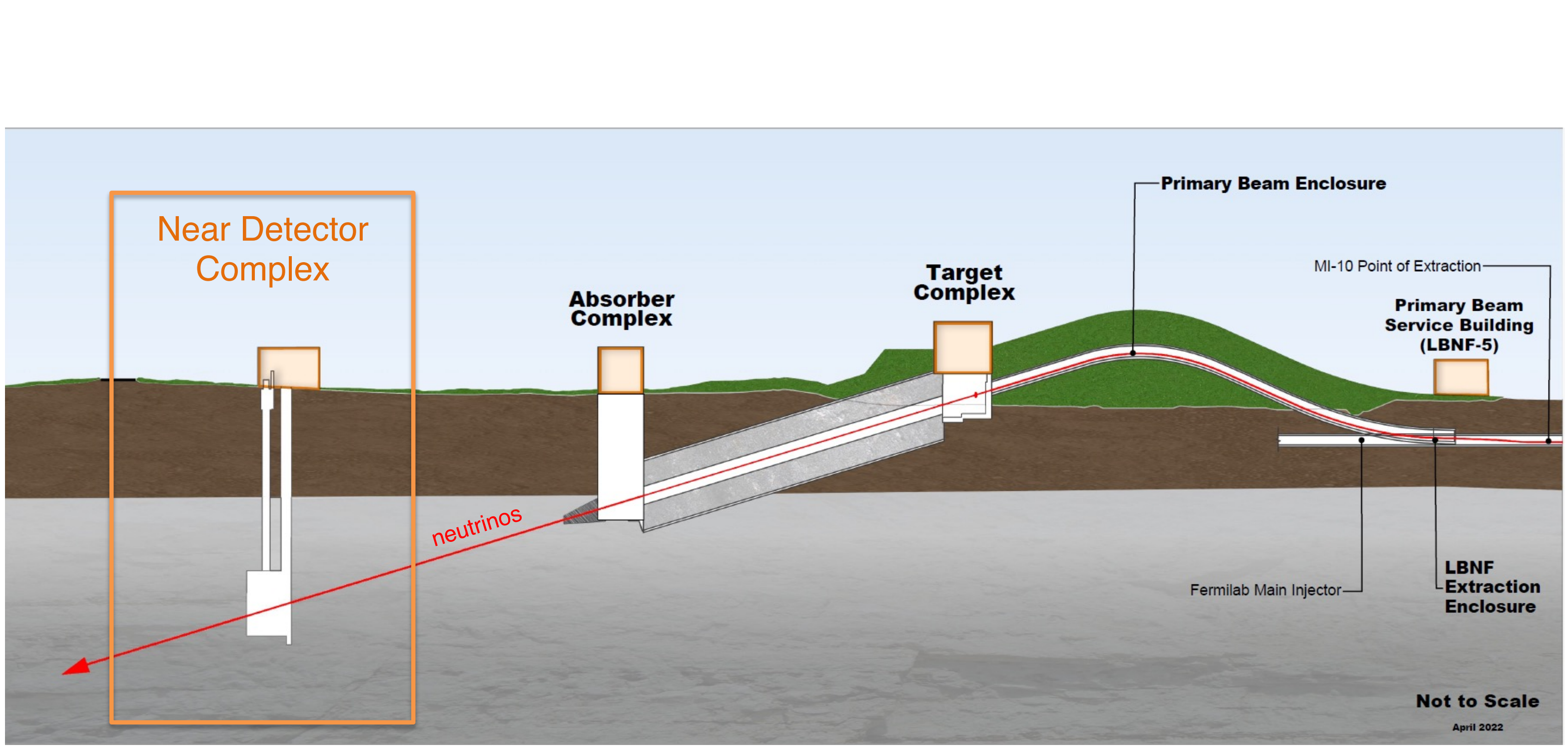
New charged particle beam run in 2024

Two 750 t prototypes ~8 x 8 x 8 m^3 (1:20 scale)

Validation of all FD components at full scale

Near Detector Facility

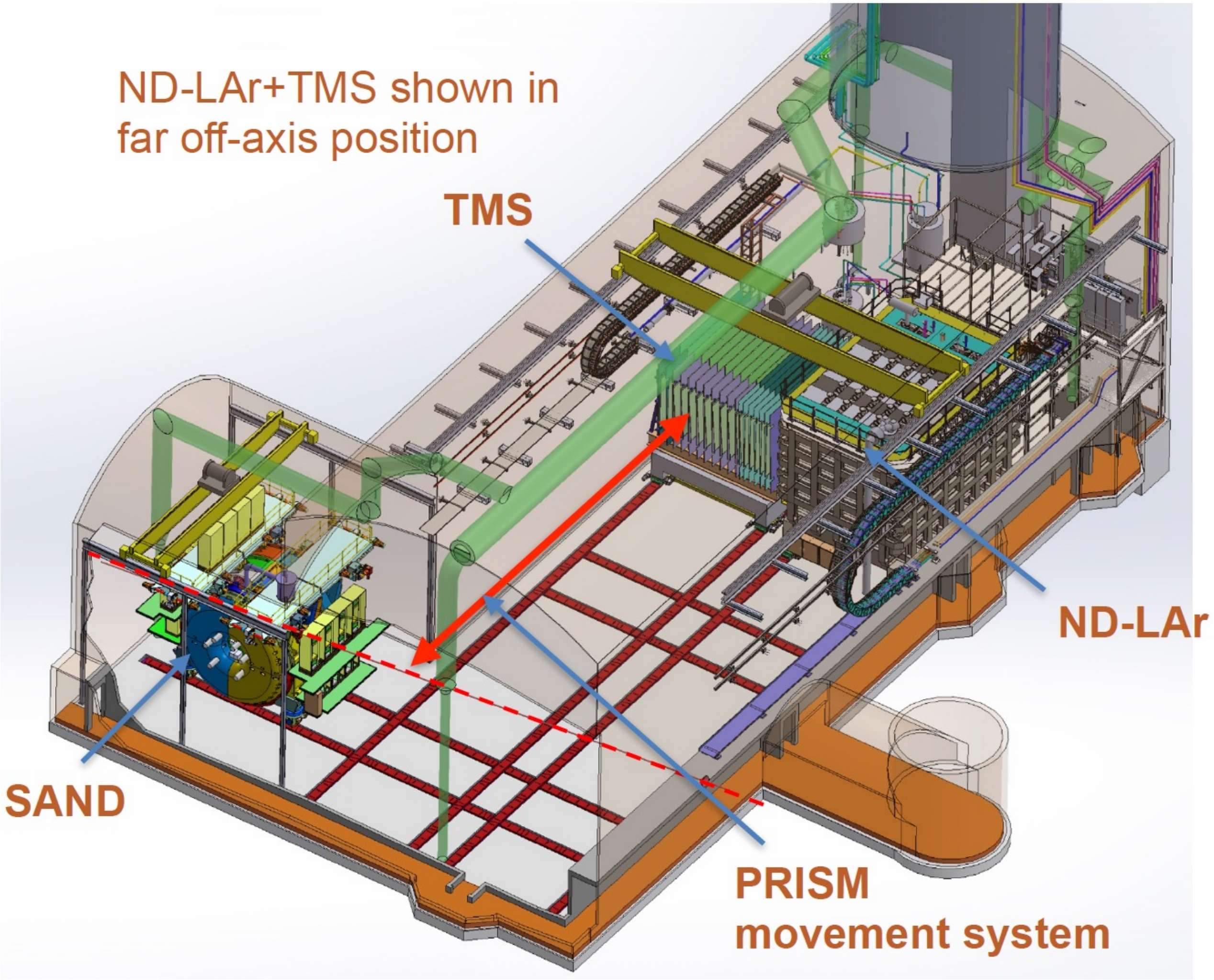




Hall location : 574 m from LBNF target; 60 m underground

Near Detector Hall Beneficial Occupancy by 2028

Near Detector Complex Phase I

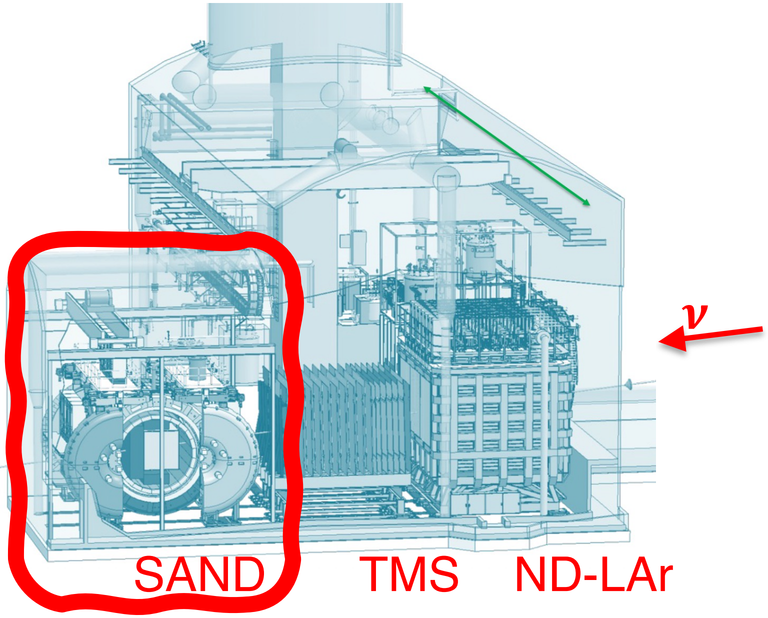


- **Measure the neutrino beam rate & spectrum** to predict un-oscillated event rates in the far detector
- **Constrain systematic uncertainties** (flux, cross sections, detector response) for oscillation measurements
- **Independent physics program**

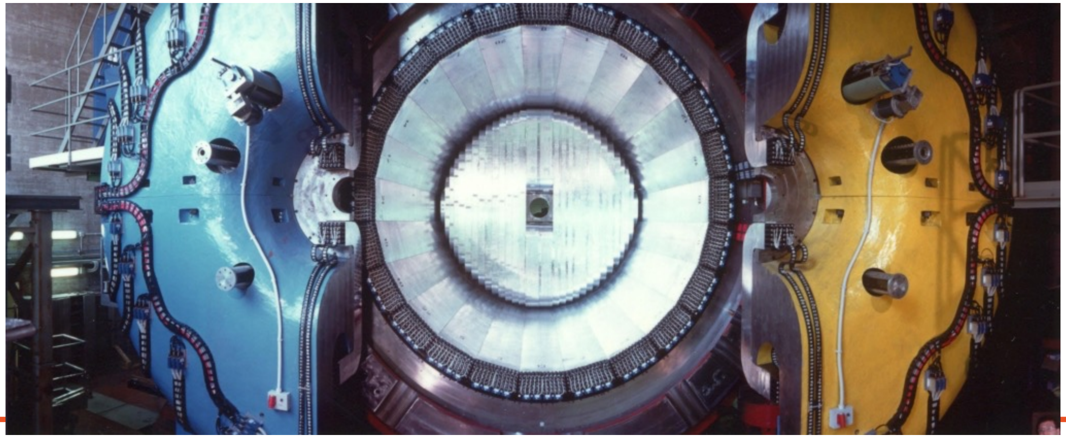
- **ND-LAr** → measurement of neutrino-nucleus interaction with the same target as the Far Detectors (~100 t Lar segmented TPC w/ pixelated readout)
- **TMS** → muon spectrometer for ND-LAr
- **ND-LAr+TMS** move up to ~29 m off-axis
- **SAND S**ystem for on **A**xis **N**eutrino **D**etection

SAND in DUNE

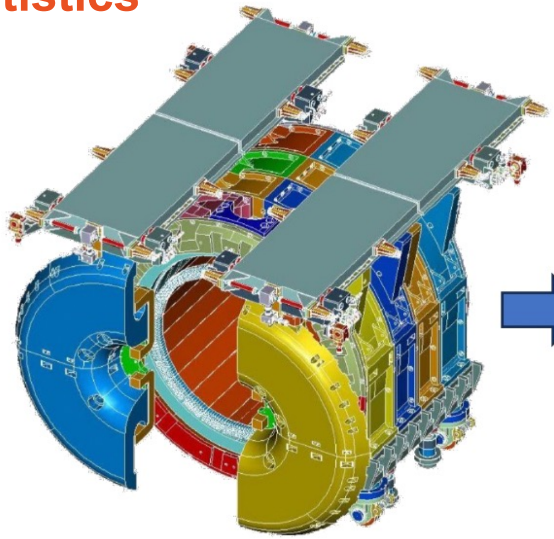
- **on-axis, stationery**
- superconducting **magnet & Ecal from KLOE**
- transparent **target/tracker** (CH2, C targets)
- **GRAIN :** a novel LAr detector – **track imaging** with scintillation light

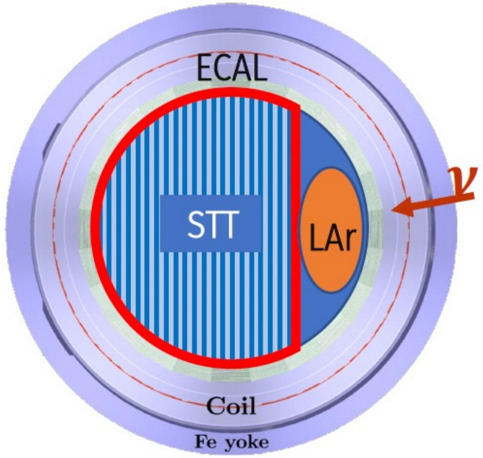


- ➢ **On axis ν spectrum monitor** : detect changes in the beam on a weekly basis
- ➢ ν_μ , $\overline{\nu}_\mu$, ν_e , $\overline{\nu}_e$ **fluxes and energy spectra**
- ➢ **Constrain systematics from nuclear effects** bymeasuring ν and $\overline{\nu}$ cross sections on nuclei other than argon (carbon and hydrocarbons)
- ➢ **Physics program besides oscillations** exploiting **high statistics**



KLOE @LNF

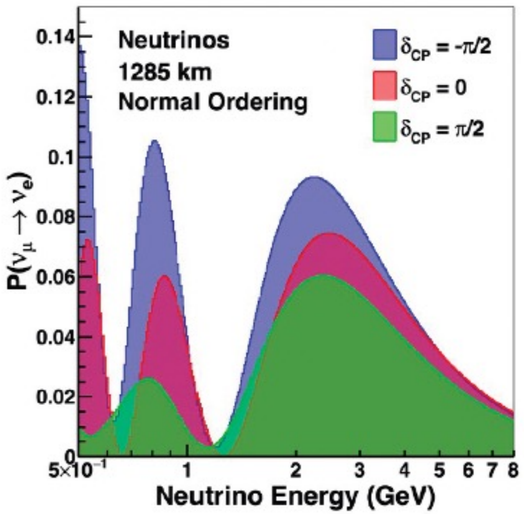




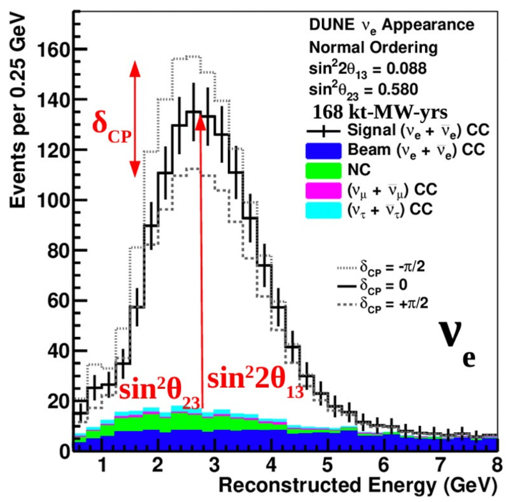
Neutrino Energy Spectra at FD

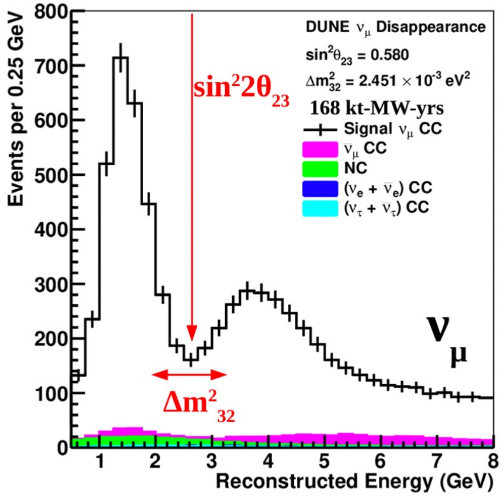
Normal Ordering

Oscillation Probabilites



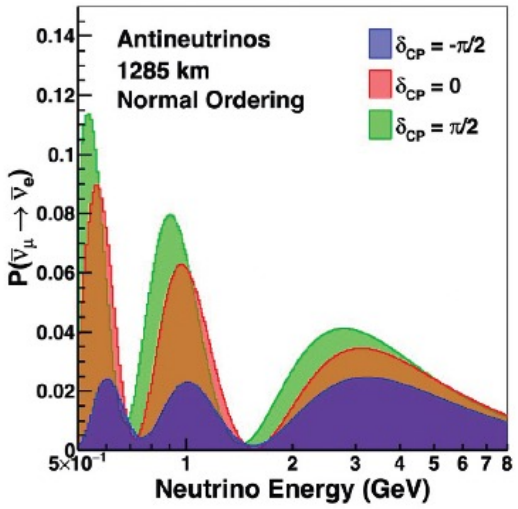
ν



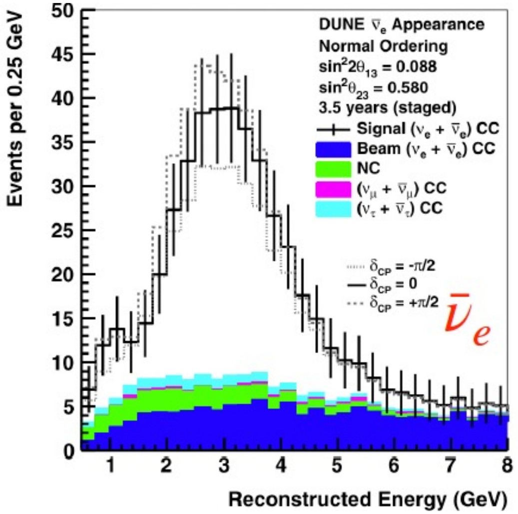


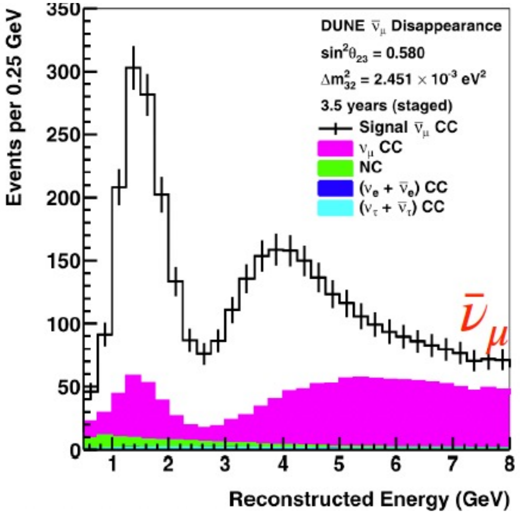
3.5 year (staged) exposure

ν . $\bar{\nu}$ energy spectra (appearance, disappearance) convolution of oscillation probabilities with neutrino beam flux and cross sections and detector response



$\bar{\nu}$

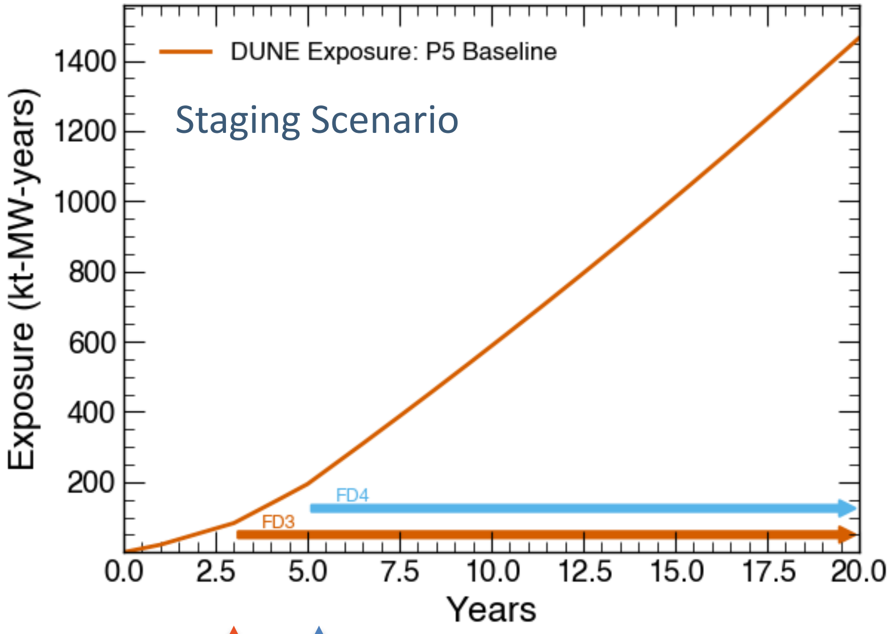




Oscillation sensitivities: simultaneous fit over 4 components of FD data (disappearance and appearance spectra) with ND constraints

EPJC (2020) 10, 978

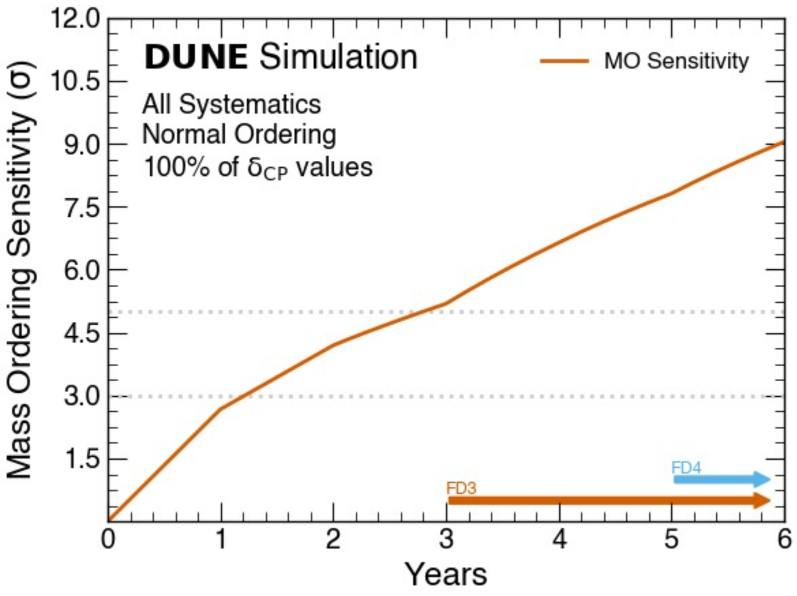
DUNE Exposure vs time



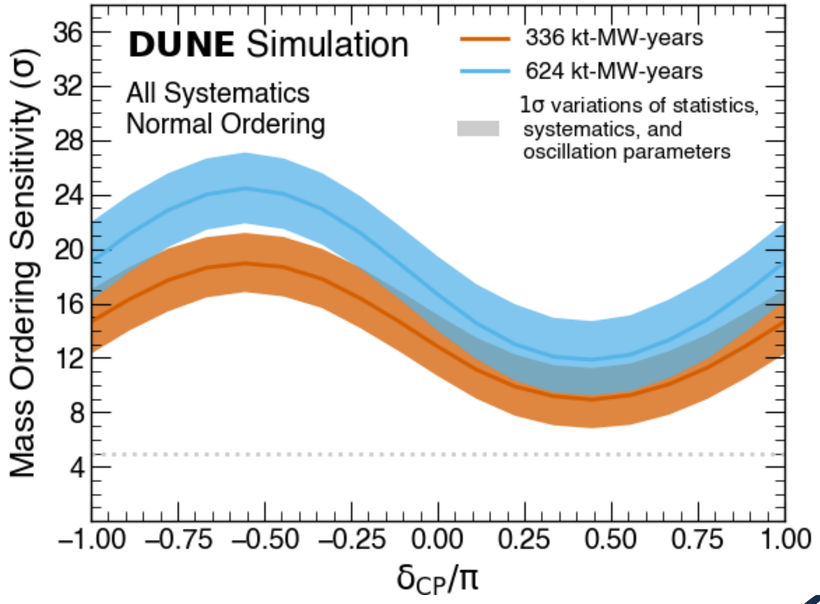
Far Detector Module 4

Phase II (+ FD Module 3 + Beam to > 2 MW)

Mass Ordering



Achieved at 5σ in Phase I

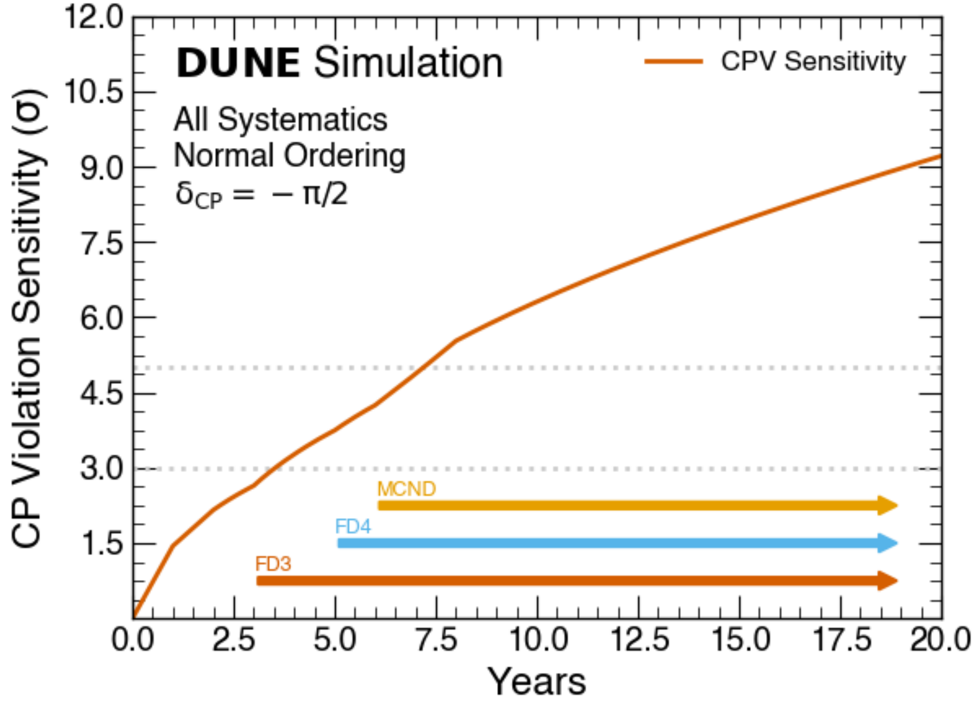


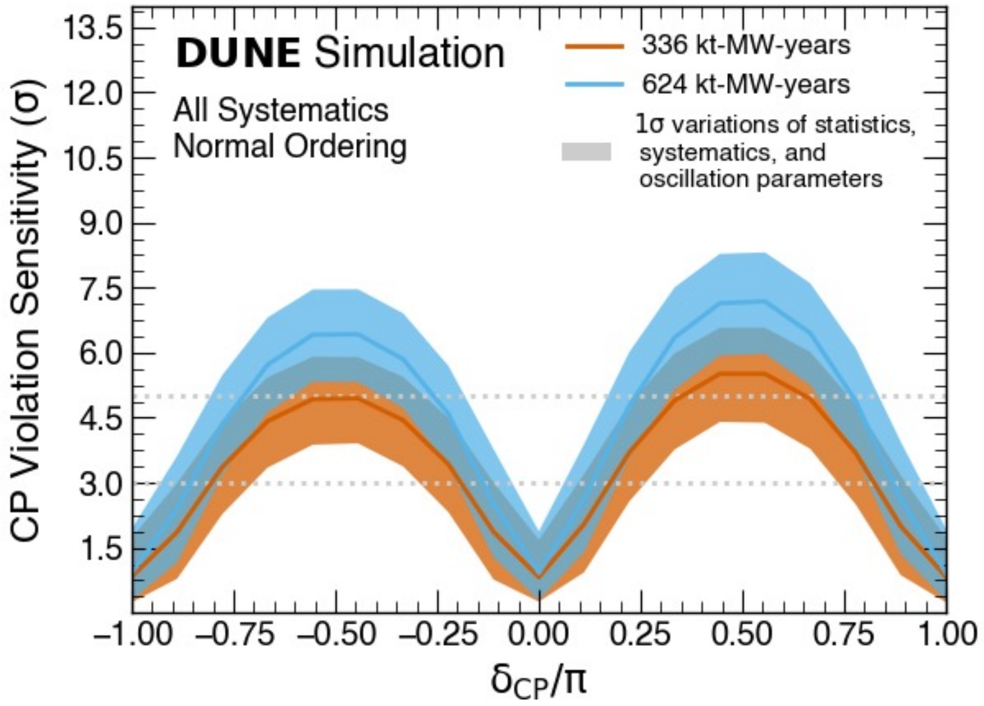
Mass Ordering vs true δ

Normal Ordering

CP Violation

Maximal CPV





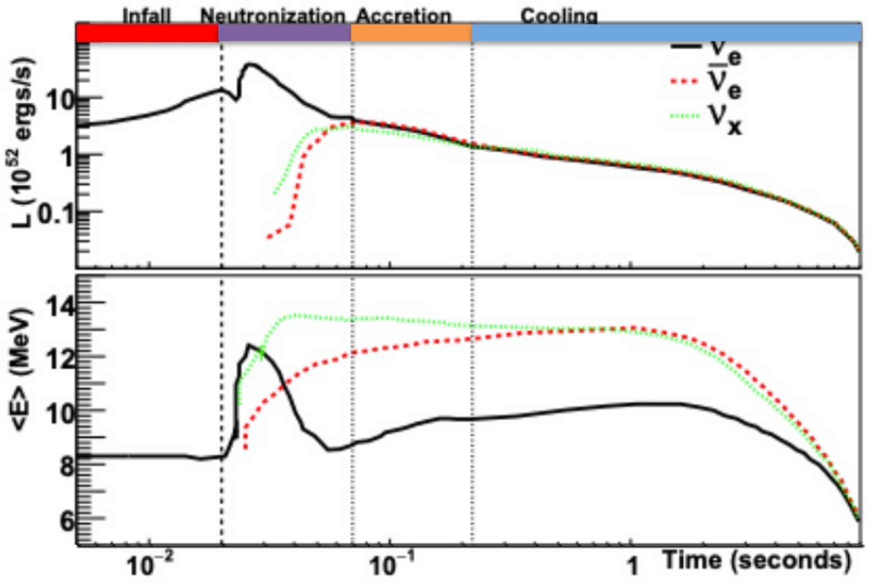
CPV can be established

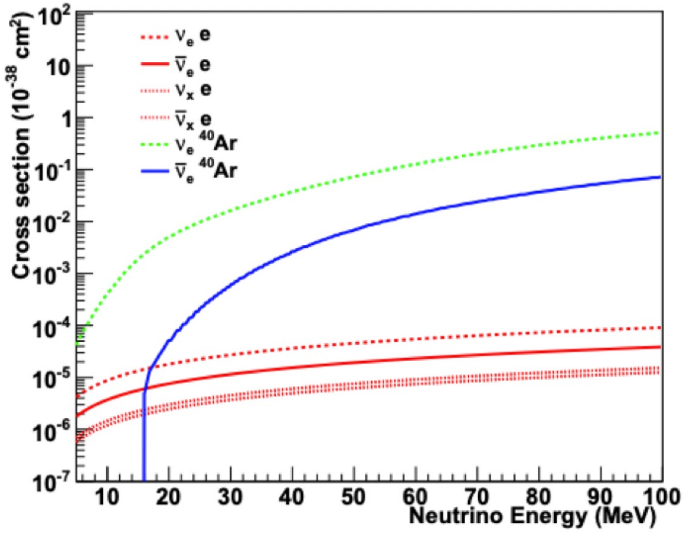
- at > 3σ in Phase I if δ_{CP} nearly maximal
- at 5σ in 7 years with Phase II

CPV significance vs true δ_{CP}

Supernova Neutrino Burst

unique sensitivity to ν_e

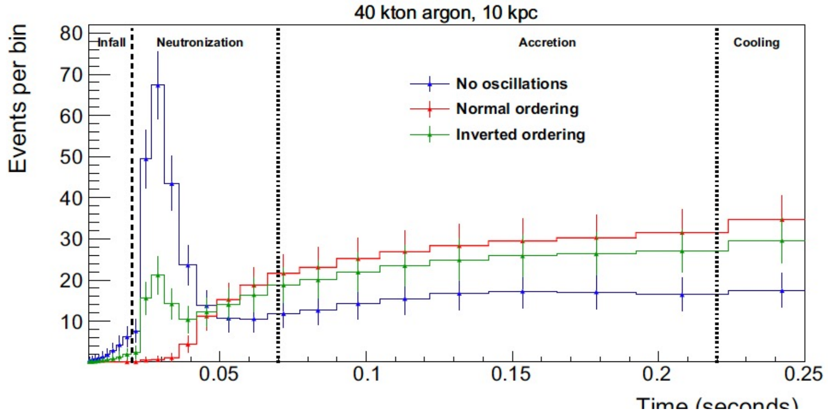


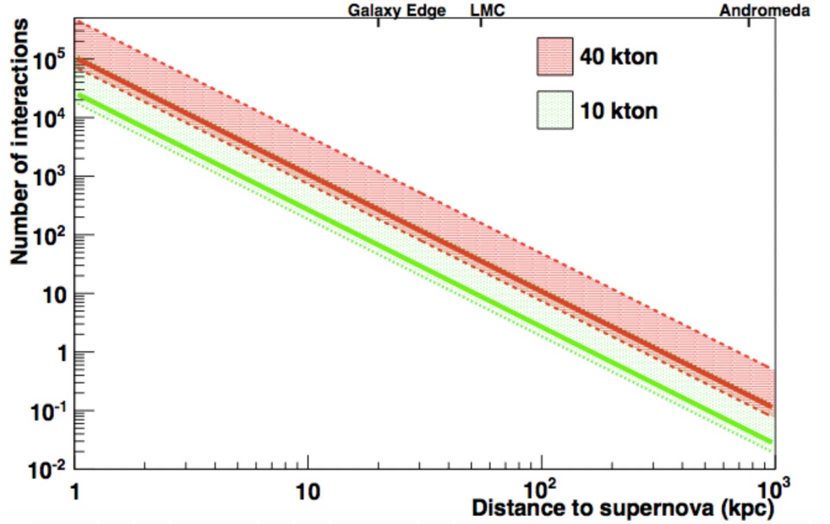


$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

ν- e scattering

1000 nu for a SN 10 kpc from Earth.



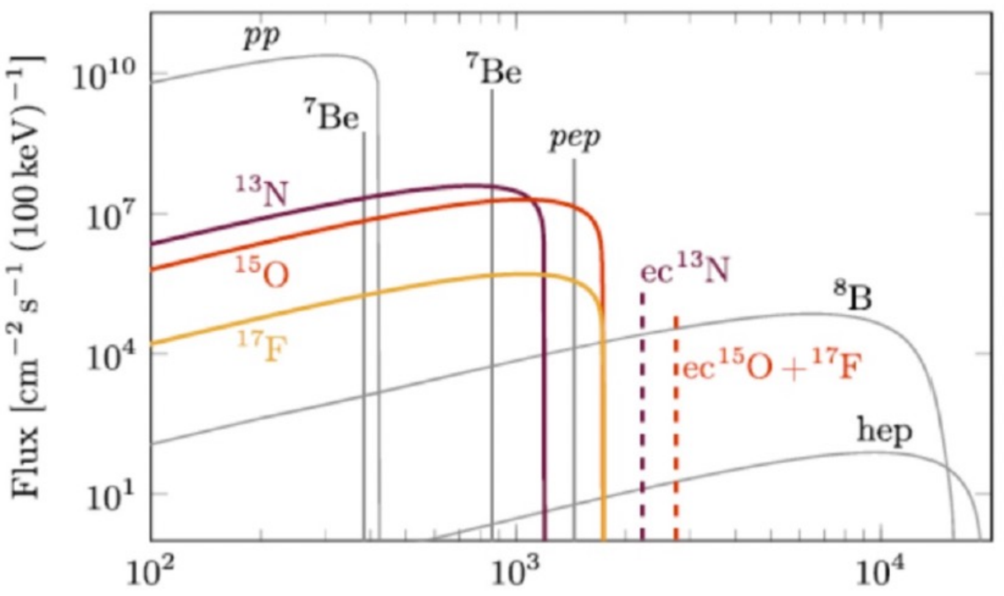


Exploiting the directionality of $\nu\!-\!e$ scattering events, direction of the supernova to ≈ 5 deg

Solar neutrinos

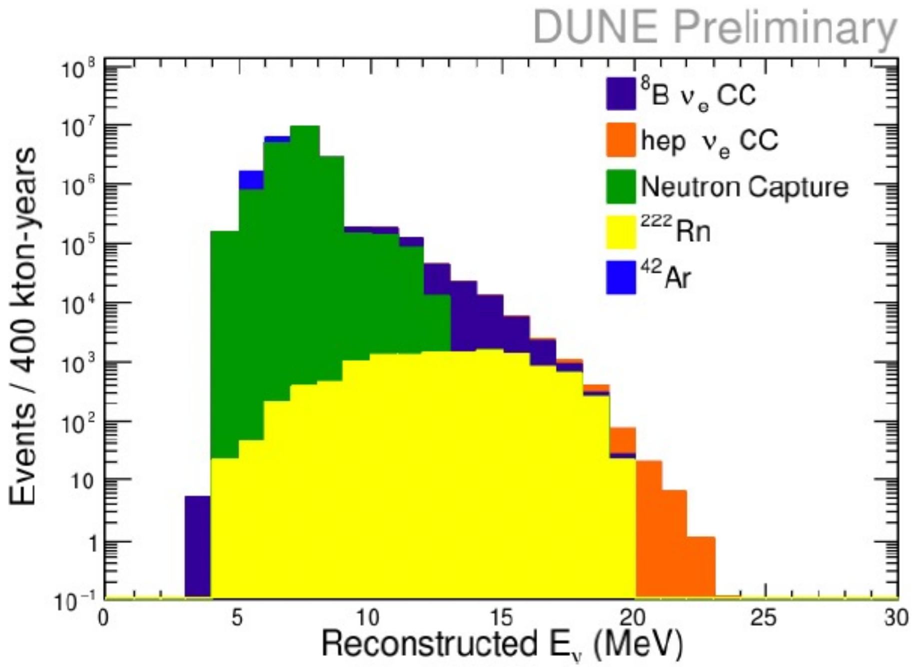
$$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$$

$$\nu_{e,\mu,\tau} + e^- \rightarrow \nu_{e,\mu,\tau} + e^-,$$



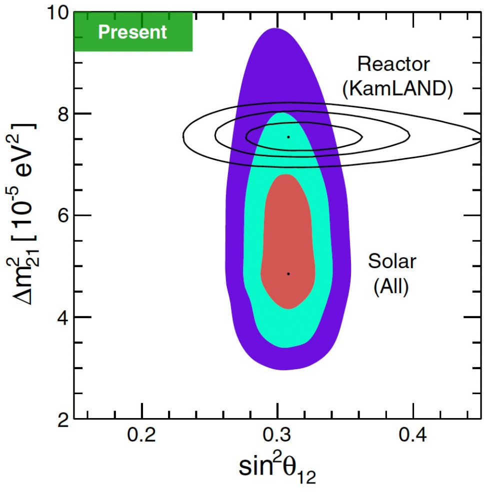
DUNE can measure ^{8}B solar flux and observe hep flux

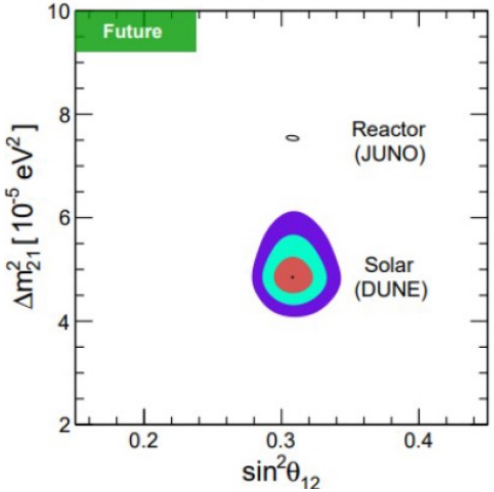
Phase I: >5σ sensitivity to hep flux



Phase II: DUNE can improve θ_{12} and Δm^2_{21}

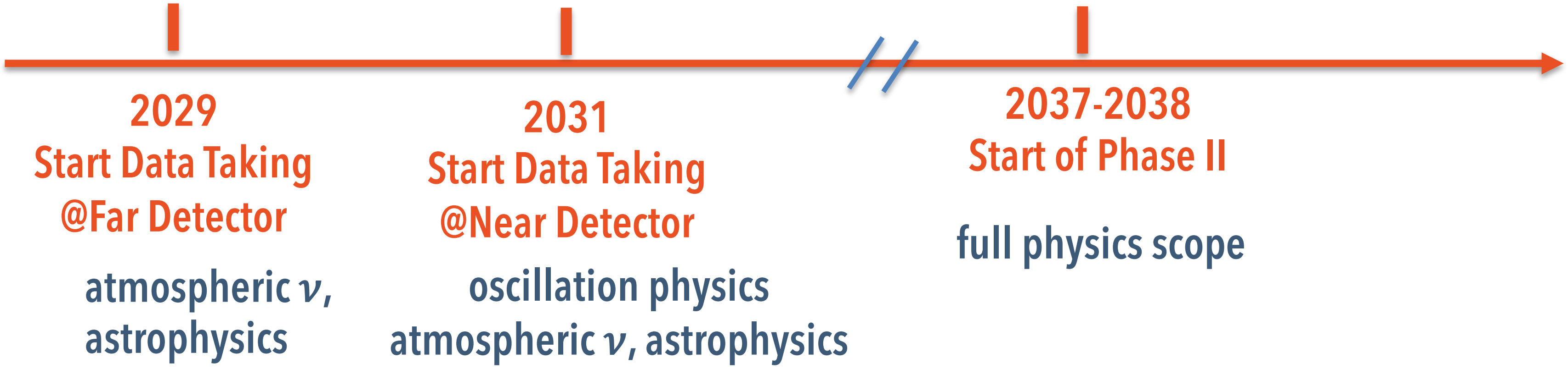
Capozzi et al., PRL **123** 131803

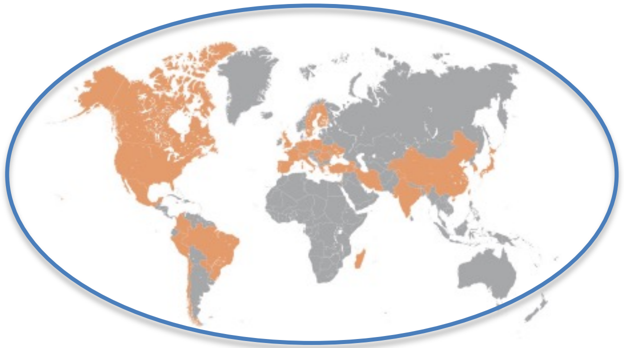




Conclusions

- LBNF/DUNE: the ultimate neutrino facility/observatory
- DUNE will enable very rich physics program in the next decades (LifeCycle 20 years):
  - Neutrino oscillations
  - Studies of MeV-scale neutrinos
  - Several BSM searches
- LBNF and DUNE making rapid progress on facility construction, detector design, and physics analysis





- 1400 collaborators
- 35 countries
- 215 institutions including CERN

DUNE Collaboration Meeting, CERN, May 2024

Thank You!