DEEP UNDERGROUND
NEUTRINO EXPERIMENT

THE DEEP UNDERGROUND NEUTRINO EXPERIMENT: STATUS AND PROSPECTS

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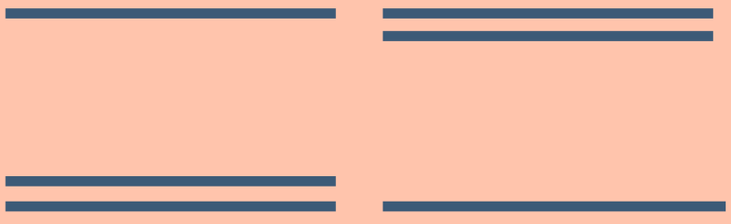
21st Rencontres du Vietnam, ICISE
July 25th, 2025

Queen Mary
University of London

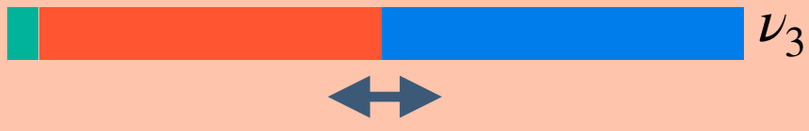
Long-baseline Oscillation Physics of Tomorrow

Goal: study the unknown PMNS parameters.

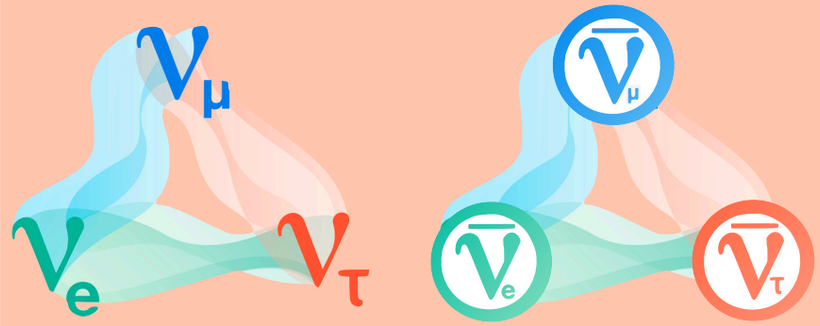
Ascertain the neutrino mass ordering, $|\Delta m^2_{32}|$.



Establish the octant of θ_{23}.



Measure δ_{CP} & determine if CP is violated.



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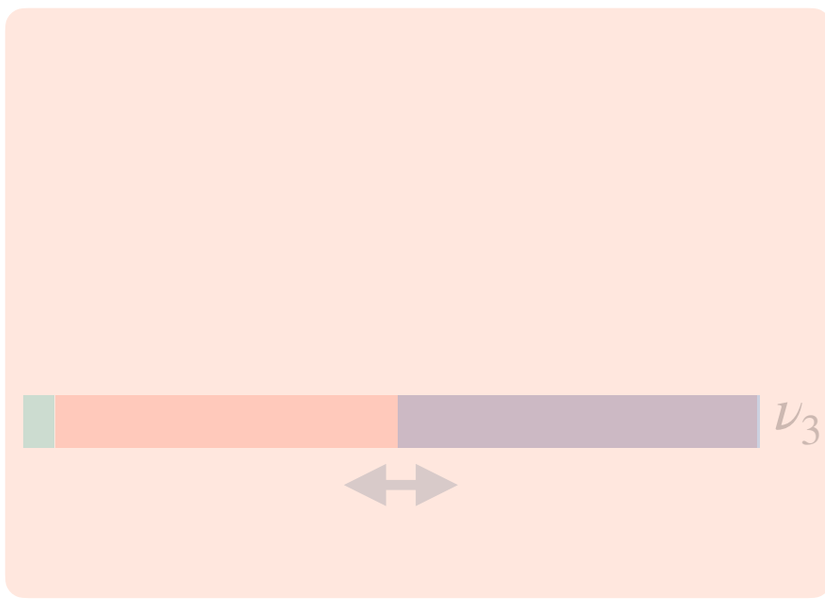
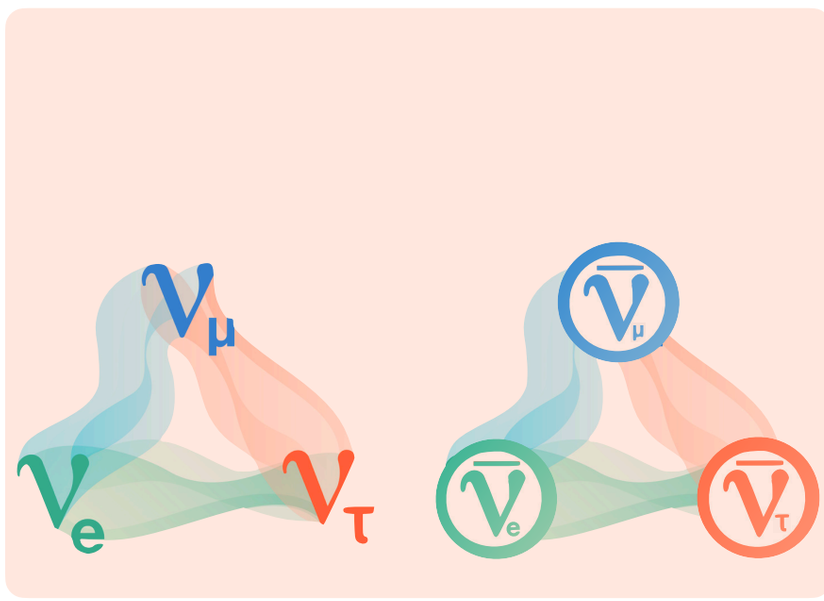


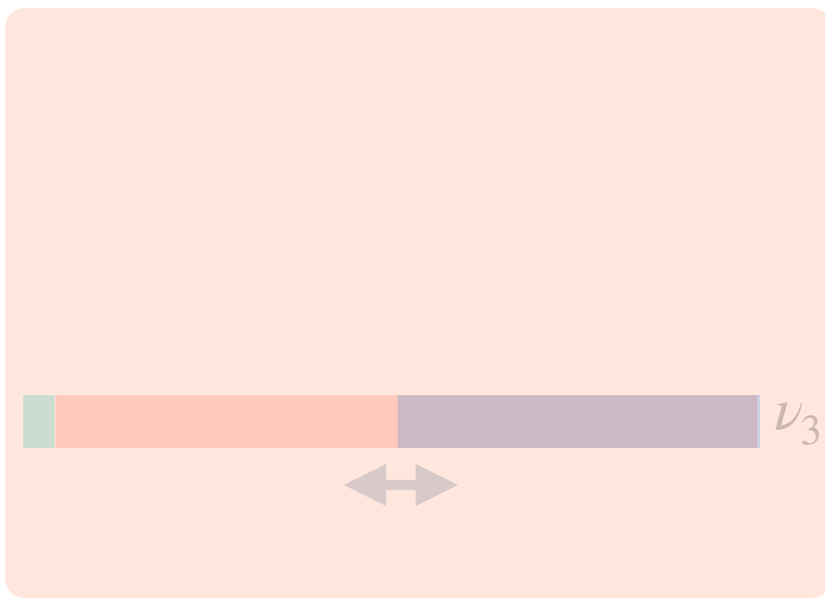


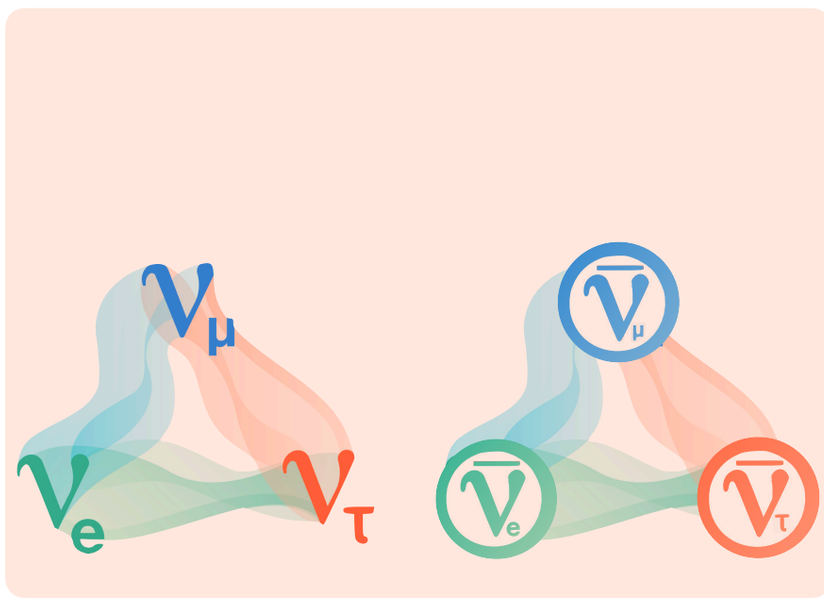
Goal: determine if the three-flavour model is correct.

- Measure neutrino and antineutrino neutrino oscillations as a function of **propagation distance** and **energy**.

- Does the three-flavour model describe the data?.
  - Yes → measure precisely the mixing angles, mass splittings and CP phase.
  - No → characterise the new physics.

Long-baseline Oscillation Physics of Tomorrow





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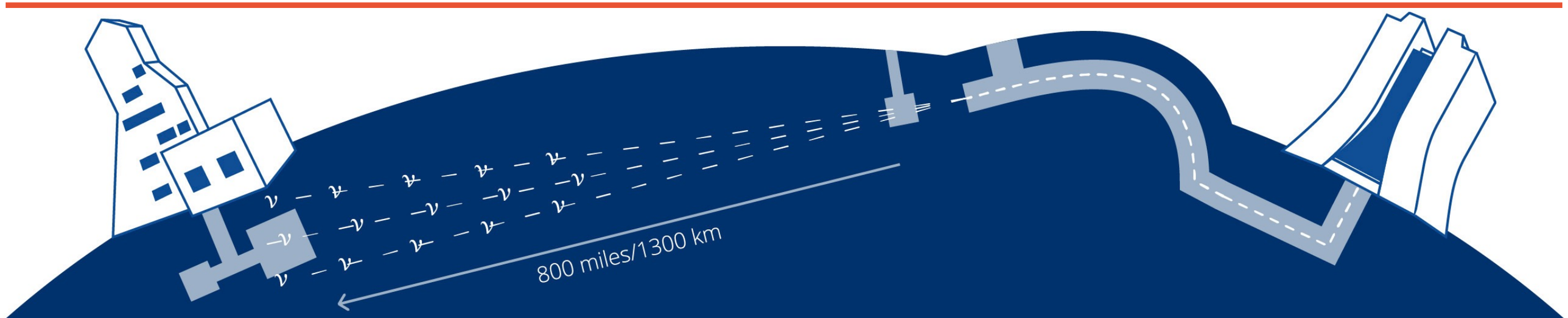
- Measure neutrino and antineutrino neutrino oscillations as a function of **propagation distance** and **energy**.
- Does the three-flavour model describe the data?.
  - Yes → measure precisely the mixing angles, mass splittings and CP phase.
  - No → characterise the new physics.
- Need for a **global program** of **complementary experiments**.

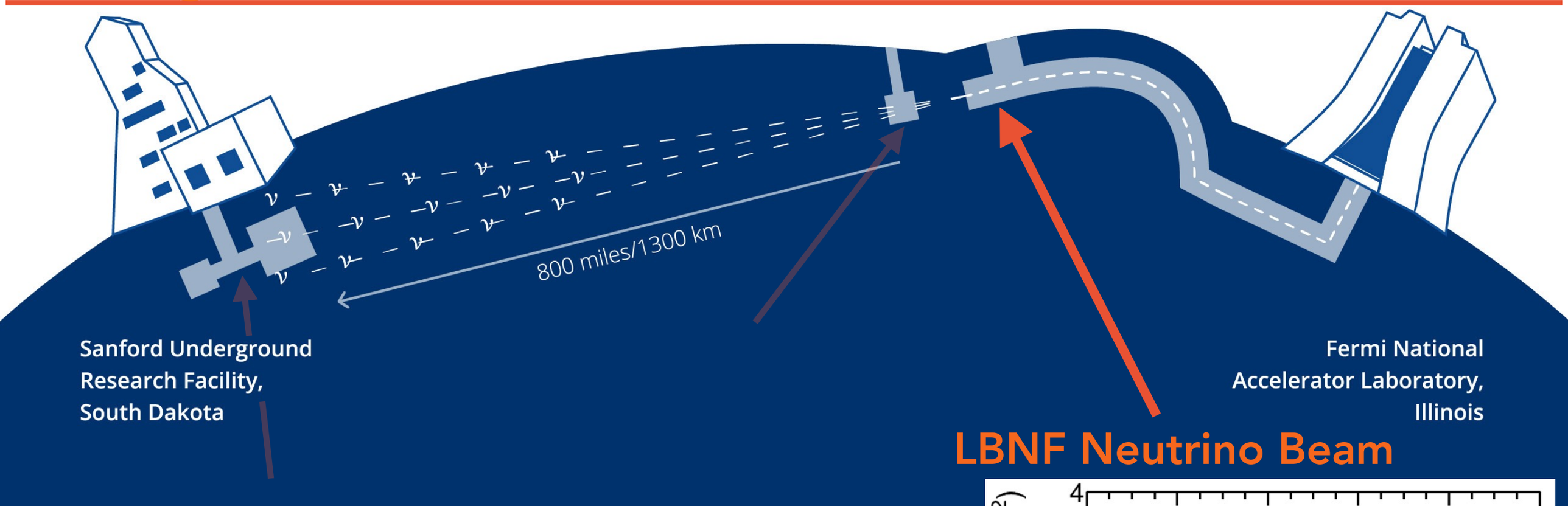


Sanford Underground Research Facility, South Dakota

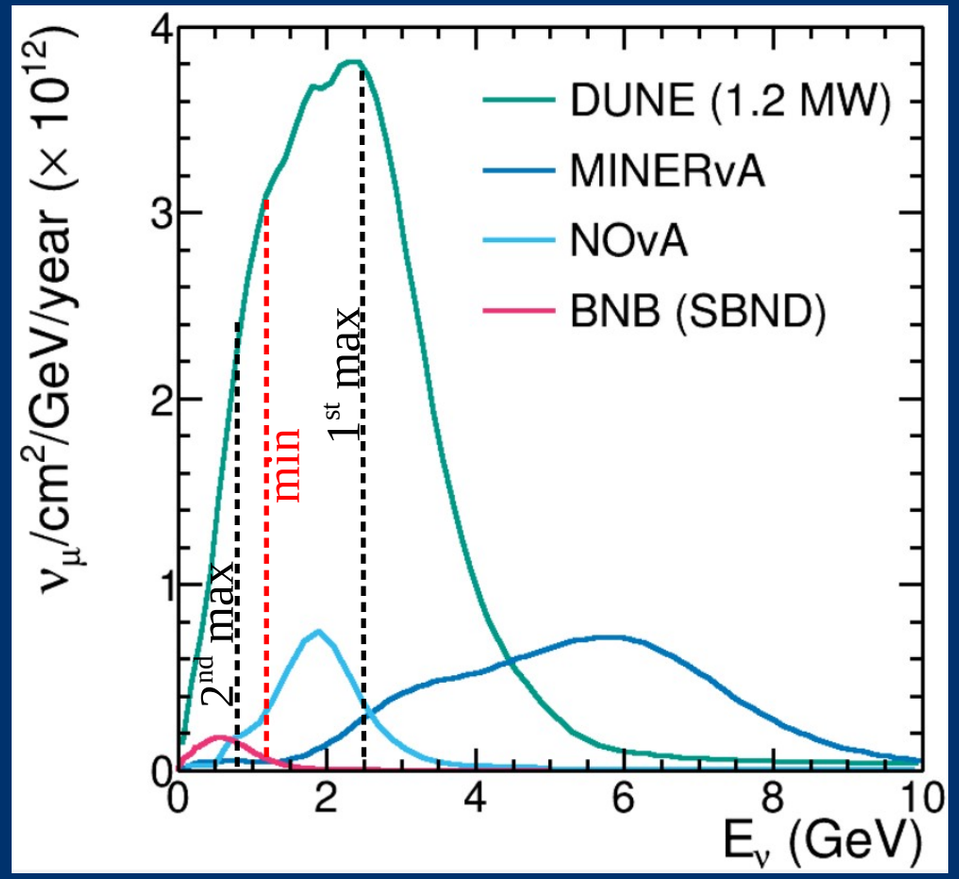
Fermi National Accelerator Laboratory, Illinois

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Design Basics



- Neutrino-enriched and antineutrino-enriched mode running.
- Very high flux peaked at ~ 2.5 GeV.
- Wideband, covering first and second oscillation maxima → lifting of δ_{CP} / $|\Delta m^2_{32}|$ degeneracy in $P(\nu_\mu \rightarrow \nu_e)$ channel.



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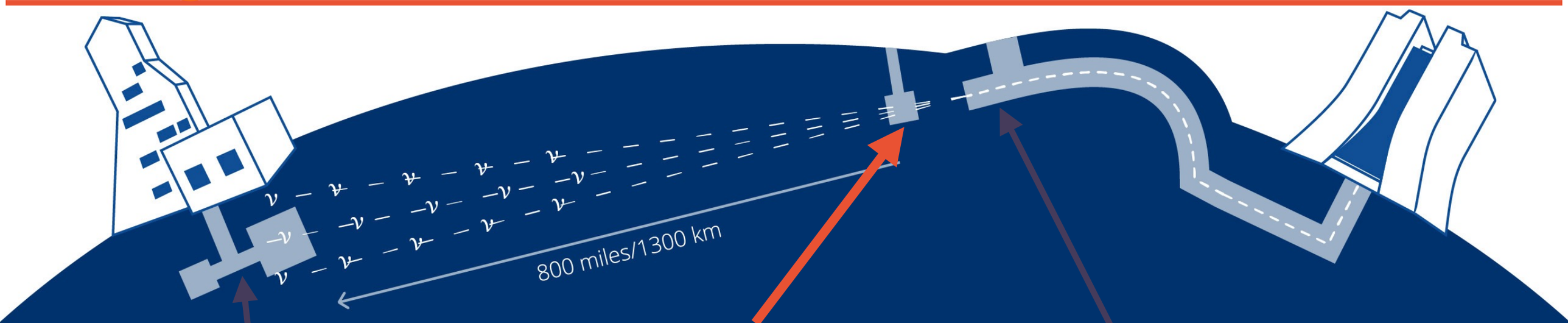
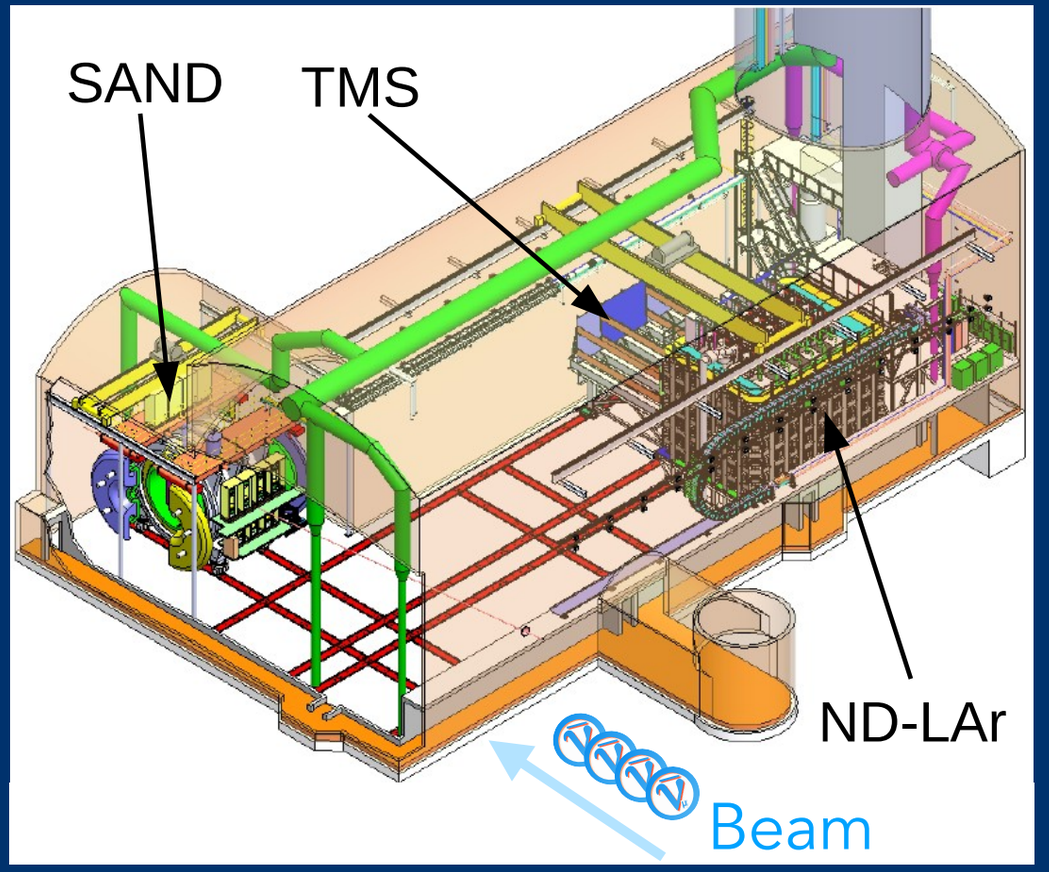


- Samples the neutrino flux before oscillations using same target & same technology as the FD → **inform oscillated predictions** at the FD.
  - Improved central value.
  - Reduced impact of systematic uncertainty.



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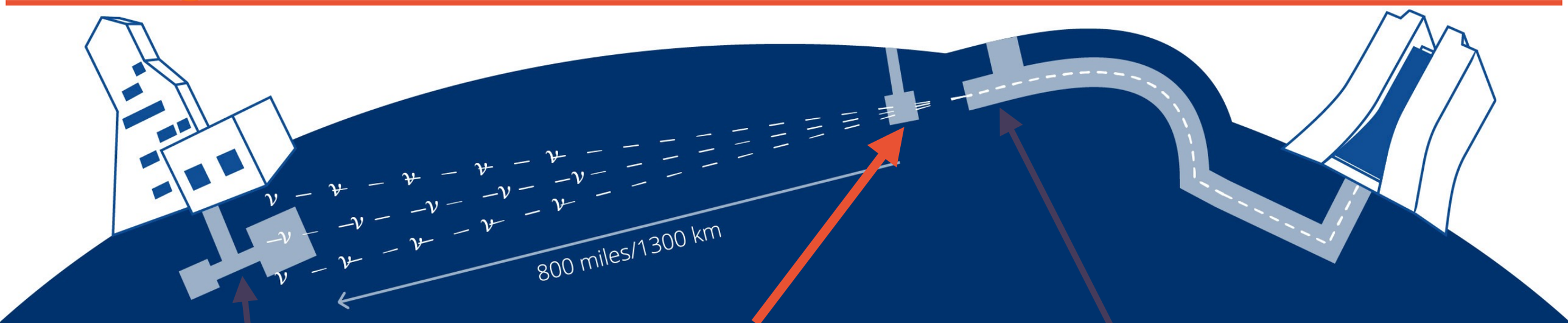
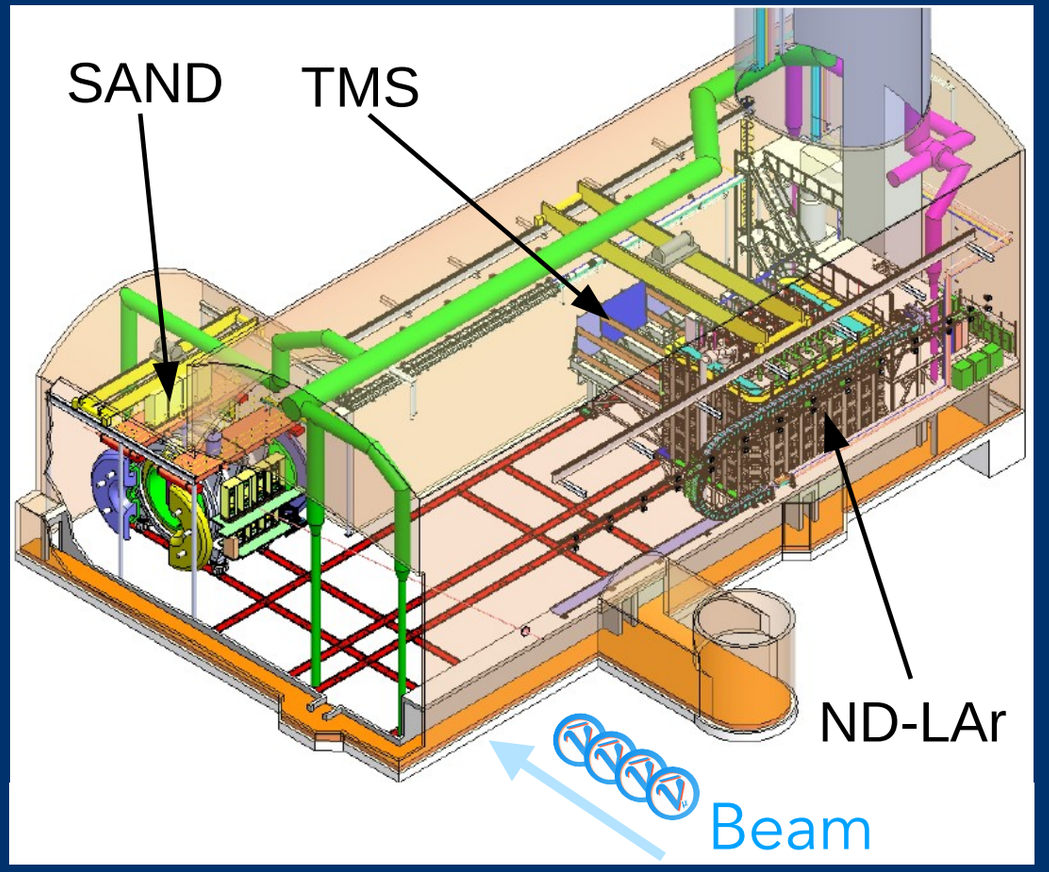


- ND-LAr+TMS: movable LArTPC with a magnetised muon spectrometer.
  - Muon sign selection.
  - Collection of data at different off-axis positions constrains energy dependence of neutrino cross-sections.

- SAND: fixed on axis - low density tracker surrounded by calorimetry in a magnetic field.
  - Control and monitor of the neutrino beam.
  - Fine grained, particle-by-particle reconstruction with low rescattering → excellent for highly exclusive neutrino-nucleus measurements.



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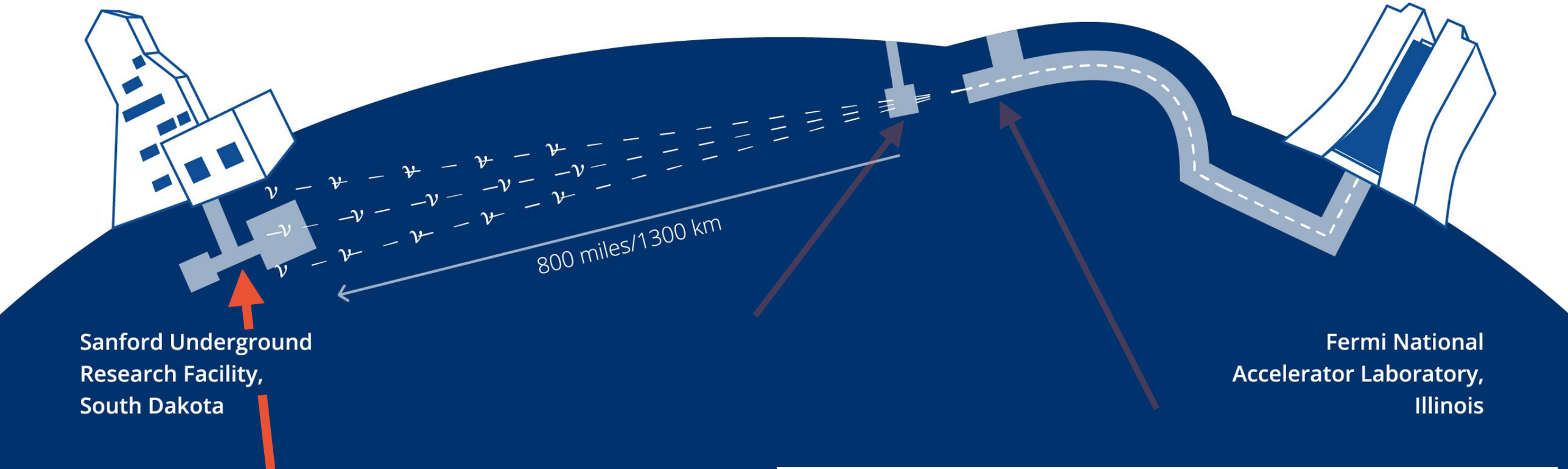
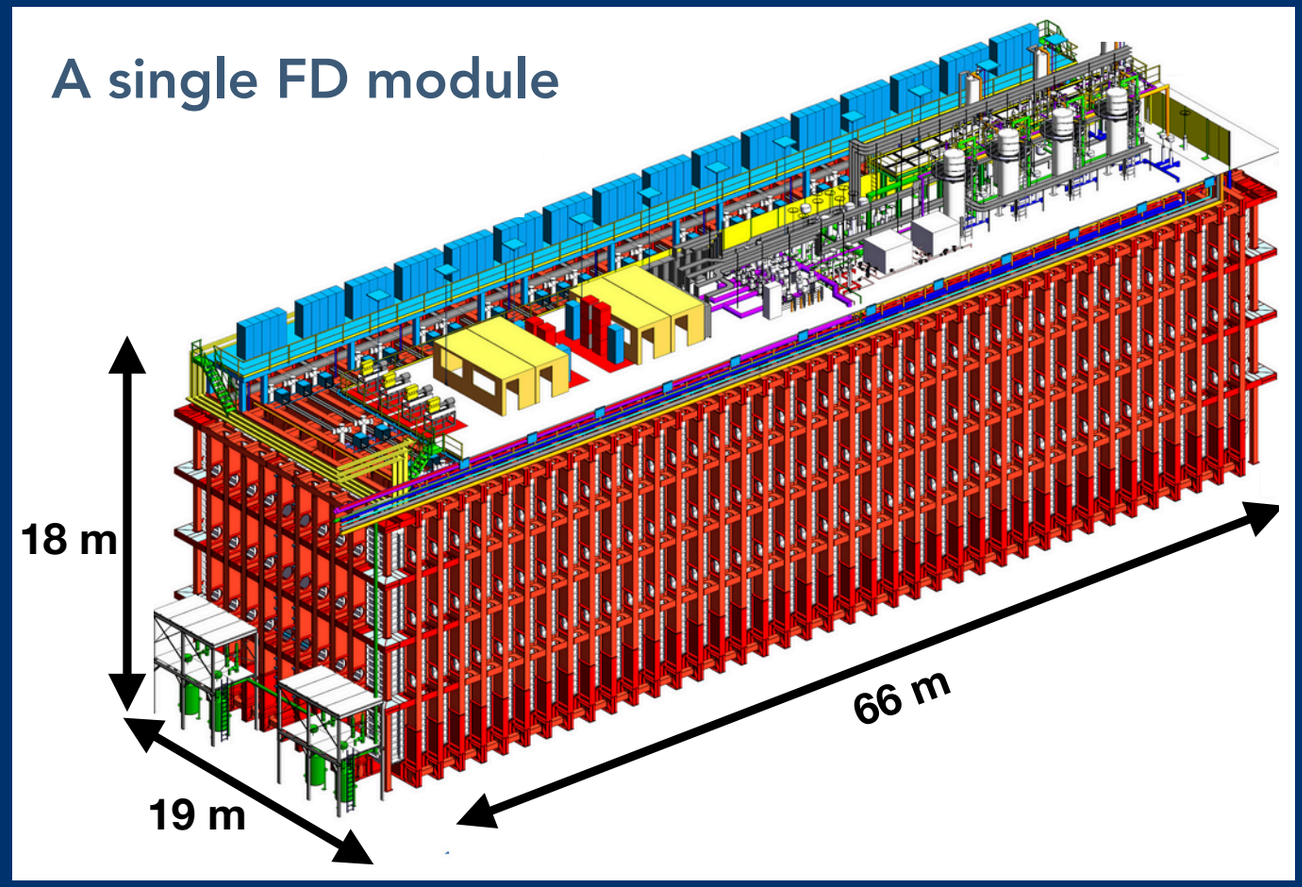
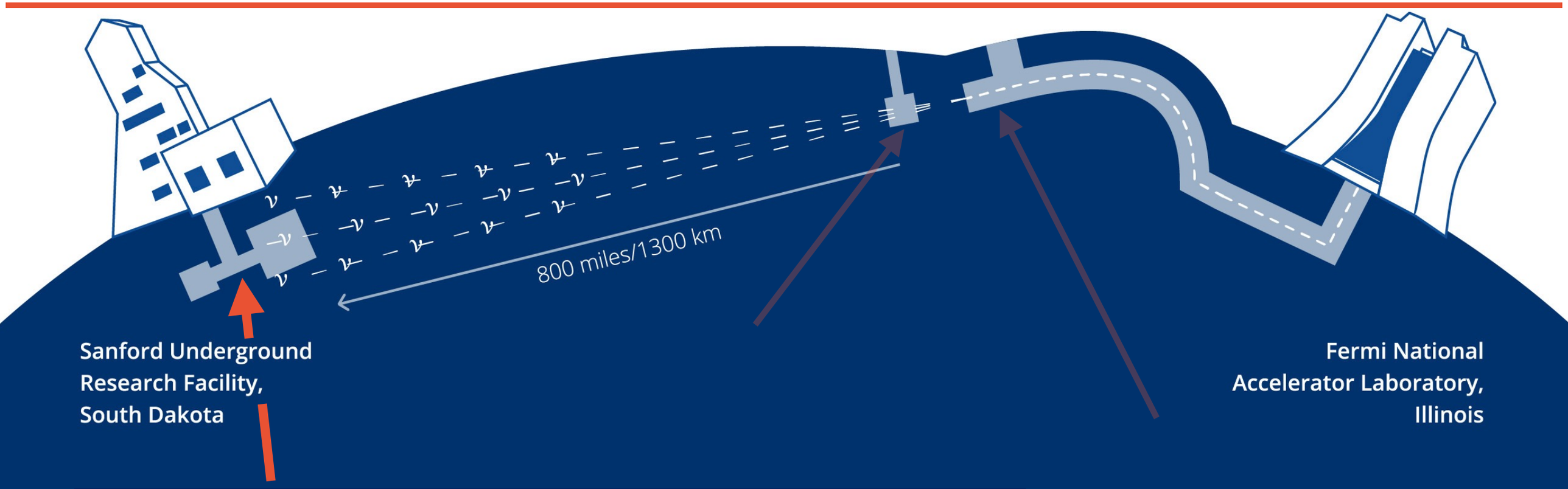


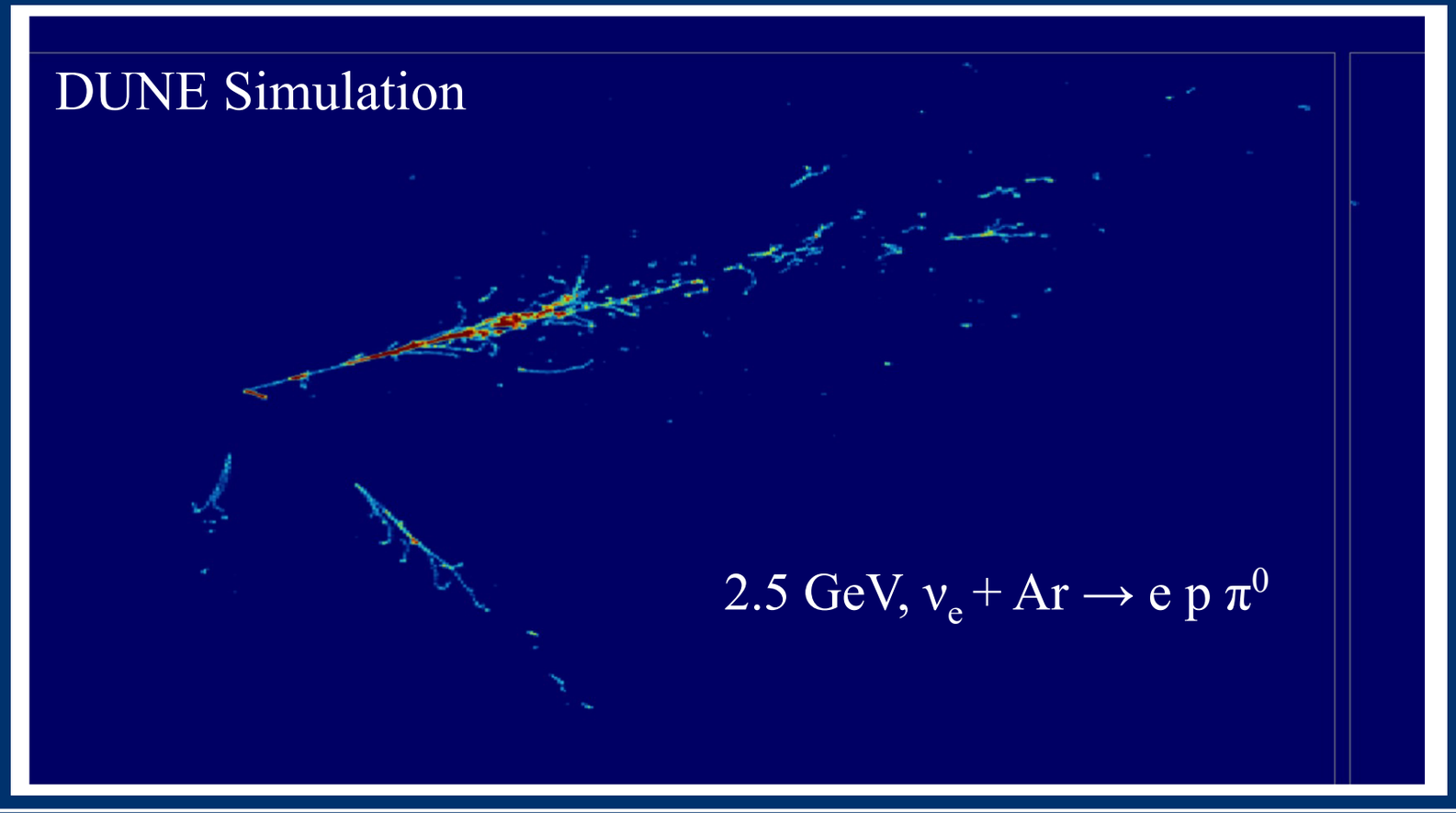
Far detector (FD) complex

- 70 kt detector 1500 m underground.
- Deployed as four modules.
  - #4 is the **module of opportunity**, several technologies under consideration.
  - #1, #2 and #3 are **LArTPCs**.



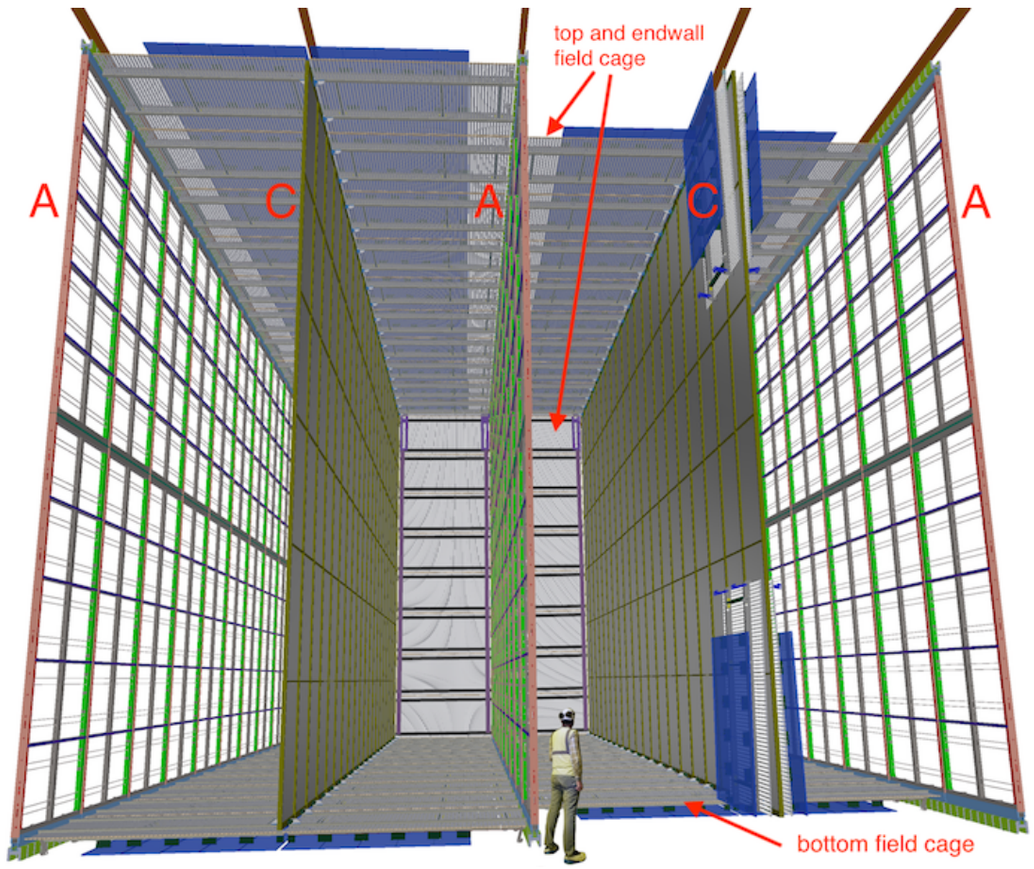
LArTPCs



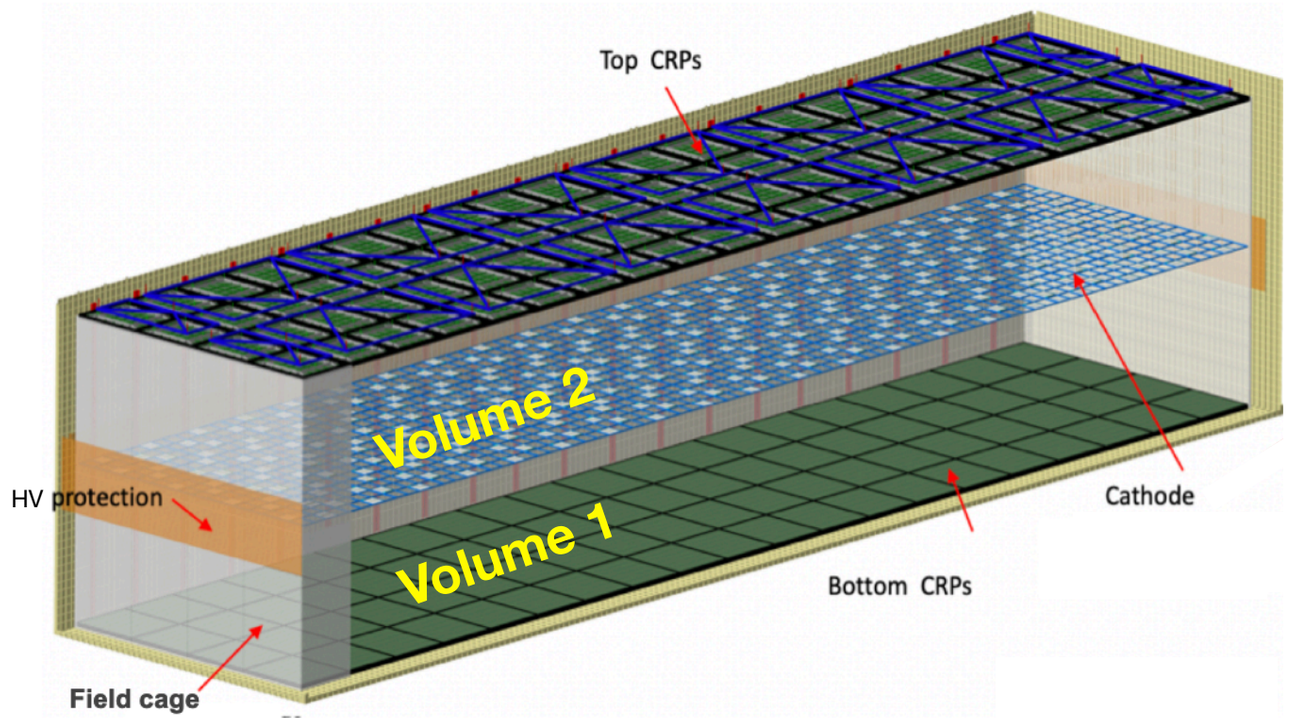


- Technology that enables event "imaging".
- Over a broad range of topologies achieves:
  - precise energy reconstruction,
  - efficient determination of particle identity.

Two LArTPC Readout Technologies



Horizontal Drift (HD)

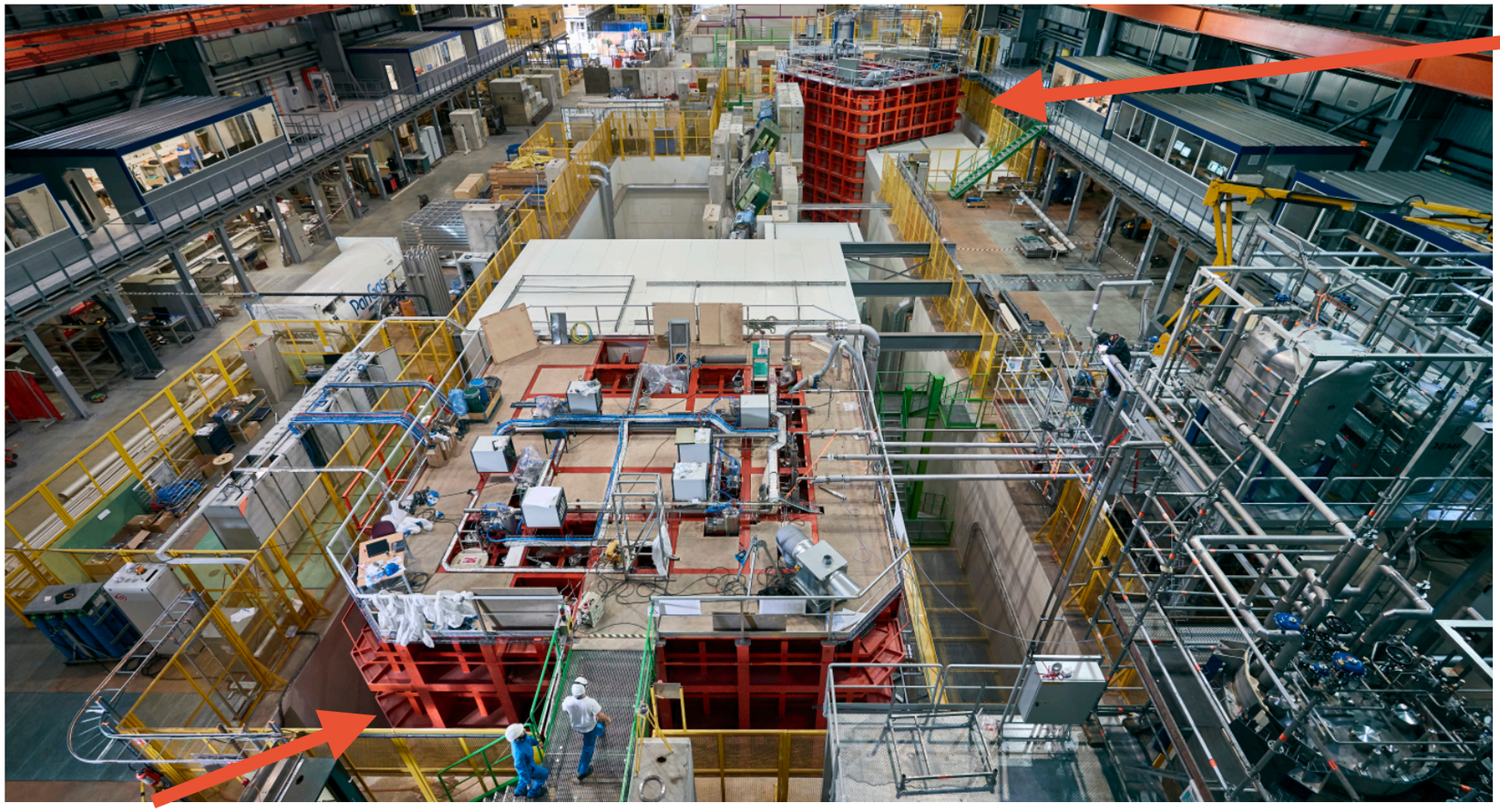


Vertical Drift (VD)

JINST 15 T08010 (2020), JINST 19 T08004 (2024)

	HD	VD
Drift Field	500 V / cm horizontally	480 V / cm vertically
Drift Regions	4, each 3.5 m long	2, each 6.5 m long
Charge Readout	Wire-based (APA)	Strip-based (CRP)
Light Readout (PDS)	X-Arapucas on anode planes	X-Arapucas on cathode plane + cryostat membrane

Two LArTPC Readout Technologies

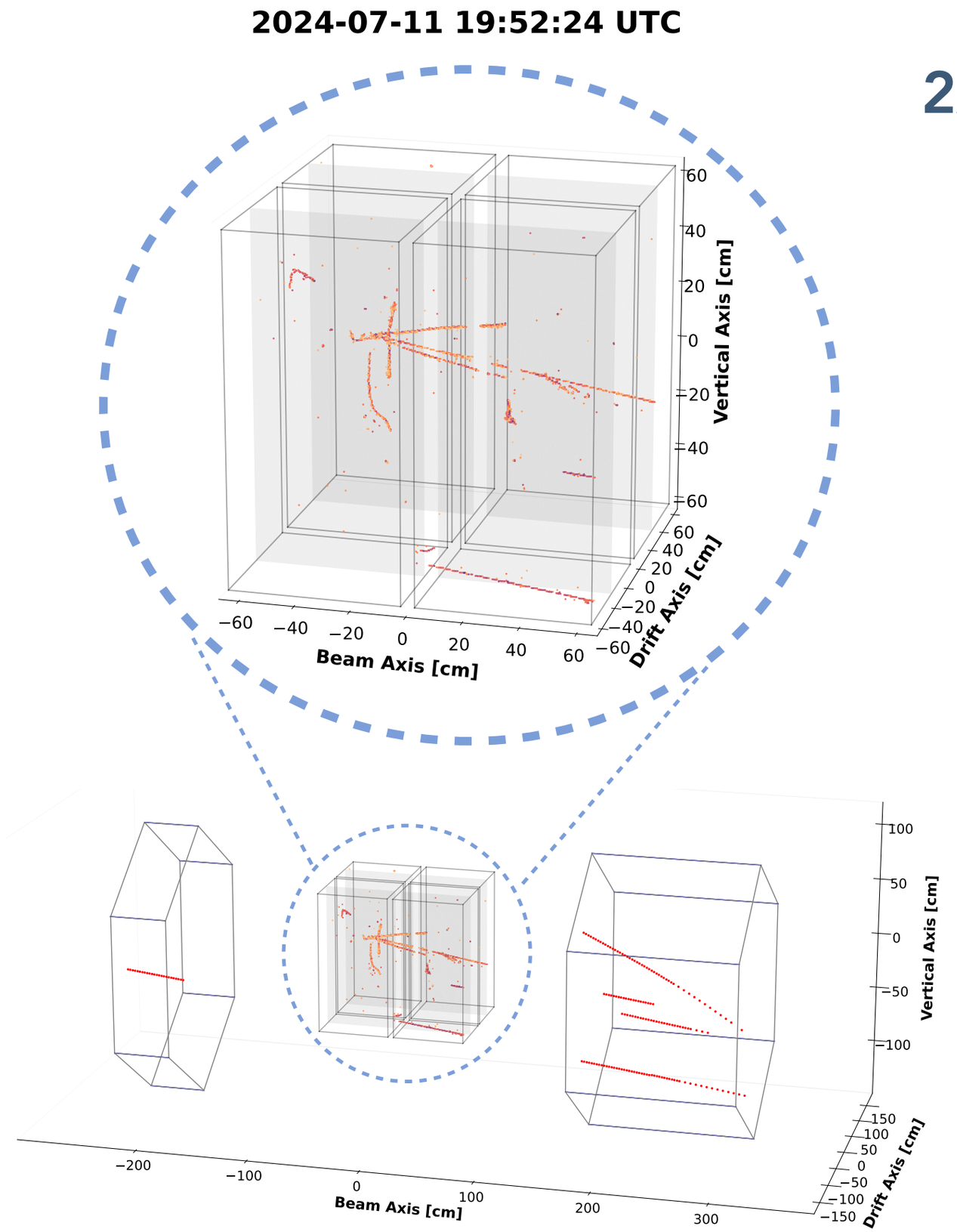


- Tested via the ProtoDUNEs at the CERN neutrino platform.
  - Each one 800 t LAr total (1/20 of an FD module).
  - Real-sized readout elements (APA, CRP, PDS).

- Successful running with cosmic interactions and charged particle beam in 2018 - 2020 (HD and VD) and again in 2024 (HD).
  - Application of pattern recognition / ML-based reconstruction software [1] and [2].
  - Charged particle / Ar cross section measurement [3].

- VD beam running is happening right now!

LArTPC Prototyping for the ND



2x2 Demonstrator for ND-LAr

- Four LArTPC modules using a pixelated charge readout.
- Modules are same as those proposed for ND-LAr but smaller (0.7 m x 0.7 m x 1.4 m).
- Sits between sets of repurposed MINERvA scintillator modules in the NuMI neutrino beam.
- Successful commissioning in July 2024, 4.5 days of beam data before accelerator complex damage.
- Invaluable experience:
  - Extension to Full Scale Demonstrator.
  - Informing simulations of full NDLAr.

Installation Plans

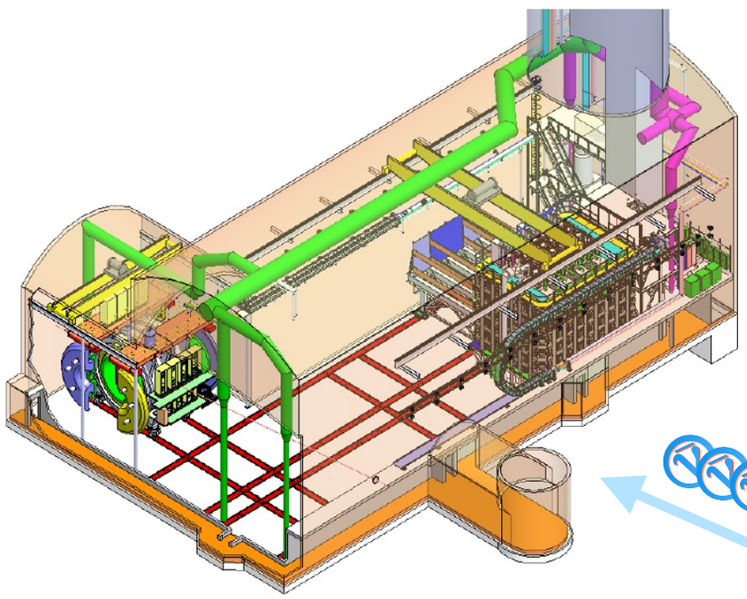
DUNE's construction will be **staged** → continuous progress toward physics goals beginning this decade.

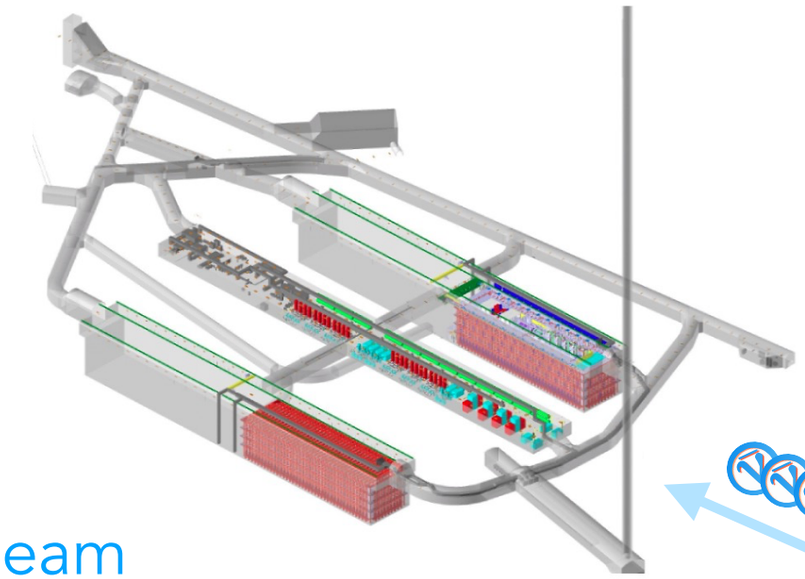
Phase I

- **Beam:** 1.2 MW beam intensity (2 MW with ACE-MIRT).
- **Movable ND:** ✓
- **ND configuration:** ND-LAr, TMS, SAND.
- **FD configuration:** Two 17 kt LArTPC modules - first VD second HD.

Phase II

- **Beam:** 2.4 MW beam intensity.
- **Movable ND:** ✓
- **ND configuration:** ND-LAr, ND-GAr, SAND.
- **FD configuration:** Three 17 kt LArTPC modules and one module of opportunity.





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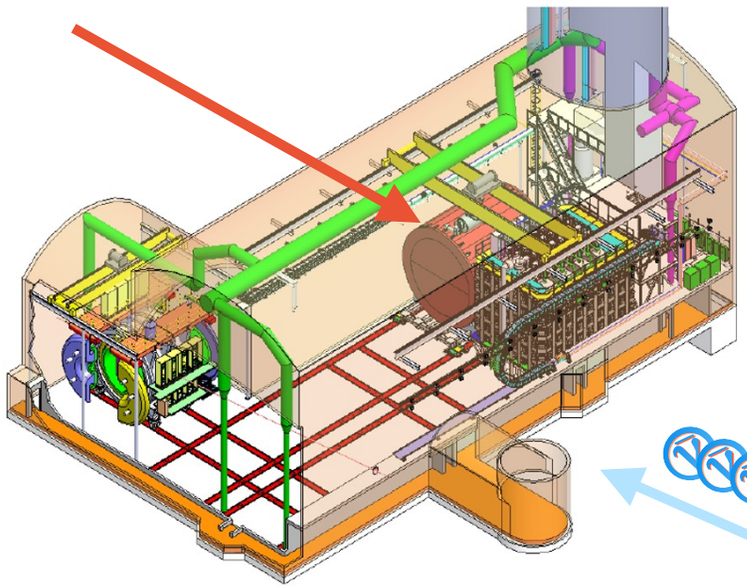
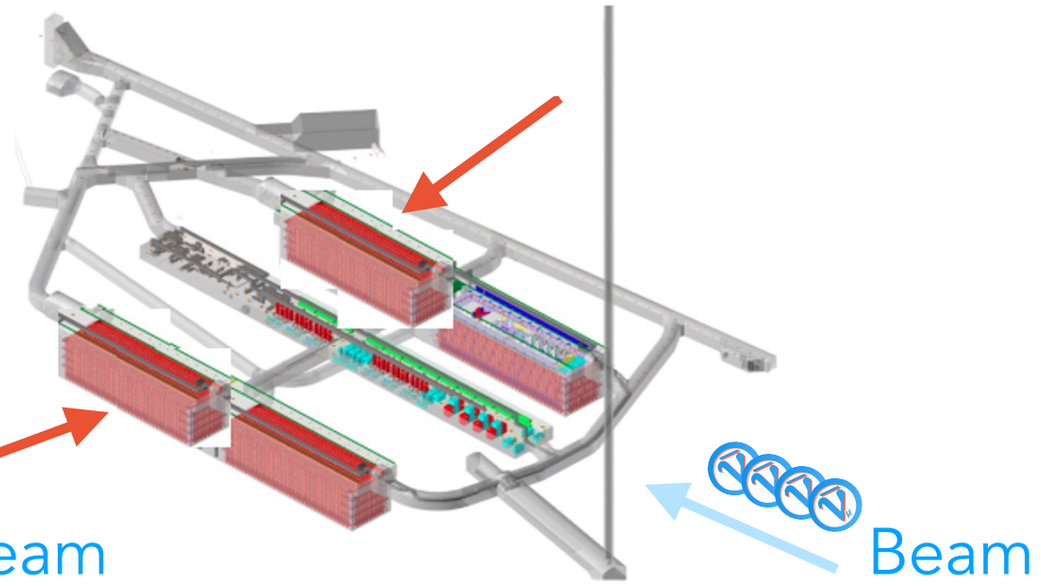
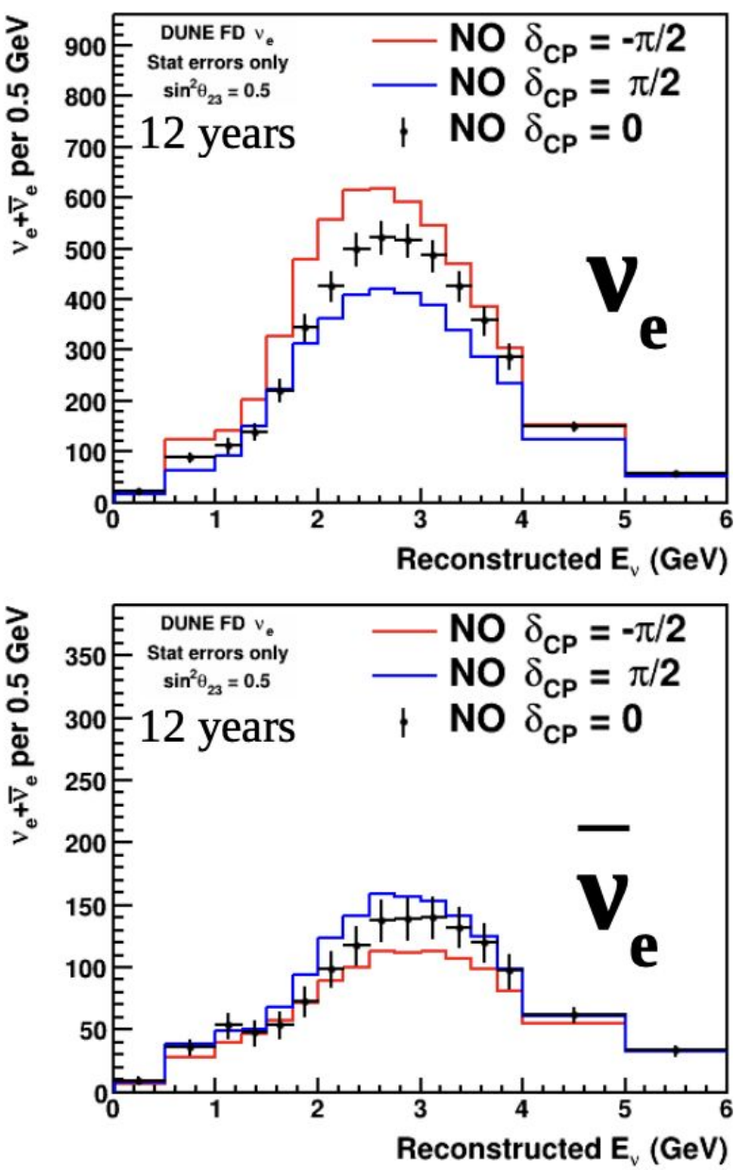
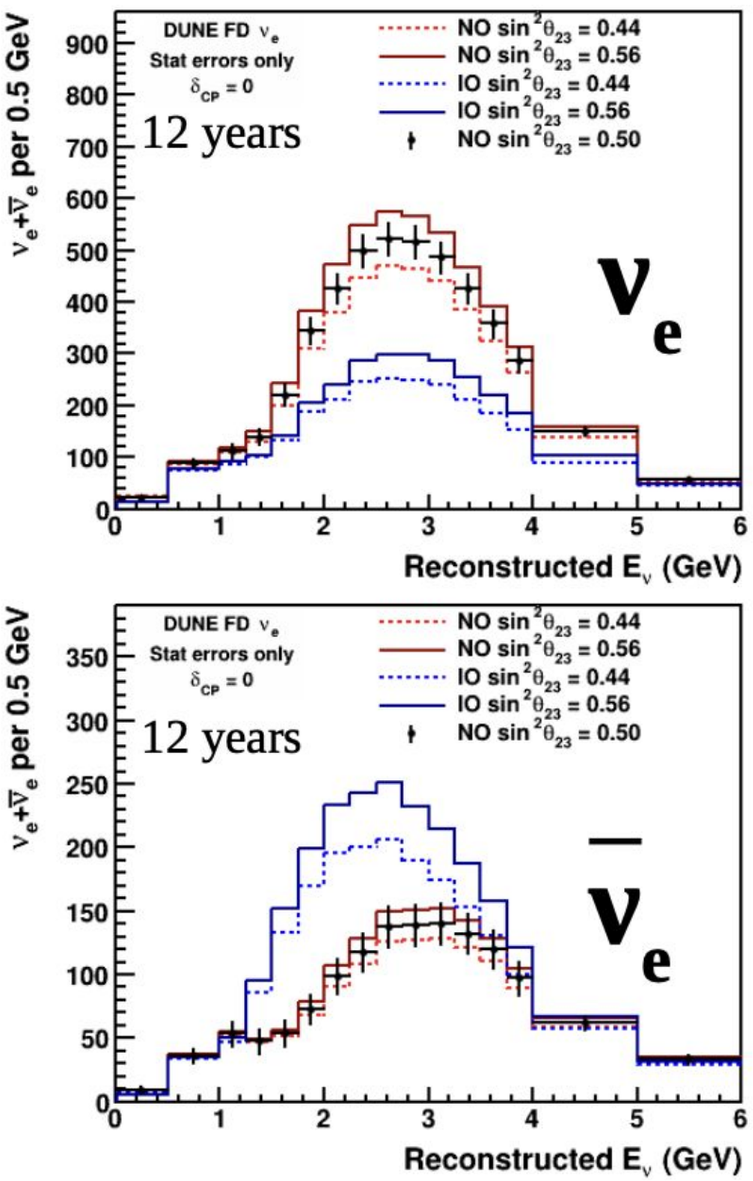




Oscillation Physics Reach

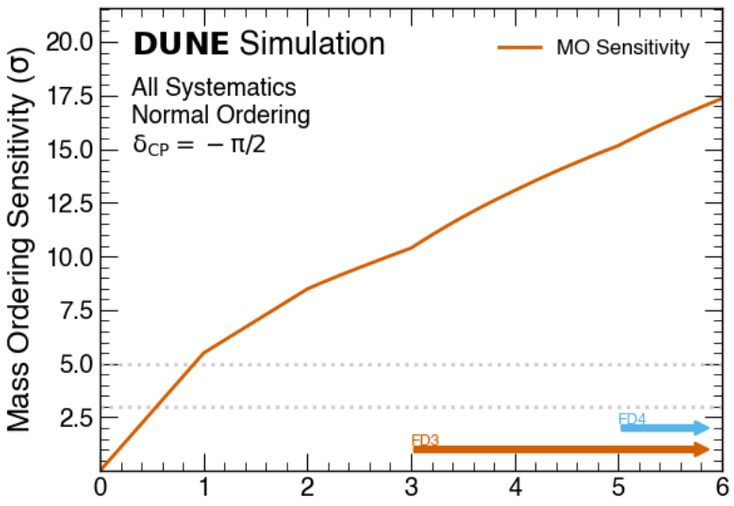


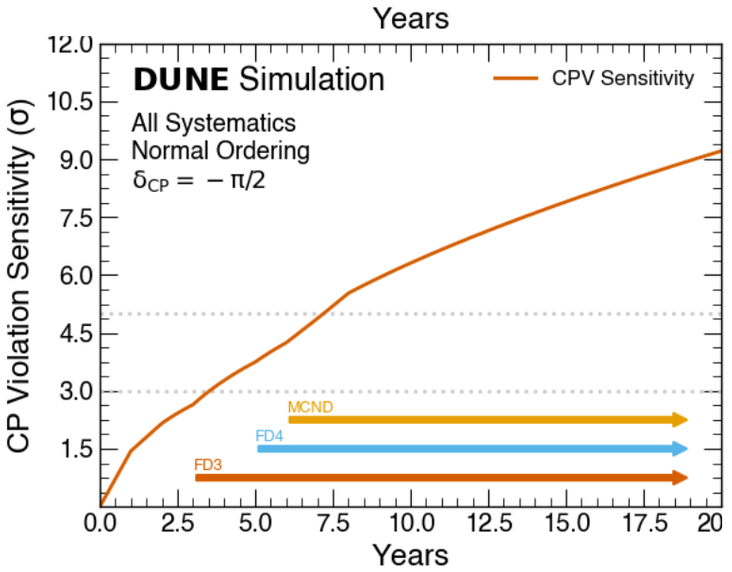


- DUNE probes δ_{CP} and the mass ordering (MO) by comparing $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$.
- MO, δ_{CP} and θ_{23} all affect the asymmetry in the number of appearing ν_es and $\bar{\nu}_e$s, and spectral shapes in different ways → handle on resolving degeneracies.
- If there is new physics → may be no combination of MO, δ_{CP} and θ_{23} that fits the data!

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

Oscillation Physics Reach





- If nature is kind:
  - $> 5\sigma$ sensitivity to the MO in 1 year.
  - $> 3\sigma$ sensitivity to CPV in 3.5 years.

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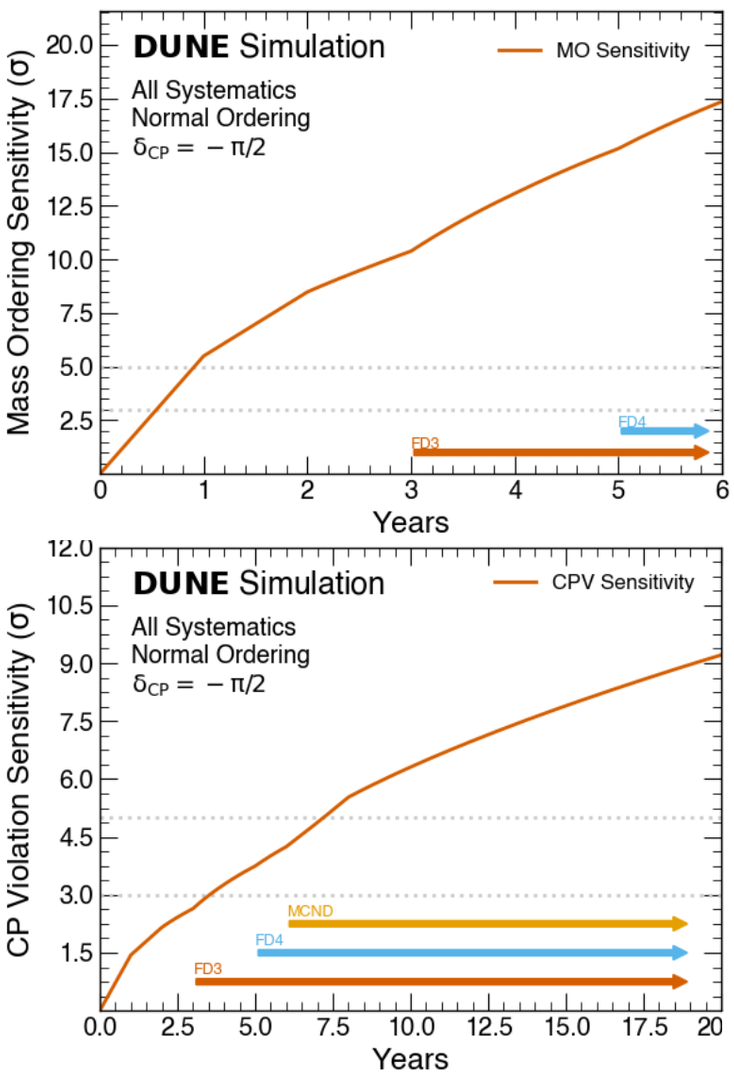
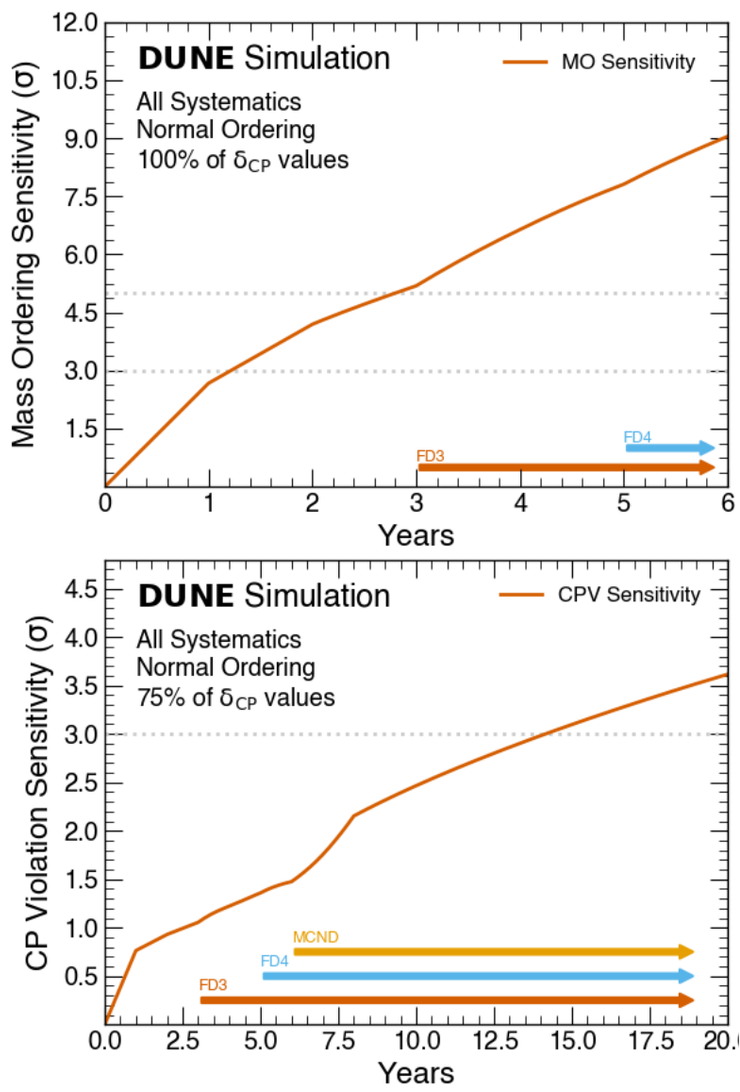
Oscillation Physics Reach





- If nature is kind:
  - $> 5\sigma$ sensitivity to the MO in 1 year.
  - $> 3\sigma$ sensitivity to CPV in 3.5 years.
- If nature is unkind:
  - $> 5\sigma$ sensitivity to the MO in 3 years.
- In the long term, can establish CPV over 75% of δ_{CP} values at $> 3\sigma$.

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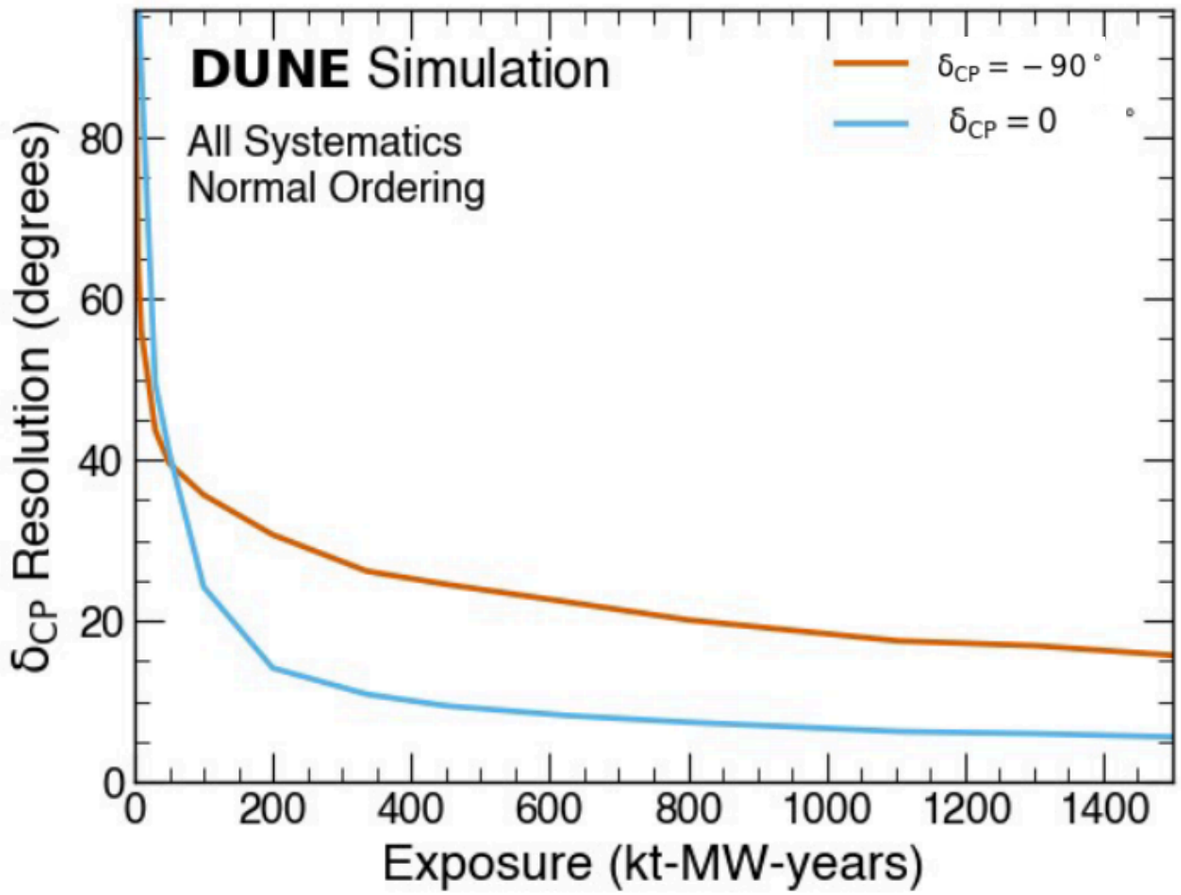
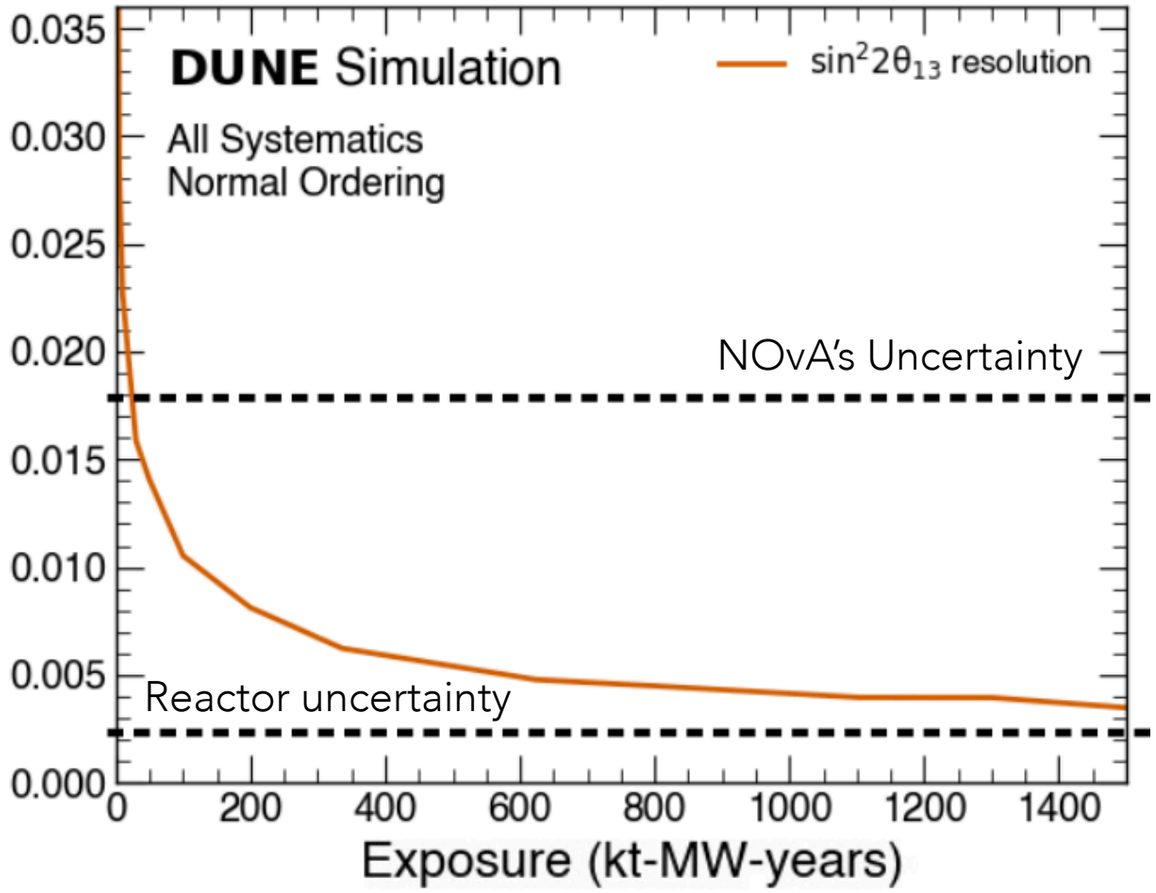
Oscillation Physics Reach





- Ultimate precision of $6 - 16°$ in δ_{CP}.

- World-leading precision among long baseline experiments on θ_{13} and Δm^2_{32}.
  - Interesting comparison with reactor experiments → new physics!

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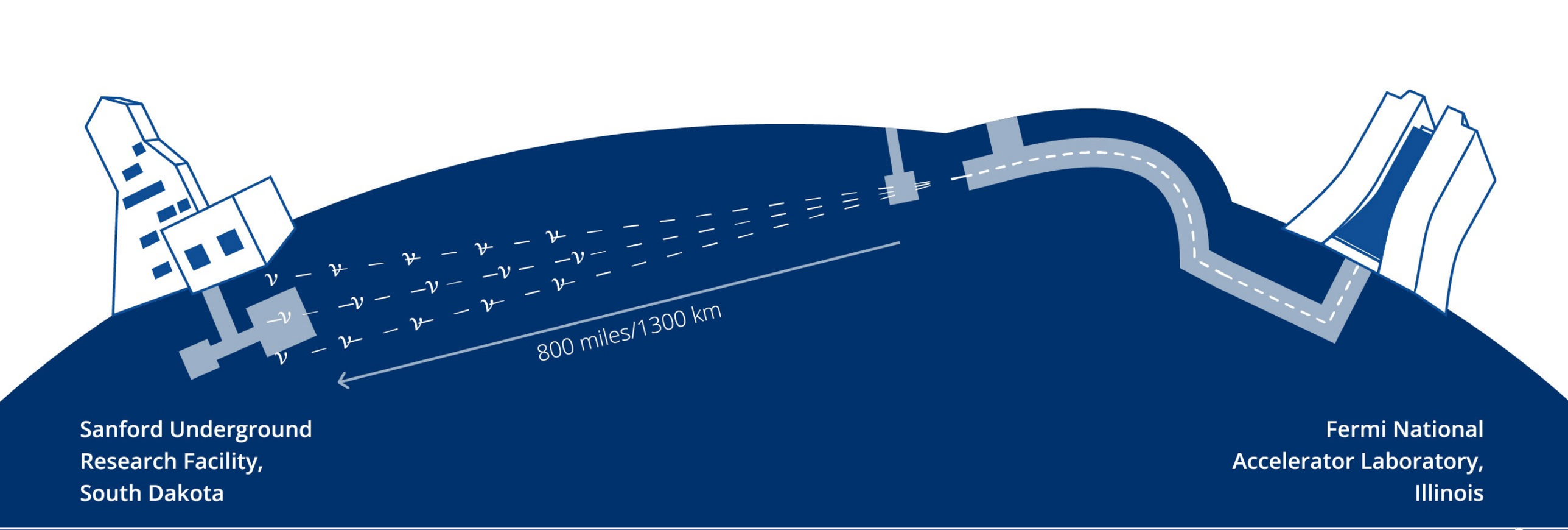
DUNE is a Neutrino Observatory

- **Large, sensitive underground detectors** are well-suited for studying natural sources of neutrinos.



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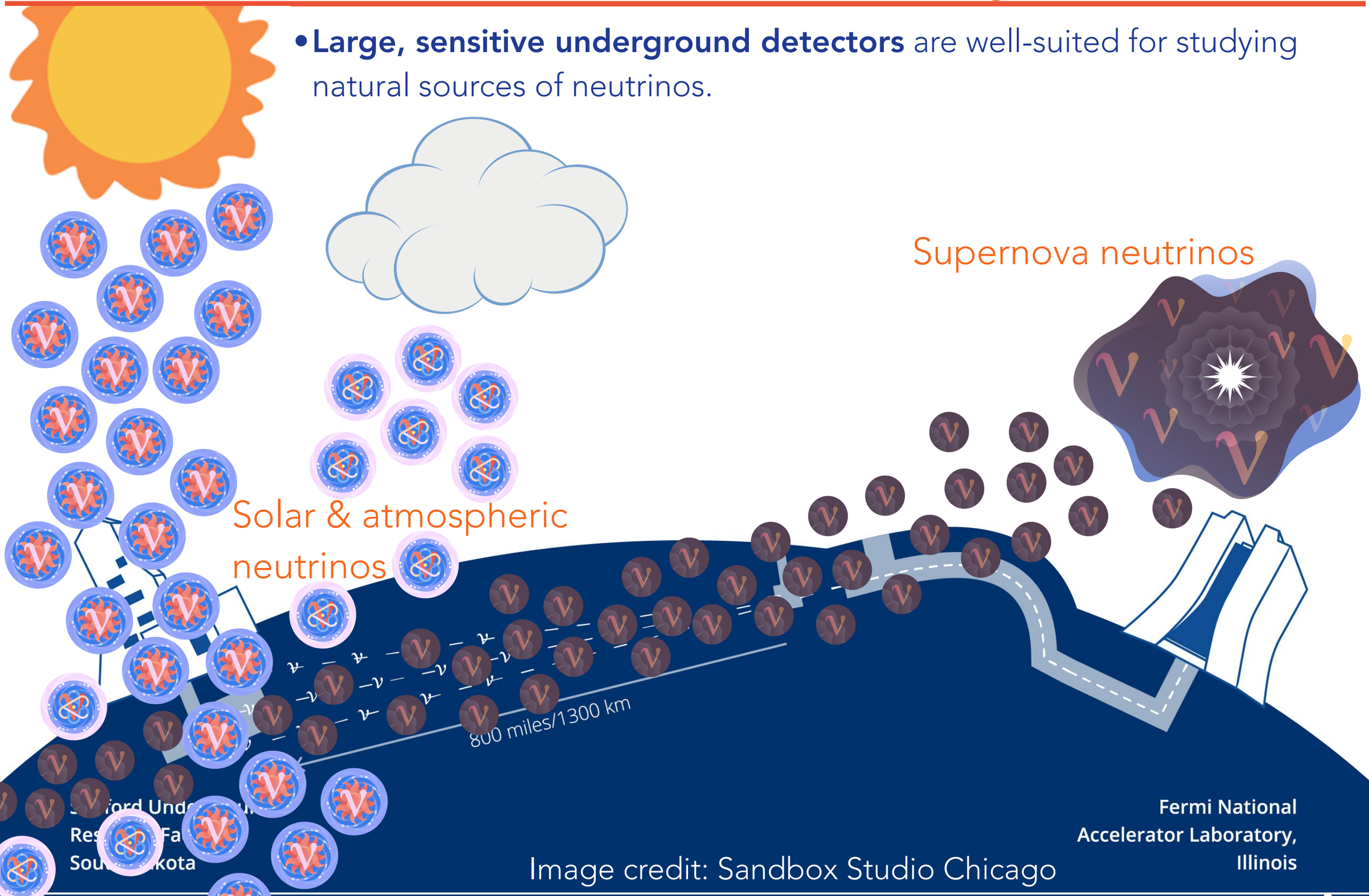

Image credit: Sandbox Studio Chicago

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- **Large, sensitive underground detectors** are well-suited for studying natural sources of neutrinos.

- Argon target gives a unique sensitivity to MeV-scale electron neutrinos.
  - $\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^* \; (E_\nu > 1.5 \text{ MeV})$
  - $\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^* \; (E_\nu > 7.5 \text{ MeV})$
  - $\nu_X + e^- \rightarrow \nu_X + e^-$

- Complementary in the global program (HyperK, JUNO), predominantly see $\bar{\nu}_e$ via IBD.

Supernova neutrinos

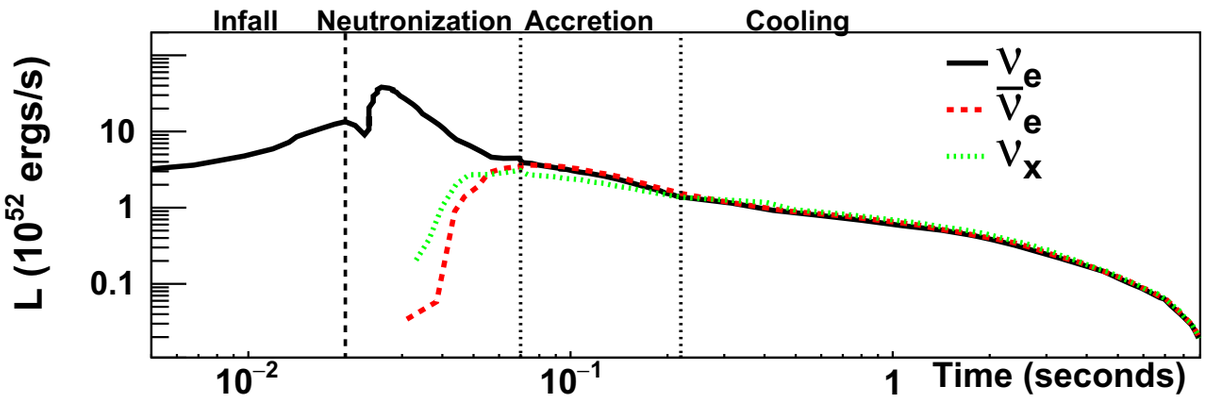
Solar & atmospheric neutrinos

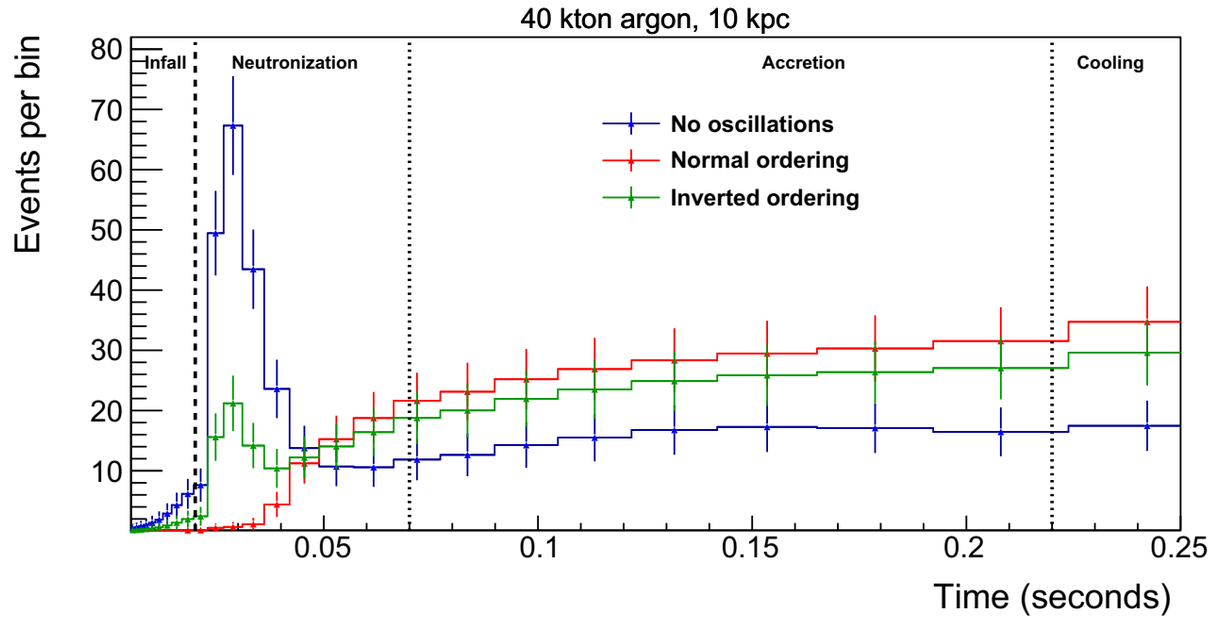
800 miles/1300 km

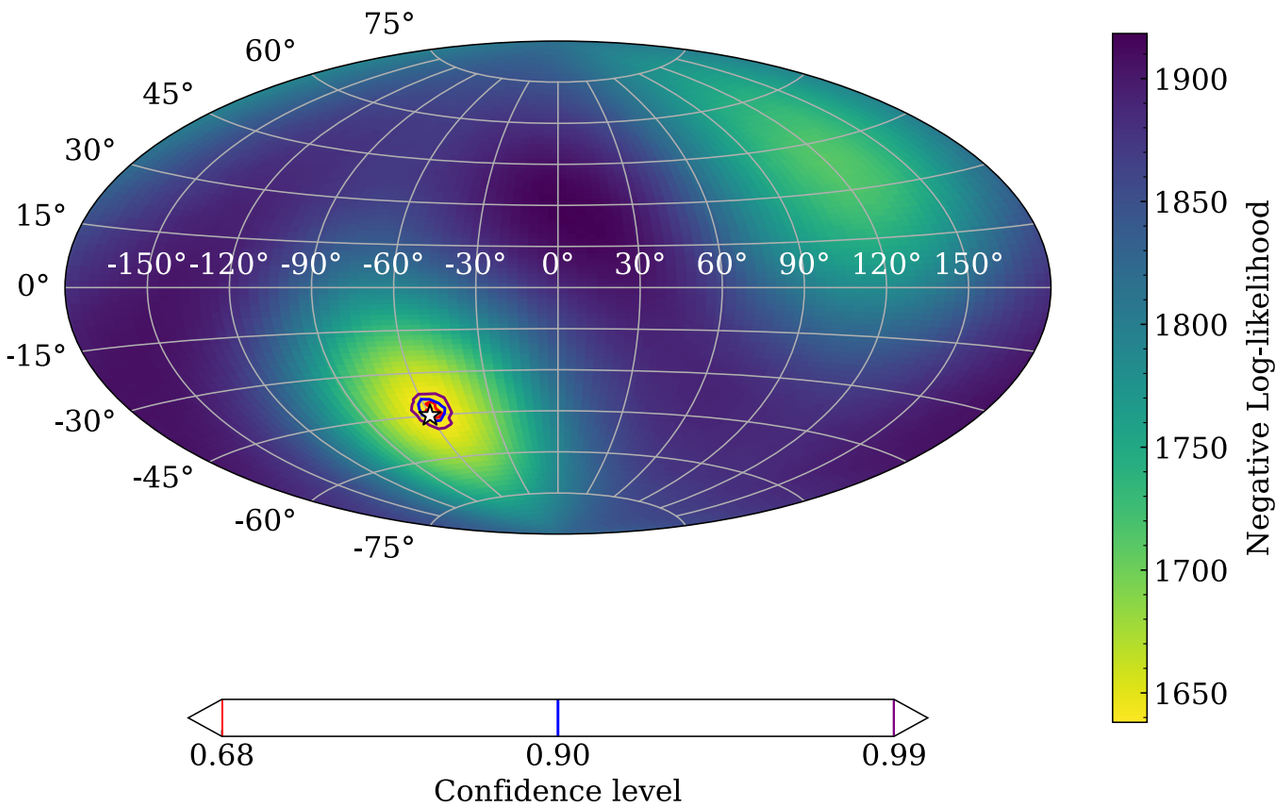
Fermi National Accelerator Laboratory, Illinois

Image credit: Sandbox Studio Chicago

Capturing Neutrinos from a Supernova







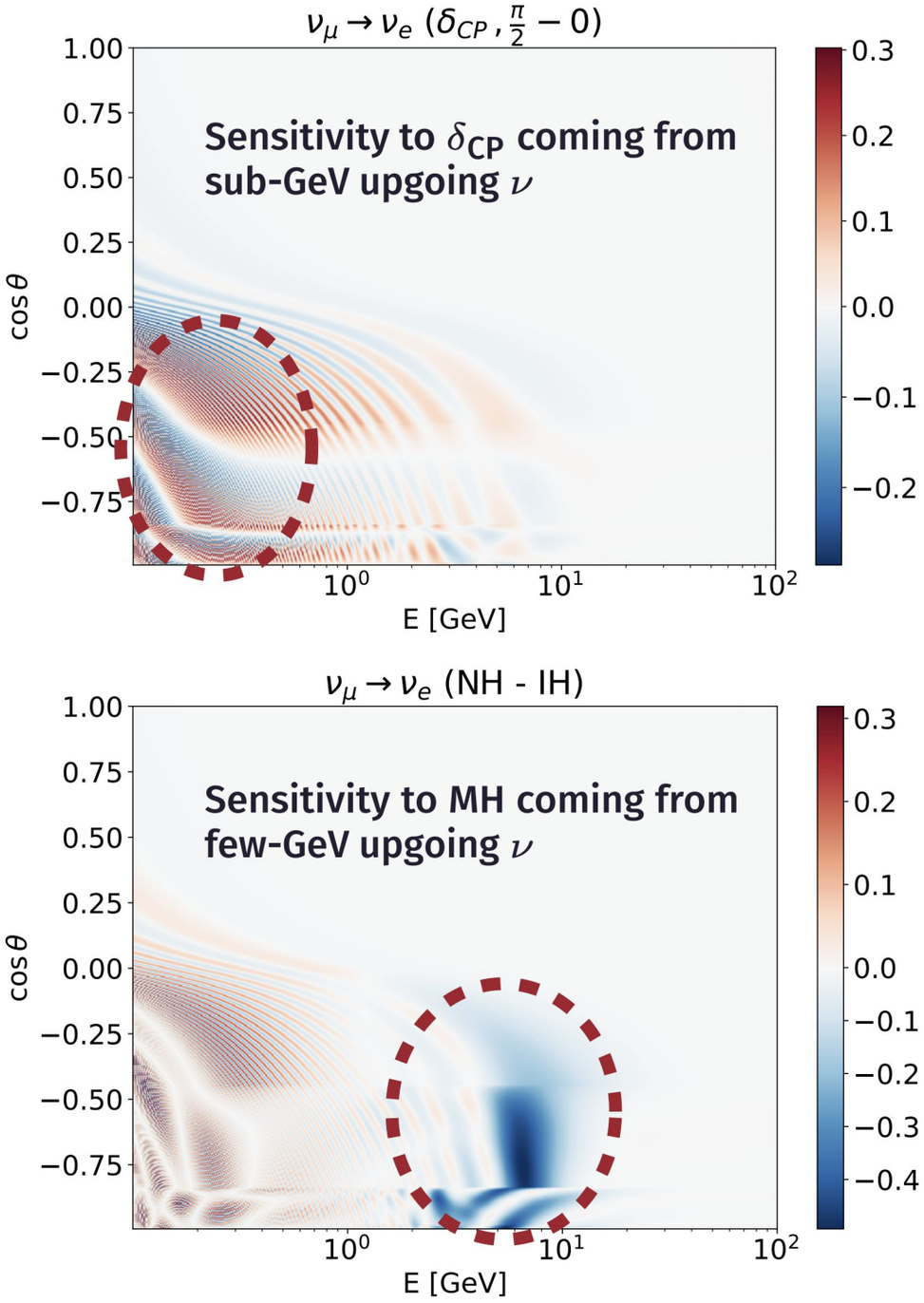
Eur. Phys. J. C 81, 423 (2021), PRD 111, 092006 (2025)

- **Supernova Bursts** (SNB) provide a huge number of neutrinos in all flavours over O(1-10) seconds.

- Time and energy spectra from these neutrinos provide information about:
  - **Neutrino physics:** mass ordering → ν_es in neutronisation burst.
  - **Supernova physics:** core collapse mechanism, black hole formation.

- ν_e elastic scatter for pointing → participation in the SN early warning system for MMA.

Atmospheric Neutrinos



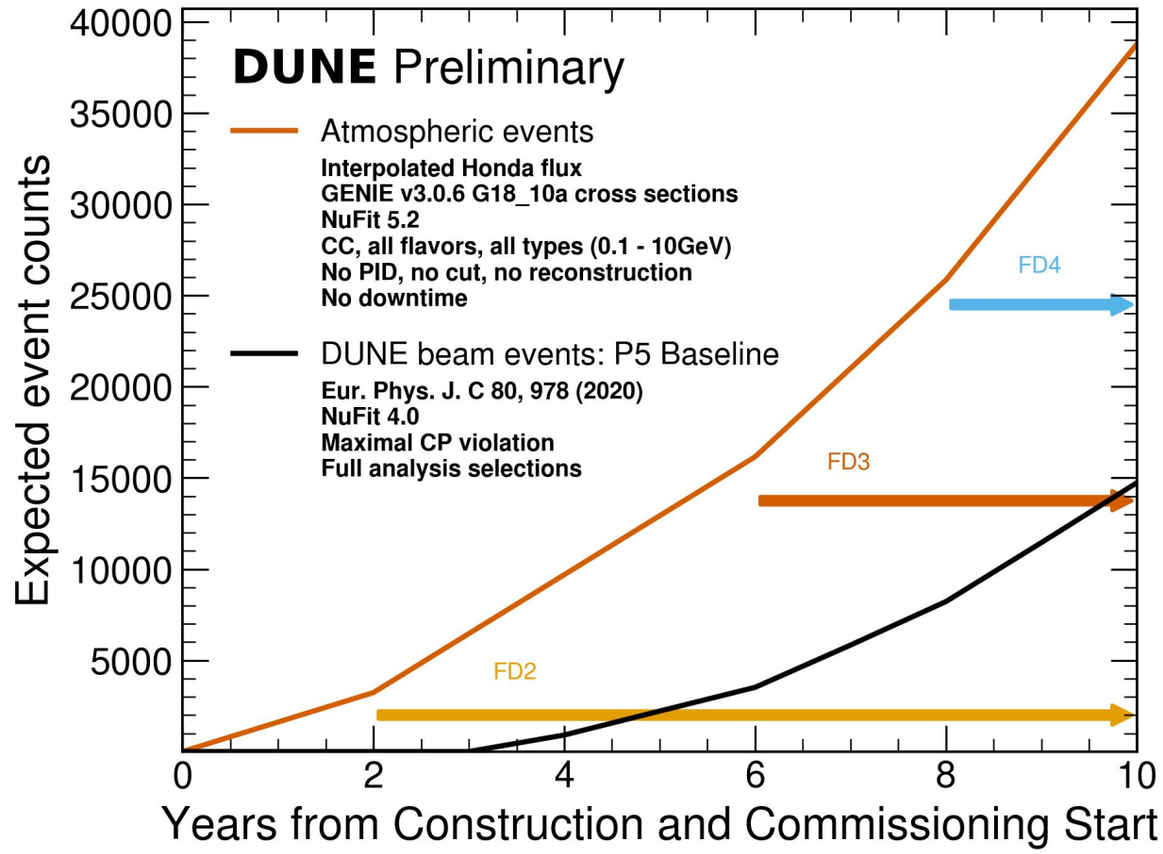
- Normalisation of sub-GeV up-going atmospheric neutrinos driven by δ_{CP} → ability to reconstruct through low hadronic kinetic energy thresholds.
- Matter resonance effects occur in the 2 to 10 GeV region:
  - Complementary measurement of mass ordering to beam.
- Sensitivity to oscillations at higher energies but ability to fully contain these events is a challenge.

Slide credit: Daniel Barrow

Atmospheric Neutrinos

- See O(10^3) events per year → don't have the mass of IceCube, KM3Net or HyperK.

- Compensated by low detection thresholds and mm-level imaging, feeding through to:
  - energy resolution,
  - direction reconstruction.

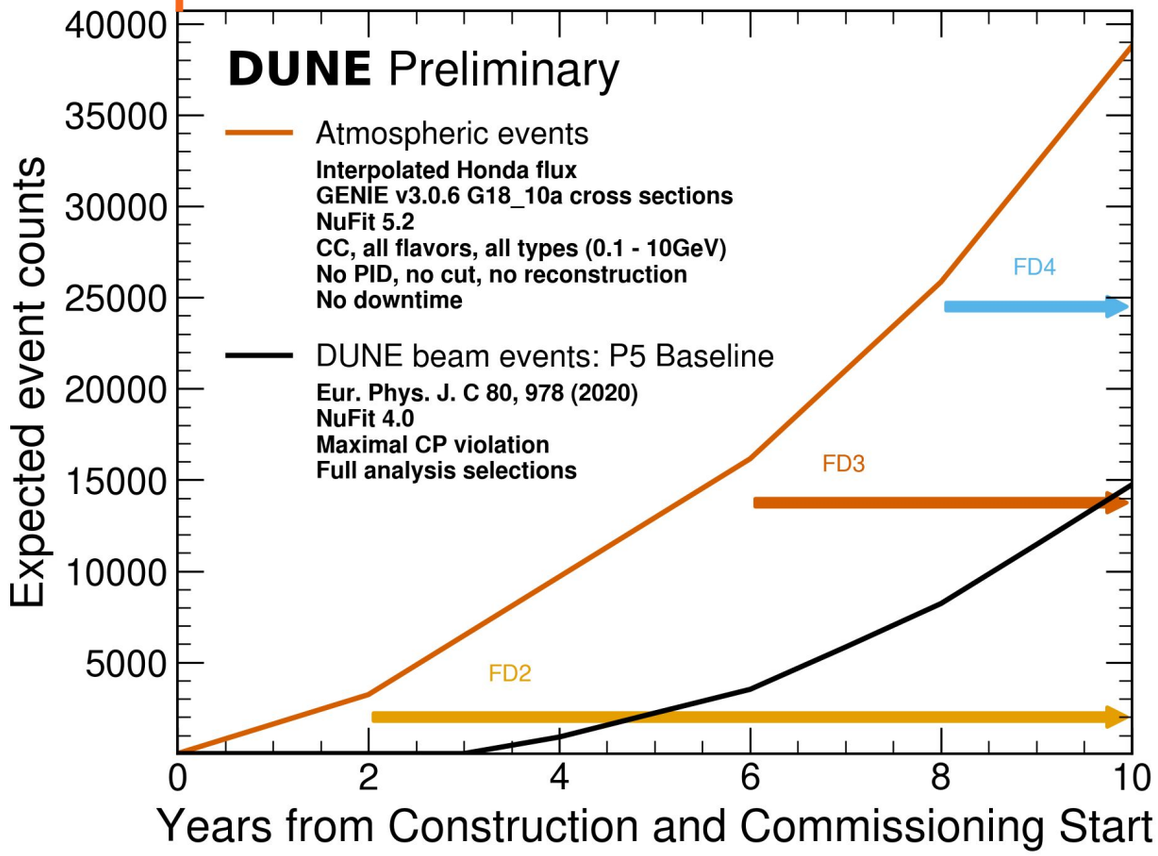


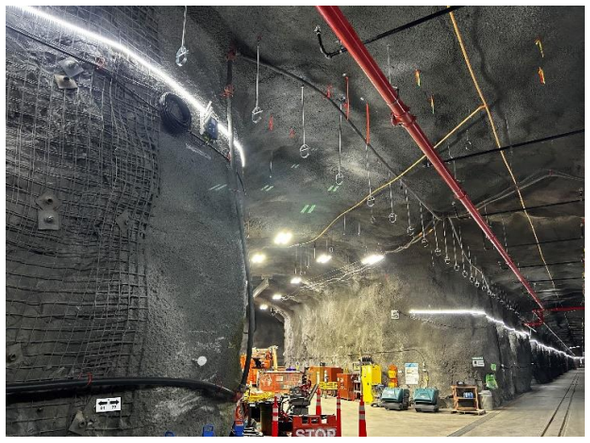
Path to First Physics

Q3, ’25

Q4, '29

You are here!





Path to First Physics

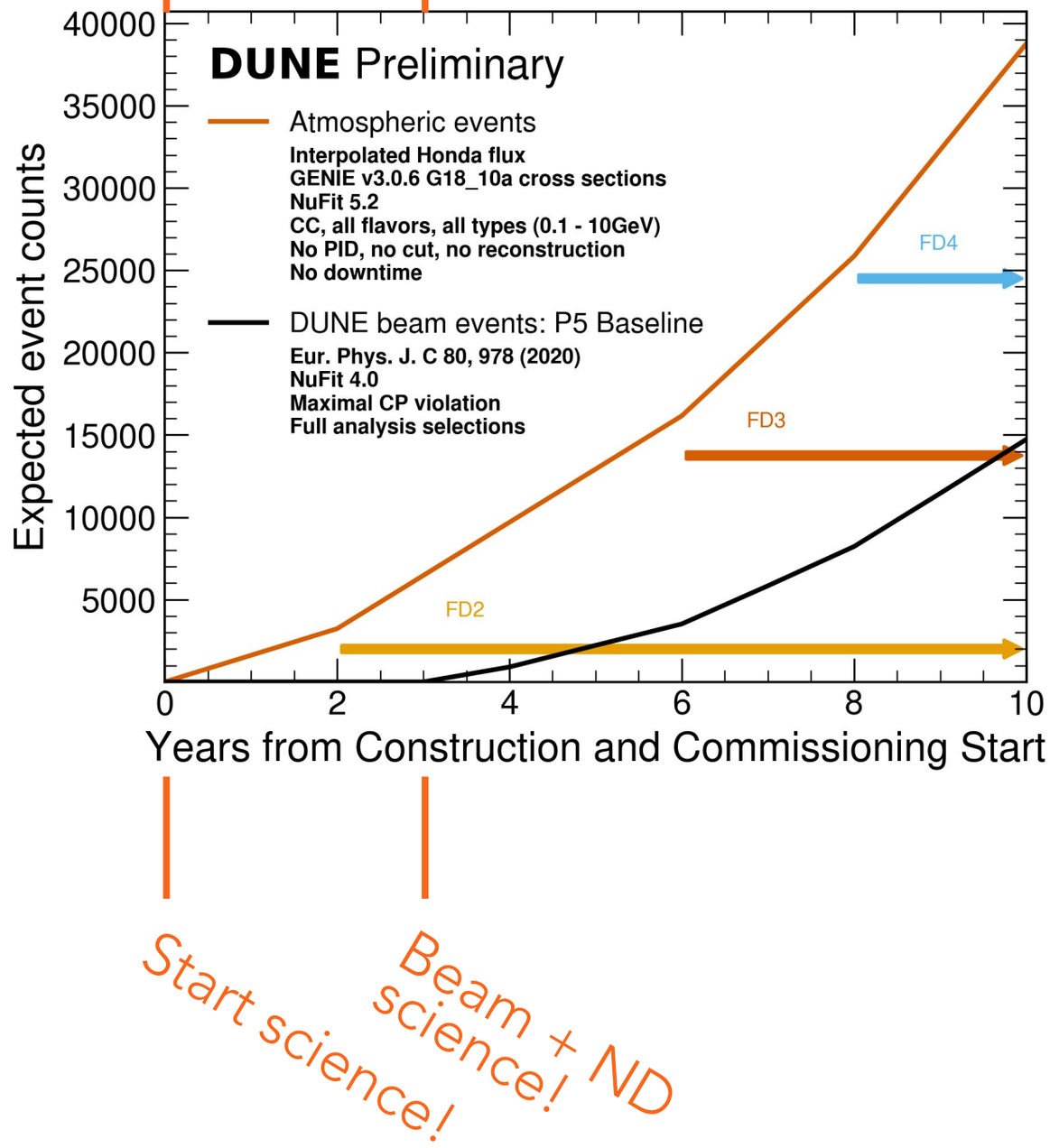
Q3, ’25 | Q4, ’25 | Q2, ’27 | Q1, ’29 | Q4, '29 | Q4, ’32

★ You are here!

Start of FD cryostat construction

Start of FD construction

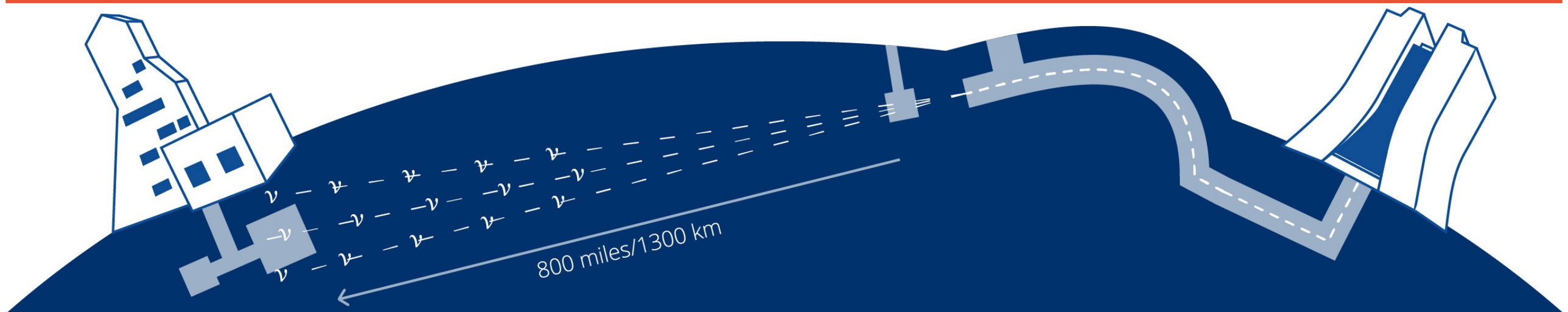
Start of ND installation



Start science!

Beam + ND science!

Summary



- DUNE is a long-baseline neutrino oscillation experiment and neutrino observatory.
- Extensive, successful prototyping program which remains very active.
- Construction work continues, with the start of science this decade.

The DUNE Collaboration May 2025