The DUNE Experiment: Overview and Status

Ioana Caracas, for the DUNE Collaboration

i.caracas@uni-mainz.de

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JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Neutrino Oscillations

- Now well understood process: mixing between mass and flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

PMNS matrix contains three mixing (**θ_{12}, θ_{13}, θ_{23}**) angles and **δ_{CP}** → non-zero δ_{CP} means neutrinos and anti-neutrinos oscillate differently

- Using the PMNS matrix we can calculate the probability of neutrino oscillations:

$$P(\nu_\alpha \to \nu_\beta) \approx \sin^2(2\theta) \sin\left(\frac{\Delta m^2_{ij}\, L}{4E}\right)$$

oscillation amplitude ~ $f(\theta)$

oscillation frequency ~ $f(\Delta m_{ij}^2)$

with

L: traveled distance

E: neutrino energy

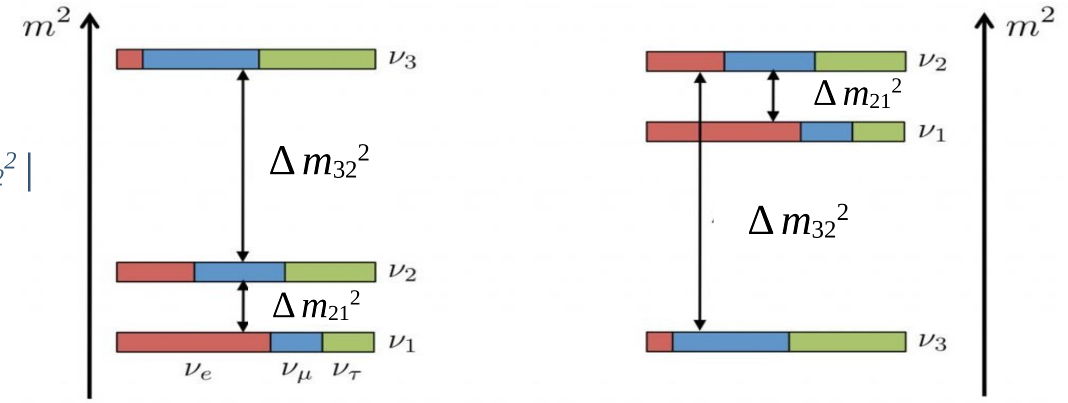
$\Delta m_{ij}^2 : m_i^2 - m_j^2$

- L and E are experiment specific

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}}_{\text{Atmospheric + LBL } \nu} \underbrace{\begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ s_{13}e^{-i\delta_{CP}} & 0 & c_{13} \end{pmatrix}}_{\text{Reactor + LBL } \nu} \underbrace{\begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{Solar } \nu} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Neutrino Oscillations

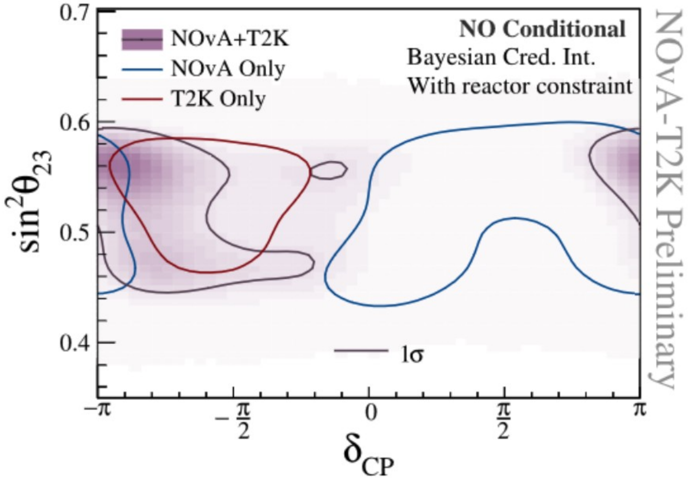
- Constrained parameters: $\theta_{12}, \theta_{13}, \theta_{23}, \Delta m_{21}^2$, $|\Delta m_{32}^2|$
- Open questions:
  sign Δm_{32}^2 (mass ordering), θ_{23} octant, δ_{CP}



- **Goal:** measure the unknown PMNS parameters
  → complementary experiments – neutrino and antineutrino oscillations at different propagation distances and energies

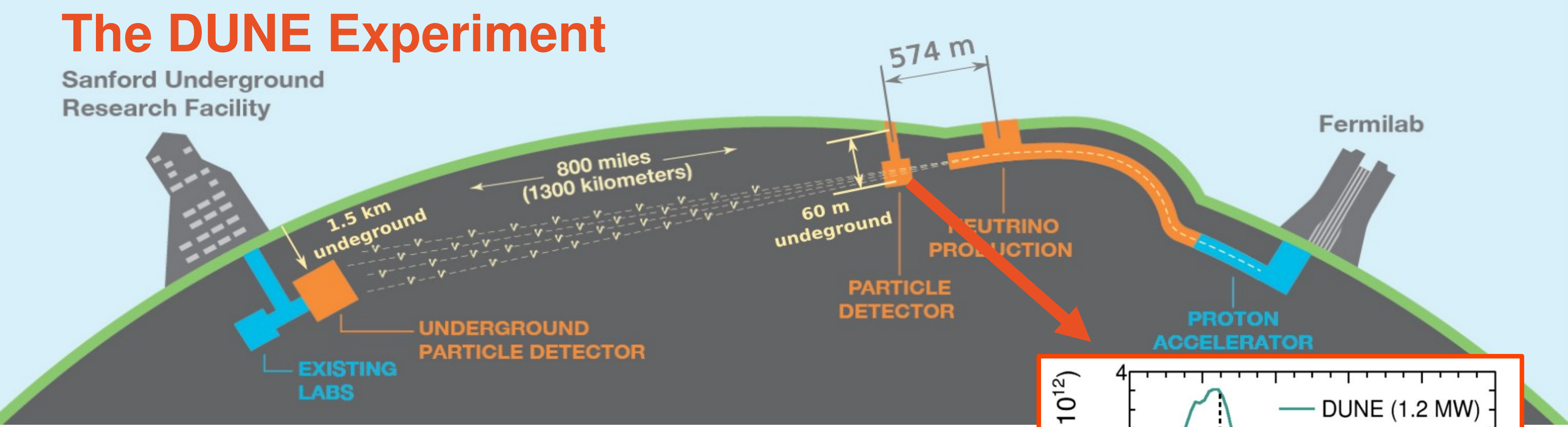
  – there is some tension in δ_{CP} value for NO

NOvA only: Phys. Rev. D106, 032004 (2022)
T2K only: Eur. Phys. J. C83, 782 (2023)



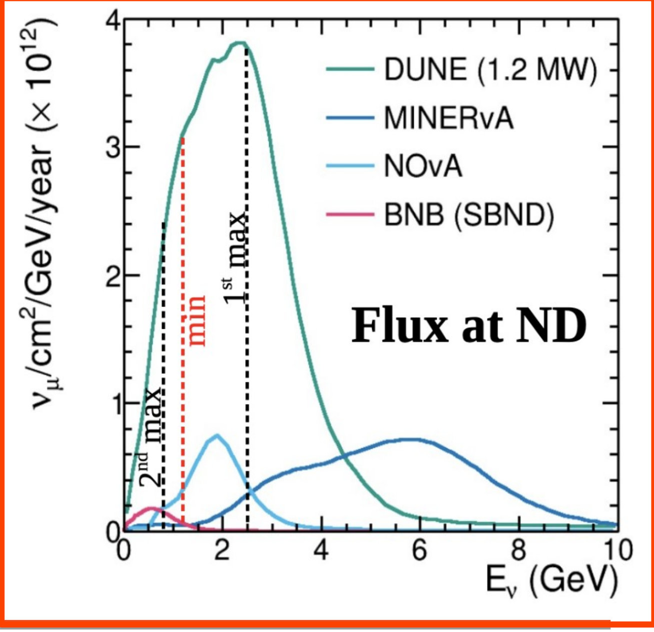
- **DUNE**: very high δ_{CP} and mass ordering sensitivity

The DUNE Experiment



Muon neutrino beam

- 1.2 MW beam power → upgradable to 2.4 MW
- very large neutrino flux peaking at ~ 2.5 GeV
- neutrino and anti-neutrino measurements
- wide energy band (both oscillation maxima)
  → disentangle CPV effects from mass ordering in $\nu_\mu \rightarrow \nu_e$ channel

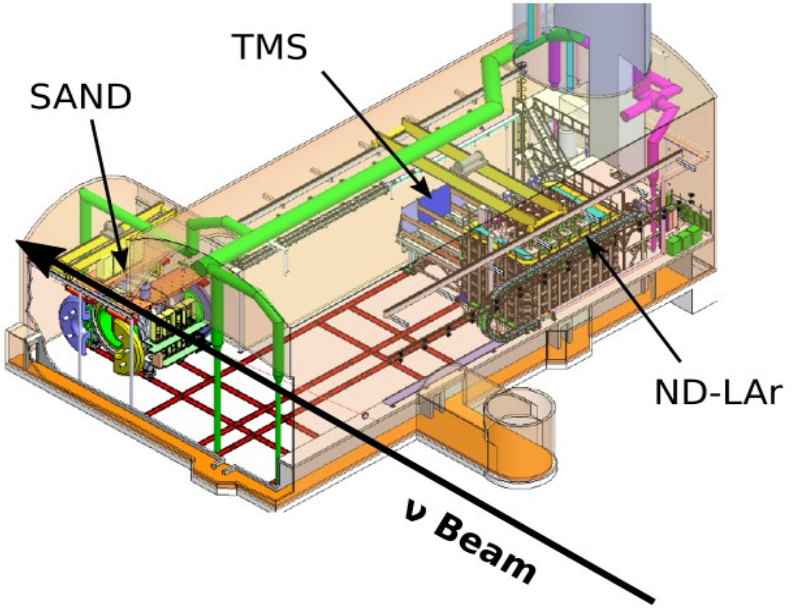


The Near Detector (ND) Complex

Main goals: sample un-oscillated neutrino flux
constrain DUNE flux and x-sec systematics

– consists of 3 detectors:

ND-LAr: 50 t FV LArTPC with pixelated readout
– same target as the far detector



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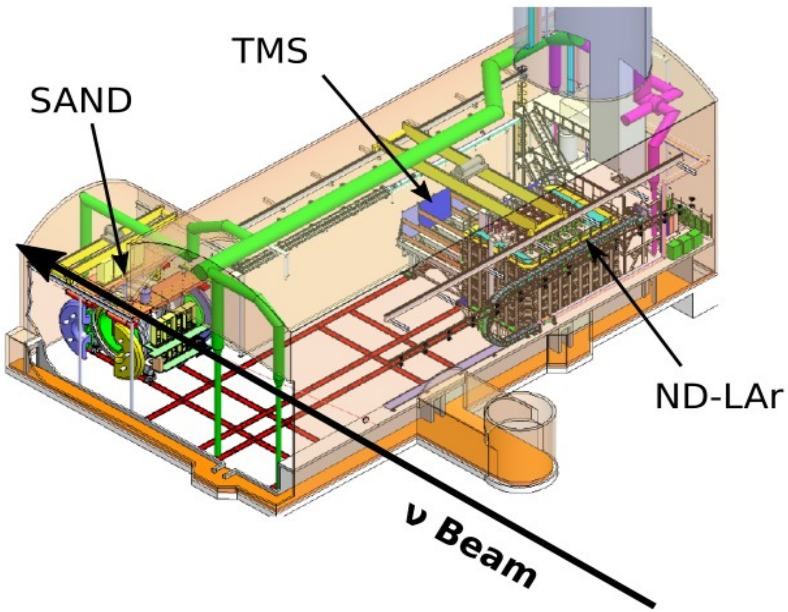
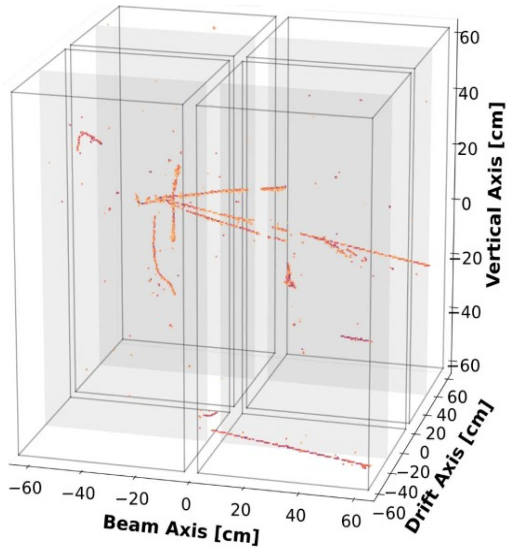


ND-LAr: 50 t FV LArTPC with pixelated readout

– same target as the far detector

→ *Technology tested at FERMILAB (2024) with NuMI neutrino*



2x2 ND-LAr prototype

– 4 LArTPC modules
– pixelated charge readout
– successful commissioning in July 2024, 4.5 days of beam data
– crucial information: simulations towards full ND-LAr
– continue to run in calbration mode until NuMI gets back

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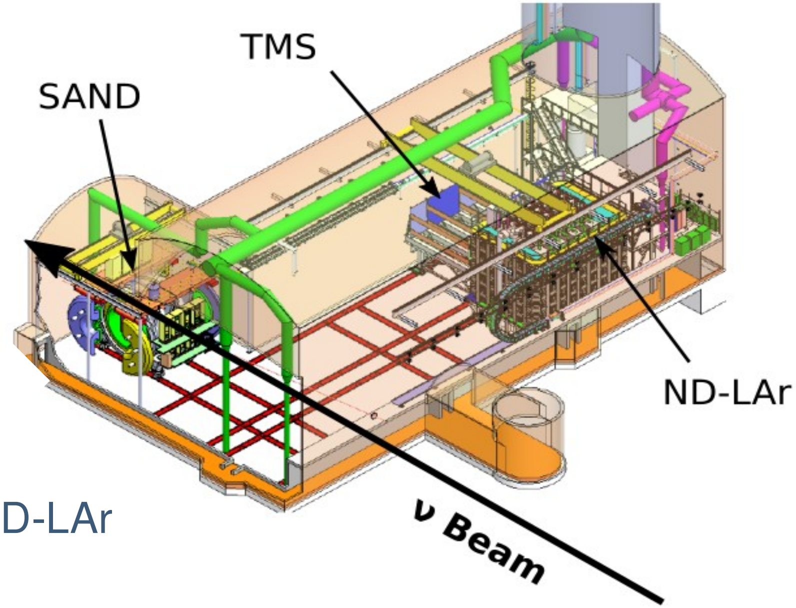
TMS: The Muon Spectrometer
– magnetized muon tracking system: catch μ escaping from ND-LAr

SAND: fixed on-axis detector monitor the ν beam
– tracker surrounded by Ecal in magnetic field



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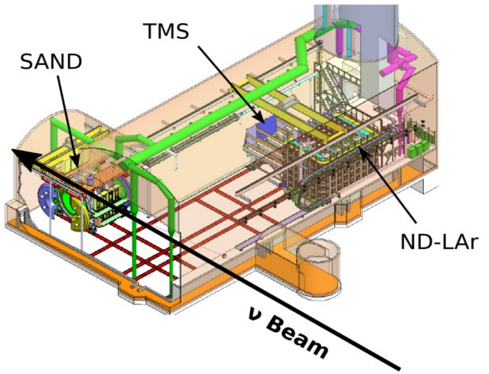
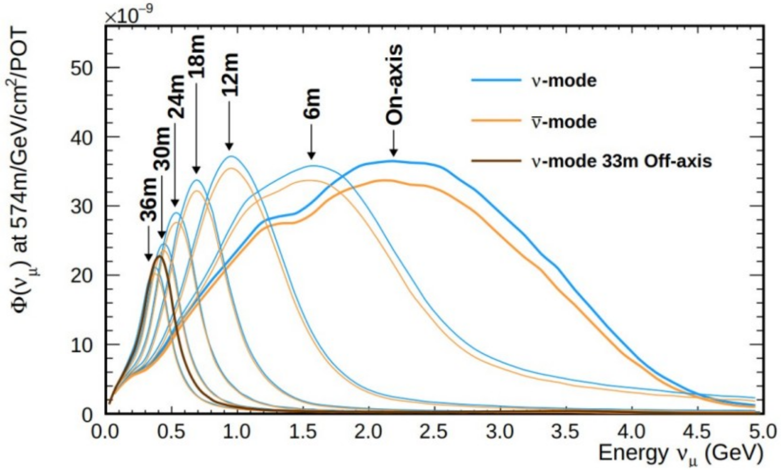


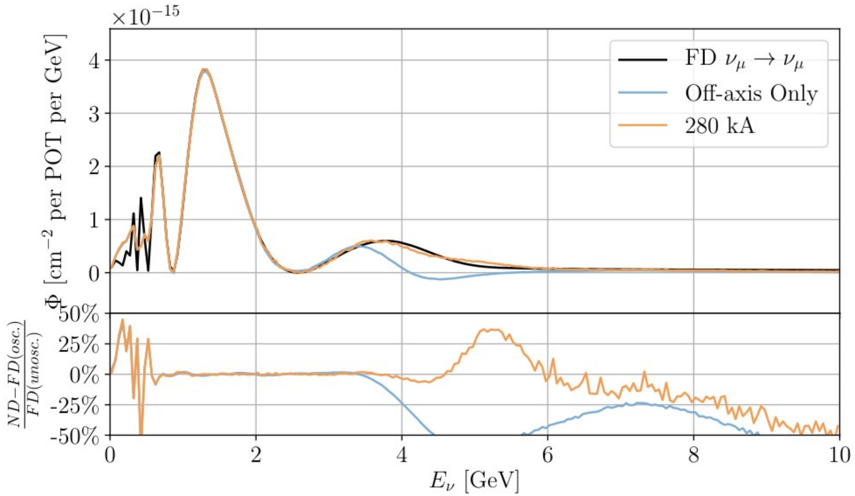
Main goals: sample un-oscillated neutrino flux
constrain DUNE flux and x-sec systematics

ND-LAr and **TMS** can be moved up to 28.5 m off-axis

→ **DUNE-PRISM concept**

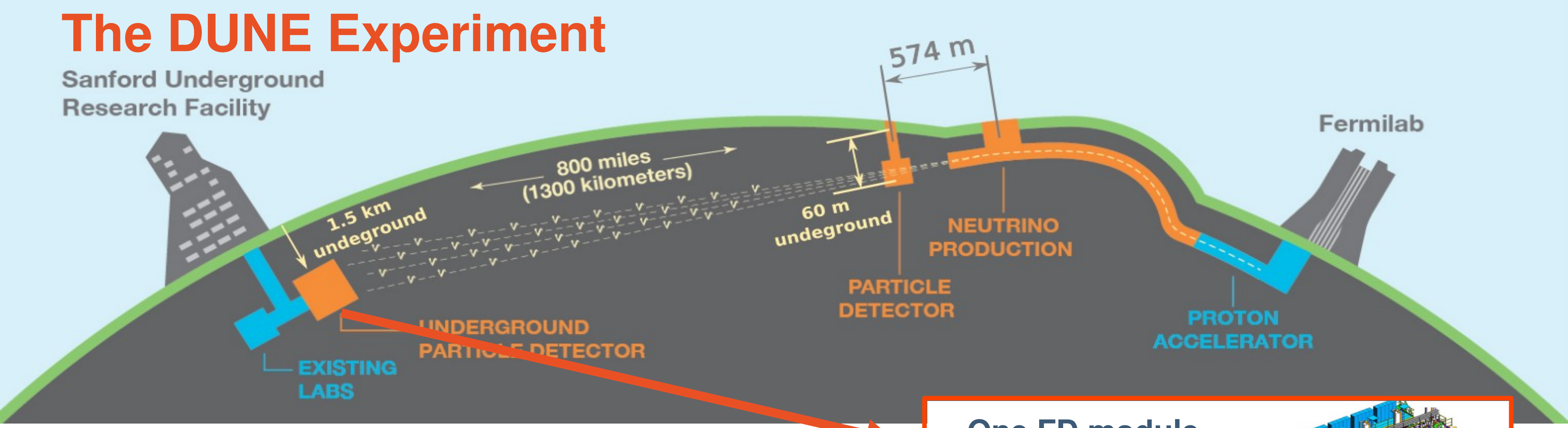
– neutrino flux spectrum changes with the off-axis position → sample different neutrino fluxes





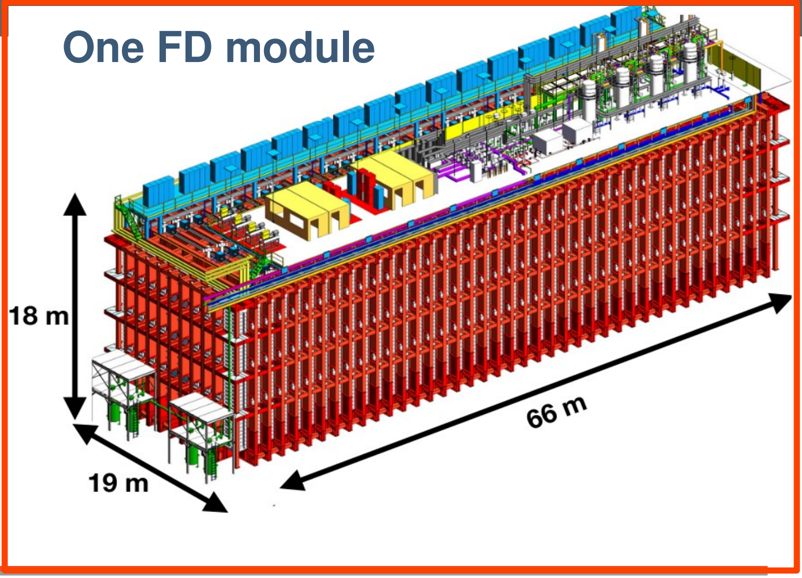
Linear combination of ND data at different off-axis positions → reproduce the oscillated neutrino far detector spectrum (minimum x-sec dependence)

The DUNE Experiment

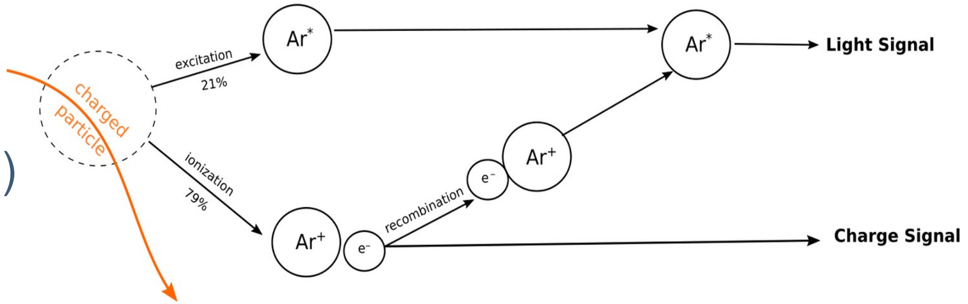


Far Detector (FD) complex

- 70 kt (4 x 17kt) detector 1.5 km underground (1300 km away from the ND)
- Deployed as 4 modules
  - 3 x LArTPCs (#1, #2, #3)
  - 1 x module of opportunity #4 (several detector technologies being explored)



LAr TPCs

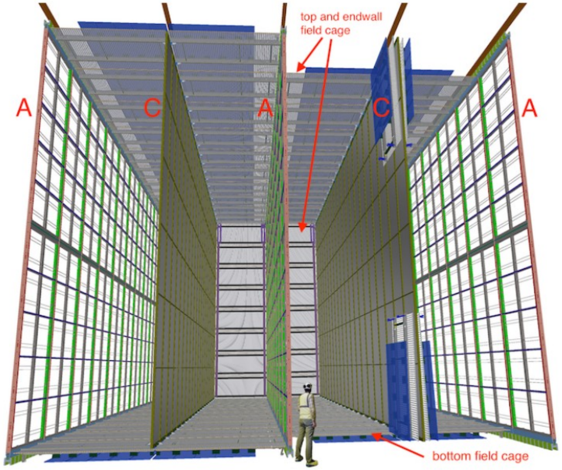


- Charged particles excite and ionize LAr
  → charge (3D imaging) & light signals (timing)

- DUNE has two main TPC designs:

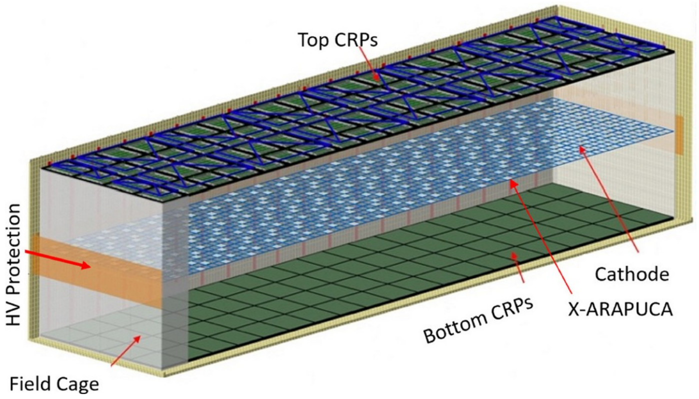
Horizontal Drift

– 4 drift volumes, drift field = 500 V / cm
– Charge detection: wire-based (APAs)
– Light detection: X-ARAPUCAs on anode planes

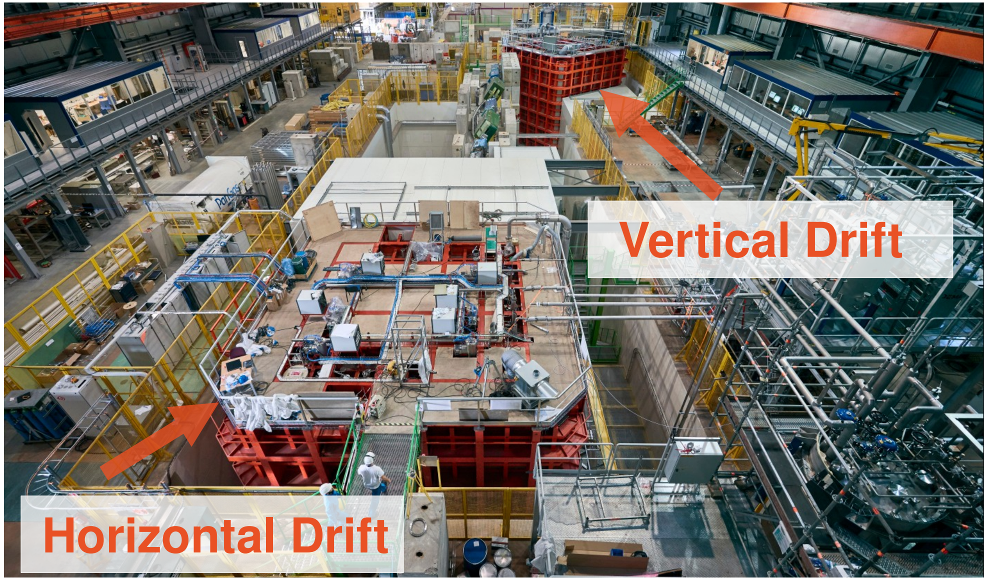


Vertical Drift

– 2 drift volumes, drift field = 480 V / cm
– Charge detection: strip-based (CRPs)
– Light detection: X-ARAPUCAs on cathode plane and behind field cage

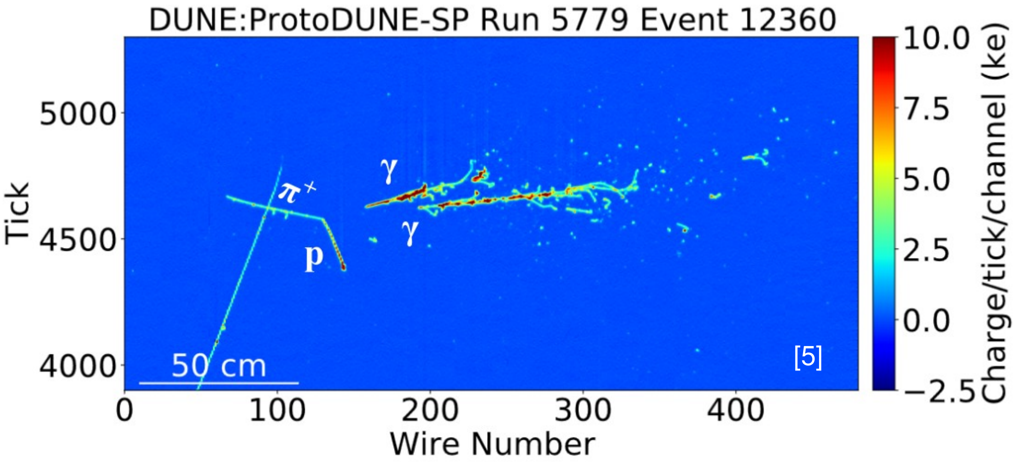


LAr TPCs – ProtoDUNE @ CERN



- ProtoDUNEs at CERN neutrino platform: validate and test FD technologies [1]
  - – 1/20 of an FD module volume (800 t LAr)
  - – full-scale readout components: APA, CRP
- Successful running with cosmic and hadron and beam data (2018-2020 and 2024)

– benchmark reconstruction algorithms (pattern recognition / ML-based software) [2], [3]
– charged particles Ar cross section measurements [4]

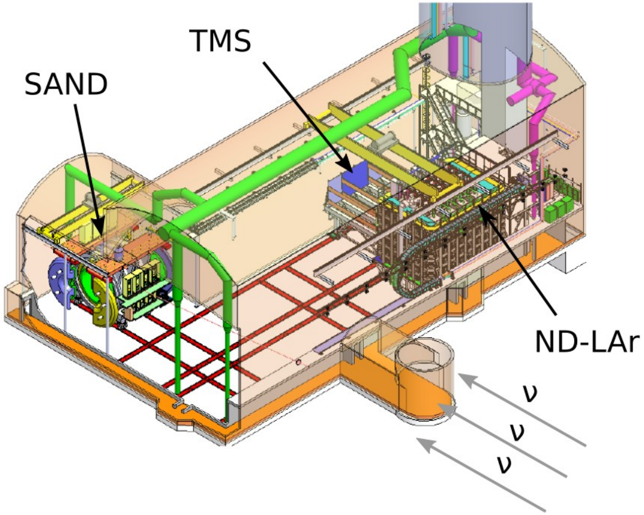


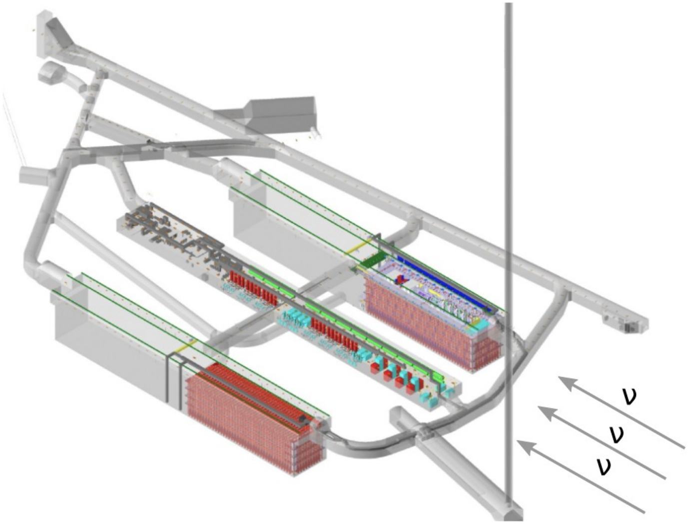
DUNE Plans and Installation

DUNE construction will happen in 2 phases → continuous progress towards the physics goals beginning this decade

Phase I

- 1.2 MW beam intensity
- 2 x 17 kt FD modules (10 kt FV each)
- ND: ND-LAr + TMS + SAND
- PRISM moveable system





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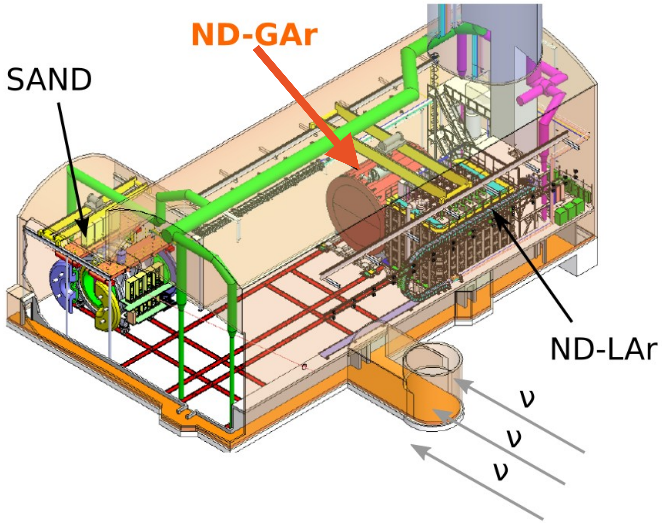
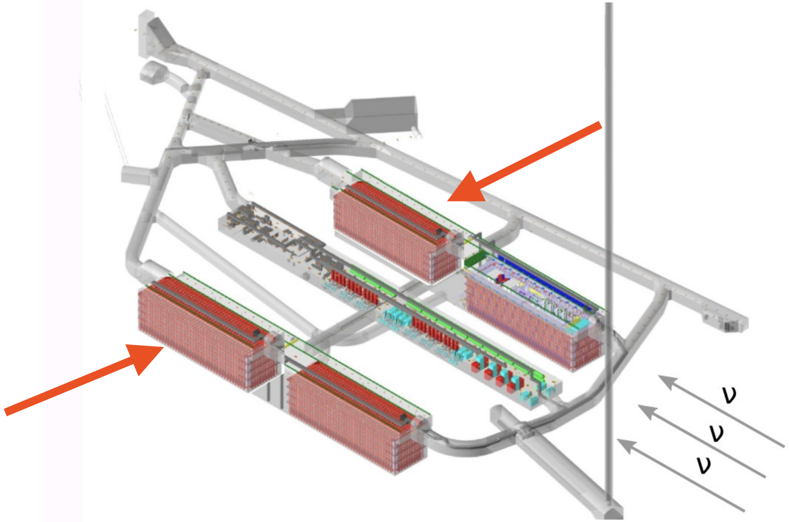
Phase I

- 1.2 MW beam intensity
- 2 x 17 kt FD modules (10 kt FV each)
- ND: ND-LAr + TMS + SAND
- PRISM moveable system

Phase II

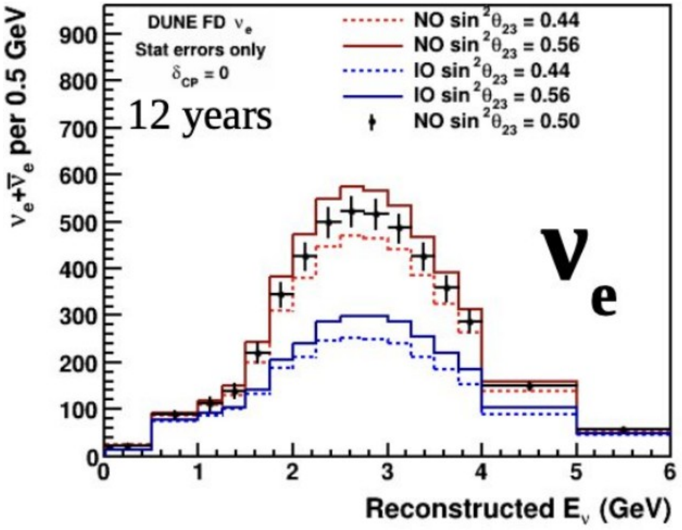
- 2.4 MW beam intensity
- 4 x 17 kt FD modules (10 kt FV each)
- TMS upgraded to ND-GAr → enhance interaction physics capabilities

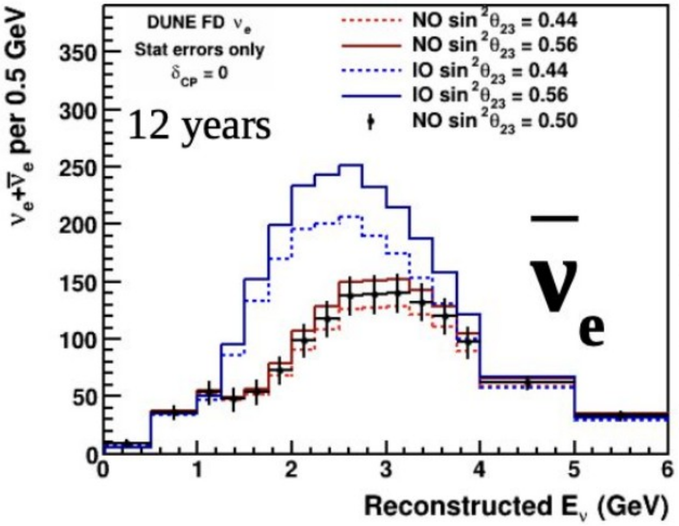


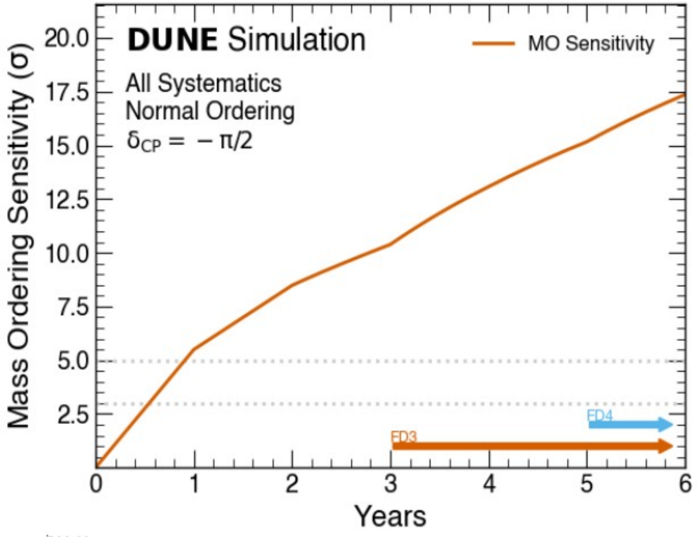


Oscillation Physics with DUNE

- DUNE: **neutrino mass ordering (MO)**
- $\nu_e + \overline{\nu}_e$ spectrum will be sensitive to θ_{23} and MO
- Best case scenario ($\delta_{CP} = -\pi / 2$): **> 5σ sensitivity to the MO in 1 yr**







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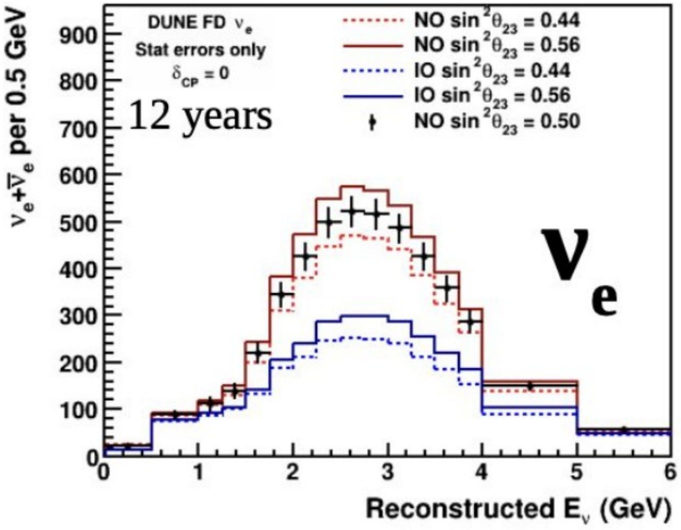
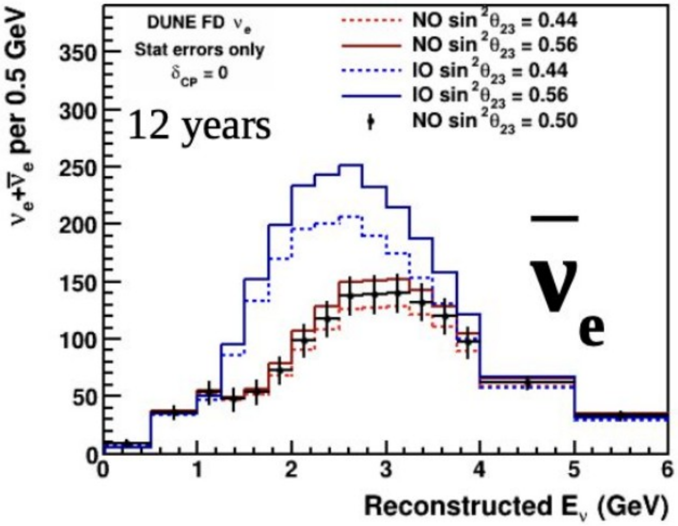
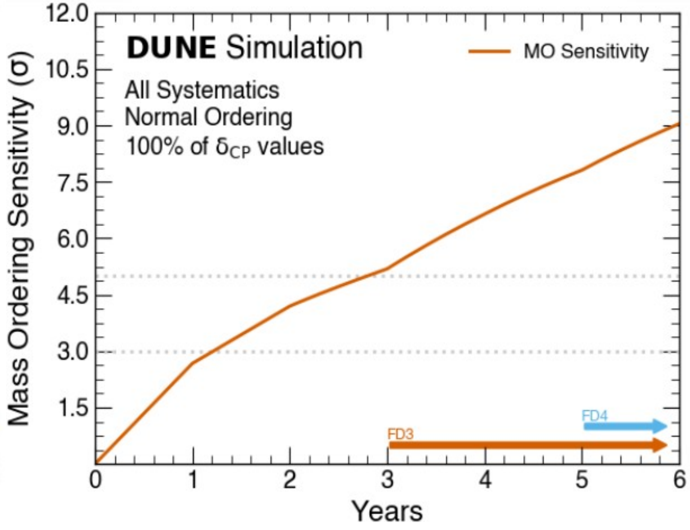
- All δ_{CP}: **> 5σ sensitivity to the MO in 3 yrs**

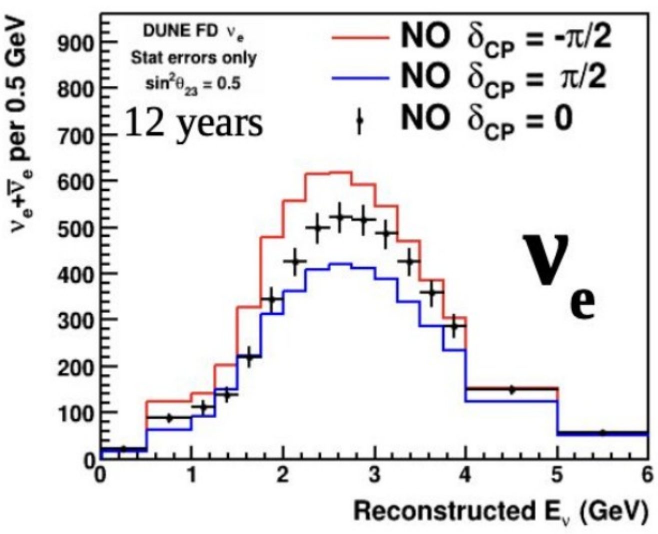


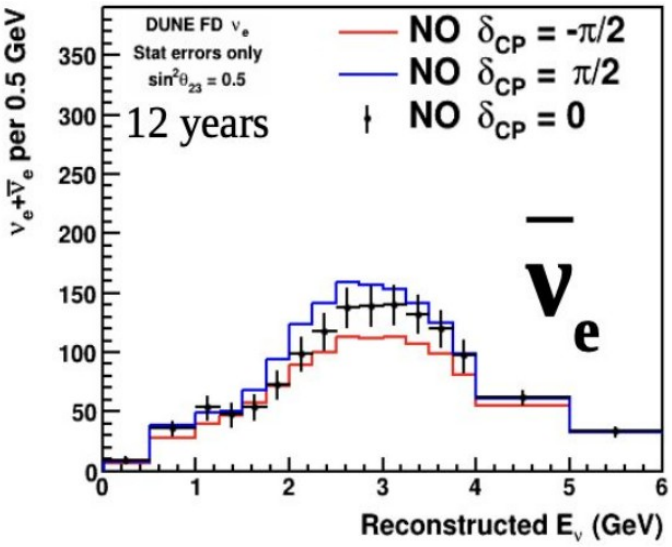


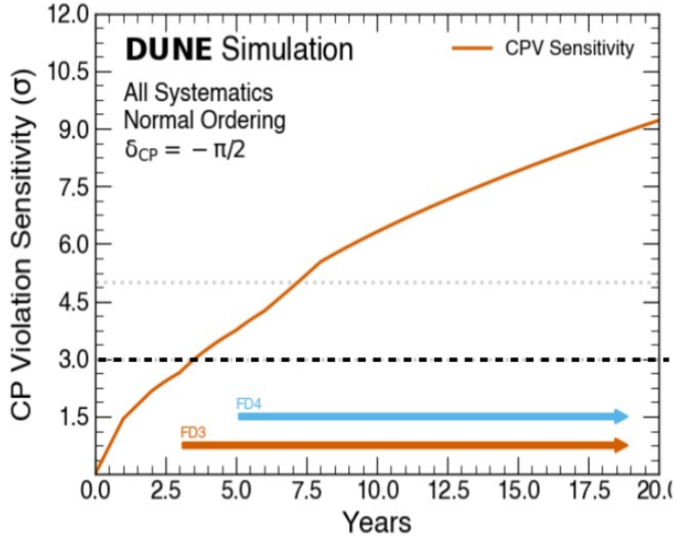


Oscillation Physics with DUNE

- DUNE: discovery potential of **CP violation**: compare $P(\nu_\mu \rightarrow \nu_e)$ with $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- Best case scenario (δ_{CP} = -π / 2): **> 3σ sensitivity to CPV in 3.5 yrs**







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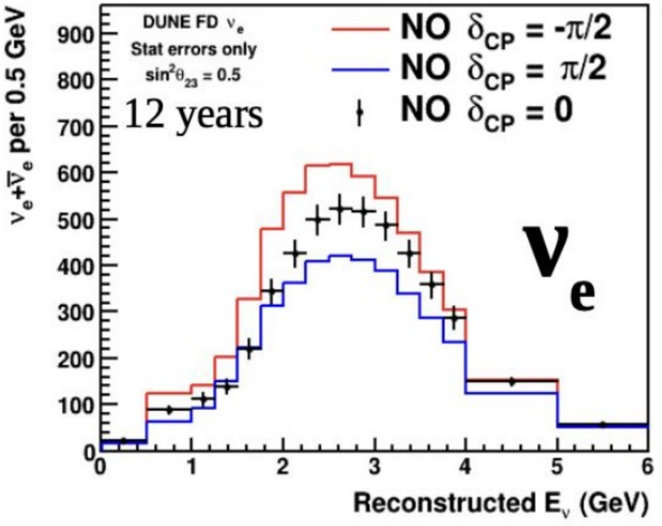
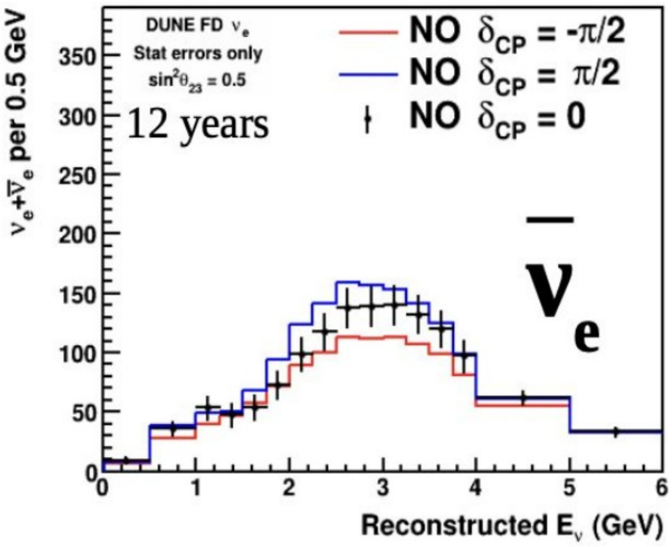
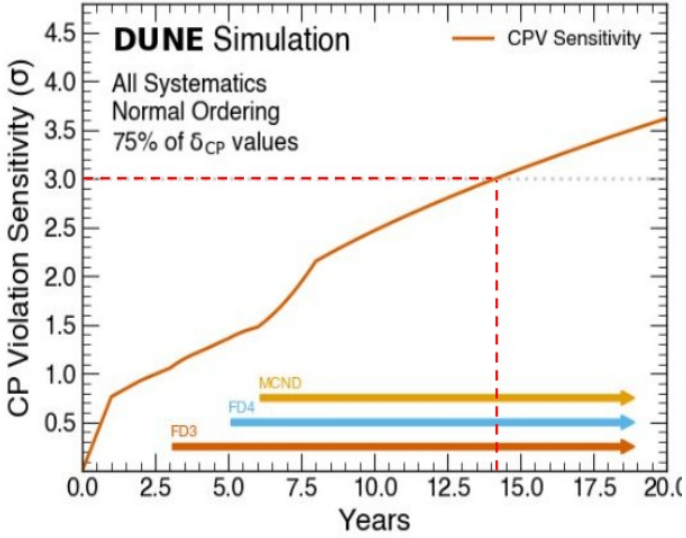
- Best case scenario ($\delta_{CP} = -\pi / 2$): **> 3σ sensitivity to CPV in 3.5 yrs**
- If nature is unkind: **> 3σ sensitivity to CPV over 75% of δ_{CP} values** in the long term







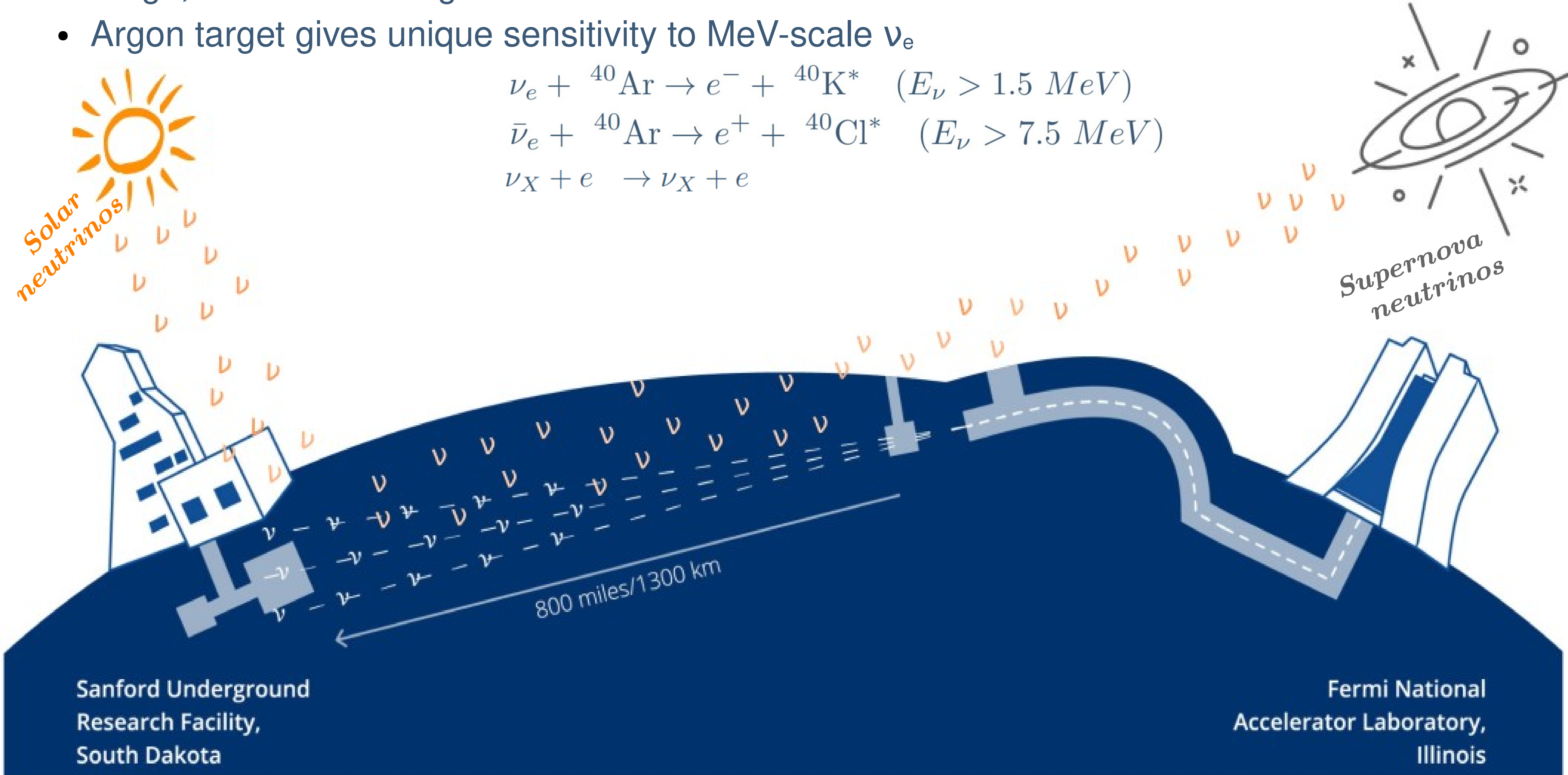
DUNE: Neutrino Observatory

- Large, sensitive underground detector
- Argon target gives unique sensitivity to MeV-scale ν_e

$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^* \quad (E_\nu > 1.5\ MeV)$$

$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \rightarrow e^+ + {}^{40}\mathrm{Cl}^* \quad (E_\nu > 7.5\ MeV)$$

$$\nu_X + e \rightarrow \nu_X + e$$



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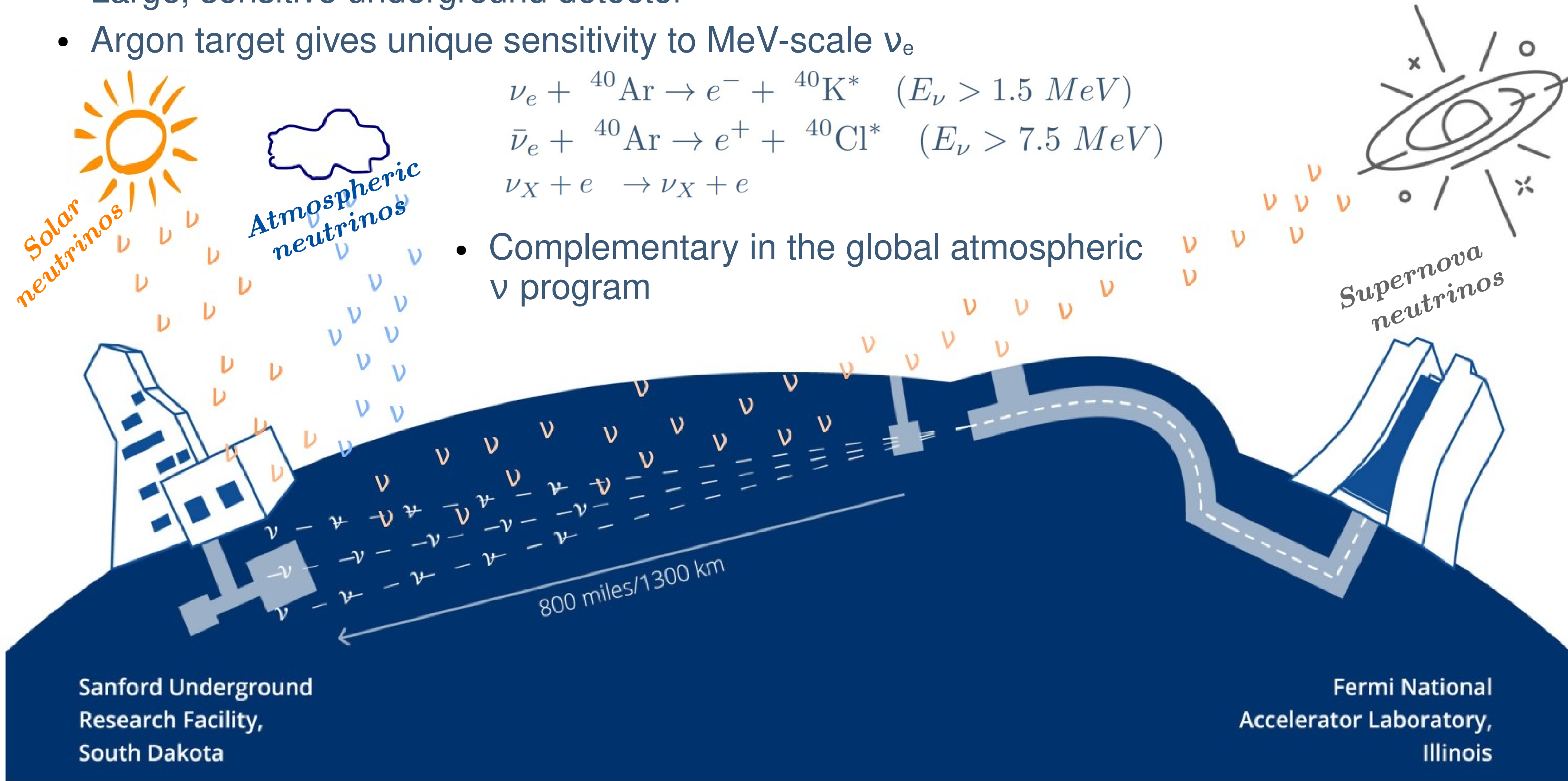
$$\nu_X + e \rightarrow \nu_X + e$$

- Complementary in the global atmospheric ν program

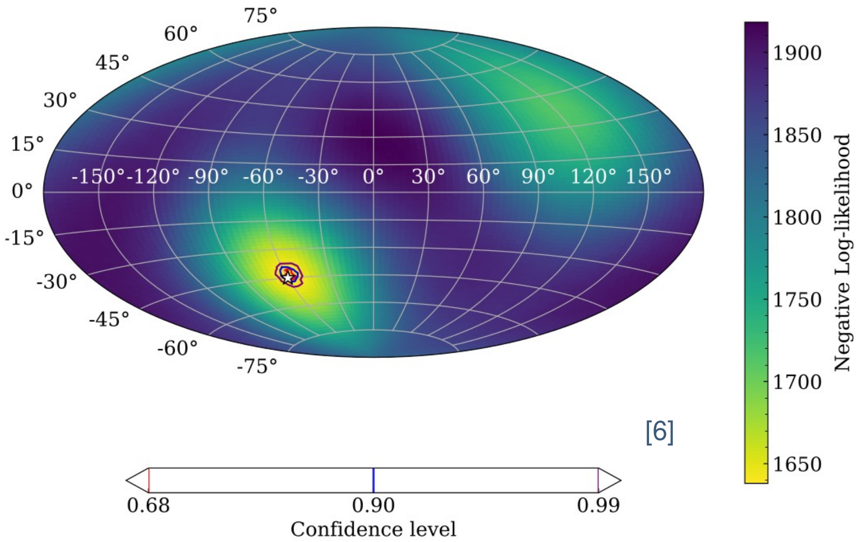


DUNE: Beyond accelerator neutrinos

Supernova ν

– neutrino MO
– core collapse mechanism, black hole formation
– pointing capabilities

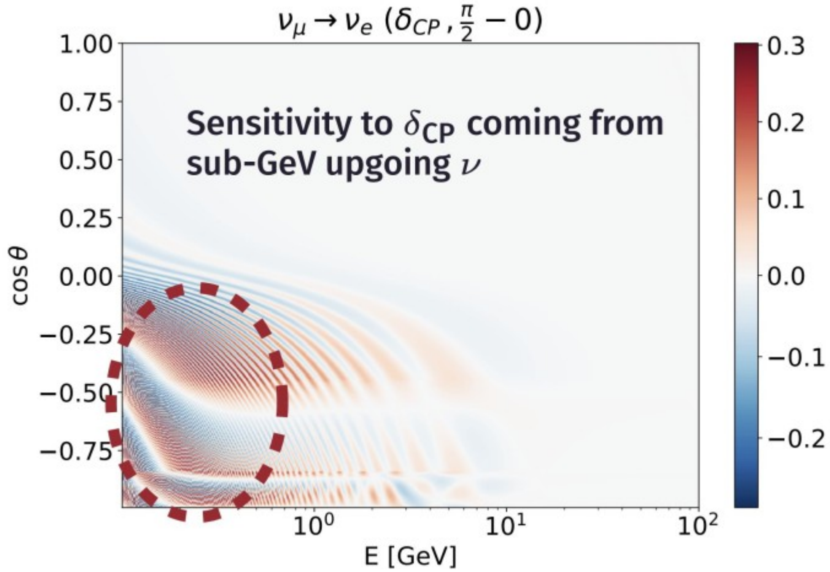
→ DUNE will participate in SN early warnings



[6]

Atmospheric ν

– probing CPV with sub-GeV ν
– complementary measurement of MO to beam
– BSM studies



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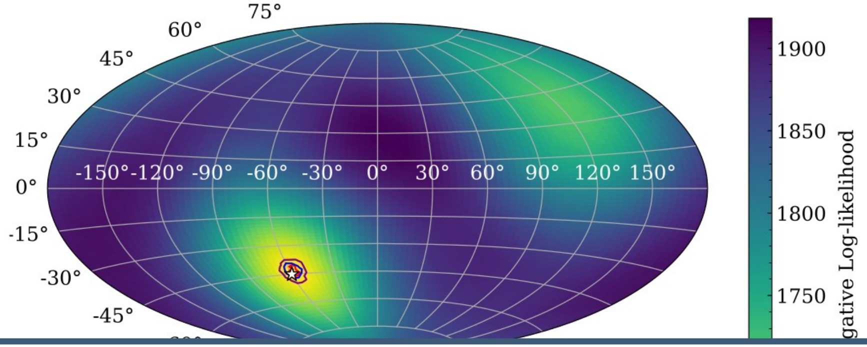
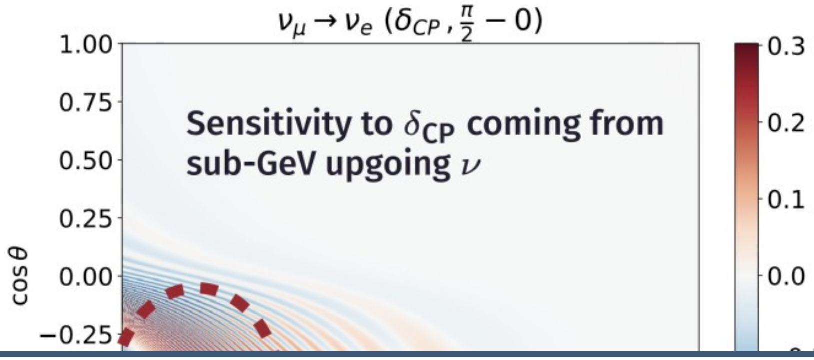


Atmospheric ν

δ_{CP} | Δm^2_{32} | BSM
0.1 GeV — 1 GeV — 15 GeV

– probing CPV with sub-GeV ν
– complementary measurement of MO to beam
– BSM studies



DUNE will also open a wide range of possibilities for **BSM physics** (proton decay, sterile neutrinos, light dark matter ...)

DUNE Milestones

2024 – Far site excavation completed last year

2025 – Far site building and site infrastructure is ongoing

2026 – Far site cryogenic installation by early 2026

2027 – Far Detector installation by mid 2027

2029 – Non-beam physics start by the end of 2029
– solar, atmospheric and astrophysics neutrinos

2031 – The beam will be available at the end of 2031

2032 – Beam physics with ND ~ 2032

Summary

- DUNE is a long-baseline neutrino oscillation experiment and neutrino observatory
  - mass ordering, δ_{CP}
  - precise measuring of neutrinos including oscillation parameters, cross sections etc
  - non-beam neutrino physics: supernova, solar, atmospheric
  - BSM physics with high-intensity beams and large capable detectors
- Successful prototyping program – remains very active
- Construction work continues with first non-beam physics expected to start by the end of 2029

References

[1] https://ep-news.web.cern.ch/proto-dune-cern-new-technologies-new-discoveries

[2] Abed Abud, A., Abi, B., Acciarri, R. et al. Separation of track- and shower-like energy deposits in ProtoDUNE-SP using a convolutional neural network. Eur. Phys. J. C 82, 903 (2022). https://doi.org/10.1140/epjc/s10052-022-10791-2

[3] Abud, A.A., Abi, B., Acciarri, R. et al. Reconstruction of interactions in the ProtoDUNE-SP detector with Pandora. Eur. Phys. J. C 83, 618 (2023). https://doi.org/10.1140/epjc/s10052-023-11733-2

[4] A. Abed Abud35, B. Abi156, R. Acciarri66, M. A. Acero12, M. R. Adames193, G. Adamov72, M. Adamowski66, D. Adams20, M. Adinolfi19 et al. (DUNE Collaboration) First measurement of the total inelastic cross section of positively charged kaons on argon at energies between 5.0 and 7.5 GeV, Phys. Rev. D 110, 092011 https://doi.org/10.1103/PhysRevD.110.092011

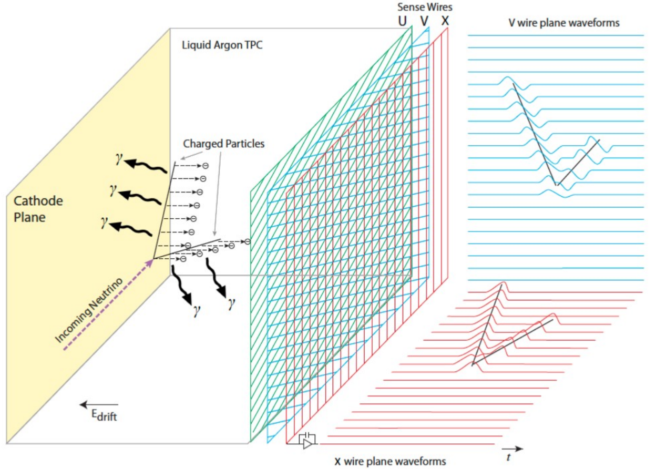
[5] B. Abi *et al* 2020 *JINST* 15 P12004 First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform https://iopscience.iop.org/article/10.1088/1748-0221/15/12/P12004

[6] C. Brizzolari on behalf of the DUNE collaboration 2024 *JINST* 19 C0300, The ProtoDUNE Photon Detection System: technology validation and performance https://iopscience.iop.org/article/10.1088/1748-0221/19/03/C03001

[7] DUNE-TDR, https://doi.org/10.48550/arXiv.2002.03005

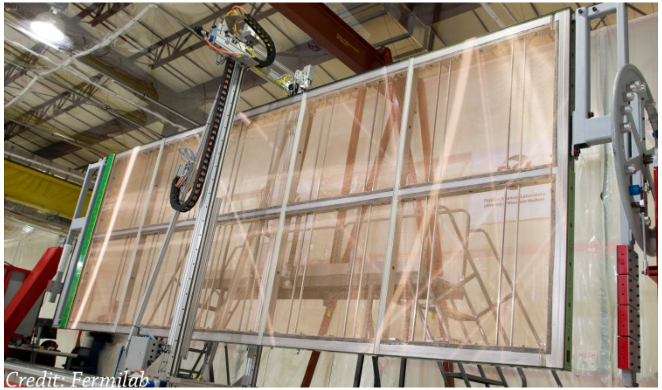
Backup

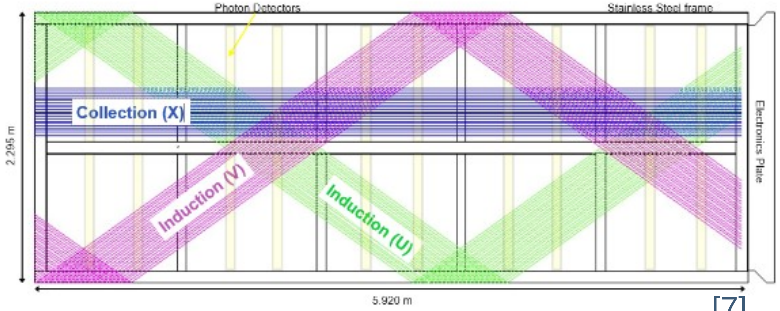
- APAs: 4 induction planes + 2 collection planes
  – double sided (3 and 3 planes)



[7]

APA frame: 2.3 m x 6m:

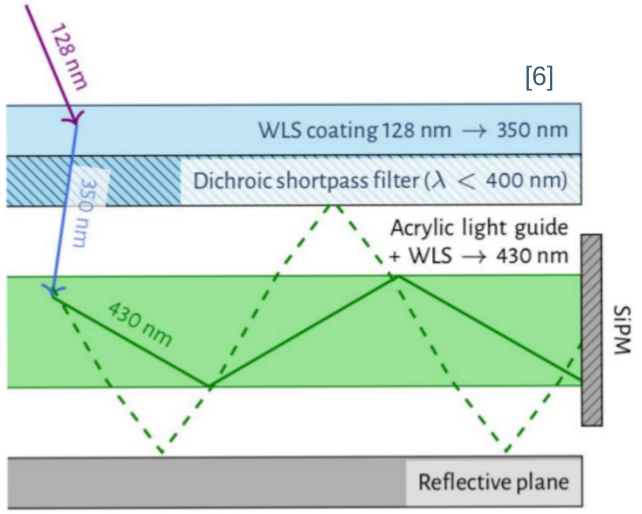




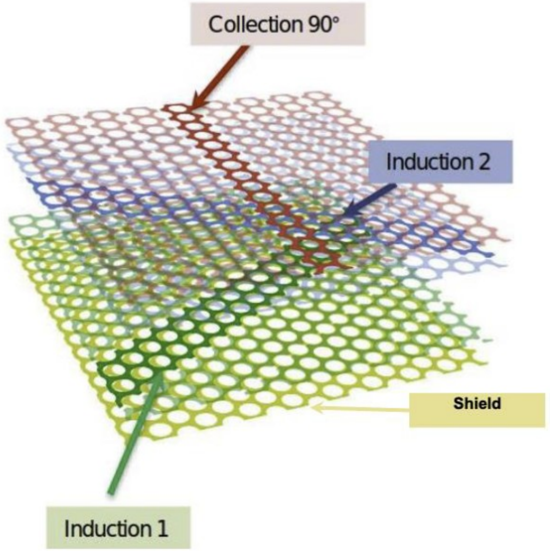
[7]

Backup

- **x-ARAPUCA** device: collect 128 nm scintillation light



- CRPs: collect charge



Three-view anode layout (+30°, –30°, 90°):

- 2.4 mm hole diameter
- 5.1 mm collection, 7.65 mm induction strip pitches
- 3072 readout channels per CRP