

# DUNE: Overview and Status

Edgar Valencia-Rodriguez on behalf of the DUNE Collaboration

XIX Mexican Workshop on Particles and Fields

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Leon, Mexico



**Ciencia y Tecnología**  
Secretaría de Ciencia, Humanidades, Tecnología e Innovación

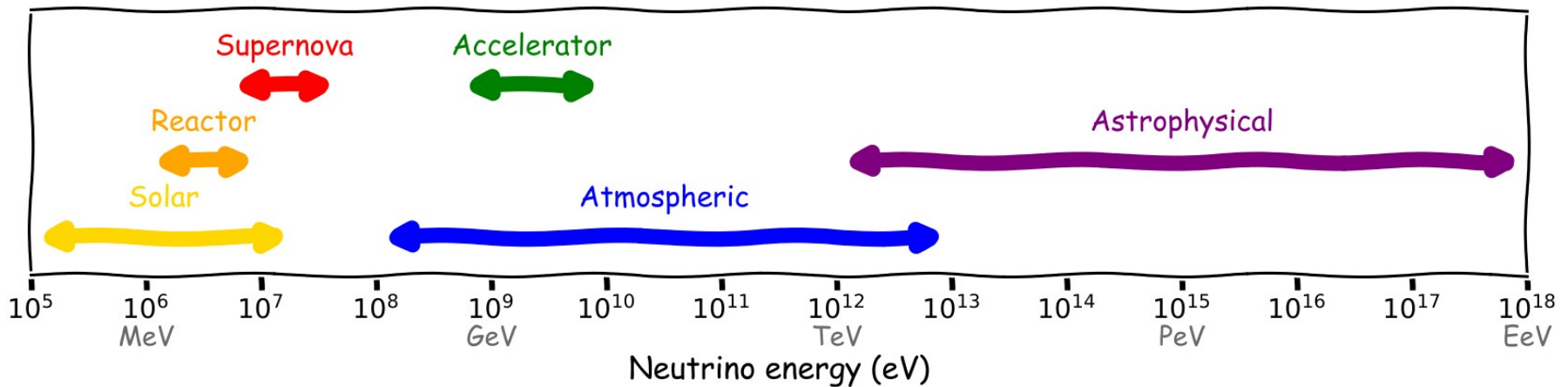


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# Neutrino Sources

- Neutrinos comes from Natural (Terrestrial and Extraterrestrial) and Artificial Sources.



- Different sources and broad energy range from meV to EeV
- Neutrino Experiments works with neutrinos from MeV to PeV
- DUNE can detect and mesure several neutrino sources.

# Neutrino Physics

- Neutrinos: nearly massless, neutral leptons proposed in 1930 and discovered mid-1950s
- Neutrinos are the most abundant particles in the universe
- They comes in 3 flavors ( $\nu_e, \nu_\mu, \nu_\tau$ )
- Flavour oscillations have been observed
- Oscillations only sensitive to  $\Delta m^2$

Flavor States

Pontecorvo – Maki – Nakagawa – Sakata  
 $U_{\text{PMNS}}$  Mixing Matrix

Flavor States

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

# Neutrino Physics

- PMNS Parameterisation: 3 mixing angles ( $\theta_{12}$ ,  $\theta_{13}$ ,  $\theta_{23}$ ) and 1 CP-violating phase ( $\delta_{CP}$ ).

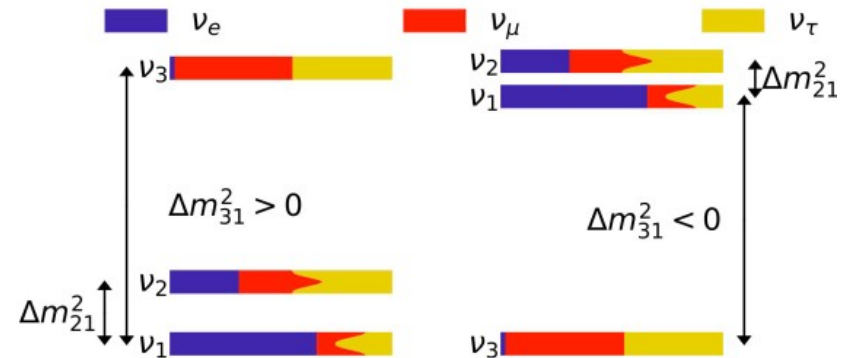
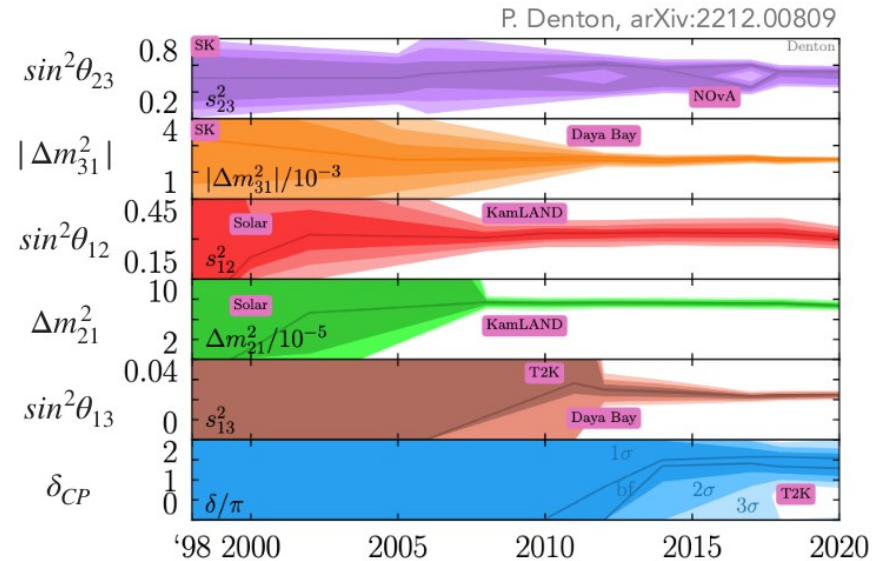
$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta_{CP}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

**Atmospheric**  
 $\nu_\mu \rightarrow \nu_\tau$ 
**Reactors**  
 $\nu_\mu \rightarrow \nu_e$ 
**Solar**  
 $\nu_e \rightarrow \nu_{\mu,e}$

- Where:  $c_{ij} = \cos\theta_{ij}$  and  $s_{ij} = \sin\theta_{ij}$
- We know:  $\theta_{12}$ ,  $\theta_{23}$ ,  $\theta_{13}$ ,  $\Delta m^2_{21}$ ,  $|\Delta m^2_{31}|$
- Unknown: mass ordering (sign of  $\Delta m^2_{31}$ ) and  $\delta_{CP}$

# Neutrino Physics

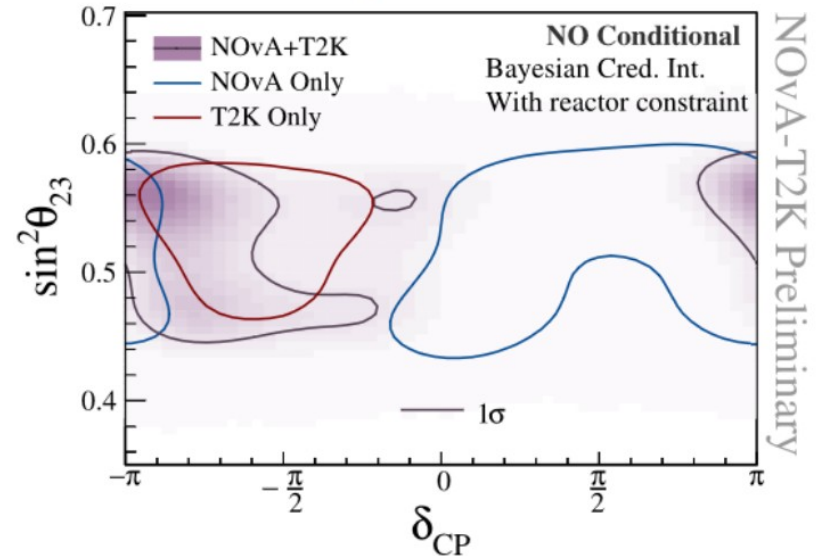
- Assuming three flavor neutrinos, oscillations depend on 3 mixing angles, 2 mass splitting and 1 phase
- Open questions:
  - Is the 3-flavor neutrino picture correct?
  - Is PMNS unitary?
  - Is  $\nu_3$  the heaviest (normal ordering) or the lightest (inverted ordering)?
  - What is the sign of  $\Delta m_{31}^2$ ?



# Neutrino Physics

- Studies of solar (electron) neutrino flux (Ray Davis, 1960s) consistently found fewer than expected.
- Late 1990s/early 2000s: SNO (Ontario) and Super-Kamiokande (Japan) determine that neutrinos oscillate.

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



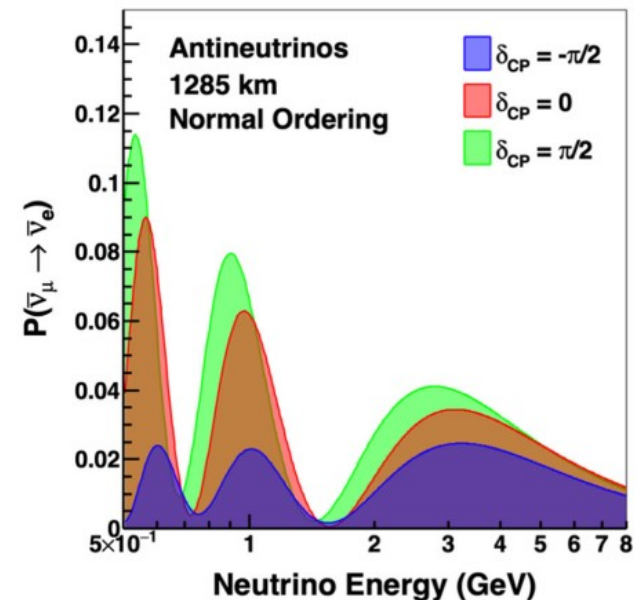
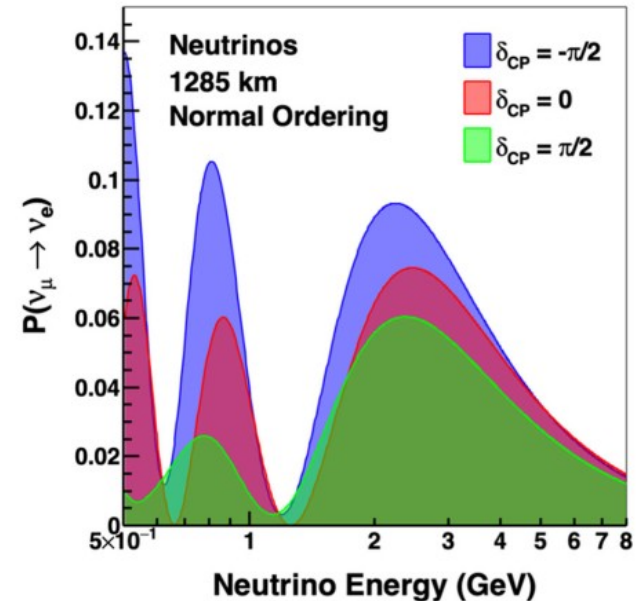
- Using the PMNS matrix, we can calculate the probability of a transition from one flavor state to another.

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu(t) \rangle|^2 \approx \underbrace{\sin^2(2\theta)}_{\text{oscillation amplitude } \sim f(\theta)} \underbrace{\sin\left(\frac{\Delta m_{ij}^2 L}{4E}\right)}_{\text{oscillation frequency } \sim f(\Delta m_{ij}^2)} \quad \text{where}$$

$L$ : traveled distance  
 $E$ : neutrino energy  
 $\Delta m_{ij}^2 = m_i^2 - m_j^2$

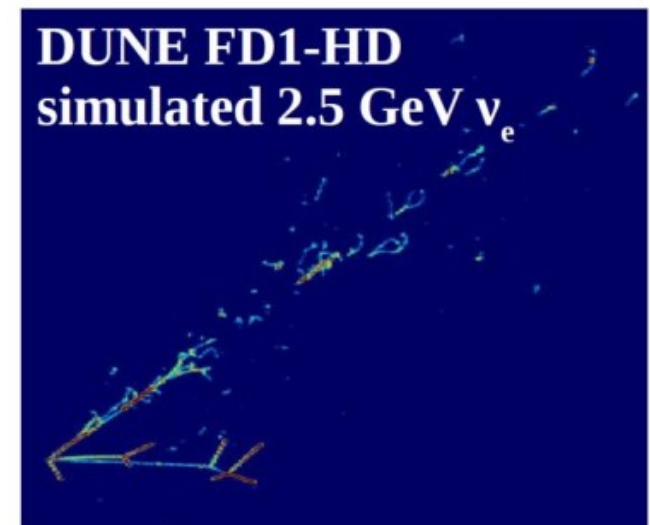
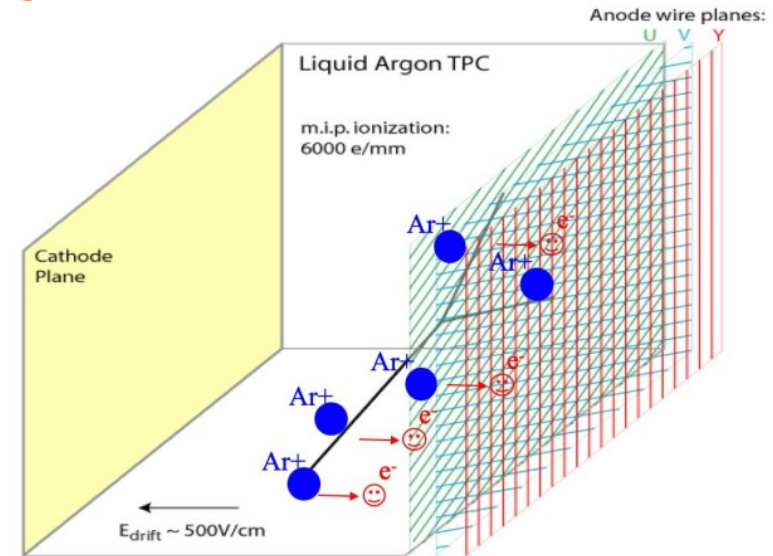
# Neutrino Physics

- Therefore, if we know the amount of neutrinos initially and after some time has passed, we can determine each component of this probability.
- Neutrinos oscillate: created in 1 flavour, probability to later detect a given flavour evolves with time:
  - Probability for oscillation evolves as  $L/E$
  - Rotation angles, mass splitting dictate location and amplitude of probability dips
  - Complex phase encapsulates potential differences in  $\nu$ , anti- $\nu$  oscillations



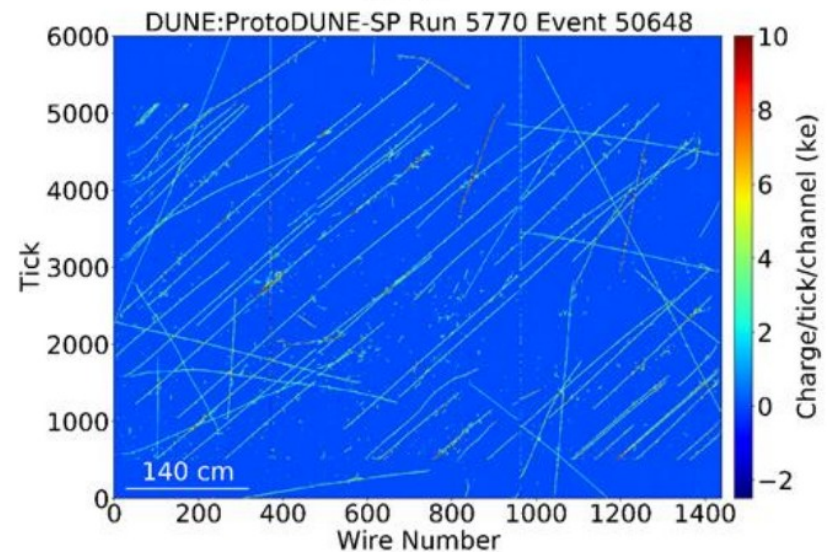
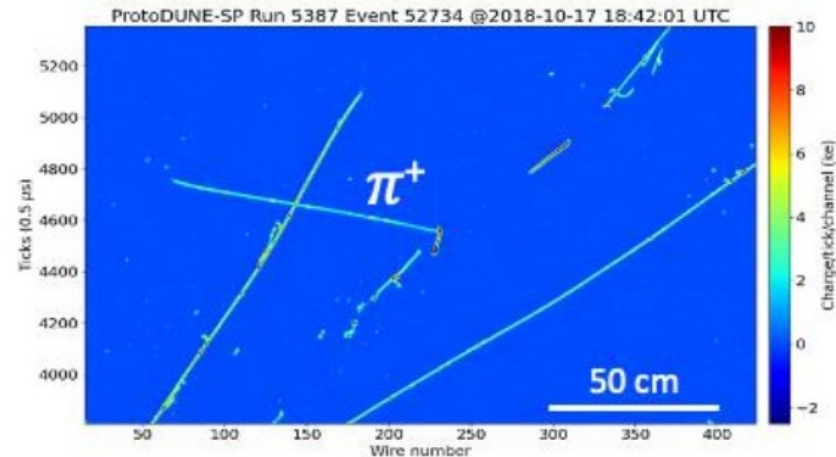
# Liquid Argon Time Projection Chamber (LArTPC)

- LAr-based TPC neutrino detector proposed by Carlo Rubbia in 1977
- Technology demonstrated in early 1990s by the ICARUS collaboration
- Particles reconstructed from ionization and scintillation light
- Charged particles lose energy as they pass through LAr
- The energy goes into producing electron-ion pairs and scintillation light



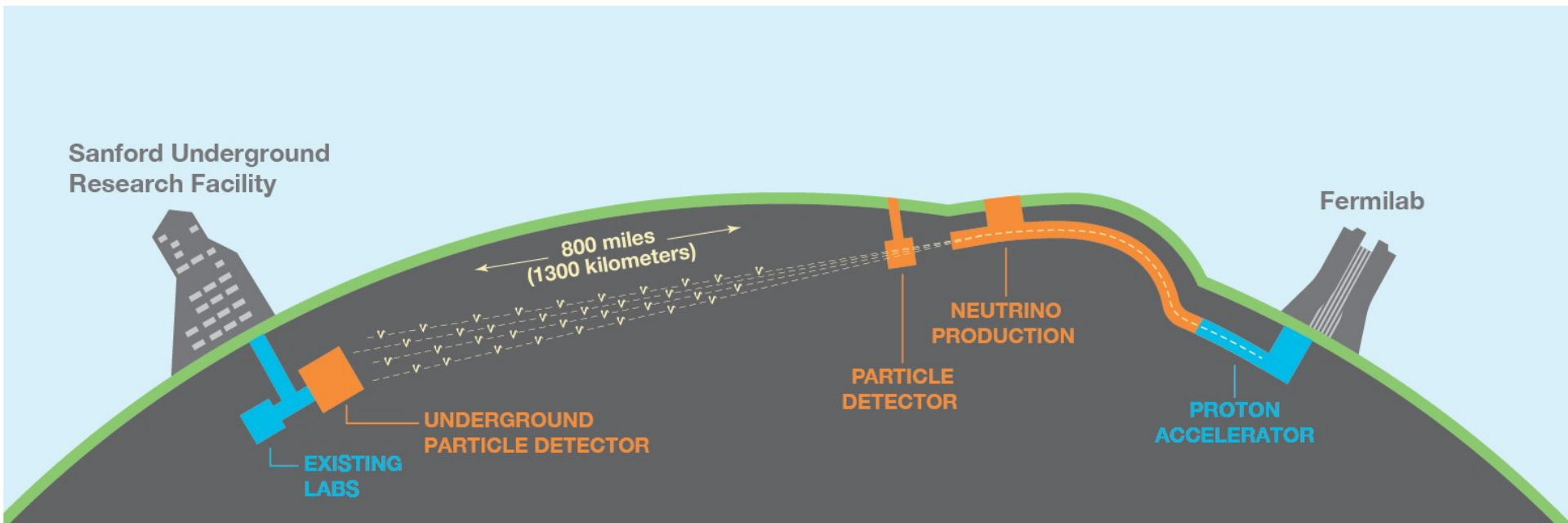
# Liquid Argon Time Projection Chamber (LArTPC)

- An electric field established within the LAr volume drifts the electrons toward the anode plane at constant speed
- Ionization drift in electric field towards sensing elements (slow signal,  $v \sim 0.16$  cm/ $\mu$ s):
  - Low threshold for ionization: 23.6eV/e<sup>-</sup>
- Scintillation light (128 nm) with:
  - fast emission (6 ns) from Argon dimers and slow emission (1.3  $\mu$ s) from Argon triplets.
  - LAr is transparent to its own scintillation



ProtoDUNE-SP events. 1 GeV/c pion candidate (top) and large cosmic shower event (bottom). JINST 15 P12004

# The Deep Underground Neutrino Experiment (DUNE)



- Intense, wideband (anti)neutrino beam, ( $\sim 100$  MeV – 10 GeV)
- New neutrino beam at Fermilab (upgradeable  $> 2$  MW, most powerful beam ever built). Long operational program
- Long-baseline: 1300 km.
- Liquid Argon TPC technology

# The DUNE Collaboration

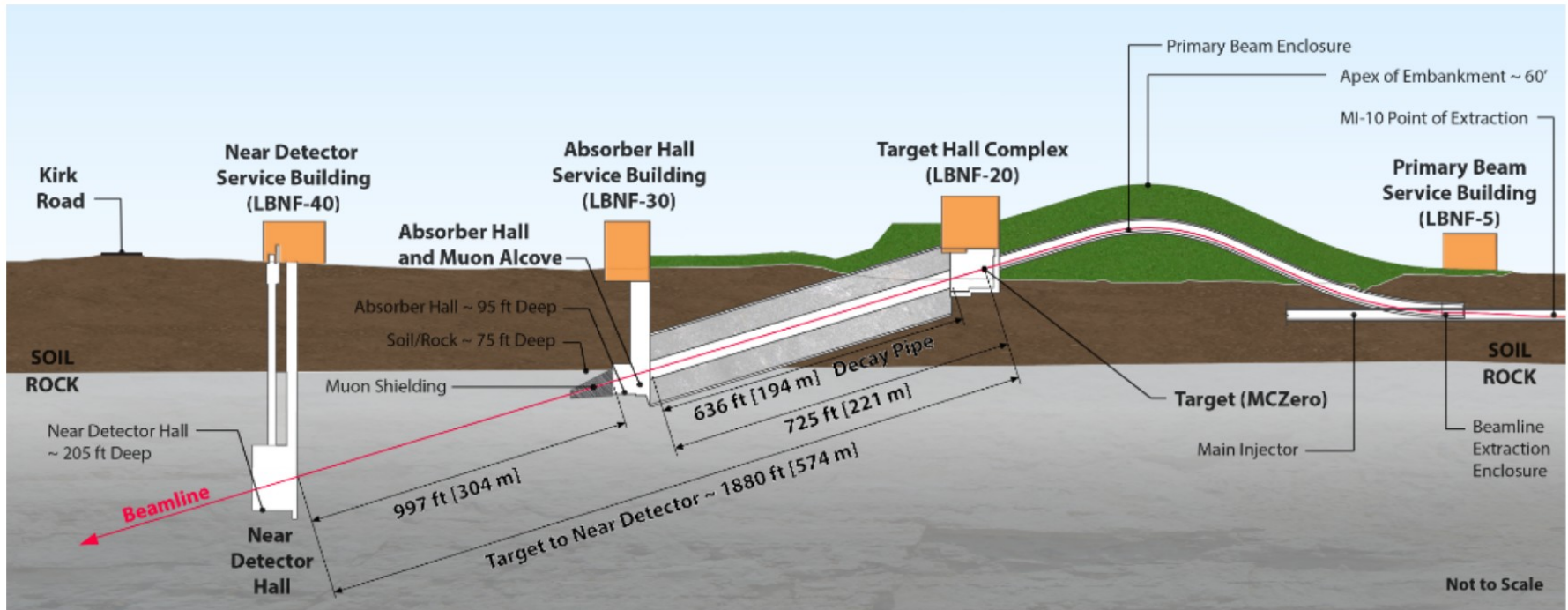
1400+  
Scientists and  
engineers

200+  
Laboratories and  
Universities

35+  
Countries

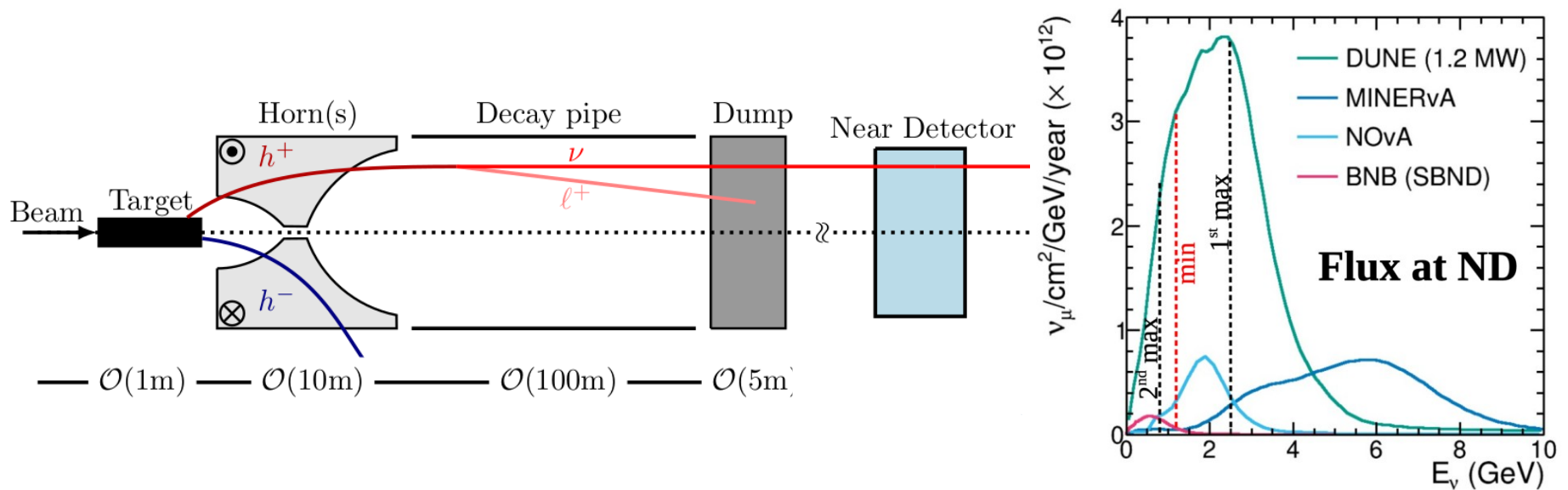


# The DUNE Experiment: Beam Line



- Proton beam: 1.2 MW, upgradeable to 2.4 MW
- 60-120 Proton GeV from FNAL accelerator complex
- Initial upward pitch, bent down at  $5.8^\circ$  to reach Sanford
- Horns/beam line designed to maximize CP violation sensitivity.

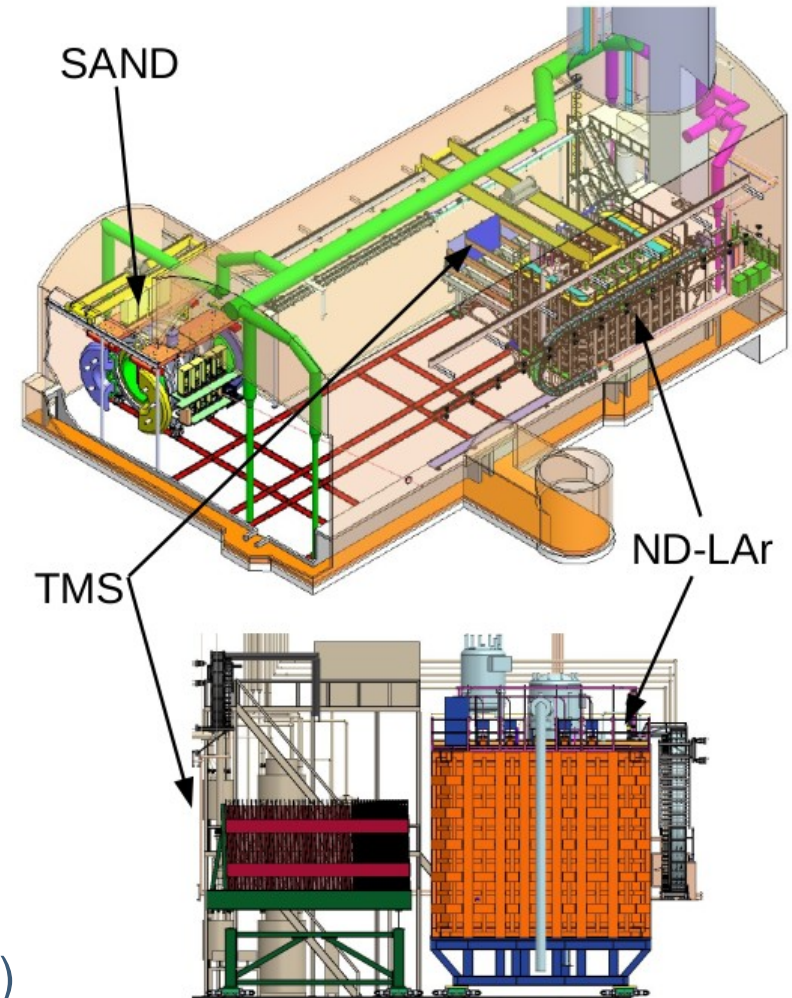
# The DUNE Experiment: Beam Line



- Accelerator-based neutrino experiments rely on the key points:
  - Intense controlled quasi-pure  $\nu$  (or anti- $\nu$ ) beam
  - ND flux measurement predicts flux at the FD
  - Near detectors (Close to the beam production site) to study the neutrino flux content & spectrum before oscillations
  - Giant massive far detectors located at the oscillation peak to study the disappearance of  $\nu_\mu$  and the appearance of  $\nu_e$ .

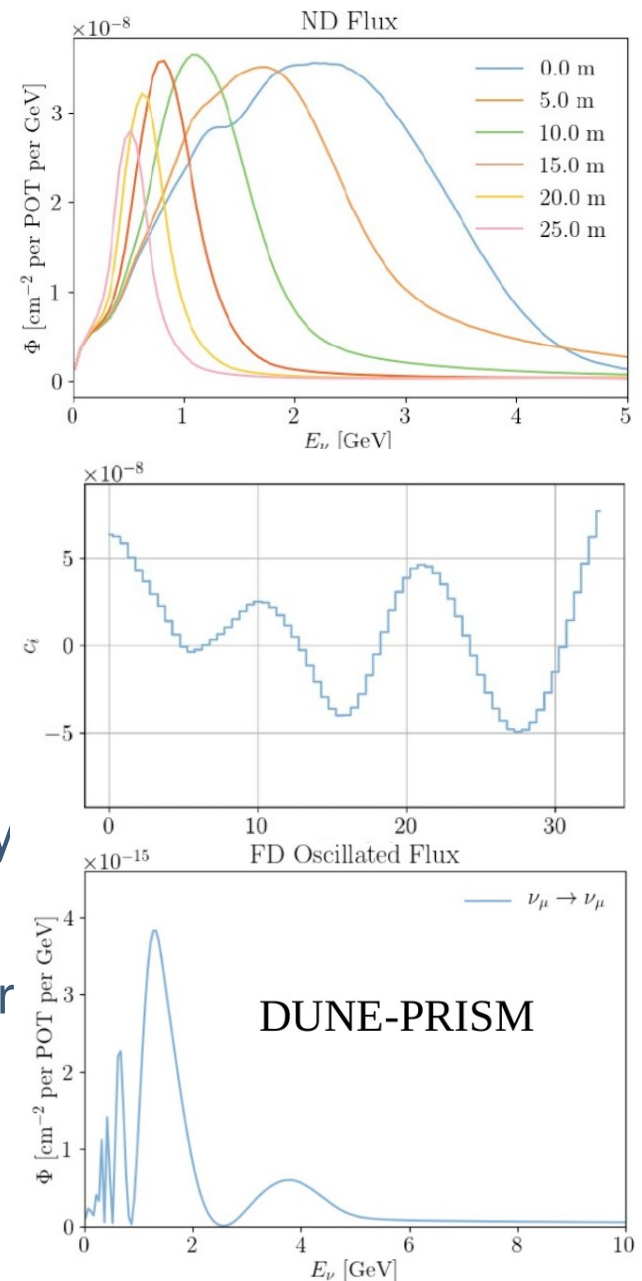
# The DUNE Experiment: Near Detector (ND)

- Measures the unoscillated flux, constrains systematic uncertainties (xsec, flux, ...) and predicts the far detector event rate
- Located 574 m downstream of neutrino beam source and includes three components:
  - ND-LAr: a 67 t LArTPC
  - TMS: The Muon Spectrometer (muon catcher)
  - SAND: System for on Axis Neutrino Detection, a multipurpose magnetized detector
- ND-LAr+TMS moves (PRISM technique)

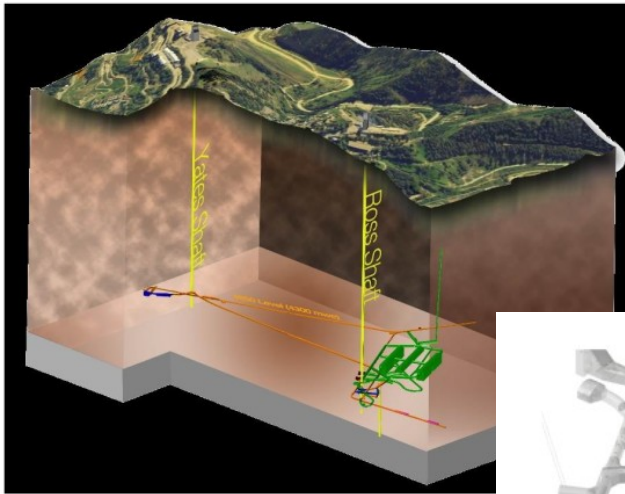


# PRISM Technique

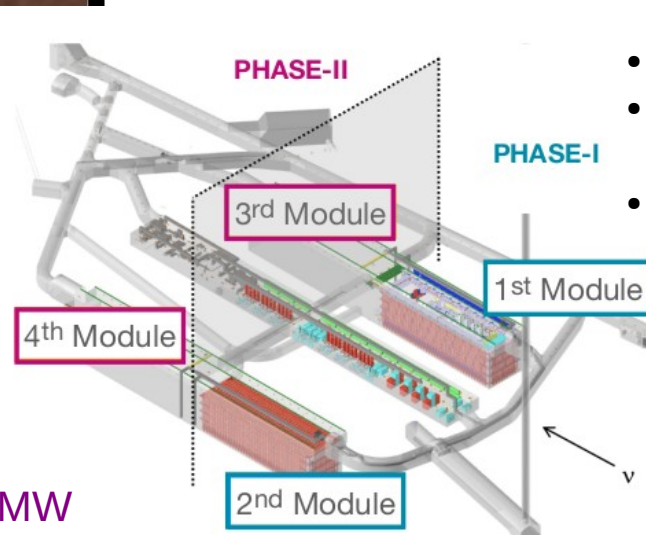
- Movable (28.5 m): PRISM technique
- Directly probing neutrino energy dependence
- Linear combination of off-axis data to predict the flux at the far detector to predict a particular set of oscillation parameters
- FD flux  $\neq$  ND flux  $\rightarrow$  uncertainties in energy dependence of cross sections, response, etc.
- ND flux changes with angle due to pion decay kinematics
- Take ND data in different fluxes  $\rightarrow$  build linear combination to match FD oscillated spectra
- Robust analysis approach with very minimal dependence on interaction modeling



# The DUNE Experiment: Far Detector (FD)



- A massive 70 kt detector deployed in 4 modules in two different caverns
- Sanford Underground Research Facility (SURF)
- ~1300 km apart from ND
- 1500 m underground (4300 m.w.e.)



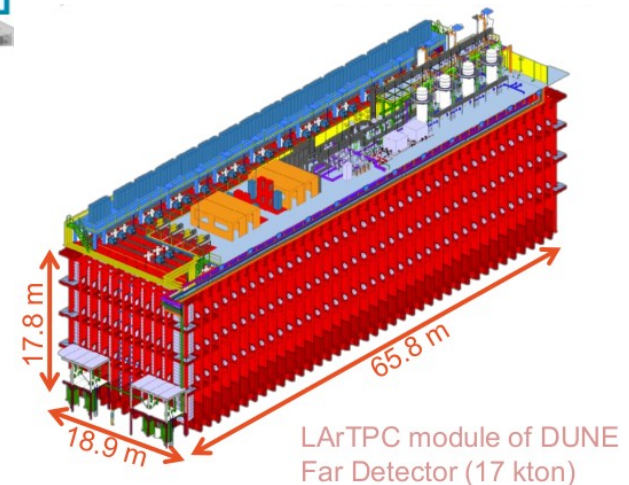
## PHASE-I

- Full Near and Far site facilities
- 1.2 MW upgradable neutrino beam line
- Far Detector (FD): Two LArTPCs modules (17 kt each)

## PHASE-II

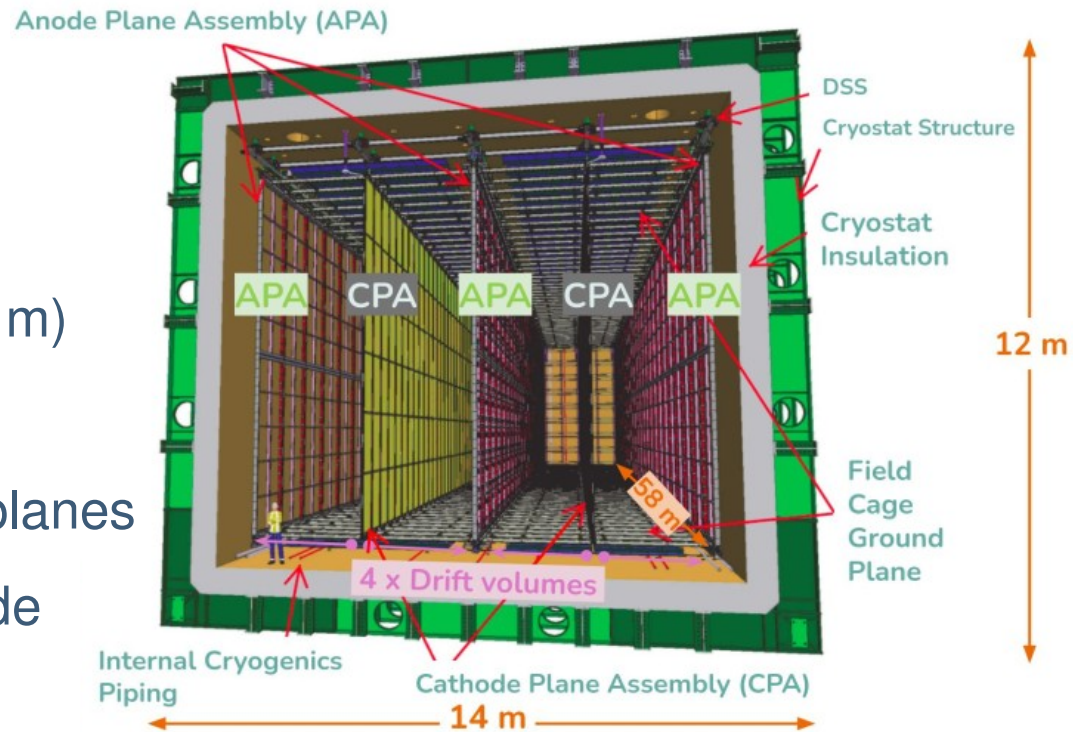
- Beam line upgrade to  $> 2\text{ MW}$
- Two additional FD modules (four in total for 70 kt)
- A more capable ND

- Modules 1, 2 and 3: LArTPCs
- Module 4: Module of Opportunity

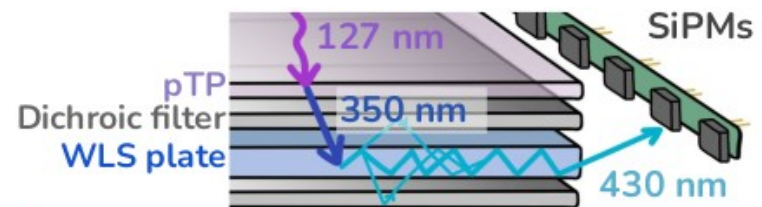


# Far Detector Horizontal Drift (FD-HD)

- Established and validated technology
  - TPC size:  $(12 \times 4 \times 58.2) \text{ m}^3$
  - 4 horizontal drift regions (3.5 m)
  - Drift Voltage 500 V/cm
  - Vertical cathode and anode planes
  - Photon detectors on the anode planes
- 
- Photon detection based on X-ARAPUCAs
  - X-ARAPUCA: very high reflective photon trap with SiPMs



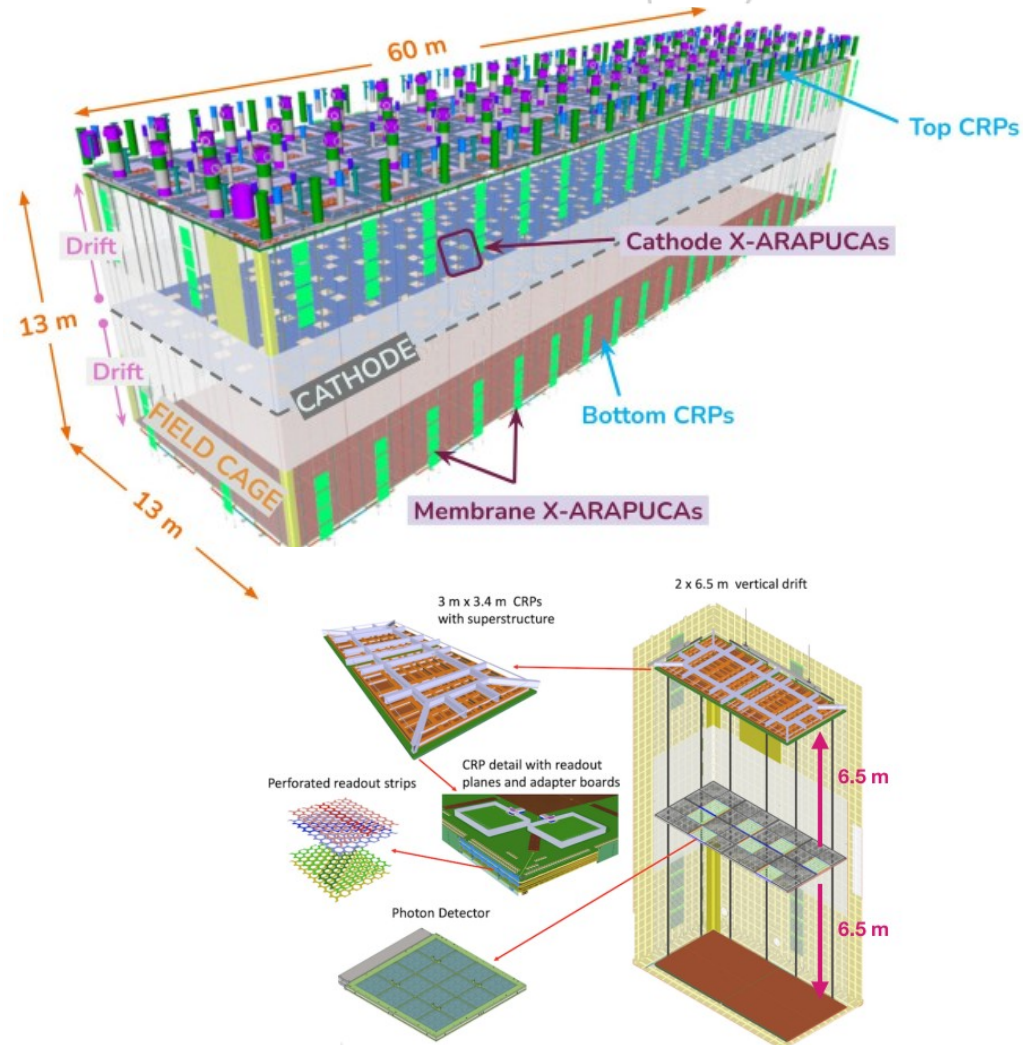
*DUNE collaboration. JINST 15 (2020) T08010*



# Far Detector Vertical Drift (FD-VD)

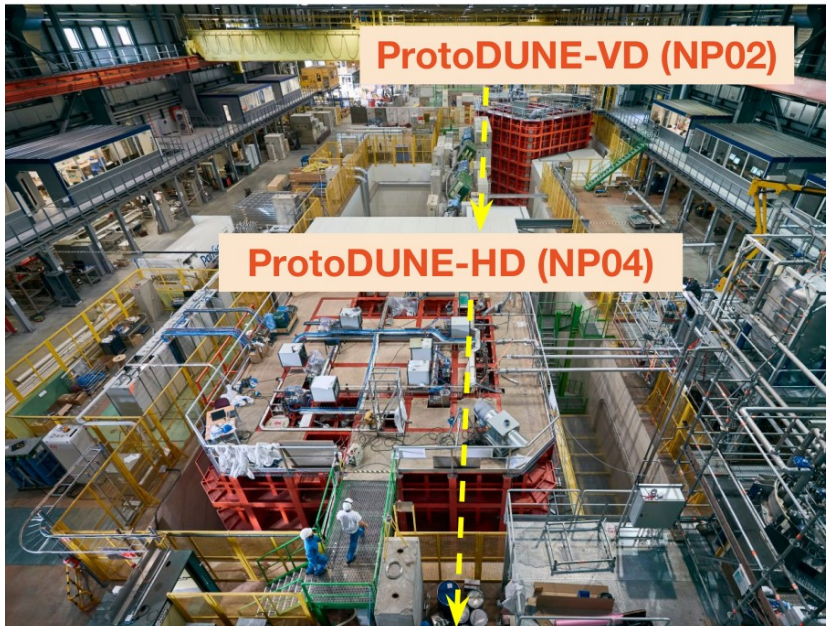
DUNE collaboration. JINST 19 (2024) 08 T08004

- 2 volumes separated by a cathode
- Cathode suspended at mid-height
- 6.5 m drift distance (drift field 450 V/cm, HV: 294 kV)
- 2 anode planes (top & bottom)
- Anode comprised of stacked, segmented and perforated printed
- PCBs with etched electrodes
- X-ARAPUCAs on the cathode plane and membrane walls

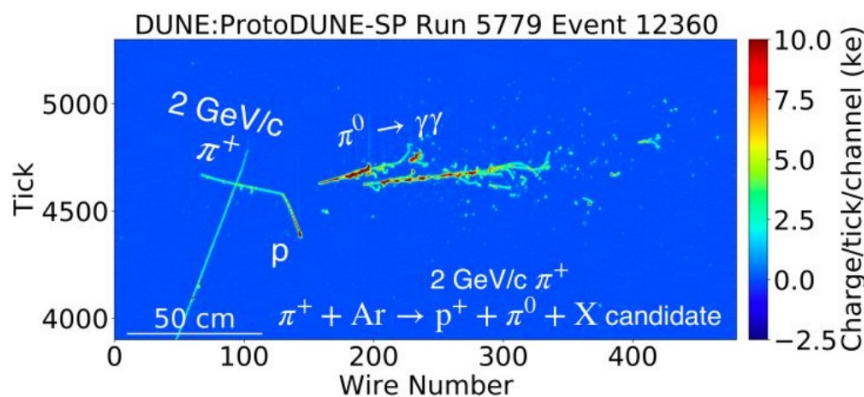


# The DUNE Experiment: ProtoDUNE at CERN

Starting 2016, the North Hall of CERN was extended to hold the Neutrino Platform.

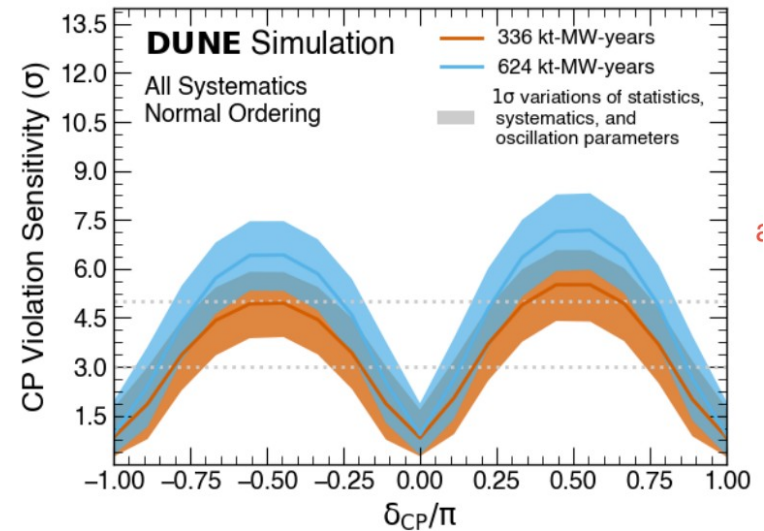


- 800 t LAr total (1/20 of one FD module)
- Real-size readout elements (APA, PDS, CRP)
- Successful phase-I (2018 – 2020)
  - DUNE. JINST 15 (2020) P12004
- ProtoDUNE-HD campaign in 2024
  - Test upgraded components in their final design and take more beam data
- ProtoDUNE-VD campaign in 2025
  - Test the VD concept for the first time at large scale

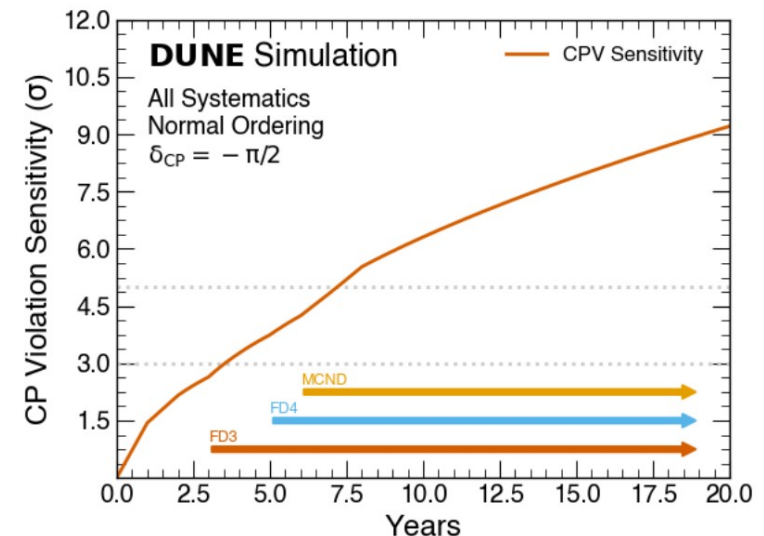


# CP Sensitivity

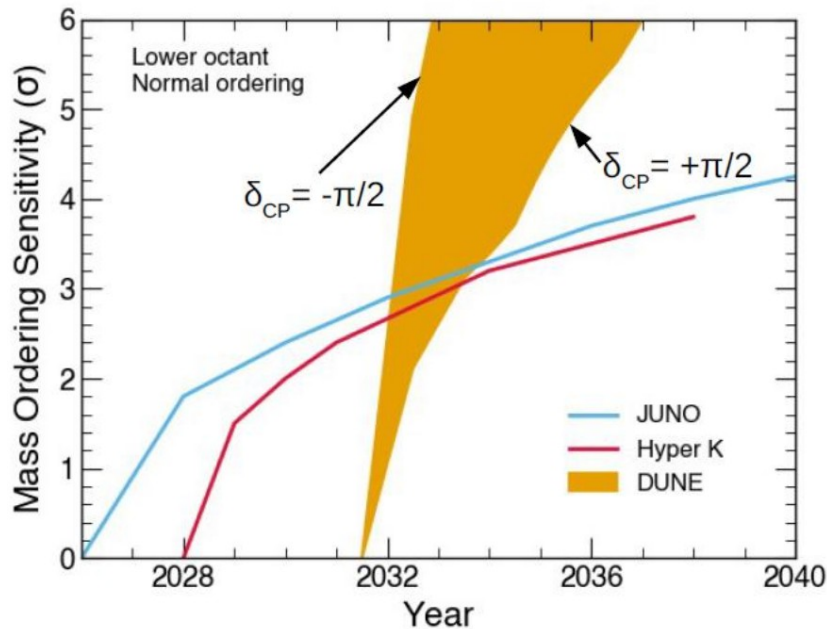
- DUNE has the best ultimate  $\delta_{CP}$  resolution, especially if CP is violated
- DUNE can resolve degeneracies between different values of  $\delta_{CP}$  with broad L/E spectrum
- After 10 years exposure there is significant CP violation ( $\delta_{CP} \neq 0, \pi$ ) discover potential across true values of  $\delta_{CP}$  and for both hierarchies
- DUNE can establish CPV over 75% of  $\delta_{CP}$  values at  $>3\sigma$  (worst case scenario)
- DUNE can establish CPV over 50% of  $\delta_{CP}$  values at  $>5\sigma$



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



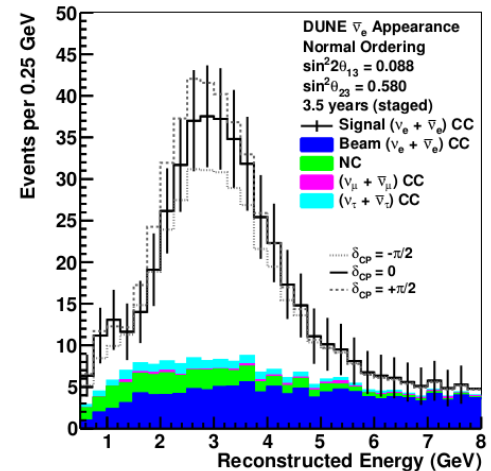
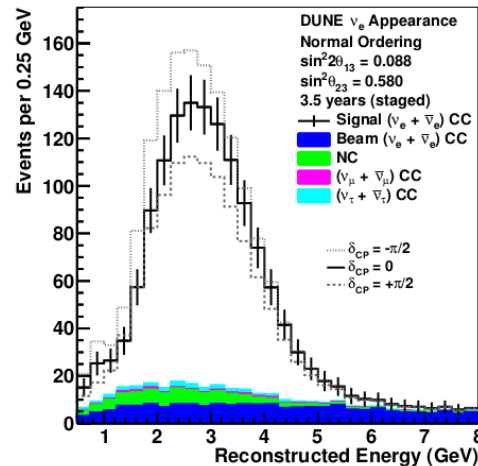
# Mass Ordering Sensitivity



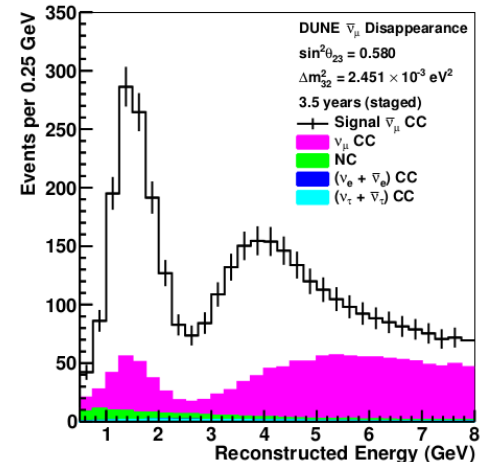
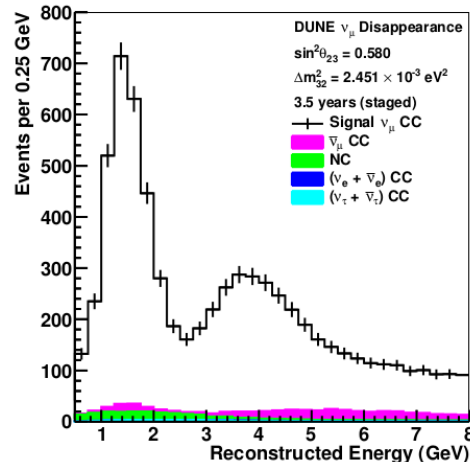
- DUNE's mass ordering (MO) sensitivity depends on true oscillation parameter
- Because of the long baseline, anti- $\nu/\nu$  asymmetry from matter effect is expected to be larger than the largest possible CP-violating difference
  - The MO will be determined by measuring electron neutrino appearance.
- DUNE is the only experiment to determine the mass ordering to  $5\sigma$  (within 5 years for any value of  $\delta_{CP}$ )
- DUNE's MO determination is crucially important as input to experiments that measure:
  - neutrino absolute mass
  - $\delta_{CP}$  assuming MO is known

# Oscillation Parameters

- DUNE is a multi-purpose experiment, it has many advantages:
  - More robust to parameter degeneracies
  - Better long-term precision
  - More robust to unexpected results
  - Much better sensitivity to new physics in neutrino oscillations
- The Far Detector (FD) measures the  $\nu_\mu$  disappearance and the  $\nu_e$  appearance over a wide range of energy using multi-kiloton LArTPC technology

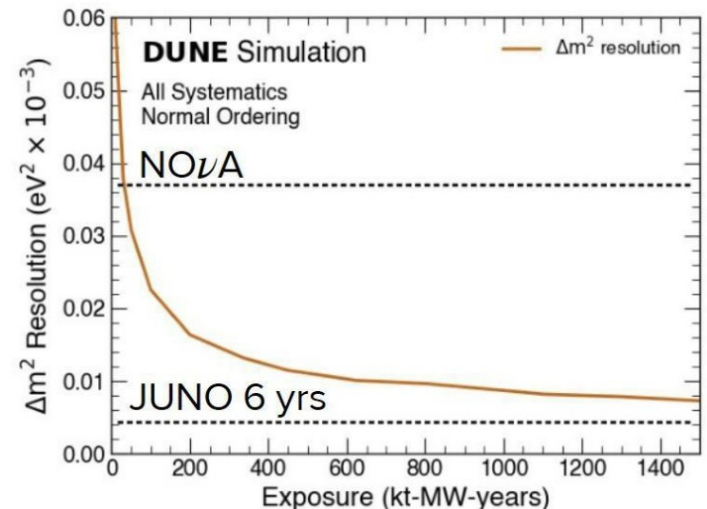
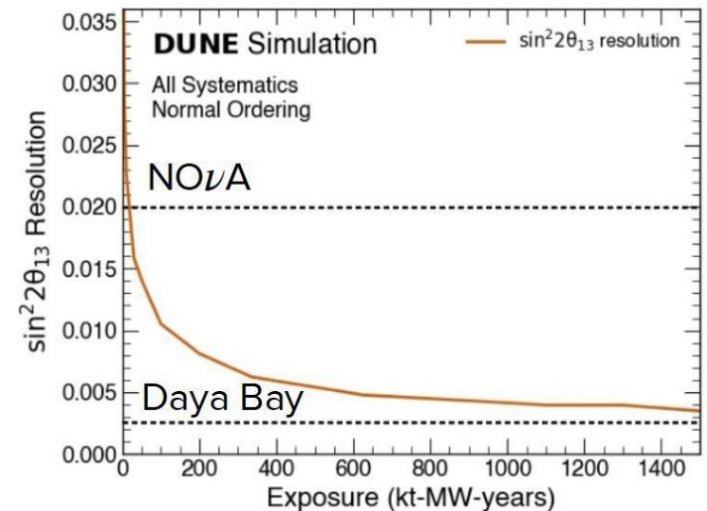


DUNE Technical Design Report (TDR) arXiv:2002.03005



# Oscillation Parameters

- Measurements of  $\theta_{13}$  obtained from  $\nu_e$  appearance in long-baseline experiments and  $\nu_e$  disappearance in reactor experiments are only equivalent if unitarity is assumed
- DUNE approaches JUNO precision of  $\Delta m^2_{32}$ 
  - Comparisons between  $\nu_\mu$  and  $\nu_e$  disappearance are possible as DUNE approaches JUNO precision
- Opportunity to test the 3-flavor paradigm
- Repeat the measurement with antineutrino beam!



# Low Energy Interactions in LAr

- Liquid Argon has a particular sensitivity to the  $\nu_e$  component of a Supernova Neutrino Burst (SNO).

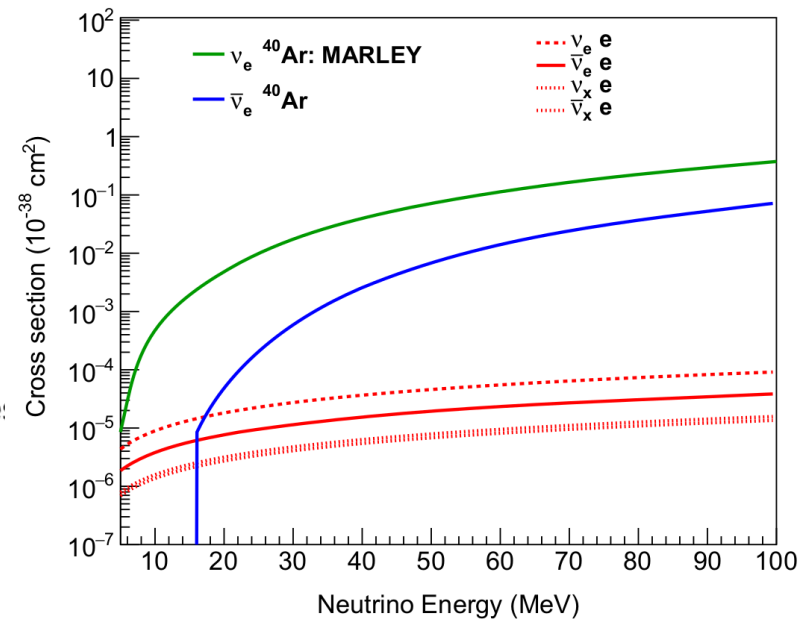
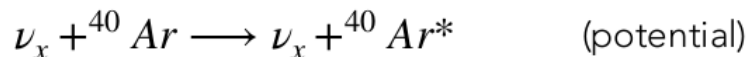
## 1. Charge-current interactions on Ar



## 2. Elastic scattering on electrons



## 3. Neutral current interactions on Ar

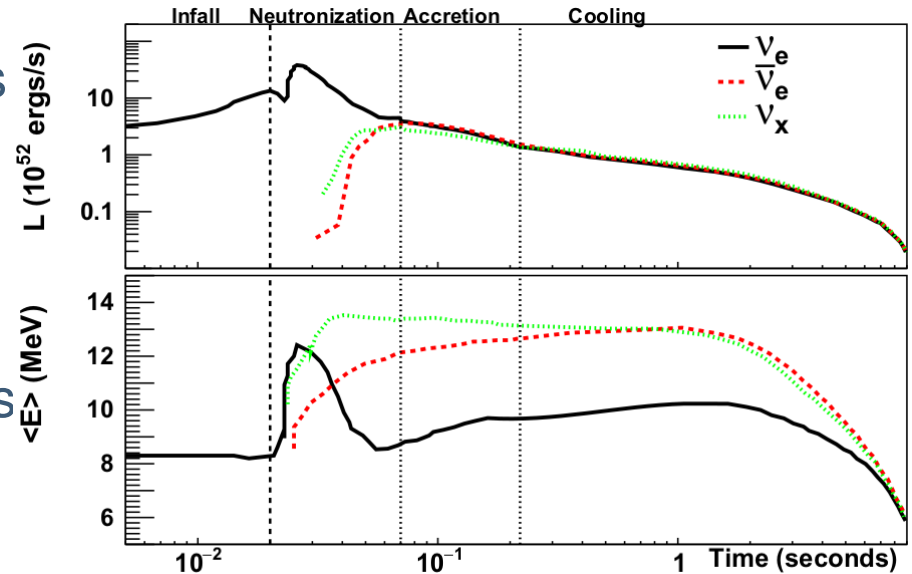


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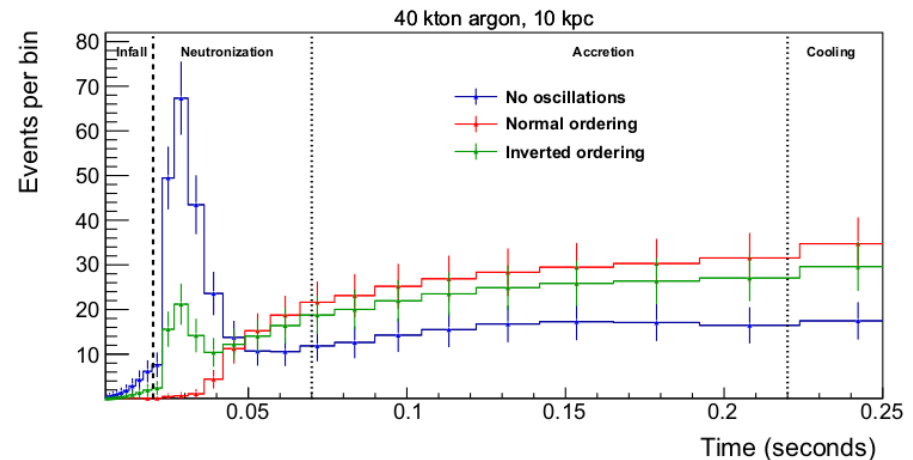
- MARLEY (Model of Argon Reaction Low Energy Yields)

# Supernova Neutrino

- SNB are a huge source of neutrinos of all flavours
- 1-3 SNB per century in our Galaxy (10 kpc)
- DUNE will observe natural neutrinos produced by a SNB and the Sun.
- $\sim 5^\circ$  pointing resolution depending on SNB location
- The flavor and time structure of the detected neutrinos, particularly during the neutronization burst, could offer valuable hints not only about the SNB explosion process but also neutrino mass ordering as well.



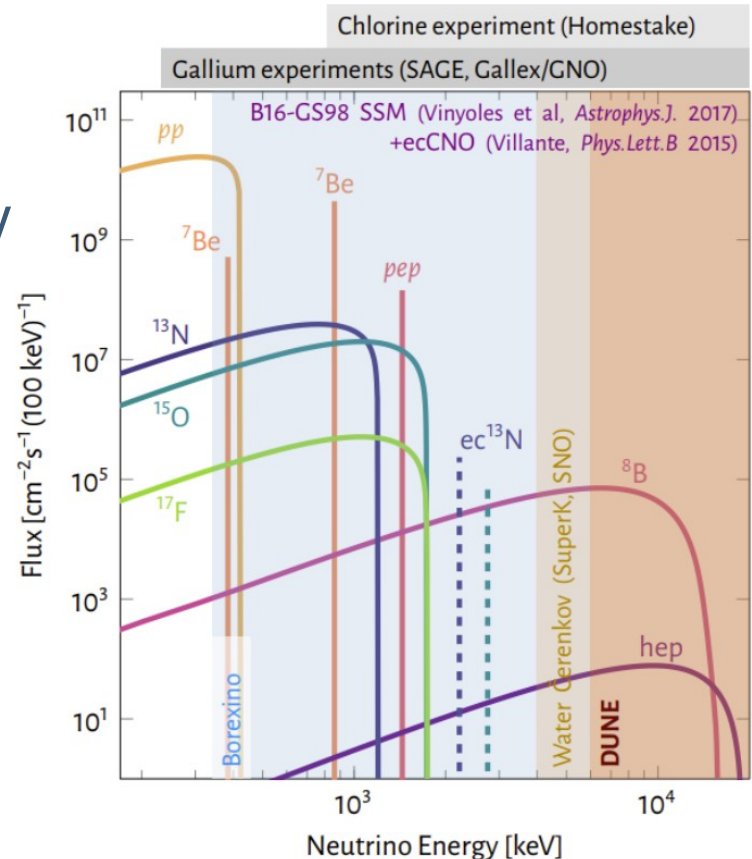
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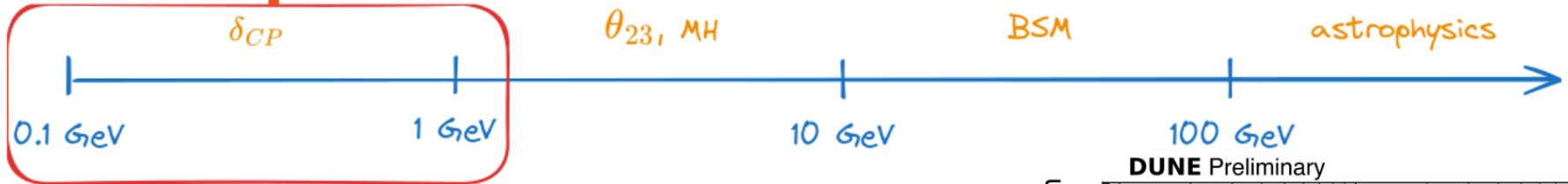
# Solar Neutrinos at DUNE

- Use the large  ${}^8\text{B}$  flux to measure the oscillation parameters
- Attempt to measure (discover!) the hep flux using the CC interaction
- DUNE FD will have sensitivity to hep neutrinos flux with energy above  $\sim 5$  MeV
- DUNE can improve upon existing solar oscillation measurements via day-night asymmetry induced by matter effects
- Control of background is crucial:
- Most challenging backgrounds are fast neutrons from cavern and gammas from neutron activation in rock, that extend well beyond 5 MeV

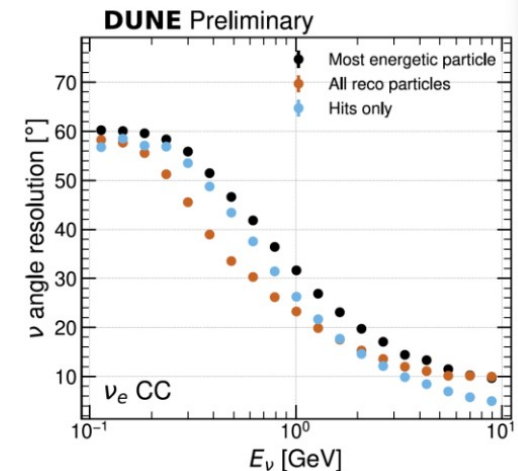
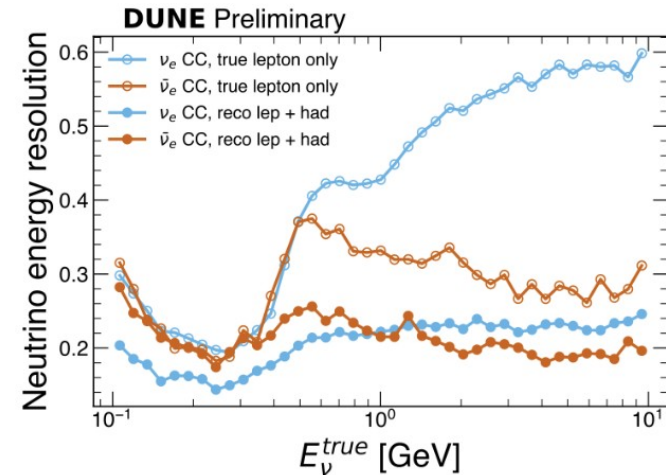
After 100 Kton years:  
 $O(2 \times 10^5)$  CC events from  ${}^8\text{B}$   
 $O(3 \times 10^2)$  CC events from hep



# Atmospheric Neutrinos



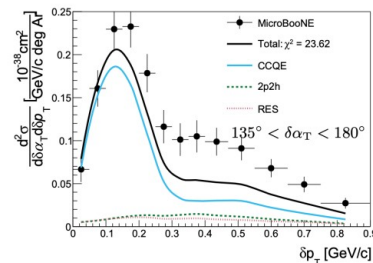
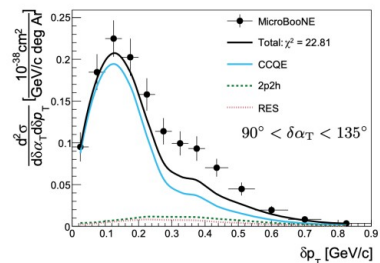
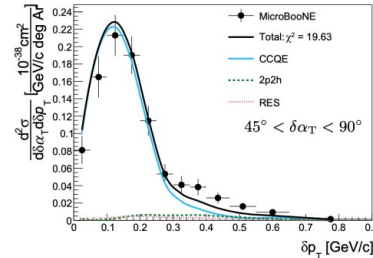
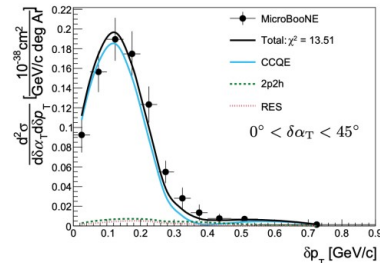
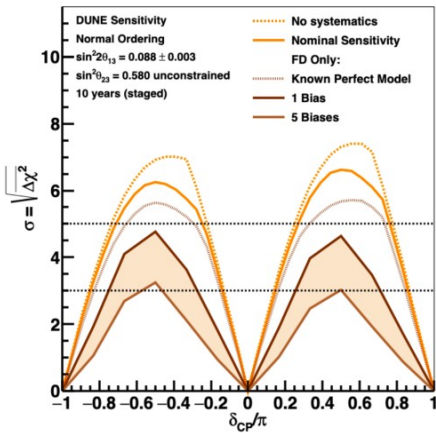
- Normalisation of sub-GeV up-going neutrinos driven by  $\delta_{CP}$  :
- Can be reconstructed: low hadronic KE thresholds
- Subject to nuclear effects and cross-section systematics
- Atmospheric neutrinos will be measured at the FD
- Also one of the earliest measurements!
- Particle identification improves angular resolution for low energies ( $E_\nu < 1.0$  GeV)



# Cross-Sections

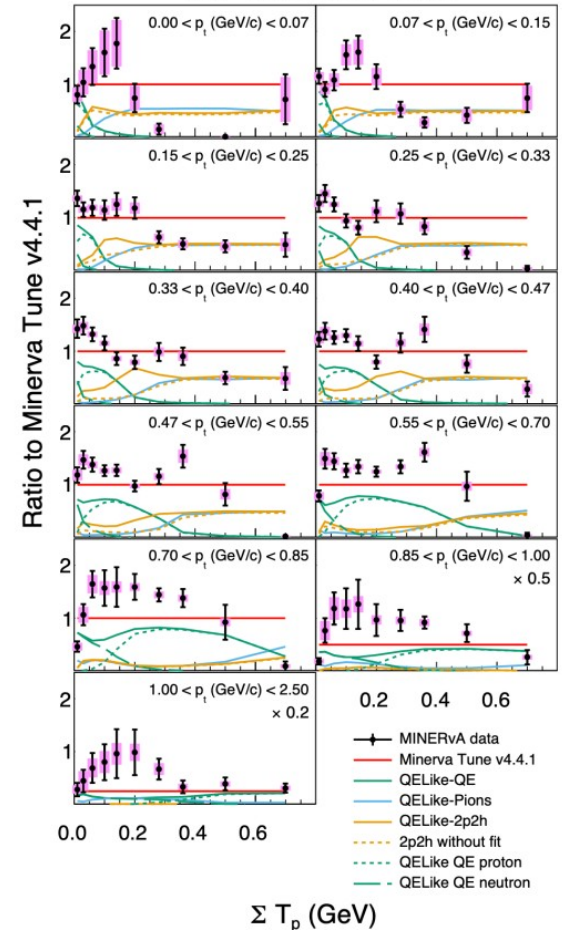
- Incorrect x-sec model Impact to the  $\delta_{CP}$  sensitivity
- Interaction uncertainties are the dominant source systematics for the LBL analyses
- Modeling neutrino-nucleus is not easy

MicroBooNE  
arXiv:2407.10962



MINERvA  
arXiv:2203.08022

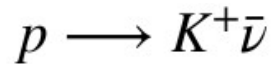
1.50 < P\_|| (GeV/c) < 3.50



# Proton Decay

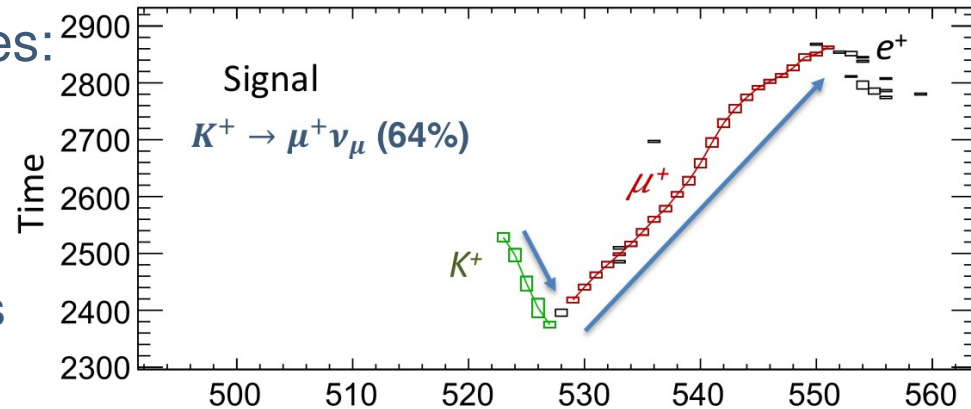
- DUNE will be an excellent detector to perform nucleon decay searches:
  - Underground location
  - Very large fiducial mass
  - Milimetrical Imagine capabilities

- Golden Channel in DUNE



- DUNE Can image the three particles
- LArTPC allow for the observation of the entire decay channel
- Main background for this channel in DUNE are atmospheric neutrinos

DUNE Collaboration. ArXiv: 2002.03005



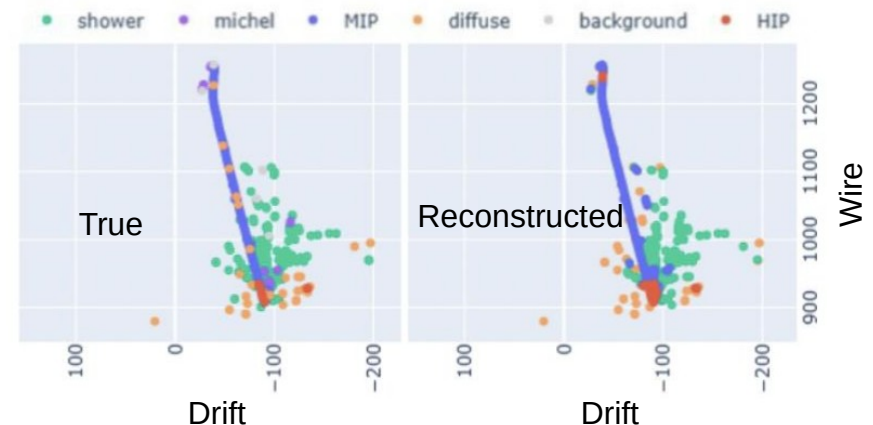
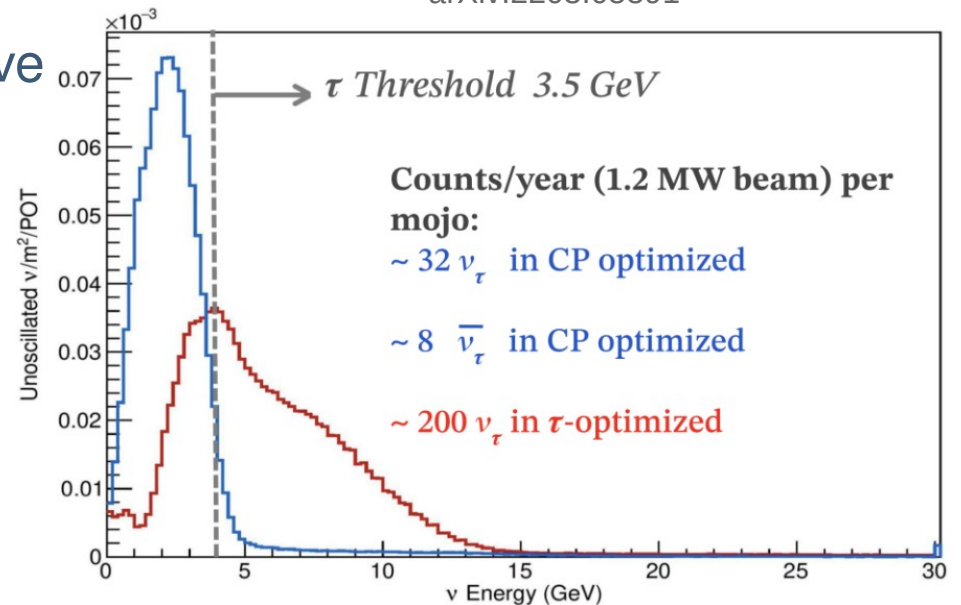
- $K^+$  typically below Cherenkov threshold
- Hiper-K can identify this channel by timing ( $\mu$  &  $e$ ) and the observation of the muon
- DUNE sensivity comparable to Cherenkov detectors:

$$\tau/\text{Br}(p \rightarrow \bar{\nu}K^+) > 1.3 \times 10^{34} \text{ years}$$

# $\nu_\tau$ Appearance in DUNE beam

arXiv:2203.05591

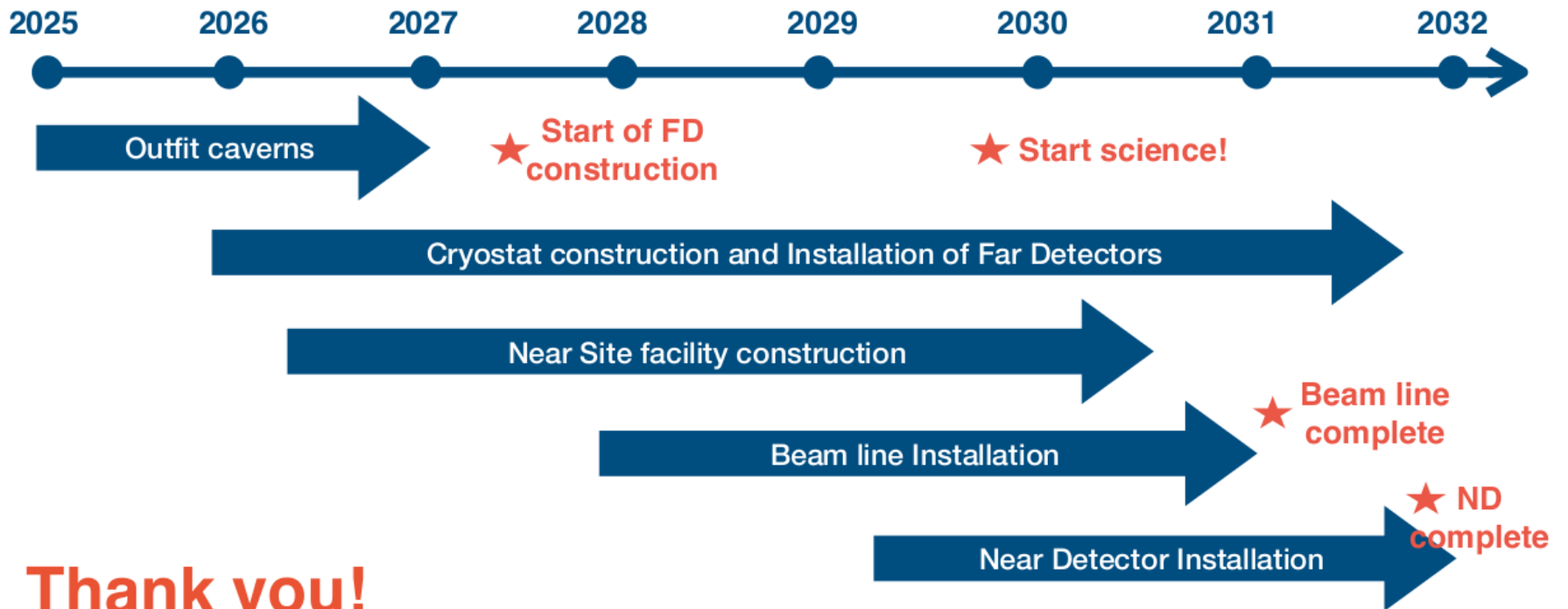
- DUNE has a substantial flux above 3.5 GeV CC threshold  $\rightarrow$  possibility to measure  $\nu_\tau$  appearance
- Imaging capabilities of DUNE's LArTPCs makes it possible to reconstruct complex final states kinematically
- ML-driven reconstruction based on hierarchical graph neural network (GNN) being pursued
- Opportunity to directly measure 3-flavor oscillations and test unitarity



# And Beyond the Standard Model

- In addition, DUNE also opens up a wide range of possibilities for BSM physics, thanks to its high-intensity beam and large-scale, high-precision capable detectors.
- Sterile Neutrino oscillations (ND-to-FD, or within ND)
- Heavy Neutral Leptons
- Non-standard interactions
- Large Extra Dimensions
- Imaging of LArTPC enables DM-e detection, enhanced by moving off-axis due to differences between DM-e and  $\nu$ -e rates vs angle
- DUNE is sensitive to extremely rare processes due to intense beam, for example tridents potentially enhanced by  $Z'$
- DUNE is sensitive to low-mass, low-coupling dark matter, which complements higher mass searches at colliders:
- Ability to detect low-energy particles (iBDM at left, signal is a soft e/p and spatially proximate  $e^+ / e^-$  pair)
- Ability to reconstruct direction including hadrons (BDM) produced in Sun or Galactic Center at right

# LBNF/DUNE: Timeline and Milestones



Thank you!

DUNE Collaboration Meeting @ Fermilab 2025

# BackUp



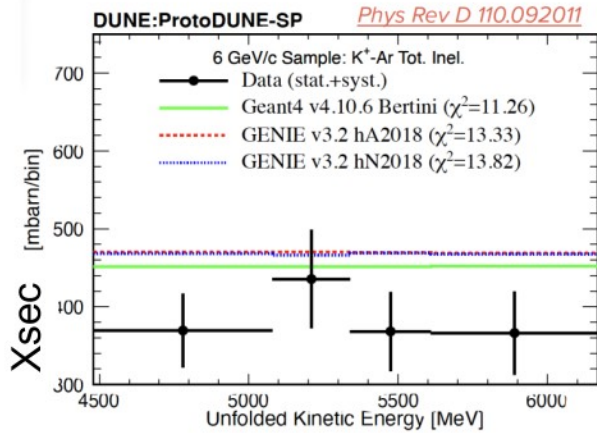
# Neutrino Physics

Most neutrino oscillation parameters are now known with a precision of ~3%

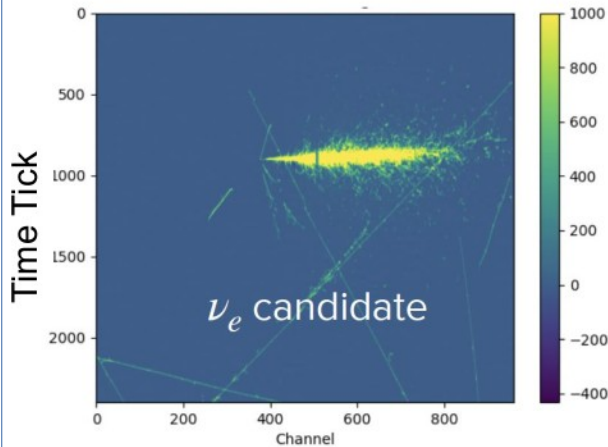
M. Tortola, Neutrino2024

parameter	best fit $\pm 1\sigma$	$3\sigma$ range	
$\Delta m_{21}^2 [10^{-5}\text{eV}^2]$	$7.55^{+0.22}_{-0.20}$	6.98–8.19	2.7%
$ \Delta m_{31}^2  [10^{-3}\text{eV}^2]$ (NO)	$2.51^{+0.02}_{-0.03}$	2.43–2.58	1.0%
$ \Delta m_{31}^2  [10^{-3}\text{eV}^2]$ (IO)	$2.41^{+0.03}_{-0.02}$	2.34–2.49	
$\sin^2 \theta_{12}/10^{-1}$	$3.04 \pm 0.16$	2.57–3.55	5.4%
$\sin^2 \theta_{23}/10^{-1}$ (NO)	$5.64^{+0.15}_{-0.21}$	4.23–6.04	3-4%
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.64^{+0.15}_{-0.18}$	4.27–6.03	
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.20^{+0.05}_{-0.06}$	2.03–2.38	2.6%
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.20^{+0.07}_{-0.04}$	2.04–2.38	
$\delta/\pi$ (NO)	$1.12^{+0.16}_{-0.12}$	0.76–2.00	10-15%
$\delta/\pi$ (IO)	$1.50^{+0.13}_{-0.14}$	1.11–1.87	

# ProtoDUNE-HD Performance and Results

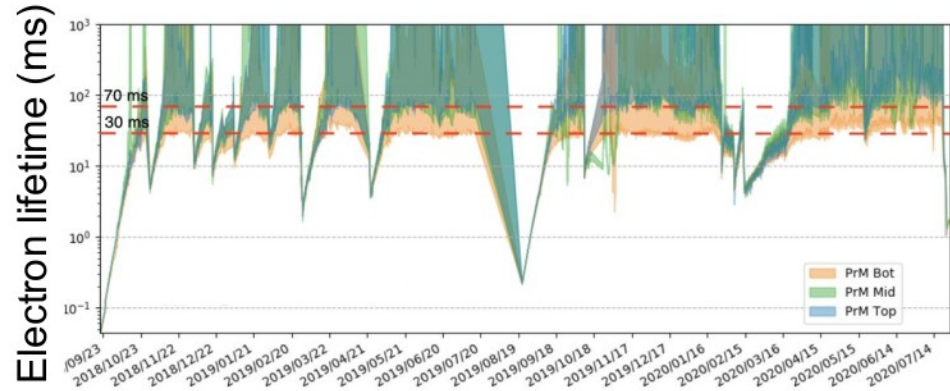


First measurement of kaon cross section on Ar at 5 GeV

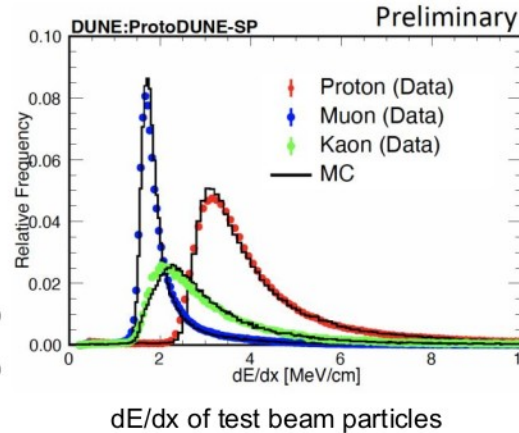


Parasitic neutrinos in SPS beam

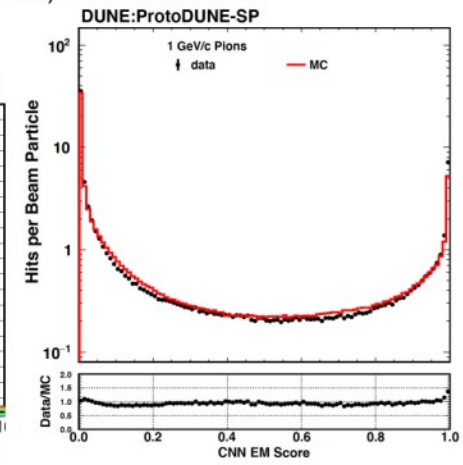
13



LAr purity (electron drift lifetime) > 30ms achieved



dE/dx of test beam particles



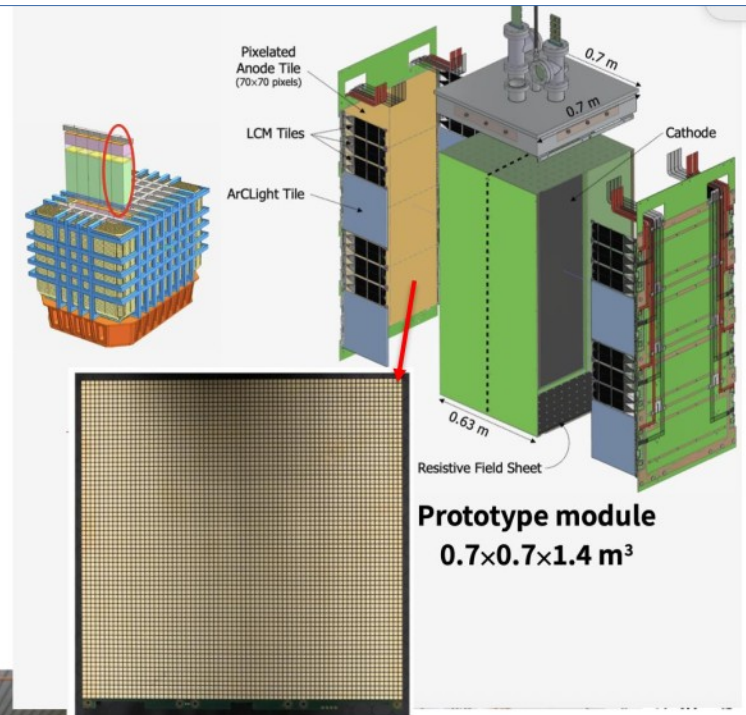
ML based PID

Jianming Bian - UCI

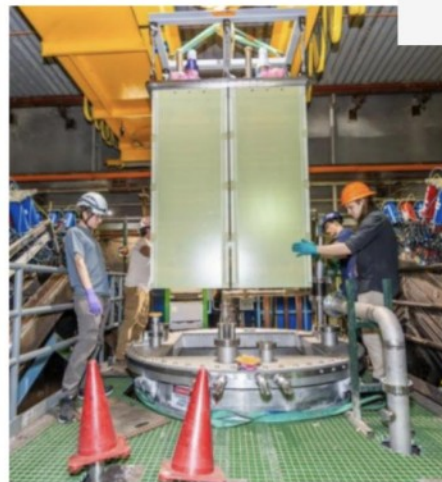


# ND-LAr Prototype at Fermilab

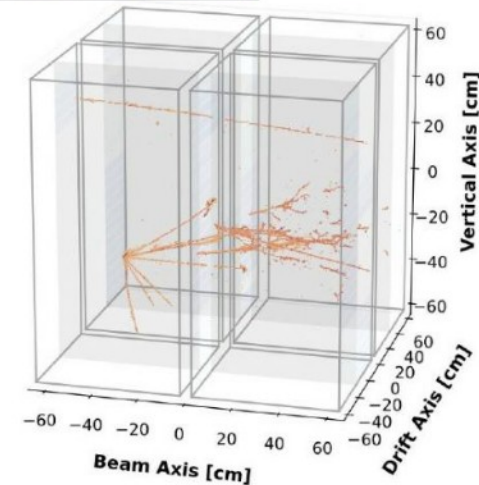
- 2x2 prototype of ND-LAr operated in NuMI neutrino beam in summer 2024
- Pixel readout LArTPC → direct 3D image
- Neutrino data taken
- Analysis ongoing, additional beam run planned for 2026



14

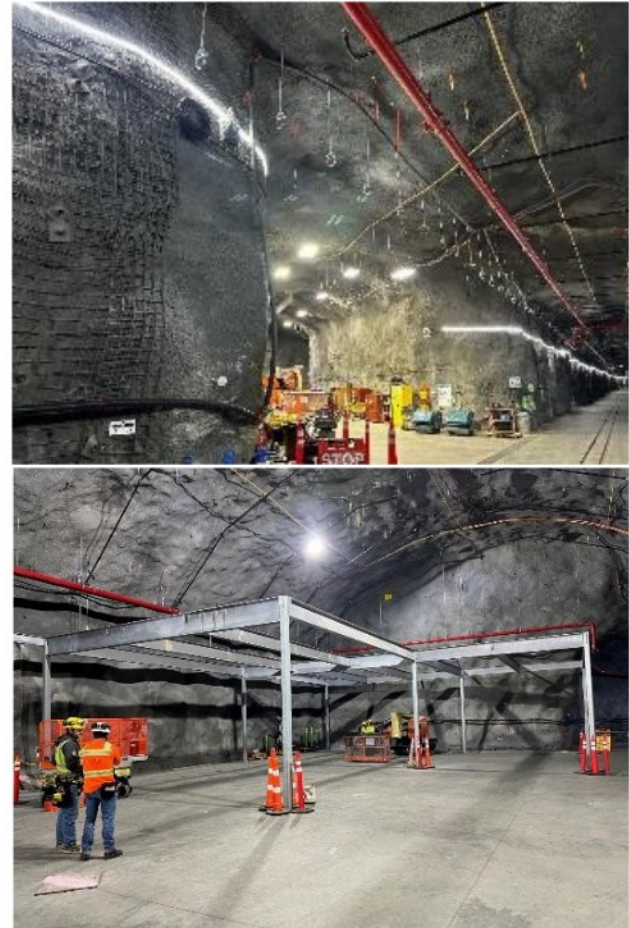


Jianming Bian - UCI



# Far site status

- Excavation complete in 2024
- Building & Site Infrastructure work ongoing (plumbing & fire suppression, top; central utilities cavern steel installation, bottom)
- Estimate cryostat installation to begin in early 2026



53

Chris Marshall - Fermilab colloquium



# Cryostat materials in South Dakota

- Cryostat beams constructed at CERN and shipped to South Dakota
- Preparing for lowering into cavern for start of installation in early 2026
- Warm structure installation in 2026, then cold structure in 2027 in parallel with warm detector components
- Cold side of detector to be installed in 2028



54

Chris Marshall - Fermilab colloquium



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# PIP-II at Fermilab is the engine of the LBNF beam



55

Chris Marshall - Fermilab colloquium

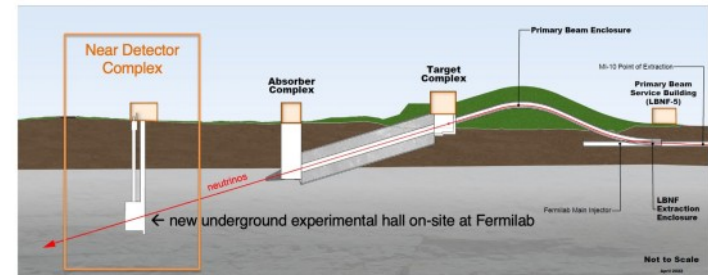


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ROCHESTER

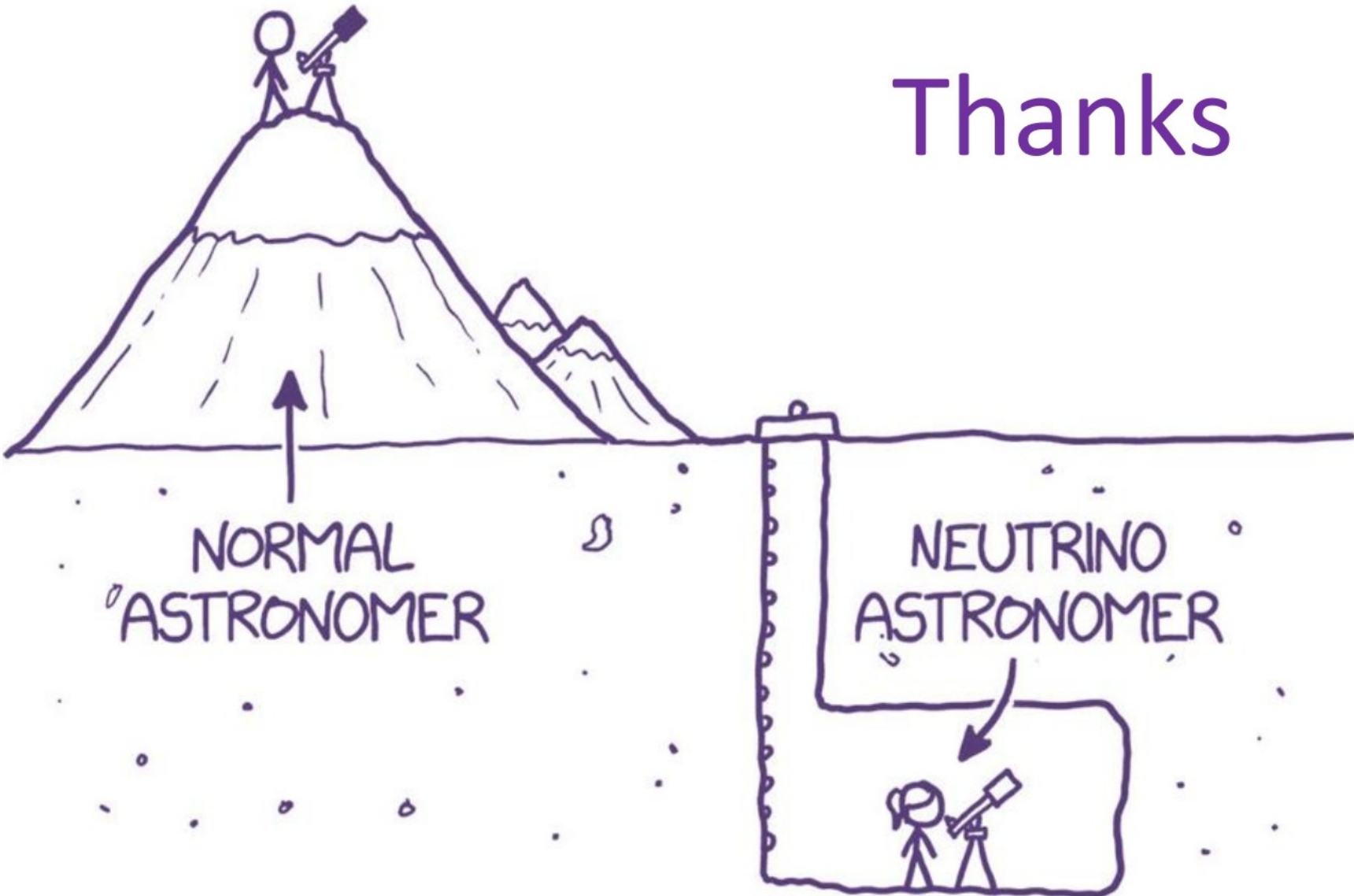


# Near site complex construction

- Preparation is underway for construction of the near site surface building
- Facility construction to begin next year
- Detector installation in 2029
- Physics data with full ND+FD+beam in early 2030s



# Thanks



Credit: Randall Munroe