



**BERKELEY LAB**



# The Deep Underground Neutrino Experiment (DUNE): Prospective Physics Program and Status

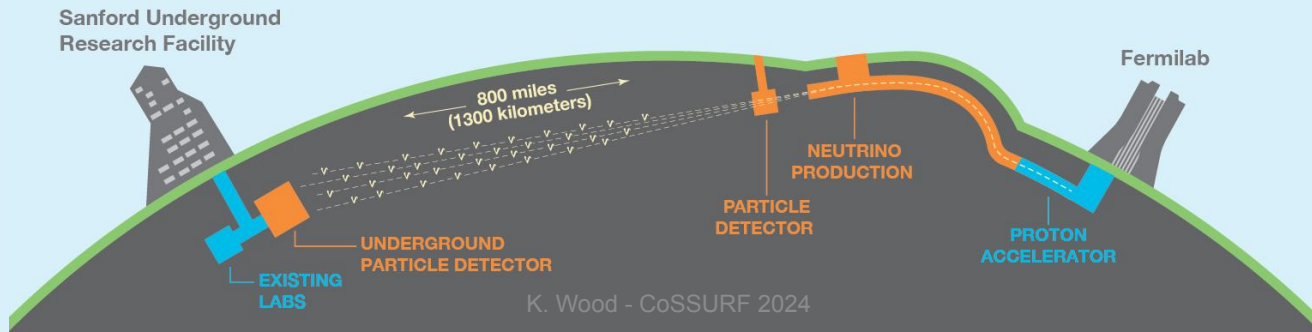
Kevin Wood, [kwood@lbl.gov](mailto:kwood@lbl.gov), on behalf of the DUNE Collaboration

CoSSURF 2024, Sanford Underground Research Facility

May 14, 2024

# DUNE Overview / Outline

- DUNE's primary science goal is to precisely and unambiguously measure **neutrino oscillation** parameters (+ SNB, proton decay)
- DUNE will measure the flavor oscillations of **accelerator neutrinos** over a **long baseline**
- Next generation experiment that improves upon the current generation experiments: **T2K** and **NOvA**



# Neutrino Oscillations

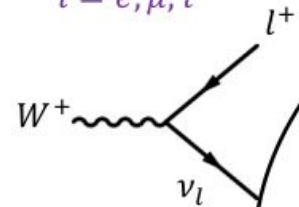
produced in flavor eigenstates

propagate in mass eigenstates

observed in flavor eigenstates

**flavor states**

$l = e, \mu, \tau$



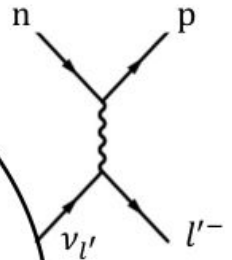
**mass states**

$i = 1, 2, 3$

$$|\alpha(0)\rangle = |\nu_l\rangle = \sum_i c_i |\nu_i\rangle$$

$$|\alpha(x)\rangle = \sum_i c_i |\nu_i\rangle e^{-ip_i x}$$

$$\Rightarrow |\langle \nu_{l'} | \alpha(x) \rangle|^2 \neq \delta_{ll'}$$

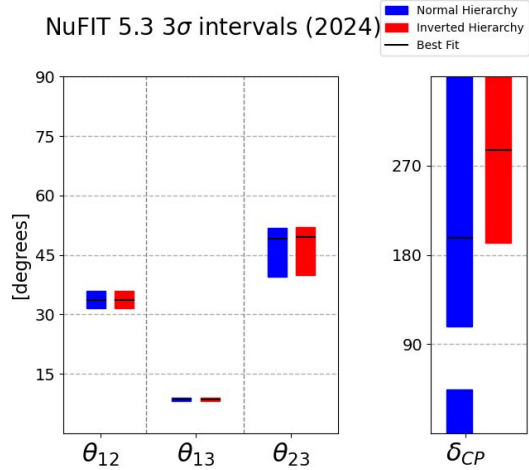
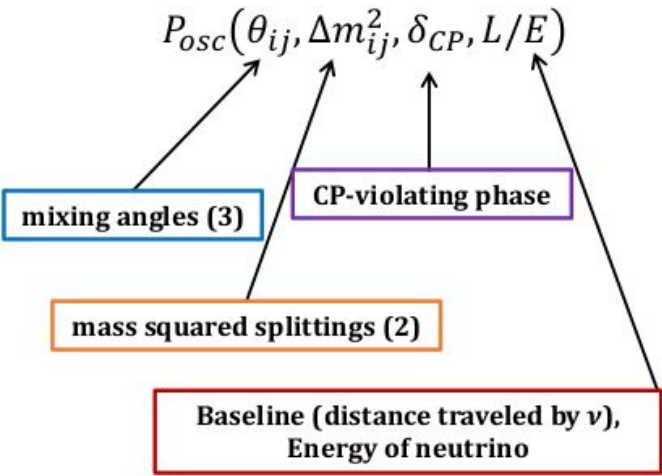


$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}}_{\text{Majorana phases (no effect on oscillations)}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$s_{ij} \equiv \sin \theta_{ij}$   
 $c_{ij} \equiv \cos \theta_{ij}$

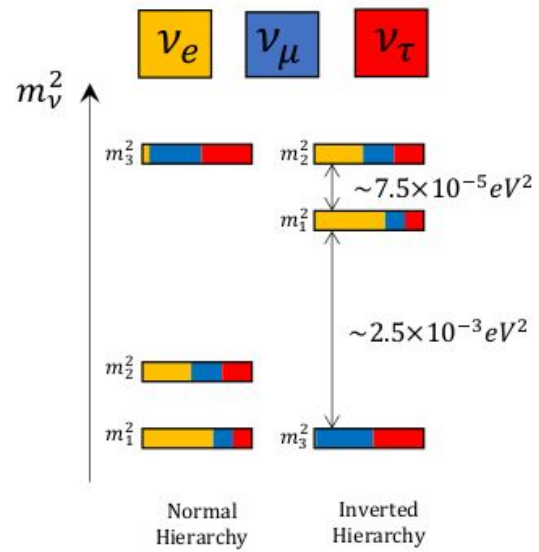
$U_{PMNS}$

# What do we (not) know?



NuFIT 5.3 (2024), [www.nu-fit.org](http://www.nu-fit.org)  
 JHEP 09 (2020) 178 [arXiv:2007.14792]

$\Delta m^2$ 's measured at few-% level



Neutrinos oscillate!

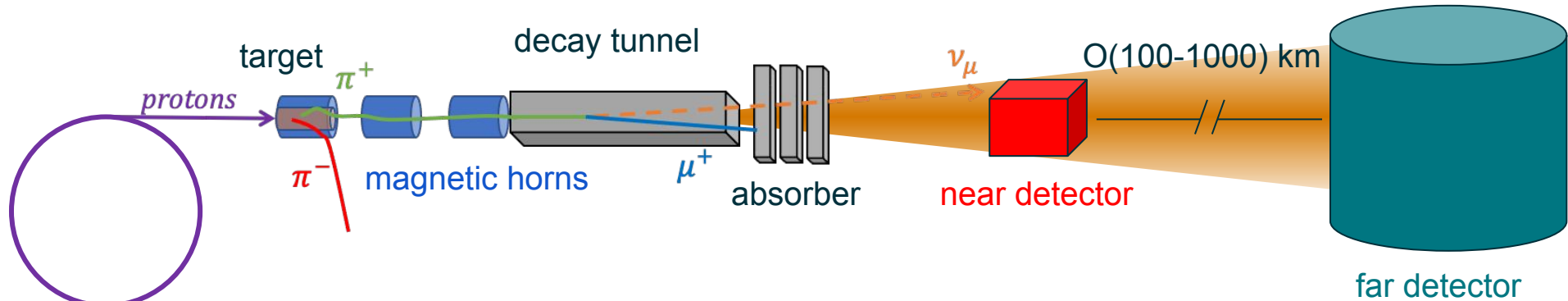
Octant of  $\theta_{23}$ ?

CP Violated?

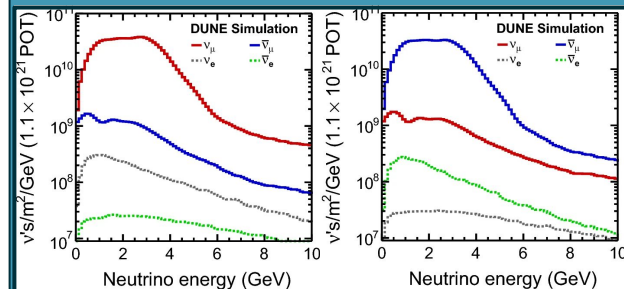
Mass hierarchy?

Mass nature/origins

# Long-baseline, Accelerator Neutrino Oscillations

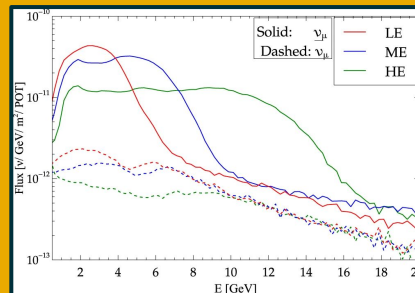


## Operate in $\nu$ OR $\bar{\nu}$ mode



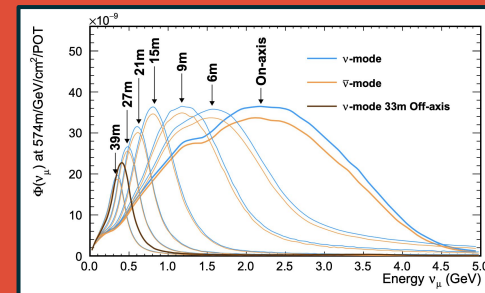
Abi, B., Acciarri, R., Acero, M.A. et al. Long-baseline neutrino oscillation physics potential of the DUNE experiment. Eur. Phys. J. C 80, 978 (2020)

## Tunable neutrino source



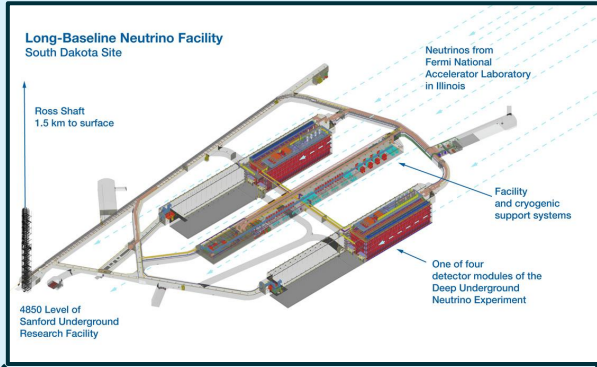
Masud, M., Bishai, M. & Mehta, P. Extricating New Physics Scenarios at DUNE with Higher Energy Beams. Sci Rep 9, 352 (2019)

## The off-axis “trick”



Deep Underground Neutrino Experiment (DUNE), Far Detector Technical Design Report, Volume II: DUNE Physics. arXiv:2002.03005

# DUNE's Far Detectors



## *The Theia Detector*

L. Pickard, Tuesday @ 5:00pm MT, "DUNE Phase II"

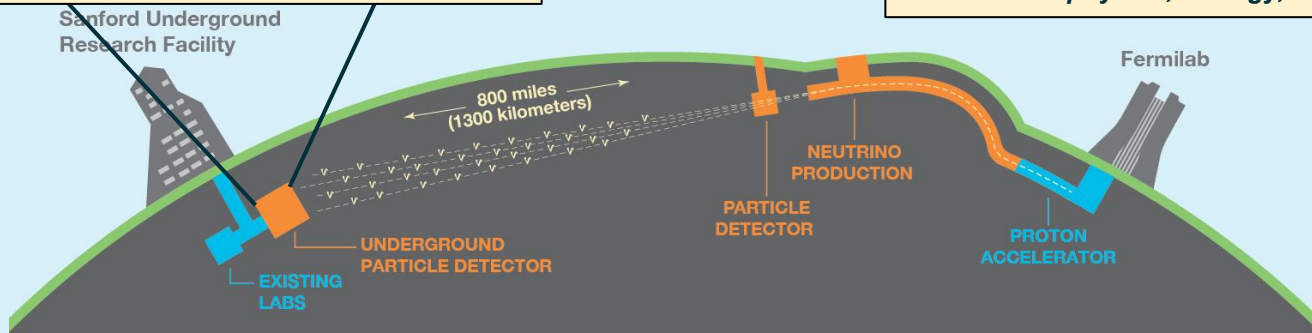
## *A SURF Low Background Module (SloMo)*

C. Jackson, Tuesday @ 5:20pm MT, "DUNE Phase II"

- Nearly a mile underground @ SURF
- Phase I: 2 single-phase LArTPCs ~17kton each
  - Vertical drift
  - Horizontal drift
- Phase II: addition of 3rd LArTPC module + 4th module of opportunity

## *Overview of the DUNE Phase-II Program*

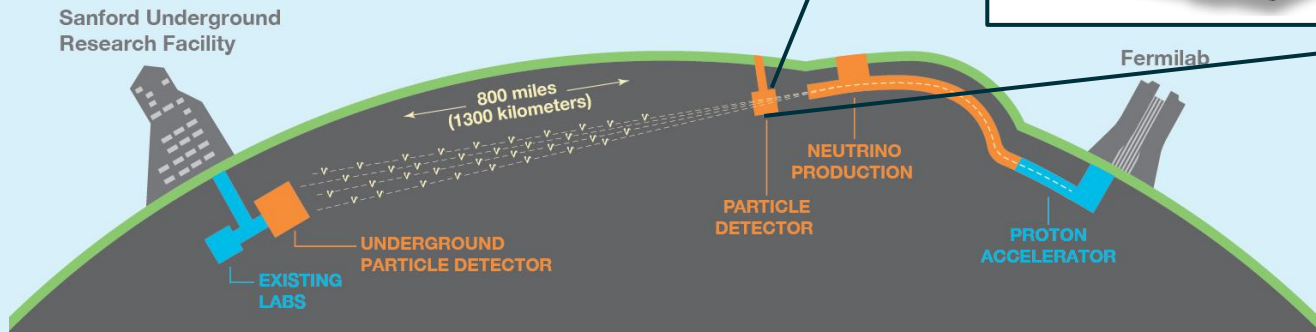
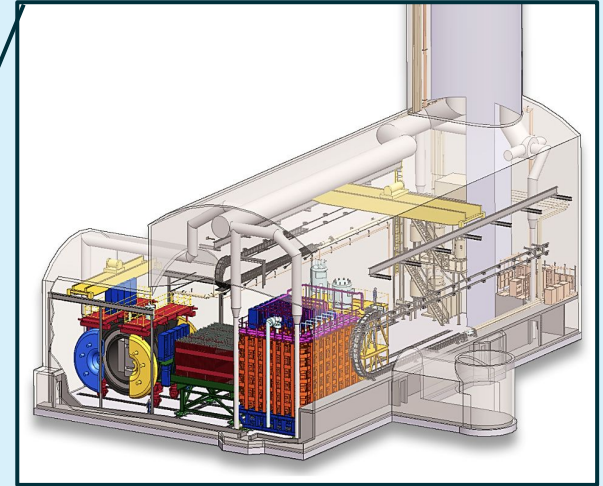
S. Gollapinni, Thursday @ 10:30am MT, "Plenary: Nuclear Astrophysics, Biology, DUNE Phase II"



# DUNE's Near Detectors

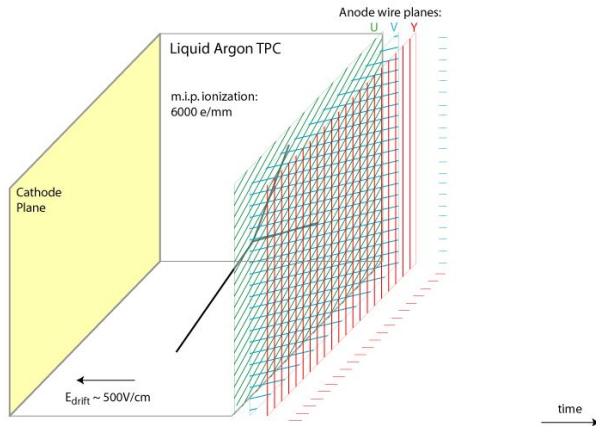
- ND-LAr: LArTPC, analogous to FD
- Muon spectrometer (TMS)
  - Phase II: Upgrade to e.g. GArTPC
- SAND: Monitor flux, constrain interaction systematics
- PRISM: Move ND-LAr + TMS up to 28.5 meters ( $2.8^\circ$ ) off axis

*DUNE: ND-LAr and the 2x2 Demonstrator, K. Wood  
Tuesday @ 2:50pm MT, "Neutrino Oscillations"*



# LArTPC Detection Principles

- DUNE's far detector technology: Liquid Argon Time Projection Chamber (LArTPC)
- ND-LAr at the near detector complex matches
- Variety of readout technologies (wires, strips, pixels) but same basic detection principles:



Courtesy of Bo Yu (BNL)

- Energy deposited into LAr
  - Ionization electrons
  - Scintillation light
- Charge signal drifted towards readout planes by electric field  $\sim 500$  V/cm
  - Slow: up to O(few ms)
- Light detection system measures prompt signal
  - Timing information, including  $t_0$  for 3D reco

**ARIADNE Design and Technology for DUNE**  
K. Mavrokoridis, Tuesday @ 5:40pm MT, "DUNE Phase II"

**SoLAr: a novel approach to multipurpose LArTPCs for neutrino physics**  
D. Guffanti, Tuesday @ 4:40pm MT, "DUNE Phase II"

**APEX Design and VD Technology for DUNE FD3**  
W. Shi, Tuesday @ 4:20pm MT, "DUNE Phase II"

**Calibrating DUNE LArTPC Detectors Using Low-Energy Radioactive Decays**  
M. Mooney, Thursday @ 5:00pm MT, "Supernova & Solar Neutrinos"



# Current Generation Experiments

T2K far site



T2K near site

Japan

NOvA far site

NOvA near site

USA

See *NOvA+T2K Joint Analysis Results*, G. Pawloski, “Neutrino Oscillations” parallel session

T2K	NOvA
Flux peak $\sim 600$ MeV	Flux peak $\sim 2$ GeV
295 km baseline	810 km baseline
CCQE dominant interaction mode	Broad mix of interaction modes
Reconstruct energy from lepton kinematics	Calorimetric energy reconstruction
FD $2.5^\circ$ off axis	FD $1.5^\circ$ off axis
Different ND and FD technologies	Functionally identical ND and FD
ND constrains systematics in the model ( <i>fit</i> )	ND <i>tunes</i> FD pred. without fitting

# Current Generation Experiments

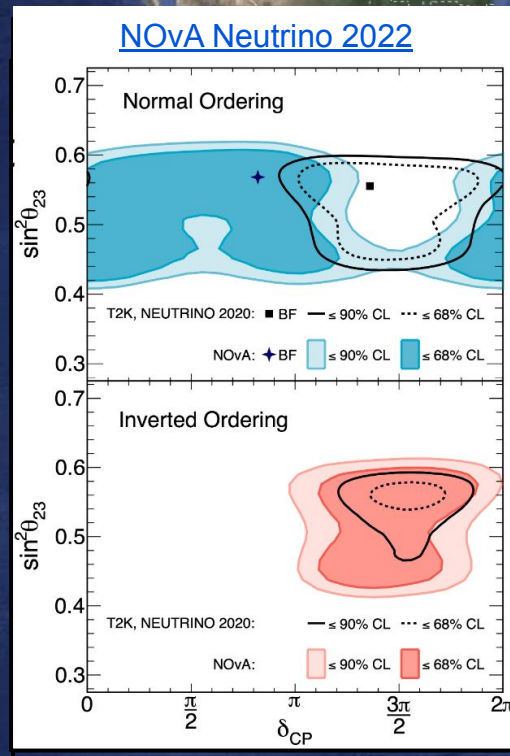
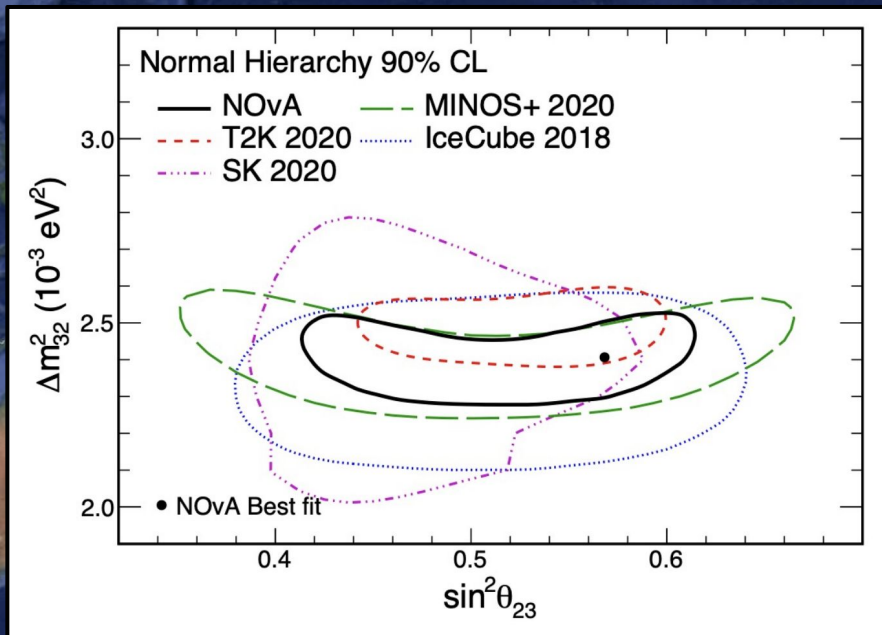
T2K far site      T2K near site

Japan

NOvA far site

NOvA near site

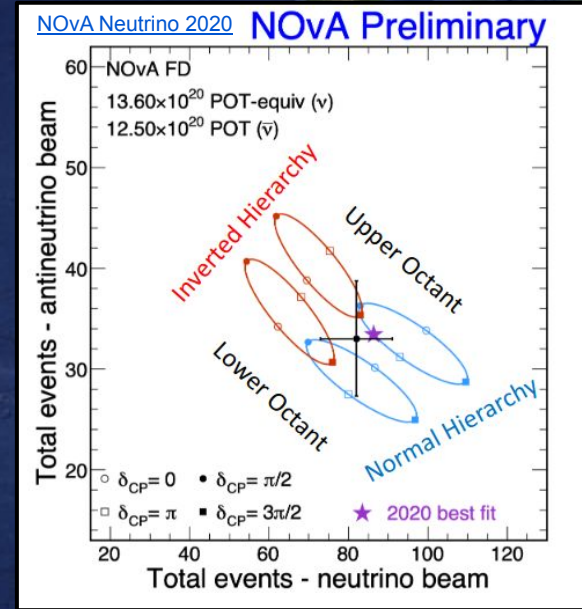
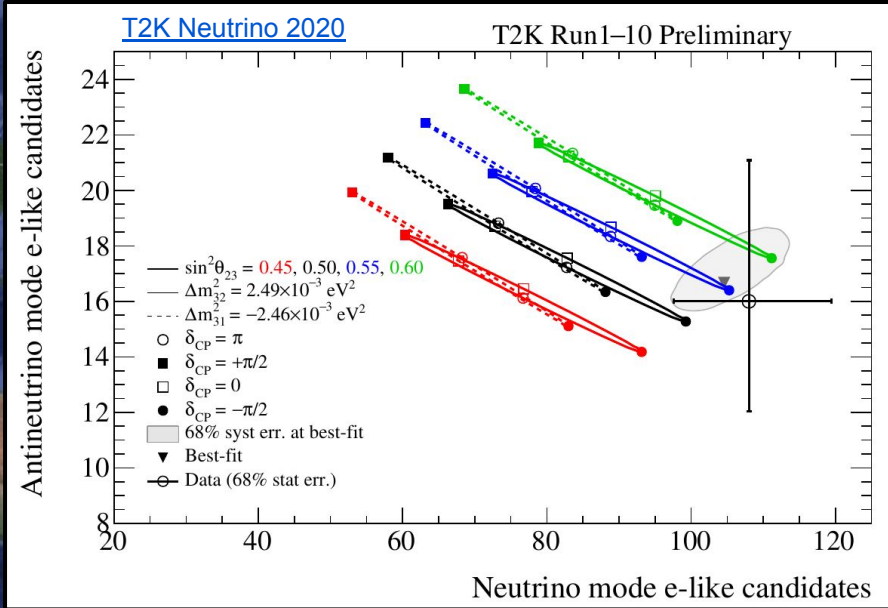
USA



# Current Generation Experiments

T2K far site  T2K near site  
Japan

NOvA far site  NOvA near site  
USA

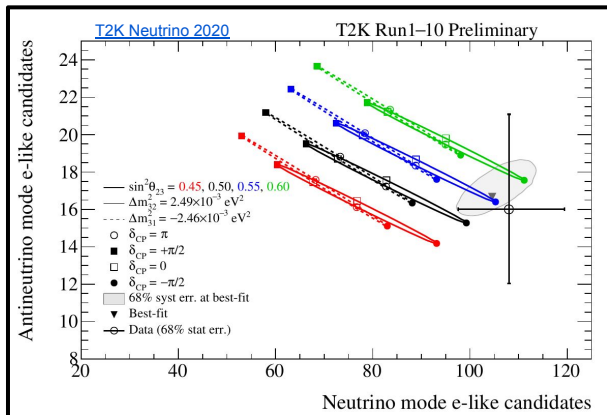


# A Matter of Mass Ordering Sensitivity

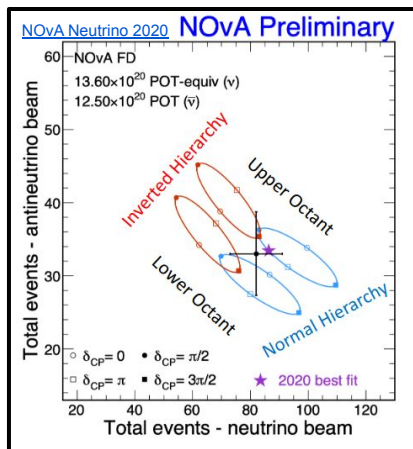
- Mass ordering sensitivity benefits from longer baselines
- Forward coherent scattering channel available to electron neutrinos
- Effect of suppressing/enhancing expected electron neutrino appearance rate depending if Nature feature normal or inverted neutrino mass ordering
  - Vice versa for electron antineutrinos

*NB: DUNE'S wideband beam offers more oscillation information in it's spectral shape than shown here.*

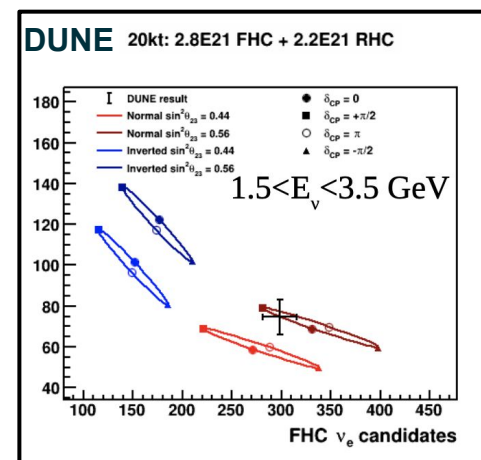
L = 295 km



L = 810 km

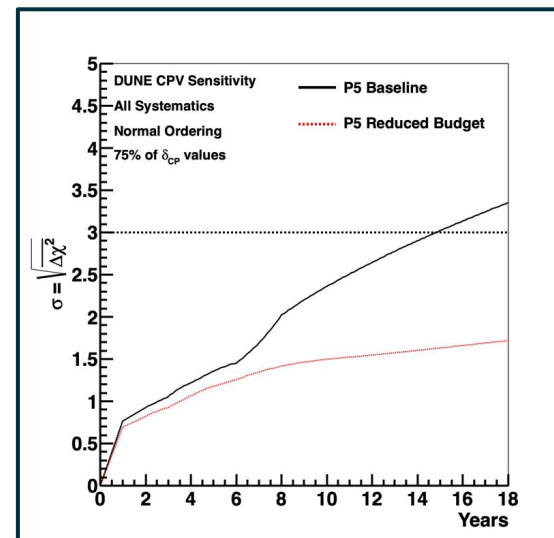
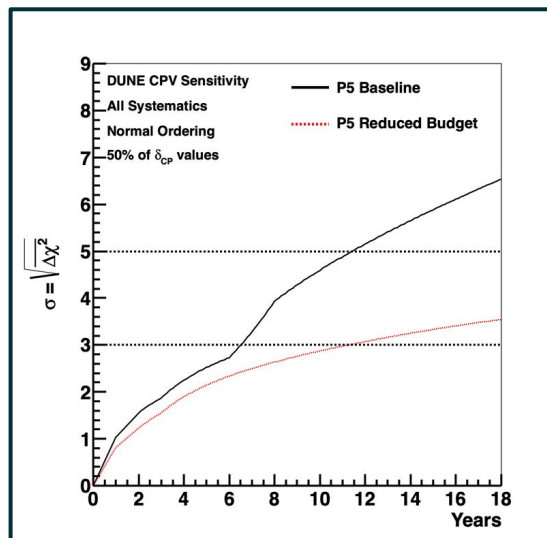
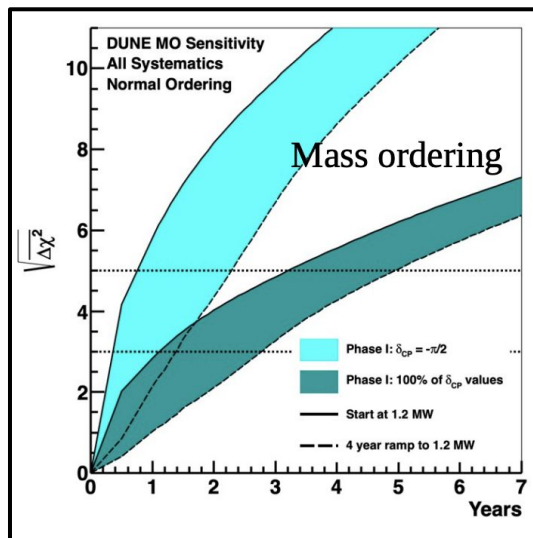


L = 1300 km



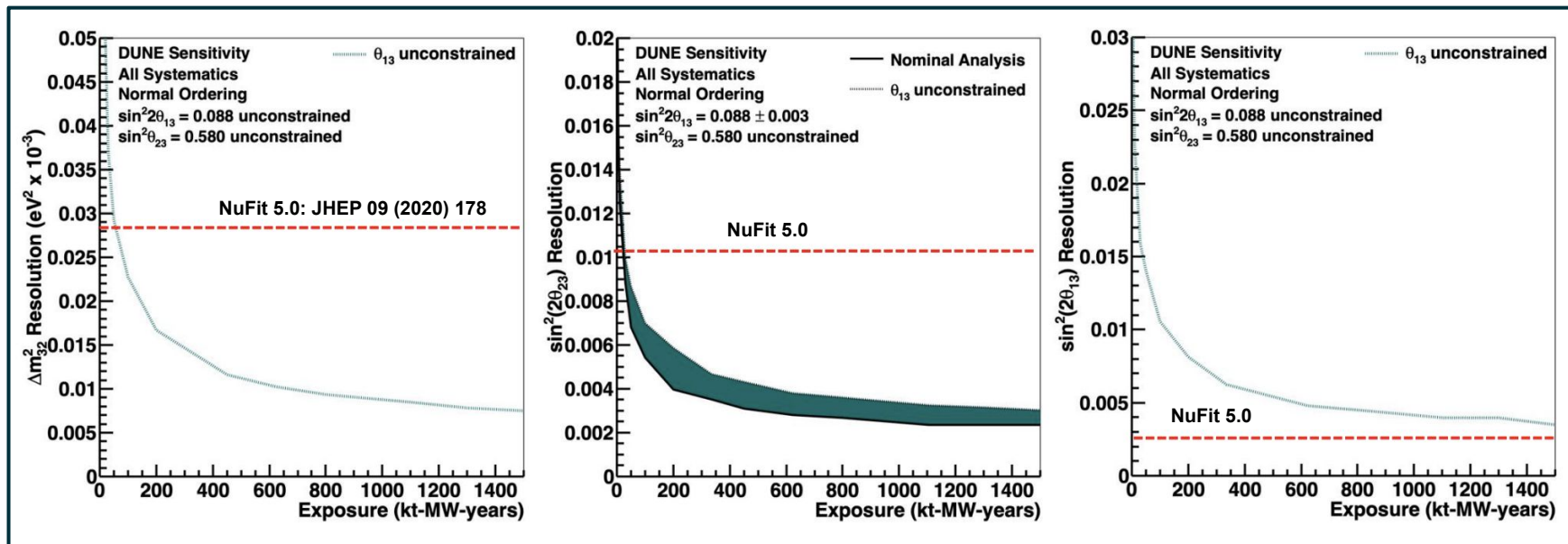
# DUNE: Mass Ordering and $\delta_{CP}$

- DUNE will measure the mass ordering ( $>5\sigma$ ) within first few years of coming online
- No mass ordering  $\leftrightarrow \delta_{CP}$  ambiguity paves the way for CPV discovery potential
  - In favorable budget scenario, P5 recommended staging scenario enables DUNE have CPV measurement potential at  $>5\sigma$  ( $>3\sigma$ ) for 50% (75%) of true  $\delta_{CP}$  values



# DUNE: Bringing Precision to PMNS

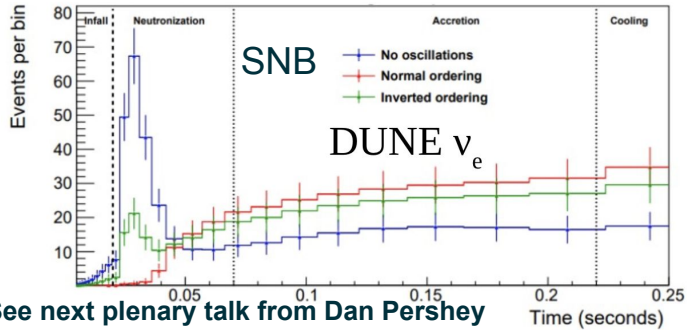
- DUNE will also greatly improve constraints on  $\Delta m^2_{32}$  and  $\sin^2(2\theta_{23})$ 
  - Electron neutrino appearance will also constrain  $\sin^2(\theta_{23}) \rightarrow$  octant sensitivity
- Competitive precision on  $\sin^2(2\theta_{13})$  with reactors in the long term



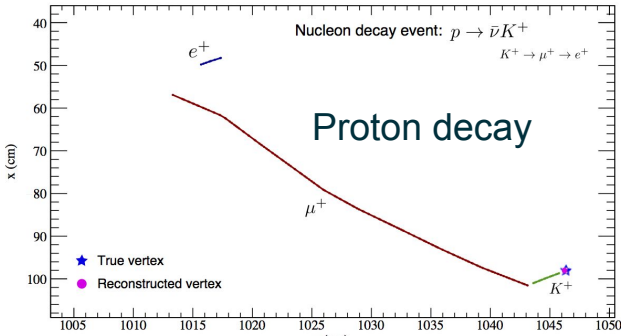
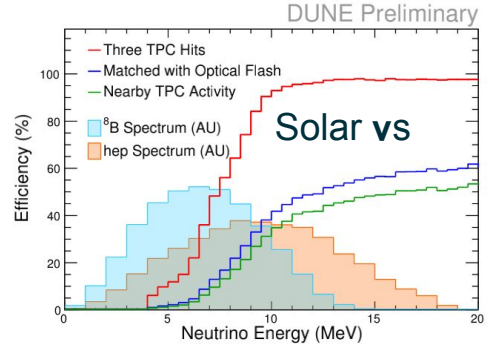
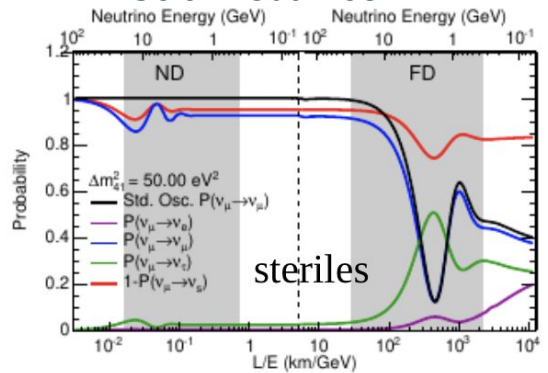
# Beyond 3-Flavor Beam Oscillations

- DUNE has a rich physics program that goes beyond 3-flavor beam oscillations:
  - Supernovae neutrino burst (SNB) sensitivity
  - Nucleon decay
  - Atmospheric neutrinos
  - Sterile neutrino searches
  - More BSM
  - Solar neutrinos

**DUNE Low Energy Physics with Solar and Supernova Neutrinos**  
 G. Sinev, Thursday @ 4:20pm MT, "Supernova & Solar Neutrinos"



See next plenary talk from Dan Pershey



**Baryon Number Violation Searches Using the DUNE Far Detector, J. Barrow**  
 Wednesday @ 2:30pm MT, "Proton Decay"

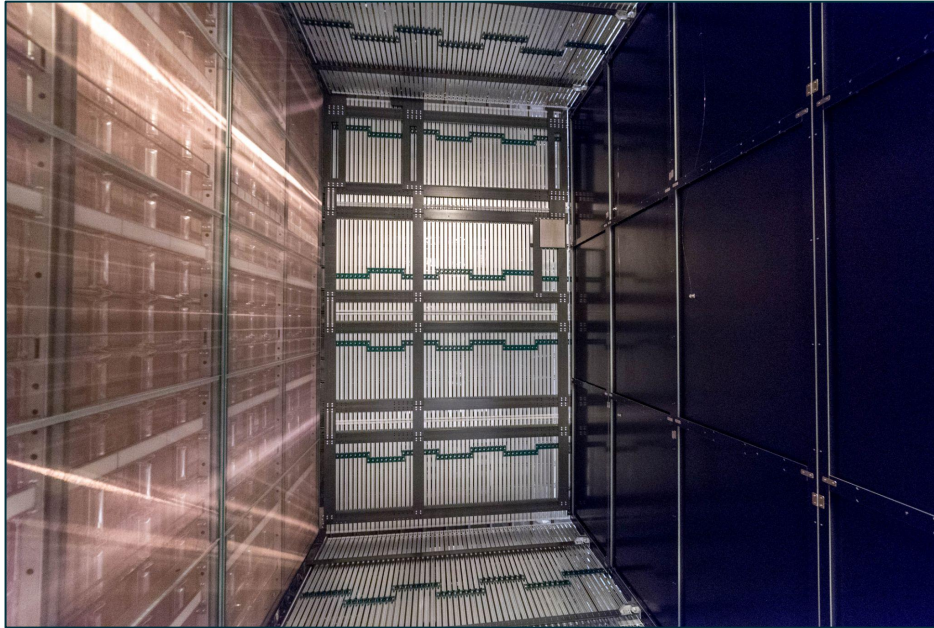
# Far Site Excavation Complete

- Excavation of LBNF caverns at SURF completed in the beginning of 2024!
- On track to have FD1 operational by 2029 and FD2 by 2031

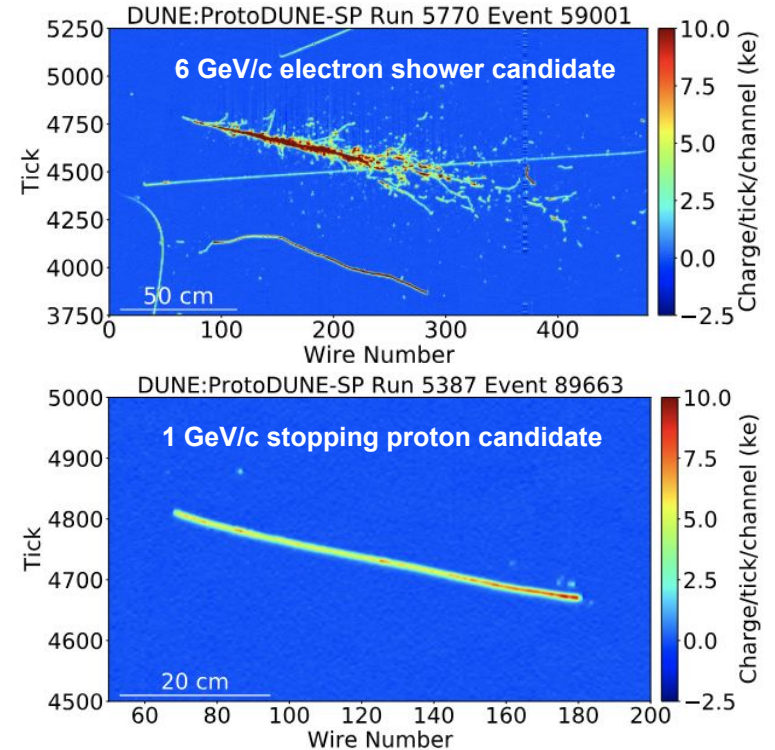




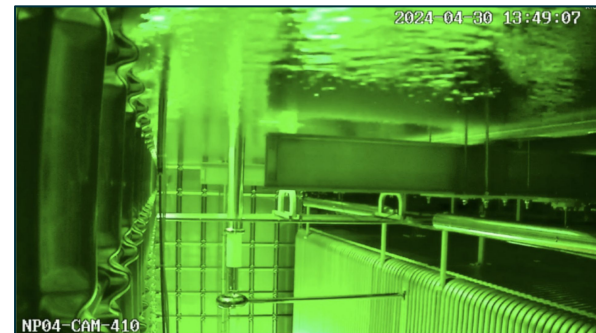
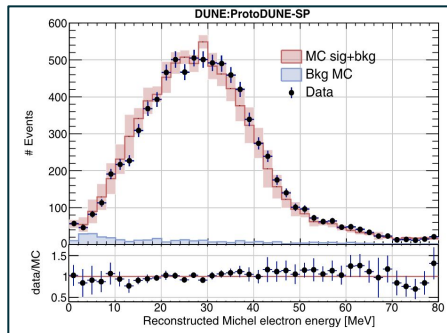
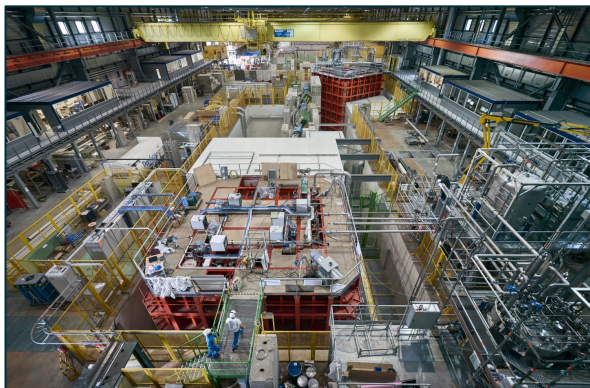
- 800 ton (1:25) FD prototypes with full scale components at CERN neutrino platform.



single phase / horizontal drift protoDUNE detector



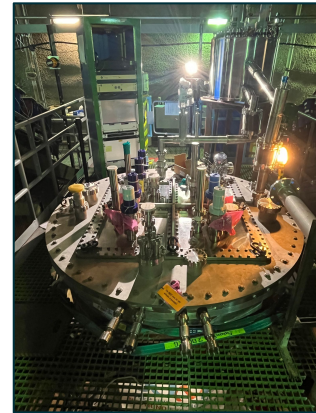
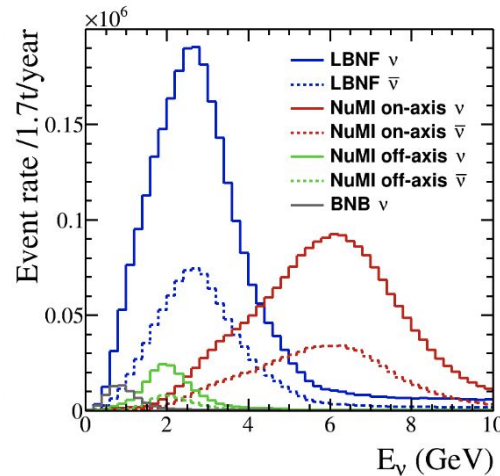
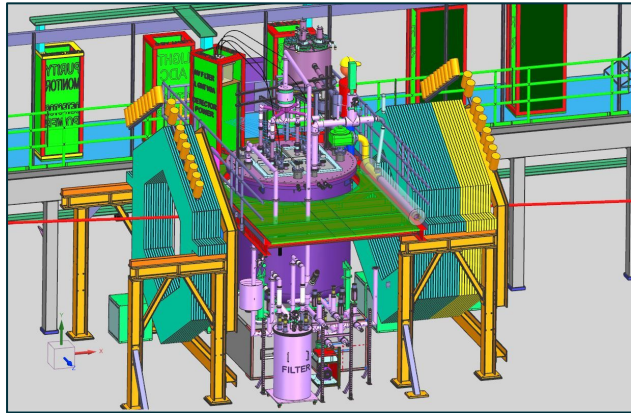
- 800 ton (1:25) FD prototypes with full scale components at CERN neutrino platform.
  - ProtoDUNE-SP → ProtoDUNE-HD (FD module 1). Test beam Run1 in 2018\*
  - ProtoDUNE-DP → ProtoDUNE-VD (FD module 2).
- \*Yielding publications and thesis, with more in the pipeline
- ProtoDUNE-HD is gearing up for a 2nd run. Filled with LAr April 30, 2024.
- After run, move LAr to ProtoDUNE-VD for operations



# The 2x2 Demonstrator



- Demonstration of ND-LAr design in reconstructing neutrino interactions
- 2x2 array of 1.2 x 0.6 x 0.6 m<sup>3</sup> modules containing >300K pixel channels
- @ Fermilab underground facility between repurposed MINERvA planes
- Will measure neutrino interactions in the GeV-energy regime from the NuMI beam



**DUNE: ND-LAr and the 2x2 Demonstrator, K. Wood  
Tuesday @ 2:50pm MT, "Neutrino Oscillations"**

***DUNE has a very ambitious and exciting physics program, and the collaboration is working diligently towards bringing the experiment online in the early 2030s.***

- More details in many other talks at CoSSURF 2024:
  - *DUNE: ND-LAr and the 2x2 Demonstrator*, K. Wood, Tuesday @ 2:50pm MT, “Neutrino Oscillations”
  - *APEX Design and VD Technology for DUNE FD3*, W. Shi, Tuesday @ 4:20pm MT, “DUNE Phase II”
  - *SoLAR: a novel approach to multipurpose LArTPCs for neutrino physics*, D. Guffanti, Tuesday @ 4:40pm MT, “DUNE Phase II”
  - *The Theia Detector*, L. Pickard, Tuesday @ 5:00pm MT, “DUNE Phase II”
  - *A SURF Low Background Module (SLoMo)*, C. Jackson, Tuesday @ 5:20pm MT, “DUNE Phase II”
  - *ARIADNE Design and Technology for DUNE*, K. Mavrokoridis, Tuesday @ 5:40pm MT, “DUNE Phase II”
  - *Baryon Number Violation Searches Using the DUNE Far Detector*, J. Barrow, Wednesday @ 2:30pm MT, “Proton Decay”
  - *Overview of the DUNE Phase-II Program*, S. Gollapinni, Thursday @ 10:30am MT, “Plenary: Nuclear Astrophysics, Biology, DUNE Phase II”
  - *DUNE Low Energy Physics with Solar and Supernova Neutrinos*, G. Sinev, Thursday @ 4:20pm MT, “Supernova & Solar Neutrinos”
  - *Radiological Backgrounds in DUNE Far Detectors*, S. Westerdale, Thursday @ 4:40pm MT, “Supernova & Solar Neutrinos”
  - *Calibrating DUNE LArTPC Detectors Using Low-Energy Radioactive Decays*, M. Mooney, Thursday @ 5:00pm MT, “Supernova & Solar Neutrinos”

# Closing

***DUNE has a very ambitious and exciting physics program, and the collaboration is working diligently towards bringing the experiment online in the early 2030s.***

- More details in posters at CoSSURF 2024:
  - *Power Over Fiber for the DUNE Vertical Drift Photon Detection System*, D. Silverio
  - *A Novel Neutron-Based Calibration System for DUNE*, W. Johnson
  - *Quality Assurance for Potential Supernova Neutrino Detections with DUNE at SURF*, T. Rath
  - *Probing the Solar Neutrino Day/Night Effect*, M. Fodroci

# Thanks!

*January 2024 DUNE Collaboration Meeting @ CERN*

