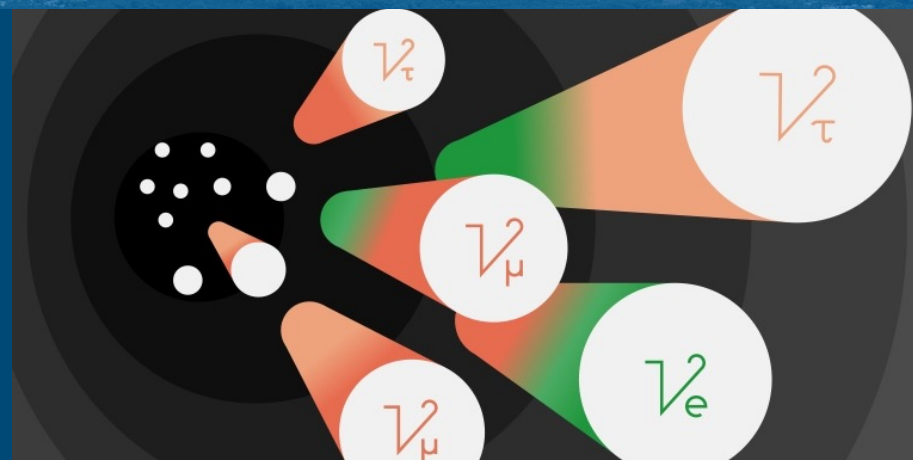


# NEUTRINOS AND CP VIOLATION



ZELIMIR DJURCIC

ARGONNE NATIONAL LABORATORY

UNIVERSITY OF NOVI SAD PHYSICS COLLOQUIM, APRIL 16, 2026.



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# Talk Overview

- Introduction to Neutrino Properties
- Example of Neutrino Experiment
- What have we learned so far?
- CP violation
- Long-baseline neutrino oscillation experiment DUNE
- Other Sources of neutrino CP violation
- Summary





# INTRODUCTION



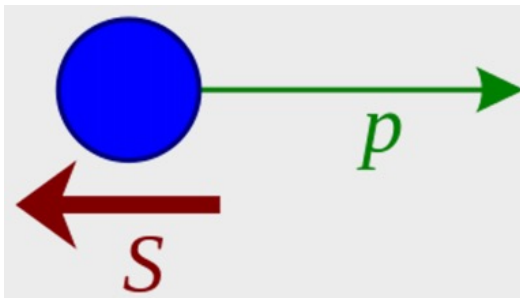
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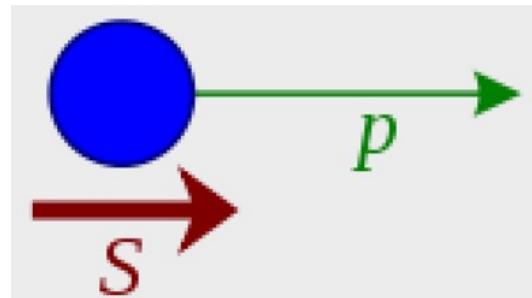


# What are Neutrinos?

- Spin 1/2 fermions partnered with a charged lepton.
- What have we learned about neutrinos:
  - Left-handed weak interactions
  - Three flavors ( $\nu_\alpha$  with  $\alpha = e, \mu, \tau$ )
  - Very light masses ( $m_i$  with  $i = 1, 2, 3$ )
  - Mixing between mass and flavor states.



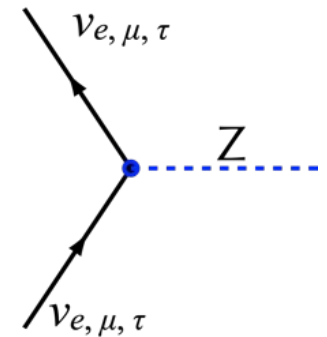
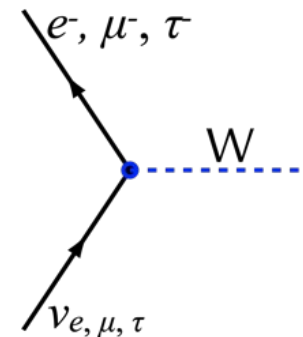
Left-Handed Neutrino



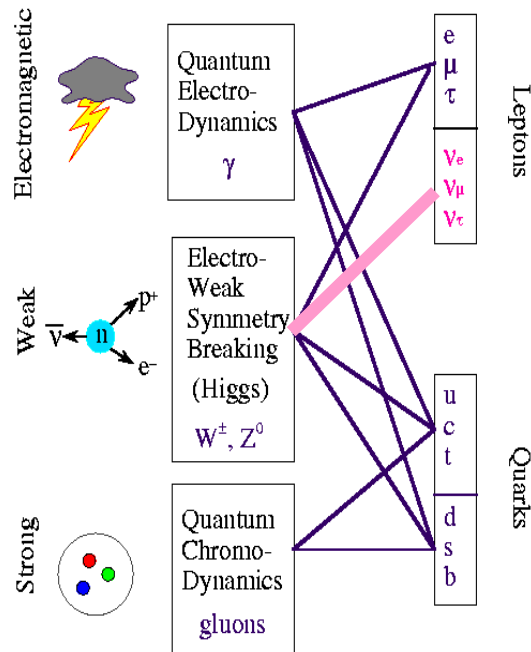
Right-Handed Anti-Neutrino

## Standard Model of Elementary Particles

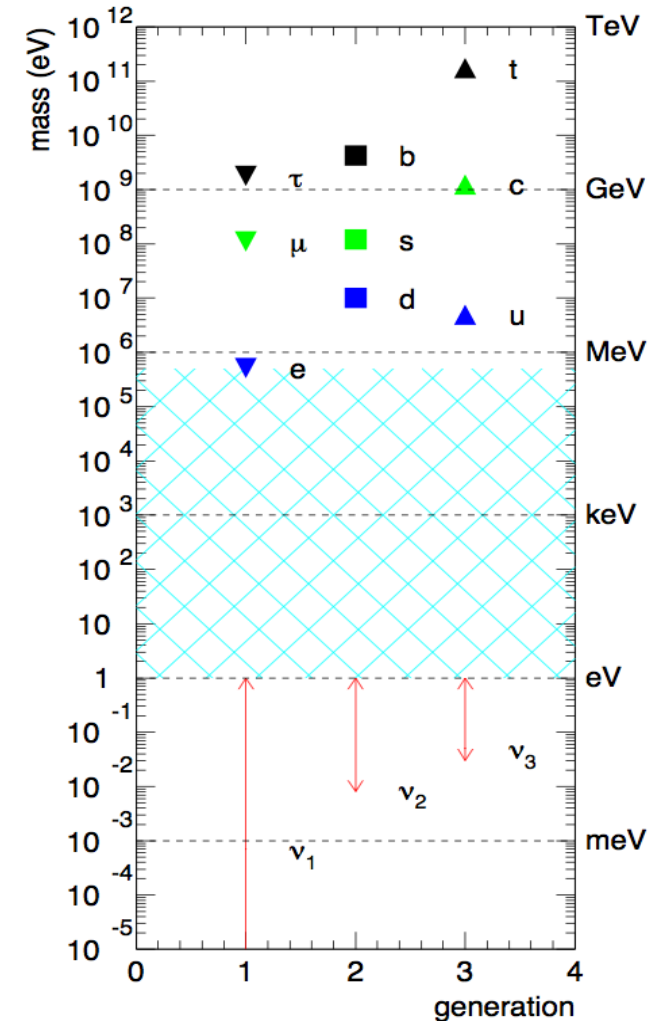
| three generations of matter (fermions) |                                                                 |                                                                  |                                                                   |                    |                                                | interactions / force carriers (bosons) |                                               |
|----------------------------------------|-----------------------------------------------------------------|------------------------------------------------------------------|-------------------------------------------------------------------|--------------------|------------------------------------------------|----------------------------------------|-----------------------------------------------|
| I                                      |                                                                 |                                                                  | II                                                                |                    |                                                | III                                    |                                               |
| mass<br>charge<br>spin                 | $\approx 2.2 \text{ MeV}/c^2$<br>$\frac{2}{3}$<br>$\frac{1}{2}$ | $\approx 1.28 \text{ GeV}/c^2$<br>$\frac{2}{3}$<br>$\frac{1}{2}$ | $\approx 173.1 \text{ GeV}/c^2$<br>$\frac{2}{3}$<br>$\frac{1}{2}$ | $0$<br>$0$<br>$1$  | $\approx 124.97 \text{ GeV}/c^2$<br>$0$<br>$0$ | $0$<br>$0$<br>$1$                      | $\approx 91.19 \text{ GeV}/c^2$<br>$0$<br>$1$ |
|                                        | u<br>up                                                         | c<br>charm                                                       | t<br>top                                                          | g<br>gluon         | H<br>higgs                                     |                                        |                                               |
|                                        | d<br>down                                                       | s<br>strange                                                     | b<br>bottom                                                       | $\gamma$<br>photon |                                                |                                        |                                               |
|                                        | e<br>electron                                                   | $\mu$<br>muon                                                    | $\tau$<br>tau                                                     | Z<br>Z boson       |                                                |                                        |                                               |
|                                        | $\nu_e$<br>electron neutrino                                    | $\nu_\mu$<br>muon neutrino                                       | $\nu_\tau$<br>tau neutrino                                        | W<br>W boson       |                                                |                                        |                                               |



# Standard Model of Particle Physics

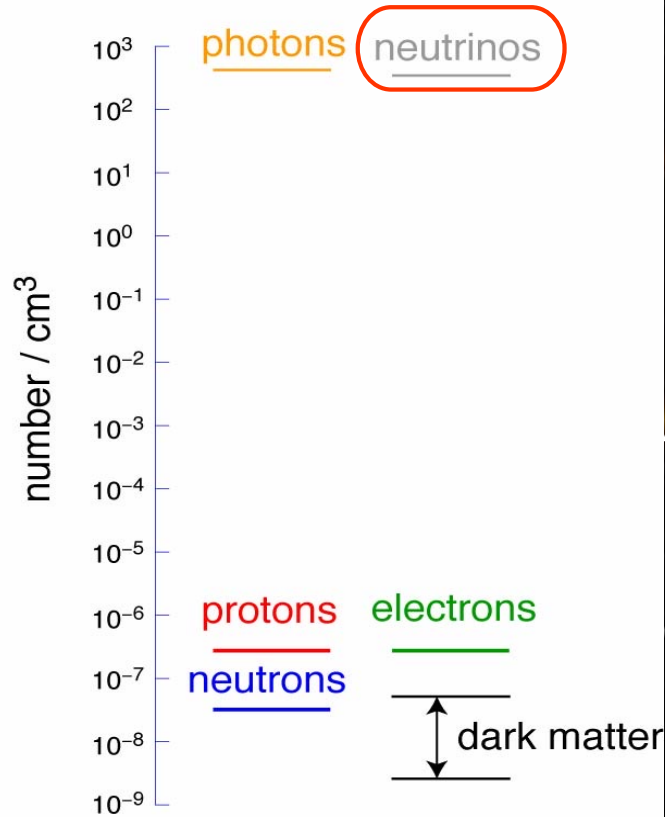


- **Neutrino Mass?**
  - Unlikely to come from a linear coupling between the particle and the Higgs boson field.



# Neutrinos Are Special

## The Particle Universe



- The most abundant matter particles in the Universe after photons
  - 336 cosmic neutrinos/cm<sup>3</sup>
  - (comparable to 411 CMB photons/cm<sup>3</sup> ).
- Neutrinos play a crucial role
  - energy production in the Sun
  - nucleo-synthesis: BBN, SN.
- Responsible for generating the baryon asymmetry of the Universe?
  - Matter dominance.



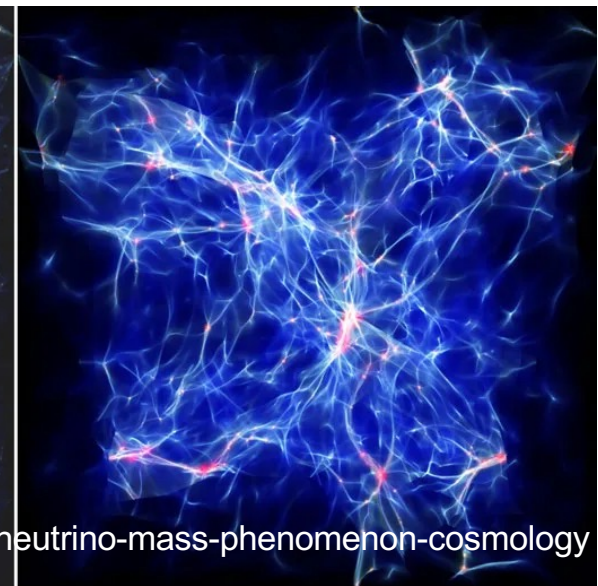
# Neutrinos and the Universe

- Neutrinos profoundly impact the evolution of the universe.
  - Even their extremely tiny masses are expected to have a definite imprint on the universe at the largest scales.

$m_\nu = 0$  eV



$m_\nu > 0$  (eV's range)

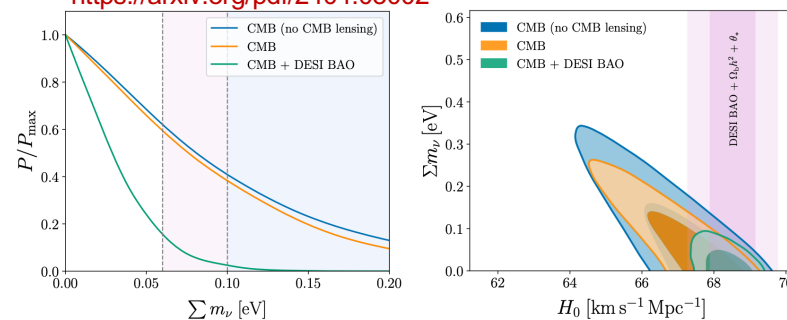


<https://www.sciencenews.org/article/neutrino-mass-phenomenon-cosmology>

Neutrino mass curbs the formation of fine details of the cosmic web.

- Measurement of neutrino mass through cosmological observations
  - Sum of neutrino masses.

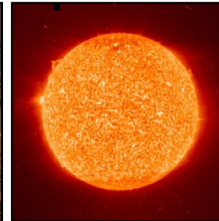
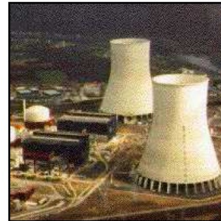
<https://arxiv.org/pdf/2404.03002>



# Neutrino Sources

- Neutrinos come from “everywhere”.

Nuclear Reactors



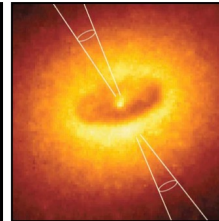
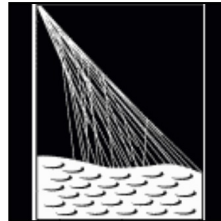
Sun

Particle Accelerators



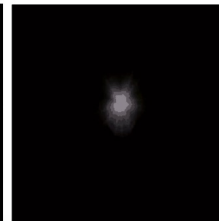
Supernovae  
(star collapse)

Earth's Atmosphere  
(Cosmic Rays)



Astrophysical Sources

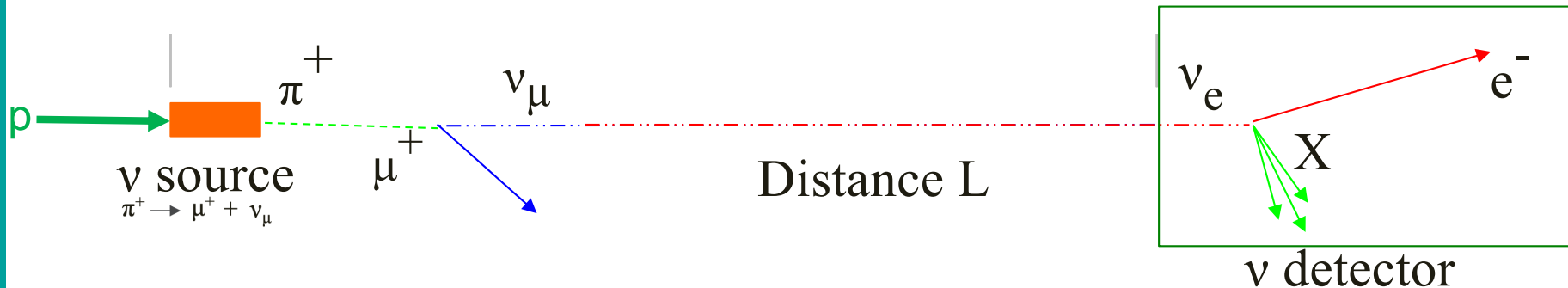
Earth's Crust  
(Natural  
Radioactivity)



Big Bang  
( $336 \text{ v/cm}^3$ )

## How do we know neutrinos are “massive”?

- It has been observed that neutrinos change a flavor when travelling over a distance.

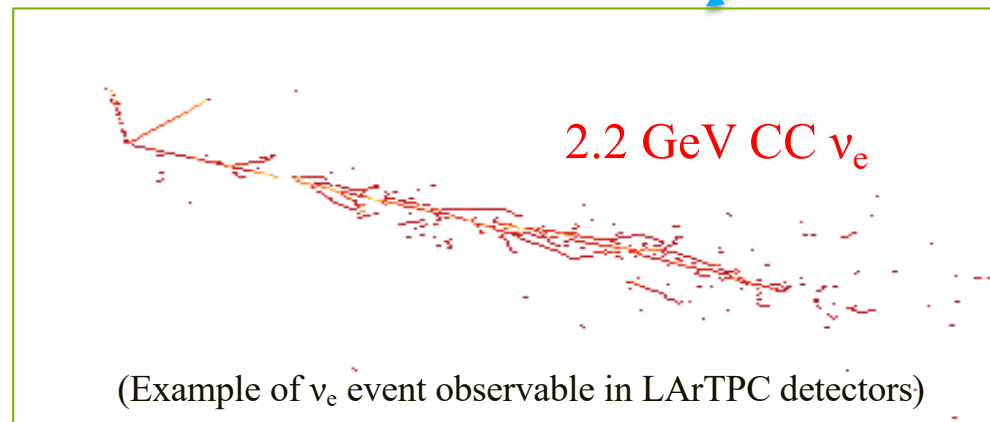
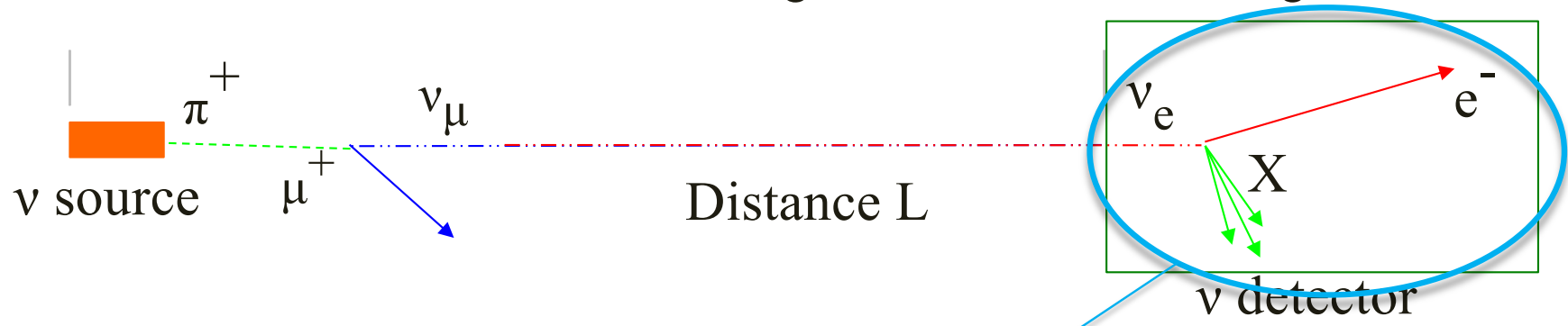


- Explained by neutrino mixing:
  - Neutrinos have (different) masses:  $m_1, m_2, m_3$ .
  - Mass states ( $\nu_1, \nu_2, \nu_3$ ) and flavor states ( $\nu_e, \nu_\mu, \nu_\tau$ ) (objects that participate in weak interaction) are not identical.
  - Such behavior may be explained by quantum mechanics, if the flavor states ( $\nu_e, \nu_\mu, \nu_\tau$ ) are a linear combinations of the mass states ( $\nu_1, \nu_2, \nu_3$ ).

$$|\nu_\alpha\rangle = \sum_{k=1}^n U_{\alpha k} |\nu_k\rangle \quad (\alpha = e, \mu, \tau)$$

## How do we know neutrinos are “massive”?

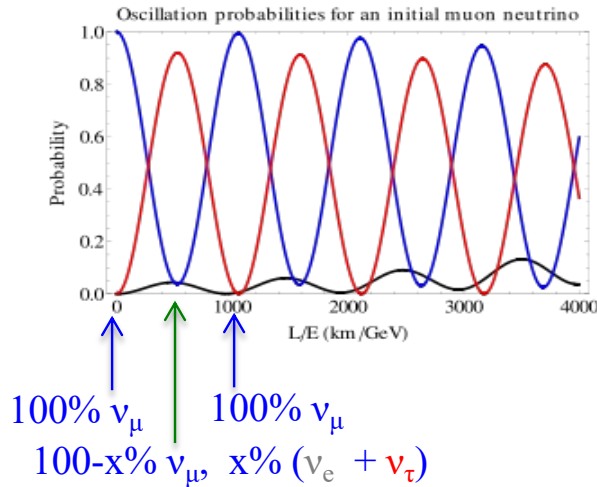
- It has been observed that neutrinos change a flavor when travelling over a distance.





# Neutrino Oscillation

- Spontaneous change of neutrino flavor is what we call a neutrino oscillation.



-We know there are at least three neutrinos out there.

-With three known neutrinos the mixing of flavor and mass eigenstates is written in a form of so-called PMNS (Pontecorvo–Maki–Nakagawa–Sakata) matrix:

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

Example: Assume only two neutrinos  $\nu_1, \nu_2$  mix

$$|\nu_\mu(t)\rangle = -\sin \theta |\nu_1\rangle + \cos \theta |\nu_2\rangle$$

$L$  is the distance from point of creation of neutrino beam to detection point

$\Delta m^2$  is the difference of squared mass of the two neutrino states

$$P_{\text{osc}} = \sin^2 2\theta \sin^2 1.27 \Delta m^2 [\text{eV}^2] \left[ \frac{L[\text{km}]}{E[\text{GeV}]} \right]$$

$\theta$  is the mixing angle

$E$  is the energy of the neutrino beam

# Neutrino Oscillations

- Three neutrino mixing:

$$|\nu_\alpha\rangle = \sum_{i=1}^3 U_{\alpha i} |\nu_i\rangle$$

Pontecorvo, Maki, Nakagawa, Sakata (PMNS) 3x3 mixing matrix

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

$\theta_{23}$



Atmospheric + LBL acc.

$\theta_{23} \approx 45^\circ$   
Maximal?

$\theta_{13}, \delta_{CP}$



SBL reactors + LBL acc.

$\theta_{13} \approx 9^\circ$   
 $\delta_{CP} ?$

$\theta_{12}$



Solar + LBL reactors

$\theta_{12} \approx 33^\circ$

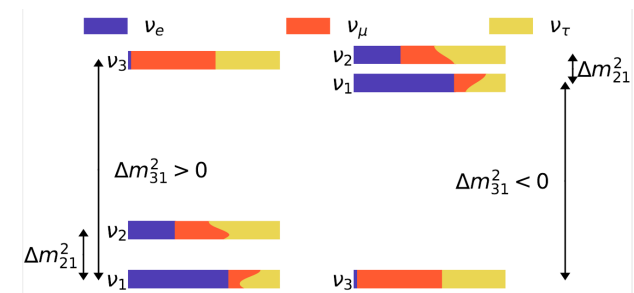
Current precision oscillation parameters ~6-20 %

Oscillation probability

$$P_{\nu_\alpha \rightarrow \nu_\beta}(L, E) = \delta_{\alpha\beta} - 4 \sum_{i>j} \text{Re} [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin^2 \left( \frac{\Delta m_{ij}^2 L}{4E} \right) - 2 \sum_{i>j} \text{Im} [U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^*] \sin \left( \frac{\Delta m_{ij}^2 L}{2E} \right)$$

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

Neutrino mass spectrum



Normal Ordering

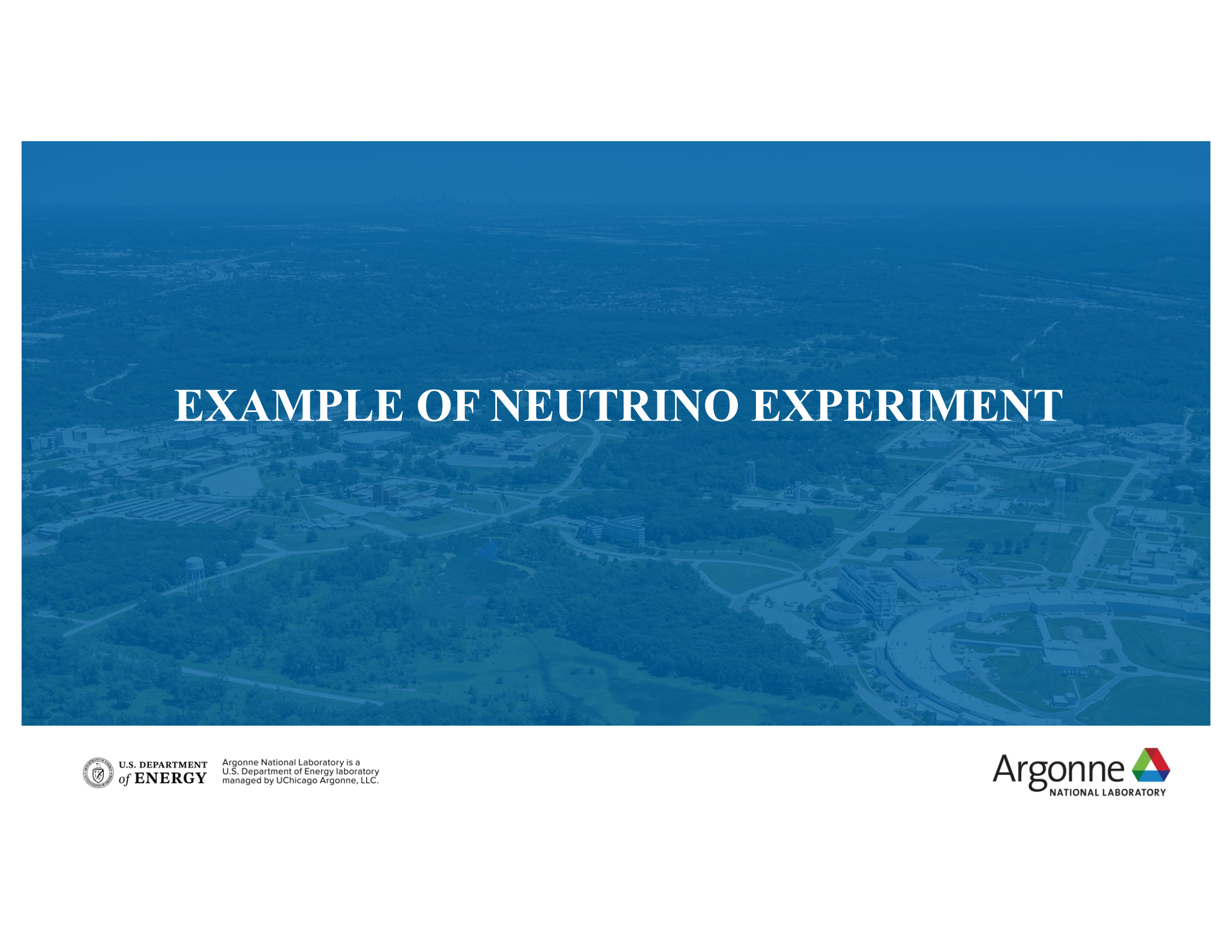


Inverted Ordering

Solar + atmospheric + LBL reactor + LBL accelerator

$$\Delta m_{21}^2 \approx 7.5 \times 10^{-5} \text{ eV}^2$$

$$|\Delta m_{31}^2| \approx 2.5 \times 10^{-3} \text{ eV}^2 \quad \text{Sign?}$$

An aerial photograph of a large campus, likely Argonne National Laboratory, with a blue overlay. The image shows various buildings, roads, and green spaces. The text "EXAMPLE OF NEUTRINO EXPERIMENT" is centered in white.

# EXAMPLE OF NEUTRINO EXPERIMENT



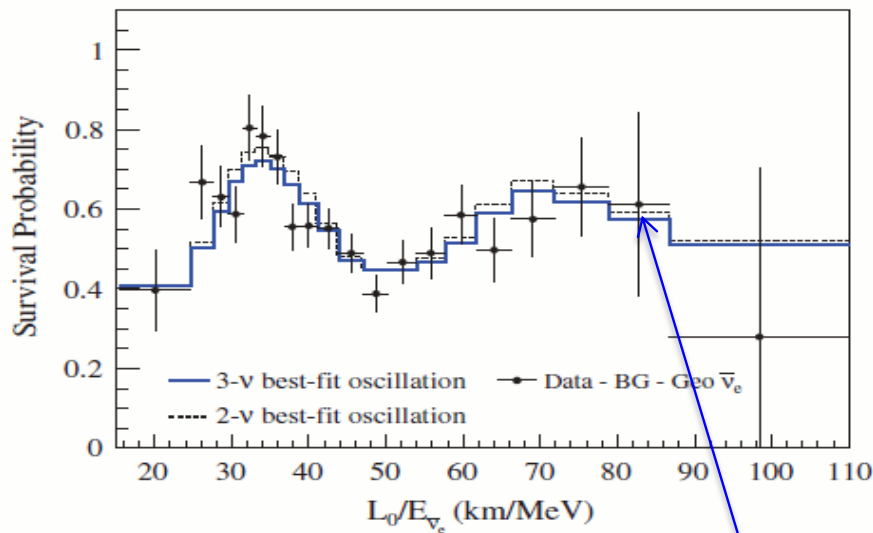
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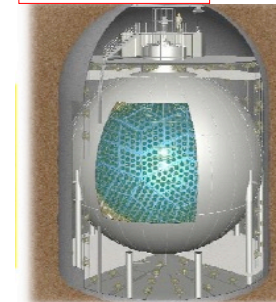
# Example of Neutrino Experiment

- KamLAND experiment: reactor anti-neutrino disappearance experiment  
-demonstrated neutrino mixing and provided precise measurement of  $\Delta m_{21}^2$ .



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \Delta_{21} - \sin^2 2\theta_{13} (\cos^2 \theta_{12} \sin^2 \Delta_{31} + \sin^2 \theta_{12} \sin^2 \Delta_{32})$$

(becomes 2-v oscillation if  $\theta_{13} = 0!$  )

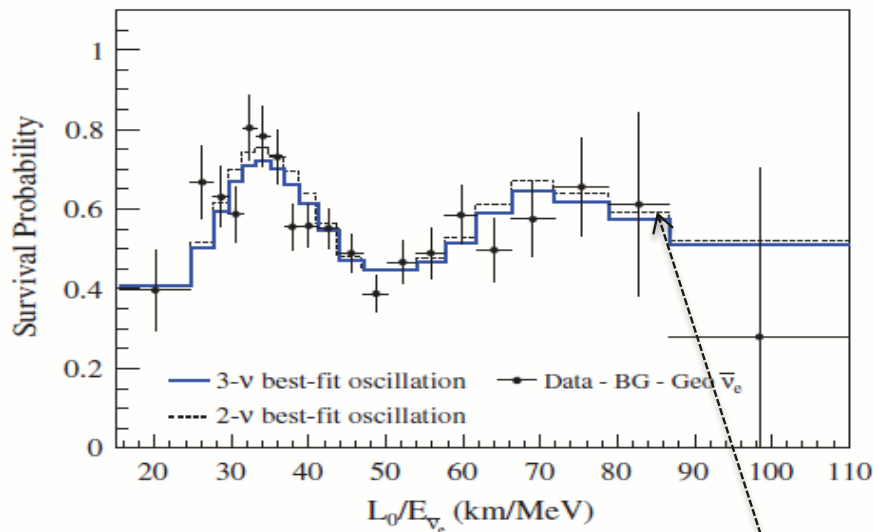


- My PhD thesis
- radio-assay
- NAA
- oscillation analysis



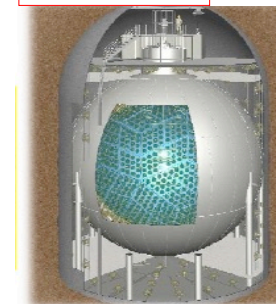
# Example of Neutrino Experiment

- KamLAND experiment: reactor anti-neutrino disappearance experiment  
-demonstrated neutrino mixing and provided precise measurement of  $\Delta m_{21}^2$ .



$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \sin^2(1.27 \Delta m_{21}^2 L[m] / E_\nu[MeV])$$

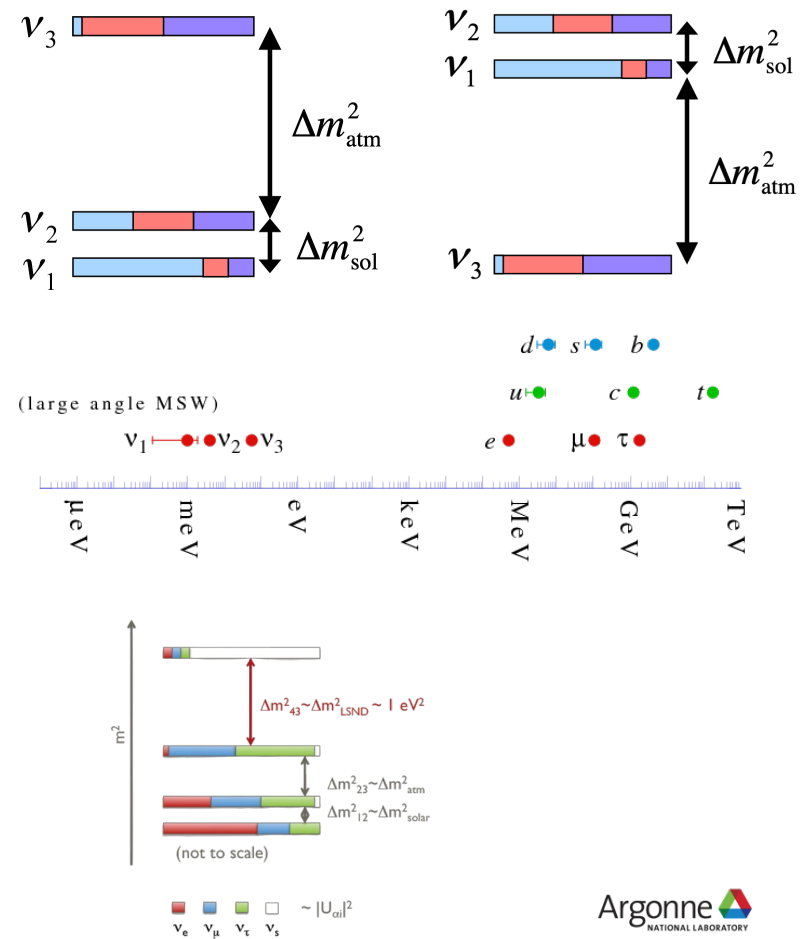
(becomes 2-v oscillation if  $\theta_{13} = 0!$  )



- My PhD thesis
- radio-assay
- NAA
- oscillation analysis

# Open Questions in Neutrino Physics

- What is the absolute **neutrino mass** scale?
- Are neutrinos their own antiparticle? **Dirac** or **Majorana**?
- Why are neutrinos much lighter than the other fermions?
- What is the neutrino **mass ordering**?
- Do neutrinos and antineutrinos oscillate differently? Do neutrinos **violate CP**?
- Are there any **sterile neutrino** states? If so, what are their masses?
- Is our **three-flavor** picture of oscillations complete?

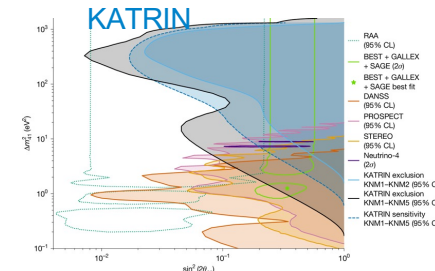


# Recent Neutrino Results

- **Direct neutrino-mass** measurement based on 259 days of KATRIN data

*Science* 388 (2025) 6743

- $m_\nu < 0.45$  eV at 90%CL (best fit value  $m_\nu^2 = -0.14^{+0.13}_{-0.15}$  eV<sup>2</sup>)



- **Sterile-neutrino** searches

- MicroBooNE - *Nature* 648, 64–69 (2025)
- KATRIN - *Nature* 648, 70–75 (2025)

- Observation of an **ultra-high-energy cosmic neutrino** with KM3NeT

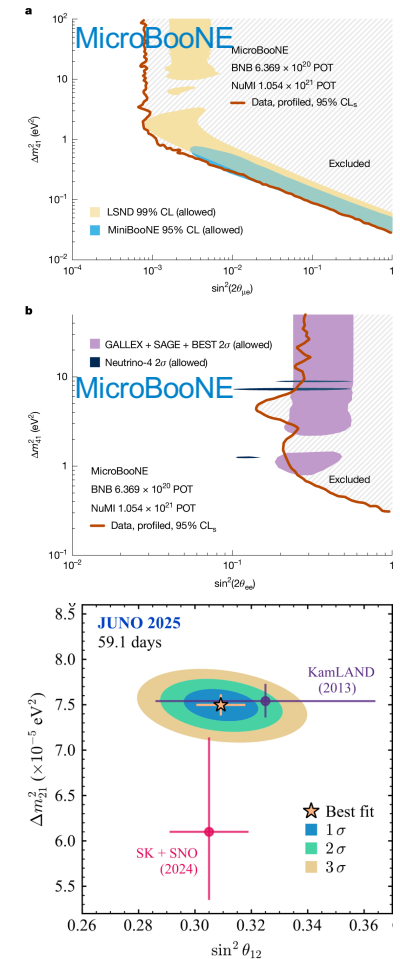
*Nature* 638, 376-382 (2025)

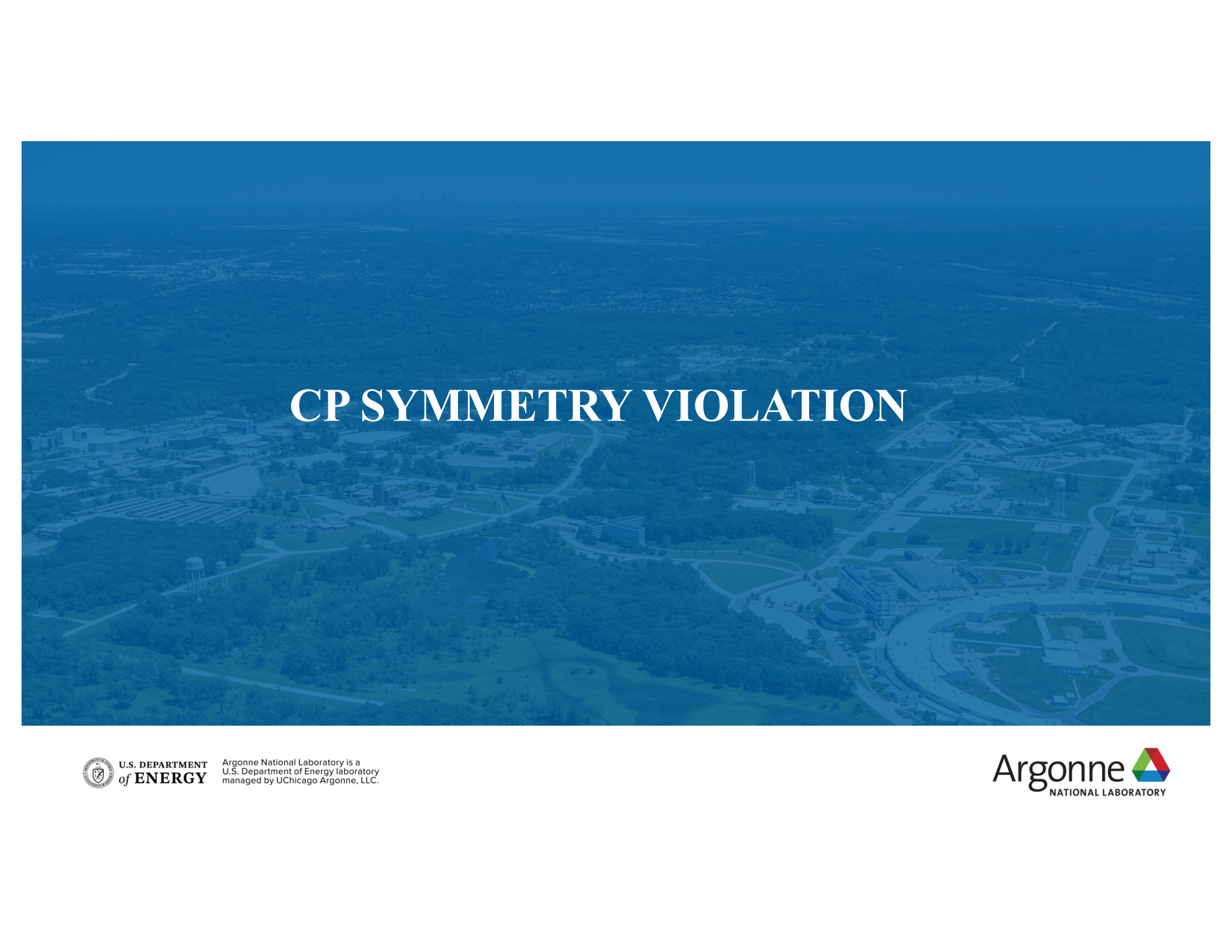
- **Constraints** on Neutrino Physics from **DESI** DRD2 BAO and DR1 Full Shape

*Phys.Rev.D* 112 (2025) 8, 083513, arXiv:2507.12401, *Phys.Rev.Lett.* 135 (2025) 8, 081003

- **Neutrino oscillations**

- First measurement of reactor neutrino oscillations at **JUNO**  
*arXiv:2511.14593*
- **Joint neutrino oscillation analysis** from the **T2K** and **NOvA** experiments  
*Nature* 646, 818-824 (2025)





# CP SYMMETRY VIOLATION



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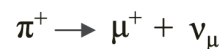
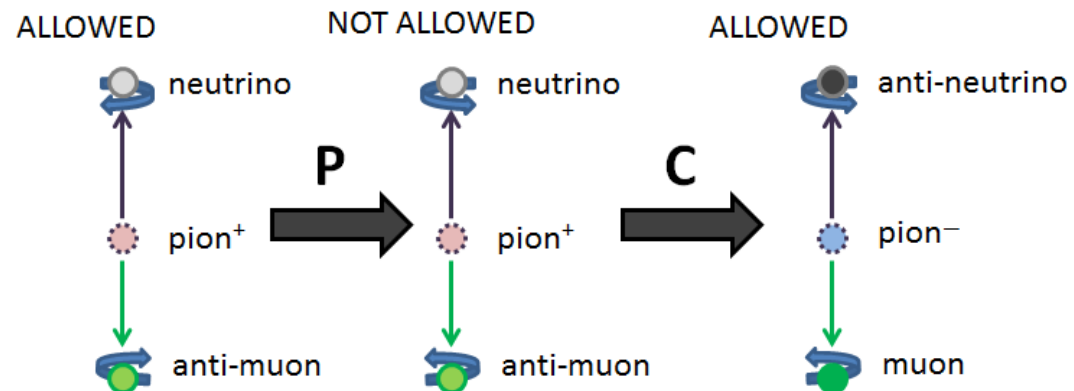
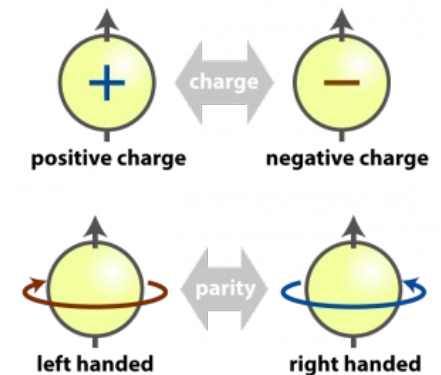
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# What is the CP symmetry?

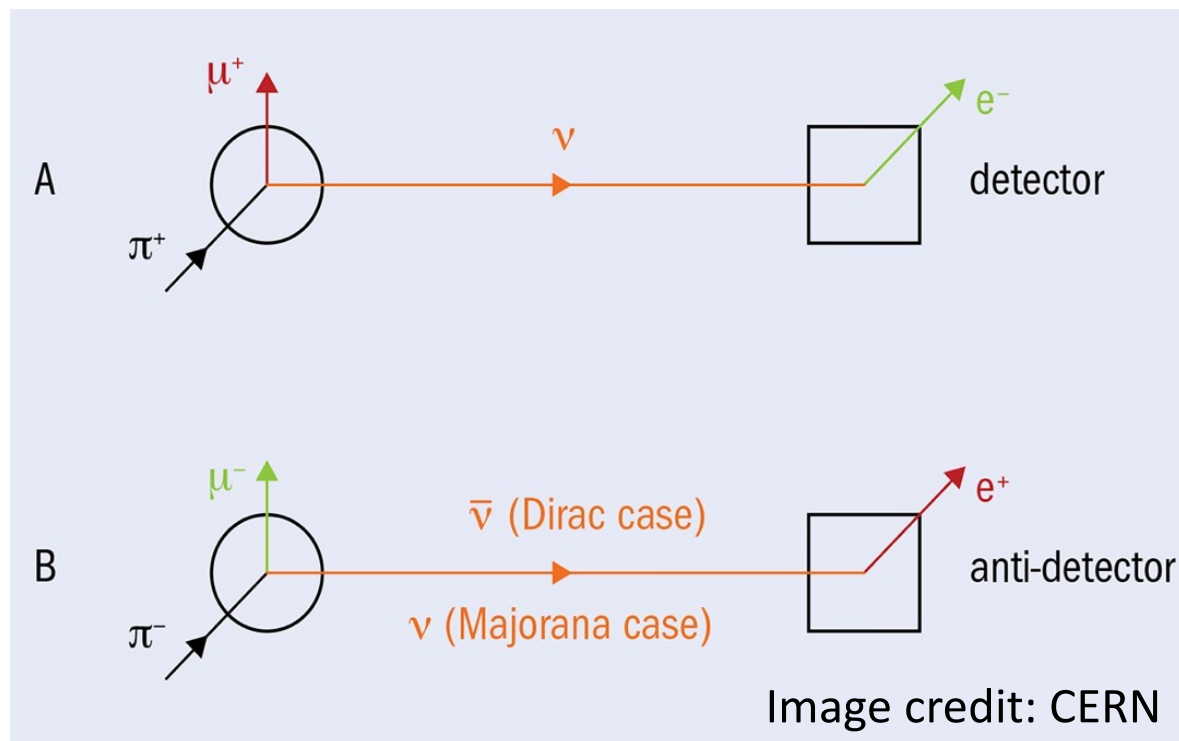
- The CP symmetry is the product of two transformations
  - C for charge conjugation
  - P for parity.
- A process in which all particles are exchanged with their antiparticles equivalent to the mirror image of the original process.
- Neutrino - antineutrino?



M. Strassler 2013

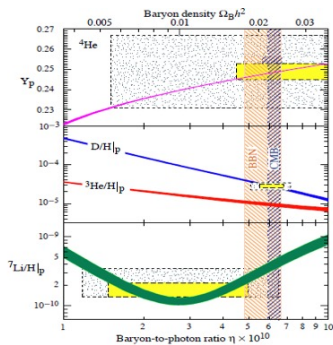
## Test CP violation with neutrinos

- The pursuit for leptonic CP violation is based on comparing the rates for two CP-mirror-image processes.



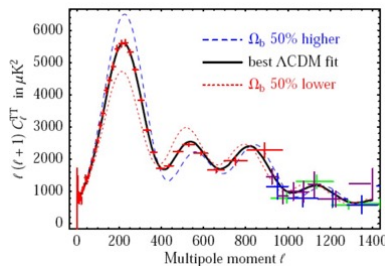
# Baryon Asymmetry of the Universe

- The baryon asymmetry question is also known as the matter-antimatter asymmetry problem
- The observed imbalance in baryonic matter (the type of matter experienced in everyday life) and antibaryonic matter in the observable universe.



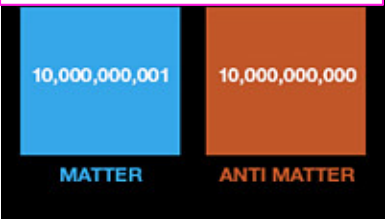
- The abundances of the primordial elements and the height of the peaks of the CMB power spectrum depend on the ratio of baryons-to-photons

$$\eta_B = (6.11 \pm 0.19) \times 10^{-10}$$

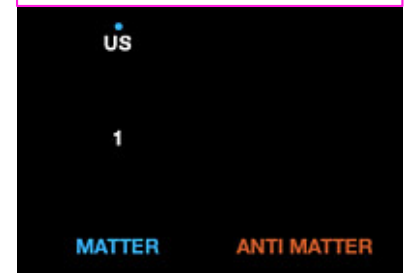


- Neutrinos might help us to understand the striking feature of the Universe: only matter, virtually no anti-matter!
- Did neutrinos stop the early universe from annihilating itself?

Big Bang produced slightly different amounts of matter and anti-matter, with some tiny asymmetry?

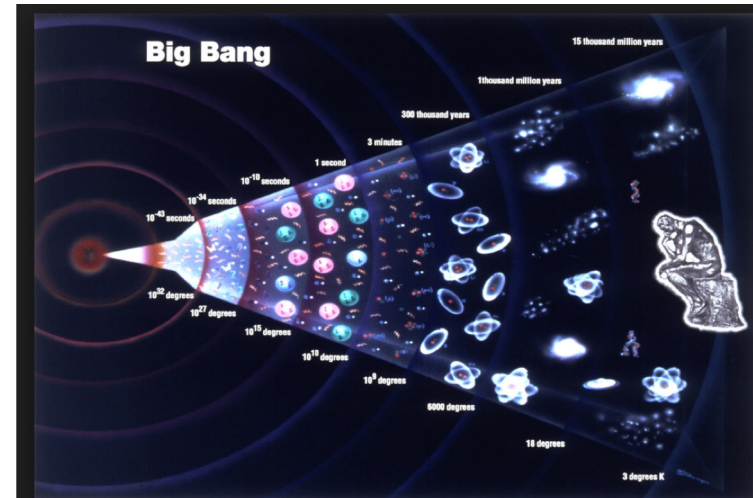
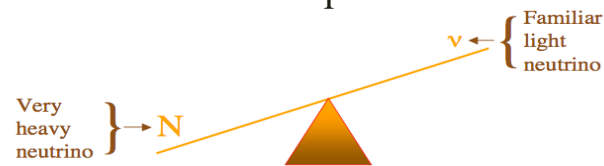


Then matter and anti-matter annihilated leaving just us?  
Where did  $10^{10}$  baryons go?



# Why is neutrino CP violation important?

- Observation of CP-violation would make it more likely that the baryon-antibaryon asymmetry of the universe arose through leptogenesis.
- The theory of leptogenesis linked to the see-saw theory  
-As consequence the light neutrinos have GUT-scale partners.



See for example:  
Phys. Rev. D 108, L101302 (2023)

- The matter-antimatter asymmetry of the universe may be explained through CP-violating decays of heavy partners  
-Produce a state with unequal numbers of Standard Model leptons and antileptons.

$$N \rightarrow L^- + \phi^+ \quad \text{and} \quad N \rightarrow L^+ + \phi^- \quad (\phi^+, \phi^- \text{ - Standard-Model Higgs})$$

- The Standard Model processes convert such a state into the world around us with an unequal number of baryons and antibaryons (so-called Baryogenesis).
- It is thought that CP-violation would be very unlikely to appear in the heavy sector without happening in light neutrinos.



# PROBING CP VIOLATION WITH NEUTRINOS



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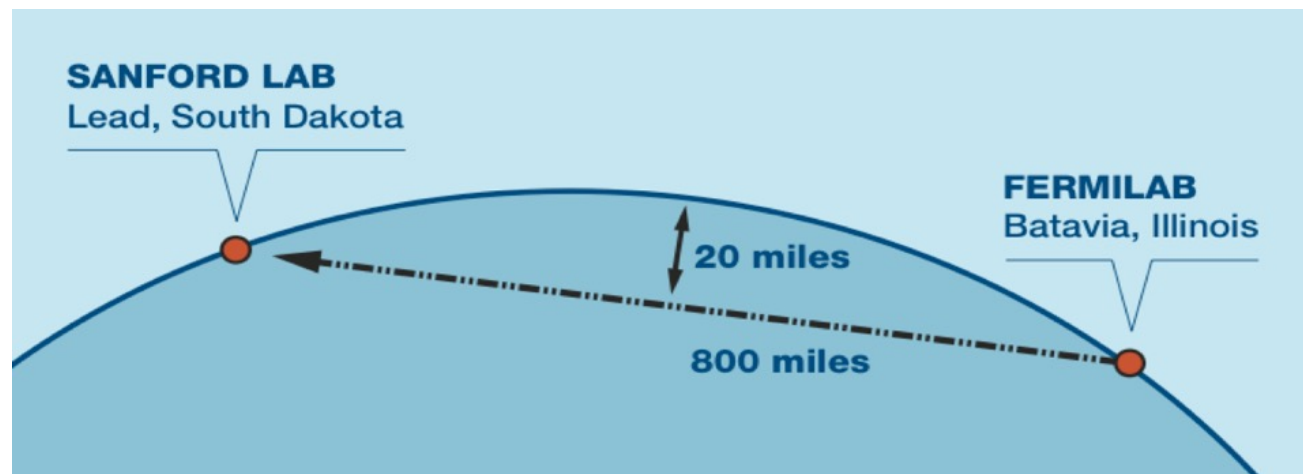
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## Probing CP violation with neutrinos

- The observation of CP violation in the lepton sector would be a strong indication (even if not a proof) of leptogenesis as the origin of the baryon asymmetry.
- CP violation would be measured as a difference of neutrino and anti-neutrino oscillation probabilities.

$$P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin \delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$



# Neutrino Oscillations at Long-Baseline

- $\nu_\mu$  Disappearance Probability

$$P(\nu_\mu \rightarrow \nu_\mu) \simeq 1 - 4 \cos^2 \theta_{13} \sin^2 \theta_{23} [1 - \cos^2 \theta_{13} \sin^2 \theta_{23}] \sin^2 \Delta_{3i}$$

$$\simeq 1 - \sin^2 2\theta_{23} \sin^2 \Delta_{3i}$$

- $\nu_e$  Appearance Probability

See for example: Nunokawa, Parke, Valle,  
 "CP Violation and Neutrino Oscillations",  
 Prog. Part. Nucl. Phys. 60 (2008) 338-402, or arXiv:0710.0554 [hep-ph]

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 \theta_{23} \sin^2 2\theta_{13} \frac{\sin^2(\Delta_{31} - aL)}{(\Delta_{31} - aL)^2} \Delta_{31}^2$$

$$+ \cos \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos \Delta_{32} \left( \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \right) \left( \frac{\sin(aL)}{aL} \Delta_{21} \right)$$

$$- \sin \delta \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \sin \Delta_{32} \left( \frac{\sin(\Delta_{31} - aL)}{(\Delta_{31} - aL)} \Delta_{31} \right) \left( \frac{\sin(aL)}{aL} \Delta_{21} \right)$$

$$+ \cos^2 \theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(aL)}{(aL)^2} \Delta_{21}^2,$$

$$\Delta_{ij} = \Delta m_{ij}^2 L / 4E_\nu$$

CP-violation parameter  $\delta_{CP}$   
 Mass hierarchy (sign of  $\Delta m_{31}^2$ ) } Need measure this!

Size of  $\sin^2 \theta_{23}$  Use the results of accelerator muon neutrino oscillation measurement

Mixing angle  $\theta_{13}$  Take the value from reactor electron anti-neutrino oscillation experiments

$$a = G_F N_e / \sqrt{2} \simeq \frac{1}{3500 \text{ km}}$$

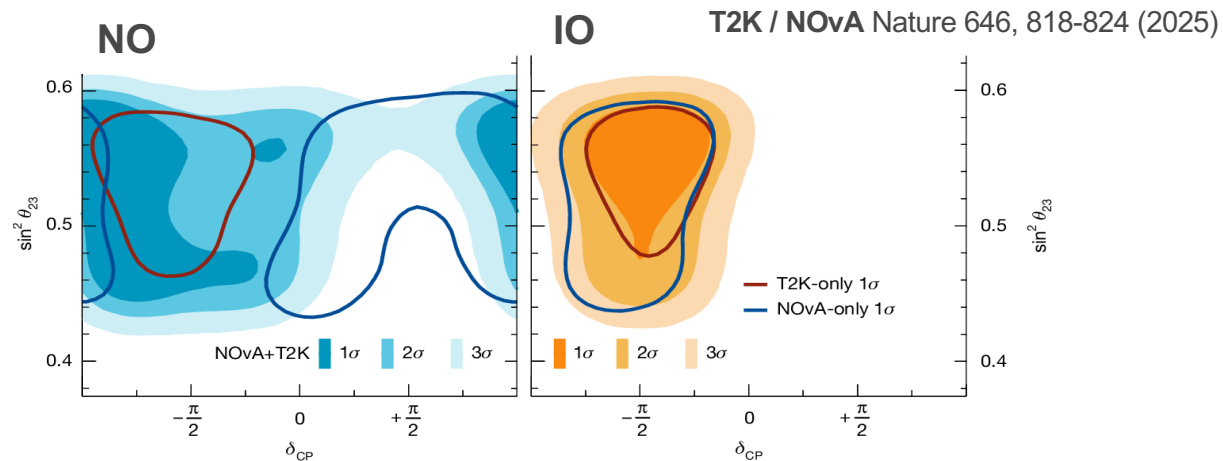
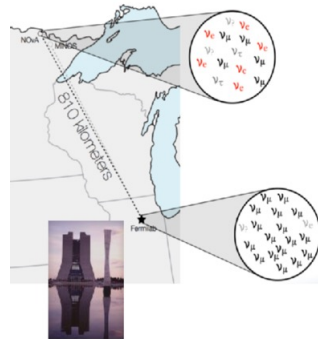
$aL = 0.08$  for  $L = 295 \text{ km}$  (T2K)  
 $aL = 0.23$  for  $L = 810 \text{ km}$  (NOvA)  
 $aL = 0.37$  for  $L = 1300 \text{ km}$  (DUNE)

# Neutrino Oscillations at Long-Baseline

- Current long-baseline experiments producing oscillation physics results

-NOvA (US)

-T2K (Japan)



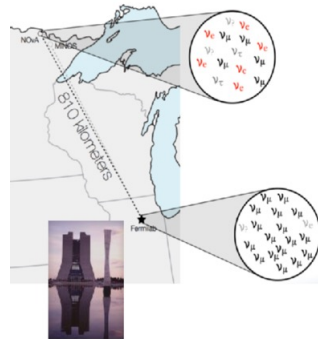


# Neutrino Oscillations at Long-Baseline

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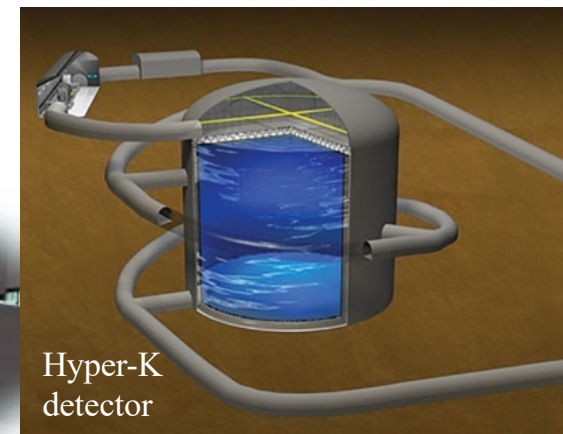
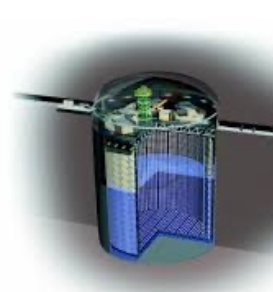
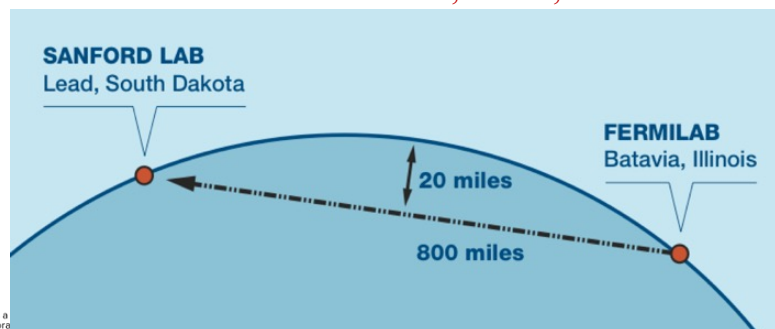


- Future long-baseline neutrino experiments (now under construction)

- DUNE (US)

- HyperK (Japan)

➤ DUNE is major US Focus  
-ANL, IF-NS, IF-Z involved!





# Future Long-Baseline Neutrino Experiments

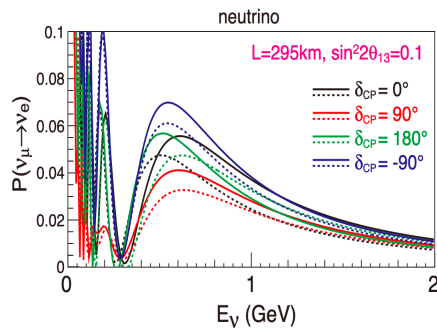
**T2HK** (Tokai to HyperK) approach (L=295km):  
Minimize matter effects and maximize statistics to  
focus on CPV discovery (MO and other parameters  
must be known by other means)

Narrow-band beam ( $\sim 0.6$  GeV; 500 kW  $\rightarrow$  1.3 MW)  
and Water-Cerenkov detector (190 kt fiducial)

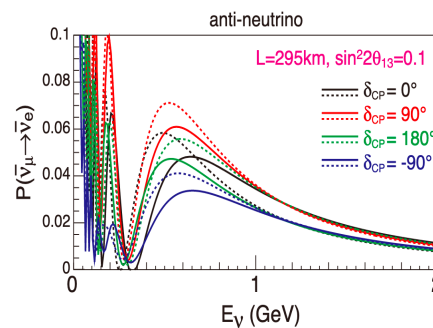
**DUNE** (FNAL to SURF) approach (L=1285km):  
measure **first and second oscillation maxima** to  
disentangle CPV and matter effects and access to all  
neutrino oscillation parameters

Wide-band beam (0.5-5 GeV; 1.2  $\rightarrow$  >2 MW) and liquid  
Argon TPC (>40 kt fiducial)

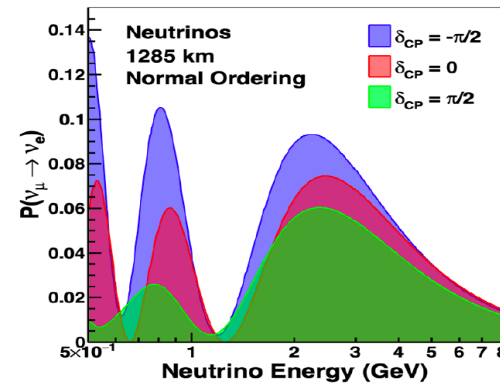
**HK**  $P(\nu_\mu \rightarrow \nu_e)$



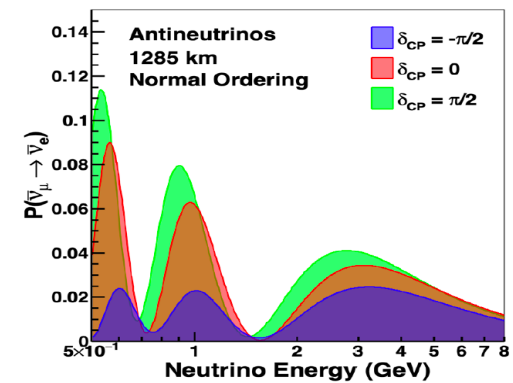
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



**DUNE**  $P(\nu_\mu \rightarrow \nu_e)$



$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$



arXiv:1609.04111



# DUNE NEUTRINO EXPERIMENT



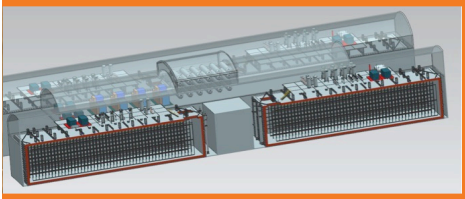
U.S. DEPARTMENT  
of ENERGY

Argonne National Laboratory is a  
U.S. Department of Energy laboratory  
managed by UChicago Argonne, LLC.

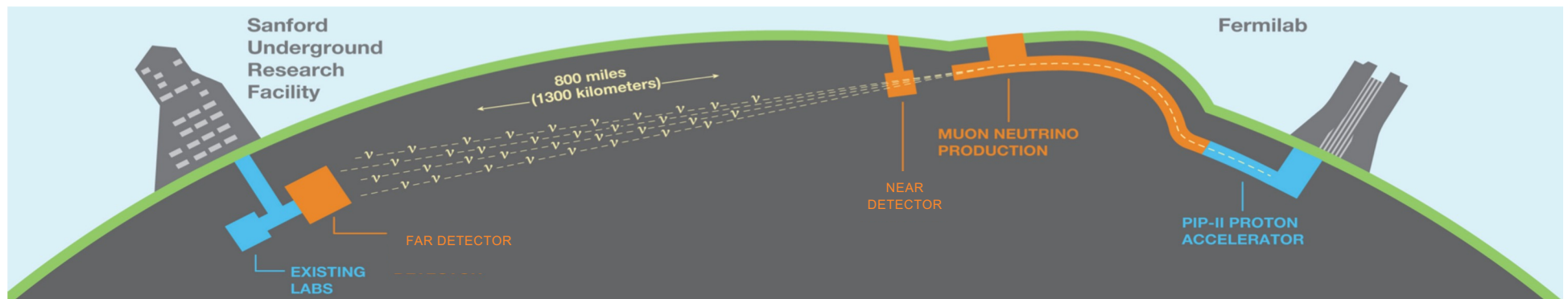




100



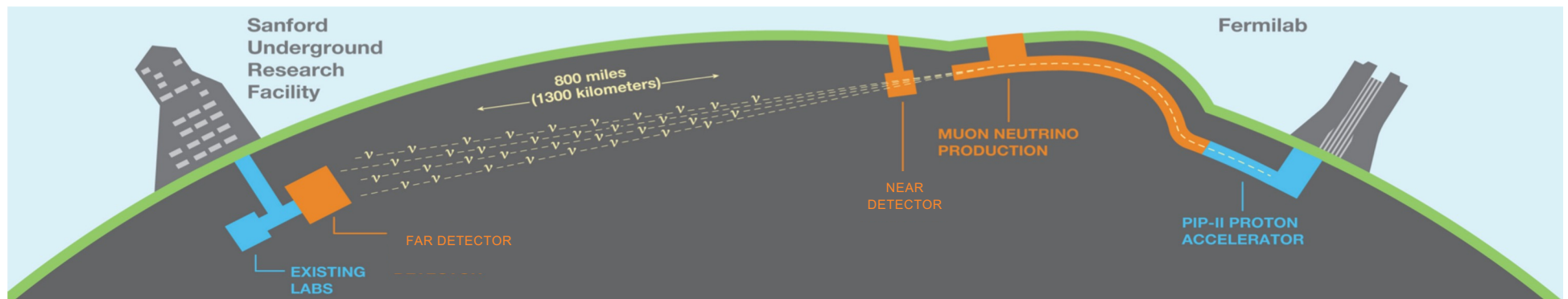
# The Deep Underground Neutrino Experiment



**DUNE TDR Volumes:** JINST 15 (2020) 08, T08008, T08009, T08010, arXiv:2002.03005,  
JINST 19 (2024) 08, T08004,  
**ND CDR** Instruments 5 (2021) 4, 31.

- The **most powerful neutrino beam in the world** ( $>2$  MW) will be sent from Fermilab (Chicago) to SURF (South Dakota) along 1300 km distance to be detected by four liquid argon **far detector** modules (70 kton LAr) at 1.5 km deep underground and a **near detector** complex at 560 m from the neutrino source.

# The Deep Underground Neutrino Experiment



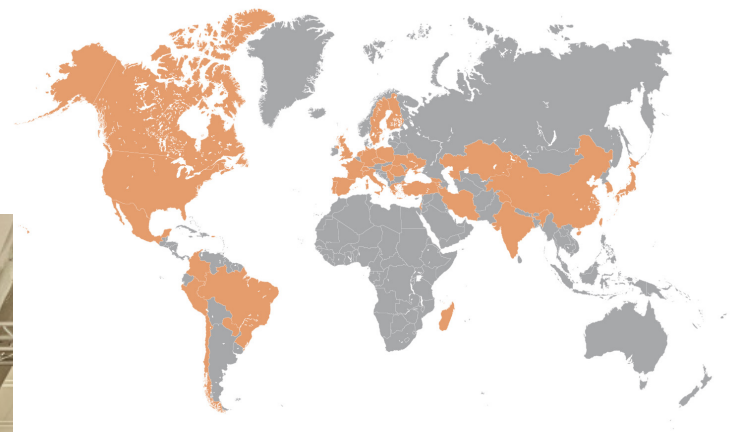
1. The **very long baseline** enables an unambiguous measurement of the **neutrino MO** (no degeneracy between CPV and matter effect)
2. The **wide-band neutrino energy spectrum** enables detailed fitting of the **oscillation parameters**
3. The **LArTPC technology** enables precise reconstruction of the **neutrino interactions**
4. The **ND complex with movable NDs** enables unprecedented control of **systematic uncertainties**
5. The **FD underground location** enables **astrophysical measurements**.



# DUNE Collaboration

## ➤ International collaboration

- 1548 collaborators, 222 institutions
- 40 countries incl. CERN



Argonne National Laboratory is a  
U.S. Department of Energy laboratory  
managed by UChicago Argonne, LLC.



# Major Goals of DUNE Experiment

- Primary focus of the DUNE science program is on fundamental open questions in particle physics and astroparticle physics:

## 1) Neutrino Oscillation Physics

- CP Violation in the leptonic sector

“Our best bet for explaining why there is matter in the universe”

- Mass Ordering
- Precision Oscillation Physics & testing the 3-flavor paradigm

## 2) Supernova burst physics & astrophysics

- Galactic core collapse supernova with sensitivity to  $\nu_e$

Time information on neutron star or even black-hole formation

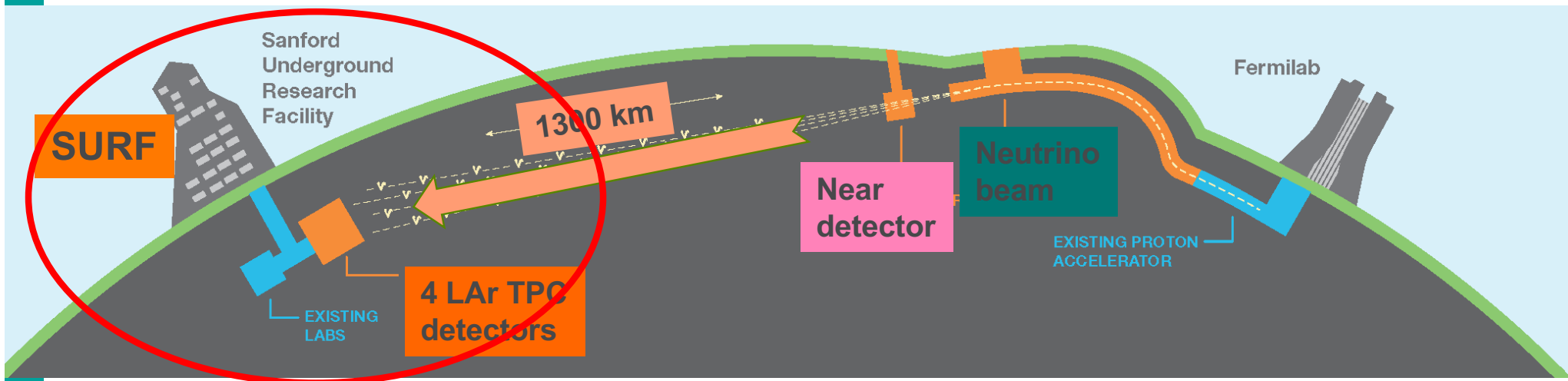
## 3) Beyond Standard Model Physics

- Nucleon Decay

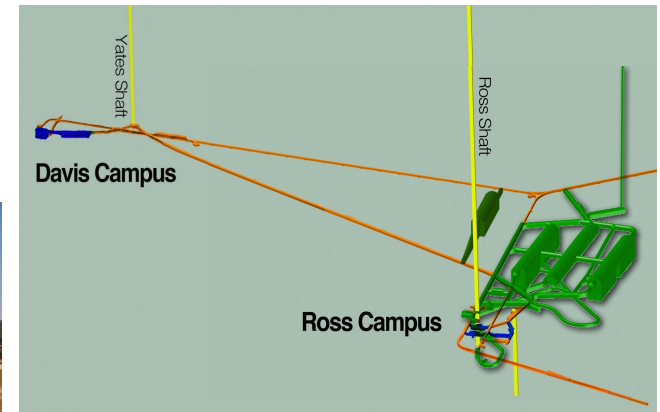
e.g., the SUSY-favored mode,  $p \rightarrow K^+ \bar{\nu}$

Any would be a major discovery

# Far Detector at SURF (Sanford Underground Research Facility)



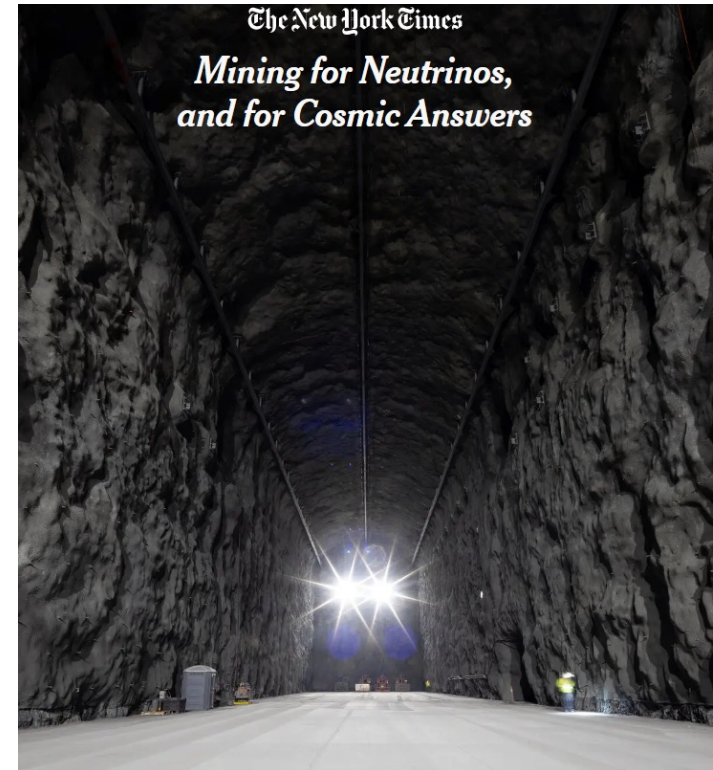
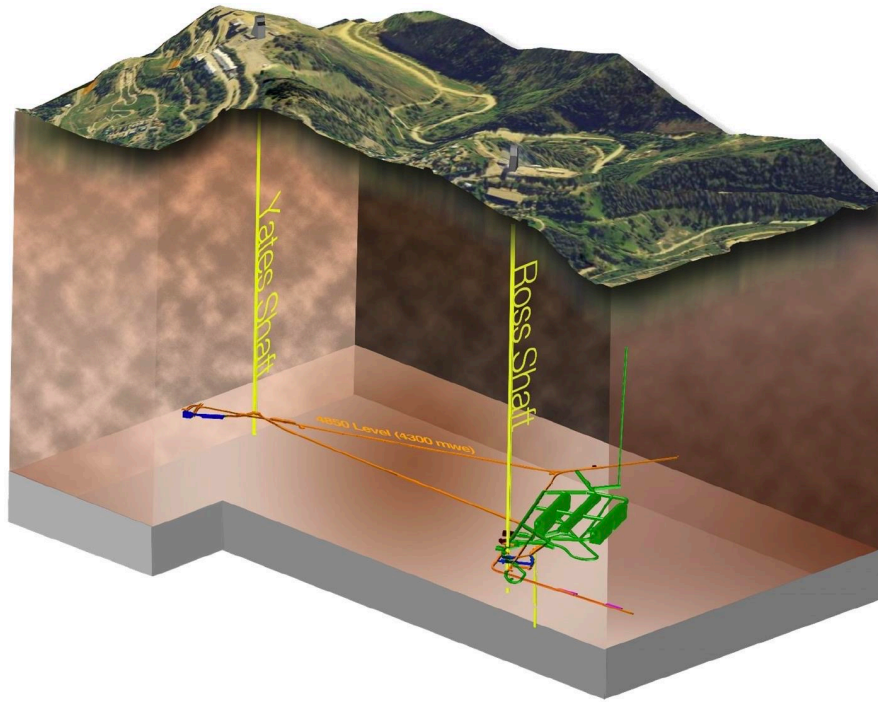
- Gold mine repurposed into underground laboratory
- Deepest laboratory in the US (1.5 km underground)
- Two main campuses
  - Davis Campus - Homestake Experiment, LUX (LZ), MAJORANA demo.
  - Ross Campus - DUNE, possibly future ton-scale  $0\nu 2\beta$  experiment.





# DUNE Caverns Excavation

- Excavation of huge caverns for DUNE particle detector is complete  
-Far Detector installation to follow-up!



<https://news.fnal.gov/2024/02/excavation-of-colossal-caverns-for-fermilabs-dune-experiment-completed/>



# DUNE Caverns Excavation

- I visited the SURF lab a year ago  
DUNE site, Ray Davis Jr. (The Nobel Prize in Physics 2002)



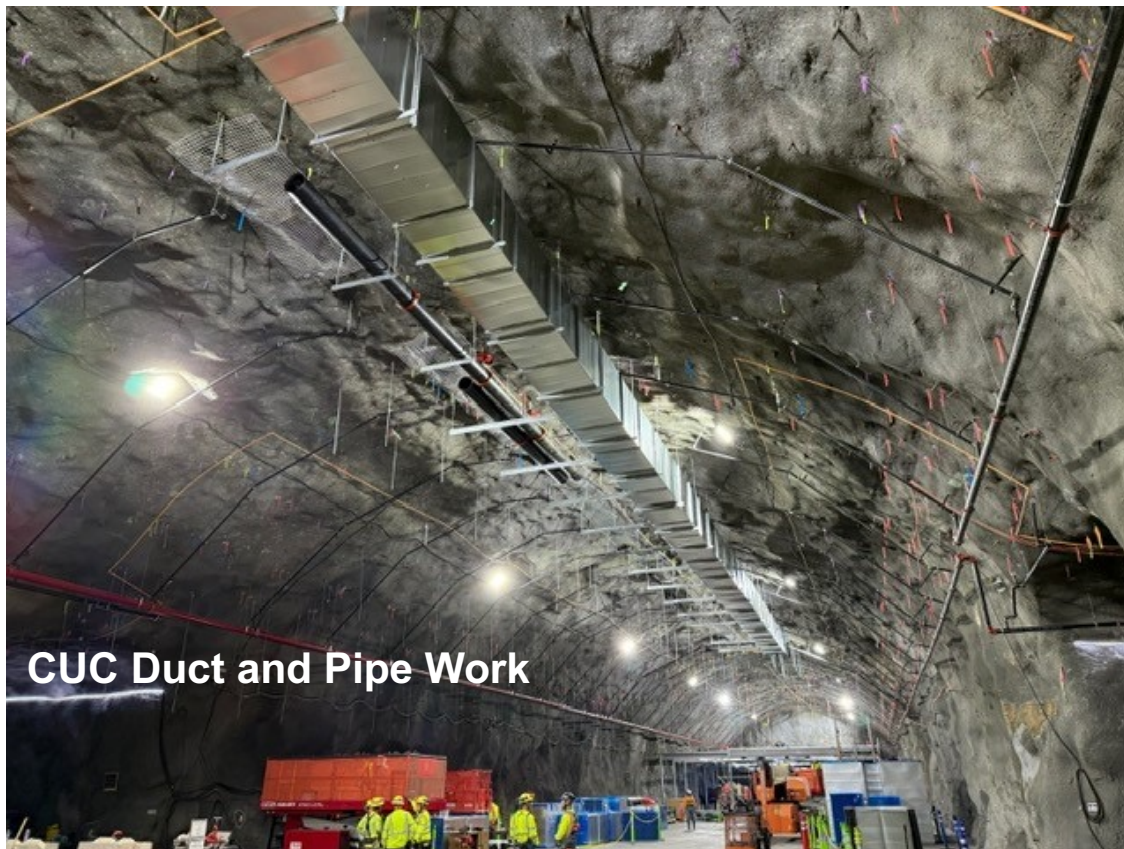


# SURF Caverns Completed in 2024



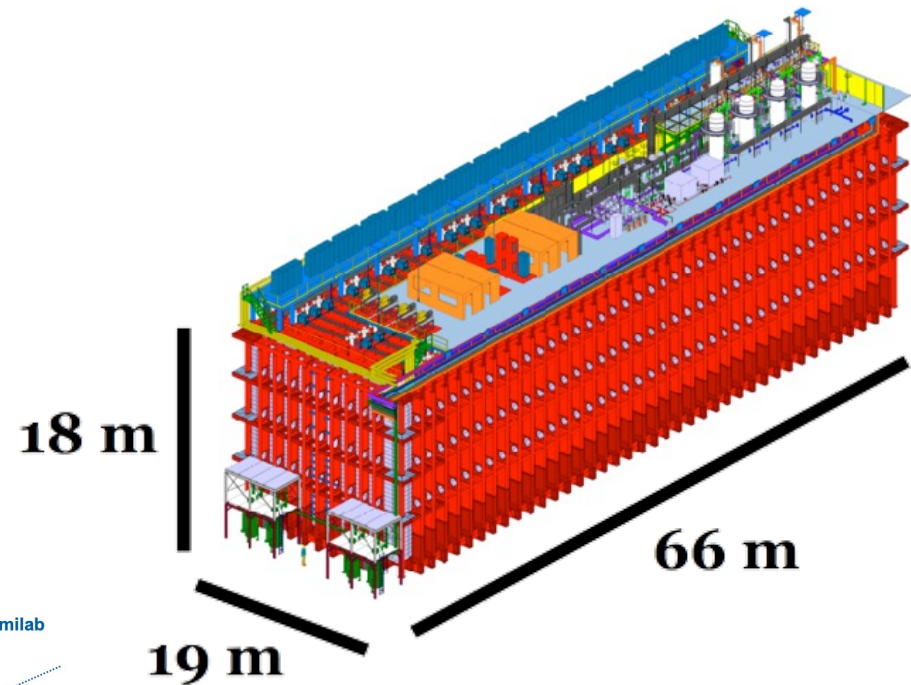
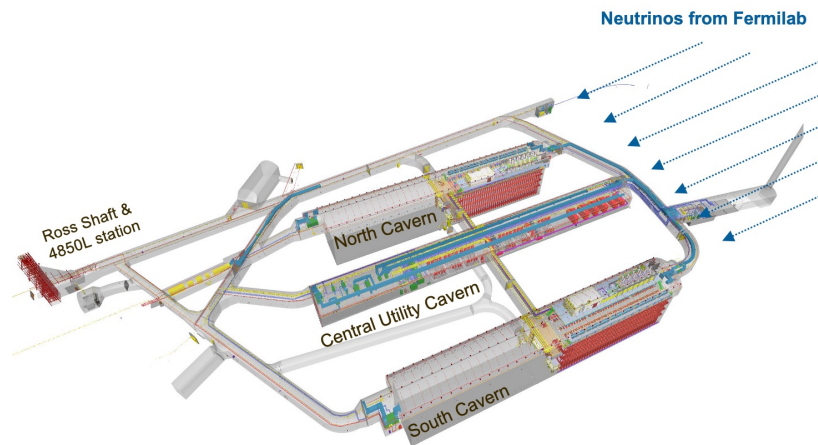


# Caverns Status



# DUNE Far Detector at SURF

- **Three main caverns**
  - 4 detector halls in 2 caverns
  - 1 support cavern (cryogenics + DAQ)
- **Detectors based on LArTPC technologies**
  - Same cryostat dimensions (66m x 19m x 18m)
  - 17 kt total LAr mass (70kt total)
- **Detectors installed in staged approach over several years**
  - Installation after cavern completion
  - Two Far Detectors commissioned before beam starts



A mile underground: the large caverns and detectors of DUNE: <https://youtu.be/zoxjRsIzd4k>



# DUNE Cryostat Transportation and Assembly



Black Hills  
**Pioneer**

Friday, January 19, 2024 Vol. 148 No. 161 Since 1876 \$1.50

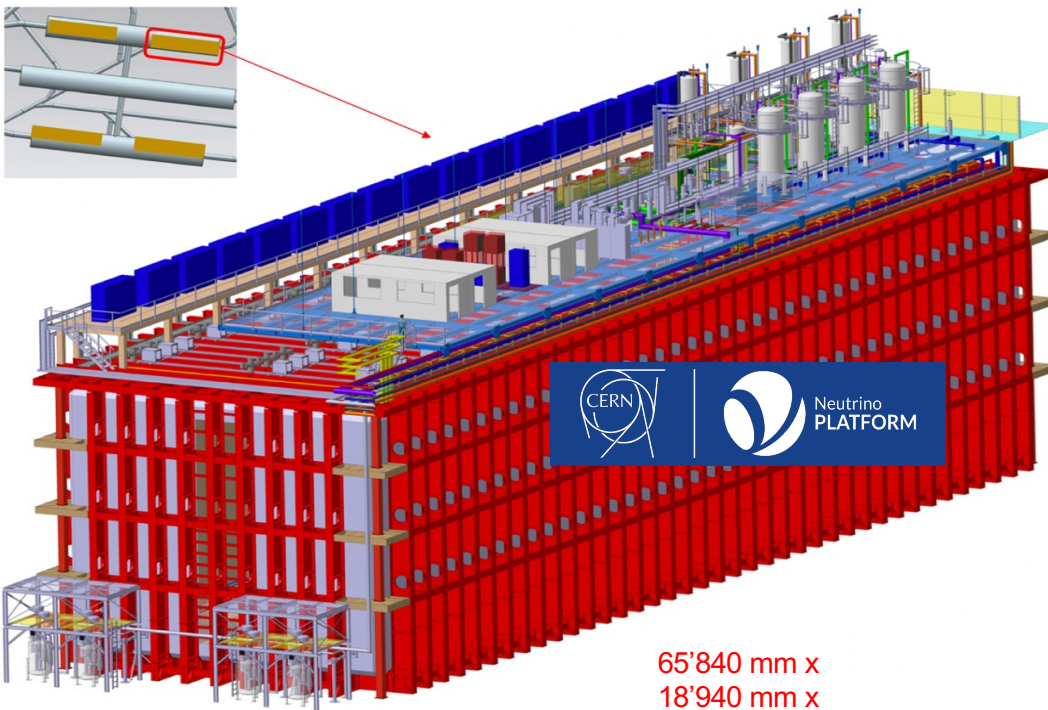
## First components for DUNE experiment in Lead



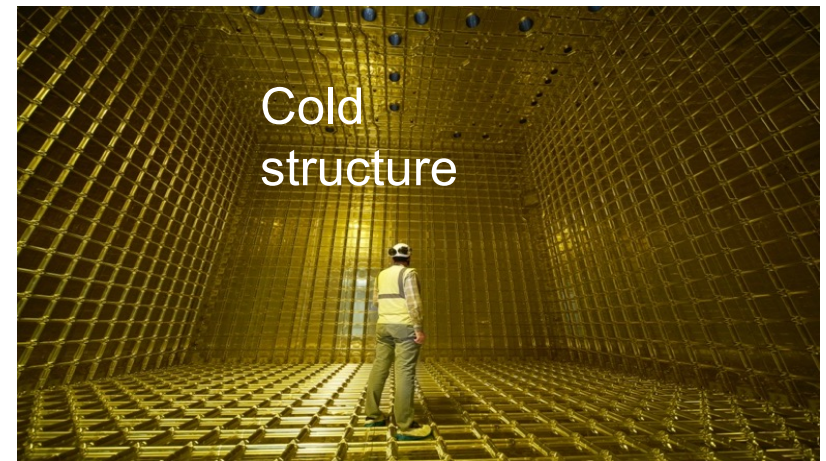


# CERN LBNF/DUNE Cryostats

- CERN has committed to contribute in-kind 2 FD cryostats to the LBNF/DUNE project
- Cryostat setup and installation starting **2026** at SURF.



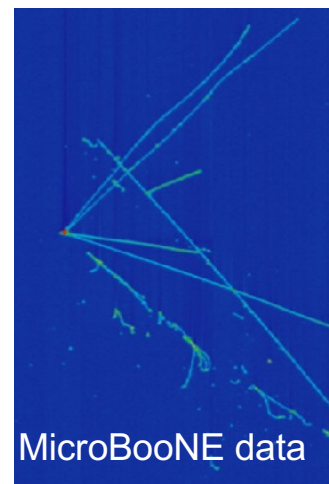
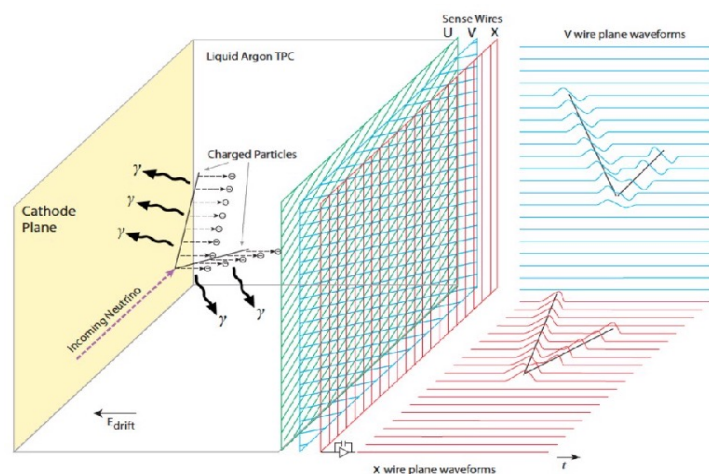
65'840 mm x  
18'940 mm x  
17'840 mm  
(L x W x H)



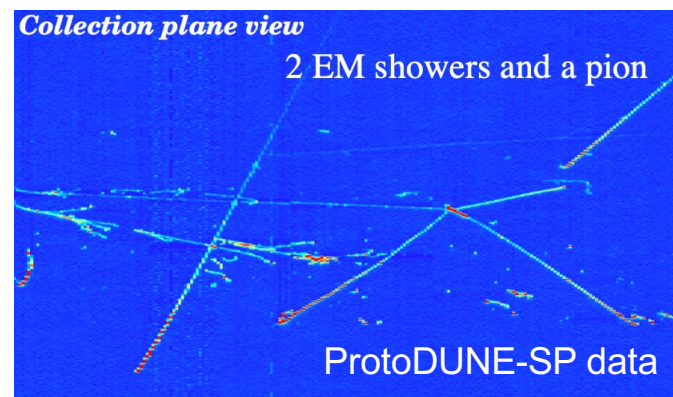
# DUNE LArTPC DETECTOR CONCEPT

- **Liquid Argon Time Projection Chamber (LArTPC)**

- Precision tracking and calorimetry
- Time “zero” from scintillation photons.



- *Energy release from charged particles in LAr:*
  - drift electron charge (TPC)
  - scintillation light (Photon System)

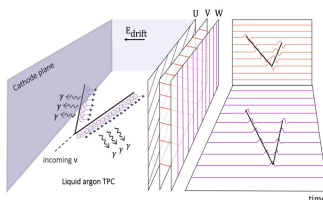
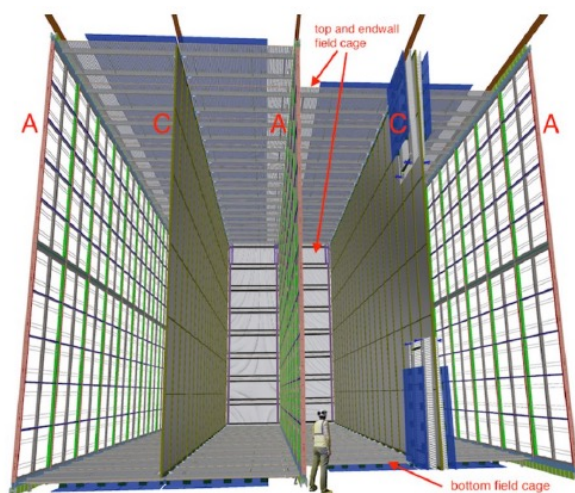


- DUNE detector development is underway through R&D with large-scale prototyping
  - The overarching goal is to demonstrate that the DUNE Far and Near Detectors meet the scientific requirements and technical specifications to measure neutrino CP violation.



# Far Detector Technologies

**FD-HD:** JINST 15 (2020) 08, T08010

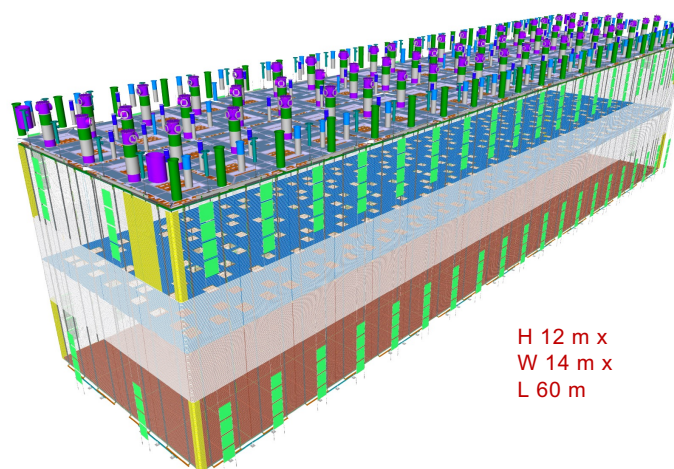


H 12 m x  
W 14 m x  
L 58 m

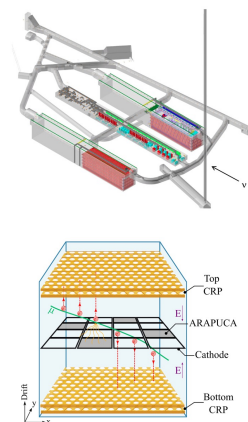
## Horizontal drift (FD-HD)

- Four 3.6 m drift regions
- Wire readout plane (APA) technology
- X-ARAPUCA photon detectors integrated in anode planes

**FD-VD:** JINST 19 (2024) 08, T08004



H 12 m x  
W 14 m x  
L 60 m



## Vertical drift (FD-VD)

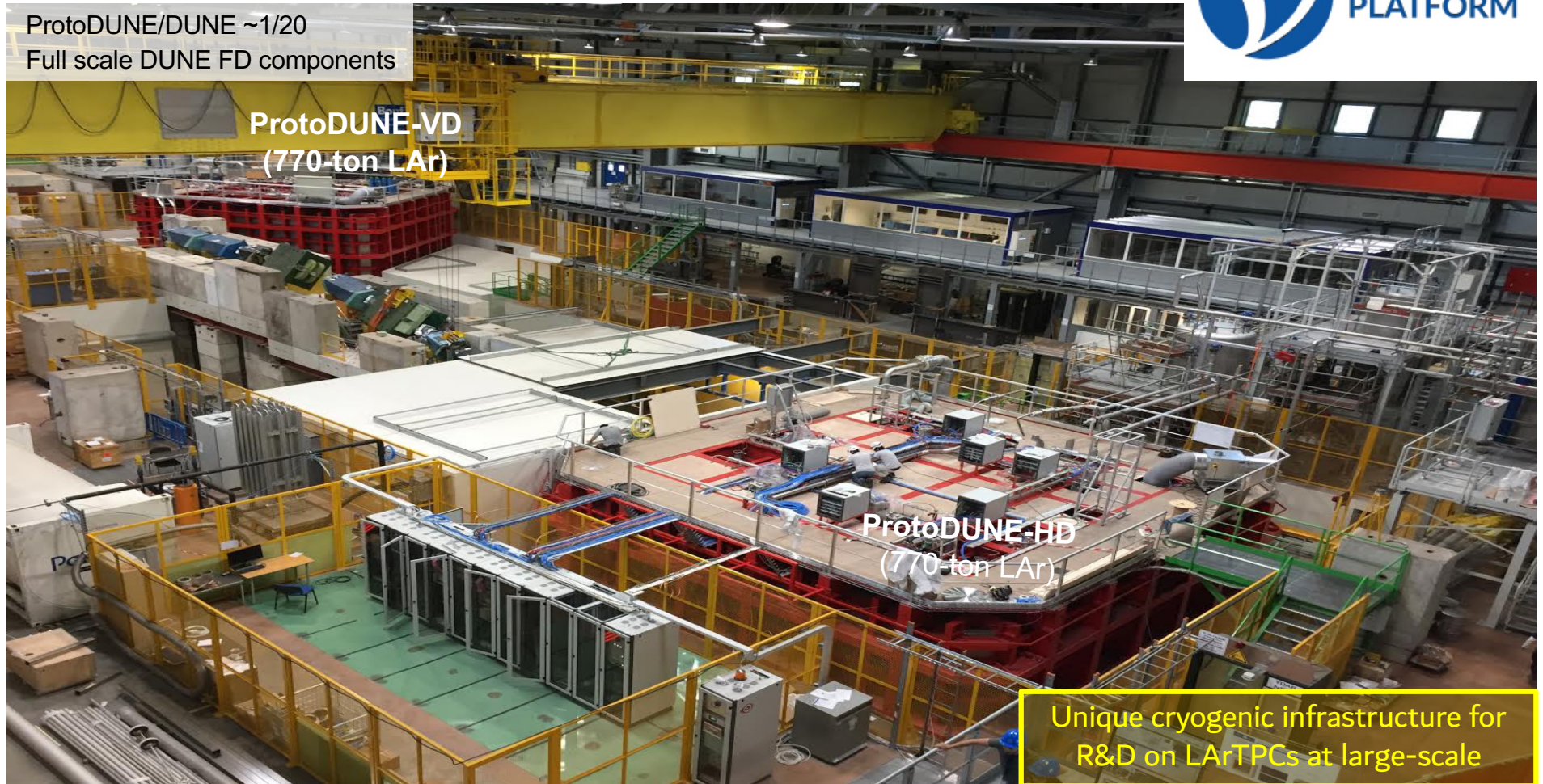
- Two 6.25 m drift regions and central cathode
- Charge readout plane (CRP) technology
- X-ARAPUCA photon detectors integrated in cathode plane and membrane walls

# DUNE Far Detector Prototyping

- ProtoDUNEs at CERN Neutrino Platform



ProtoDUNE/DUNE ~1/20  
Full scale DUNE FD components



ProtoDUNE-VD  
(770-ton LAr)

ProtoDUNE-HD  
(770-ton LAr)

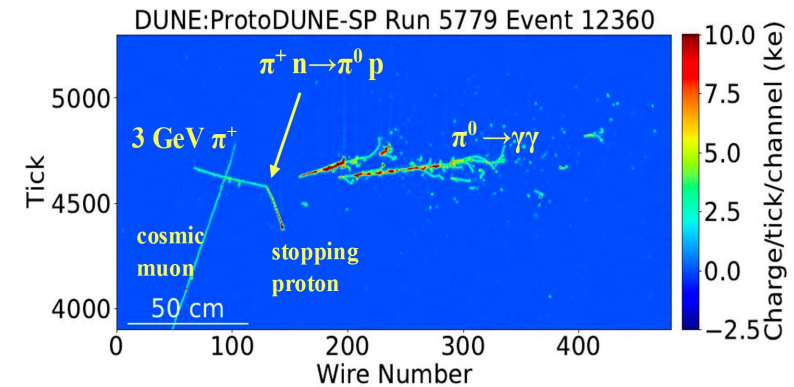
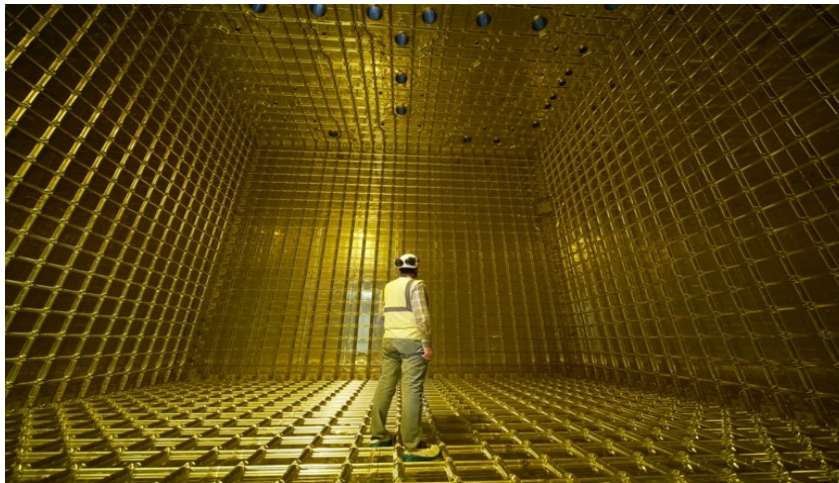
Unique cryogenic infrastructure for  
R&D on LArTPCs at large-scale



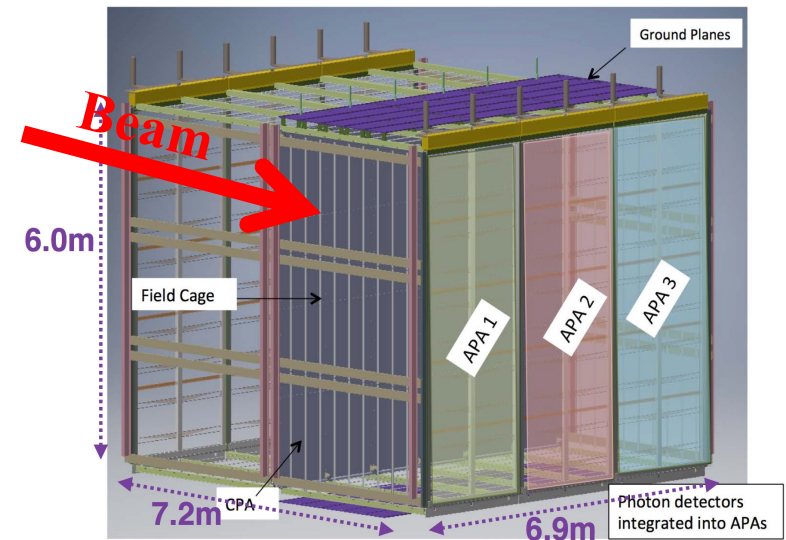
# DUNE Experiment: ProtoDUNE Phase I

## ➤ 1st Phase of ProtoDUNEs

- Construction and operation of ProtoDUNEs at CERN (2018-2020)
- Successful demonstration of the DUNE LAr TPC performance
- Several completed or ongoing analyses (hadron-Ar cross sections...).
- Beam Particles: electrons, kaons, muons, protons, pions ( $e$ ,  $K^\pm$ ,  $\mu$ ,  $p$ ,  $\pi^\pm$ ).
- Cosmic-ray muons.



ProtoDUNE-SP TPC



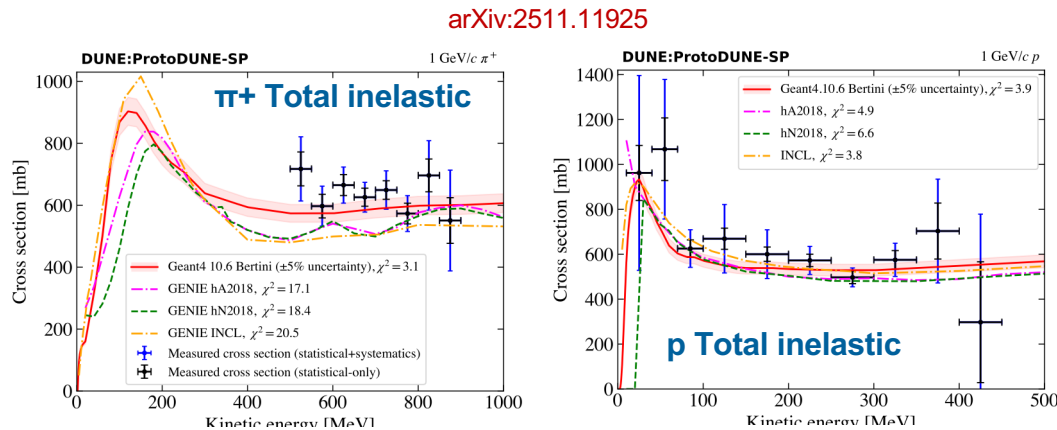
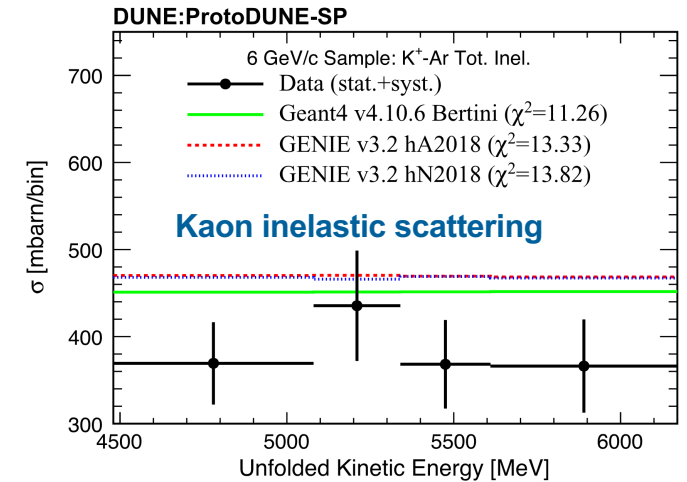


# ProtoDUNE Physics Results

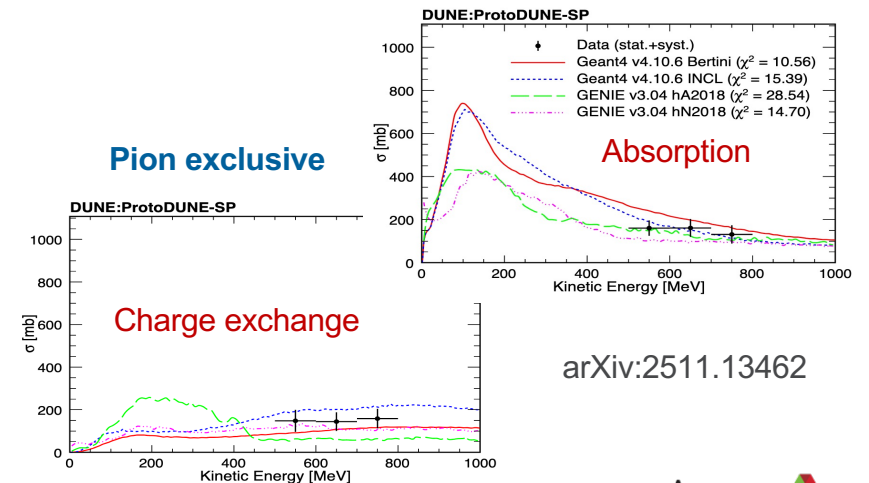
- Measurement of  $p/\pi/K - \text{Ar}$  cross sections (inclusive/exclusive)**

- DUNE relies on the reconstruction of ongoing particles emitted in  $\nu$ -Ar interaction to reconstruct neutrino energy & flavor
- Final State Interactions in the nucleus biases the reconstruction through absorption, charge exchange, ...
- Hadron-Ar scattering data help us to better model intra-nuclear interactions.

Phys. Rev. D 110 (2024) no.9, 092011



arXiv:2511.11925



arXiv:2511.13462

# DUNE Experiment: ProtoDUNE Phase II

## ProtoDUNE-HD (NP04)

- 2020-2023 construction, 2024 operation
- Final technical solutions for all FD-HD subdetectors
- Data taken with charged-particle test-beam and cosmic muons at CERN in 2024

## ProtoDUNE-VD (NP02)

- Installation completed in Nov 2024
- Charged-particle beam data taken in 2025 and continuing with cosmic runs

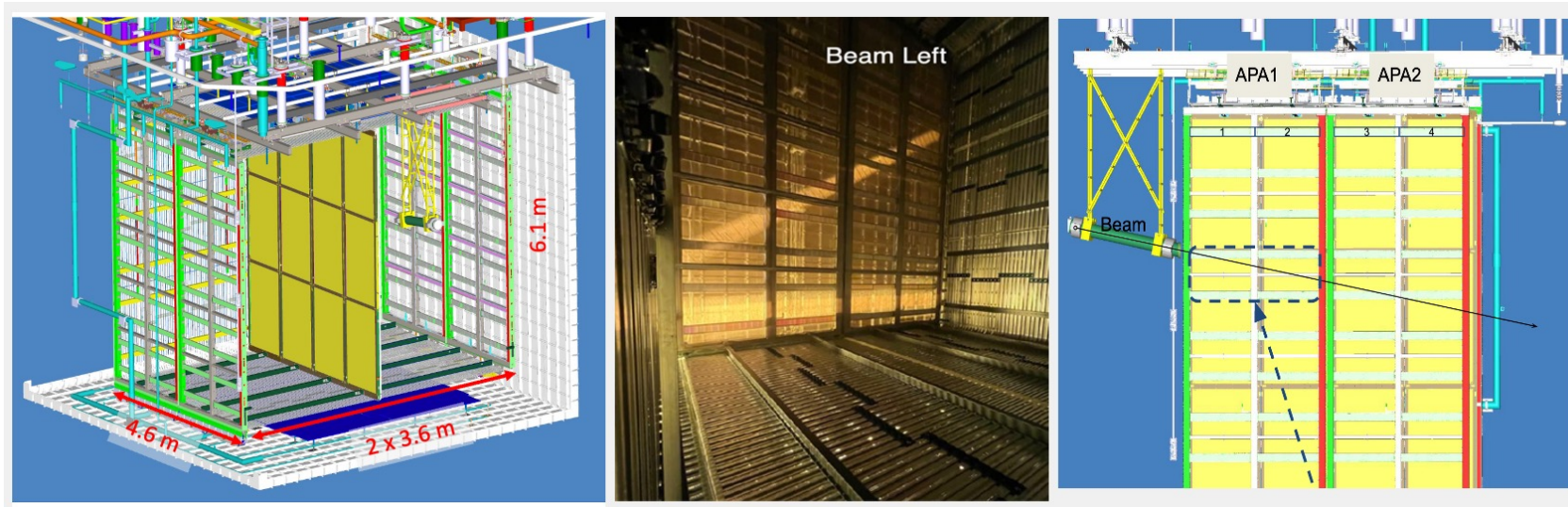


ProtoDUNE-HD

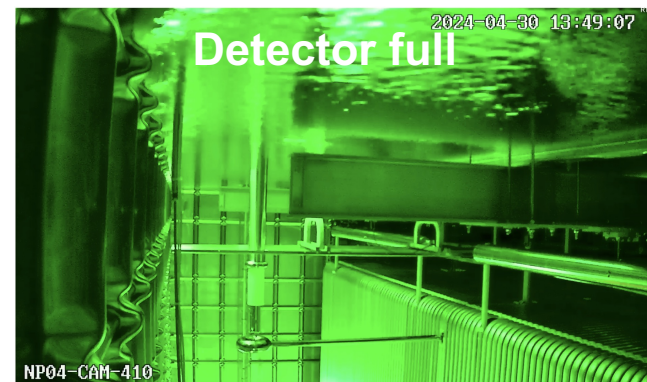


ProtoDUNE-VD

# ProtoDUNE-HD (NP04)



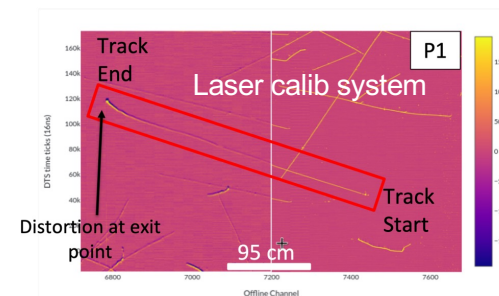
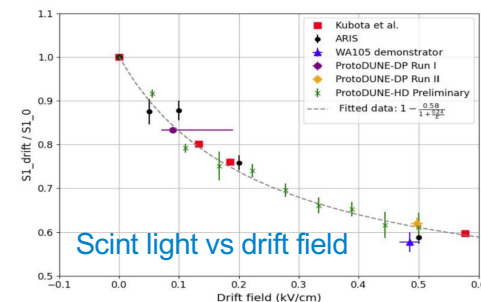
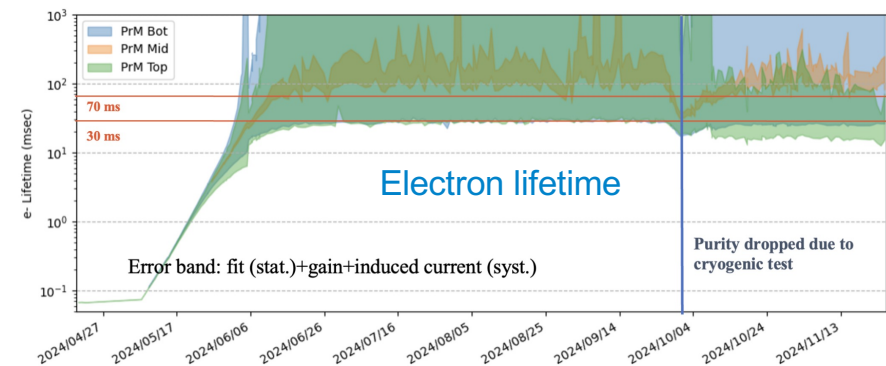
- 2 APAs (instead of 3) per wall
- Drift volume further from the cryostat (longer beam pipe)
- New calibration systems (laser, neutron source).



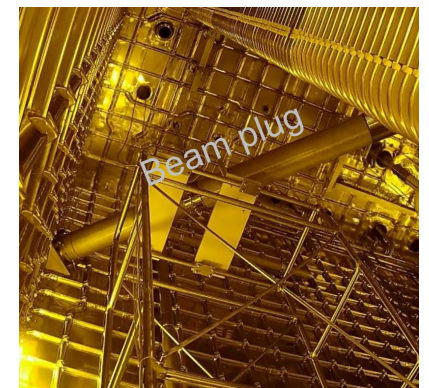
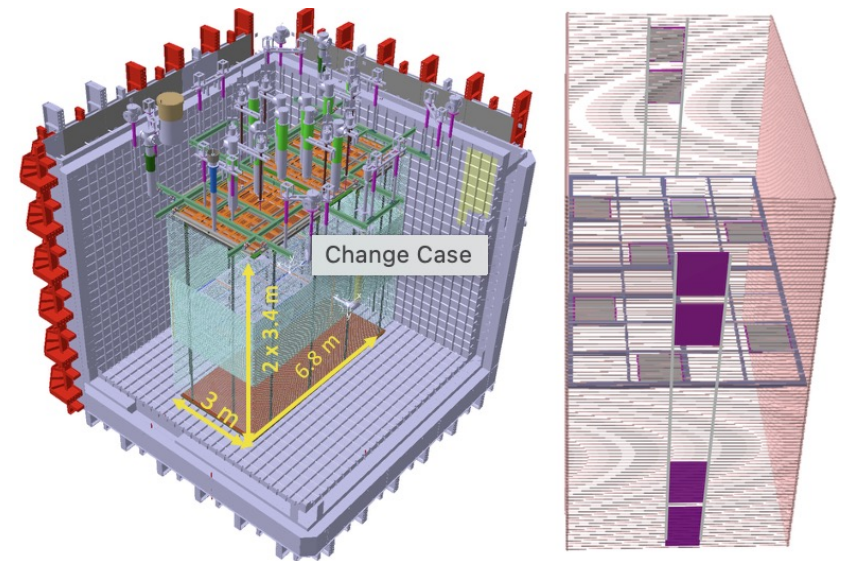


# ProtoDUNE-HD Performance

- Achieved electron lifetime above 70 ms
- Excellent electronics noise performance
- Stable HV system performance
- Successful operation of photon detector components and laser calibration system
- Successful demonstration of self-triggering capabilities
- ProtoDUNE-HD recorded over 28 million triggers, including cosmics, beam and calibration data
- Successfully utilized 10 weeks of SPS beam (pions, electrons, kaons, protons) at 1-7 GeV.



## ProtoDUNE-VD (NP02)

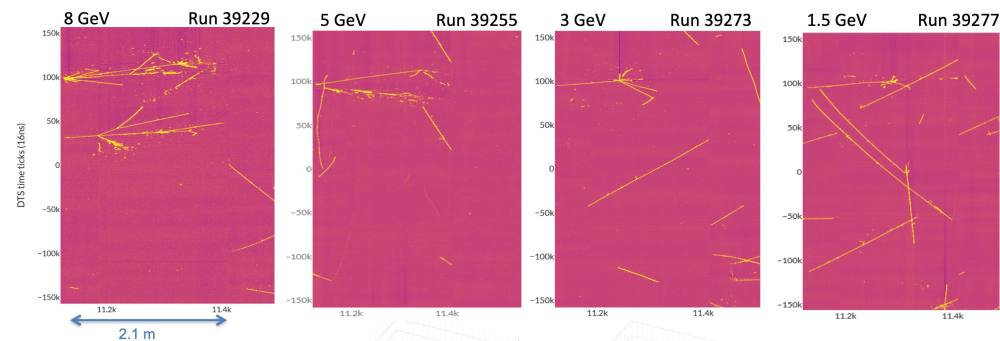


- 2 top CRPs + 2 bottom CRPs
- Cathode in the middle hanging from the top CRPs
- Field cages hanging independently from the cryostat roof
- 8 Photon Detection modules on the cathode and 8 modules on the walls.

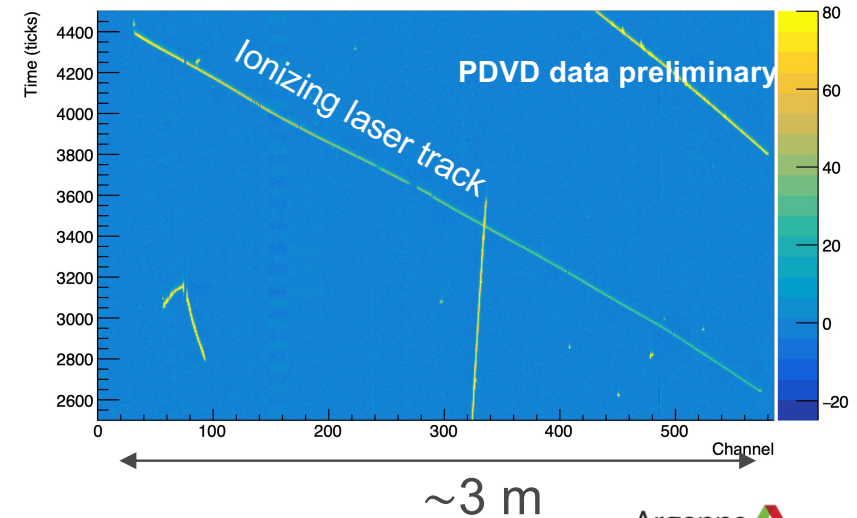
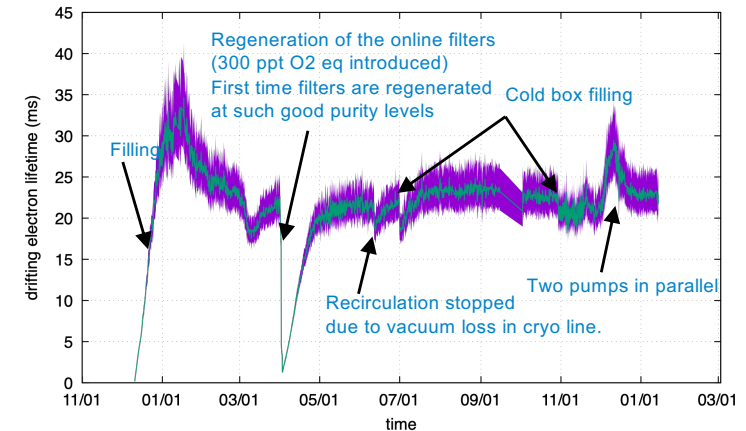


# ProtoDUNE-VD Performance

- LAr purity stable at 25 ms far exceeding the design requirement
- High Voltage very stable at nominal value (300 kV reached)
- Good signal to noise ratio and great performance by all sub systems (DAQ, top and bottom electronics, photon system)
- Collected beam data for 5 weeks from July to Sept 2025
  - > 4M events recorded at different energies
- Operation continues: pulsed neutron source and Xe doping run
- Events triggered by beam - pion candidates:



Electron lifetime



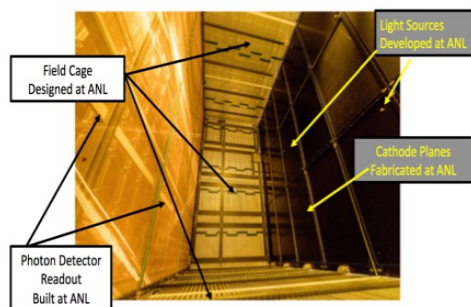


# DUNE Experiment: ProtoDUNE Phase I and Phase II

➤ ANL's (my group) recent DUNE focus was on ProtoDUNEs to enable DUNE far detector construction.

| Prototype (phase) | FD Type | System Design and Fabrication by ANL |                 | Prototype Status |
|-------------------|---------|--------------------------------------|-----------------|------------------|
| ProtoDUNE-SP (I)  | HD      | HVS/CPA                              | PDS Readout     | Completed 2022   |
| FD preparation    | HD      | Full size CPA                        | test Ash River  | 2022-2023        |
| ProtoDUNE-HD (II) | HD      | HVS/CPA                              | PDS Calibration | 2023-2024        |
| ProtoDUNE-VD (II) | VD      |                                      | PDS Calibration | 2024-2025        |

➤ Illustration:

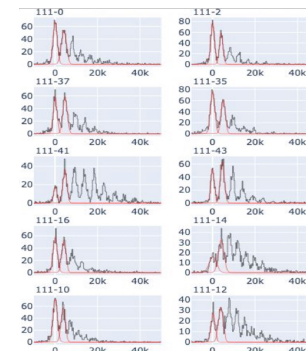


CERN: ProtoDUNE-SP (phase I)



Ash River: DUNE FD-HD CPA;  
ProtoDUNE-HD CPA

- All ANL subsystems performed well in tests and prototypes
  - Successful collection of test-beam, cosmic-ray, calibration data.
  - Presence at CERN during commissioning, installation, operations
  - Convened ProtoDUNE-SP PDS operations and analysis
  - Enabled science focus (next slide).



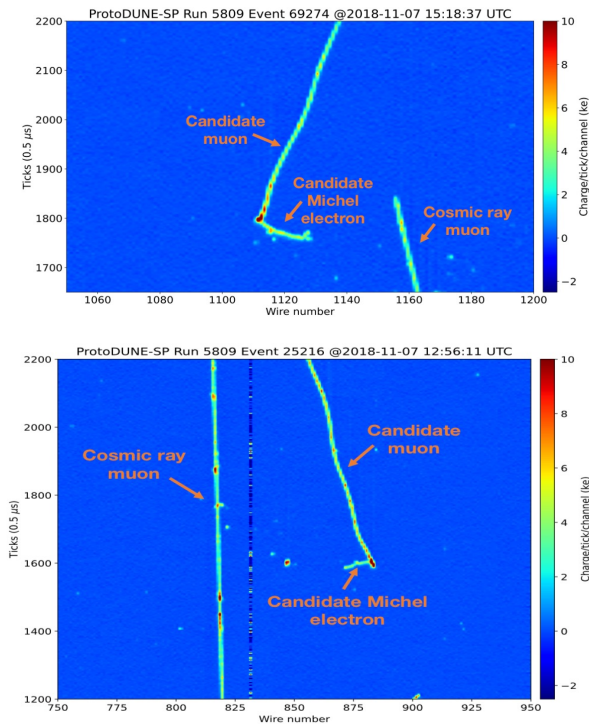
CERN: ProtoDUNE-HD (phase II)

JINST 15 (2020) 12, P12004: "First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform".

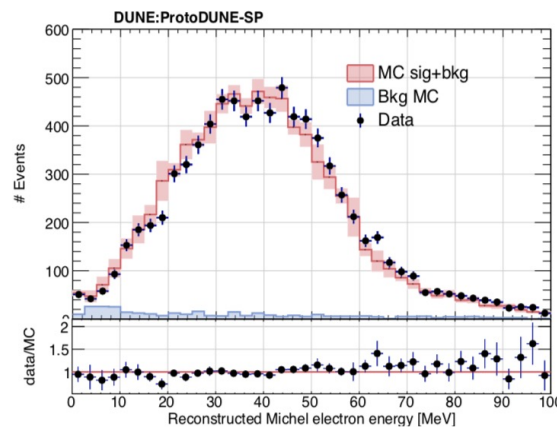
# ProtoDUNE Phase I: Example of Physics Result

## ➤ Low-energy (Michel) Electron Reconstruction by ANL group

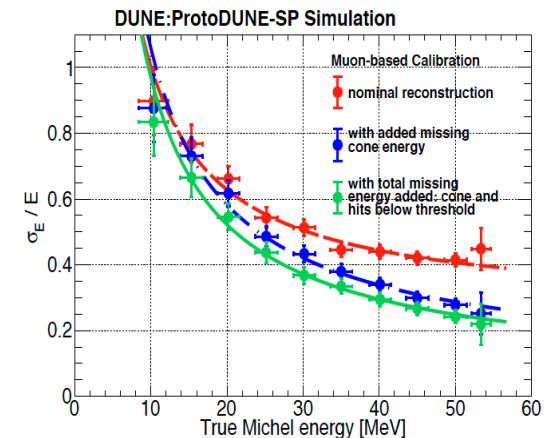
- Michel electrons from stopping cosmic ray muon decays in LArTPC.



## Michel electron energy

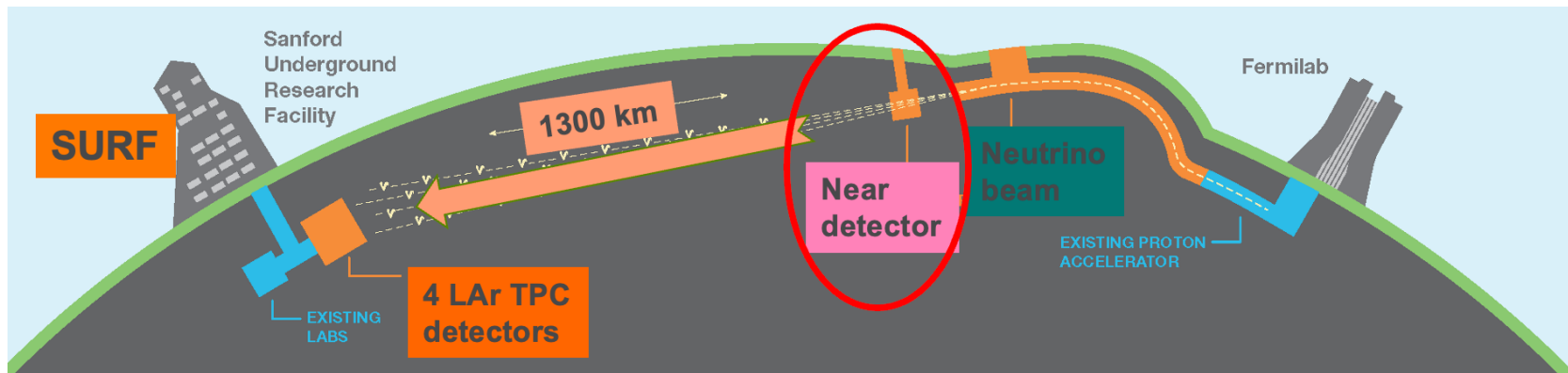


## Energy resolution

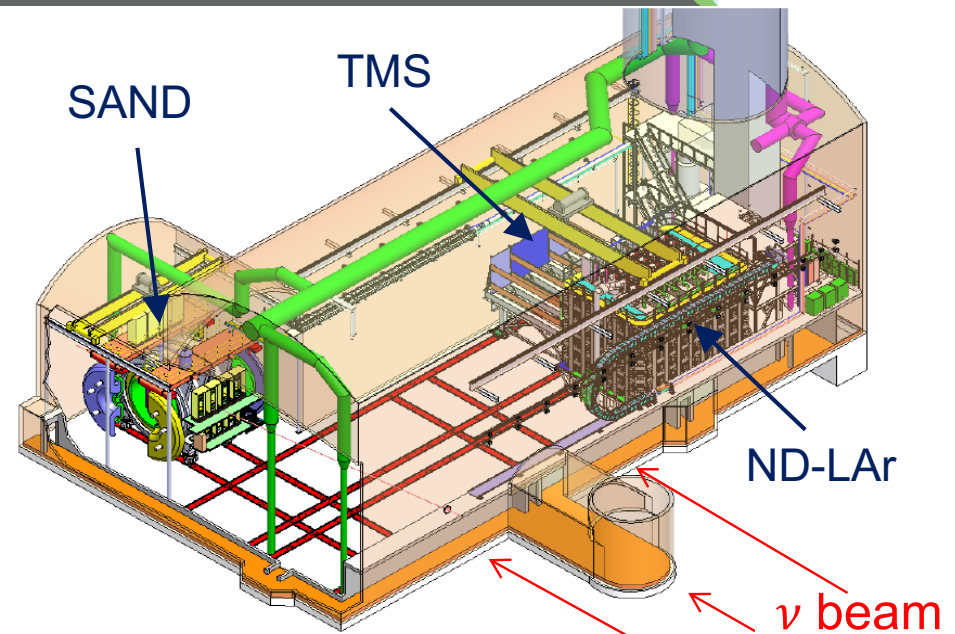


- Validate FD response to low-energy electrons
  - Reconstruct energy scale.
- Relevant for DUNE far detector physics searches
  - Low-energy supernova signals
  - Nucleon decay searches
  - Oscillation analyses.
- Results show excellent agreement between data and simulation, and with theoretically well-understood Michel electron spectrum
  - Publication: [Phys. Rev. D 107 \(2023\) 9, 092012](#).

# DUNE Near Detector Complex

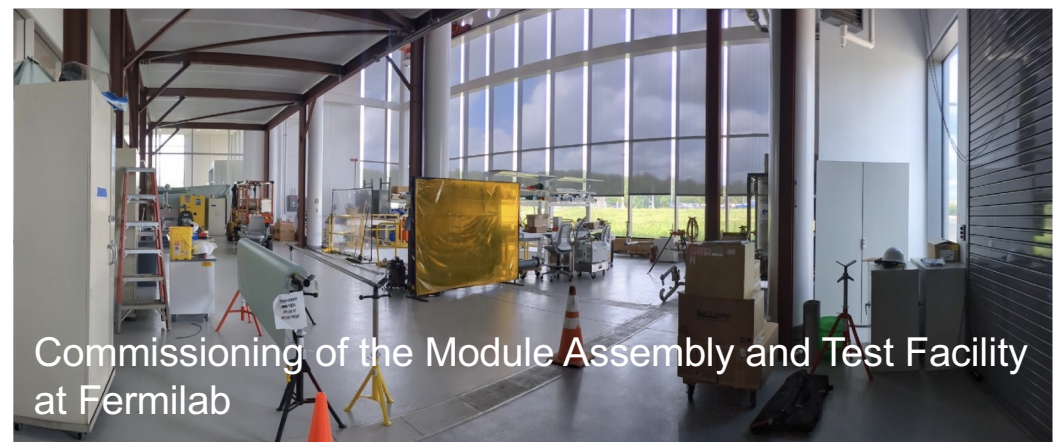
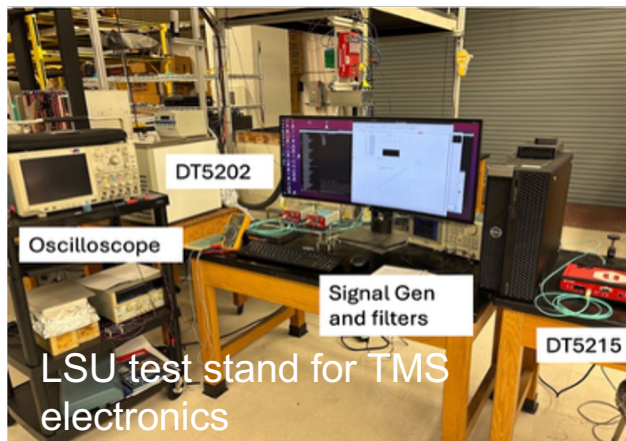


- Main purpose: enable prediction of Far Detector reconstructed spectra
- Movable detector system (DUNE-PRISM): LArTPC (**ND-LAr**) with muon spectrometer (**TMS**)
  - Off-axis data in different neutrino fluxes constrains energy dependence of neutrino cross sections
  - Same target, same technology → inform predictions of reconstructed  $E_\nu$  in Far Detector
- On-axis magnetized detector (**SAND**) for beam monitoring and neutrino measurements



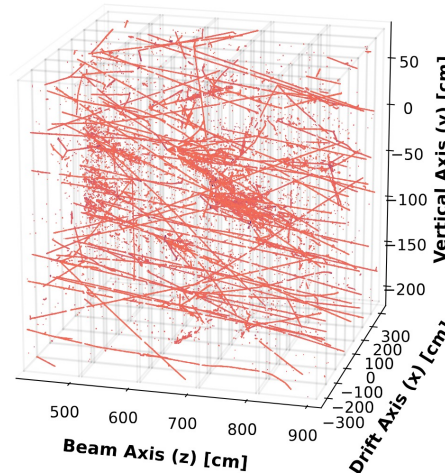


## Near Detector Progress



# 2x2 ND-LAr Detector Demonstrator at Fermilab

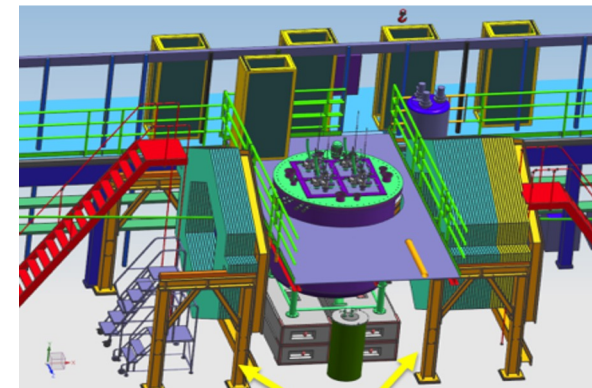
- **ND challenge:** neutrino pile-up (several dozens of neutrinos per spill)
  - Very high rate at near site motivates pixelated readout and optical modularity
- **Four LArTPC modules** built and operated in LAr in Bern with a total of ~330k pixel channels



Full spill event display simulation

- Operation of **2x2 ND-LAr in NuMI Neutrino Beam**
  - Four TPC modules installed in former location of MINOS-ND
  - Includes upstream/downstream trackers, repurposed from MINERvA
- **Goals:** Demonstrate reconstruction with natively 3D readout in a neutrino beam with similar event rate to DUNE

Instruments 8 (2024) 3, 41



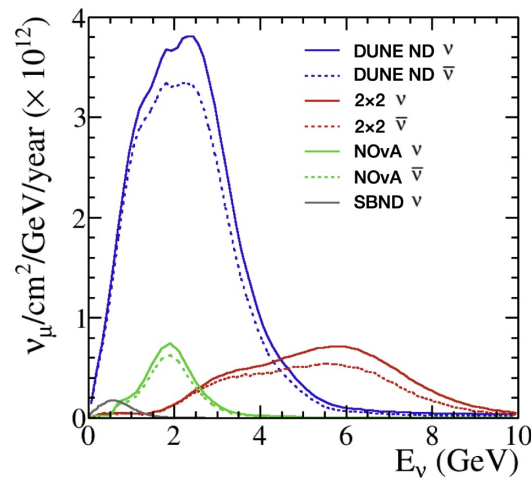


# 2x2 ND-LAr Detector Demonstrator at Fermilab

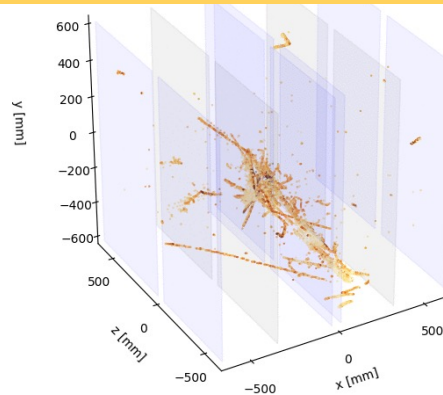
- **2x2** collected 4.5 days of physics quality data in antineutrino mode at NuMI in July 2024
  - ~45,000 neutrino interactions
  - Ongoing physics studies
- Beam-off run in 2025
- NuMI beam expected in 2026 in neutrino mode



➤ **Full-Scale Demonstrator ND-LAr** module operated at Uni Bern (70M cosmic ray events)



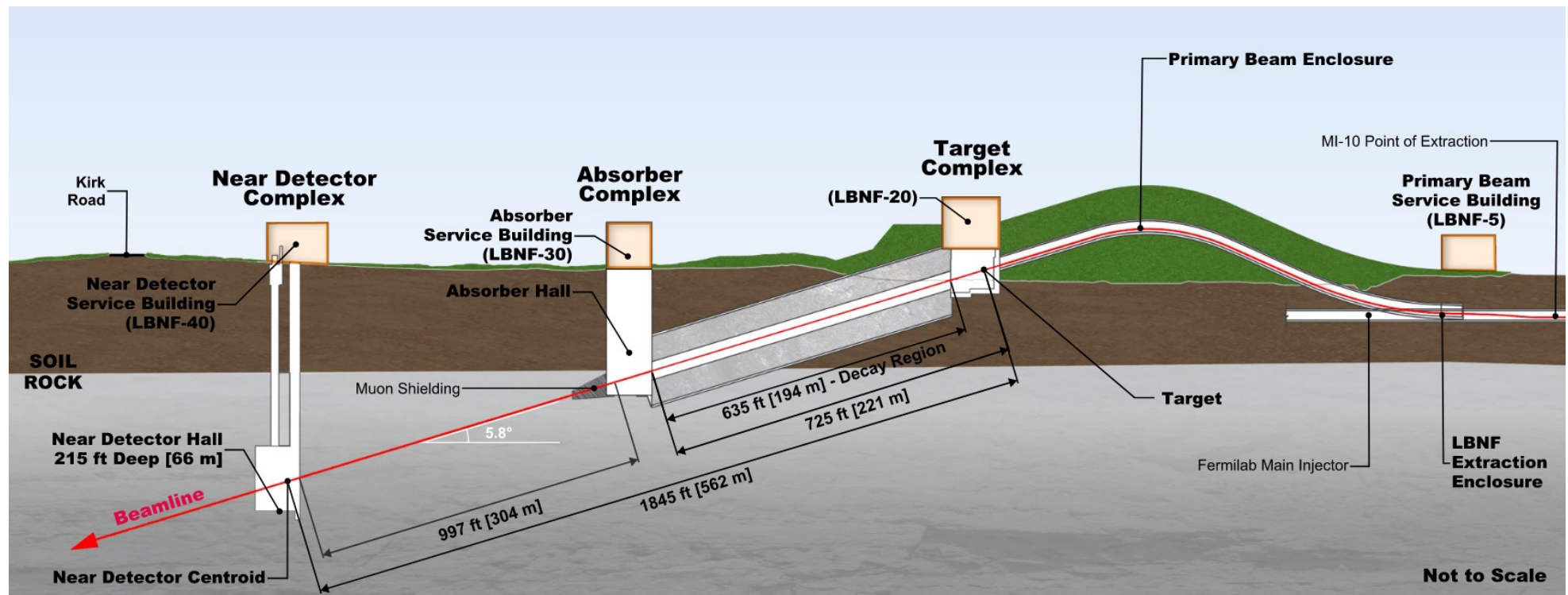
*First DUNE Near Detector 2x2 Demonstrator neutrino events (July 2024)*





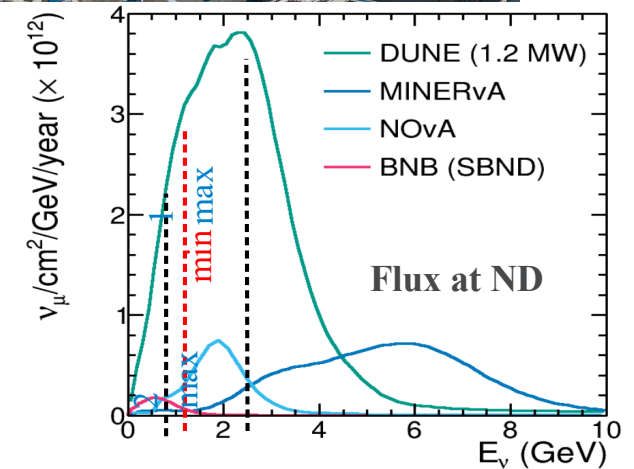
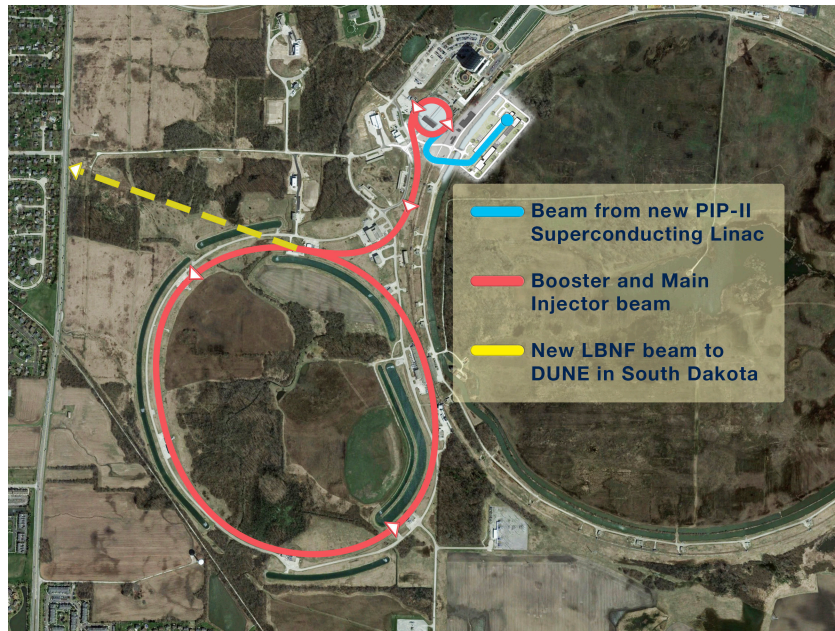
## Near site conventional facilities and beamline

- ND hall at 562 m from proton target, 66 m deep, on-site at Fermilab.



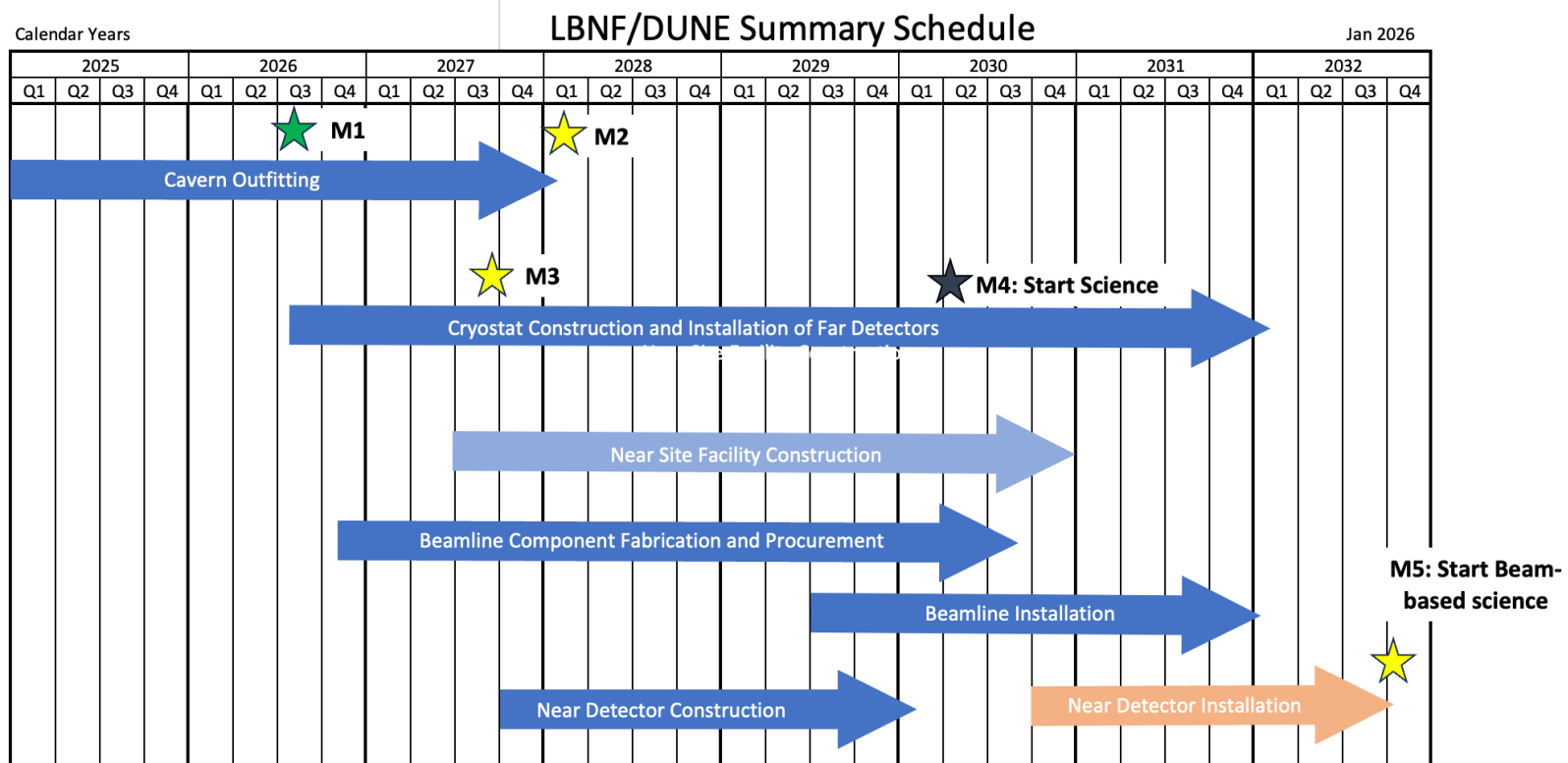
# LBNF Beam at Fermilab

- Very high flux between oscillation minimum and maximum, with coverage of second maximum
- Design phase is expected to complete in 2026.



# LBNF/DUNE Schedule

- ★ **M1:** Start of far site cryostat construction
- ★ **M2:** Far site conventional facility transition to operations complete
- ★ **M3:** Start of far detector construction
- ★ **M4:** First far detector transition to operations complete
- ★ **M5:** Start Beam-based science







# DUNE PHASE II



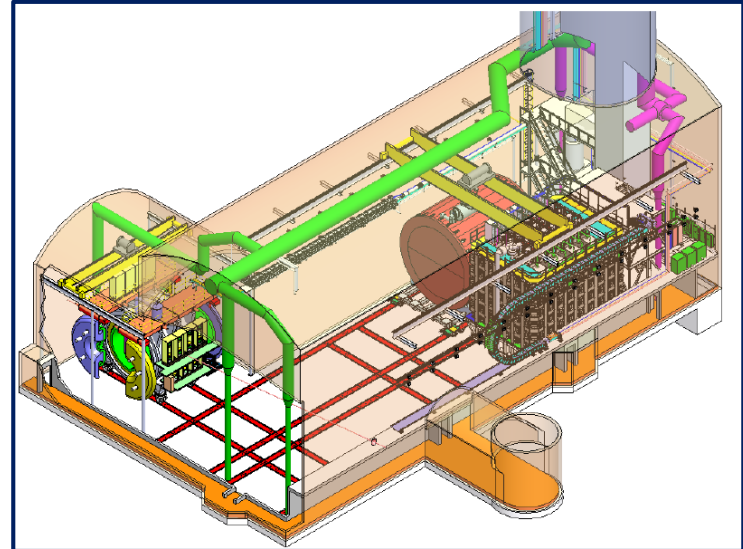
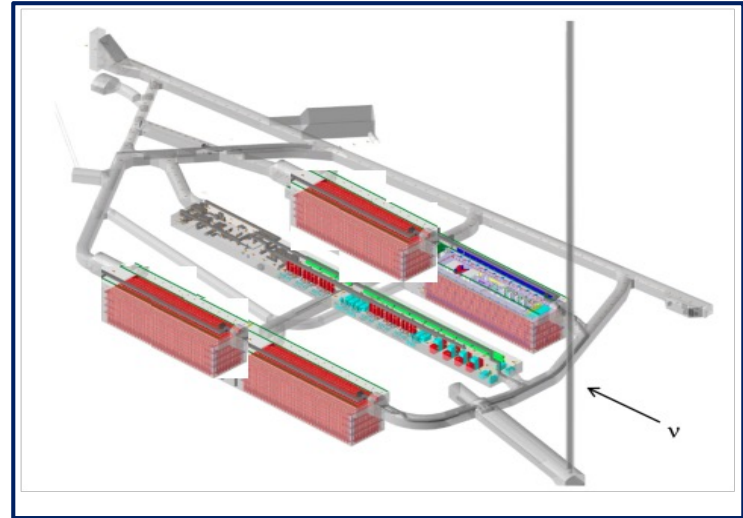
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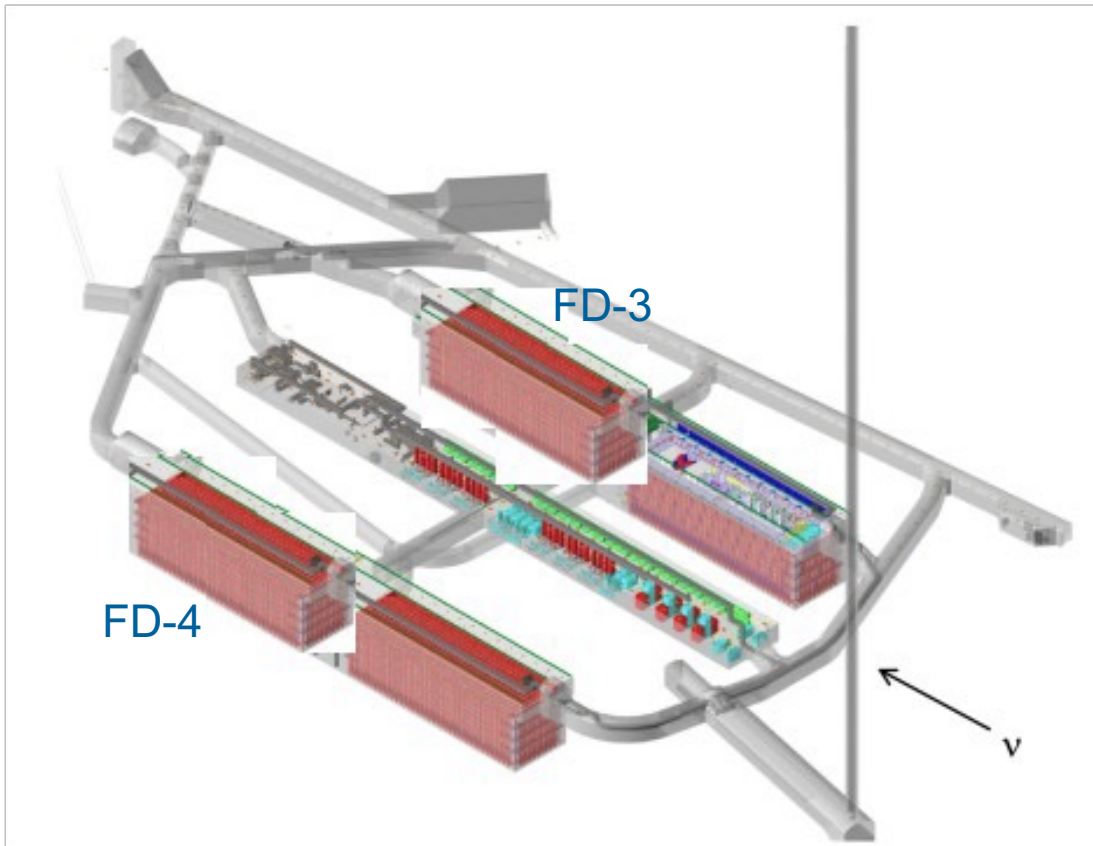


# DUNE Phases

- **DUNE Phase I** (2026 start detector installation; early 2030 physics; 2032 beam + ND)
  - Full near + far site facility and infrastructure
  - Two 17 kt LArTPC modules
  - Upgradeable 1.2 MW neutrino beamline
  - Movable LArTPC near detector with muon catcher
  - On-axis near detector
- **DUNE Phase II:**
  - Two additional FD modules ( $\geq 40$  kt fiducial in total)
  - Beamline upgrade to  $>2$  MW (ACE-MIRT)
  - More capable Near Detector (including ND-GAr)



## FD3/4 Modules of opportunity to enhance physics



- White Paper [DUNE Phase II: scientific opportunities, detector concepts, technological solutions](#).

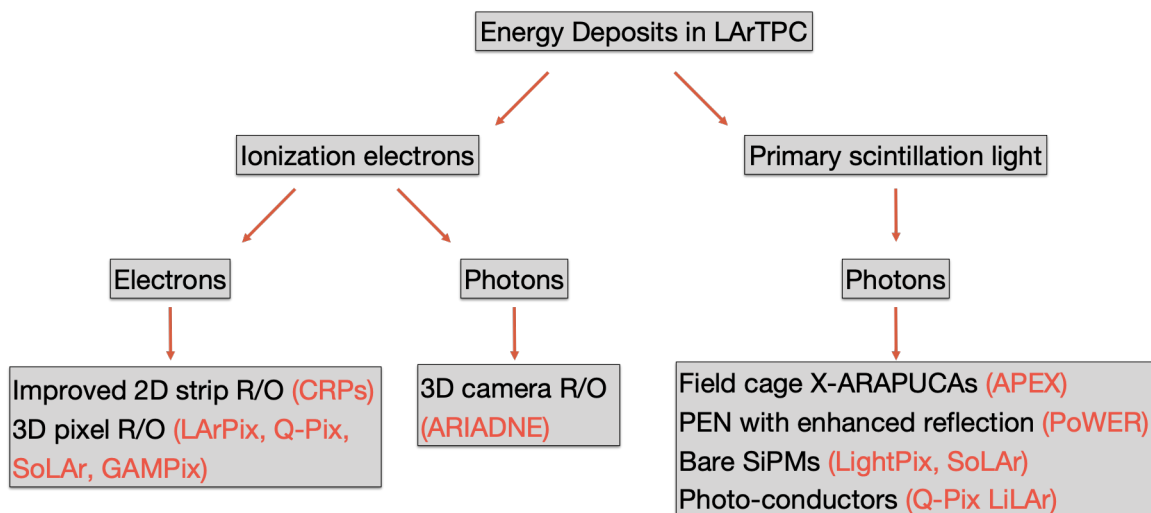
JINST 19 (2024) 12, P12005

- The phased construction program allows the development of the technology to expand the DUNE physics scope (solar, supernova neutrinos,  $0\nu\beta\beta$ , dark matter...).

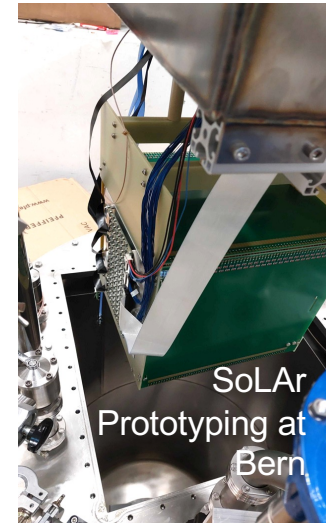


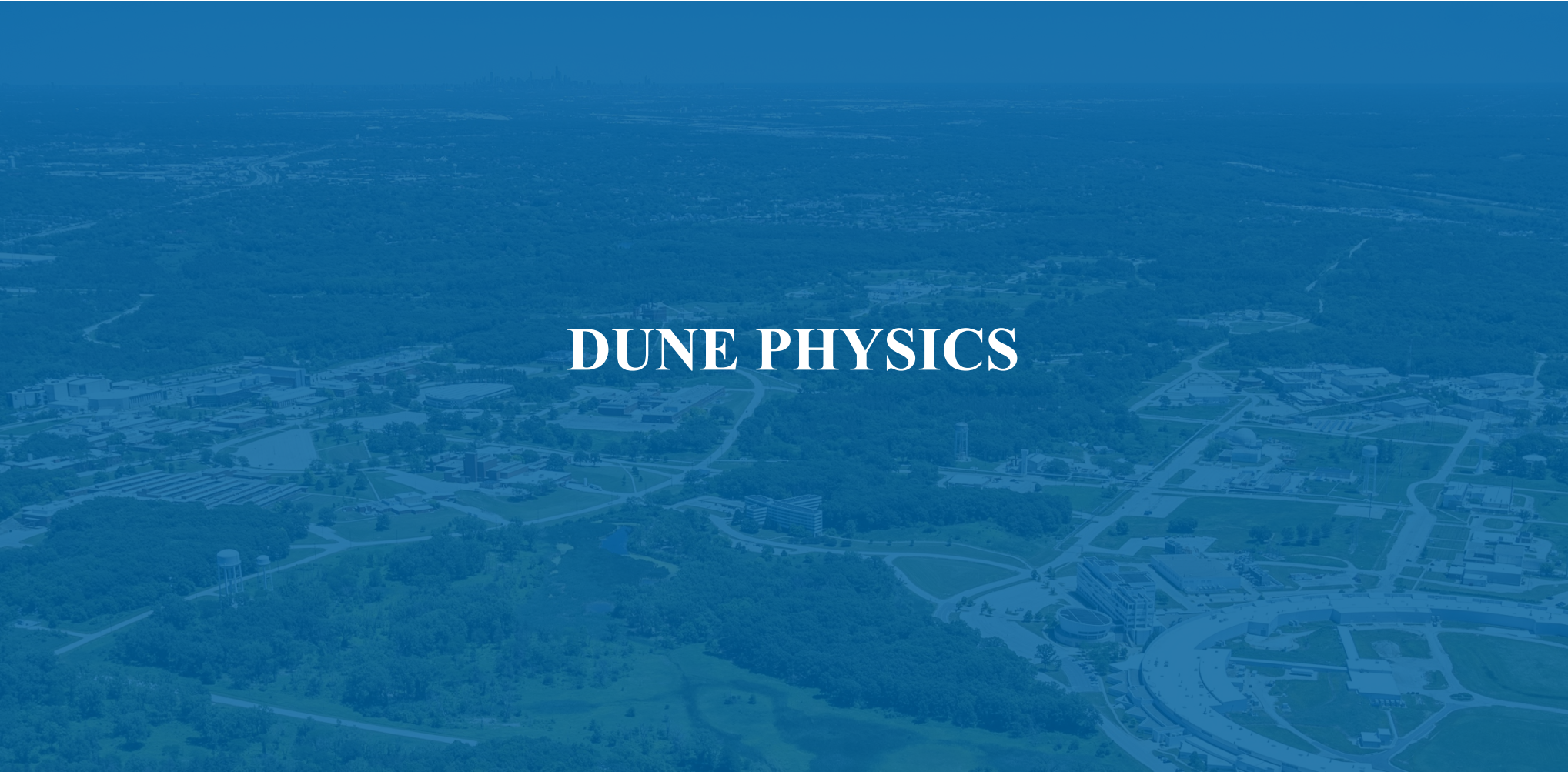
# Potential technologies

- LAr Far Detector modules: Optimized Light and Charge Readout



- Low density argon gas near detector (ND-GAr)
- Non-Argon FD Option (THEIA)
- Improved Background Mitigation





# DUNE PHYSICS



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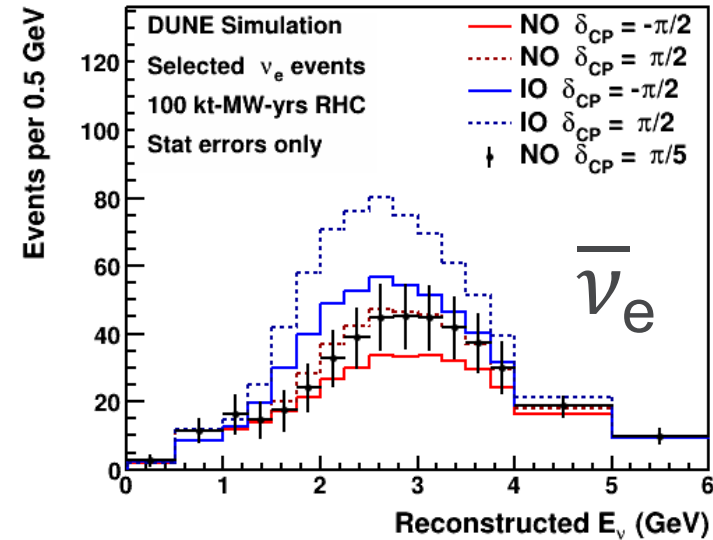
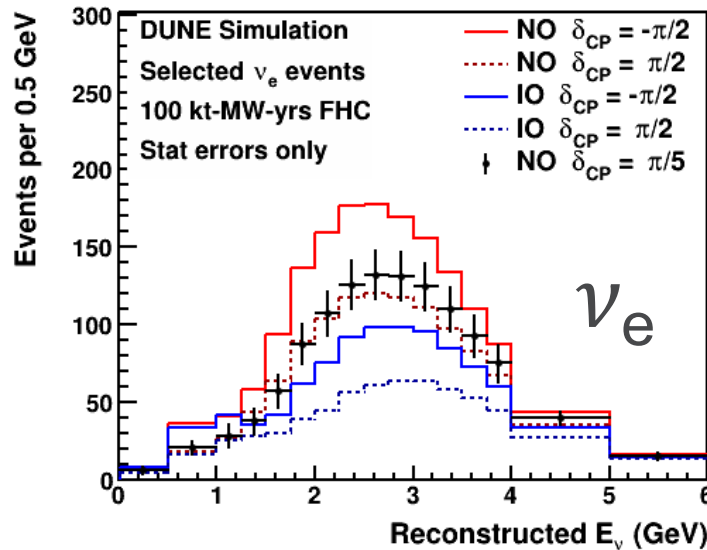
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# Neutrino energy spectra at the Far Detector

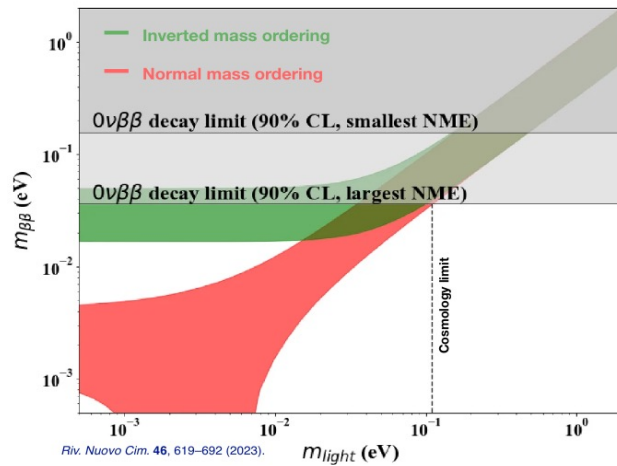
E. Phys. J. C (2020) 80:978



- Sensitivity to  $\delta_{CP}$   
-If  $\delta_{CP} \sim -\pi/2$ , DUNE measures enhancement in  $\nu_e$  and a reduction in anti- $\nu_e$  appearance.
- DUNE will measure oscillations over  $>1$  full period, long baseline  $\rightarrow$  **parameters are not degenerate, measure everything in one experiment**
- DUNE can measure **oscillation parameters at each bin of  $L/E$**   $\rightarrow$  broad  $L/E$  range is essential to resolving all parameters at once.

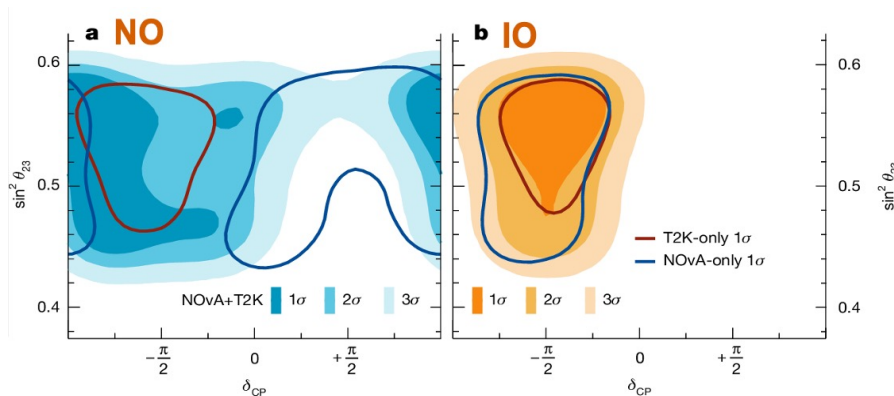


# Definitive mass ordering determination is critical



Riv. Nuovo Cim. 46, 619–692 (2023).

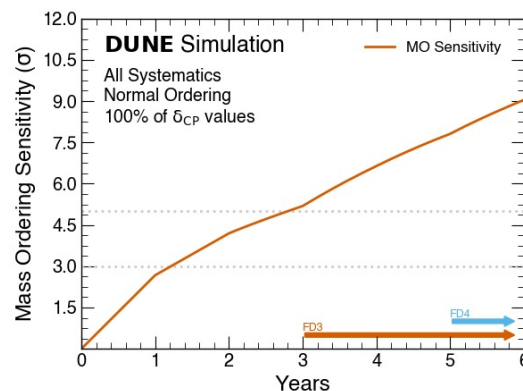
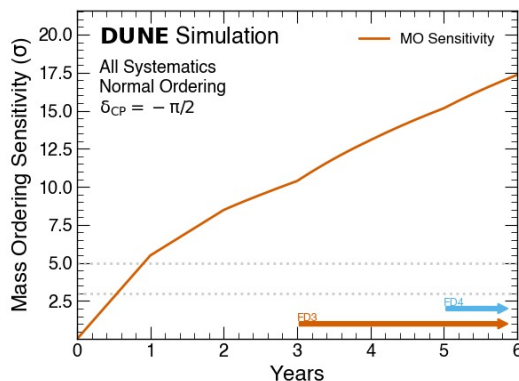
- Mass ordering affects other fields of science → want a definitive result, and we have to get it right
  - Input to cosmology
  - Informs reach and design of  $0\nu\beta\beta$
  - Informs reach and design of direct neutrino mass measurements.
- Mass ordering is needed to analyze existing and future neutrino oscillation data.



# Physics: CP violation and mass ordering

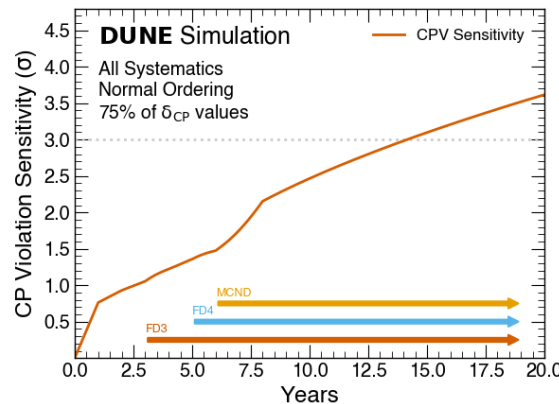
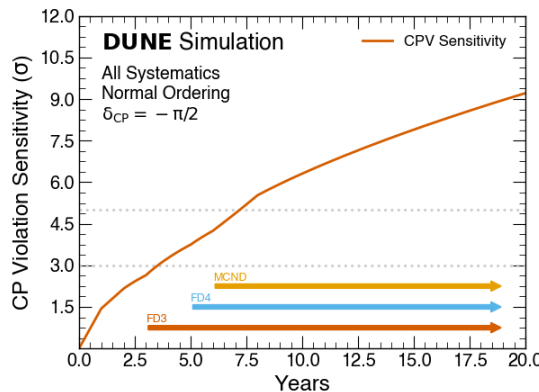
## Neutrino mass ordering

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



- For best-case oscillation scenarios, DUNE has
  - >5 $\sigma$  mass ordering sensitivity in 1 year
  - >3 $\sigma$  CPV sensitivity in 3.5 years
- For worst-case oscillation scenarios, DUNE has >5 $\sigma$  mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of  $\delta_{CP}$  values at >3 $\sigma$

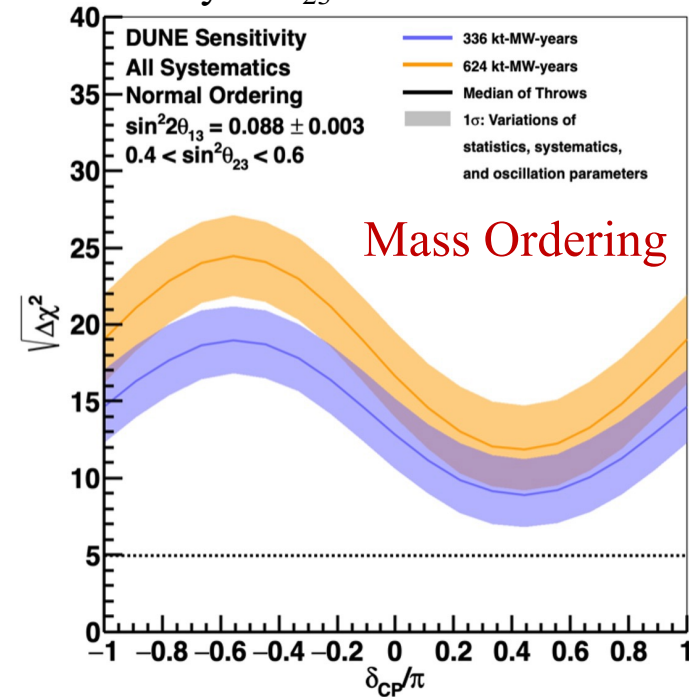
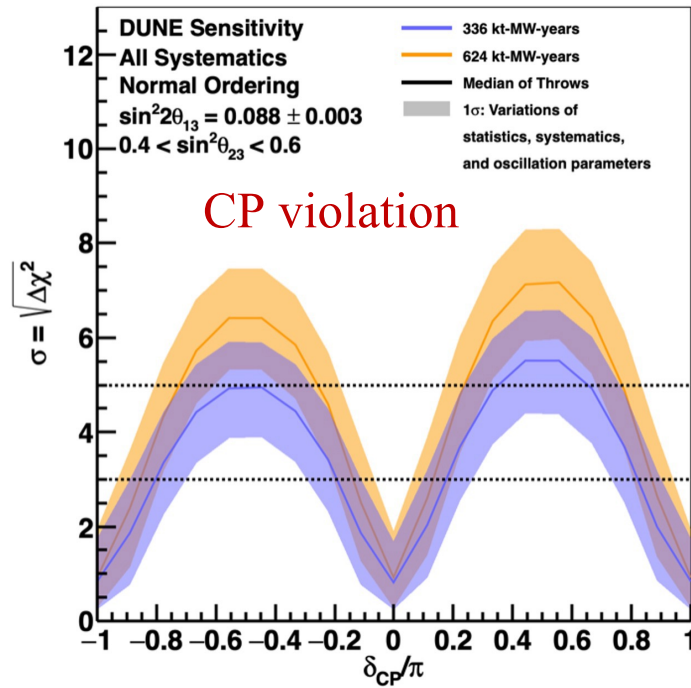
## CP violation sensitivity



# Physics: CP violation and mass ordering

*Eur. Phys. J. C*80, 978 (2020):  
“Long-baseline neutrino oscillation physics potential of the DUNE experiment”.

Bands correspond to uncertainty in  $\theta_{23}$



- $>5\sigma$  CPV discovery over a wide range of  $\delta_{CP}$
- $>5\sigma$  Mass Ordering determination for all  $\delta_{CP}$

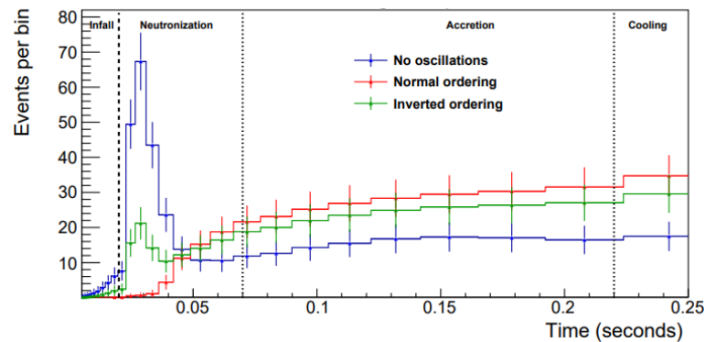


# Astrophysical neutrinos in DUNE

Unique sensitivity to MeV electron neutrinos: CC  $\nu_e + \text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$  (main channel)  
ES  $\nu_x + e^- \rightarrow \nu_x + e^-$  (pointing)

## Neutrinos from core-collapse supernovae

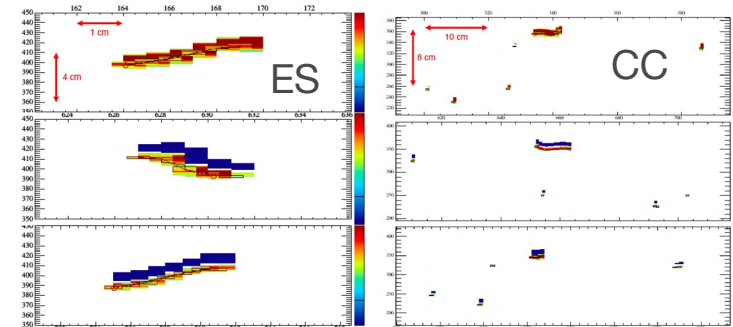
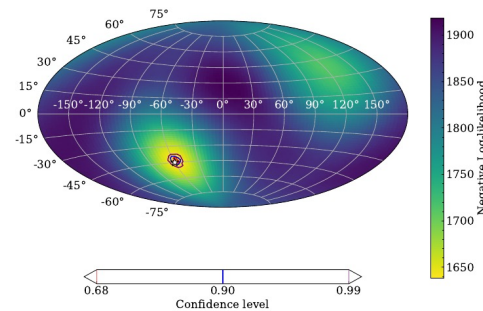
- Neutronization burst measurements  $\rightarrow$  mass ordering measurement



Eur. Phys. J. C 81 (2021) 5, 423  
Phys. Rev. D 107 (2023) 11, 112012

- Pointing capabilities: ES channel  $\sim 5^\circ$  pointing resolution (40 kt, 10 kpc)

Phys. Rev. D 111 (2025) 9, 092006



|                   | $\nu_e$ | $\bar{\nu}_e$ | $\nu_x$ |
|-------------------|---------|---------------|---------|
| DUNE              | 89%     | 4%            | 7%      |
| SK <sup>1</sup>   | 10%     | 87%           | 3%      |
| JUNO <sup>2</sup> | 1%      | 72%           | 27%     |

<sup>1</sup>Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)

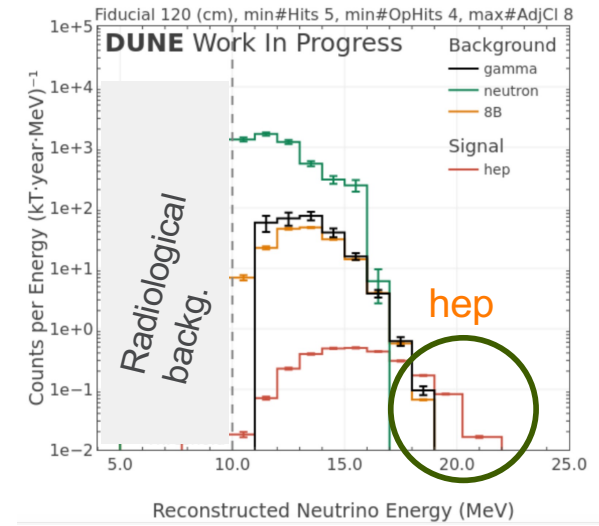
<sup>2</sup>Lu, Li, and Zhou, *Phys. Rev. D* **94** 023006 (2016)

# Astrophysical neutrinos in DUNE

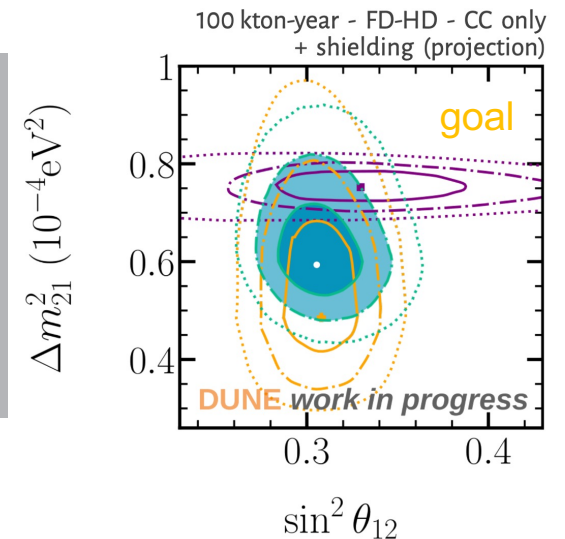
## Neutrinos from the Sun

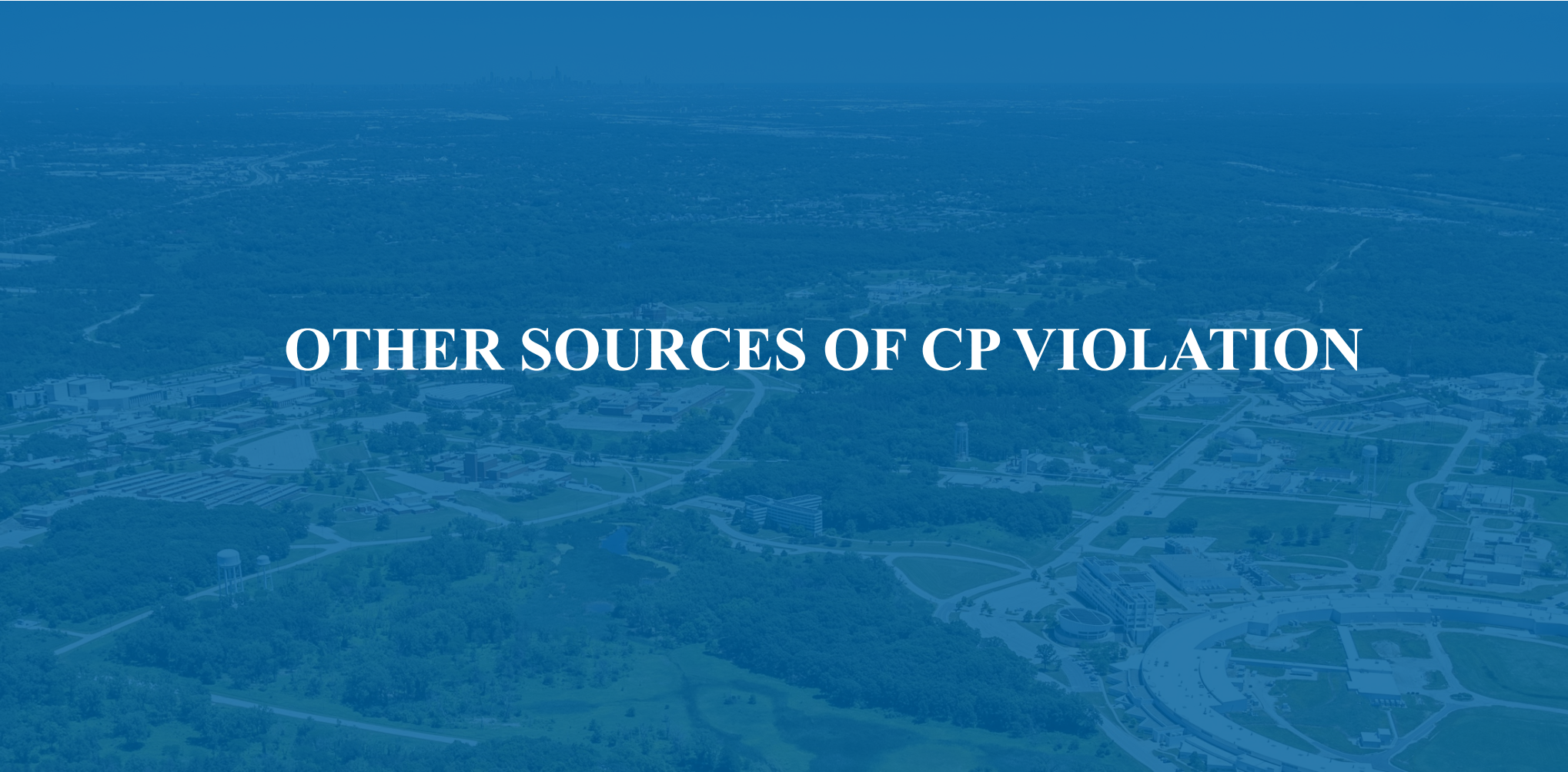
- DUNE has excellent sensitivity to  $^8\text{B}$  solar neutrinos above  $\sim 10$  MeV, and discovery sensitivity to the **hep** solar flux
- DUNE is sensitive to solar oscillation measurements via **day-night asymmetry** induced by matter effects  $\rightarrow$  comparison with JUNO

hep sensitivity in DUNE



DUNE solar oscillation sensitivity with  $^8\text{B}$





# OTHER SOURCES OF CP VIOLATION



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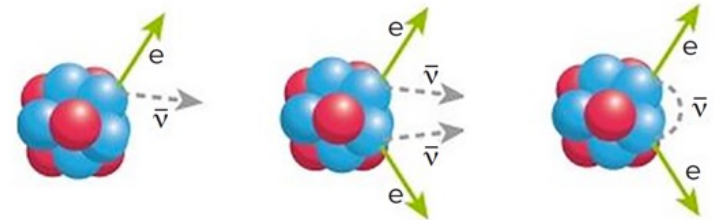
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# Majorana Neutrinos and Neutrinoless Double Beta-Decay ( $0\nu\beta\beta$ )?

- CP Violation in Majorana Neutrinos: If neutrinos are Majorana fermions there will be two additional CP violating Majorana phases.

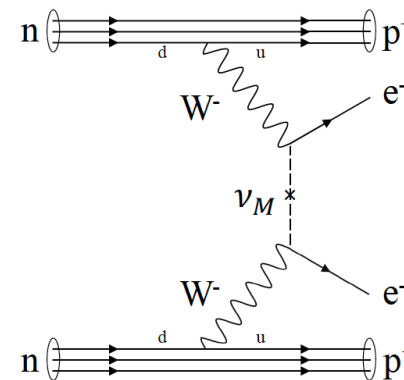
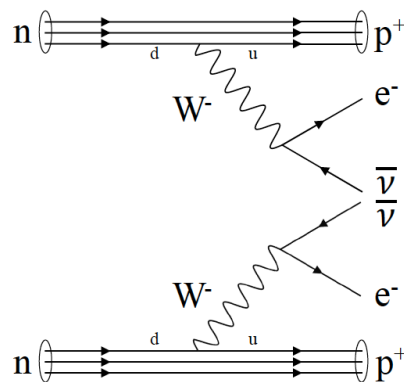


Standard  $\beta$  Decay

Double  $\beta$  Decay

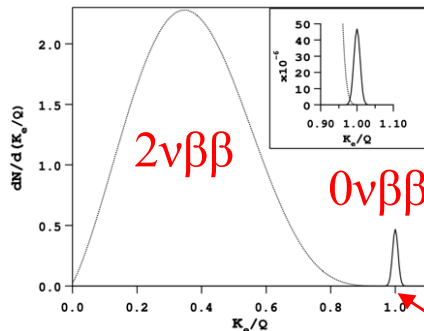
Neutrinoless Double  $\beta$  Decay

- If observed, the  $0\nu\beta\beta$  decay would demonstrate the explicit existence of lepton number violation.
  - Majorana mass term effectively produces excess of matter over anti-matter.
  - If the neutrinoless double beta-decay process occurs it may be responsible for seeding the Early Universe with ordinary matter.

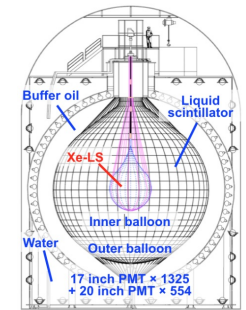


# Majorana Neutrinos and Neutrinoless Double Beta-Decay ( $0\nu\beta\beta$ )?

- Effect is attempted to be quantified through  $0\nu\beta\beta$  experiments.
- As the SM process the  $2\nu\beta\beta$  decay process conserves both baryon and lepton number  
-Observed in about a dozen isotopes.
- The  $0\nu\beta\beta$  decay is a leptogenic process that creates two out-going leptons - only possible if neutrinos are Majorana-type particles.  
-Current searches setting half-life limits of  $> 10^{26}$  years.



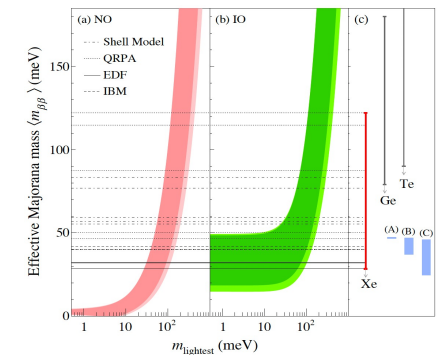
Example: KamLAND-Zen Experiment



Phys. Rev. Lett. 135, 262501 (2025)

$$[T_{1/2}^{0\nu}]^{-1} = \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2} G^{0\nu} |M^{0\nu}|^2$$

$$\langle m_{\beta\beta} \rangle = ||U_{e1}|^2 m_1 + |U_{e2}|^2 m_2 e^{i1} + |U_{e3}|^2 m_3 e^{i2}|$$

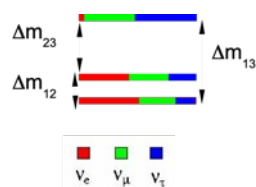


# Sterile Neutrinos?

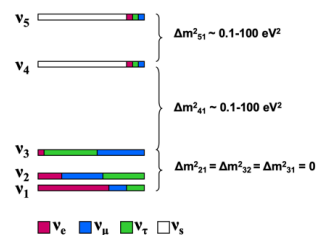
- CP violation in sterile neutrinos: If light sterile neutrinos exist and if the model is 3+2 (or higher) there will exist additional CP phases for sterile neutrinos.
- MiniBooNE results indicated  $\nu_\mu \rightarrow \nu_e$  excess of measured data over model, that could point to sterile  $\nu$ 's.

➤ Models developed with 1 or more sterile  $\nu$ 's.

In SM there are only 3 neutrinos:



If there are 2 sterile neutrinos:

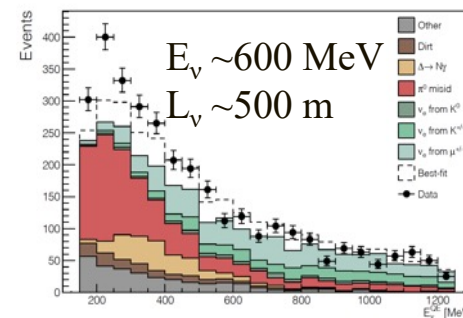


Simplified 3+2 Models for  $\nu_\mu \rightarrow \nu_e$ :

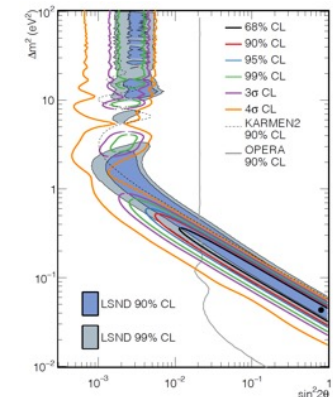
2 independent  $\Delta m^2$

3 mixing parameters

CP phases from sterile  $\nu$ 's.

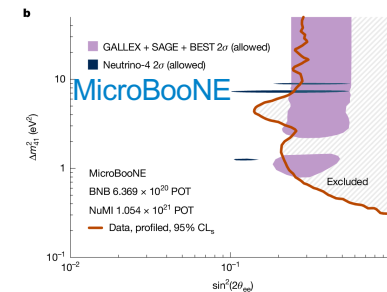
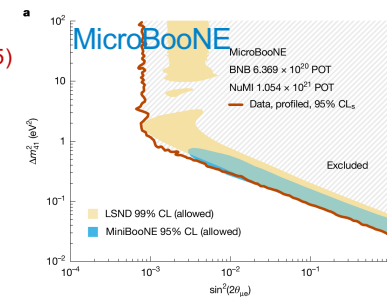


MiniBooNE: arXiv:2006.16883

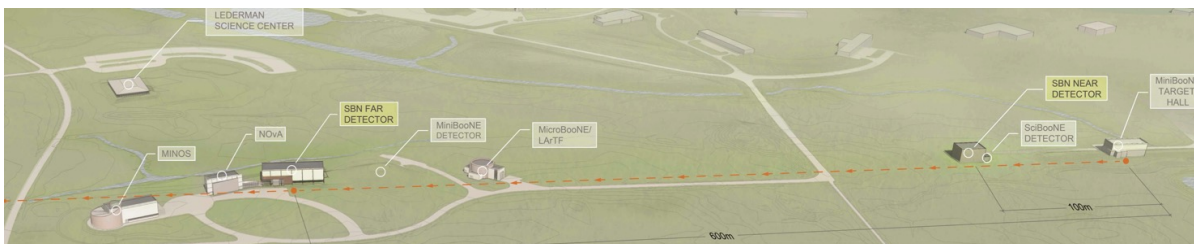


➤ MiniBooNE very recently ruled out by MicroBooNE

MicroBooNE: Nature 648, 64–69 (2025)



- To discuss this idea further: First need to find the first sterile neutrino!
- Ongoing searches with reactor and accelerator neutrinos at short L's.
- Examples: PROSPECT, MicroBooNE; see KATRIN.







# SUMMARY



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- **With the demonstration on non-zero neutrino mass, we are now positioned to investigate the question of CP-violation.**
- **The DUNE, as the next-generation long-baseline neutrino oscillation experiment**, consisting of
  - High-power, broadband neutrino beam
  - Highly capable near detector located on site at Fermilab, in Batavia, Illinois, and
  - Massive liquid argon time projection chamber (LArTPC) far detector located 1300 km from neutrino source, deep underground at the Sanford Underground Research Facility (SURF)
  - LAr TPC technology, full tracking and calorimetry.
- **The DUNE, with Near and Far Detectors, is planned to measure  $\delta_{CP}$  over a large range of values**
  - Precise measurements of all the parameters governing long-baseline  $\nu$  oscillation in single experiment
  - Sensitivity to observe neutrinos from a core collapse supernova and BSM physics processes.
  - We hope for a discovery!
- **DUNE construction is phased to provide continuous progress toward physics goals**
  - Physics should begin late 2020s (Phase I) and the collaboration is active in planning upgrades to achieve full scope in 2030s (Phase II)
  - Plenty of opportunities for additional participation.
- **Neutrinoless double-beta decay ( $0\nu\beta\beta$ ) is a powerful tool to test Lepton Number Violation**
  - Majorana phases could present additional source of CP-violation
  - Determination of absolute neutrino mass.
- **Sterile neutrinos are actively probed in short-baseline searches**
  - If light sterile neutrinos exist there will exist additional CP phases for sterile neutrinos.
  - Results are coming from several efforts.
- **This is exciting time: stay tuned for new developments in neutrino sector.**