CSU HEPPA Group and the Deep Underground Neutrino Experiment

Prof. Mike Mooney

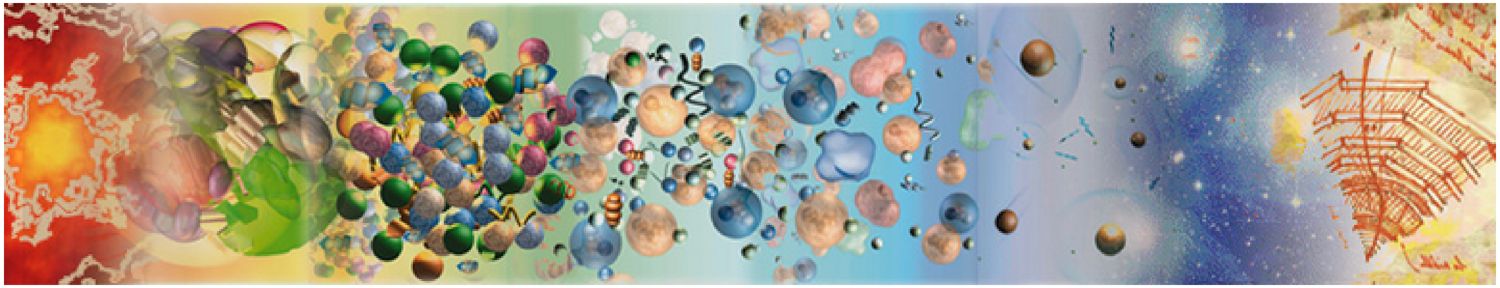
Colorado State University

QuarkNet 2020 CSU STEP UP Virtual Workshop

August 5th, 2020

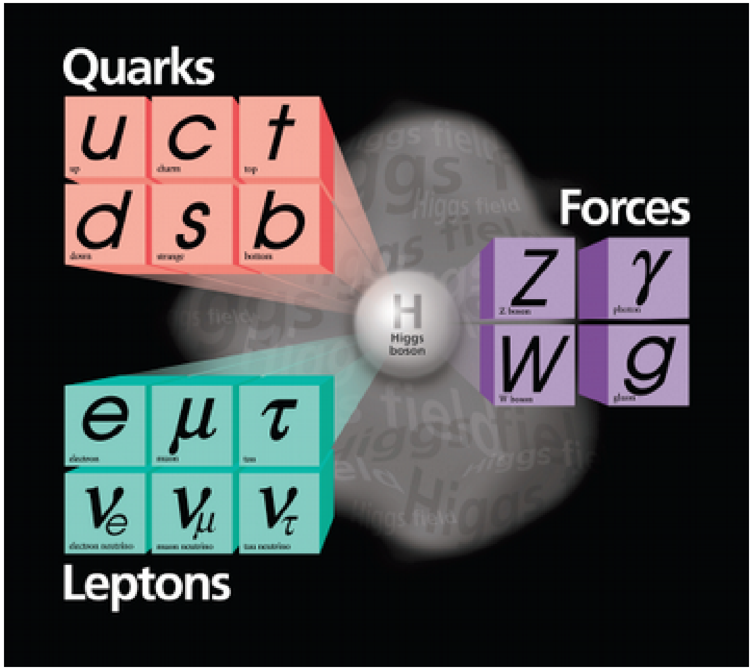
What is High Energy Physics?

- Particle physics explores the fundamental constituents of matter and energy, the interactions between them, and the nature of space and time.
- It reveals the profound connections underlying everything we see, including the smallest and the largest structures in the Universe.



Mysteries of Particle Physics

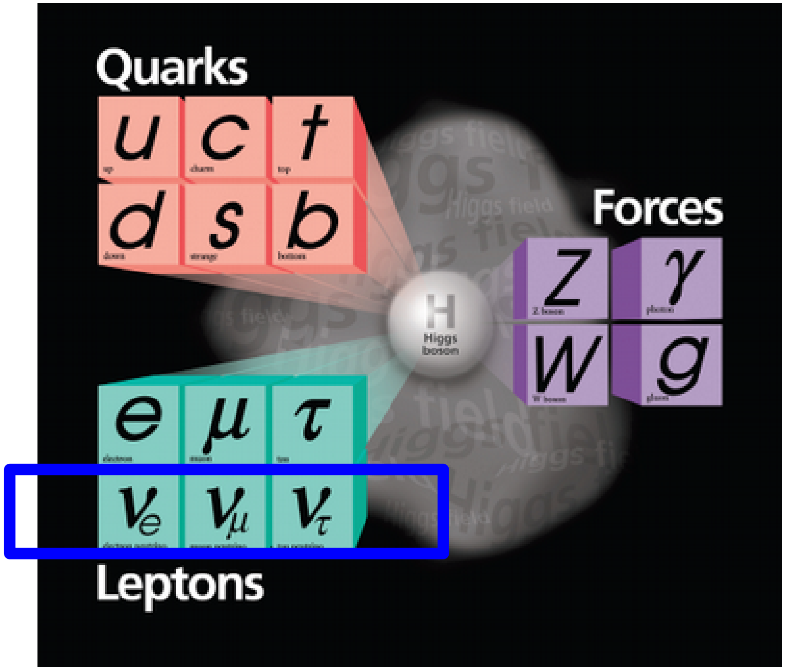
- Still **many open questions**
- We still don't understand the nature of 95% of the universe
  - What is dark matter?
  - What is dark energy?
- Gravity unexplained by Standard Model
  - Graviton? New theory?



- Do neutrinos of the Standard Model mix with other states?
  - Are there sterile neutrinos?
- What is the ordering of the neutrino mass states?
- Origin of matter-antimatter asymmetry in universe?

Mysteries of Particle Physics

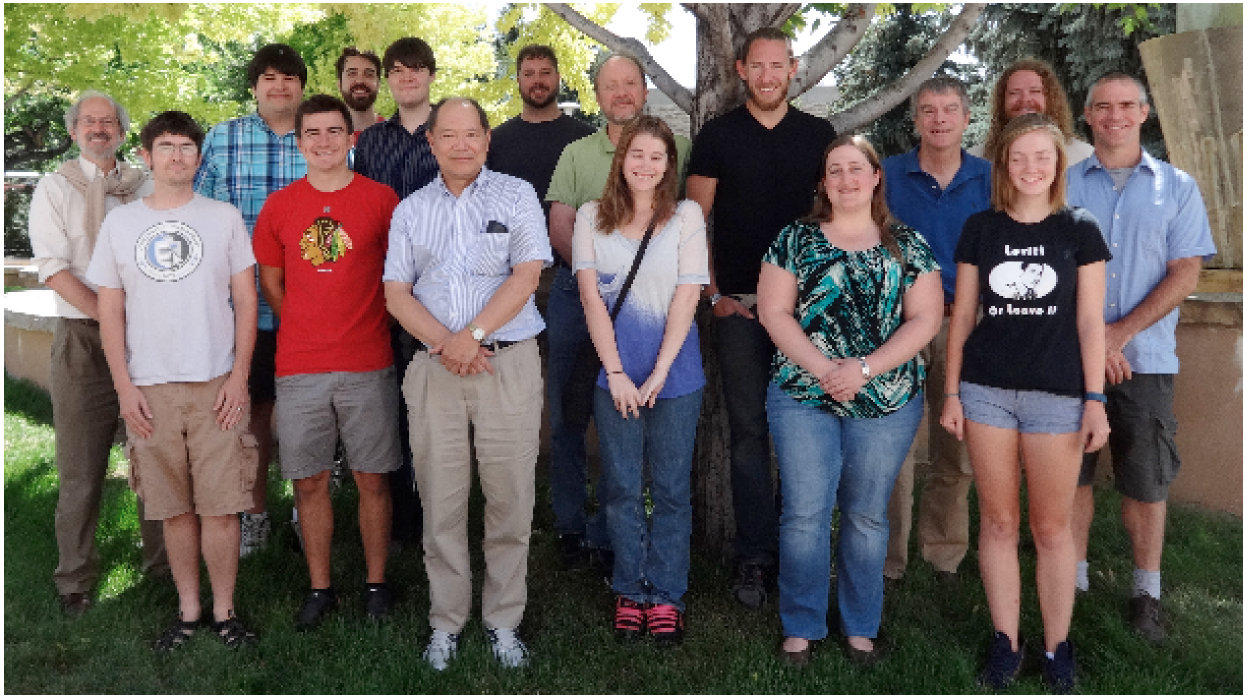
- Still **many open questions**
- We still don't understand the nature of 95% of the universe
  - What is dark matter?
  - What is dark energy?
- Gravity unexplained by Standard



Big Focus of CSU HEPPA Group!

- Do neutrinos of the Standard Model mix with other states?
  - Are there sterile neutrinos?
- What is the ordering of the neutrino mass states?
- Origin of matter-antimatter asymmetry in universe?

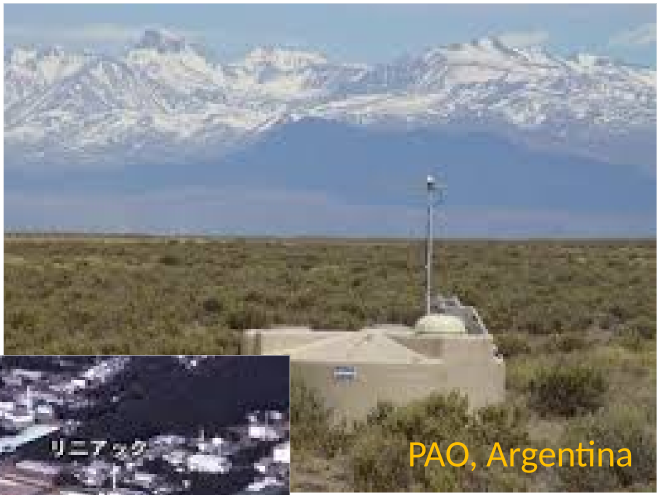
HEPPA Group Aug. 2016
(some missing 😞)



Aug. 2017

Have Physics, Will Travel!

Fermilab, IL



PAO, Argentina

Tokai, Japan

Stanford, CA

CERN, Switzerland/France

CSU HEPPA Faculty

- Prof. Mike Mooney
  - MicroBooNE, SBN, DUNE
- Prof. Norm Buchanan
  - NOνA, DUNE
- Prof. Bob Wilson
  - SBN, DUNE, T2K (formerly)
- Prof. Walter Toki – retired
  - T2K
- Prof. John Harton
  - DRIFT, DUNE
- Prof. Bill Fairbank
  - Closely related, but work is on *atomic physics* (EXO-200/nEXO, neutrinoless double beta decay experiments)


Mike

Norm



Bob

Walter

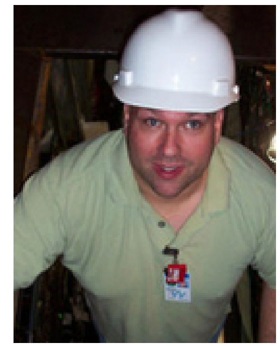


John

CSU HEPPA Faculty

- Prof. Mike Mooney
  - MicroBooNE, SBN, DUNE
- Prof. Norm Buchanan
  - NOvA, DUNE
- Prof. Bob Wilson
  - SBN, DUNE, T2K (formerly)

Mike



Norm

Bob

John

XO-200/nEXO,

New Hire:
Josh Berger
Assistant Professor

Research Focus on HEP Theory (Neutrinos, Dark Matter)

Mooney Group

Mike Mooney
Assistant Professor

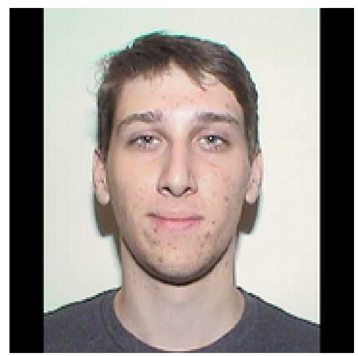
Ivan Caro Terrazas
Graduate Student

Ryan LaZur
Graduate Student

Justin Mueller
Graduate Student

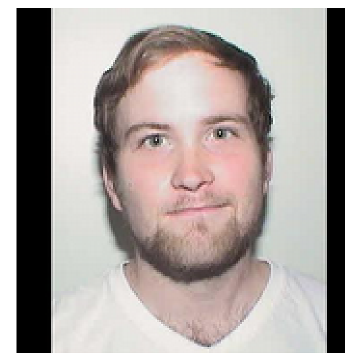
Lane Kashur
Graduate Student

Alex Flesher
Undergraduate



Erik Klemm
Undergraduate

Sean Coleman
Undergraduate



David Durney
Undergraduate

- Experiments: MicroBooNE, SBN, DUNE
- Interests: LArTPC R&D, developing novel reconstruction/calibration techniques, neutrino cross section measurements, neutrino oscillation physics

Mooney Group

Mike Mooney
Assistant Professor

Ivan Caro Terrazas
Graduate Student

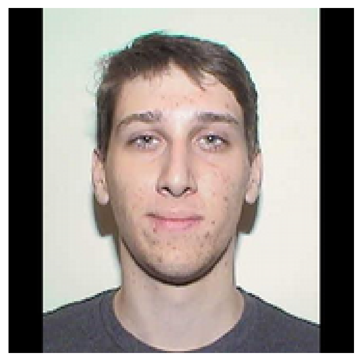
Ryan LaZur
Graduate Stude

Hannah Rogers
Former Postdoc

Now Assistant Professor at St. Catherine University

Lane Kashur
Graduate Student

Alex Flesher
Undergraduate



Erik Klemm
Undergraduate

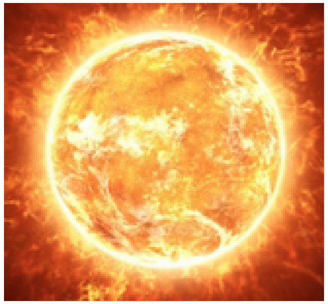
Sean C
Underg

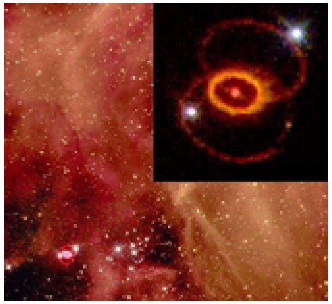
- <u>Experiments</u>: MicroBooNE, SBN, DUNE
- <u>Interests</u>: LArTPC R&D, developing novel reconstruction/calibration techniques, neutrino cross section measurements, neutrino oscillation physics

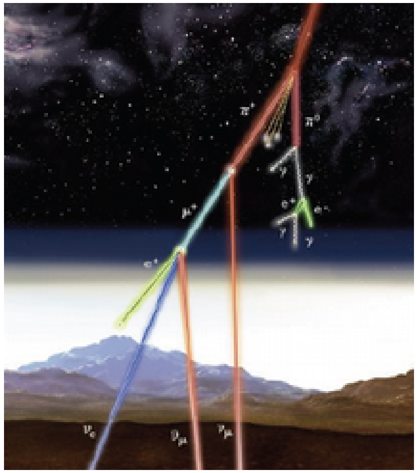
Why Care About Neutrinos?

... They're Everywhere!

- Many open questions focus on least well-known (discovered) particle: the **neutrino (ν)**
  - Elusive nature due to **weak interaction** with matter
- Produced everywhere:
  - Atmosphere
  - Nuclear reactors
  - **Particle accelerators**
  - Earth's interior
  - Sun (and other stars)
  - Supernovae
  - Big Bang

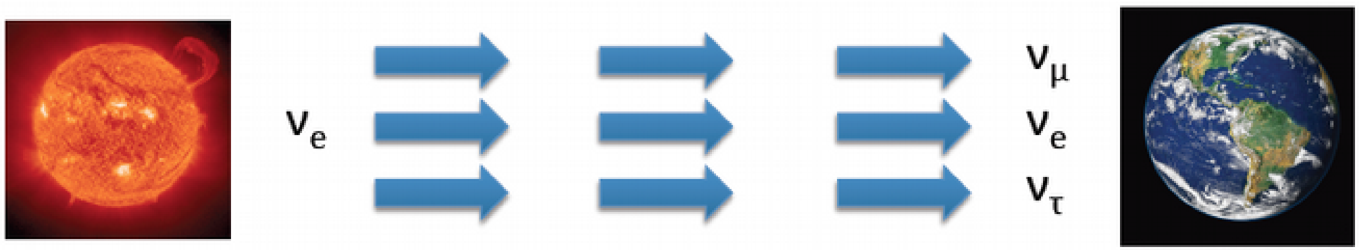




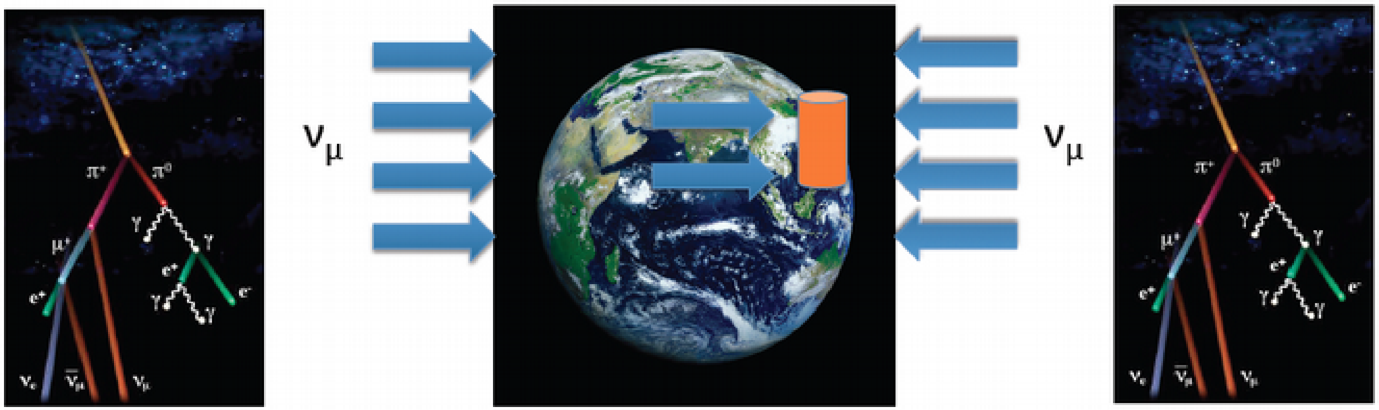


... They Change Identities!

- One of the biggest experimental surprises of last century: neutrinos **oscillate** from one flavor to another



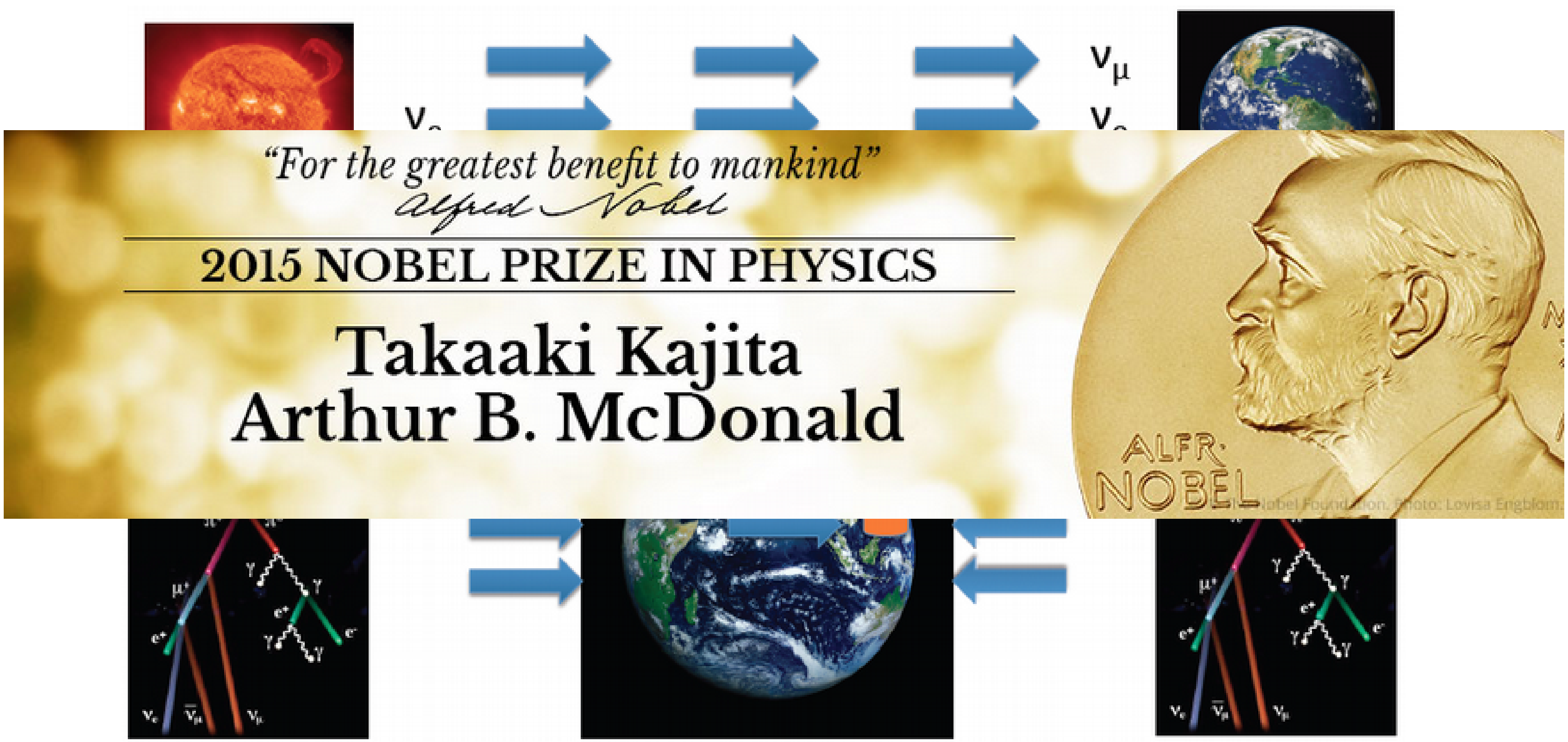
SNO Experiment: Solar Neutrino Oscillation



Super-Kamiokande Experiment: Atmospheric Neutrino Oscillation

… They Change Identities!

- One of the biggest experimental surprises of last century: neutrinos **oscillate** from one flavor to another



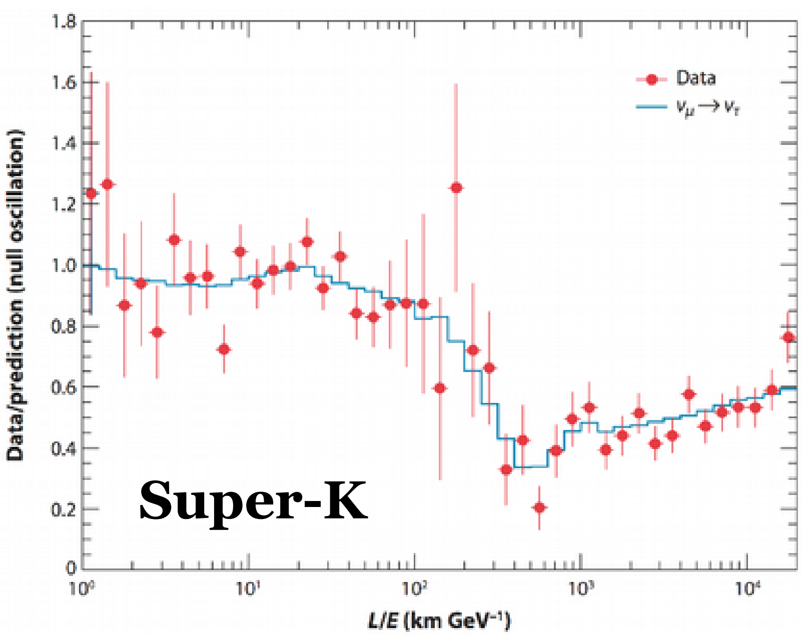
Super-Kamiokande Experiment: <u>Atmospheric</u> Neutrino Oscillation

... They Have Mass!

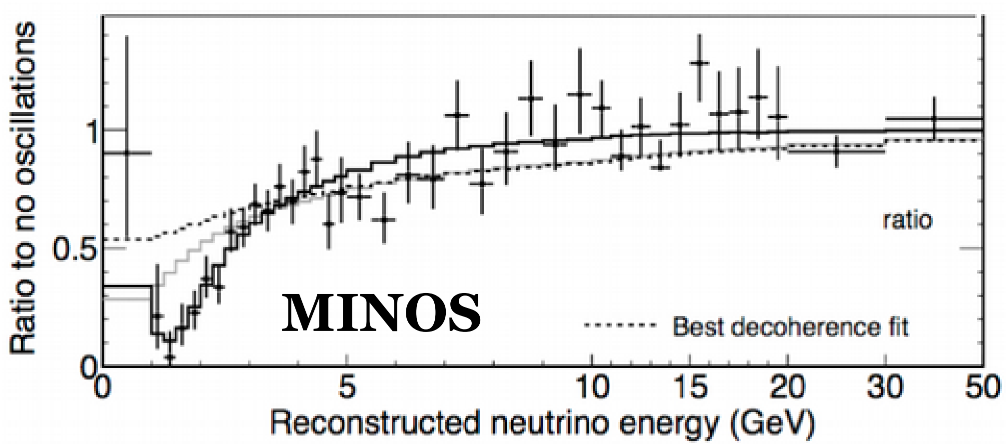
- Neutrinos oscillate → neutrino flavors mix → **neutrinos have mass!** **Not predicted by Standard Model!**

Two-Flavor Approximation:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

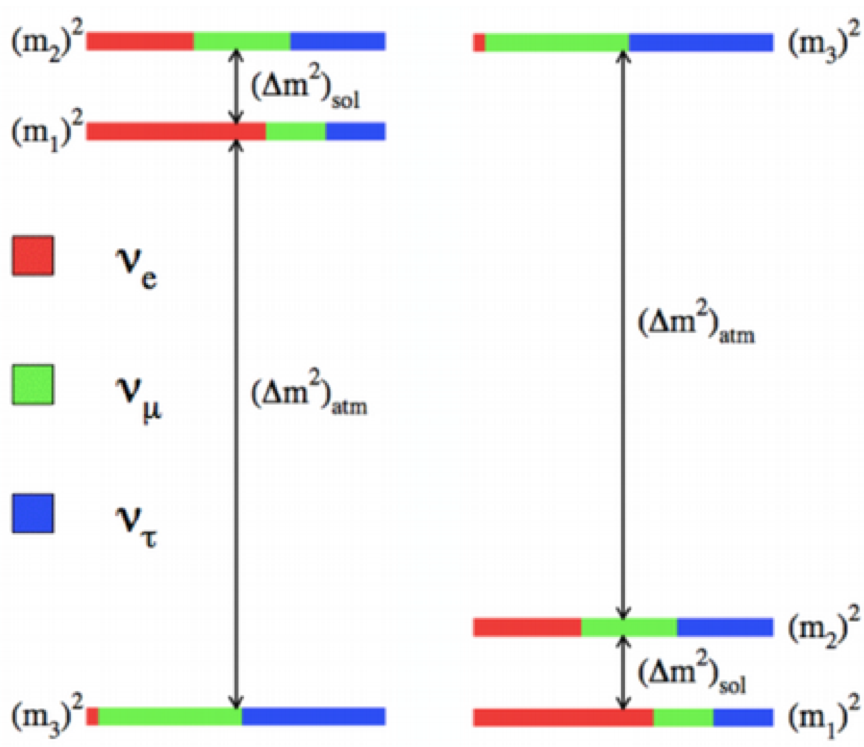


See oscillations in data, with multiple experiments using different detector technology and neutrino sources!



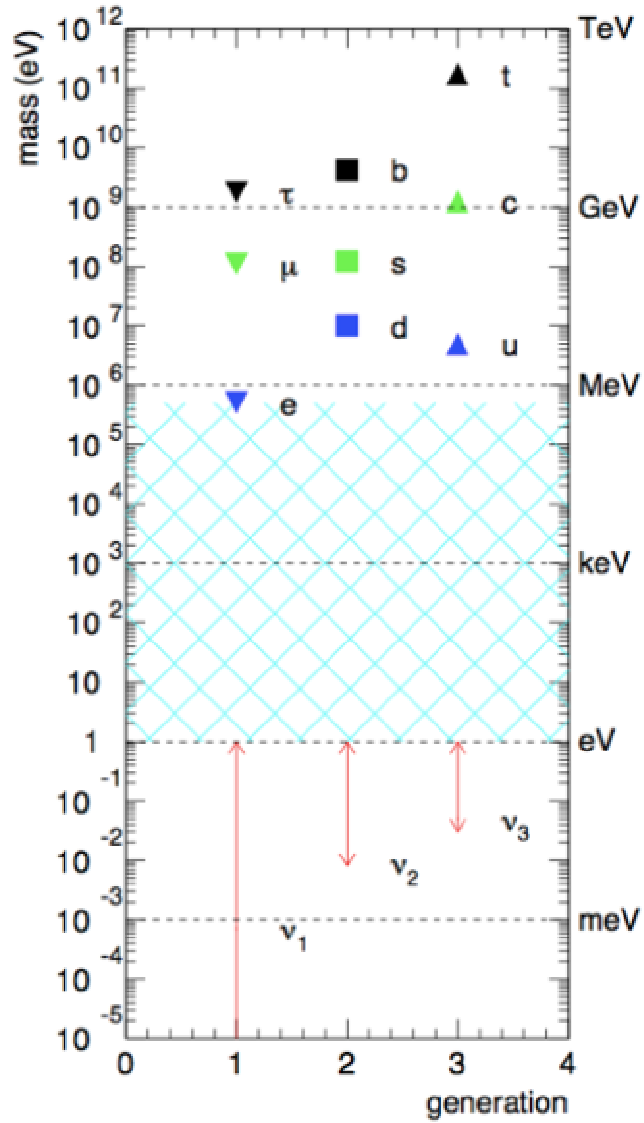
Ordering Neutrino Mass

- <u>Open question</u>: is neutrino mass ordering "normal" or "inverted"?



"Inverted" Mass Ordering

"Normal" Mass Ordering



We Are Made of Matter

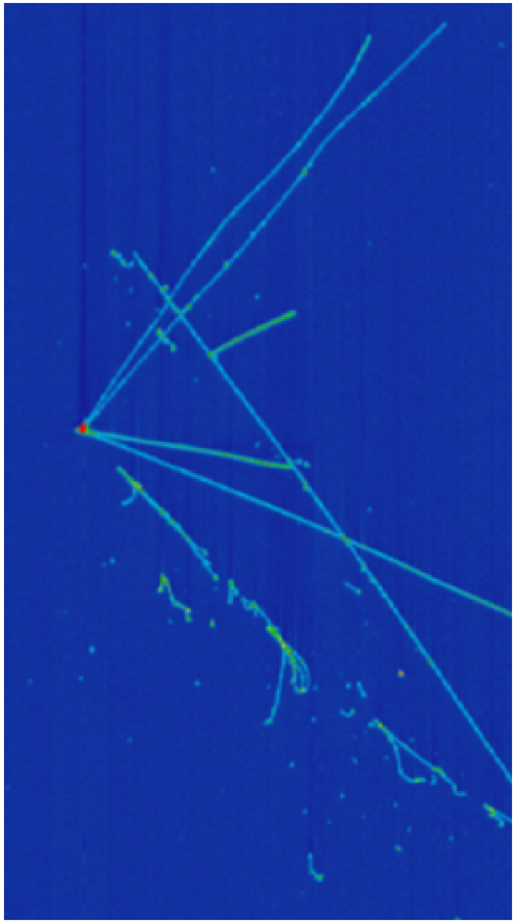
- Open question: do neutrinos **violate CP** (charge-parity)?
  - Or: do neutrinos and antineutrinos have different oscillation probabilities? (smoking-gun feature of non-zero δ_{CP})
  - Could explain **matter-antimatter asymmetry in universe**
    - … and as a result, why we exist!
    - Not enough quark sector CP violation to explain this asymmetry
  - If so, precise measurement of δ_{CP} tells us details of mechanism
  - **If not**, there must be **new physics** to explain asymmetry!

$$\boxed{\begin{gathered} P(\nu_\alpha \to \nu_\beta) \stackrel{?}{=} P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \\ \sin\delta \stackrel{?}{=} 0 \end{gathered}}$$

The LArTPC and DUNE

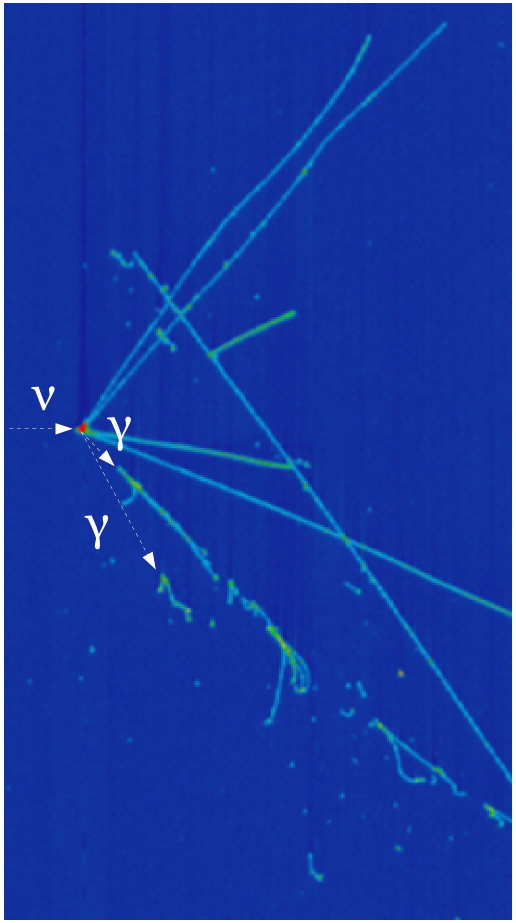
Introducing… the LArTPC

- Accelerator ν physics detector needs:
  - **Excellent calorimetry**
  - **High spatial resolution**
  - **Scalability**
- These are all traits of the LArTPC!
  - **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber
- **Excellent calorimetry** important for event reconstruction, particle ID (dE/dx)
- **High spatial resolution** allows for background rejection and particle ID
- **Scalability** → large detectors
  - **DUNE:** 40 kt LArTPC!



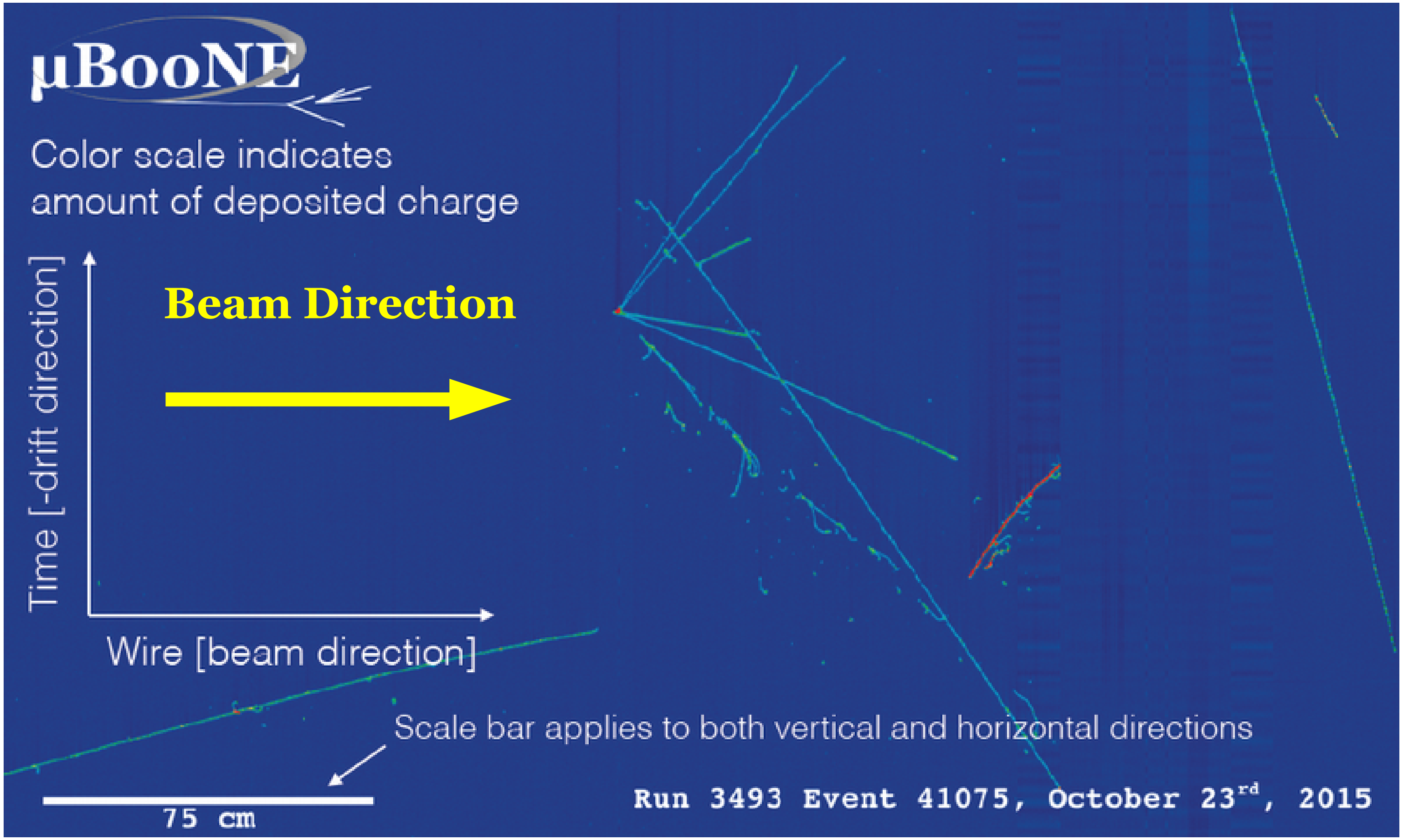
Introducing… the LArTPC

- Accelerator ν physics detector needs:
  - **Excellent calorimetry**
  - **High spatial resolution**
  - **Scalability**
- These are all traits of the LArTPC!
  - **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber
- **Excellent calorimetry** important for event reconstruction, particle ID (dE/dx)
- **High spatial resolution** allows for background rejection and particle ID
- **Scalability** → large detectors
  - **DUNE:** 40 kt LArTPC!

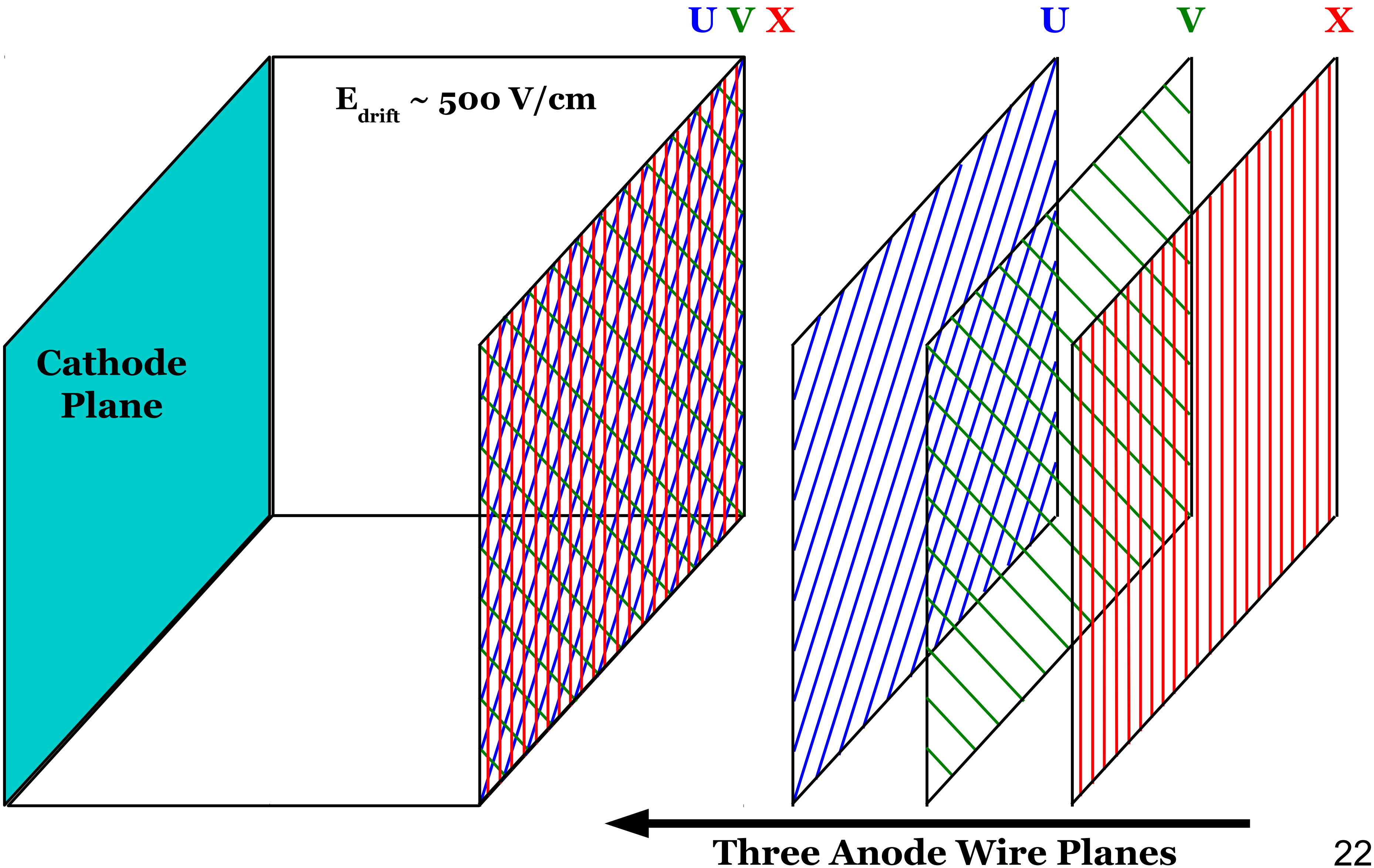


MicroBooNE Event Display

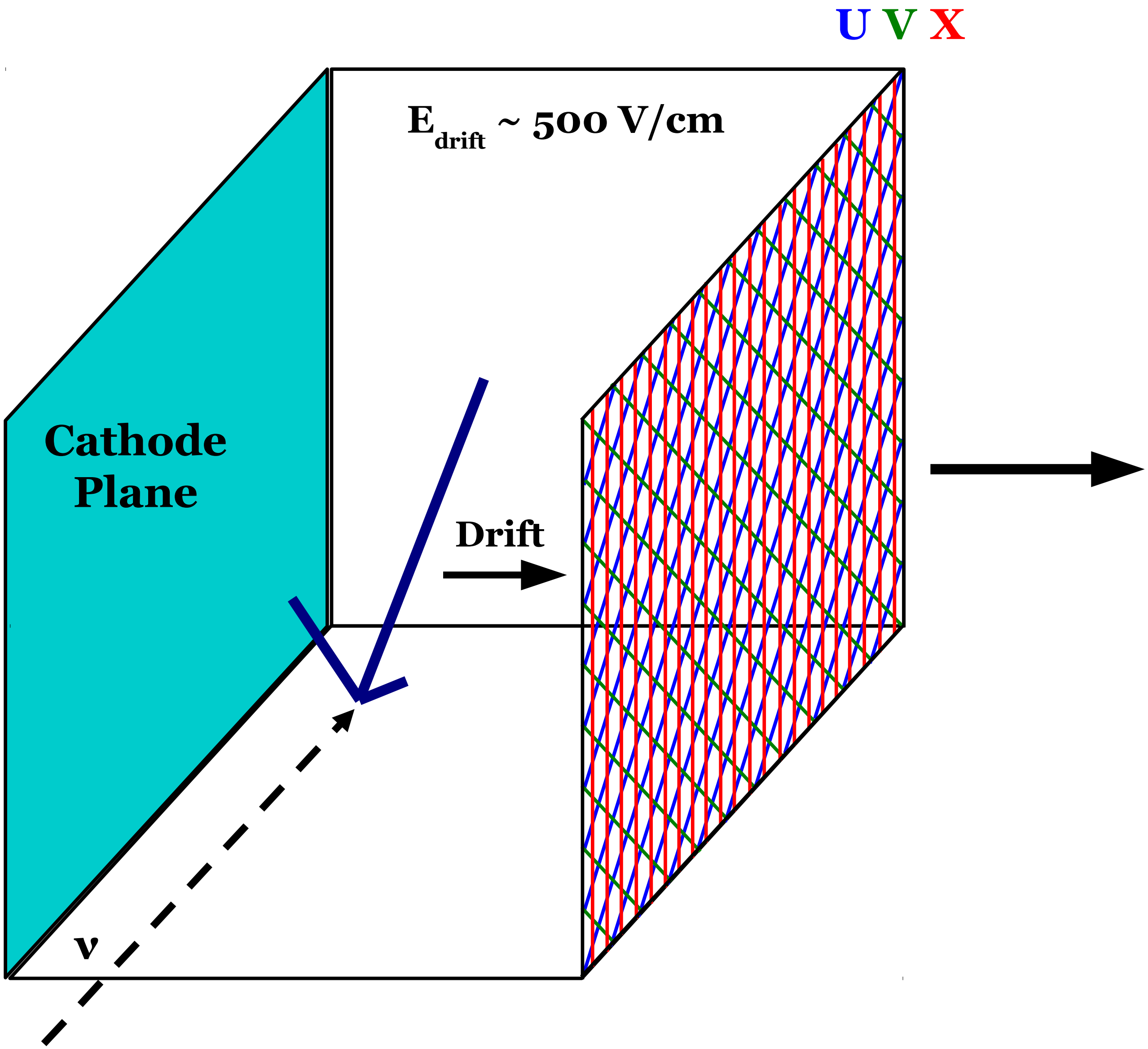
- Raw data representations are images with very fine-grained spatial resolution (~1 mm)!

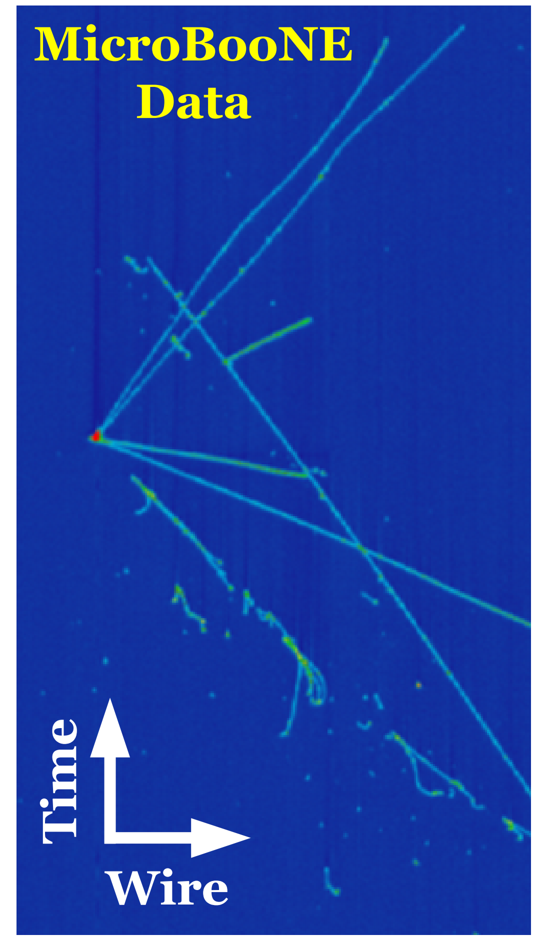


Signal Formation



Signal Formation

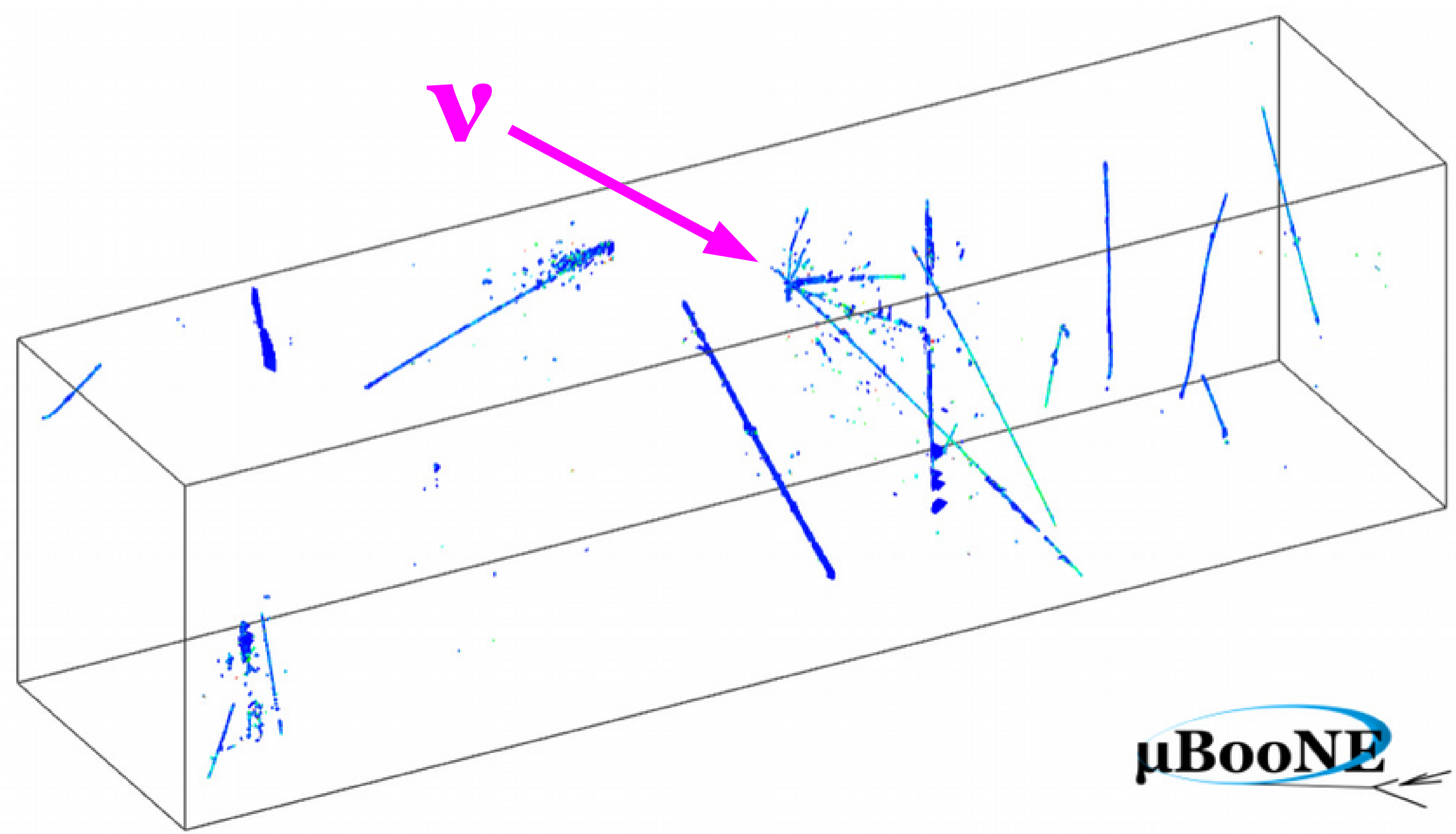




Three Images (One Per Wire Plane)

3D Event Reconstruction

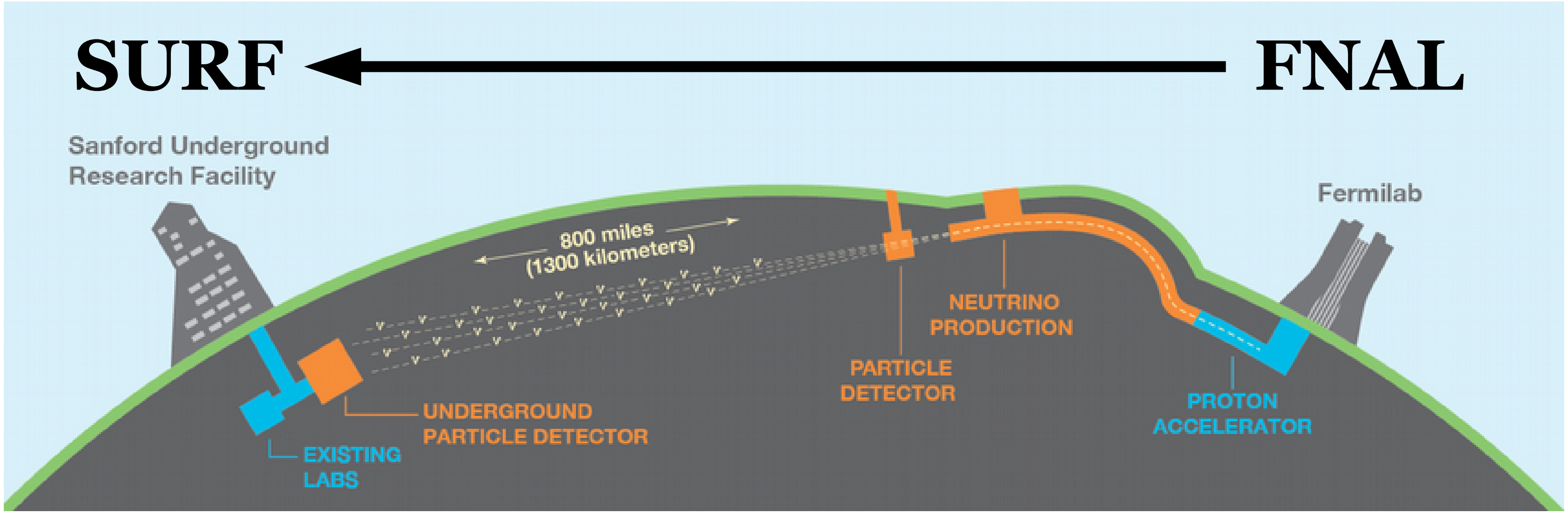
- Combine two/three 2D wire plane views → reconstruct event in **3D**
  - <u>Below</u>: **neutrino interaction** event from **data**



Introducing DUNE

- "Deep Underground Neutrino Experiment"
  - 1300 km baseline
  - Large (70 kt) LArTPC **far detector** 1.5 km underground
  - **Near detector** w/ LAr component

- Primary physics goals:
  - ν oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - $\boldsymbol{\delta_{CP}}$, θ_{23}, θ_{13}
    - **Ordering of ν masses**
  - Supernova burst neutrinos
  - BSM processes (baryon number violation, NSI, etc.)



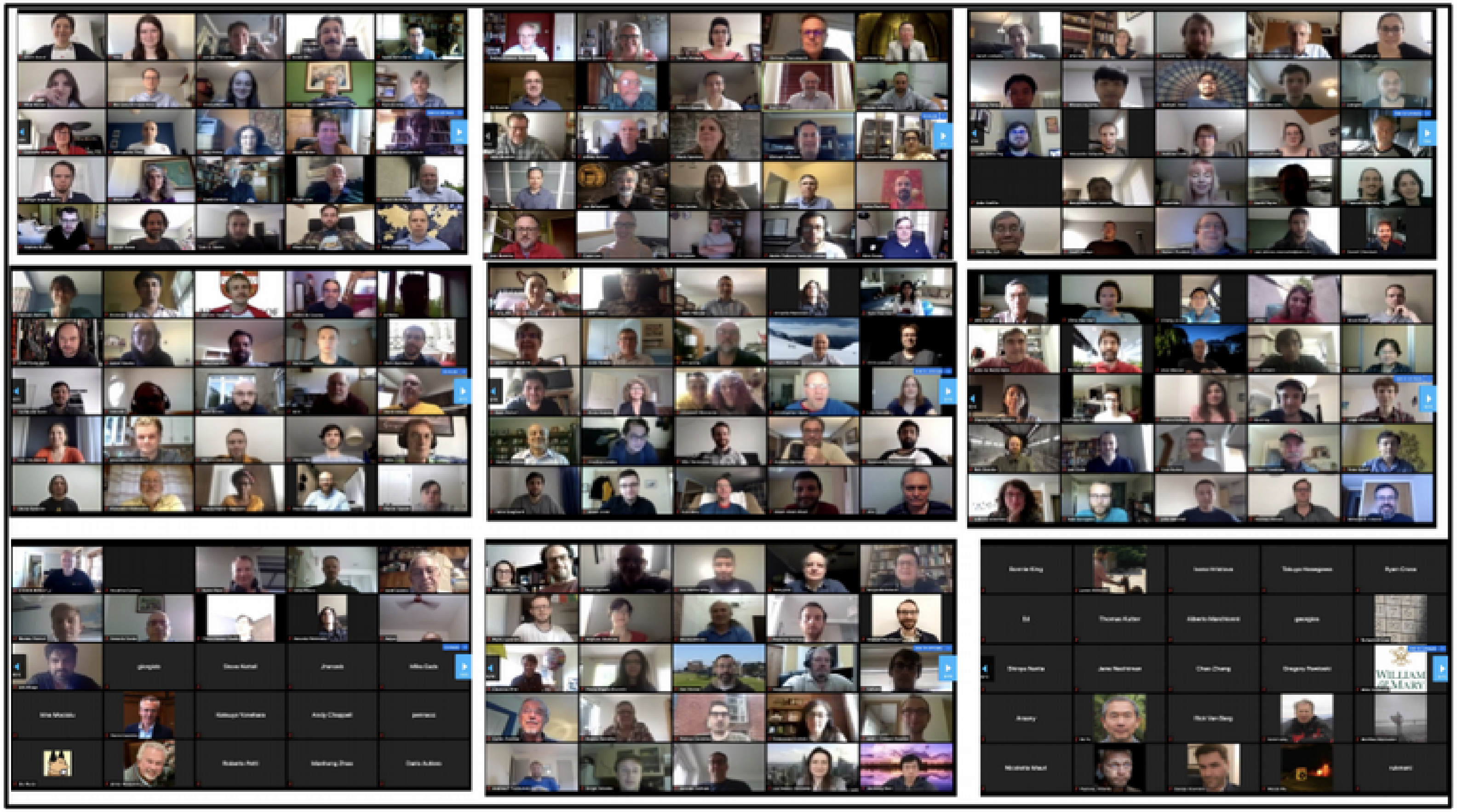
DUNE Collaboration

- **1157 collaborators** from 197 institutions in 33 countries (w/ CERN)!

May 2019 **Collaboration Meeting**

DUNE Collaboration

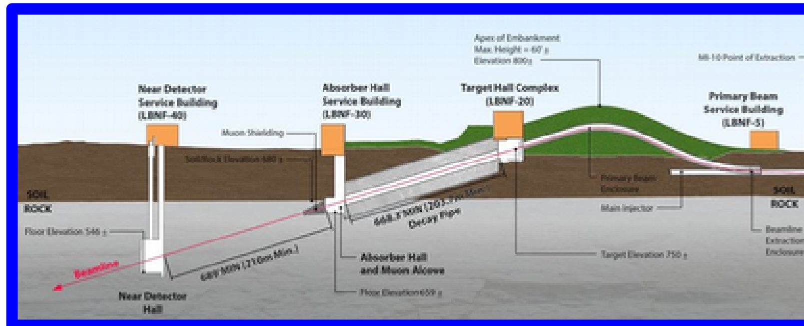
- **1157 collaborators** from 197 institutions in 33 countries (w/ CERN)!

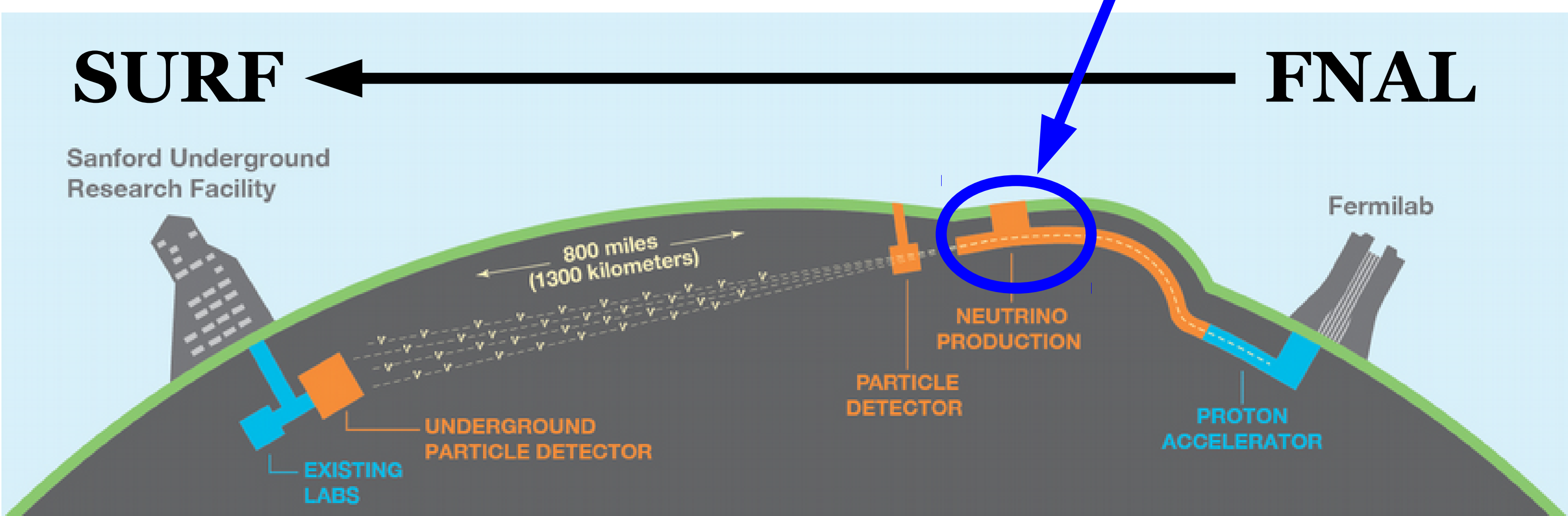


May 2020 **Collaboration Photo**

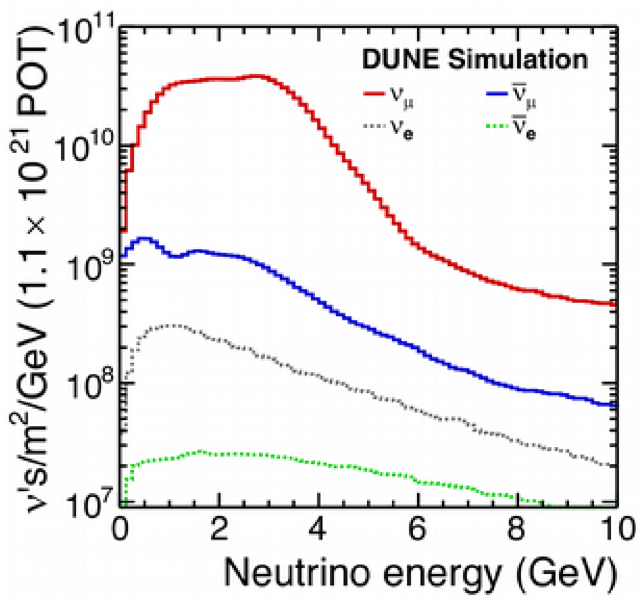
DUNE's Neutrino Source

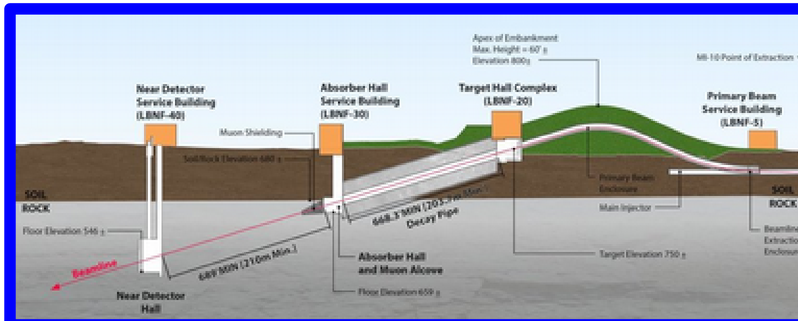
DUNE's Neutrino Source: LBNF Beam

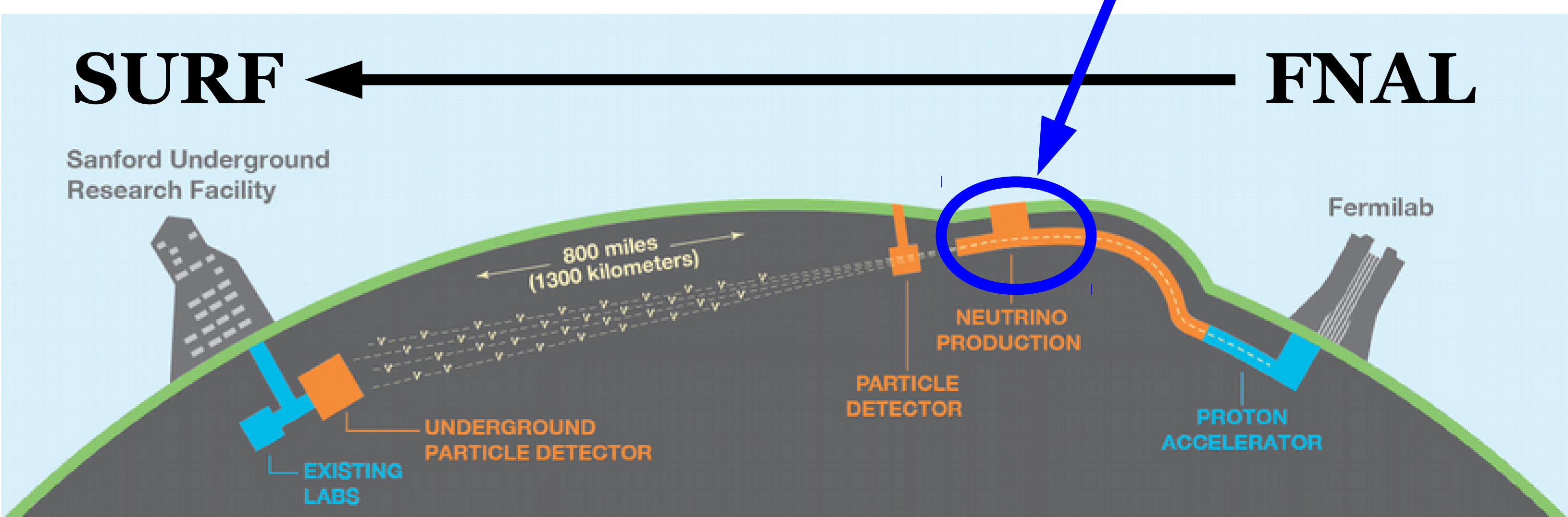




DUNE's Neutrino Source

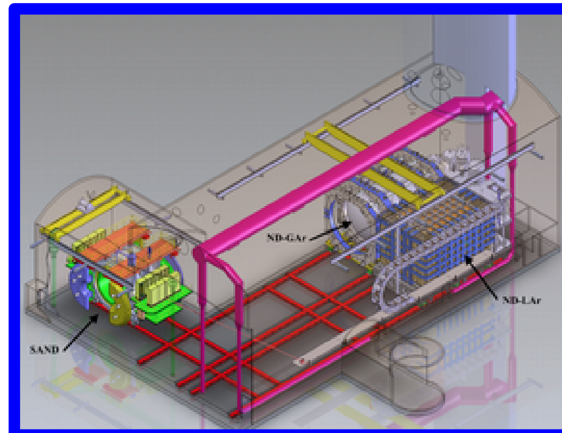


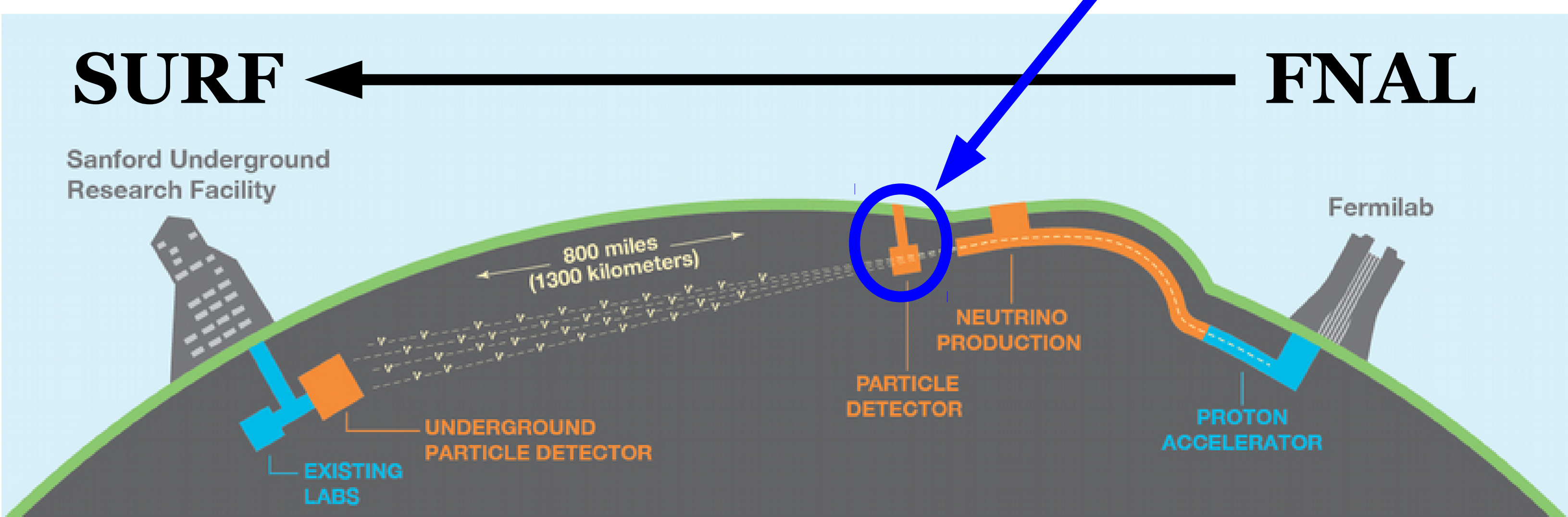




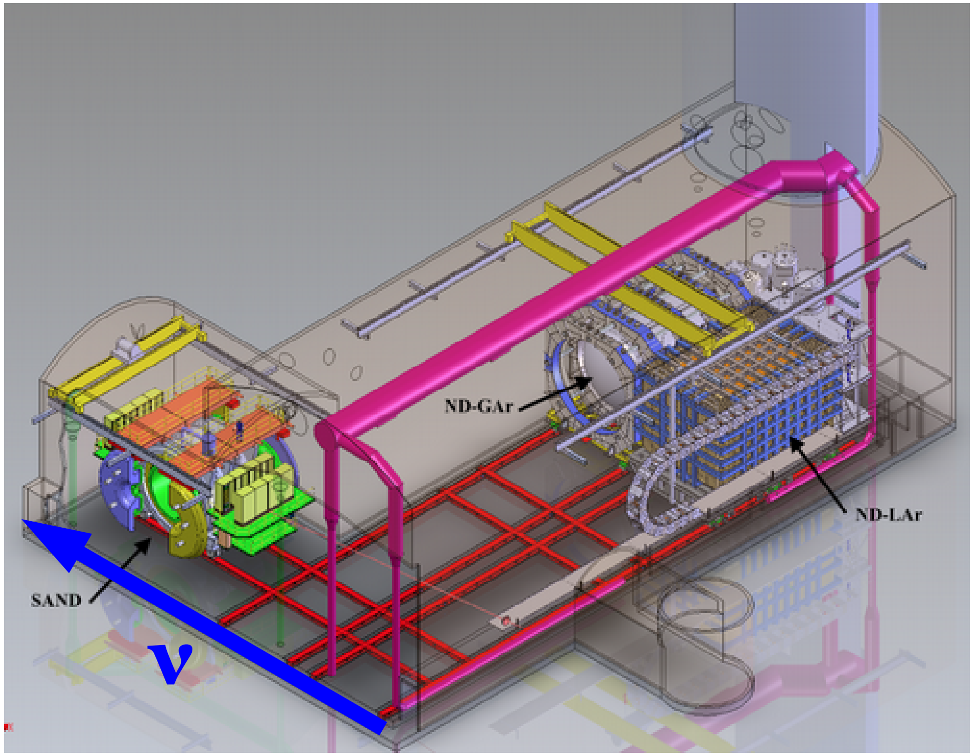
DUNE Near Detector (ND)

The DUNE Near Detector



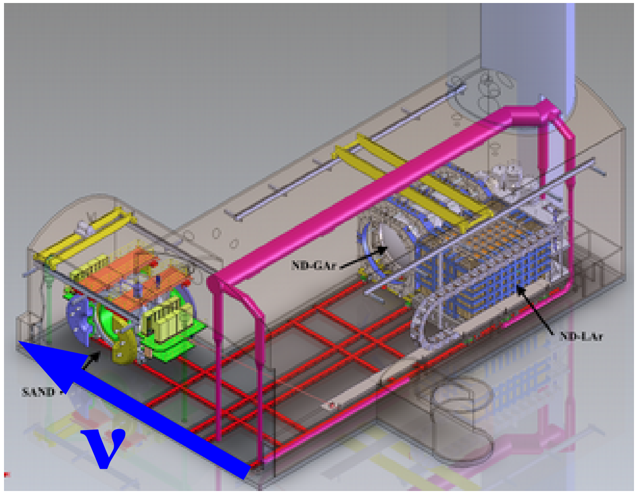


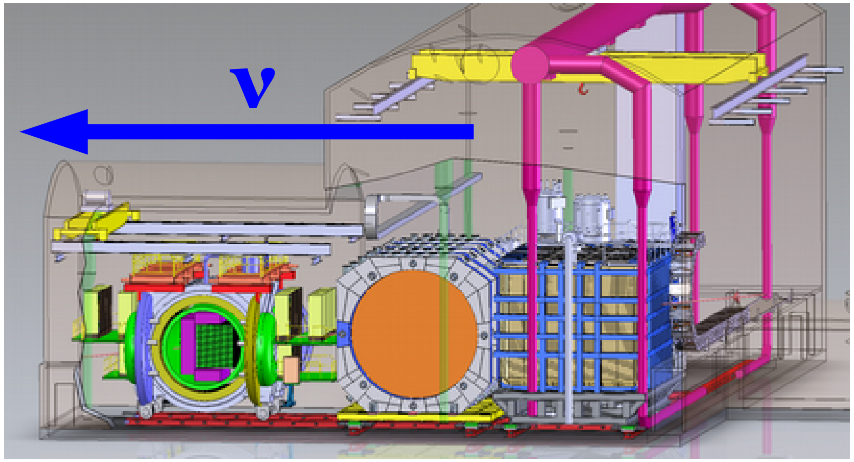
DUNE ND Overview



- DUNE ND located 574 m from neutrino beam target
- Primary purpose is to **characterize neutrino beam** and **constrain cross section uncertainties** in long-baseline neutrino oscillation analysis

DUNE ND Complex





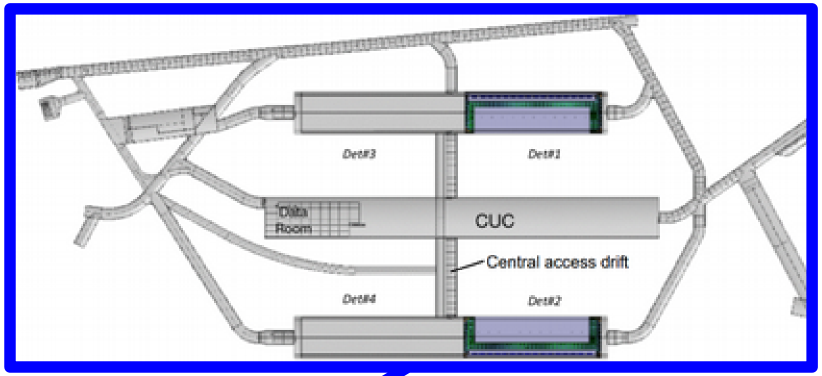
SAND ND-GAr ND-LAr

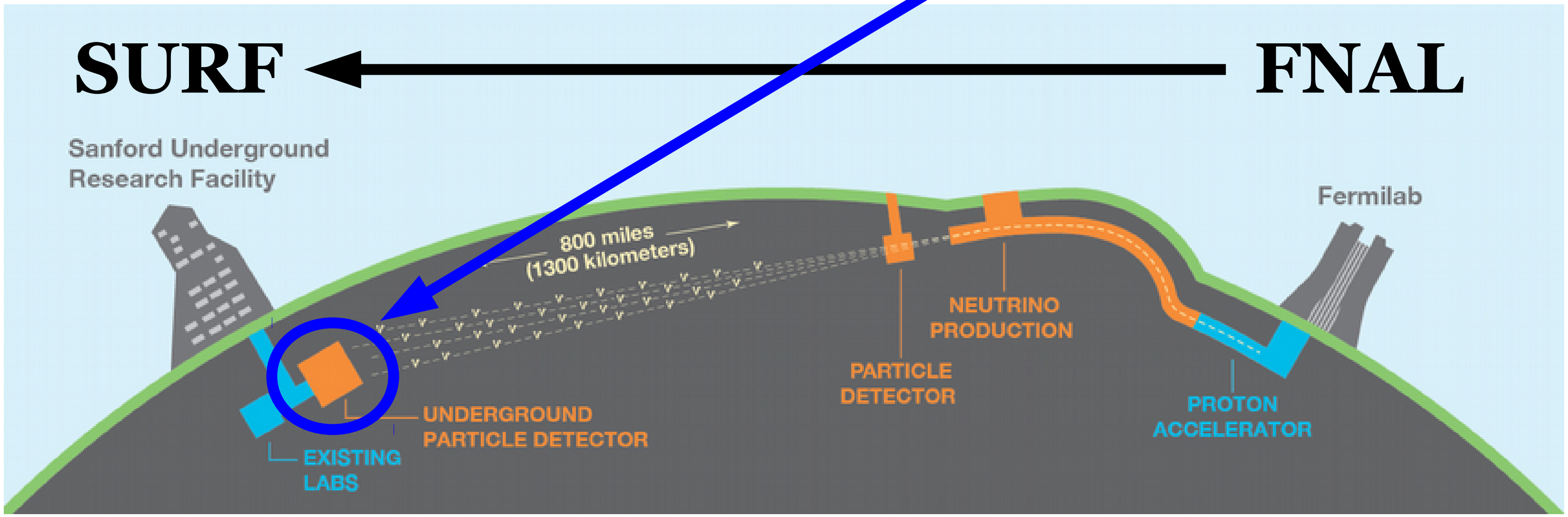
- DUNE ND complex: multiple complementary systems
  - ND-LAr: modular, pixelated LArTPC
    - Acts as primary target and is most similar to FD (both contain LAr)
  - ND-GAr: high-pressure GArTPC surrounded by ECAL and magnet
    - Constrains nuclear interaction model; muon spectrometer
  - SAND: tracker surrounded by ECAL and magnet
    - On-axis monitor of beam spectrum
- ND-LAr/ND-GAr can move off-axis (DUNE-PRISM)

DUNE Far Detector (FD)

The DUNE Far Detector:

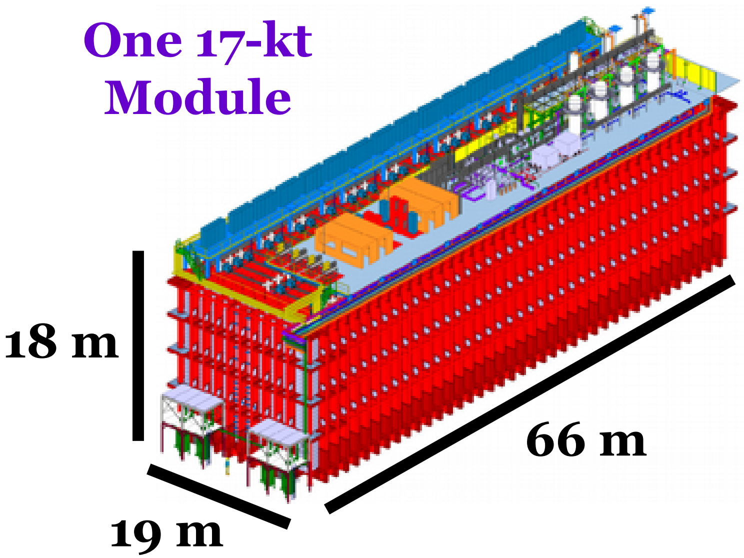
Four LArTPC Detector Modules

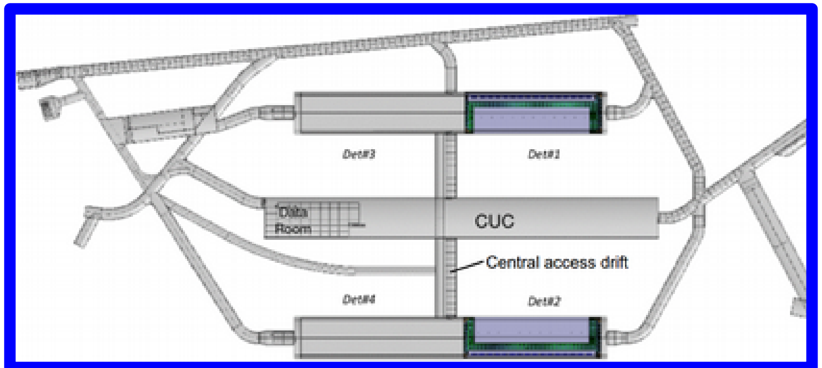


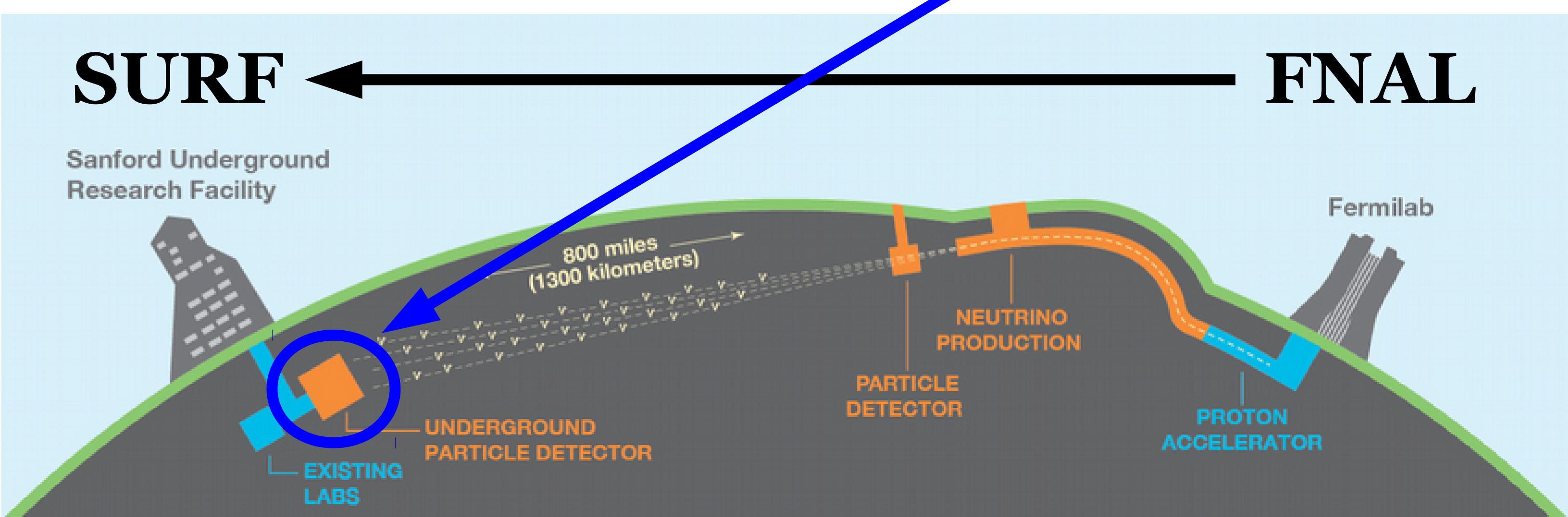


DUNE Far Detector (FD)

One 17-kt Module



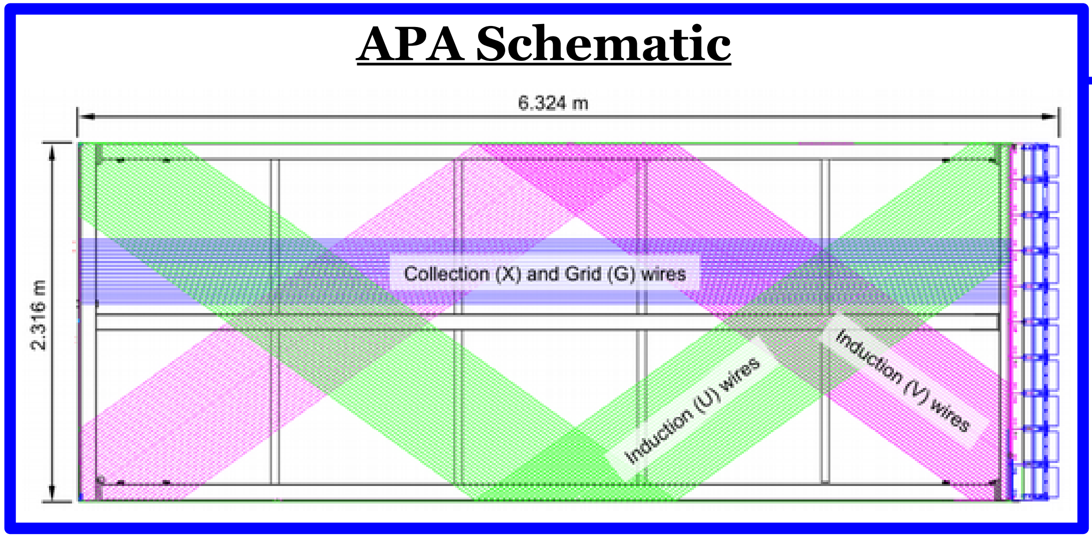


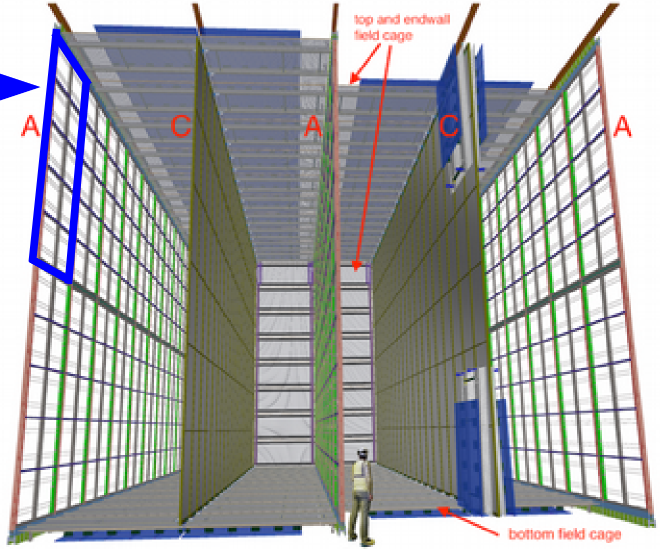


Far Detector LArTPC

- Four 17-kt modules deployed in stages
- Two far detector designs: single phase (LAr) and dual phase (LAr+GAr) – **first module will be single phase**
- Single phase FD uses modular drift cells (scalable)
  - Suspended Anode and Cathode Plane Assemblies (APAs and CPAs)
  - **Wrapped wire** to reduce # of readout channels, cabling complexity
  - 3.6 m drift, 500 V/cm field; **photon detectors** for non-beam triggering

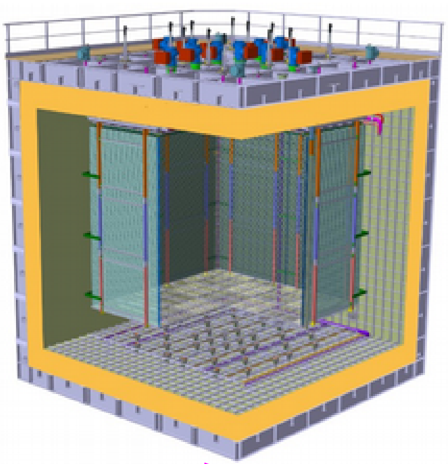
APA Schematic



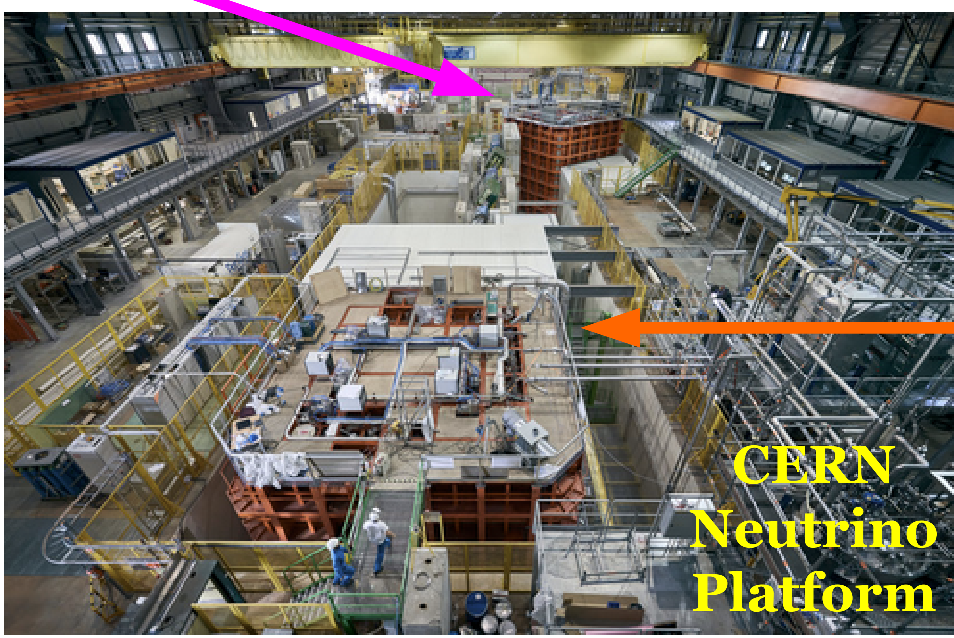


ProtoDUNEs

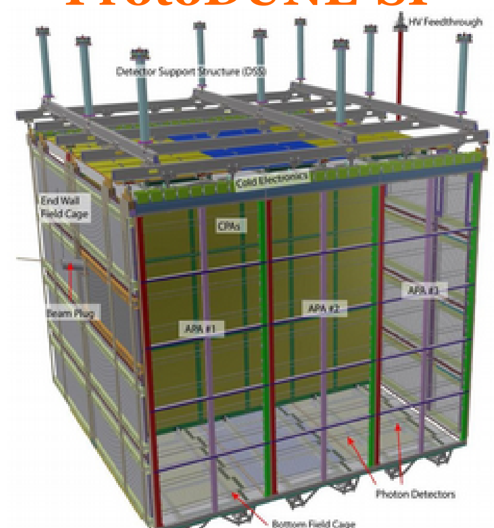
ProtoDUNE-DP



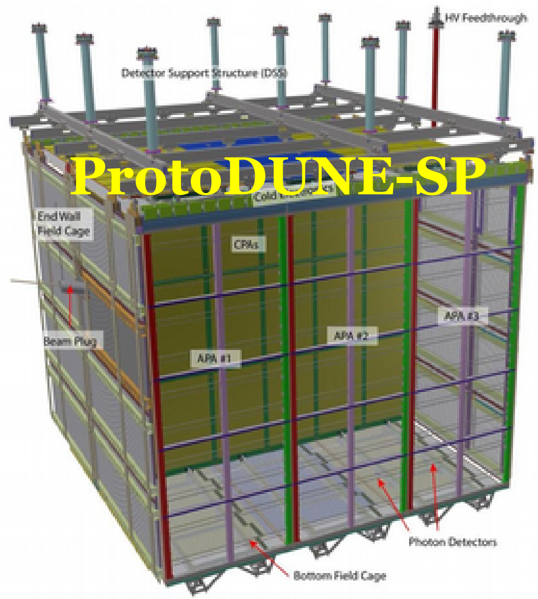
- Two 1-kt "ProtoDUNEs" in charged test beam at CERN (one per FD design)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operating since 2018; ProtoDUNE-DP since 2019



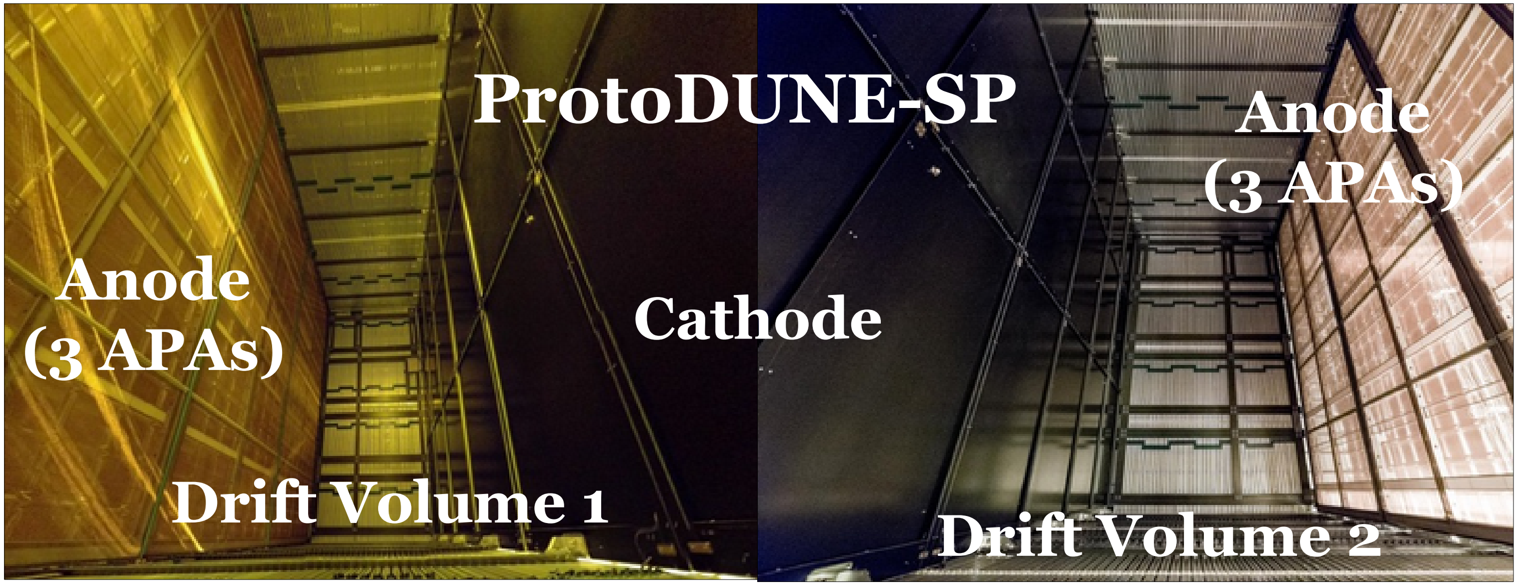
ProtoDUNE-SP



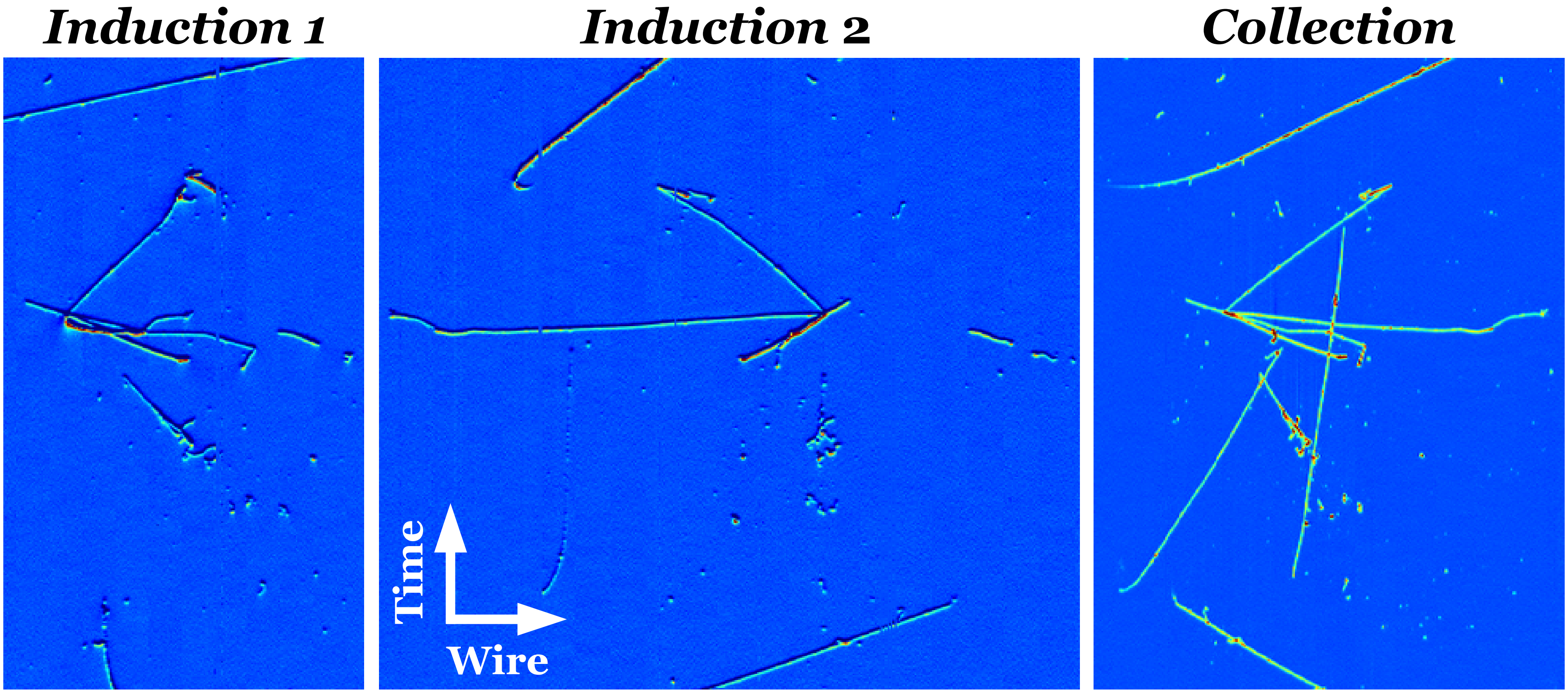
ProtoDUNEs



- Two 1-kt "ProtoDUNEs" in charged test beam at CERN (one per FD design)
- Test of component installation, commissioning, and performance
- ProtoDUNE-SP operating since 2018; ProtoDUNE-DP since 2019



First ProtoDUNE-SP Events



- First beam data events: **noise levels low** on all three planes
- S/N ratio > 10 in all cases (> 40 for collection plane)
- **Stable running** since first operations began in 2018

DUNE Far Site Excavation

- Underground excavation for DUNE far detector has begun!

Summary

- High Energy Physics and Particle Astrophysics (HEPPA) explores some of the most fundamental questions about our universe
- CSU has an internationally recognized HEPPA research group with leadership roles in the flagship domestic HEP project (DUNE)
- Major focus of research efforts are LArTPC neutrino experiments; also research on dark matter
- We love to talk about our research almost anytime, so track us down!


Questions?

BACKUP SLIDES

Neutrino Mass

- Neutrinos oscillate → neutrino flavors mix → neutrinos have mass!

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

Neutrino Flavor Eigenstates

Unitary Mixing Matrix

Neutrino Mass Eigenstates

Neutrino Mass

- Neutrinos oscillate → neutrino flavors mix → neutrinos have mass!

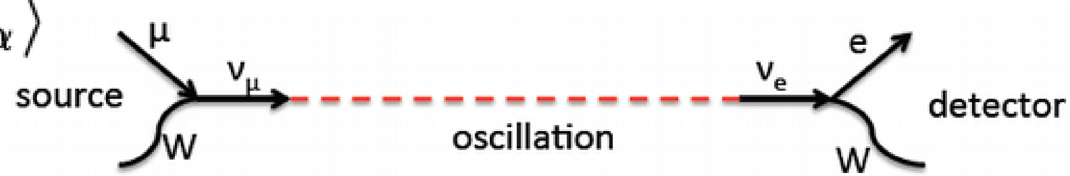
$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

Neutrino Flavor Eigenstates

Unitary Mixing Matrix

Neutrino Mass Eigenstates

$|\nu_\alpha\rangle$



Neutrino initially produced as flavor eigenstate

Neutrino Mass

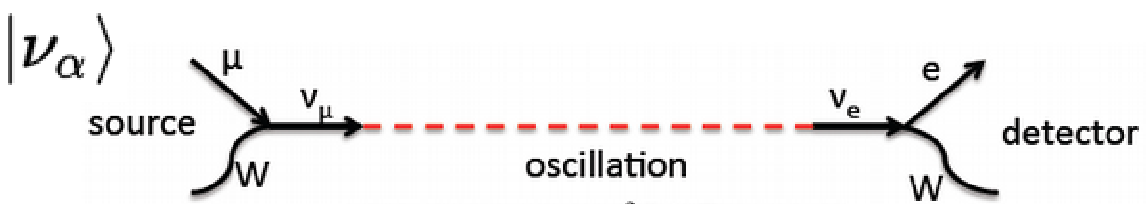
- Neutrinos oscillate → neutrino flavors mix → neutrinos have mass!

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

Neutrino Flavor Eigenstates

Unitary Mixing Matrix

Neutrino Mass Eigenstates



$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

Neutrino propagates as mass eigenstate → oscillations

Neutrino Mass

- Neutrinos oscillate → neutrino flavors mix → neutrinos have mass!

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

Neutrino Flavor Eigenstates

Unitary Mixing Matrix

Neutrino Mass Eigenstates

$$P_{\alpha\to\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

$$|\nu_\alpha\rangle$$

$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

Neutrino interacts in detector as flavor eigenstate
(multiple possible flavors with different probabilities)

Neutrino Mass

- Neutrinos oscillate → neutrino flavors mix → **neutrinos have mass!**

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle$$

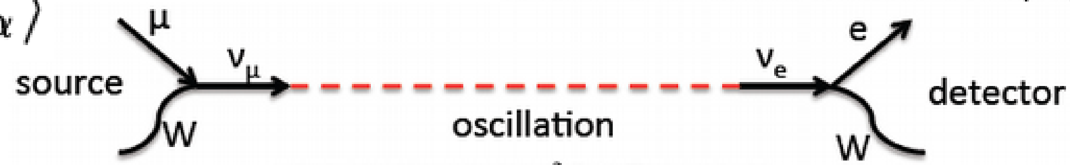
Neutrino Flavor Eigenstates

Unitary Mixing Matrix

Neutrino Mass Eigenstates

$$P_{\alpha\to\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

$|\nu_\alpha\rangle$



$$|\nu_i(L)\rangle = e^{-im_i^2 L/2E}|\nu_i(0)\rangle$$

Two-Flavor Approximation:

$$P_{\alpha\to\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(1.27\frac{\Delta m^2 L}{E}\frac{[\mathrm{eV}^2]\,[\mathrm{km}]}{[\mathrm{GeV}]}\right)$$

Why Liquid Argon?

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120	165	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3	1
Radiation Length [cm]	755.2	24	14	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3	3.8	1.9
Scintillation [γ/MeV]	19,000	30,000	40,000	25,000	42,000	
Scintillation λ [nm]	80	78	128	150	175	
Approx. Cost [$/kg]	52	330	5	330	1200	

- Argon is cheap: **~1%** of atmosphere
- Dense target (more ν-N interactions per unit time)
- High scintillation light yield, argon transparent to own light
- Relatively small radiation length for EM shower containment