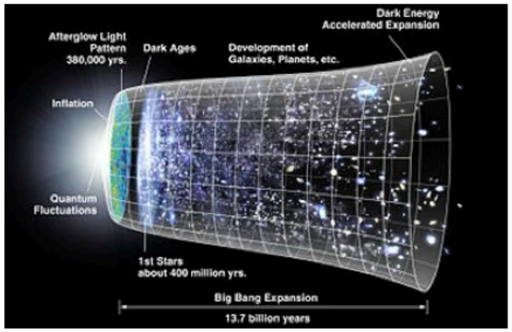
DUNE: Mapping the Predictable and Unexpected

Background: ProtoDUNE (CERN)

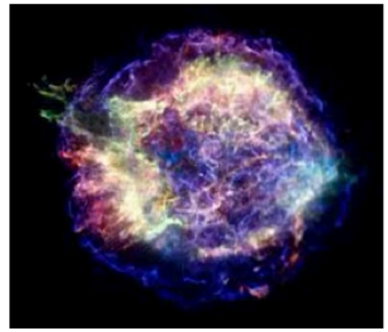
Sowjanya Gollapinni
Los Alamos National Laboratory

Particle Physics Seminar
The University of Manchester
April 24, 2026

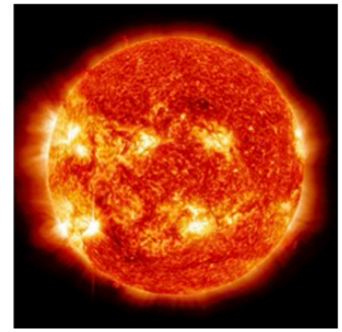
Why Study Neutrinos?



Big Bang "Relic" neutrinos (400/cm^3)



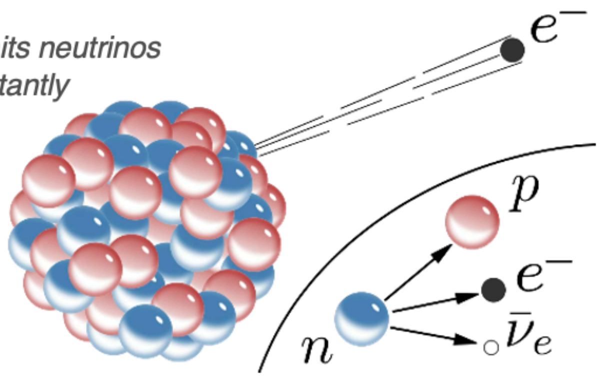
Supernovae neutrinos carry 99% of the energy



10^{38} neutrinos/sec by Sun

The big things

Nucleus emits neutrinos constantly



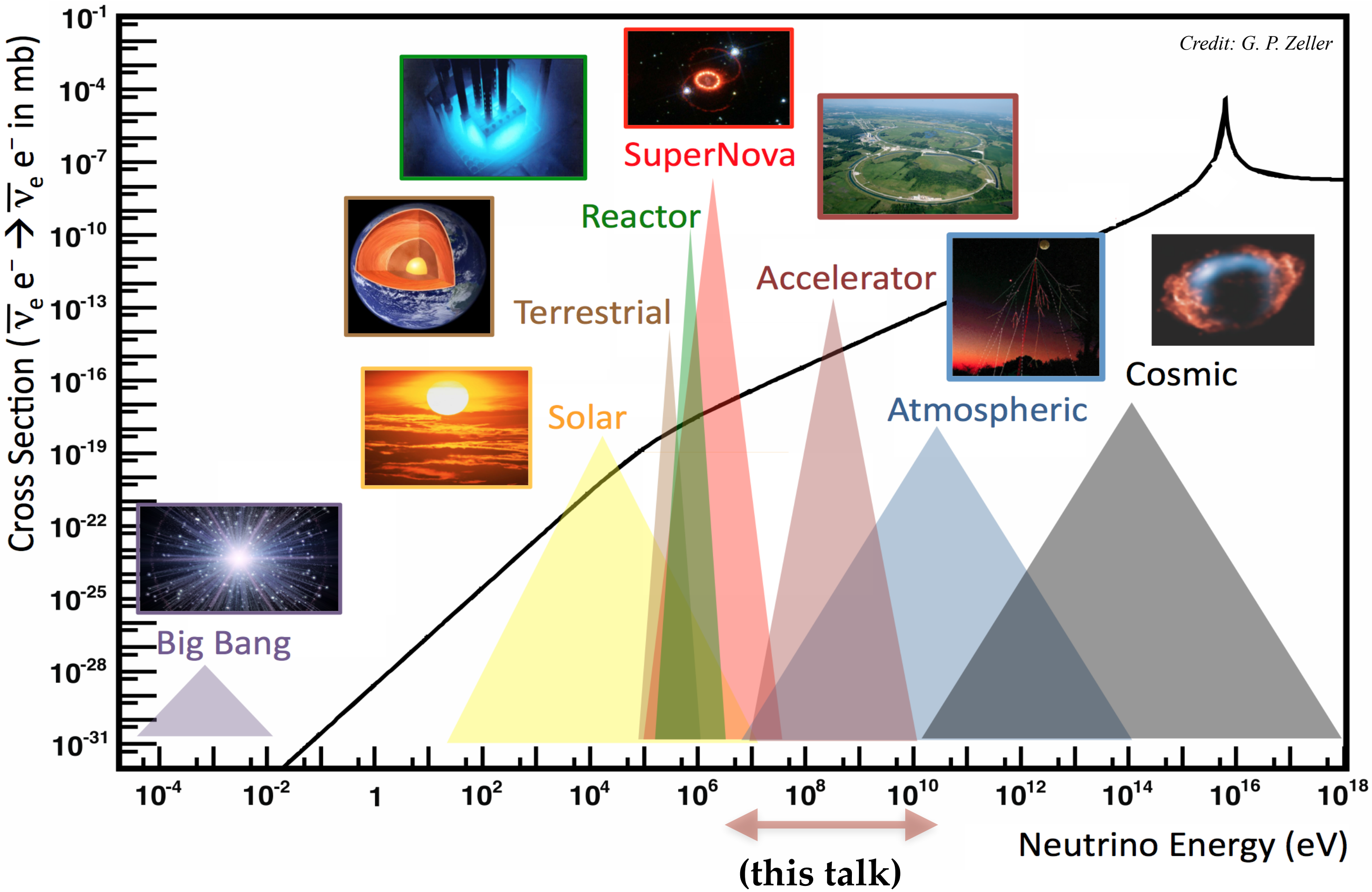
The small things

10^6 neutrinos/day

The everyday things

Almost everything emits neutrinos and in great quantities!

Neutrinos Span Multiple Frontiers



Particle Physics

AstroPhysics

Cosmology

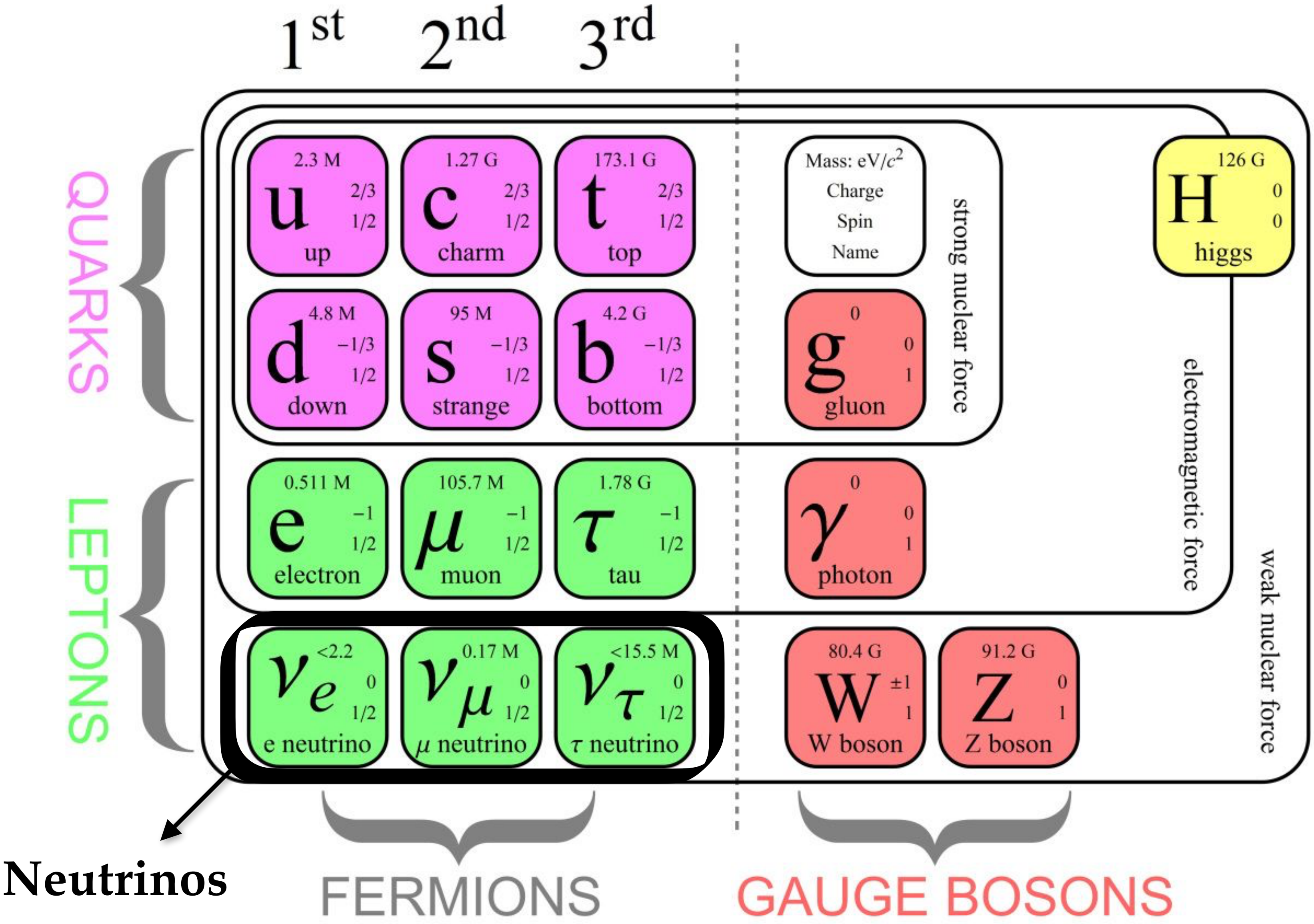
High energy Astro-particle physics

Nuclear physics

- Overwhelming number of sources, wide range of energies
- Need wide spectrum of experiments and technologies!

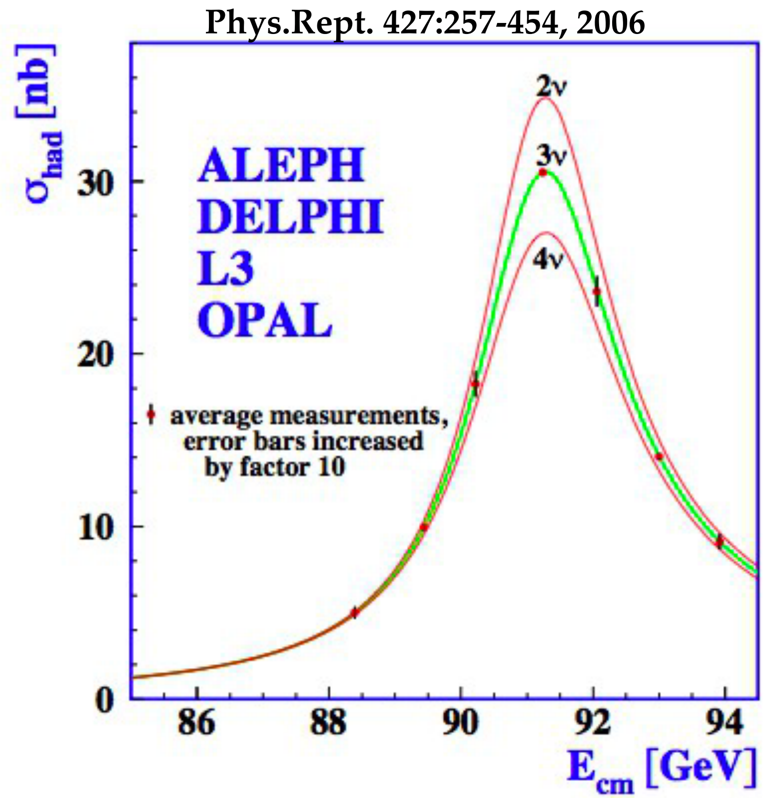
Standard Model of Elementary Particles

Theory about fundamental ingredients of matter and how they interact with each other



Neutrinos in the Standard Model

Electron Flavor **Muon** Flavor **Tau** Flavor

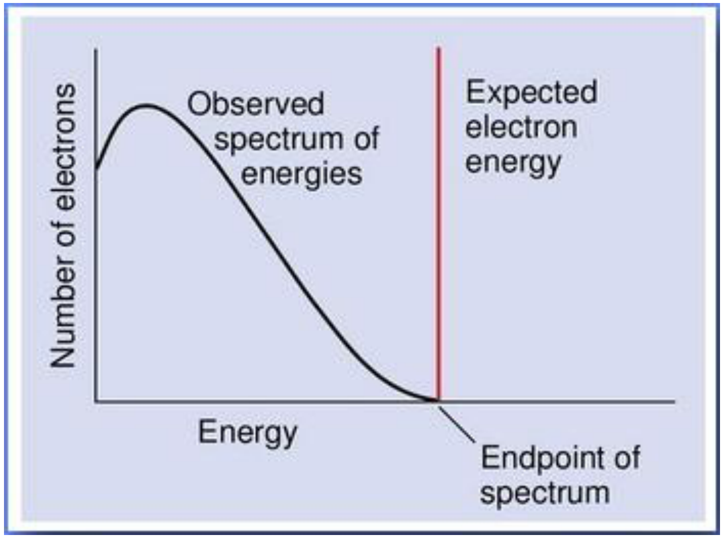


- ***Neutral*** (no charge)
- ***Standard Model (SM) predicts three active neutrino "flavors"*** (or types) — experiments at LEP confirmed that only three neutrinos couple to the Z boson
- ***Very weakly interacting*** e.g. to stop a 1 MeV neutrino need ~10 light years of lead! — need very dense, very big and very sensitive detectors

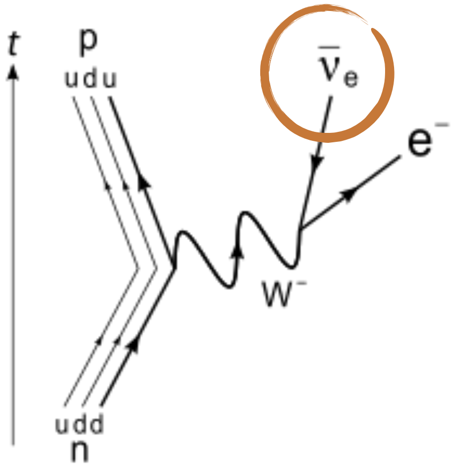
*Neutrinos have **Zero** mass according to SM*

Neutrino: A "Desperate Remedy"

Observed energies in β decay (1931)

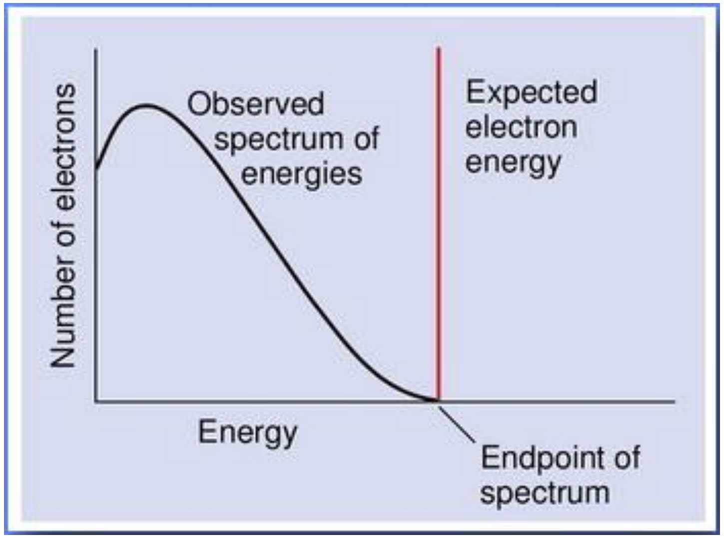


Nuclear β decay



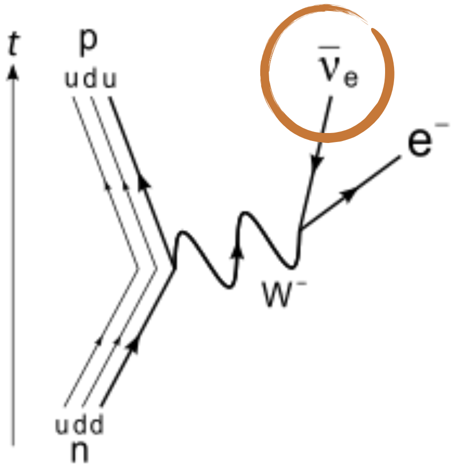
Neutrino: A "Desperate Remedy"

A desperate remedy by Pauli to explain the observed energies in β decay (1931)



"I have done a terrible thing. I have postulated a particle that cannot be detected." — **Pauli**

Nuclear β decay



Project Poltergeist

1956: F. Reines and C. Cowan finally detected the first anti-neutrino from a nuclear reactor **(Nobel Prize 1995)**

June 5, 1998

Mass Found in Elusive Particle; Universe May Never Be the Same

Discovery on Neutrino Rattles Basic Theory About All Matter

By MALCOLM W. BROWNE

TAKAYAMA, Japan, June 5 — In what colleagues hailed as a historic landmark, 120 physicists from 23 research institutions in Japan and the United States announced today that they had found the existence of mass in a notoriously elusive subatomic particle called the neutrino.

The neutrino, a particle that carries no electric charge, is so light that it was assumed for many years to have no mass at all. After today's announcement, cosmologists will have to confront the possibility that much of the mass of the universe is in the form of neutrinos. The discovery will also compel scientists to revise a highly successful theory of the composition of matter known as the Standard Model.

Word of the discovery had drawn some 300 physicists here to discuss neutrino research. Among other things, they said, the finding of neutrino mass might affect theories about the formation and evolution of galaxies and the ultimate fate of the universe. If neutrinos have sufficient mass, their presence throughout the universe would increase the overall mass of the universe, possibly slowing its present expansion.

Others said the newly detected but as yet unmeasured mass of the neutrino must be too small to cause cosmological effects. But whatever the case, there was general agreement here that the discovery will have far-reaching consequences for the investigation of the nature of matter.

Speaking for the collaboration of scientists who discovered the existence of neutrino mass using a huge underground detector called Super-Kamiokande, Dr. Takaaki Kajita of the Institute for Cosmic Ray Research of Tokyo University said that all explanations for the data collected by the detector except the existence of neutrino mass had been essentially ruled out.

Dr. Yoji Totsuka, leader of the coalition and director of the Kamioka Neutrino Observatory where the underground detector is situated, 30 miles north of here in the Japan Alps, acknowledged that his group's announcement was "very strong," but said, "We have investigated all

Continued on Page A14

Detecting Neutrinos

1. Neutrinos pass through the Earth's surface to a tank filled with 12.5 million gallons of ultra-pure water . . .
2. . . . and collide with other particles . . .
3. . . . producing a cone-shaped flash of light.
4. The light is recorded by 11,200 20-inch light amplifiers that cover the inside of the tank.

And Detecting Their Mass

By analyzing the cones of light, physicists determine that some neutrinos have changed form on their journey. If they can change form, they must have mass.

Source: University of Hawaii

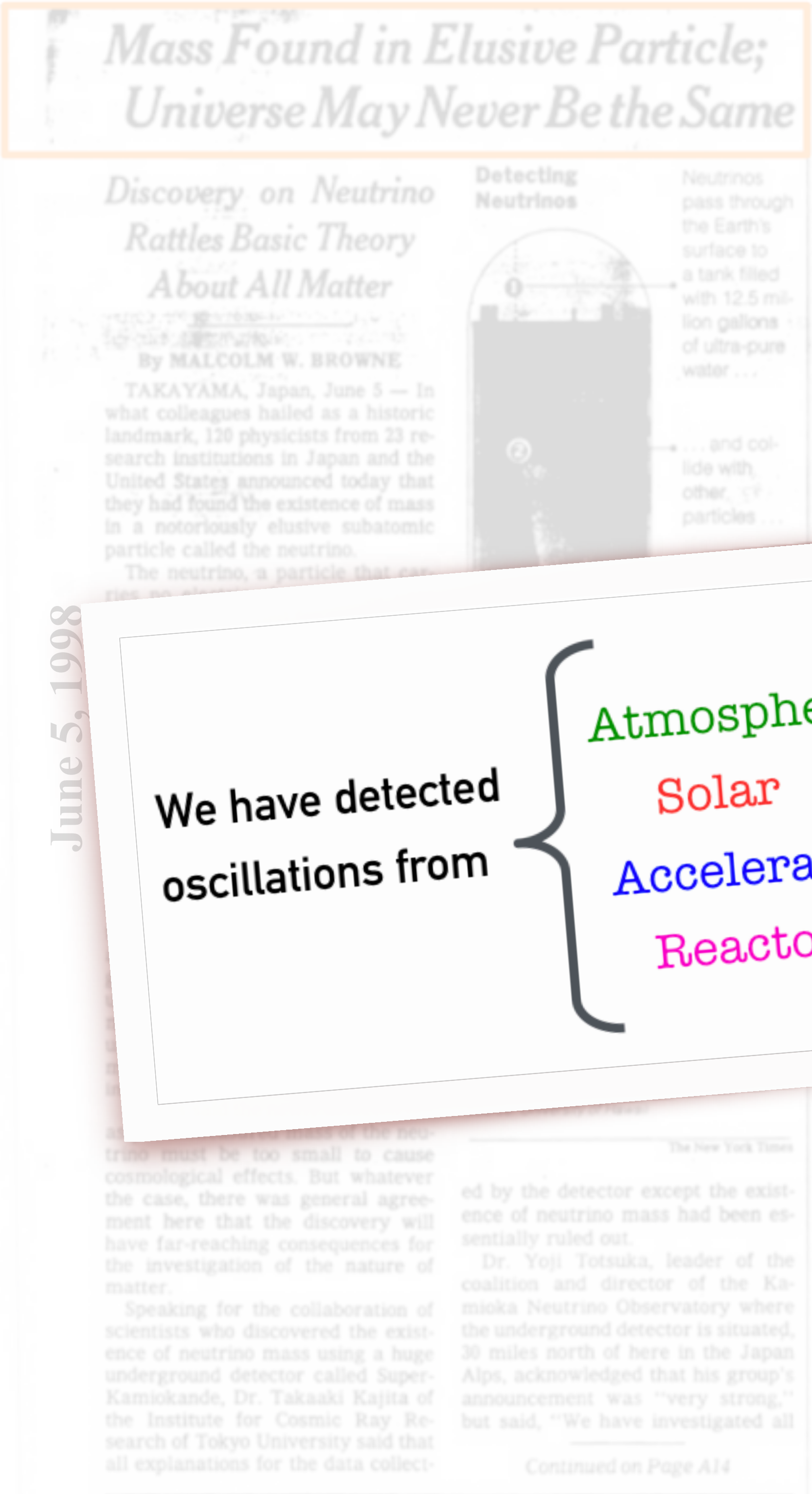
The New York Times

Neutrinos Oscillate and so they have mass!

(albeit very tiny)

Until as recently as 1998, neutrinos were considered to be *massless*

Breakthrough discovery in Neutrino Physics that ***revolutionized*** the field — *opened doors to many exciting possibilities!*



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The neutrino, a particle that car-

...

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Continued on Page A14

June 5, 1998

Neutrinos Oscillate and so they have mass!

(albeit very tiny)

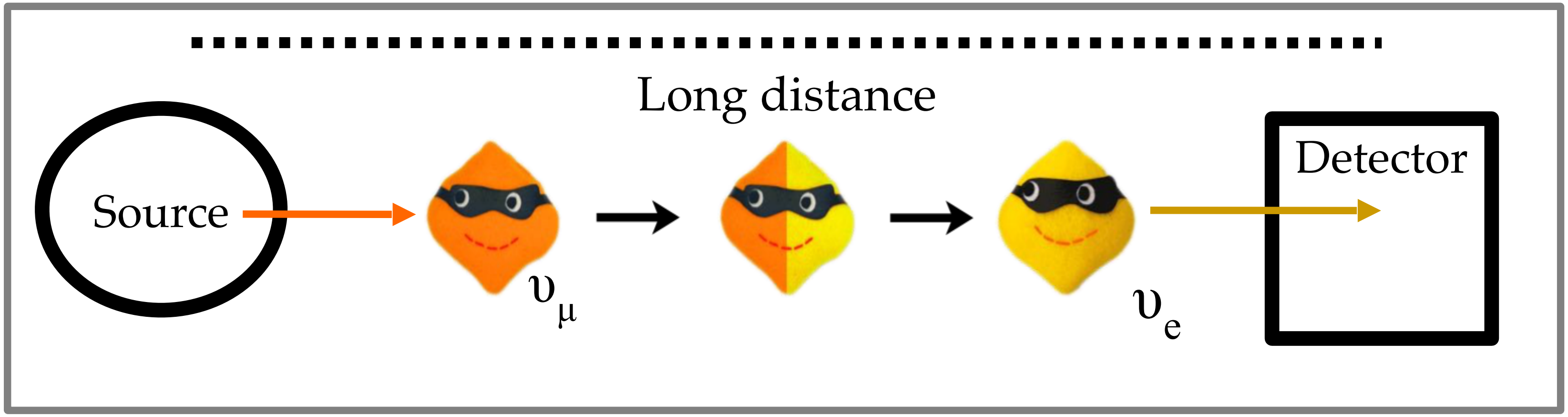
We have detected oscillations from

- Atmospheric
- Solar
- Accelerator
- Reactor

... discovery in Neutrino Physics that ***revolutionized*** the field — *opened doors to many exciting possibilities!*

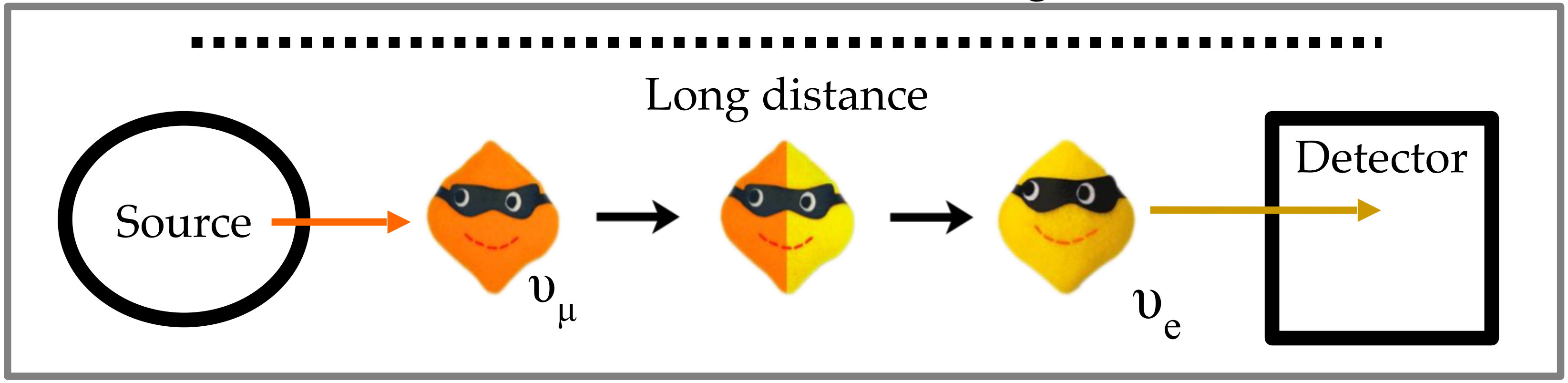
Neutrinos Oscillations

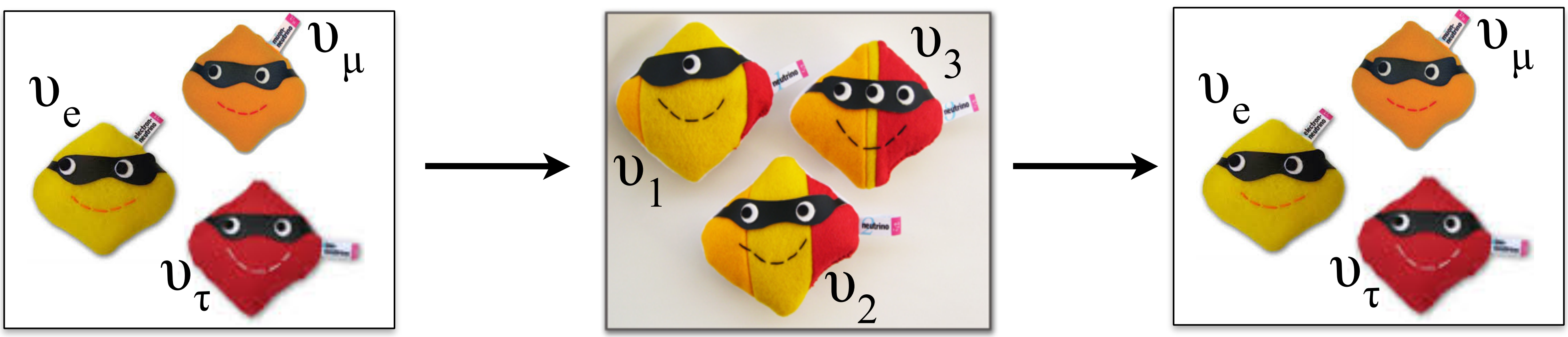
A neutrino created as one flavor can change into another flavor



The Quantum Neutrino

A neutrino created as one flavor can change into another flavor





"FLAVOR" STATES
(how they are produced)

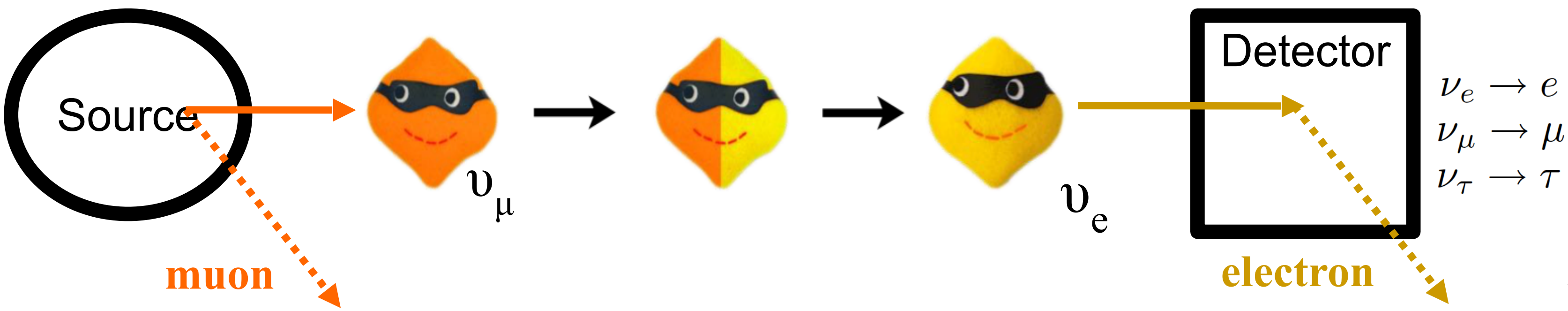
"MASS" STATES
(how they travel)

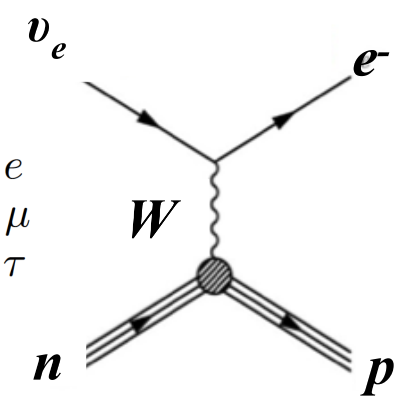
"FLAVOR" STATES
(how they interact)

Quantum mechanical evolution of states determine what is measured

Detecting Neutrinos

cannot measure the neutrino *flavor directly*, only through the *outgoing lepton*





"appearance" signal

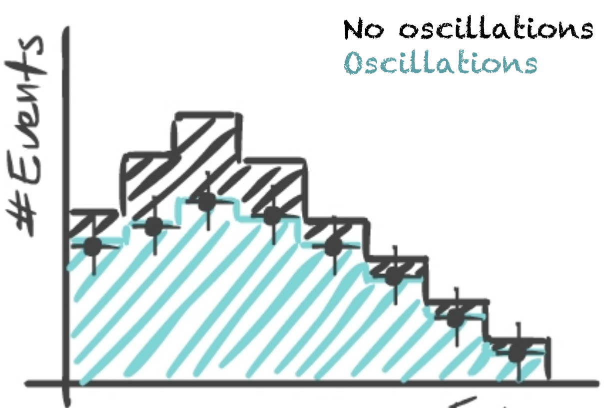
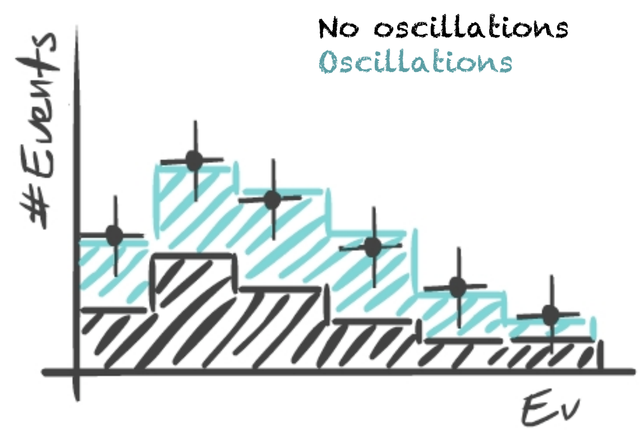


Image credit: G. Karagiorgi

ν_α "disappearance"

(look for deficit of ν_α events)



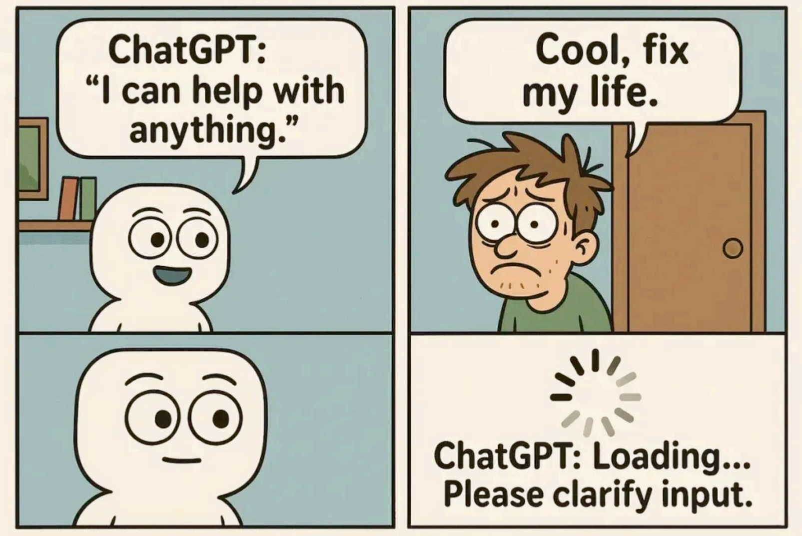
ν_β "appearance"

(look for excess of ν_β events)

Can perform "Appearance" or "Disappearance" measurements

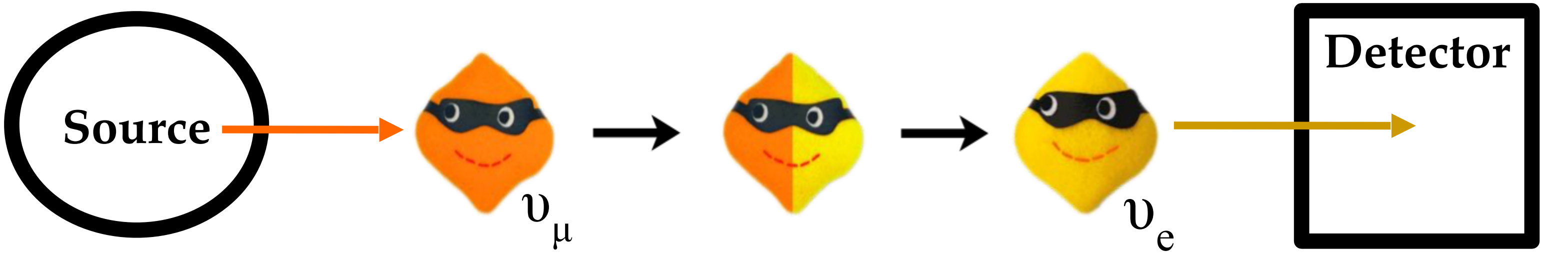
Neutrino Oscillations are a big deal today!

- *Big bang Cosmology*
- *Star formation*
- *Supernovae evolution*
- *Dark matter*
- *Matter vs Anti-matter*
- *What gives mass to neutrinos?*
- *Do neutrinos violate fundamental symmetries?*



Neutrinos make great probes for exploring incredible range of fundamental phenomenon

Oscillations in a Two-Neutrino System



Oscillation Probability

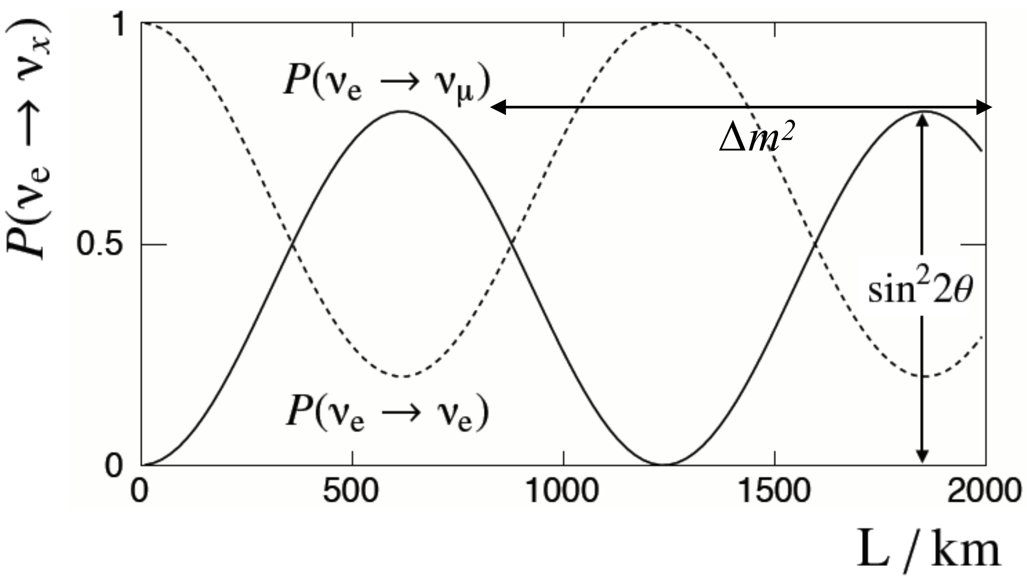
$$P_{osc} = \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$

θ is the mixing angle

$\Delta m^2 = m_1^2 - m_2^2 (eV^2)$

L is the distance that neutrino travels (km)

E is neutrino energy (GeV)



Important parameter L/E

Oscillations measured as a function of L/E

Oscillations characterized by Δm^2, $\sin^2 2\theta$

Long-baseline ~ 1000 km

Short-baseline ~ 1 km

Neutrino Oscillation Parameters

"FLAVOR" STATES

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"MASS" STATES

The "PMNS" Mixing Matrix

(analogous to "CKM" matrix for quarks)

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Atmospheric & long baseline accelerator

Reactor & Accelerator

Solar & long baseline Reactor

Neutrino Oscillations: What do we know?

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\theta_{23} & sin\theta_{23} \\ 0 & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & 0 & sin\theta_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -sin\theta_{13}e^{i\delta_{CP}} & 0 & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & 0 \\ -sin\theta_{12} & cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

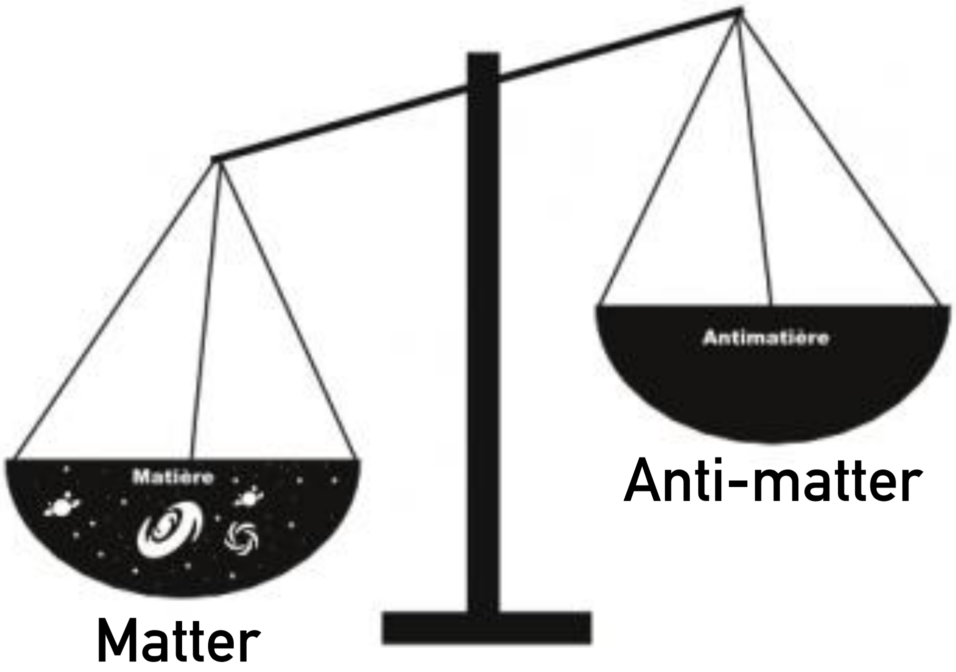
- 3 mixing angles: θ_{12}, θ_{23}, θ_{13} and a complex phase: δ_{CP}
- 2 mass squared differences: Δm^2_{21}, Δm^2_{32}
- If $\delta_{CP} \neq \{0,\pi\}$ then Charge-Parity (CP) violation in leptonic sector

- $\theta_{13} \neq 0$ opened door to CP violation in the neutrino sector

- Measuring δ_{CP} can shed light on why we live in a matter-dominated Universe

Why is Universe Matter-dominated?

A very small amount of matter persisted over antimatter at the beginning of the Universe

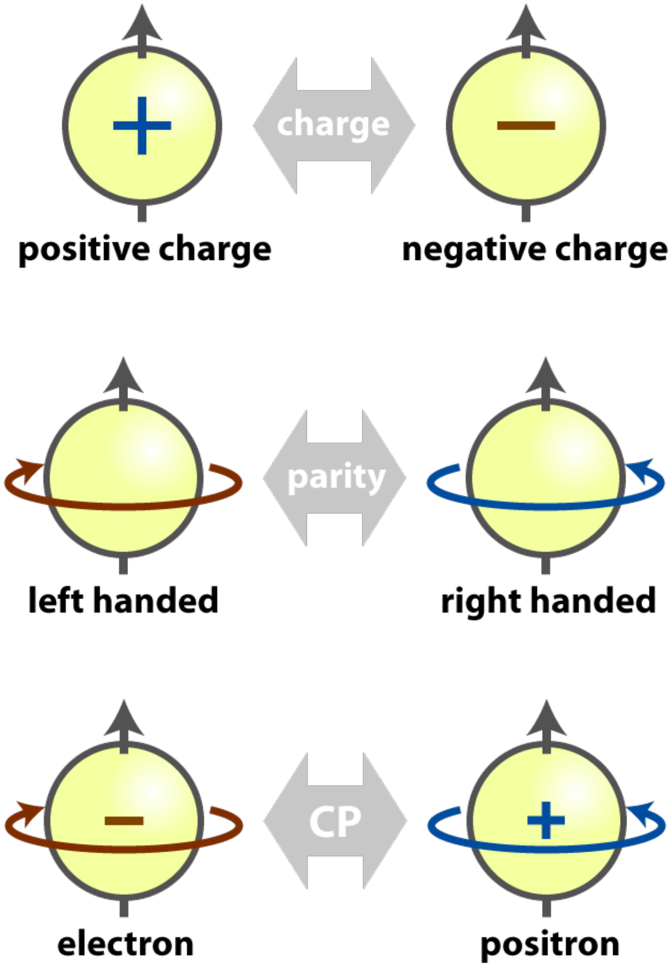


What processes can lead to this observed asymmetry?

Charge Parity Violation (CPV)

If matter and antimatter were alike, nature would be "CP-symmetric"

(C= Charge and P=Parity)



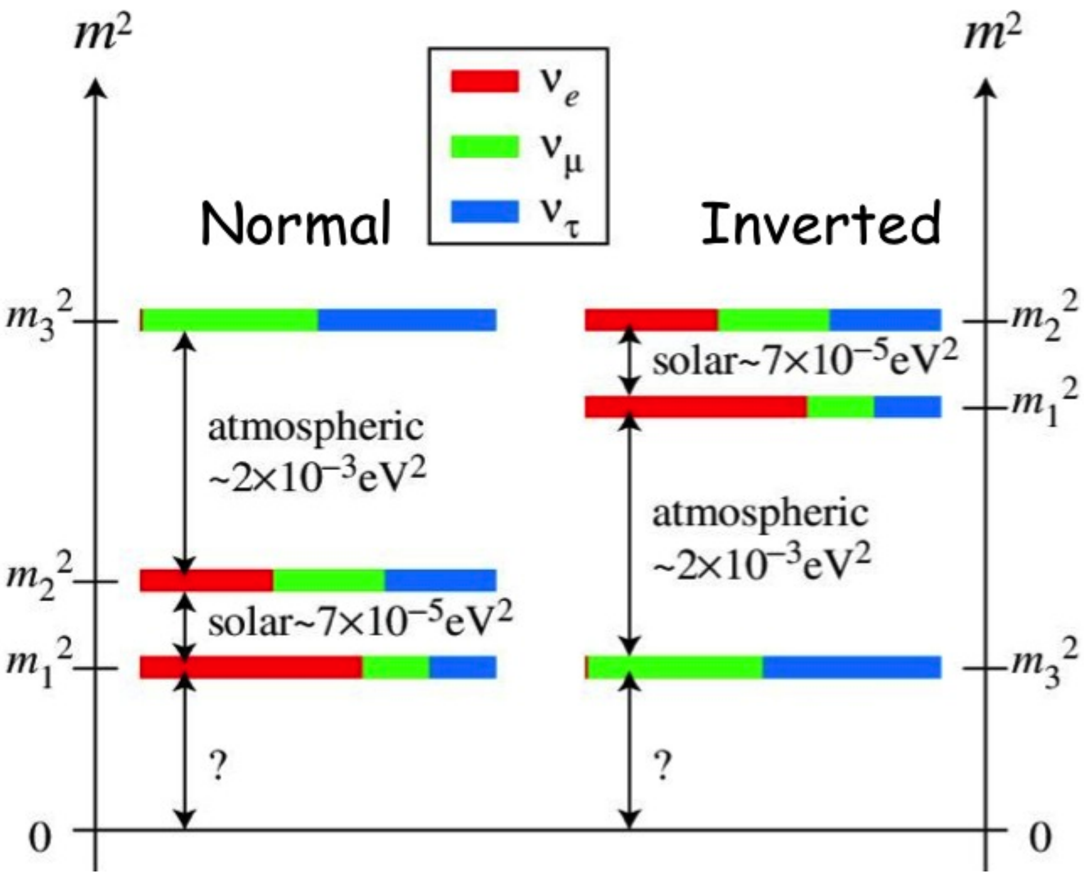
- CPV observed in other particles but *much more* is needed to explain the observed asymmetry
- Is CP violated in neutrinos and to what extent?

Neutrino Mass Hierarchy (MH)

2 mass differences: **Δm^2_{21}, $|\Delta m^2_{32}|$**

Which neutrino is the lightest and which one is the heaviest?

$\Delta m^2_{32/31} > 0$: "Normal" Hierarchy
$\Delta m^2_{32/31} < 0$: "Inverted" Hierarchy



There is a lot we still don’t know

Within SM 3-flavor mixing

- Absolute mass of neutrinos?
- Neutrinos Majorana or Dirac?
- Precision Measurement of mixing parameters?
- Which neutrino is the lightest? (Mass hierarchy)
- Is θ_{23} maximal mixing?
- CP violation in the neutrino sector?

Beyond SM 3-flavor mixing

- Are there more than 3 neutrinos?
- Other New physics e.g. non-standard interactions

SM = Standard Model

There is a lot we still don't know

e.g. KATRIN

Direct Mass Measurement Experiments

e.g. MicroBooNE, SBN

Short-Baseline Neutrino Experiments

Within SM 3-flavor mixing

- Absolute mass of neutrinos?
- Neutrinos Majorana or Dirac?
- Precision Measurement of mixing parameters?
- Which neutrino is the lightest? (Mass hierarchy)
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- CP violation in the neutrino sector?

Beyond SM 3-flavor mixing

- Are there more than 3 neutrinos?
- Other New physics e.g. non-standard interactions

Neutrinoless Double Beta Decay Experiments

e.g. LEGEND

Short- and Long-Baseline Experiments

e.g. DUNE, SBN

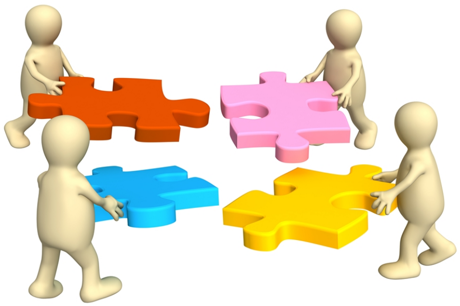
Long-Baseline Neutrino Oscillation Experiments

e.g. DUNE, NOvA, T2K

SM = Standard Model

Completing the Story of Neutrinos:

This is what we are striving for



	What is the absolute neutrino mass?	Are neutrinos Dirac or Majorana particles?	What is the neutrino mass ordering?	Is there CP violation in the neutrino sector?	Are there more than 3 neutrino flavors?	Is our picture of neutrinos correct?
β decay	✓					✓
$0\nu\beta\beta$ decay	✓	✓				✓
astrophysics and cosmology	✓		(✓)		✓	✓
Atmospheric oscillations			(✓)	(✓)	✓	✓
Reactor oscillations			(✓)		✓	✓
Accelerator oscillations			✓	✓	✓	✓

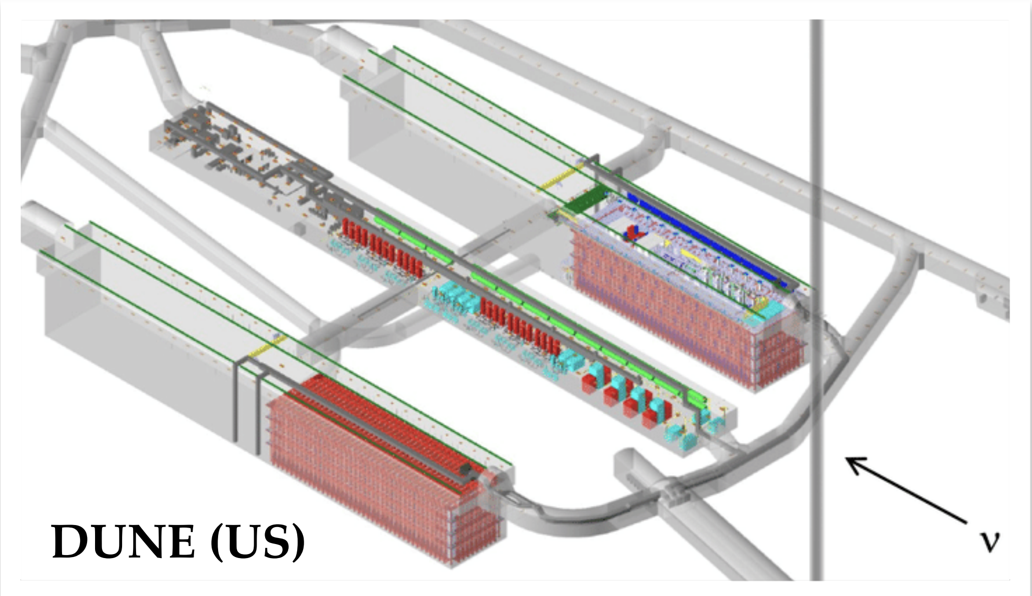
Broad Physics program — overlapping physics and technological goals

Long-Baseline Facilities Across the Globe

Japan:
T2K, Hyper-K

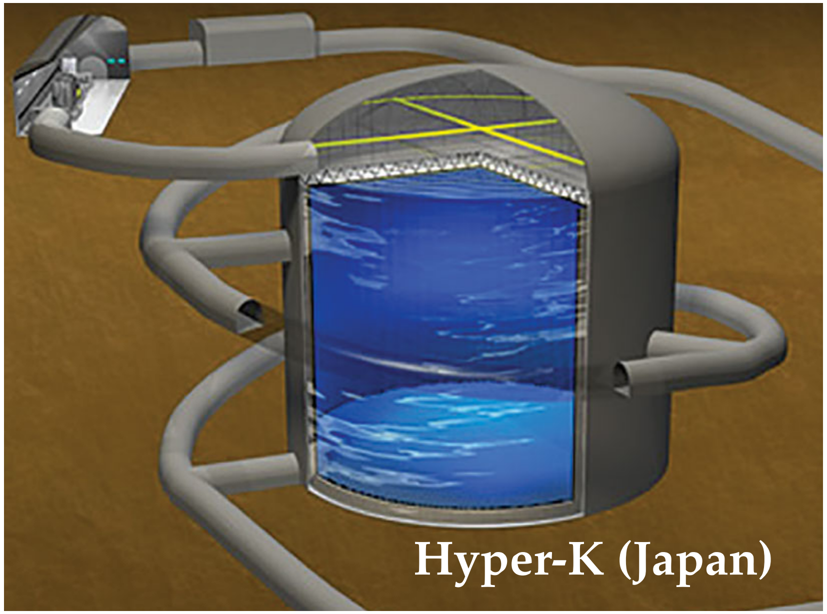
US:
NOvA, MINOS+,
DUNE

Next Generation Long-Baseline: DUNE & Hyper-K



- 40 kiloton liquid-argon detector
- 1300 km baseline
- Wide band beam (~3 GeV)
- MW-scale beam from Fermilab
- Four separate detectors, flexibility in design
- First beam data expected in 2032
- Completely measure 3-flavor picture (including CPV, MO) and New Physics

Complementary Strengths —
powerful & essential to provide cross confirmation



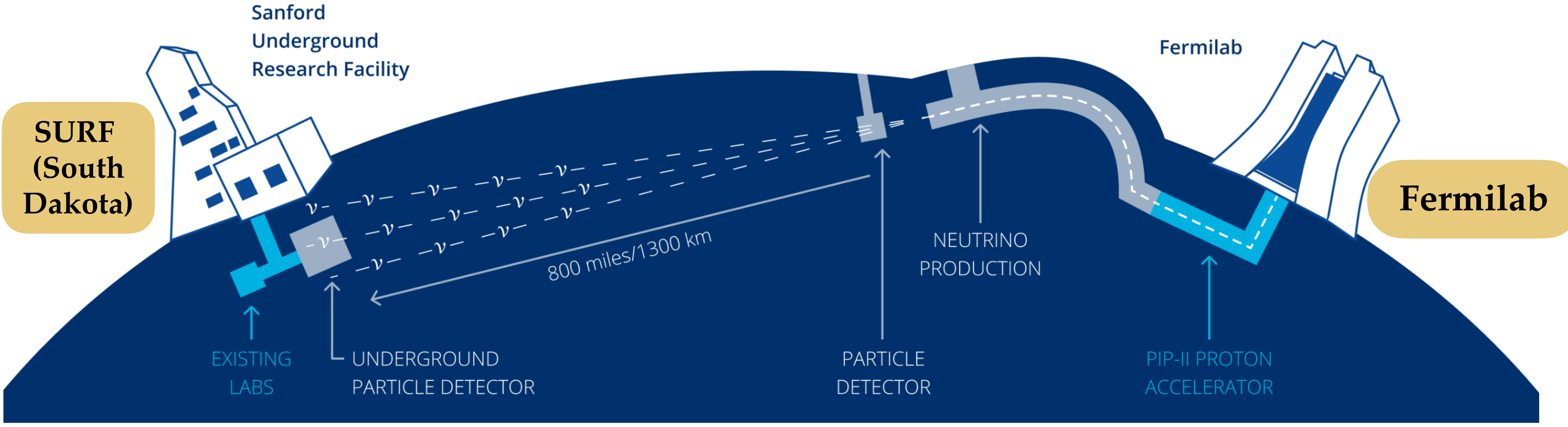
- 1 Mega ton Water Cherenkov technology
- 295 km baseline
- Narrow band beam (off axis; 0.6 GeV)
- MW-scale beam from J-PARC
- First beam data expected in 2028
- Excellent experiment to measure CPV in the 3-flavor scenario if mass ordering is known

DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

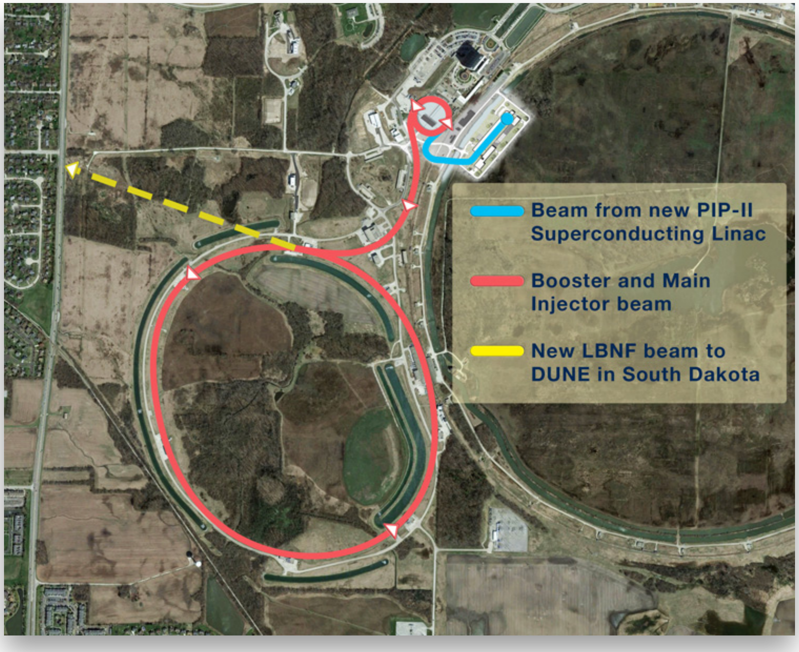
The DUNE Experiment

- MW-scale intense neutrino beam from Fermilab to South Dakota over 800 miles
- A multi-technology near detector complex (ND) at Fermilab
- Far site cavern at SURF will accommodate four 17 kt far detector (FD) modules
- The Long-Baseline Neutrino Facility (LBNF) provides the beamline & dual site facilities



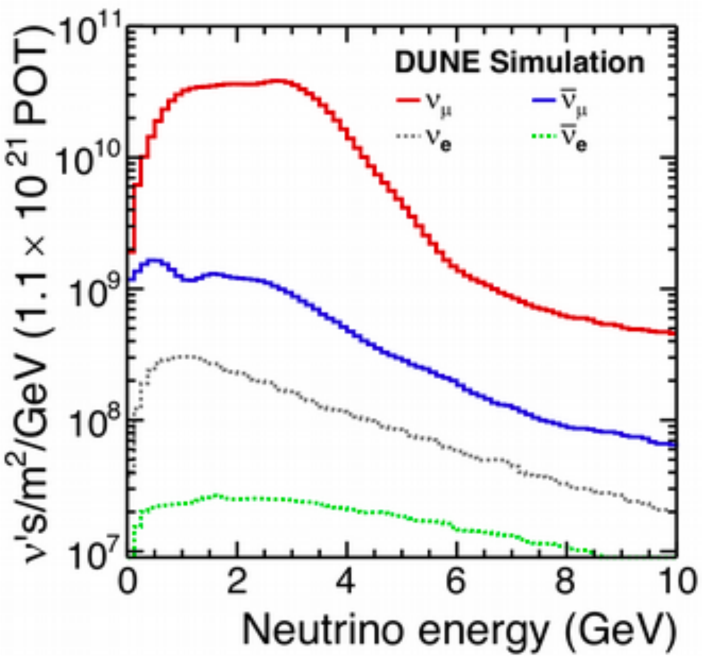
- *Rich Physics program:* Charge-Parity Violation, mass ordering, precision measurement of oscillation parameters, neutrino astrophysics, and New physics

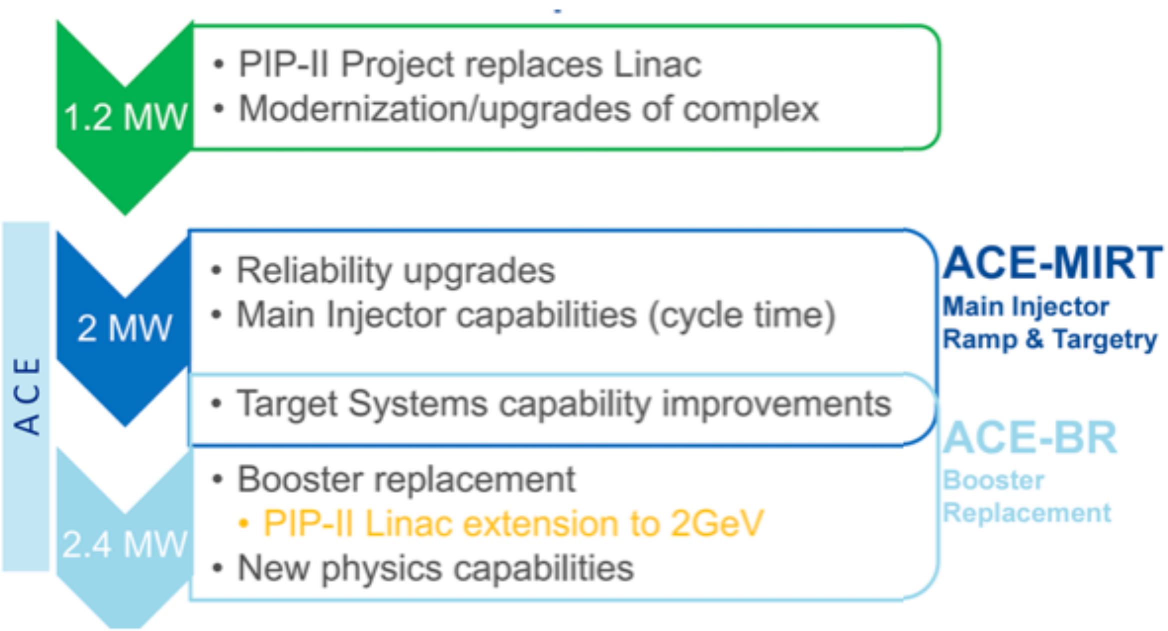
Beamline & Accelerator Upgrades



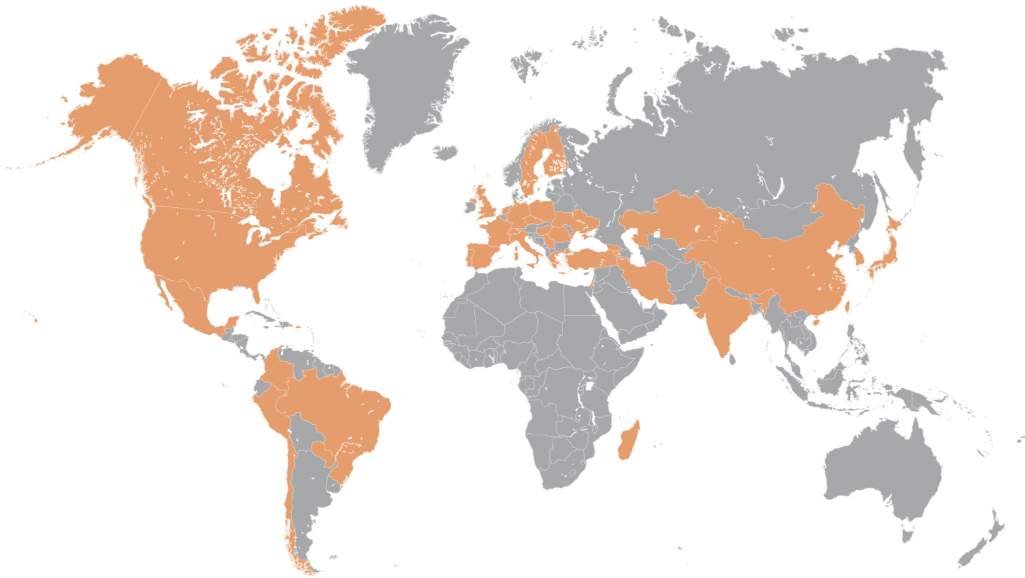
Ultimate goal is to deliver > 2 MW beam by 2031

- Proton Improvement Plan (PIP-II) is accelerator upgrade at Fermilab to reach 1.2 MW beam & create a platform for next generation upgrades
- Accelerator Complex Evolution (ACE) is planned upgrades to reach >2 MW



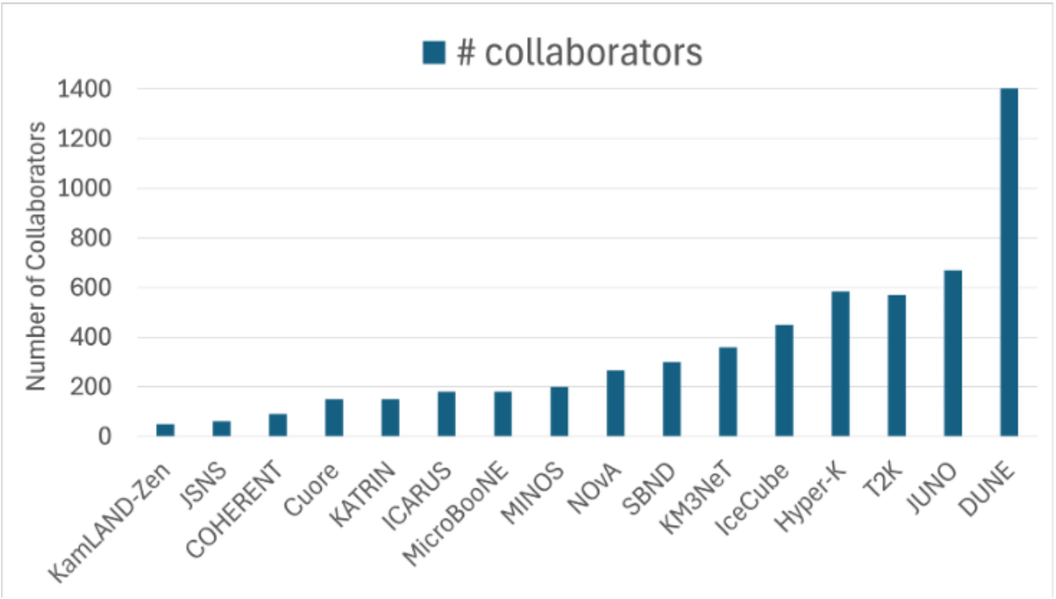


DUNE is the Largest Neutrino Collaboration Ever Assembled in History and Growing!



DUNE Co-Spokespeople

Sowjanya Gollapinni ***Dave Newbold***



More than ***1500 collaborators*** *from* ***220+ institutes*** *in 38* ***countries*** *including CERN*

Half of the collaboration is students/postdocs

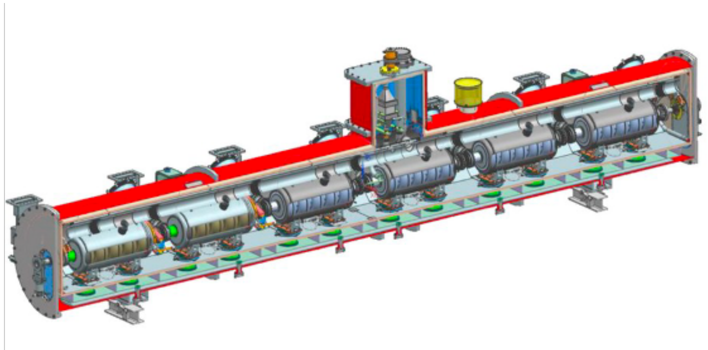
UK is the Largest International Partner in DUNE

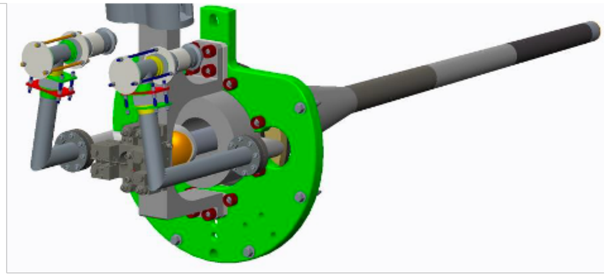
- **16 Universities and 2 National Labs (RAL and Daresbury)**
  - 142 members: 44 students, 46 postdocs, 52 faculty including 3 UKRI and Royal Society fellows. Plus, 46 technical members (e.g., engineers, techs etc.)

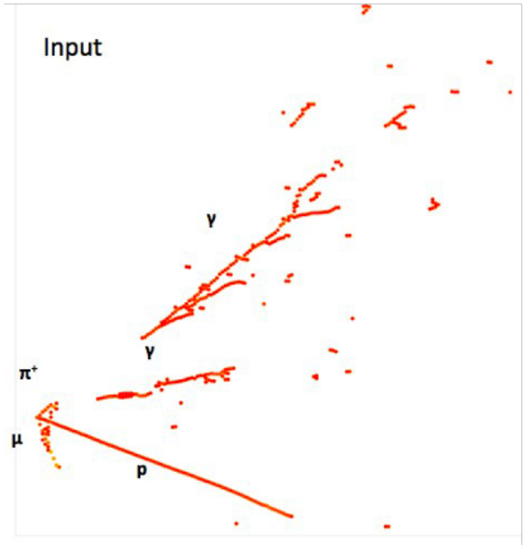
- **Strong and essential leadership from UK across multiple fronts**
  - DUNE Co-Spokesperson, Resource Coordinator, Far Detector Anode Plane Assemblies (APA) Consortium Leader, DAQ Technical Leader, DUNE Phase-II Coordinator, ProtoDUNE Horizontal Drift Run Coordination, AI/ML coordination, …
  - *Conveners:* Long-Baseline, Far Detector & Near Detector Simulation/Reconstruction, Atmospherics, Calibrations, DUNE Phase-II Near Detector GAr, and several other roles within various consortia (APA, DAQ, Computing, etc.)…

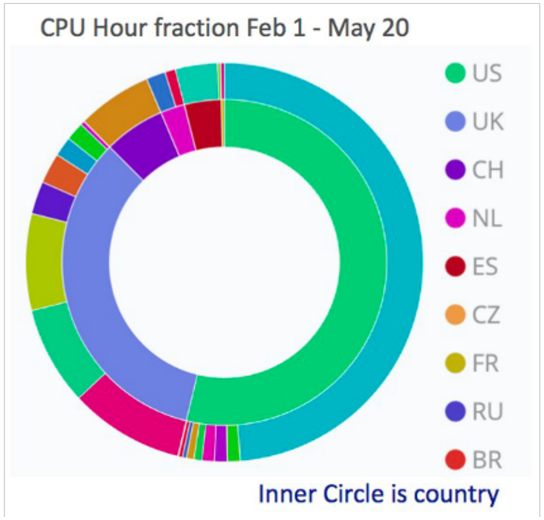
Leading Contributions from UK to DUNE/LBNF

- **PIP-II:** deliver 3 high beta superconducting RF cryomodules for end stage of PIP-II linac *— UK is one of handful of sites worldwide capable to deliver this*
- **LBNF Target:** supply 1.2 MW helium-cooled graphite target plus associated infrastructure *— UK is the only place in the world that can design high-power neutrino targets*
- **DUNE:** Anode Plane Assembly (APA) modules for Far detector; Data Acquisition (DAQ); Reconstruction Software; Distributed Computing contributions

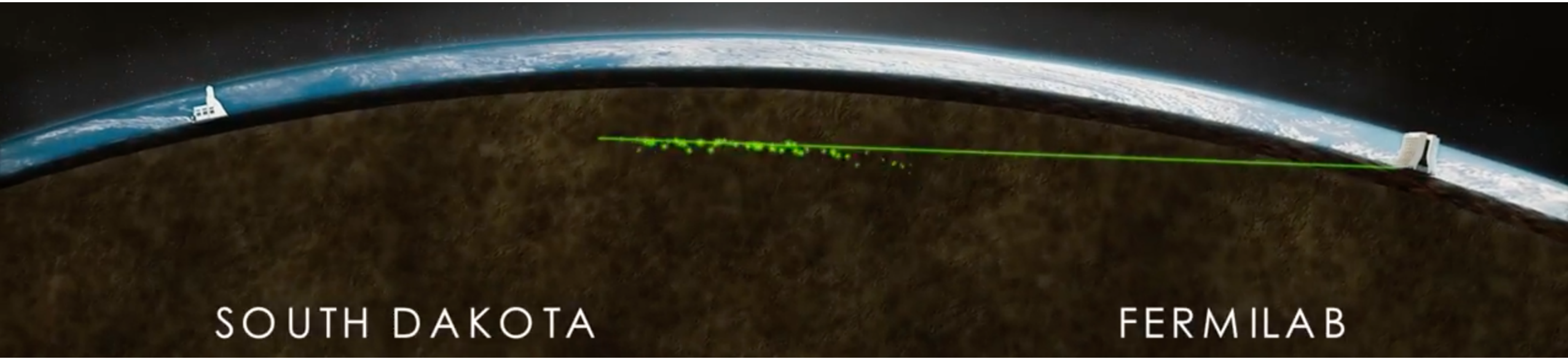


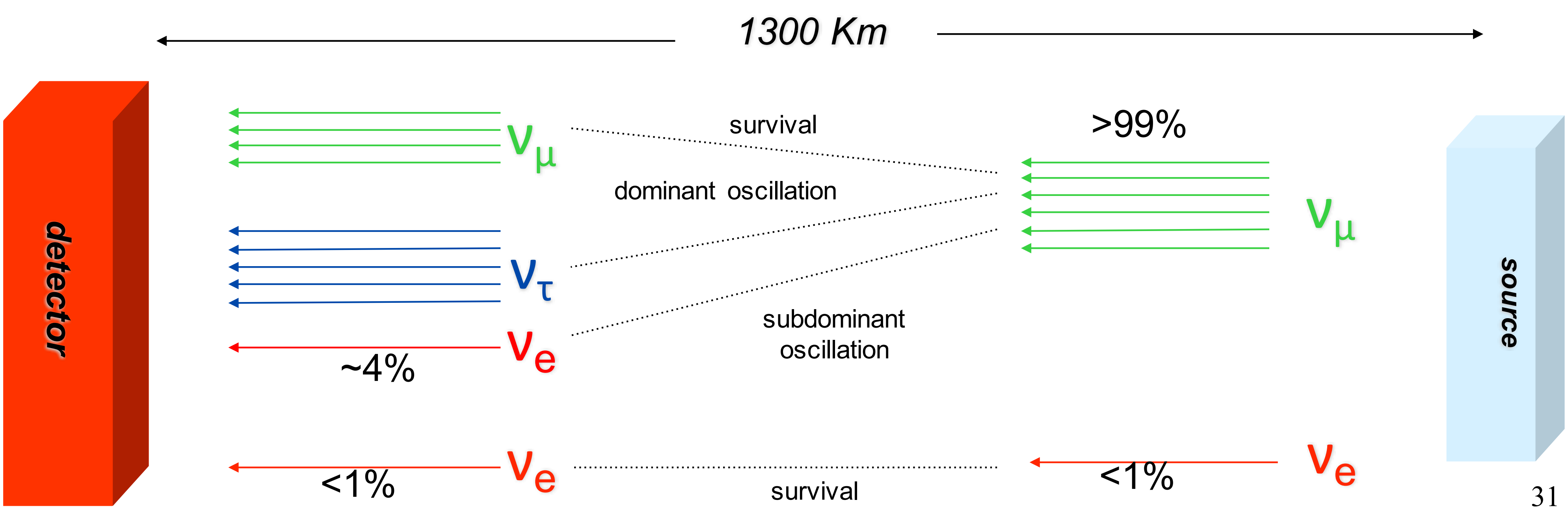






DUNE Oscillations





“Matter Effects” matter in DUNE

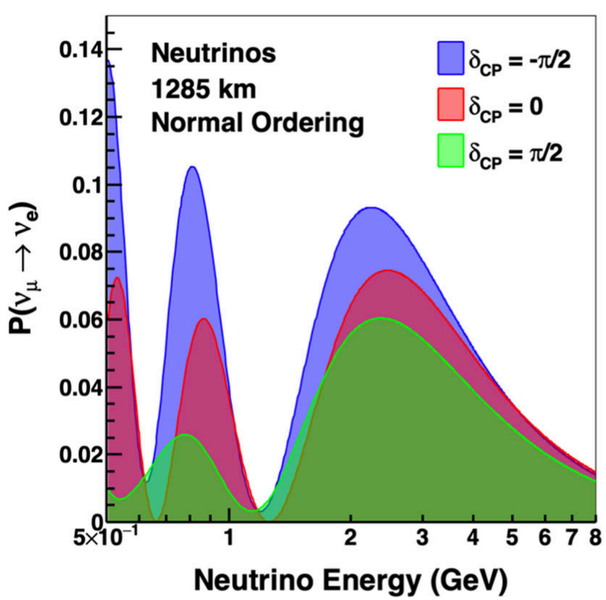
A ν_e appearance experiment in matter will be sensitive to rich physics (θ_{23}, θ_{13}, δ_{CP} , mass hierarchy and matter effects)

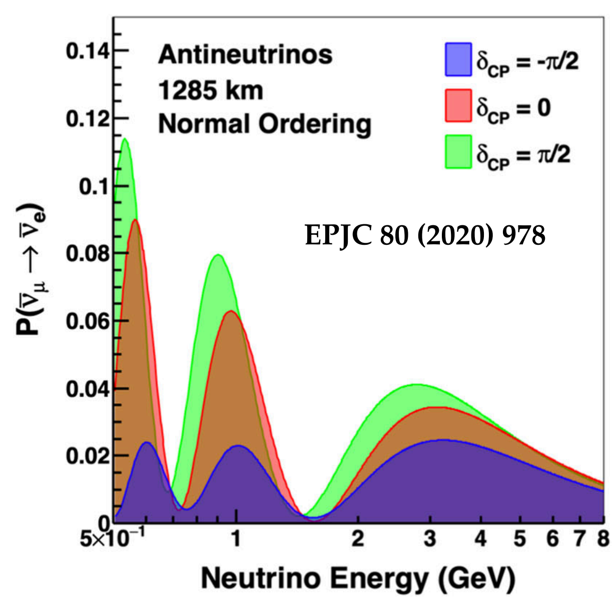
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

(For antineutrinos, a → -a and δ → -δ)





"Matter Effects" matter in DUNE

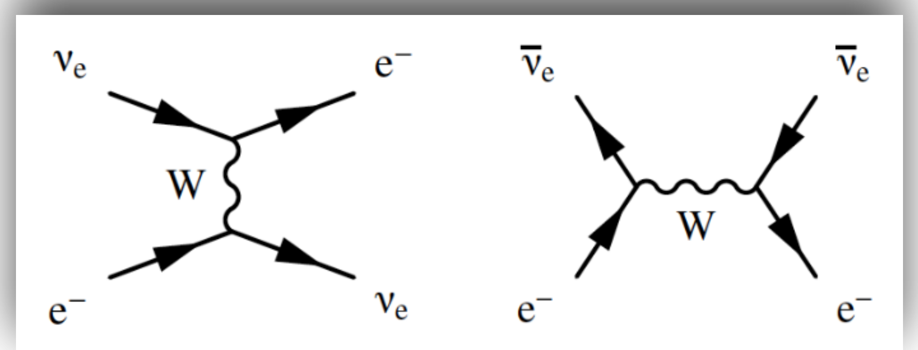
$$P(\nu_\mu \to \nu_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2 + \sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}+\delta_{CP}) + \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

$$a = G_F N_e / \sqrt{2}$$

$$\Delta_{ij} = \frac{\Delta m_{ij}^2 L}{4E}$$

(For antineutrinos, a → -a and δ → -δ)

Neutrinos travel through matter not anti-matter



- Electron density in matter causes asymmetry (through forward weak scattering) whose sign depends on the neutrino mass hierarchy
- E.g. If ***Normal Hierarchy***, matter effect enhances υ_e appearance probability and suppresses anti-υ_e appearance probability (opposite for ***Inverted Hierarchy***).

Probe CP Violation by comparing neutrino and anti-neutrino oscillations

$$P[\nu_\mu \to \nu_e] \neq P[\overline{\nu}_\mu \to \overline{\nu}_e] \ ?$$

DUNE Design Philosophy:
Measure Everything in One Experiment

- **DUNE is a multi-purpose experiment**, more like a collider detector than any previous neutrino experiments that were largely designed to measure a single parameter. This has many advantages
  - *More robust to parameter degeneracies*
  - *Better long-term precision*
  - *More robust to unexpected results*
  - *Much better sensitivity to new physics in neutrino oscillations*

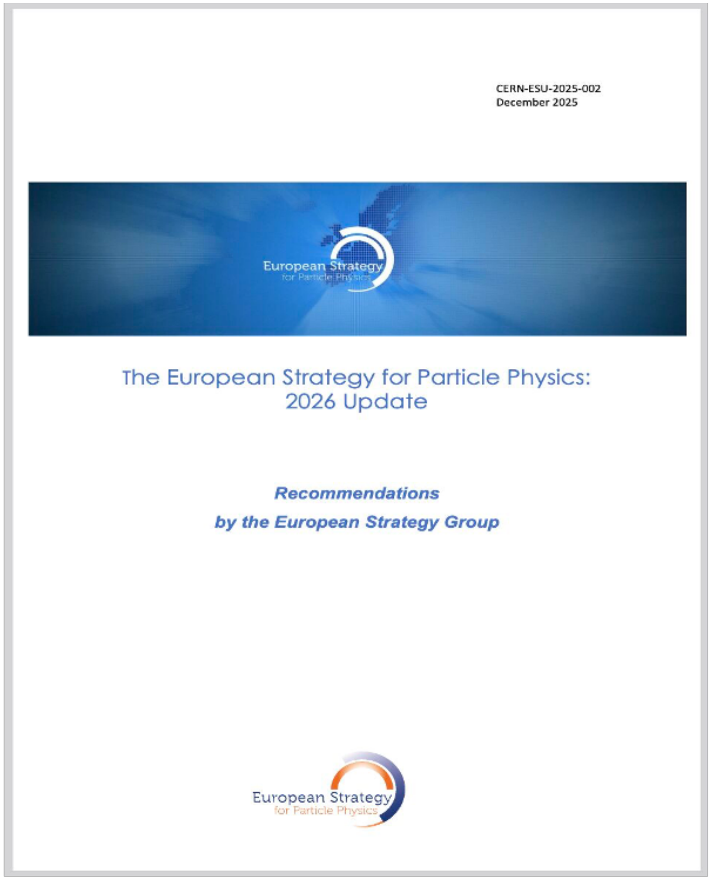
- **DUNE's unique physics program has 4 key ingredients**
  - Wide-band neutrino beam *(rich physics)*
  - Very long baseline *(break degeneracies)*
  - Liquid argon technology *(measure interactions with unprecedented detail)*
  - Movable, high-performance Near Detector *(constrain systematics)*

This allows DUNE to definitively measure Mass Ordering & measure broad range of CPV with utmost precision

European Strategy for Particle Physics 2025 Update

The 2025 ESPPU report was released in Jan 2026 and emphasized the importance of Neutrino Physics to maintain a broader and diverse research portfolio. The report called out that LBNF/DUNE remains a priority for CERN. Below is an excerpt.

"The CERN Neutrino Platform is a focal point of European participation in the global long-baseline neutrino programme. In particular, <u>the current commitments to the LBNF/DUNE project have been decisive and remain a priority for CERN</u>."


CERN-ESU-2025-002
December 2025

The European Strategy for Particle Physics: 2026 Update

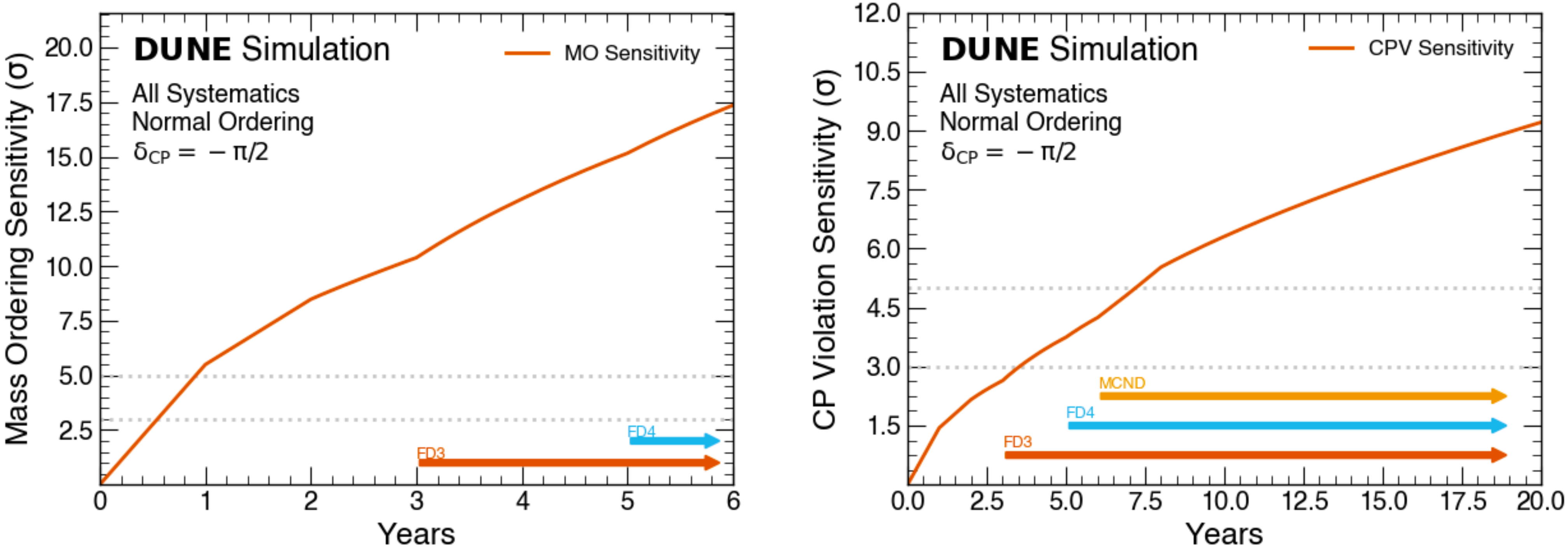
Recommendations by the European Strategy Group

https://cds.cern.ch/record/2950671/files/CERN-ESU-2025-002.pdf

MO & CPV: *If Nature is Kind*

- >5σ Mass Ordering sensitivity in 1 year
- >3σ CPV sensitivity in 3.5 years

Arrows indicate assumed staging scenarios

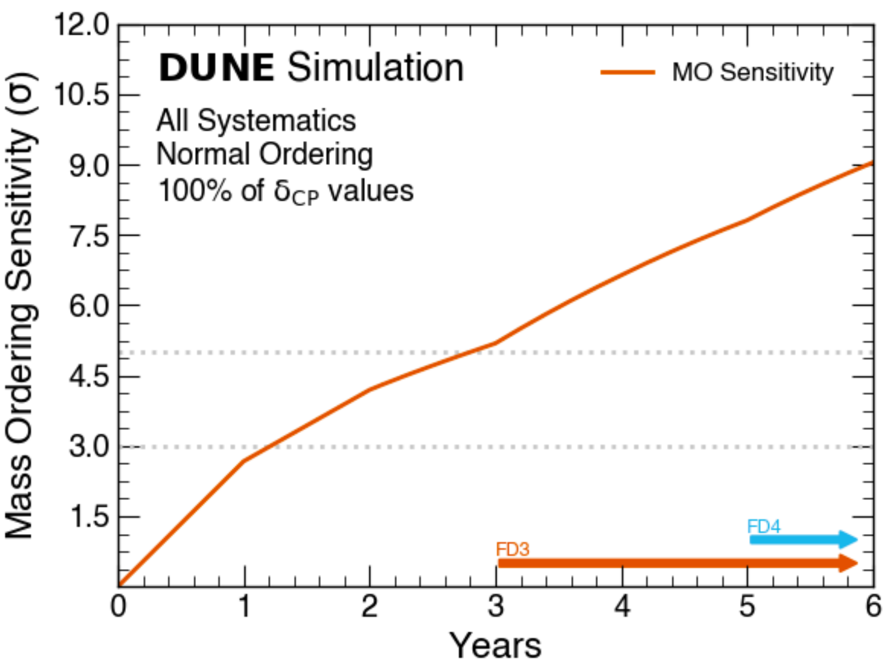


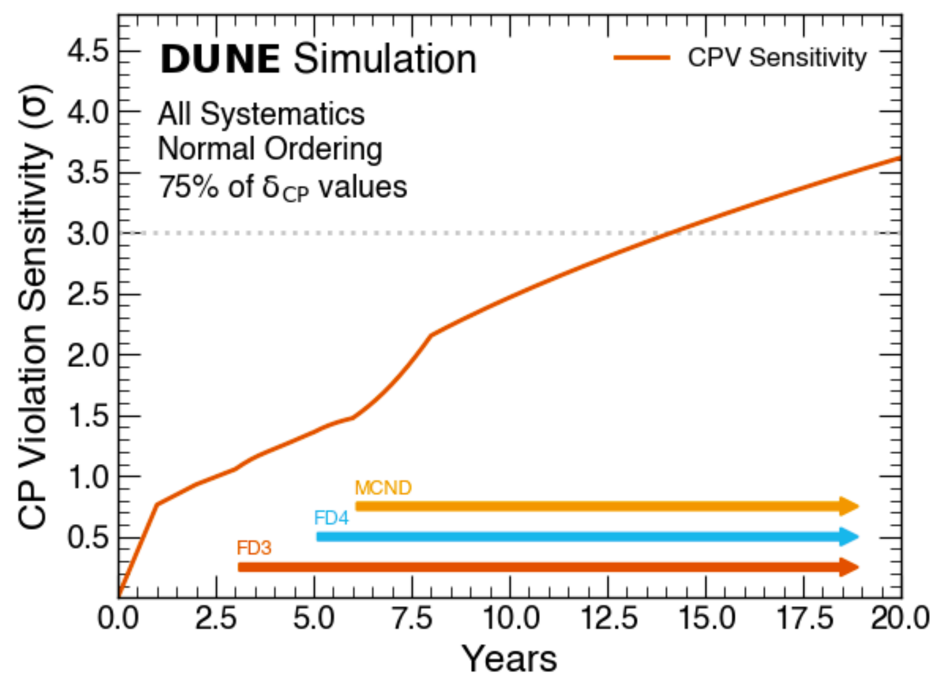
Eur. Phys. J. C 80, 978 (2020)

MO & CPV: *If Nature is Unkind*

- >5σ mass ordering sensitivity in 3 years
- In long term, DUNE can establish CPV over 75% of δ_{CP} values at >3σ

Arrows indicate assumed staging scenarios



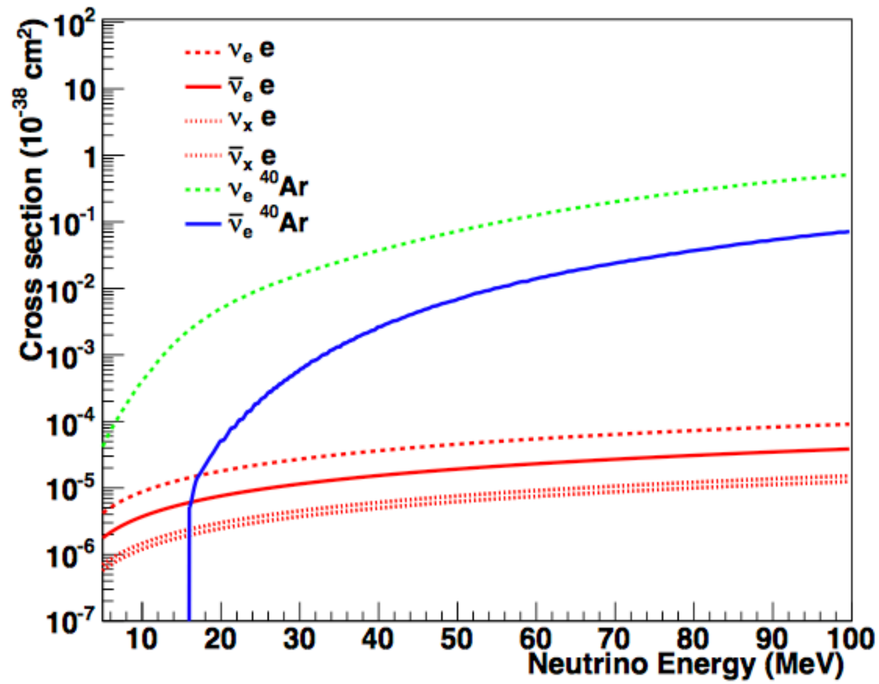


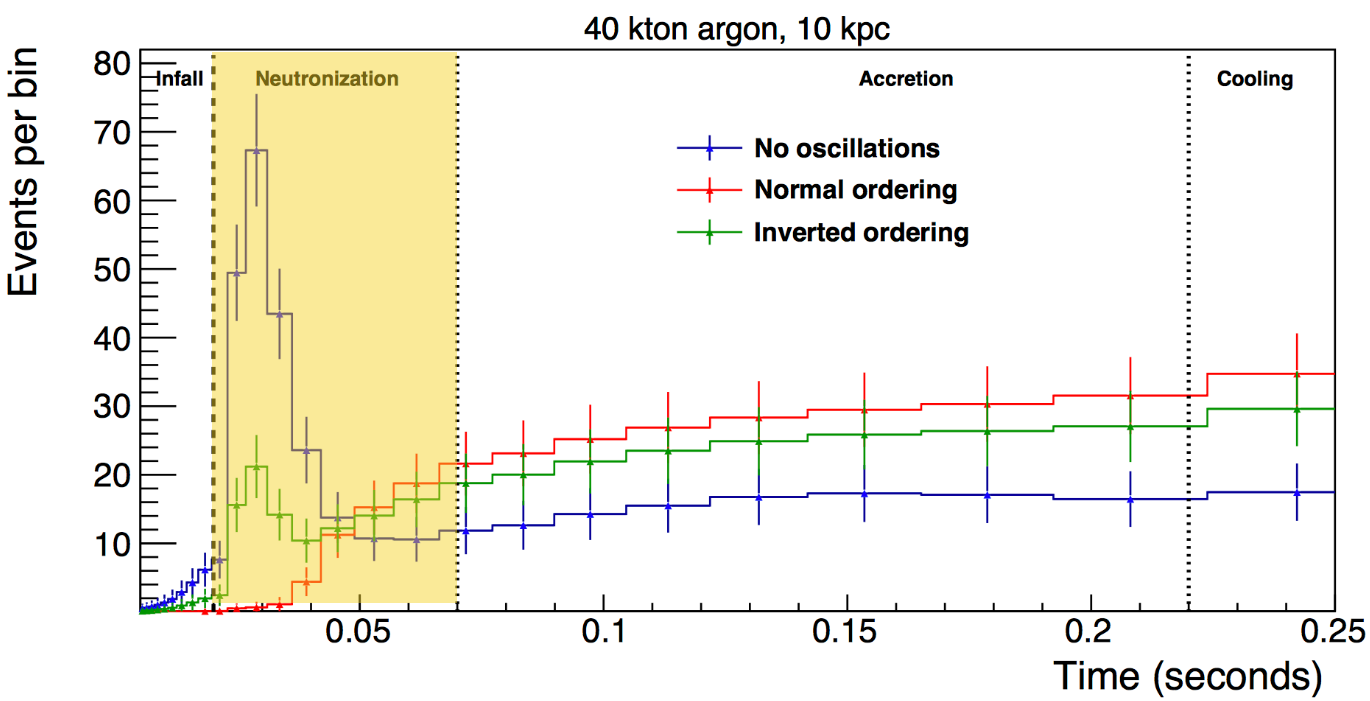
Eur. Phys. J. C 80, 978 (2020)

Astrophysics at DUNE

- Unique capability to detect MeV-scale *electron neutrinos: Charged-Current* ν_e capture of supernova neutrinos on Argon: $\nu_e + Ar^{40}(18) \rightarrow K^{40}(19) + e^-$

- Highly complementary to other experiments (Hyper-K, JUNO) that predominantly see $\bar{\nu}_e$ via Inverse Beta Decay (IBD)





Early development of the signal is sensitive to neutrino mass ordering

DUNE Publications

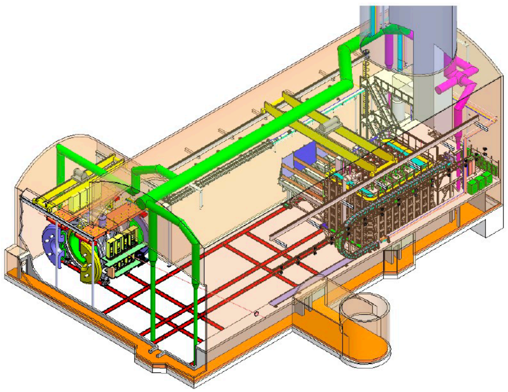
- DUNE is actively publishing on physics, software and technical topics, both collaboration-wide papers and small-author technical papers
- In 2025, 3 papers published, 6 submitted to journals and 5 more in internal review

PUBLICATION TOPIC	PUBLISHED	UNDER REVIEW
Physics	12	5
Detector	8	2
Simulation & Reconstruction	8	1
TDR/White Papers	13	
Other	1	
FULL-AUTHOR PAPERS	**42**	**8**
Small-author technical papers	**59**	

DUNE has published over 100 papers so far and more in the pipeline!

DUNE will be built in Two Phases

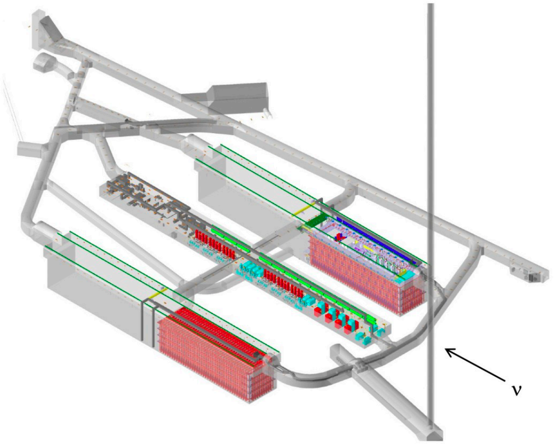
Near Detector (ND)



Phase I

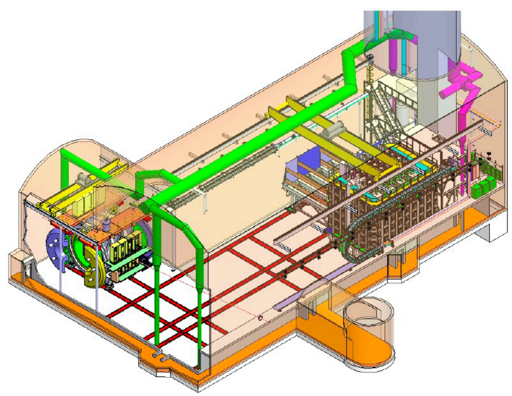
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

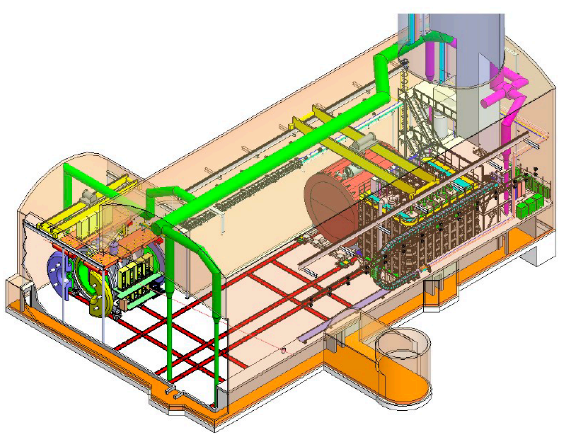
Far Detector (FD)



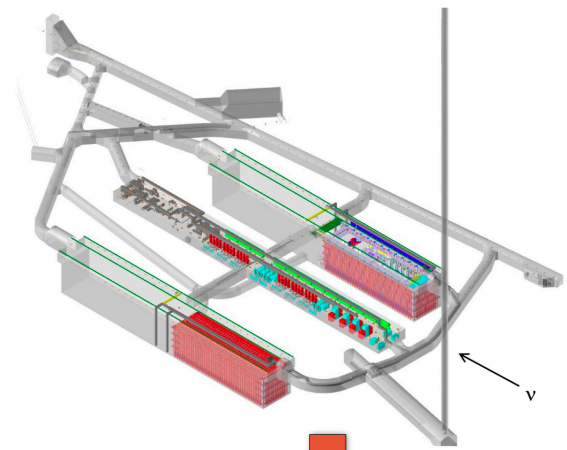
DUNE will be built in Two Phases

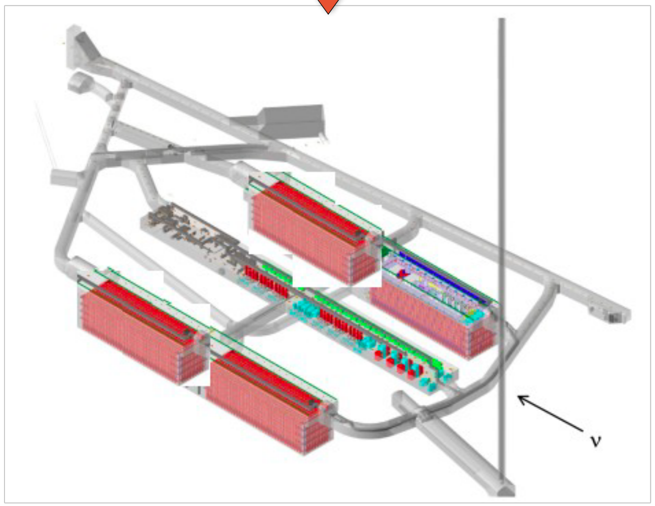
Near Detector (ND)





Far Detector (FD)





Phase I

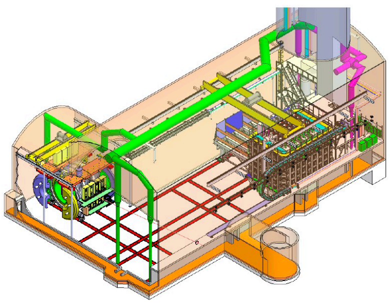
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

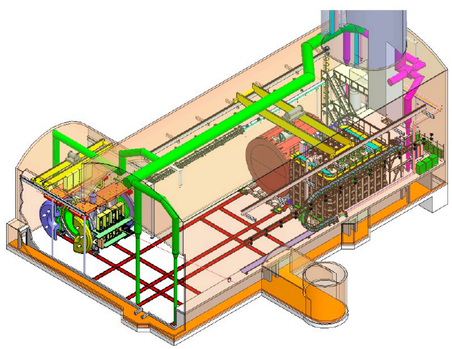
Phase II

- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (ACE Upgrades)

DUNE will be built in Two Phases

Near Detector (ND)





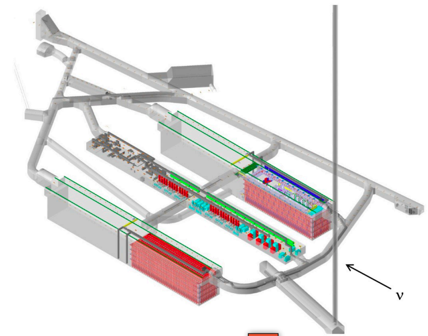
Phase I

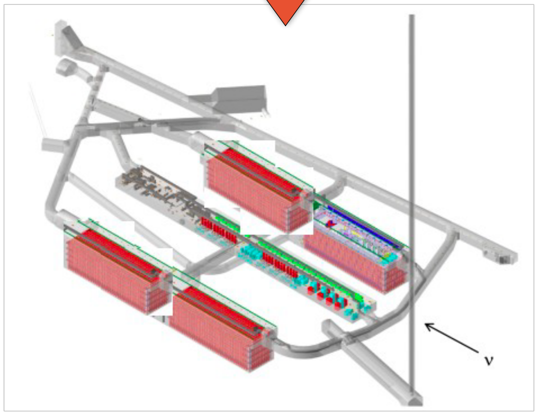
- **FD:** 2 x 17 kt LArTPC modules
- **ND:** ND-LAr+TMS (with PRISM) + SAND
- **Beam:** 1.2 MW beam line (PIP-II)

Phase II

- **FD:** 2 additional modules (total: 4 x 17 kt LAr-equivalent)
- **MCND:** ND-LAr+ND-GAr (with PRISM) + SAND
- **Beam:** > 2 MW beam line (Accelerator Upgrades)

Far Detector (FD)





JINST 19 P12005 (2024)

Parameter	Phase I	Phase II	Impact
FD mass	2 FD modules (20 kt fiducial)	4 FD modules (40 kt fiducial LAr equivalent)	FD statistics
Beam power	1.2 MW	Up to 2.3 MW	FD statistics
ND configuration	ND-LAr+TMS, SAND	ND-LAr, ND-GAr, SAND	Systematics

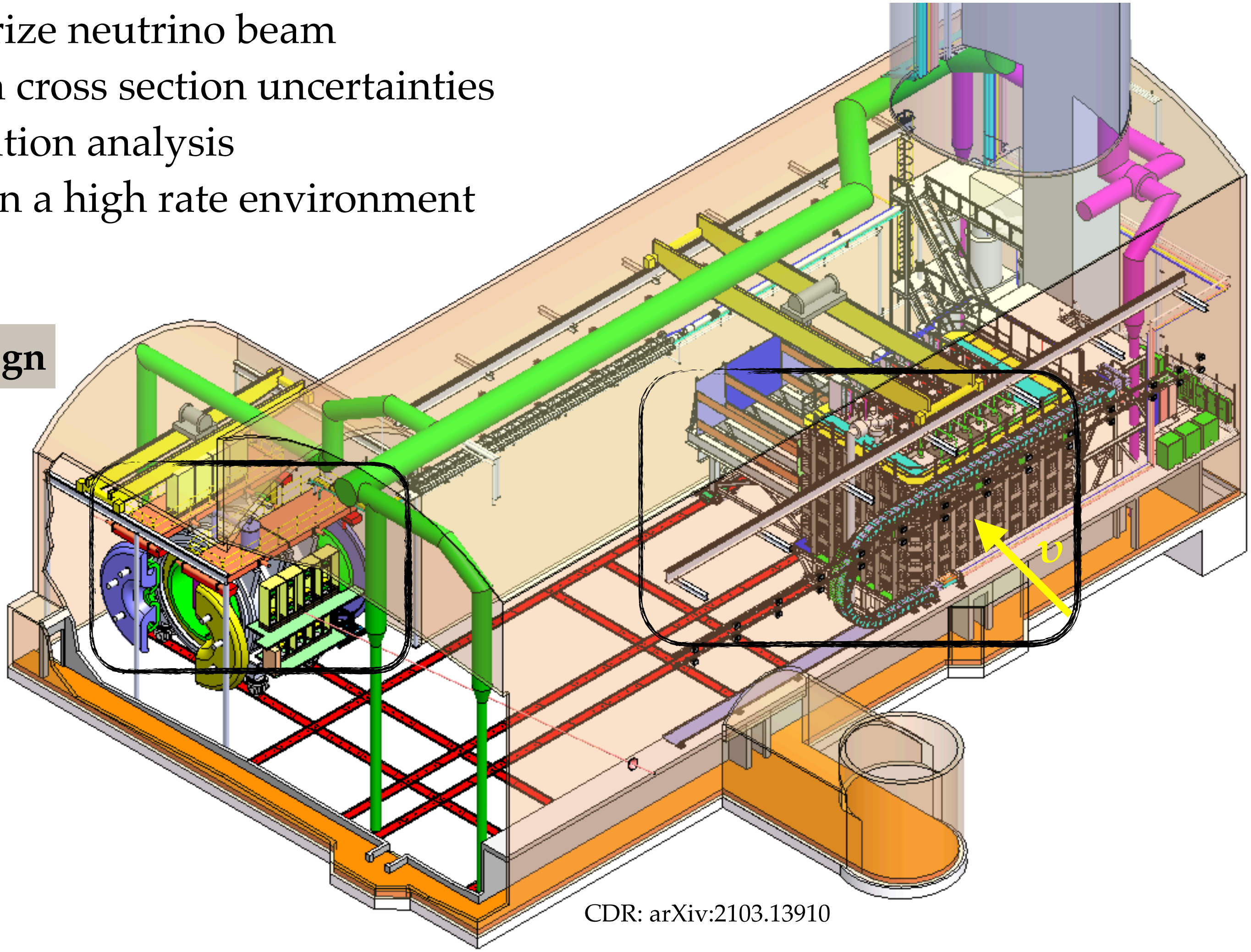
The DUNE Near Detector Complex

- Located **60 m** underground at Fermilab; **574 m** from neutrino beam target
- Comprises of multiple technologies; **will be built in 2 phases**

Primary Goals

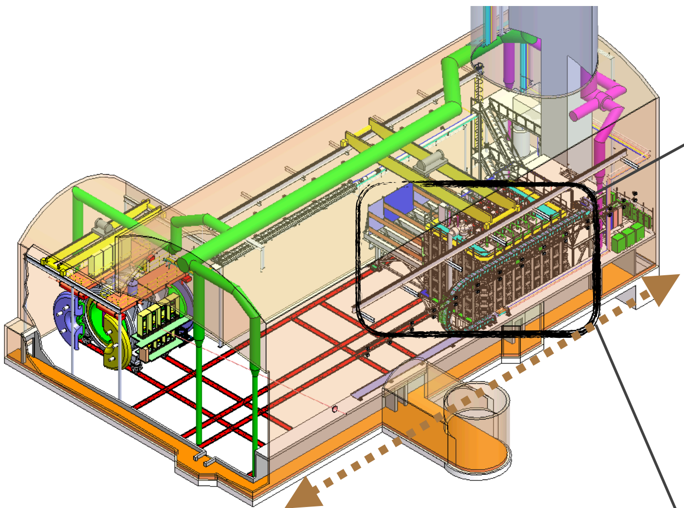
- Characterize neutrino beam
- Constrain cross section uncertainties for oscillation analysis
- Perform in a high rate environment

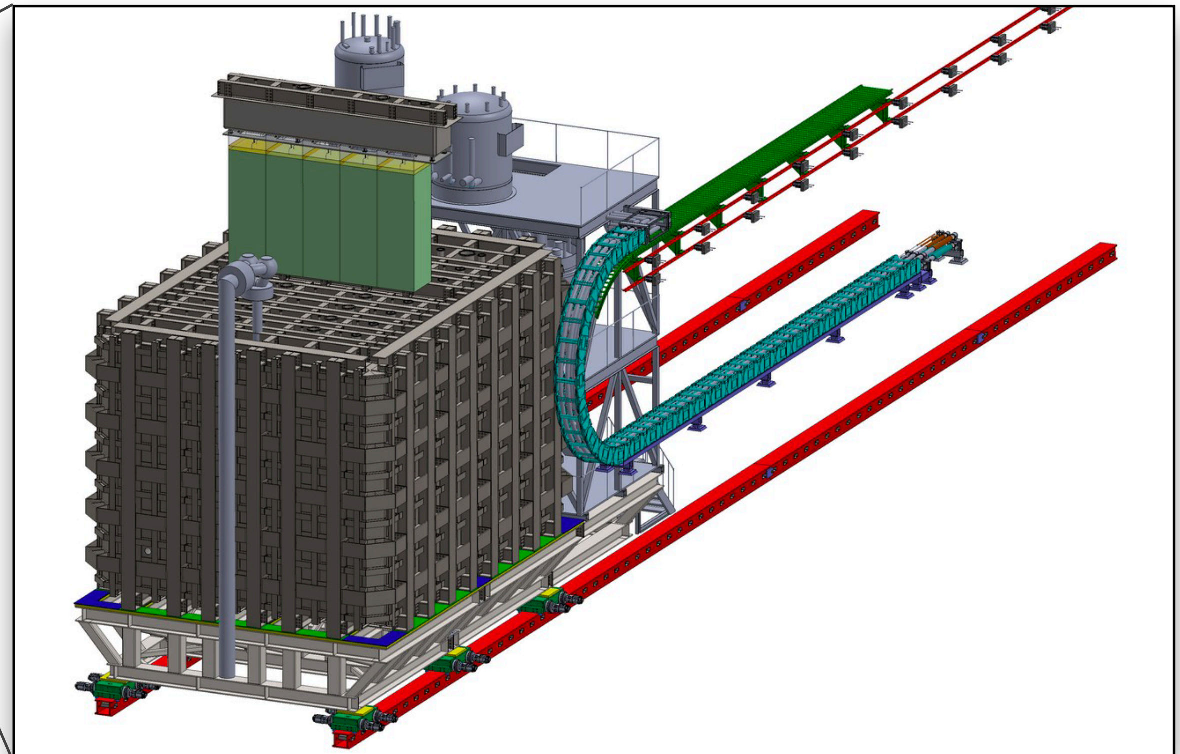
Phase 1 design

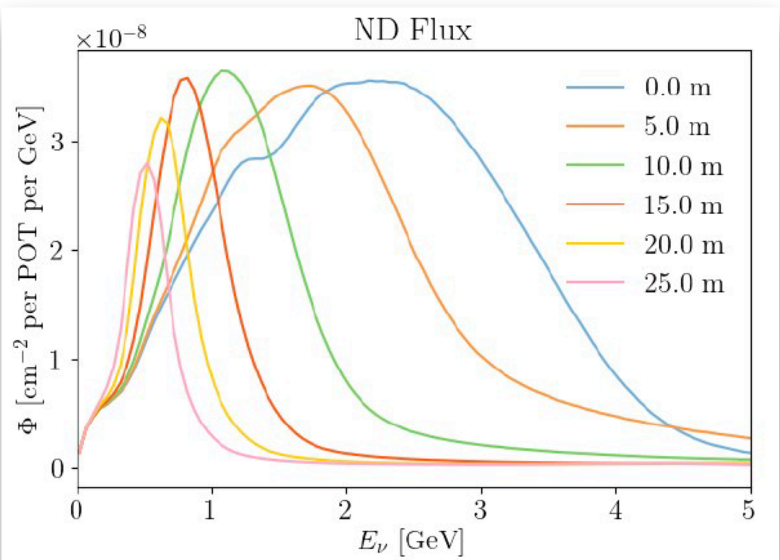


CDR: arXiv:2103.13910

The DUNE-PRISM

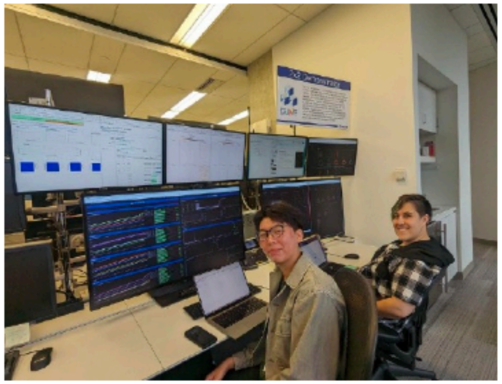


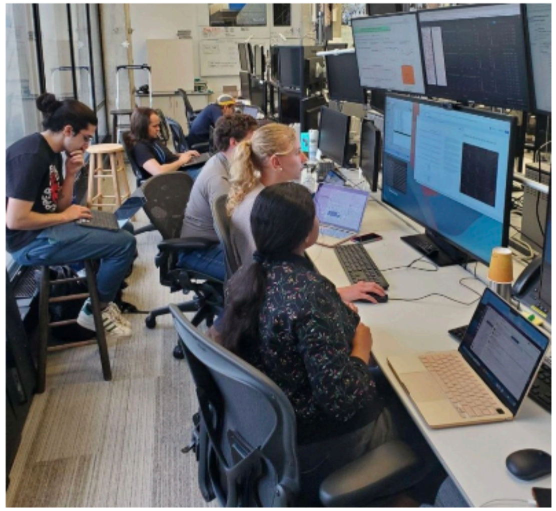




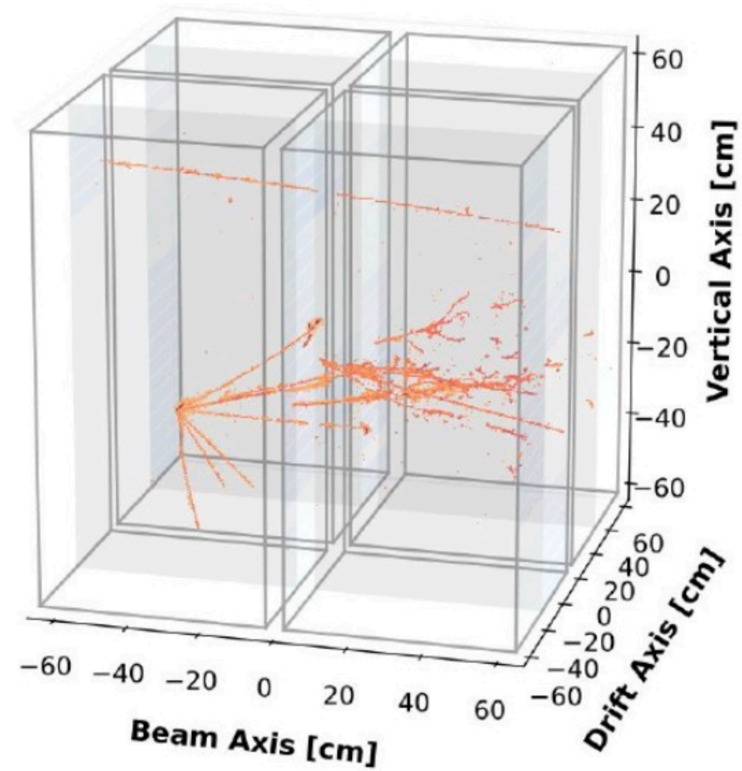
- ND flux changes with angle due to pion decay kinematics
- **ND-LAr and TMS systems can move off-axis up to 28.5 m to observe varied beam spectra**
- Will help address uncertainties in ND to FD extrapolation

ND Prototype in a Neutrino Beam at Fermilab

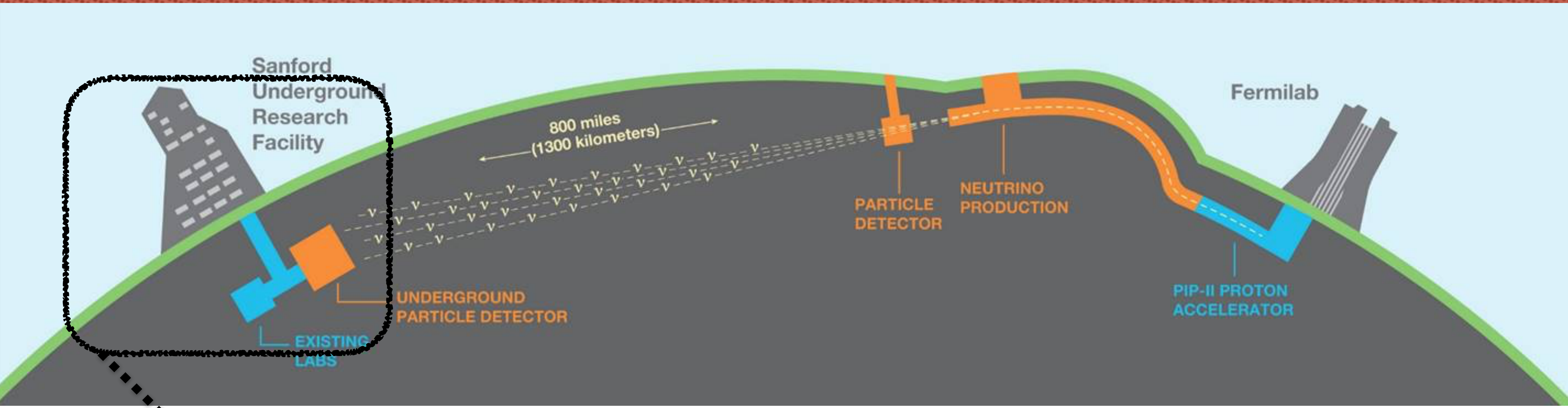


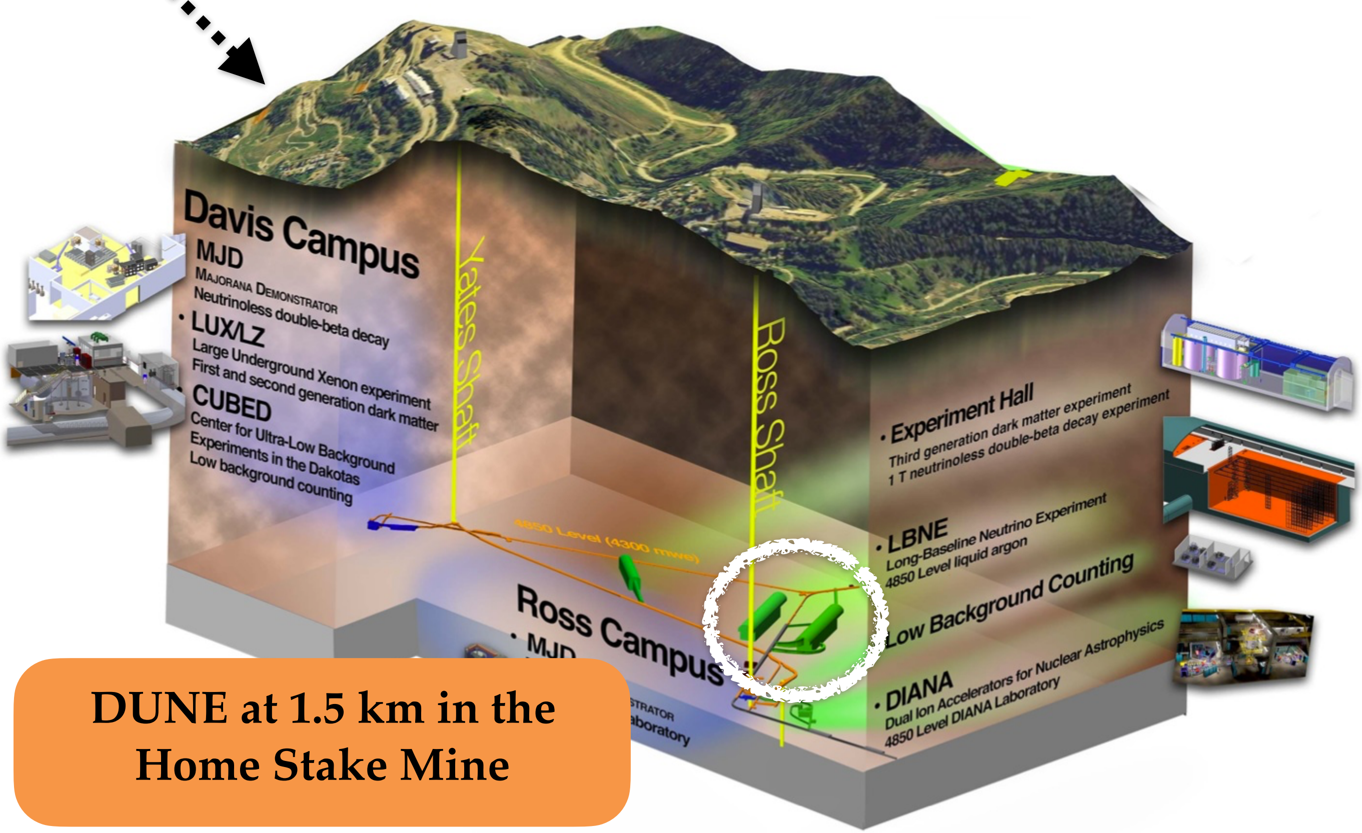


- “2x2” prototype of ND-LAr operated in NuMI neutrino beam in summer 2024 — DUNE has neutrino data!
- Analysis is ongoing, additional (longer) beam run planned for fall 2026
- A “2x2” non-beam run at Fermilab to test various upgrades and calibrations just finished



The DUNE Far Site





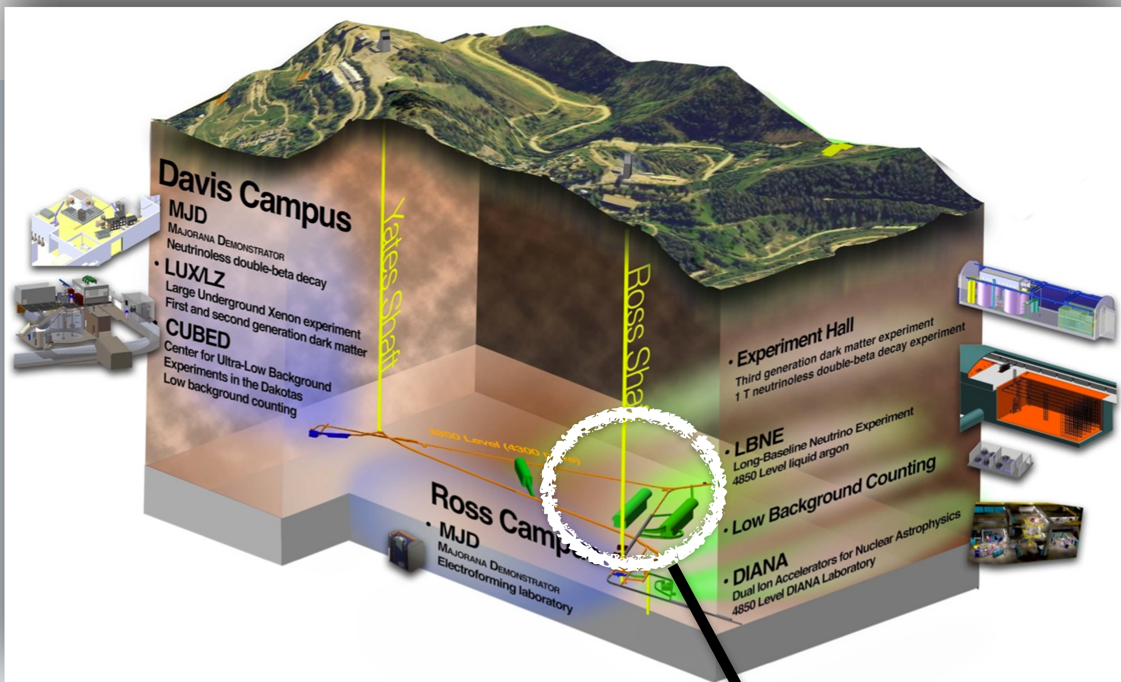
DUNE at 1.5 km in the Home Stake Mine

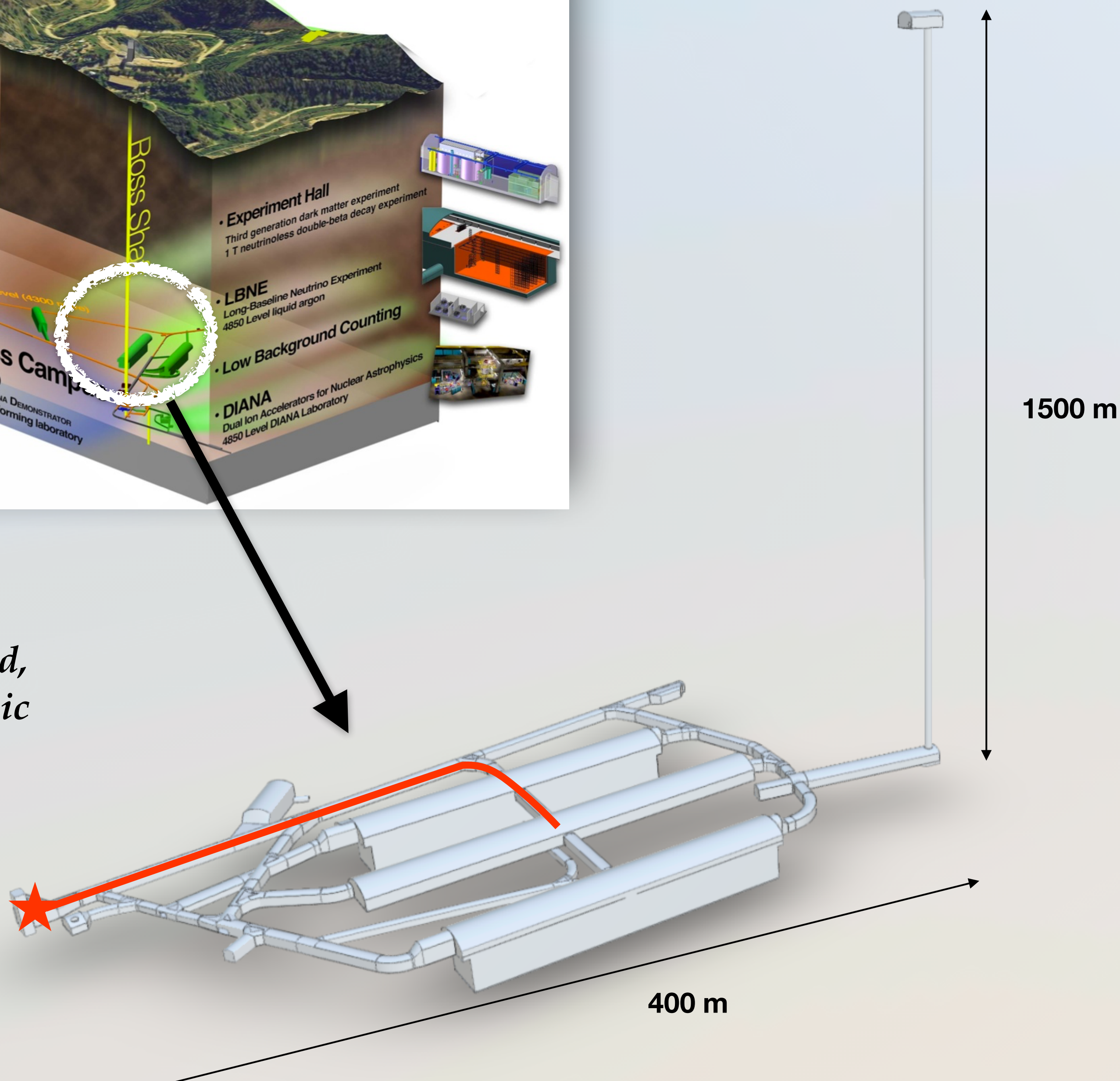
Sanford Underground Research Facility

(Lead, South Dakota)

Home Stake Gold Mine in 1889

The DUNE Far Detector

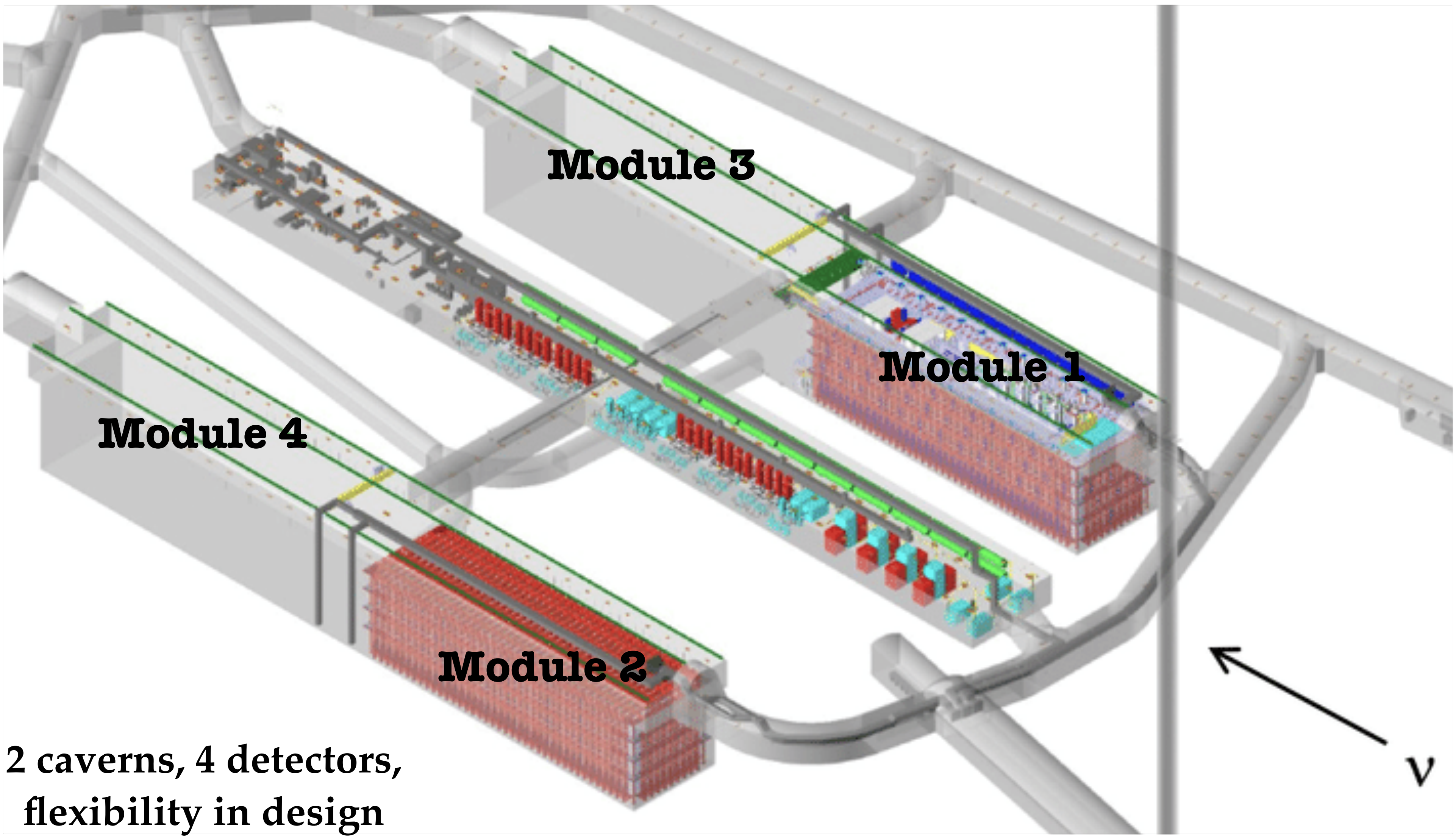




At 1.5 km underground, 10^{-6} reduction of cosmic ray rates for DUNE

The DUNE Far Detector

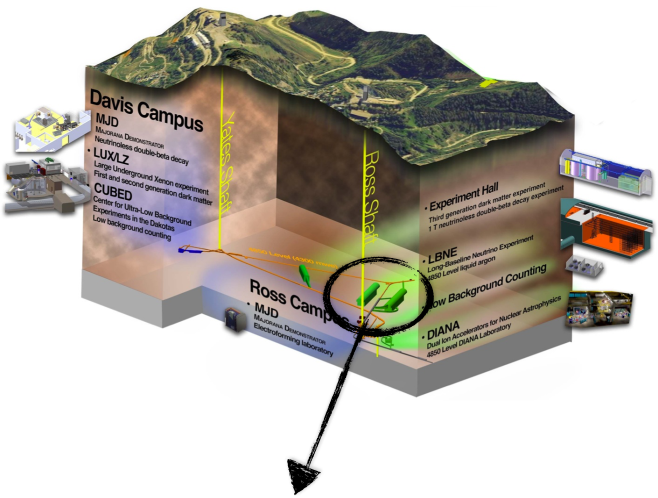
Four 17 kiloton detector modules

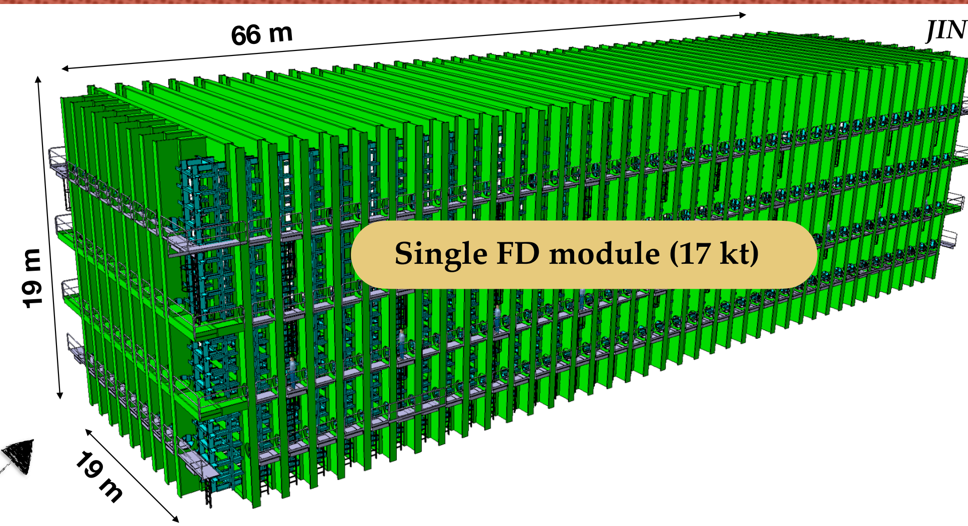


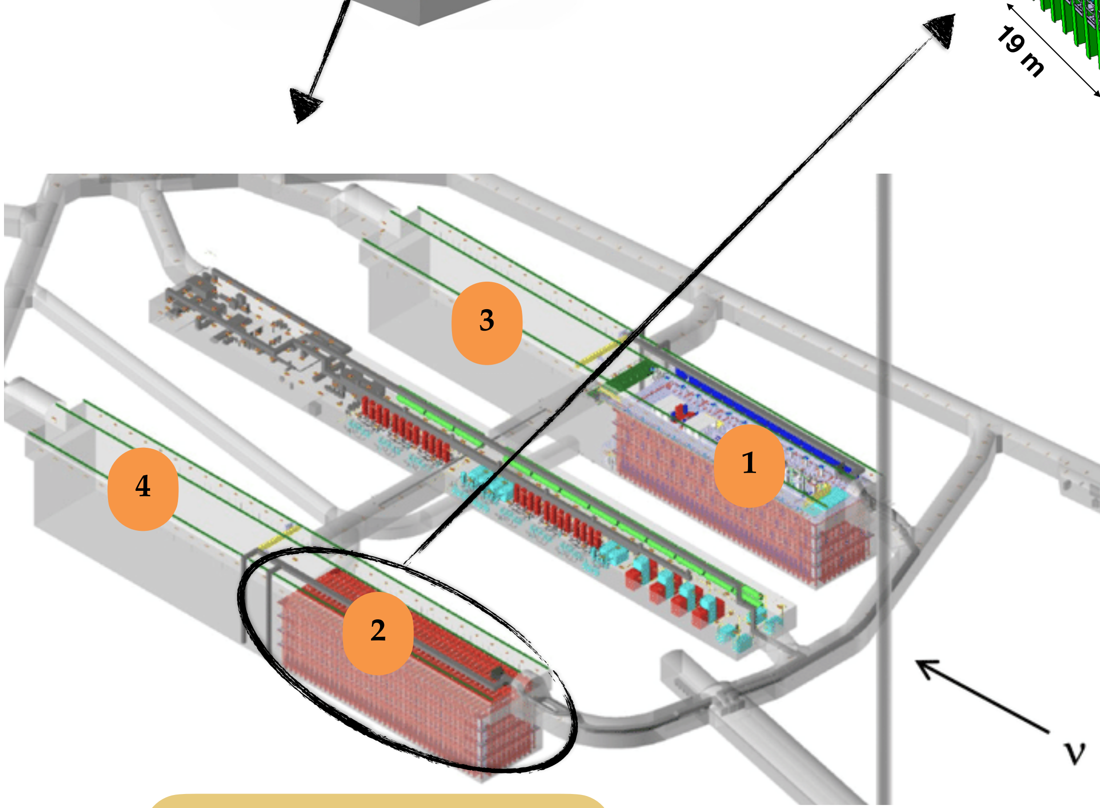
2 caverns, 4 detectors, flexibility in design

The DUNE Far Detector

JINST 15 T08010





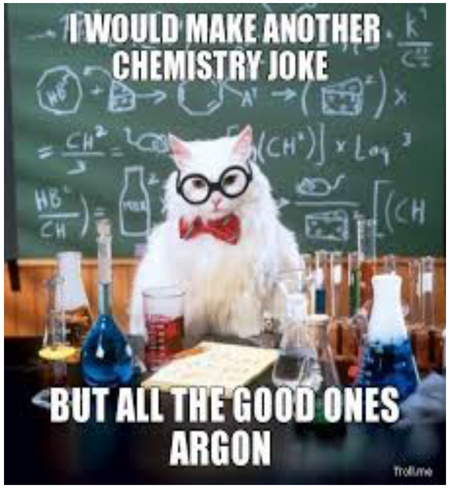


2 caverns, 4 detectors,
flexibility in design

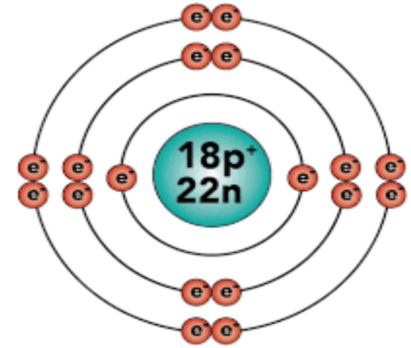
- The first two DUNE FD modules will be **Liquid Argon Time Projection Chamber (LArTPC)** detectors with 17 kt mass each

- **FD#1:** Horizontal Drift (HD)
- **FD#2:** Vertical Drift (VD)
- **FD#3:** Improved VD
- **FD#4:** Module of opportunity *(R&D ongoing; both LAr and non-war options being explored)*

Why Liquid Argon?



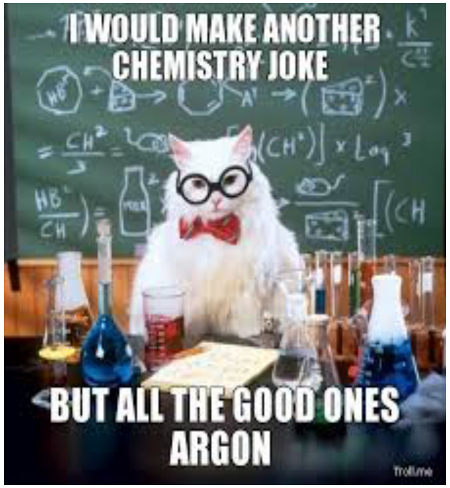
- dense
- abundant (1% of atmosphere)
- easily ionizable (55,000 electrons/cm)
- highly scintillating (transparent to light)
- pure argon results in high electron mobility implies long drift lengths



	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.2	27.1	87.3	120.0	165.0	373
Density [g/cm³]	0.125	1.2	1.4	2.4	3.0	1
Radiation Length [cm]	755.2	24.0	14.0	4.9	2.8	36.1
dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	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	

Table credit: M. Soderberg

Why Liquid Argon?



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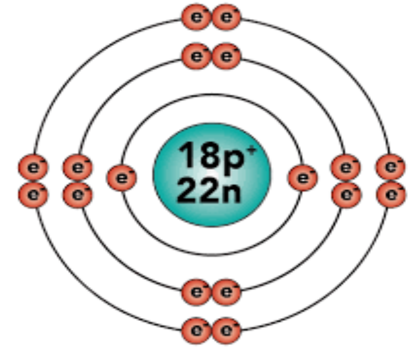


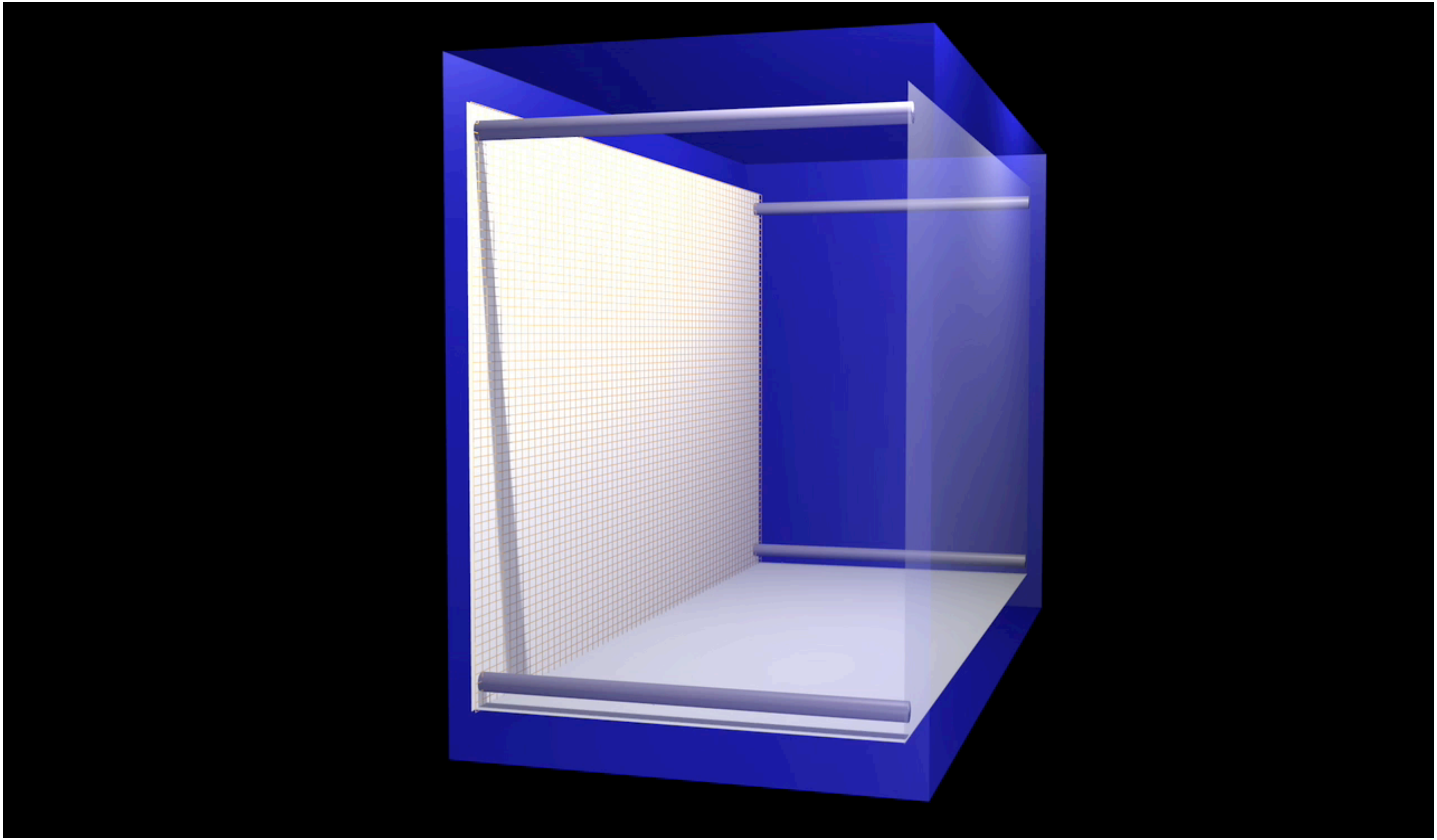
Cheap!

	He	Ne	Ar	Kr	Xe	Water
Boiling Point [K] @ 1atm	4.[illegible]	2[illegible].1	87[illegible]	1[illegible]0.0	16[illegible].0	373
Density [g/cm³]	[illegible]	[illegible]2	[illegible]	[illegible]4	3[illegible]	1
Radiation Length [cm]	755.2	[illegible]	14.0	[illegible]9	[illegible]	[illegible]
Scintillation [γ/MeV]	19,000	[illegible]	[illegible]0,000	[illegible]	42,000	
MIP dE/dx [MeV/cm]	0.24	1.4	2.1	3.0	3.8	1.9
Scintillation λ [nm]	80	78	128	150	175	

He: ~$10/L
Ne: ~$500/L
Ar: ~$2/L
Kr: ~$700/L
Xe: ~$3000/L

Table credit: M. Soderberg

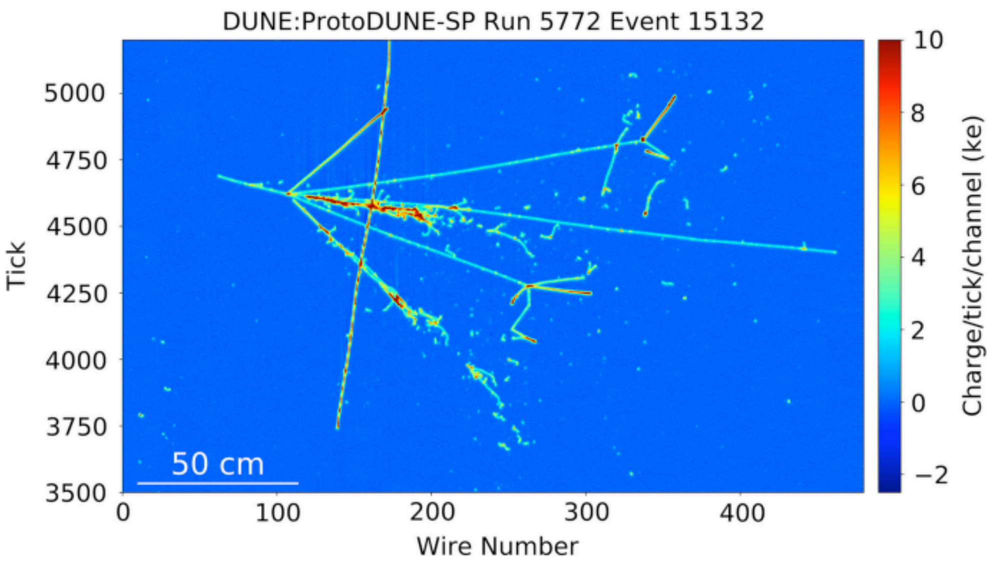
Liquid Argon Time Projection Chambers



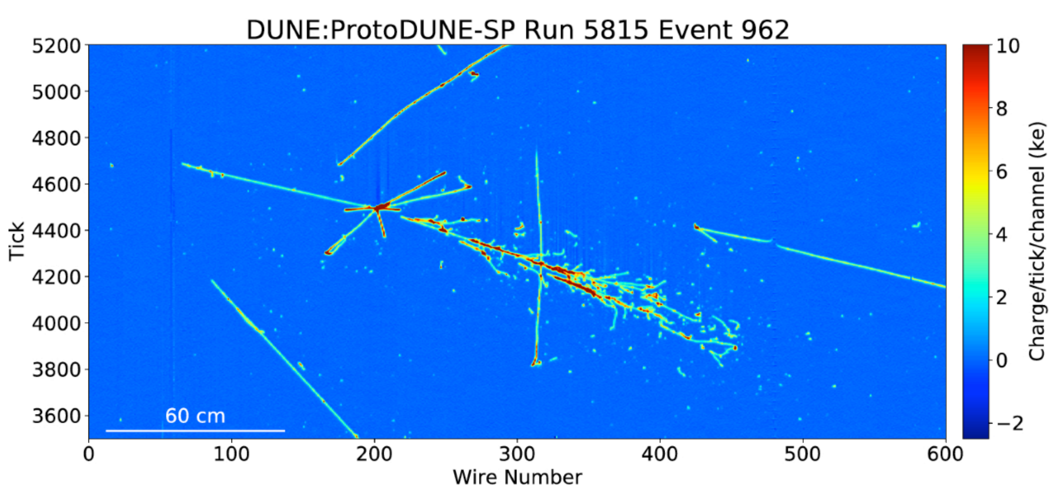
A Paradigm Shift in the Detection of Neutrinos

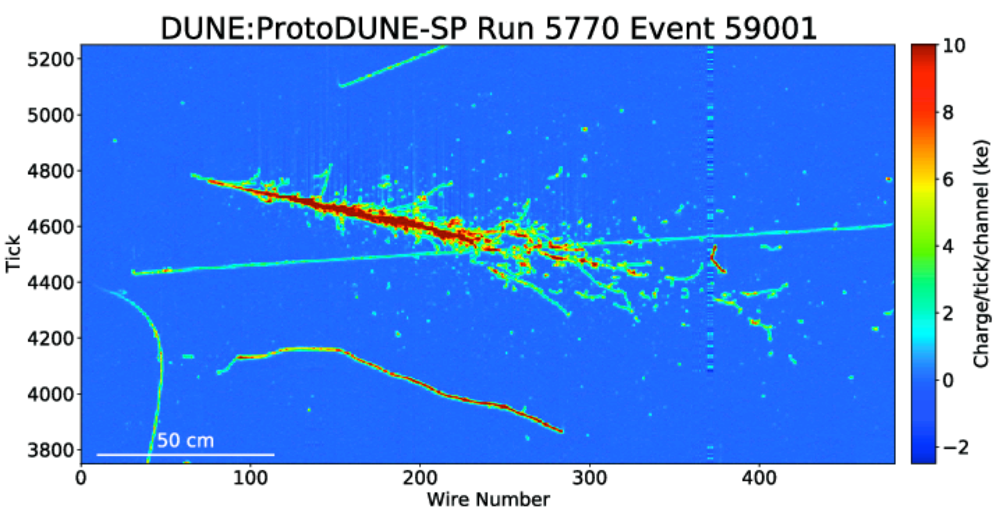
Watch the video here: https://www.youtube.com/watch?v=R5G1_hW0ZUA

Liquid Argon Time Projection Chambers

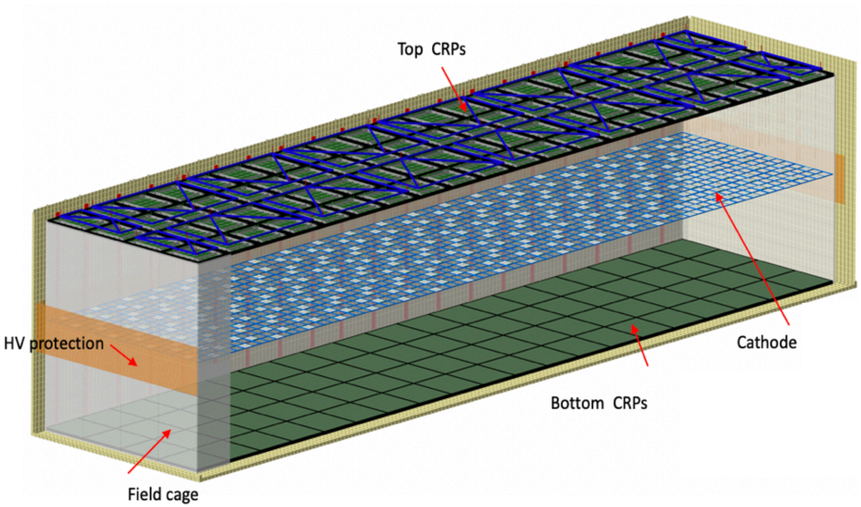


Look at the details of neutrinos like never seen before!



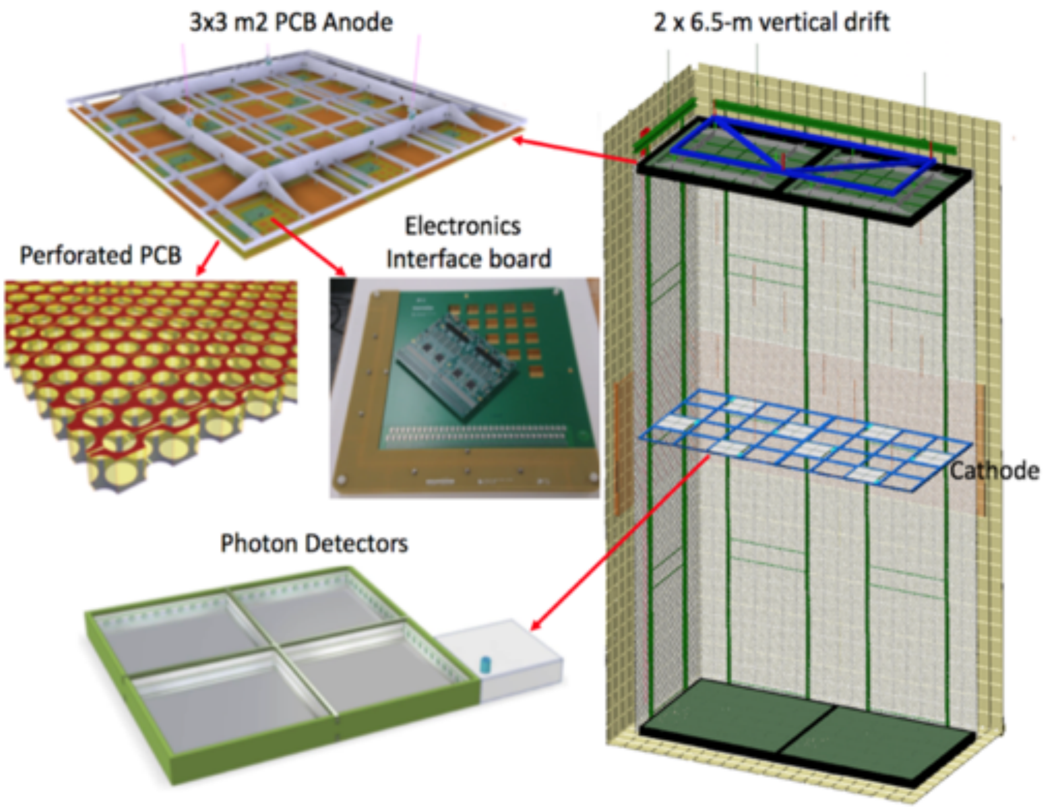


FD#2: Vertical Drift LArTPC



- VD technology evolved from extensive R&D from single and dual phase LArTPCs
- Designed to maximize active volume
- Perforated PCBs with segmented electrodes (strips) as readout units

- Charge readout units at the top and bottom
- Cathode in the middle
- Photon detectors integrated on cathode and on cryostat walls
- Two 6.5 m drift chambers
- -300kV on cathode; 450 V/cm field



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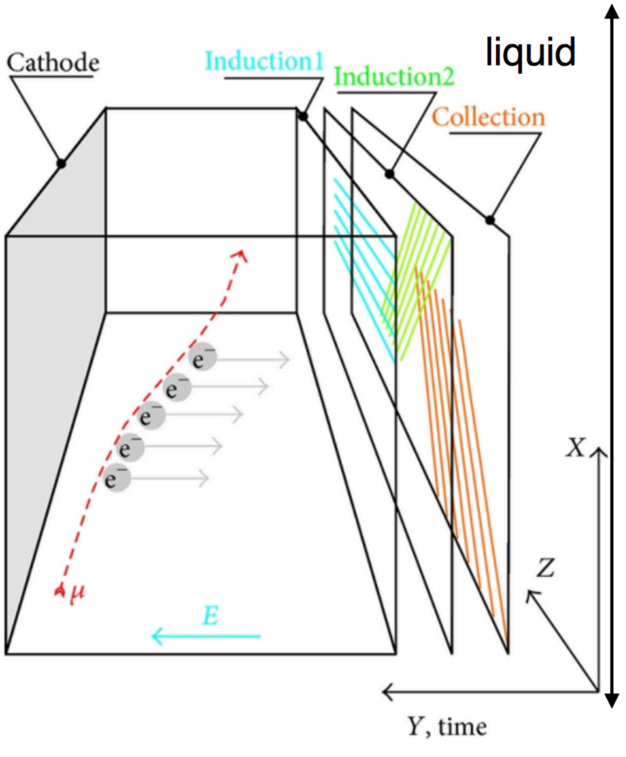
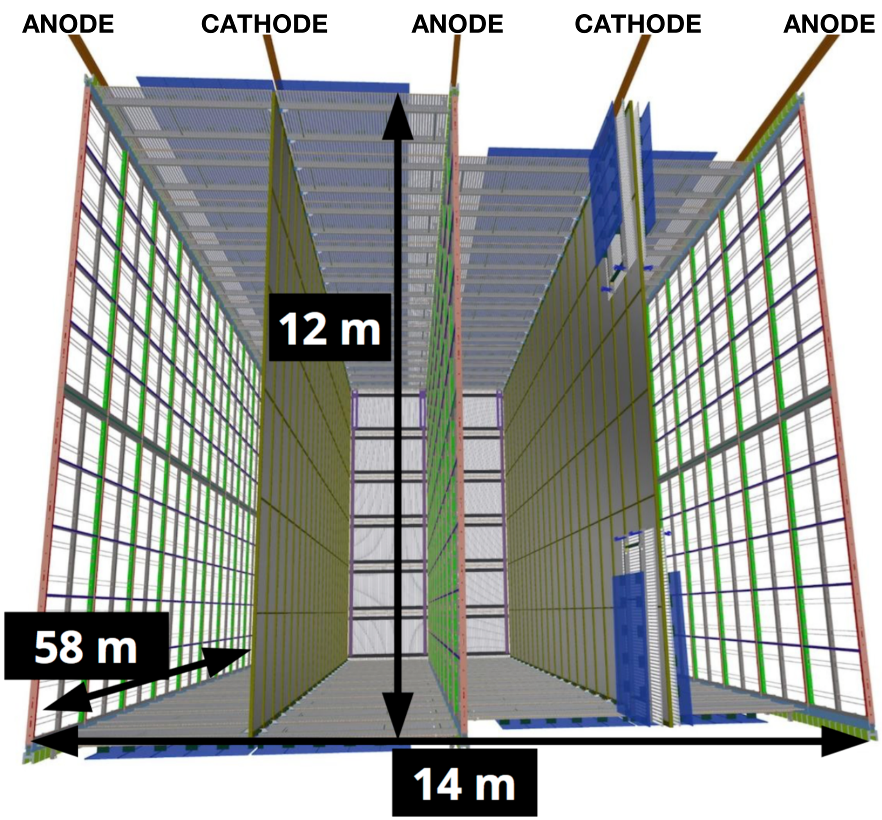
FD#1: Horizontal Drift LArTPC





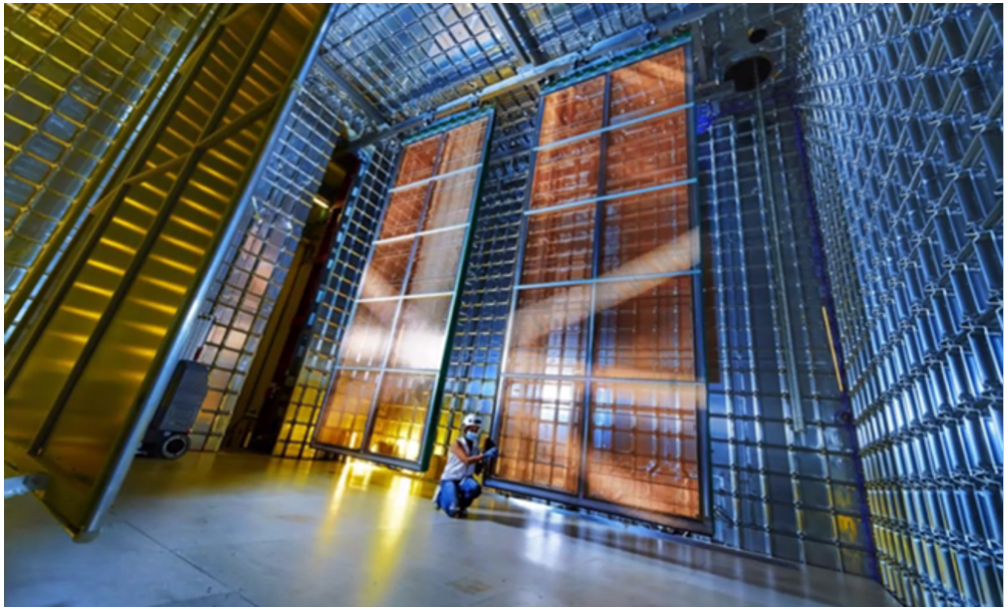
JINST 15 T08010 (2020)

- 12 m x 14 m x 58 m active volume
- Each Anode-Cathode chamber has 3.5 m drift
- Cathode at -180 kV
- 150 Anode Plane Assemblies (APAs) with 384,000 readout wires
- Anode planes have wrapped wires (readout on both sides)
- 6000 photon detection system (PDS) channels for light readout

UK is Building 90% of the APA Modules for DUNE

- Each APA is large rectangular frame (~6x2 m) with 24 km of hair-width copper-beryllium wire wound in multiple directions, tensioned and secured by thousands of hand-soldered connections — *a complicated piece of device*

- UK has the *only* large-scale APA Production facility at Daresbury delivering 137 APAs to DUNE
  - *55 of 137 are already made!*
  - Successful demonstration of APAs in 1-kiloton scale ProtoDUNE experiment at CERN



First Batch of APAs Shipped to Fermilab Last Month!

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UK detector components shipped to US for DUNE experiment

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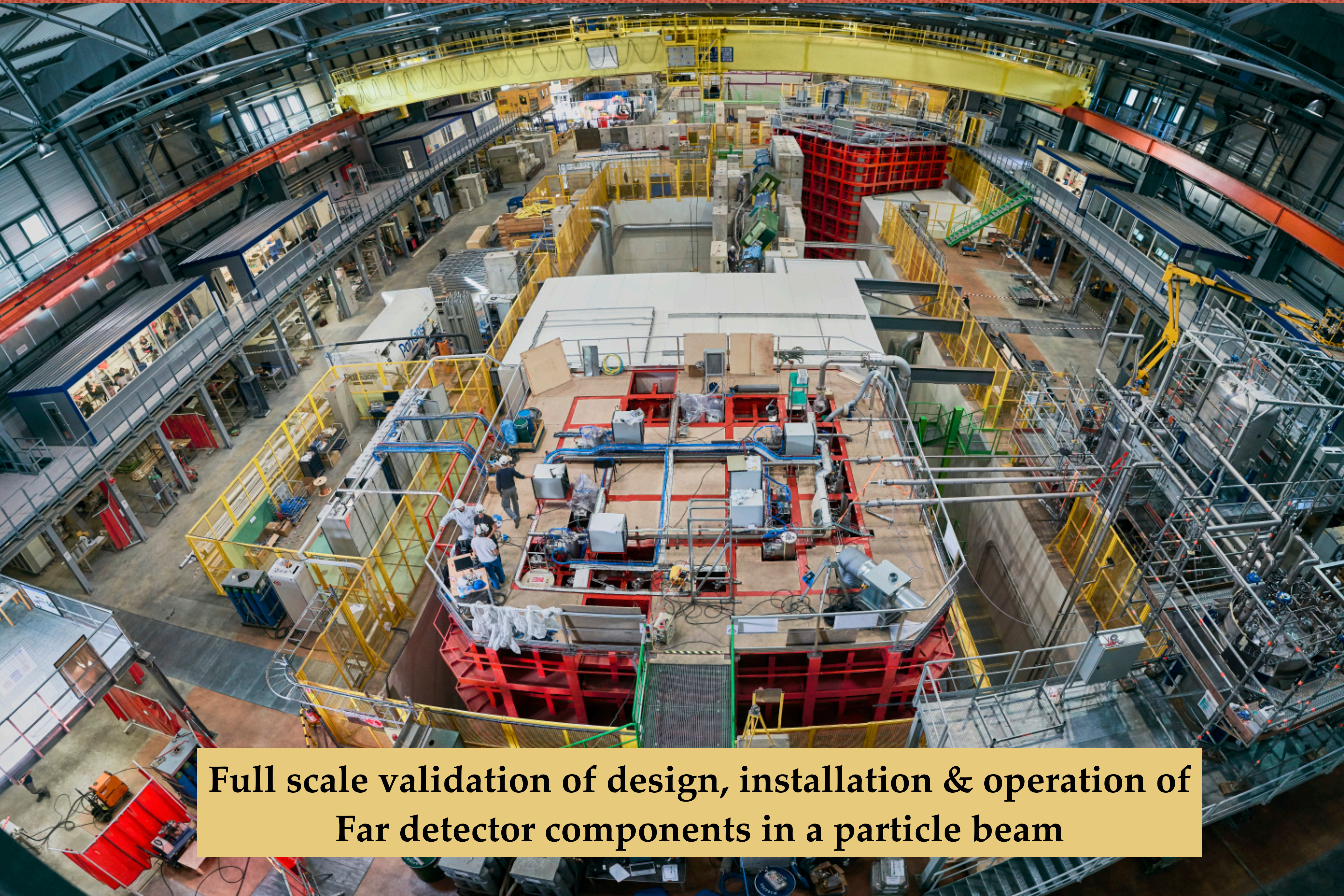
4 March 2026

Detector components built at STFC's Daresbury Laboratory have arrived at Fermilab, marking the first shipment of these detector components to DUNE experiment.

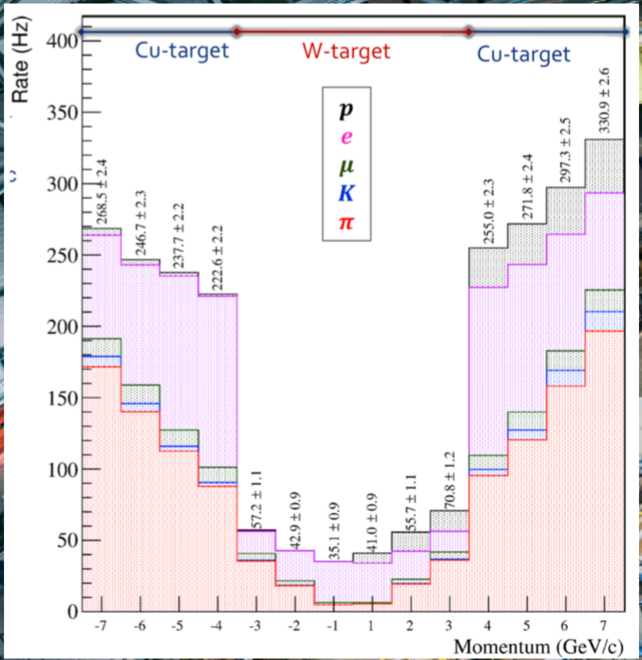
Big, Complex, Sensitive devices result in big logistics — an important milestone for DUNE!

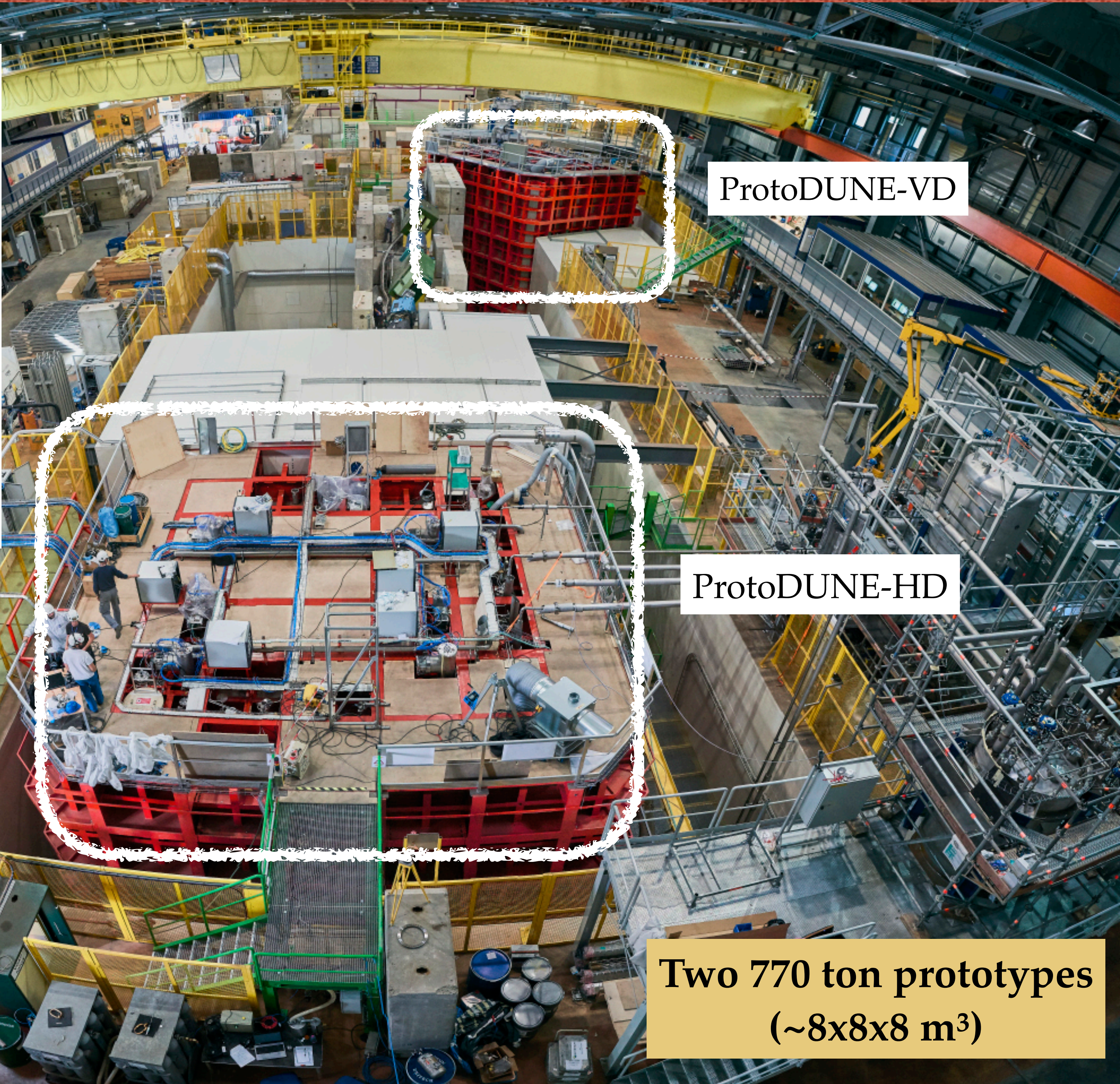
CERN Neutrino Platform



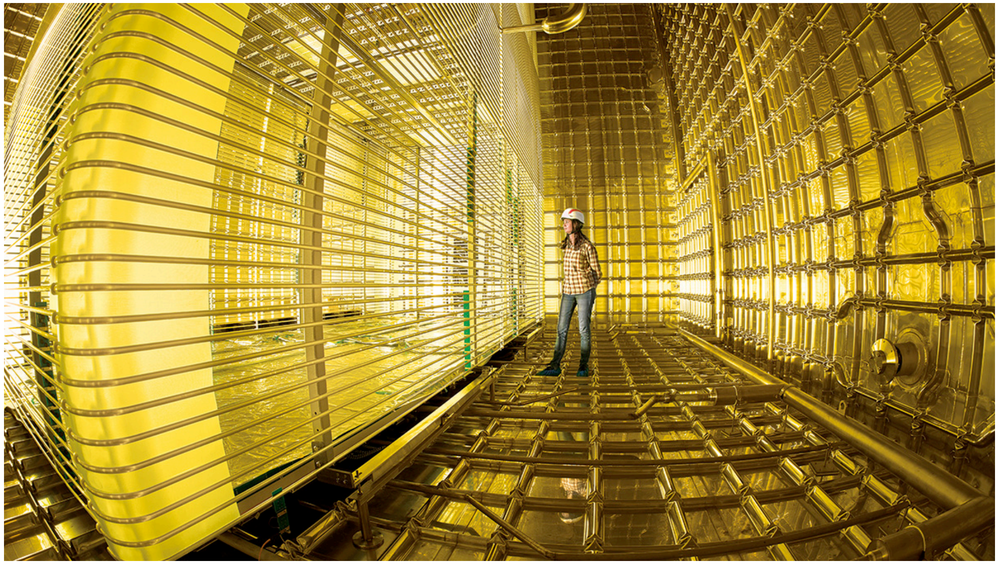
Full scale validation of design, installation & operation of Far detector components in a particle beam

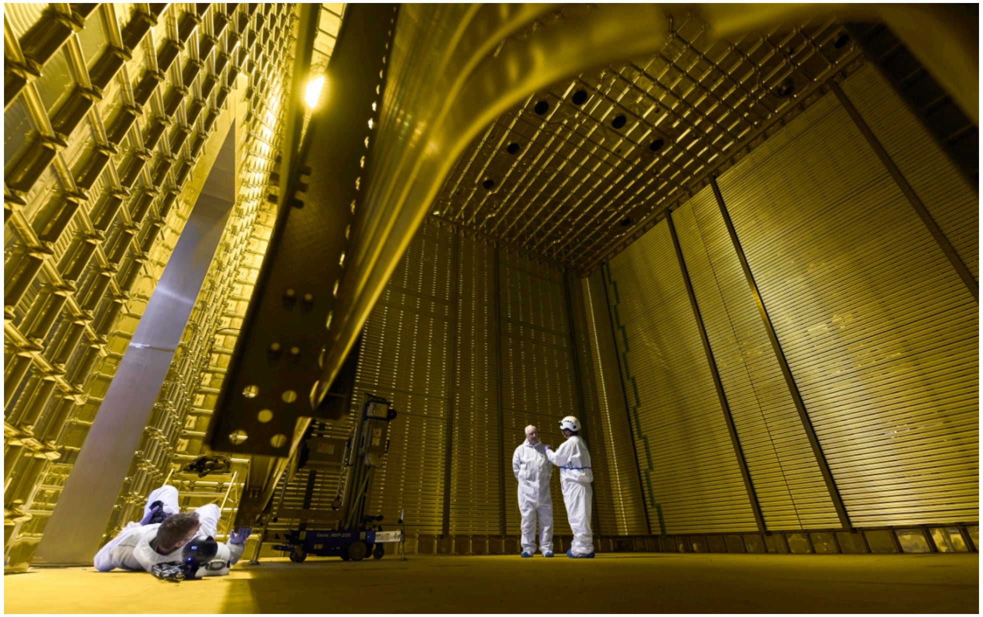
CERN Neutrino Platform

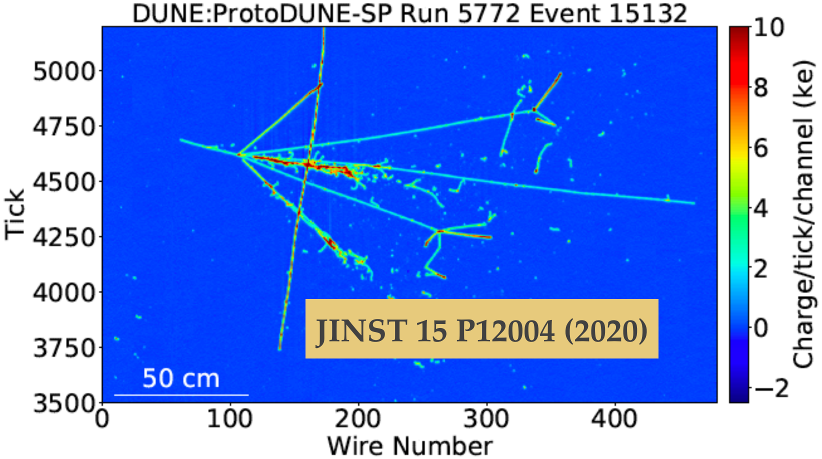




Testing DUNE Far Detector Technologies at Large Scale at CERN

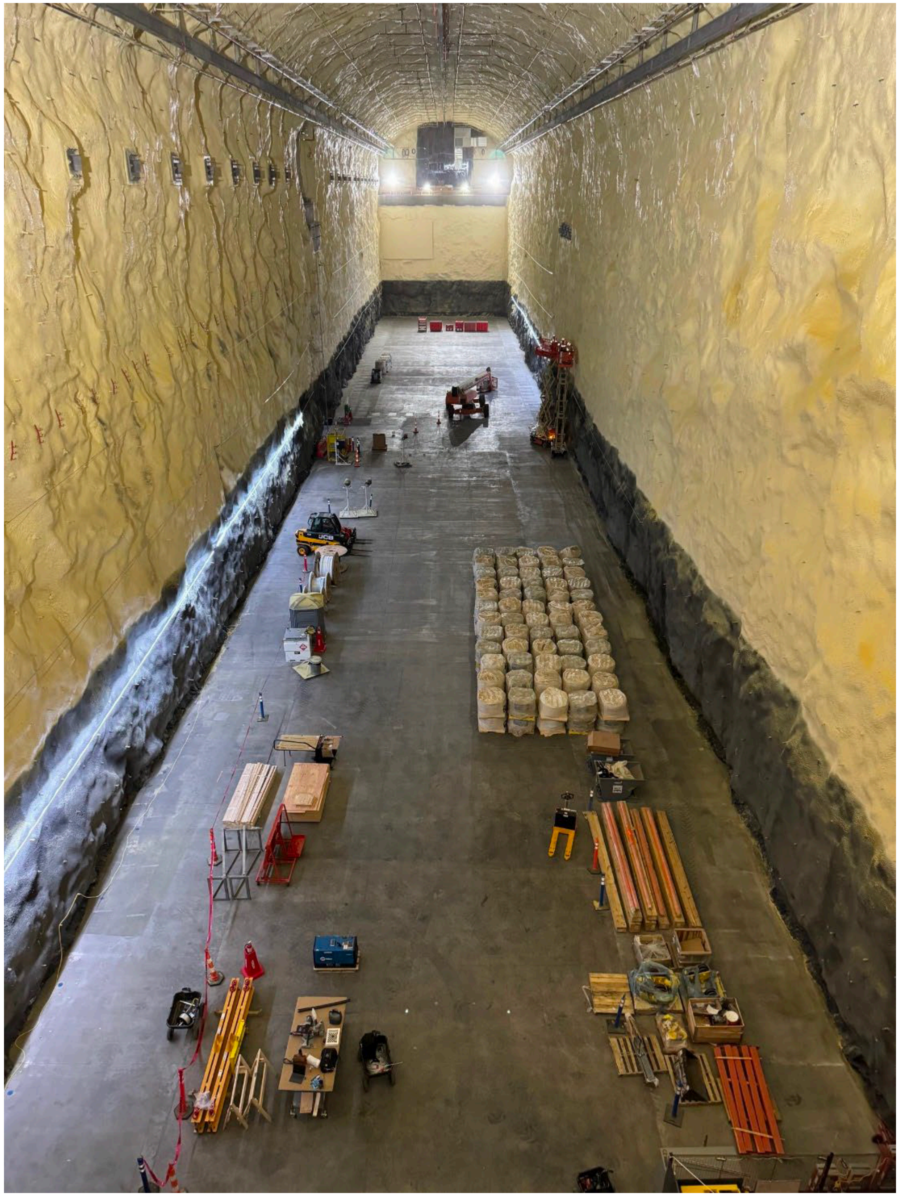






Colossal Caverns at SURF Excavated in 2024

800,000 tons of rock crushed and removed
The caverns are clean, functional labs today!



LBNF/DUNE Wins Project of the Year Award!

EVENTS NEWS SUBSCRIBE WORK WITH US LOG IN SEARCH

SANFORD UNDERGROUND RESEARCH FACILITY

ABOUT VISITOR CENTER RESEARCH EDUCATION SUPPORT SURF

Photo by Matthew Kapust

https://sanfordlab.org/news/largest-neutrino-experiment-us-wins-project-year-award

Home | News | Largest Neutrino Experiment In The U....

APRIL 13, 2026 **Announced last week**

by Tracy Marc

NEUTRINOS

Largest neutrino experiment in the U.S. wins Project of the Year Award

The largest neutrino experiment in the U.S. was named the Project of the Year by the Underground Construction Association for completing a significant and challenging underground construction project with little or no issues.

Stay up-to-date on our latest news and upcoming events.

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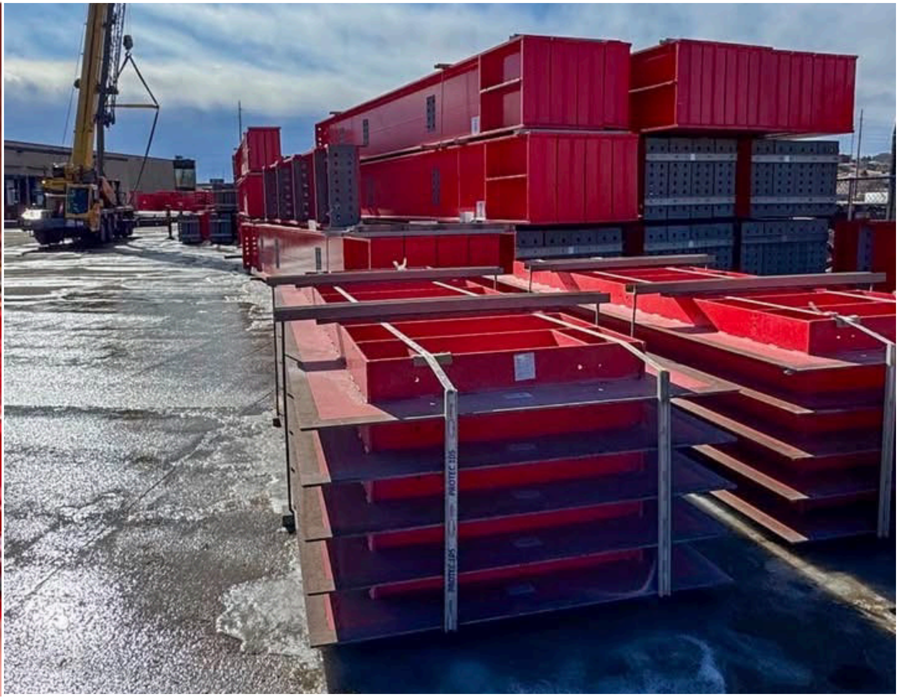
Cavern Outfitting Complete

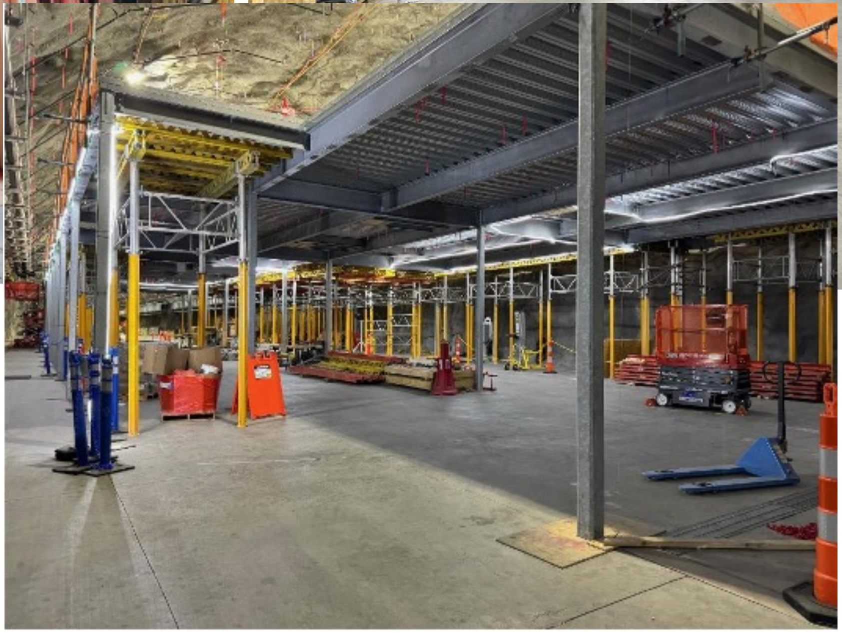
Tours and Espresso Coffee a mile underground!

All Cryostat Material Arrived at South Dakota



Cryostat Installation Starts This Year

- Cryostat material being prepared for underground transport early next year
- **Cryostat installation underground will start in August 2026**
- Detailed planning underway for material cleaning, lowering and staging cryostat beams underground including testing procedures on the surface



A working underground space!

Closing Remarks

- DUNE will measure known unknowns and unknown unknowns, all in one experiment
- DUNE technologies are mature and have been demonstrated at scale with extensive prototyping at CERN and Fermilab
- Far Detectors will be installed at SURF starting in 2027
- Data taking starts in 2029 and with beam in 2031
- **Stay tuned for many more exciting updates!**

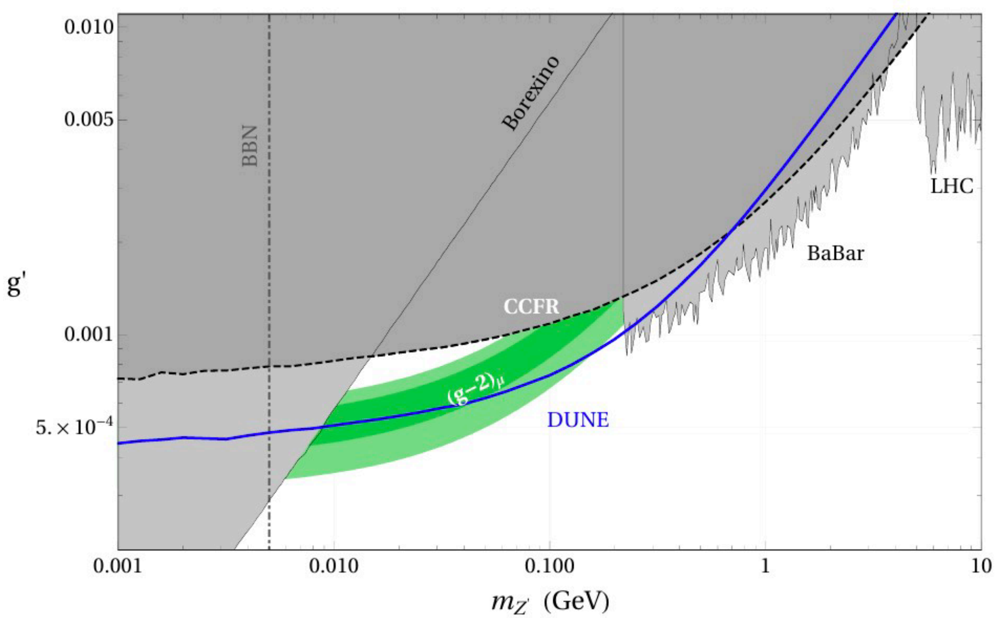

Thank you!

EXTRAS

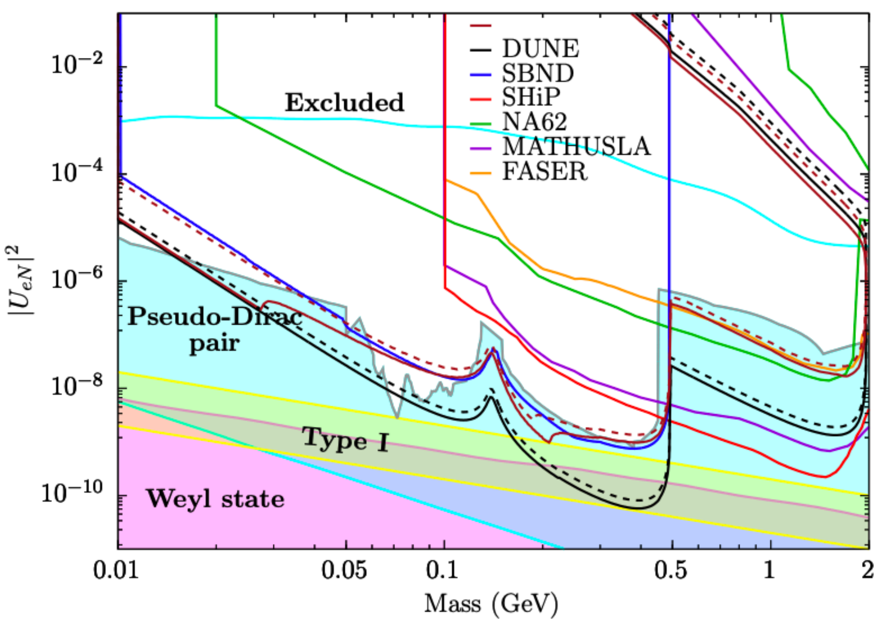
New Physics Searches at DUNE

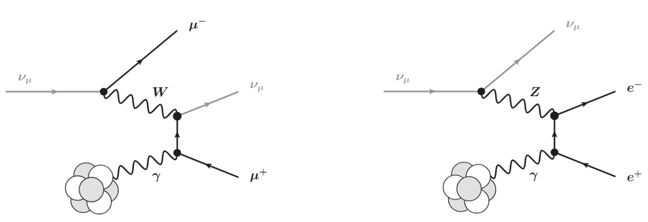
- DUNE Far Detector is sensitive to rare processes (nucleon decay, n-nbar oscillation, etc.) and new physics of cosmogenic origin
- DUNE Near Detector is sensitive to rare processes in the beamline (Heavy Neutral Leptons, Light Dark Matter) and to BSM contributions to neutrino interactions (ν tridents)

Phys. Rev. D 100, 115029 (2019)

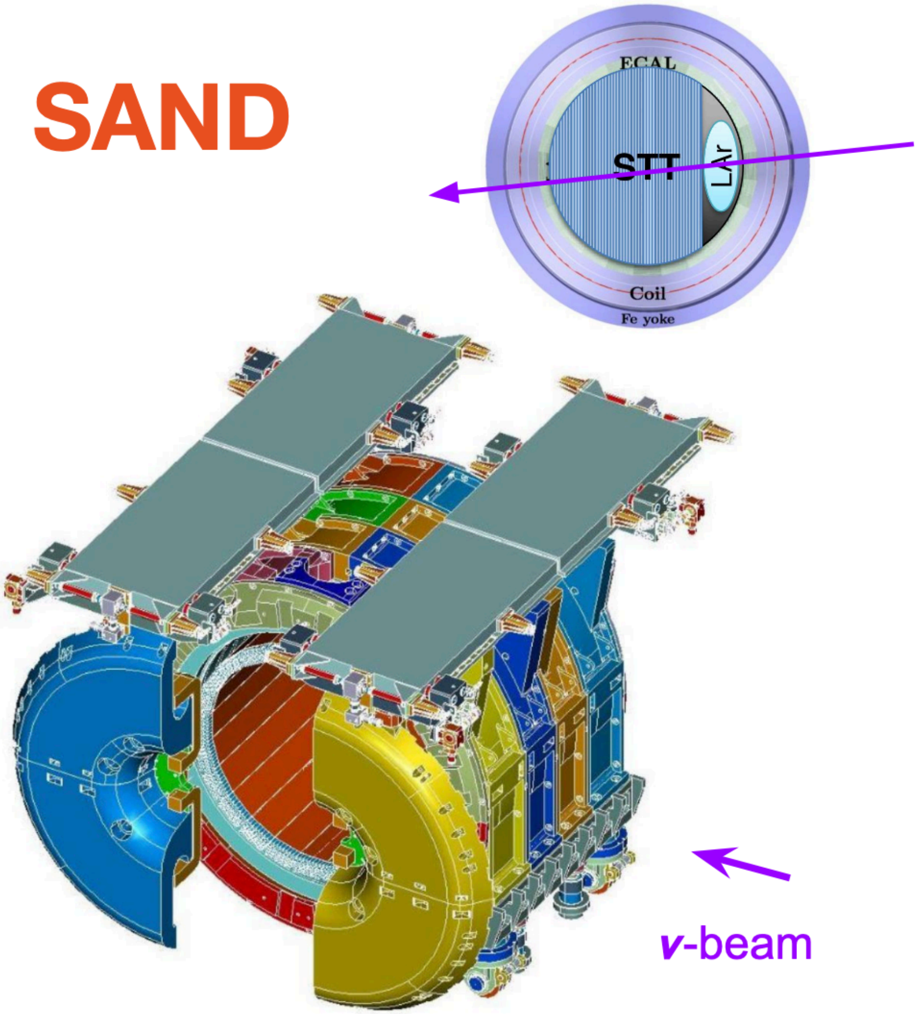


J. High Energy Phys. 2020, 111 (2020)

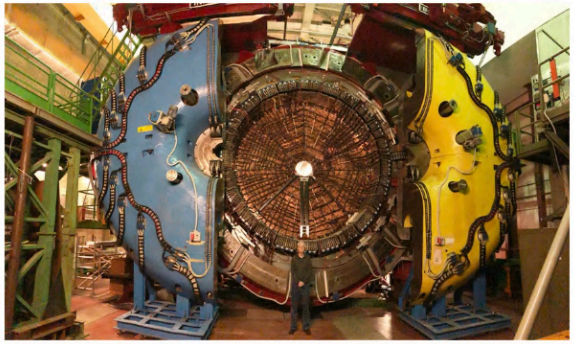


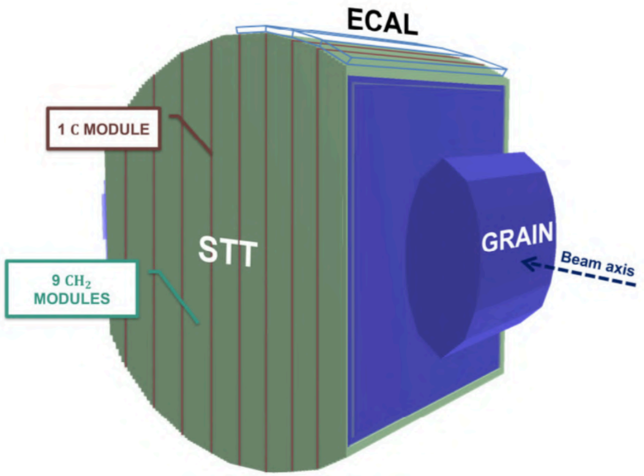


SAND



- Primary purpose is to monitor beam stability
  - Remains on-axis
- Capable of much more:
  - Flux and cross section constraints
- Repurposed elements from KLOE:
  - Superconducting solenoid magnet, 0.6 T
  - Electromagnetic calorimeter
- New elements:
  - High granularity, high resolution inner tracker integrated with changeable nuclear targets
  - 1-ton active LAr with optical readout (GRAIN)

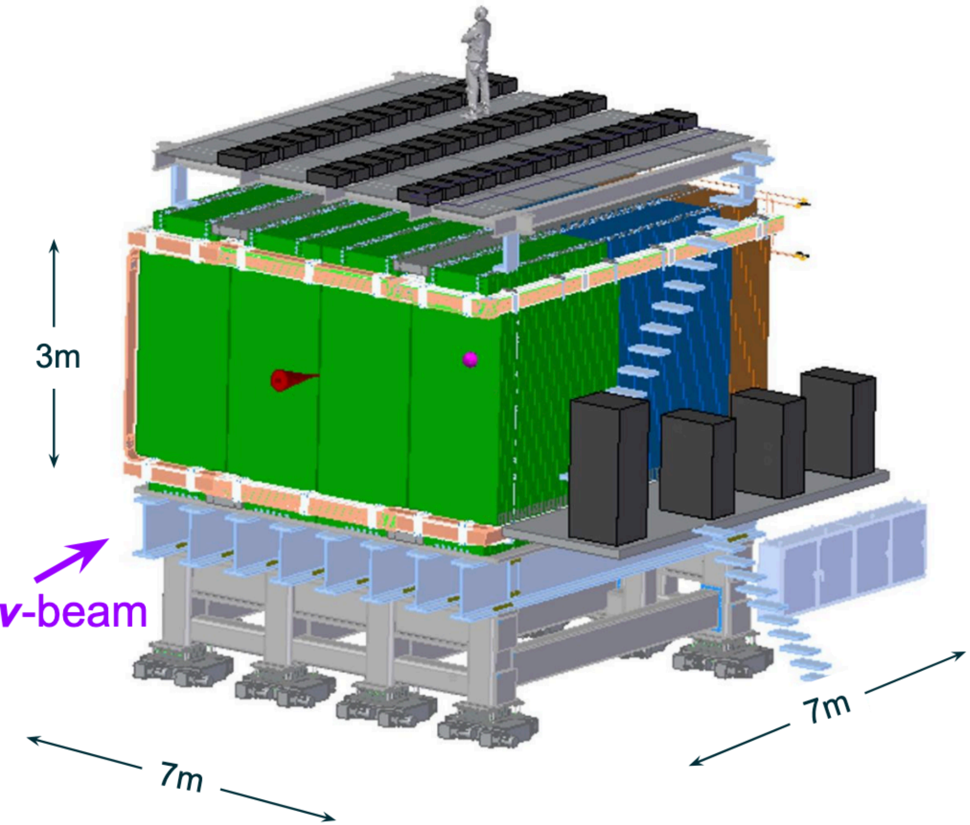




The Straw Tube Tracker (STT) is the baseline design for the SAND tracker

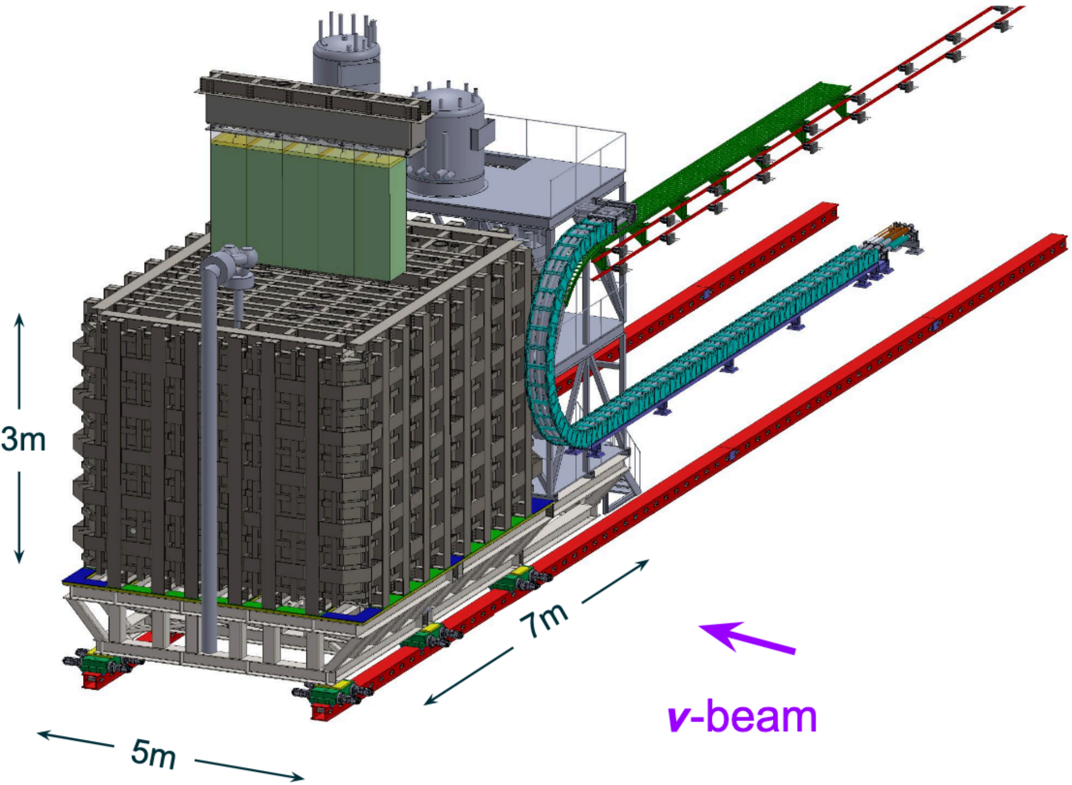
TMS

TMS



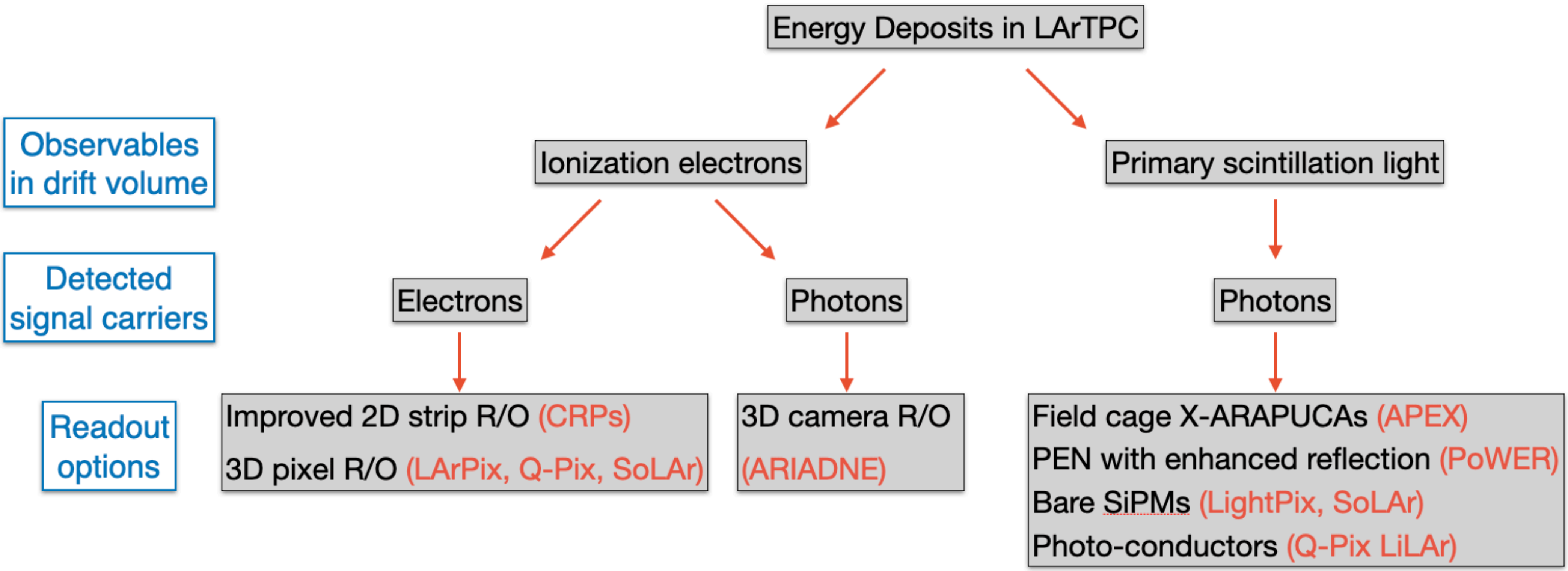
- Spectrometer for muons exiting ND-LAr
- Alternating layers of steel and scintillator
  - Momentum from range
  - Thicker steel layers downstream to range out higher momenta muons
- ~1T solenoidal magnetic field
  - Charge from curvature
- Scintillator layers consisting of bars with ~3.5cm granularity in the bending plane
- Preliminary design being optimized for cost and performance

ND-LAr

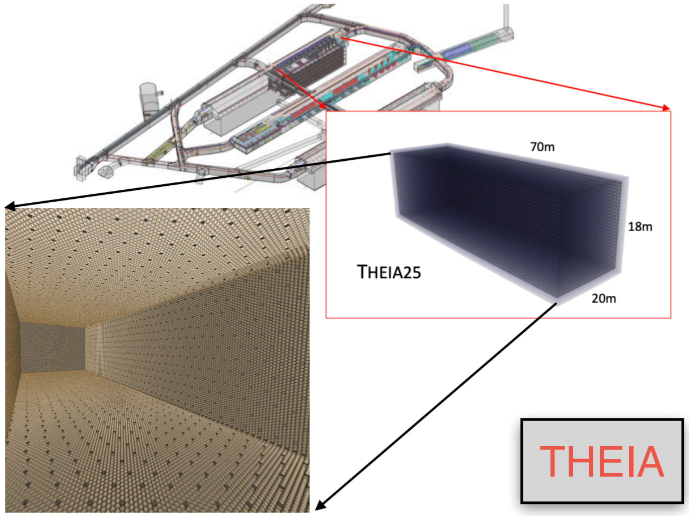


- 7x5 grid of 1x1x3 m^3 LArTPC modules
  - 7x5x3 m3 active volume
  - ~ 67 t fiducial mass
- Moveable transverse to neutrino beam
  - Sample off-axis flux
- Designed to cope with high-pileup environment
  - O(100) interactions / 1.2 MW spill
- Native 3D readout from pixelated charge readout mitigates hit ambiguity
  - $\lesssim$ 4mm pixel pitch (granularity)
  - $>$ 14M pixel channels!
- Optical segmentation provides interaction-level timing information

Phase-II Far Detectors (FD#3 & FD#4)



- VD-LArTPC as a starting point for Phase-II Far Detectors
- FD#3/4 R&D aimed at optimizing/upgrading VD designs for charge and light readout to broaden the physics program towards expanded sensitivity for MeV-scale physics
- Both Argon and non-Argon options being explored



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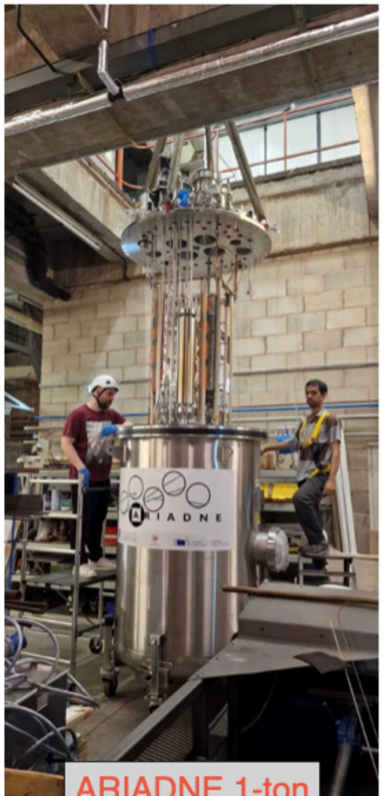
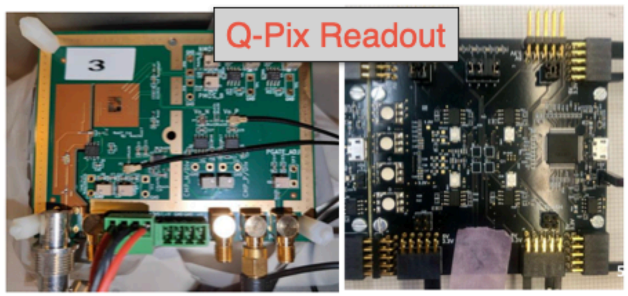
Phase-II Far Detector Prototyping (FD#3 & FD#4)

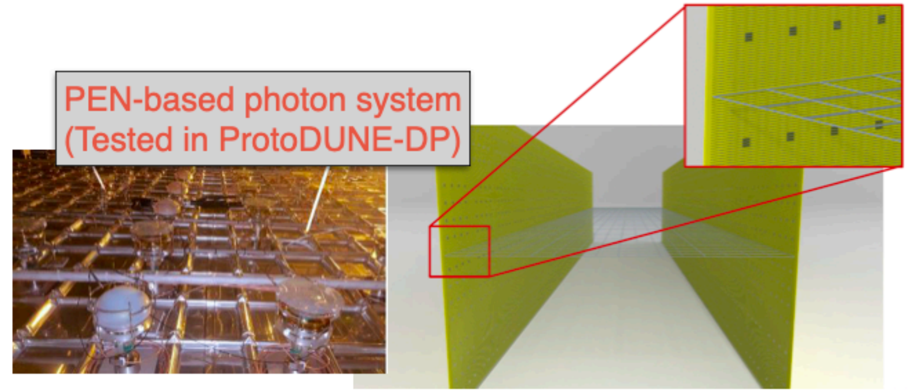
Active prototyping for Phase-II technologies (ton-scale and above) is actively underway around the world



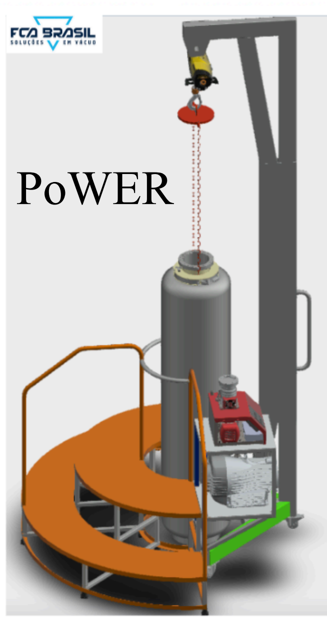
ARIADNE 1-ton Test @Liverpool

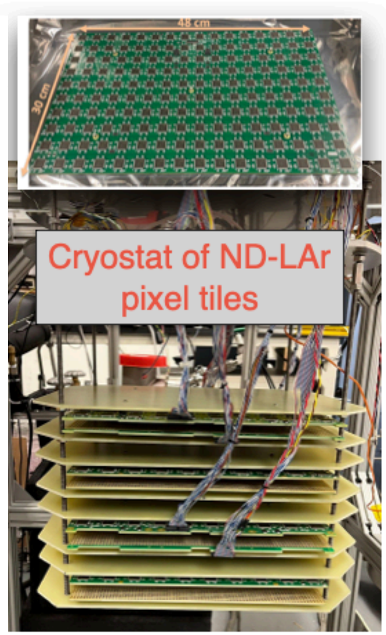


Q-Pix Readout



PEN-based photon system (Tested in ProtoDUNE-DP)





Cryostat of ND-LAr pixel tiles

THEIA Demonstrator (EOS)

APEX 2-ton prototyping

Proposal for ProtoDUNE running to test Phase-II technologies is submitted to CERN

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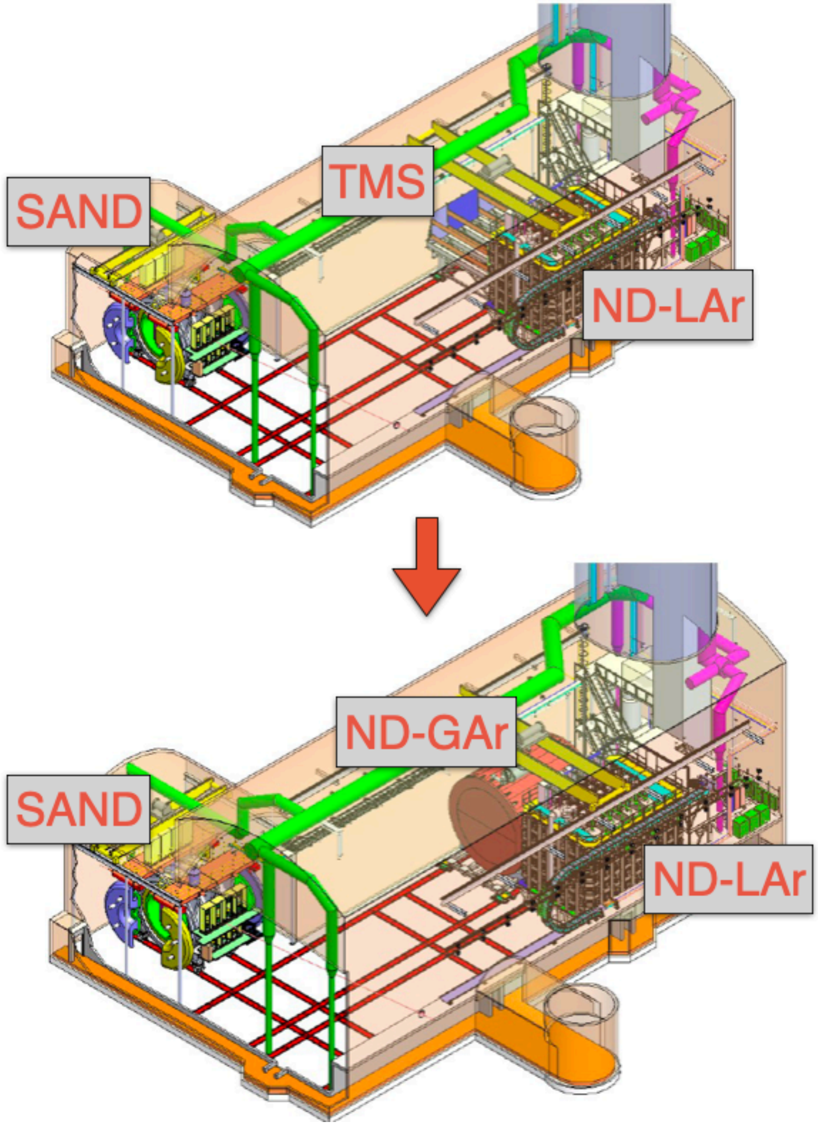
Near Detector: Phase-I to Phase-II

- Gaseous argon detector (ND-GAr) will replace the Temporary Muon Spectrometer (TMS) in DUNE ND Phase-II upgrade

- Upgrades to ND-LAr and SAND are also possible

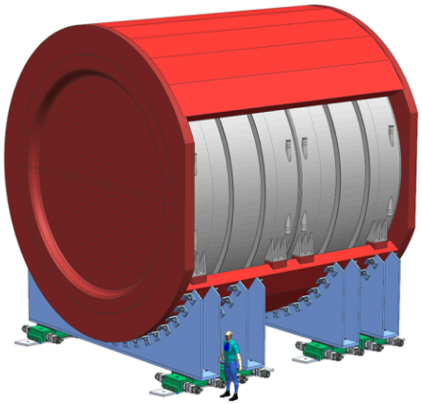
- If FD4 neutrino target is not Ar (e.g., THEIA), Phase-II ND would need to measure neutrino interactions on those target nuclei and constrain detector-related systematic uncertainties
    - *Several options under consideration*

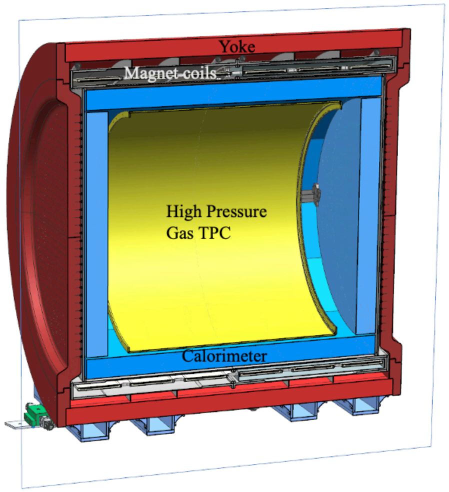


Near Detector: Phase-I to Phase-II

ND-GAr

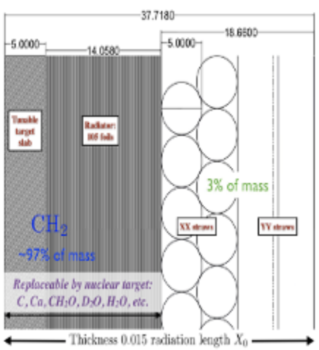
- Pressurized gaseous argon TPC at 10 bar surrounded by a calorimeter, magnet, and muon tagging system
- Will move perpendicularly to beam as part of DUNE-PRISM



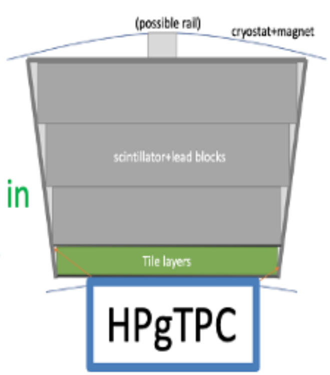


- **Several non-Ar ND options** under consideration if FD4 will be WbLS-based technology (e.g. THEIA) including options for a dedicated WbLS-ND (e.g. LiquidO or NovA-style ND)

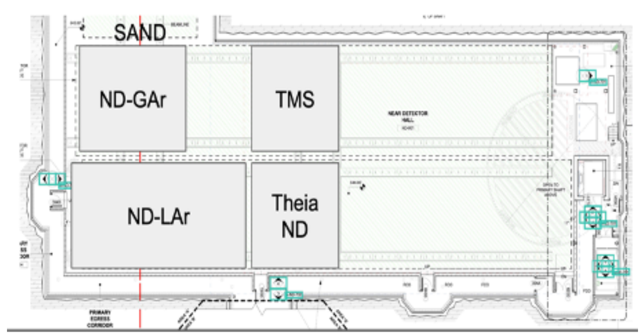
Additional nuclear targets in SAND



WbLS targets in ND-GAr ECAL

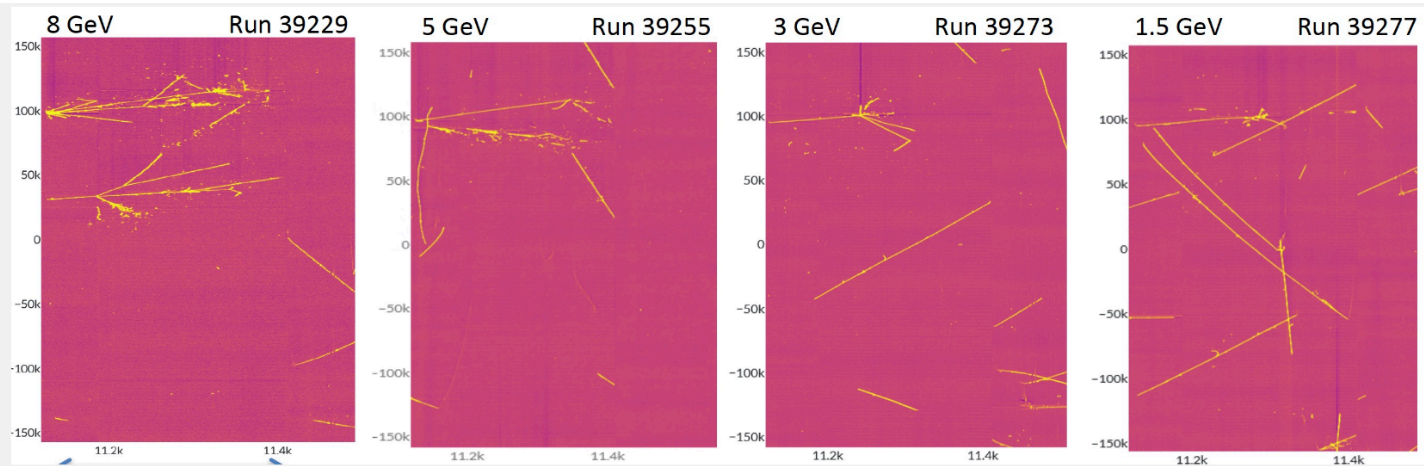


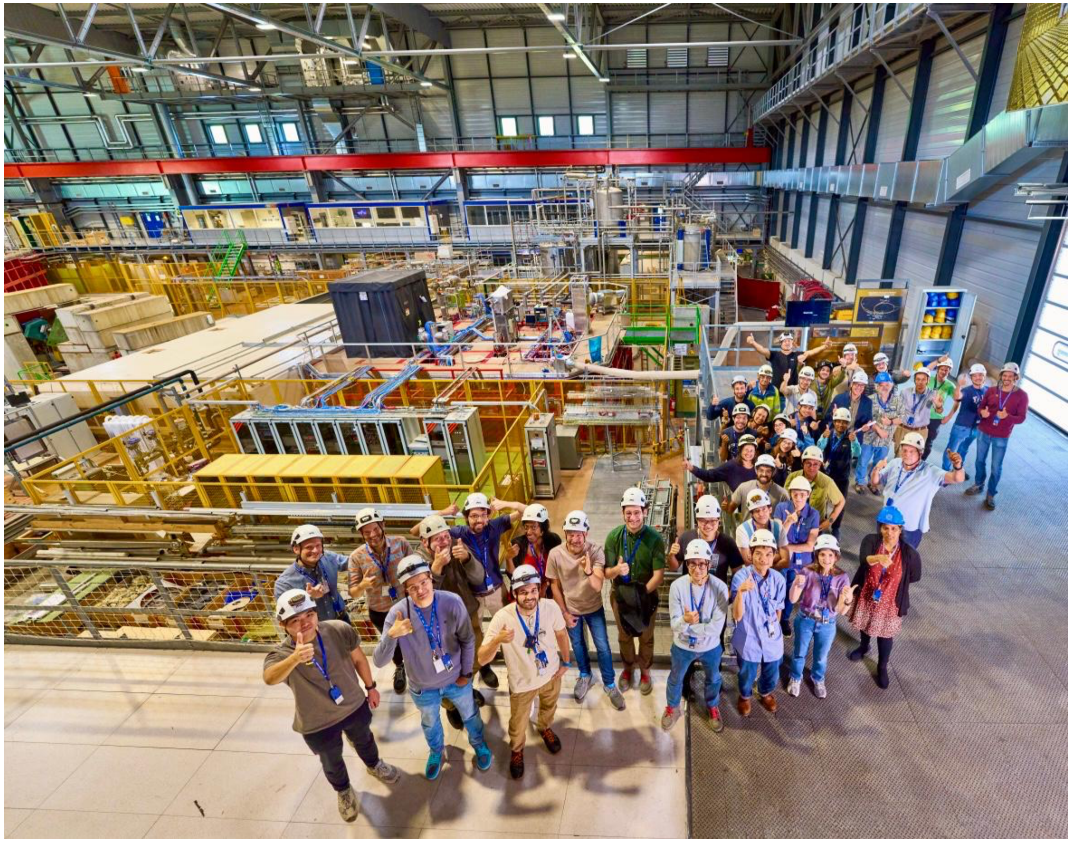
Dedicated Theia ND

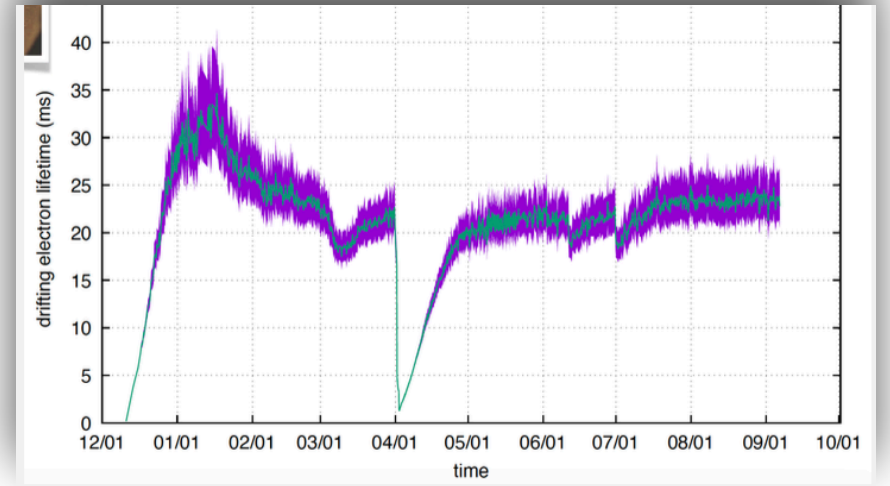


→ *Complexity*

Excellent Operational Peformance by ProtoDUNE-VD







This milestone demonstrates the Vertical Drift technology at scale for DUNE