DUNE
The Deep Underground Neutrino Experiment

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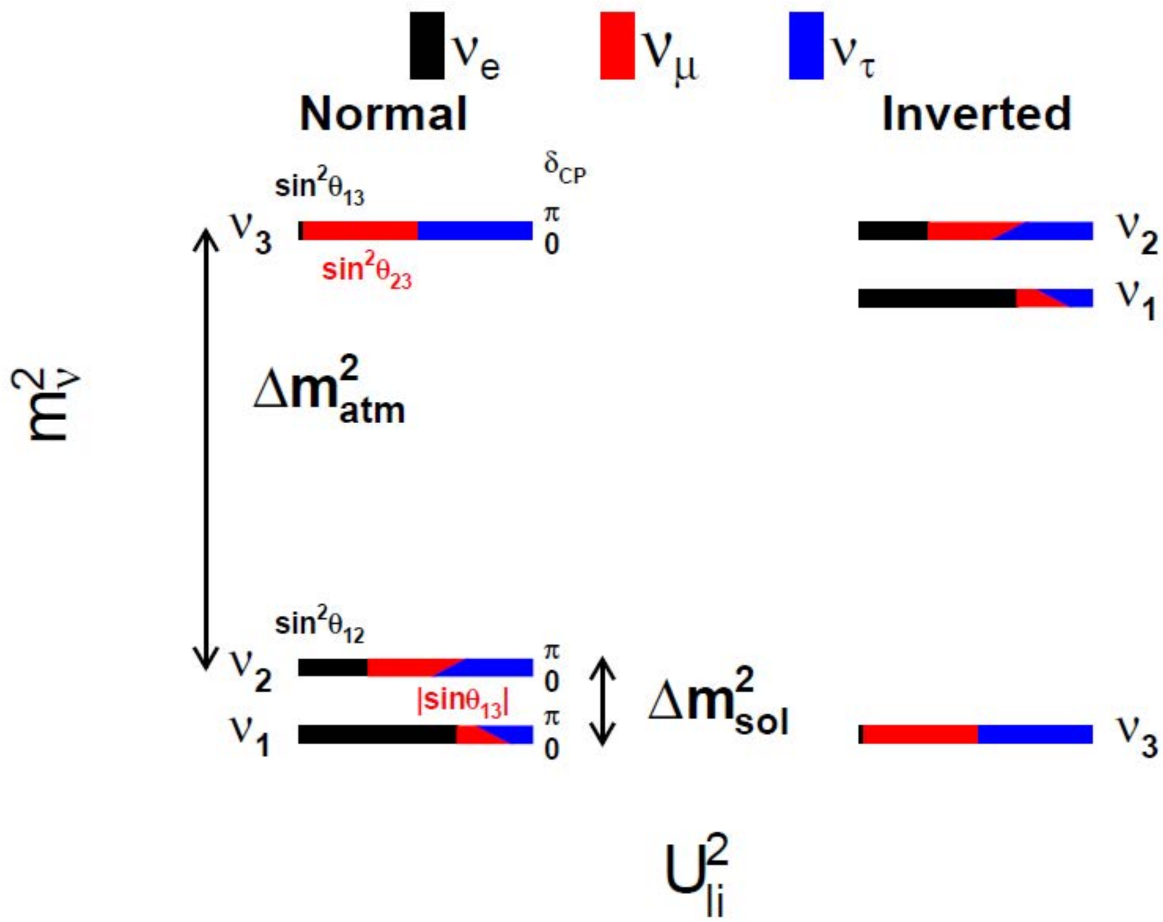
On behalf of the DUNE collaboration

Symposium on Frontiers of Underground Physics

Chengdu, 30 October 2023

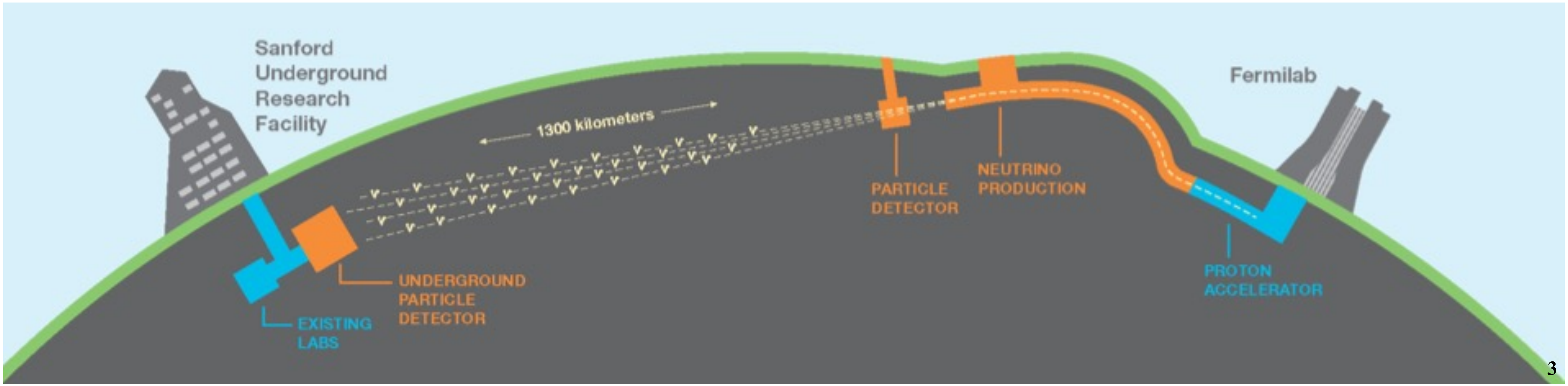
Big Questions in Neutrino Physics

- Do neutrinos have large matter anti-matter asymmetry?
- What's the neutrino mass hierarchy?
- Are neutrino Dirac or Majorana particles?
- What is the neutrino mass?
- Are there sterile neutrinos?
- …



Deep Underground Neutrino Experiment

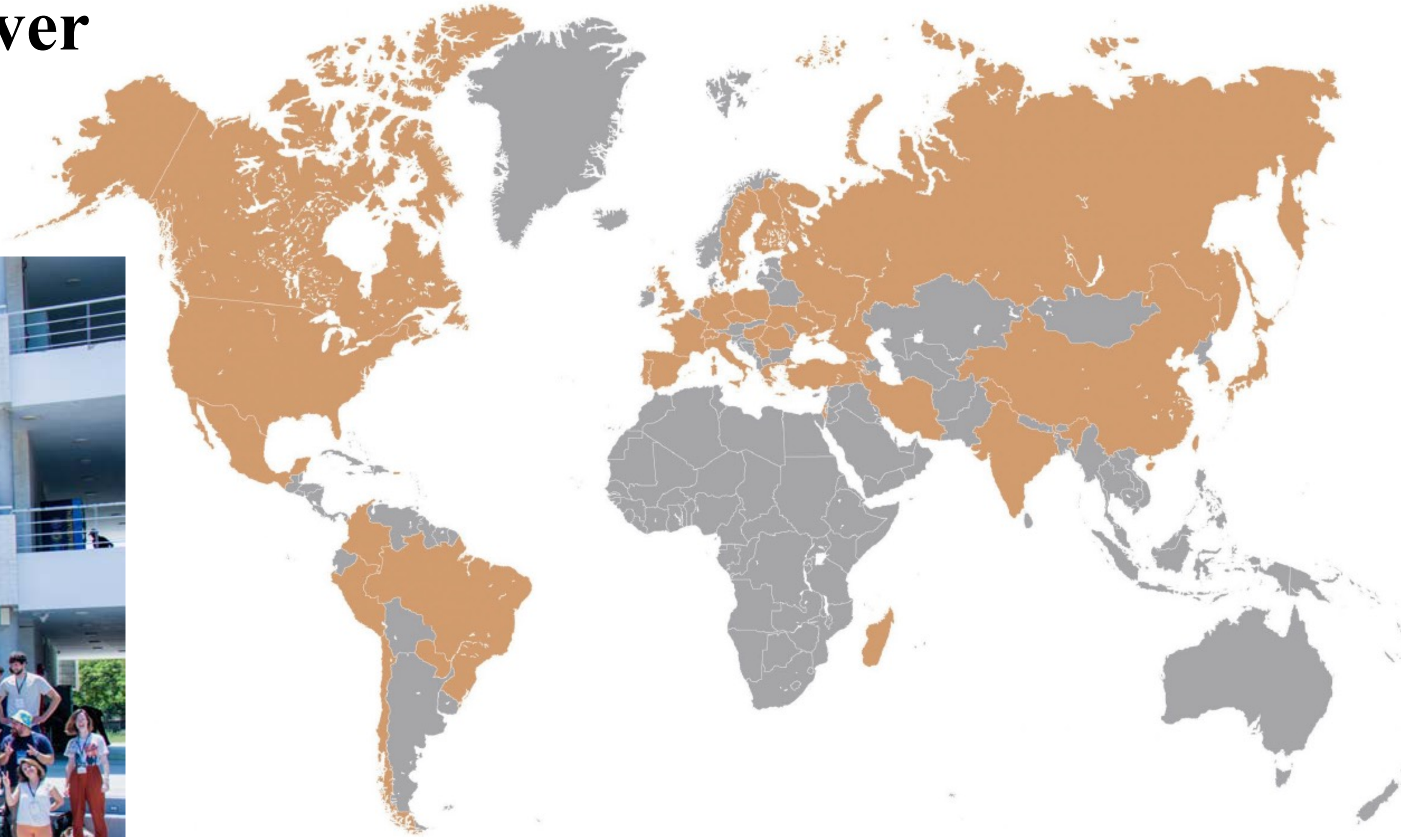
- Neutrino oscillation
  - search for leptonic CP violation
  - determine the mass ordering
  - resolve the octant ambiguity
  - test the unitarity of PMNS matrix with accelerator, atmospheric, and solar neutrinos
- Measurements with supernova neutrinos
- Search for new physics beyond the Standard Model such as
  - proton decay
  - sterile neutrino



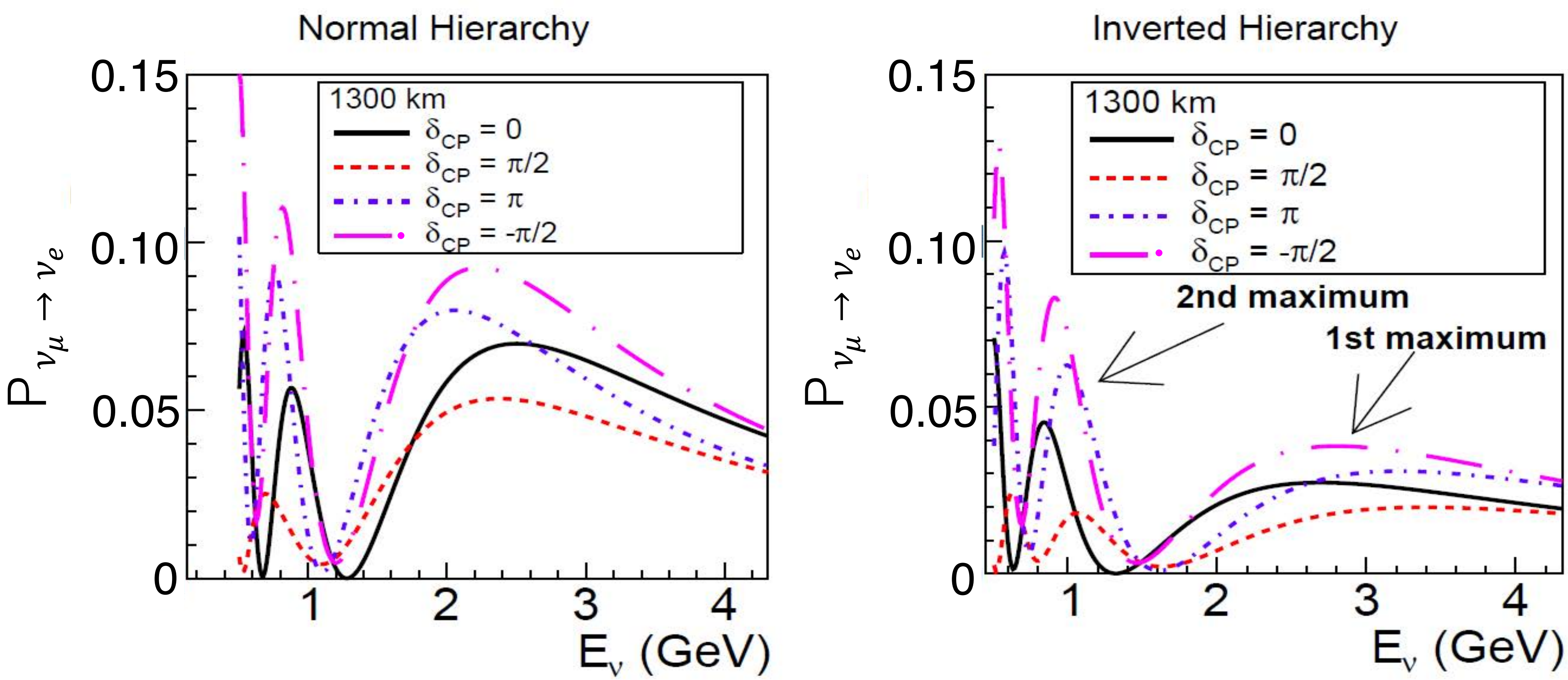
DUNE Collaboration

- **About 1,500 collaborators from more than 200 institutions in over 30 countries**

September 2023 Collaboration Meeting in Colombia

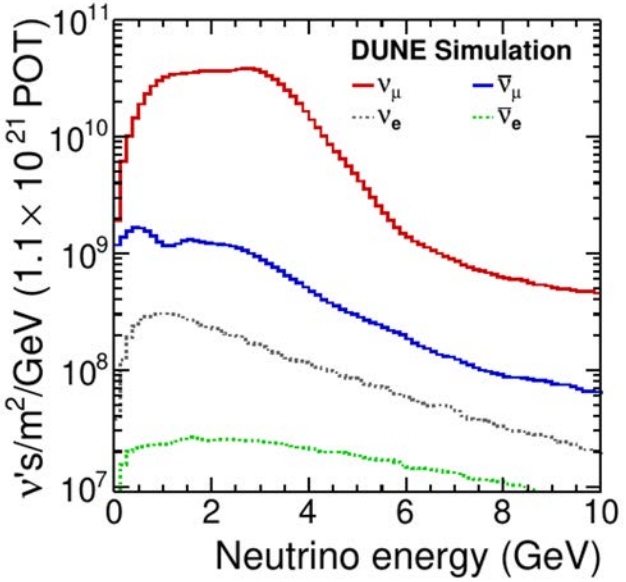


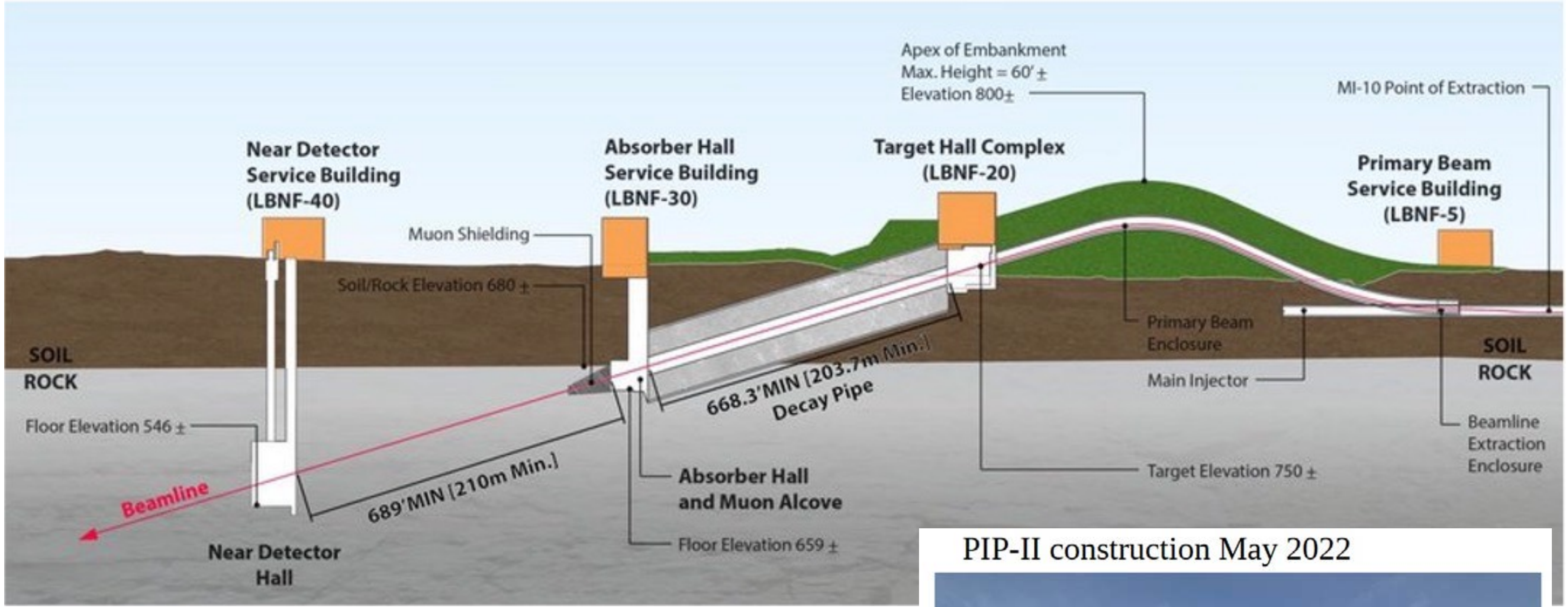
$\nu_\mu \to \nu_e$ Oscillation



- Oscillation pattern is very sensitive to the δ_{CP} and mass hierarchy
- Matter effect: coherent forward charged-current (anti)-ν_e scattering on atomic electrons

Long Baseline Neutrino Facility (LBNF)

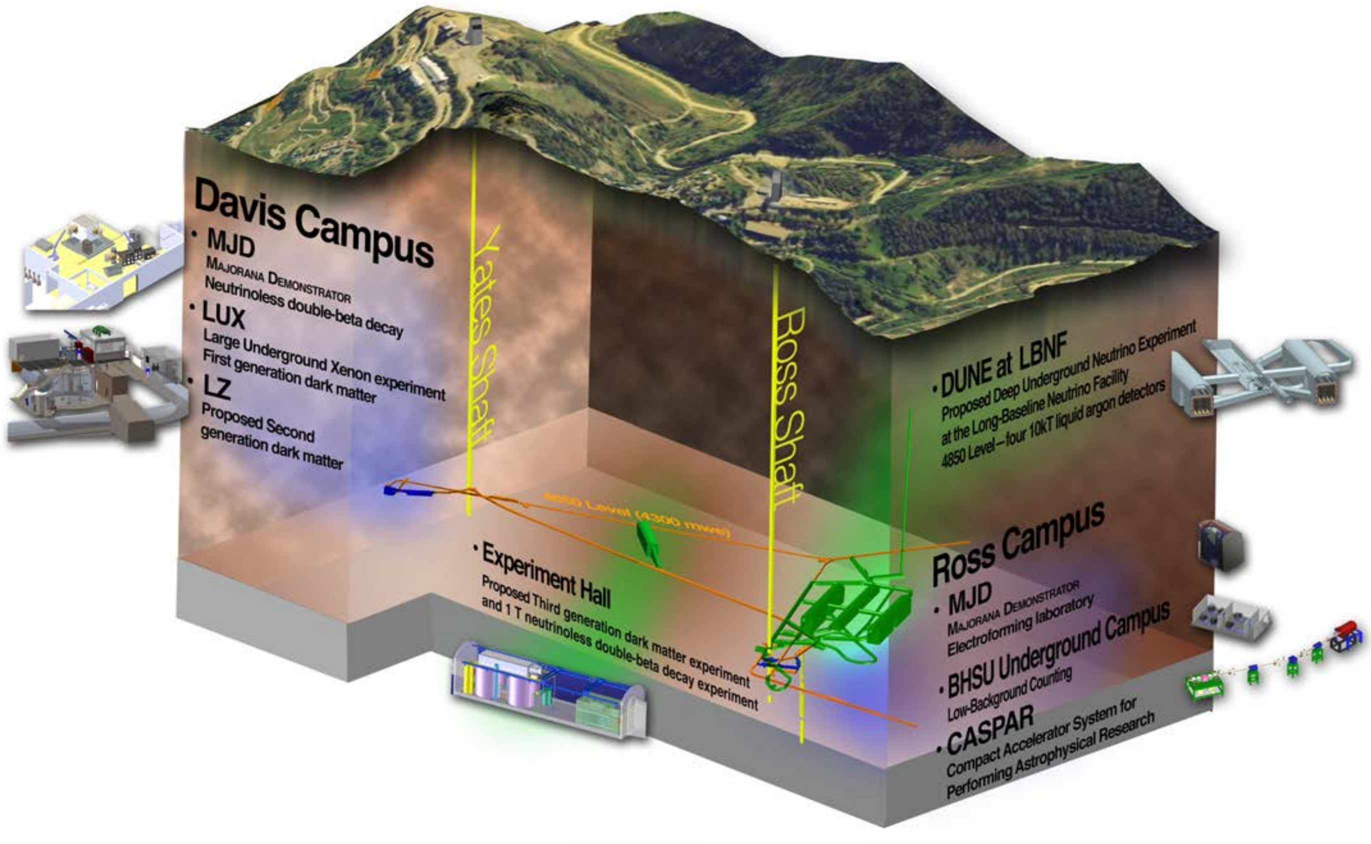


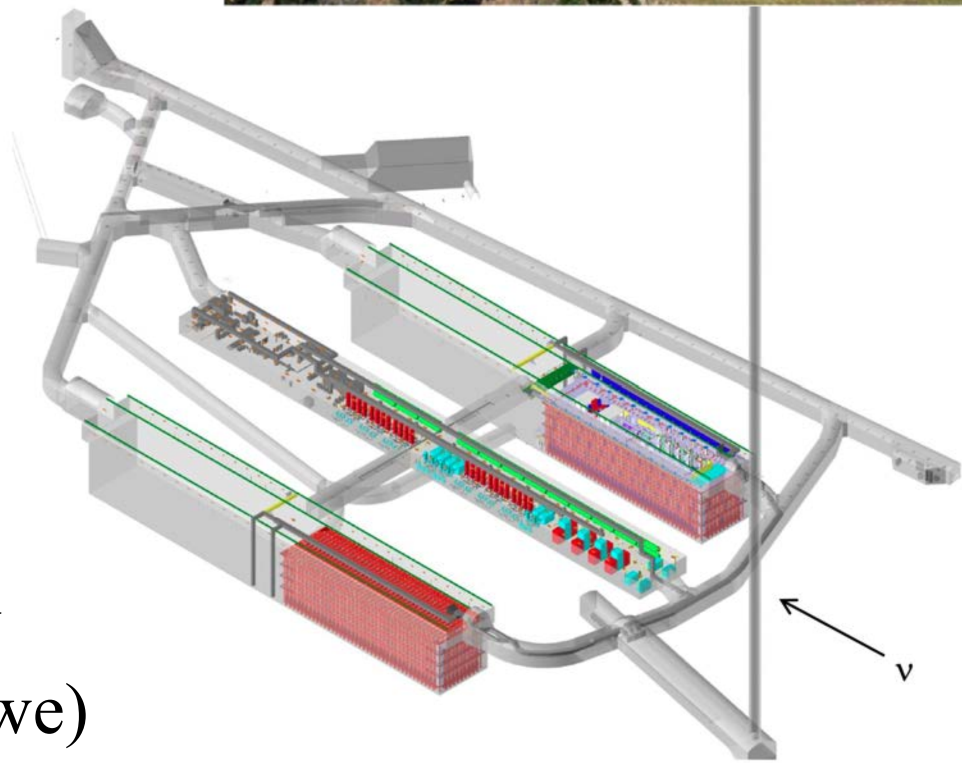


PIP-II construction May 2022

- Neutrino beam
  - Proton Improvement Plan-II (PIP-II)
  - 1.2 MW, upgradeable to 2.4 MW, 60-120 GeV protons pitching down at 5.8° before striking a graphite target
  - 0.5-5 GeV (anti)neutrinos
- Near Detector Hall close to the Fermilab site boundary

LBNF @ Sanford Underground Research Facility

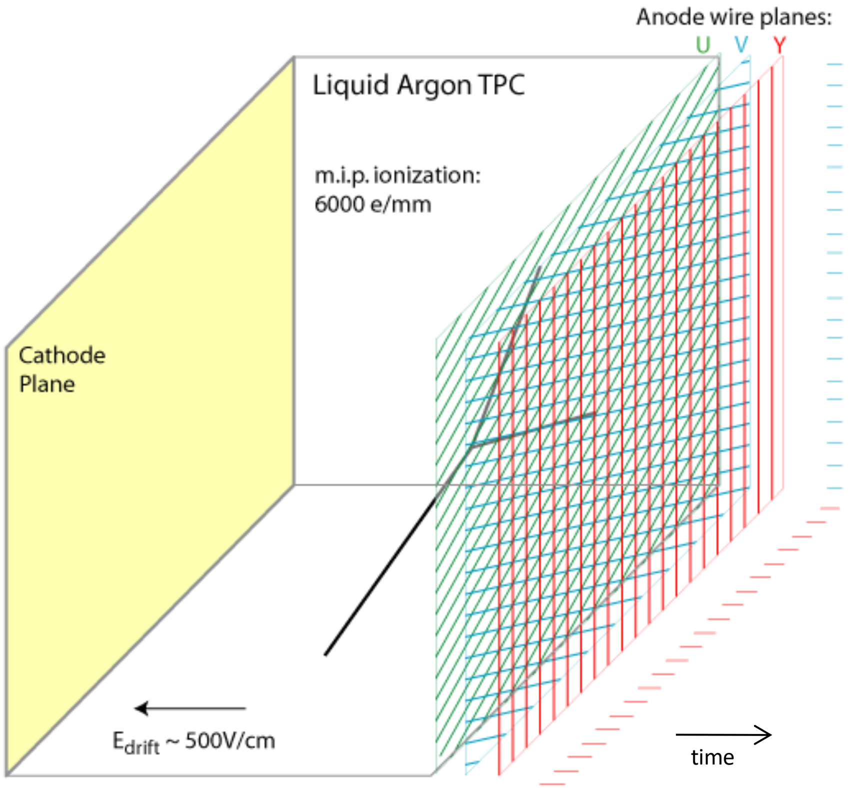




- In the Homestake gold mine, Lead, S. Dakota
- LBNF: Four caverns for detectors and 1 utility hall at 4850-ft below ground (1.5 km, 4300 mwe)

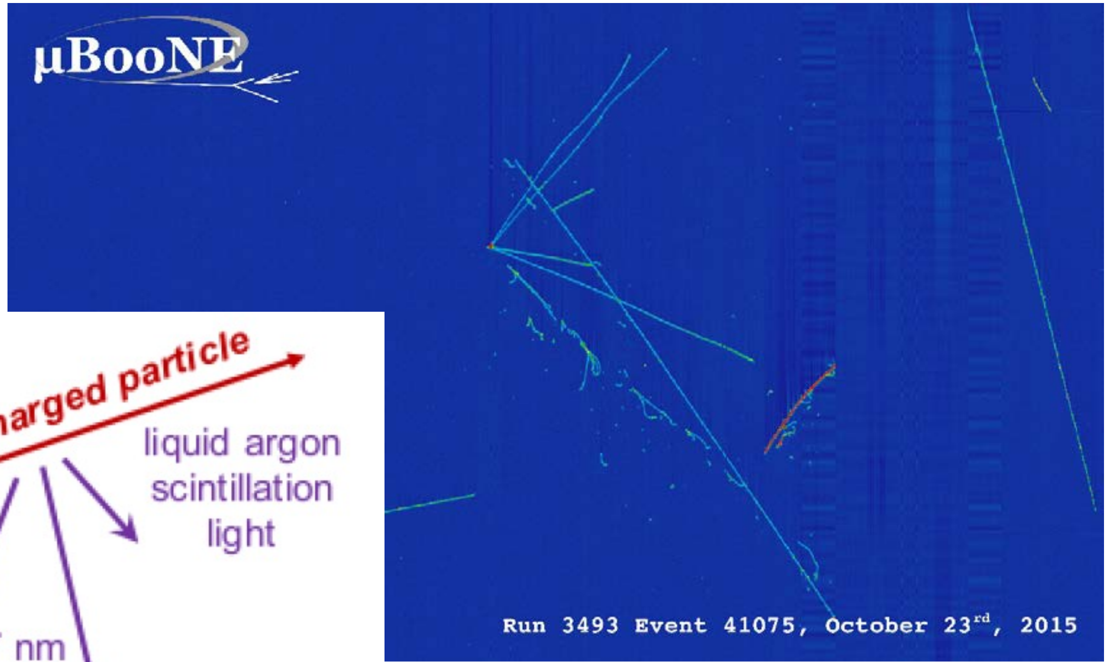
Liquid Argon Time Projection Chamber (LArTPC)

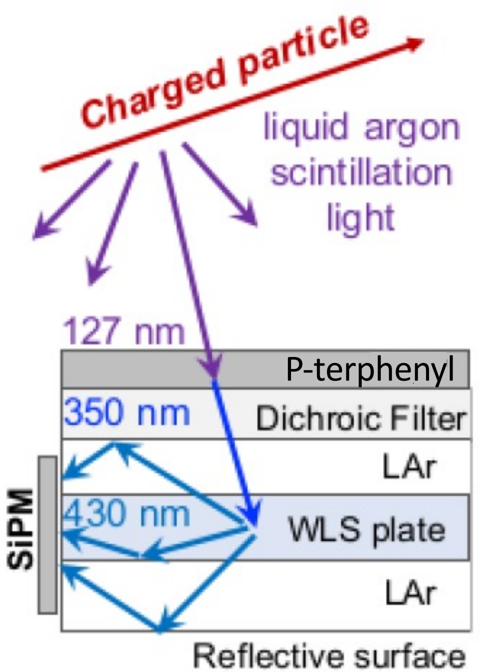
- Position resolution of ~mm with multiple 1D wire readouts



Drift velocity: 1.6 m/ms
→ several ms drift time

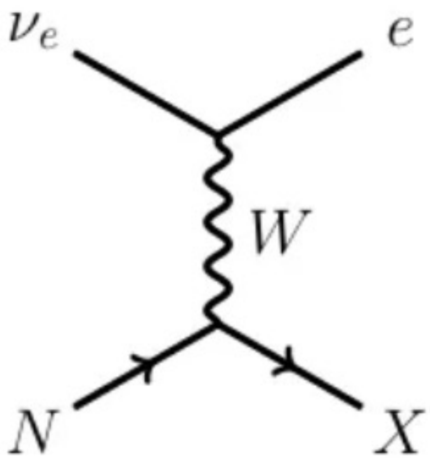
- Particle identification (PID) with energy depositions and topologies





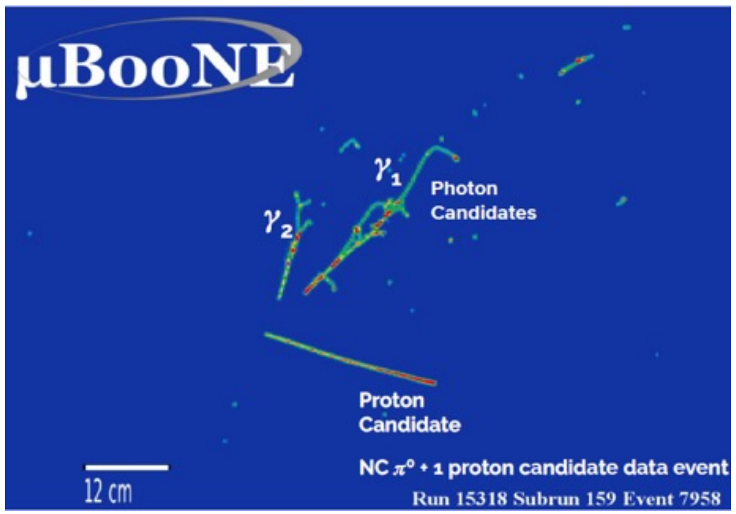
[ARAPUCA Light Detection]

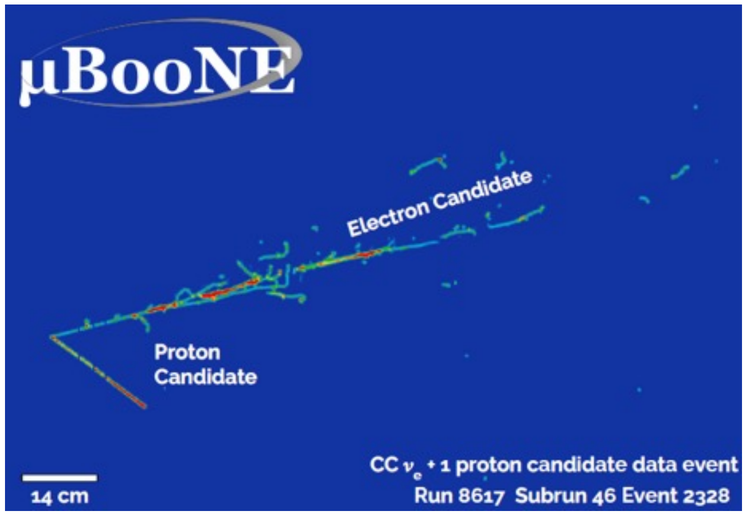
LArTPC: Excellent capability in identifying ν_e

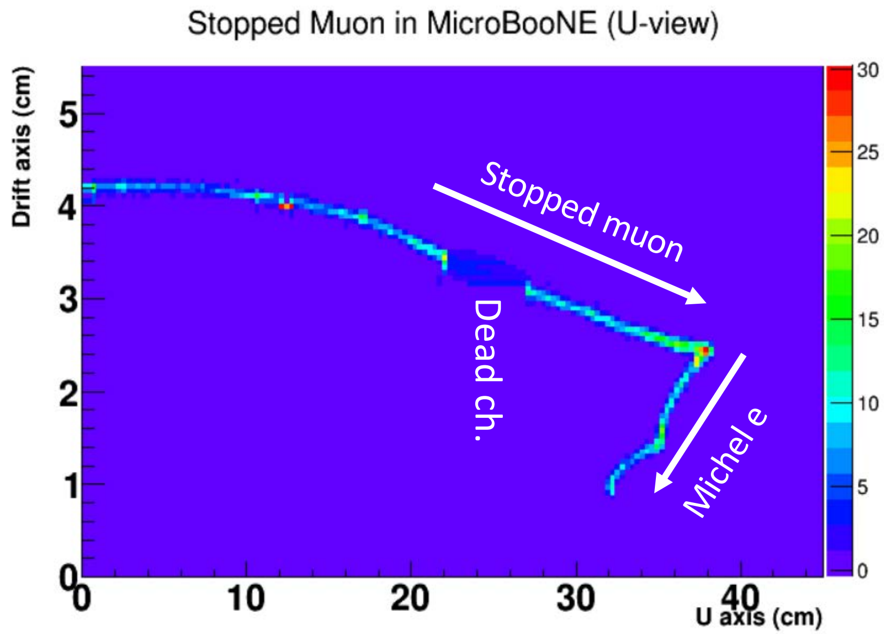


- Separation of e/γ
  - Gap Identification
  - 1 MIP vs. 2 MIP dE/dx

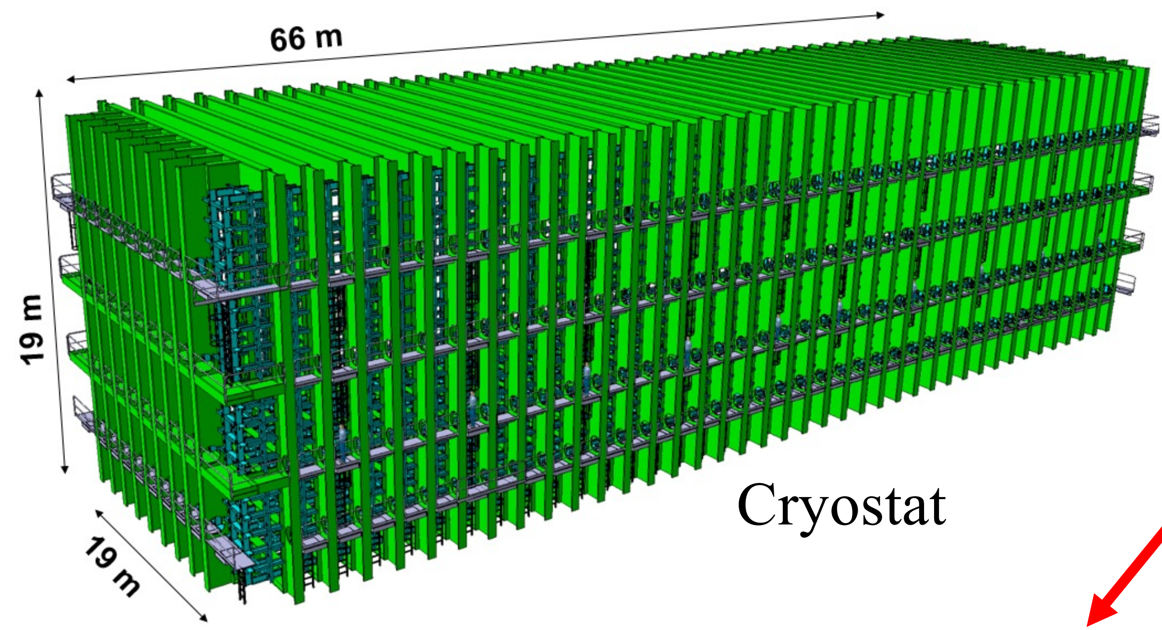
- Comparison of P_{MCS} and P_{Range} to separate low-energy e/μ for ν_e charge-current interaction



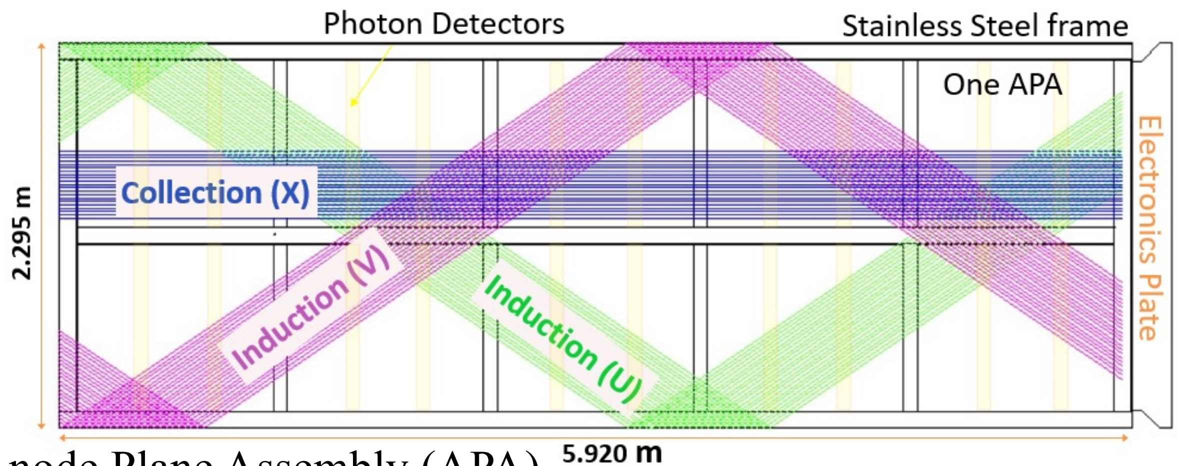




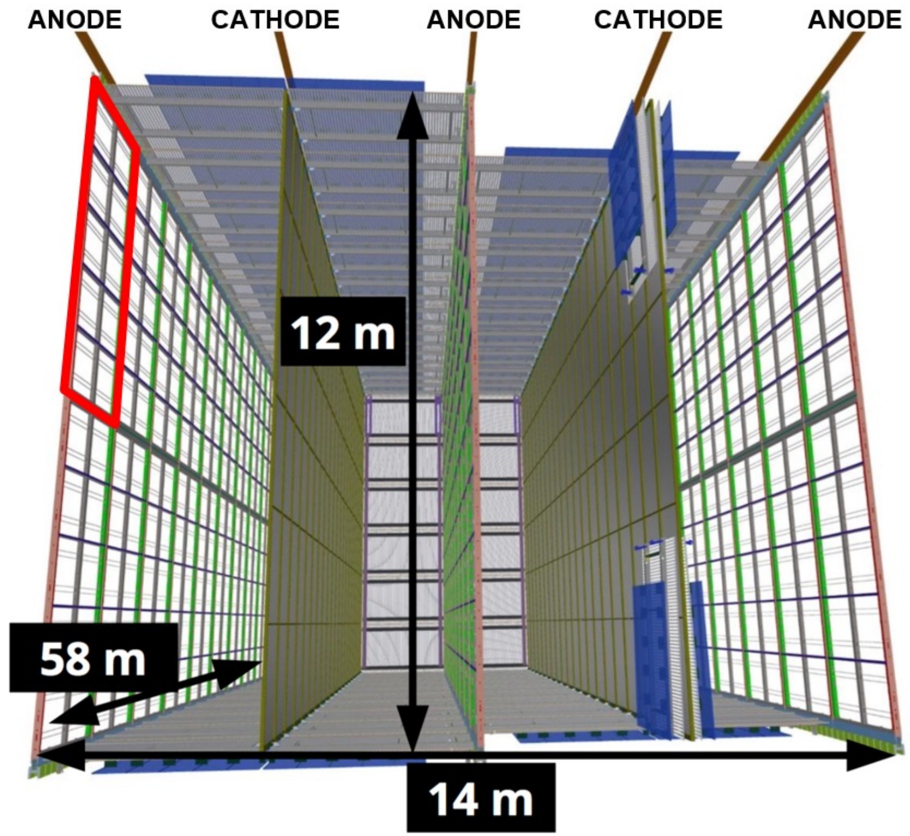
Module 1: 17-kT Horizontal-Drift LArTPC



Cryostat

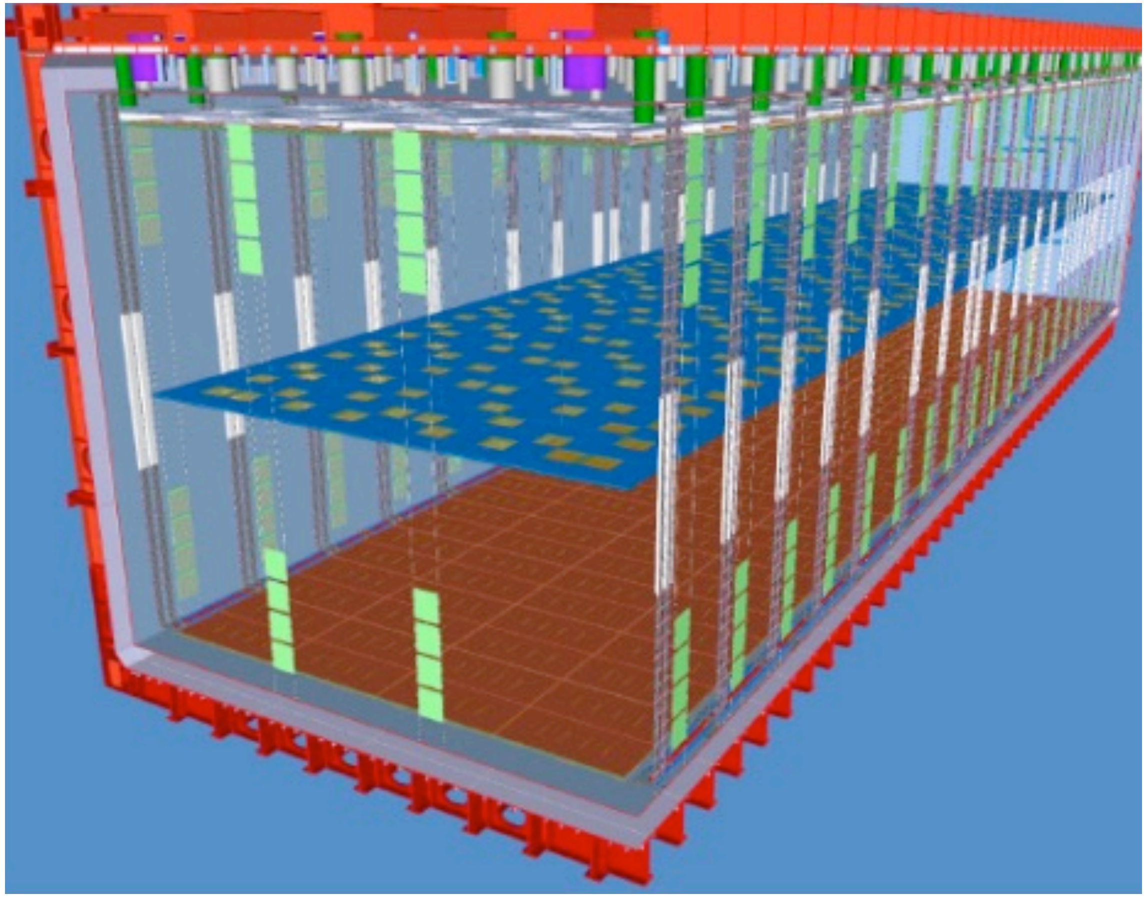


Anode Plane Assembly (APA)

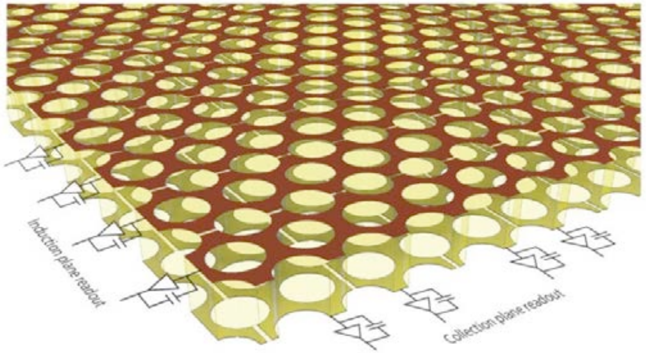


- **150 APAs** with **2560 charge readout channels,** each with three ~5 mm-pitch wire planes
- **40 light readout channels** with 1920 SiPMs

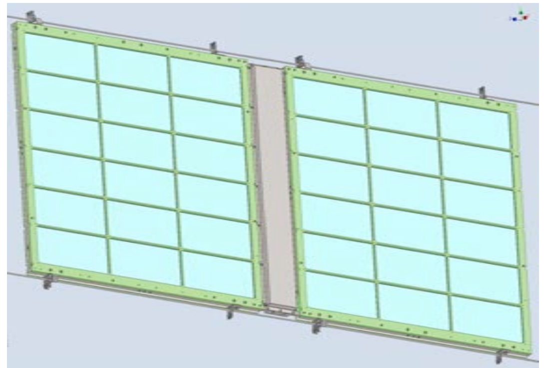
Module 2: 17-kT Vertical-Drift LArTPC



Charge readout



Light readout



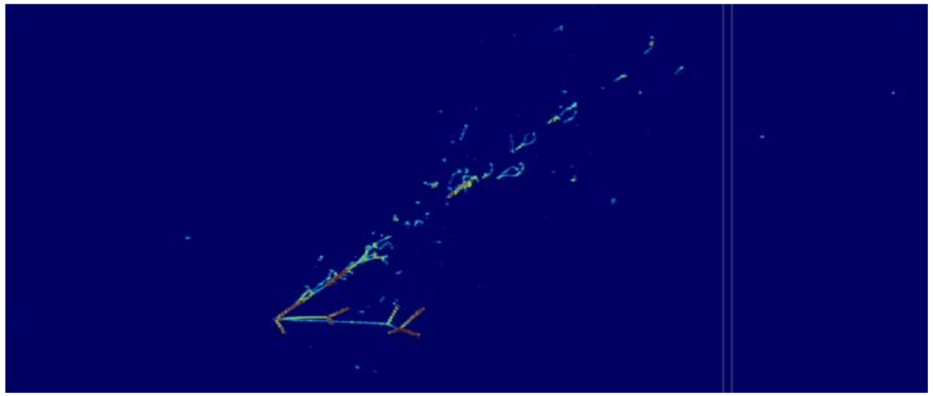
- **320 PCB-based Charge Readout** Unit, each with 1536 channels (3 views with 5-7 mm pitch)
- **672 X-ARAPUCA** Light Readout with 2 channels each (160 SiPMs)

Precision $\nu_\mu \rightarrow \nu_e$ Oscillation Measurement

- Data points show

  Normal Mass Ordering (MO),
  CP phase $\delta_{CP} = 0$,
  Octant $\sin^2\theta_{23} = 0.5$

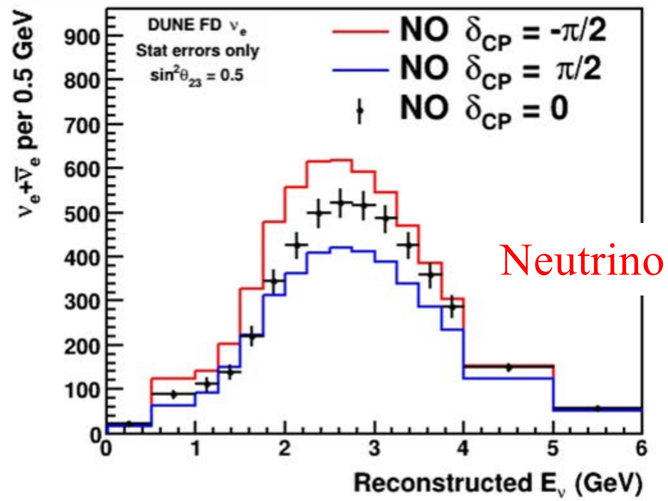
- 685 kt-MW-years exposure

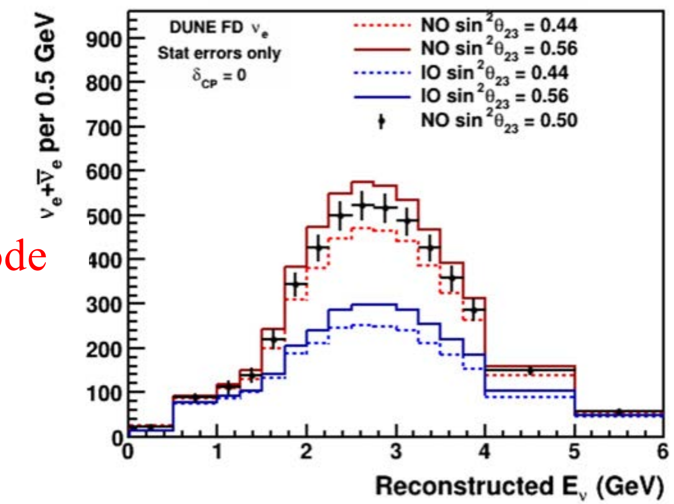


DUNE ν_e charged-current simulation

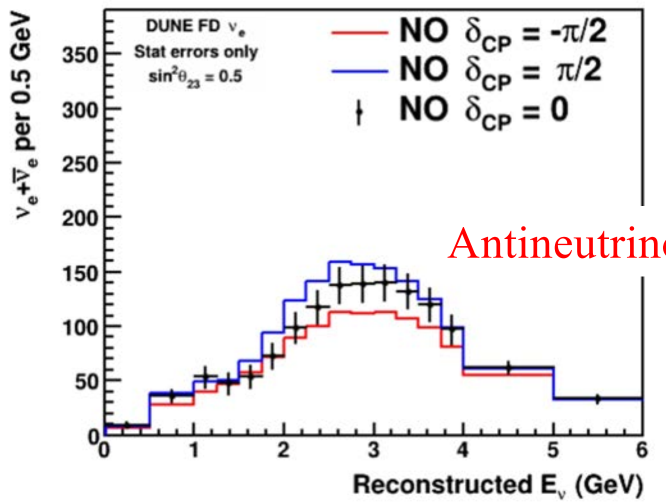
Varying δ_{CP}

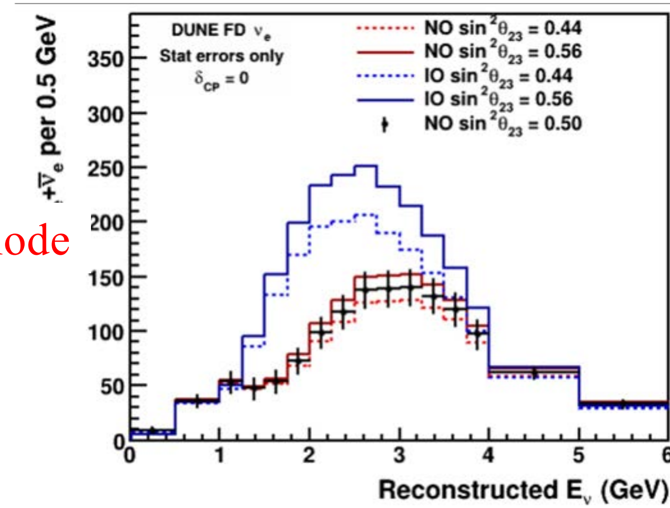
Varying MO and $\sin^2\theta_{23}$





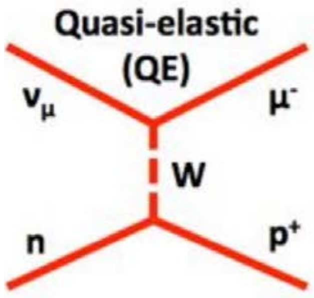
Neutrino mode



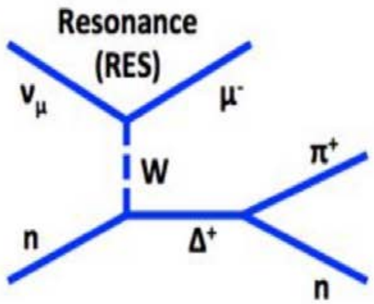


Antineutrino mode

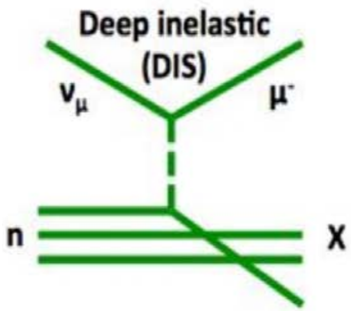
Neutrino-Argon Interaction Cross Sections



Scattering off single nucleon

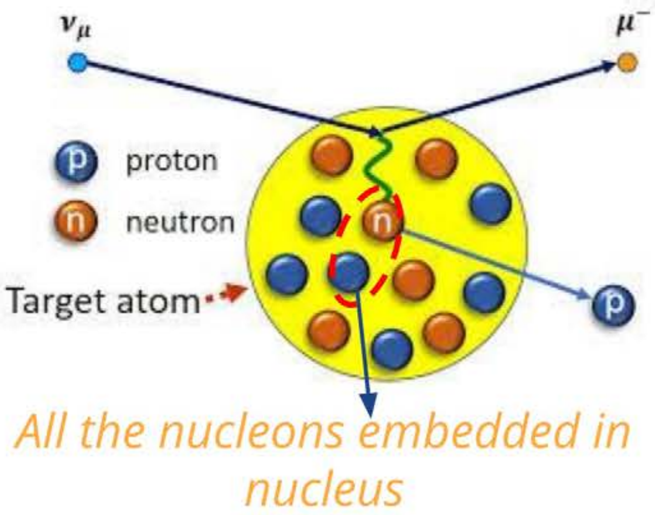


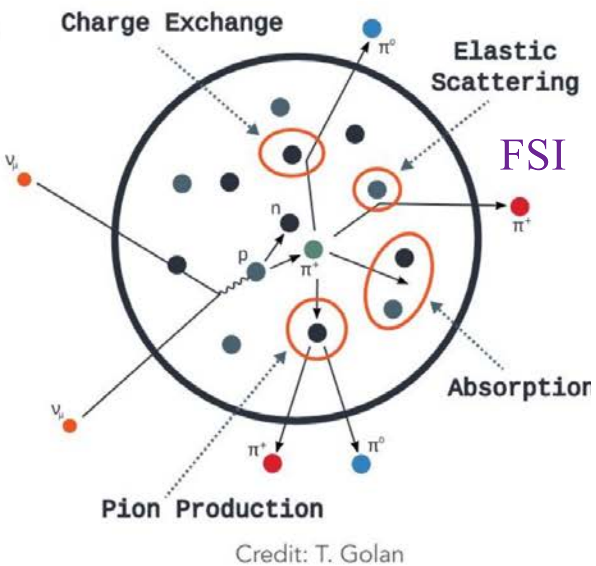
Inelastic scattering: Excites the nucleon

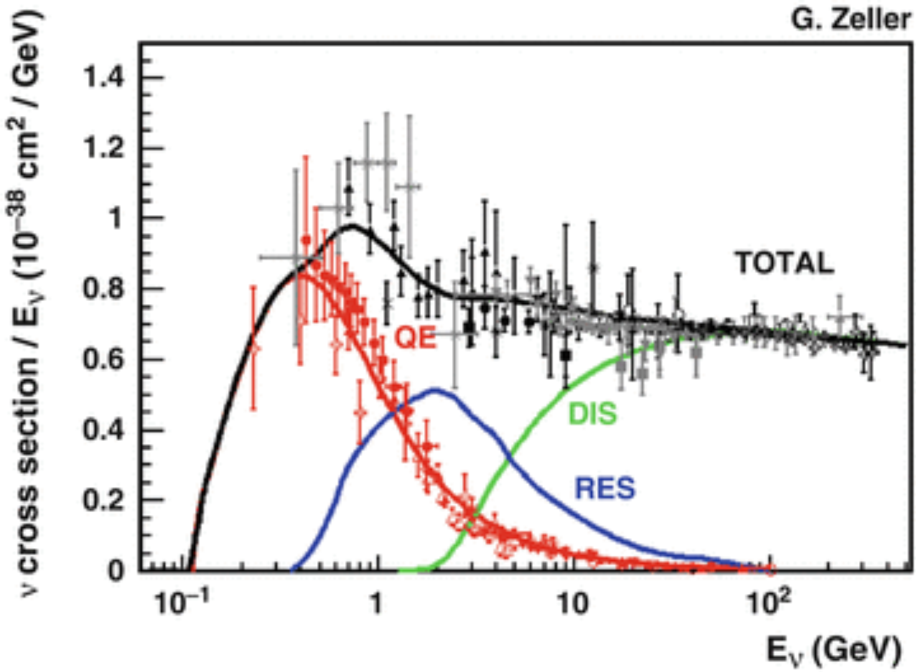


Breaks up nucleon

- Charged-current ν-Ar interaction, allowing to tag neutrino flavor, is critical to oscillation measurement
- Lack of a first-principle description of nuclear effects in neutrino-nucleus interaction

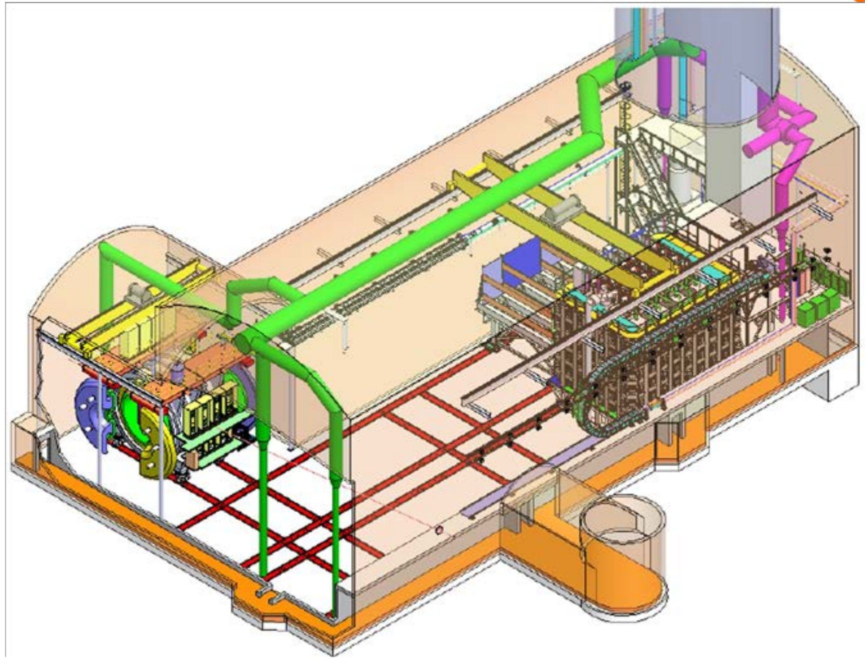






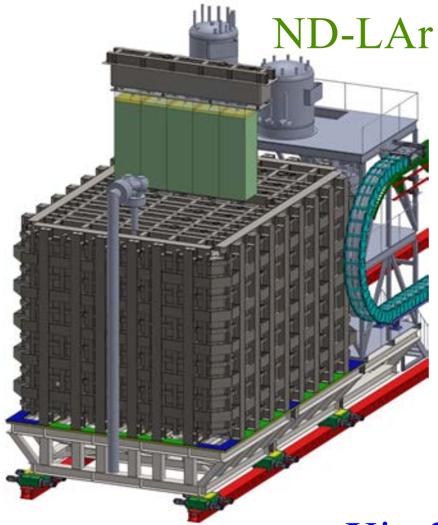
Near Detectors (ND)

- Near Detector Liquid Argon TPC (ND-LAr) + Muon Spectrometer (TMS) measure
  - ν interactions in 7×5 optically isolated liquid argon TPC modules with pixelated readout
  - TMS measures muons that exit ND-LAr

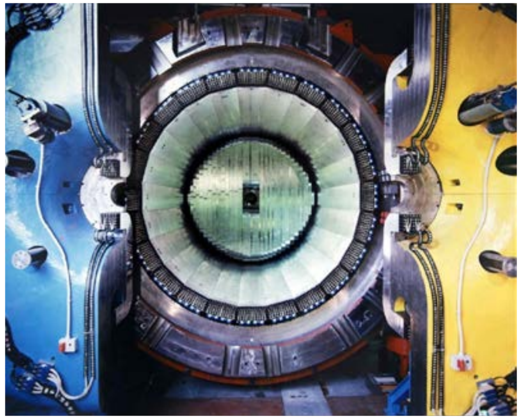


- System for on-Axis Neutrino Detection (SAND) measures neutrino interactions with various target materials (e.g. Hydrogen) and monitors the neutrino beam stability

ND-LAr

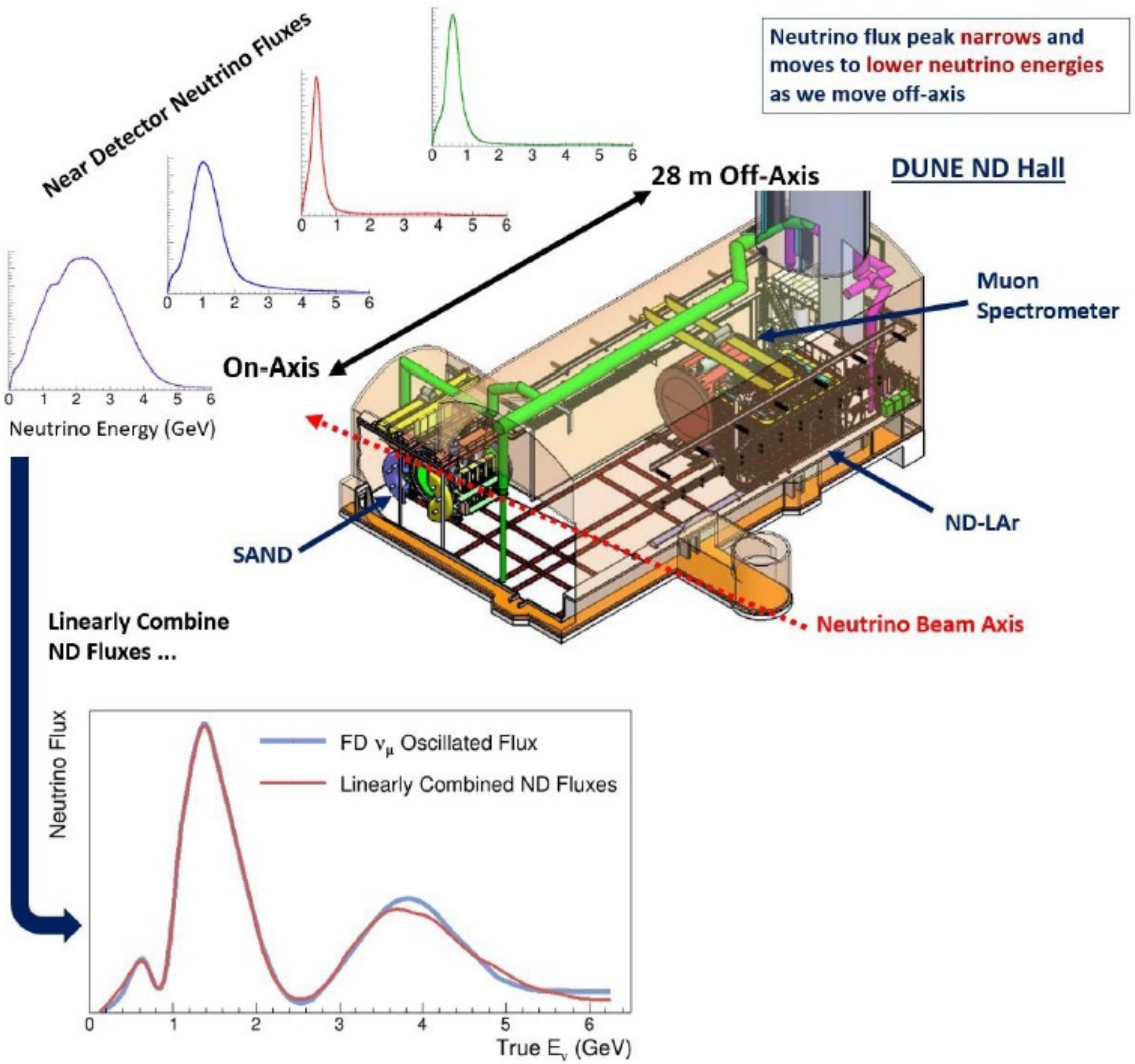


KLOE → SAND



arXiv:2103.13910

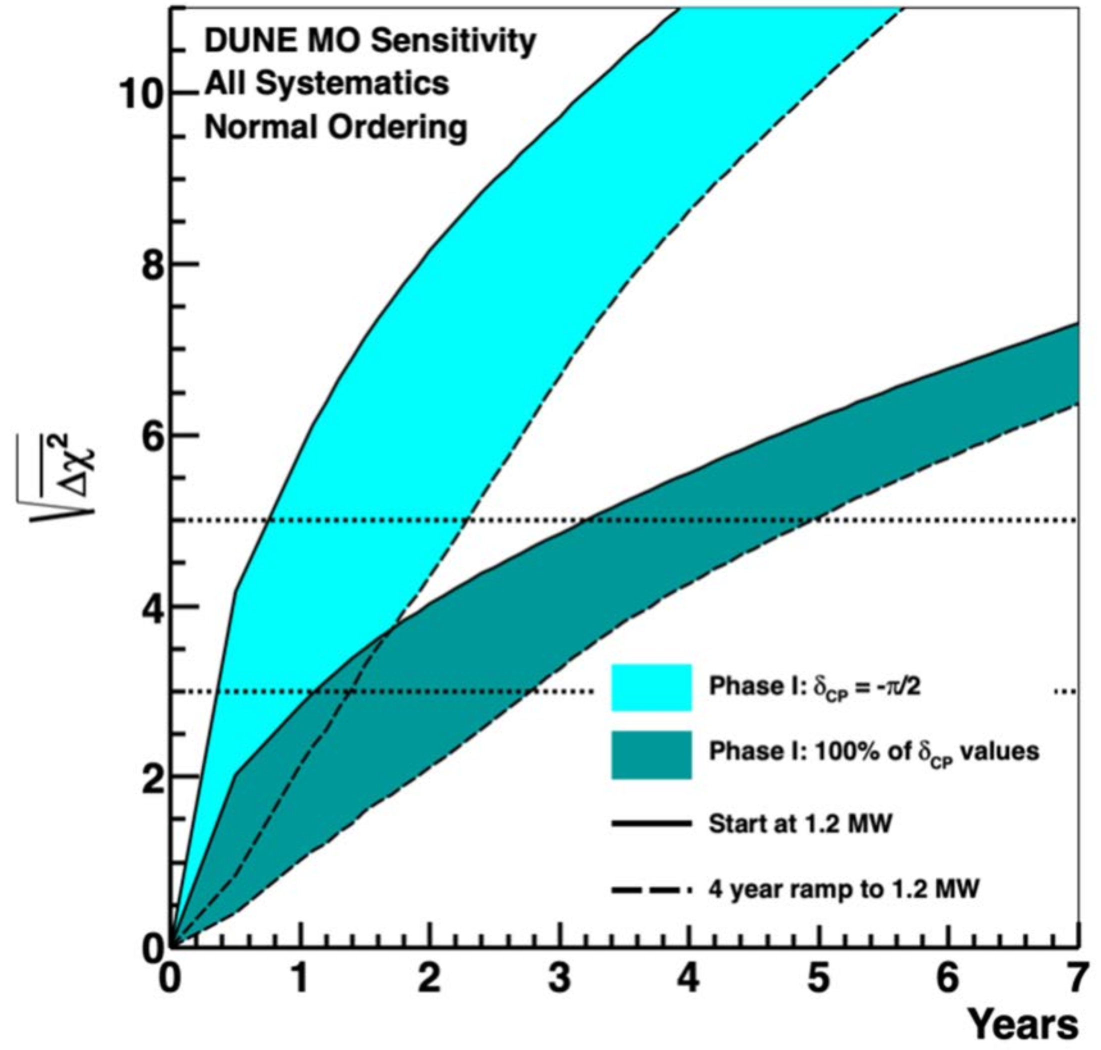
DUNE-PRISM



- Build a FD prediction **directly from ND data** by going off-axis
- Linearly combine many **ND fluxes** to **match the FD oscillated flux**
- Unknown or poorly modelled cross section effects **directly measured**
- Cancellation between ND and FD flux uncertainties

Neutrino Mass Ordering (MO)

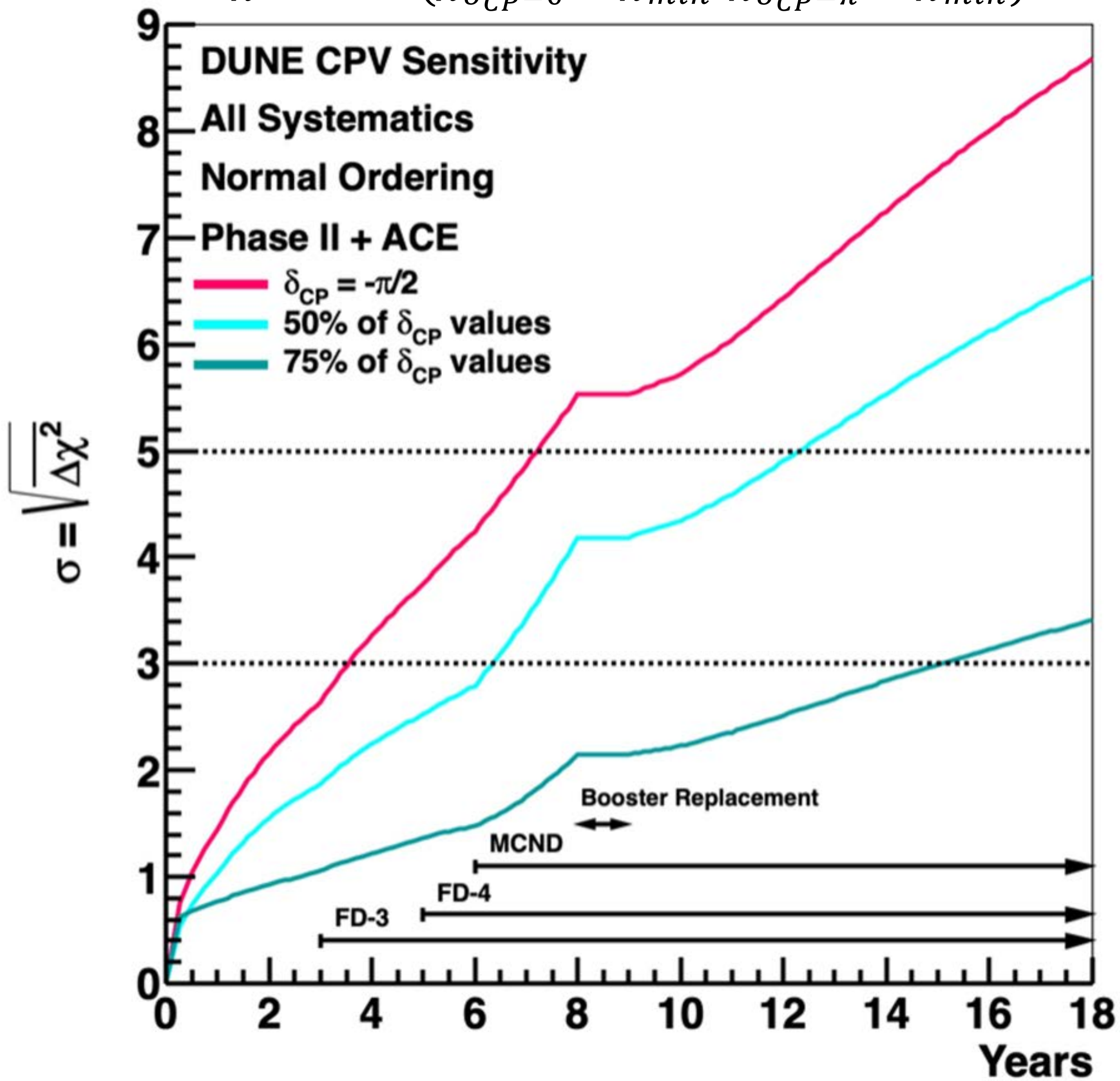
$$\overline{\Delta\chi^2} = \chi^2_{IO} - \chi^2_{NO}$$



- With a 1300-km baseline, the matter effect is very large
- Determination of the MO over **3σ in 3 years, over 5σ in 5 years** since start of data taking, independent of external inputs (e.g. θ_{13}) and δ_{CP} value

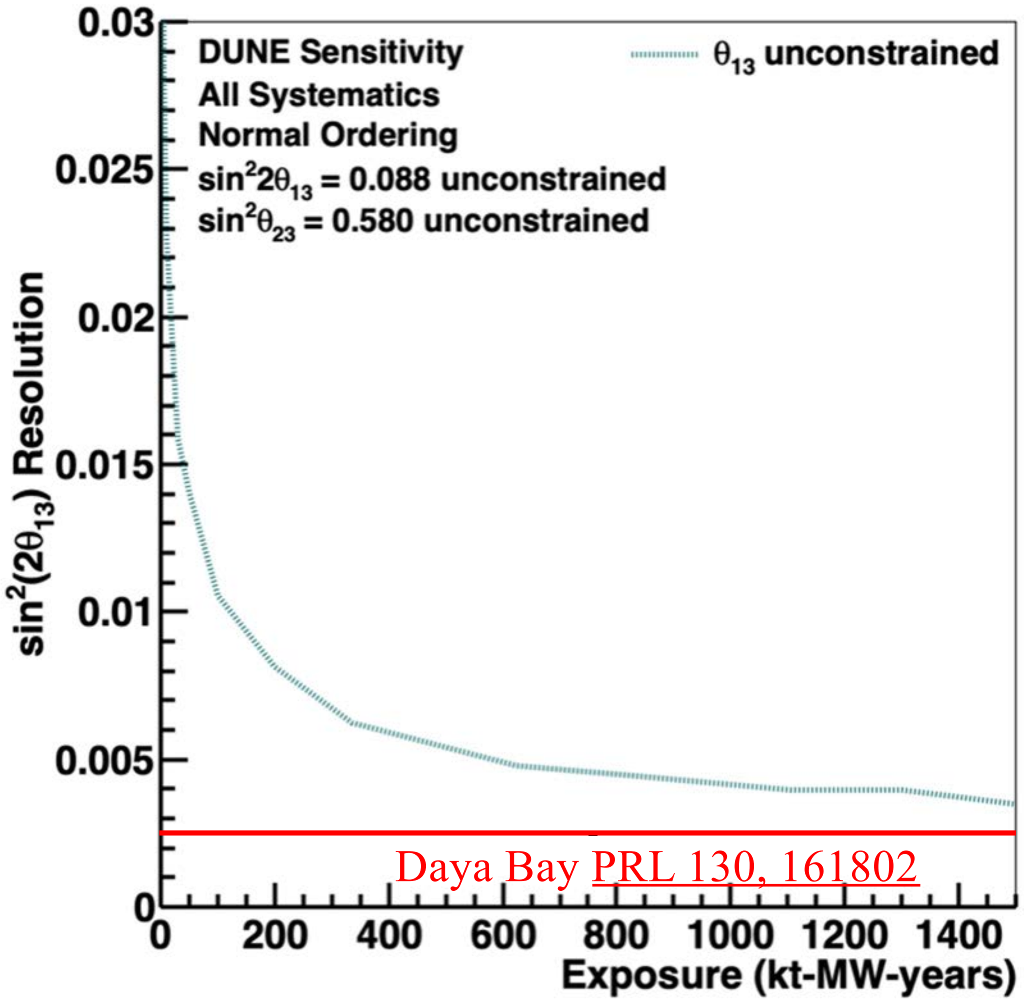
Search for Leptonic CP Violation (CPV)

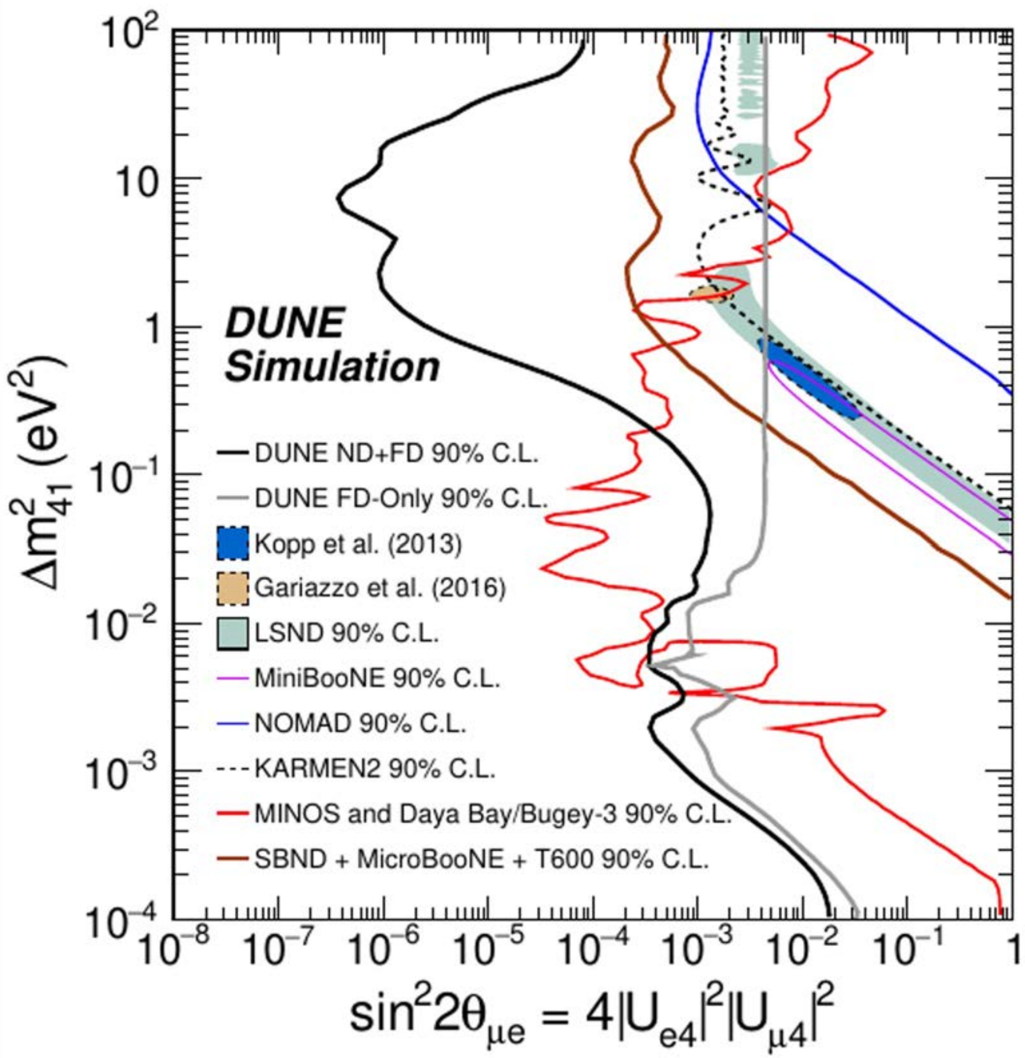
$$\overline{\Delta\chi^2} = \min\left(\chi^2_{\delta_{CP}=0} - \chi^2_{min}, \chi^2_{\delta_{CP}=\pi} - \chi^2_{min}\right)$$



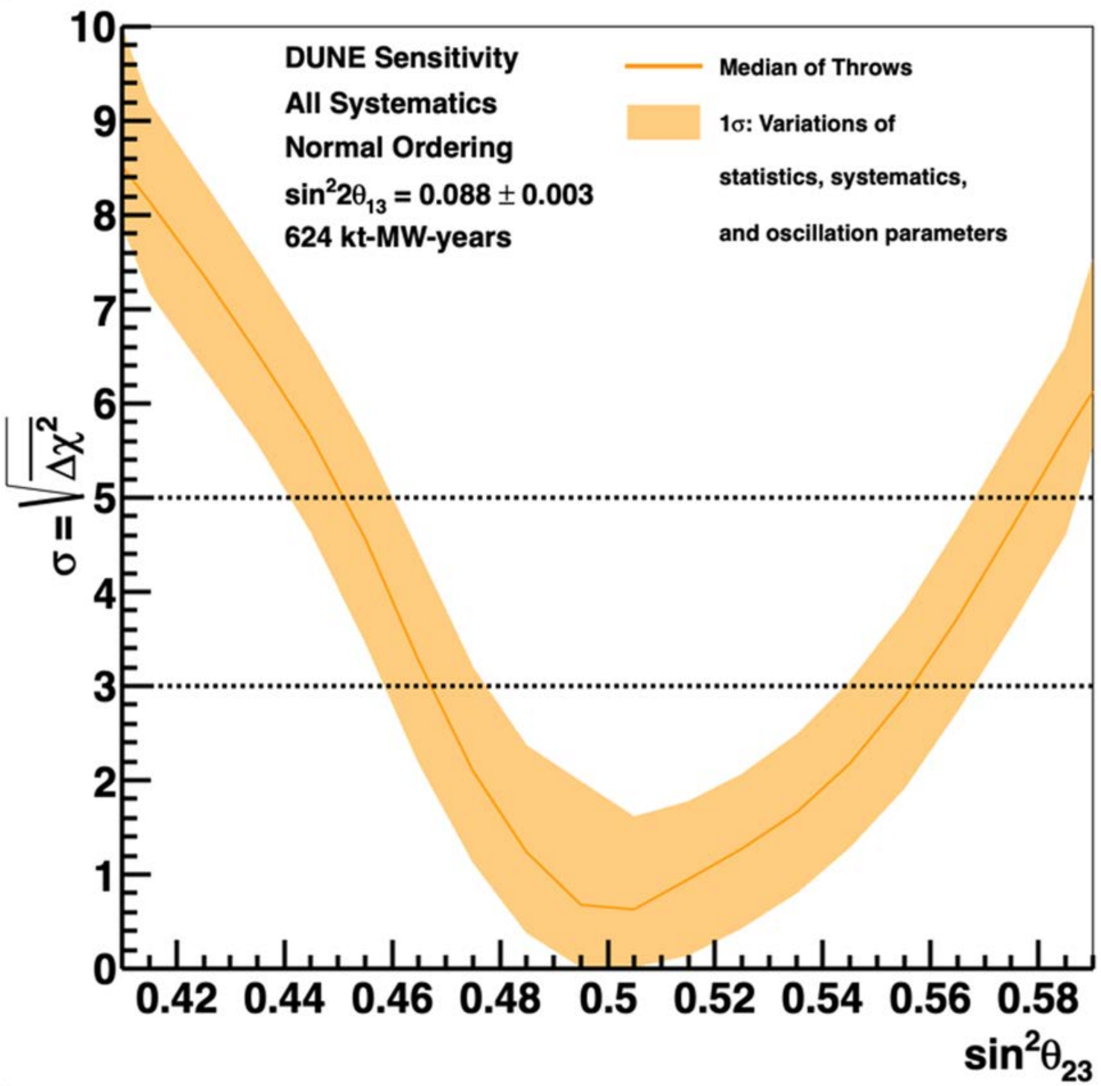
- Determination of CPV from the value of $\sin\delta_{CP}$
- Obtain sensitivity with Asimov data set
- ACE: Accelerator Complex Evolution
  - Deliver higher beam power early
  - Increase Main Injector ramp rate
  - Increase proton intensity and ramp rate of booster
- FD 3/4: Far Detector 3 & 4
- MCND: Improved systematics with Near Detector

Unitarity & Search for Sterile Neutrino



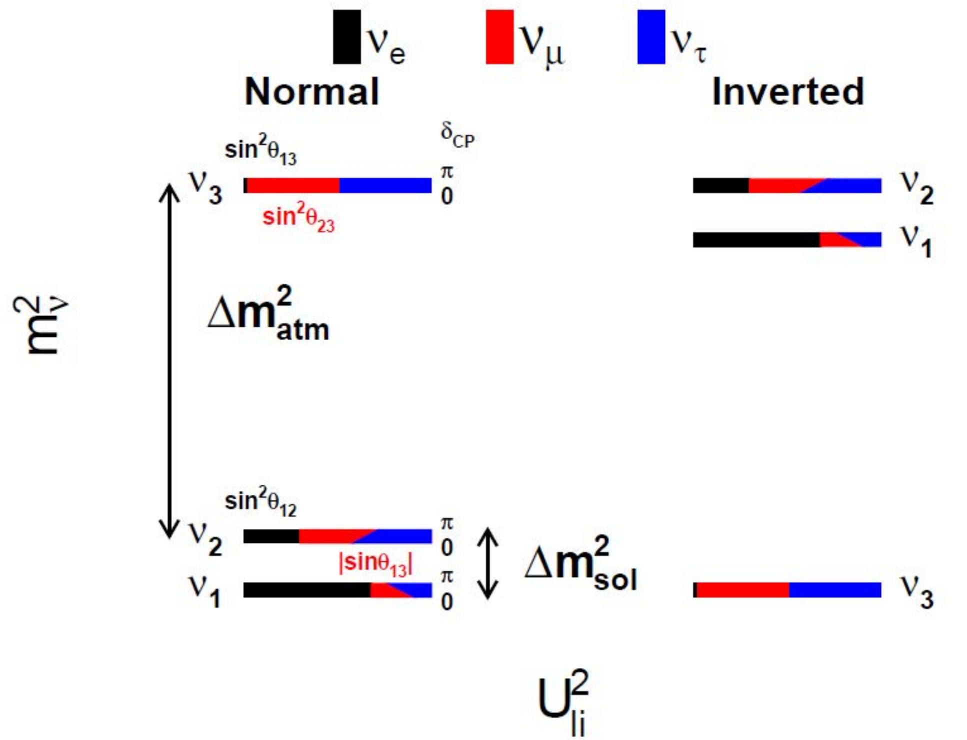


Octant Determination



- Critical input for ν mass & model building

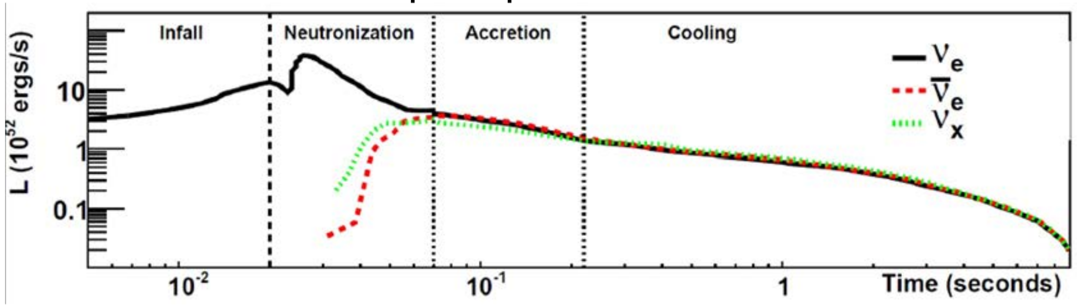
$$\sin^2\theta_{23} > 0.5 \;\rightarrow \nu_\mu > \nu_\tau \; in \; \nu_3$$
$$\sin^2\theta_{23} = 0.5 \;\rightarrow \nu_\mu = \nu_\tau \; in \; \nu_3$$
$$\sin^2\theta_{23} < 0.5 \;\rightarrow \nu_\mu < \nu_\tau \; in \; \nu_3$$

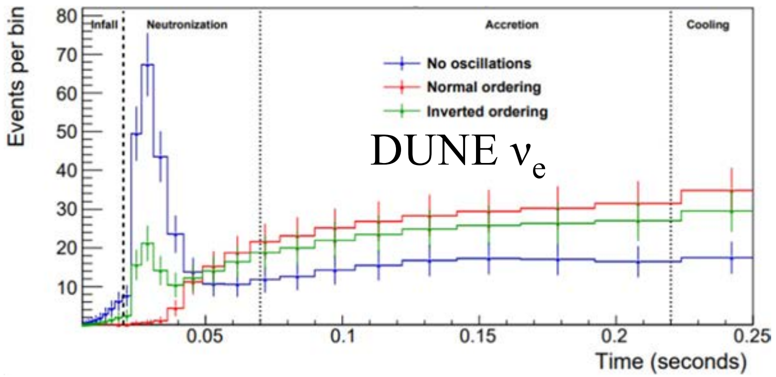


- Also, measure with tau neutrinos

Supernova Neutrino

10 kpc supernova burst



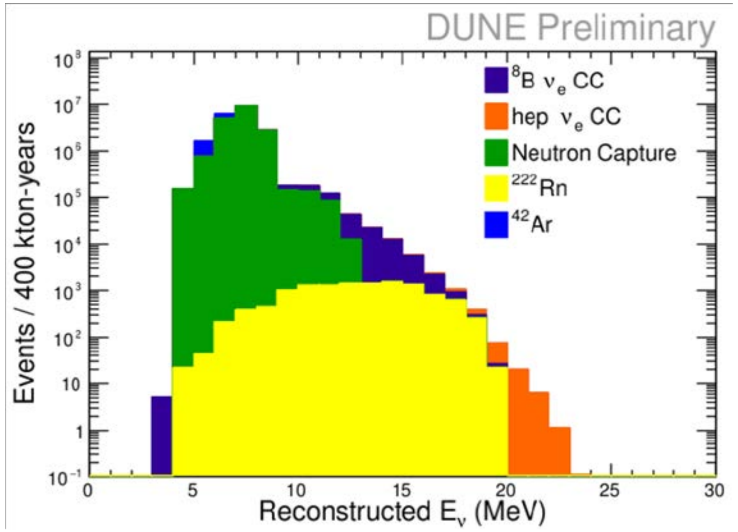


	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

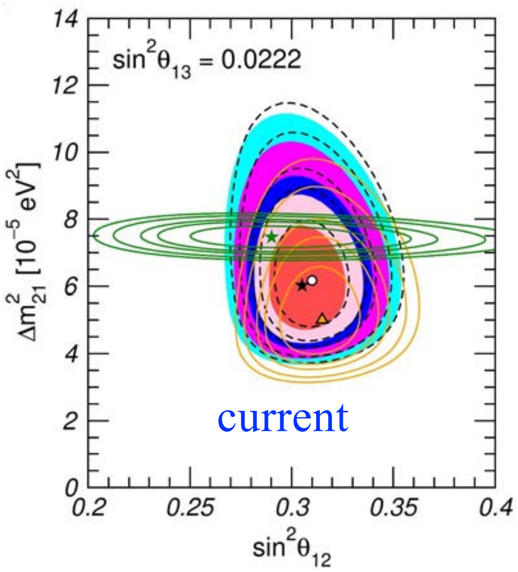
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

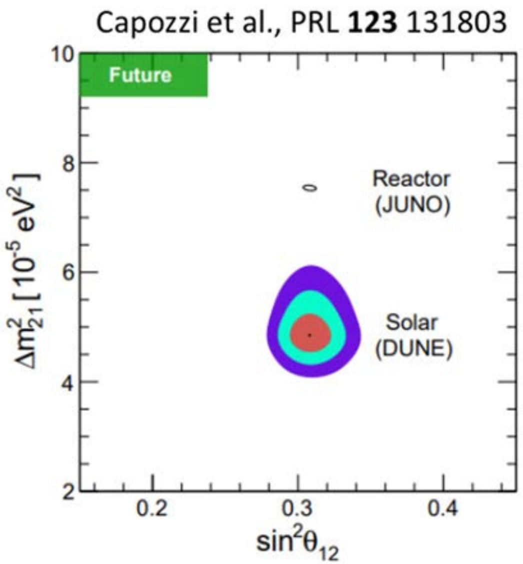
- Time (and energy) profile of the ν flux shed light on supernova physics
- Flux contains ν_e and $\bar{\nu}_e$ as well as a component of the other flavors (ν_x)
  - DUNE has **unique sensitivity to ν_e** component
- O(100)s events per Far Detector module for galactic supernova burst
  - Reach extended outside the Milky Way

Solar Neutrinos



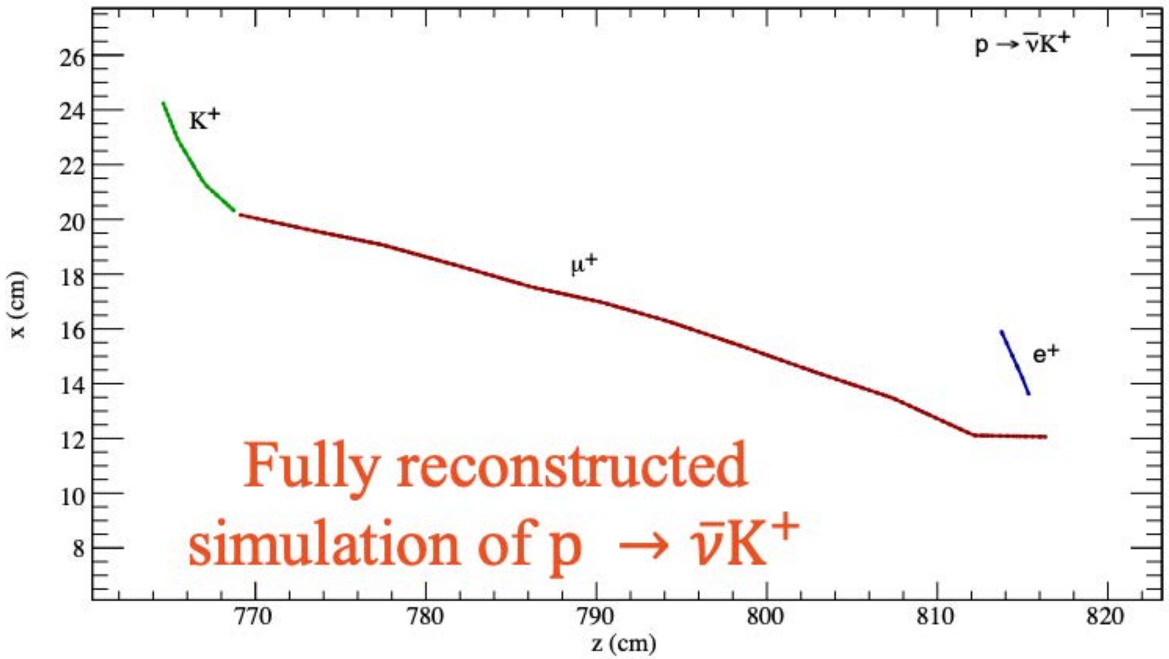
- Despite large neutron background below ~10 MeV, DUNE can measure ^{8}B solar flux and observe hep flux
  - Precision θ_{12} and Δm^2_{21} measurements with solar neutrinos



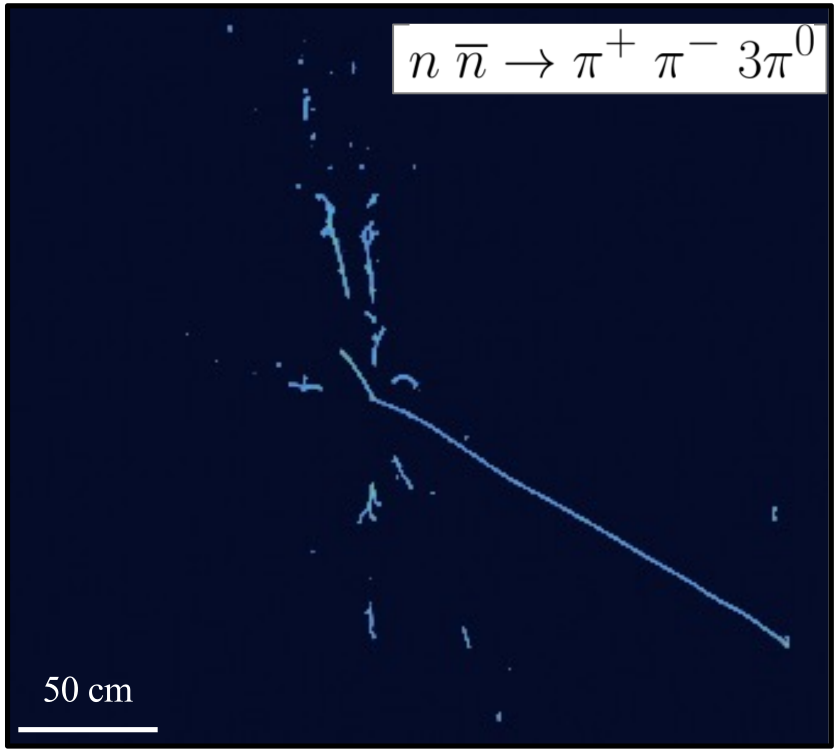


- JUNO will have by far the best precision in θ_{12} and Δm^2_{21}
- DUNE-JUNO comparison is sensitive to new physics

Searches for Proton Decay & $n - \bar{n}$ Oscillation

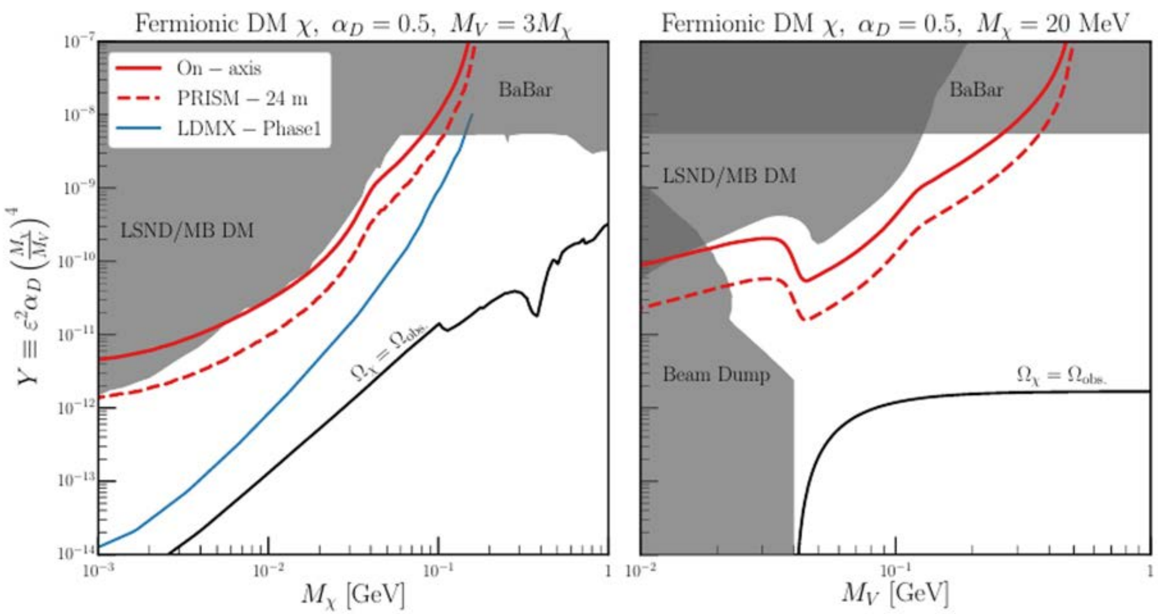


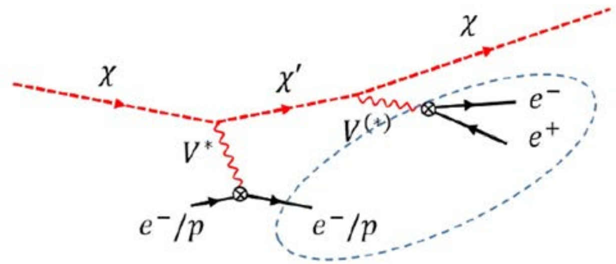
0.5 bkg events for 400 kt-yr, 30% signal efficiency
Sensitivity (no signal): $\tau/B > 1.3 \times 10^{34}$ yr (90% C.L.)

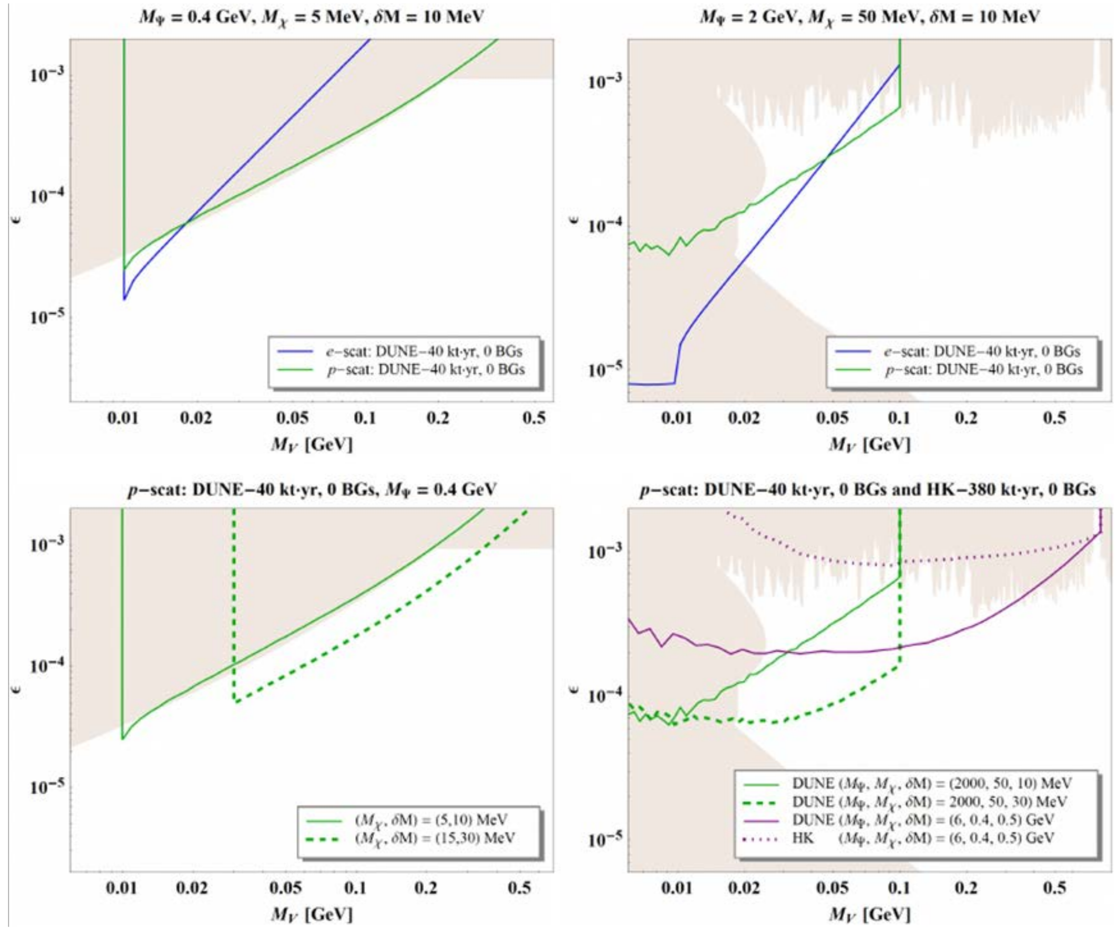


Free-neutron-equivalent sensitivity:
$\tau_{\mathrm{free,osc}} > 5.5 \times 10^8$ s (90% C.L.)

Dark matter at DUNE ND & FD

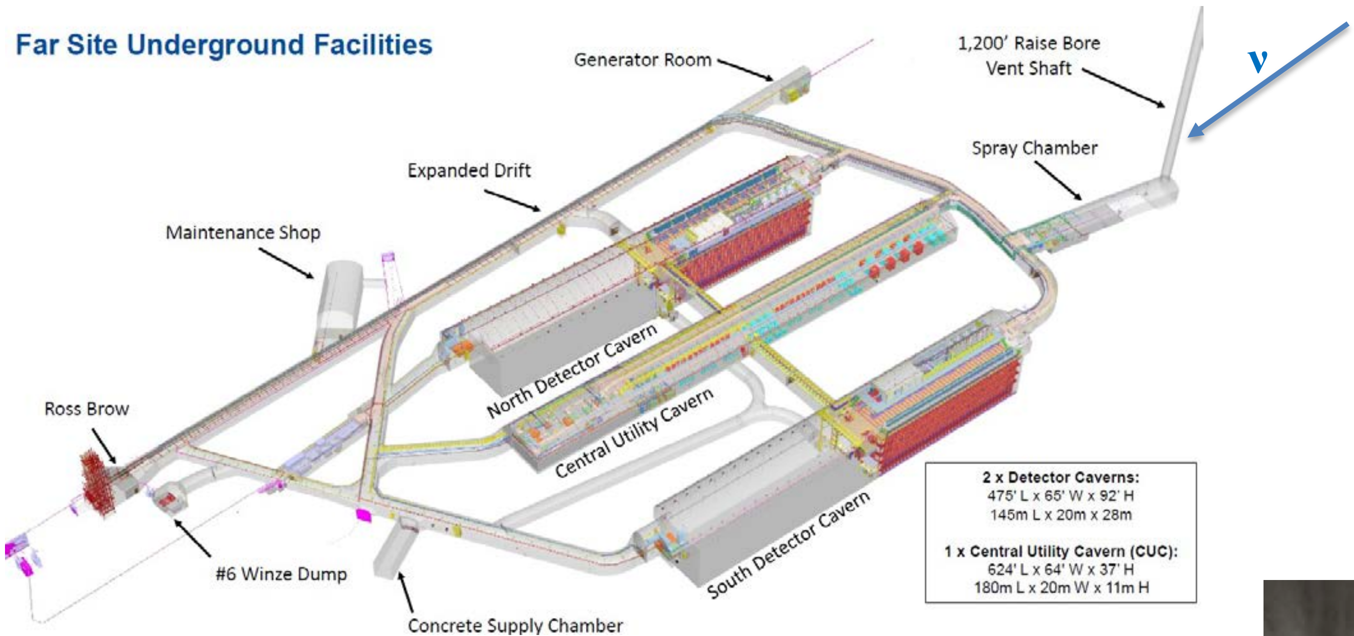






- ND-LAr is sensitive to DM produced in beamline, off-axis data helps to control SM backgrounds
- FD is sensitive to inelastic dark matter of cosmic origin

Far-Site Excavation: ~80%




North Cavern

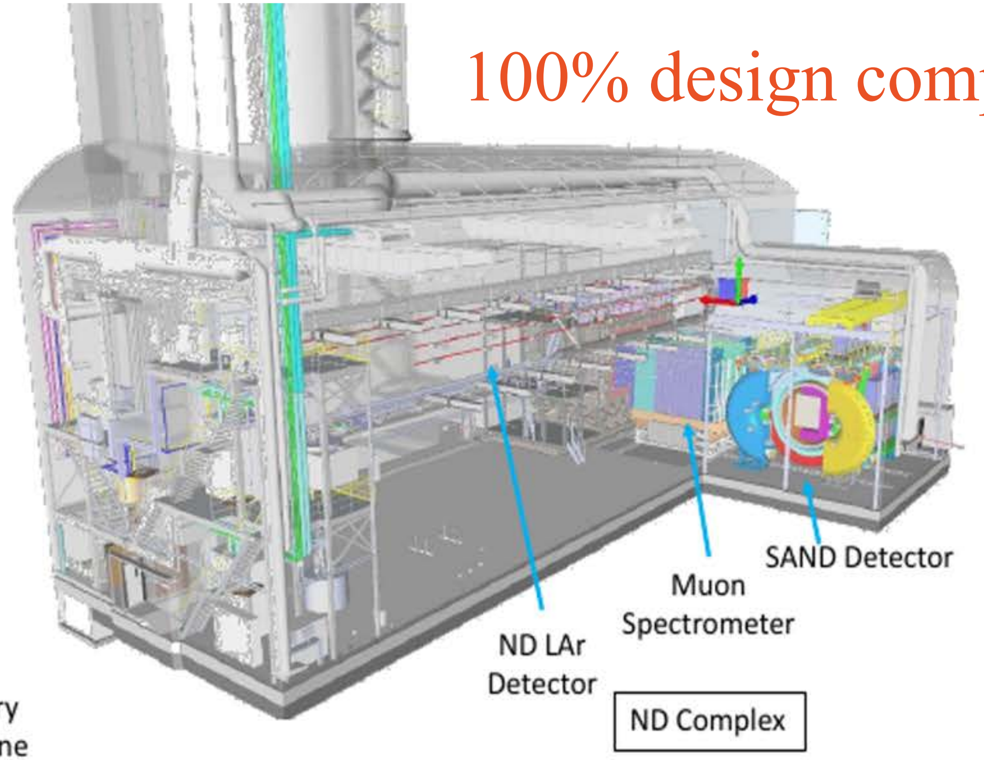

South Cavern


Central Utility Cavern

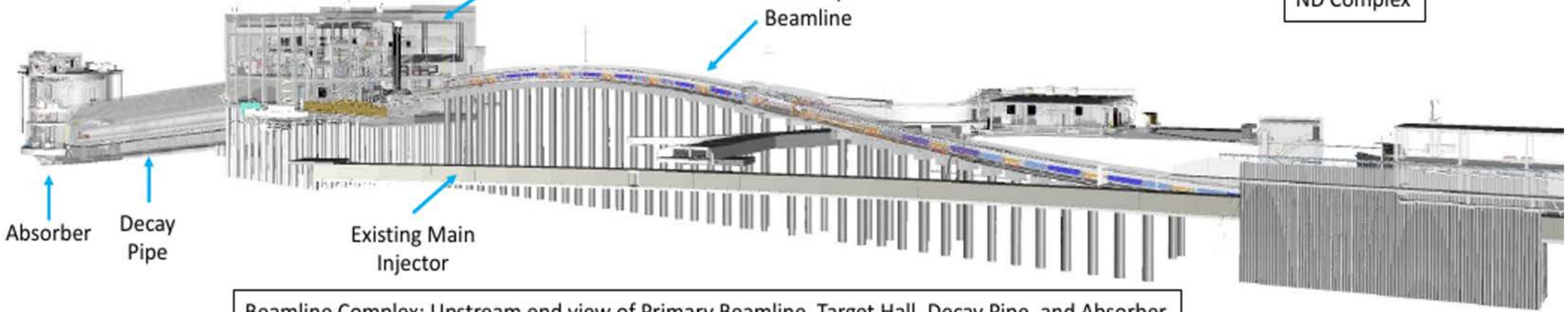
Beamline and Near Detector site @ FNAL

- Conventional facilities for the neutrino beamline and the Near Detector underground site have completed their designs

100% design complete



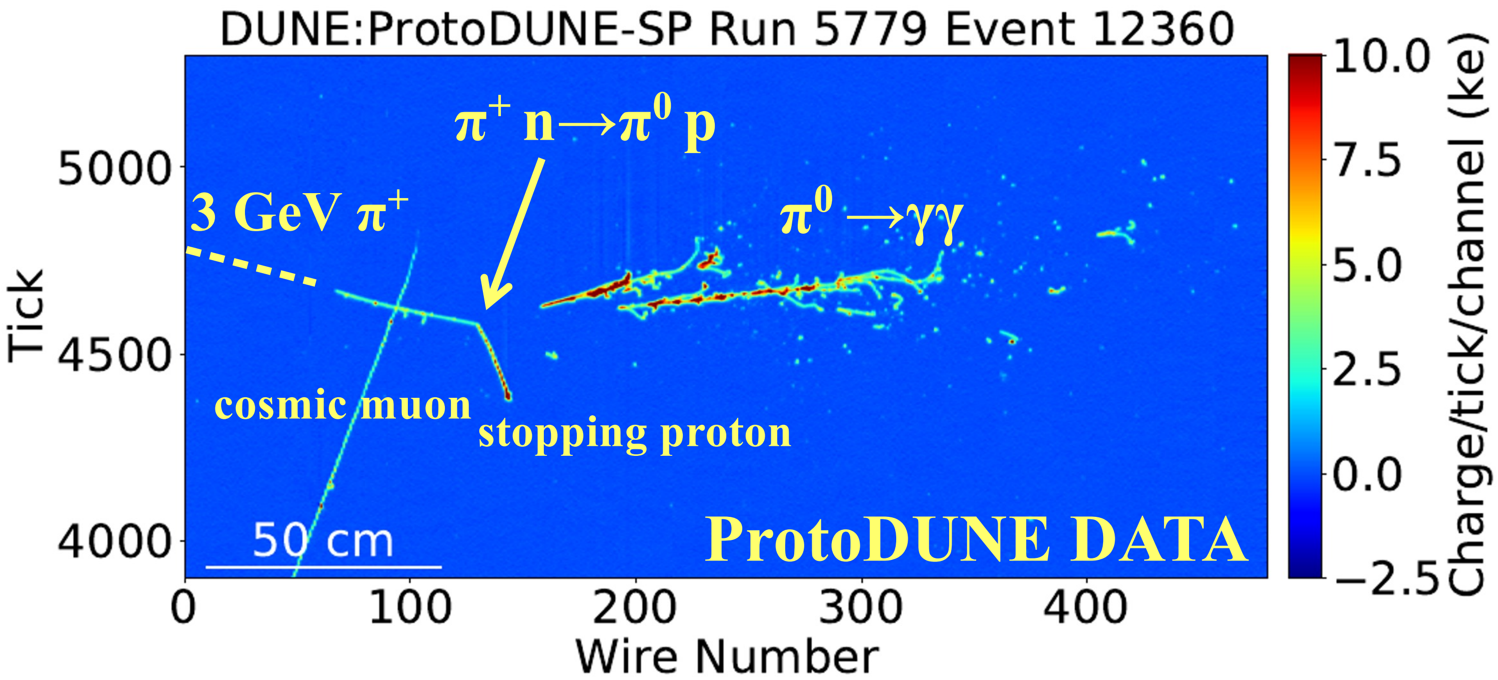
70% design complete

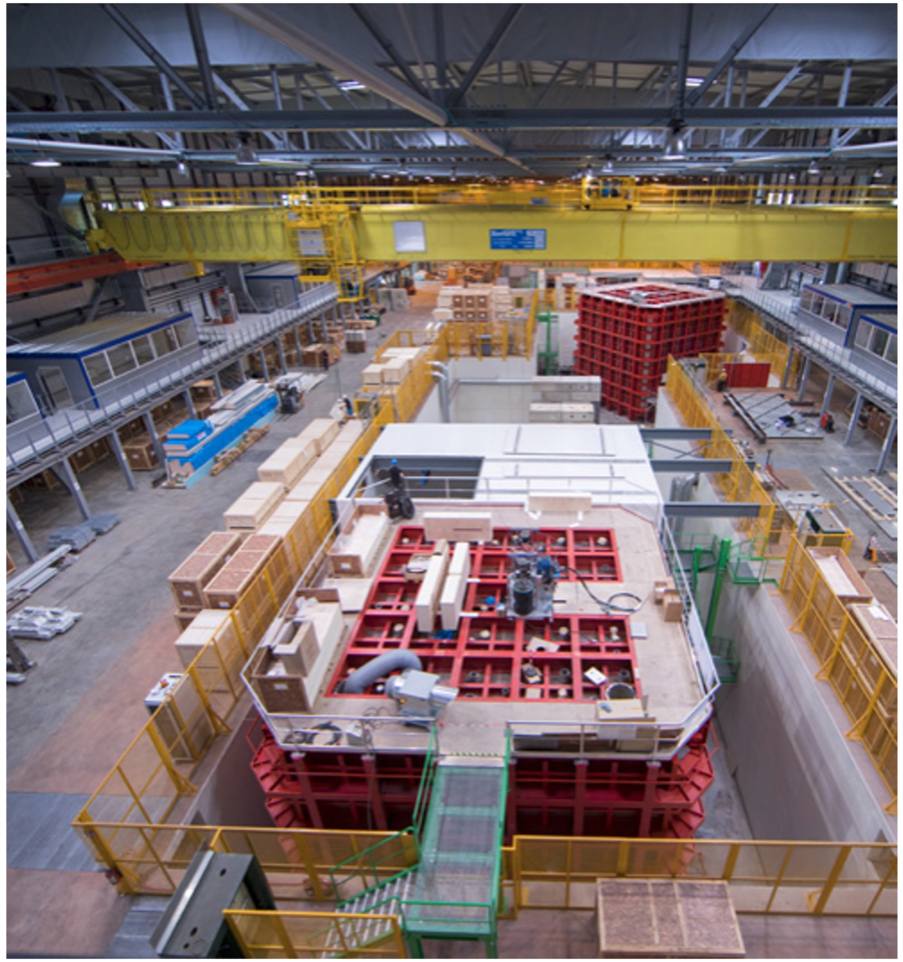


Beamline Complex: Upstream end view of Primary Beamline, Target Hall, Decay Pipe, and Absorber

Prototyping: Horizontal Drift

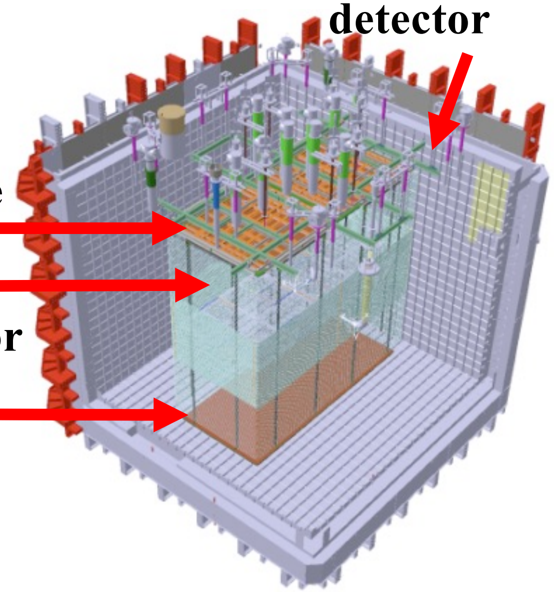
- LArTPC 3.6 m horizontal drift + photon detection
- Exposed to test beams at CERN, momentum-dependent beam composition contains e, p, $\pi^{\pm}$, $K^{\pm}$, μ in 2018 & cosmic data in 2018 – 2020
- Under installation for this year's running

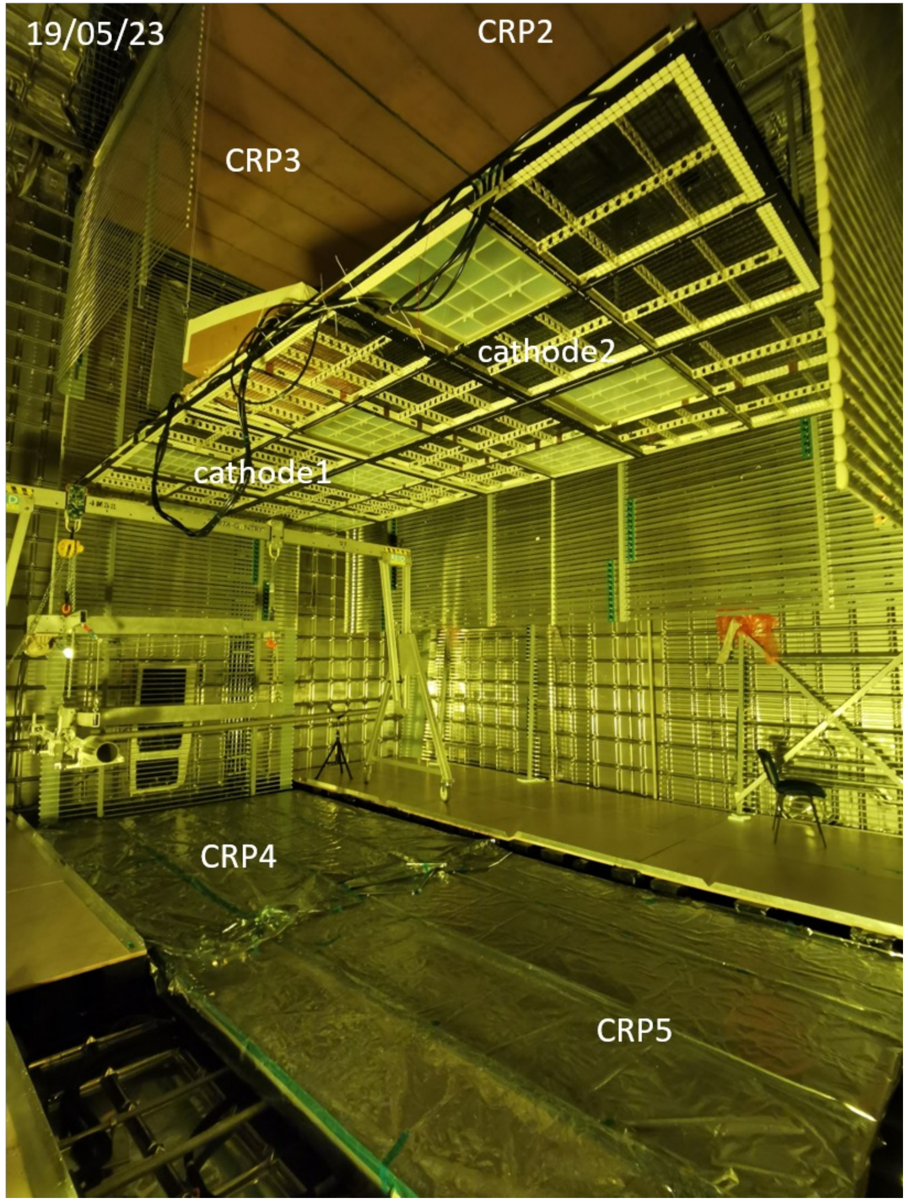




Prototyping: Vertical Drift

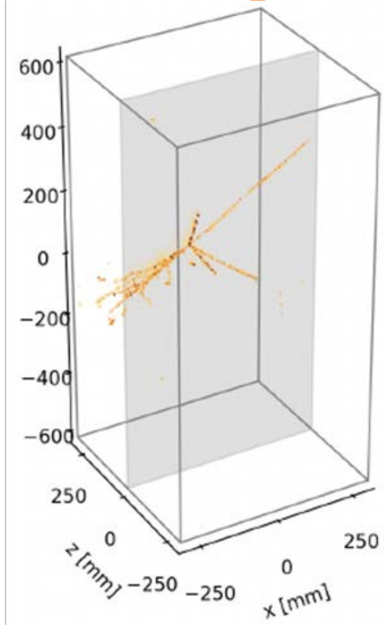
- Data taking @ CERN expected end 2023
- 8 charge readout units (3.4 m drift distance)
- 8 x-Arapuca photon detectors @ cathode and another 8 x-Arapuca photon detectors @ membrane
- 70% field cage coverage as in FD2

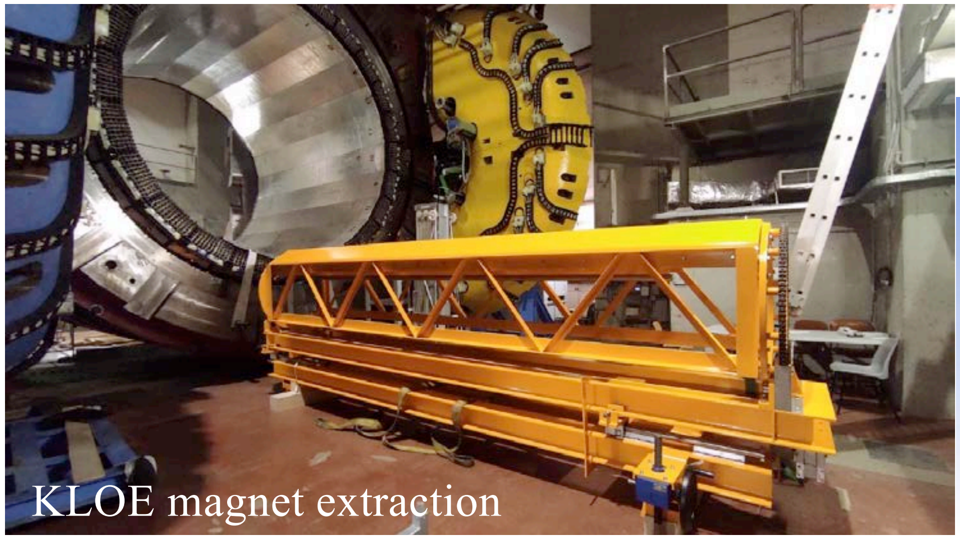




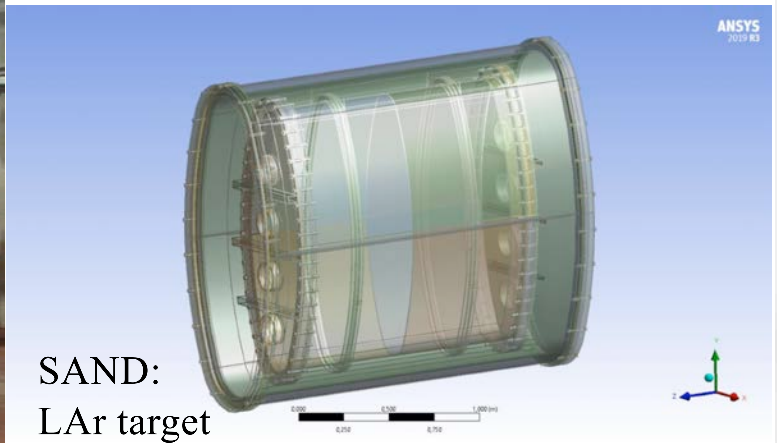
Prototyping: Near Detectors

- Four ND-LAr prototype modules operated successfully at Bern with O(100) millions cosmic rays recorded, preparing 2×2 configuration for neutrino beam test at FNAL
- SAND: KLOE magnet extraction, LAr target design, staw tube tracker construction underway
- Also, progress in DUNE-PRISM and TMS

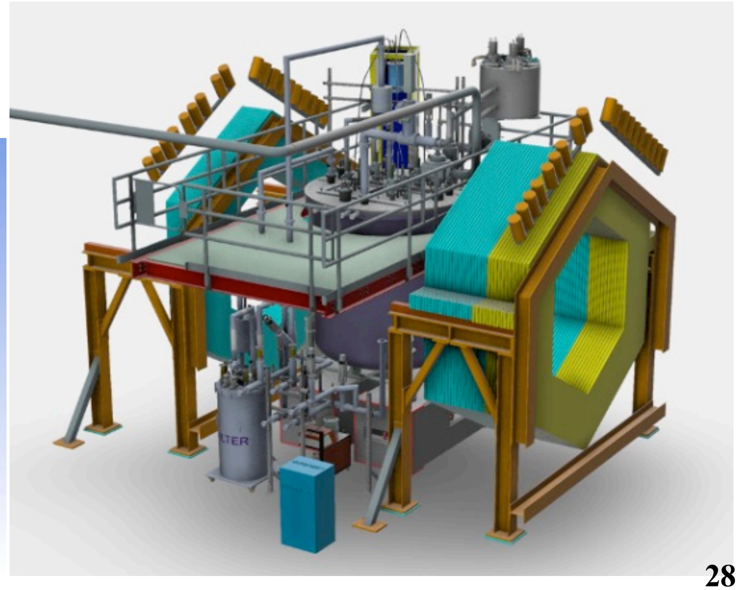




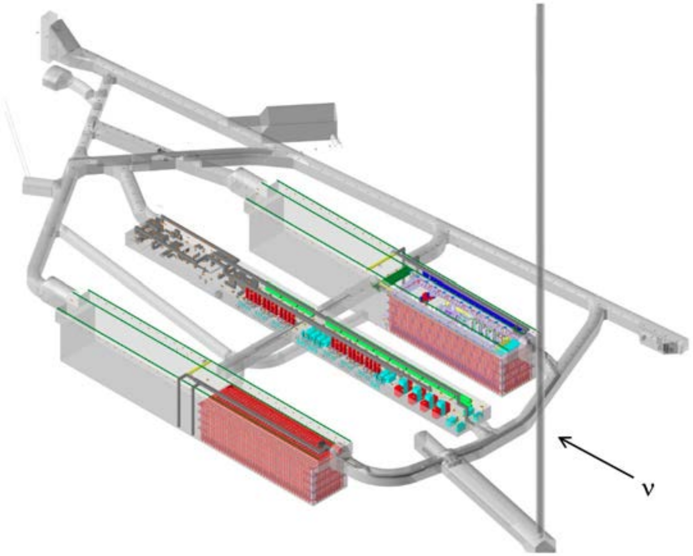
KLOE magnet extraction

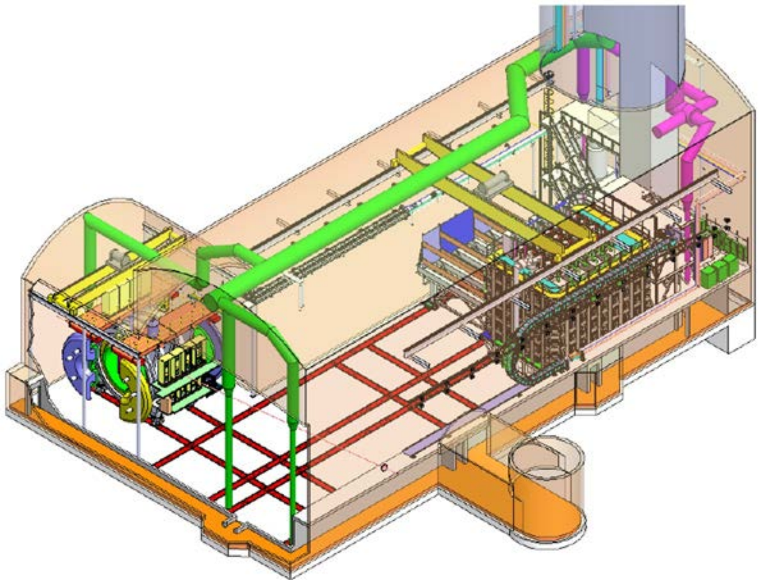


SAND:
LAr target



Schedule and Staging

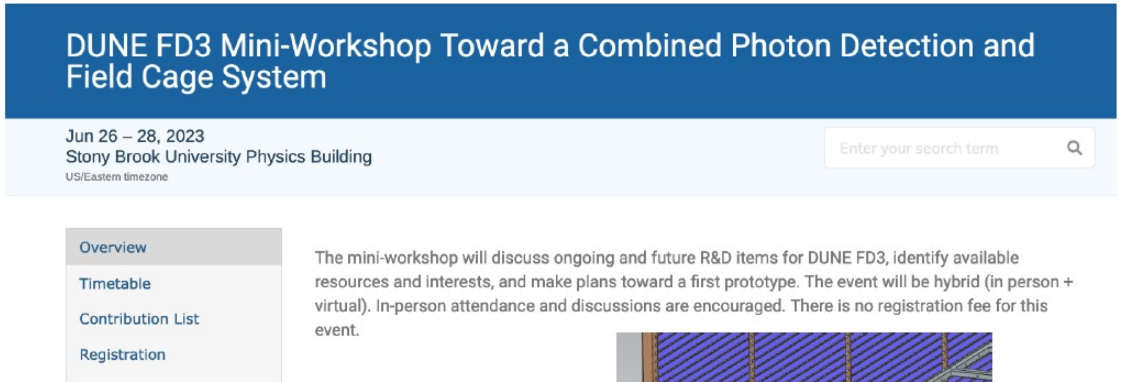


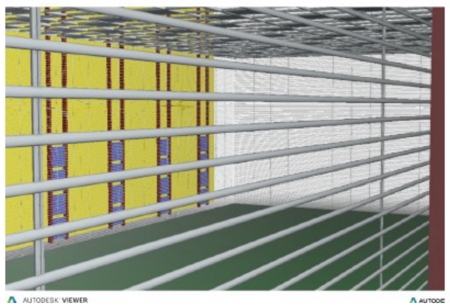


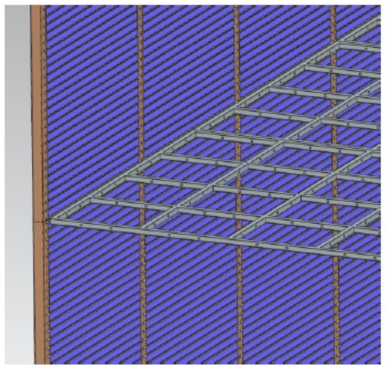
- Phase I: **FD start @ 2028; ND & Beam start @ 2031**
  - Full near + far facility and infrastructure
  - Upgradeable 1.2 MW neutrino beam
  - Two 17-kT LArTPC modules
  - Movable ND-LAr with TMS
  - SAND
- Phase II (in 2030s):
  - Two additional Far Detector modules
  - Beam upgrade to > 2 MW (with ACE)
  - More capable Near Detector

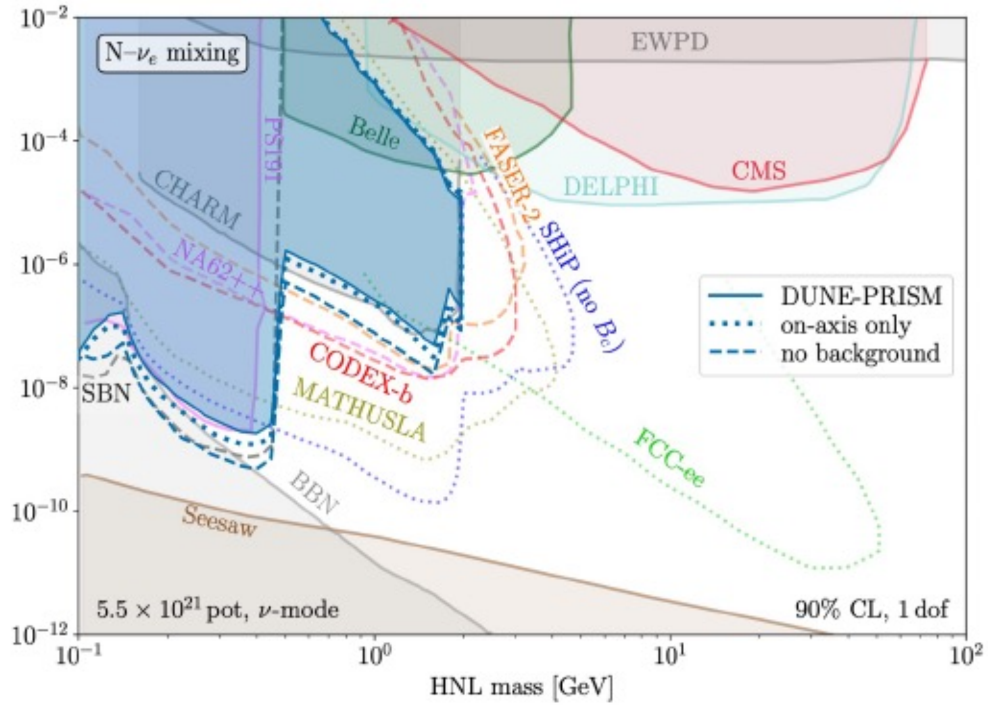
DUNE Phase II Opportunity

- Future far detector modules could extend the physics reach to lower energies and/or lower backgrounds (e.g. **Vertical Drift technology with enhanced light collection**)









- **BSM searches** enabled by Phase 2 ND will include: Neutrino Tridents, Heavy Neutral Leptons, Light Dark Matter, Heavy Axions, Tau Neutrinos

Summary

- DUNE is a best-in-class long-baseline neutrino-oscillation experiment, neutrino observatory, and new-physics search machine
- We are on track to deliver Phase I:
  - ProtoDUNE has successfully demonstrated the required LArTPC technology
  - Far-site civil construction is proceeding well, near site is fully designed, and beamline design is progressing well
  - Additional FD and ND prototyping is going well, with initial FD construction set to begin soon
- DUNE Phase-II is essential to complete and extend DUNE physics program
- **Stay tune for an exciting time of DUNE!**