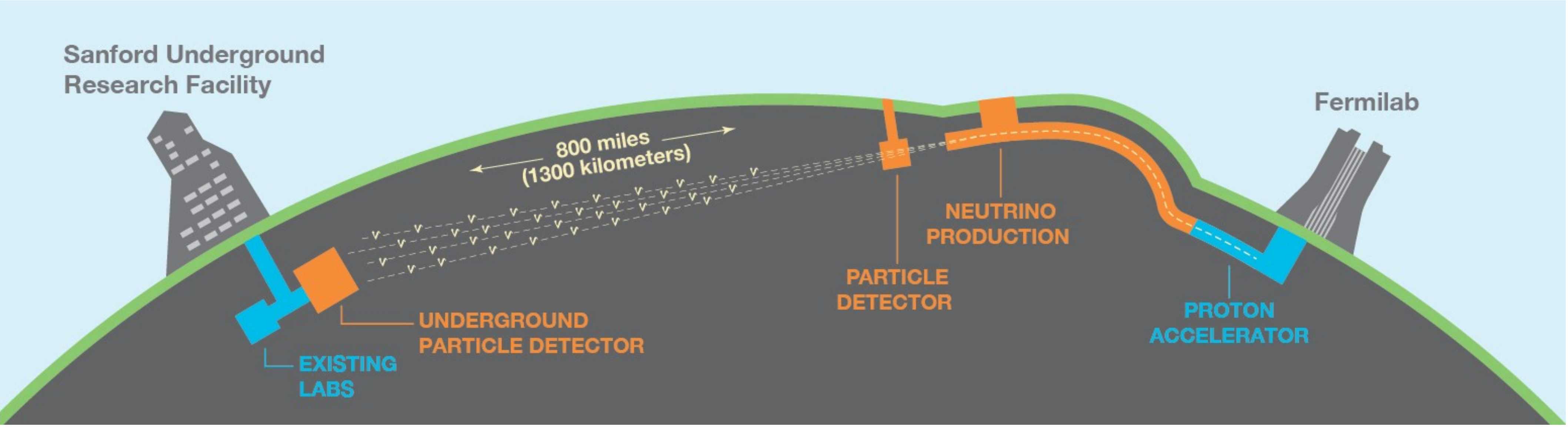
The DUNE message to Snowmass

Chris Marshall, University of Rochester
for the DUNE international collaboration
Snowmass Community Summer Study, Seattle
18 July, 2022

Tomorrow: DUNE physics in detail

- Two sessions tomorrow morning are dedicated to the DUNE physics program and P5 strategy
- 8am: Neutrino oscillation physics
  - Neutrino oscillations in DUNE (Callum Wilkinson)
  - Neutrino interactions uncertainties (Kevin McFarland)
  - The DUNE Near Detector (Dan Cherdack)
- 10am: Low-energy and BSM physics
  - MeV-scale neutrino physics in DUNE (Dan Pershey)
  - Beyond 3-flavor oscillations in DUNE (Alex Sousa)
  - Direct BSM searches (Jae Yu)

DEEP UNDERGROUND NEUTRINO EXPERIMENT



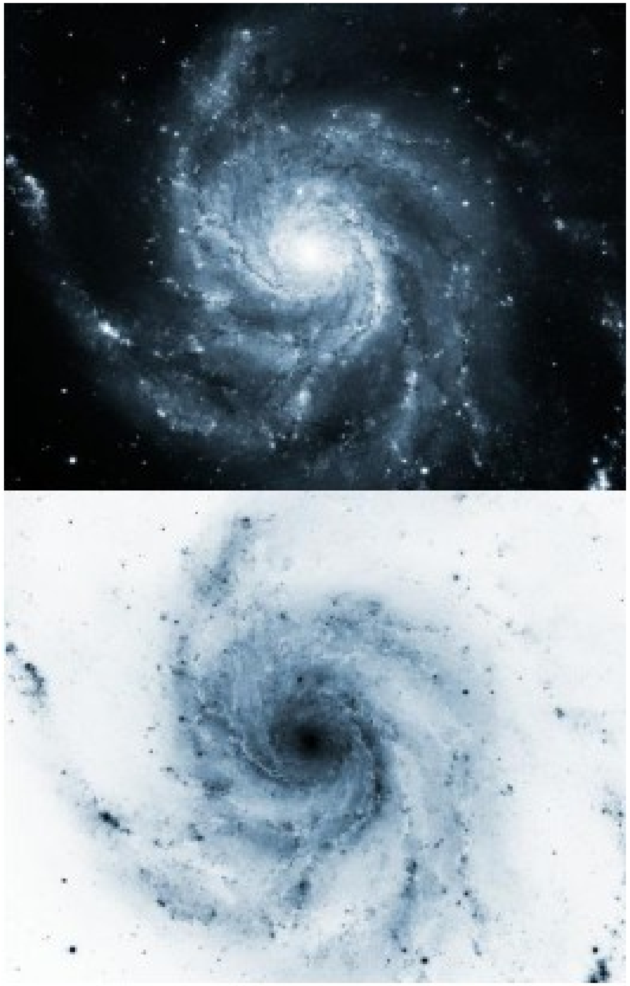
- Next-generation international neutrino & underground science experiment hosted in the United States (37 countries + CERN)
- High intensity neutrino beam, near detector complex at Fermilab
- Large, deep underground LArTPC far detectors at SURF
- Precision neutrino oscillation measurements, MeV-scale neutrino physics, broad program of physics searches beyond the Standard Model

This talk

- Motivation: neutrino oscillations as part of a broad physics program
- Designing DUNE: precision, robustness, and breadth
- DUNE physics potential
- Getting there: phased construction and opportunities for expanded scope
- The message for Snowmass

Neutrino oscillations: Big picture questions

- What is the origin of neutrino mixing? Is there an underlying flavor symmetry, and how is it broken?
- What is the origin of the neutrino masses? Why are the neutrinos so light?
- Is leptogenesis a viable explanation of the baryon asymmetry of the Universe?
- Is the νSM complete? Are there additional neutrinos?



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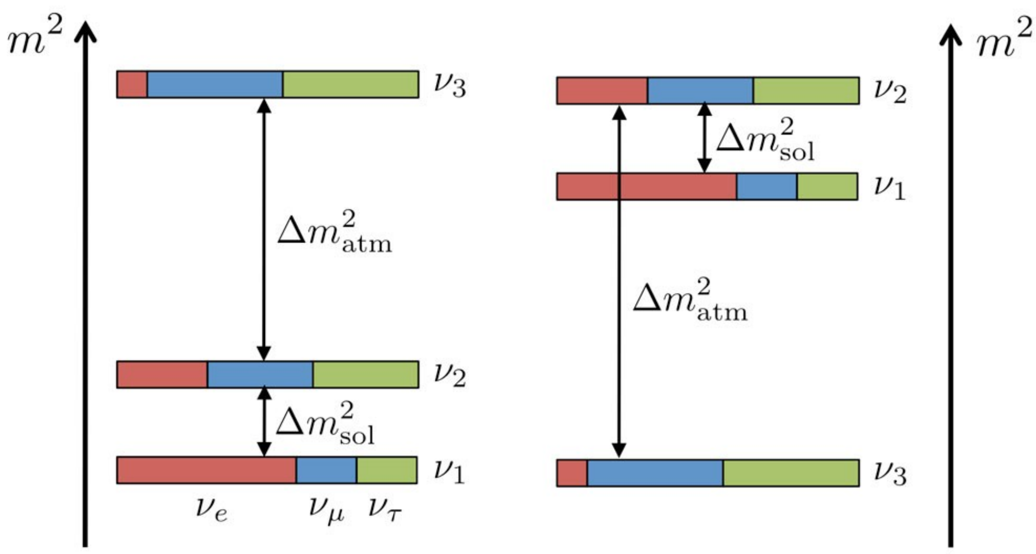
Searching for answers: precision neutrino oscillation measurements

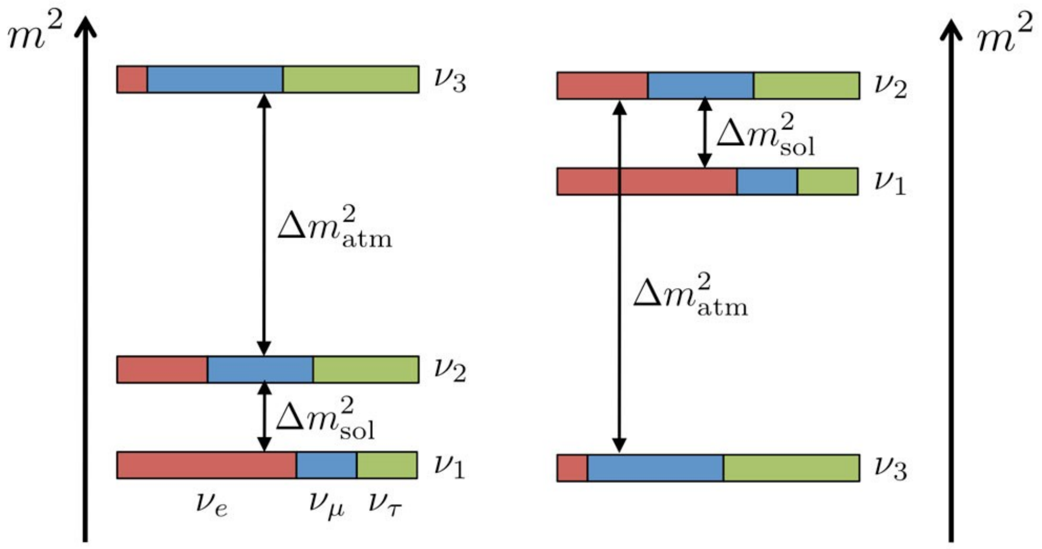
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- Measure neutrino oscillations precisely, including $\nu_\mu \rightarrow \nu_e$ that is sensitive to CP violation
- Test the three-flavor paradigm → overconstrain the system

Neutrino oscillations: current status

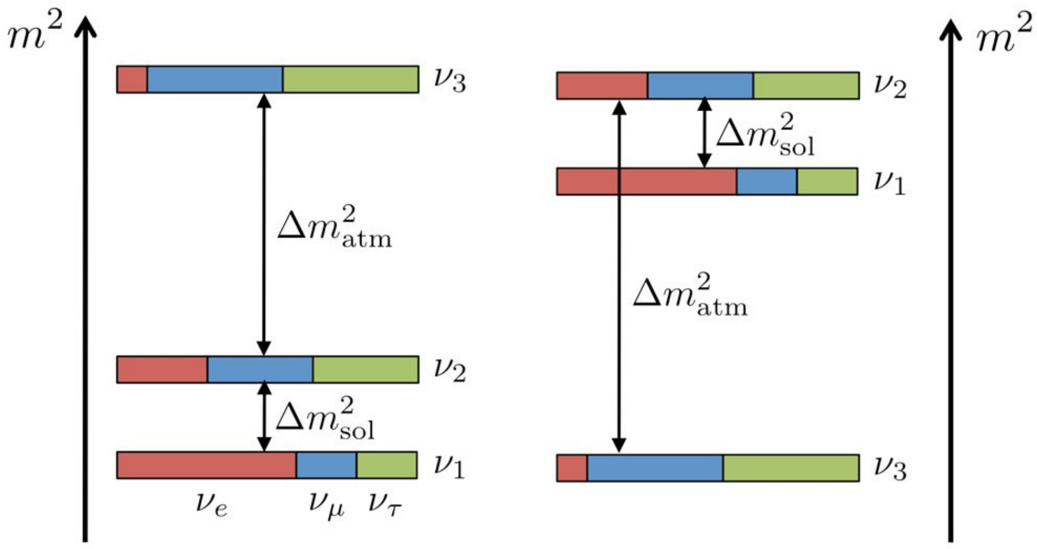
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Current precision:
  - θ_{13} ~ 2.7% (reactor $\bar{\nu}_e$ disappearance)
  - $|\Delta m^2_{32}|$ ~ 3% (reactor $\bar{\nu}_e$ disappearance and accelerator ν_μ disappearance), mass ordering unknown
  - $\sin^2\theta_{23}$ ~ 0.5 ± 0.1 (atmospheric and accelerator ν_μ disappearance + ν_e appearance)
  - δ_{CP} unknown

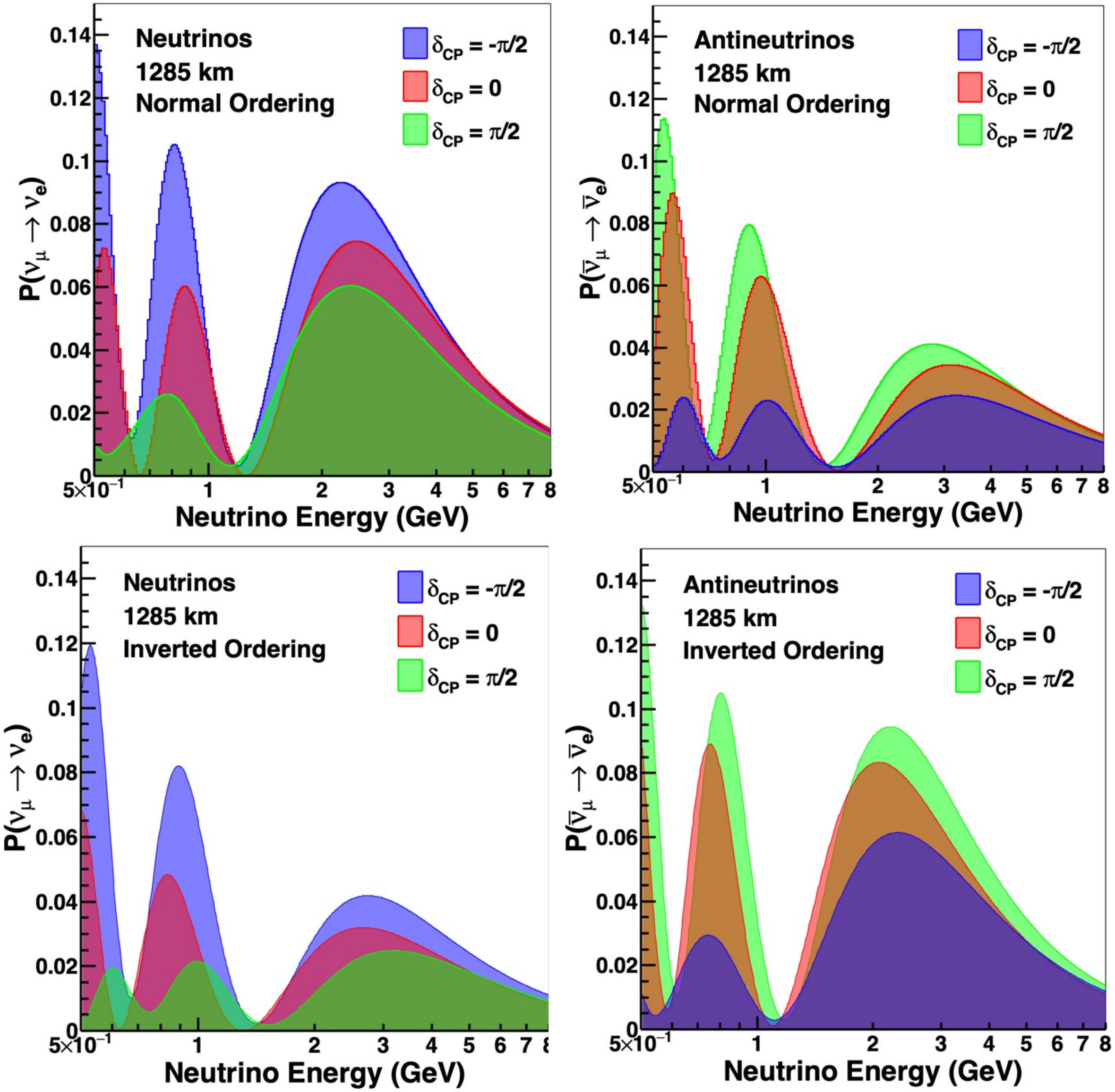
Neutrino oscillations: Next Generation goals with $\nu_\mu \rightarrow \nu_e$

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{-i\delta_{\mathrm{CP}}} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{\mathrm{CP}}} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



- Measure the mass ordering
- Measure δ_{CP}
- Improve precision on $\sin^2\theta_{23}$
  - Is it maximal?
  - Resolve the octant
- Measure θ_{13} with ν_e appearance and similar precision to reactor → unitarity test
- Make multiple measurements → does the PMNS matrix hold up?

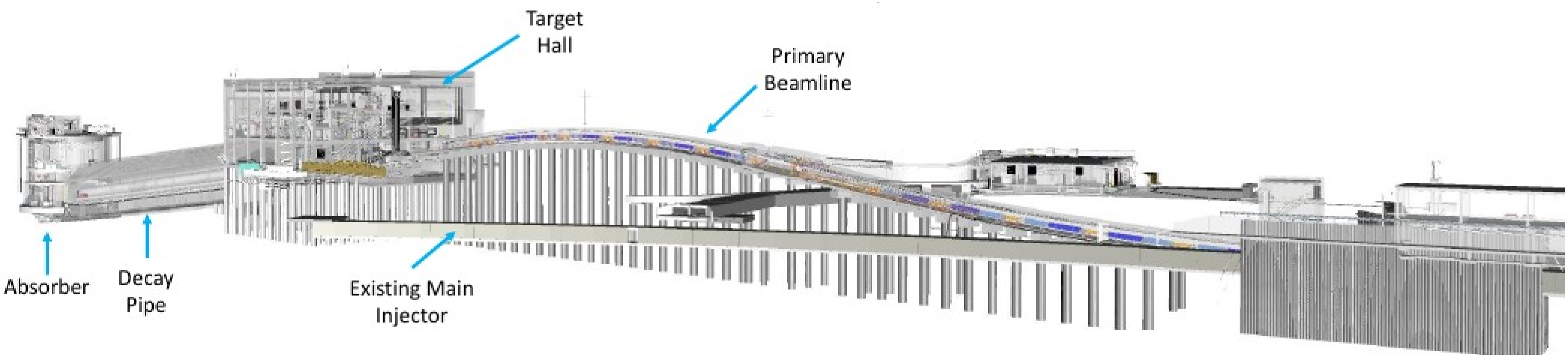
DUNE measures $\nu_\mu \rightarrow \nu_e$ vs. L/E in wideband beam



- DUNE is designed to resolve degeneracies by measuring flavor transitions as a function of energy over more than a full oscillation period
- DUNE will determine the mass ordering and measure δ_{CP}, regardless of the true values
- Expect the unexpected: DUNE is robust against systematic effects and for resolving deviations from νSM

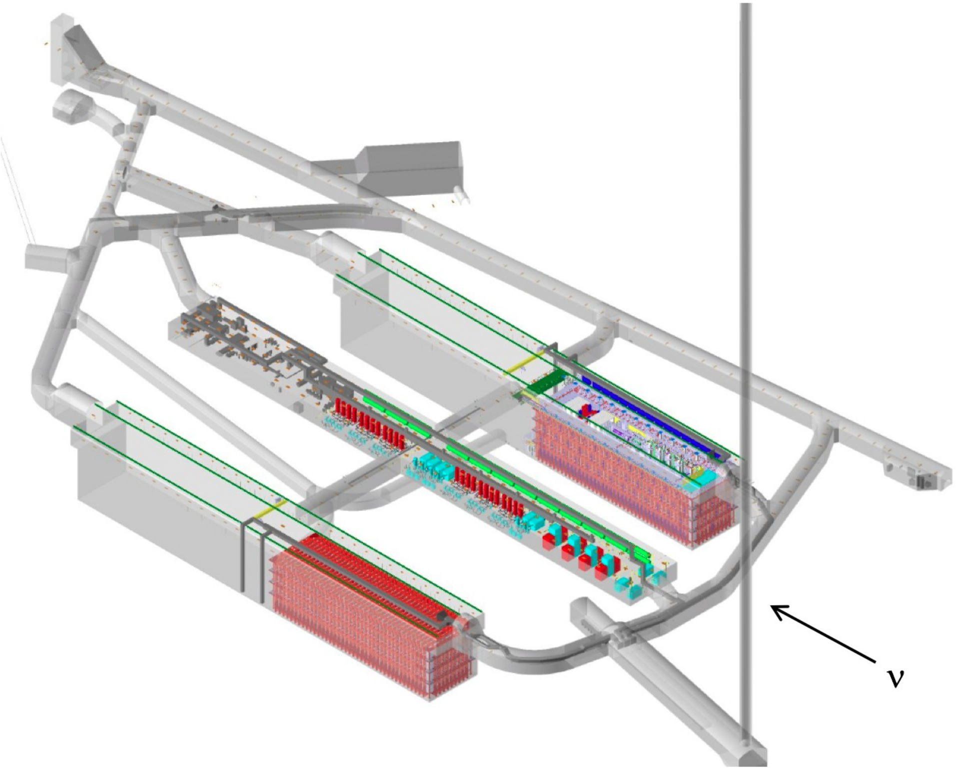
Neutrino oscillations as part of a broad physics program

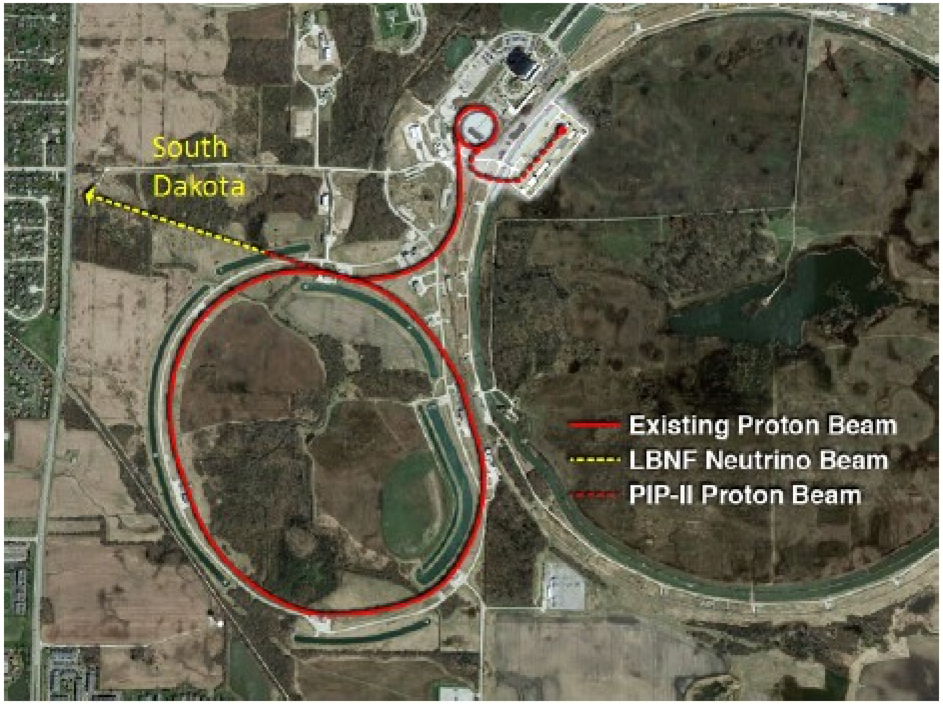
- DUNE FD has excellent low-energy neutrino and BSM sensitivity:
  - Large mass
  - Deep underground
  - High resolution
  - Low thresholds
- Boosted BSM searches → high intensity beam and capable ND



LBNF: intense beam, underground facilities and infrastructure

- 1.2 MW neutrino beam from PIP-II proton beam, upgradeable to 2.4 MW (see NF/AF session on Wednesday)
- Deep underground far site to accommodate four 17-kiloton detector modules





LBNF: intense beam, underground facilities and infrastructure

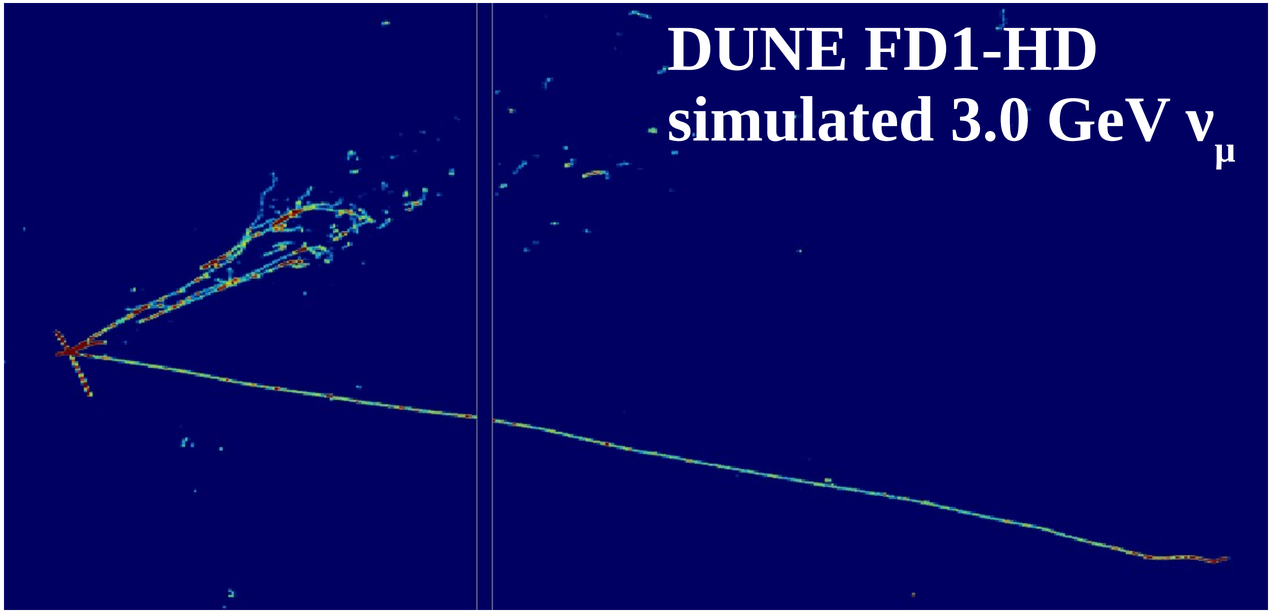
- Construction is underway at both SURF and Fermilab

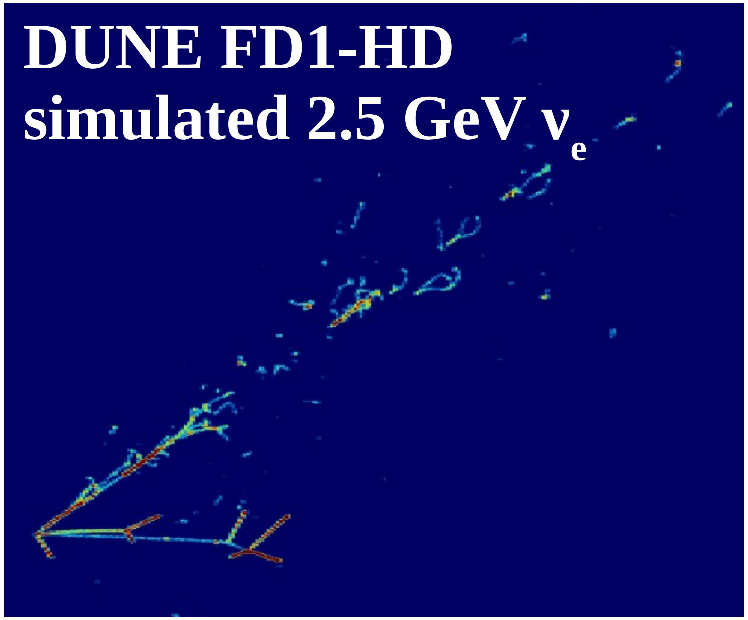
North cavern breakthrough January 2022

PIP-II construction May 2022

LArTPC technology provides exquisite resolution

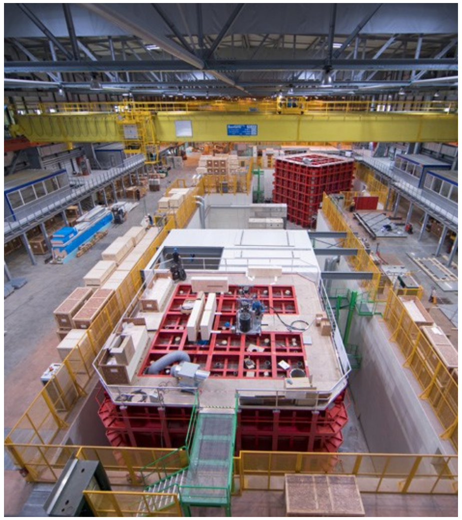
- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- Low thresholds: sensitivity to few-MeV neutrinos, hadrons

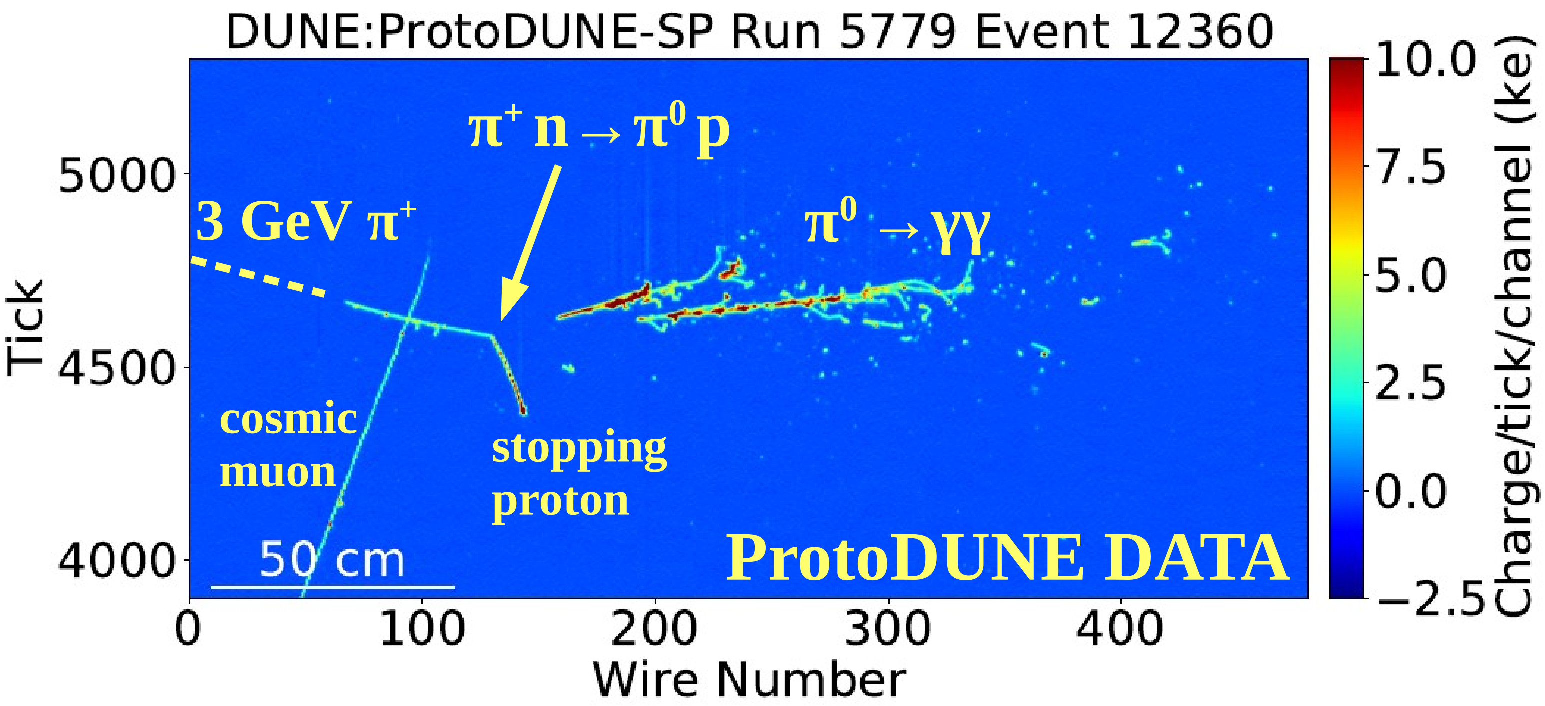




LArTPC technology provides exquisite resolution

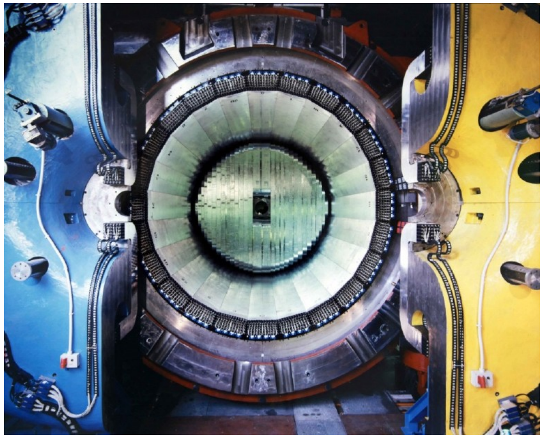
- ProtoDUNE is full scale in the drift direction
- Successful operation at CERN: low noise, stable HV, high purity → demonstrates LArTPC technology and DUNE design

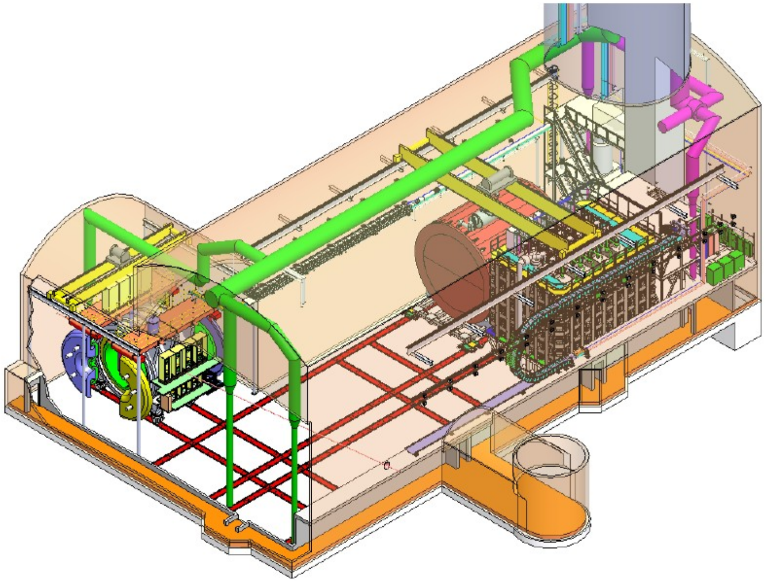


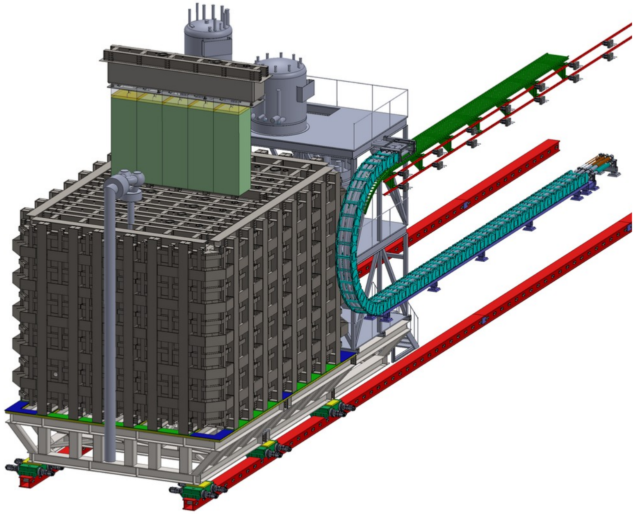


Near Detector: constraints to enable precision measurements

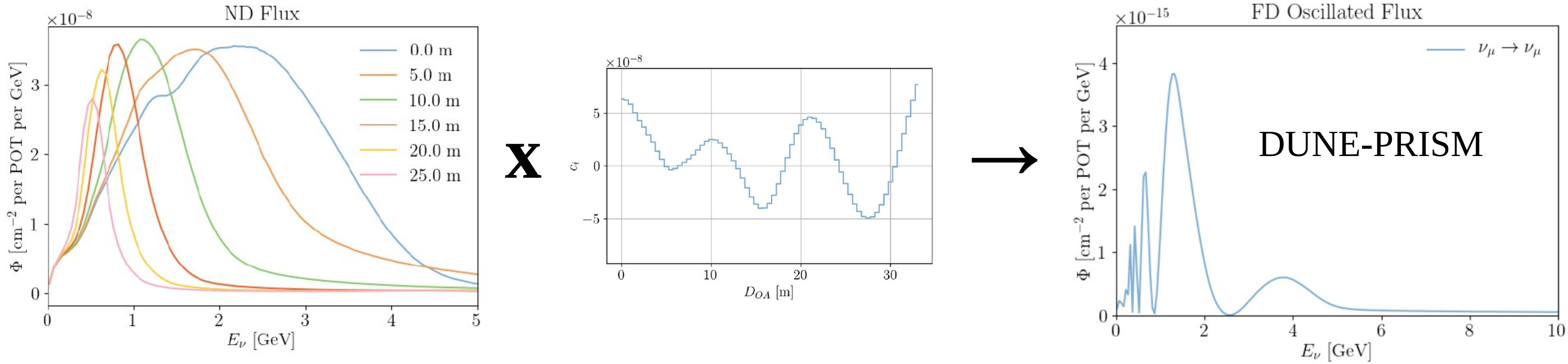
- LArTPC detector: same nuclear target and detector technology near & far
- Movement system to facilitate measurements in different neutrino fluxes
- On-axis magentized low-density tracker and spectrometer

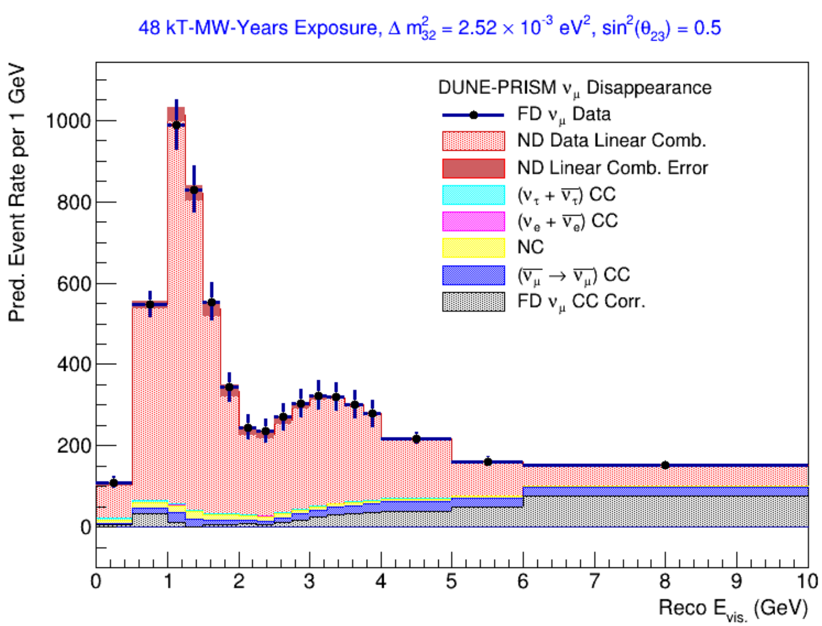






PRISM plays a critical role in enabling DUNE's precision





- FD flux ≠ ND flux → uncertainties in energy dependence of flux, cross sections
- ND flux changes with angle → take ND data in different fluxes → build linear combination to match FD *oscillated* spectra
- For LBL: robust analysis approach with very minimal dependence on interaction modeling
- Also extends dark matter sensitivity

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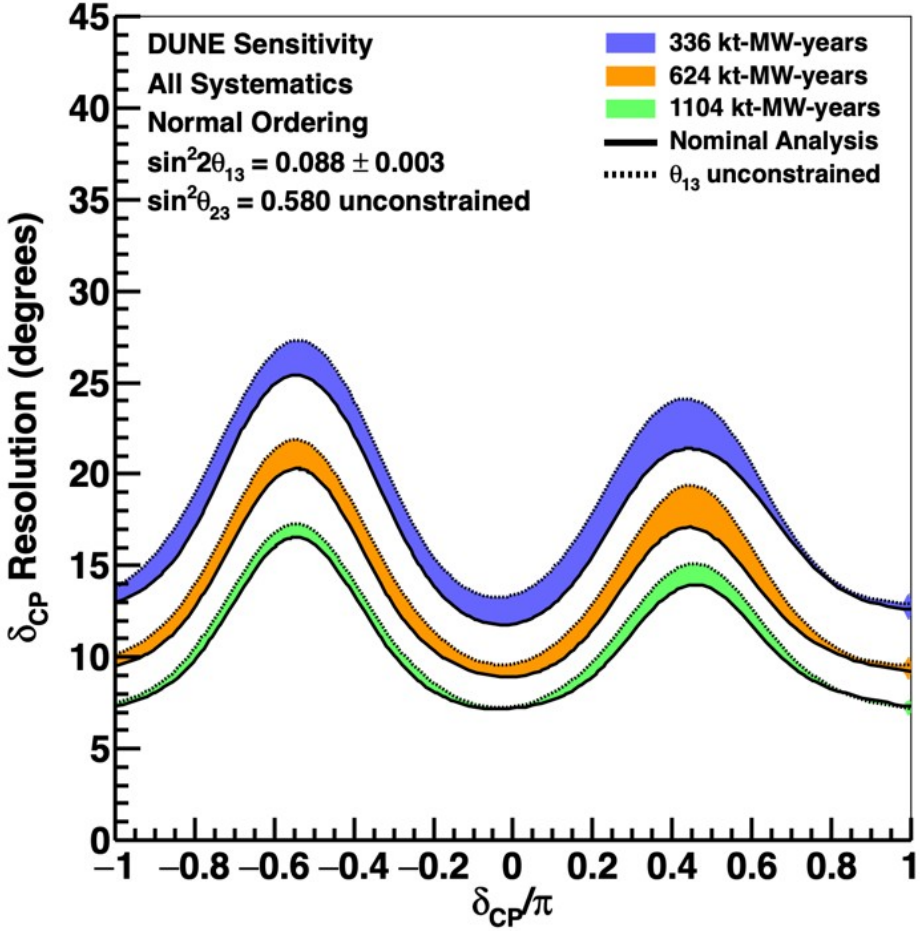
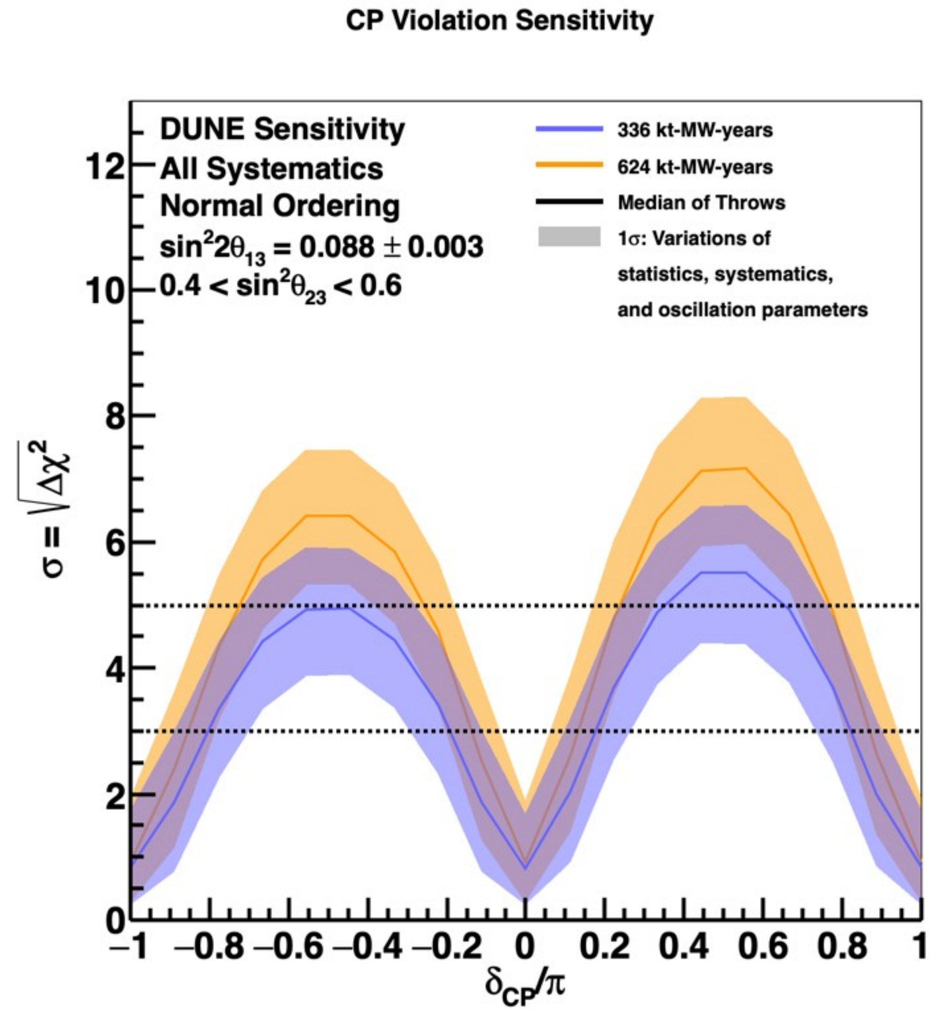
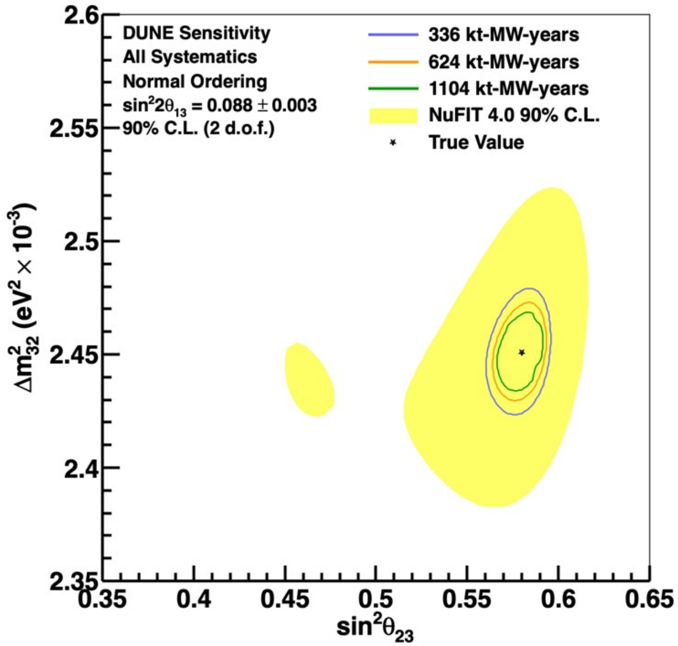
Physics potential: CP violation

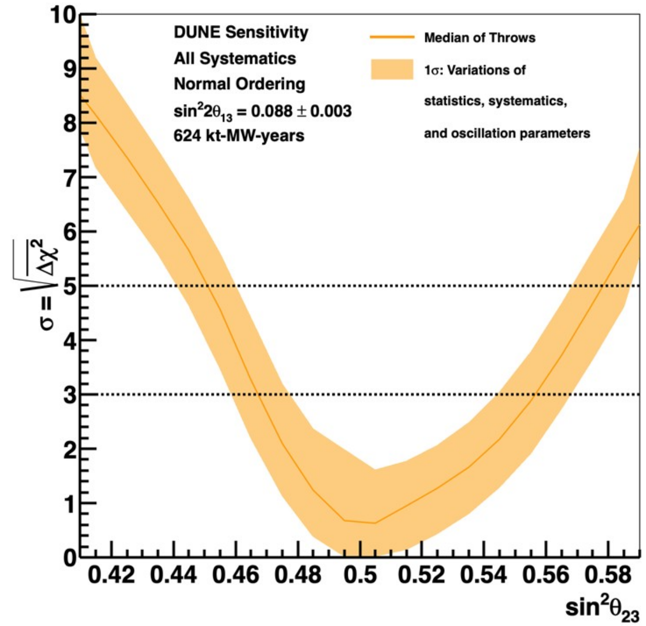


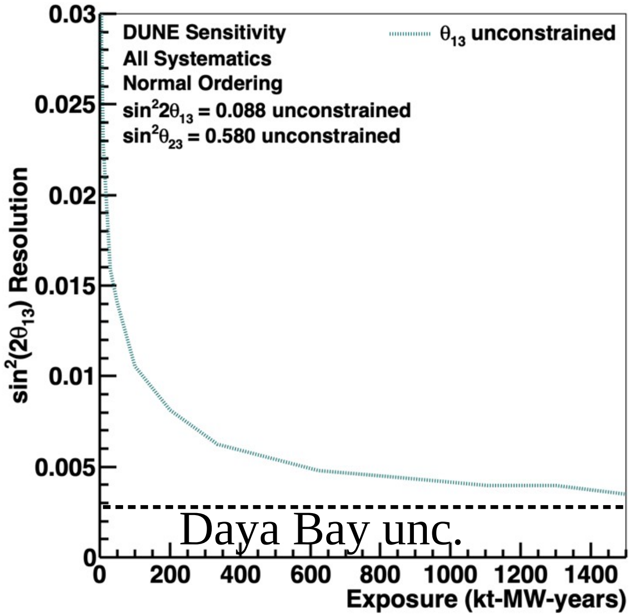


- 7° resolution to δ_{CP} without dependence on other experiments, discovery sensitivity to CP violation over a broad range of possible values

Physics potential: precision measurements, non-unitarity tests

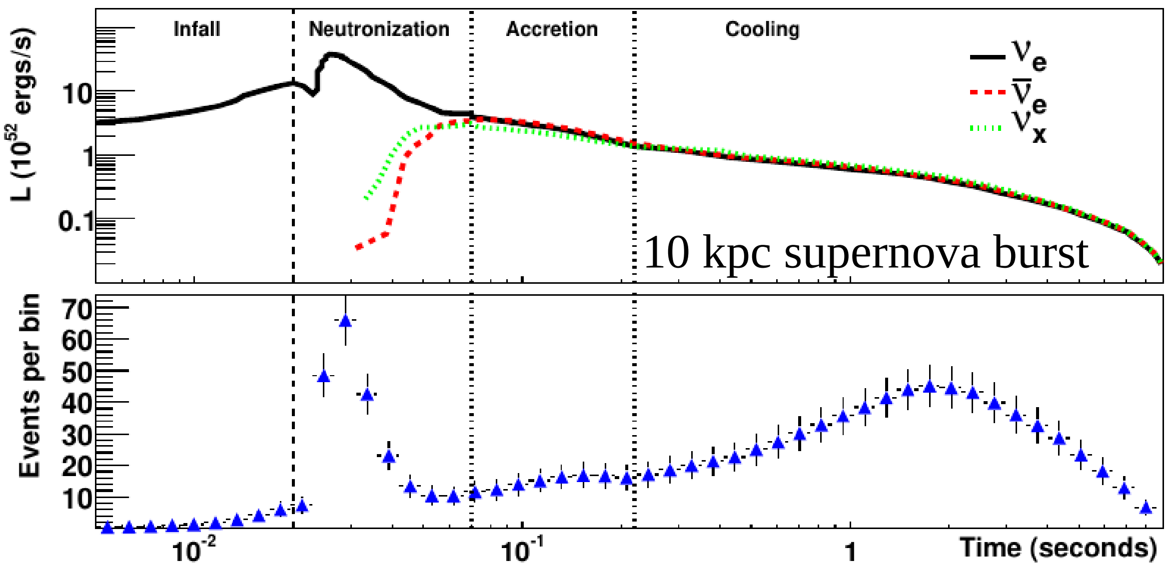


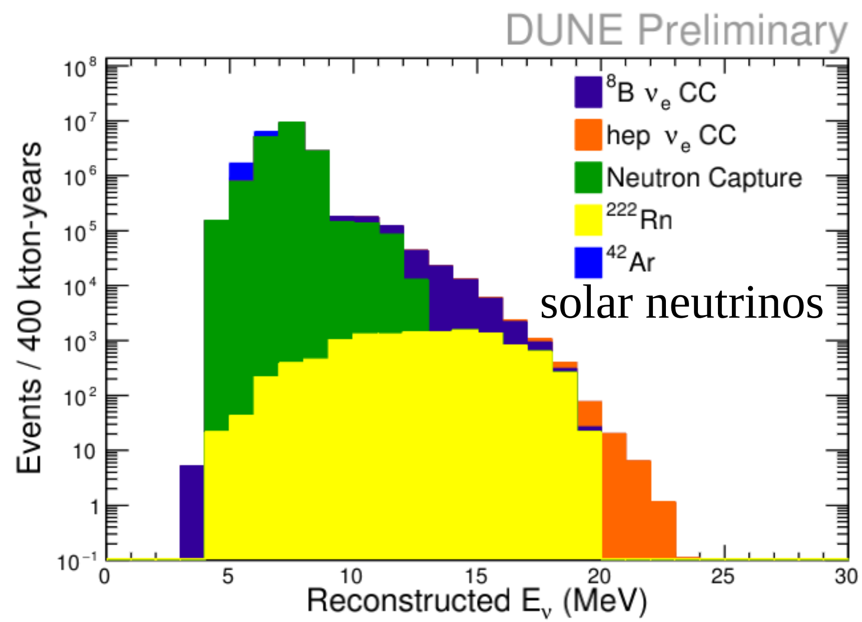




- Excellent on Δm^2_{32} and θ_{23}, including octant, and unique PRISM measurement technique that is less sensitive to systematic effects
- Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

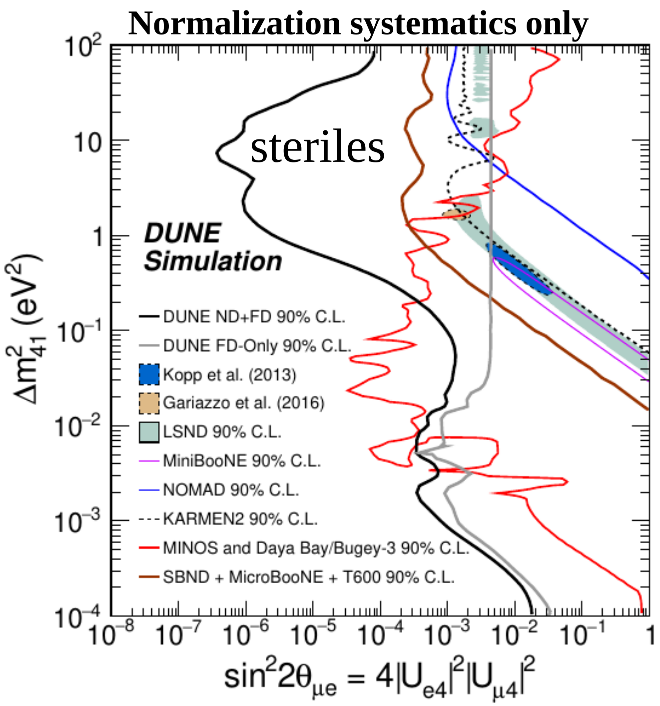
MeV-scale physics: unique opportunities with ν_es

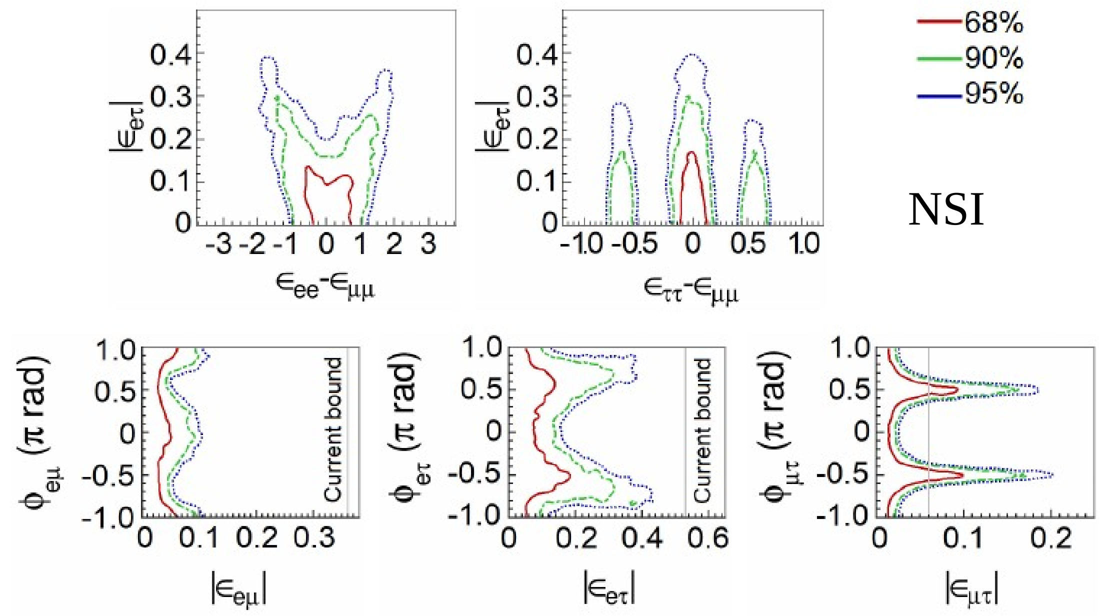




- Large detector + underground + low thresholds = sensitivity to supernova neutrinos
- Ar target makes DUNE uniquely sensitive to ν_e flux $\rightarrow$ measure neutronization burst, and highly complementary to other water/hydrocarbon detectors which measure predominantly $\bar{\nu}_e$
- Solar neutrino sensitivity to ^{8}B and discovery potential of hep flux, with capability to measure solar mixing parameters θ_{12} and Δm^2_{12}

Beyond the 3-flavor SM picture: non-standard oscillation effects



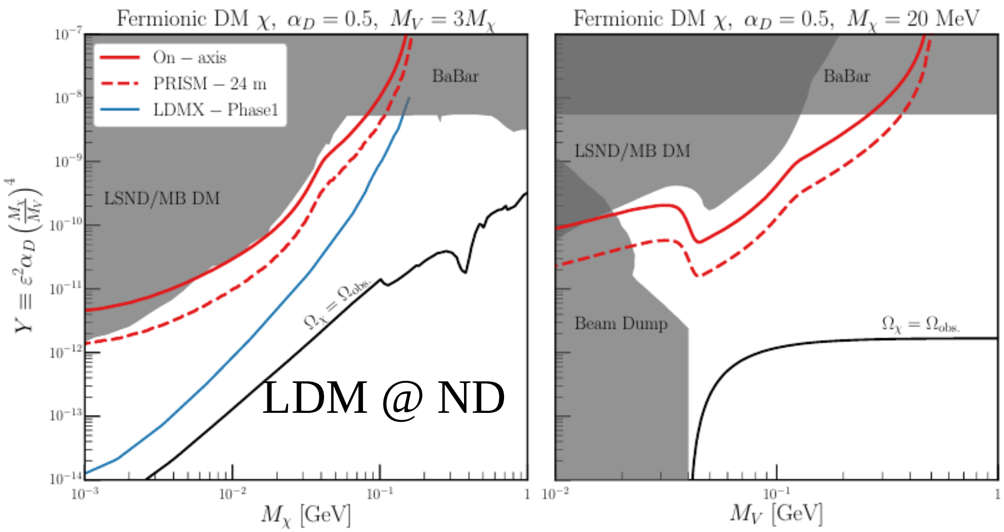


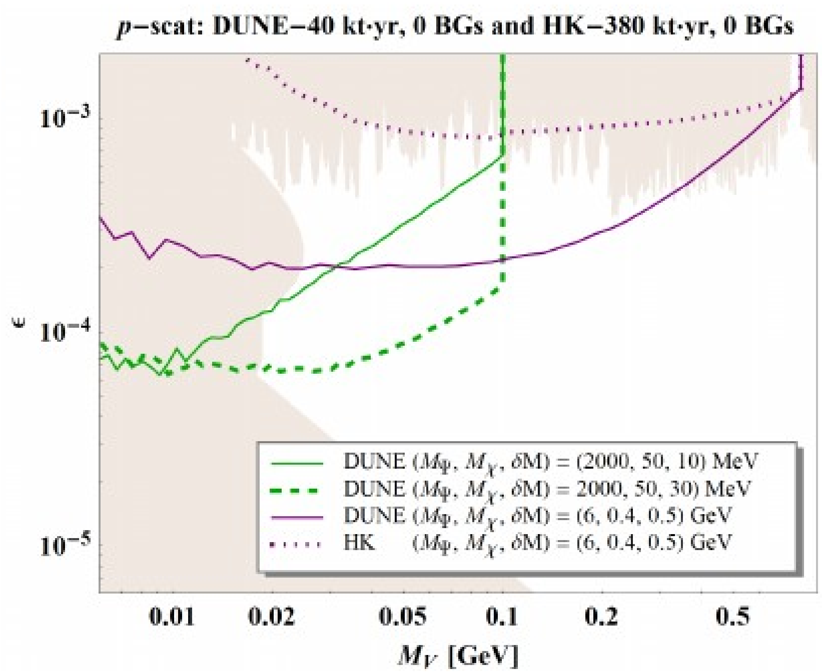
- Combination of ND + FD, and broad energy spectrum → broad Δm^2 coverage for sterile searches
- Both ND and FD have excellent μ/e resolution, and also ability to tag τ charged currents → complete 3-flavor test
  - Unique to DUNE: ability to run high-energy beam optimized for ν_τ appearance
- If inconsistency is observed, having multiple experiments at different baselines but the same L/E will be important for understanding the origin

DUNE is an excellent BSM physics experiment

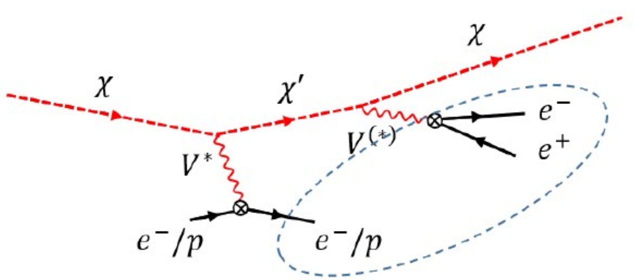
- For exotics of cosmic origin:
  - Large target mass
  - Deep underground → low background
  - Exquisite imaging, sensitivity to hadrons
- For exotics produced in hadron-nucleus collisions:
  - Very intense proton beam
  - Excellent detectors at ~500m, including a 150-ton detector (scattering), and a large, low density detector (decays)

Not just Neutrino Frontier: Dark matter at DUNE ND & FD





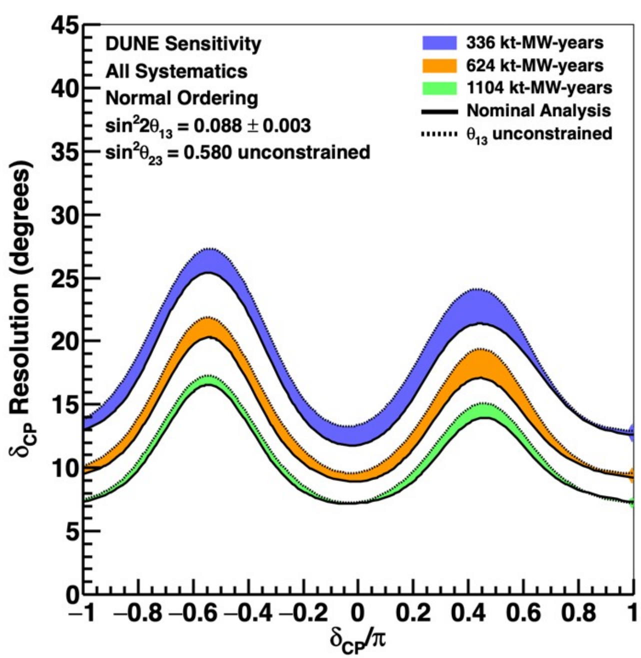
- ND-LAr is sensitive to DM produced in beamline, off-axis data helps to control SM backgrounds

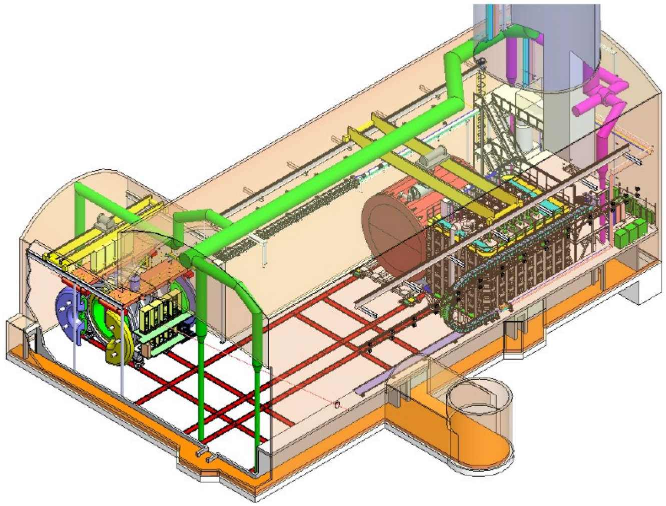


- FD is sensitive to inelastic dark matter of cosmic origin

Why DUNE?
Precision, robustness, breadth

- DUNE will make the strongest, most robust mass ordering measurement, regardless of δ_{CP} and θ_{23}, and regardless of the performance of other experiments
- DUNE will make the most precise measurement of δ_{CP}, no matter the true values of unknown parameters, and without relying on other experiments





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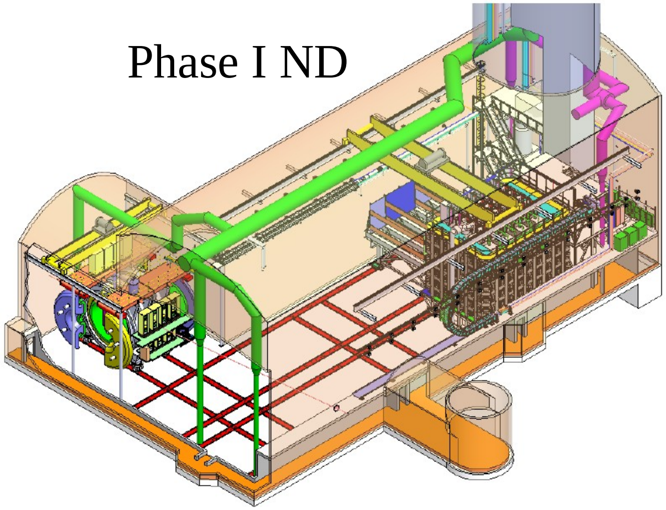
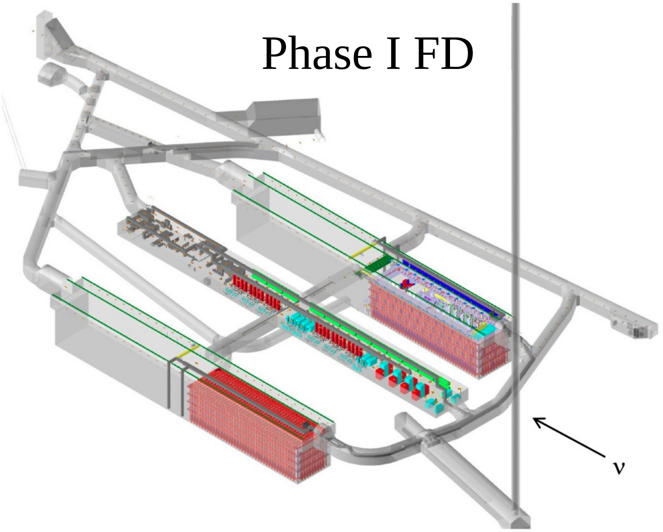
Getting there: phased construction

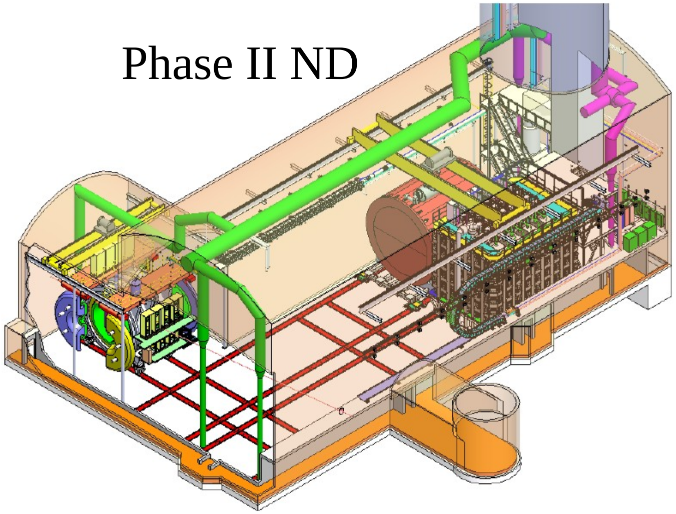
- As was always envisioned, DUNE construction is phased
- DUNE Phase I:
  - Neutrino beam with 1.2 MW intensity
  - Two 17kt LAr TPC FD modules, but underground facilities and cryogenic infrastructure to support four modules
  - Near detector: ND-LAr + TMS (movable), SAND
- Construction schedule is funding limited → changes to the funding profile have a significant impact on the schedule
- Current CD1-RR schedule has FD 1&2 taking physics data in 2029, beamline and ND by 2031
- The US DOE scope of Phase I was reviewed last week in CD1-RR

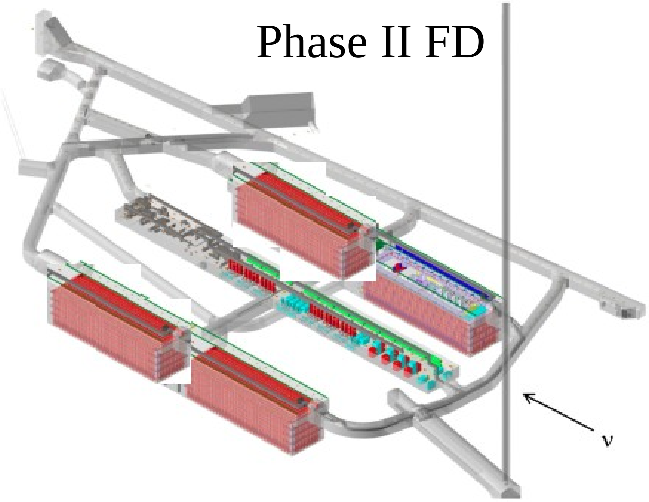




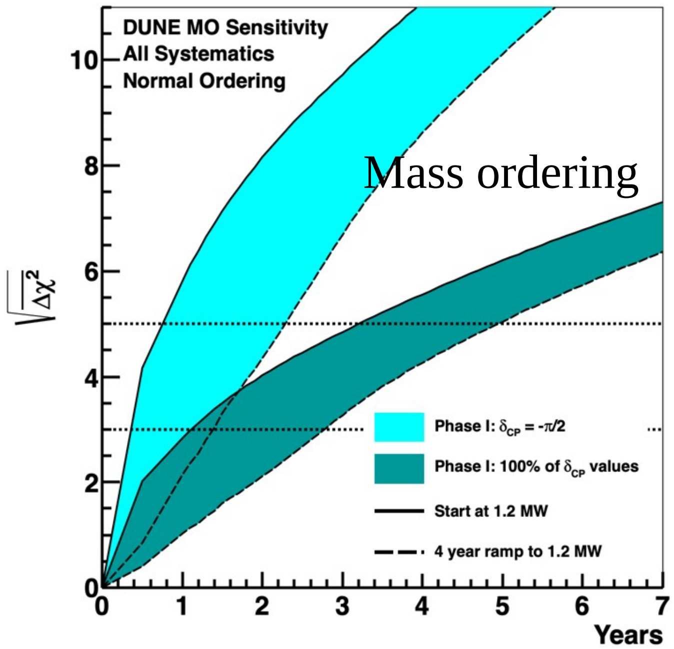
Getting there: Phase II upgrades

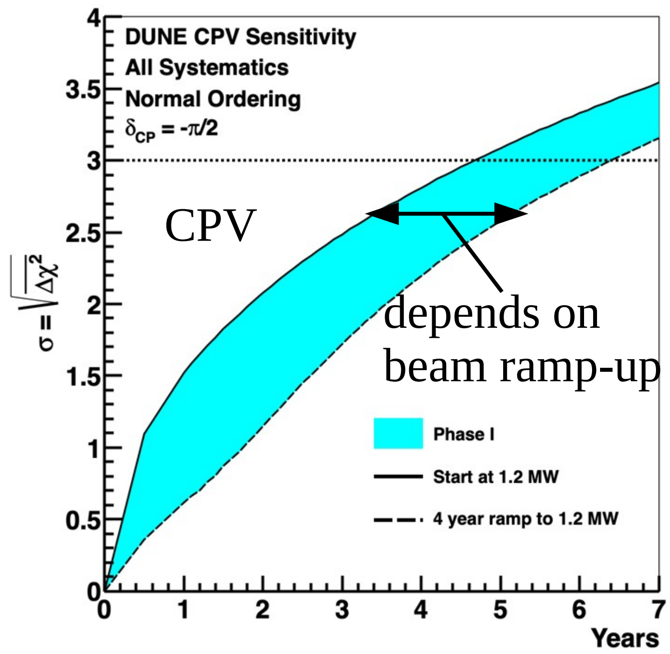
- DUNE Phase II:
  - Fermilab proton beam upgrade to 2.4 MW
  - Two additional 17kt FD modules
  - Near detector: ND-LAr + MCND (movable), SAND
- Beam upgrade benefits all Fermilab experiments: dedicated session Wednesday on Booster replacement options (AF2-AF5-NF)
- ND upgrade is driven by improved performance at reducing systematics → talk on ND-GAr in Wednesday session (NF)
- Opportunities to expand physics scope with 3rd & 4th FD modules: dedicated session Wednesday (NF)

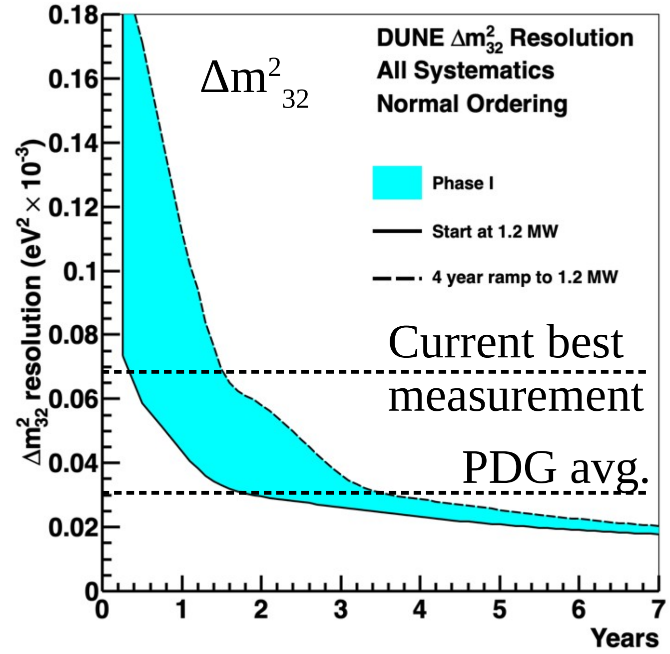




DUNE Phase I: world-leading MO, sensitivity to maximal CPV







- Phase I will do world-class long-baseline neutrino oscillation physics:
  - Only experiment with 5σ mass ordering capability regardless of true parameters
  - Discovery of CPV at 3σ if CP violation is large
  - High precision disappearance parameters, (e.g. surpass current Δm^2_{32} error in ~2-3 years)

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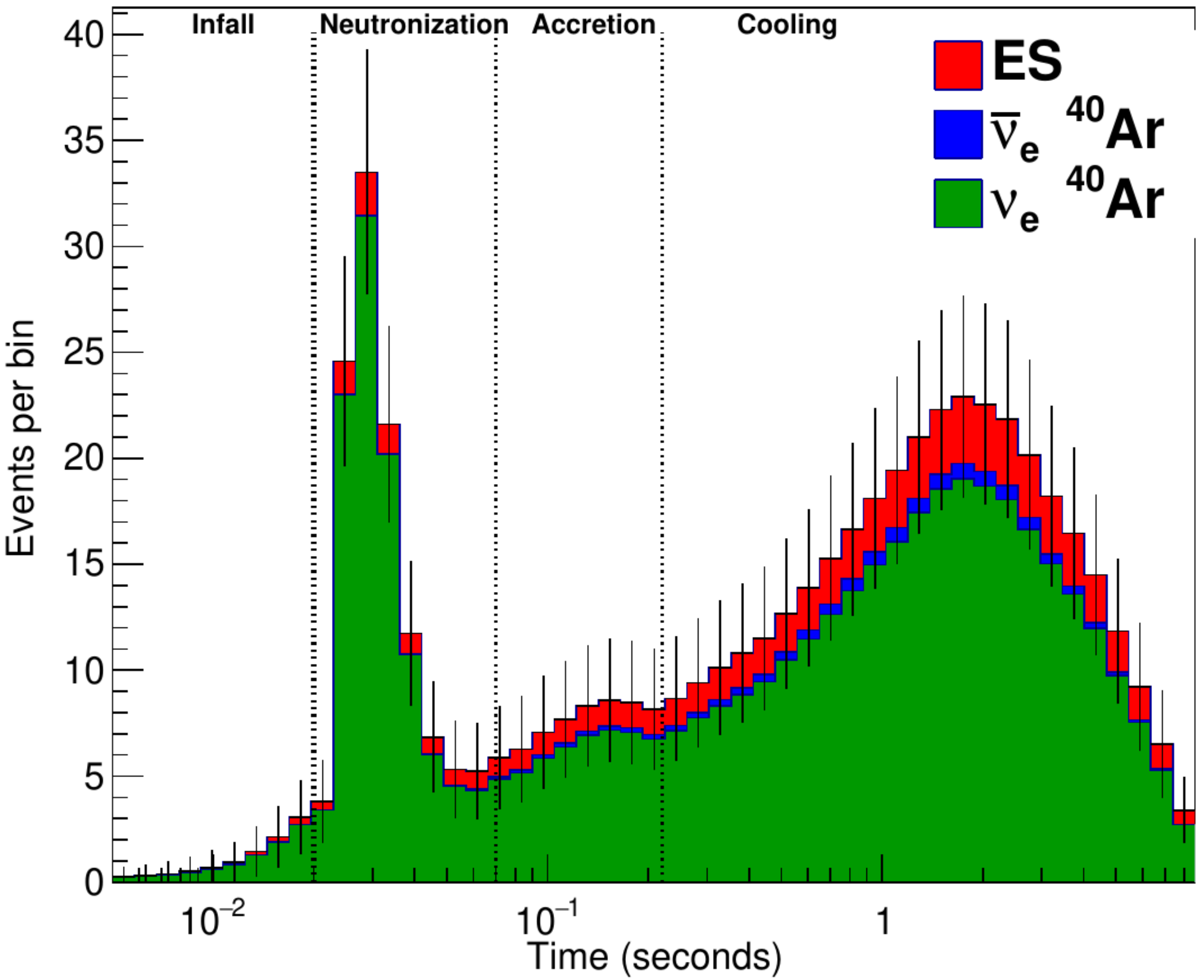
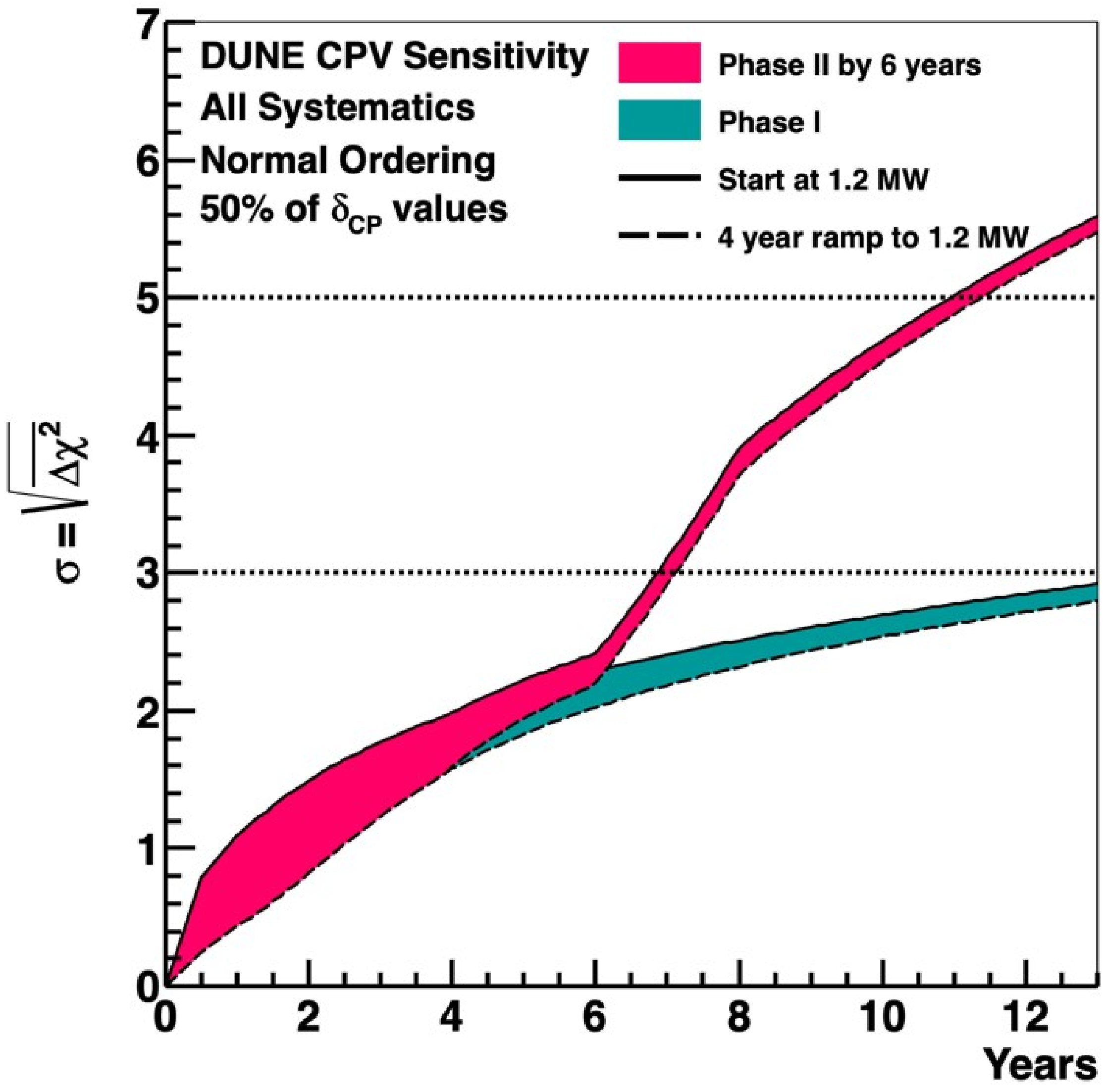
Non-beam physics with Phase I



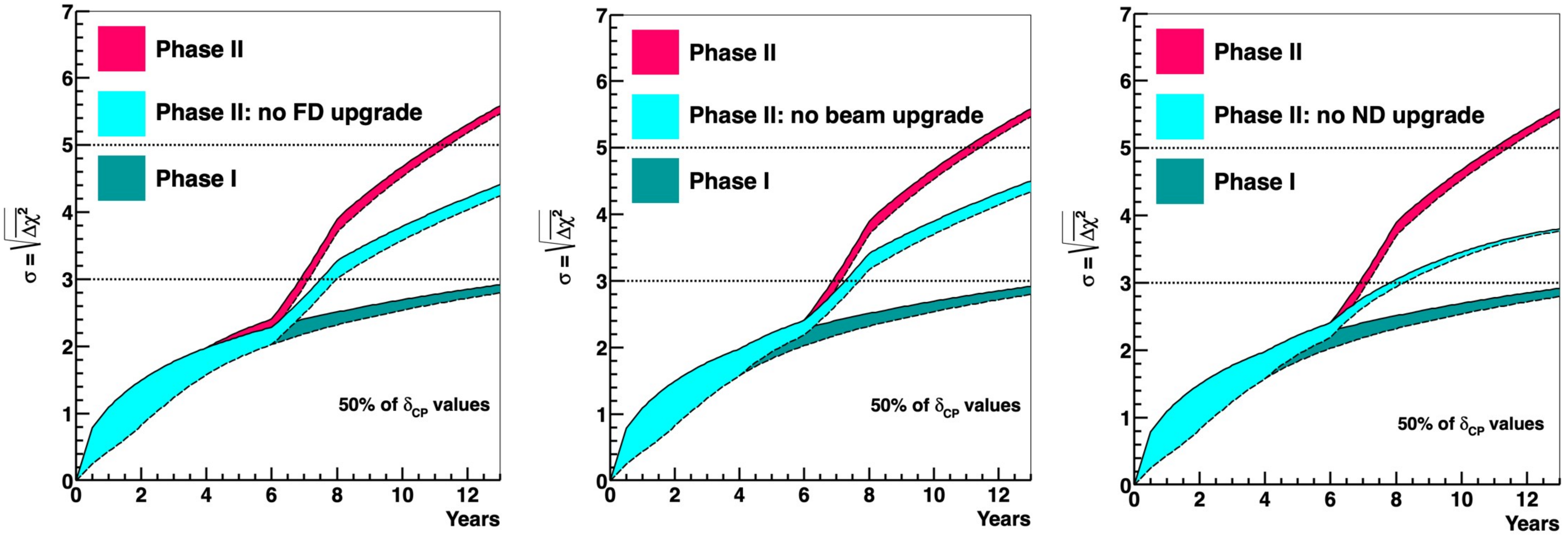
- DUNE is already very sensitive to a galactic supernova burst with Phase I
- Shown is the time distribution for a hypothetical 10 kpc SNB with 20 kton fiducial mass

DUNE's long-term goals require full scope (Phase II)



- DUNE needs full Phase II scope to achieve precision physics goals defined in P5 report
- CPV sensitivity for 50% of δ_{CP} values shown, precision measurements are similarly affected
- Timescale for precision physics is driven by achieving full scope on aggressive timescale, early ramp-up is not as relevant

Phase II requires 40kt, 2.4MW, upgraded near detector

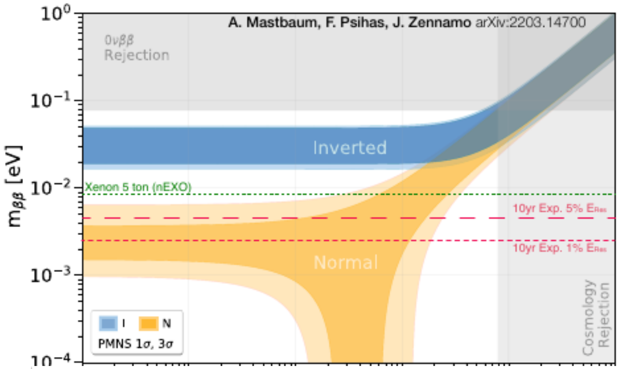


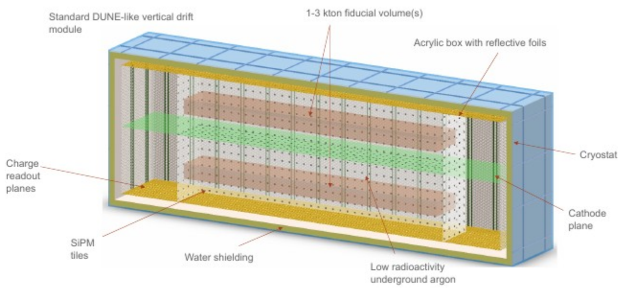
- To achieve the precision physics goals, including CPV sensitivity for a broad range of δ_{CP} values, all three upgrades are required
- Plots show the effect of removing one of them, resulting in a significant loss of sensitivity

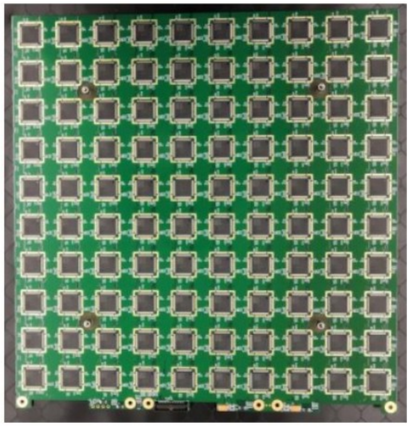
Module(s) of opportunity

- Technologies for FD-3 and FD-4 are not yet established → opportunities to expand the physics reach of DUNE
- Many exciting ideas from the community
- Dedicated MoO session on Wednesday morning
- MoO Workshop open to community: 2-4 November in Valencia, Spain: https://congresos.adeituv.es/dune_science/ficha.en.html

MoO: expanding scope while preserving core physics







- Additional 20 kton fiducial mass is critical for core oscillation physics, low energy and BSM goals of DUNE – it is part of Phase II
- It is a priority for DUNE that FD-3 and FD-4 meet the needs of the LBL program, including the systematic constraints of the Near Detector
- We welcome ideas for expanding the scope → the broader HEP community should decide which scope expansions to pursue

DUNE's message to Snowmass

Snowmass 2021

- DUNE Phase I should be realized in this decade
  - Every effort should be made to resolve funding profile issues that could delay first physics results into the 2030s
- Realization of the full DUNE Phase II should be the highest priority
  - Pursue upgrades aggressively such that the full DUNE scope is achieved in the 2030s
- R&D work to design detectors that broaden the physics scope while fulfilling the core goals of DUNE should be supported

The 2014 P5 report emphasized the importance of LBNF/DUNE

Recommendation 12: In collaboration with international partners, develop a coherent short- and long-baseline neutrino program hosted at Fermilab.

For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range of possible values of the unknown CP-violating phase δ_{CP}. By current estimates, this goal corresponds to an exposure of 600 kt*MW*yr assuming systematic uncertainties of 1% and 5% for the signal and background, respectively. With a wideband neutrino beam produced by a proton beam with power of 1.2 MW, this exposure implies a far detector with fiducal mass of more than 40 kilotons (kt) of liquid argon (LAr) and a suitable near detector. **The minimum requirements to proceed are the identified capability to reach an exposure of at least 120 kt*MW*yr by the 2035 timeframe, the far detector situated underground with cavern space for expansion to at least 40 kt LAr fiducial volume, and 1.2 MW beam power upgradable to multi-megawatt power. The experiment should have the demonstrated capability to search for supernova (SN) bursts and for proton decay, providing a significant improvement in discovery sensitivity over current searches for the proton lifetime.**

Recommendation 13: Form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S. To proceed, a project plan and identified resources must exist to meet the minimum requirements in the text. LBNF is the highest-priority large project in its timeframe.

The PIP-II project at Fermilab is a necessary investment in physics capability, enabling the world's most intense neutrino beam, providing the wideband capability for LBNF, as well as high proton intensities for other opportunities, and it is also an investment in national accelerator laboratory infrastructure. The project has already attracted interest from several potential international partners.

Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino facility.

DUNE is emphasized in 2020 European Strategy

European Strategy Update

Major developments from the 2013 Strategy

B. The existence of non-zero neutrino masses is a compelling sign of new physics. The worldwide neutrino physics programme explores the full scope of the rich neutrino sector and commands strong support in Europe. Within that programme, the Neutrino Platform was established by CERN in response to the recommendation in the 2013 Strategy and has successfully acted as a hub for European neutrino research at accelerator-based projects outside Europe. ***Europe, and CERN through the Neutrino Platform, should continue to support long baseline experiments in Japan and the United States. In particular, they should continue to collaborate with the United States and other international partners towards the successful implementation of the Long-Baseline Neutrino Facility (LBNF) and the Deep Underground Neutrino Experiment (DUNE).***

DUNE is well on its way to achieving Phase I

- Assembled international collaboration of >1300 scientists and engineers from 37 countries + CERN (and counting)
- Built, operated, and analyzed ProtoDUNE large-scale prototype at CERN, demonstrating the detector design will work
- Produced detailed technical design report of the Far Detector SP module and physics program, and conceptual design report for Near Detector
- Far site excavation, preparation for beamline and near site conventional facilities underway
- **DUNE is well on its way to Phase I → let's finish what we started**

UNIVERSITY of ROCHESTER

Thank You

DUNE Collaboration, May 2022, Fermilab