DUNE: science and status

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SURF User Association annual meeting
26 October, 2022

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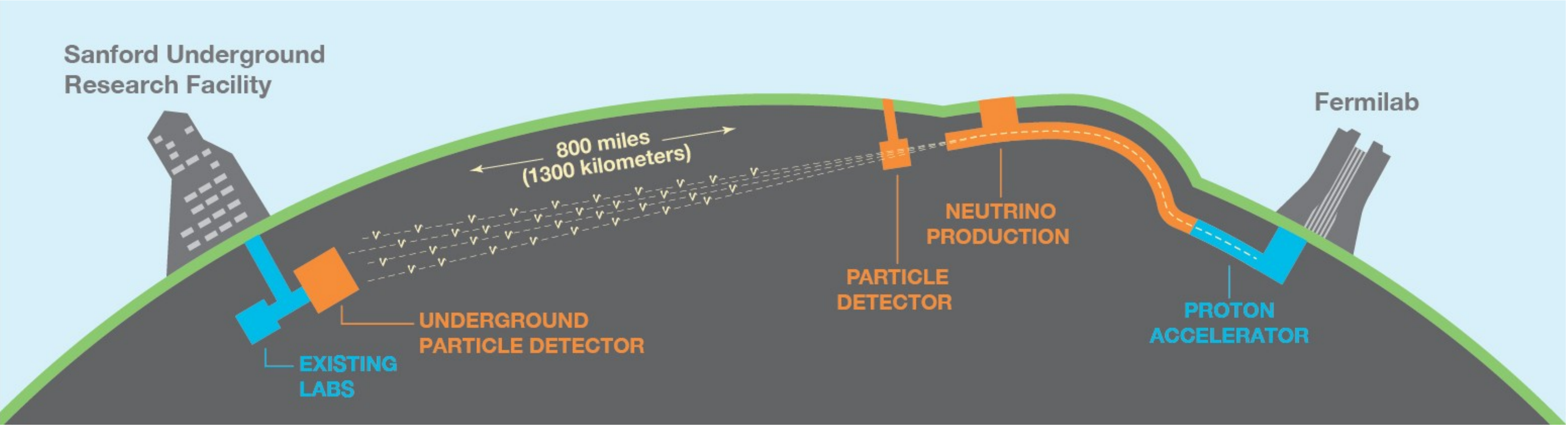
DUNE

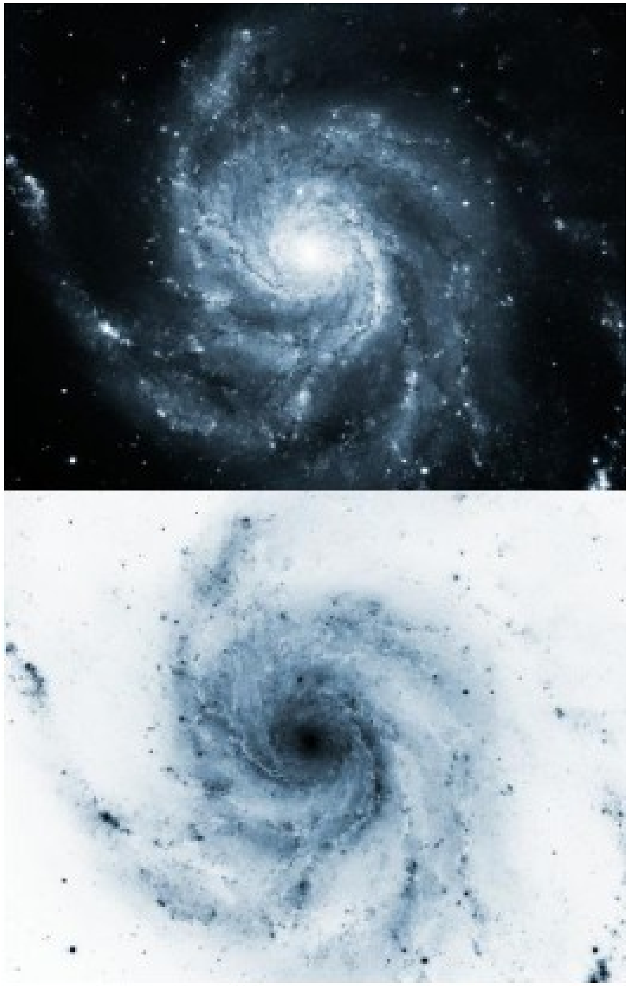
DEEP UNDERGROUND NEUTRINO EXPERIMENT



- 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

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?



2015 P5 recommendation: Pursue the physics of neutrino mass

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

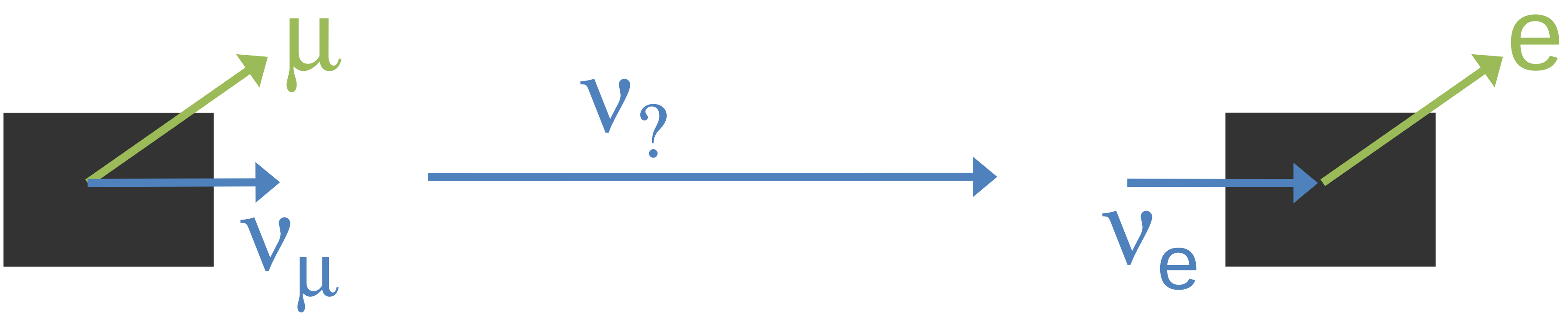
For a long-baseline oscillation experiment, based on the science Drivers and what is practically achievable in a major step forward, we set as the goal a mean sensitivity to CP violation[2] of better than 3σ (corresponding to 99.8% confidence level for a detected signal) over more than 75% of the range 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.

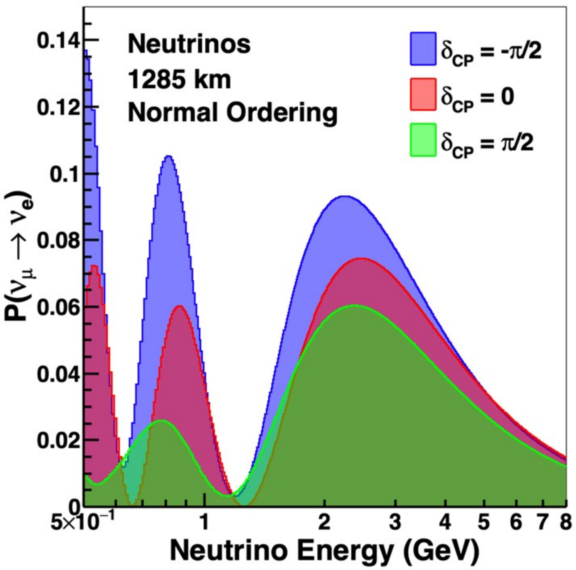
Recommendation 14: Upgrade the Fermilab proton accelerator complex to produce higher intensity beams. R&D for the Proton Improvement Plan II (PIP-II) should proceed immediately, followed by construction, to provide proton beams of >1 MW by the time of first operation of the new long-baseline neutrino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

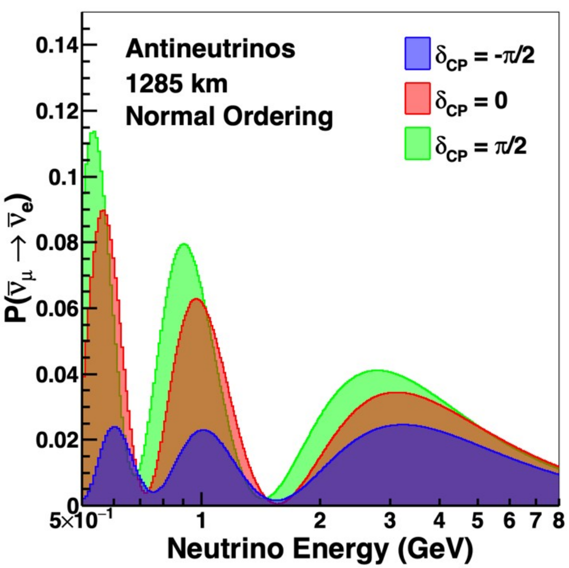
Measuring neutrino oscillations



- Produce a beam of muon (anti-)neutrinos
- Allow them to travel a long distance, L
- Measure electron (anti-)neutrinos in the Far Detector, including measuring the energy, E → oscillations depend on L/E
- Very roughly:
  - Number of "appeared" ν_e → amount of neutrino mixing
  - Energy (L/E) of ν_e → difference in neutrino masses
  - Asymmetry between $\nu_e/\bar{\nu}_e$ → CP violation & mass ordering

Ingredients of a precision neutrino oscillation experiment

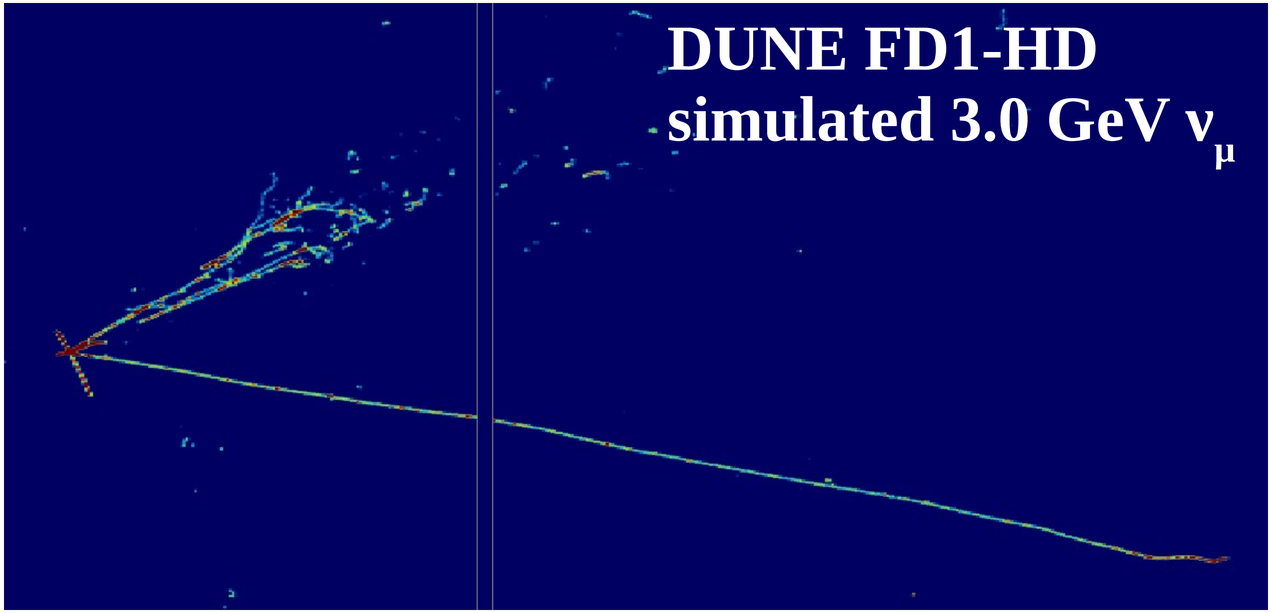


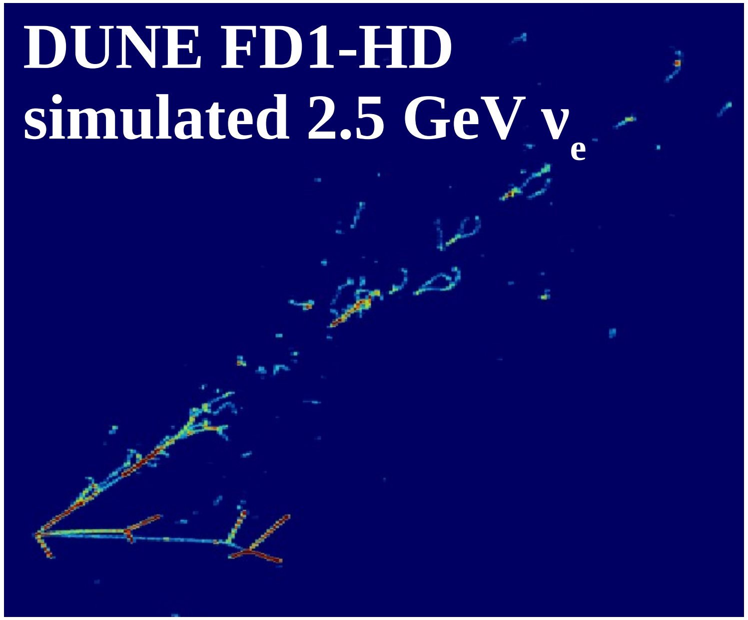


- DUNE measures $\nu_\mu \rightarrow \nu_e$ transitions of neutrinos and antineutrinos, as a function of L/E, over more than a full oscillation period
- Large asymmetry between neutrinos and antineutrinos due to the matter effect, smaller one due to CP violation
- This requires:
  - Very intense beam, switchable between $\nu/\bar{\nu}$
  - Massive far detector, that can precisely measure the neutrino energy
  - Flux, cross section, detector uncertainty constraints from near detector

LArTPC technology provides exquisite imaging & resolution

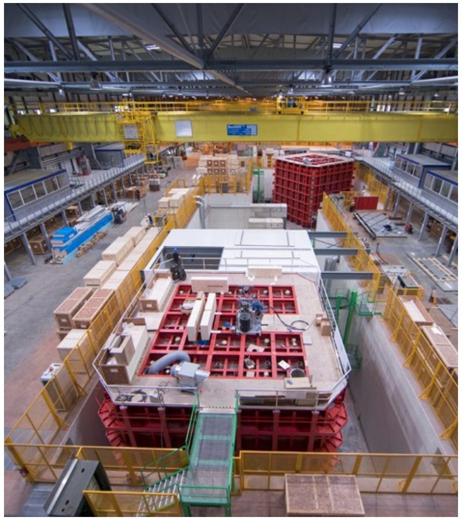
- Clean separation of ν_μ and ν_e charged currents
- Precise energy reconstruction over broad E_ν range
- Low thresholds: sensitivity to few-MeV neutrinos, charged hadrons, low-energy BSM signatures

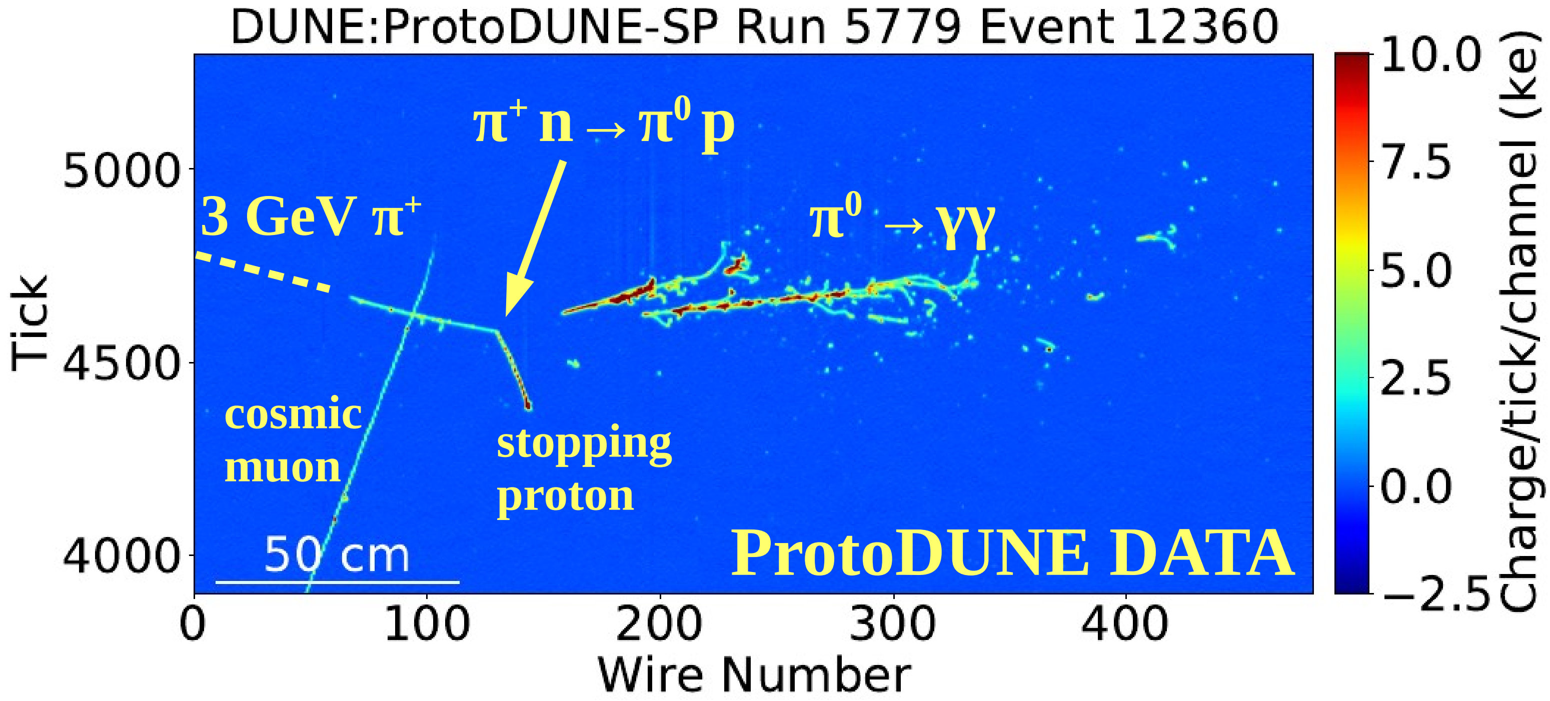




LArTPC technology is demonstrated: ProtoDUNE

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





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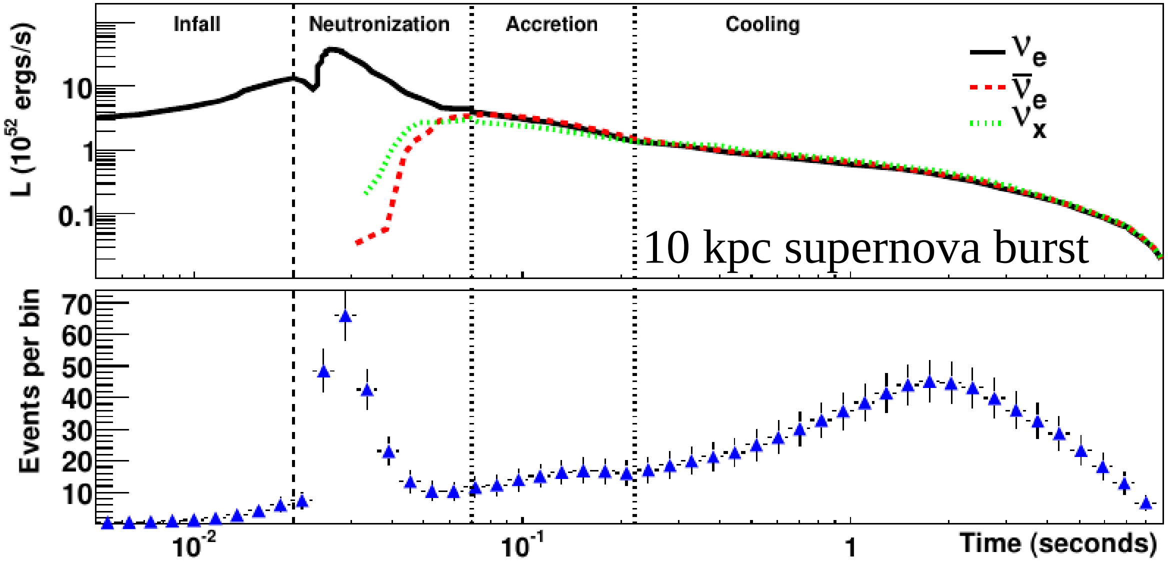
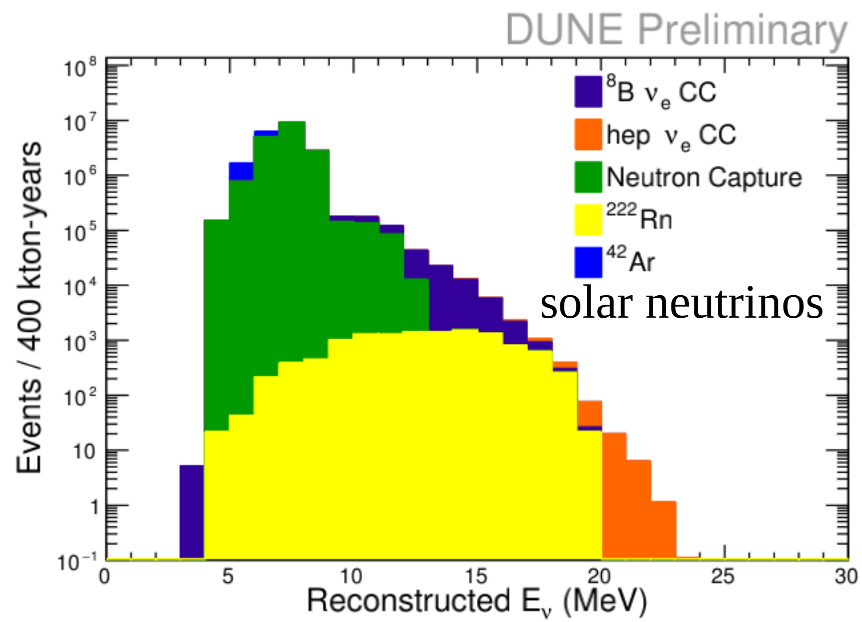
MeV-scale physics: unique opportunities with ν_es

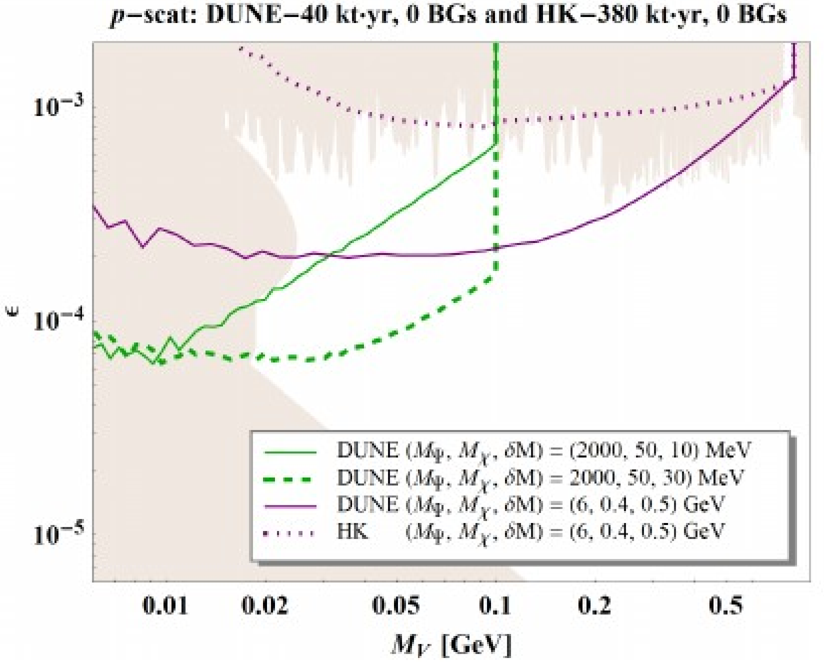


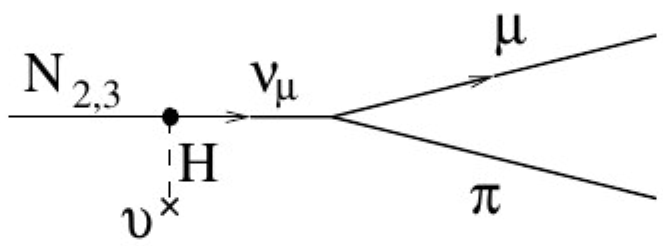


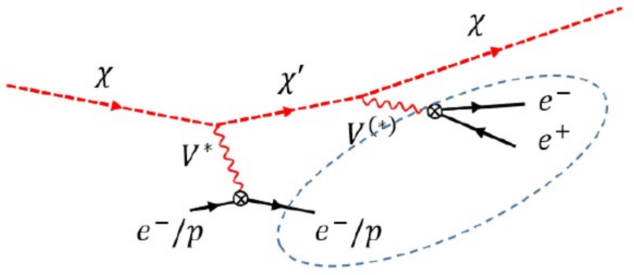
- Large detector + deep underground + low thresholds = sensitivity to supernova neutrinos
- Ar target makes DUNE uniquely sensitive to ν_e flux → measure neutronization burst, and highly complementary to other water/hydrocarbon detectors which measure predominantly $\bar{\nu}_e$
- Solar neutrino sensitivity to ^{8}B and discovery potential of hep flux

Not just neutrinos: Dark sector searches at DUNE

- Inelastic dark matter *scattering* at the Far Detector
- Boosted dark matter *production* in the beam line, detected in the Near Detector by *scattering* or *decay*







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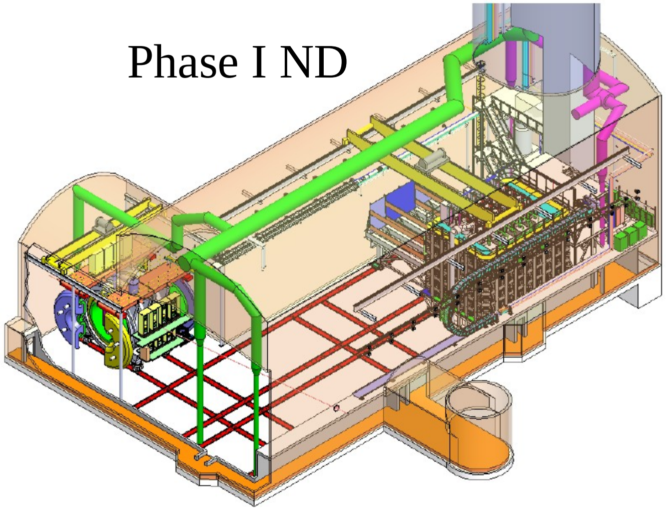
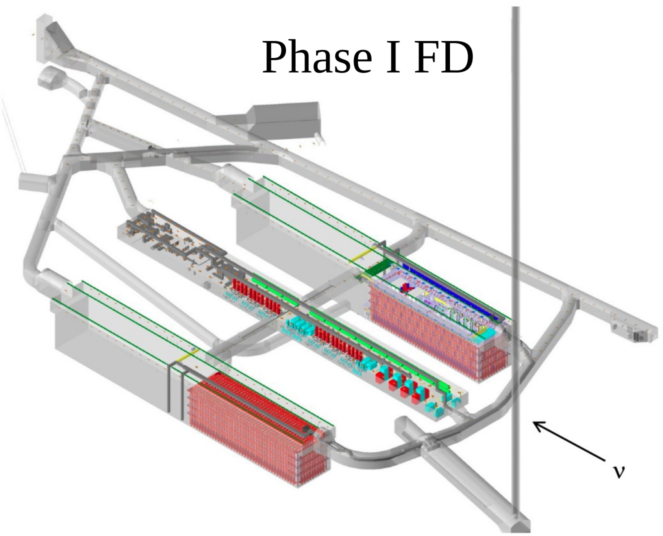
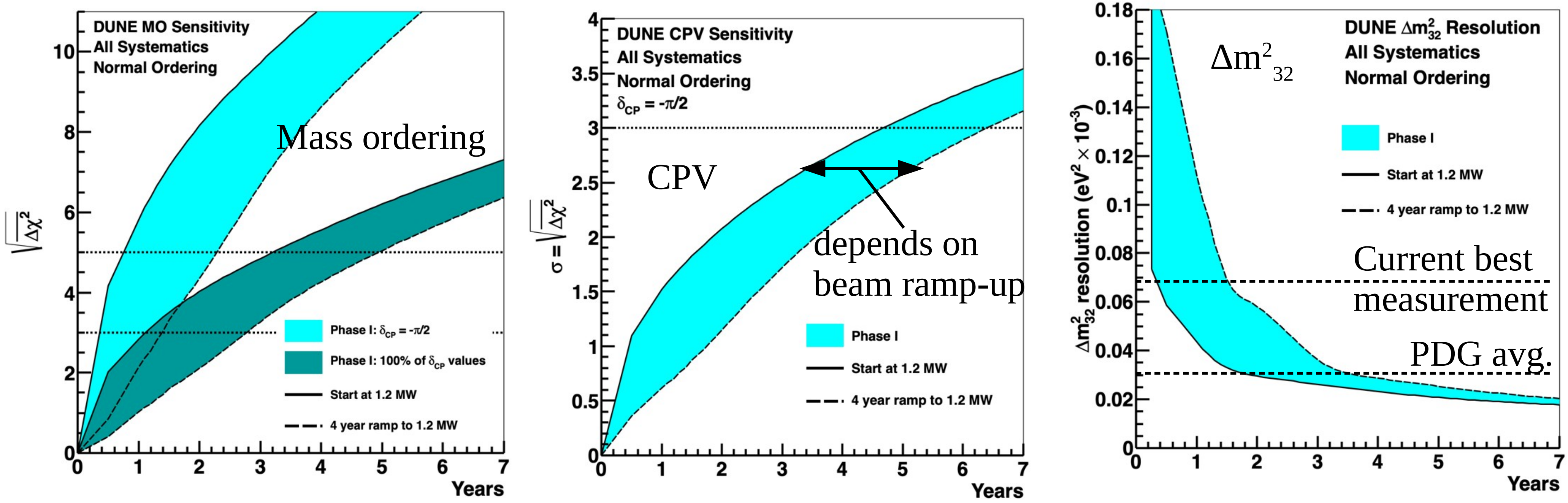
Building LBNF/DUNE: Phase I

- As was always envisioned, DUNE construction will be phased
- Phase I:
  - Full LBNF: beamline & near site at Fermilab, cavern space & infrastructure for *four* FD modules at SURF
  - 1.2 MW neutrino beam
  - Two FD LArTPC modules
  - Phase I Near Detector





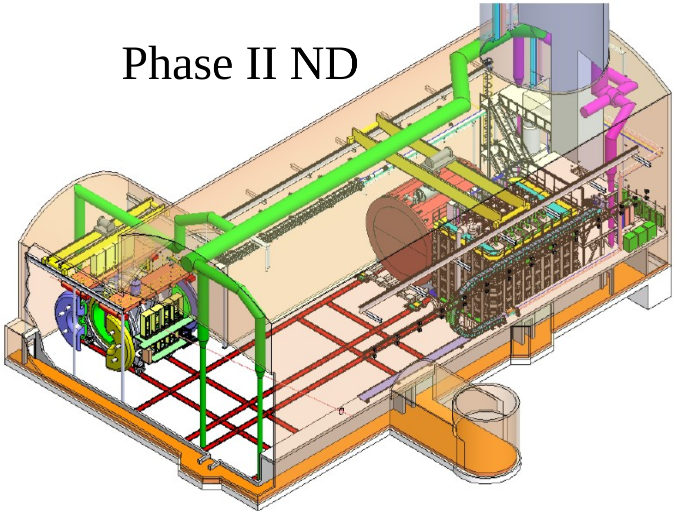
DUNE Phase I: definitive MO, sensitivity to maximal CPV

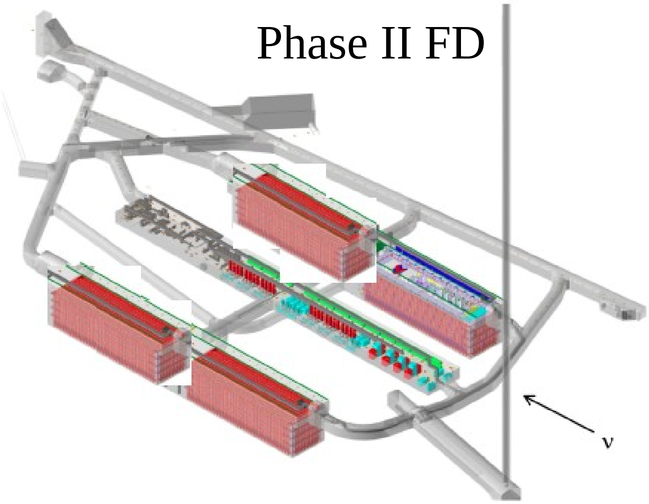


- Phase I will do world-class long-baseline neutrino oscillation physics:
  - Only experiment with 5σ mass ordering capability regardless of true parameters
  - Discovery of CPV at 3σ if CP violation is large
  - High precision disappearance parameters, (e.g. surpass current Δm^2_{32} error in ~2-3 years)

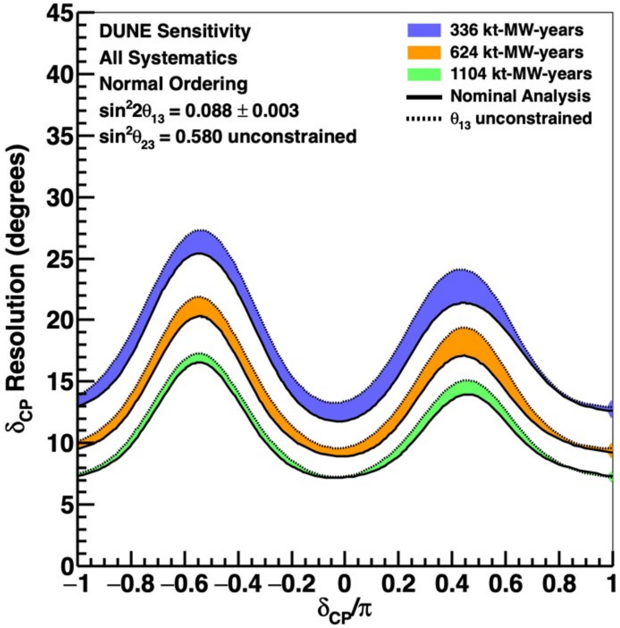
Building LBNF/DUNE: Phase II

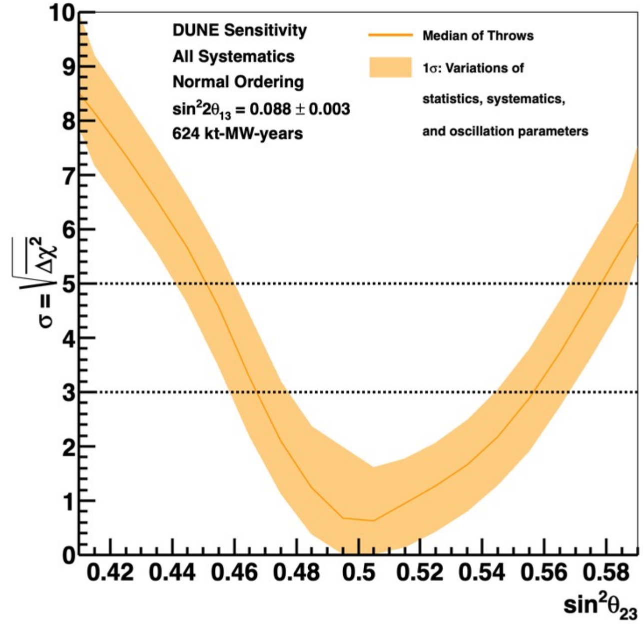
- Phase II upgrades use conventional facilities and infrastructure that are part of the Phase I DUNE project
- Phase II:
  - Fermilab proton beam upgrade to 2.4 MW
  - Two additional 17kt FD modules
  - Near detector upgrade
- Beamline and ND upgrades will use existing infrastructure, except for target
- Proton beam upgrade will benefit all Fermilab experiments, and potentially enable new ideas

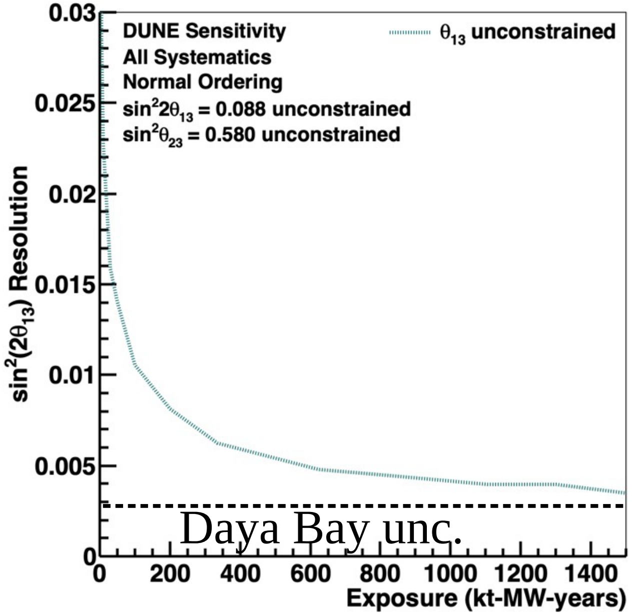




DUNE Phase II: world-leading precision, test 3-flavor paradigm







- Measure δ_{CP} to 6-16° → >5σ CPV over >50% of δ_{CP} values
- Measure θ_{23} and Δm^2_{32} → resolve θ_{23} octant if non-maximal
- Measure θ_{13} with precision comparable to reactors → indirect test of PMNS non-unitarity

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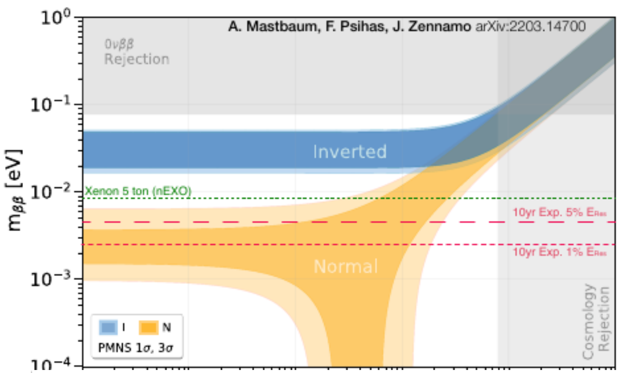
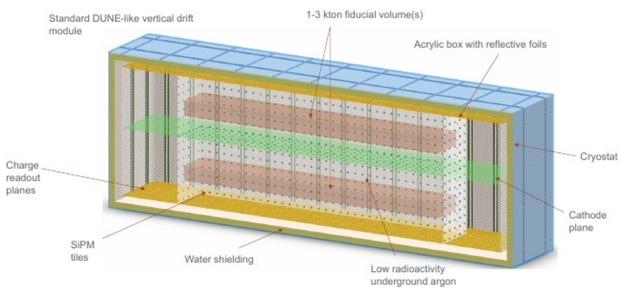
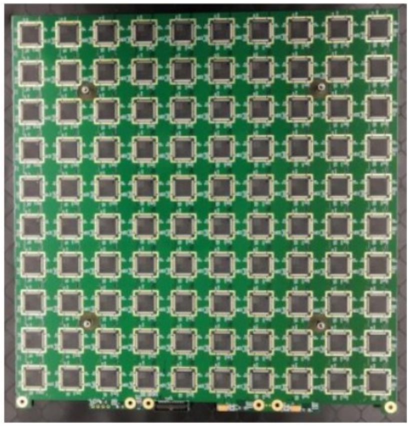
FD-3 and FD-4
“Module of Opportunity”







- Additional 20 kton FD mass is critical for DUNE’s core oscillation physics goals
- One possibility is to reuse the FD-1 or FD-2 design
- Ideas for design modifications that ***preserve core DUNE physics*** and also ***expand physics scope*** are being explored
- Ideas include using underground argon and additional shielding to enhance low-energy program, Xe doping for 0νββ reach, pixelated charge readout LArTPC, non-LAr-based detectors, and much more
- Workshop next week in Valencia, Spain
  https://congresos.adeituv.es/dune_science/

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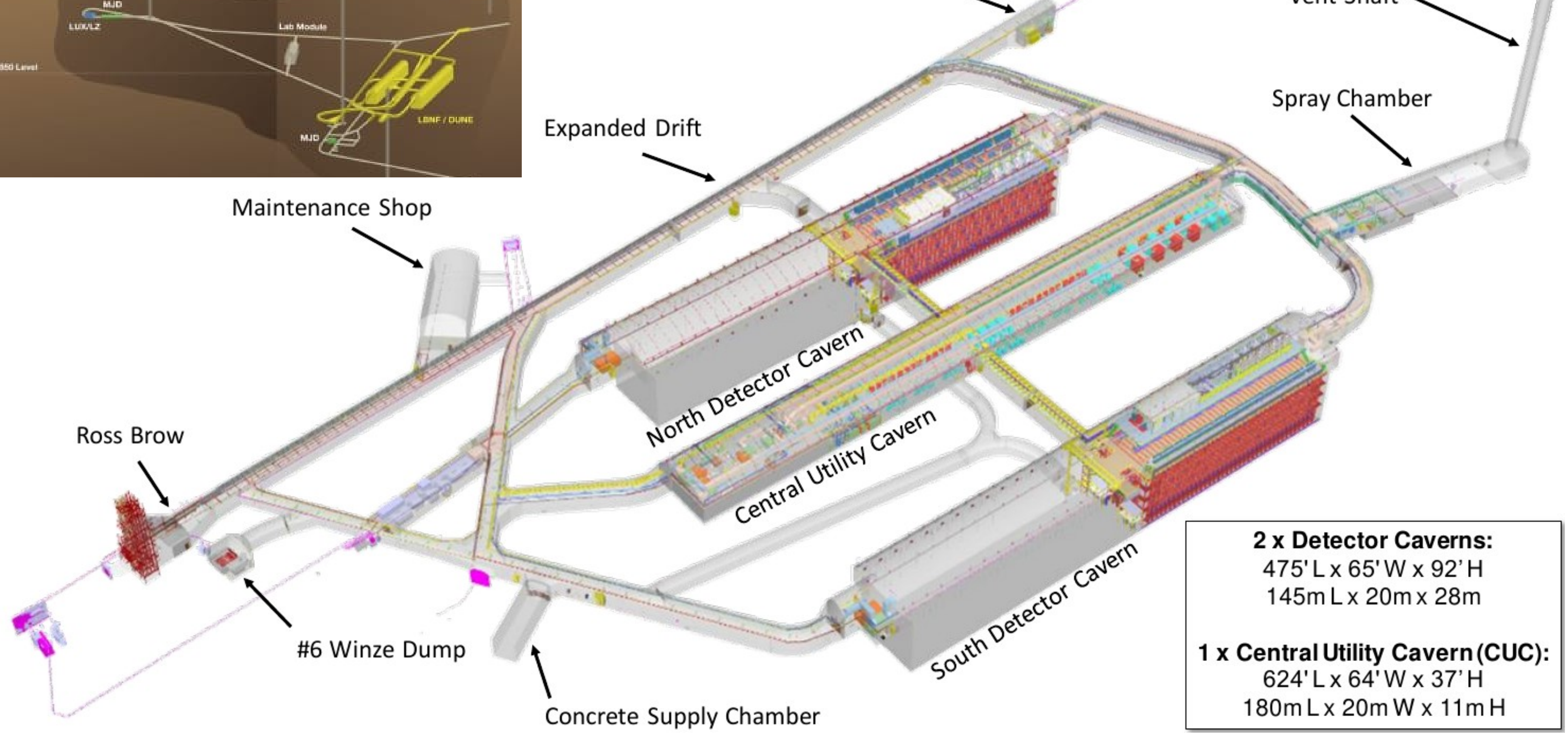
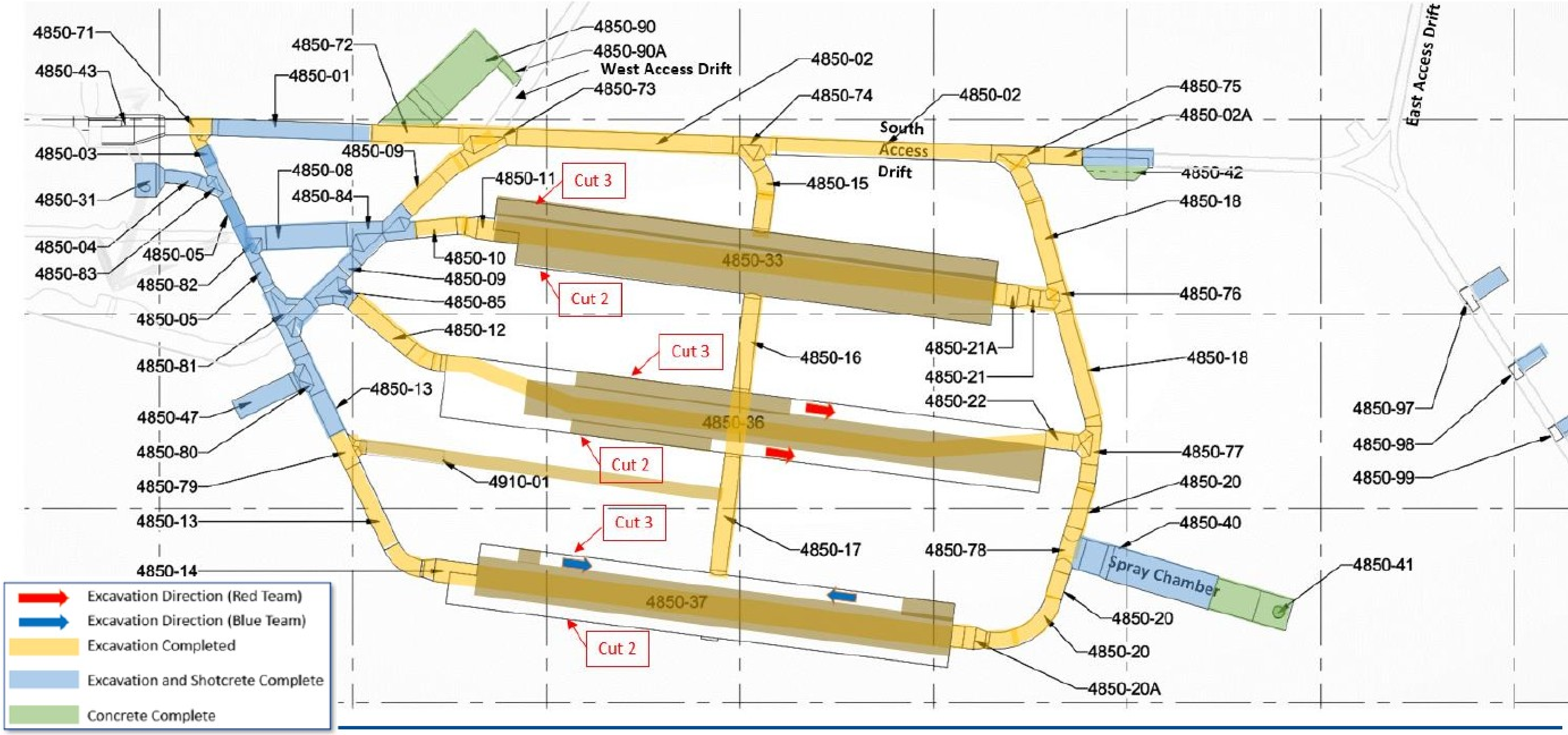
LBNF at SURF: what it will look like



2 x Detector Caverns:
475' L x 65' W x 92' H
145m L x 20m x 28m

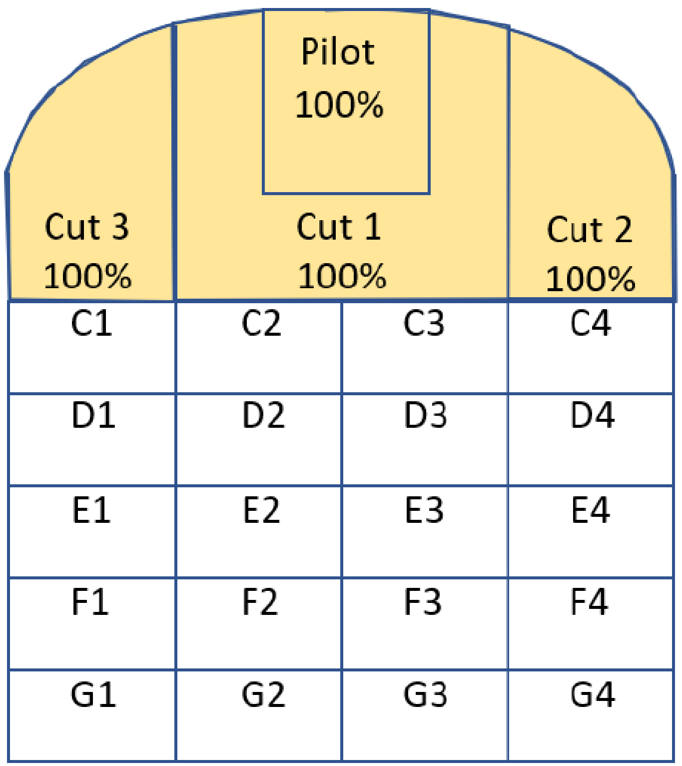
1 x Central Utility Cavern (CUC):
624' L x 64' W x 37' H
180m L x 20m W x 11m H

LBNF at SURF: excavation status

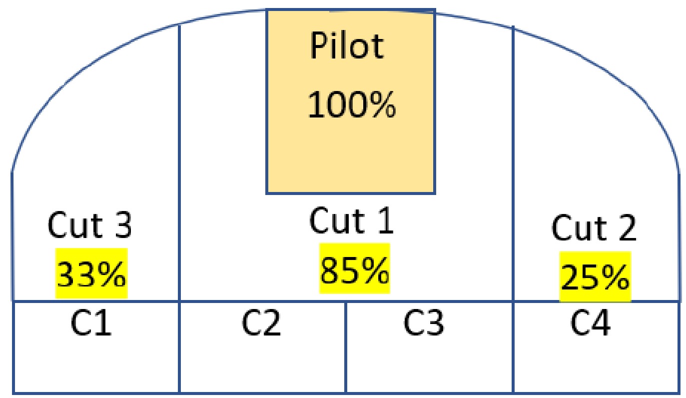


- Excavation is 42% complete by rock volume (as of Oct 24)
- All drill-and-blast excavation complete except main caverns, Ross Brow

Detector cavern excavation status

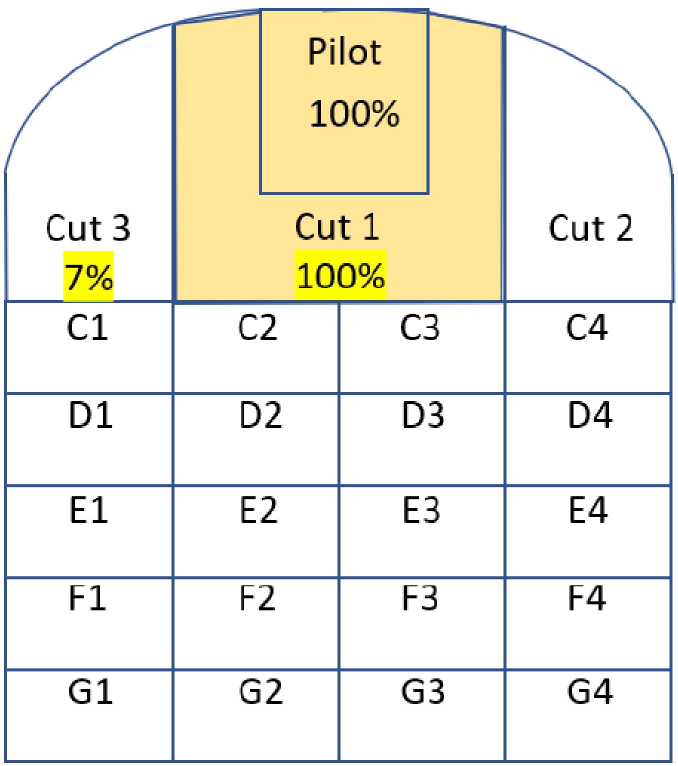


North Cavern



Note: Cut 1 (West end) will be completed after Cut 2 & 3

Central Utilities Cavern



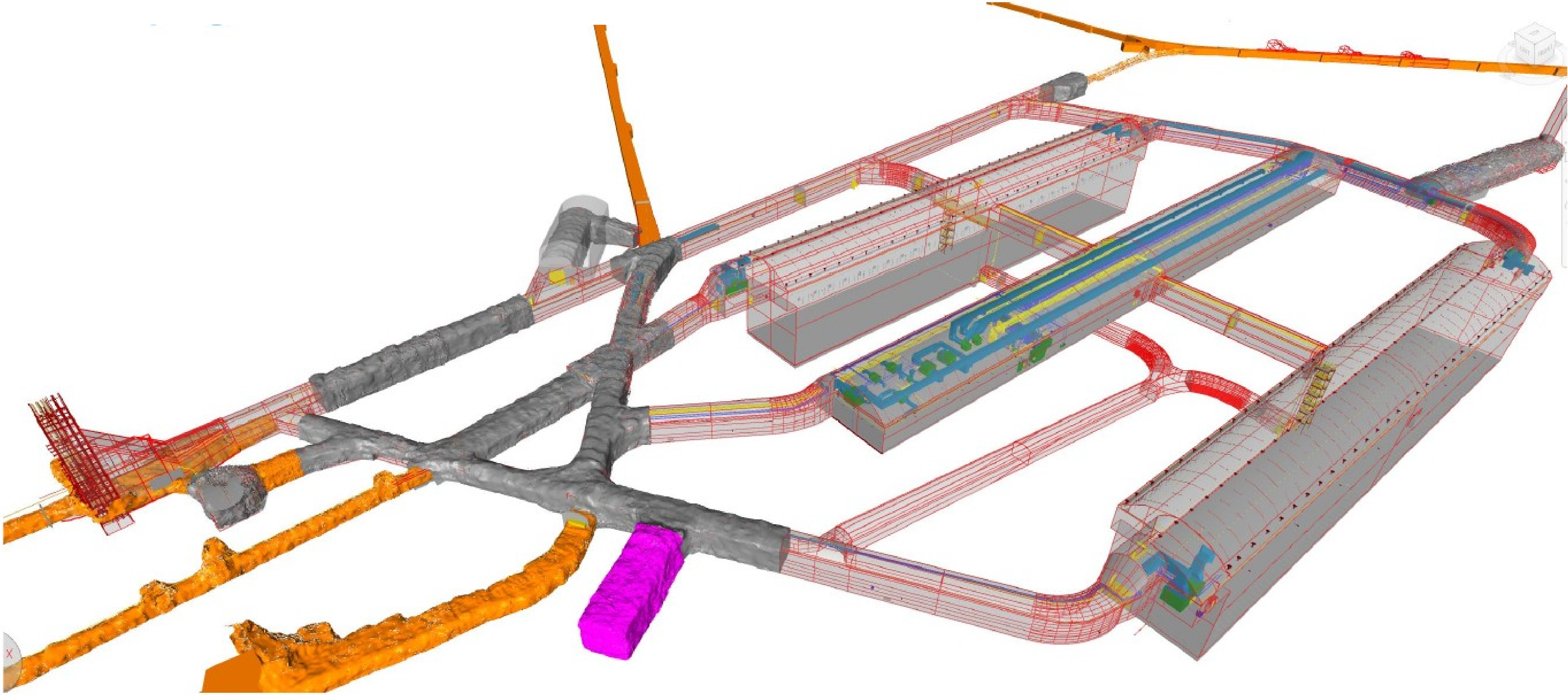
South Cavern

- Percentages are as of Monday, October 24
- Top cuts of North cavern are complete, with progress in all three caverns

Excavation photos

Access drift (top left), north cavern looking east (top right), Asmeret Berhe (DOE Office of Science Director) and Lia Merminga (FNAL Director) visit July 2022

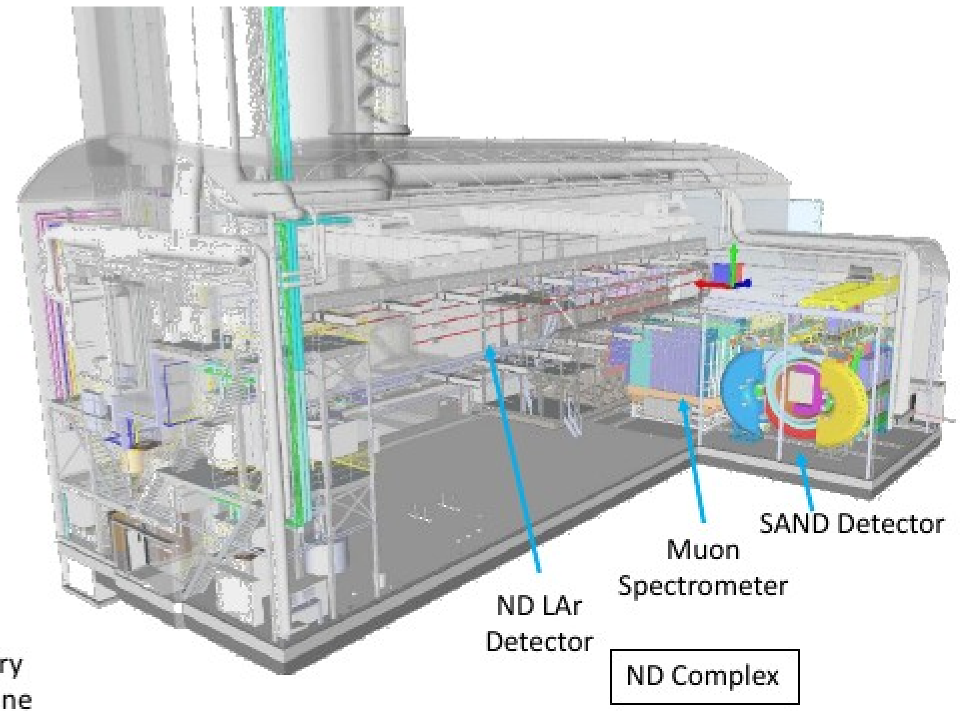
Developing "as-built" model of LBNF Far site

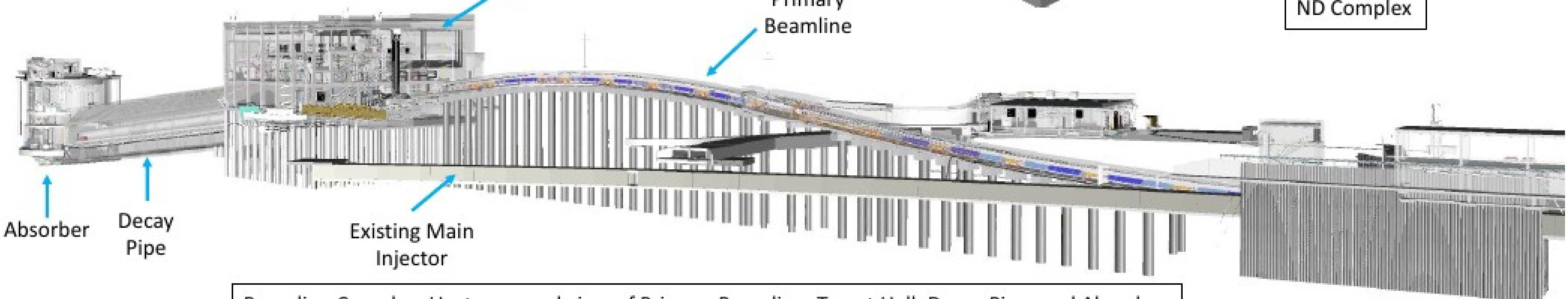


- Based on laser scan of completed excavated spaces
- Red lines show nominal design dimensions

Beamline and Near site progress

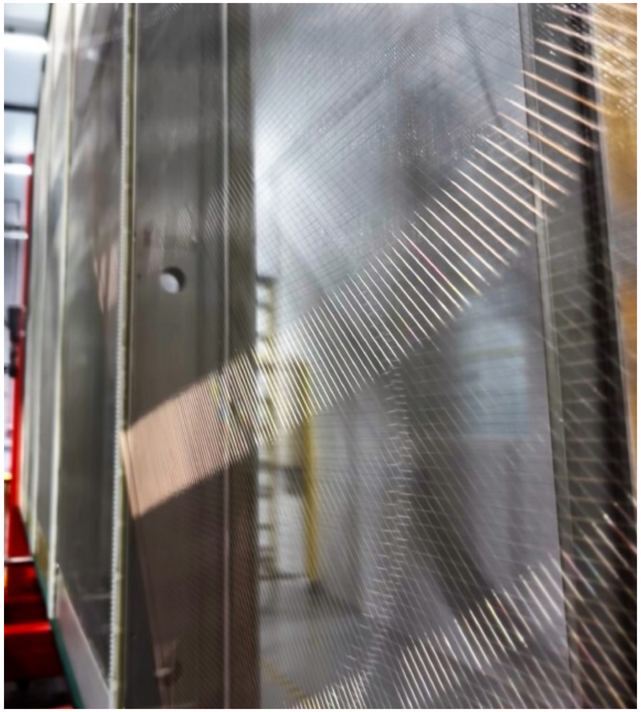
- Near site conventional facilities at 100% final design, beamline >66% final design and on track
- Schedule is funding limited





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

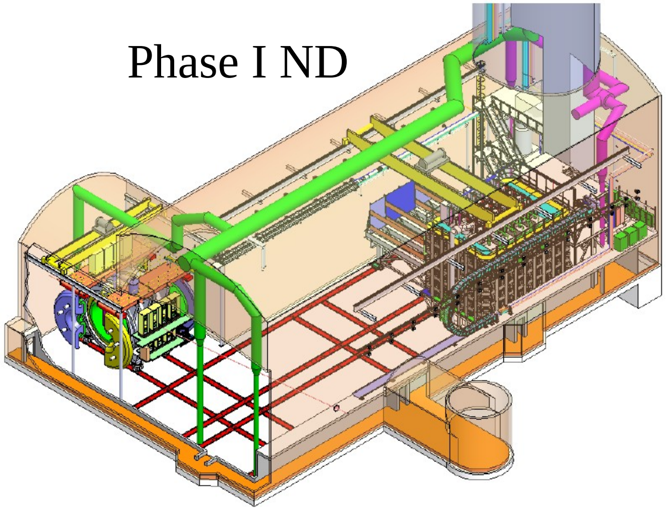
We're also building detectors...

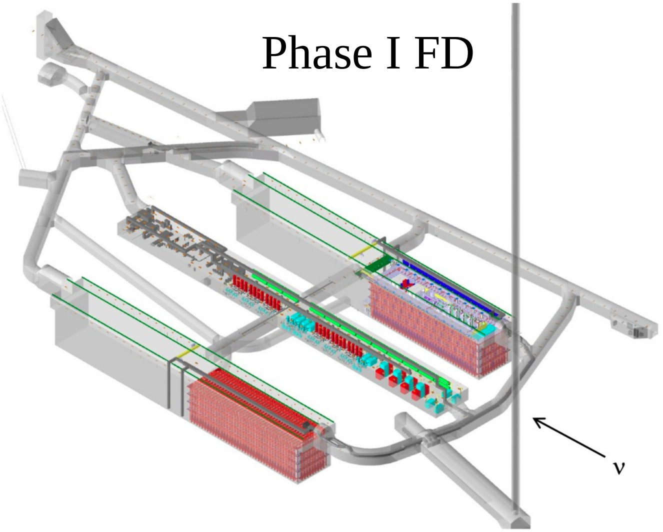


- FD anode plane construction is underway at Daresbury Lab in UK, first assemblies have been shipped to CERN for cold box testing

DUNE Phase I schedule milestones

- 2024 Far site excavation complete, cryostat installation begins
- 2026 Detector installation begins
- 2027 Cooldown and fill FD-1
- 2028 Start of Science with FD-1
- 2029 Start of Science with FD-2
- 2031 Beamline & Near Detector complete





Finishing the job: DUNE Phase II

- There has been tremendous progress on oscillation physics with the current experiments and the DUNE/LBNF program since the last P5. However, the primary questions about the three-flavor paradigm remain unanswered, and the motivations for answering them, and probing new physics beyond the three-flavor paradigm, are undiminished. **Completion of existing experiments and execution of DUNE in its full scope are critical for addressing the NF science drivers**. Both Phase I and Phase II are part of the original DUNE design endorsed by the last P5. DUNE Phase I will be built in the current decade and DUNE Phase II (two additional far detector (FD) modules, a more capable near detector (ND), and use of the 2.4 MW beam power from the FNAL accelerator upgrade) is the priority for the 2030s.

Snowmass 2021

- DUNE is pursuing Phase II upgrades with a goal of completing the full scope in the 2030s
- FD-1 and FD-2 have 4-5 years from first occupancy of cavern space to physics
- DUNE aims to begin installing detectors in Caverns 3 & 4 in the early 2030s

Summary

- DUNE has a broad physics program of neutrino oscillations, particle astrophysics, and searches for physics beyond the Standard Model
- DUNE is well on its way: designs nearing completion, excavation progressing rapidly, detector construction ramping up