The DUNE Experiment

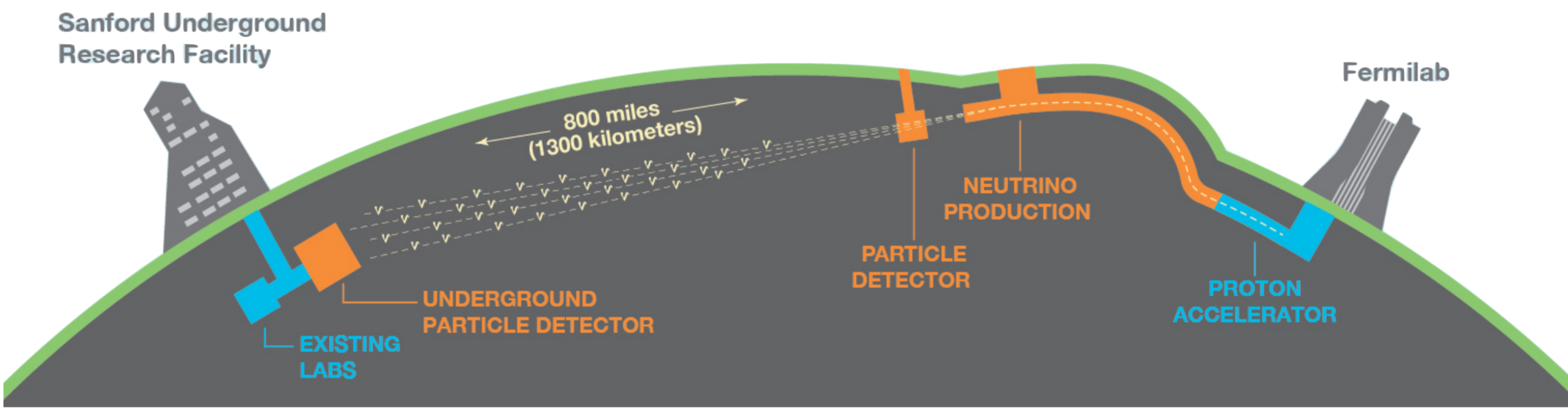
Pip Hamilton

Recontres du Vietnam Flavour

17th August 2022

Imperial College London

What is DUNE?



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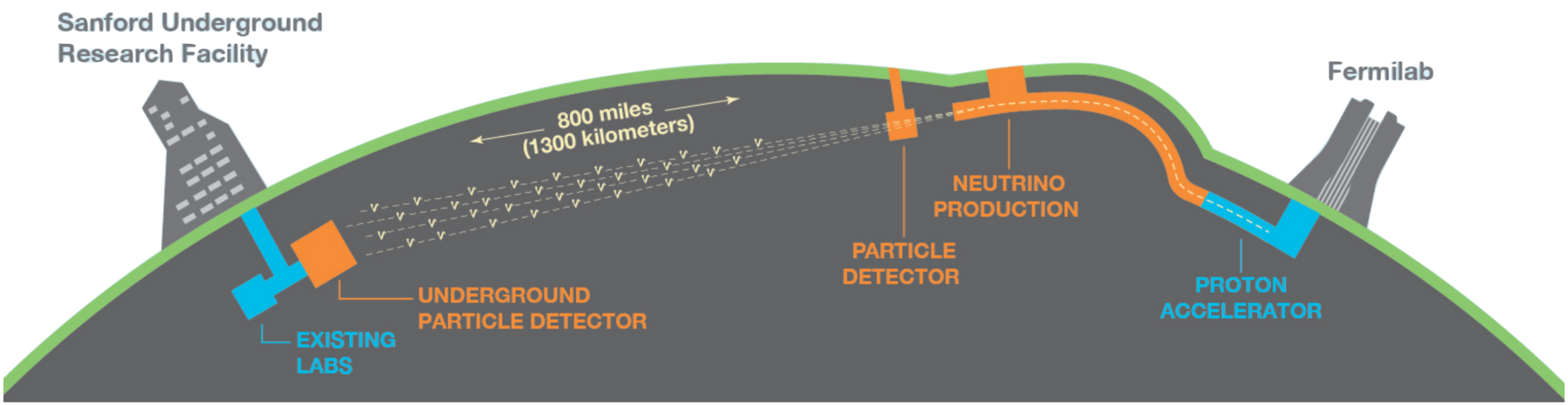

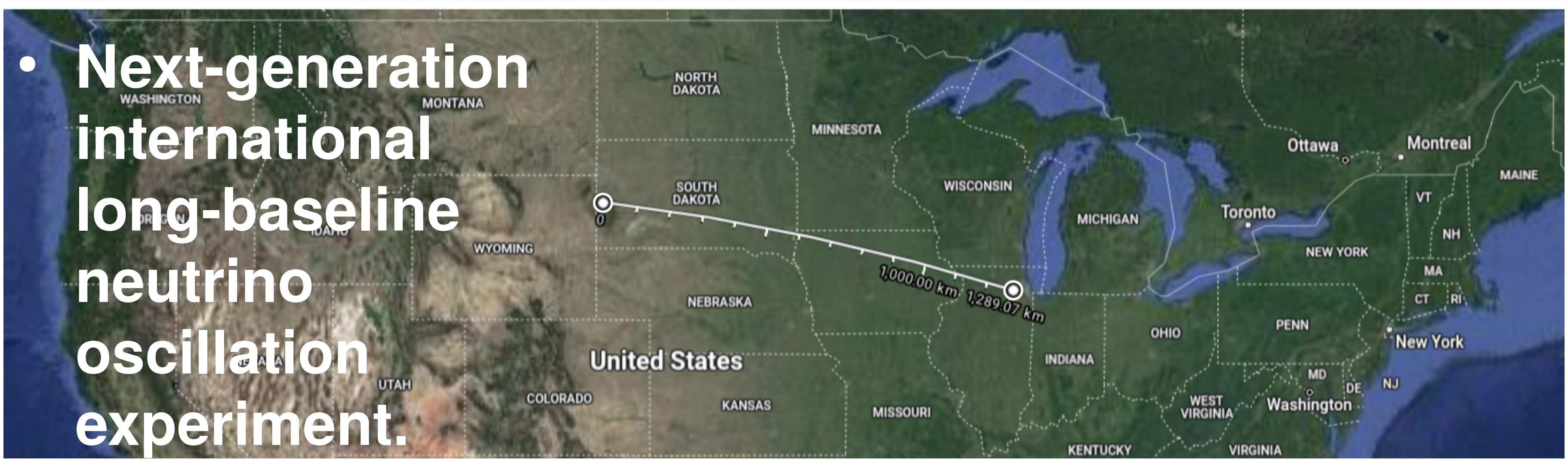

- **Next-generation international long-baseline neutrino oscillation experiment.**

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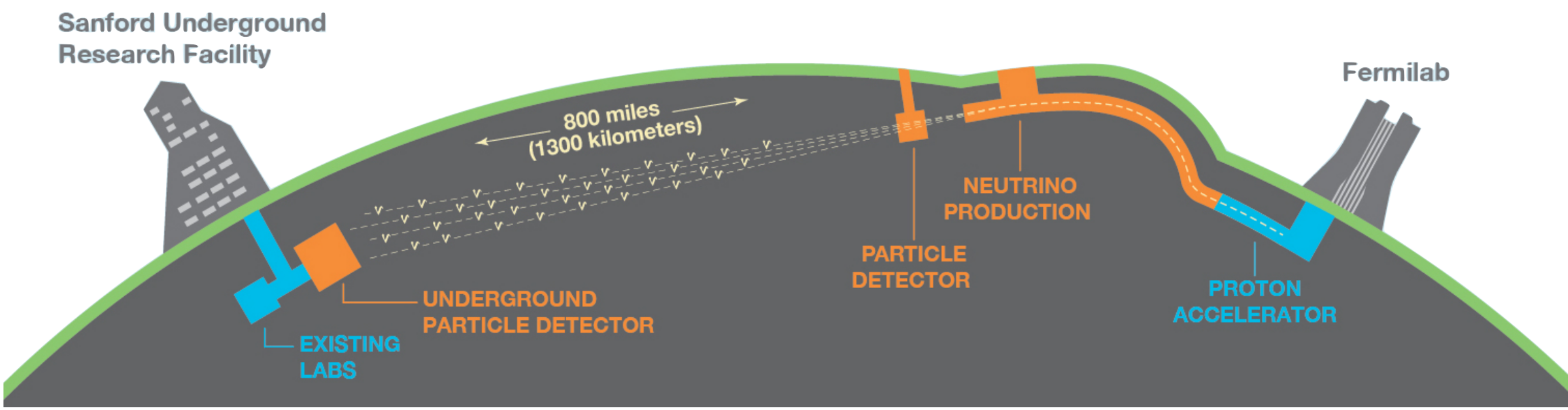

- Next-generation international long-baseline neutrino oscillation experiment.
- Pushing neutrino beam and detector frontiers.

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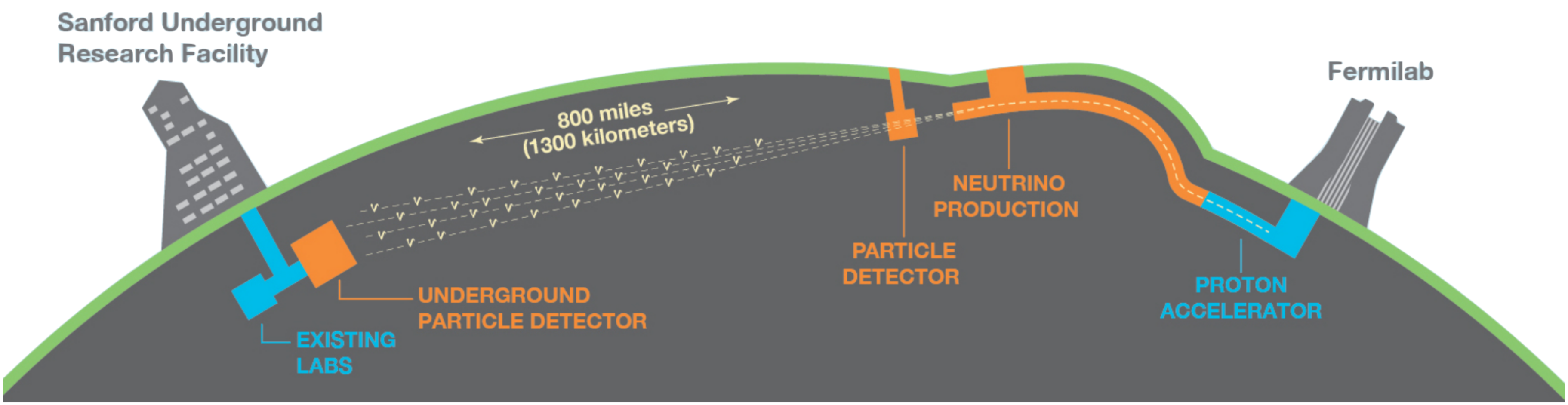
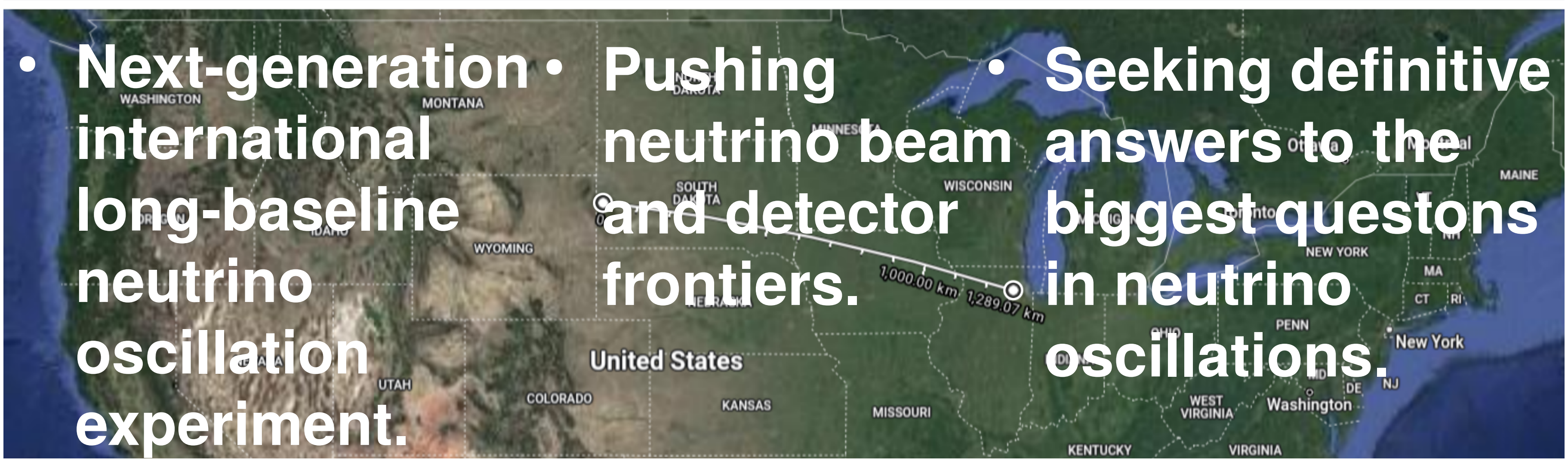




- Next-generation international long-baseline neutrino oscillation experiment.
- Pushing neutrino beam and detector frontiers.
- Seeking definitive answers to the biggest questons in neutrino oscillations.

Neutrino Oscillations

PMNS mixing matrix:

$$c_{ij} = \cos\theta_{ij}, \, s_{ij} = \sin\theta_{ij}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

7 parameters of interest:

- 3 neutrino masses m_i
- 3 mixing angles θ_{ij}
- CP-violating phase δ

Probability of flavour change:

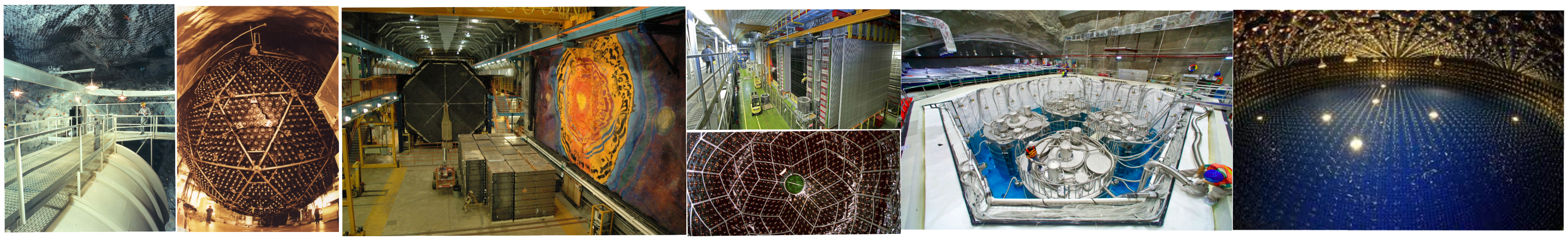
$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

(2-flavour approximation)

PMNS assumes only 3 flavours.

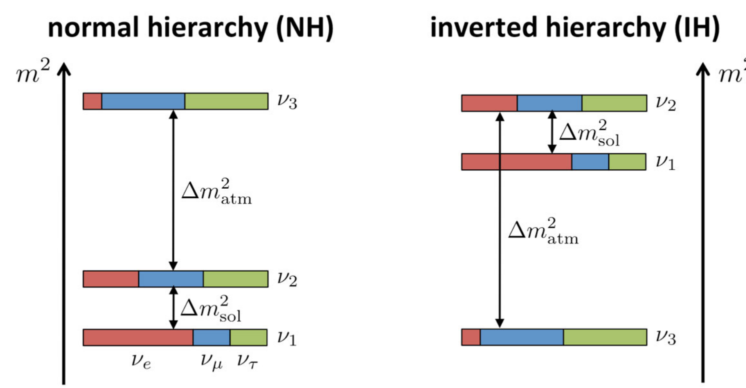
*at oscillation maximum

Oscillations – Open Questions



We are standing on the shoulders of decades of research measuring the PMNS matrix. We must push the frontiers of sensitivity to answer the big questions that remain.

- **Is δ_{CP} non-zero? What is its value?**
- **Mass ordering – is m_3 the heaviest or the lightest?**
- **Is $\sin^2\theta_{23}$ maximal? What is the octant?**



Oscillations – Open Questions

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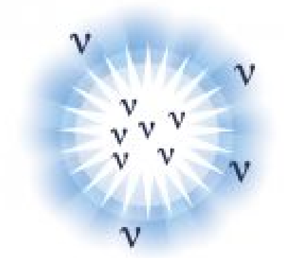
Probing these questions offers a window on the bigger picture:

- Is neutrino mixing behind the baryon asymmetry of the universe?
- What is the origin of the neutrino masses?
- Are there more flavours of neutrino out there? Does the PMNS matrix need expanding?

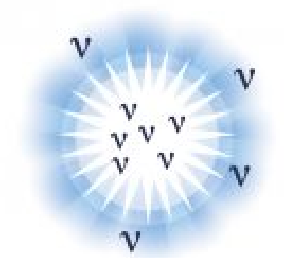


Oscillations – Open Questions

- **Is δ_{CP} non-zero? What is its value?**
- **Mass ordering – is m_3 the heaviest or the lightest?**
- **Is $\sin^2\theta_{23}$ maximal? What is the octant?**

DUNE will tackle all these questions!

Groundbreaking design for the precision era:



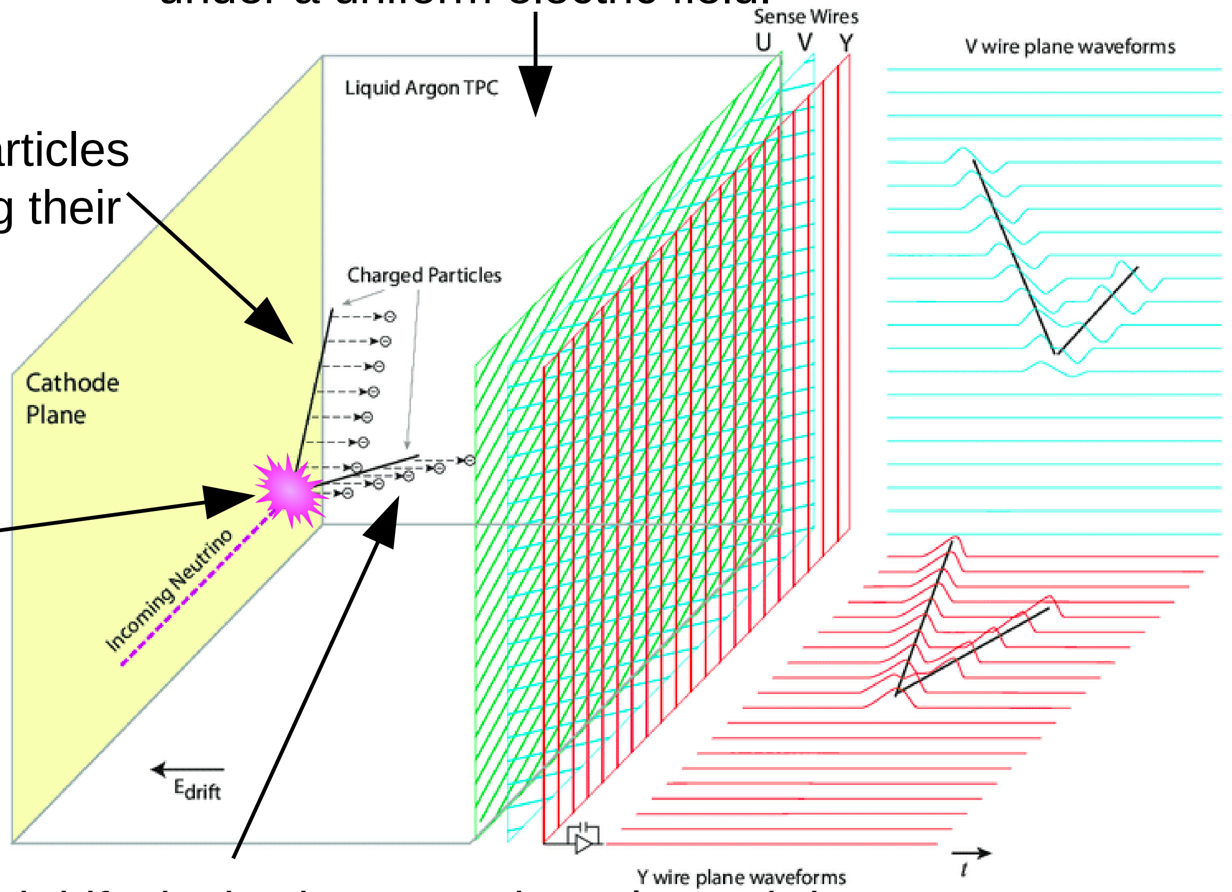
- World's most powerful neutrino beam.
- Liquid argon time projection chamber (LArTPC) detector technology.

LArTPC Detector Technology

1. Volume of liquid argon held under a uniform electric field.

2. Charged particles ionise Ar along their path.

4. Ar scintillation light gives a timestamp for the interaction: combine with known drift speed to reconstruct 3rd dimension.



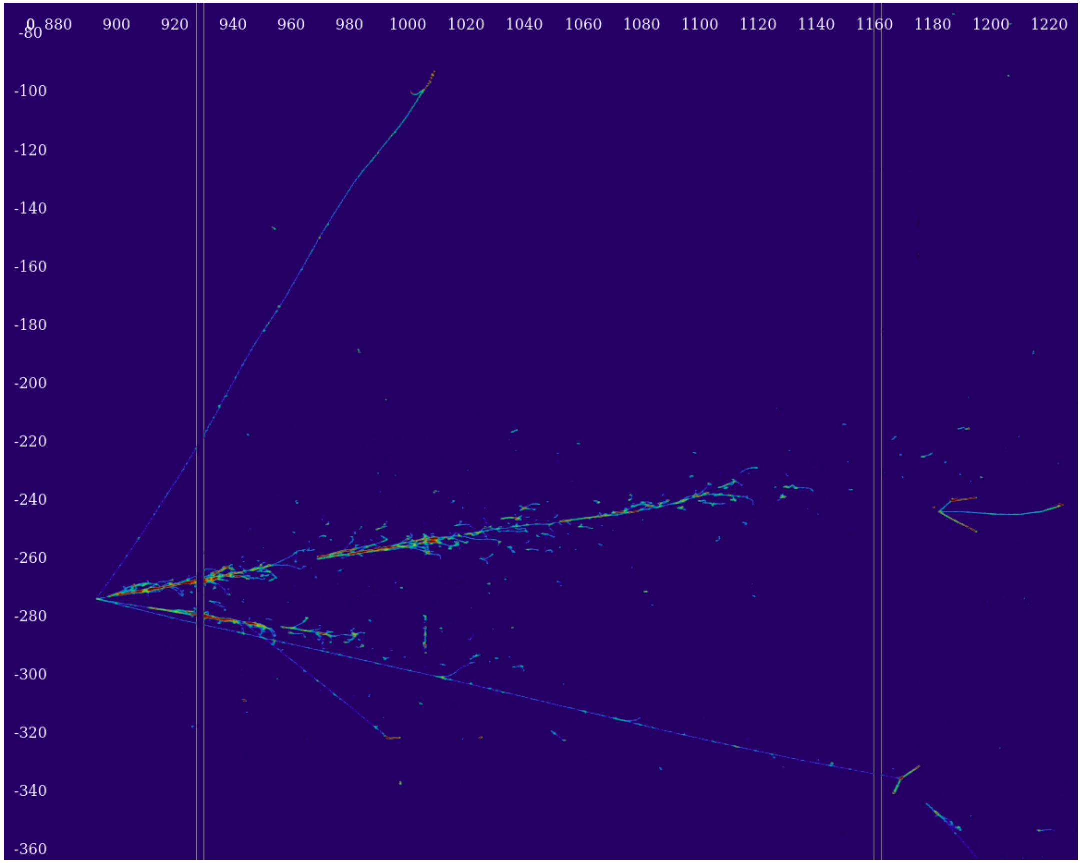
3. E-field drifts ionisation to readout planes (wires, pixels, strips…) where it is collected.

LArTPC Detector Technology

- Exquisite, millimetre-scale imaging of neutrino interactions.
- Reconstruction of the neutrino energy key for precision on oscillation.

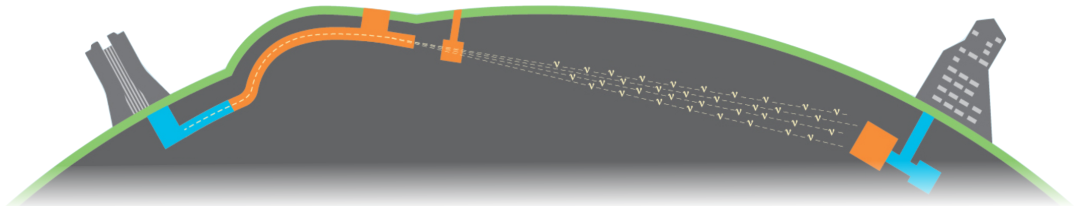
$$P_{\alpha\rightarrow\beta} = \sin^2(2\theta)\sin^2(\frac{\Delta m^2 L}{4E})$$

- DUNE is exploiting this technology at the largest ever scale.



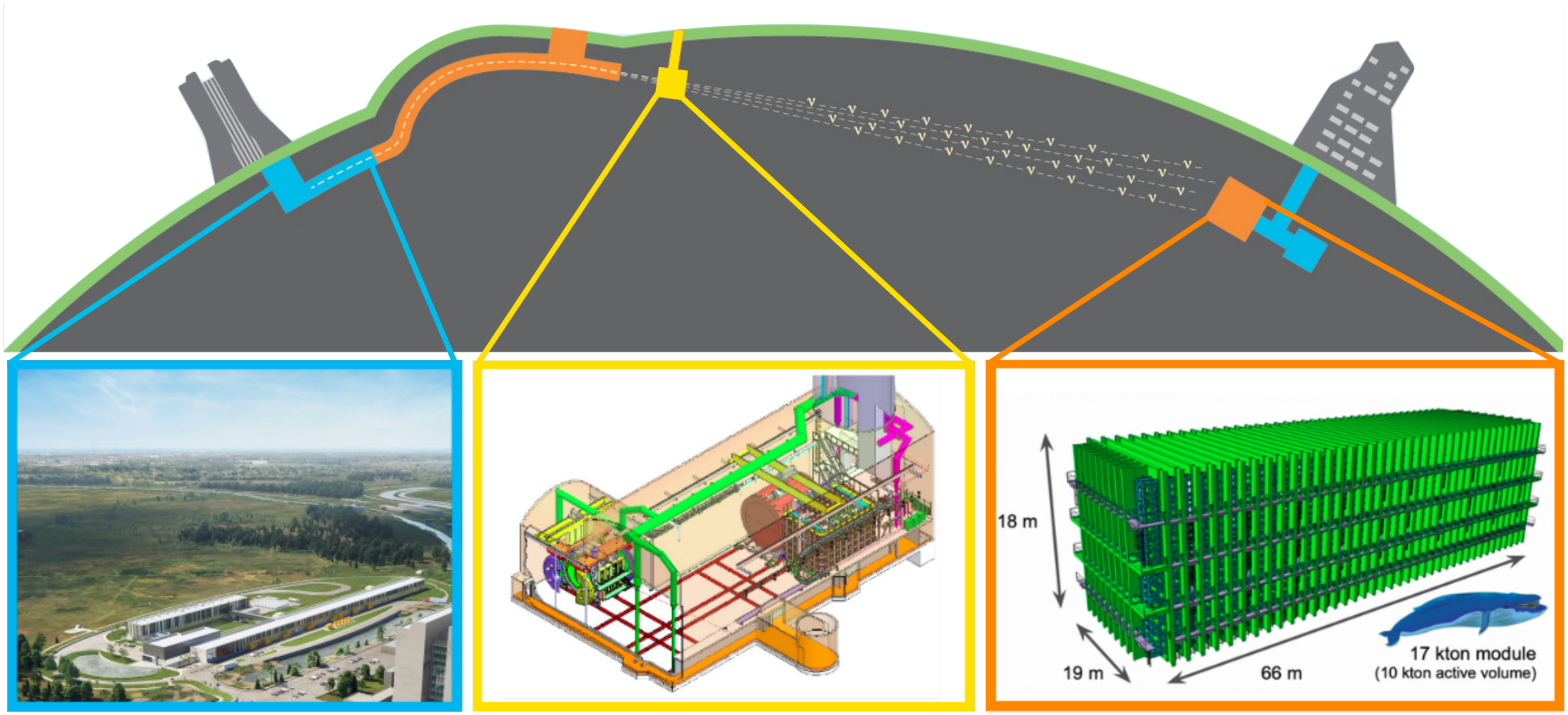
DUNE far detector simulation,

$\nu_e + Ar \rightarrow e^- + \pi^+ + \pi^- + \pi^0 + p$



The Experiment

The DUNE Experiment



Beam: brand new 1.2 MW ν_μ beam.

Near site: suite of 3 different detectors

Far site: World's largest LArTPCs.

To achieve this scale, project broken into 2 phases.

Phase 1 – a complete oscillation experiment.

Phase 2 – upgrades to each part.

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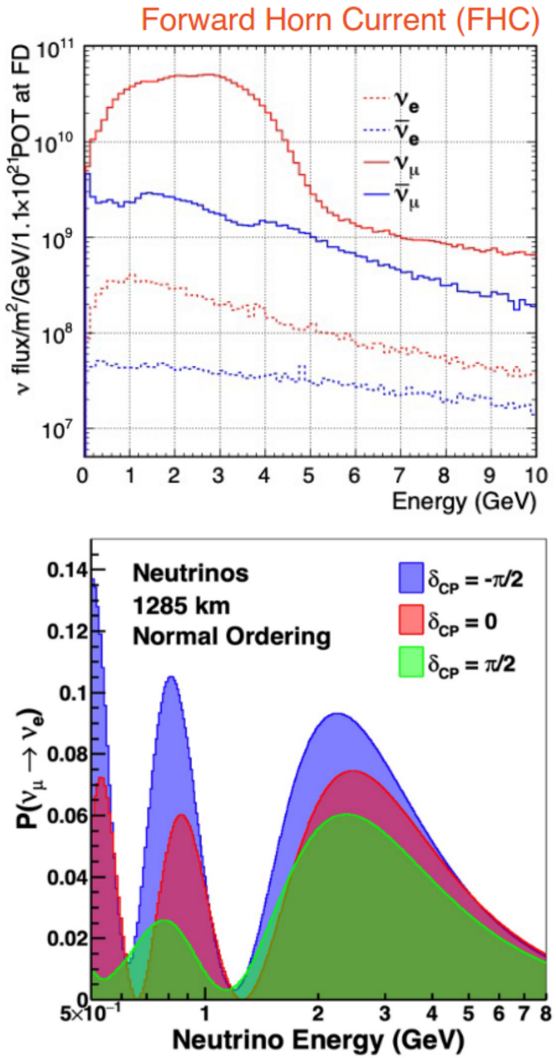
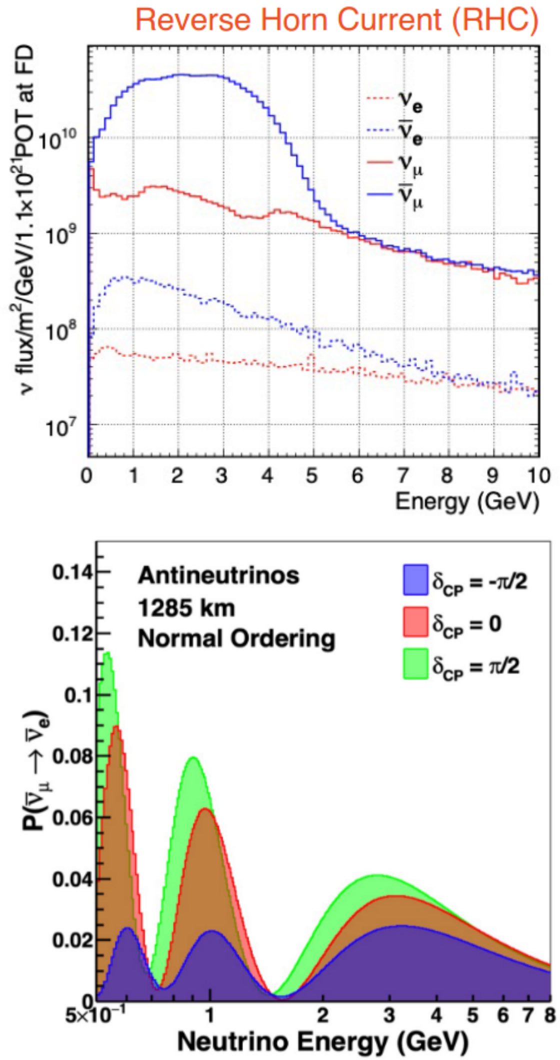
Beam: PIP-II

- Record intensity: 1.2 MW, upgradeable to 2.4 MW in Phase 2.
- Wide-band energy spectrum lets us see 2nd oscillation maximum.

ν mode



$\bar{\nu}$ mode



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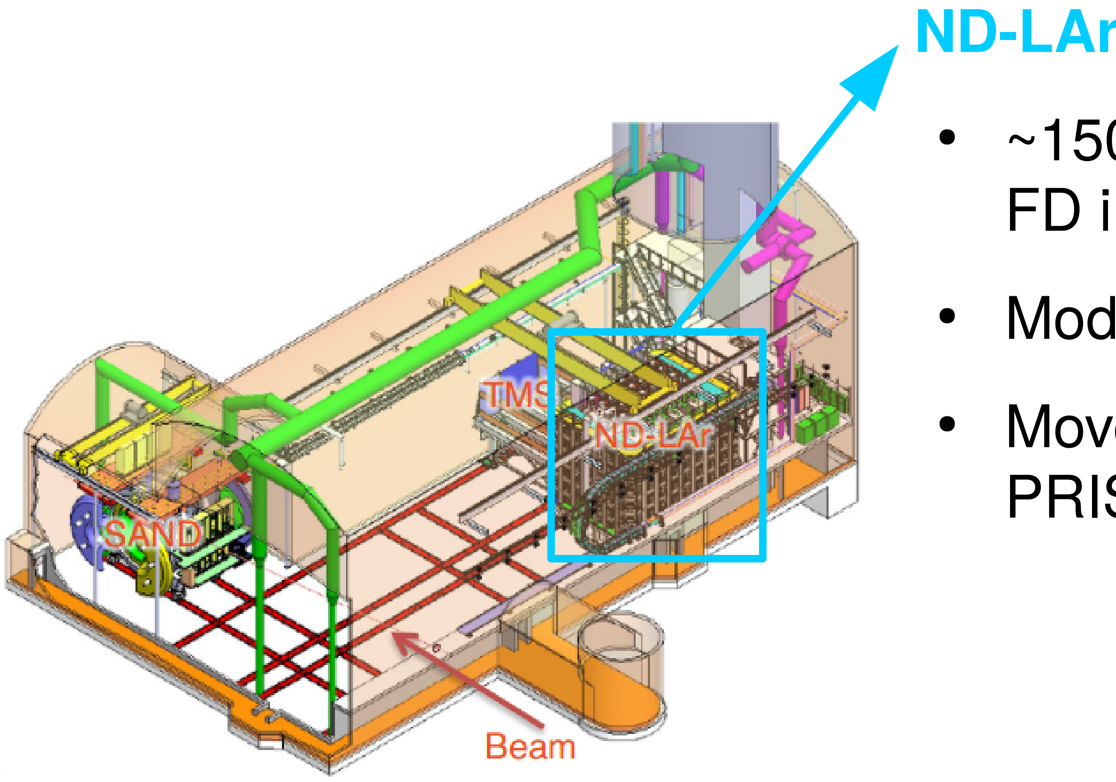
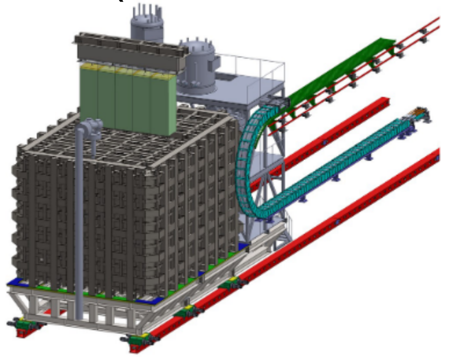
Near Detectors

The DUNE near detectors measure the unoscillated neutrino beam, and constrain neutrino-argon cross-sections and uncertainties on the LArTPC response.

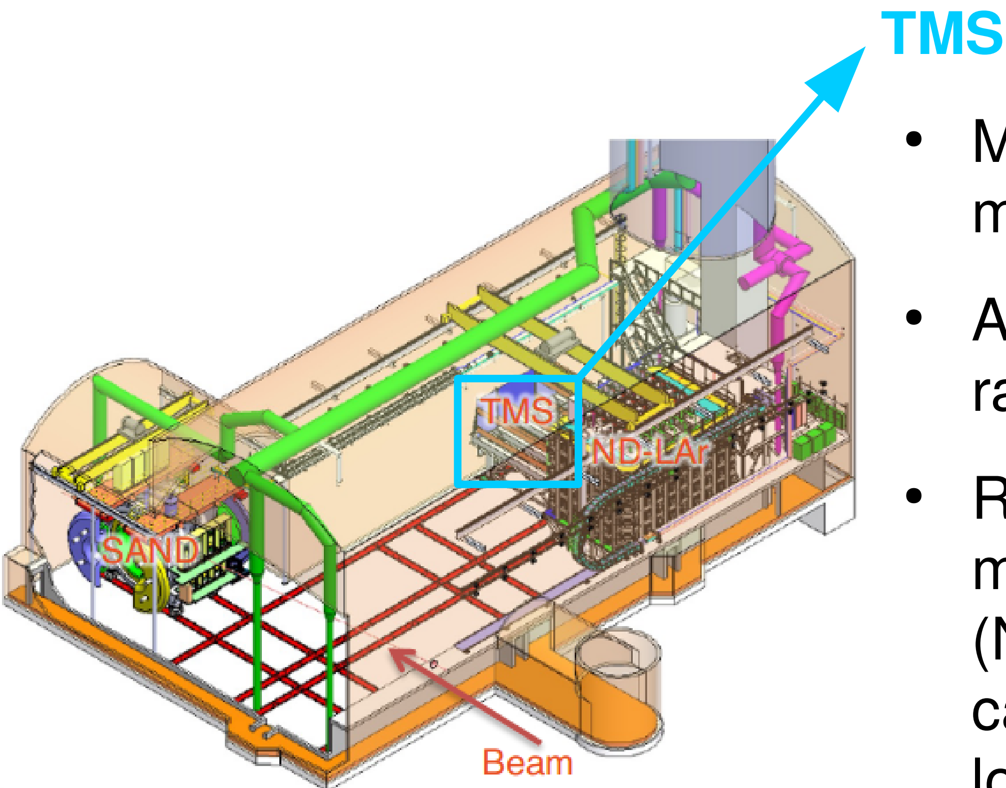


- ~150 tonne LArTPC, matching FD interaction medium.
- Modular, with pixel readout.
- Moves on a rail (DUNE-PRISM).



Near Detectors

The DUNE near detectors measure the unoscillated neutrino beam, and constrain neutrino-argon cross-sections and uncertainties on the LArTPC response.



- Muon range stack measuring muon momentum in ND-LAr.
- Also moves on DUNE-PRISM rail.
- Replaced in Phase 2 with magnetised gas TPC + ECal (ND-GAr): adds groundbreaking capability for cross-sections with lower energy thresholds.

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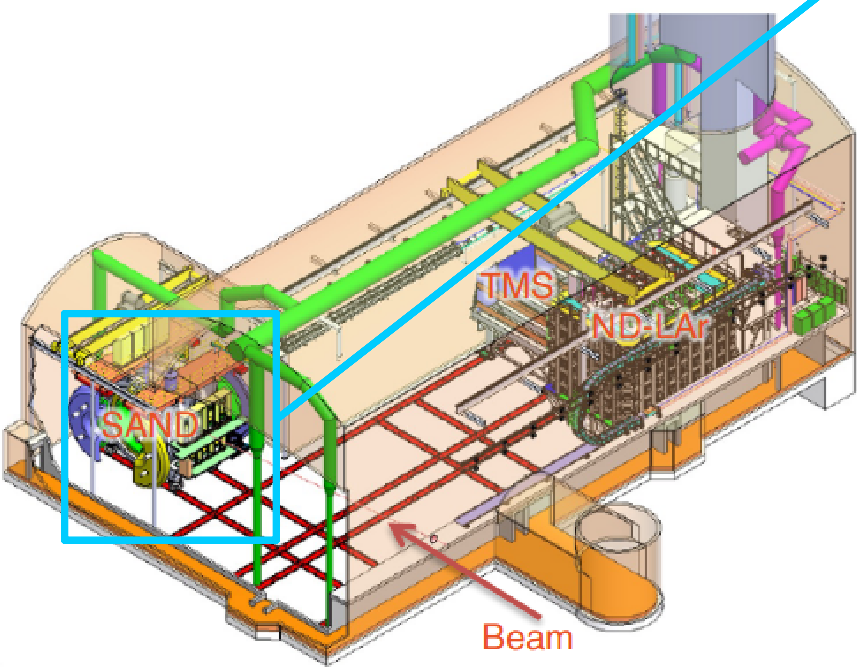
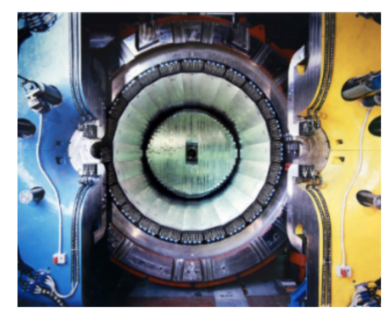
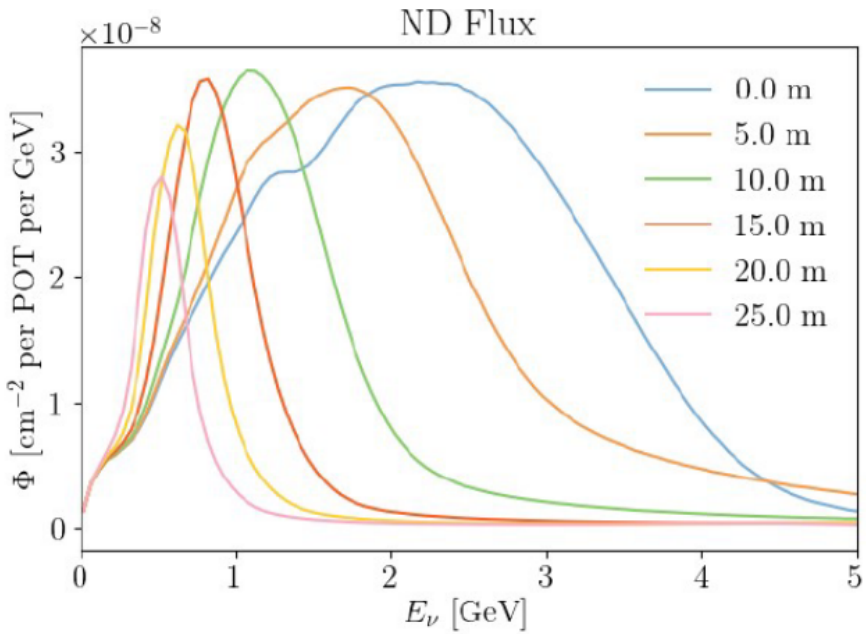


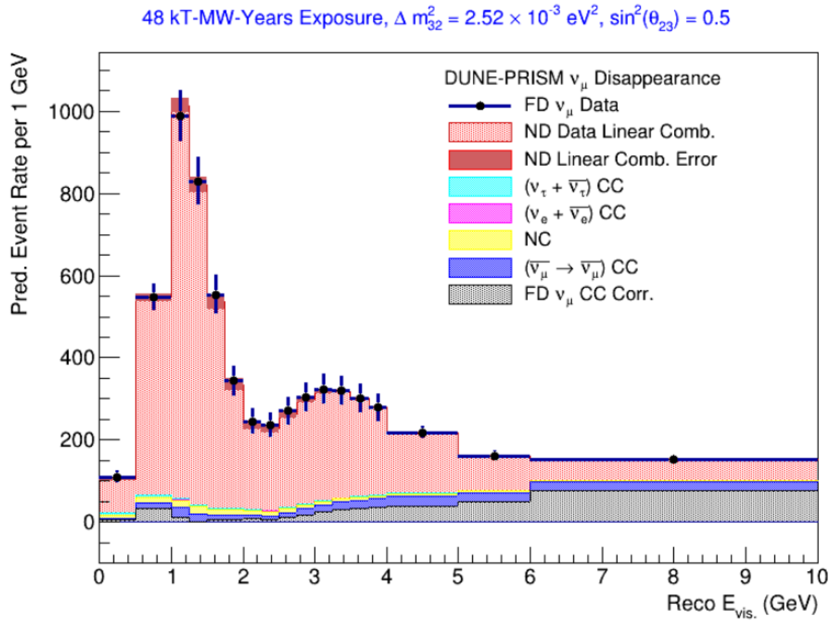
SAND

- Magnetised, low-density tracker and spectrometer.
- On-axis beam monitor.
- Measures ν interactions on various targets.



DUNE-PRISM

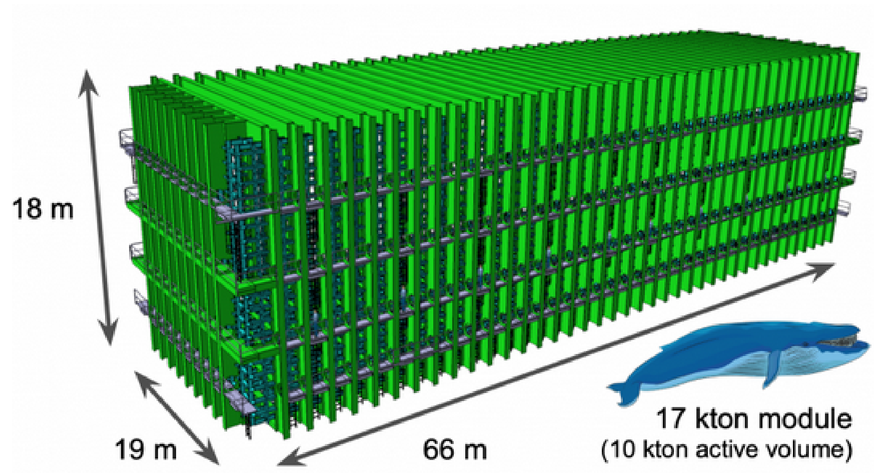


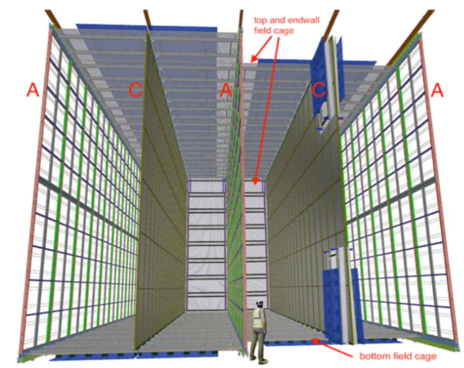


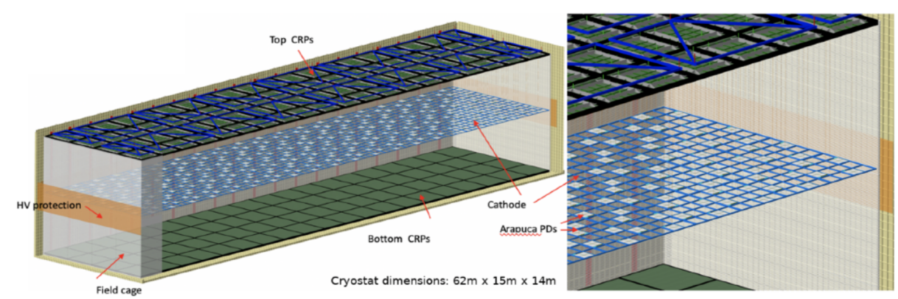
- Old problem for oscillation experiments: flux at far detector ≠ flux at near detector, preventing clean cancellation of systematics due to energy-dependent interaction modelling uncertainty.
- Different off-axis angles sample different beam energy distributions. Off-axis effect used by e.g. T2K at fixed angles.
- Through a linear superposition of data at **different** off-axis angles, we can construct a flux that matches the oscillated flux at the far detector (for a given value of the oscillation parameters).
- Construct fluxes at many different oscillation parameter values and fit to data.

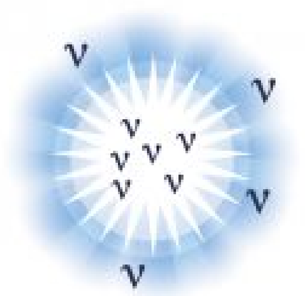
Far Detectors

- 2 17 kton LArTPC modules (rising to 4 in Phase 2), 1.6 km underground at the Sanford mine.
- First module is a wire readout horizontal drift LArTPC.
- Second module has vertical drift, instrumented with with charge readout plane strips (developed through the DUNE dual phase prototype).



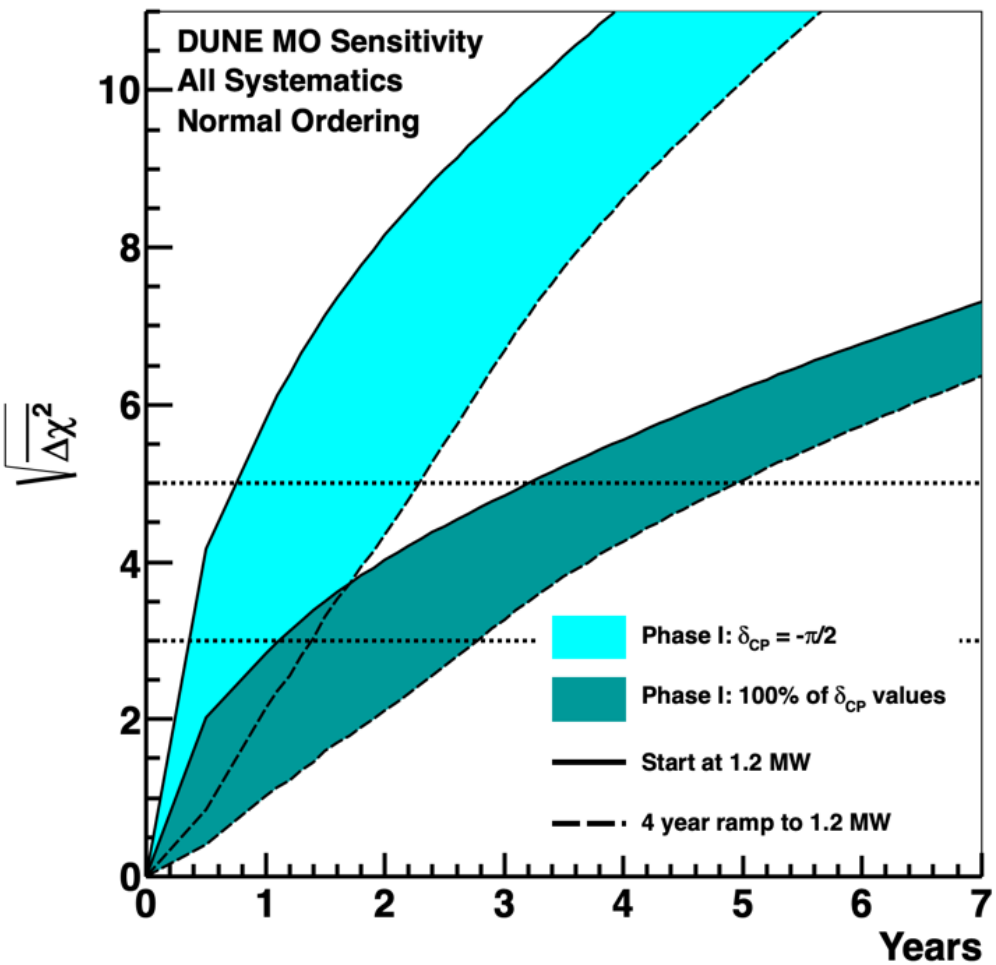






Sensitivity

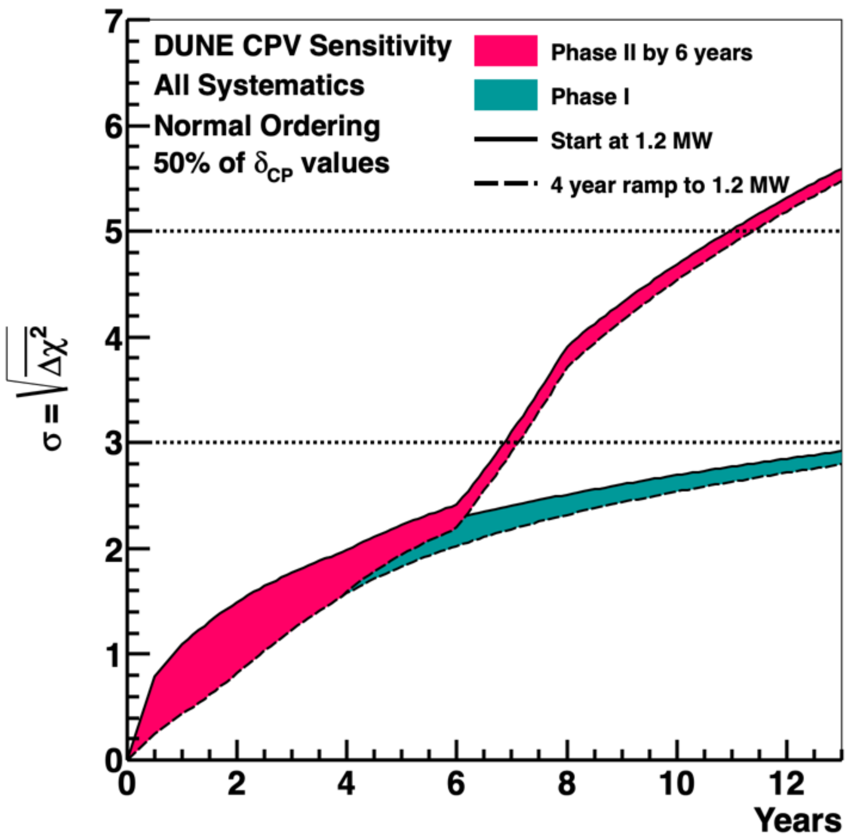
Sensitivity: Mass Ordering

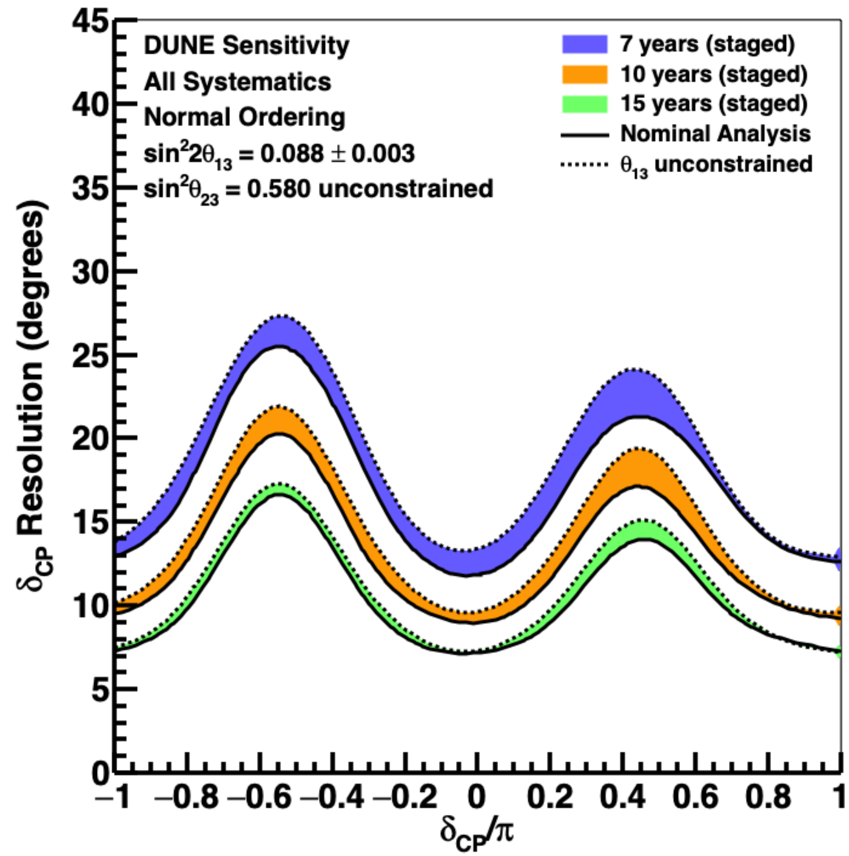


- DUNE will definitively resolve the mass hierarchy, exploiting strong normal vs. inverted hierarchy differences in FD spectrum.
- 5σ discovery within 5 years, independent of other parameters.

Sensitivity: δ_{CP}

- 5σ sensitivity to CP violation over broad range of values.
- Resolution on value of δ_{CP} as precise as 7°.





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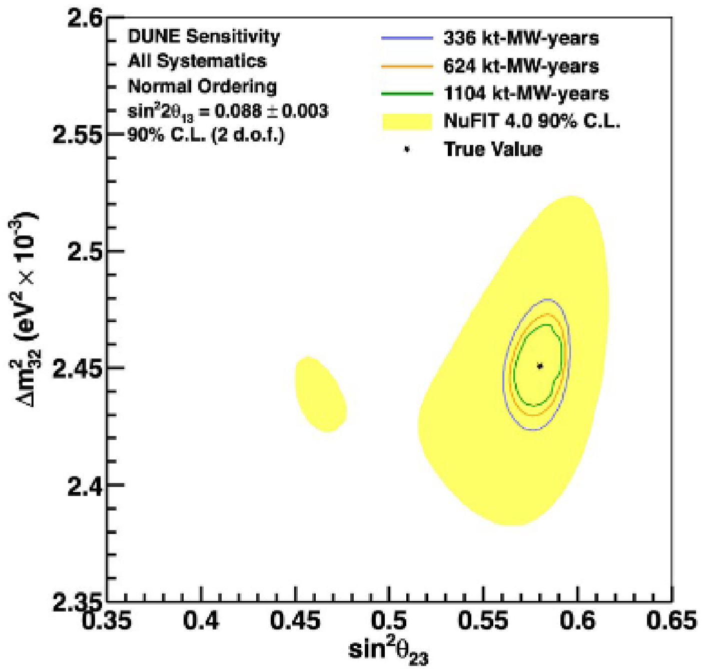
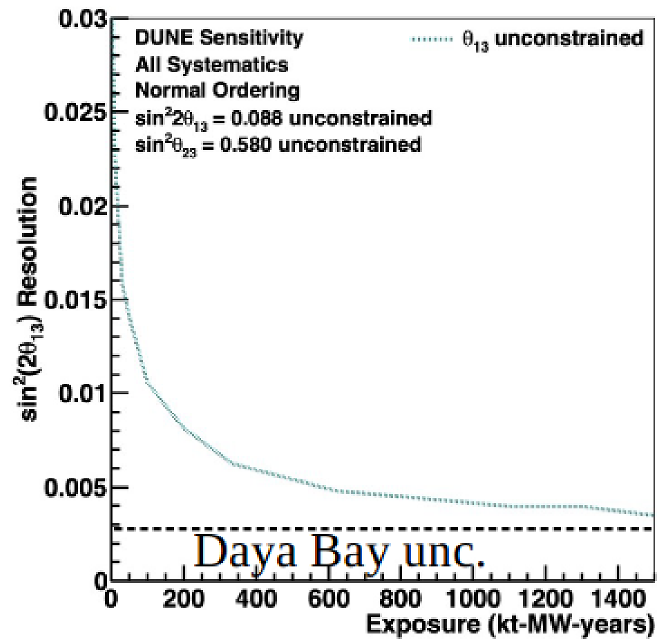
Sensitivity: θ_{23} & θ_{13}

- High-precision measurements of $\sin^2\theta_{23}$ and Δm^2_{32}, able to determine octant.
- Independent of external θ_{13} measurement ⇒ can test PMNS matrix unitarity through comparison to reactor data.

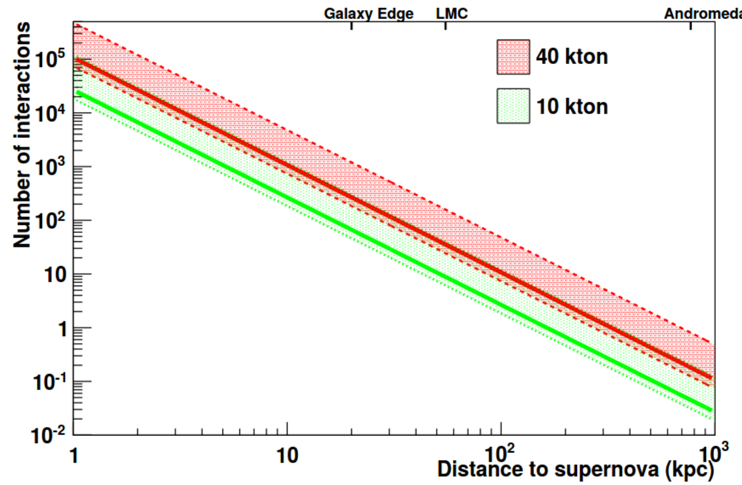


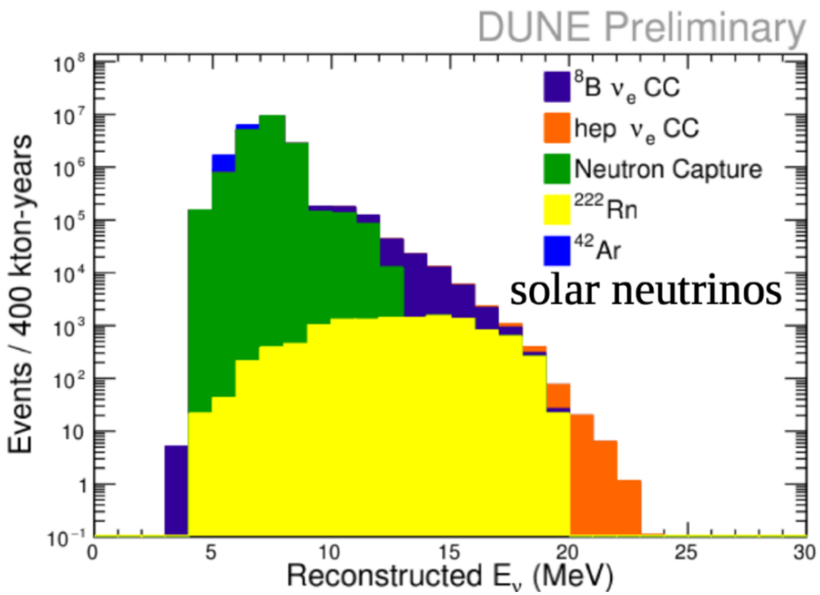


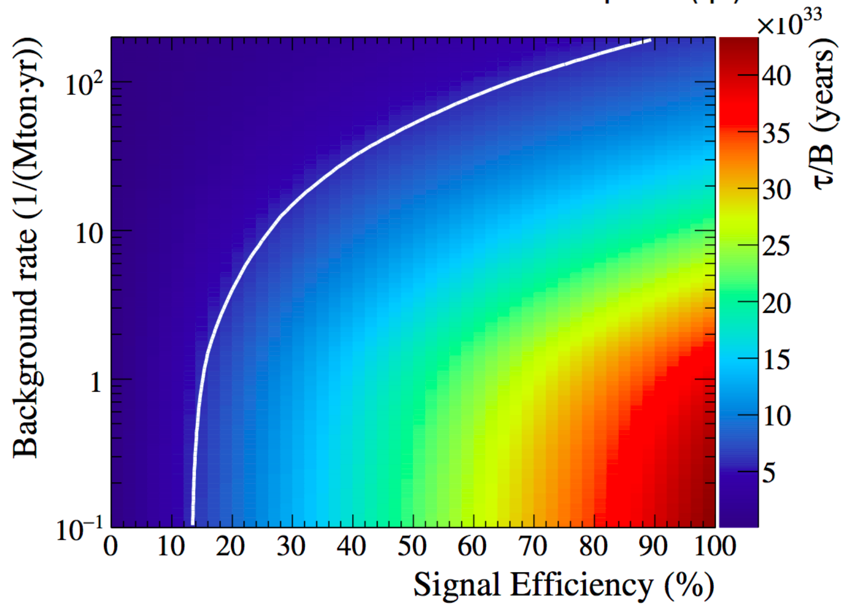
Other Measurements

- Supernova neutrinos.
- Solar neutrinos.
- Nucleon decay.

...and more!







Other Measurements

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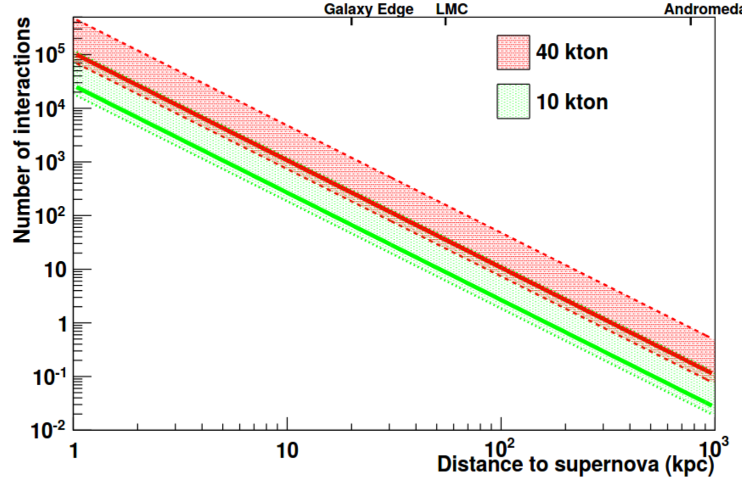
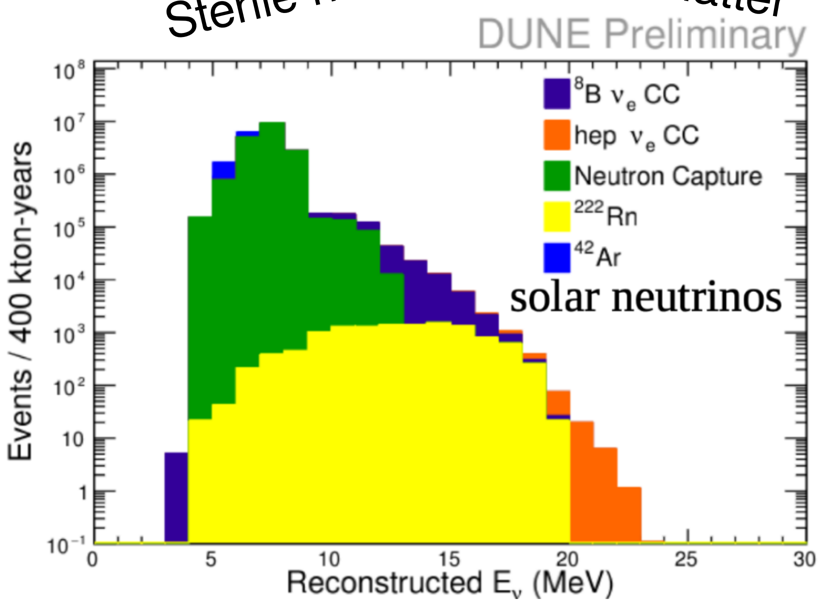
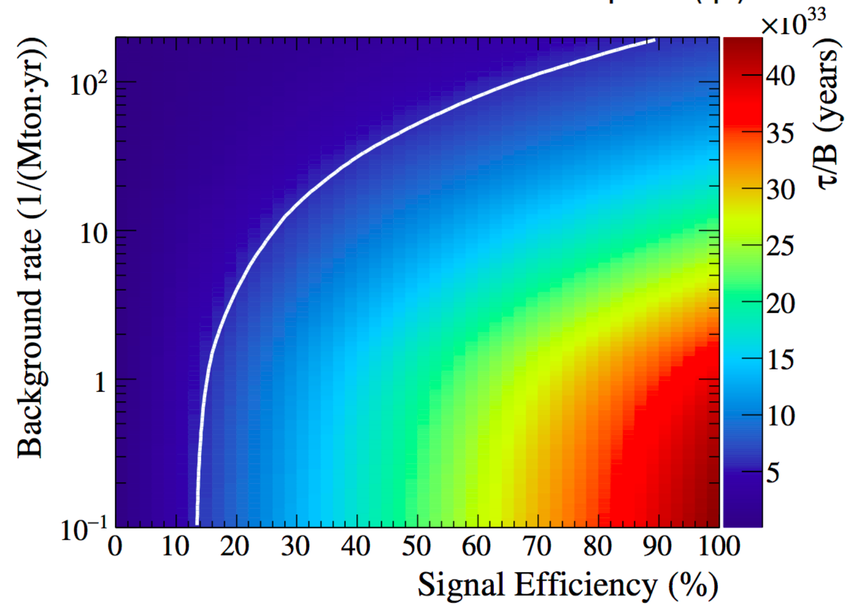
- Solar neutrinos.
- Nucleon decay.

...and more! Heavy neutral leptons Sterile neutrinos Dark Matter







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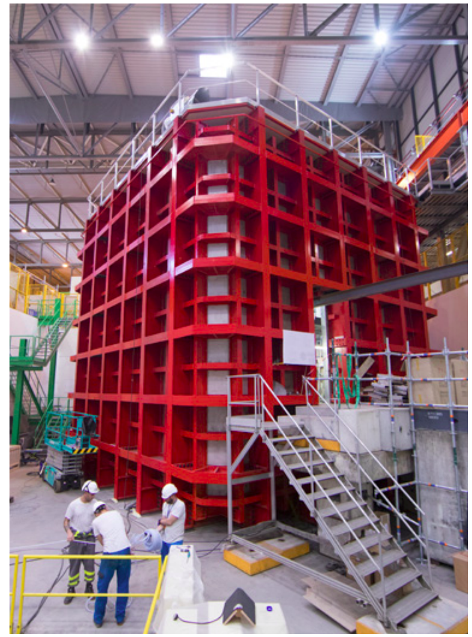
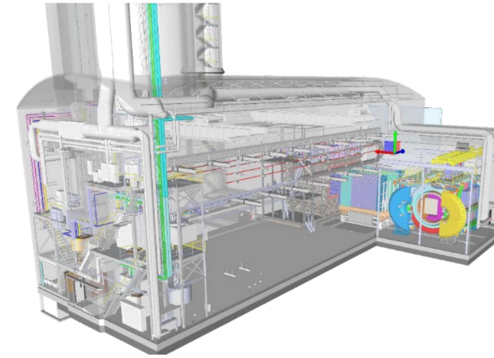
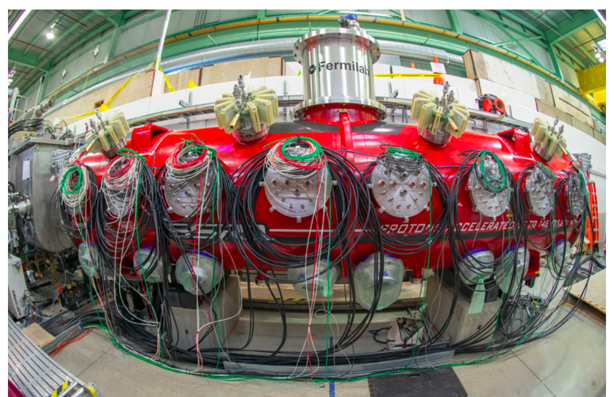
Current Status

Work is well underway across all areas of the experiment, with our first beam data expected in 2030.



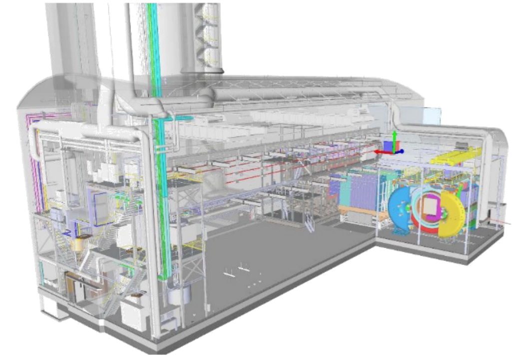


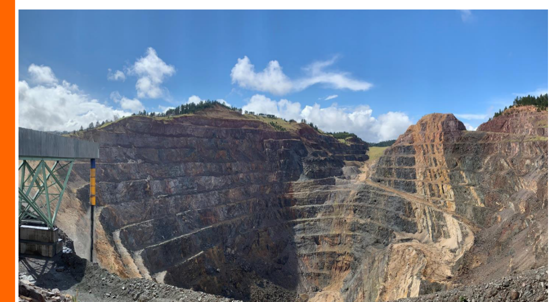


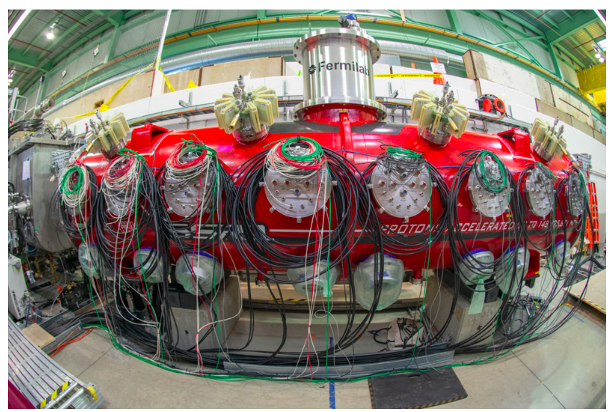
Current Status

ProtoDUNE(s):

- World's largest LArTPCs to date, operating with the DUNE readout at CERN.
- Shows scalability.
- Already producing physics results.







Current Status

Near Detectors:

- Finished design for the ND facility.
- Prototyping and testing underway for all 3 detectors.

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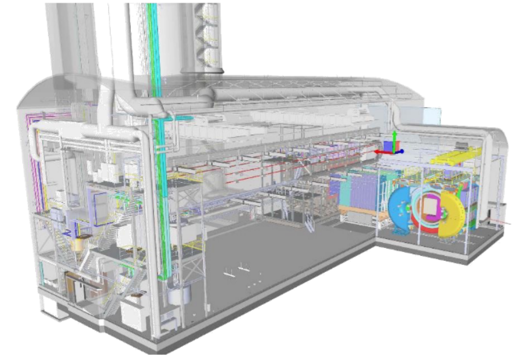
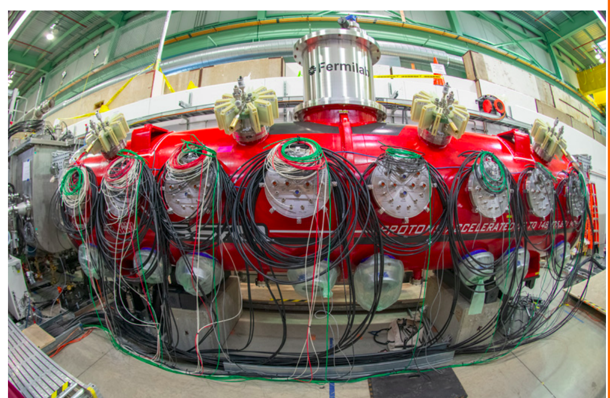
Current Status

Far Site:

- Excavation one-third complete, progressing on schedule.
- FD anode plane factory up and running in the UK.

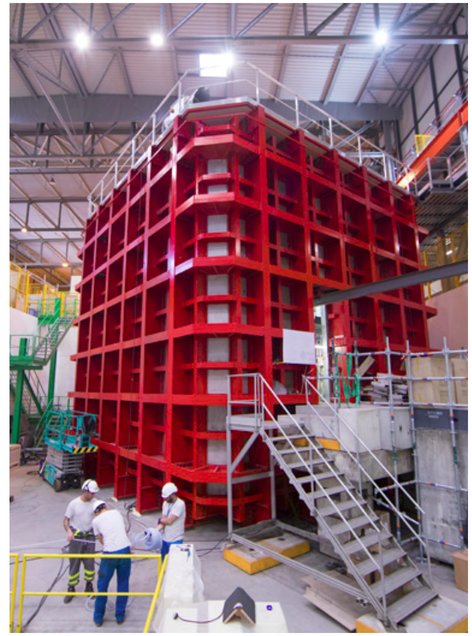


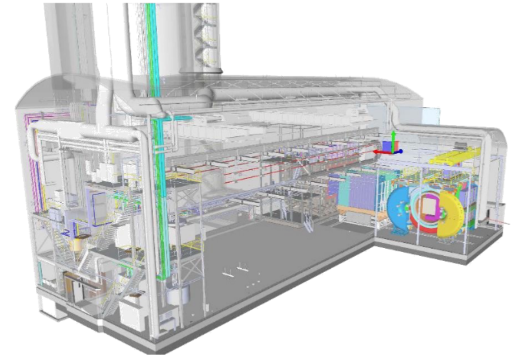


Current Status

PIP-II

- Facility under construction at Fermilab.
- Equipment already being delivered and tested.





Summary

- DUNE is a next-generation oscillation experiment that will take our understanding of the PMNS matrix into the precision era.
  - World-beating measurement of the mass hierarchy.
  - 5σ sensitivity to CP violation across much of the parameter space.
  - High precision on θ_{23}. **- DUNE can do it all!**
- More than just a headline measurement, but a facility to serve the forefront of neutrino physics for decades to come.
  - **World-class beam** – PIP-II.
  - **World-class detector technology** – LArTPCs, DUNE-PRISM.
  - **World-class subterranean facilities.**
  - **Broad programme of measurements beyond PMNS.**

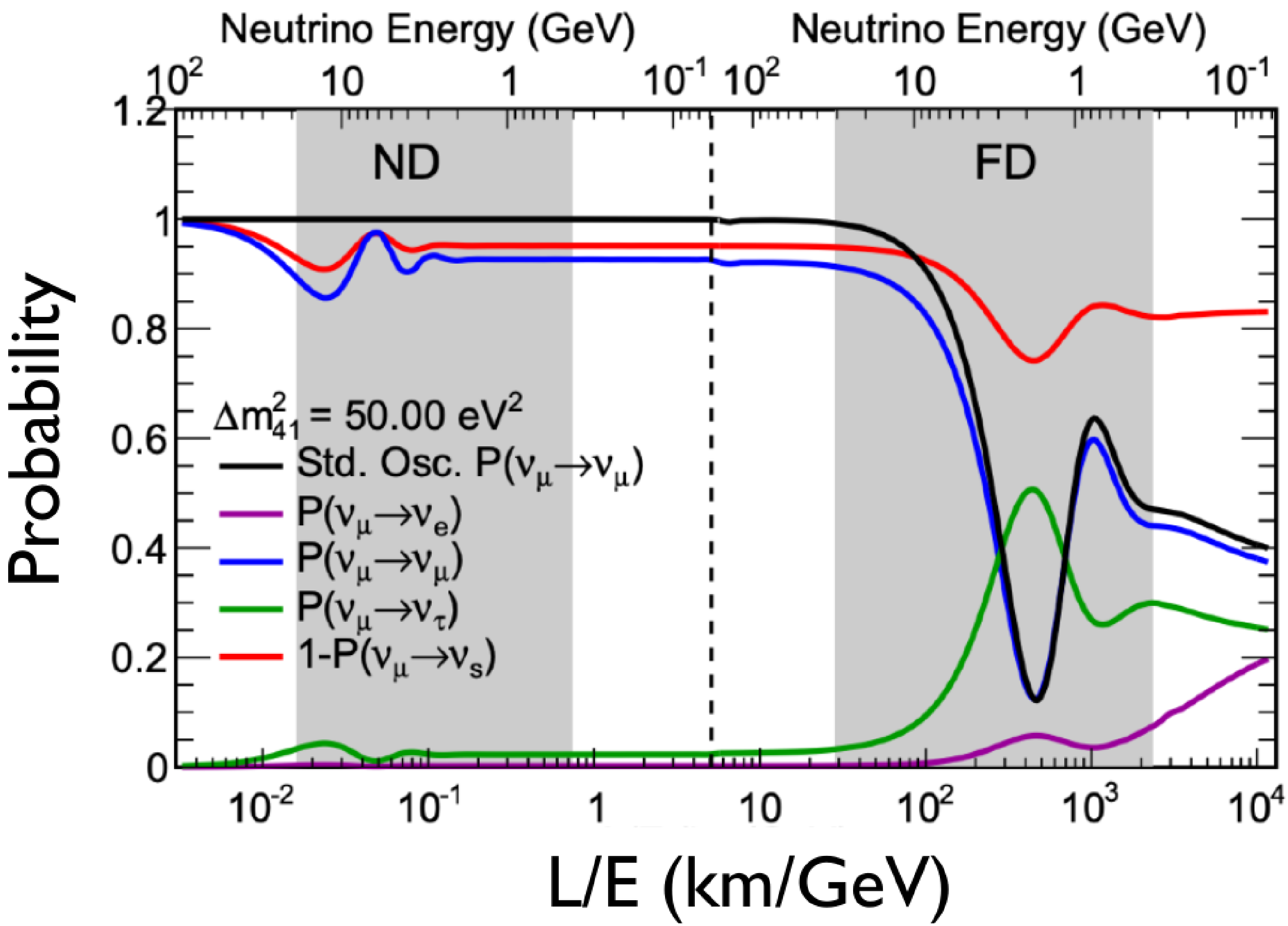
    - Supernovae - Nucleon Decay - New Particles
- **Progress is well underway!**

Thank you for your attention

The global DUNE collaboration...

...plus ~1200 collaborators just off-screen, from over 200 institutions in over 30 countries!

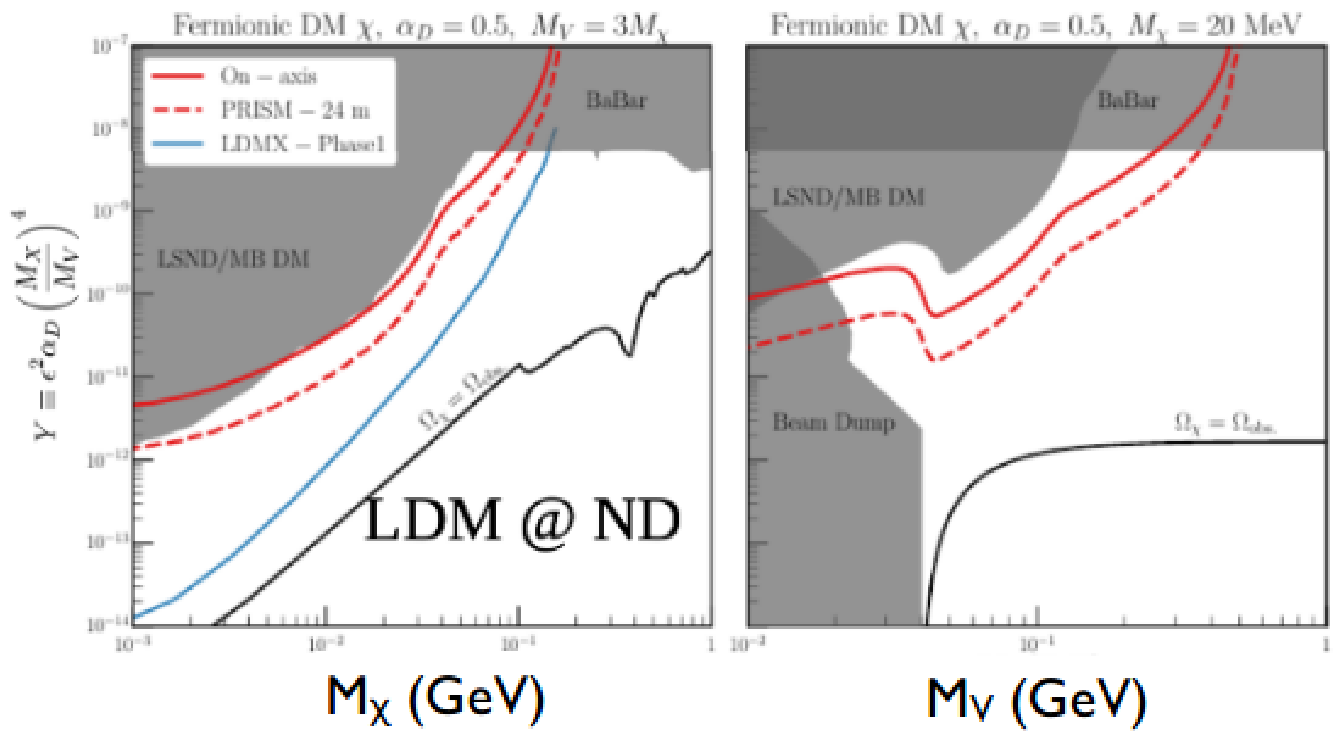
Backup: Sterile Sensitivity



Backup: Dark Matter Sensitivity

Sensitive to:

- Beamline DM at near detector (off-axis angle helps control SM backgrounds)
- Boosted cosmogenic DM at far detector.



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Backup: Heavy Neutral Leptons

Looking for decay of new particle in LAr. World-leading sensitivity in some areas of phase space.