Probing the secrets of neutrinos with the DUNE experiment

The Deep Underground Neutrino Experiment

DUNE physics goals

1. Make precise measurements of the oscillation parameters
2. Resolve the neutrino mass hierarchy
3. Determine whether CP is violated in neutrinos and measure δ_{CP}
4. Check the unitarity of the PMNS matrix
5. Be ready to detect low-energy neutrinos from a supernova
6. Other beyond the standard model physics

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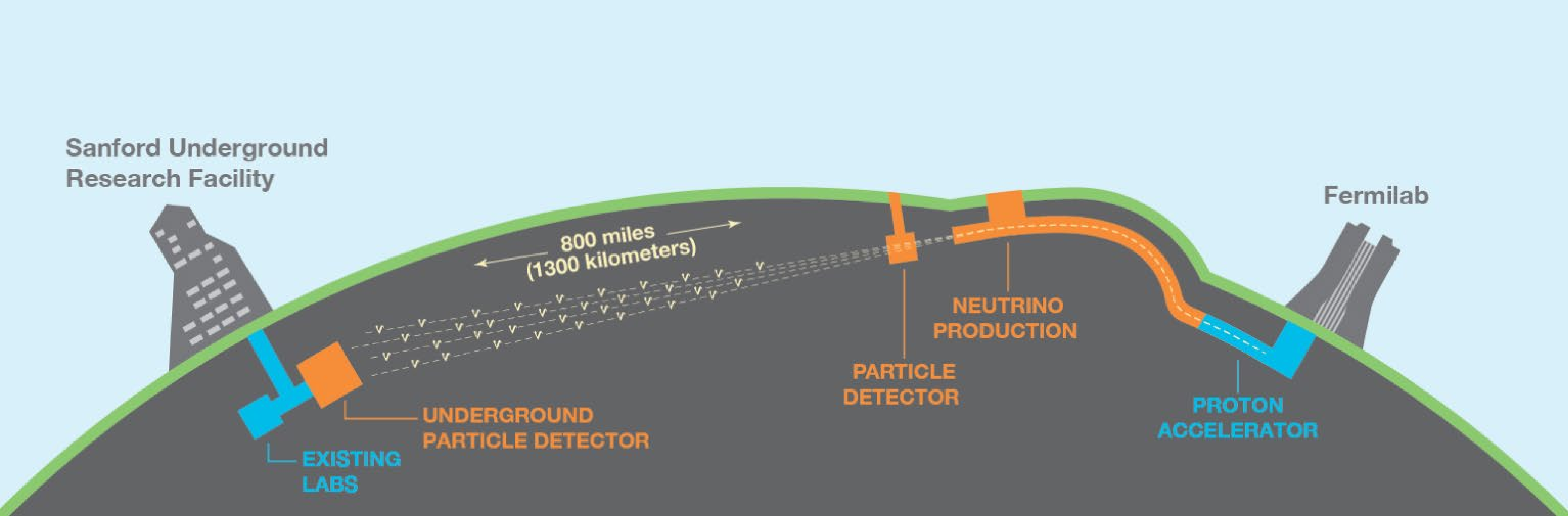
DEEP UNDERGROUND NEUTRINO EXPERIMENT



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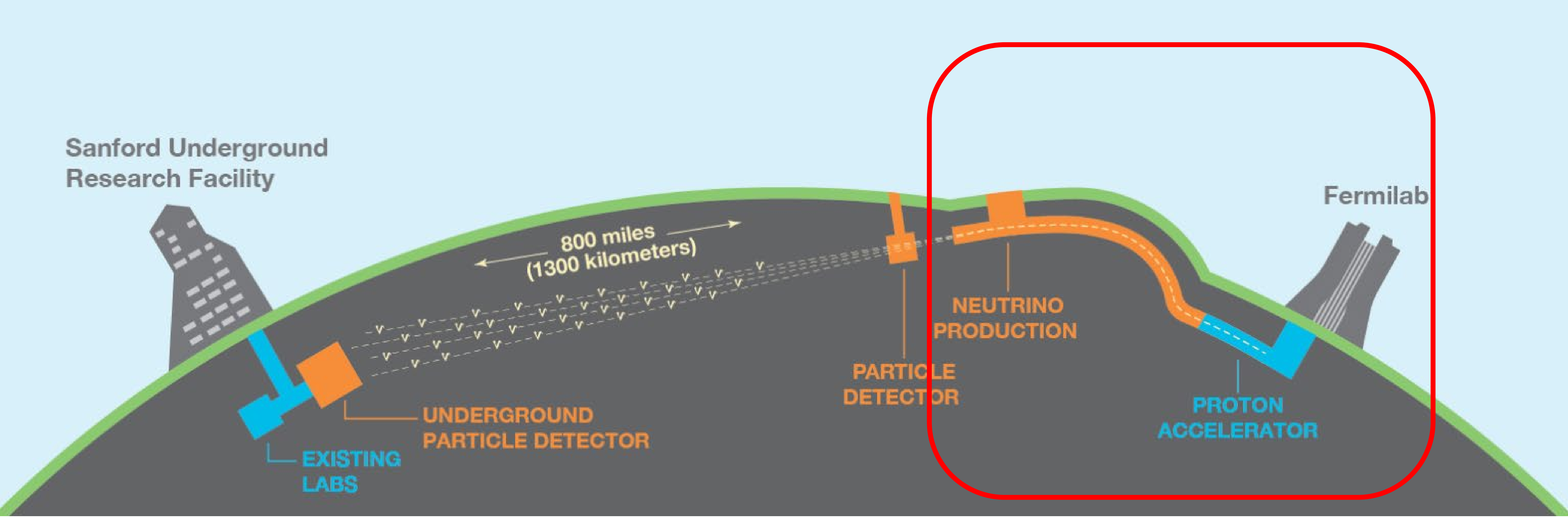
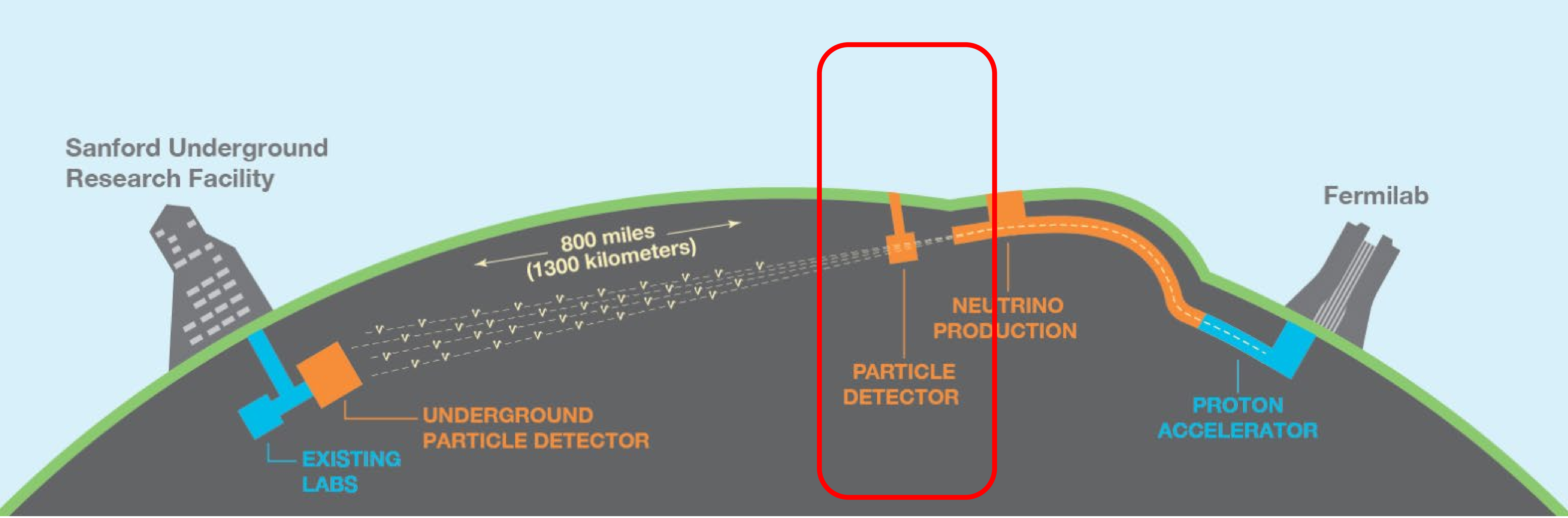


DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



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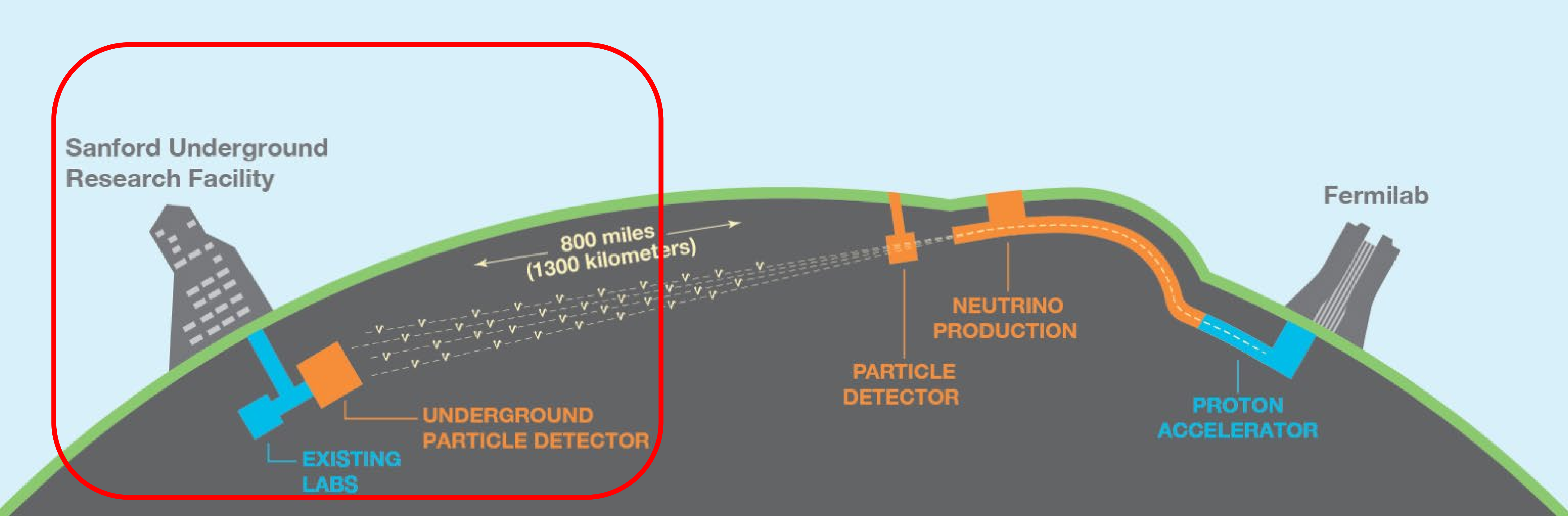
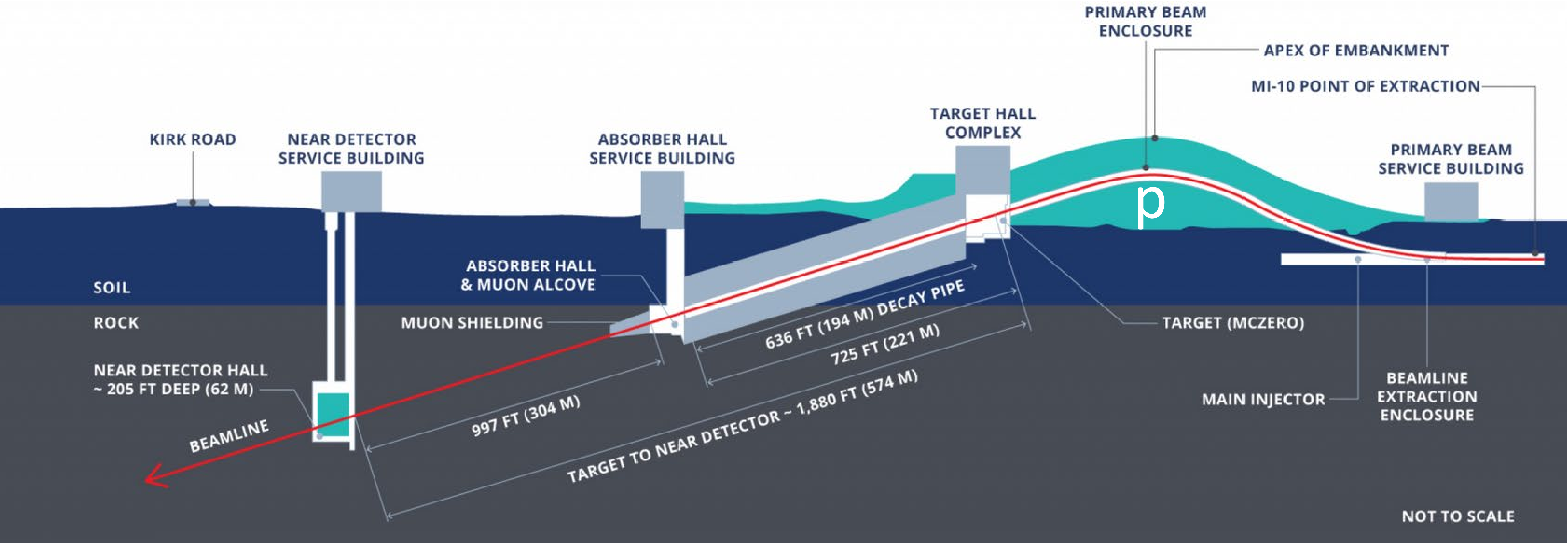


World's most intense neutrino beam



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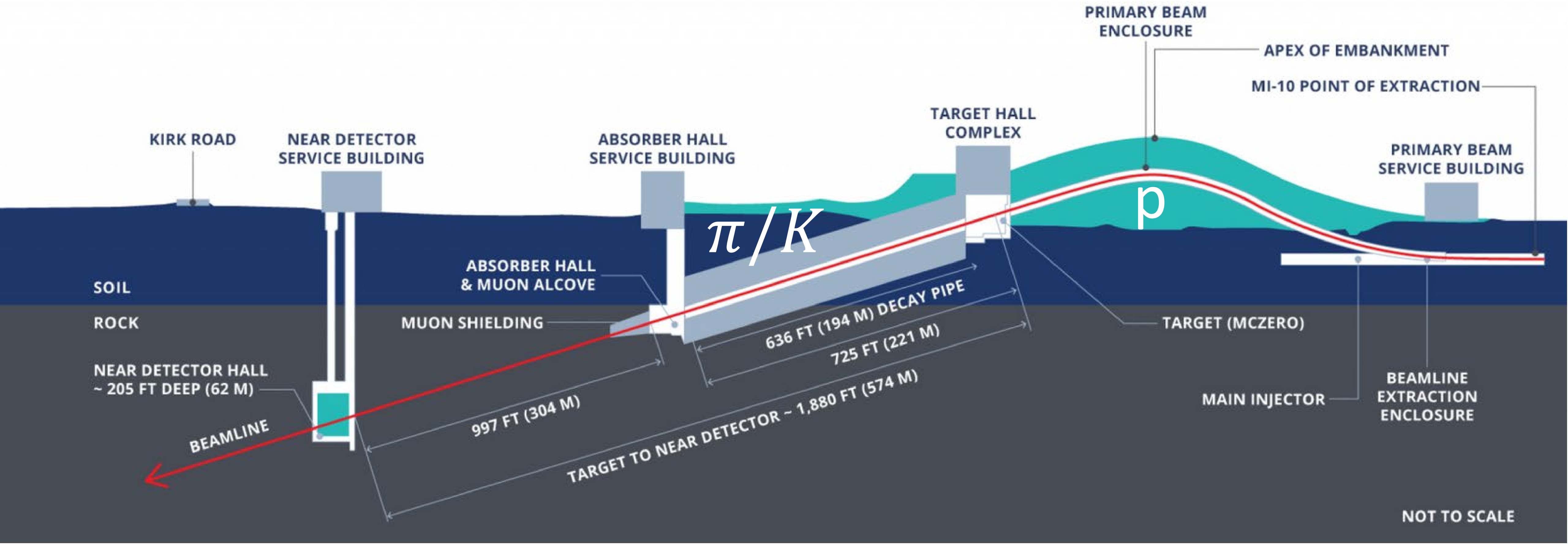

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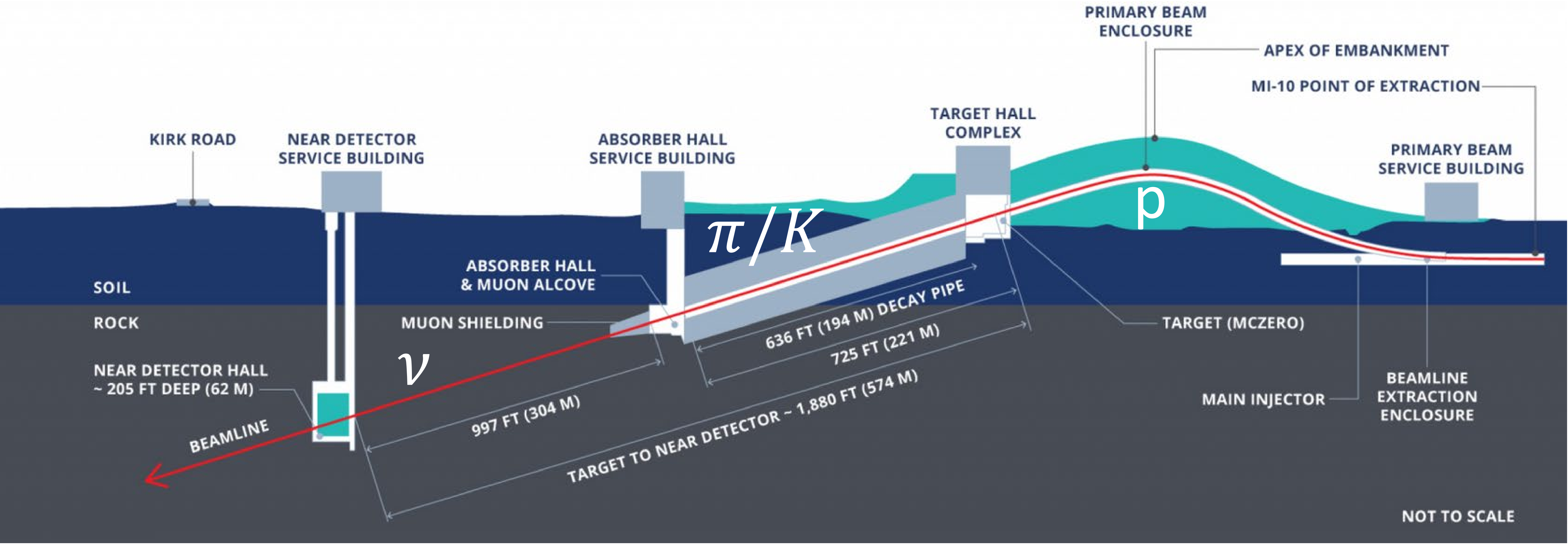

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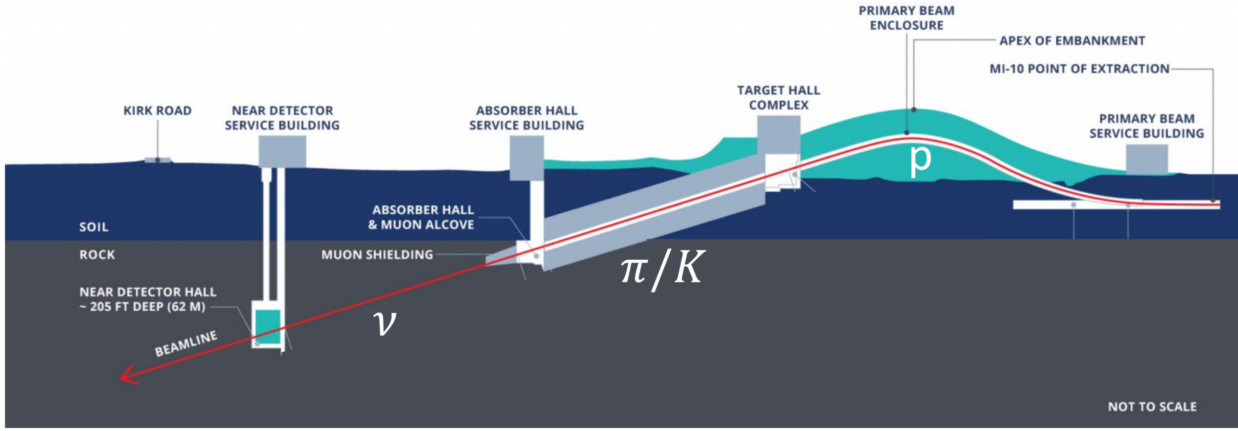

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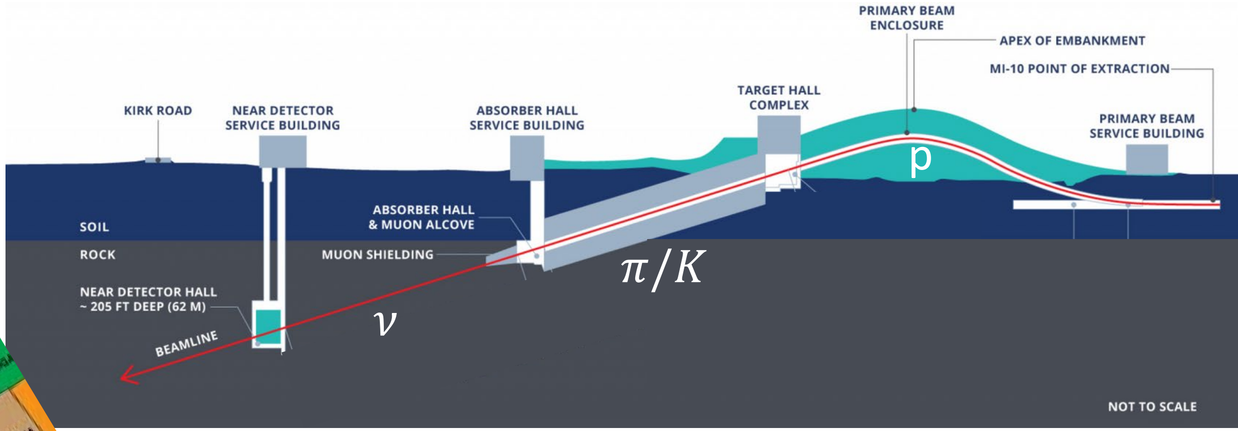

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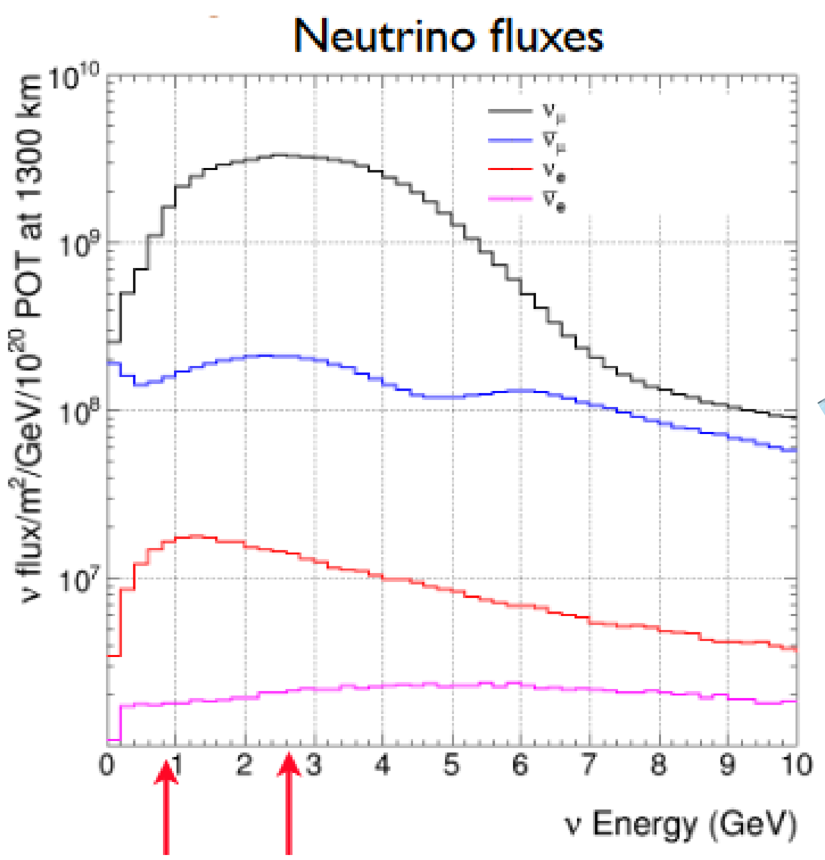
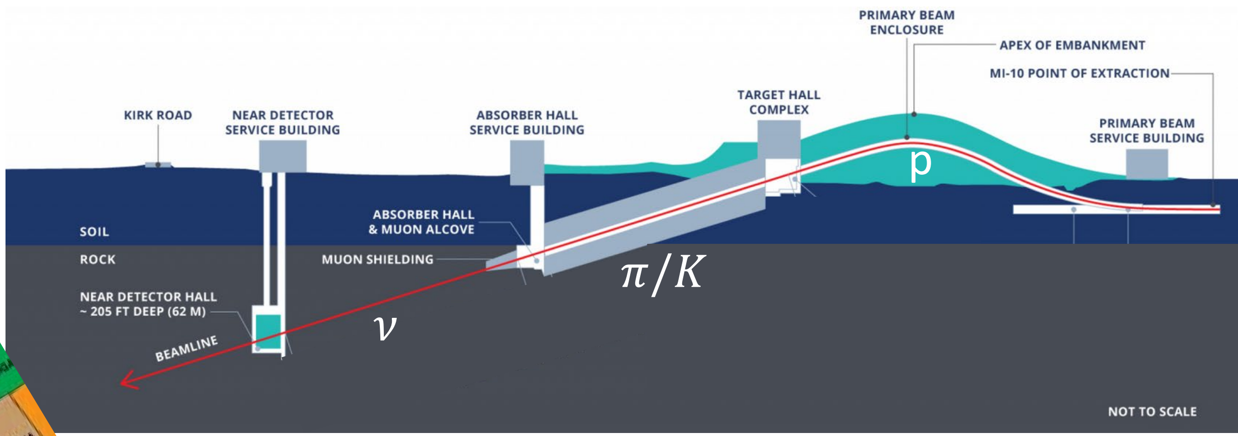
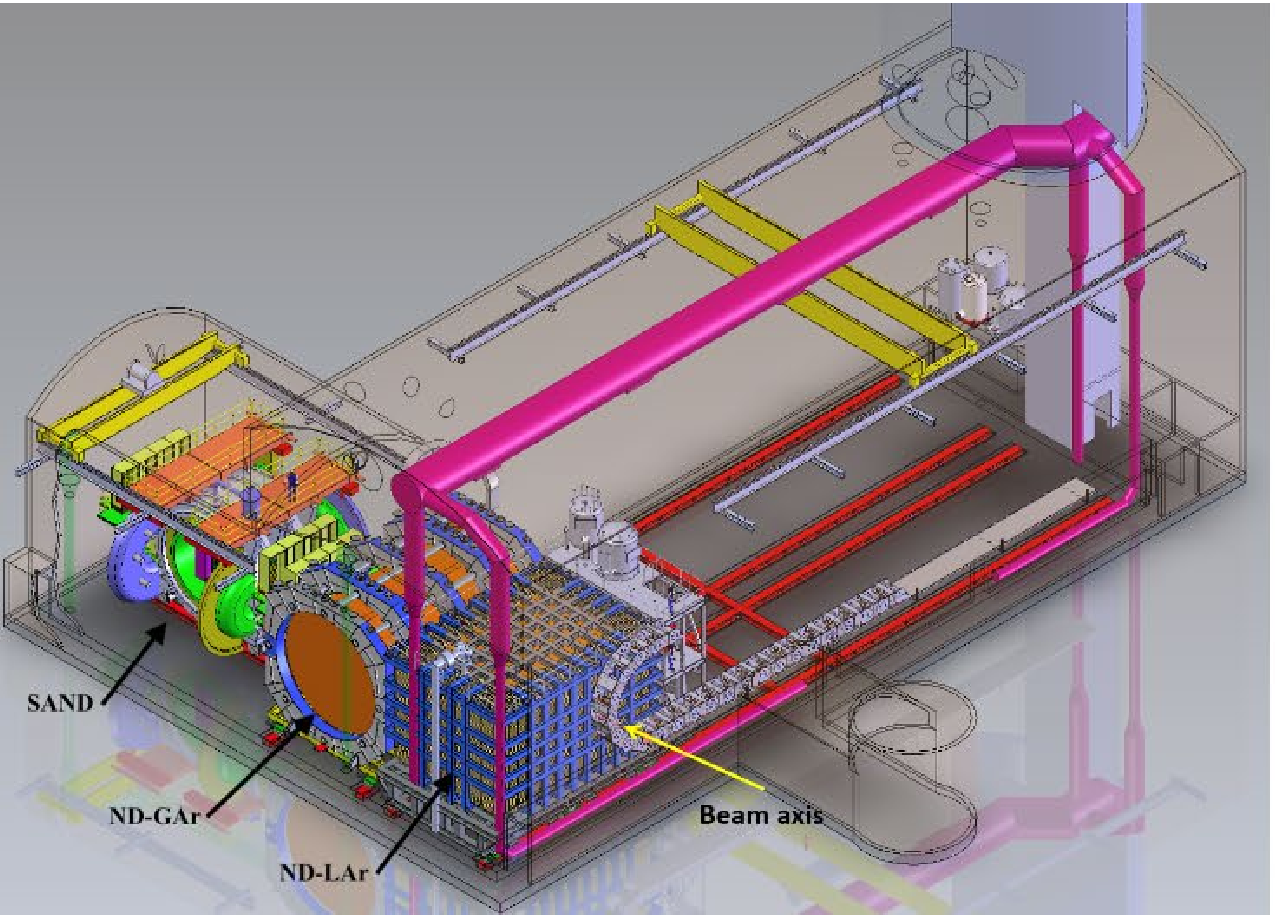
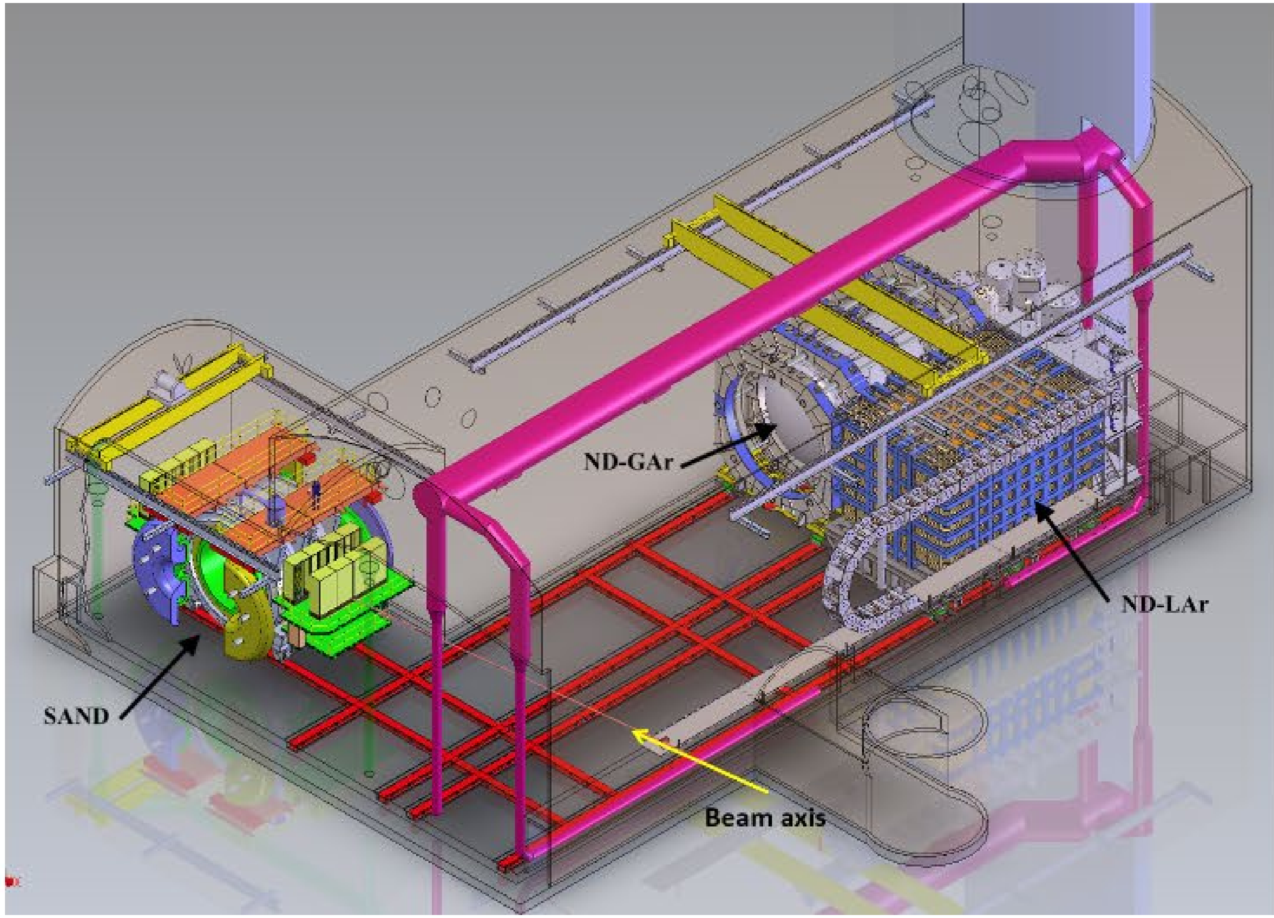


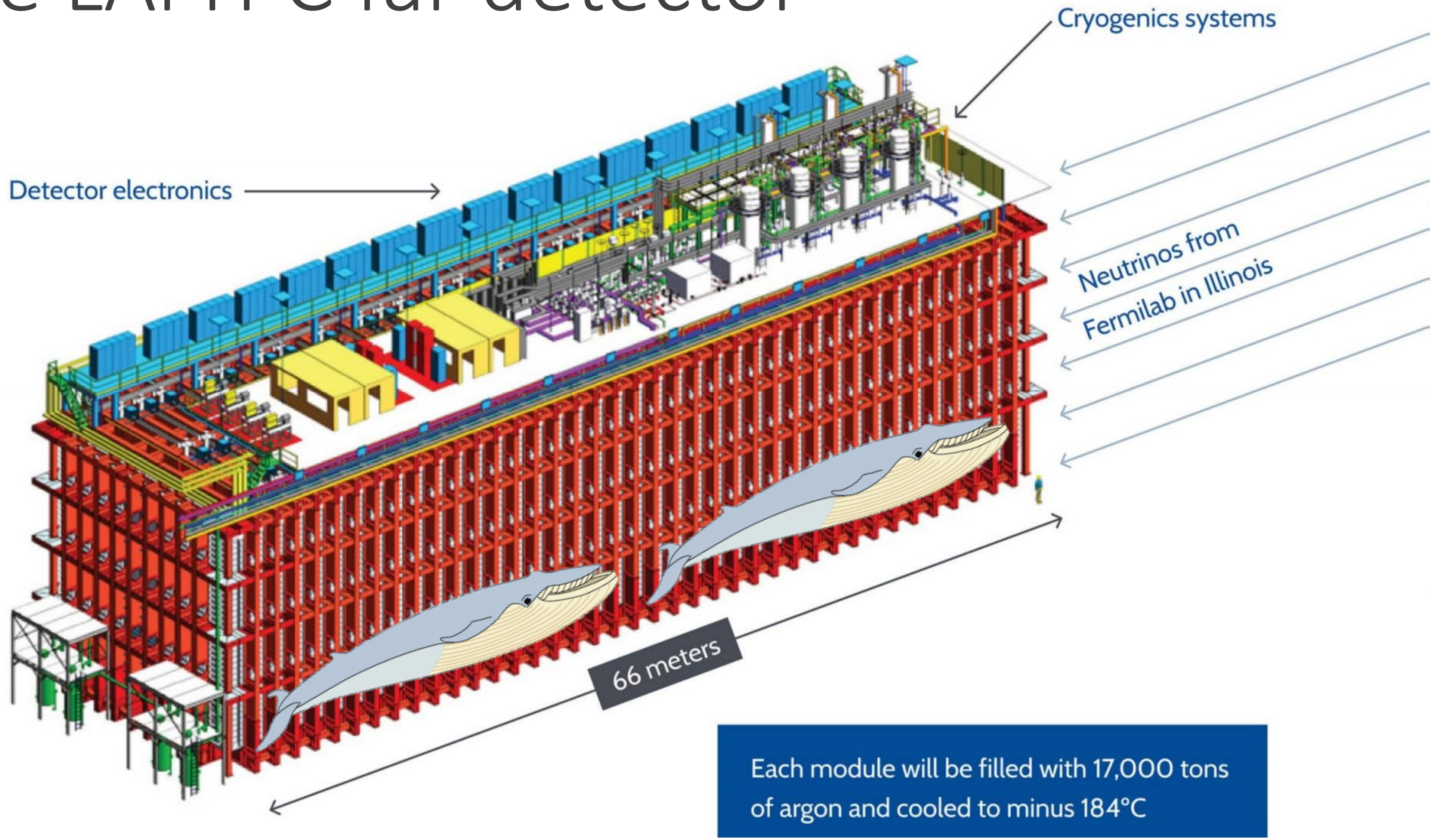


Moveable near detector

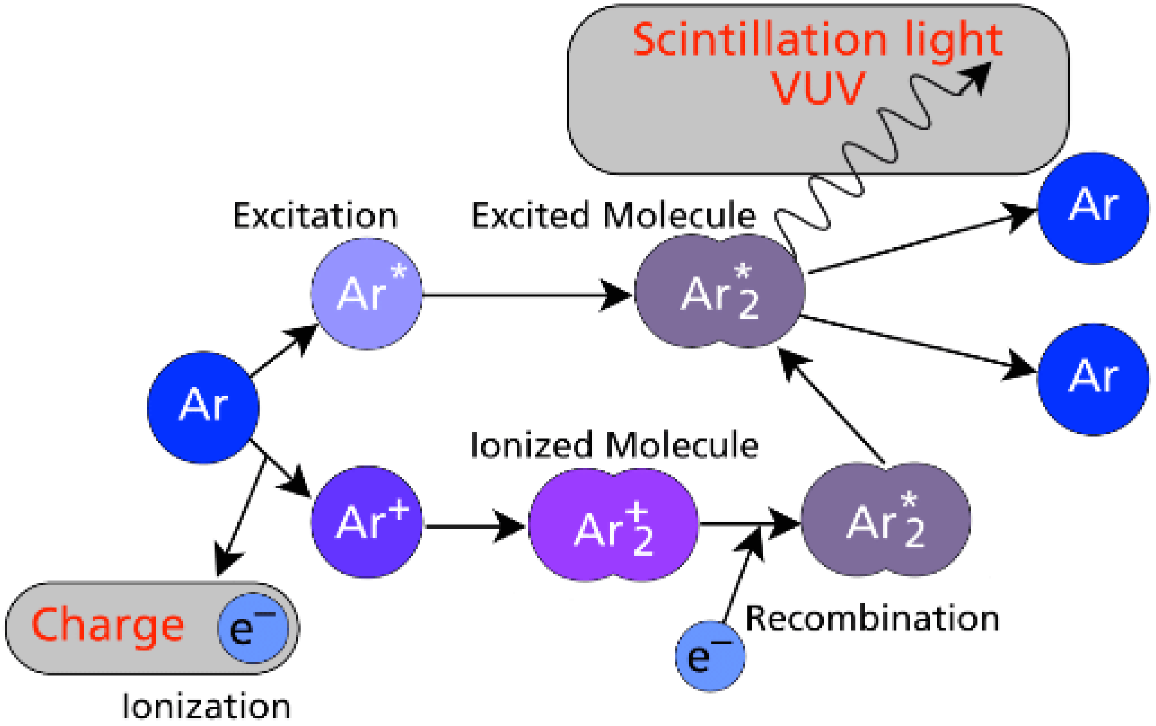




Large LArTPC far detector



Liquid argon neutrino detection



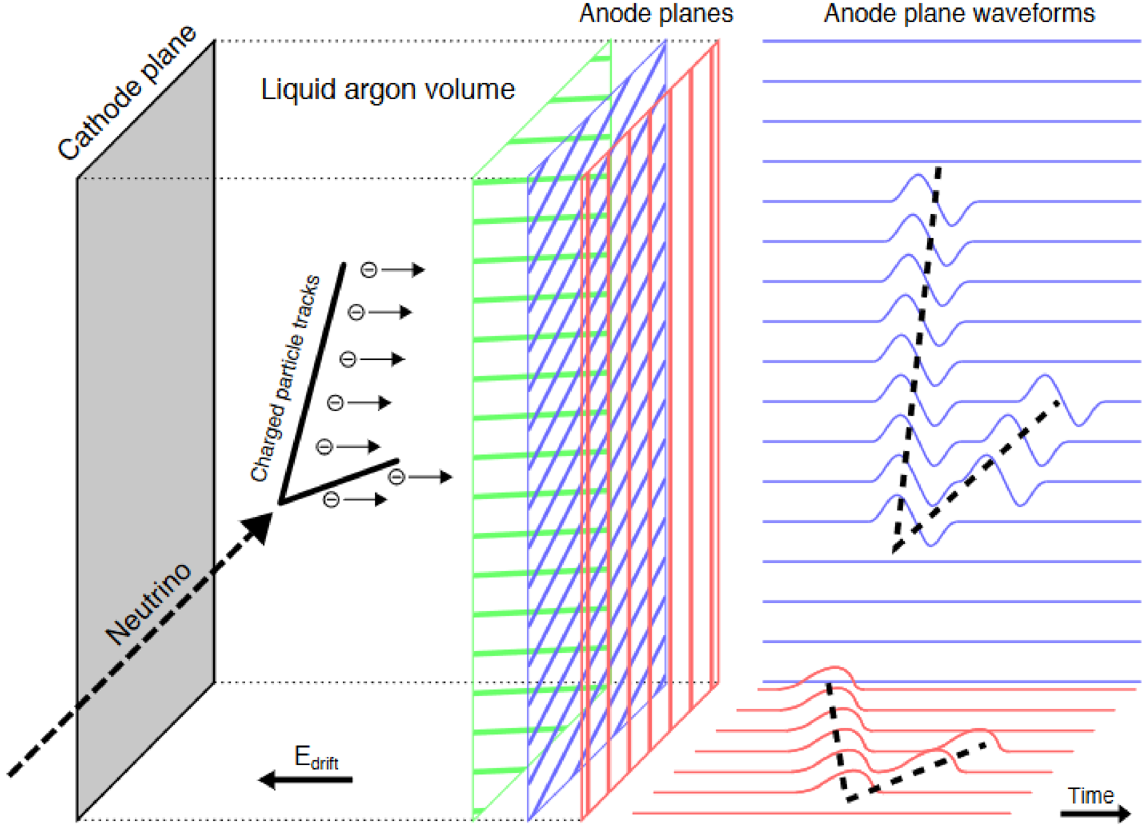
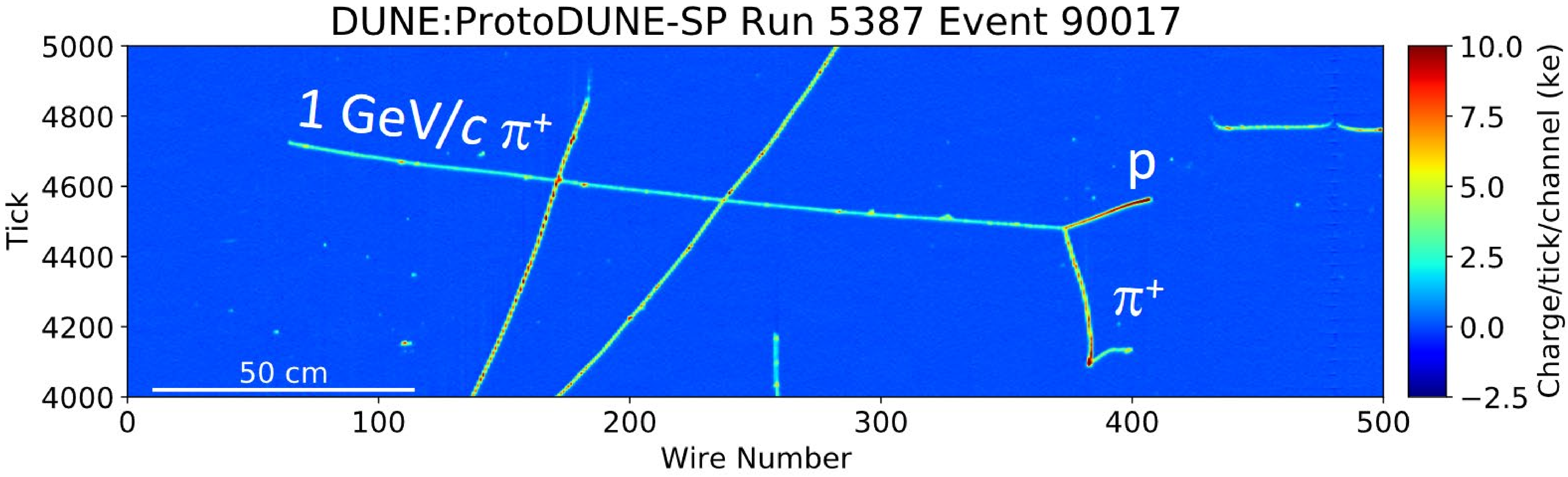


Image like event reconstruction



CP-violation measurements in DUNE

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U_{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

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

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin(\delta) \sin(\frac{\Delta m_{12}^2}{4E} L) \sin(\frac{\Delta m_{13}^2}{4E} L) \sin(\frac{\Delta m_{23}^2}{4E} L)$$

We know the mixing angles and mass differences

We can measure $P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)$

So, we can calculate δ_{CP}?

Measuring δ_{CP} - matter effect

NO! We are not in vacuum! In matter
$P(\nu_e \rightarrow \nu_\mu) \neq P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$ even if $\delta_{CP} = 0$
because matter is not CP-symmetric!

$P(\nu_e \rightarrow \nu_\mu) - P(\bar{\nu}_e \rightarrow \bar{\nu}_\mu)$ has three terms in matter (see backup for formula)

(ref: https://arxiv.org/pdf/hep-ph/9703351.pdf)

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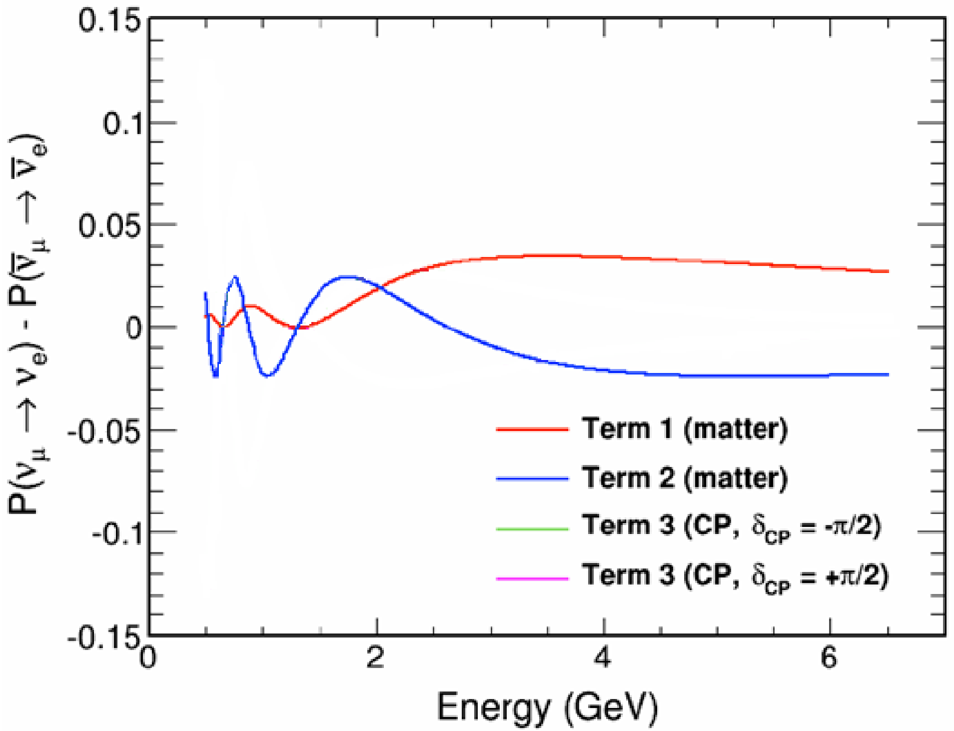

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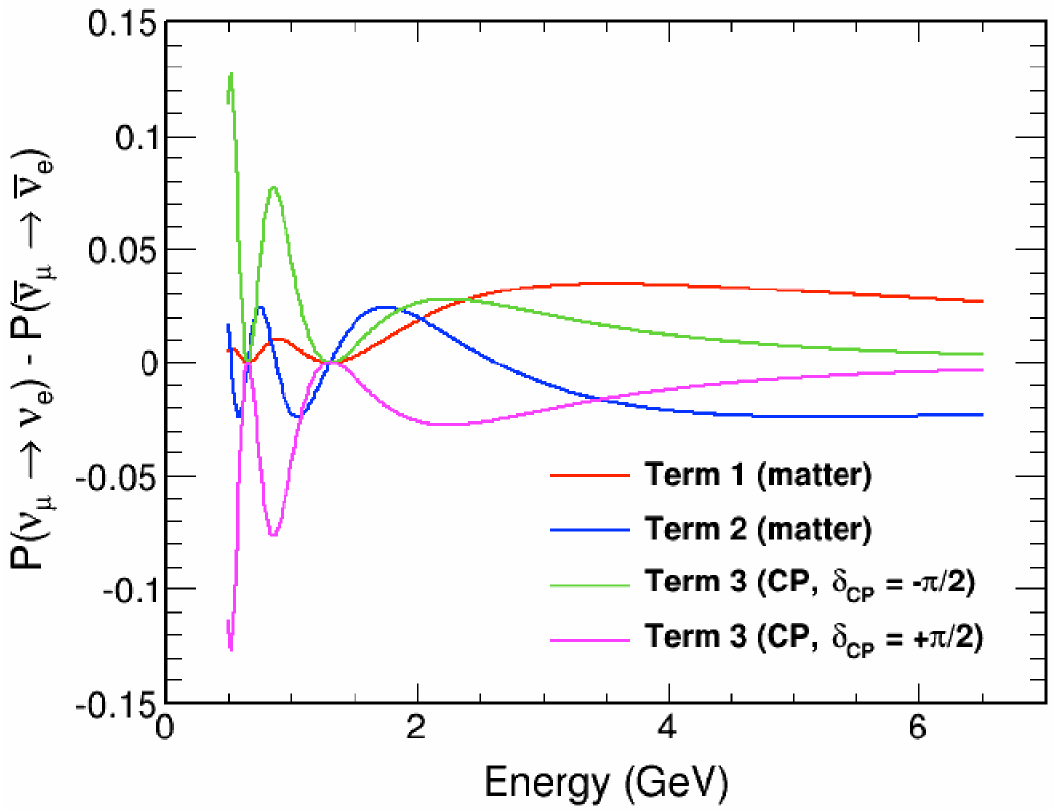

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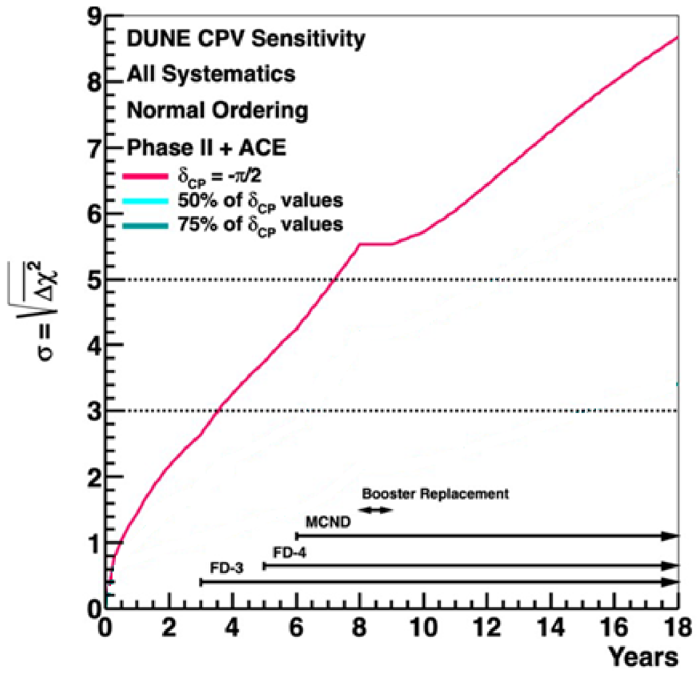
DUNE has good CP violation sensitivity



Exact timeline depends on the timing of the detector updates!

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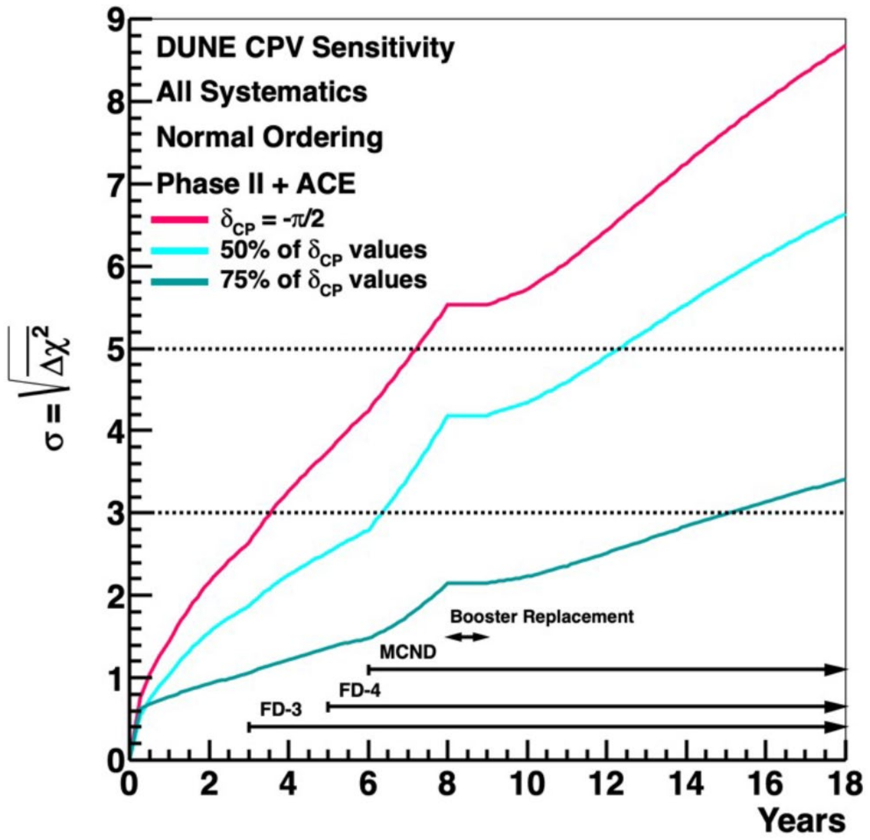

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DUNE is unique

Due to its long baseline of 1300 km, neutrino oscillations between the DUNE near and far detectors will be significantly altered by matter effects

DUNE will use an on-axis ν_μ and $\overline{\nu_\mu}$ beam with a broad range of energies including the first and second oscillation maxima

These features will enable DUNE to resolve the neutrino mass hierarchy and perform precision measurements of the oscillation parameters, search for CP violation in neutrinos and measure δ_{CP} in a single experiment. DUNE will also test the unitarity of the PMNS matrix

DUNE is sensitive to the ν_e component of a supernova neutrino flux

Backup slides

Matter effect

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu) \approx \frac{16A}{\Delta m_{31}^2} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$
$$- \frac{2AL}{E} \sin\left(\frac{\Delta m_{31}^2 L}{2E}\right) c_{13}^2 s_{13}^2 s_{23}^2 (1 - 2s_{13}^2)$$
$$-8 \frac{\Delta m_{12}^2 L}{2E} \sin(\delta) \sin^2\left(\frac{\Delta m_{13}^2}{4E} L\right) s_{13} c_{13}^2 c_{23} s_{23} c_{12} s_{12}$$

$$A = 2\sqrt{2}\, G_F n_e E$$

- Experimental strategies:
  1. Keep L small, then the matter effect is small and can be neglected
     - High flux at a single energy
  2. Make L large and measure the matter effect
     - Need multiple energies to disentangle matter effect and CP-violation

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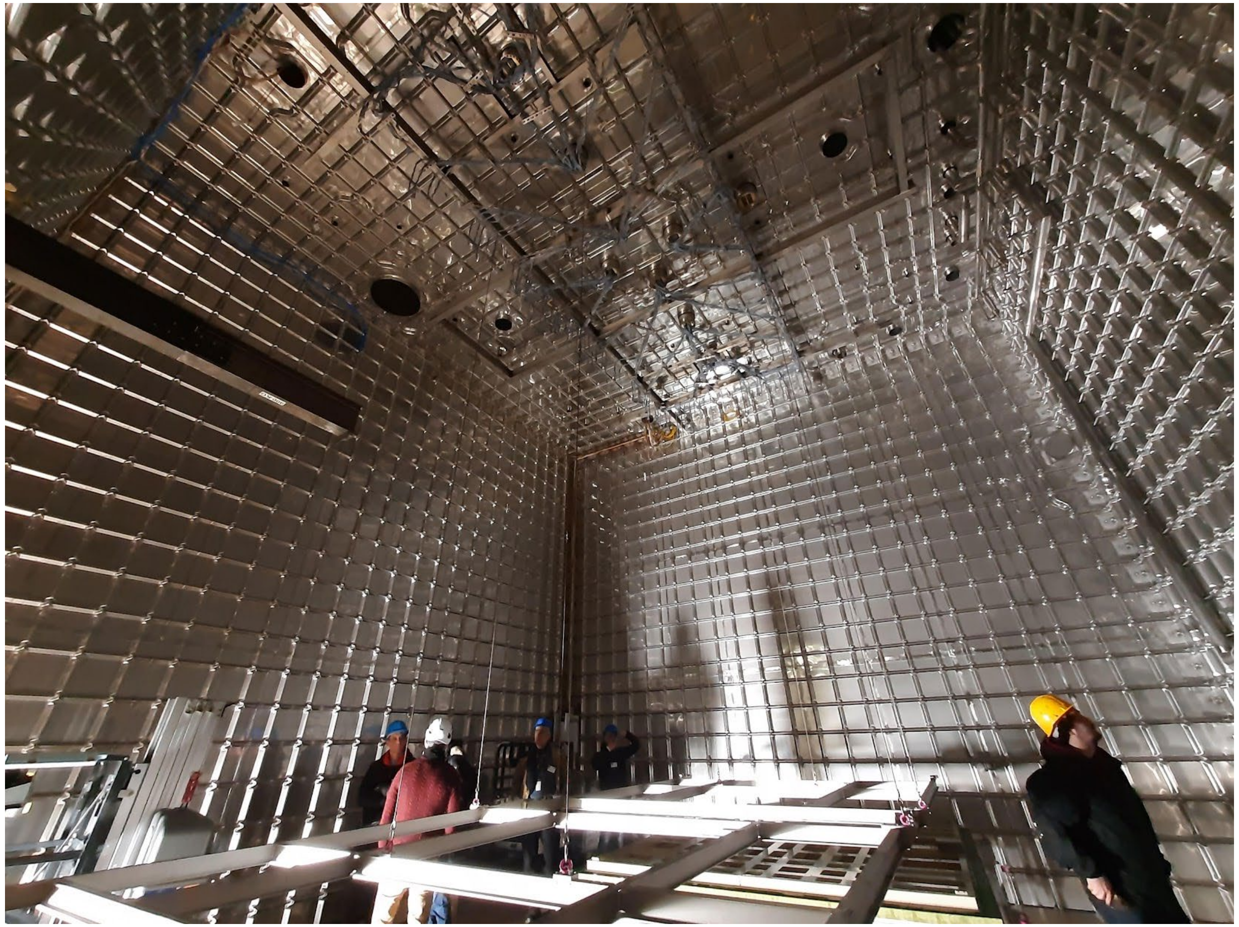
Hyper Kamiokande

DUNE

DUNE facts

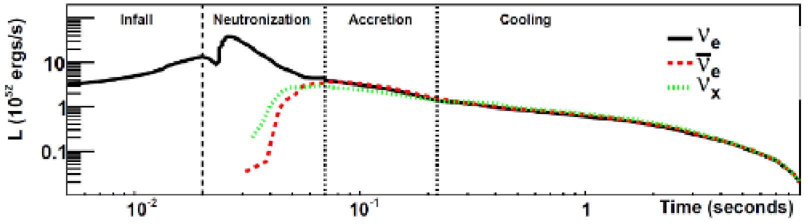
- 120 kt MW yr exposure by 2035
- 40 kt liquid argon
- 1.2 MW beam power upgradeable to 2.4 MW
- 1443 collaborators
- FD caverns excavation now at 65% completion

ProtoDUNEs at CERN neutrino platform



Supernovae

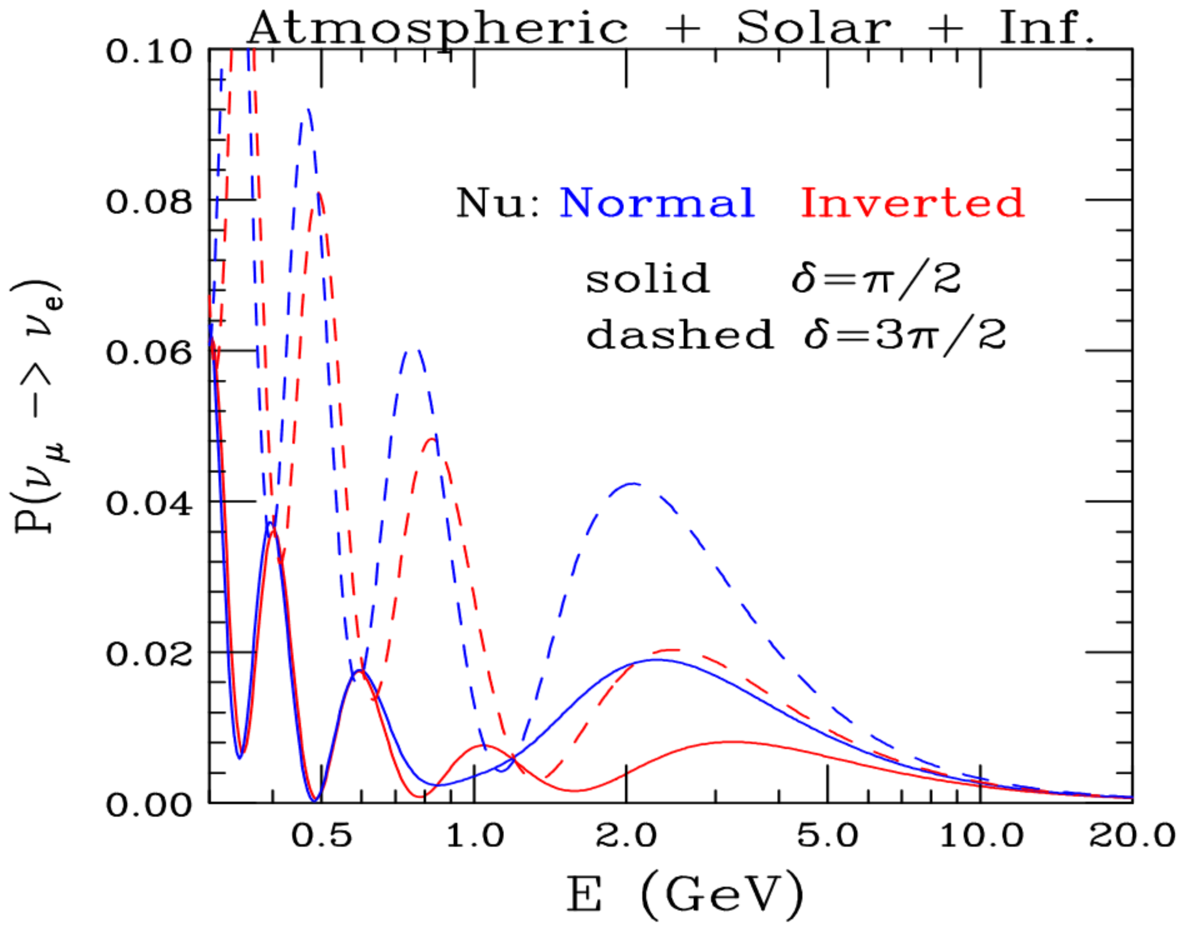
DUNE measures SNB ν_es;
other experiments measure $\bar{\nu}_e$

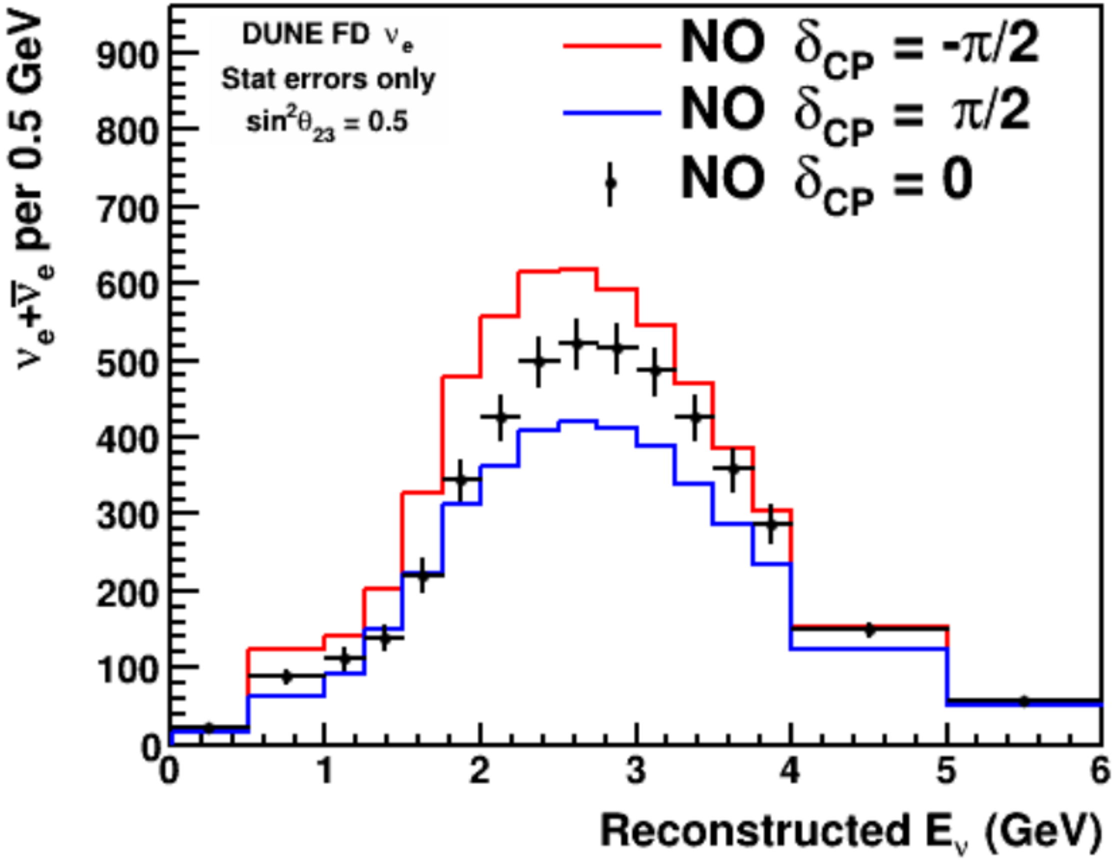


	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

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

Oscillation probability

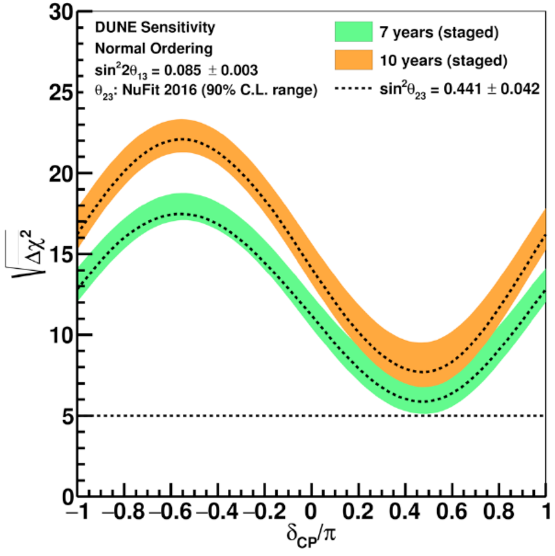




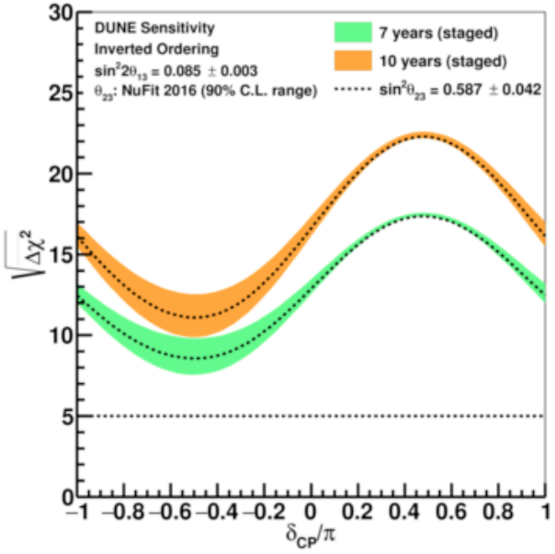
CP-violation sensitivity

Sensitivity to determination of mass hierarchy as a function of true value of δ_{CP}.
Bands represent range of sensitivity for different values of θ_{23} (NuFit 2016 90% C.L. range).
Significance increases with increasing θ_{23}.
θ_{13} and Δm_{31}^2 have smaller effect on significance than θ_{23}.

Normal ordering



Inverted ordering



Mass hierarchy

Number of neutrino types N = 2.996±0.007*

m_ν < 1.1 eV (90% C.L.)*

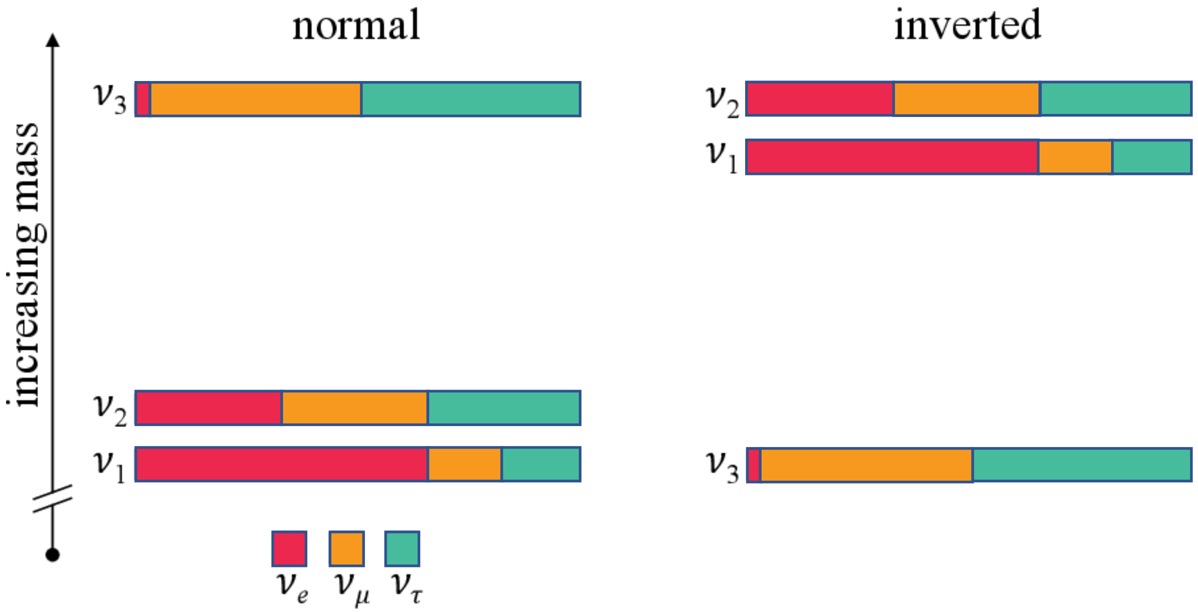
Flavour eigenstates ≠ mass eigenstates

$m_2 > m_1$

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

Mixing angles $\theta_{12}, \theta_{23}, \theta_{13}$ and a phase δ_{CP}

*R.L. Workman *et al.* (Particle Data Group), Prog.Theor.Exp.Phys.**2022**, 083C01 (2022)



Neutrino oscillations

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

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

with $s_{ij} = \sin(\theta_{ij})$ and $c_{ij} = \cos(\theta_{ij})$, $\theta_{23} \sim 45°$, $\theta_{13} \sim 9°$, $\theta_{12} \sim 30°$

Open questions in neutrino physics

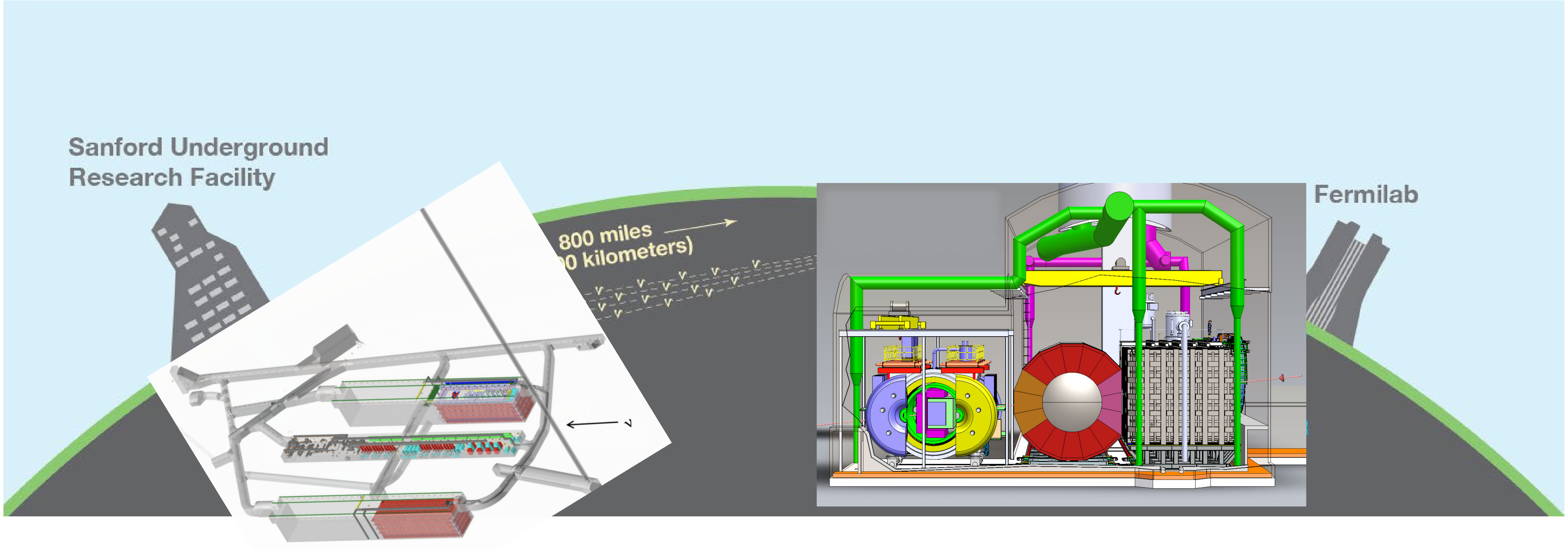
1. Neutrino mass hierarchy: It is still not known whether the masses of the three known types of neutrinos (electron, muon, and tau neutrinos) are ordered in a specific way, known as the "mass hierarchy." This is an important question because it affects the behavior of neutrinos as they travel through matter and can impact the number of neutrinos detected in experiments.
2. Neutrino oscillations: Neutrinos are known to oscillate between different types as they travel through space. However, the exact mechanism behind this phenomenon is not well understood, and more precise measurements are needed to fully understand it.
3. CP-violation: CP-violation refers to the idea that the laws of physics are not the same if particles are replaced with their antiparticles and left and right are swapped. Neutrinos are believed to exhibit CP-violation, but the degree to which they do so is not yet known.
4. Neutrino mass: The mass of neutrinos is still not precisely known, and researchers are working to determine it more accurately.
5. Sterile neutrinos: In addition to the three known types of neutrinos, there may be additional, "sterile" neutrinos that do not interact through the weak force. However, the existence of sterile neutrinos has not been confirmed, and their properties, if they do exist, are not well understood.

DUNE physics contribution

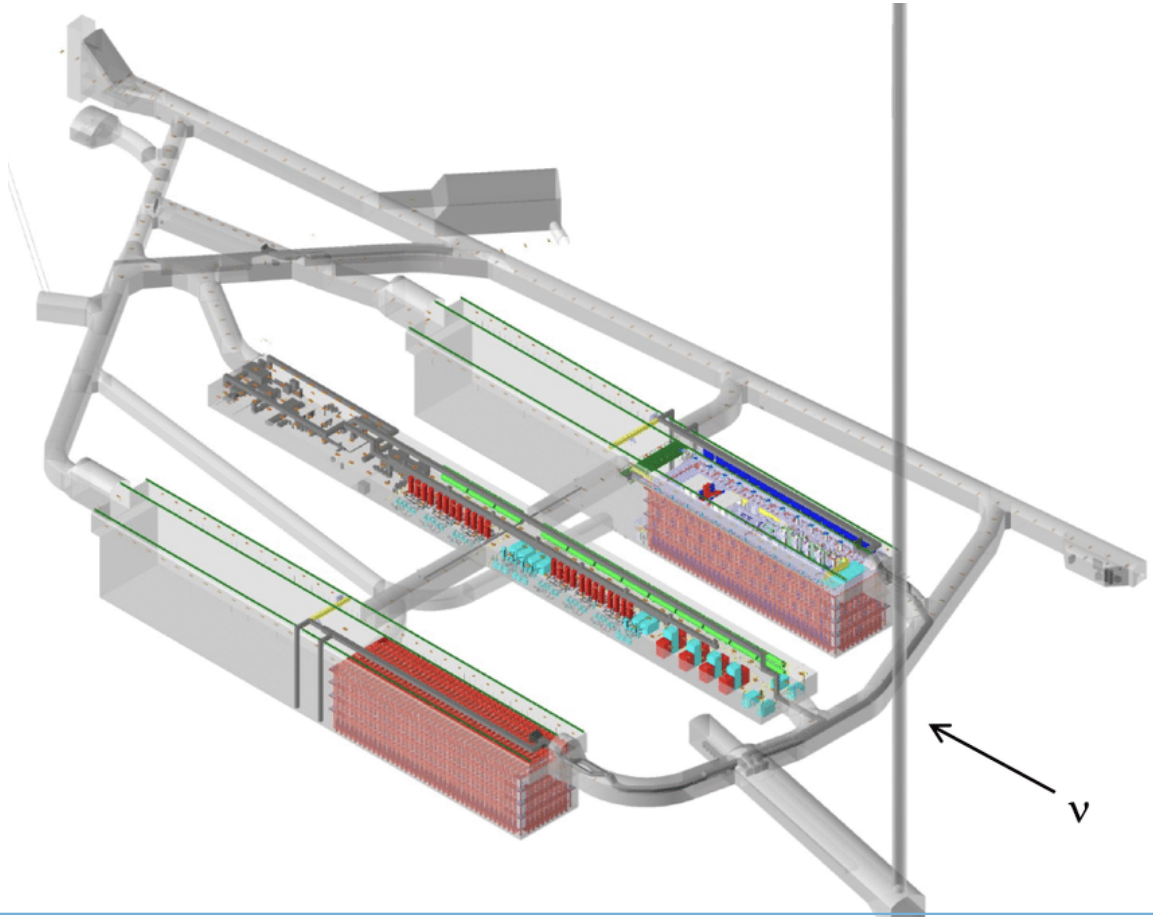
The primary science program of the LBNF/DUNE experiment focuses on fundamental open questions in neutrino and astroparticle physics:

- precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ oscillations with the goal of
    - measuring the charge-parity (CP) violating phase δ_{CP} — where a value differing from zero or π would represent the discovery of CP-violation in the leptonic sector, providing a possible explanation for the matter-antimatter asymmetry in the universe;
    - determining the neutrino mass ordering (the sign of $\Delta m^2{}_{31} \equiv m^2{}_3 - m^2{}_1$), often referred to as the neutrino mass hierarchy;
    - precision tests of the three-flavor neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and ν_μ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies;
- search for proton decay in several important decay modes, for example $p \rightarrow K^+\nu$, where the observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces;
- detection and measurement of the ν_e flux from a core-collapse supernova within our galaxy, should any occur during the lifetime of the DUNE experiment.

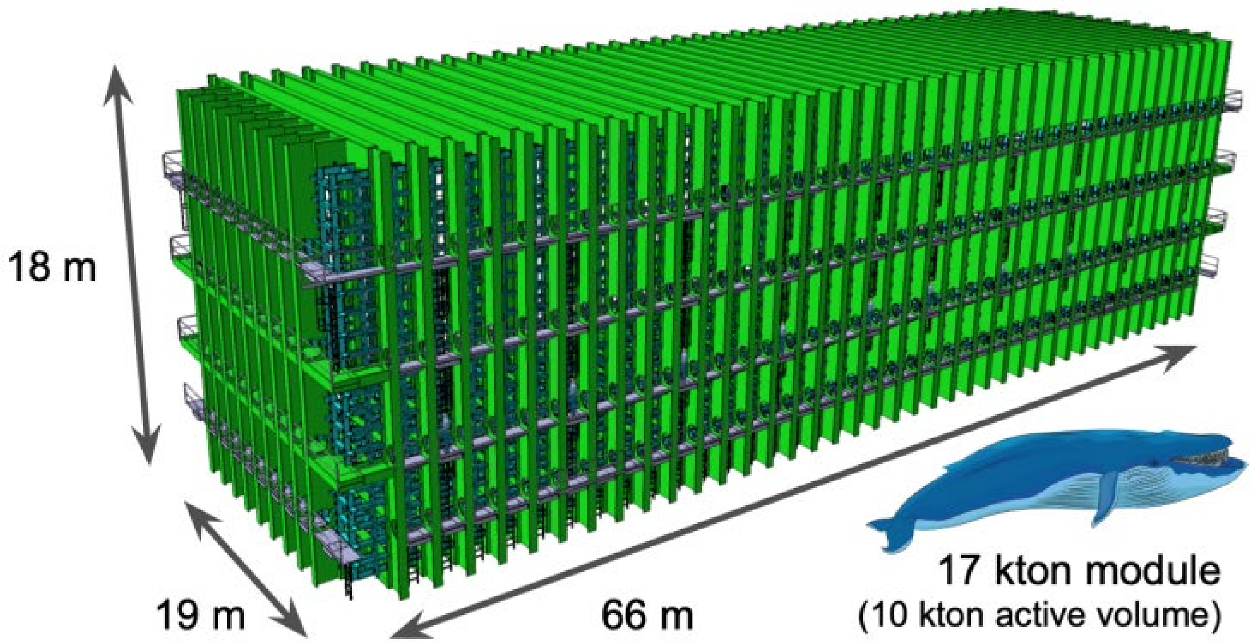
Near detector at Fermilab and far detector at SURF

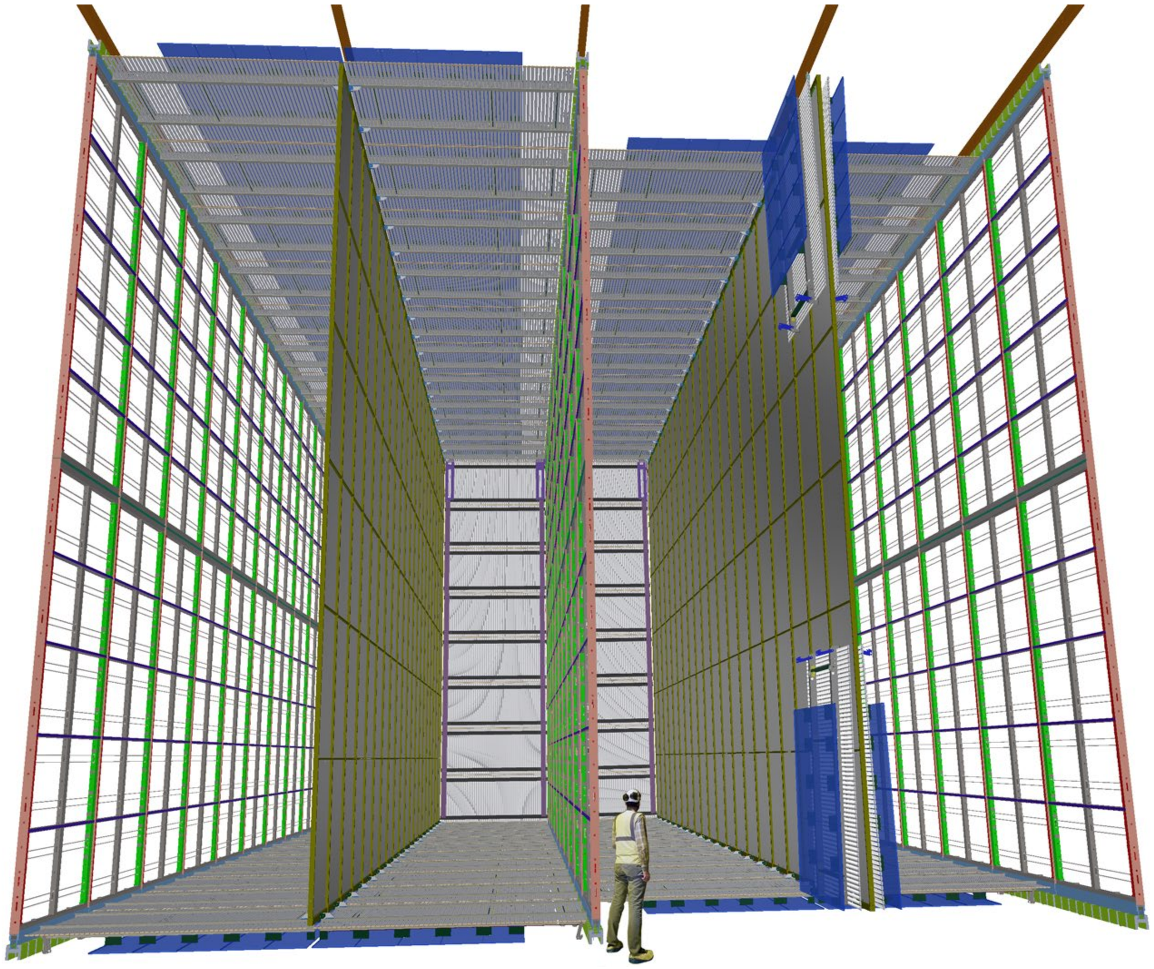


Far detector consists of 2(4) cryostats



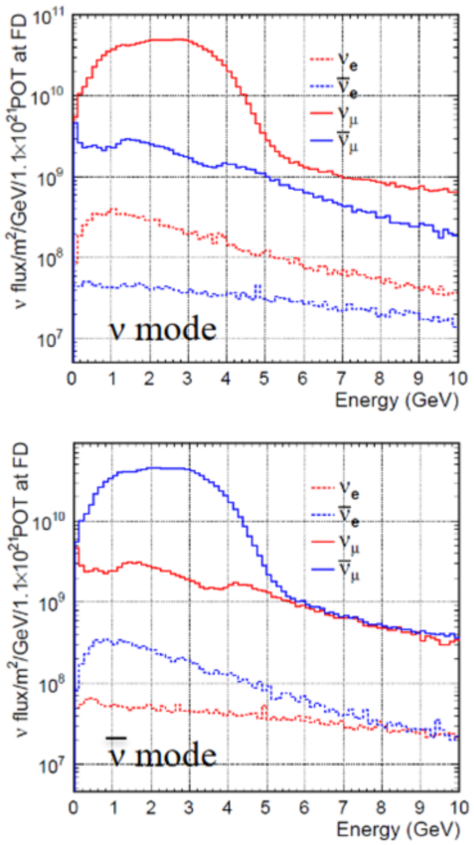
Each cryostat will be filled with 17 kton LAr



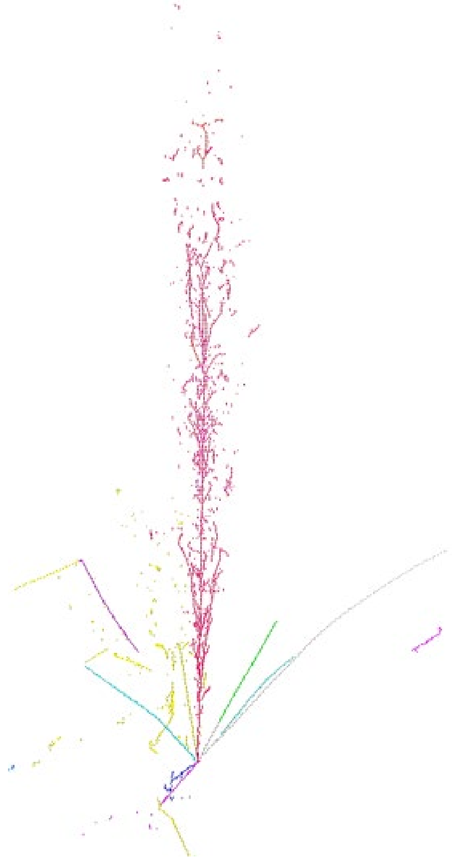


Measurement process

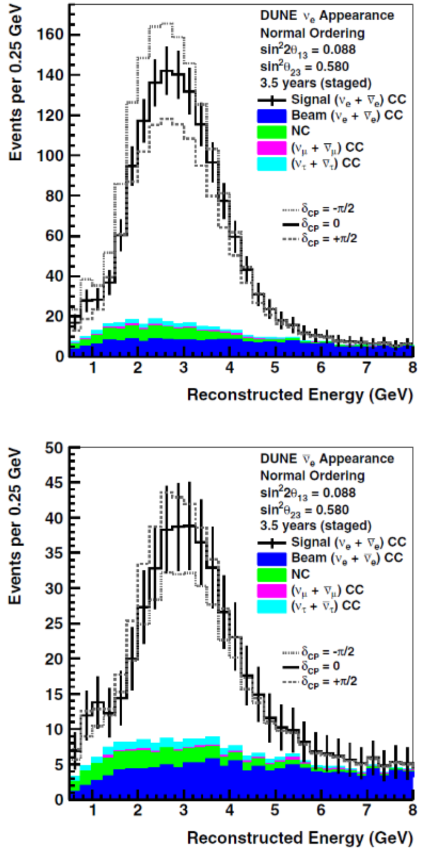
Neutrino beam



Reconstructed event



Signal to background



Discovery potential