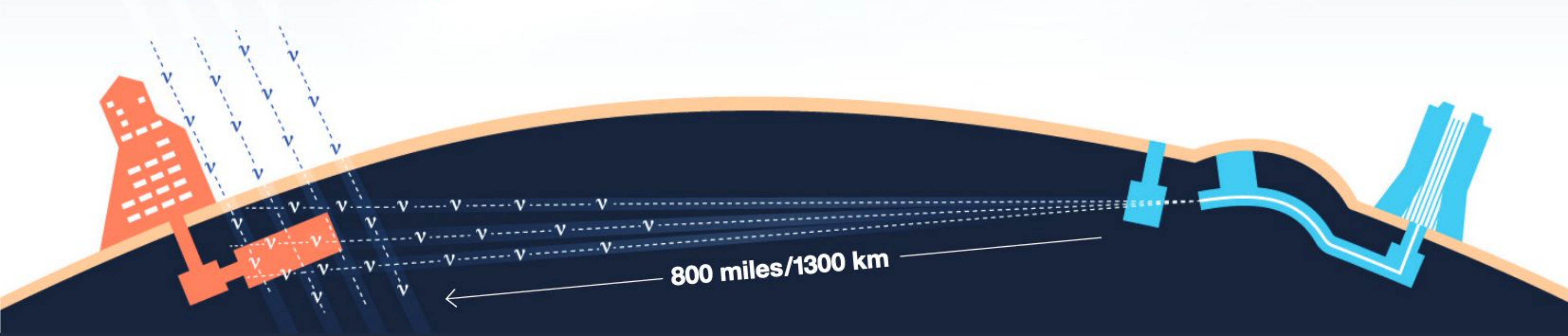
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

Claire David

YORK UNIVERSITÉ UNIVERSITY



May 6th, 2021 Summer Particle Astrophysics Workshop

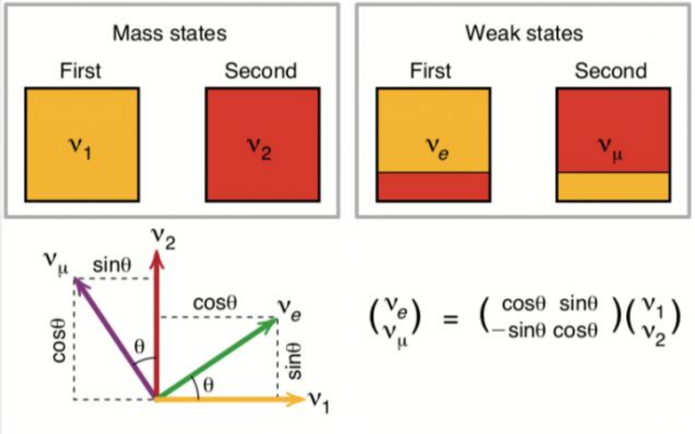
What we know about neutrinos

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

- There are 3 neutrino flavours in the Standard Model: electron, muon and tau
- Neutrinos interact only via the weak force (W and Z bosons)
- **Neutrinos oscillate** = they change flavour over time

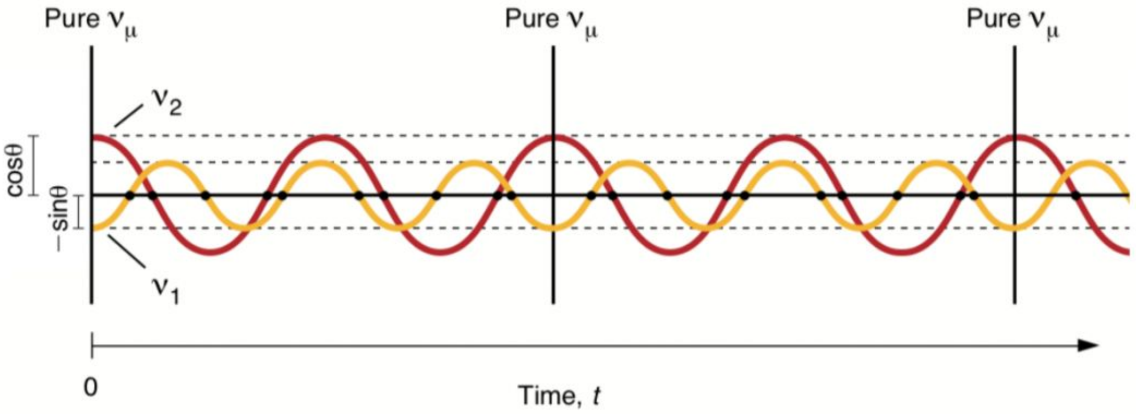
Neutrino oscillations

Simplified 2 neutrino model.



$$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

Superposition of mass eigenstates with different ‘phases’



Time evolution ⇒ periodic ‘appearance’ and ‘disappearance’ of a weak/flavour state.

Probability for the neutrino to oscillate from flavour α to β is:

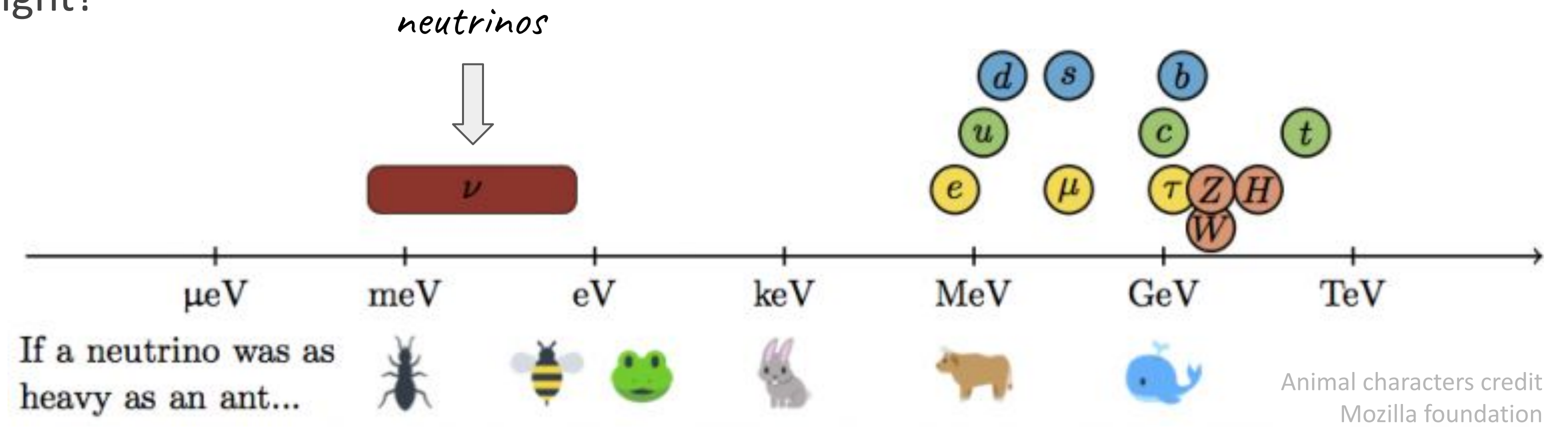
$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta \sin^2 \frac{(m_1^2 - m_2^2)L}{4E}$$

L : distance travelled
E: neutrino energy

What we don't know yet

What we don't know about neutrinos

- Why so light?

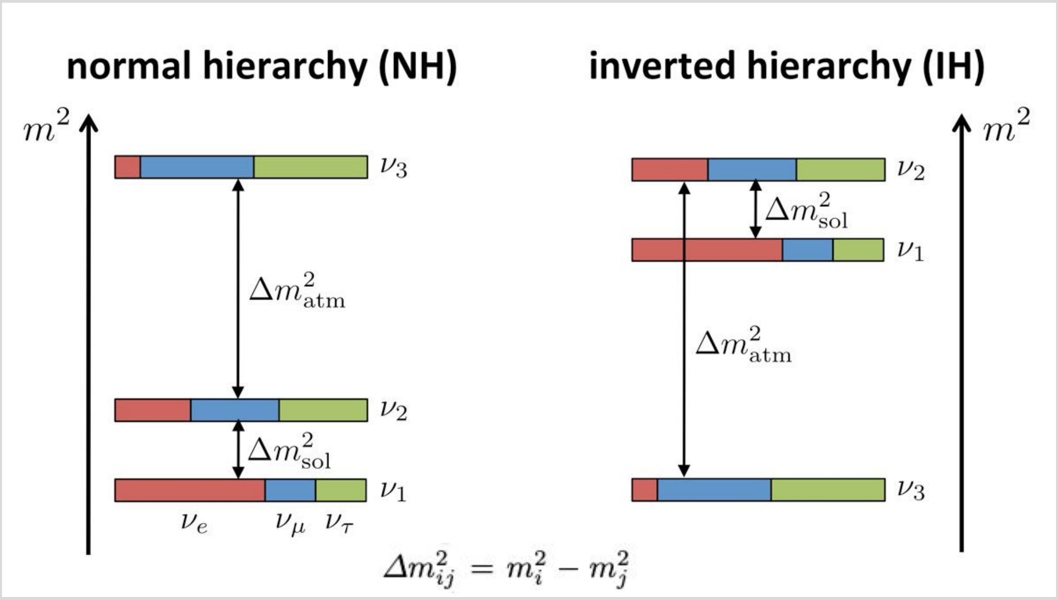


Animal characters credit
Mozilla foundation

- Which mechanism give neutrinos their masses?

Mass hierarchy

Is the ν_1 mass eigenstate with most ν_e the lightest one? Or is ν_3 the lightest?



Does ν_3 have more ν_μ or ν_τ ?

CP violation

Are neutrinos oscillating the same way as antineutrinos?

If not:

⇒ CP violated in the leptonic sector

Potential groundbreaking discovery!

Symmetry Magazine

How to know?

By measuring the phase δ_{CP}

if you like maths/matrices, see backup slides 30 - 31

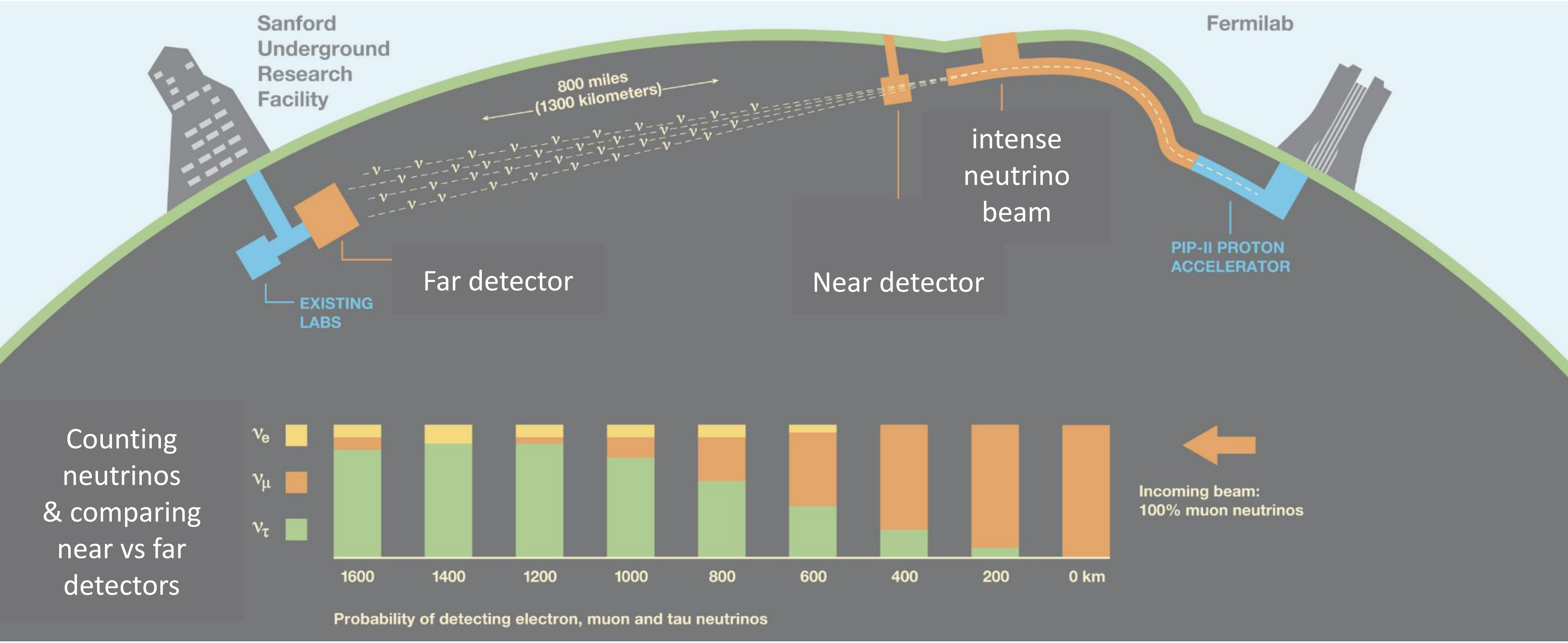
DUNE will compare probabilities: $P(\nu_\mu \rightarrow \nu_e)$ vs $P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)$

DUNE

Deep Underground Neutrino Experiment

DUNE, a long baseline oscillation experiment

Key feature: DUNE will measure neutrinos’ properties before and after oscillations



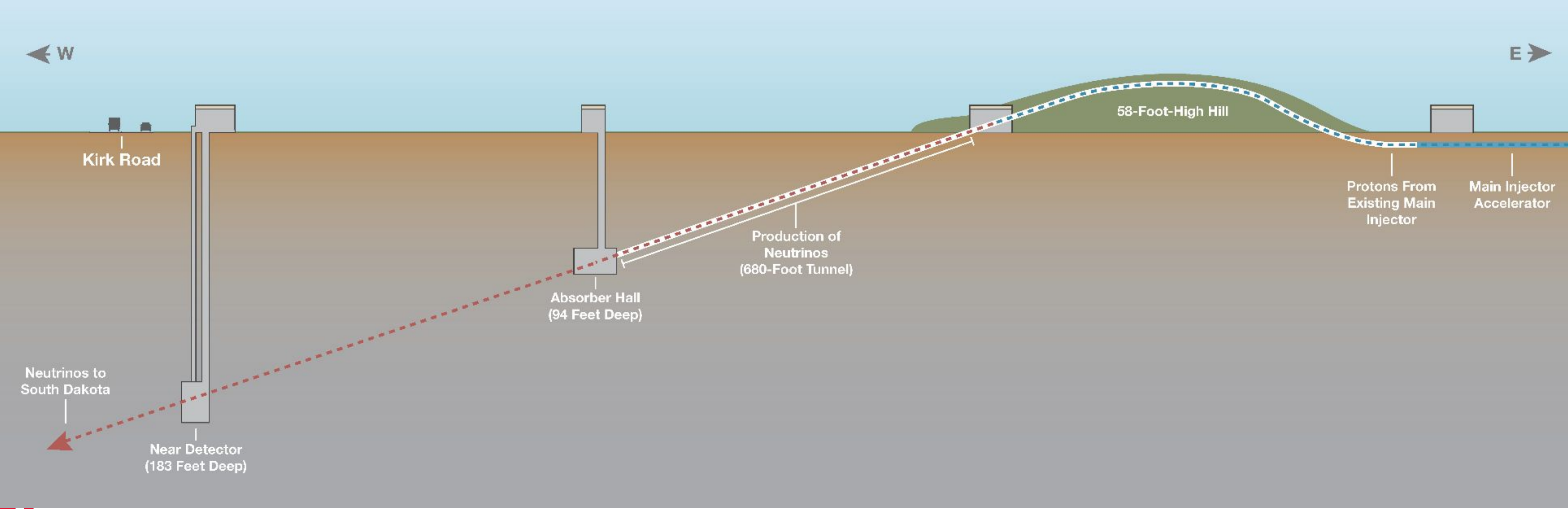
intense neutrino beam

Far detector

Near detector

Counting neutrinos & comparing near vs far detectors

Producing the most intense neutrino beam in the world



DUNE's neutrino beam

DUNE powered by Fermilab's accelerator complex GIF! : Long Baseline Neutrino Facility (LBNF)

Step 1: Get some protons (Fermilab's main injector)

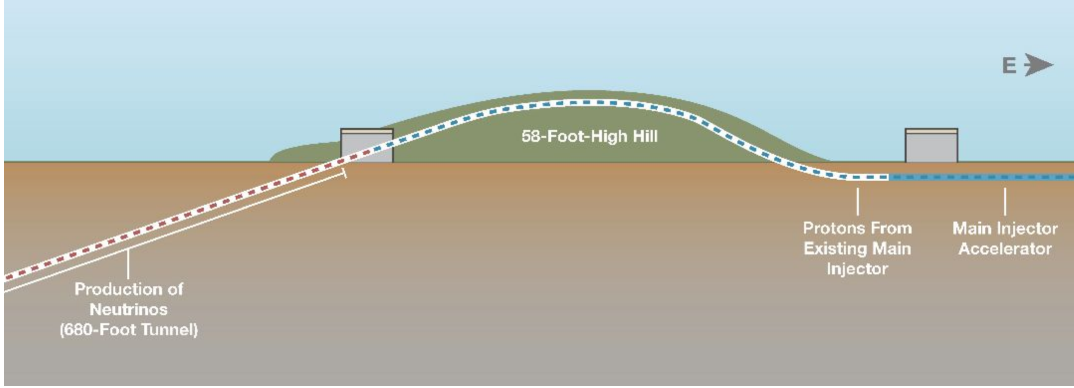
Accelerate them to 60 - 120 GeV. Power: of 1.2 Megawatt (upgrade later to 2.4 MW)

Step 2: Aim

Neutrinos are neutral: no steering!

Beamline draped along 18m hill

Protons angled at -5.8° → South Dakota



Step 3: SMASH!

Protons hit a target:

1.5-meter-long rod of graphite

will get to 500 °C in few ms

Cooled by gaseous helium at 720 km/h

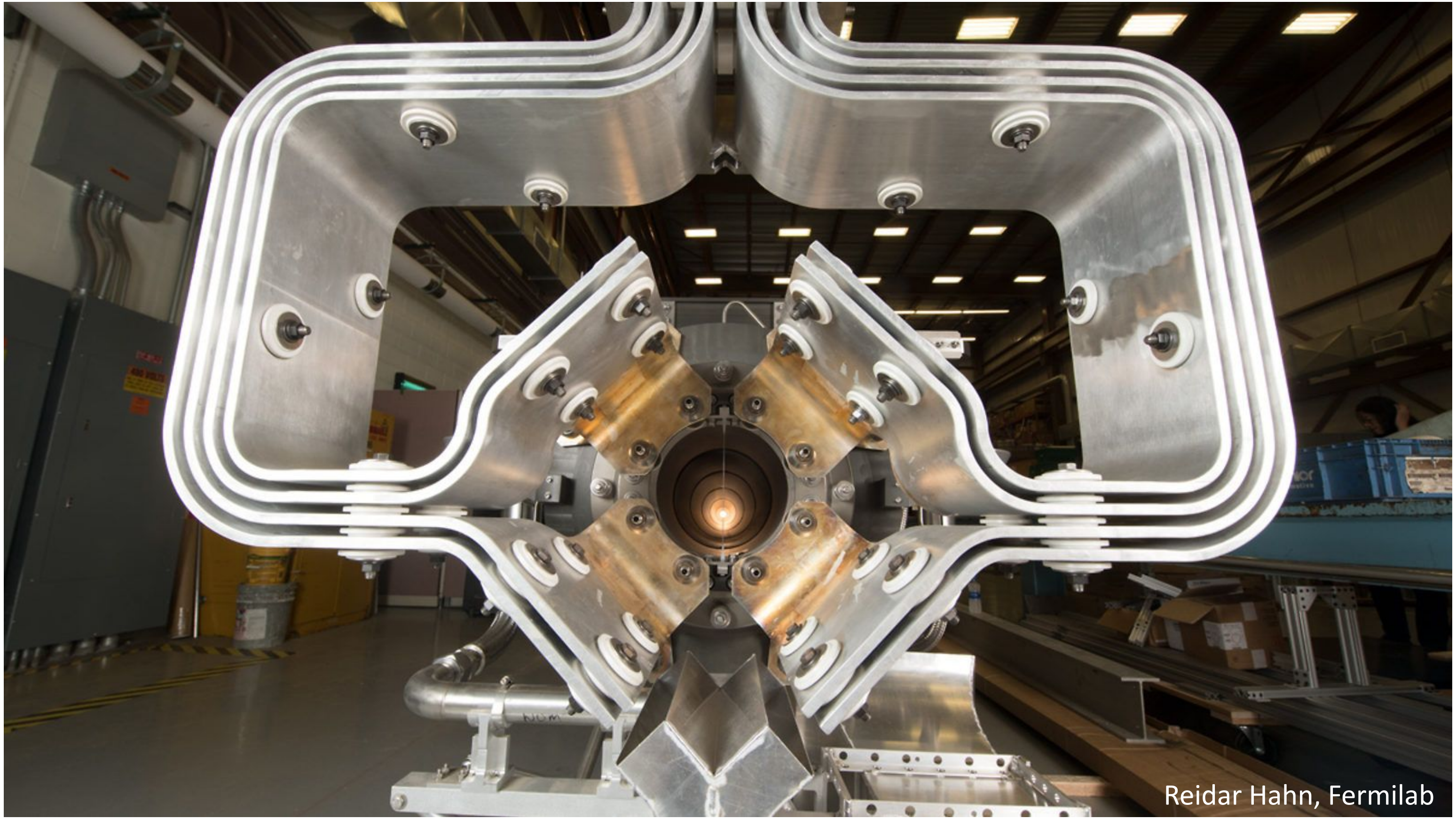
Step 4: focus the debris

Pions & kaons focused by horns = giant magnets

Horns receive 300,000 amp electromagnetic pulse/s!

LBNF's striplines

supplying the current to the horns

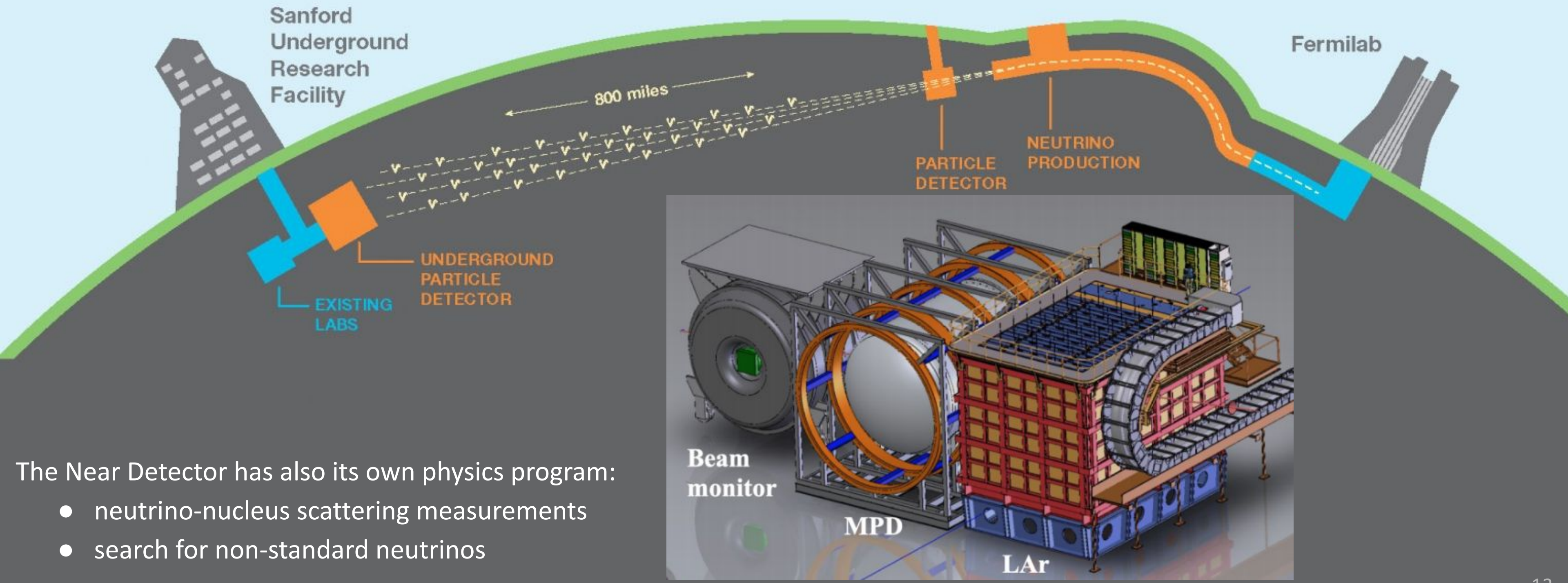


Reidar Hahn, Fermilab

DUNE’s Near Detector complex

Monitor the beam + measure the neutrino flux before oscillations ⇒ will reduce uncertainties

Main challenges: 50 interactions within microseconds! ⇒ need new detector design



The Near Detector has also its own physics program:

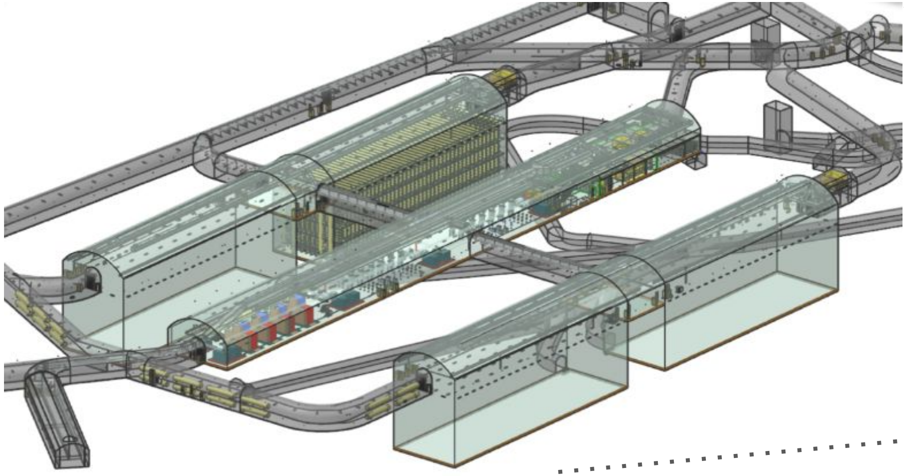
- neutrino-nucleus scattering measurements
- search for non-standard neutrinos

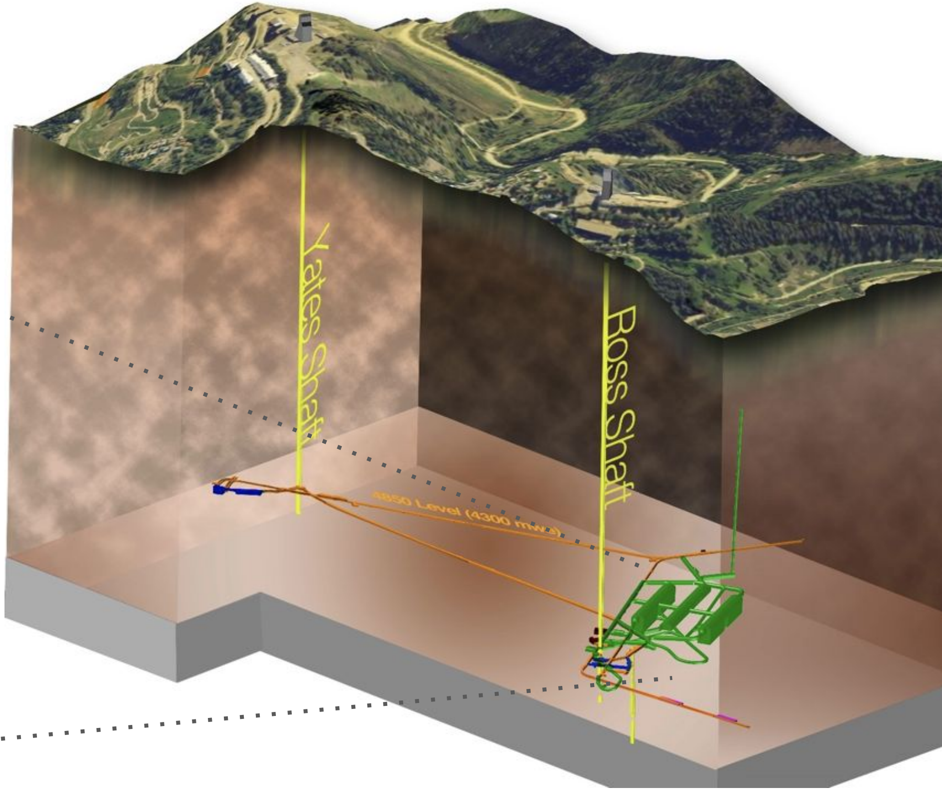
1285 km later…

DUNE's Far Detector

4 modules of 17 kt of liquid argon

Largest cryogenic instrument ever (89 kT)



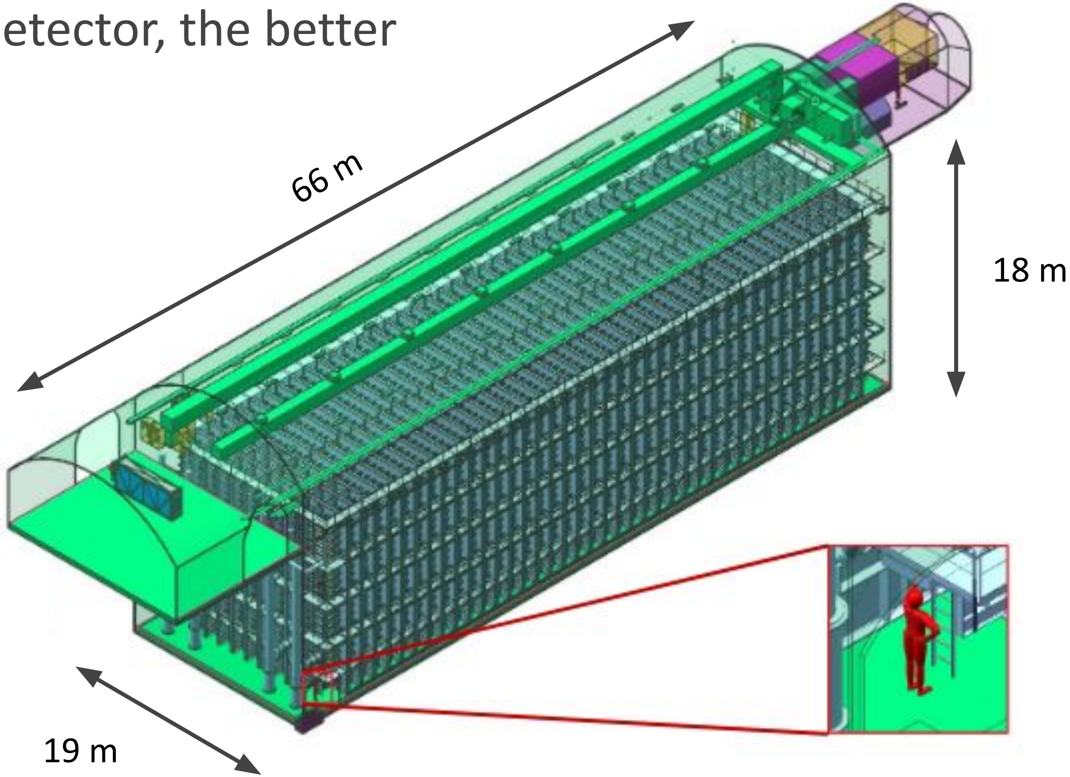


Modules installed in stages & different detection technologies.

First module: single phase Liquid Argon Time Projection Chamber → LArTPC

DUNE’s Far Detector module

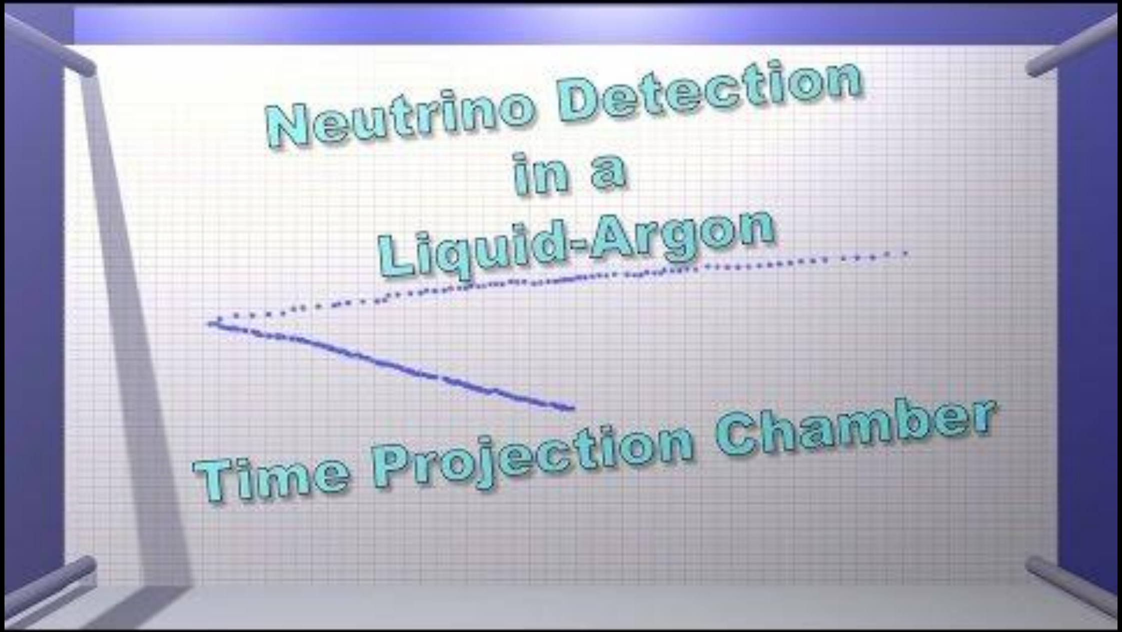
The bigger the detector, the better



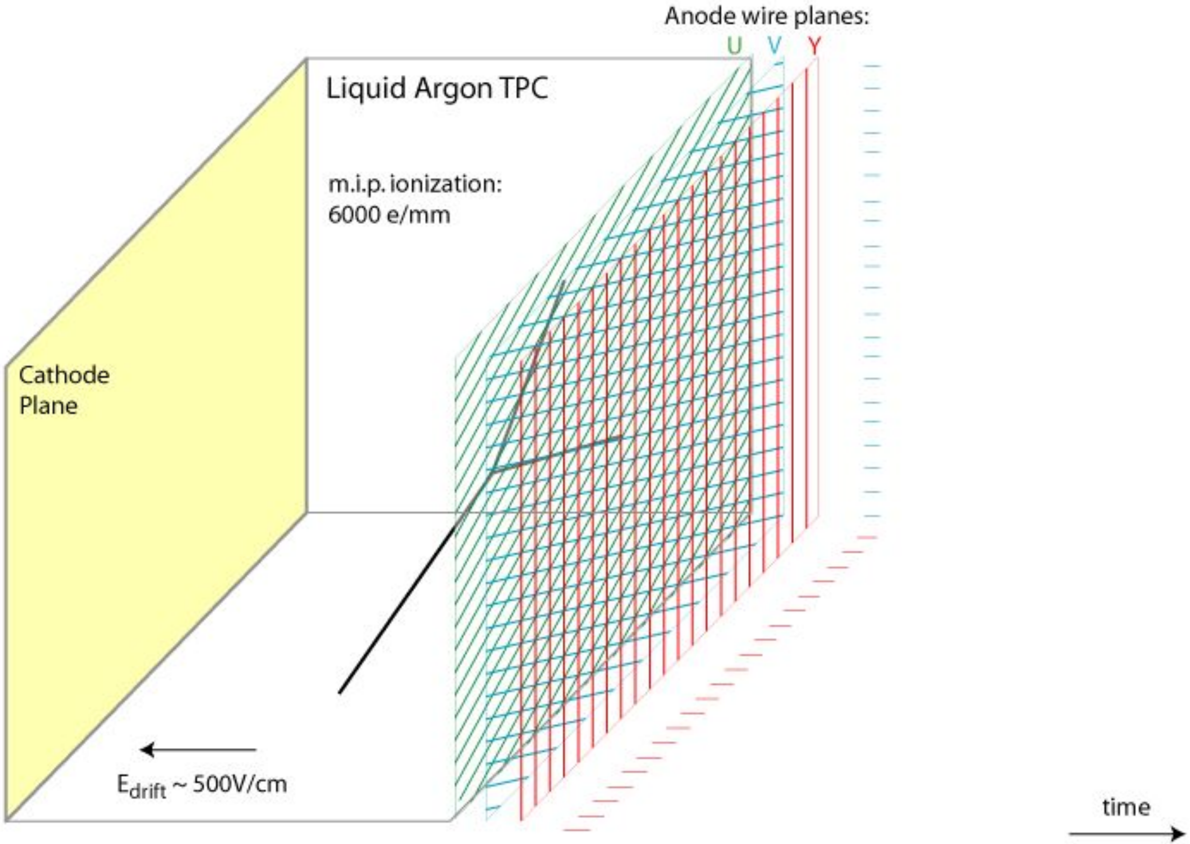
How are neutrinos detected?

How a Time Projection Chamber works

Link



How a Time Projection Chamber works

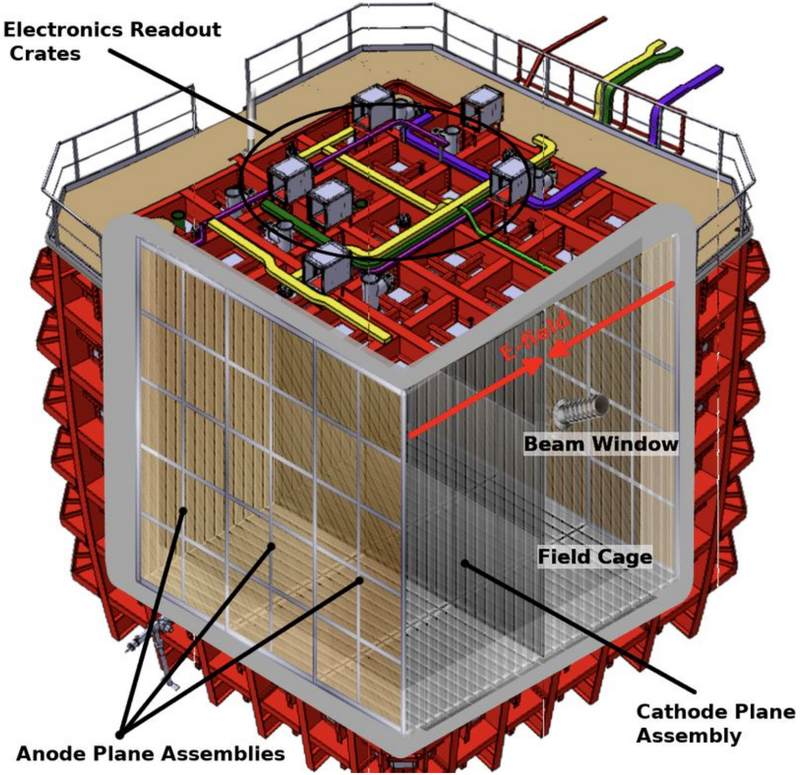


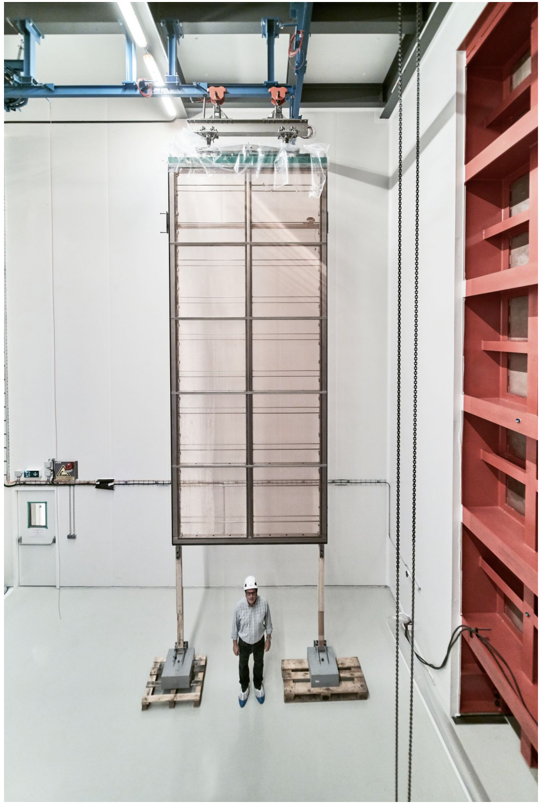
How does a real neutrino event look like?

Meanwhile at CERN…

ProtoDUNE: prototyping effort

CERN neutrino platform: 2 prototypes 1/20th the size of DUNE | 770 t total LAr mass

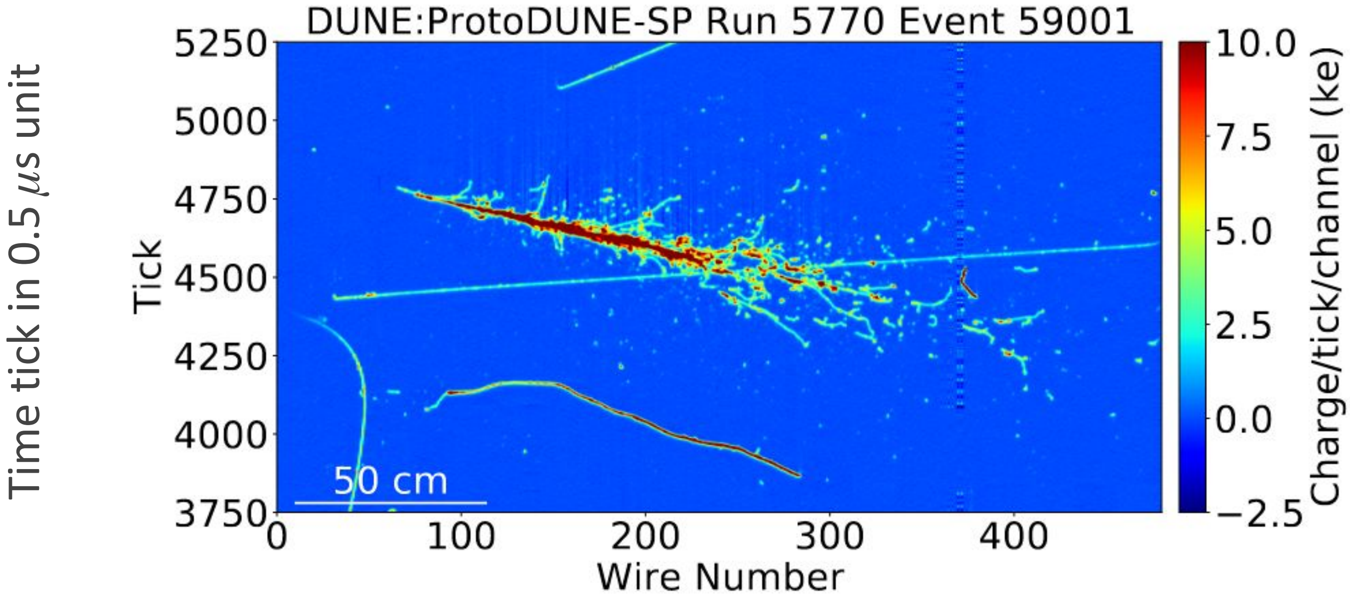





PanGas

ProtoDUNE event display

A 6 GeV/c electron candidate:



LArTPC technology:

excellent energy & spatial resolution, high background rejection, low energy threshold

Event reconstruction and classification

Pattern recognition

↓

3D neutrino event

Machine learning

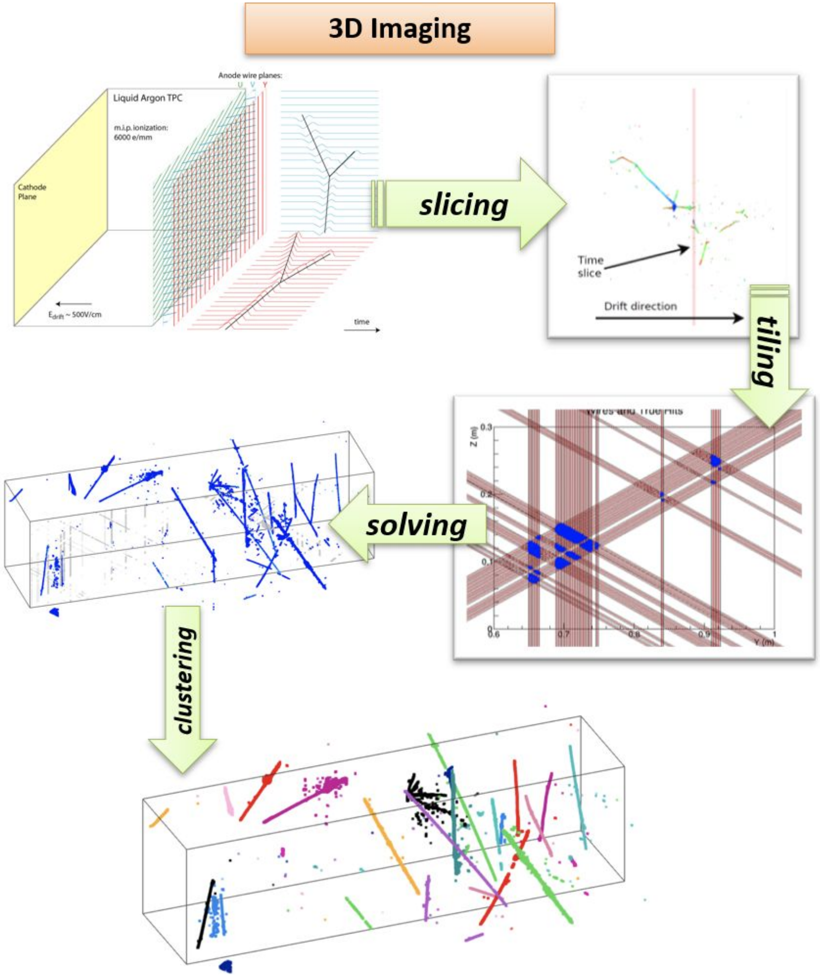
convolution neural network (CNN)

↓

Classification

“Neutrino interaction classification with a convolutional neural network in the DUNE far detector”

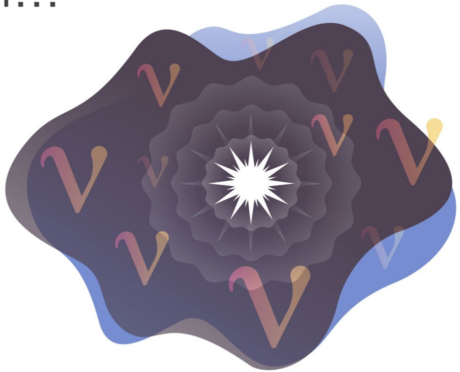
[arXiv:2006.15052](https://arxiv.org/abs/2006.15052)



Bonus: supernova detection

DUNE’s Far Detector will be sensitive to core-collapse supernova in Milky Way neighborhood

- Estimated to occur every 30-200 years
- Challenges on readout systems & computing: more than 100 TB within 100 seconds
- Unique information:
  - 99% of energy is carried away by neutrinos
  - cosmology: core-collapse mechanism, black hole formation…
  - particle physics: flavour transformations in core, mass hierarchy, extra dimensions…



Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment
arXiv:2008.06647

Timeline

2021 **2029** **2036**

R&D

DUNE construction

DUNE operations

Continued physics
exploitation
beyond operations

Opportunities for students

Detector development: instrumentation, data acquisition, prototype characterization, etc…

Data analysis: programming, data analysis techniques, machine learning, stats, visualization…

Extra: international collaboration, scientific writing, oral communication, travels, fun :-)

DUNE is gearing toward big discoveries in particle physics. A once-in-a-lifetime chance to join!

Learn more at www.dunescience.org and atwork.dunescience.org

More *details*

What we know

- There are 2 basis that are ‘rotated’ , with superposition of states:

Flavour eigenstates
neutrino in detection
through weak interaction

$\nu_e \quad \nu_\mu \quad \nu_\tau$

Mass eigenstates
neutrino in propagation
free flight

$\nu_1 \quad \nu_2 \quad \nu_3$

- The Pontecorvo–Maki–Nakagawa–Sakata (PMNS) unitary matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \left(\begin{array}{c} \text{PMNS} \\ \text{matrix} \end{array} \right) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

What we know

- Parametrization:

  3 rotations

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

Complex phases for massless neutrinos

⇓

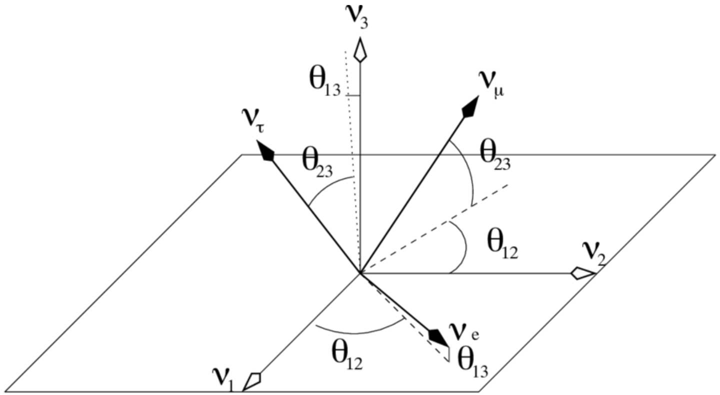
$$\begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}1 & 0 & 0\\ 0 & e^{i\alpha_1/2} & 0\\ 0 & 0 & e^{i\alpha_2/2}\end{pmatrix}$$

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

Only 4 parameters:

3 angles : θ_{12} , θ_{13} , θ_{23}

1 phase δ_{CP}



Number freak?
Check www.nu-fit.org

Neutrino oscillation in matter

Oscillation probability of $\nu_\mu \rightarrow \nu_e$ through matter in the standard three-flavor model:

$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2(\Delta_{31}-aL)}{(\Delta_{31}-aL)^2}\Delta_{31}^2$$

$$+\sin 2\theta_{23}\sin 2\theta_{13}\sin 2\theta_{12}\frac{\sin(\Delta_{31}-aL)}{(\Delta_{31}-aL)}\Delta_{31}\times\frac{\sin(aL)}{(aL)}\Delta_{21}\cos(\Delta_{31}\pm\delta_{\mathrm{CP}})$$

$$+\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(aL)}{(aL)^2}\Delta_{21}^2,$$

Asymmetry:

$$\mathcal{A}_{\mathrm{CP}} = \frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

$$\sim \frac{\cos\theta_{23}\sin 2\theta_{12}\sin\delta_{\mathrm{CP}}}{\sin\theta_{23}\sin\theta_{13}}\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right) + \text{matter effects}$$

Fermi constant

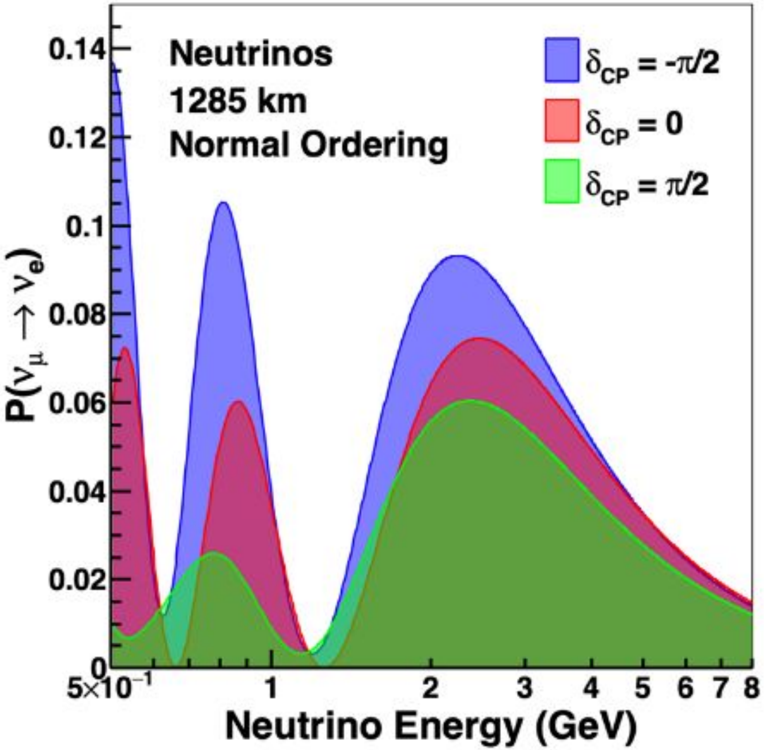
number density of electrons in Earth's crust

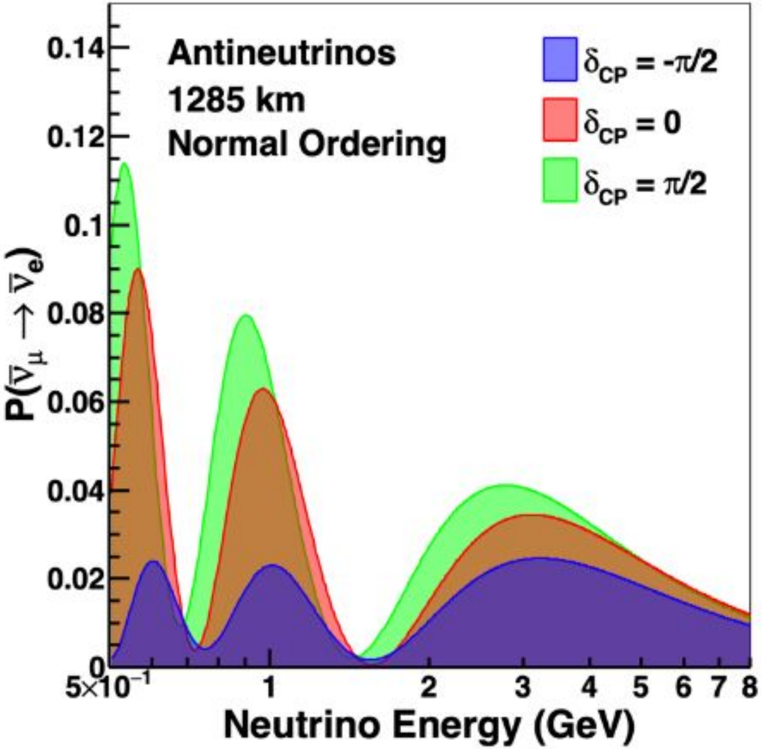
$$a = \pm\frac{G_F N_e}{\sqrt{2}} \approx \pm\frac{1}{3500\ \mathrm{km}}\left(\frac{\rho}{3.0\ \mathrm{g/cm^3}}\right)$$

$$\Delta_{ij} = 1.267\Delta m_{ij}^2 L/E_\nu$$

In the GeV range of E_ν, the degeneracy between the asymmetries from matter effect and C_{PV} effect is resolved for baselines > 1200 km.

Appearance probability in DUNE   L = 1285 km

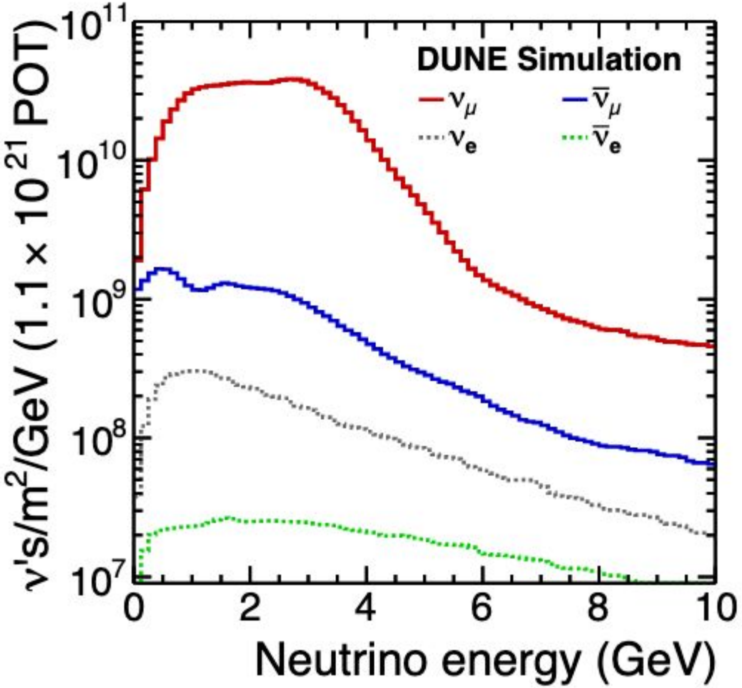




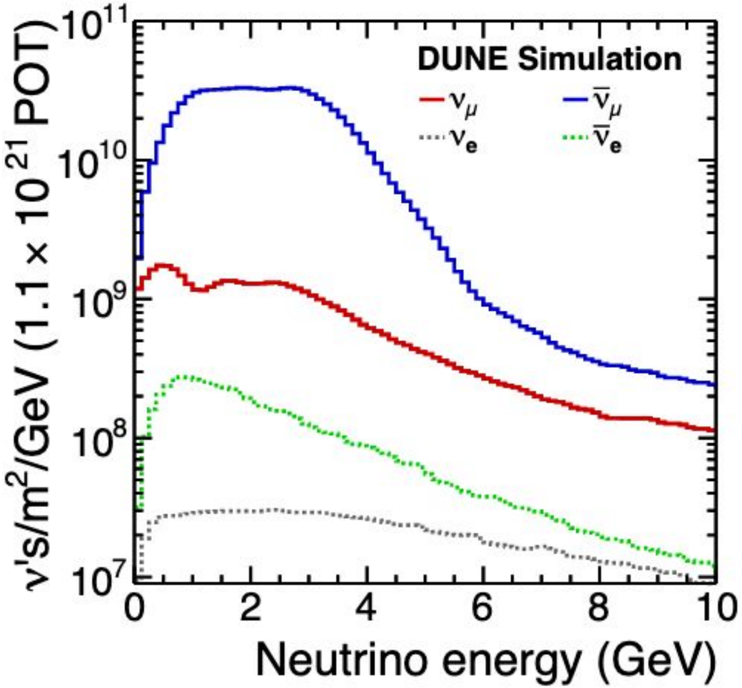
source: arXiv:2006.16043

Energy spread

NEUTRINO FLUXES



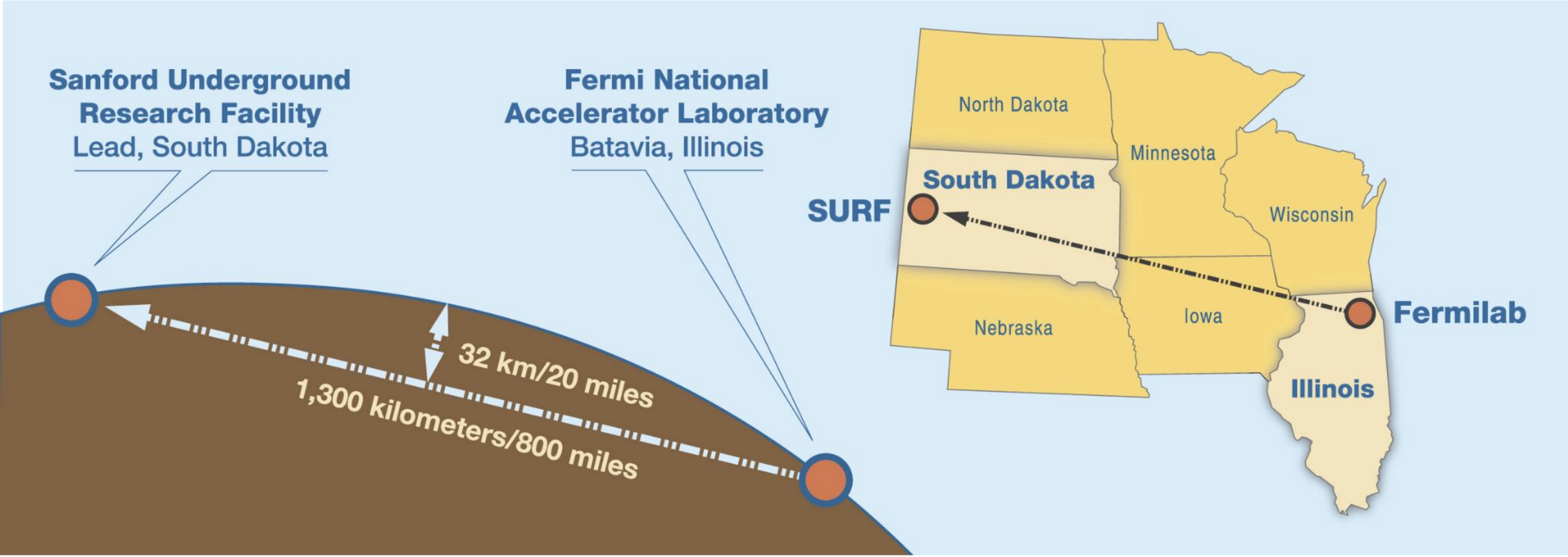
ANTINEUTRINO FLUXES



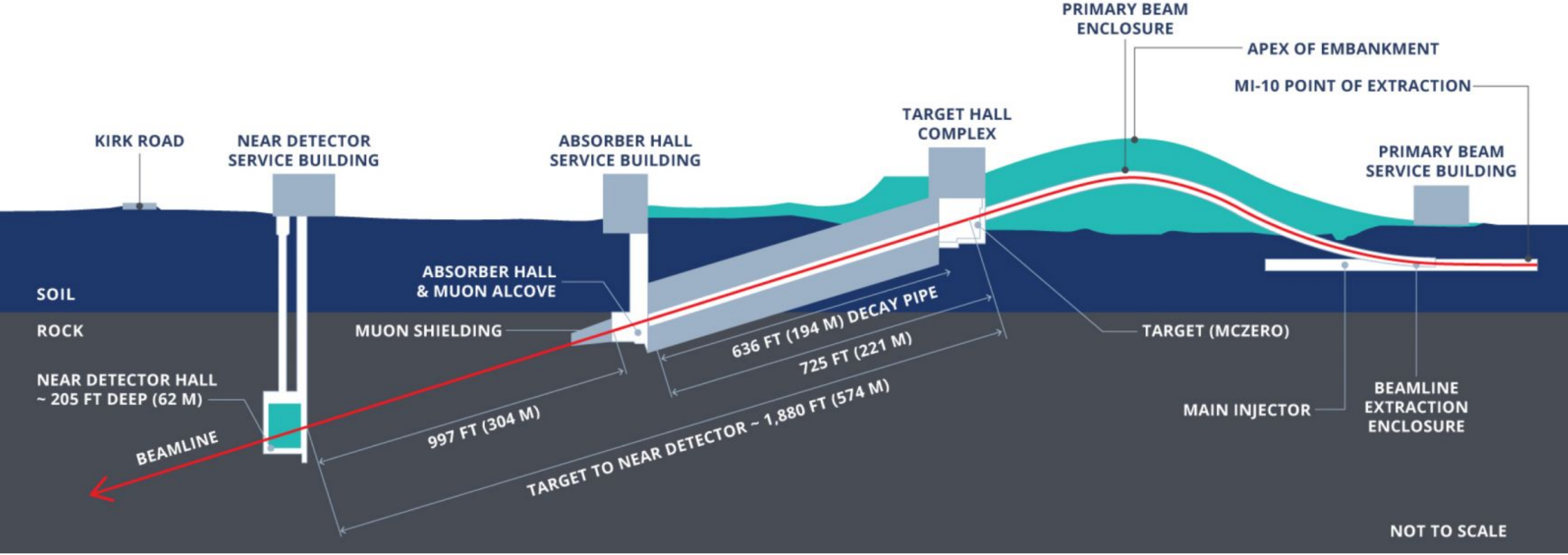
Deep Underground Neutrino Experiment

DUNE is a "long baseline neutrino oscillation experiment."

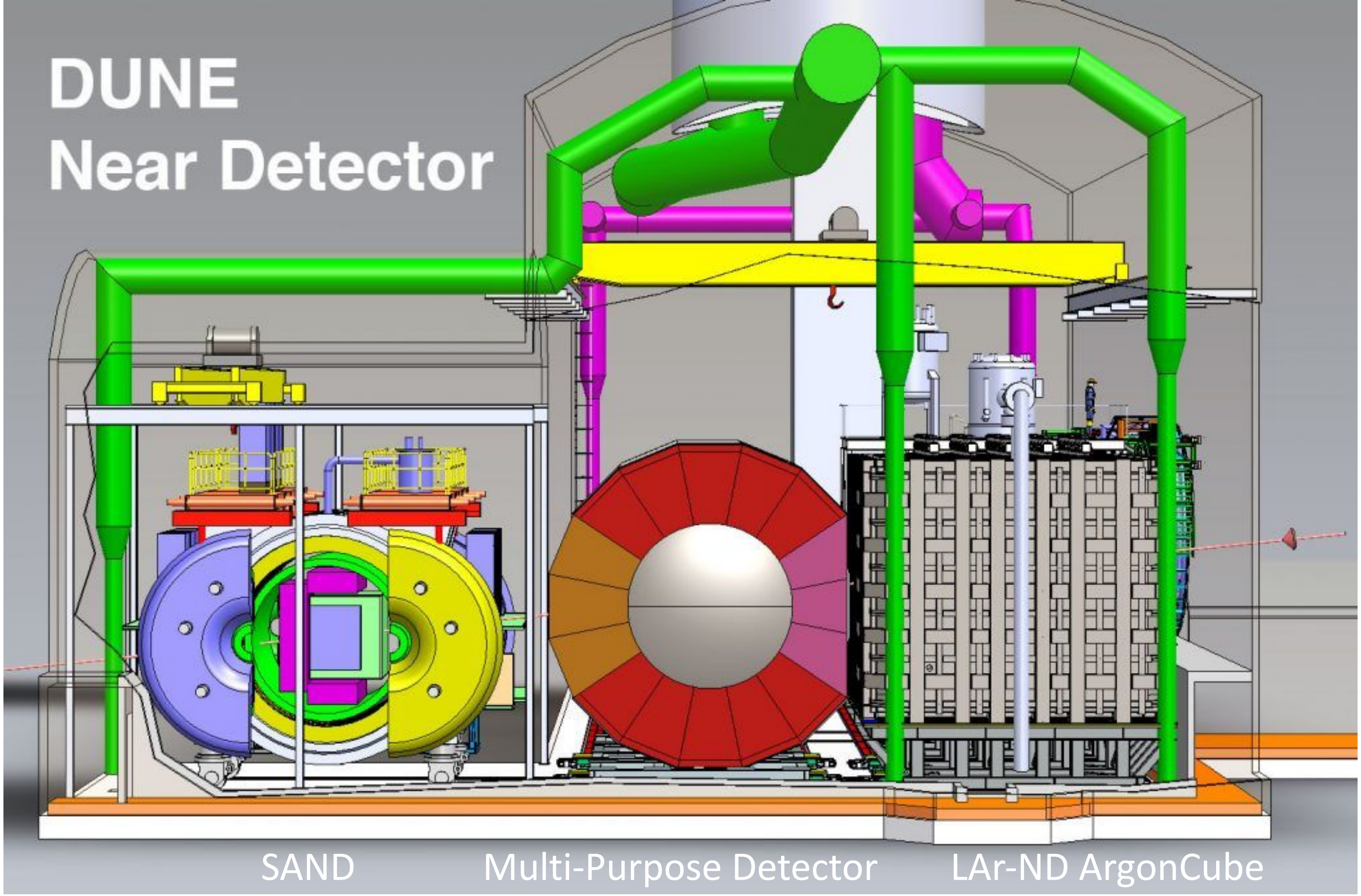
Intense beam of neutrino is sent through Earth to a far away detector (called far detector)



Beam


PRIMARY BEAM ENCLOSURE
APEX OF EMBANKMENT
MI-10 POINT OF EXTRACTION
TARGET HALL COMPLEX
KIRK ROAD
NEAR DETECTOR SERVICE BUILDING
ABSORBER HALL SERVICE BUILDING
PRIMARY BEAM SERVICE BUILDING
ABSORBER HALL & MUON ALCOVE
SOIL
ROCK
MUON SHIELDING
636 FT (194 M) DECAY PIPE
725 FT (221 M)
TARGET (MCZERO)
NEAR DETECTOR HALL ~ 205 FT DEEP (62 M)
997 FT (304 M)
TARGET TO NEAR DETECTOR ~ 1,880 FT (574 M)
BEAMLINE
MAIN INJECTOR
BEAMLINE EXTRACTION ENCLOSURE
NOT TO SCALE

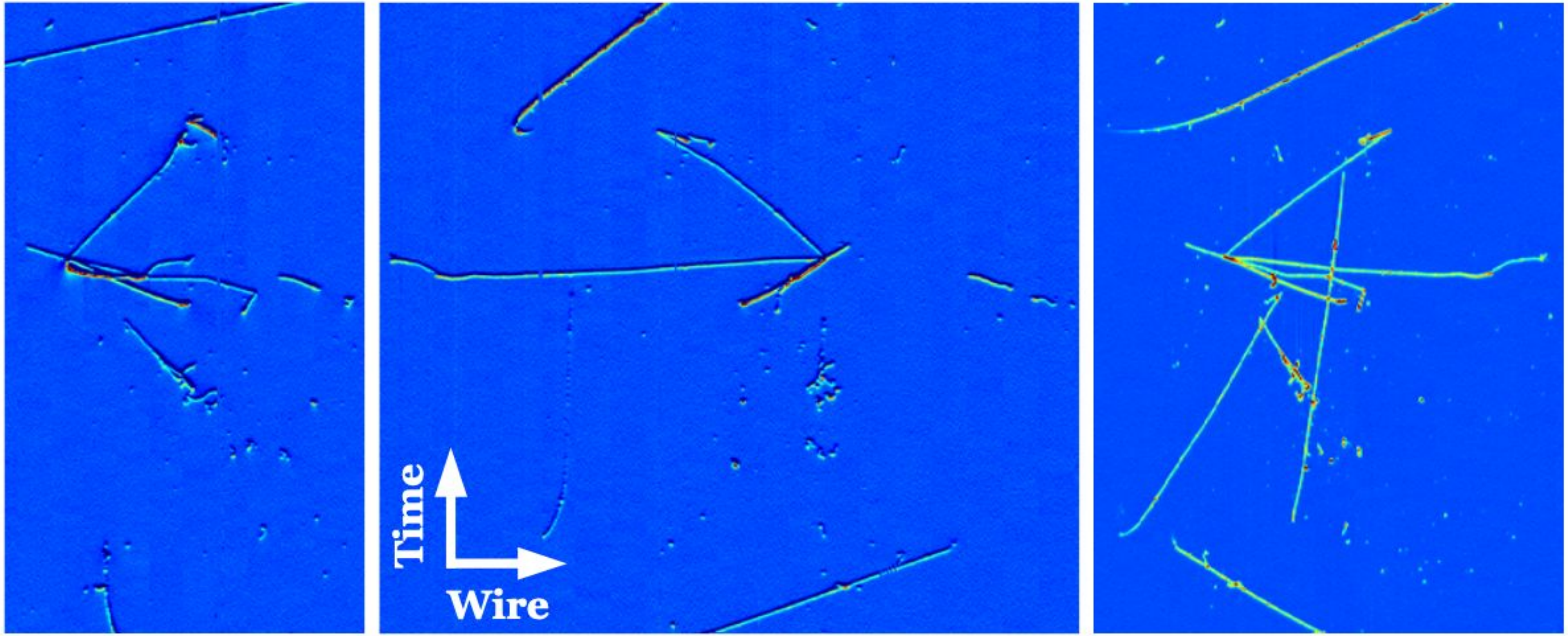
DUNE Near Detector



Event display in protoDUNE

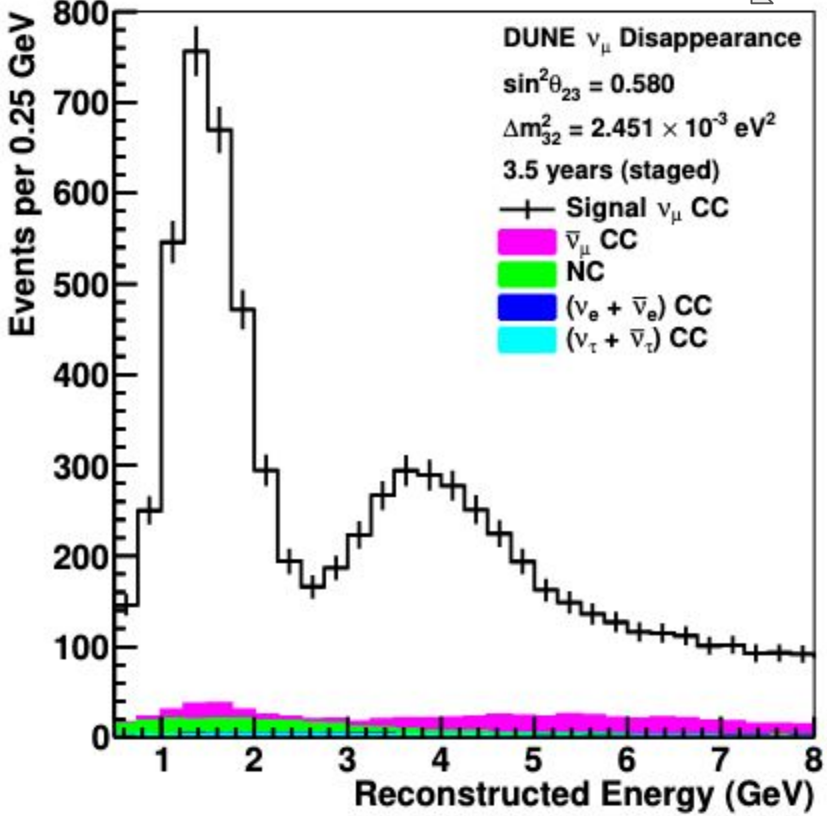
First beam data events: noise levels low → S/N ratio > 10 in all planes , > 40 for collection plane

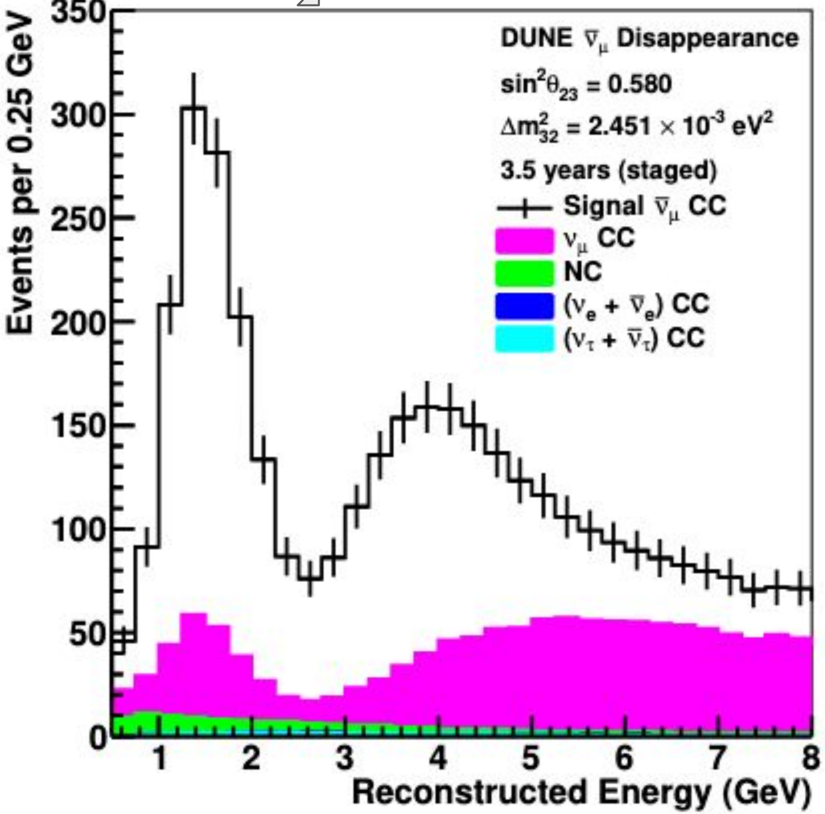
Stable running since first operations began in 2018



Induction plane 1 Induction plane 2 Collection plane

Neutrino oscillations: ν_μ and $\bar{\nu}_\mu$ disappearance



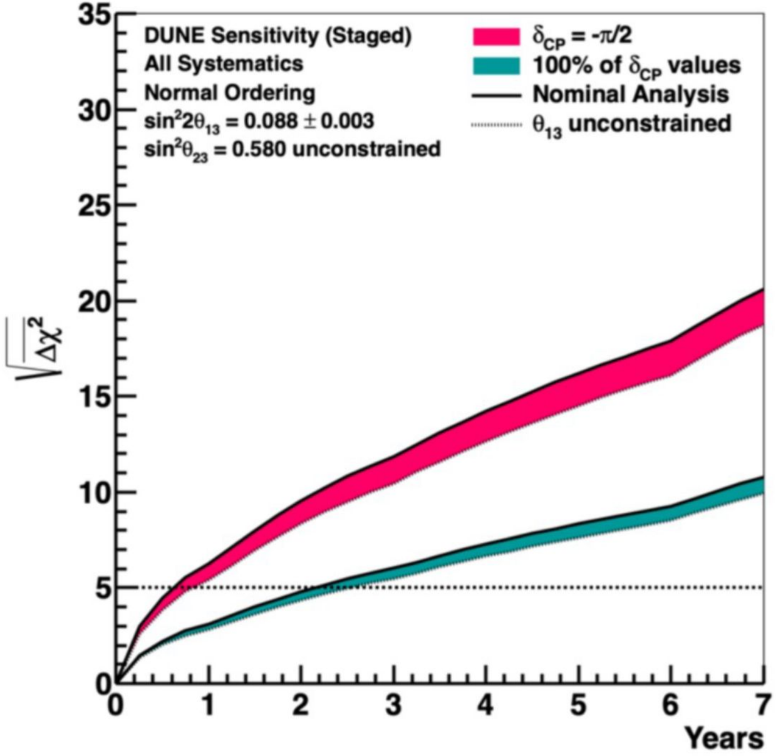


Sensitivity plots

What we should expect

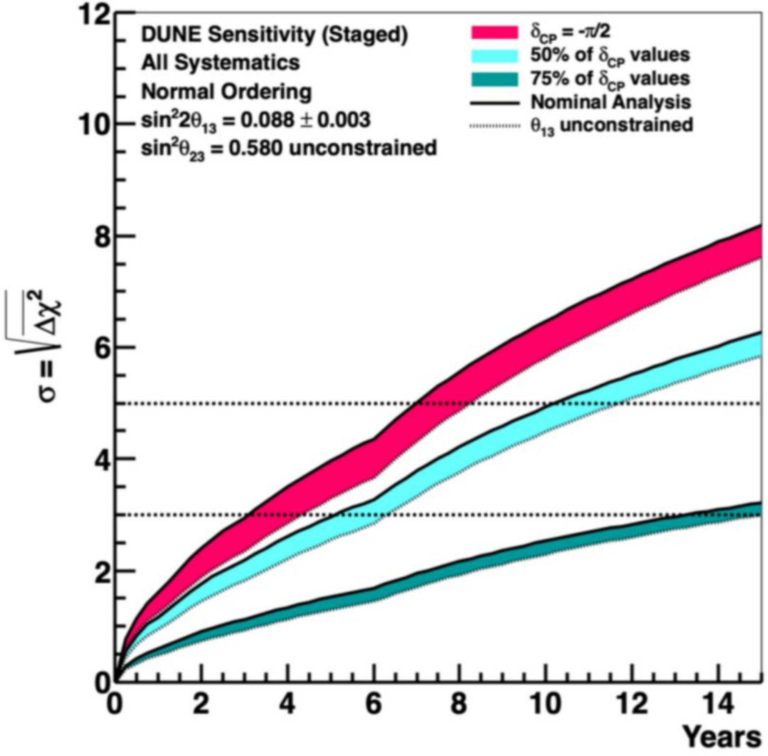
Sensitivity vs time

Mass Hierarchy sensitivity



5σ after 2 years of running

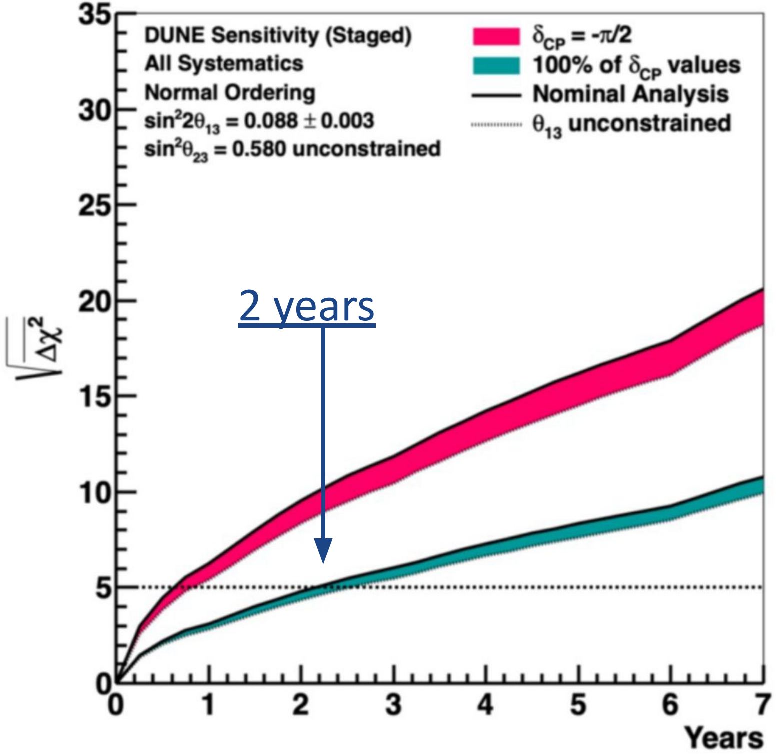
CP Violation Sensitivity



5σ sensitivity after 10 years for 50% of δ_{CP} values

Sensitivity vs time

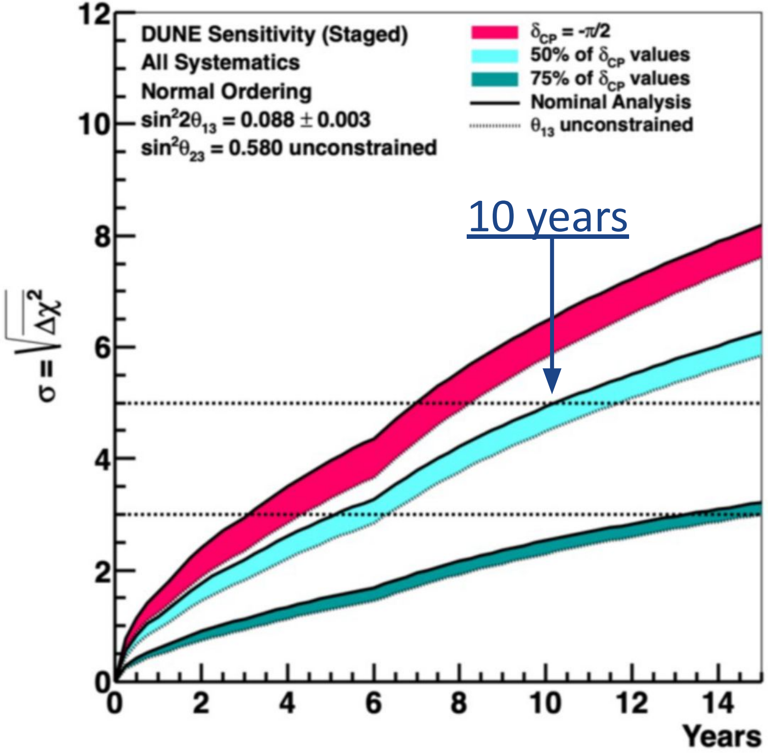
Mass Hierarchy sensitivity



2 years

5σ after 2 years of running

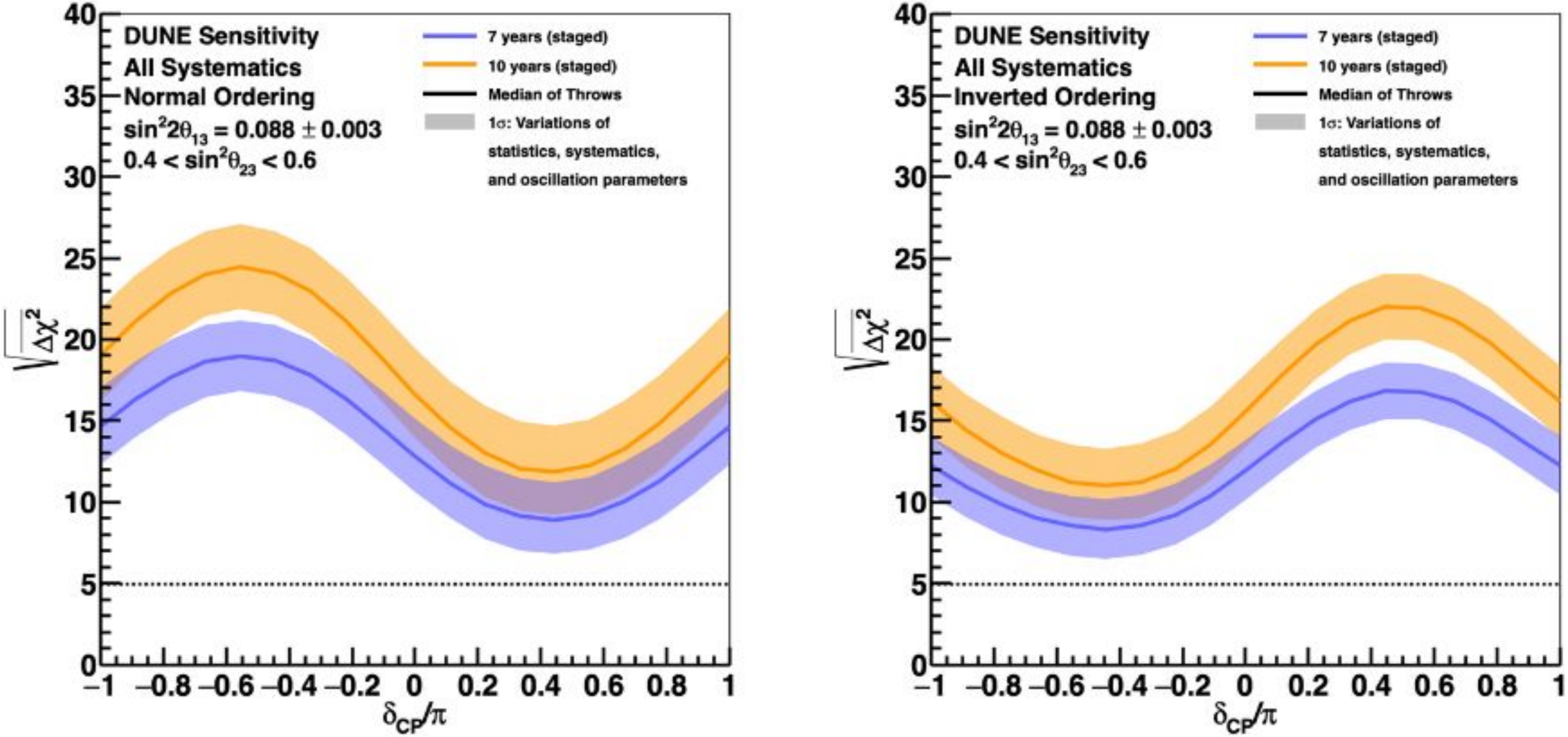
CP Violation Sensitivity



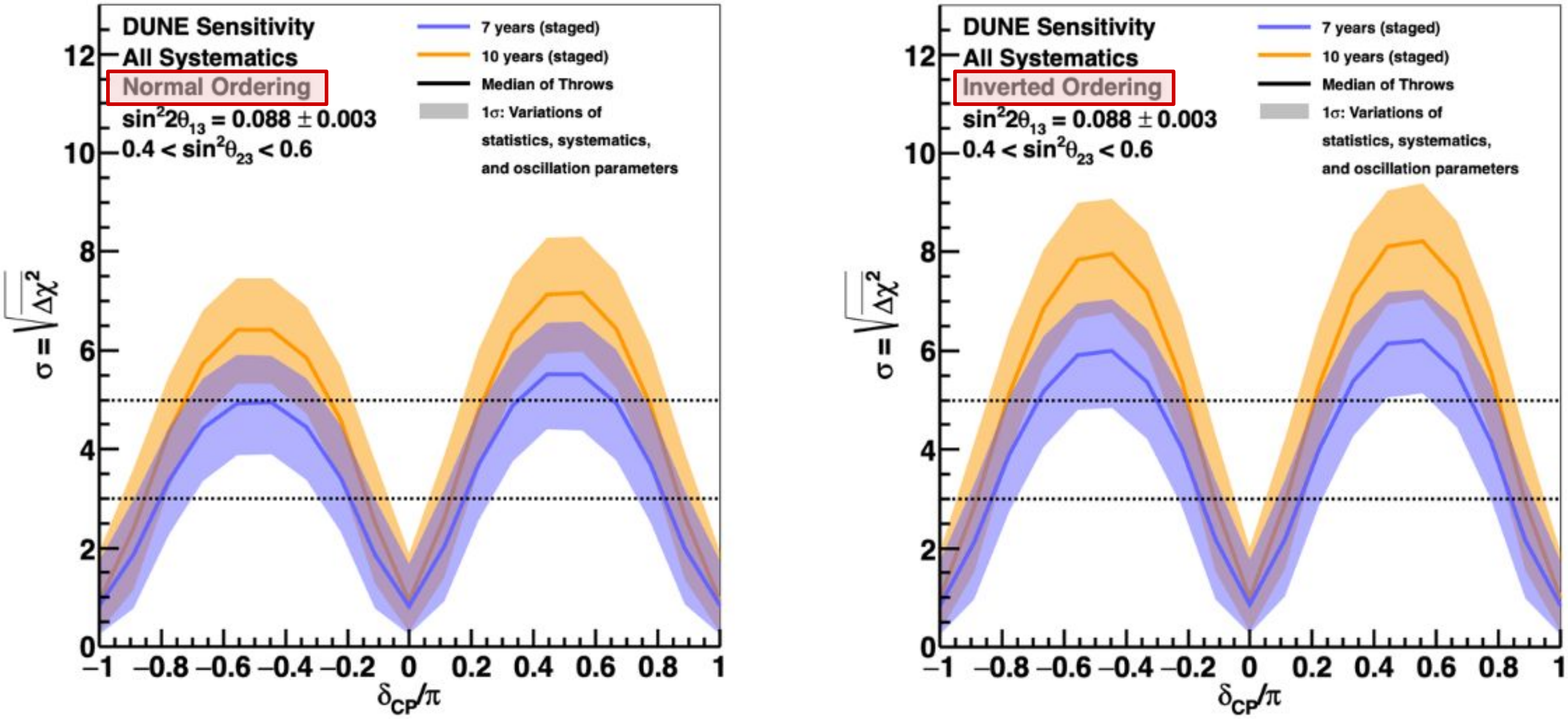
10 years

5σ sensitivity after 10 years for 50% of δ_{CP} values

Mass hierarchy sensitivity



CP-violation significance vs true $\boldsymbol{\delta}_{CP}$



Significant CP violation discovery potential over wide range of true δCP values in 7-10 years (staged)

Core-collapse supernova in DUNE's FD