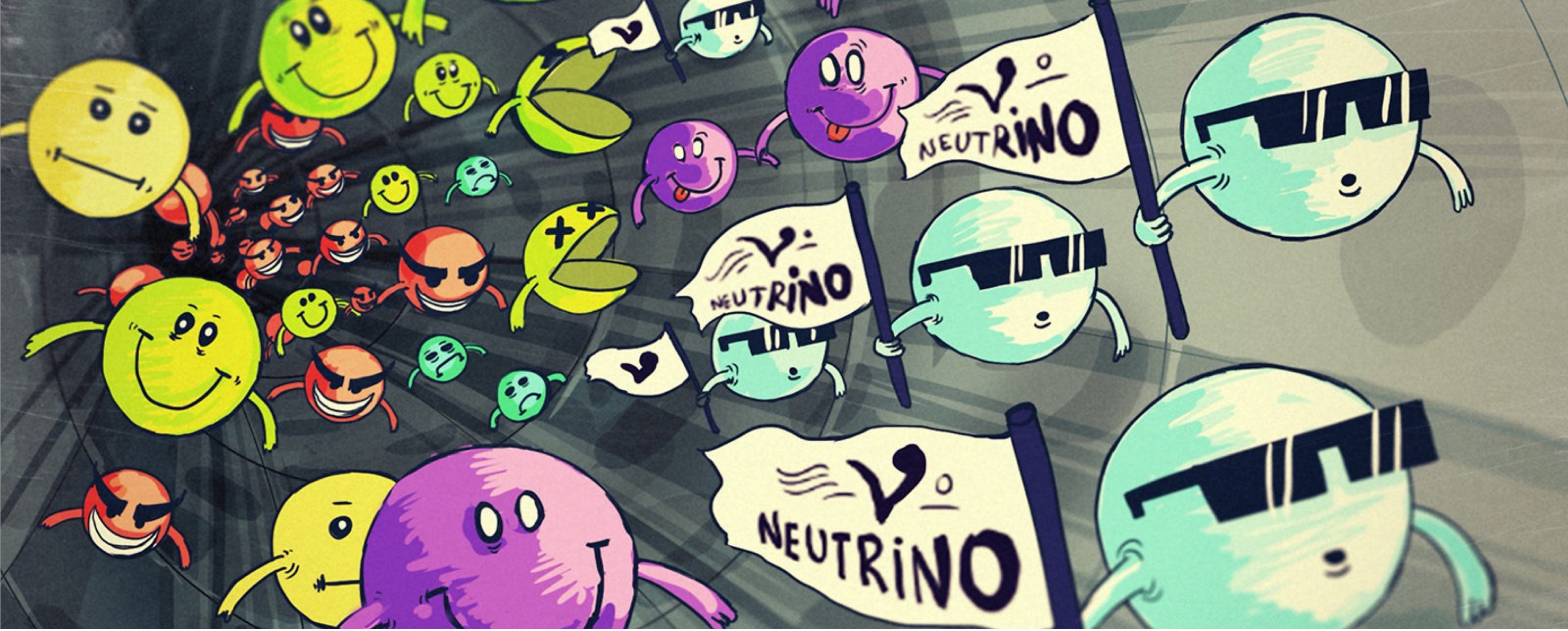


Accelerator Neutrinos

Louise Suter

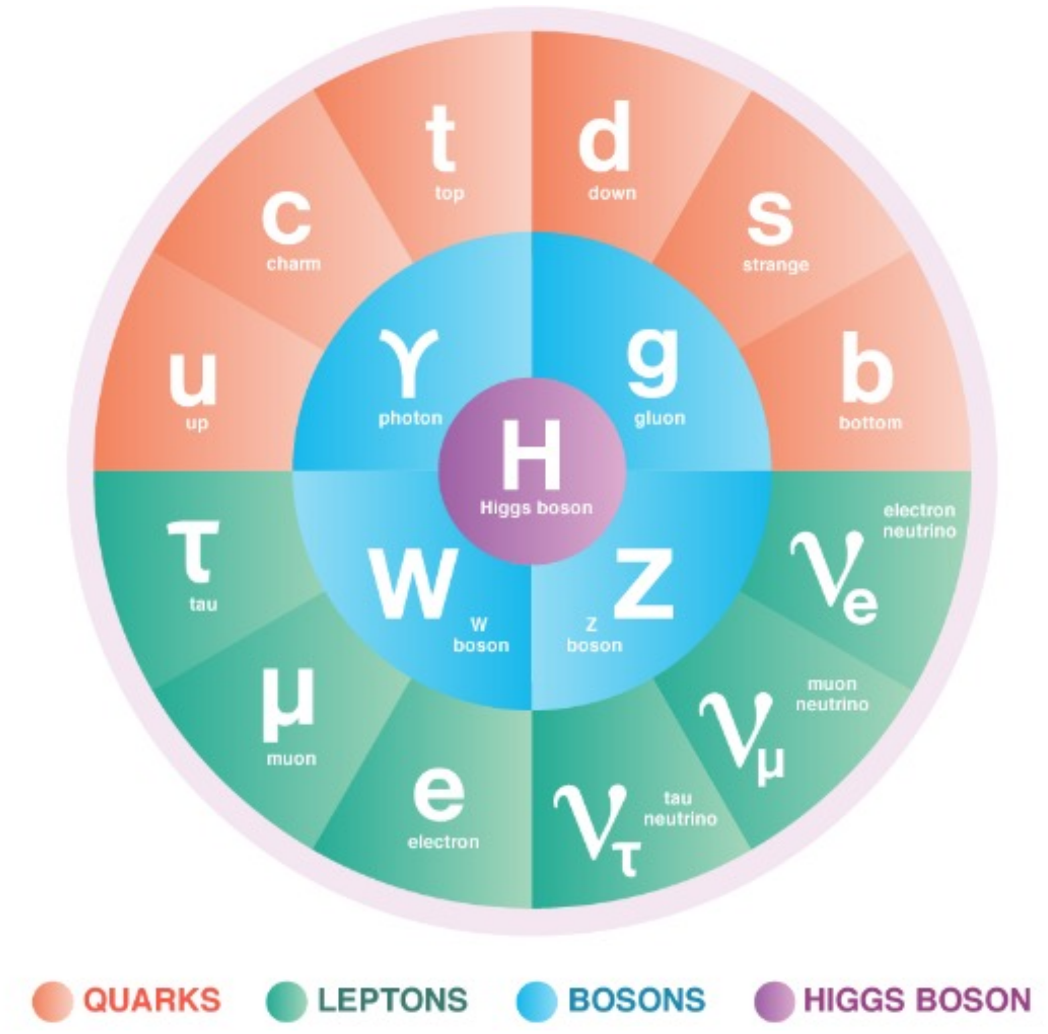
June 28th 2023

Fermilab

Outline

- Neutrino introduction
- Oscillation introduction
- Neutrino beams
- Accelerator neutrino experiments
  - Current long baseline neutrino program
  - Future long baseline neutrino program

What we know about neutrinos



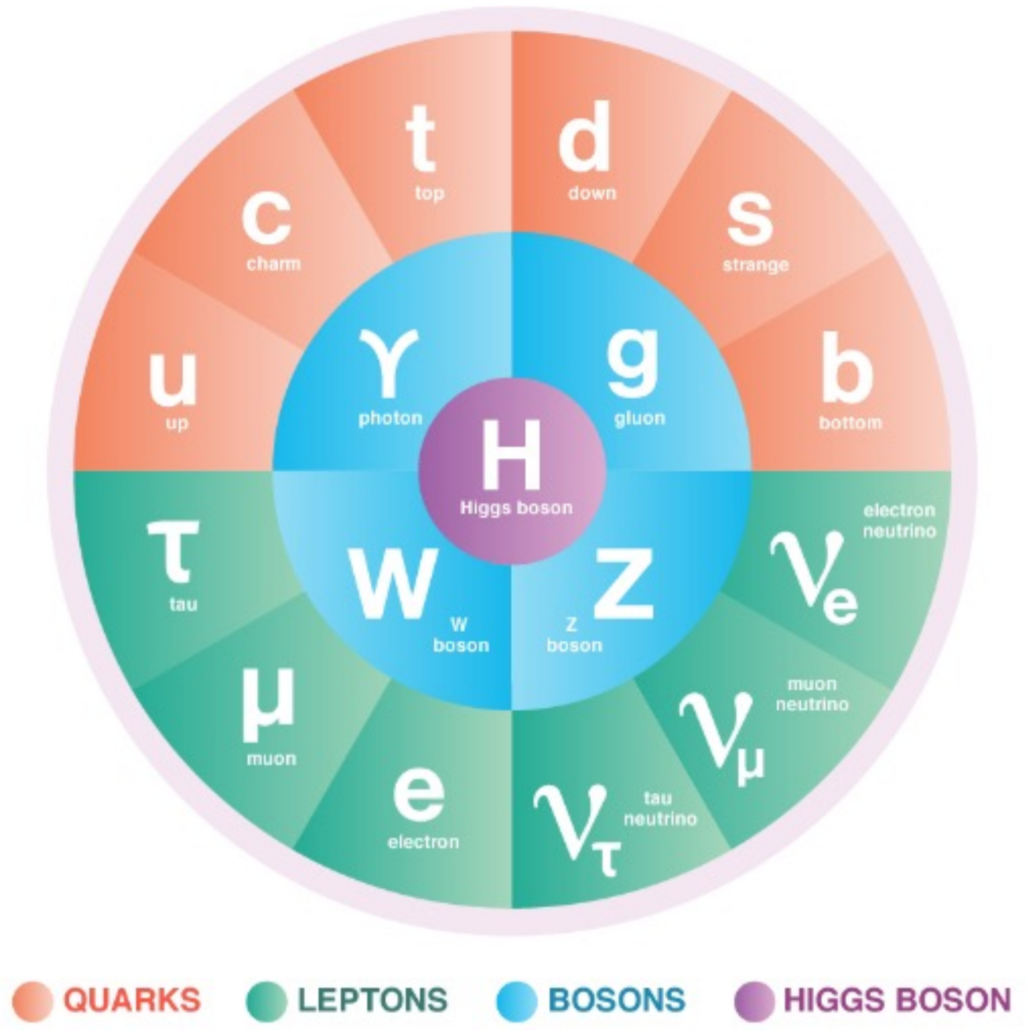
We know there are at least three types of neutrinos

We know neutrinos oscillate and that they have mass

Currently, this is the only clear laboratory observation of BSM physics.

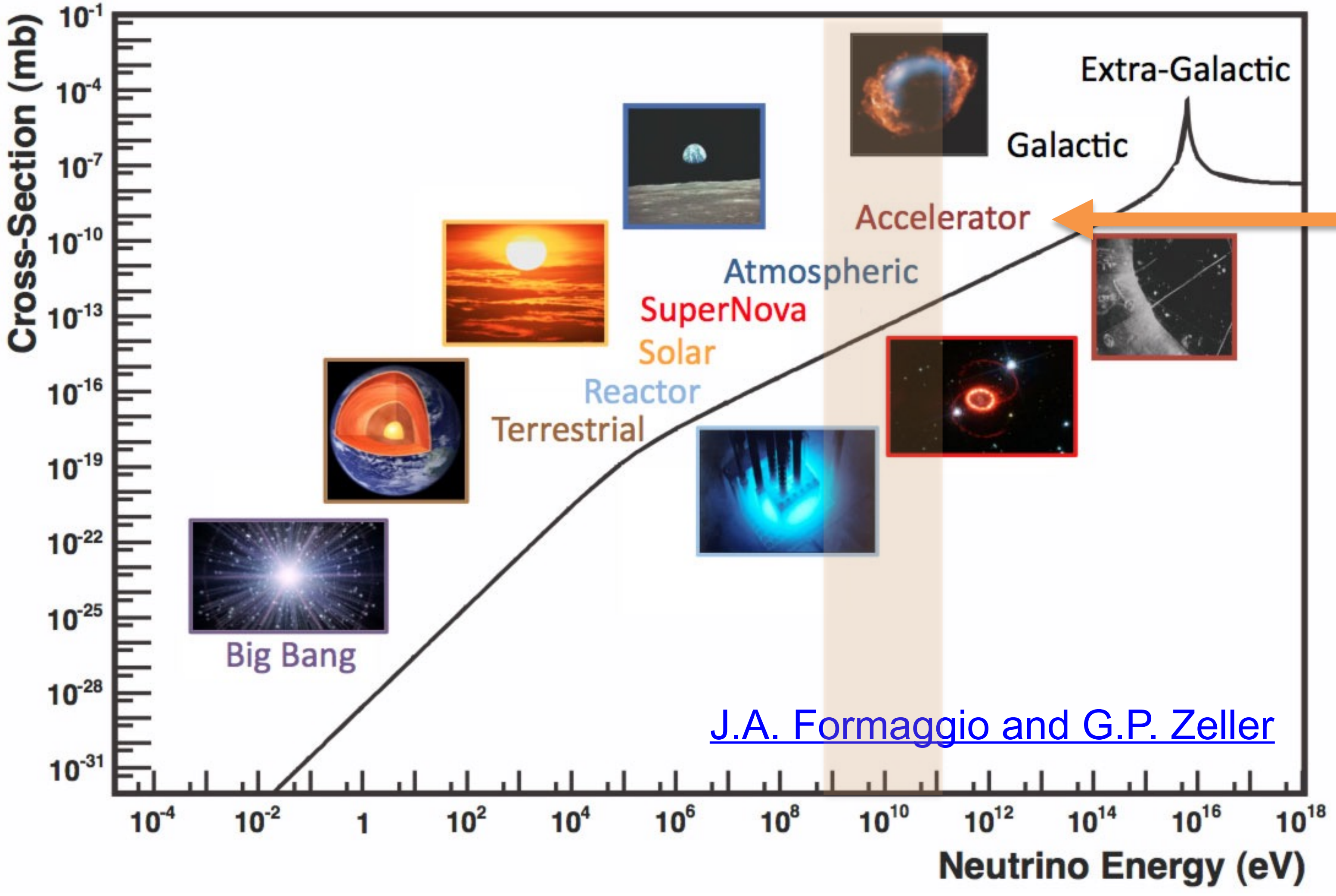
But many aspects of neutrino physics are puzzling, and the experimental picture is incomplete

We don’t know lots, but accelerator neutrino experiments can help!



- What is the origin of neutrino mass?
- **How are the masses ordered (referred to as mass hierarchy)?**
- What are the masses?
- **Do neutrinos and antineutrinos oscillate differently?**
- **Are there additional neutrino types or interactions?**
  - Are there additional symmetries?
  - Are there additional interactions (NSI) ?
  - Are there additional (sterile) neutrinos?
- Are neutrinos their own antiparticles?

Some of these questions can be explored with neutrinos made via an accelerator



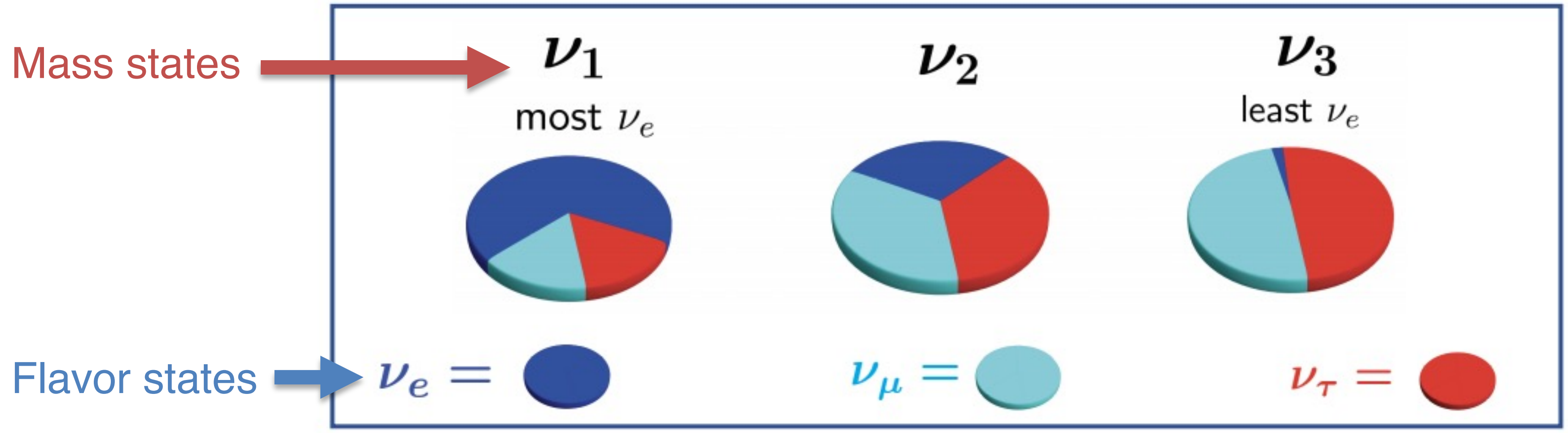
Accelerator neutrinos generally in the ~ 1-10 GeV range

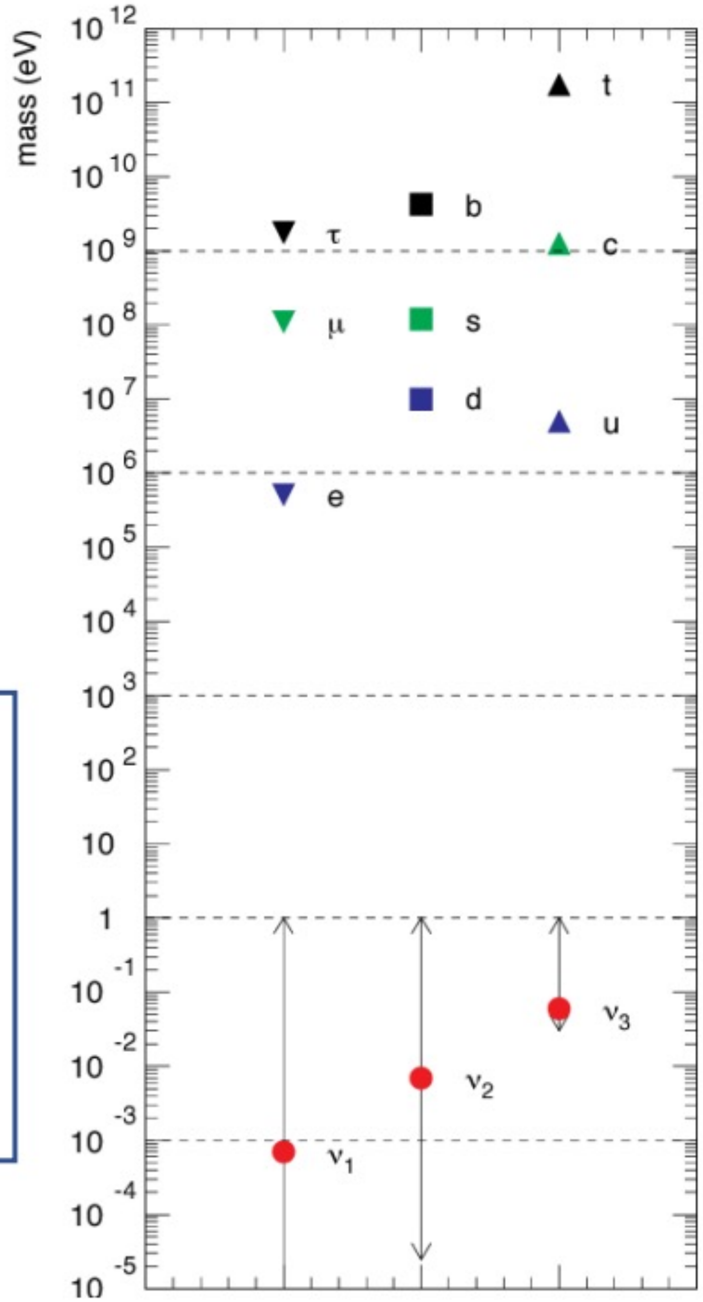
Neutrinos come in a wide variety of energies from many sources

The neutrino cross section (on the y axis) is a measure of how likely the neutrino is to be stopped by regular matter. The higher energy a neutrino has, the more likely it is to interact.

Neutrinos are very light (m_ν < a few eV), electrically neutral, and only interact via weak force (and gravity)

Interact in three flavor states, which are not the same as their mass states.





Mixing angles used to describe flavor make up of mass states

Neutrino Oscillations

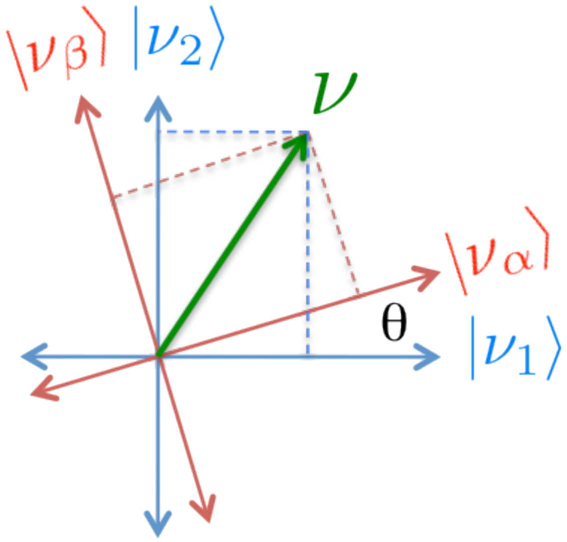
Flavor states may be written as linear combination of mass states (and vice versa) using a mixing (rotation) matrix

$\nu_\alpha = \nu_e, \nu_\mu, \nu_\tau$
are the flavor states

$$|\nu_\alpha\rangle = \sum_k U_{\alpha k} |\nu_k\rangle$$

PMNS matrix

$\nu_k = \nu_1, \nu_2, \nu_3$
are the mass states

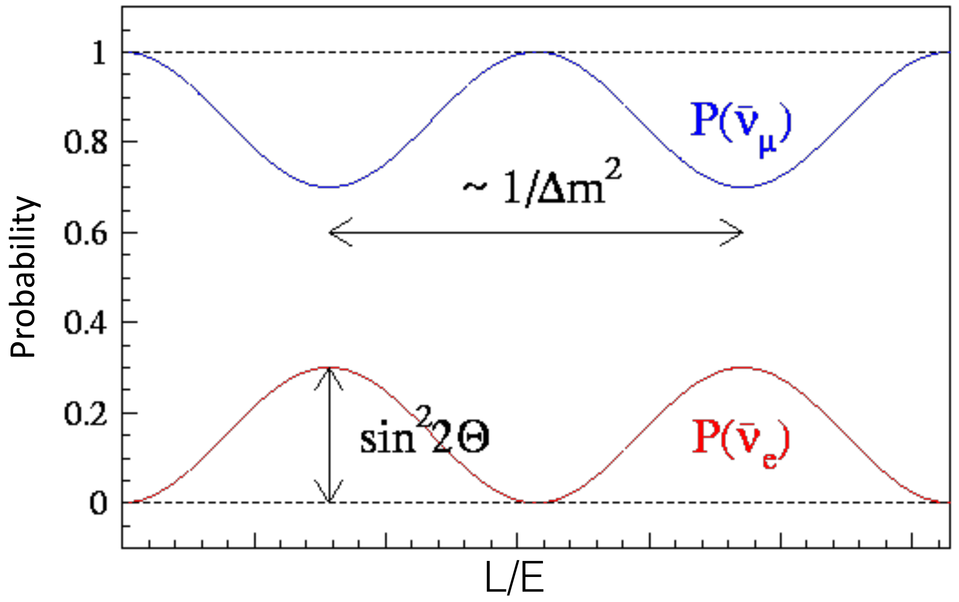


For two neutrinos

$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$

Neutrino Oscillations

Over time the states will become out of phase, they oscillate, and we can derive a simple formula to describe the probability



2 neutrino case:

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

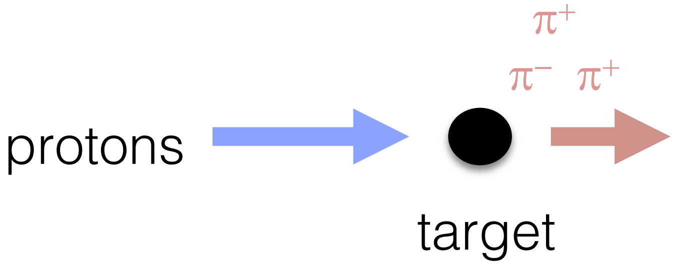
- Oscillation probability depends on the
  – mixing angles, Δm^2 (mass differences), and L/E (baseline/energy)

Neutrino oscillation experiments measure amplitude (θ) and frequency (Δm^2)

Accelerator neutrino experiments all nominally work on the same simple design:

1) Start with a source of neutrinos with a known flavor composition

Create ~100% muon-neutrino beam

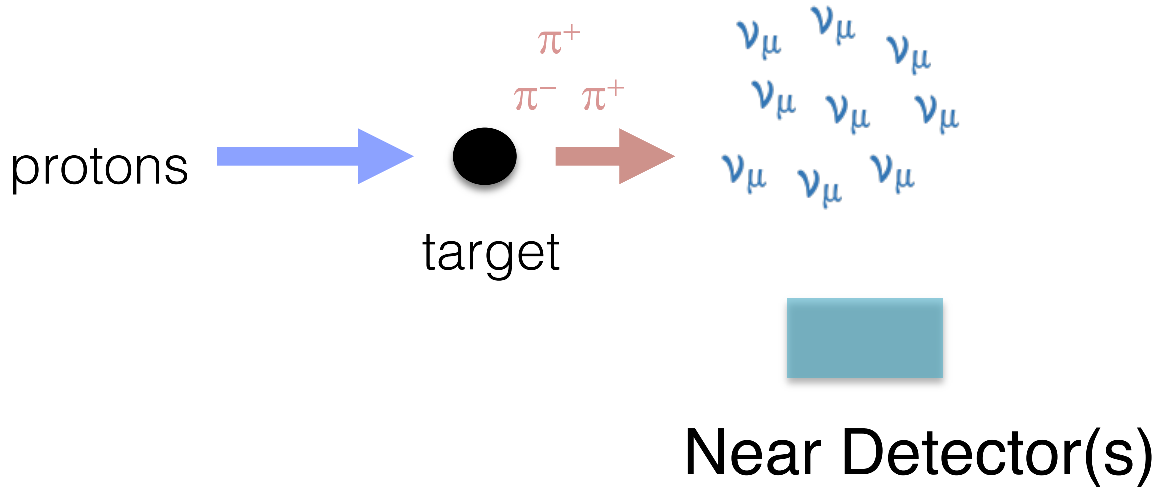


Accelerator neutrino experiments all nominally work on the same simple design:

2) Measure beam close to source before it oscillates

Create ~100% muon-neutrino beam

Characterize beam and interactions



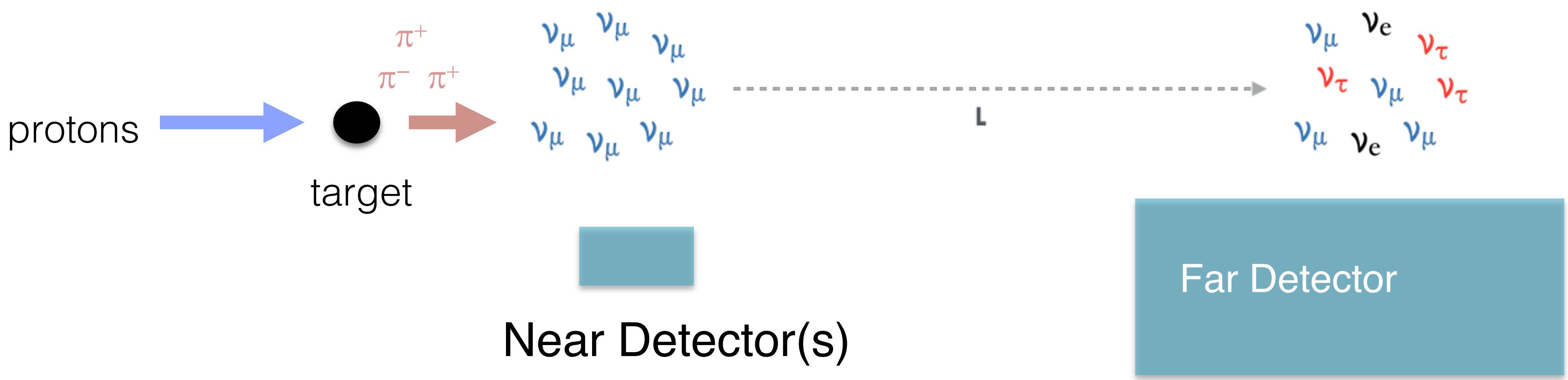
Accelerator neutrino experiments all nominally work on the same simple design:

3) Measure beam again after neutrinos traveled some distance

Create ~100% muon-neutrino beam

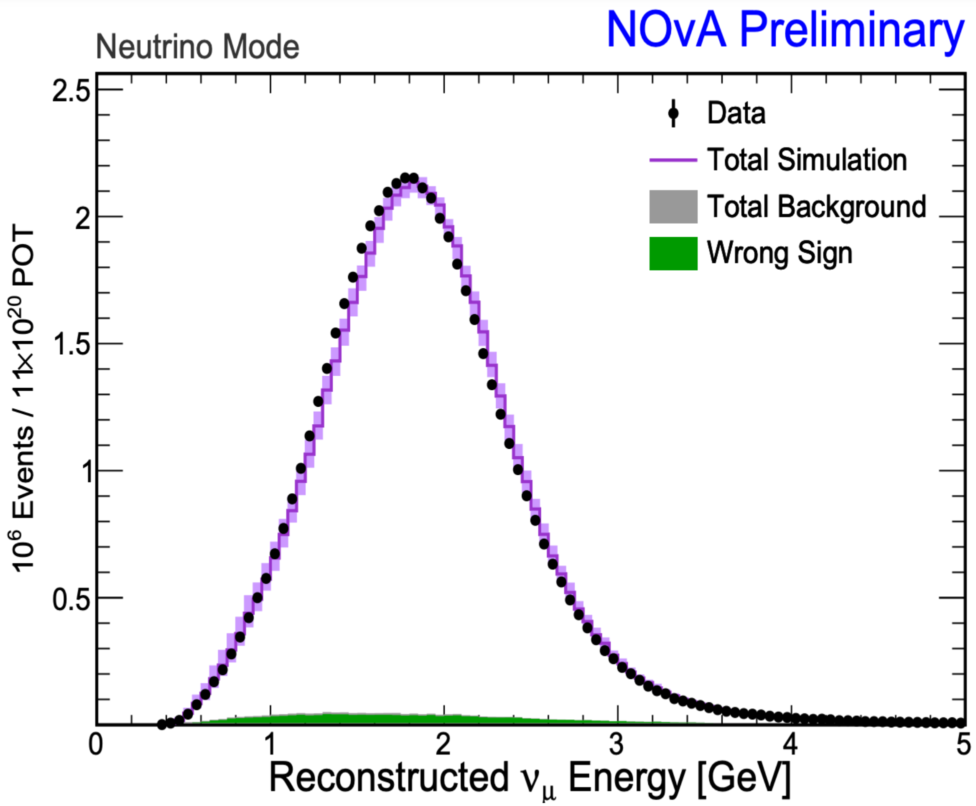
Characterize beam and interactions

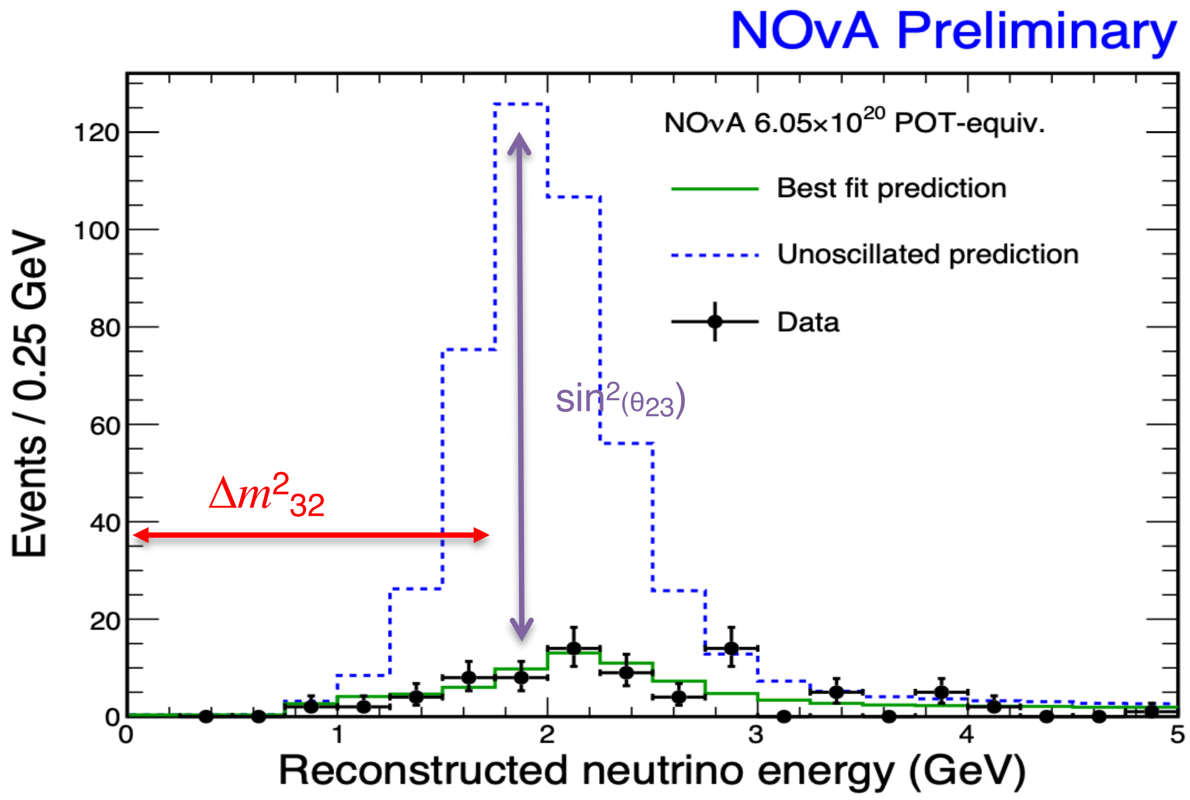
How many of the original flavor have disappeared, and how many of a new flavor have appeared?



Near Detector:
Characterize beam, interactions, and make use to make prediction of what will see at the FD

Far Detector: Compare ND prediction with data, and extract oscillation parameters

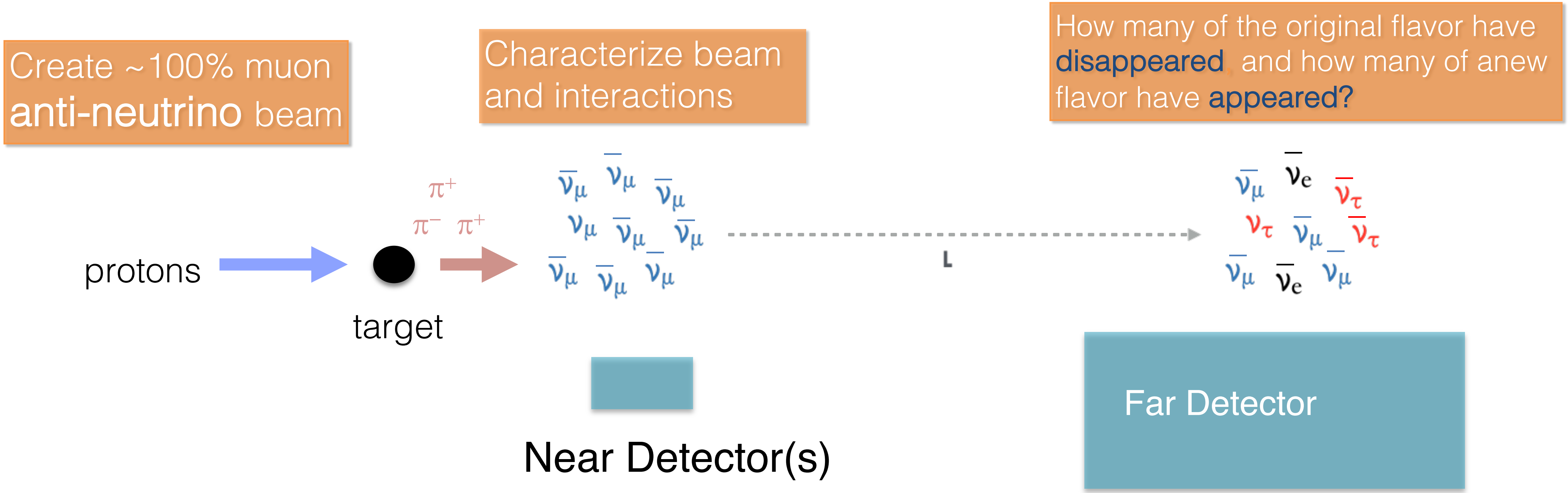




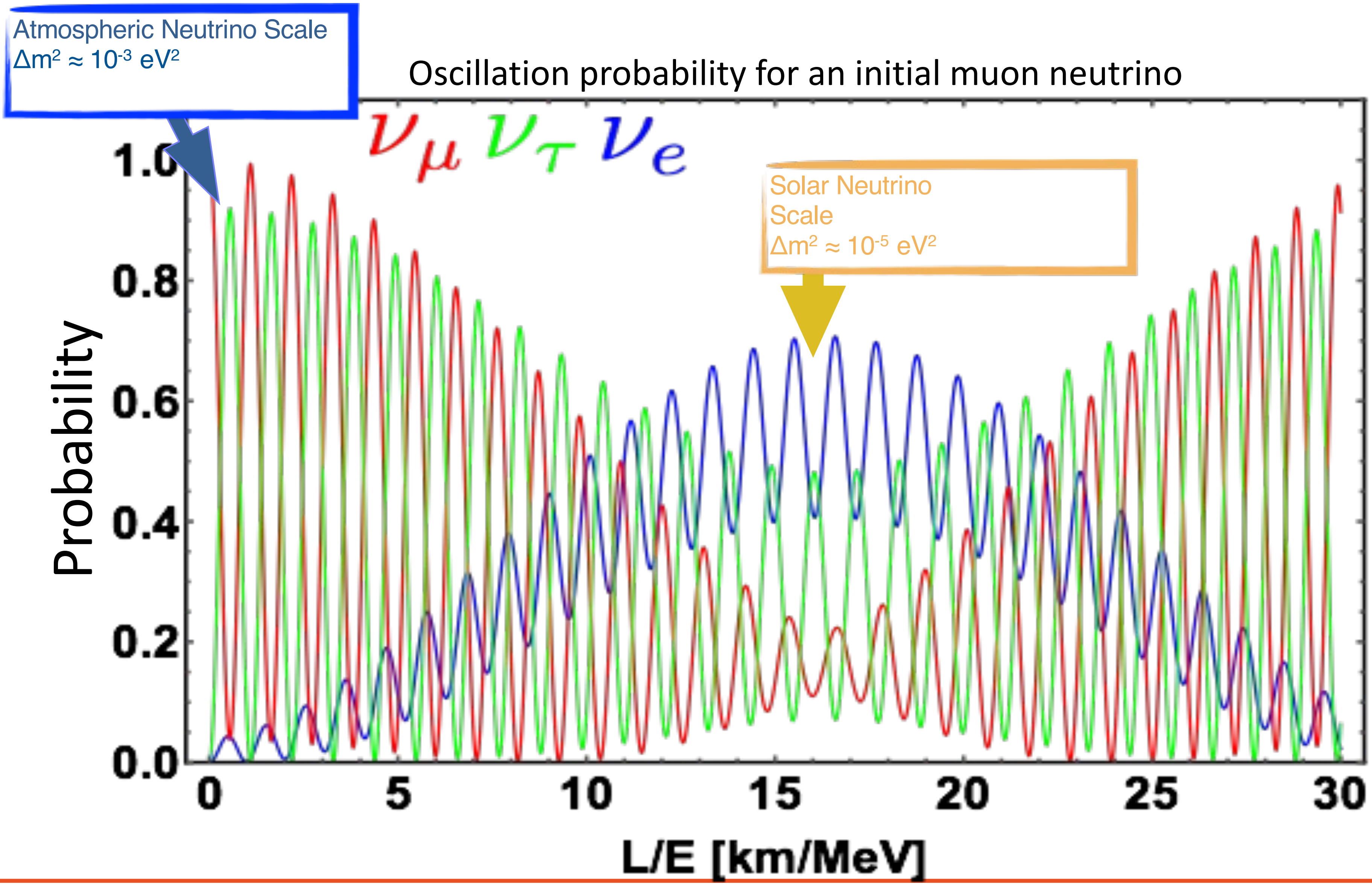
Neutrino oscillation experiments measure amplitude (θ) and frequency (Δm^2)

Power of accelerator neutrino experiments:

4) Repeat 1-3 with anti-neutrinos



Life gets a bit more complicated with 3 neutrinos



Life gets a bit more complicated with 3 neutrinos

Neutrino mass mixing matrix, PMNS, factorizes into three terms

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} \Bigg\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \Bigg\rangle$$

$$\Delta m^2_{32} \simeq 2 \times 10^{-3} \mathrm{eV}^2 \quad L/E = 500\ \mathrm{km/GeV}$$

$$\Delta m^2_{31} \approx \Delta m^2_{32}$$

$$\Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2 \quad L/E = 15,000\ \mathrm{km/GeV}$$

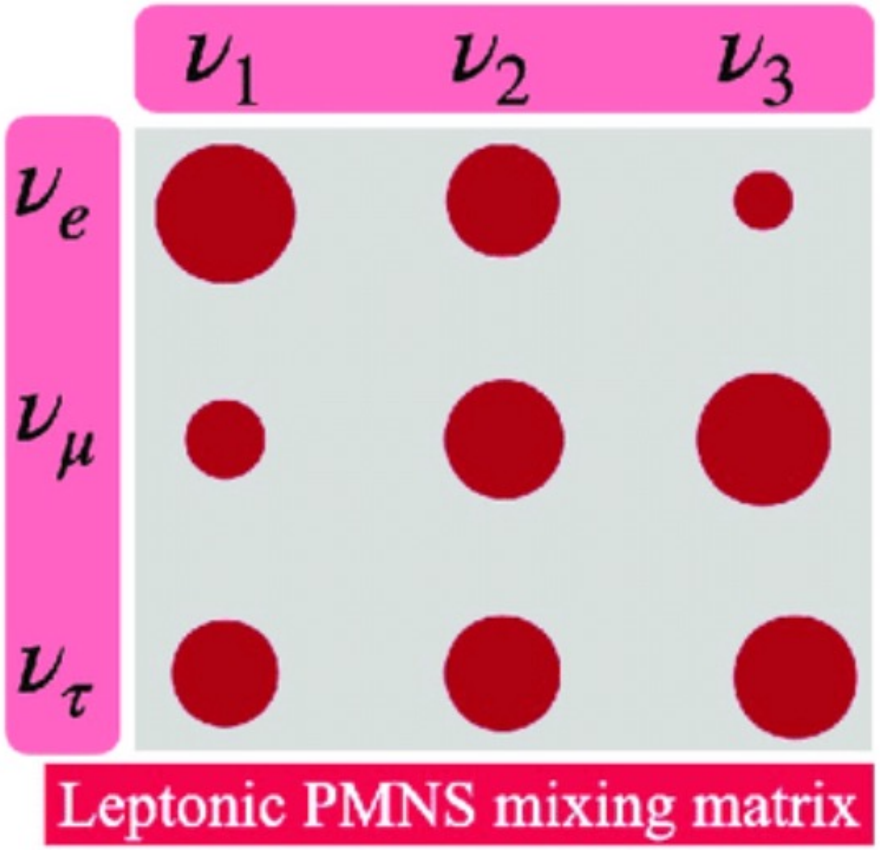
$$c_{\alpha\beta} = \cos_{\alpha\beta}$$
$$s_{\alpha\beta} = \sin_{\alpha\beta}$$

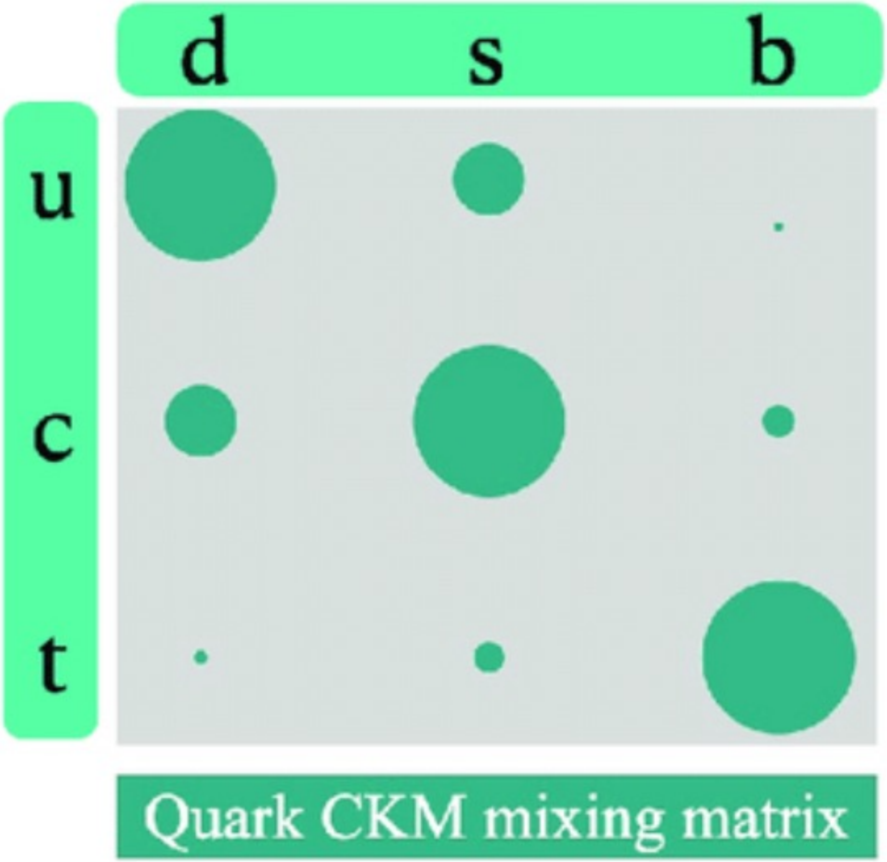
$\nu_\mu \to \nu_\mu$
$\nu_\mu \to \nu_\tau$
atmospheric and long baseline

$\nu_e \to \nu_e$
$\nu_\mu \to \nu_e$
reactor and long baseline

$\nu_e \to \nu_e$
$\nu_e \to \nu_\mu + \nu_\tau$
solar and reactor

Many parts of PMNS matrix not well constrained and we do not understand the relative sizes of these values or nor the relationship between quarks and neutrinos





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Life gets a bit more complicated with 3 neutrinos

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$$\Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2$$
$$L/E = 15,000 \ \mathrm{km/GeV}$$

$$\cancel{P_{\alpha\alpha} \approx 1 - \sin^2(2\theta) \sin^2 \left(\frac{1.27 \Delta m^2 [\mathrm{eV}^2] L_\nu [\mathrm{km}]}{E_\nu [\mathrm{GeV}]} \right)}$$

Extending to full three flavors

$$\sin^2(2\theta) = 4 \sin^2\theta_{23} \cos^2\theta_{13} (1 - \sin^2\theta_{23} \cos^2\theta_{13})$$

$$\Delta m^2 = \Delta m^2_{32} + \Delta m^2_{21} \sin^2\theta_{12} + \Delta m^2_{21} \cos\delta_{CP} \sin\theta_{13} \tan\theta_{23} \sin 2\theta_{12}$$

Also need to account for affect due to neutrinos interacting with matter: MSW = Mikheyev–Smirnov–Wolfenstein effect

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix} \Big\rangle = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix} \Big\rangle$$

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Probability is modified as neutrinos travel through matter. Need to modify θ_{13} to θ_M, where

$$\sin^2 2\theta_M = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (A - \cos 2\theta_{13})^2} \qquad A = \pm 2\sqrt{2} G_F n_e E_\nu / \Delta m^2_{13}$$

- Electron neutrinos experience additional interactions with the electrons in matter
- These “matter effects" allow accelerator and atmospheric experiments to probe the neutrino mass ordering

$P(\nu_\mu \rightarrow \nu_e)$ complexity is the foundation of the current accelerator neutrino physics program

$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2\Delta(1-A)}{(1-A)^2} + \alpha\tilde{J}\cos(\Delta \pm \delta_{CP})\frac{\sin\Delta A}{A}\frac{\sin\Delta(1-A)}{(1-A)} + \alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\Delta A}{A^2}$$

$$\alpha = \Delta m^2_{21}/\Delta m^2_{31}$$
$$\tilde{J} = \cos\theta_{13}\sin 2\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}$$
$$\Delta = \Delta m^2_{31}L_\nu/4E_\nu$$
$$A = \pm 2\sqrt{2}G_F n_e E_\nu/\Delta m^2_{13}$$

$P(\nu_\mu \rightarrow \nu_e) \propto \theta_{23}, \Delta m^2_{23}, \theta_{13}, \delta_{cp}$

$P(\nu_\mu \rightarrow \nu_e) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$

Has sensitivity to some of the biggest questions in the field

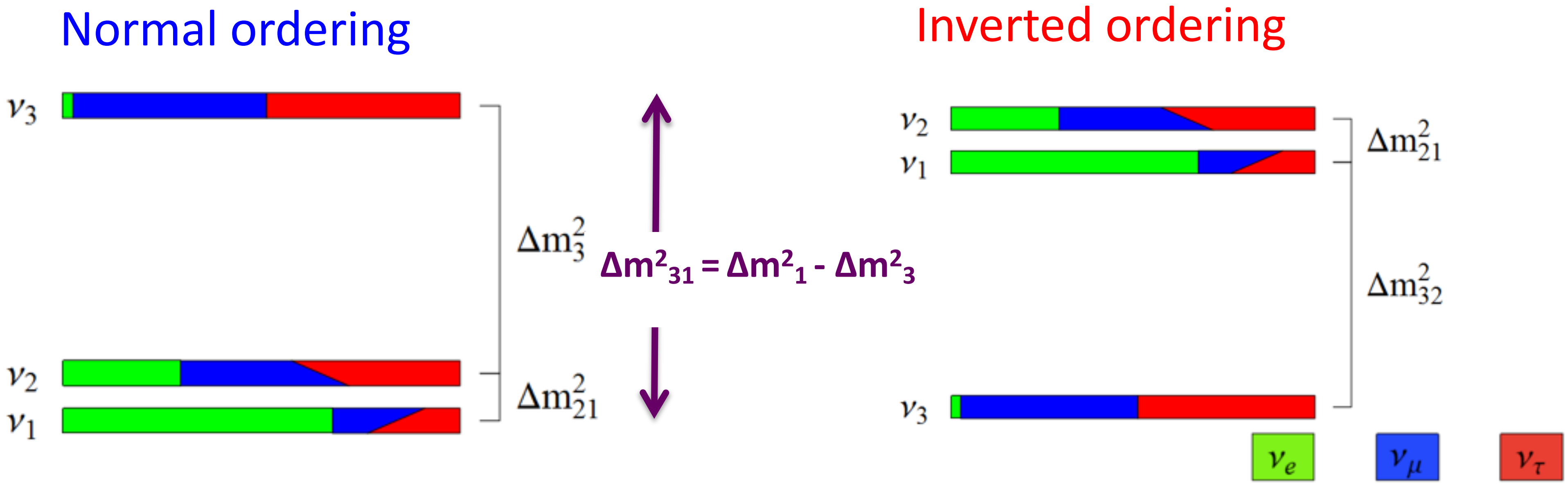
See talk by Patricia Vahle

Order of the neutrino masses

We do not know the absolute masses of neutrinos (just upper limits), but with oscillations, we can measure the differences between two mass states
Since we have three neutrino flavors, need two mass splittings

$$\Delta m^2_{32} \simeq 2 \times 10^{-3} \mathrm{eV}^2 \qquad \Delta m^2_{21} \simeq 8 \times 10^{-5} \mathrm{eV}^2$$

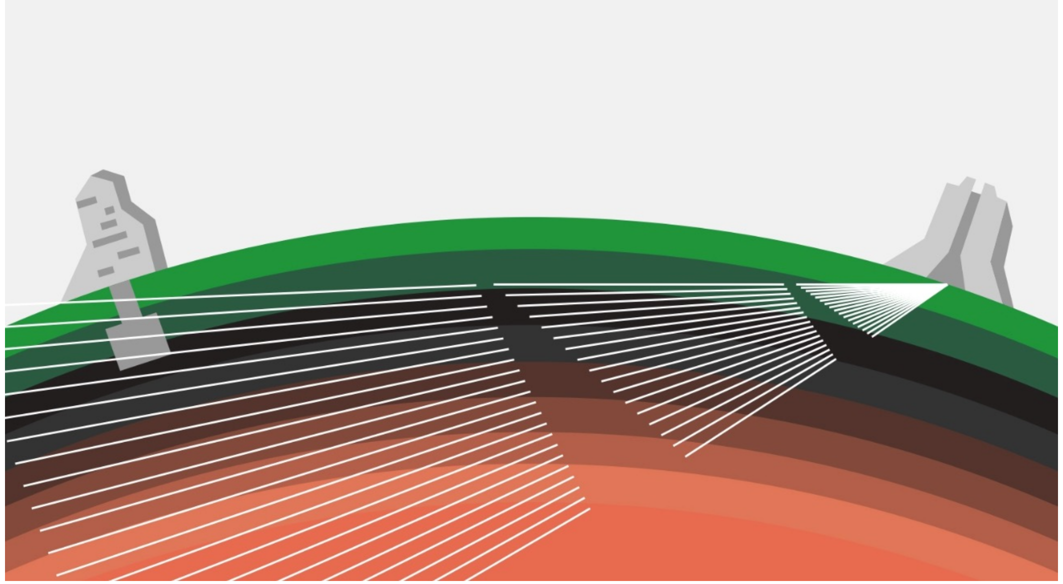
Measuring Δm^2_{32} as positive or negative informs us of the ordering



Neutrino mass ordering

Sensitivity to mass order depends on how far through earth neutrinos travel (baseline)

Electron-neutrinos interact with electrons in the earth which changes the probability



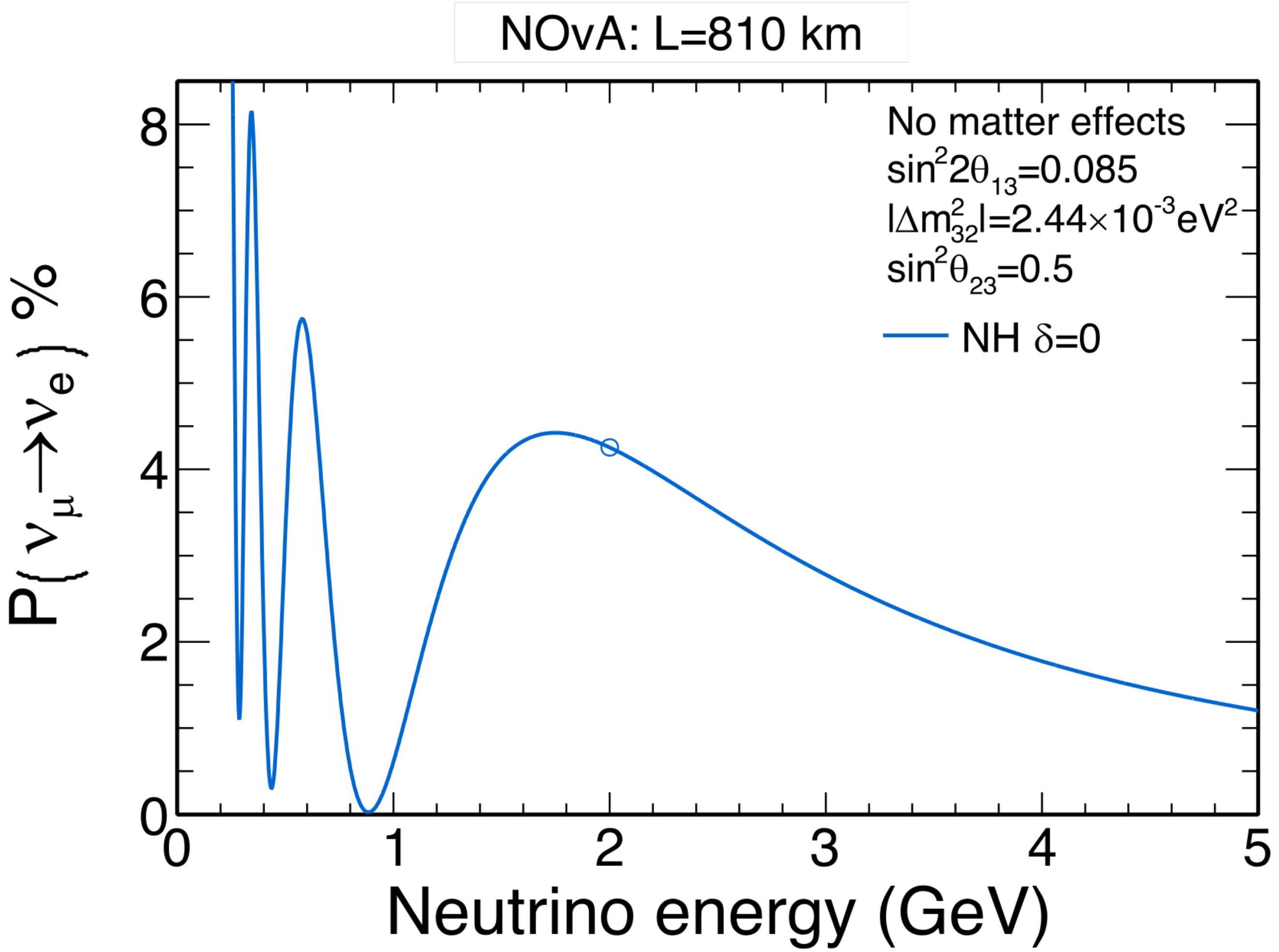
T2K Hyper-Kamiokande — 295 km

NOvA MINOS — 810/735 km

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT — 1300 km

Ordering has significant implications for astrophysics, cosmology, and neutrino-less double beta decay experiments.

$P(\nu_\mu \to \nu_e)$ 'ν_e appearance' oscillation probability



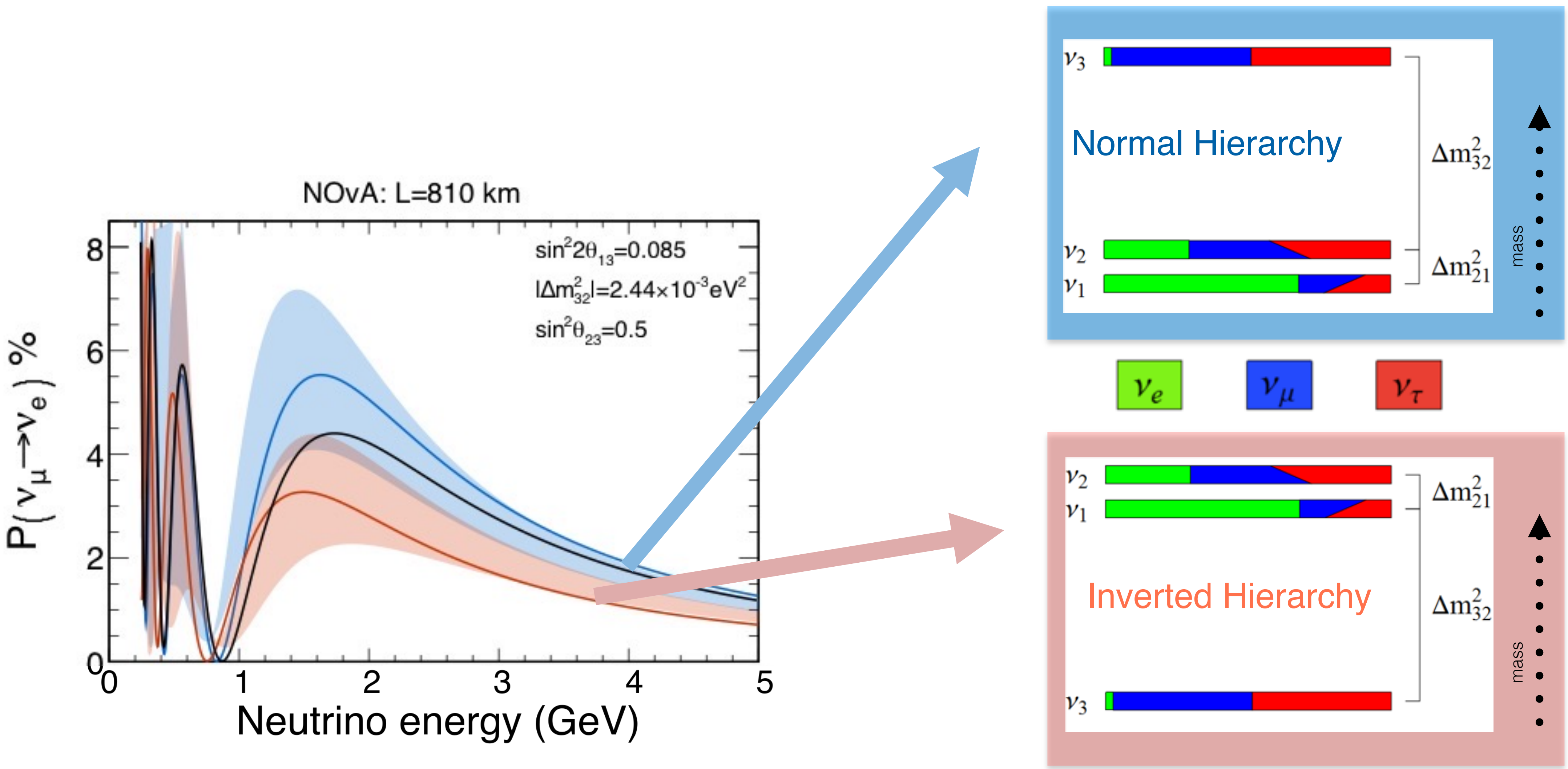
Vacuum oscillation probability at NOvA Far Detector

Baseline - 810 km
Beam energy peak - 2 GeV

Designed to give max number of muon neutrinos oscillating to electron neutrinos

No matter effects and CP conservation

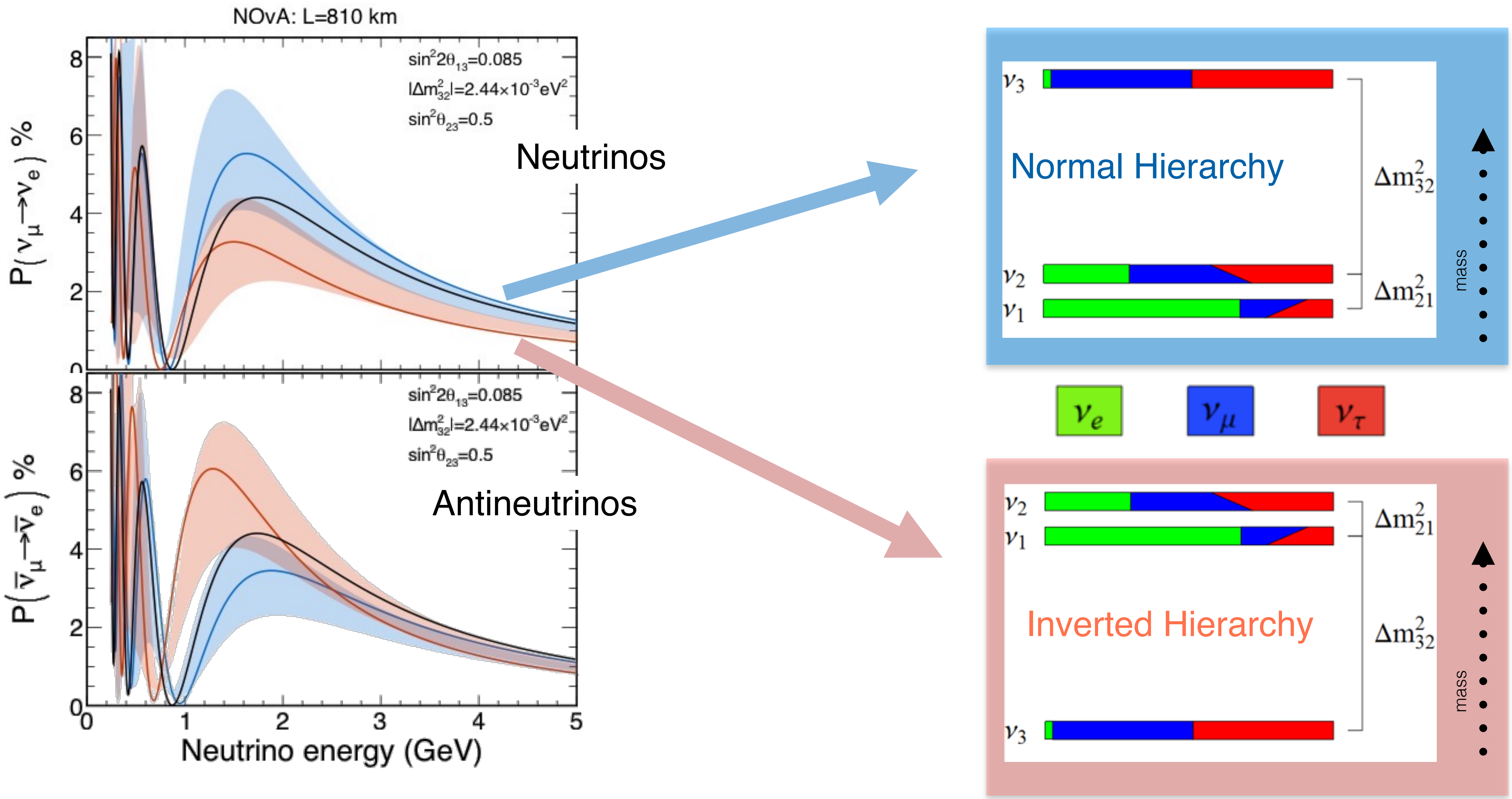
Neutrino Mass Hierarchy



Matter effect: Electron neutrinos experience additional interactions with electrons in the earth

Neutrino Mass Hierarchy

We can determine the ordering by looking to see if neutrinos (anti-neutrinos) are enhanced or suppressed

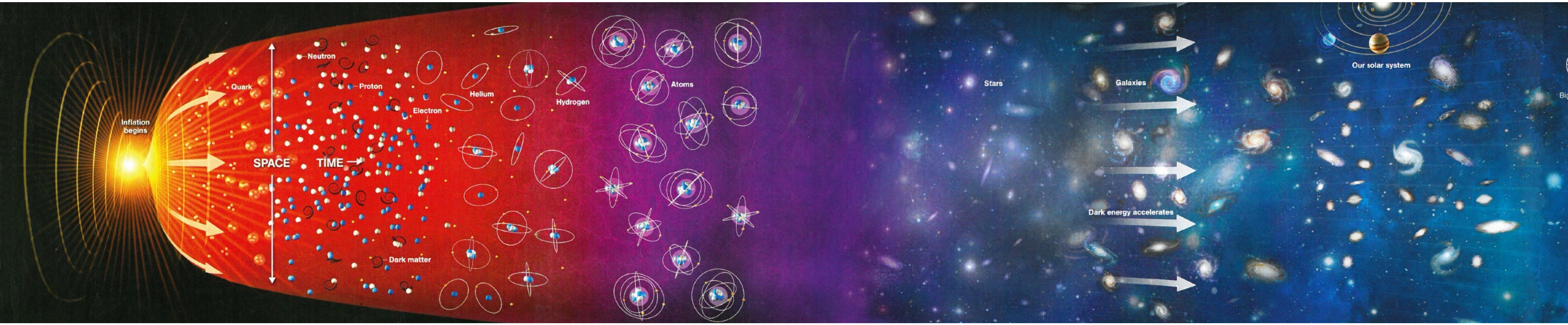


Matter effect: Electron neutrinos experience additional interactions with electrons in the earth

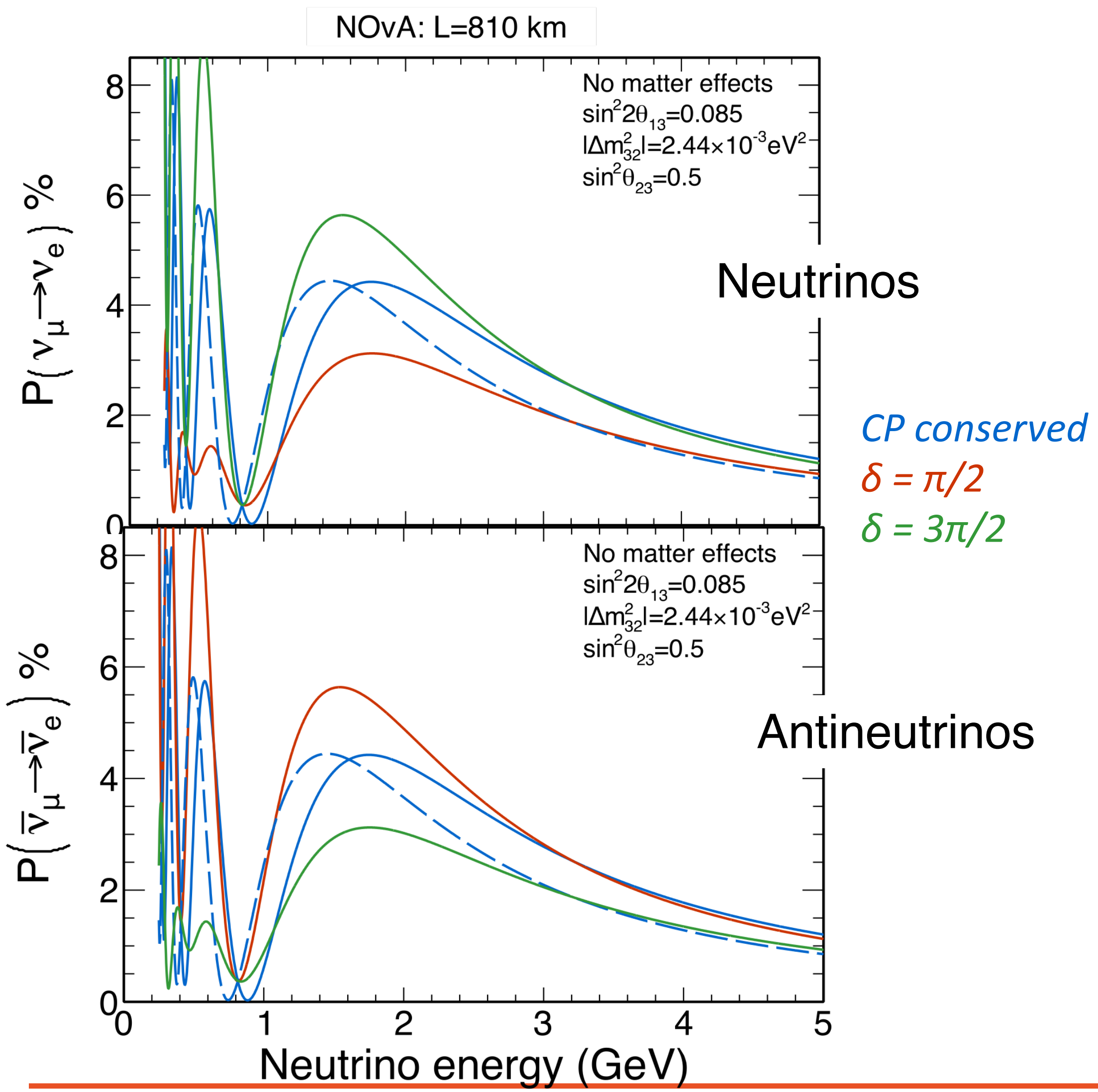
Do neutrinos and anti-neutrinos oscillate the same?

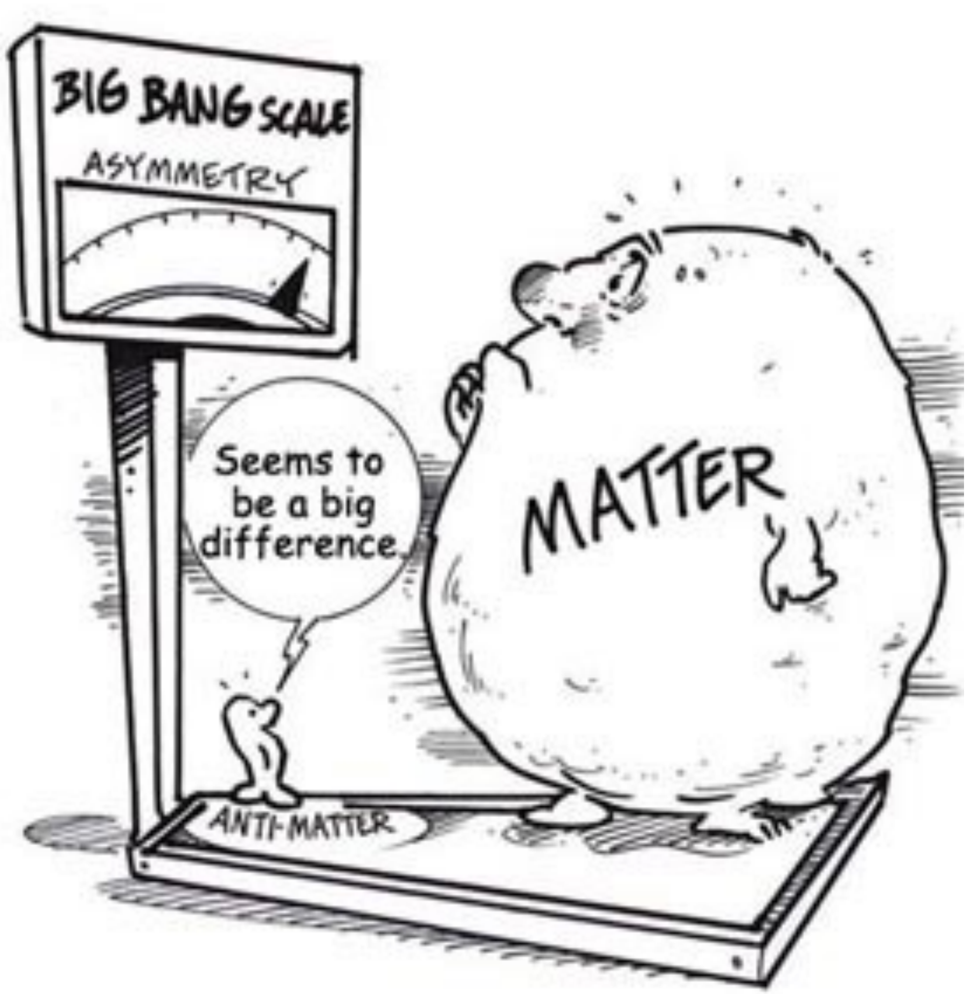
Neutrino mass matrix has phase δ_{CP} which allows neutrino and anti-neutrino oscillation rates to be different

This could potentially be part of one of the biggest questions in particle physics.
Why do we live in a universe only made of matter?

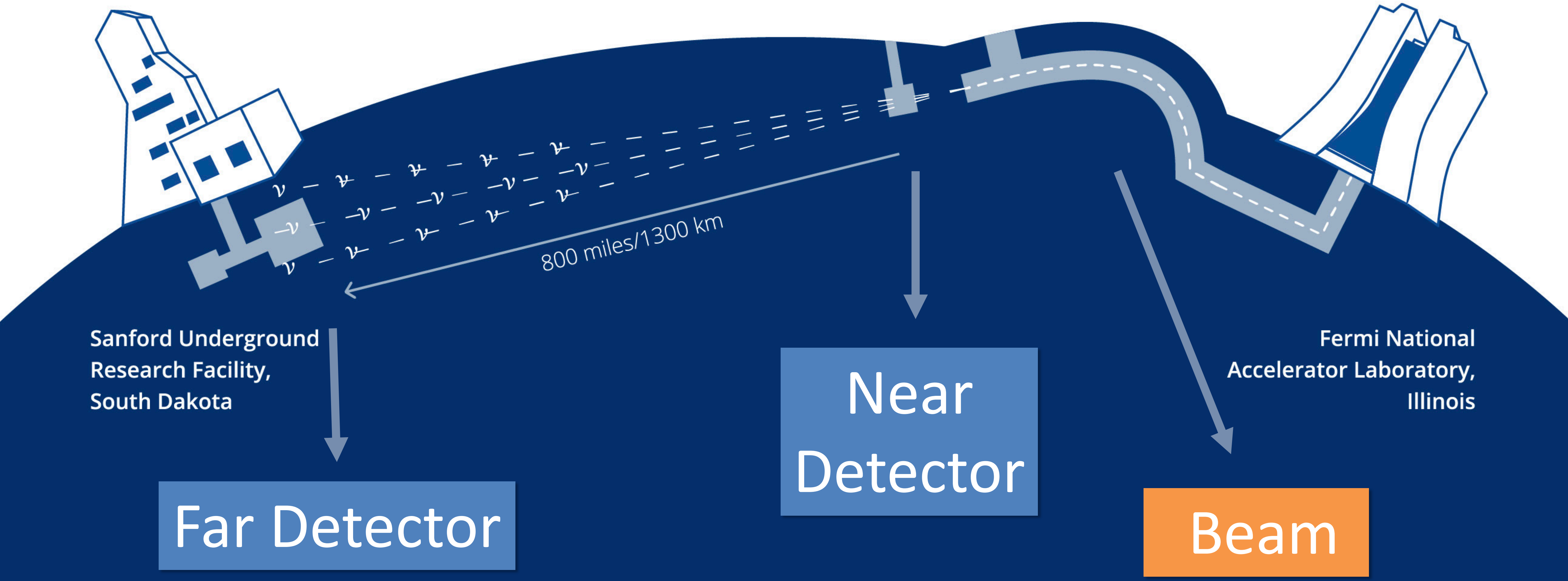


Charge Parity Violation

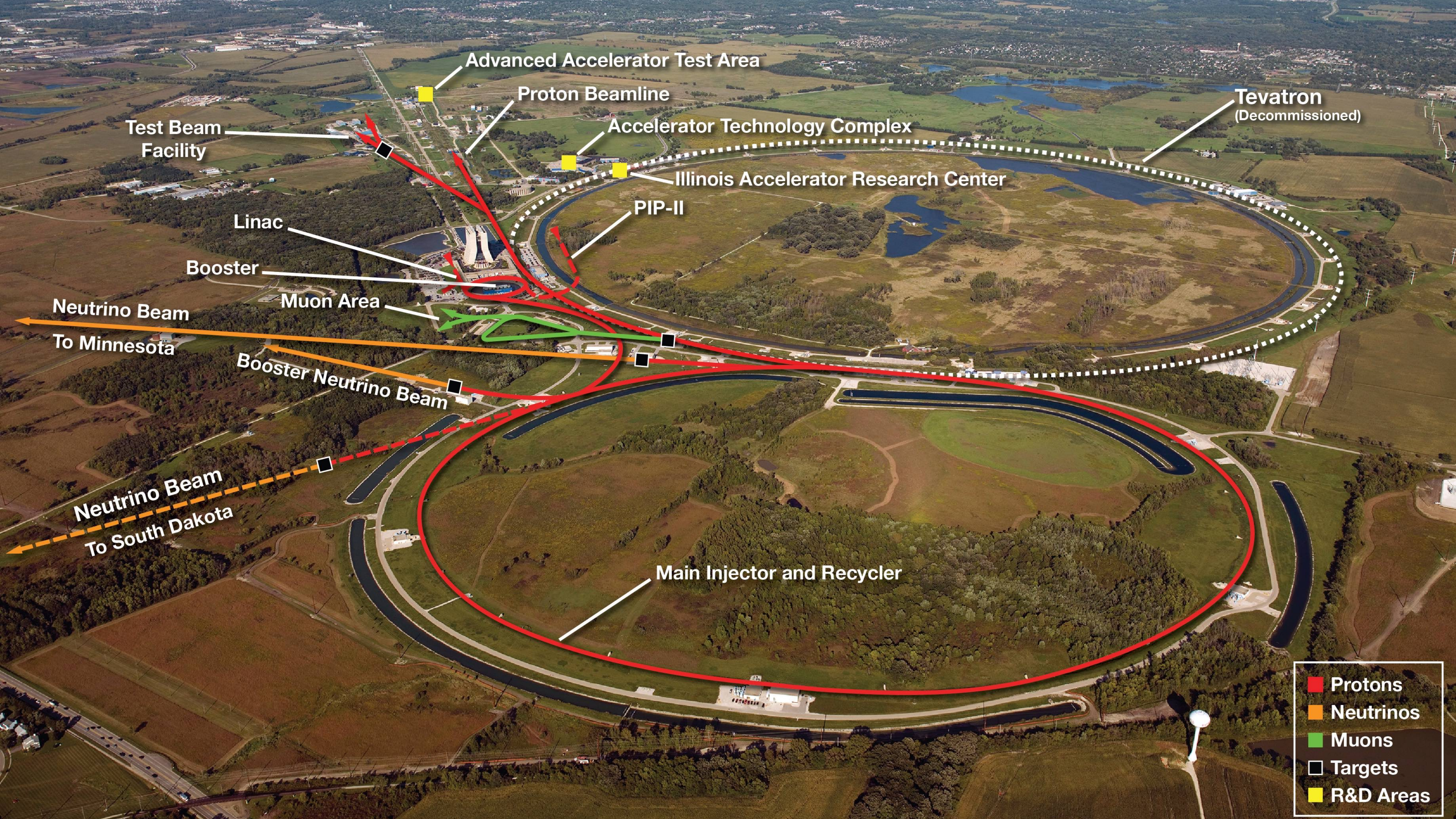


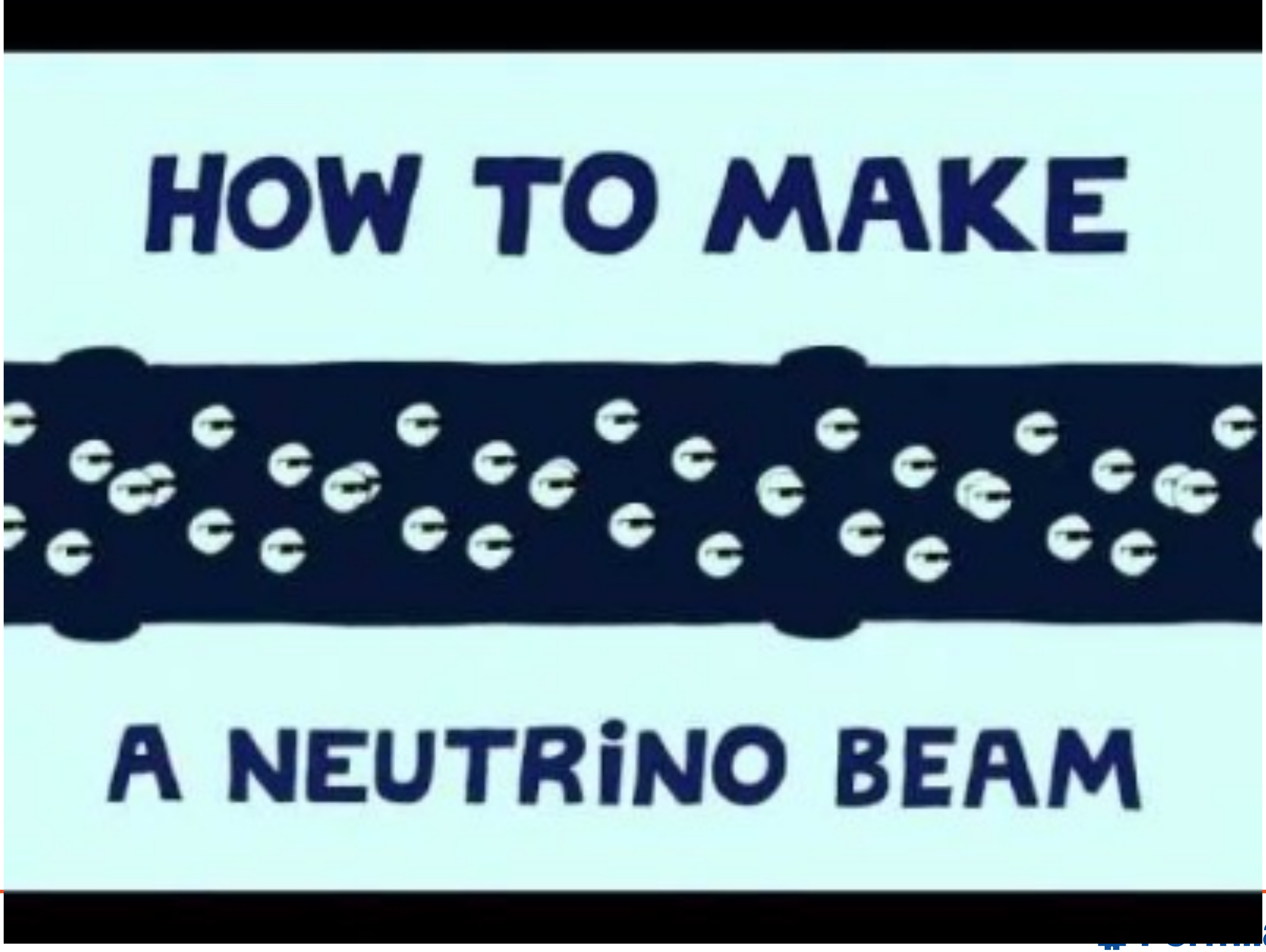


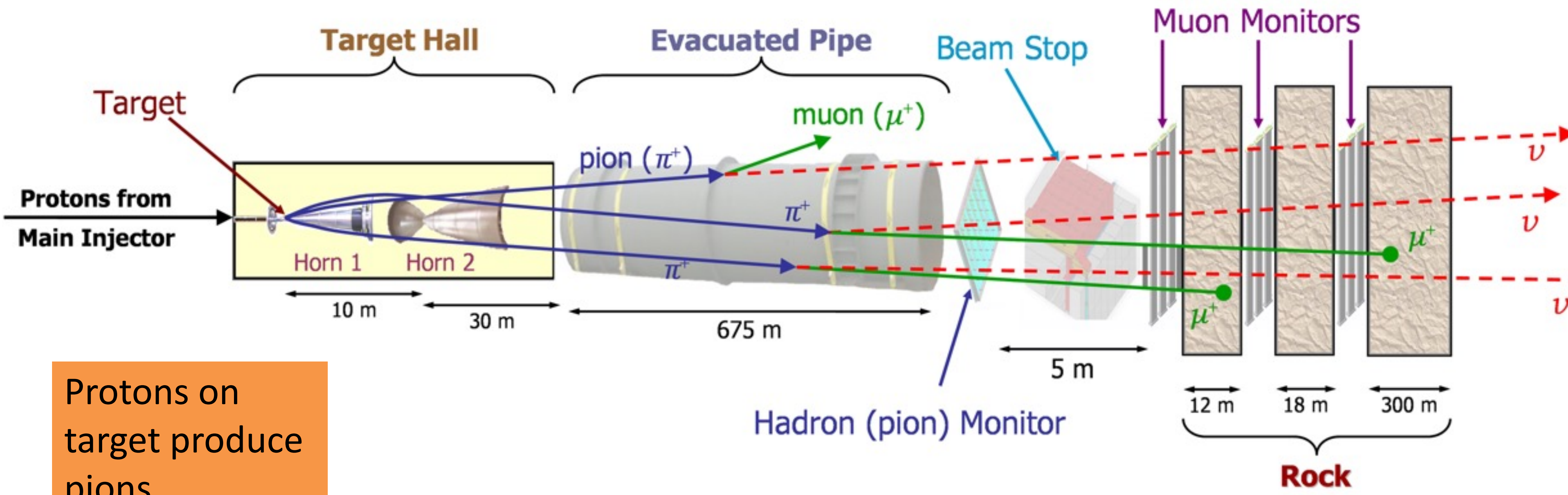
If there is CP violation, we will see an enhancement or suppression that will be opposite for neutrinos and anti-neutrinos



The design of accelerator oscillation experiment


Advanced Accelerator Test Area
Proton Beamline
Test Beam Facility
Accelerator Technology Complex
Tevatron (Decommissioned)
Illinois Accelerator Research Center
PIP-II
Linac
Booster
Muon Area
Neutrino Beam To Minnesota
Booster Neutrino Beam
Neutrino Beam To South Dakota
Main Injector and Recycler
Protons
Neutrinos
Muons
Targets
R&D Areas


HOW TO MAKE
A NEUTRINO BEAM



Protons on target produce pions

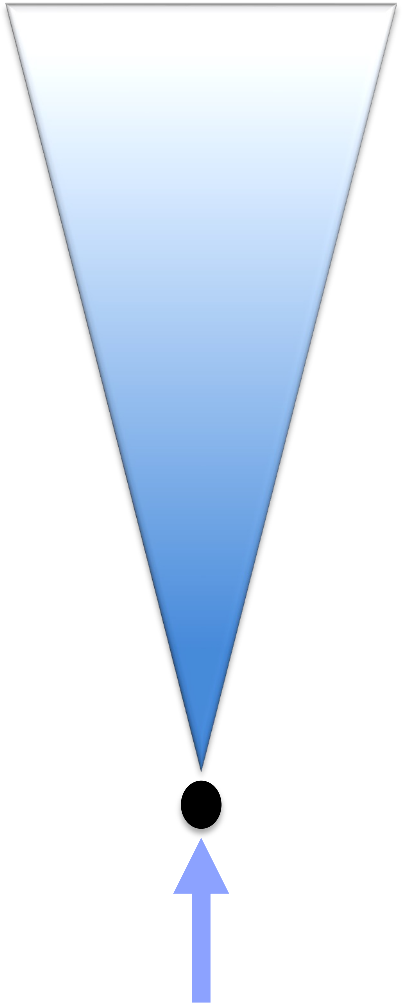
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

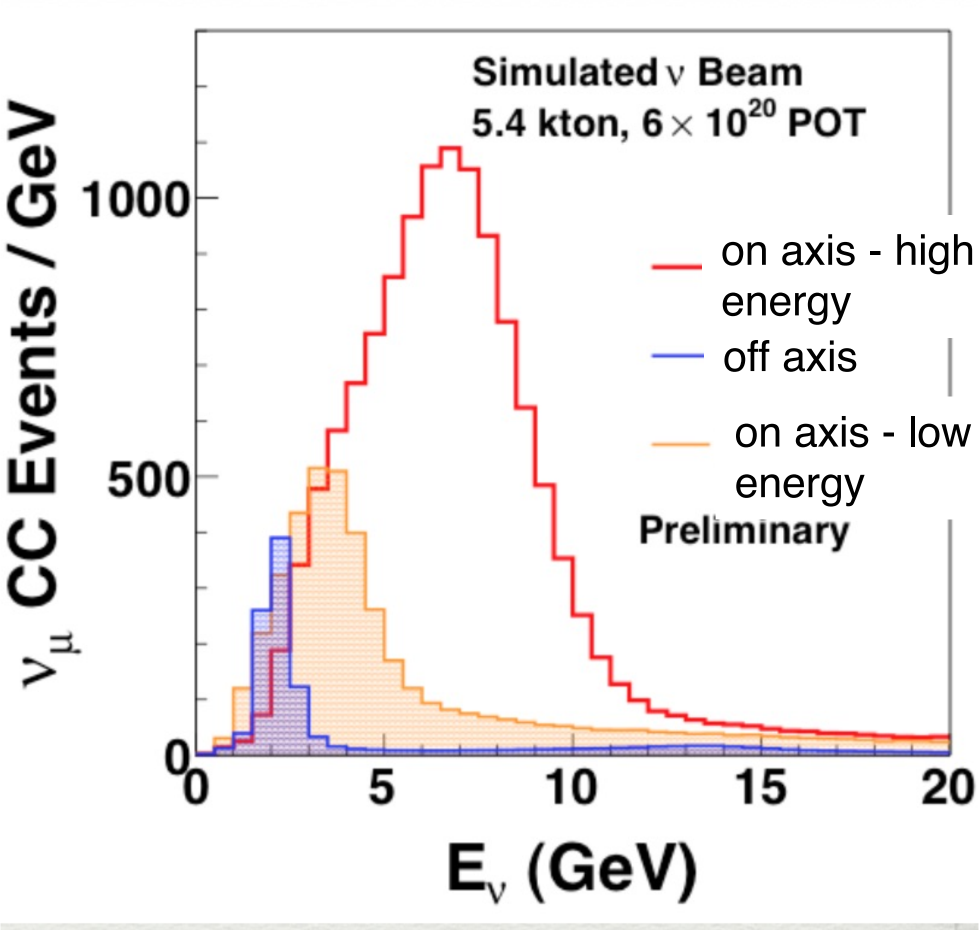
$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$$

Changing the horn current we select either positive or negative pions -> **make neutrino or anti-neutrino beam**

Pions decay to produce muon and muon neutrino ~ 100% of the time (0.999877)

Going off the central beam axis





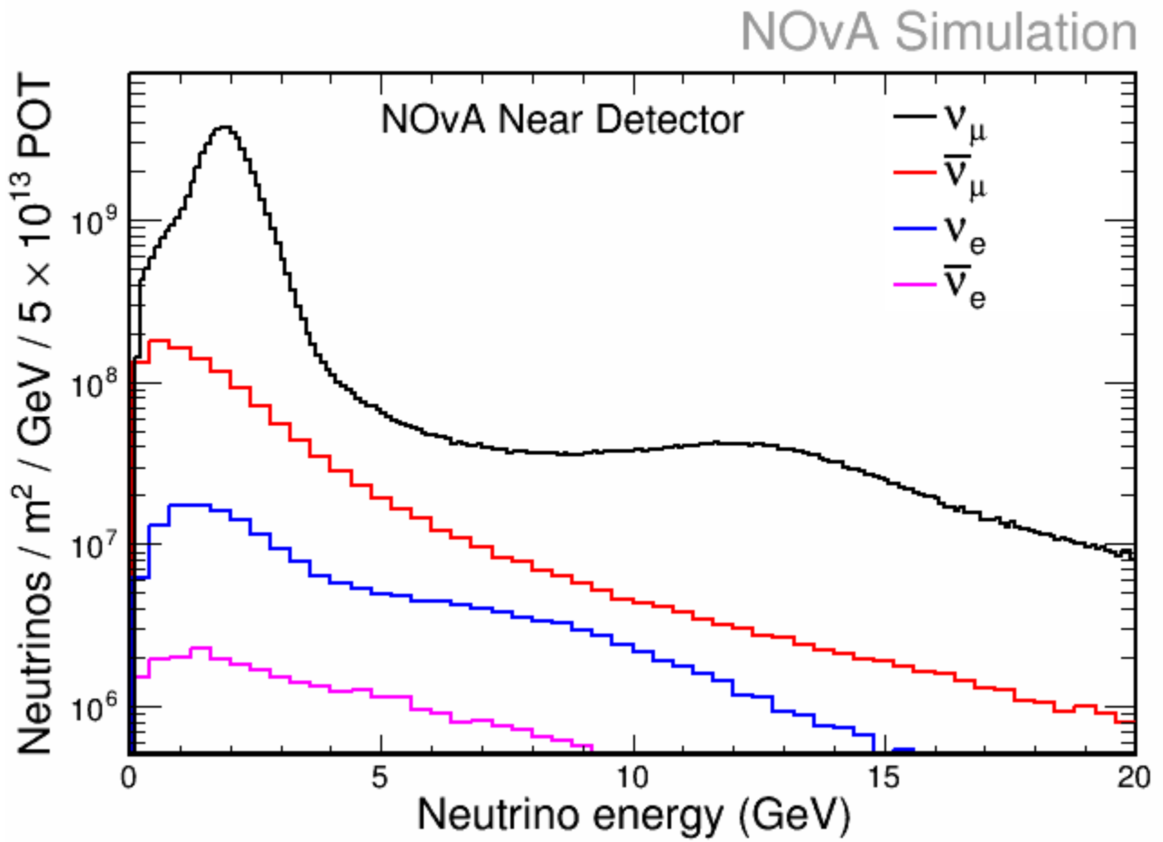
Neutrino detectors have historically had relativity poor energy resolution, specifically for higher energy events.

Placing the detector off-axis makes a much narrow energy beam

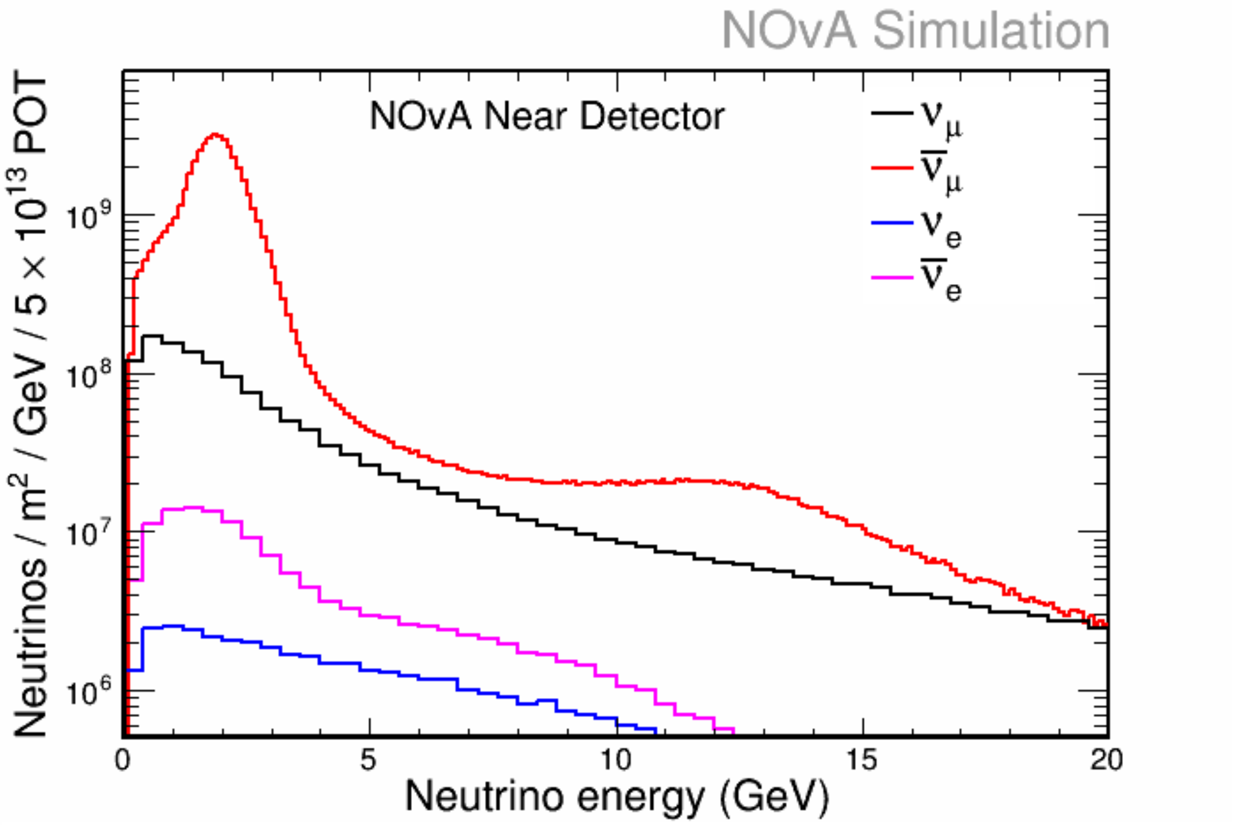
But there are advantages of both
- DUNE will be on axis

NOvA and MINOS were on and off axis in the same beam

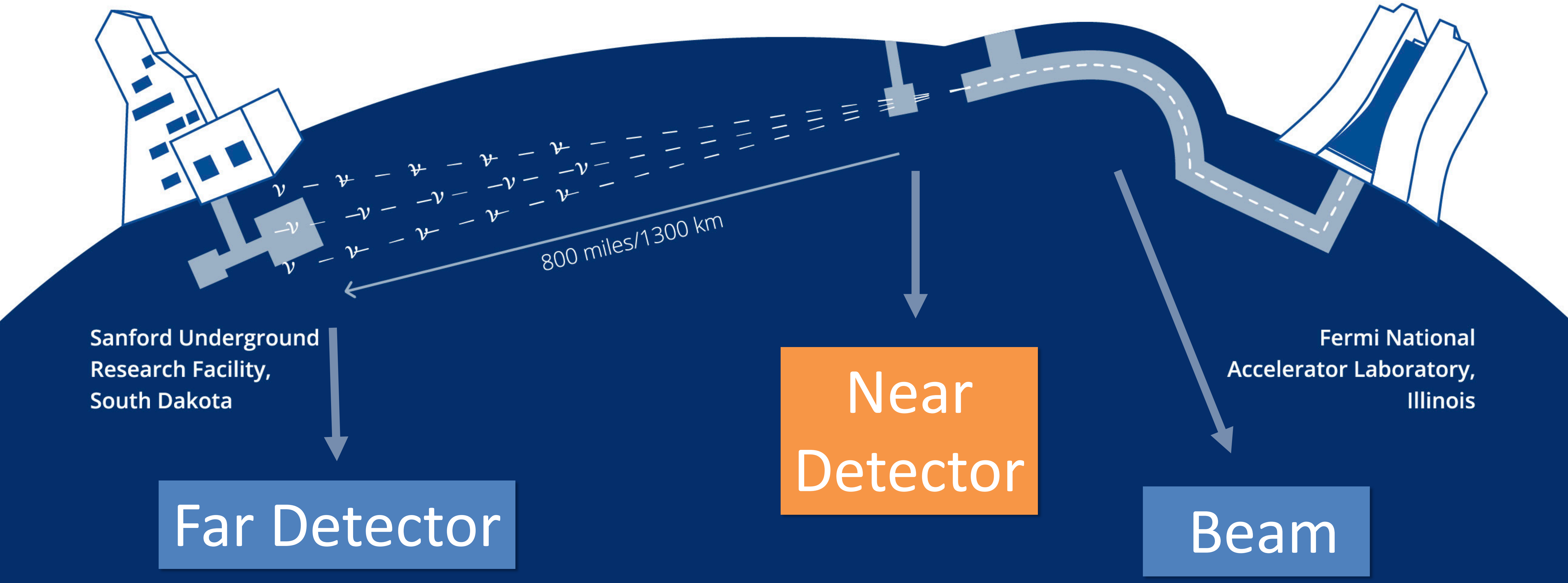
Neutrino beam



Anti-neutrino beam



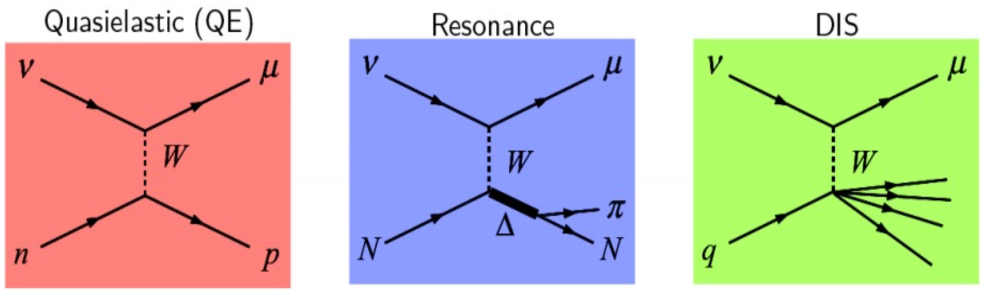
- In reality, the beam is not a 100% muon neutrino beam
- We produce (anti)neutrino and ν_e backgrounds, especially at higher energies, and the overall rate is unknown to about 10%.
- Need a near detector to measure exactly what was produced so we know what to expect at the Far



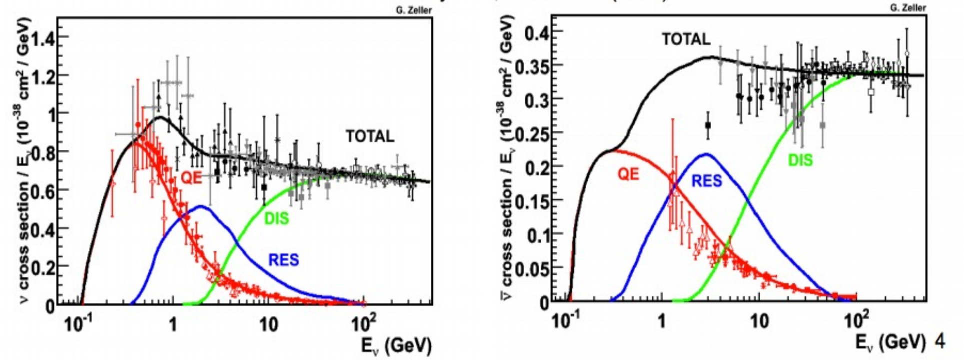
The design of accelerator oscillation experiment

Neutrino interactions and reconstruction are some of the biggest challenges we face

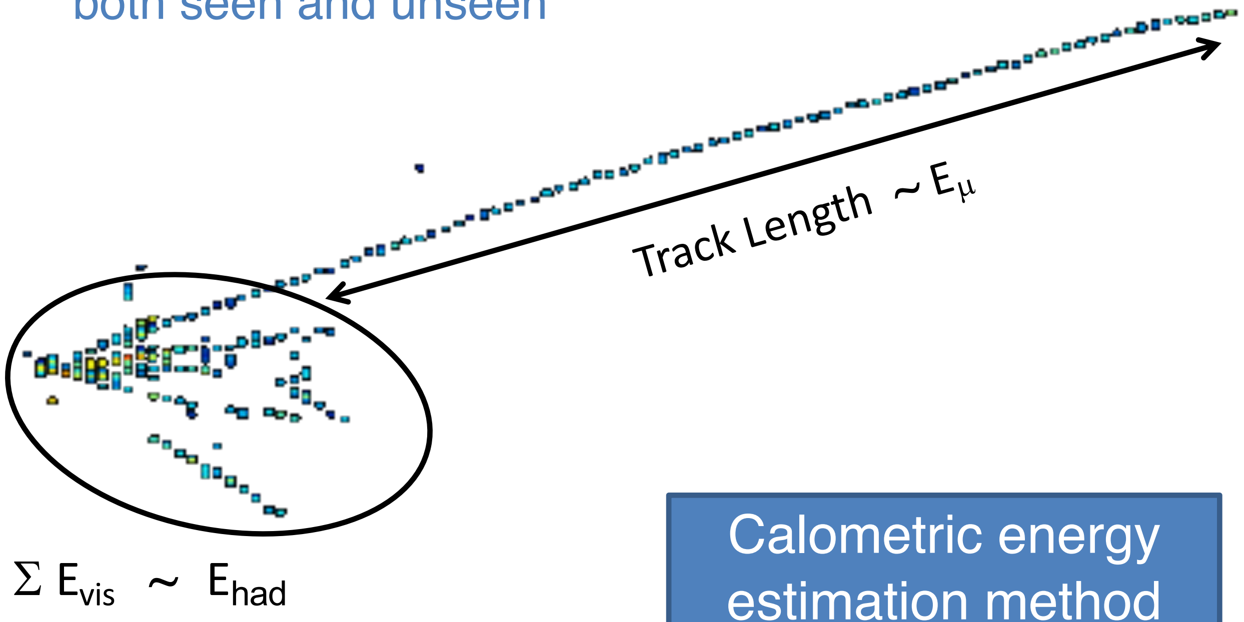
- Neutrinos will interact (via charge current) and product a lepton, and some number of other hadrons
- Large uncertainty on neutrino cross-sections, need to measure and not reply on simulation



Rev. Mod. Phys. 84, 1307–1341 (2012)



- We don't see the neutrino itself so need to reconstruct incoming neutrino energy from its interaction in the detector
- Challenging problem to account for all particles both seen and unseen



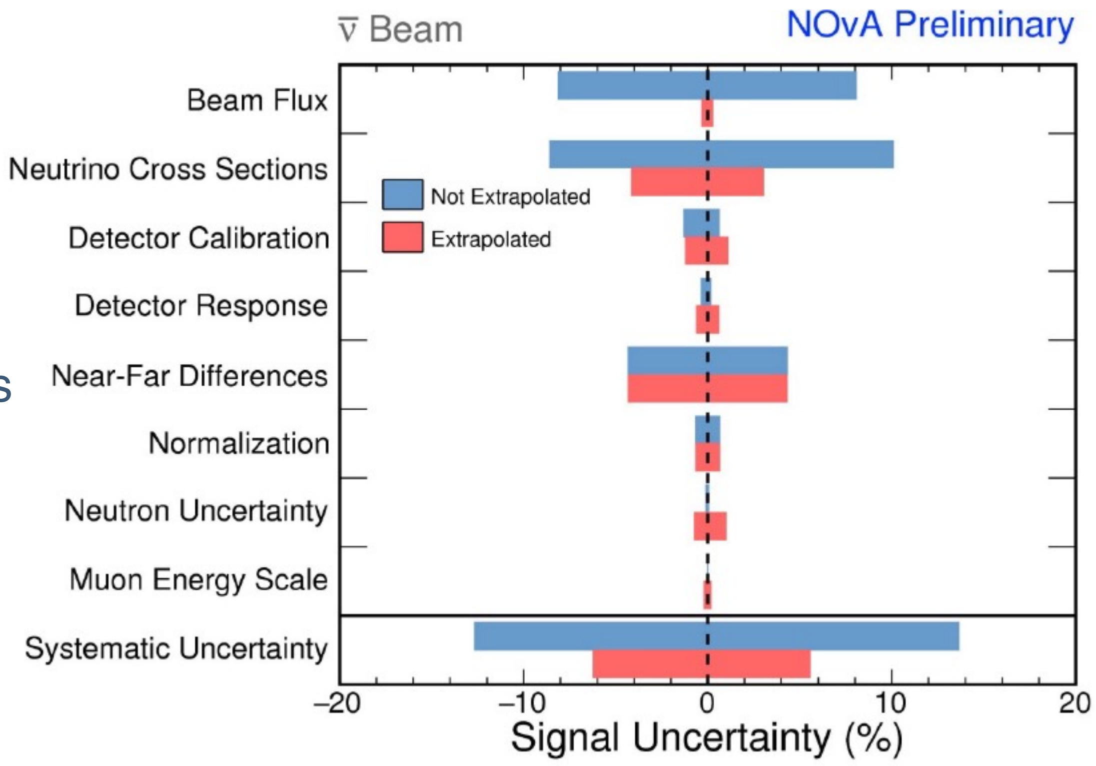
Calometric energy estimation method

$$E_\nu = E_\mu + E_{had}$$

Near Detector (s) and uncertainties

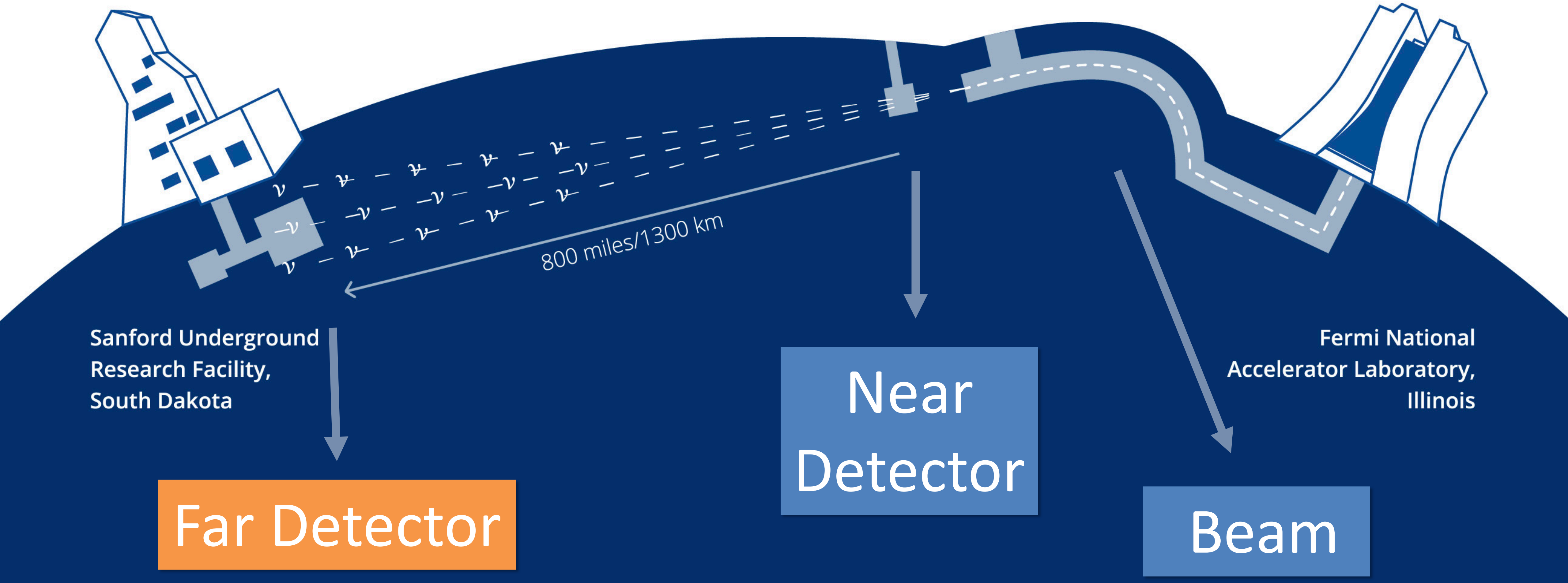
- Its very hard to predict (and simulate) accurately what neutrinos will do
  - We need to measure the flux of neutrinos produced from the beam
  - We need to measure the neutrino cross-section with the material of our detector
  - We need to measure how our detectors respond to neutrinos
- The better we know all these things (smaller uncertainties) we better we can measure of the neutrino properties

Near Detectors both serve to measure the rate of neutrino interaction and to help constrain the associated uncertainties



Using ND constraint

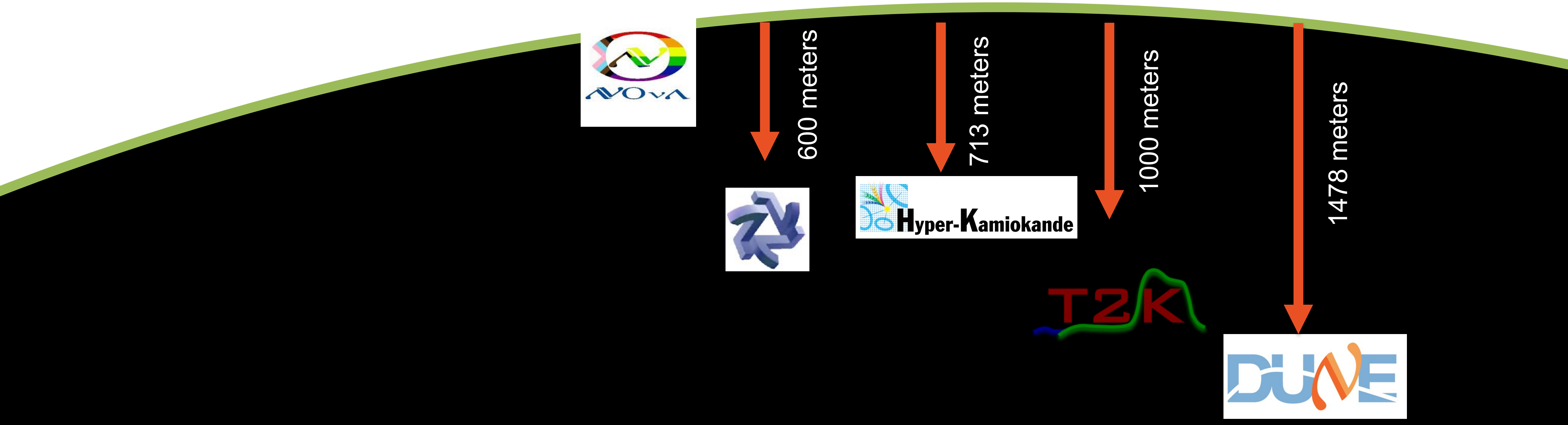
Not using ND constraint



The design of accelerator oscillation experiment

Far Detector (s)

- Neutrino interactions are rare - think about 1 per day at the Far Detector
- Far Detectors are generally designed to be as large and dense as possible
  - Generally homogeneous and made from a cheap and easily available material
- Many many more events from cosmic rays will interact in these detectors, can remove these by going underground or by having fast electronics



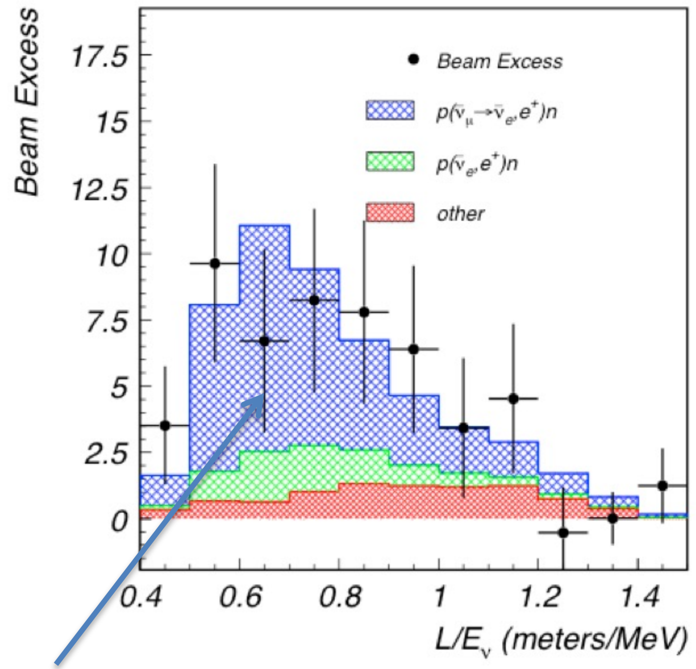
The experiments

Short baseline accelerator neutrino experiments

Could there be more than 3 types of neutrinos?

- Past experiments, LSND and MiniBooNE, have results that could be interpreted as due to a new neutrino with a mass of ~1 eV
- But we know there are only 3 types of neutrinos that interact with matter, and they are all lighter than 1eV
- Call this potential new type a “sterile neutrino”, we would only see it through oscillations

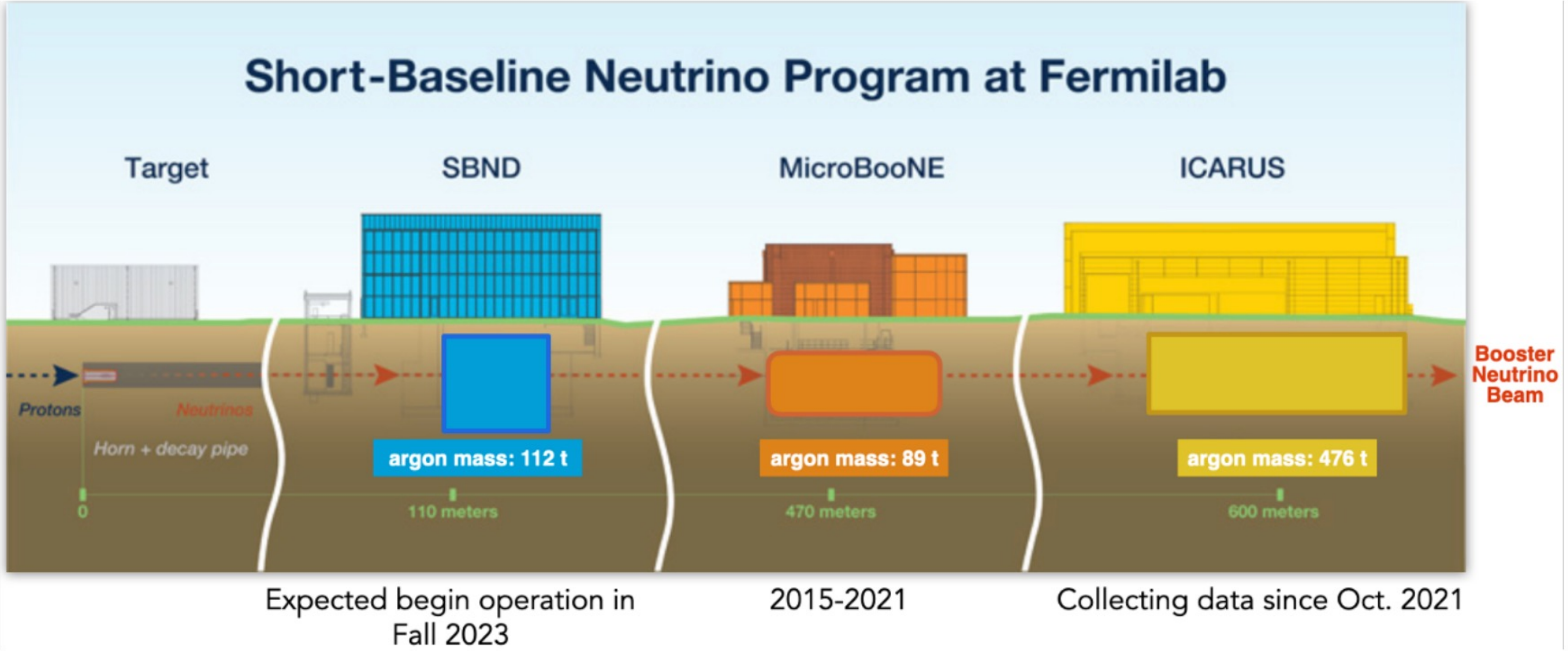
Phys.Rev.D64:112007,2001



Blue sample is fitted ν_e appearance

Short baseline accelerator neutrino experiments

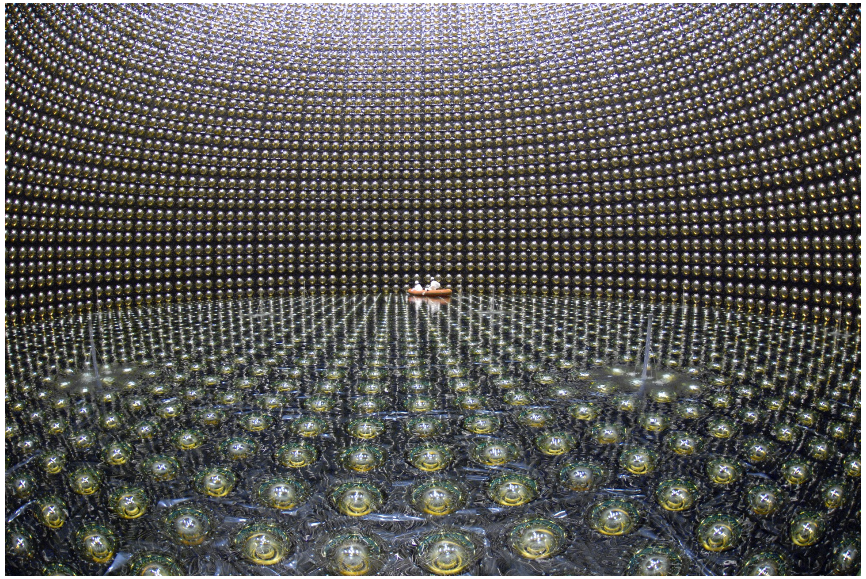
Placing experiments at different distances (baselines) enables us to probe different mixings and mass splittings.
Short baseline experiments are placed to probe a mass difference around 1eV

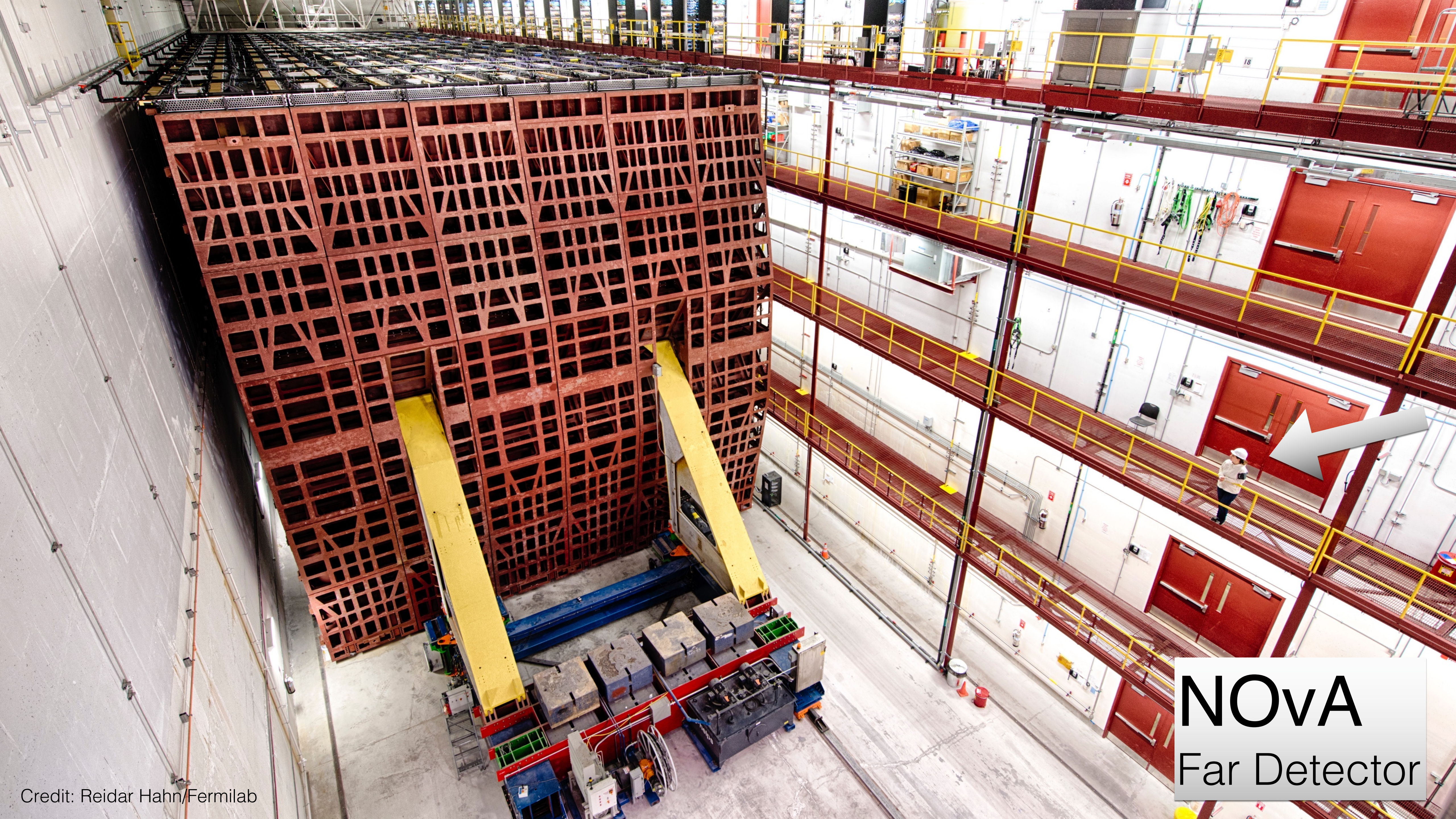


MicroBooNE released its results in 2021, and results from ICURAS and SBND are still to come

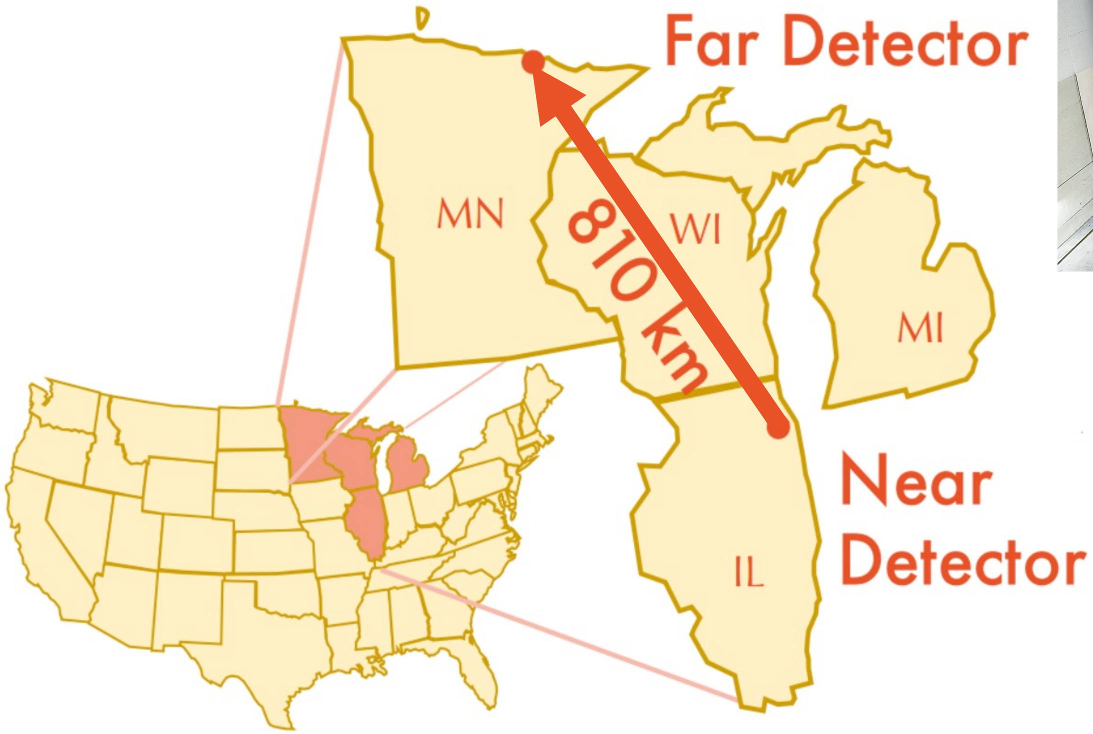
No answer on sterile neutrinos, as yet

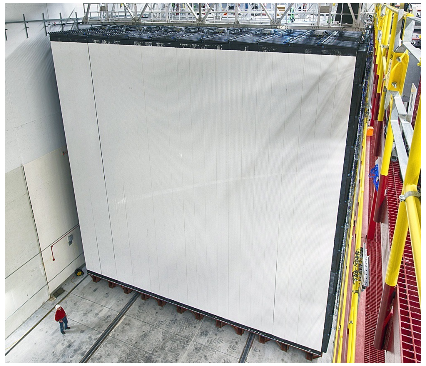
Currently running long baseline accelerator neutrino experiments

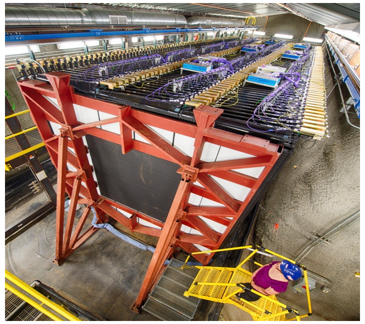



NOvA
Far Detector
Credit: Reidar Hahn/Fermilab

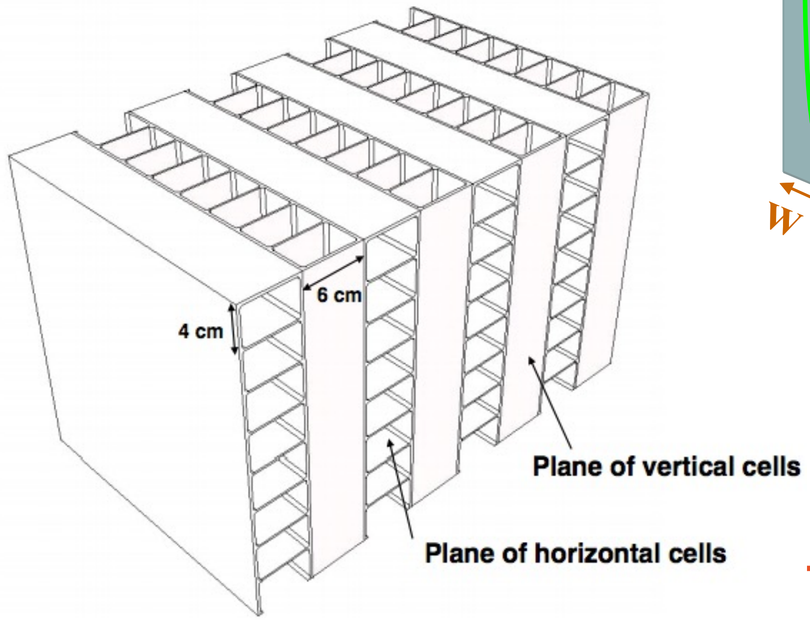
NOvA: Off-axis long-baseline neutrino oscillation experiment
Uses NuMI (neutrinos from main injector) high energy neutrino beam

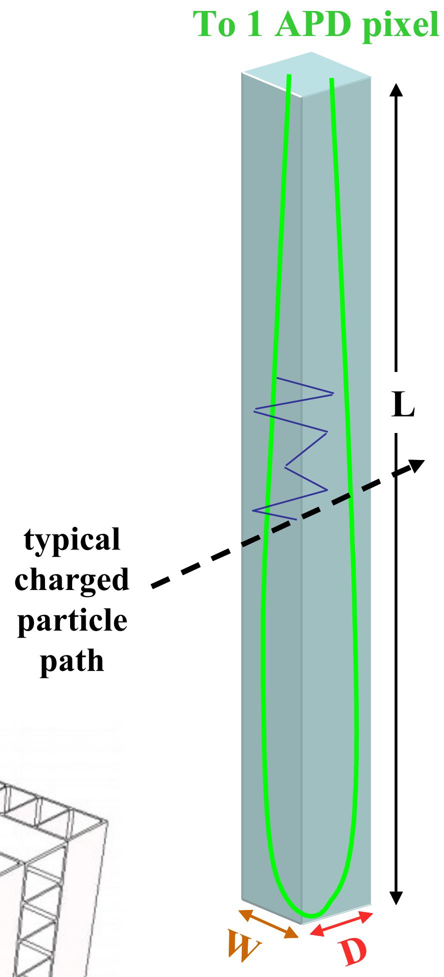


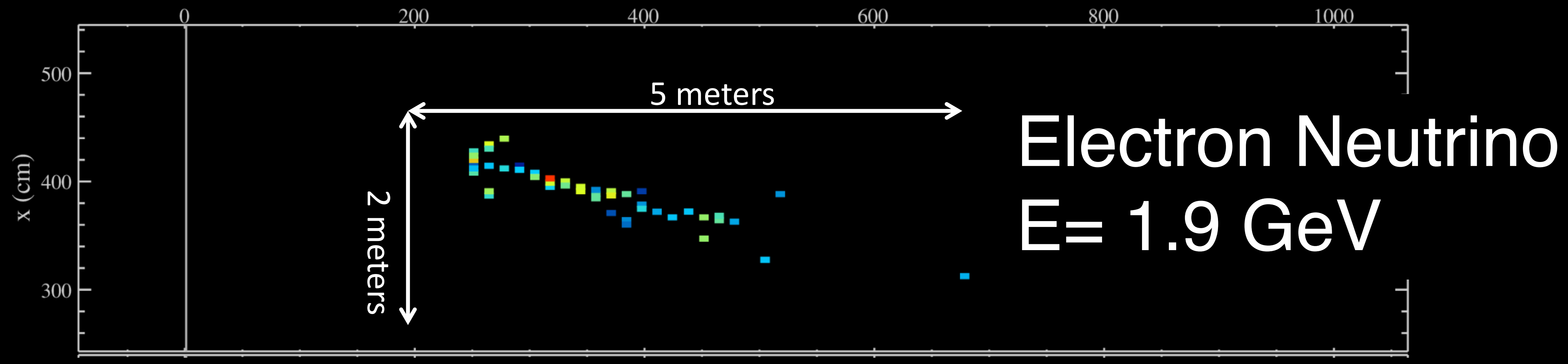


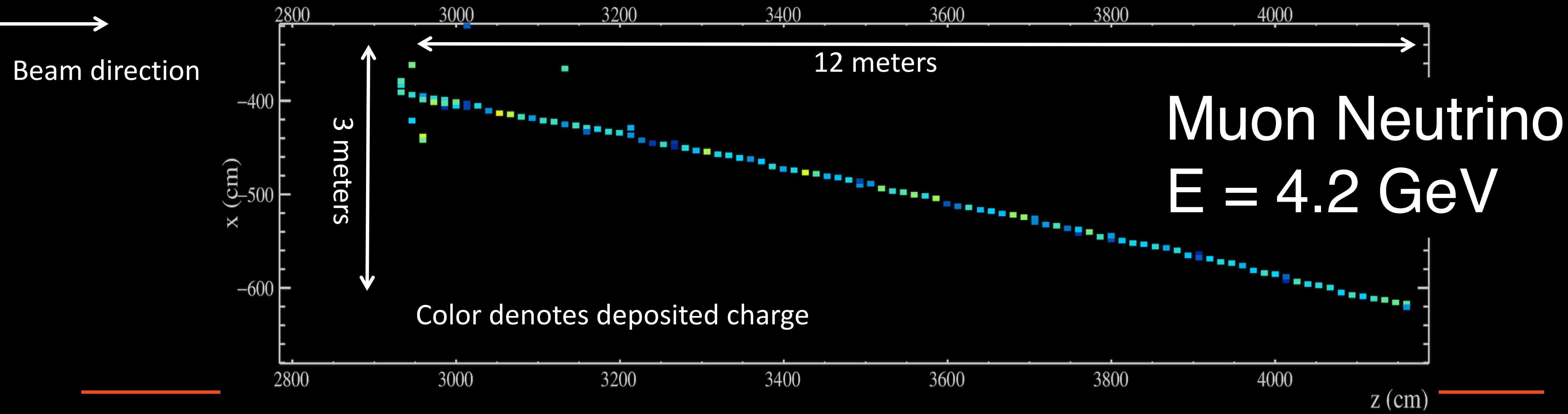


Longest baseline of currently running experiments






Electron Neutrino
E= 1.9 GeV
5 meters
2 meters
x (cm)
500
400
300
0
200
400
600
800
1000


Muon Neutrino
E = 4.2 GeV
Beam direction
12 meters
3 meters
Color denotes deposited charge
x (cm)
−400
−500
−600
2800
3000
3200
3400
3600
3800
4000
z (cm)

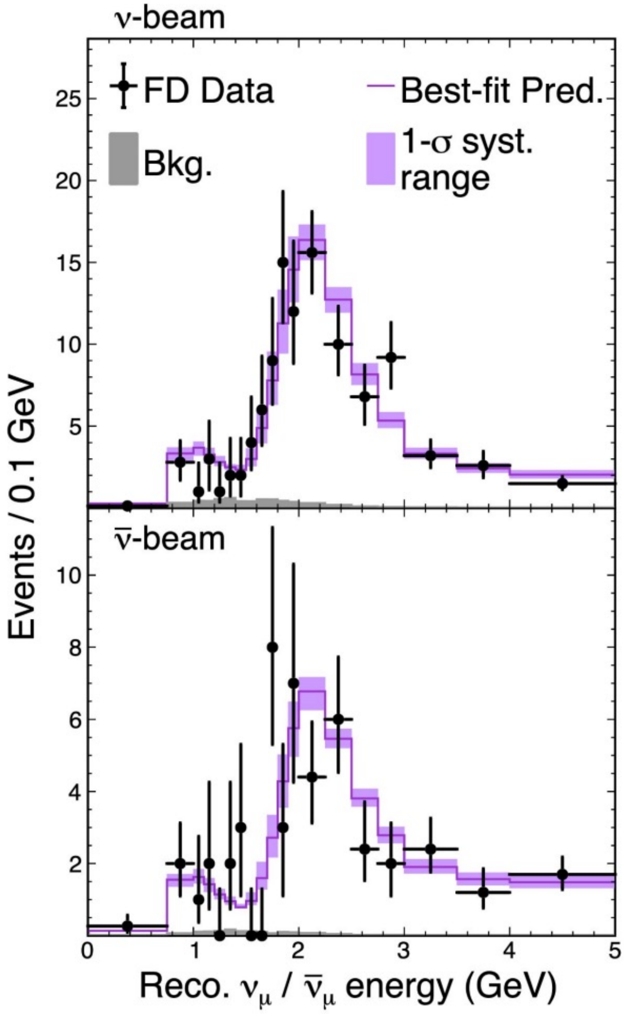
Electron and muon neutrinos and antineutrinos in the Far Detector

Muon and electrons leave distinct signals in detectors.

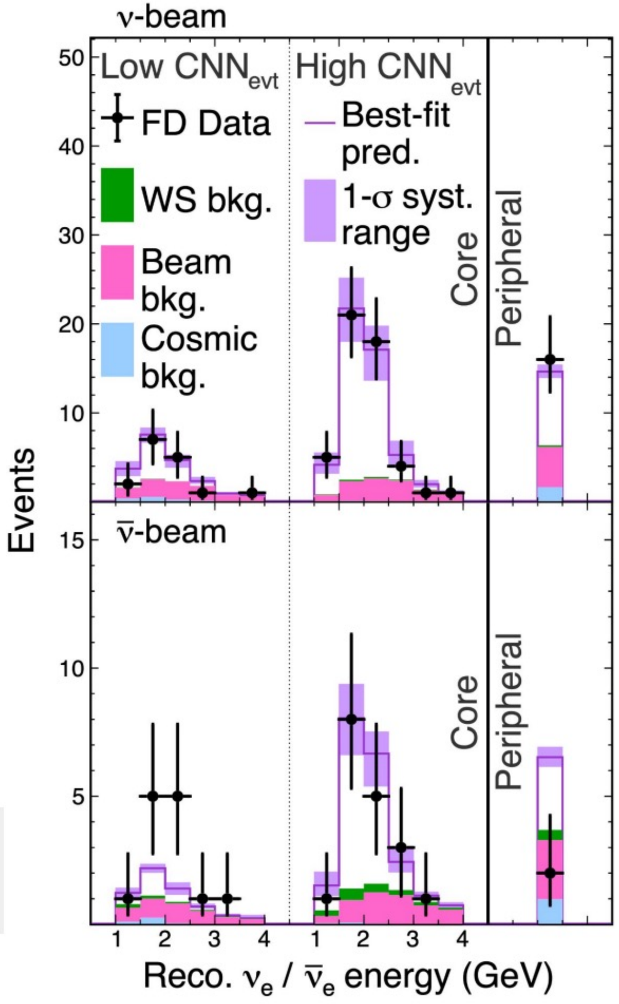
Use algorithms (machine learning) to identify and work out the energy deposited.

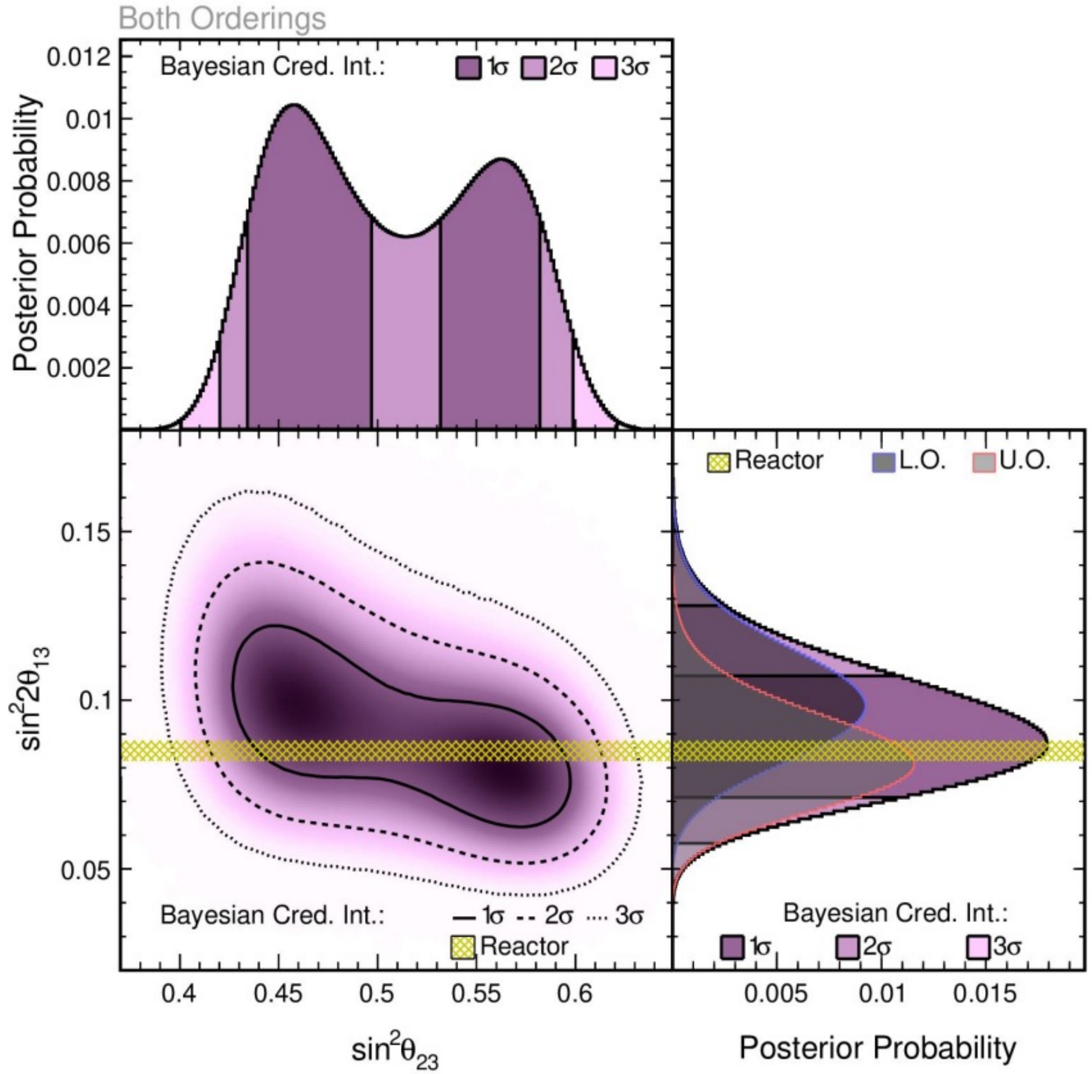
Compare ND prediction to FD data to extract the oscillation parameters that best match it and exclude values that don't.

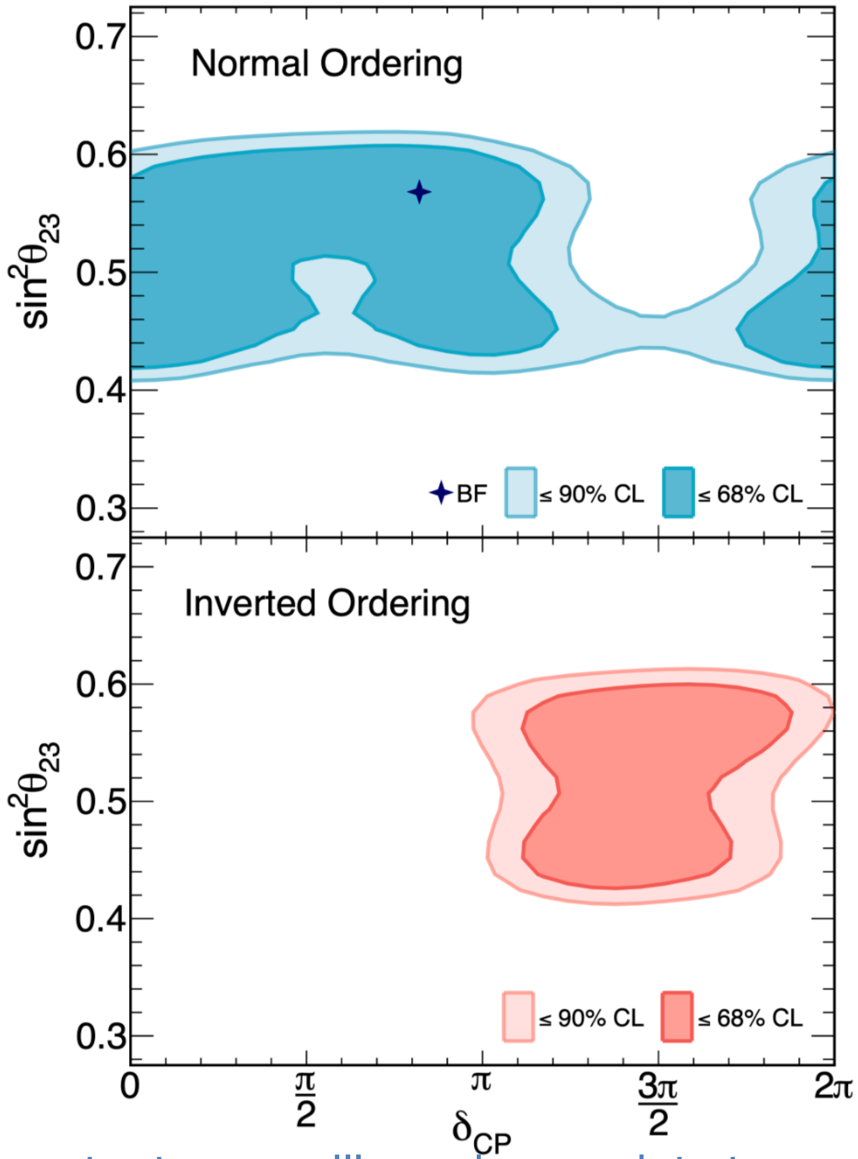
Muon neutrinos



Electron neutrinos



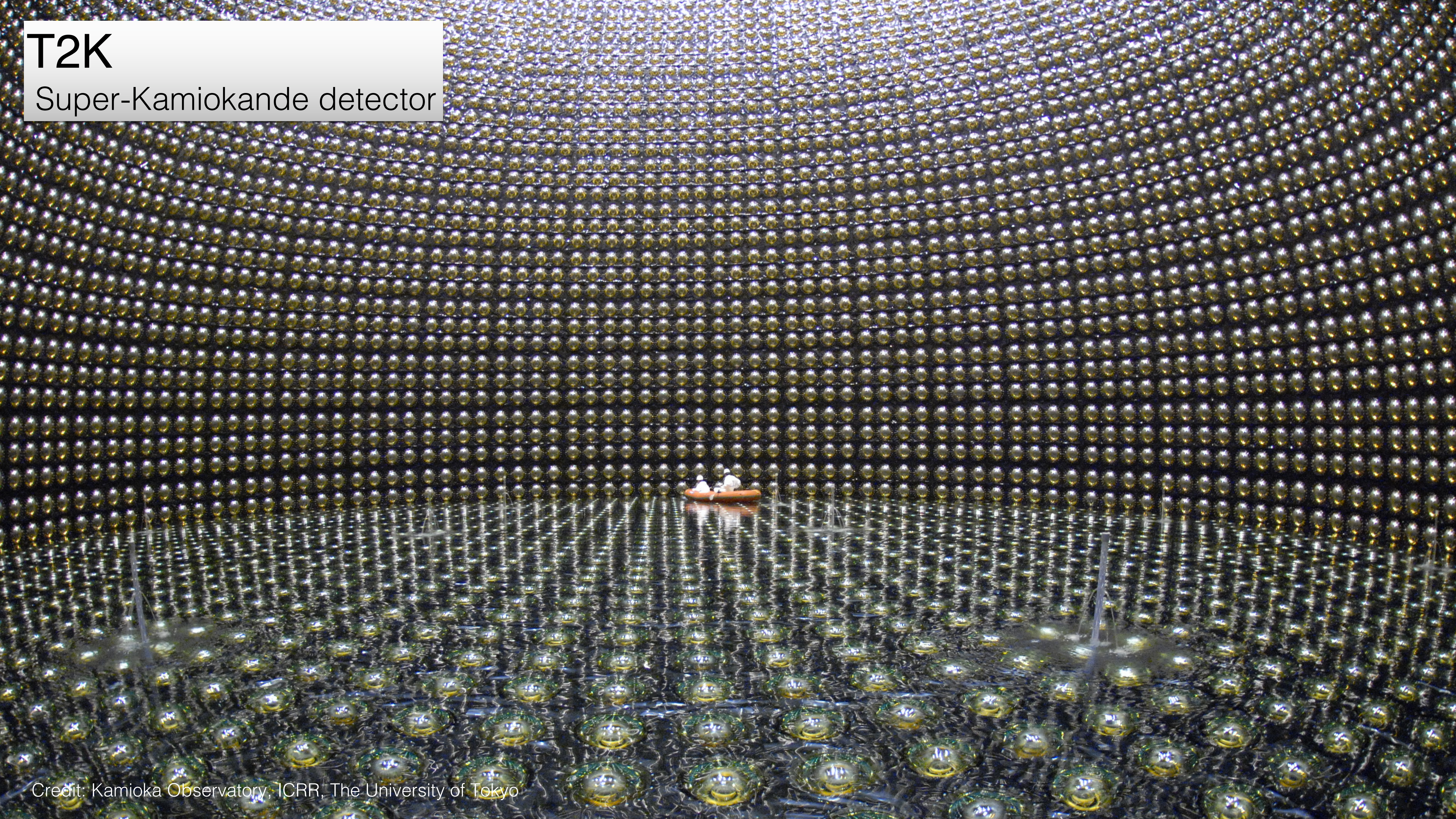




The parameters can have a lot of overlap in how they affect the FD event rate, so will need more data to say is neutrinos are CP conversing or what the mass order is

T2K

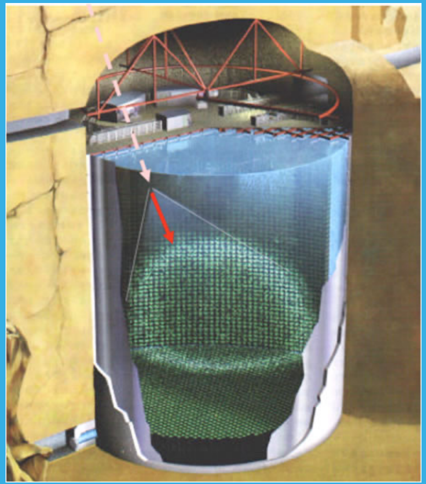
Super-Kamiokande detector



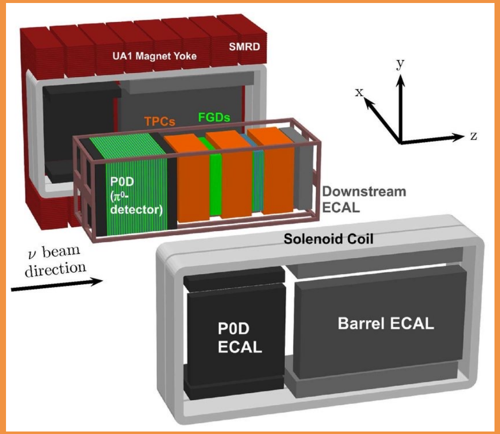
Credit: Kamioka Observatory, ICRR, The University of Tokyo

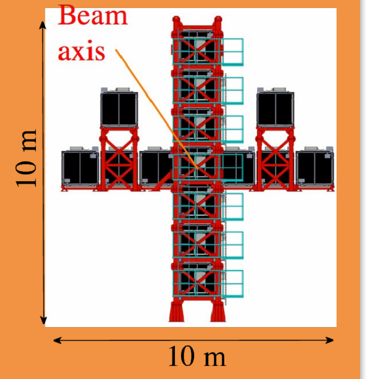
T2K: Off-axis long-baseline neutrino oscillation experiment

Far Detector, Super-Kamiokande

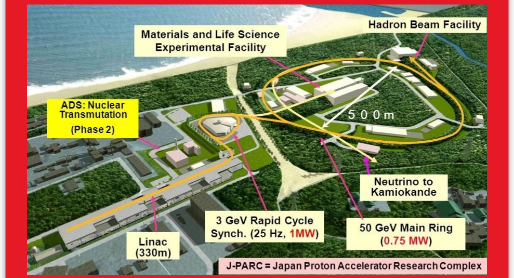


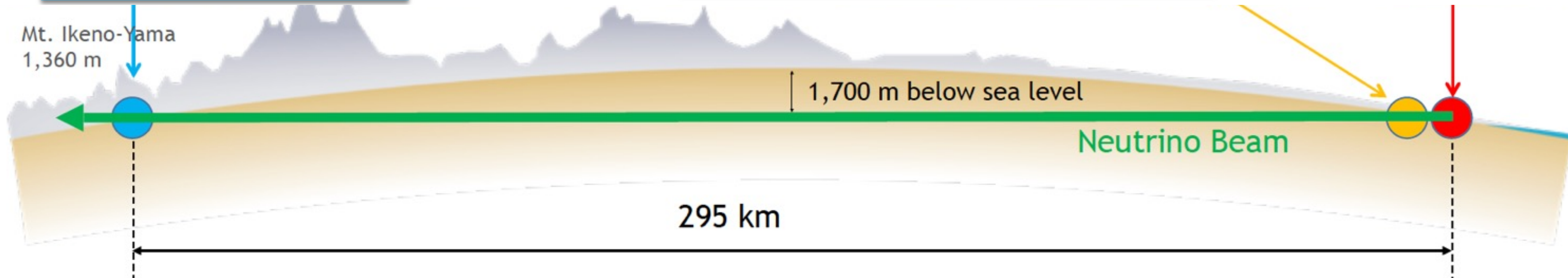
Near Detectors: ND280 and INGRID

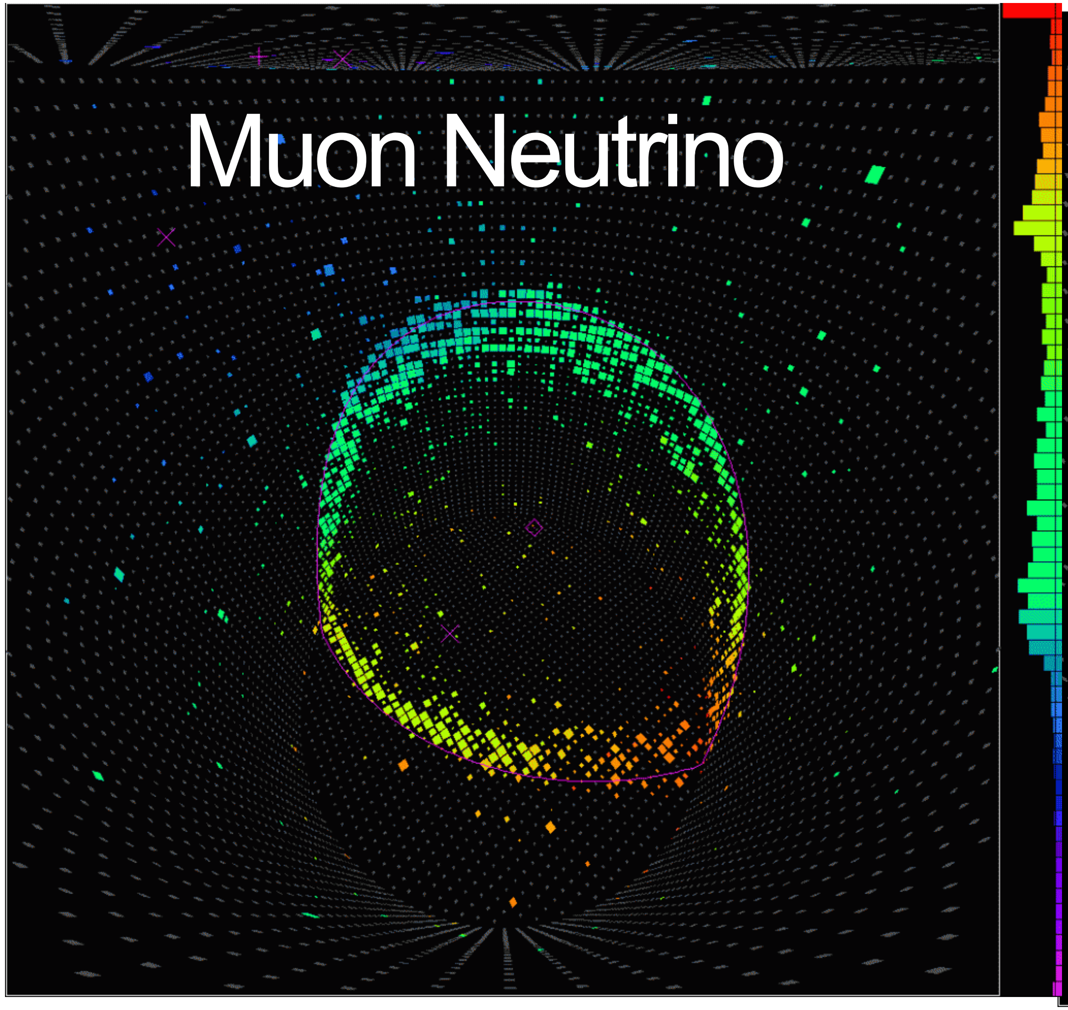


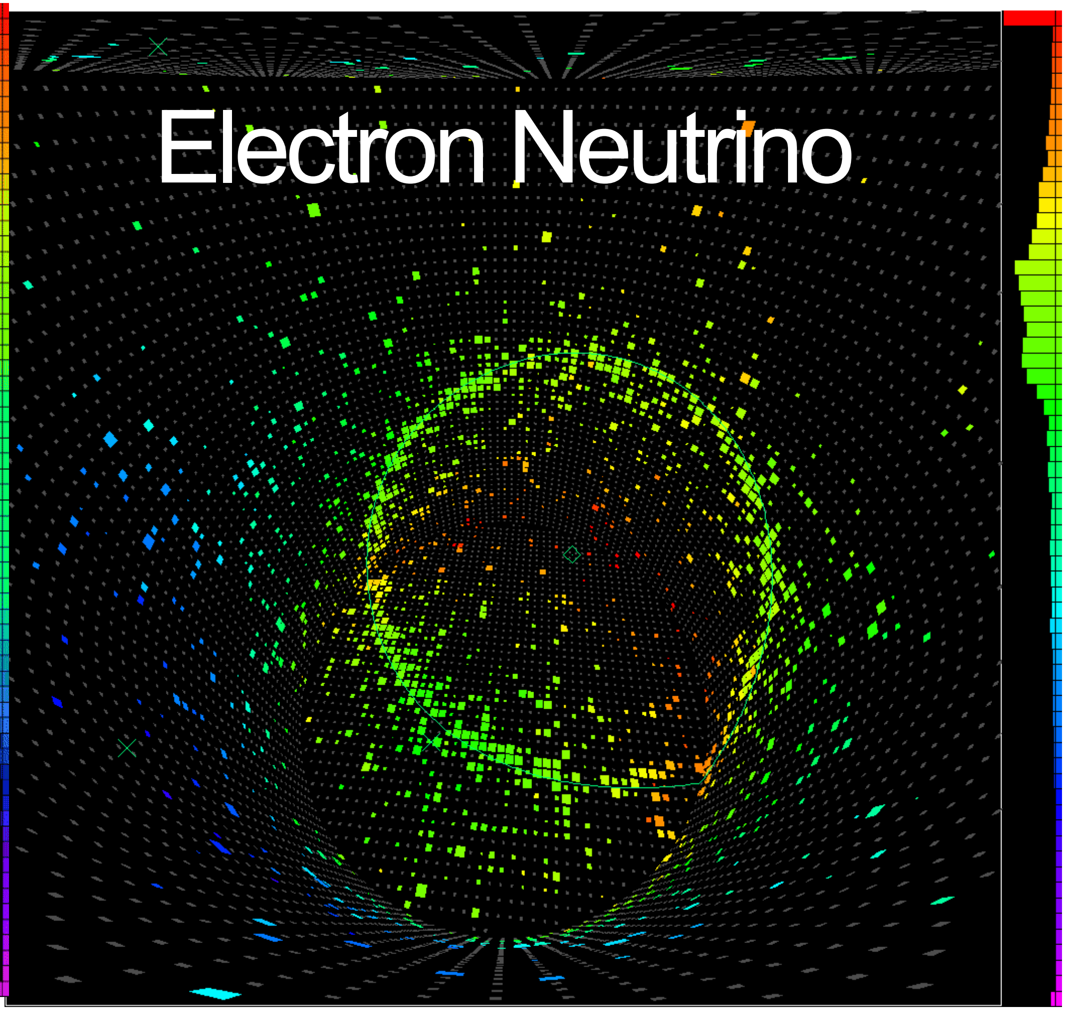


J-PARC



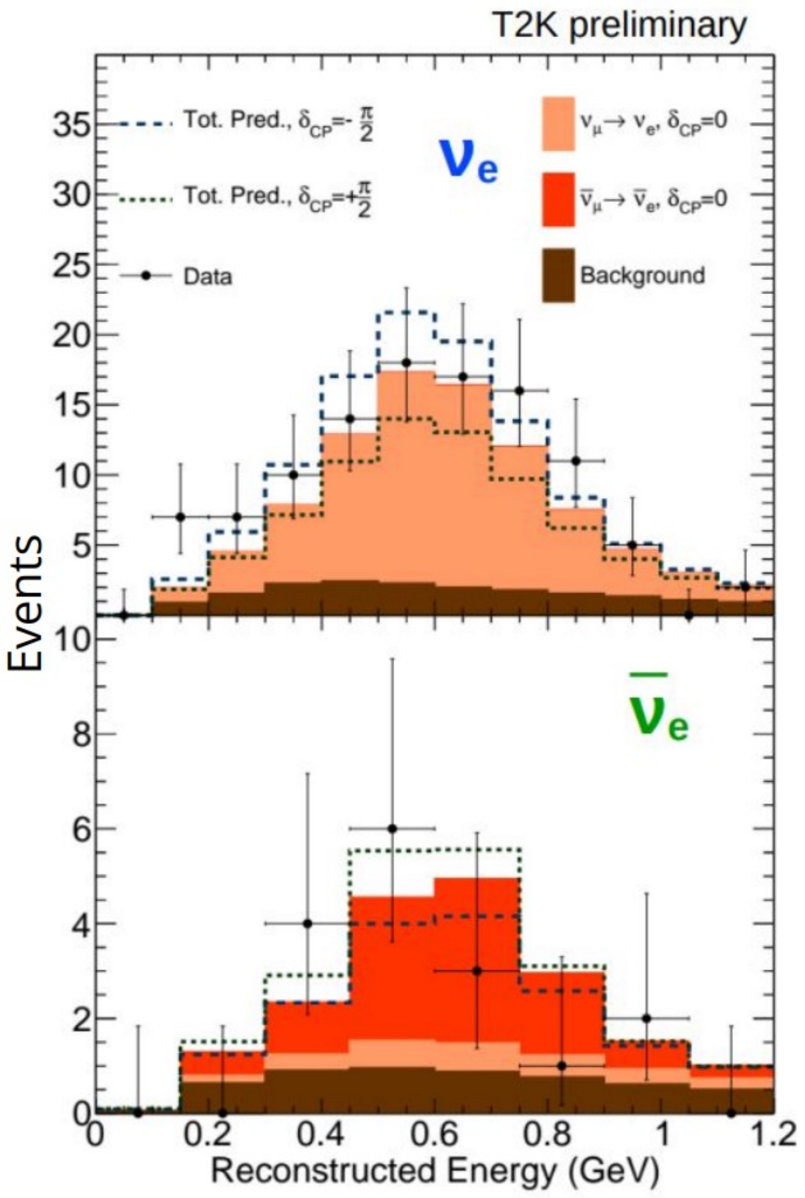






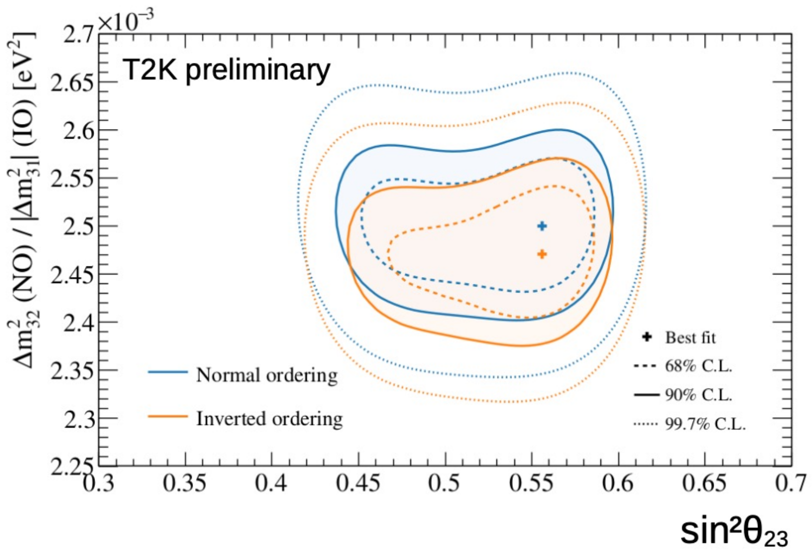
Far Detector, Super-Kamiokande, is water cherenkov detector
Stainless-steel tank, 39.3m diameter and 41.4m tall, filled with 50,000 tons of ultra pure water

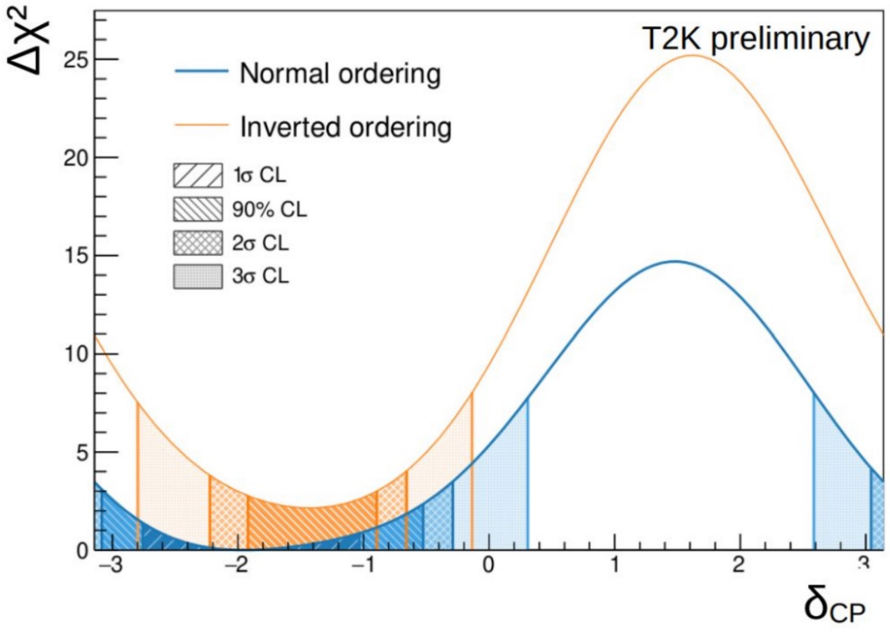
The detector provides excellent e/μ separation and background rejection



Selected electron-like events.

T2K fits selected electrons and muons to determine the most likely true oscillation probabilities



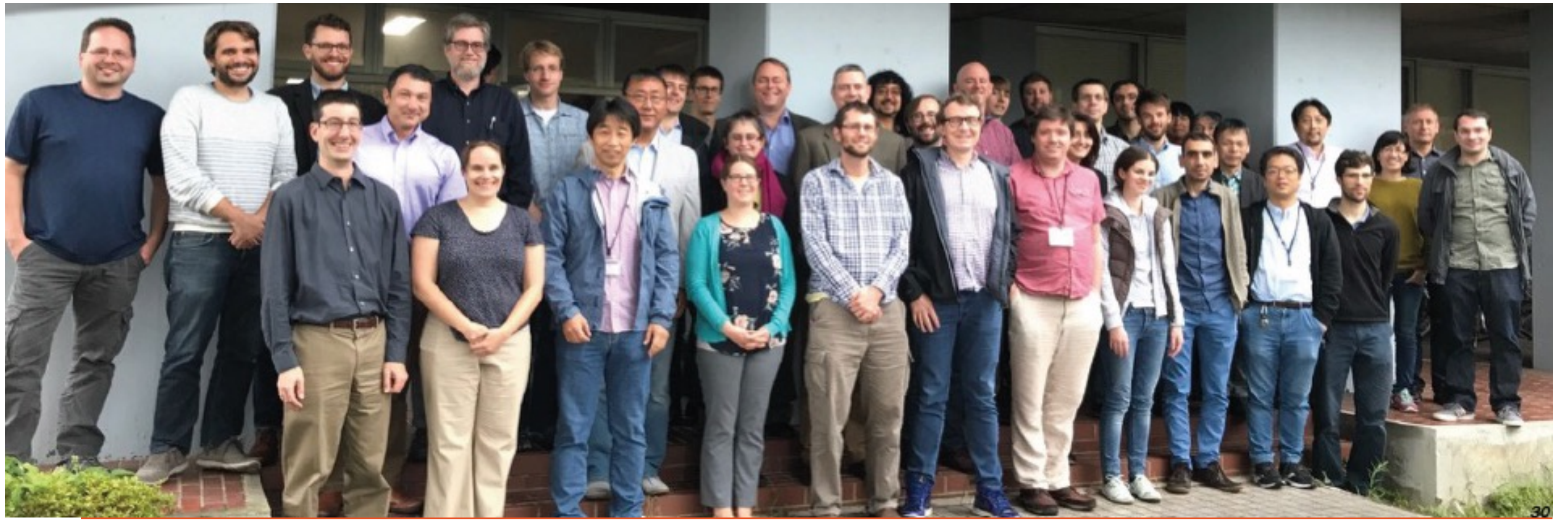


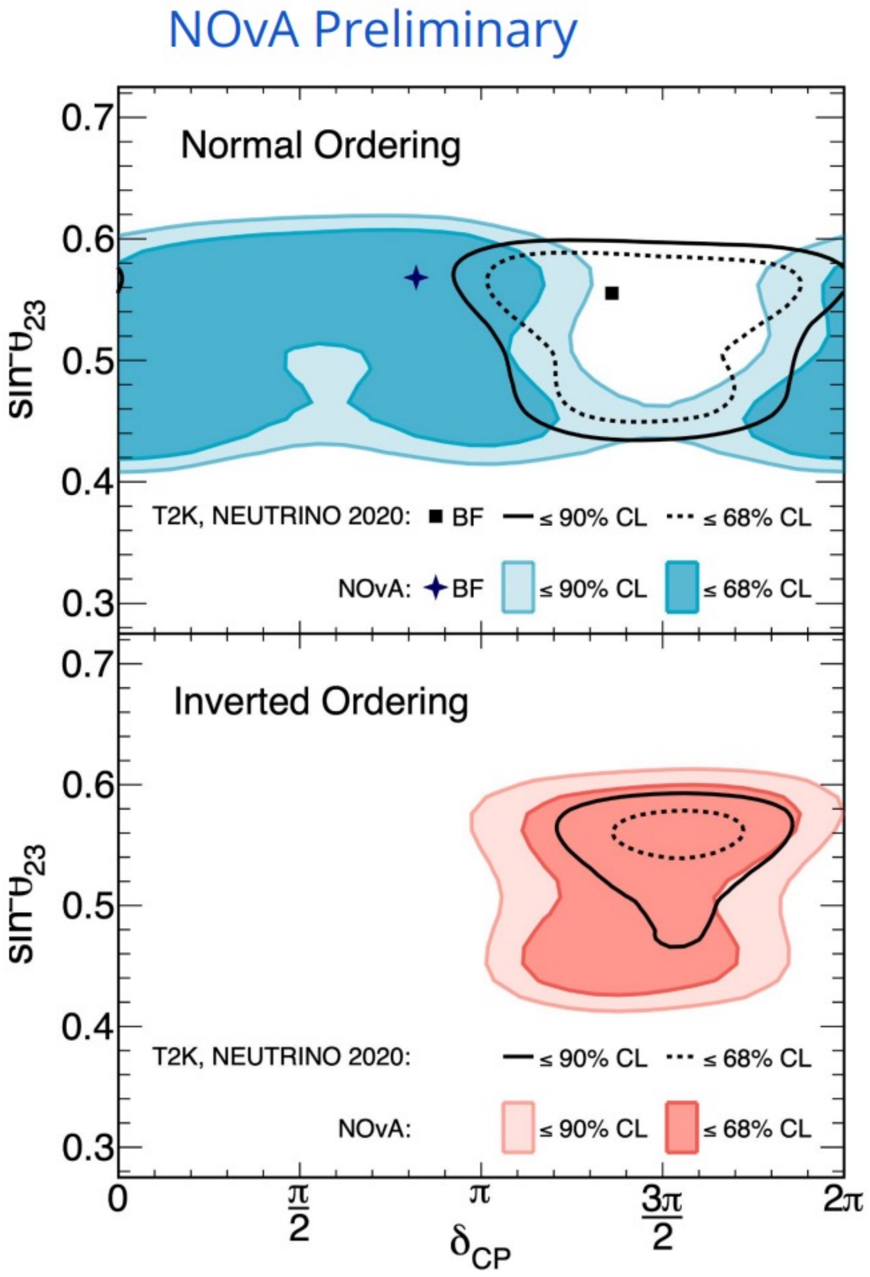
More data need to make strong statement on mass ordering

Combing T2K and NOvA

- Experiments are complementarity, have different baselines, energy ranges and detector technologies
- The two collaborations are working on a joint analysis
  - Increased sensitivity
  - Ability to break the degeneracy between mass ordering and δCP

Results expected with the next year



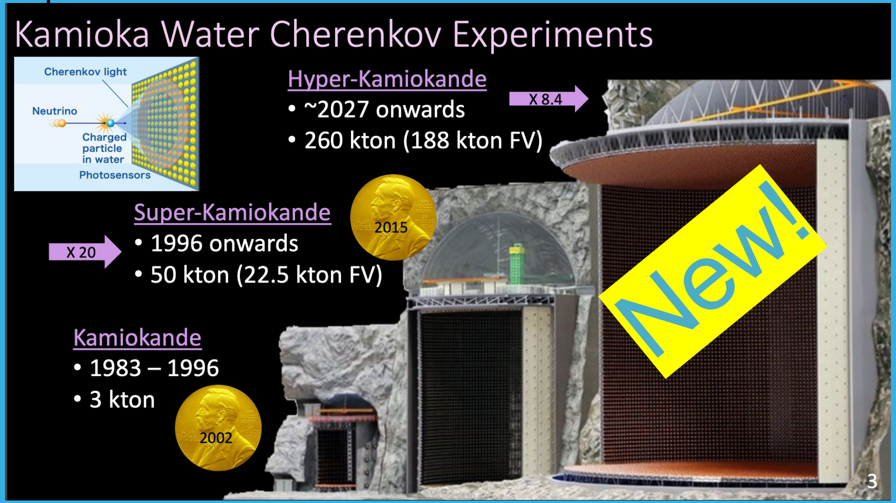


DUNE
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

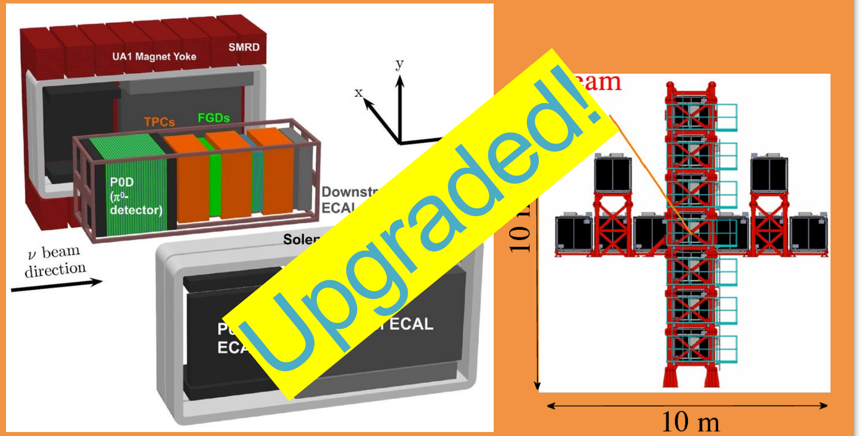
Future accelerator neutrino experiments

Hyper-Kamiokande

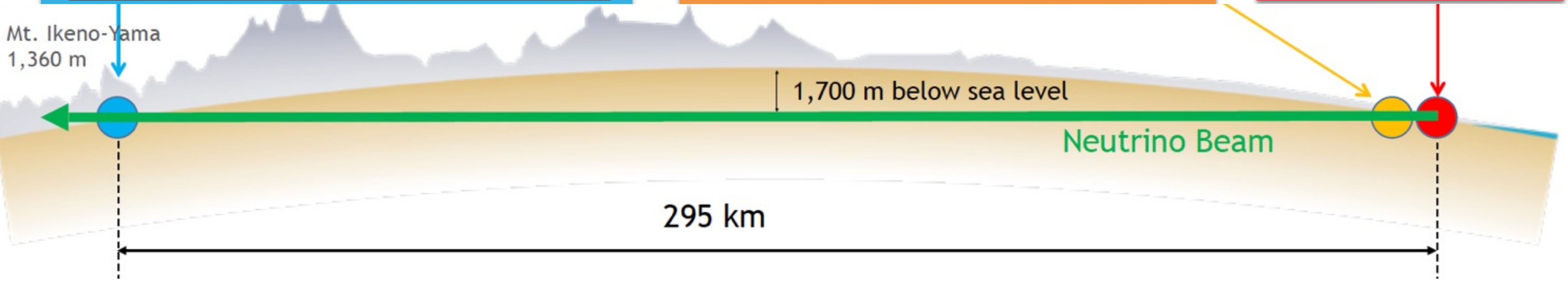
Far Detector, Super-Kamiokande



Near Detectors: ND280 and INGRID



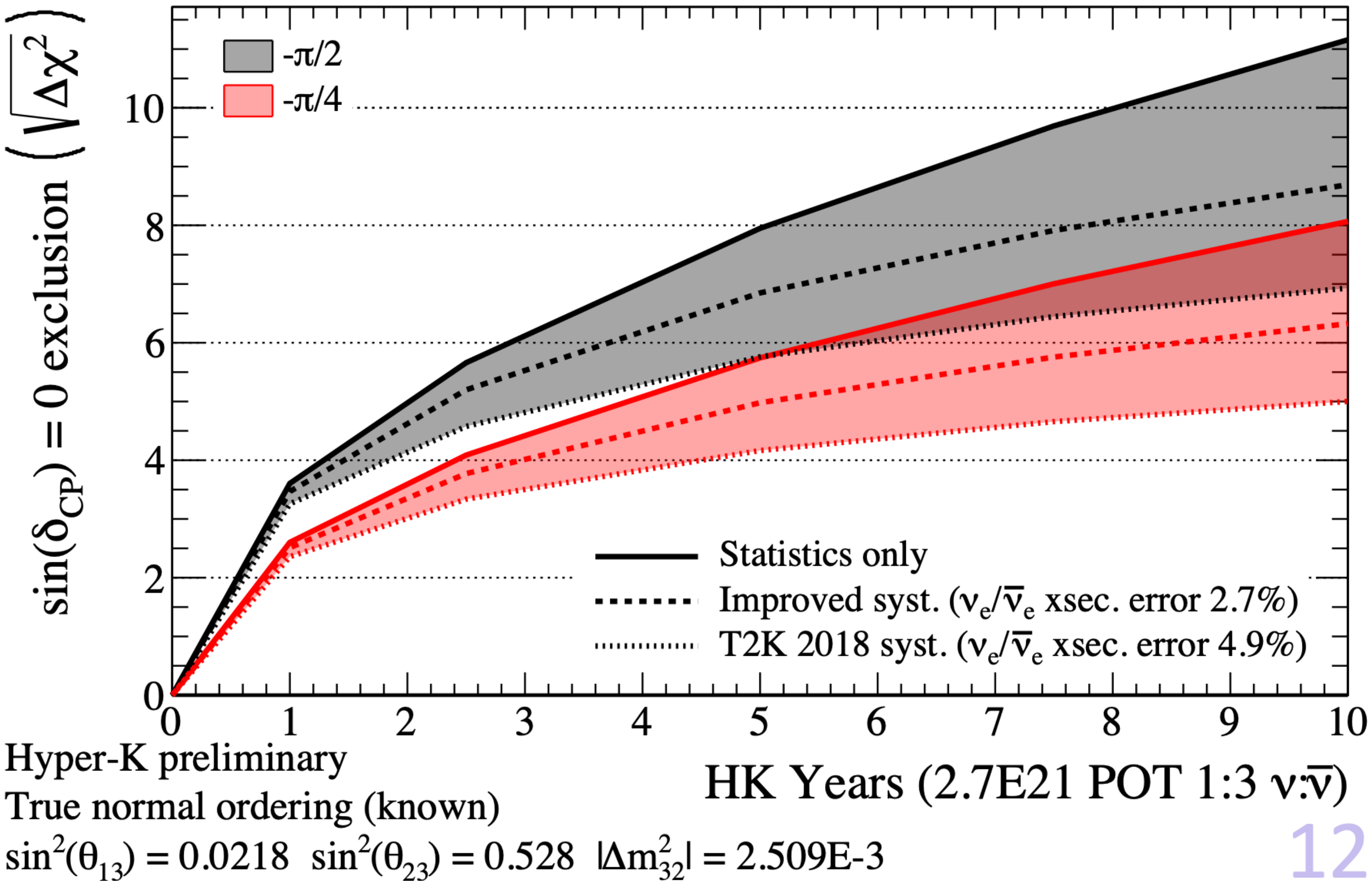
J-PARC



- Same beam as T2K, but now upgraded to 1.3 MW
- Leverages upgraded T2K near detectors
- New Far Detector planned to start operations in 2027

Hyper-K physics sensitivity

Hyper-Kamiokande

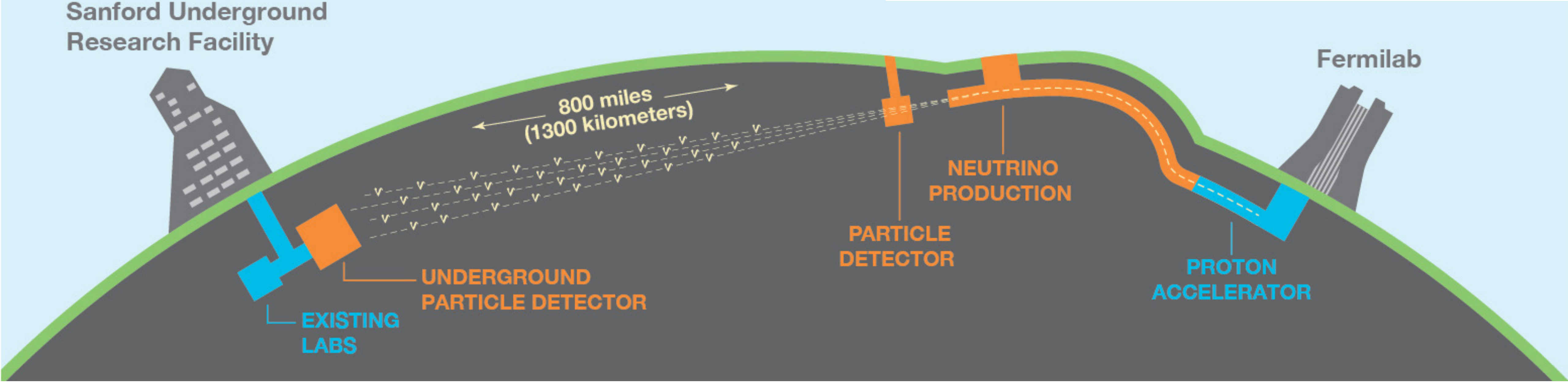


Competitive and very different from DUNE

- Hyper-K sensitivity is focused on δ_{cp} where DUNE physics program is broader

- Narrowband beam and shorter baseline
  - Significantly reduced sensitivity to mass ordering compared to DUNE
  - Reusing many T2K components and well-vetted technology leads to potential faster ramp up and small uncertainties in the early years
  - Lower energy beam can reduce some complexity

Fermilab

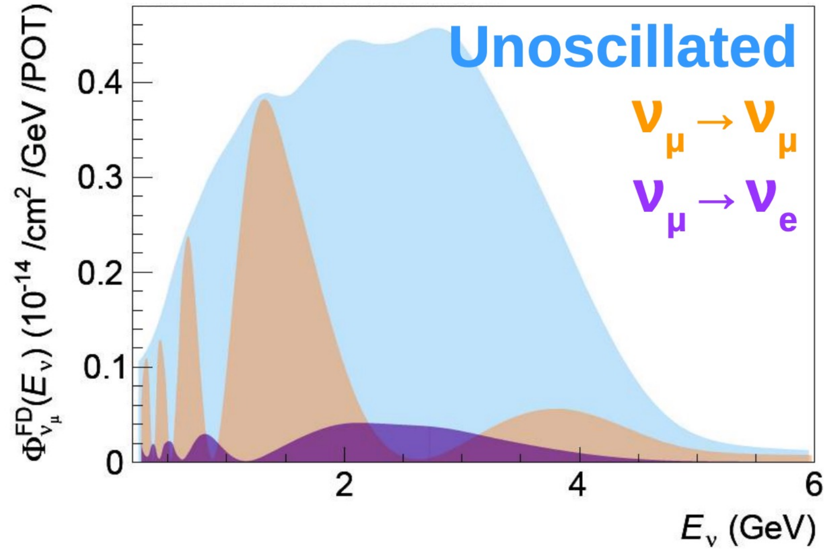


DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

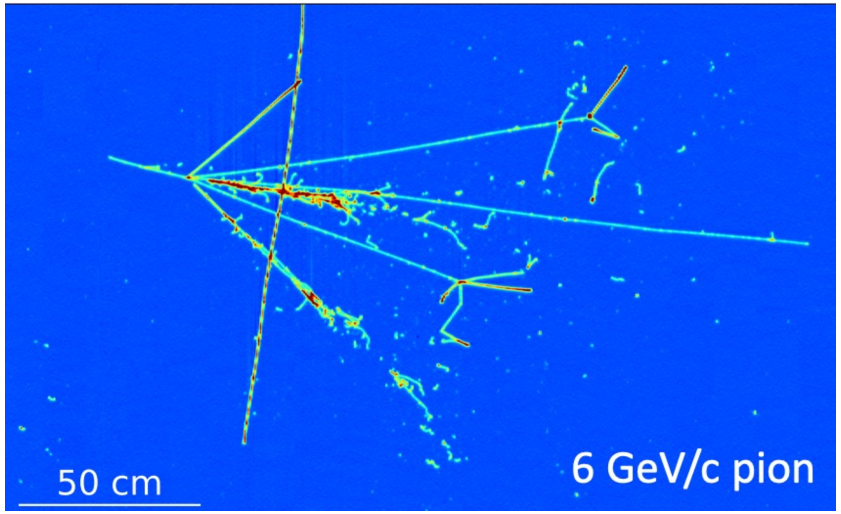
- **LBNF beam:** New high-intensity 1.2 MW beam, using PIP-II upgrade, upgradable to > 2 MW
- **Far detector:** Large on-axis 1.5 km underground in Sanford Underground Research Facility (SURF) in SD
- **Near Detector:** A capable near detector complex at Fermilab to ensure uncertainties are adequately constrained

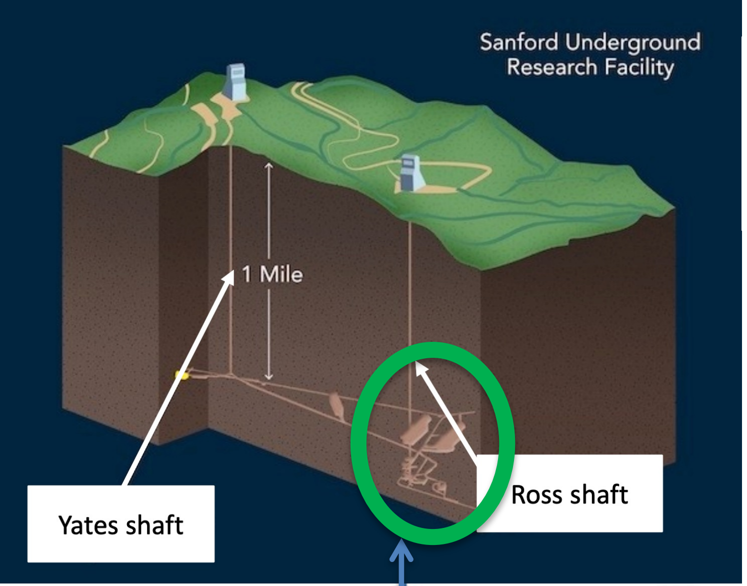
DUNE concept

- **Unique** - The combination of the long baseline and the wide energy of the beam give DUNE unique insights into neutrino oscillation.
  - Baseline: breaks the experimental degeneracy between the neutrino mass ordering and the determination of δ_{CP}.
  - Wideband beam and on-axis: DUNE can measure ν_e appearance as a function of L/E (fixed L, wide range E), over more than a full oscillation period
- **Precision:** LArTPC technology is a game changer
  - MeV scale energy resolution, with ND percent level uncertainty constraints. Precision particle reconstruction, including of hadronic part of the interaction
- **Breath:** broad physics program

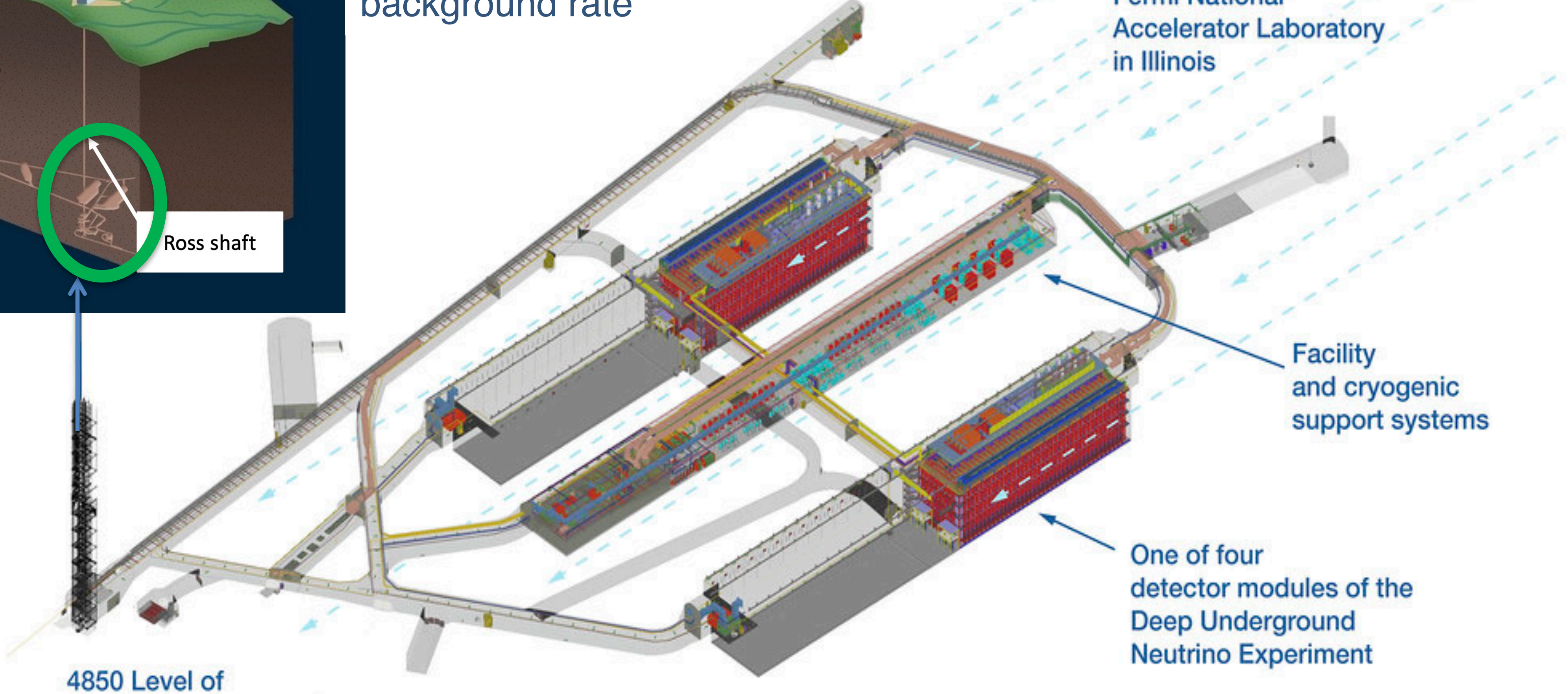


ProtoDUNE-SP Events

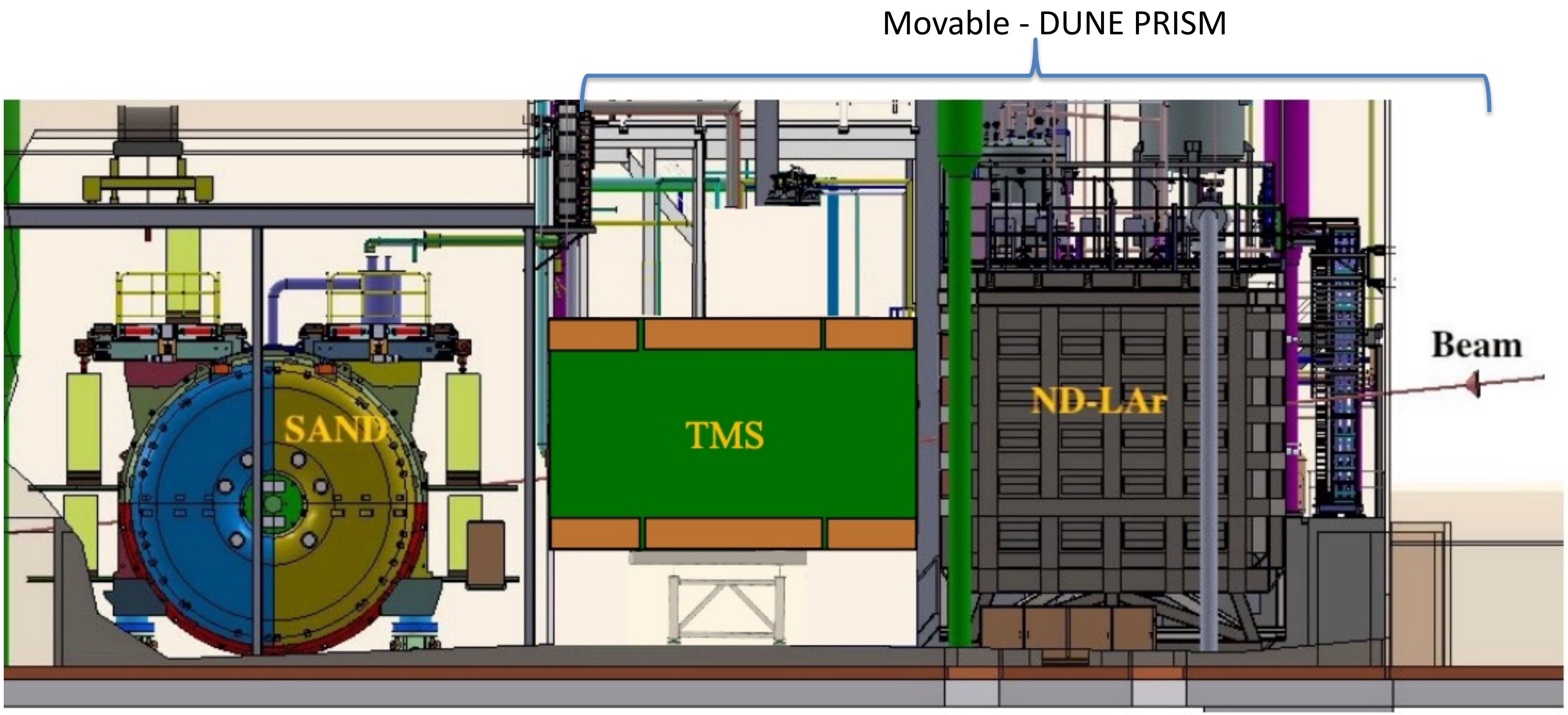




The underground location provides a low background rate



DUNE has four detectors, the first two will be finished in 2028-2029
Beam will be ready in ~2028 (with plans to further upgrade) and Near Detector in ~2030 (upgrade planned)



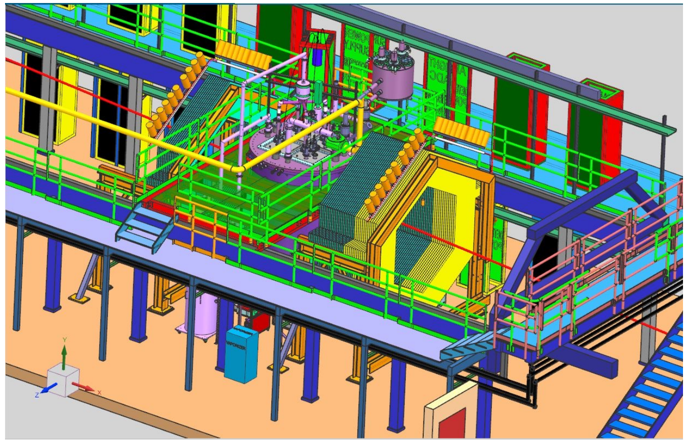
System for on-Axis Neutrino Detection

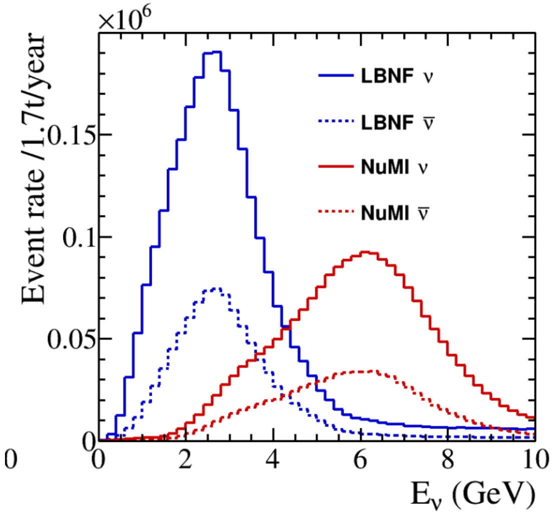
The muon spectrometer

Liquid Argon Near Detector

Prototype - 2x2 demonstrator+ MINERvA

- Located in the NuMI beam in the MINOS underground area.
- Mirroring design of ND-LAr +TMS,
- Will see a comparable rate to the near detector
- **Will start taking data in 2023!**



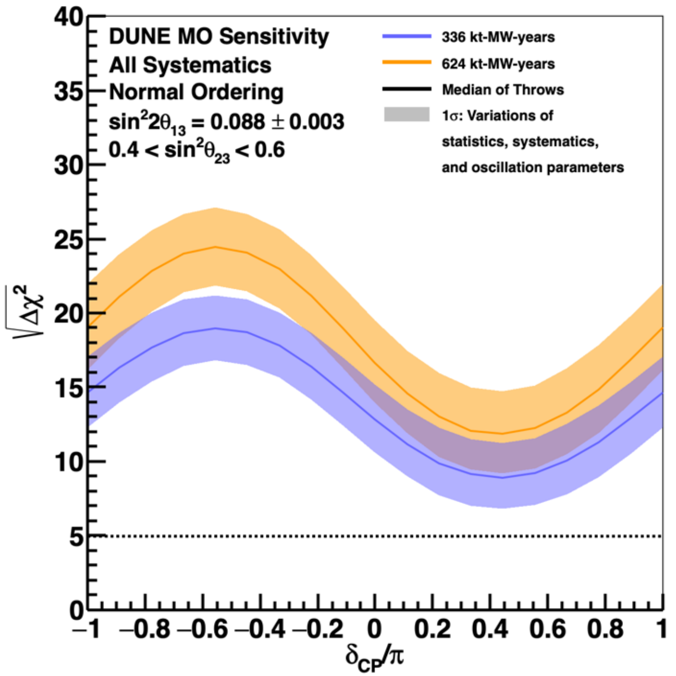


Fermilab

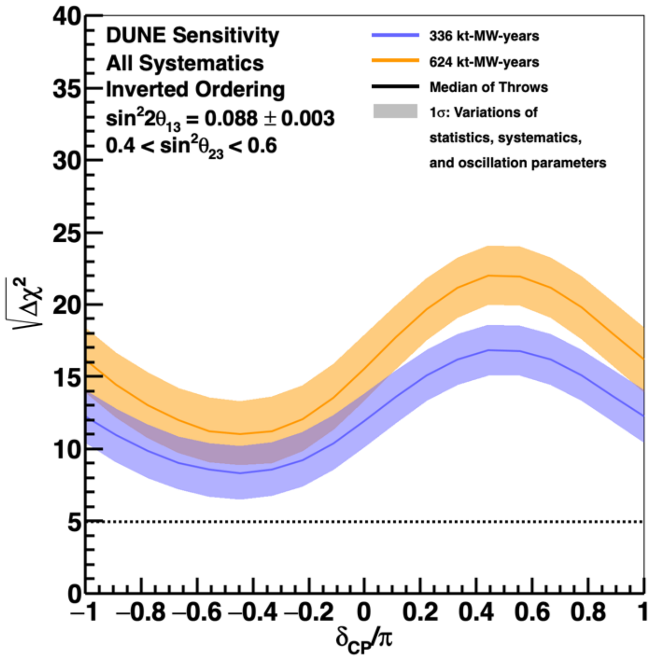
Neutrino Mass Ordering Sensitivity

- DUNE has an unrivaled ability to definitively resolve the mass ordering independent of other experiments.
- **Definitive determination of mass ordering for all possible parameters, after just a few years**.

True Normal Ordering



True Inverted Ordering



Width of band represents 68% of throws (stats, systematics, oscillation parameters)

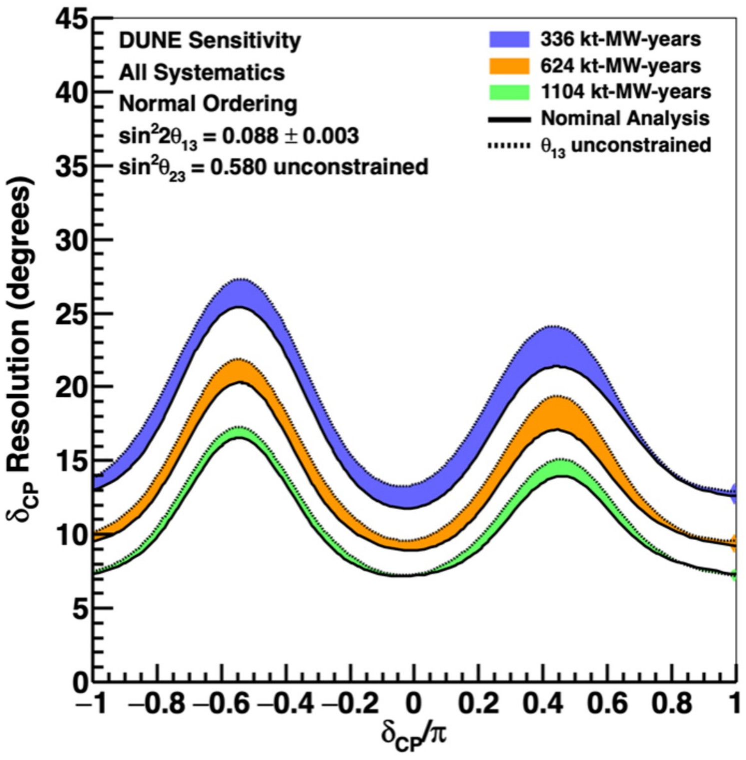
CP Violation Sensitivity

Width of band represents 68% of throws (stats, systematics, oscillation parameters)

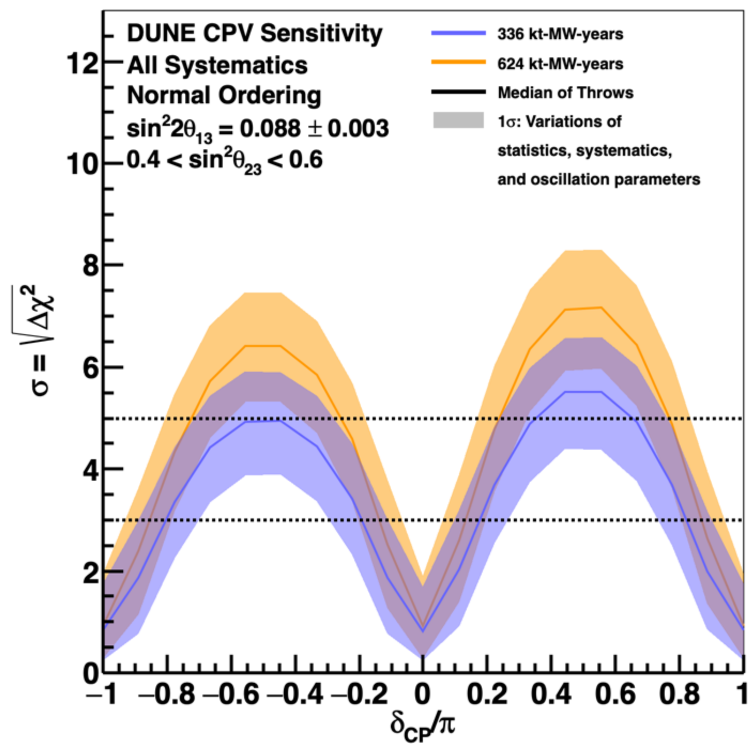
Significant CP violation discovery potential over wide range of δ_{CP} space in 7-10 years

5σ discovery potential for CP violation over > 50% of δ_{CP} values

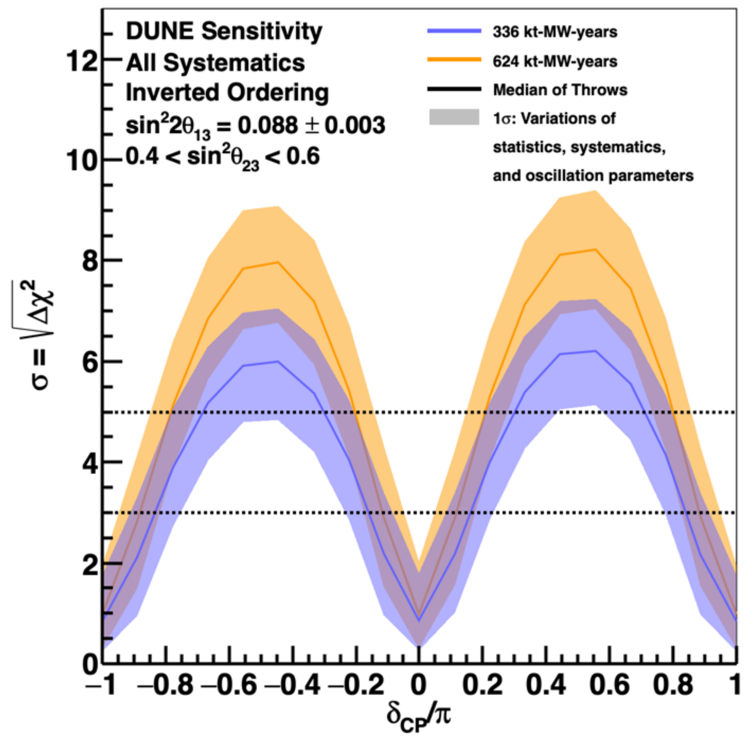
7-16° resolution to δ_{CP} (with external input for only solar parameters)



True Normal Ordering



True Inverted Ordering



Fermilab

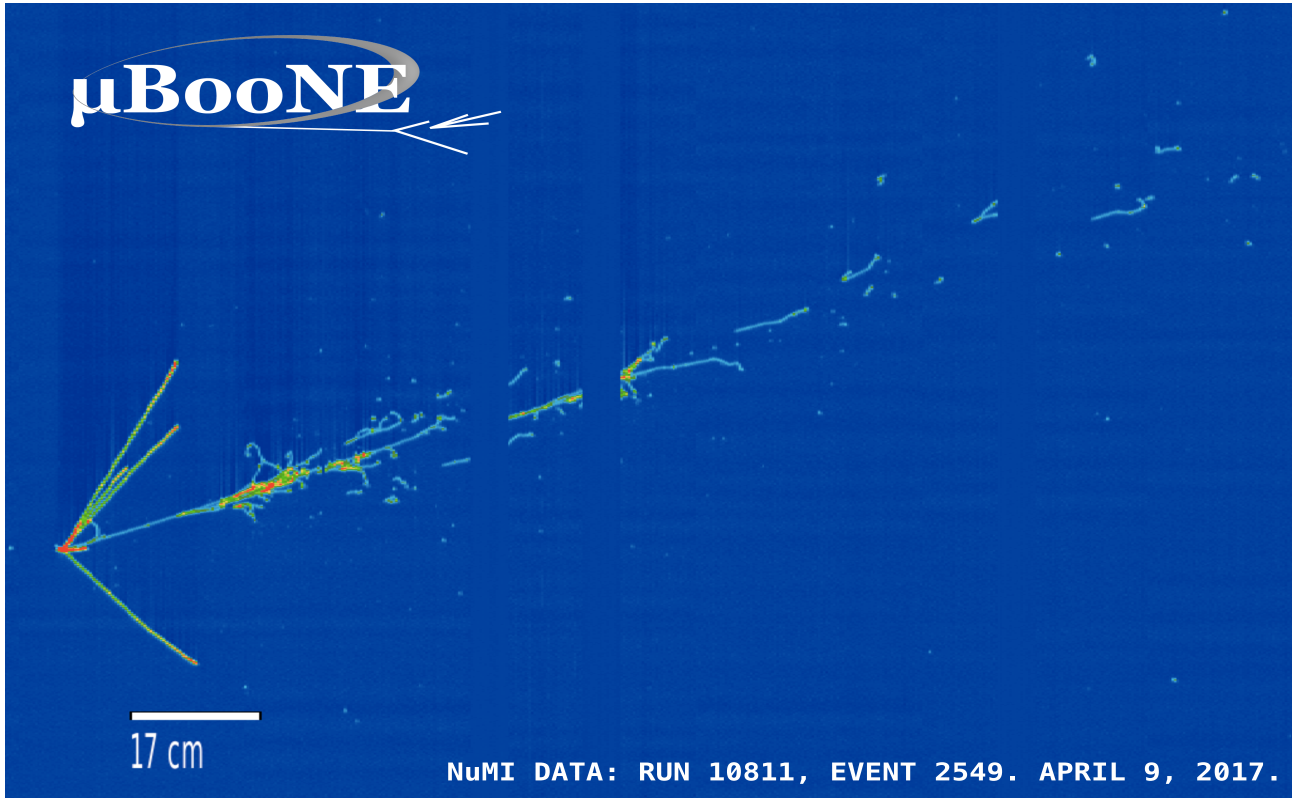
Conclusion

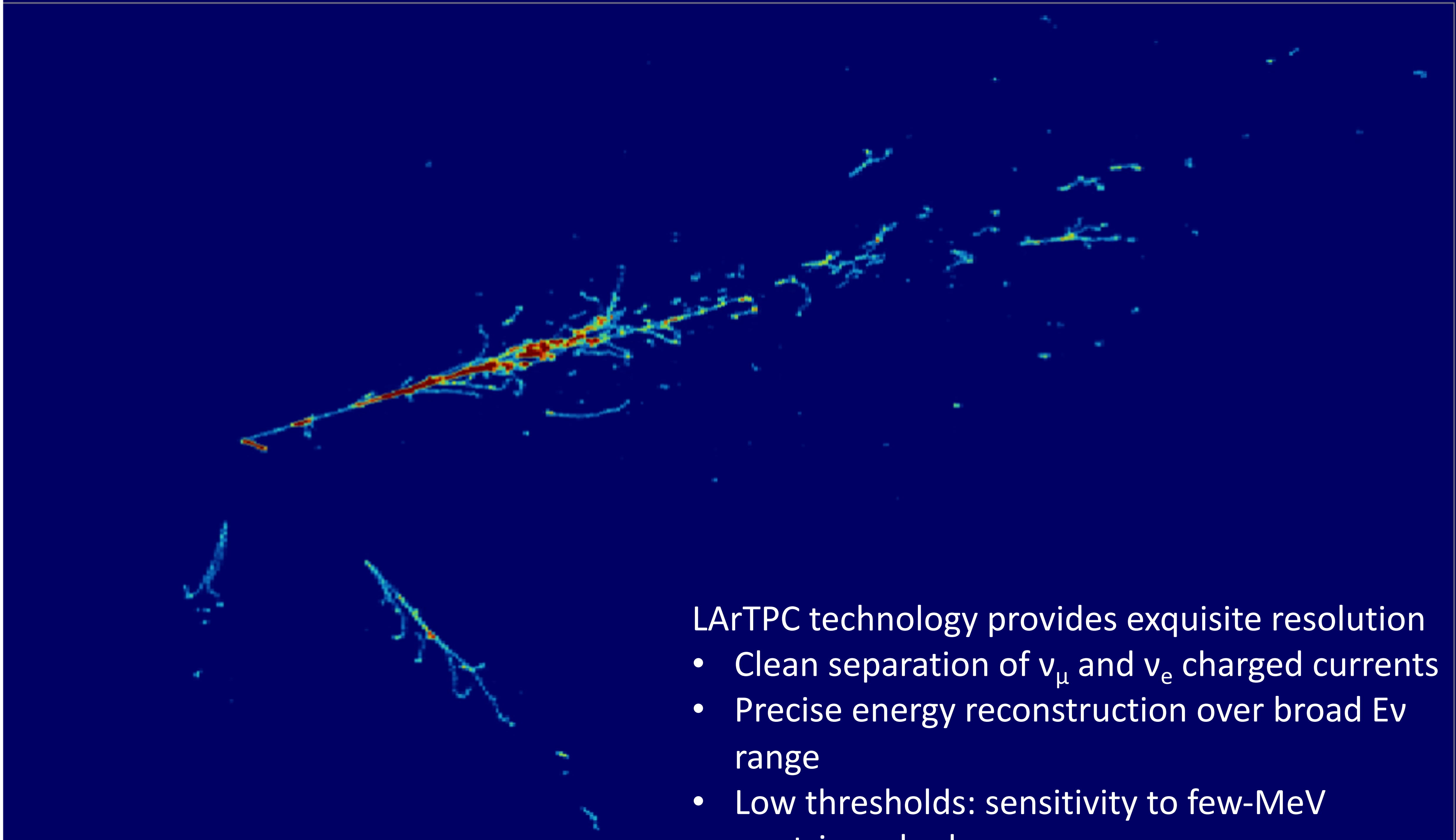
- Next-generation experiments currently being built will significantly improve our understanding of neutrinos
- Come join us!

Short baseline accelerator neutrino experiments

- All three detectors of Fermilab's Short Baseline Neutrino Program are Liquid Argon Time Projection Chambers (LArTPCs)
  - Some of the first of the detector of this type.
  - They have clearly demonstrated its potential and our ability to run LArTPC and analyze their data.
- **MicroBooNE released its results in 2021, and results from ICURAS and SBND are still to come**

No answer on sterile neutrinos, as yet





LArTPC technology provides exquisite resolution

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

Project Status

NEUTRINO 2022

2020 2021 2022 2023 2024 2025 2026 2027

MOU signed, May 2020

Ground-breaking May 2021

Access tunnel complete, Feb 2022

Approach and Peripheral tunnels, Summer 2022

Cavern Excavation

Tank Construction

Installation

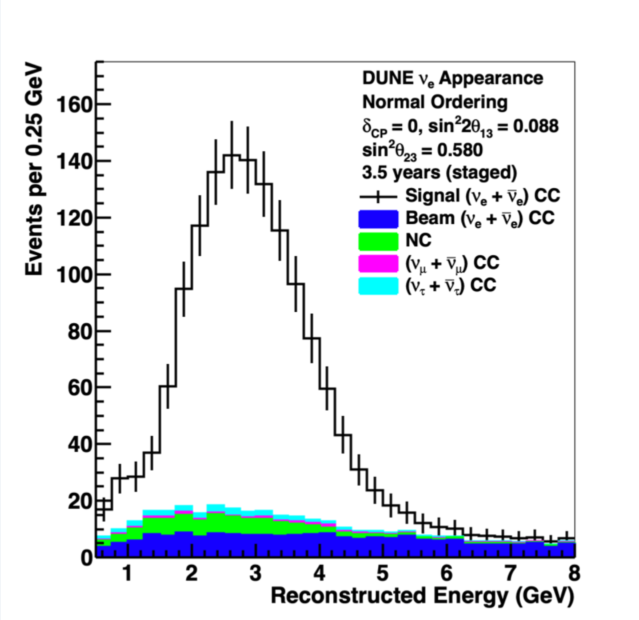
Water filling

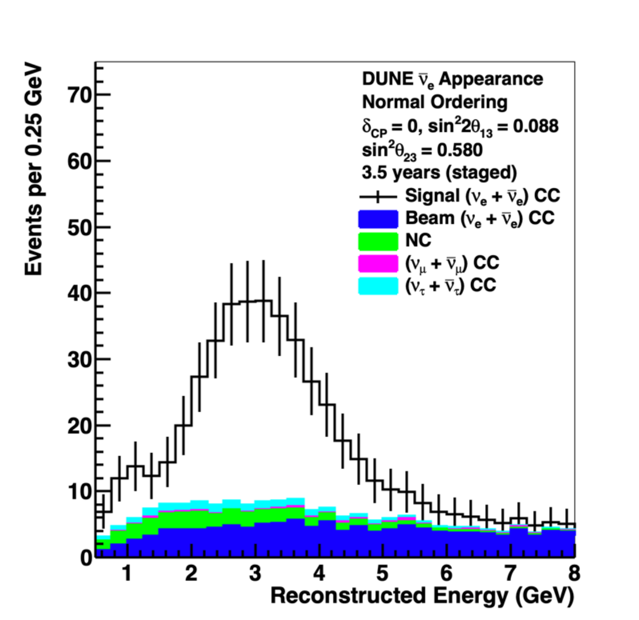
PMT production

Operation starts 2027

7

Electron final state
appearance channel
$\nu_\mu \to \nu_e$

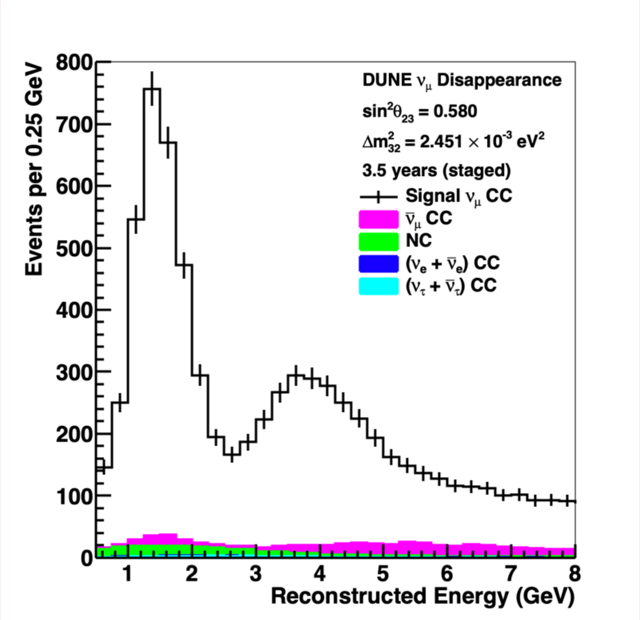


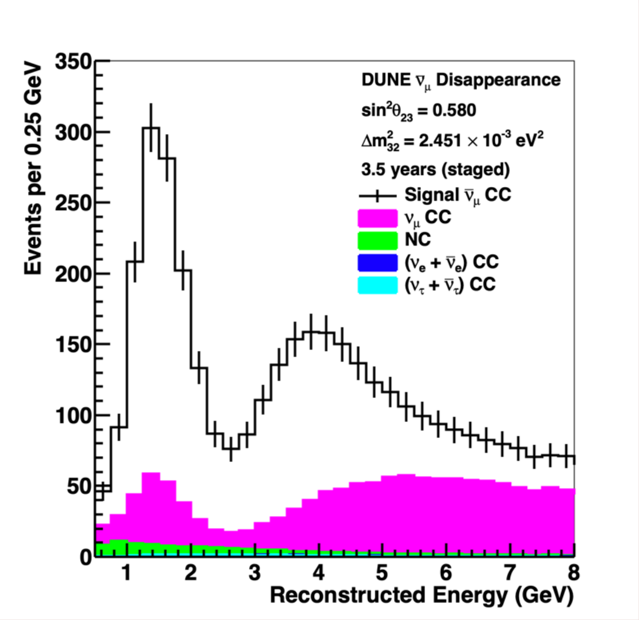


1000s ν_e events

Neutrino beam **Antineutrino beam**

Muon final state
disappearance channel
$\nu_\mu \to \nu_\mu$





10,000s ν_μ events

The DUNE design will enable:

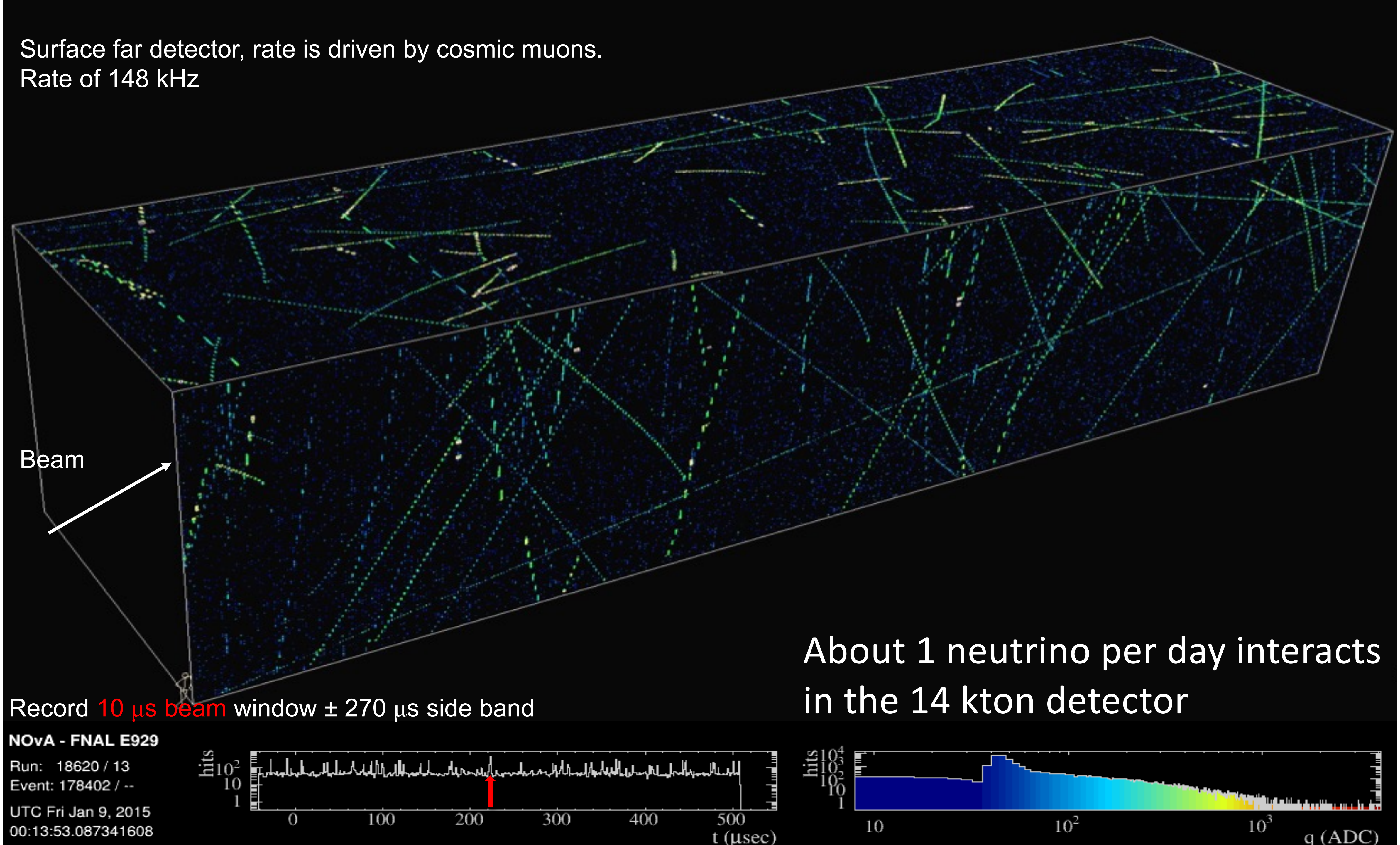
- Program of neutrino oscillation measurements using both a neutrino and anti-neutrino beam.
  - Determination of the mass ordering for all possible parameters
  - 5σ discovery for CP violation for a wide range of possible values of δ_{CP}
- World leaving measurements of oscillation parameters, including both mass splitting and all 3 mixing angles!
  - An independent measurement of $\sin^2 2\theta_{13}$ with precision comparable to reactors
  - Solar neutrino oscillation measurements studies suggest significant improvement on Δm^2_{21}
  - World's best measurements of atmospheric parameters. Including significant sensitivity to the θ_{23} octant
  - Sensitivity to neutrino oscillations from atmospheric neutrinos

- **Unlike all other neutrino experiments, DUNE will not need external inputs enabling us to really stress test the PNMS matrix**

- Design including wide-beam really strengthens our BSM program - nonstandard neutrino interactions, sterile, CPT, extra dimensions, and more

Fermilab

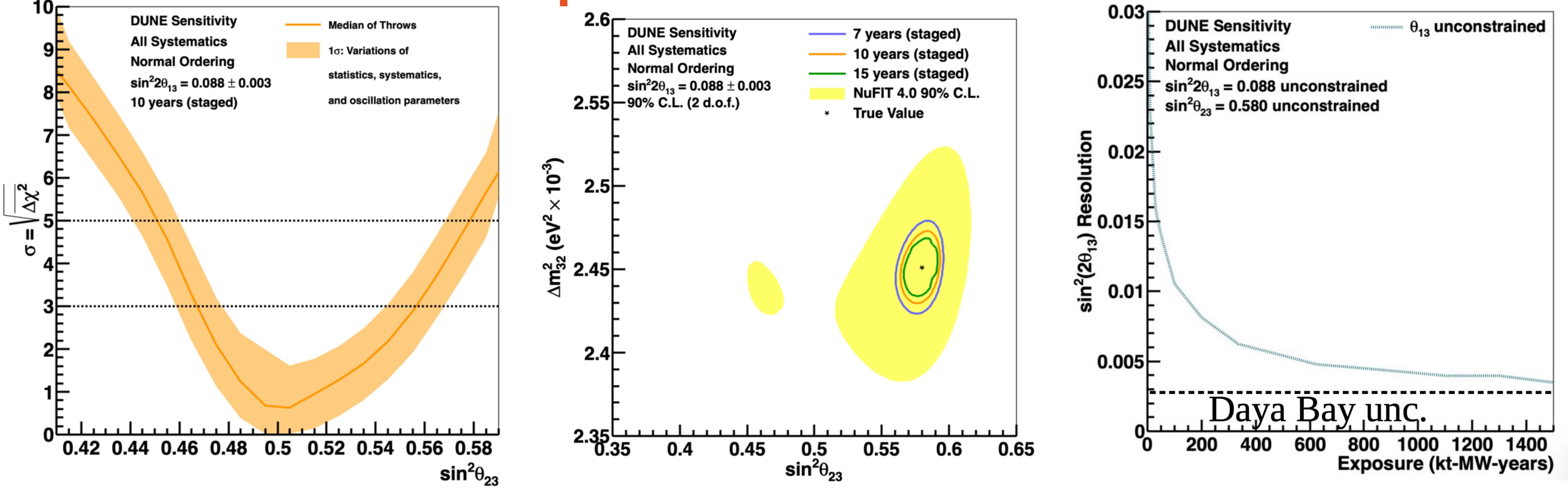
Surface far detector, rate is driven by cosmic muons.
Rate of 148 kHz



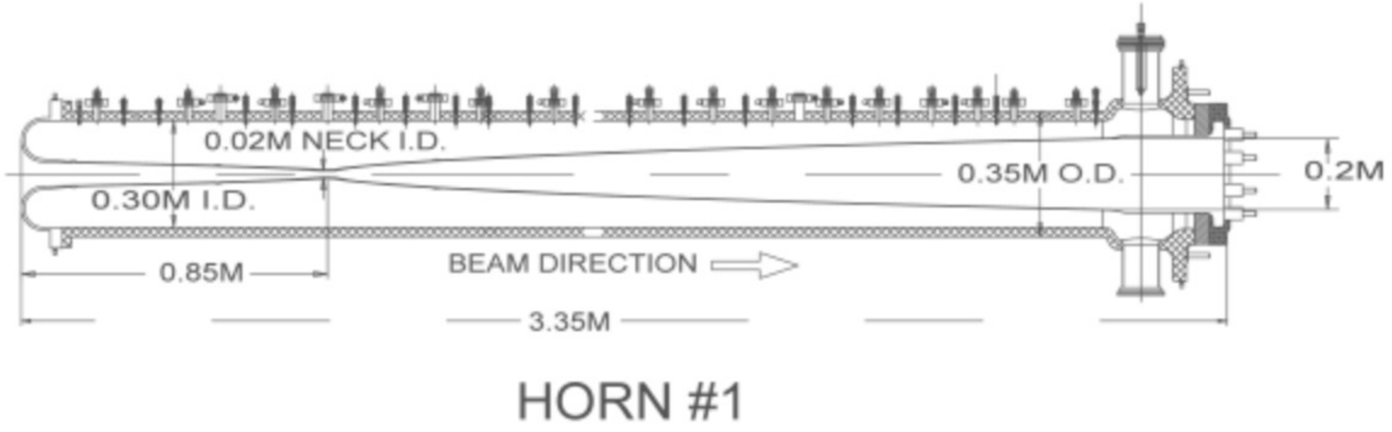
Record 10 μs beam window ± 270 μs side band

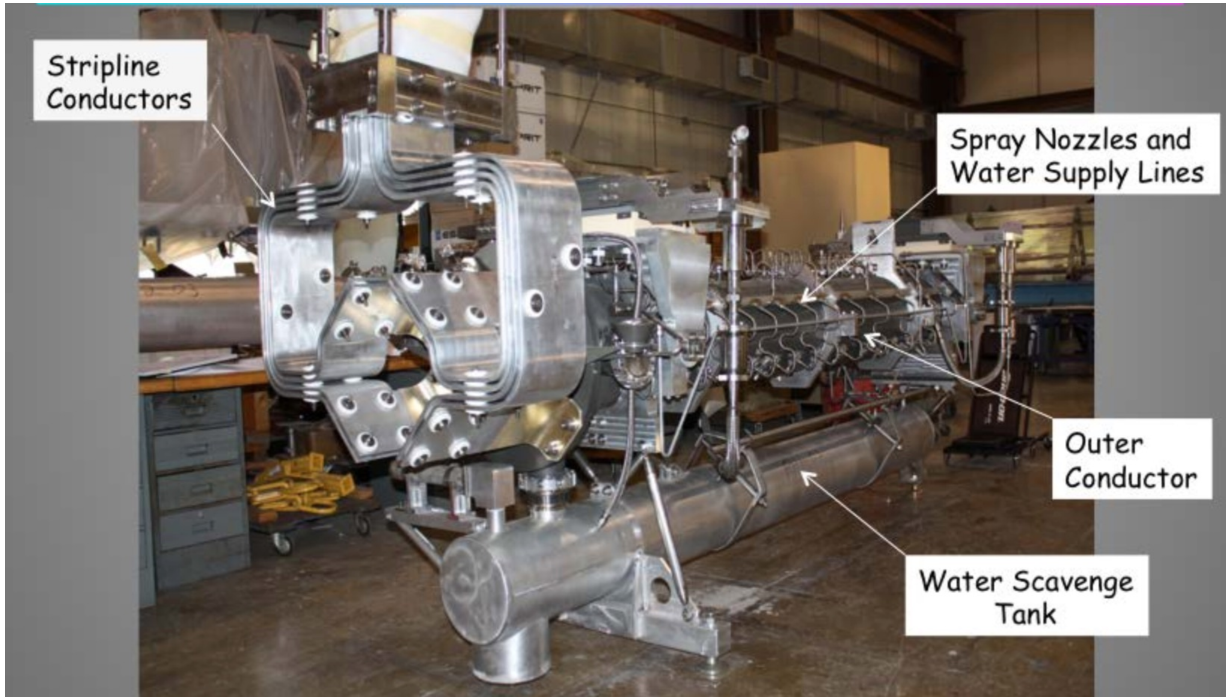
About 1 neutrino per day interacts in the 14 kton detector

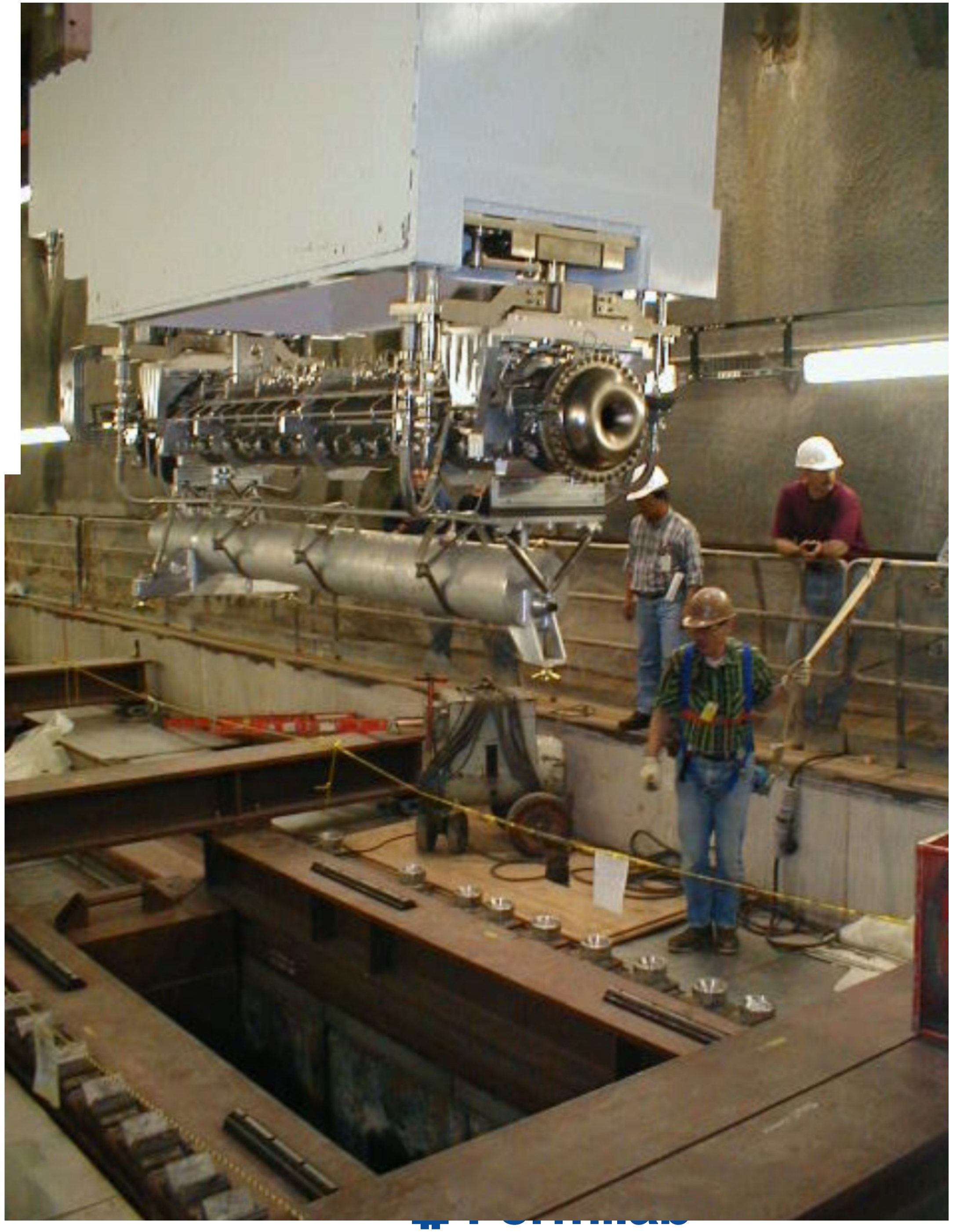
Significant improvement in precision measurement of atmospheric mixing parameters



High-precision measurements of mixing parameters also allow tests for inconsistencies that could point us to physics beyond the three-flavor model.
Ultimate reach does not depend on external θ_{13} measurements, and comparison with reactor data directly tests PMNS unitarity

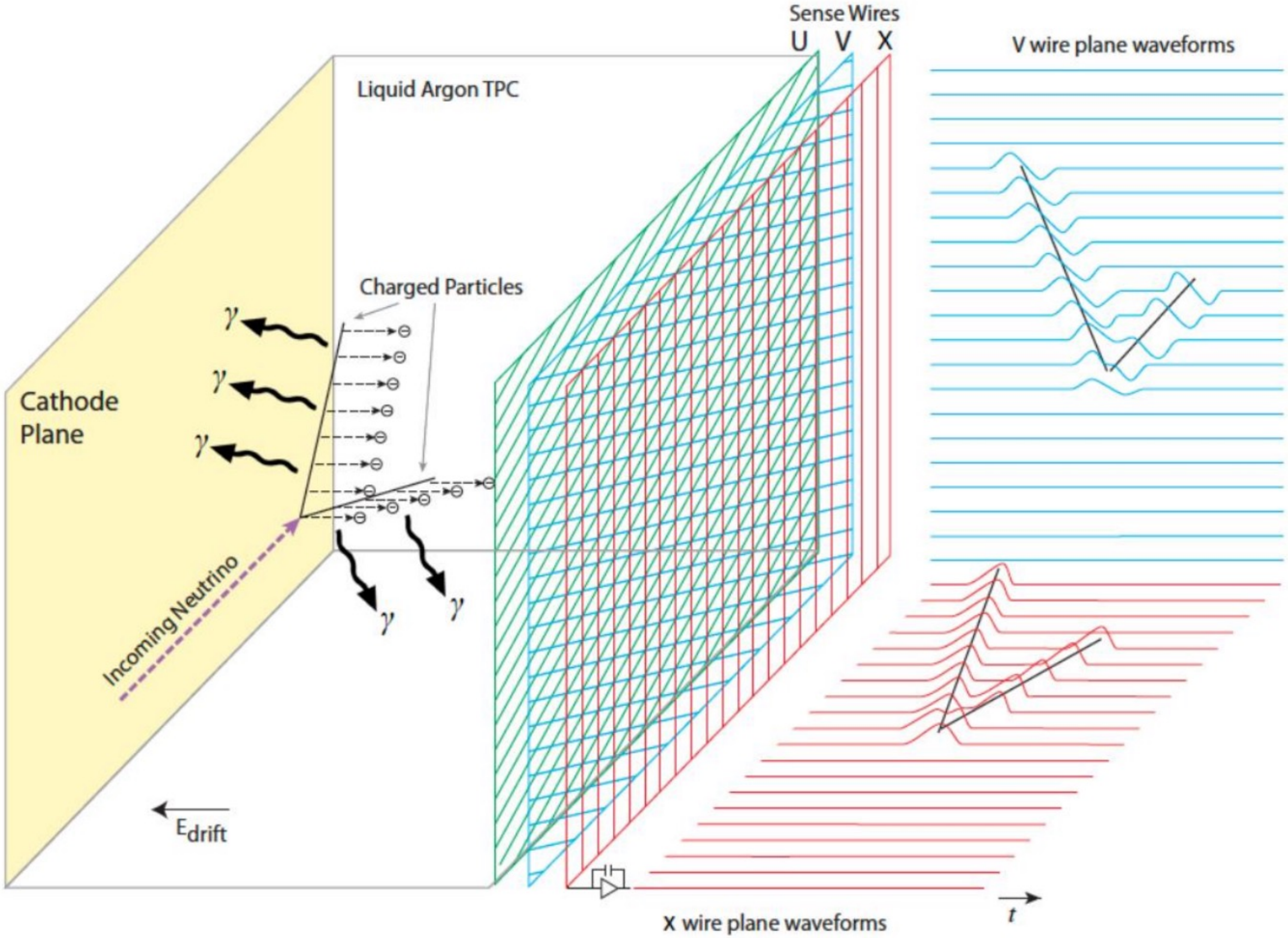






NuMI Horn 1 and positioning module installation in beamline chase

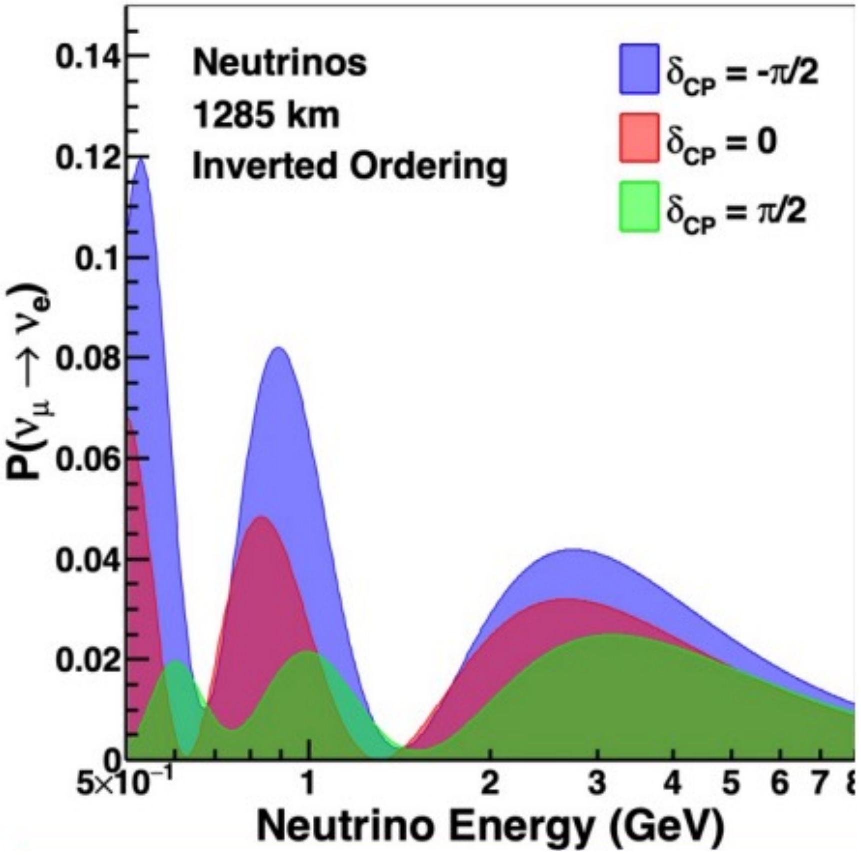
How LAr TPCs work



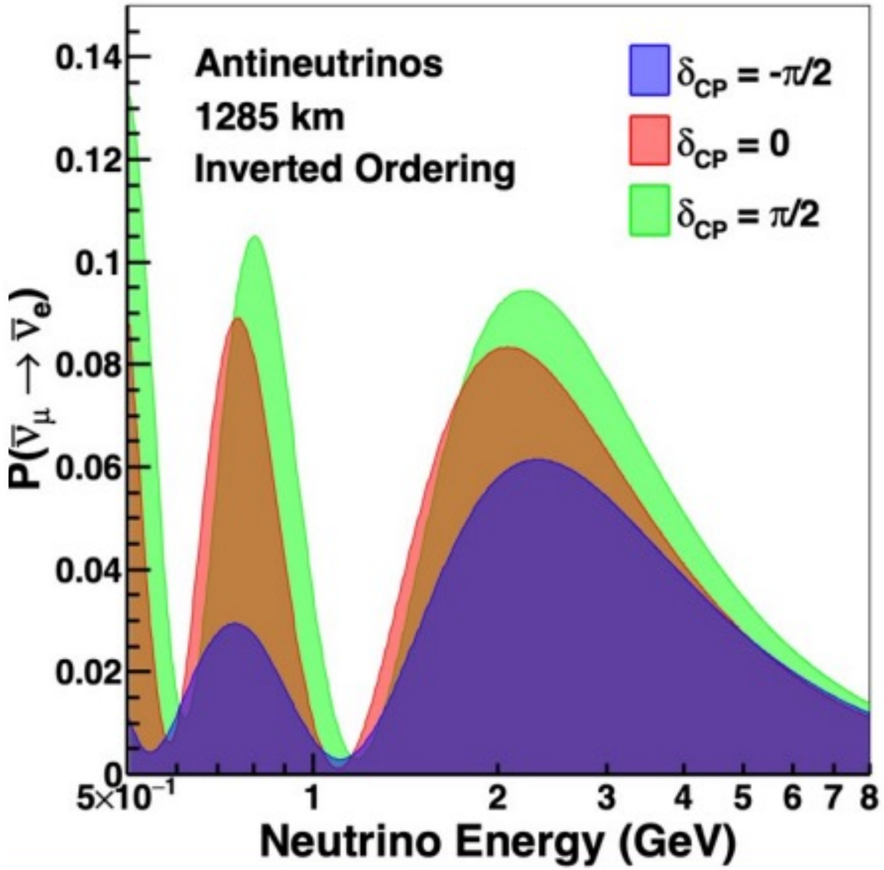
- Neutrinos interact in argon, producing charged particles
- Argon scintillates and photon detectors quickly detect light, used to trigger.
- Charged particles ionize the argon and electrons slowly drift to the anode
- Anode is instrumented (readout wires or pixels)
- Combining charge and light enables 3D event reconstruction with mm precision

Electron neutrino oscillation probability

Neutrino beam



Anti neutrino beam

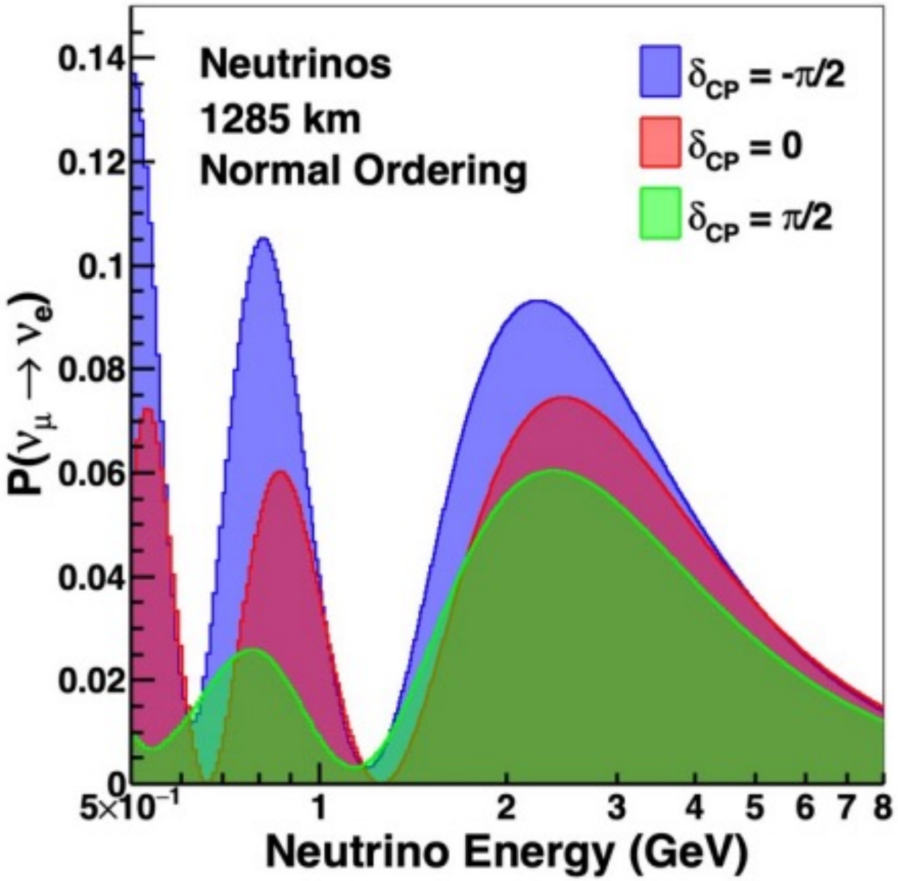


In **inverted ordering** neutrino suppressed and antineutrino-enhanced

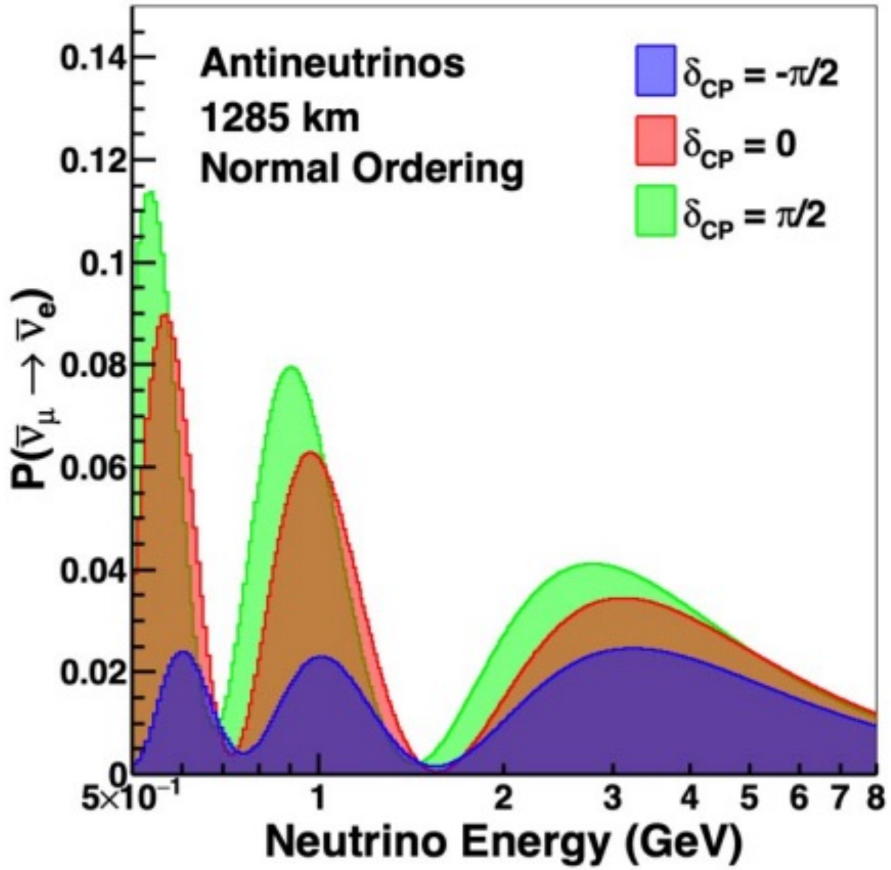
The effect of CP phase is reversed for neutrinos and anti-neutrinos.
The power of accelerator neutrino experiment over other sources is ability to easily switch between beam modes

Electron neutrino oscillation probability

Neutrino beam



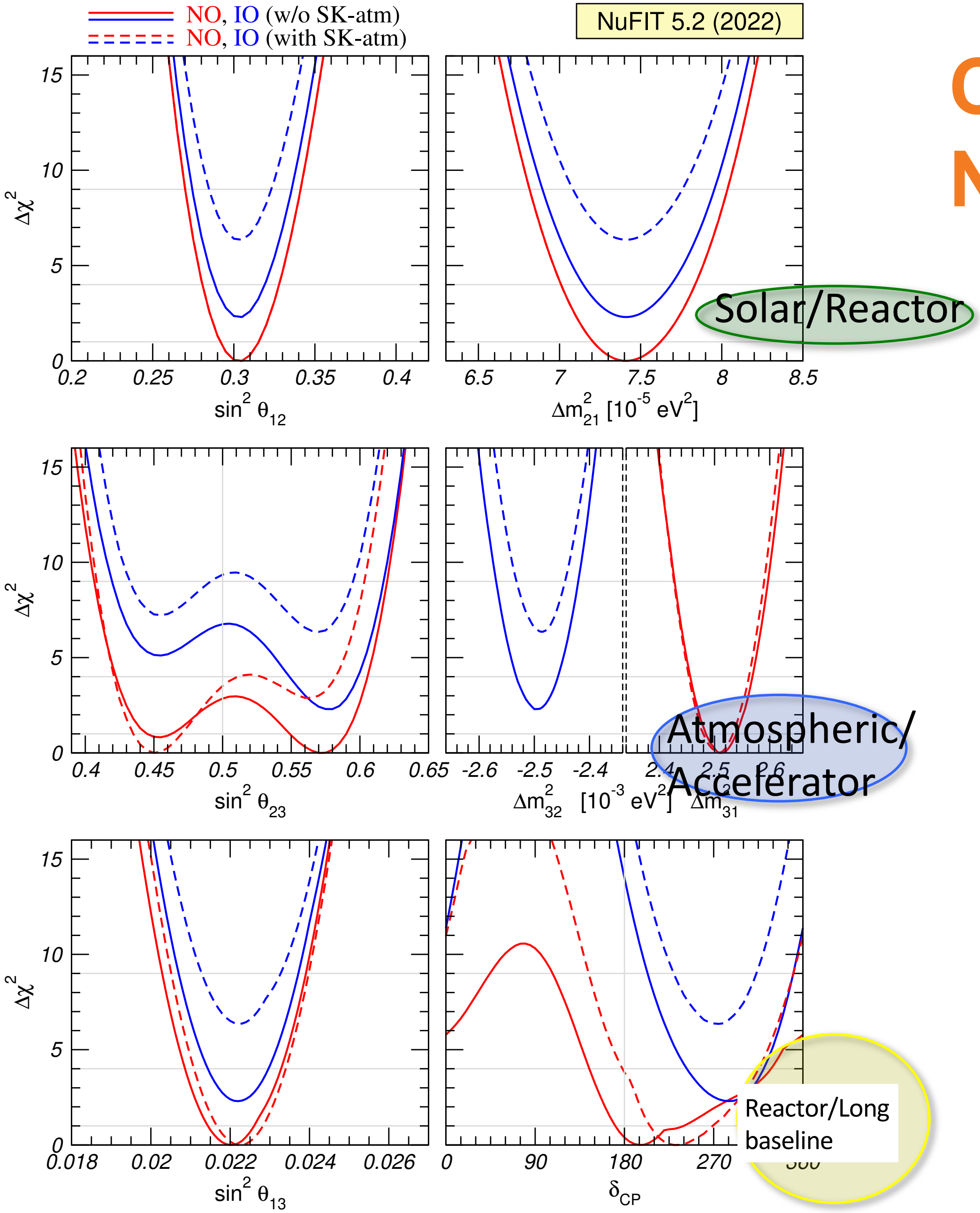
Anti-neutrino beam



In **normal ordering** neutrino enhanced and antineutrino-suppressed

The effect of CP phase is reversed for neutrinos and anti-neutrinos.
The power of accelerator neutrino experiment over other sources is ability to easily switch between beam modes

Current status 3-flavor oscillation NuFit 5.2 (Nov 2022)



- Mass ordering - or sign of larger mass splitting unknown
  - Some preference for normal ordering
- θ_{23} octant unknown
  - Some preference for upper octant
- δ_{CP} unknown
  - Some regions of possible phase space excluded at 3σ

Including:
Accelerator experiments – MINOS, T2K, NOvA
Reactor experiments – KamLAND, Reno, Daya Bay,, Double-Chooz
Atmospheric experiments - IceCube/DeepCore, SK1-4 and external atmospheric neutrino fluxes
Solar experiments - • SK, SNO, Borexino, SAGE, Gallex & GNO, Chlorine total rate, and including external info of Standard Solar Model

JHEP 09 (2020) 178 [arXiv:2007.14792] , NuFIT 5.2 (2022), www.nu-fit.org.