Accelerator Based Neutrino Experiments

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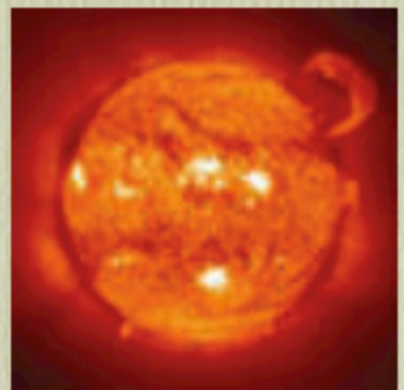
Topics

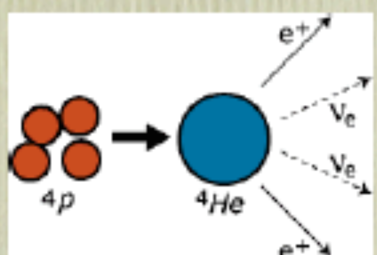
- Neutrino Properties
  - Neutrino Flavor Oscillations
  - Mass and Mixing
  - Mass hierarchy and CP-violation
- Neutrino Oscillation Experiments using Accelerators
  - Why long baseline?
  - Why underground?
  - Why so large?

Neutrinos are abundant in our universe

Remnants of the Big Bang
(~1000 per cubic cm)

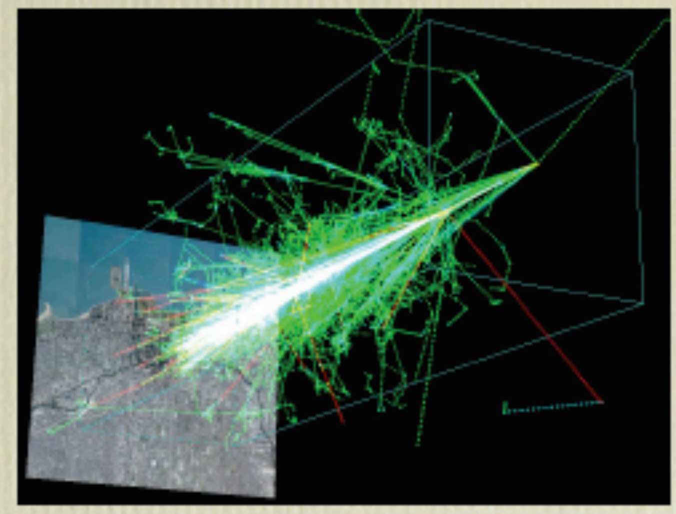
Our Sun is powered by nuclear reactions





(100 billion per sq cm every second)

Cosmic ray interactions



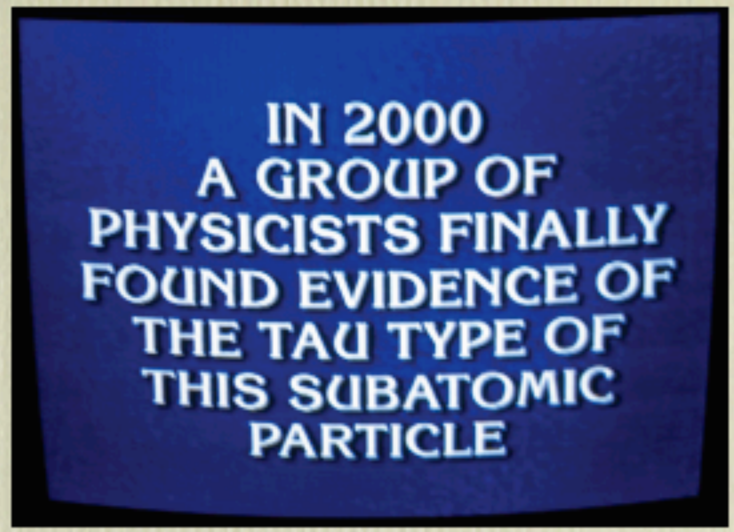
Supernovae
(99% of energy is emitted as neutrinos)

Nuclear Power Plants

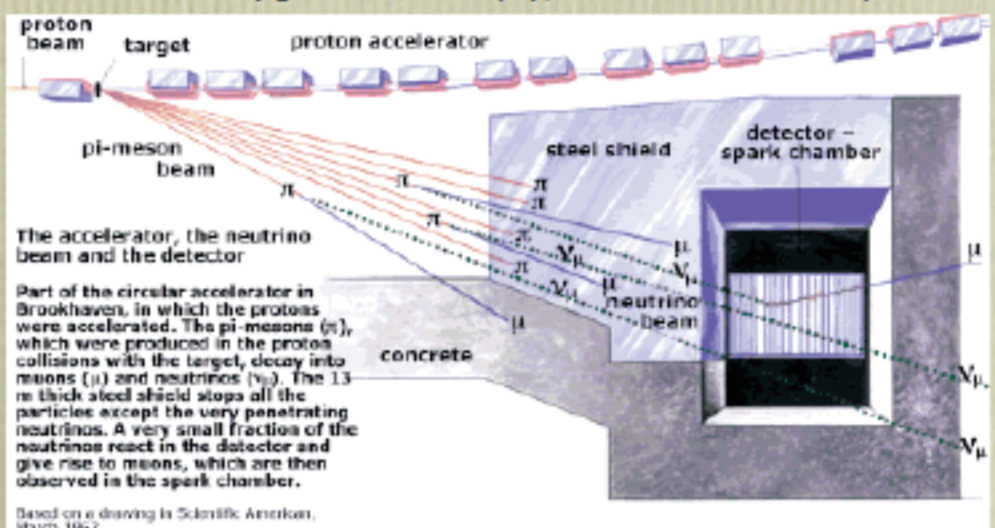
... but difficult to detect

postulated in 1932

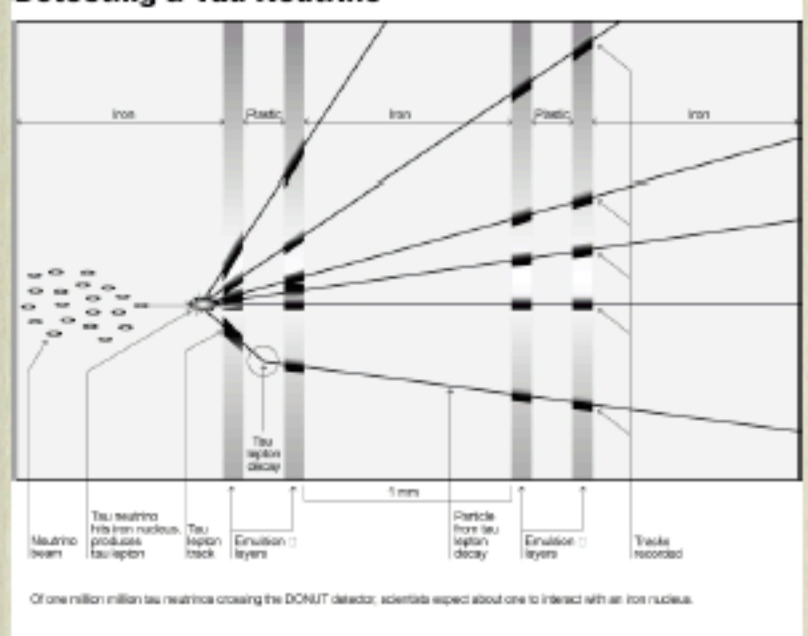
1st detected in 1956



2 neutrino hypothesis (~1947) confirmed in 1961



Detecting a Tau Neutrino



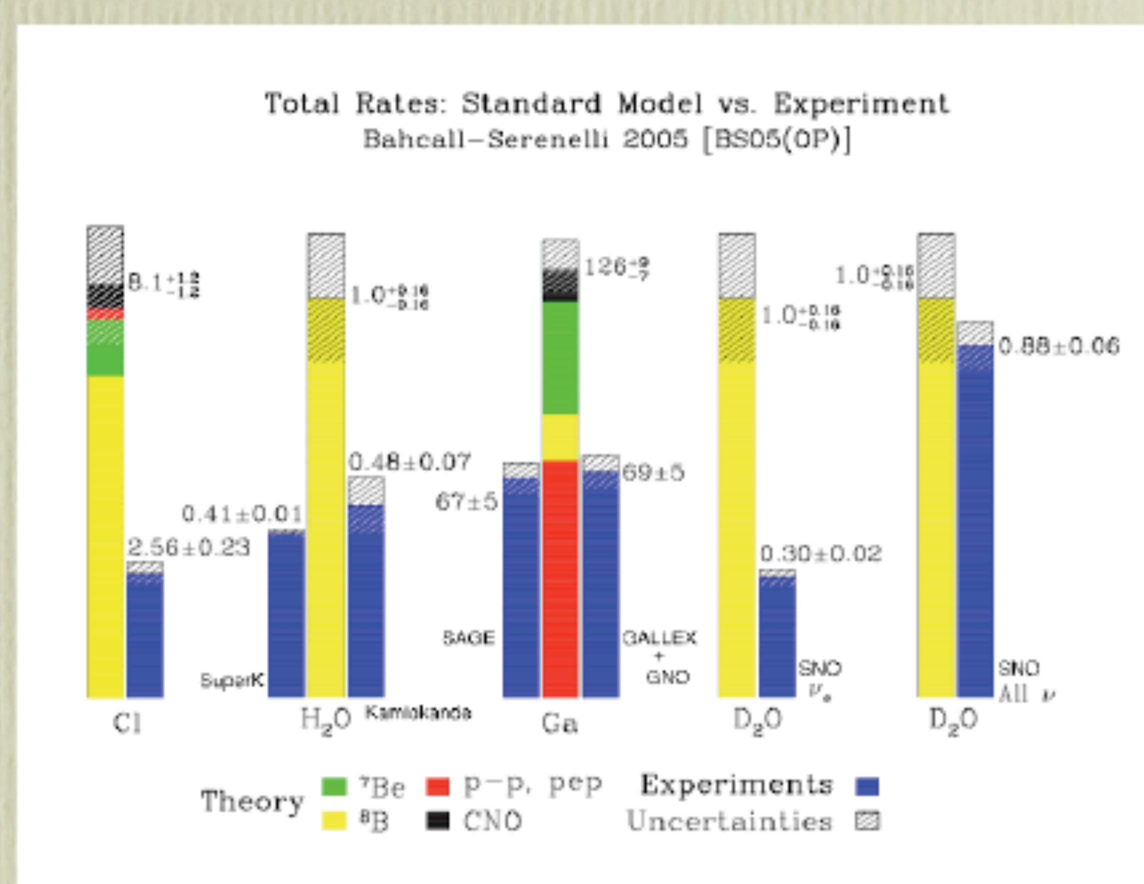
The Solar Neutrino Mystery

~1970 : detecting solar neutrinos via the inverse β-capture

$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar$

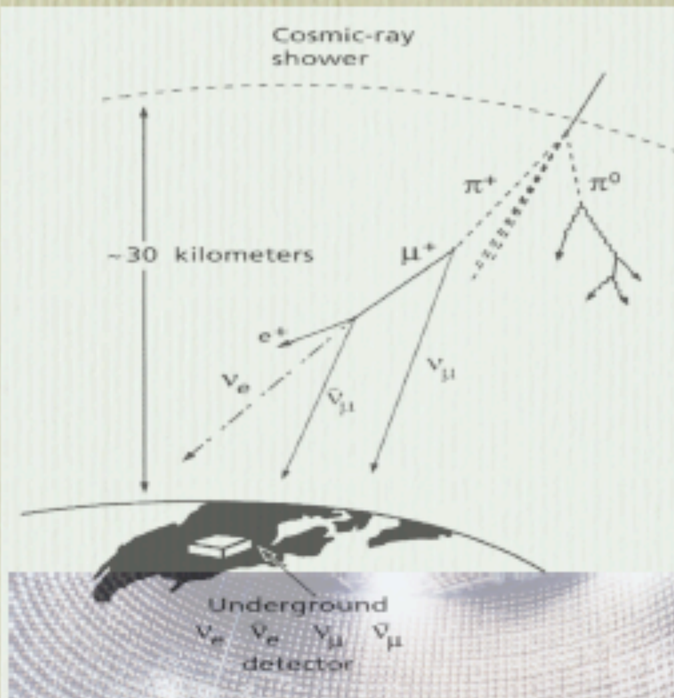
Only about 1/3 of the number expected were observed.

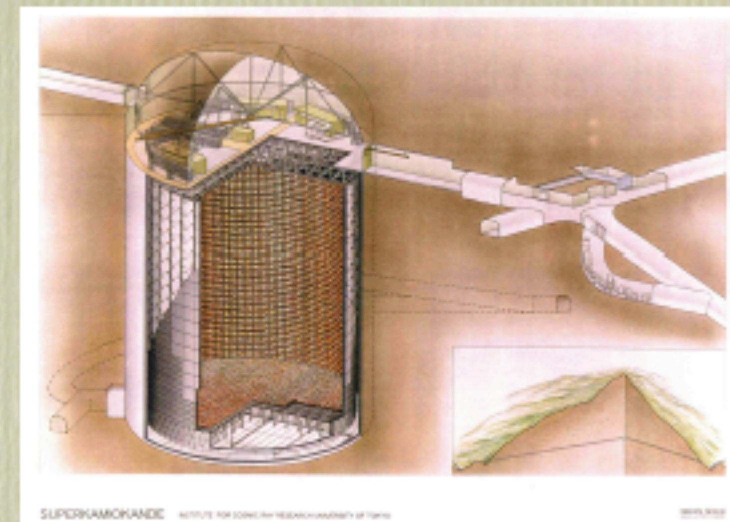
100,000 gallons of perchlorethylene
10^{30} atoms of chlorine



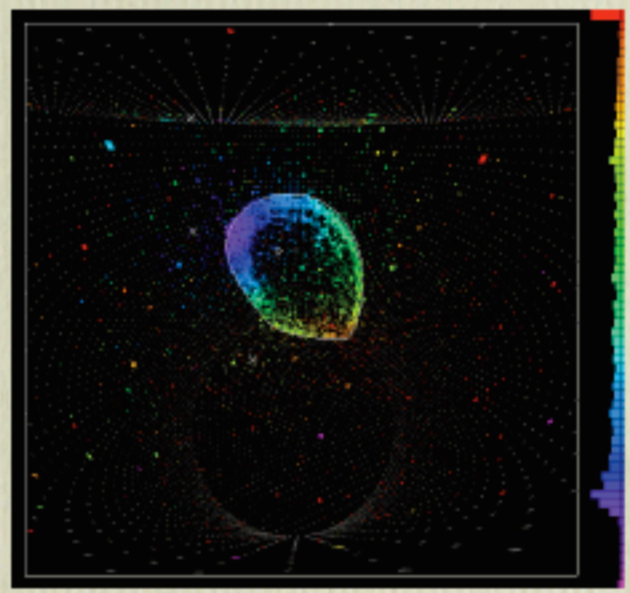
Over the next 30 years the deficit would be observed in many different detectors

more “missing” neutrinos .....





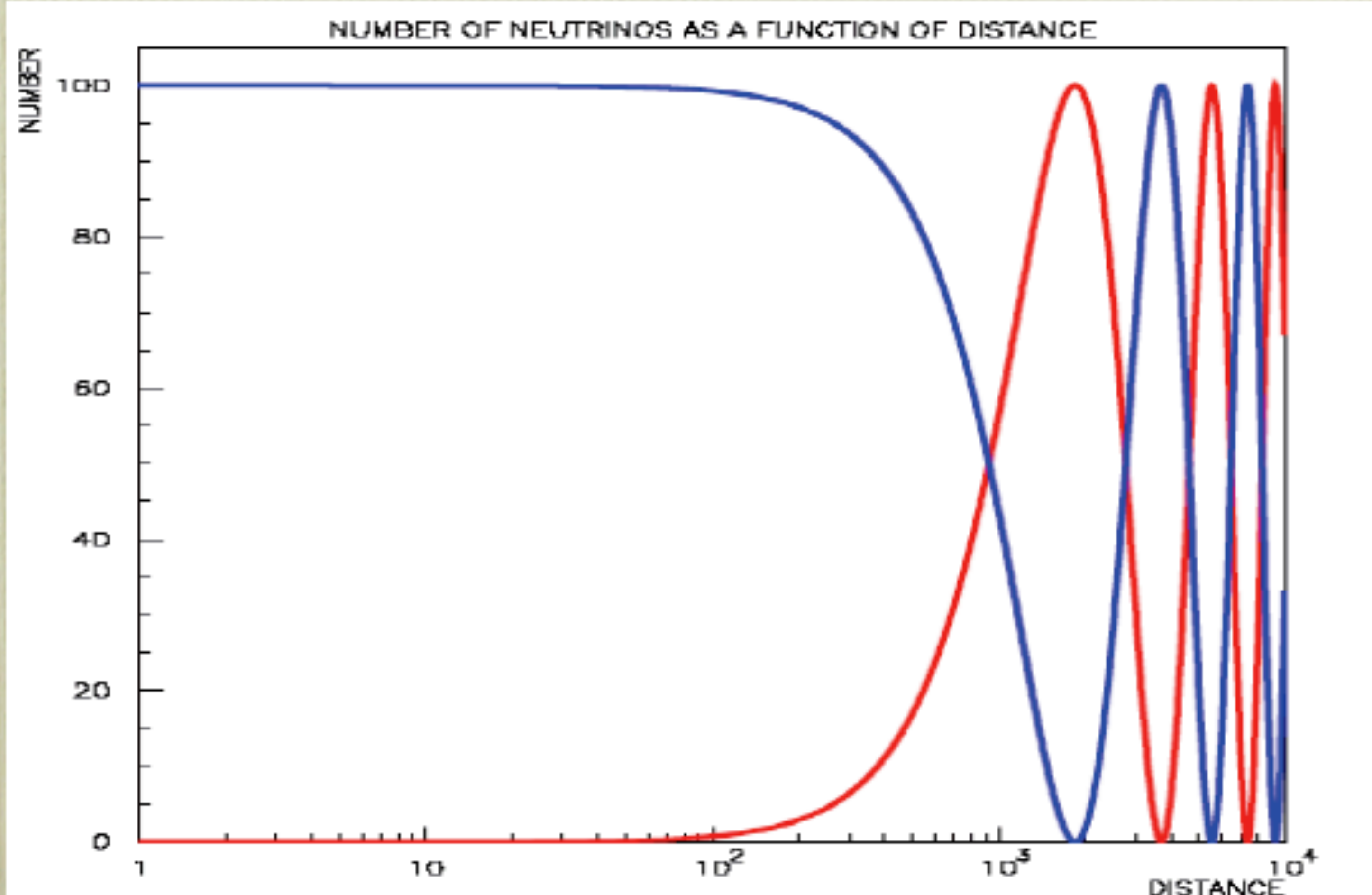
1/2 the predicted # of muon neutrinos are not detected



The Hypothesis : neutrinos have mass;oscillate between mass states

$$P(\nu_a \rightarrow \nu_b) = \alpha \cdot \sin^2\left(\frac{1.267 \cdot \Delta m^2 \cdot L}{E}\right)$$

Oscillation Probability depends on :
neutrino energy
mass difference
distance traveled



Solar and atmospheric data indicated that if the missing neutrinos were indeed due to oscillations, then the mass differences were very small :

$$\Delta m_{12}^2 \approx 8 \times 10^{-5} \qquad \Delta m_{23}^2 \approx 3 \times 10^{-3}$$

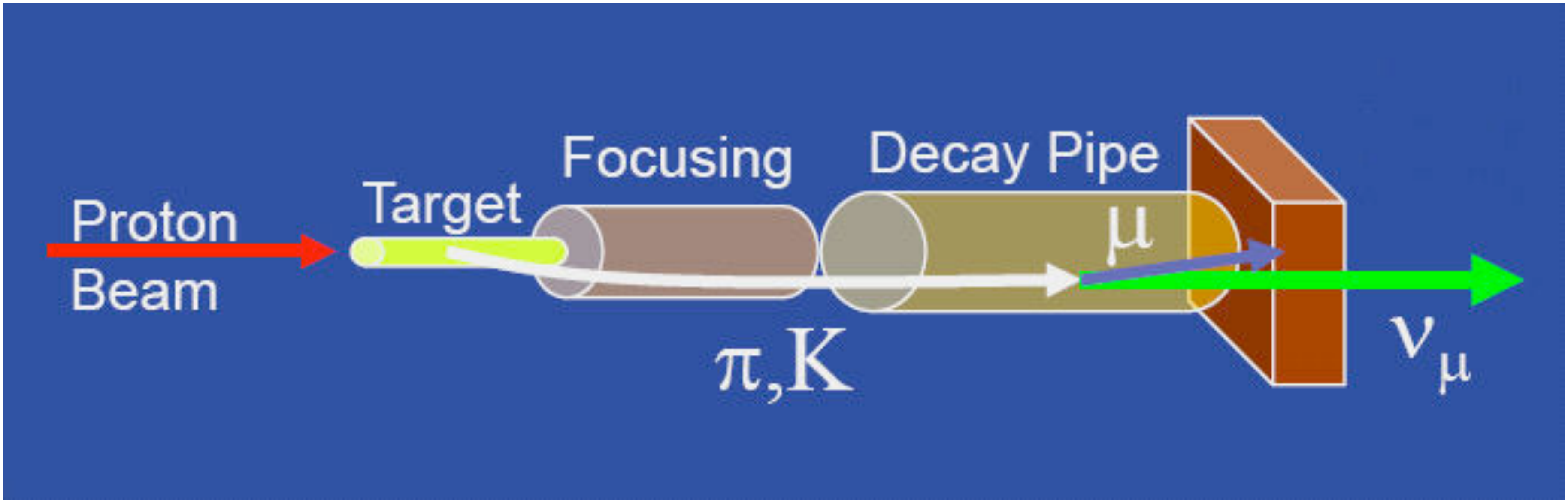
Knowing these mass scales guides the design of a controlled laboratory experiment.

Neutrinos can be made at a proton accelerator :

i.e. **Fermilab Main Injector**

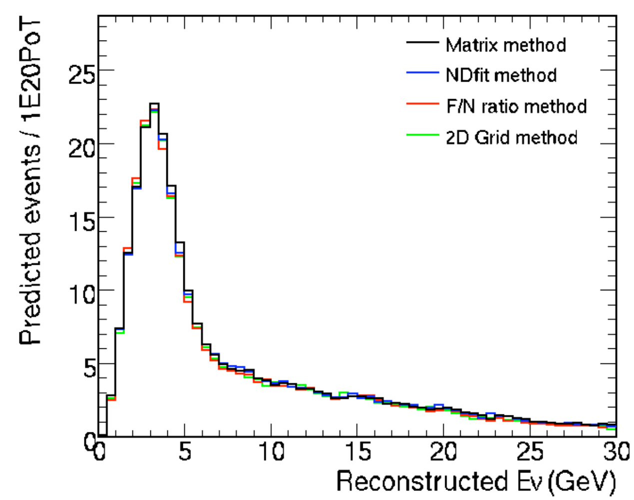
~10^{14} protons, travelling near the speed of light, can be extracted every 1 – 2 seconds

Ingredients in a neutrino beam

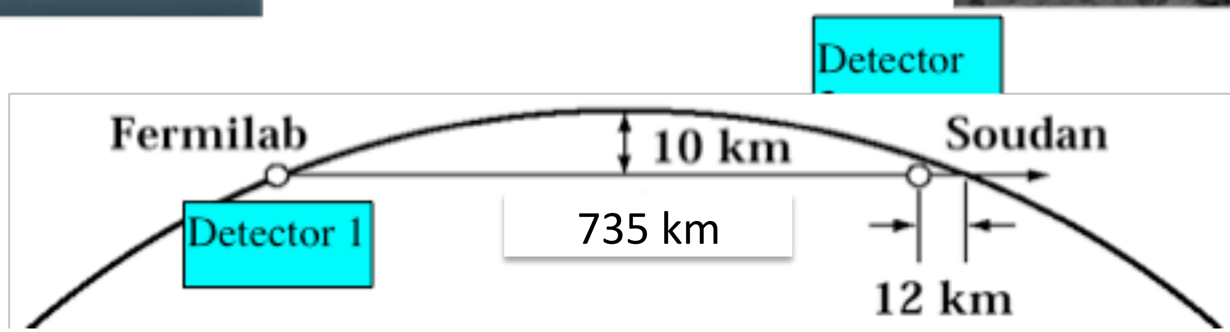


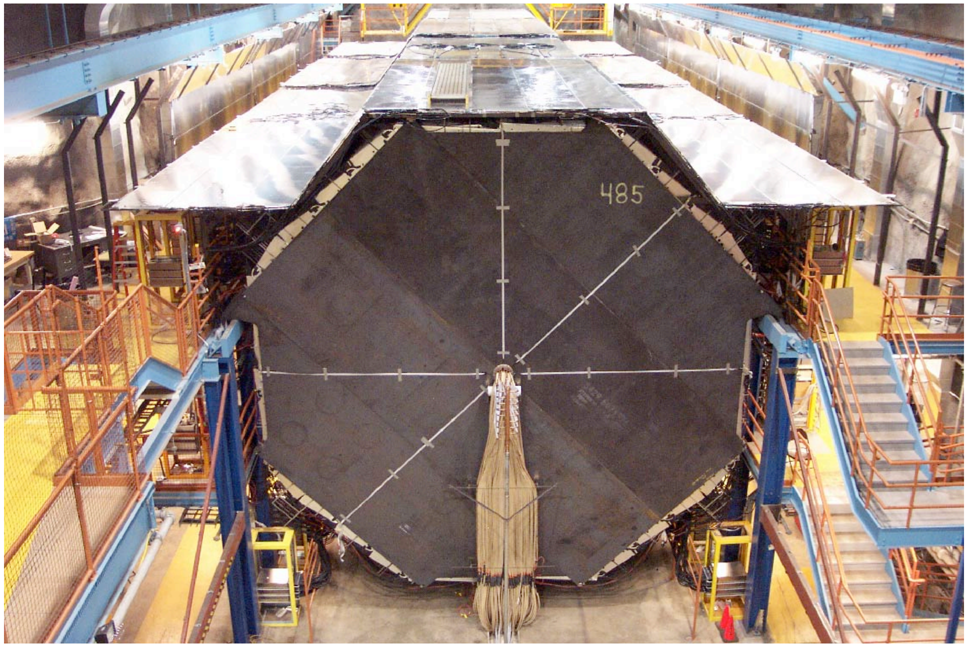
At Fermilab we can produce
~ 10^{11} neutrinos/m^2/10^{14} protons

$$P(\nu_\mu \rightarrow \nu_\tau) = f(\Delta m^2_{23}, E_\nu, L)$$

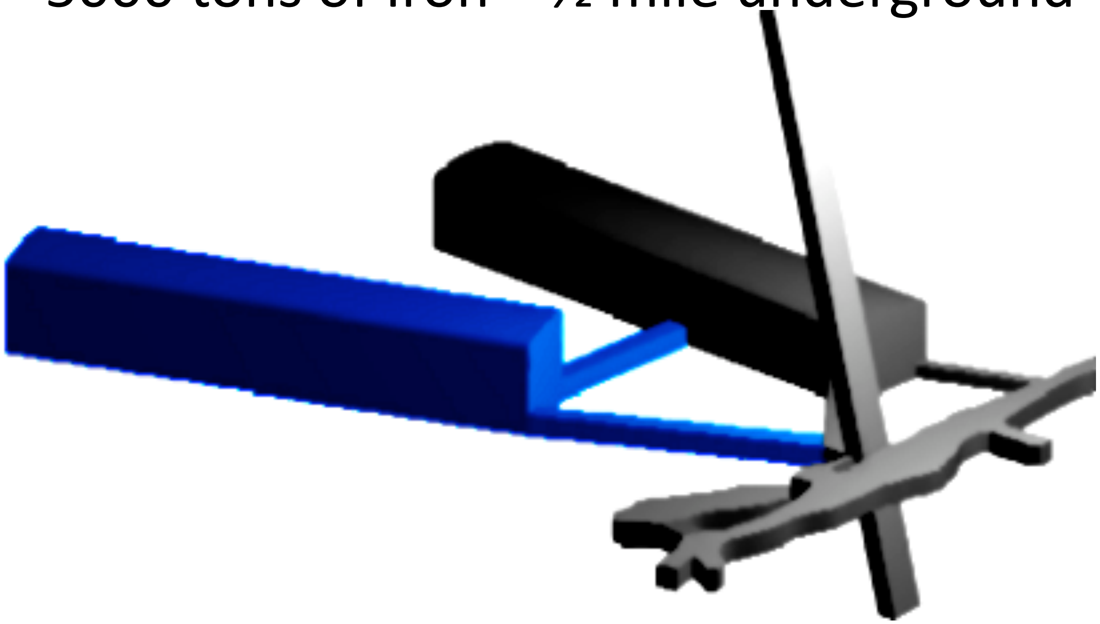


MINOS - Main Injector Neutrino Oscillation Search
(Minnesota-Illinois)



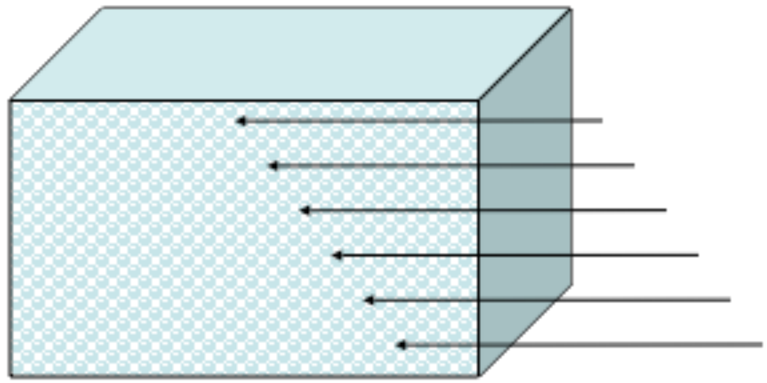


5000 tons of Iron – ½ mile underground



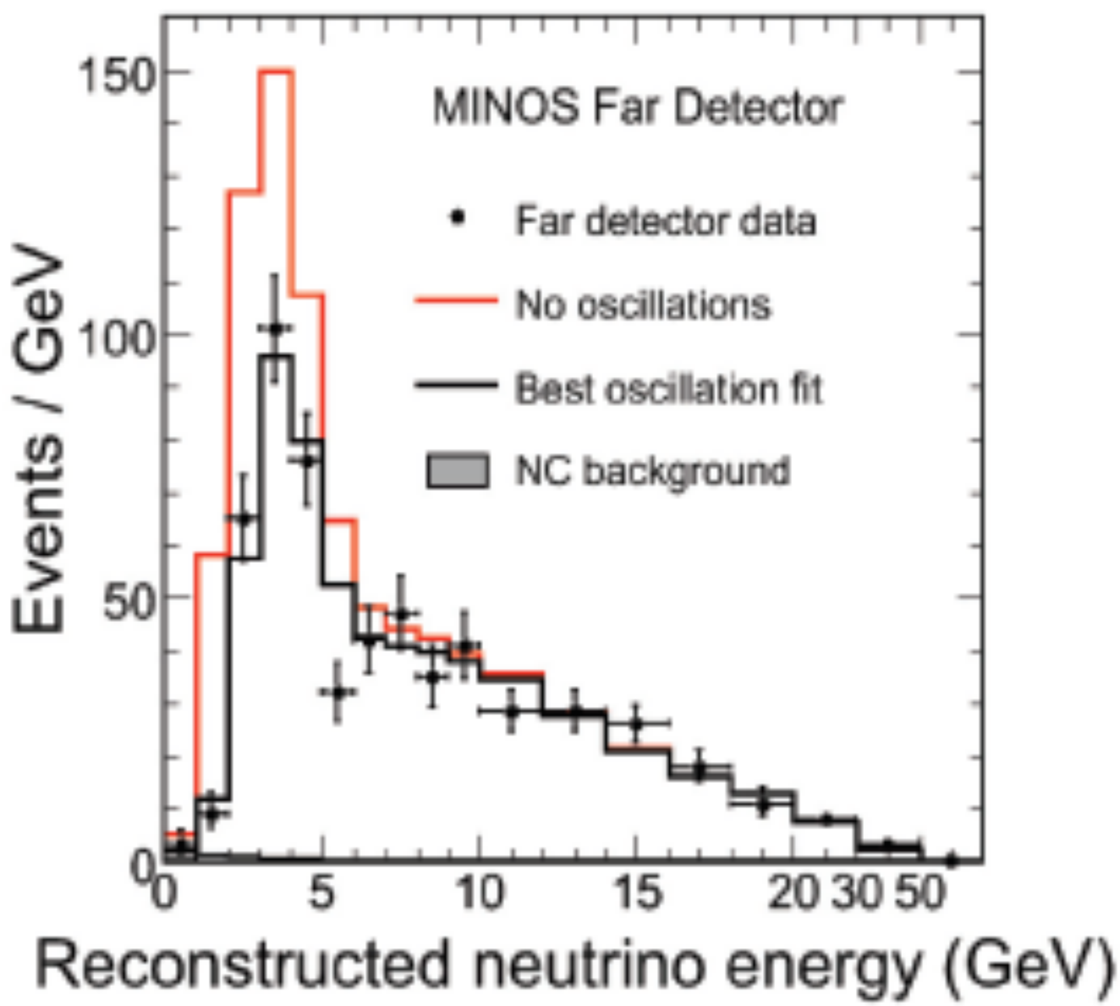
Why is it so difficult to detect neutrinos?

Consider a "beam" of particles, incident on a mass of material (i.e. atomic scattering centers)

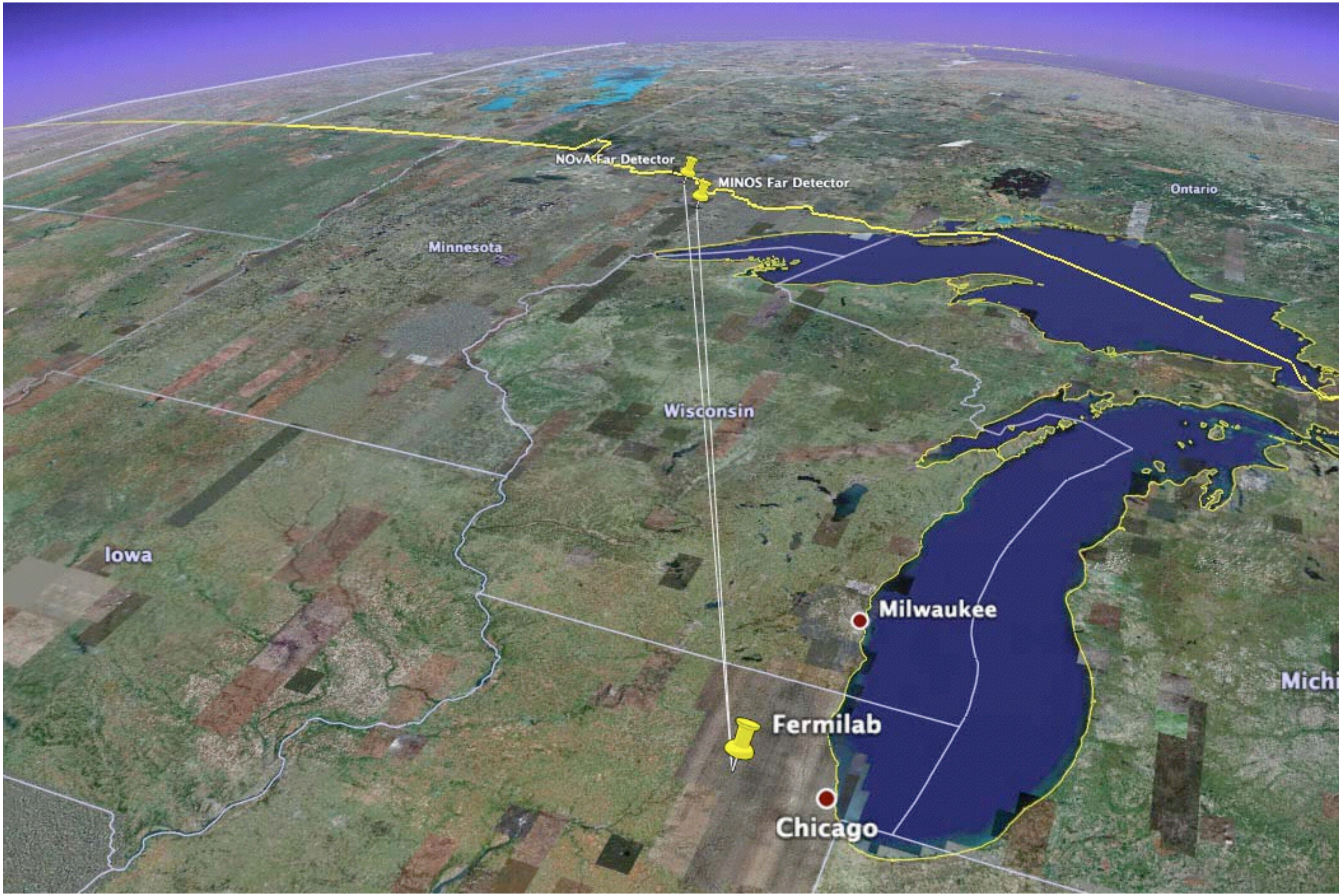


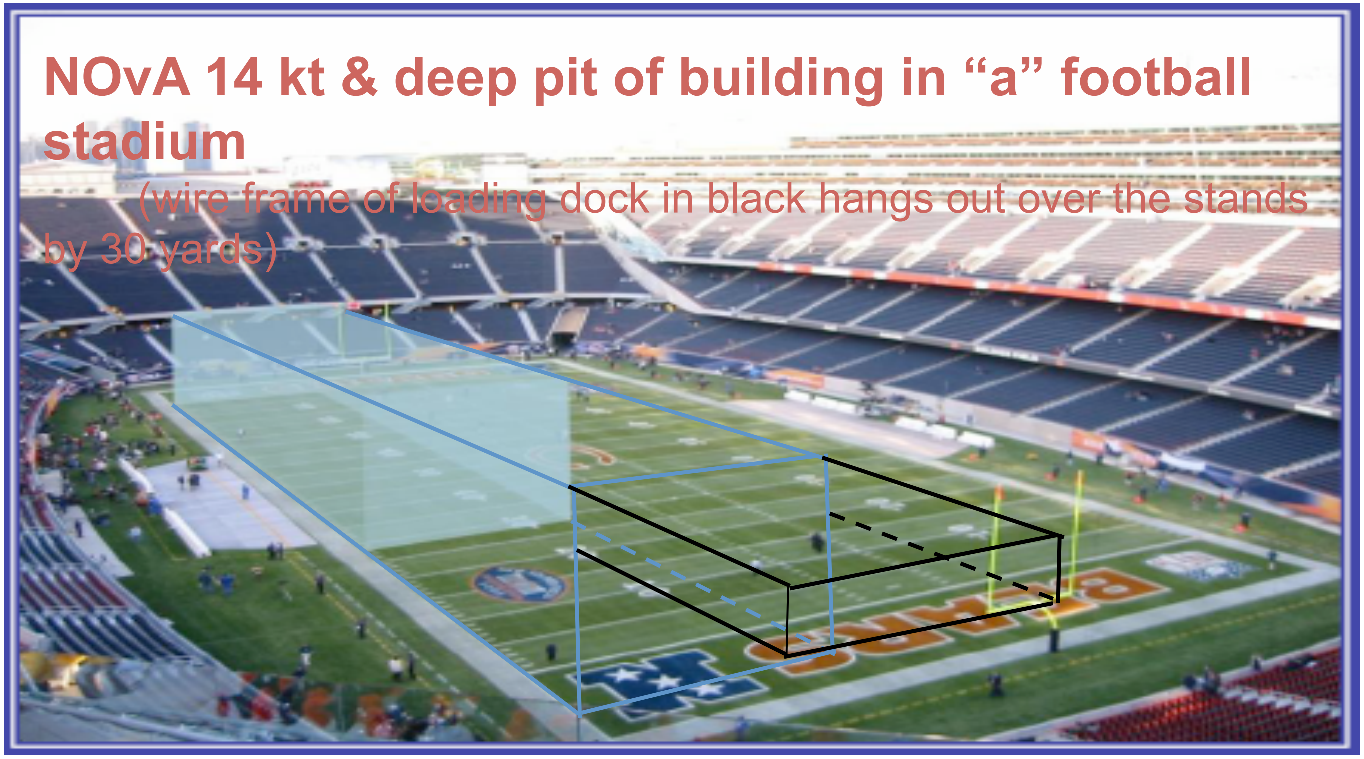
The **probability** that one of the particles will interact depends on the number of scattering centers, i.e. protons/neutrons, density of the scattering centers, the intensity of the beam, and the energy of the beam

No oscillations – expect ~ 3 events/day;   observe ~ 1- 2



NOνA : NuMI Off-Axis



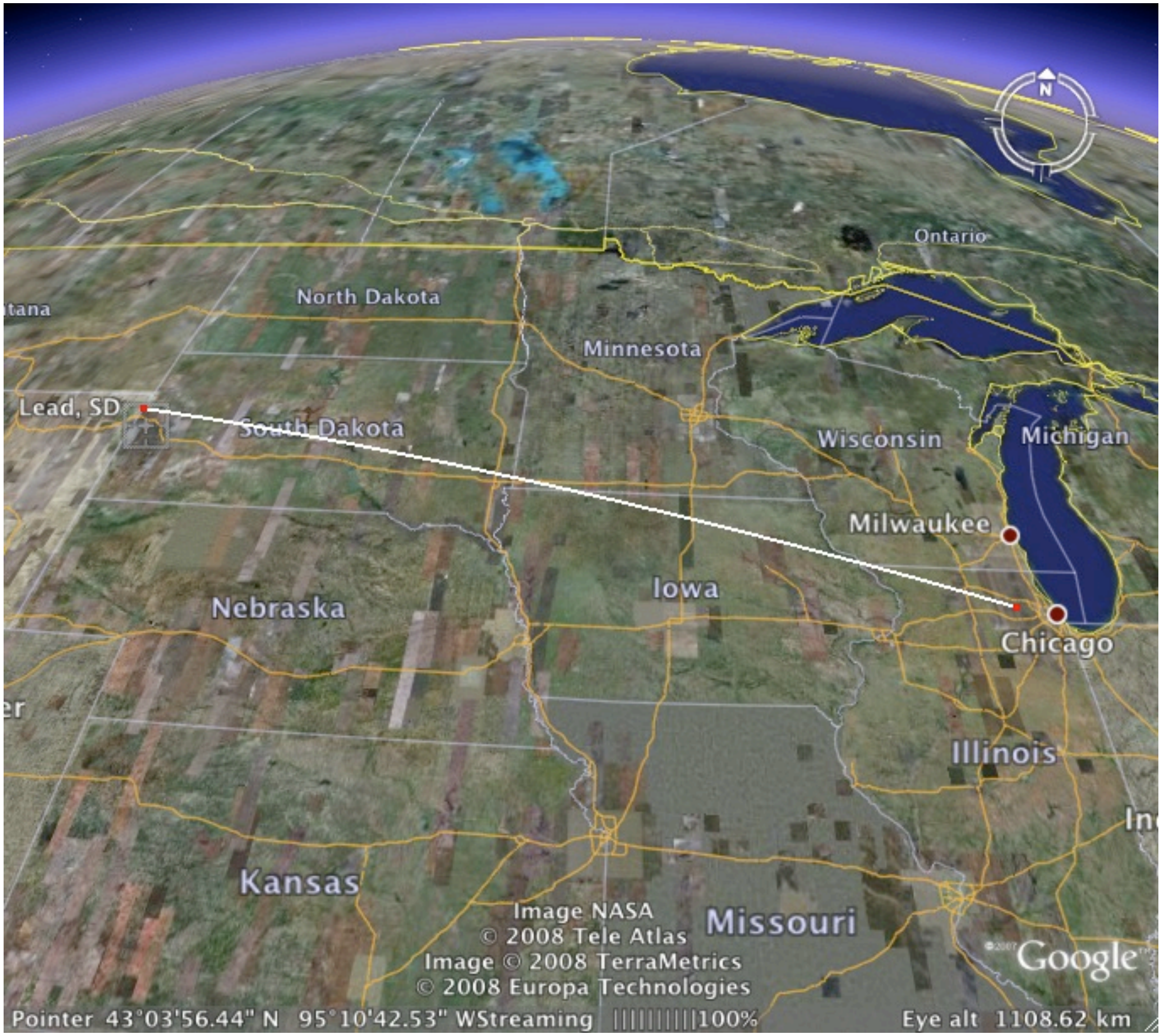


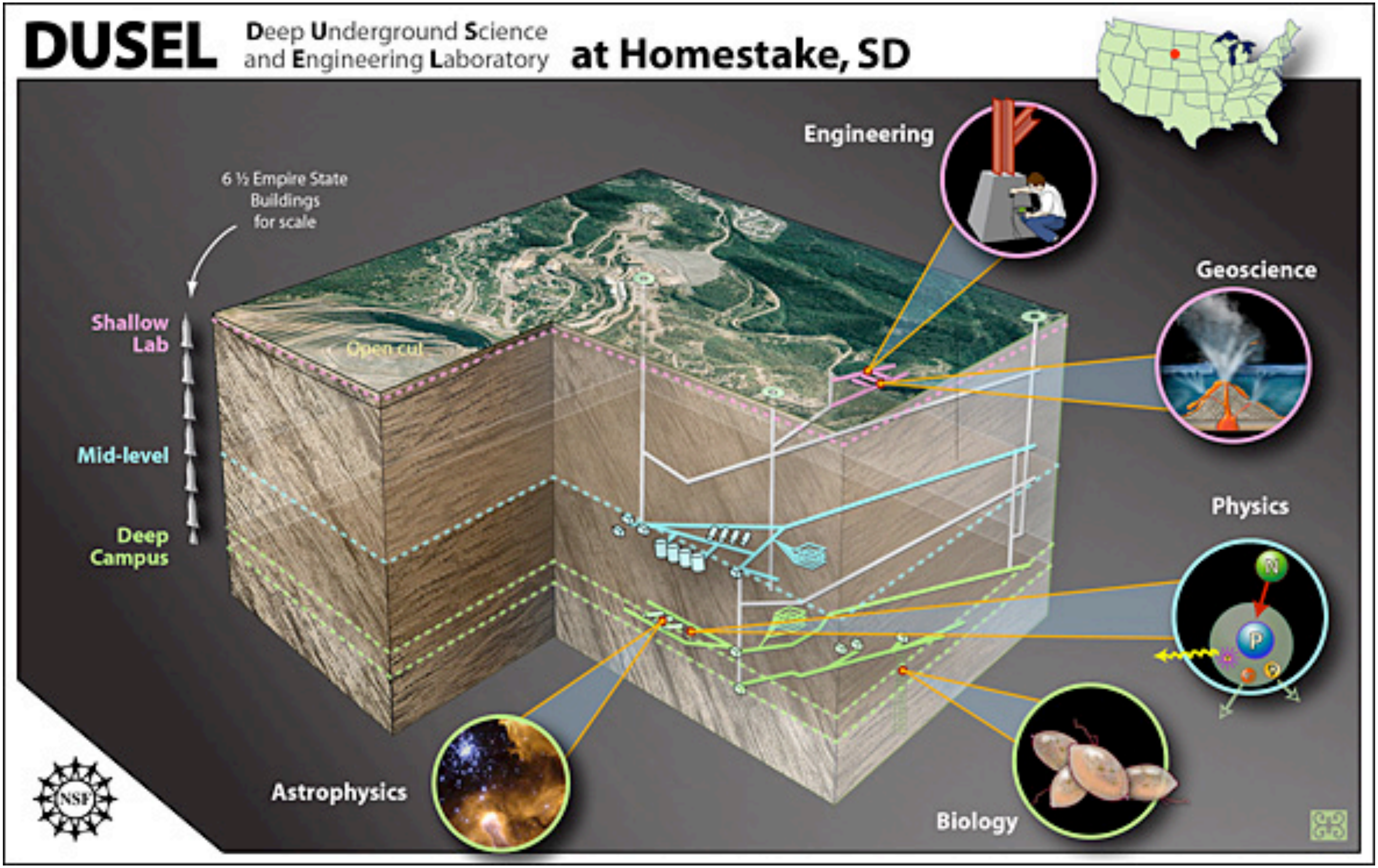
Start data taking with full detector in 2013 with 6×10^{20} POT/year

Run 3 years producing neutrinos and 3 years producing anti-neutrinos

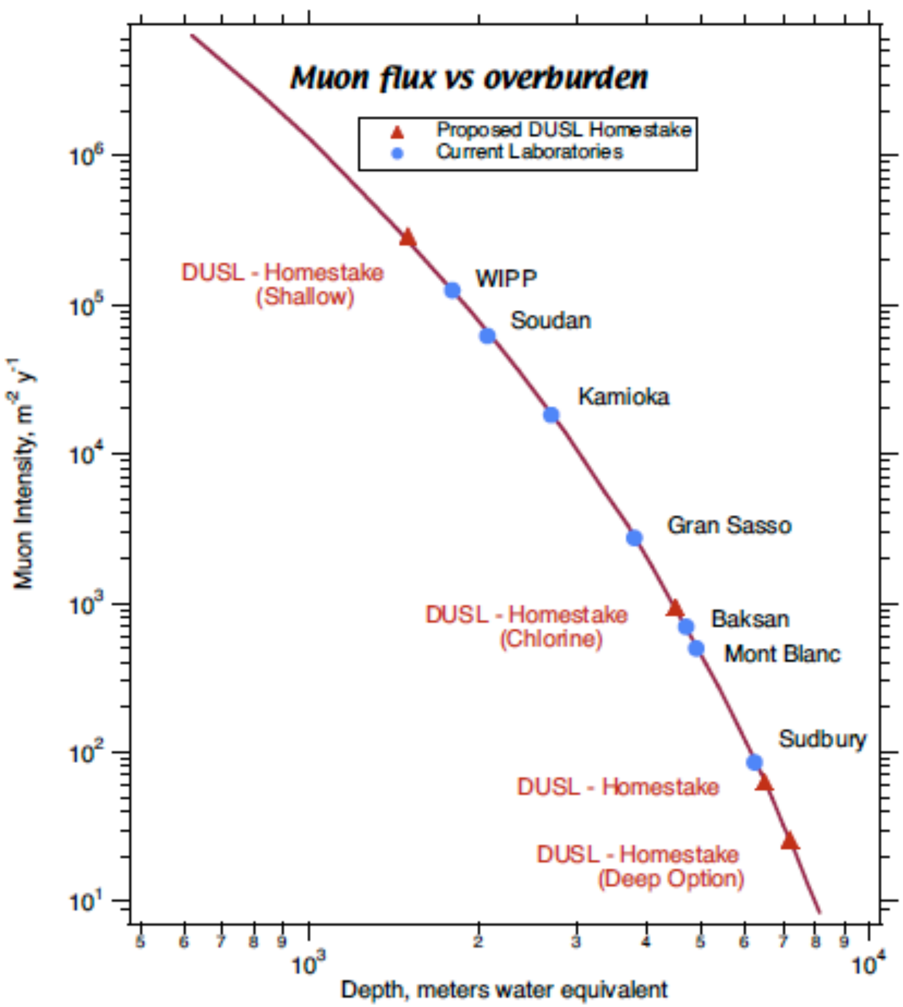
All goes well – significant data taking complete in 2019-2020

Fermilab to Homestake DUSEL (1290km)




DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
6 ½ Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
Open cut
Engineering
Geoscience
Physics
Astrophysics
Biology
NSF

Why Go Underground?

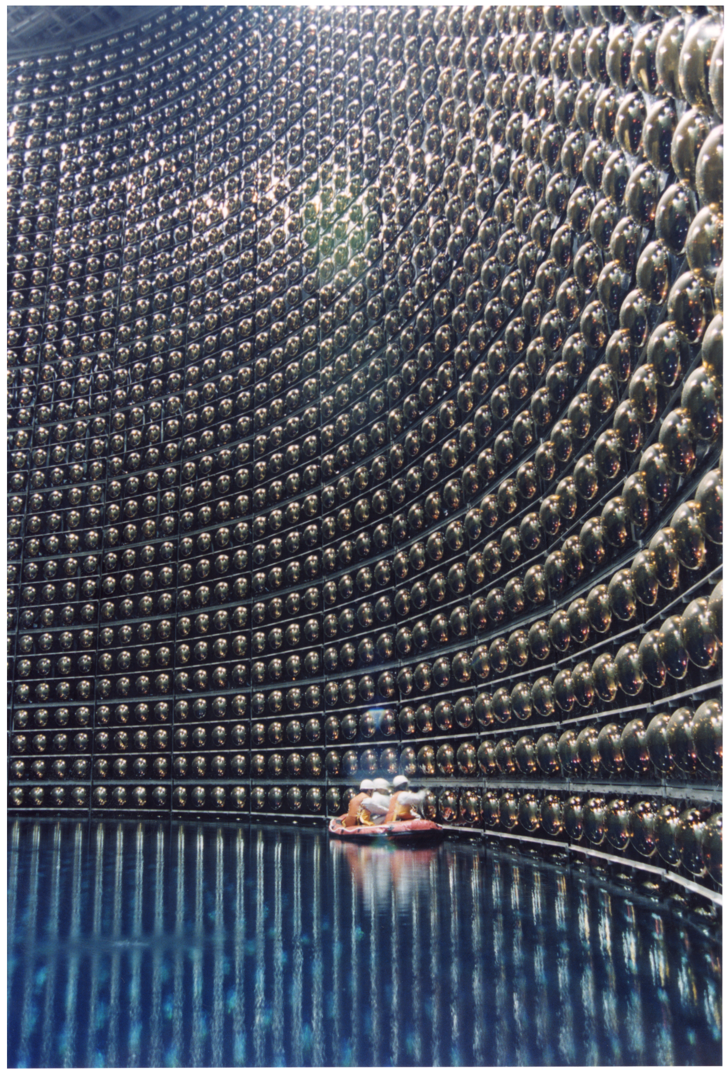


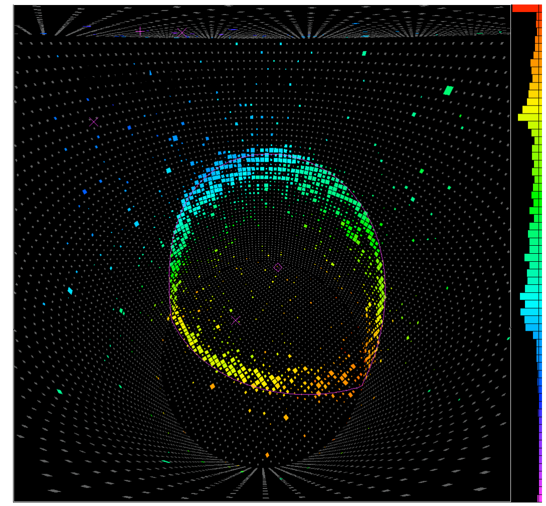
Depth reduces the rate of cosmic ray muons and associated interactions occurring in the detector which can mimic or confuse the information about the real events of interest.

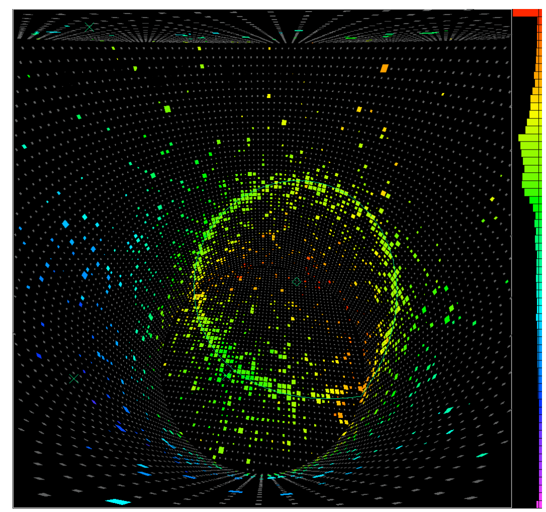

HOMESTAKE
Waste Water Treatment
Open Cut
Yates Complex
Town of Lead
~ 1km
Ross Complex
Kirk Canyon Adit

Planning the world's largest detectos

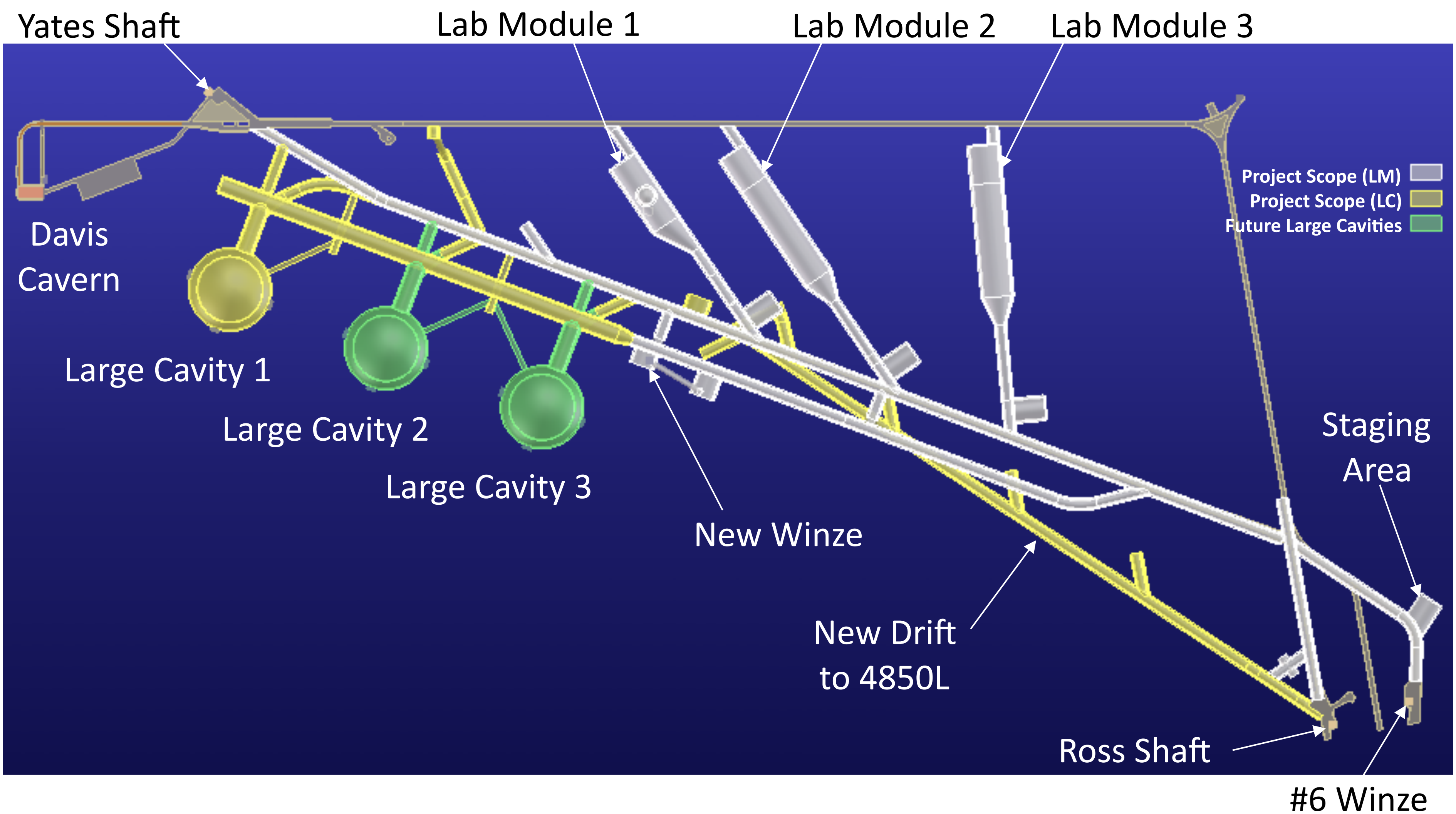
- Super-K (taking data in Japan)
  - 13K 20" PMT
  - 40% coverage
  - 50 kT total mass
  - 39 m diameter
  - 42 m height
- LBNE - proposed
  - 60 K 10" PMT per 100kT FV module (25%)
  - ~55 m diameter
  - ~60 m height

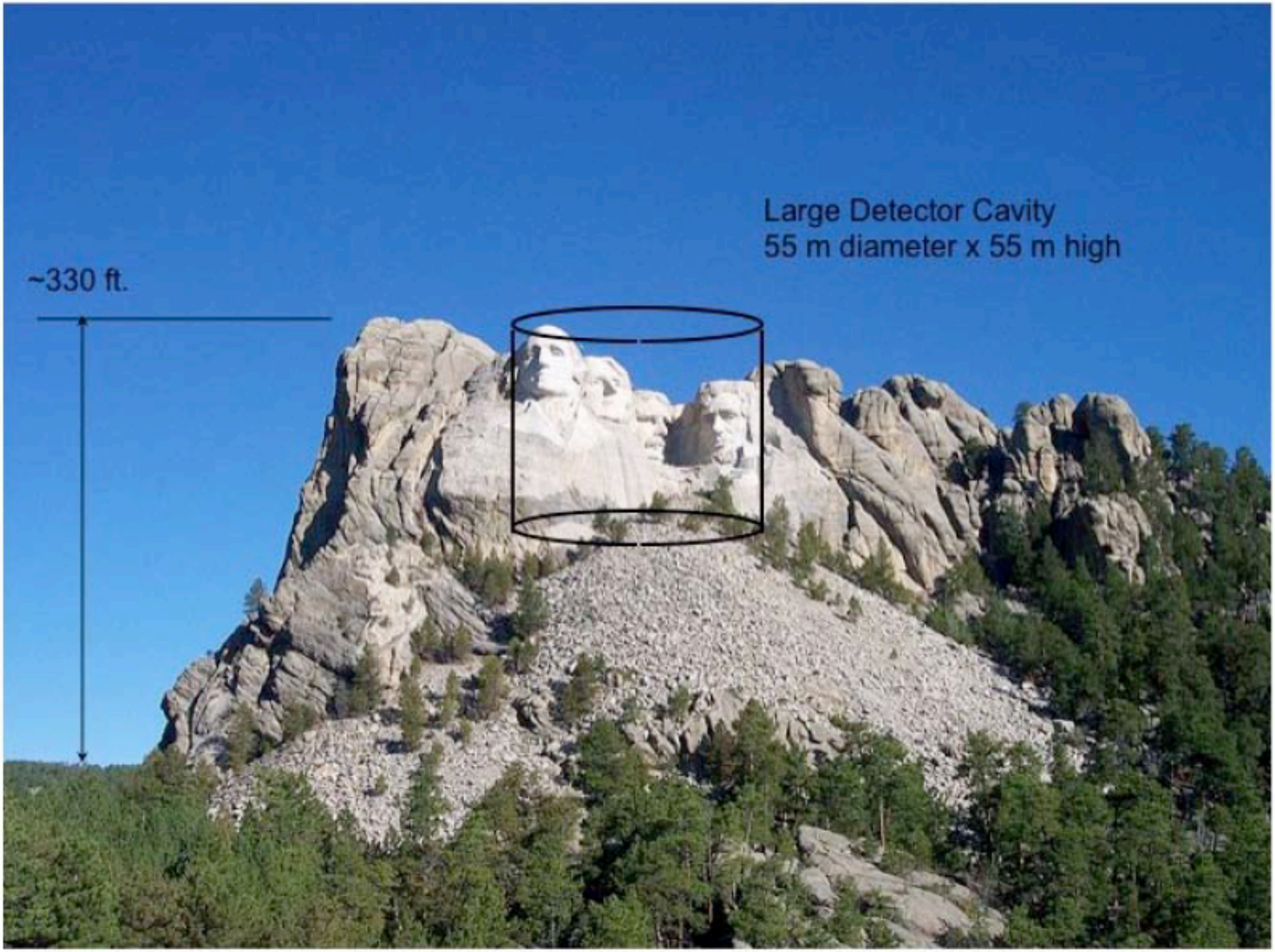






4850 Level Developmental Baseline for PDR:
Three Lab Modules & Three Large Cavities, Plan View




Large Detector Cavity
55 m diameter x 55 m high
~330 ft.


Tevatron
Project X
(proposed)
MINOS - NOvA
BooNE
LBNE
(proposed)
Main Injector

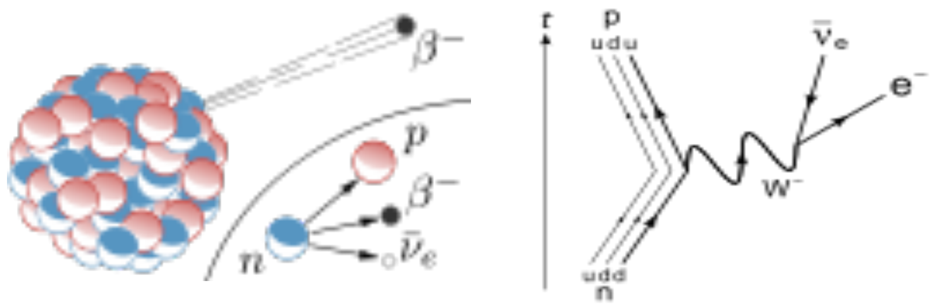
Summary

- Experiments to study nature's tiniest particles require tools of unprecedented scale.
- By producing neutrinos at an accelerator we are able to systematically study the properties of the neutrinos, in particular the behavior of the neutrino versus anti-neutrino.
- These experiments might possibly lead us to uncover one of the most compelling questions about our universe.

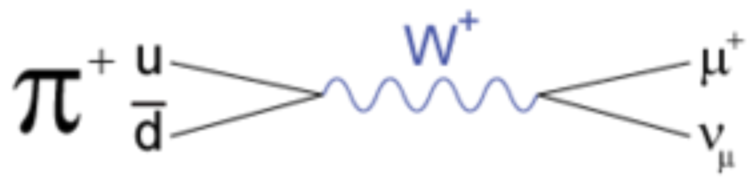
Thank you

Backup Material

Neutrino Production



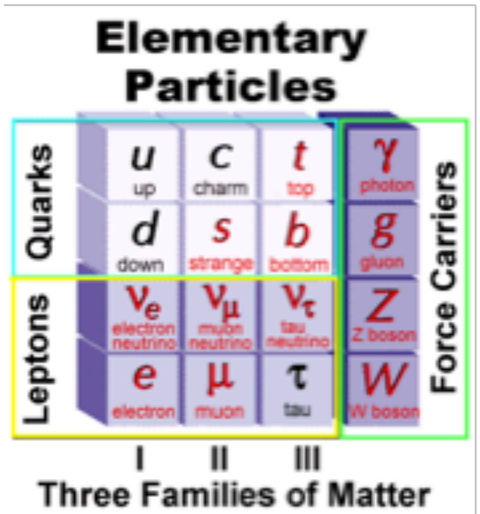
Radioactive b-decay

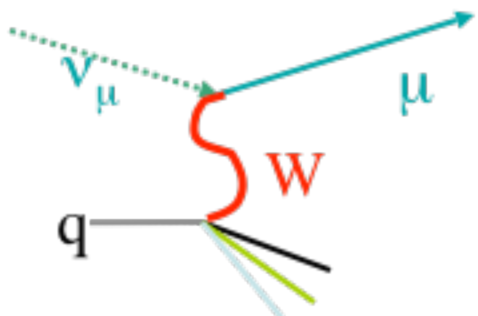


$$D_s^+ \rightarrow \tau + \nu_\tau$$
$$\downarrow$$
$$\mu + \nu_\mu + \nu_\tau$$

Neutrinos are produced in the weak interaction Typically from the decay of radioactive nuclei, pion and other sub-atomic particles, from both natural and man made sources….

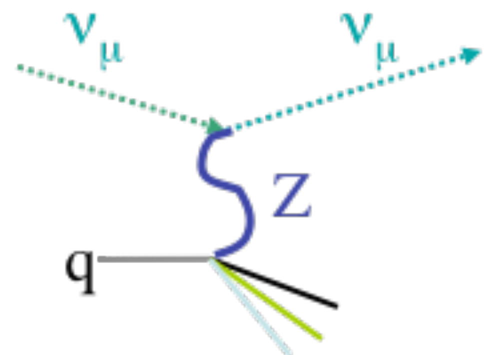
Neutrino Flavors & Interactions





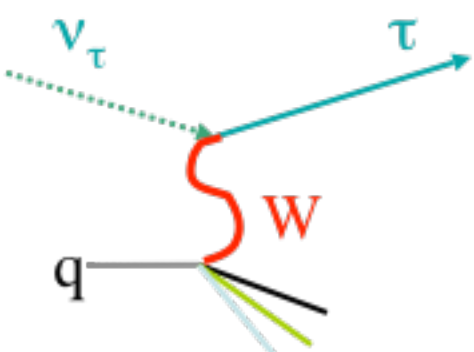
$\nu_\mu + N \rightarrow \mu^- + X$

Charged current



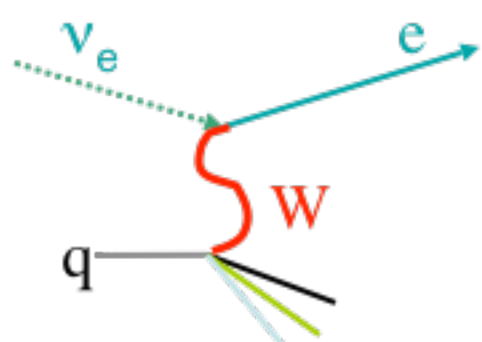
$\nu_\mu + N \rightarrow \nu_\mu + X$

Neutral current



$\nu_\tau + N \rightarrow \tau^- + X$

Tau Charged current



$\nu_e + N \rightarrow e^- + X$

Electron Charged current

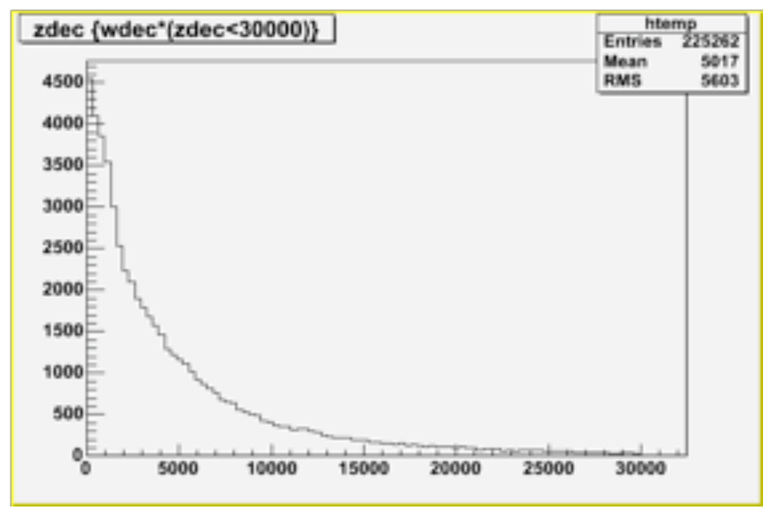
Neutrinos come from π decay

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

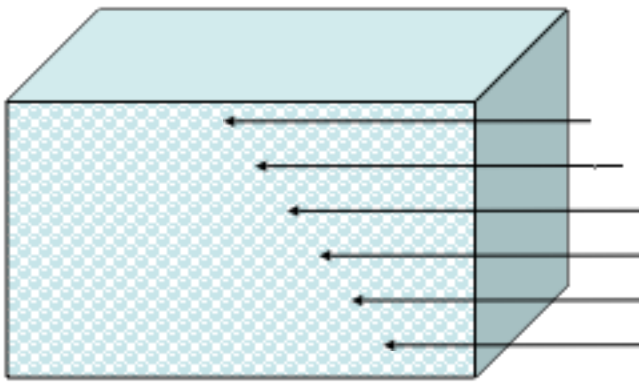
$$\tau_\pi = 2.6 \times 10^{-8} \text{ sec}$$

The average distance, d, traveled by an unstable, relativistic particle before it decays is given by $d = \gamma c \tau$, where $\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$ and c is the speed of light

For a 10 GeV π,
$\gamma \sim 27$, and $d \sim 220$ m



For a beam of neutrinos ……



~6× 10^{9} nuclei in a 1000 tons of iron

# of ν interactions = $\Phi \times \sigma/n \times N_n$

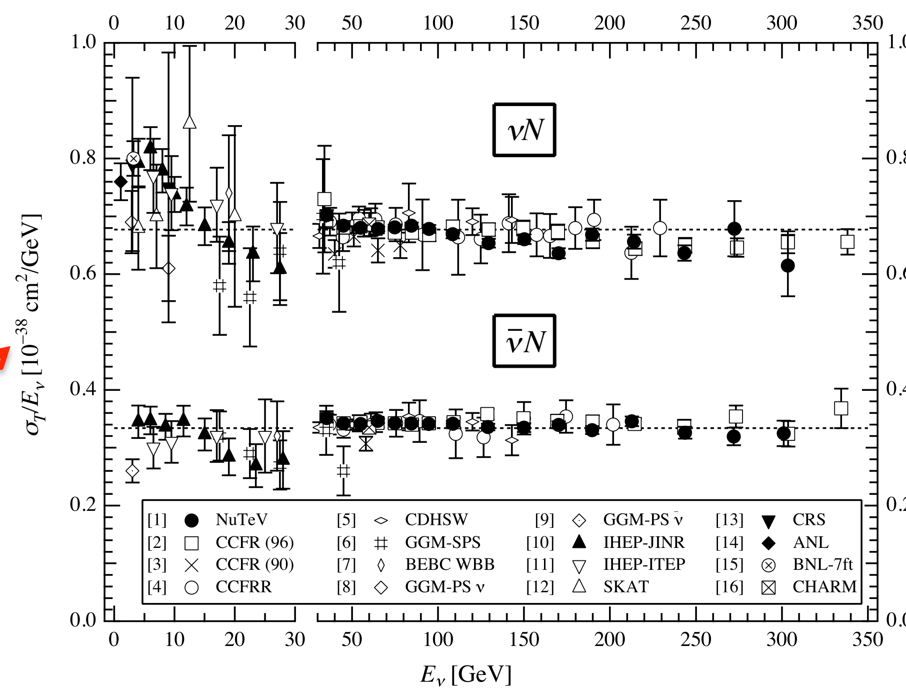
Φ = neutrinos/unit area

σ/n = cross section per nucleon (probability of interaction)

N_n = number of nuclei in the target

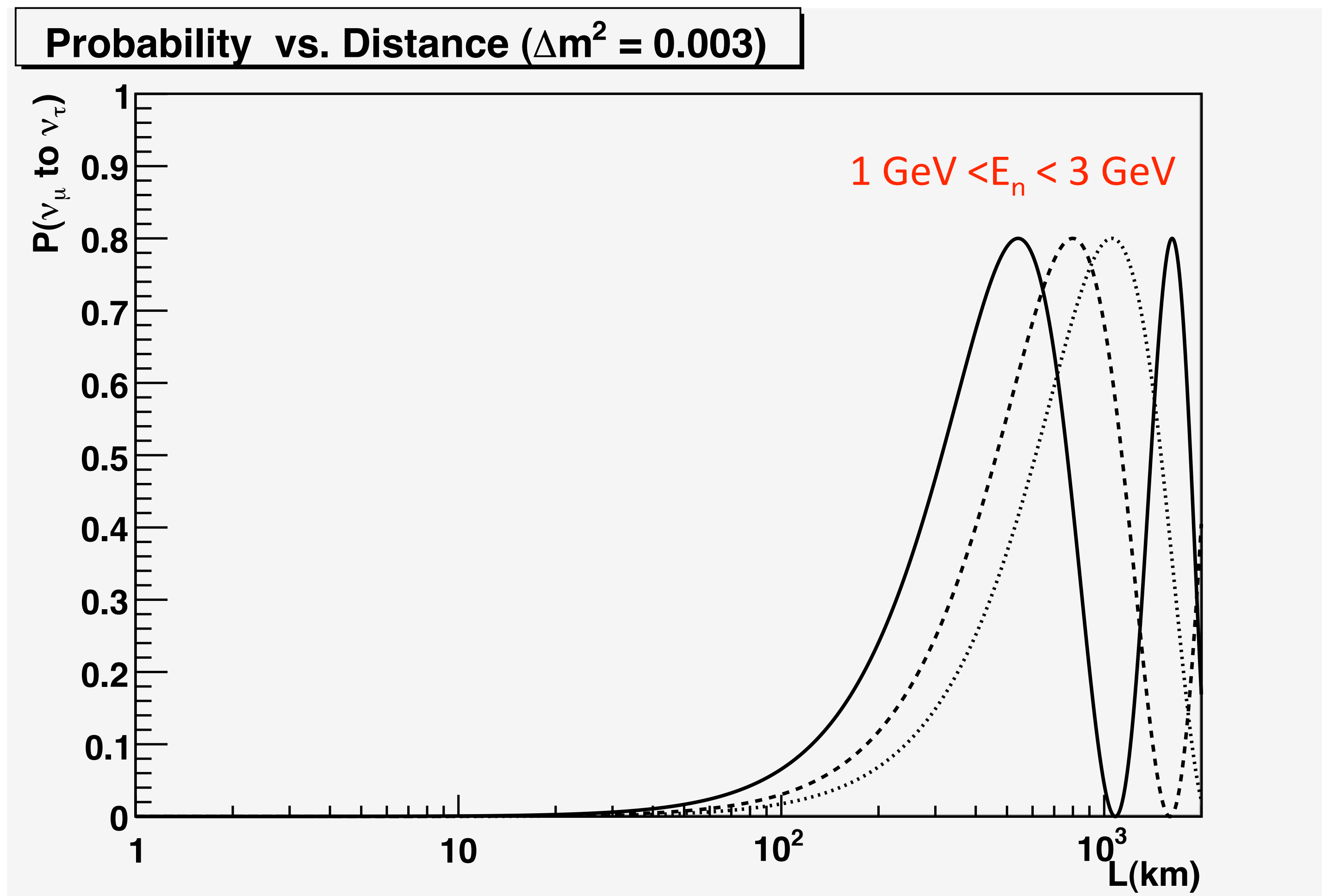
Recall our flux is
~10^{11} neutrinos/m^{2}/10^{14} protons

10^{-38}



It takes a lot of neutrinos (protons), and target material to compensate for the very small cross section

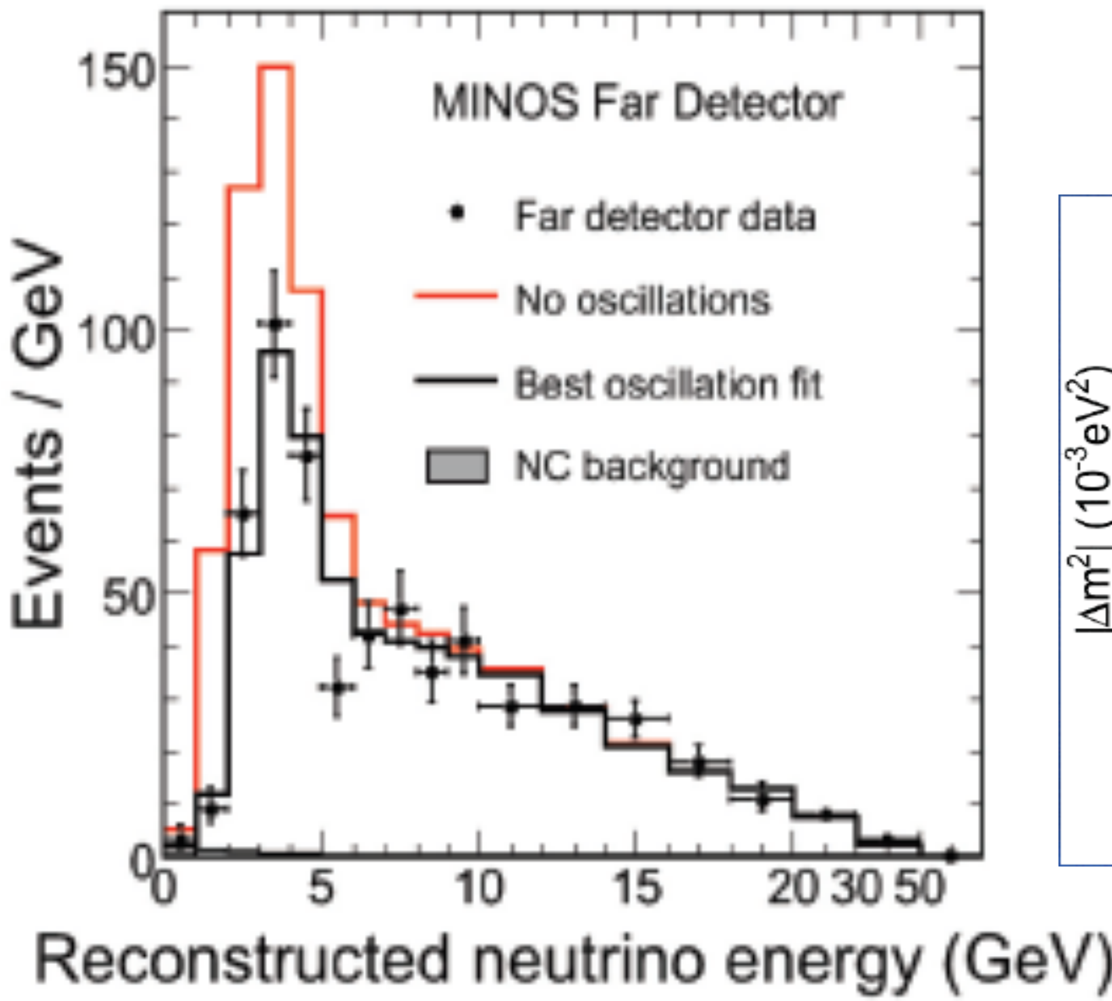
Why do we go over a "long baseline"?

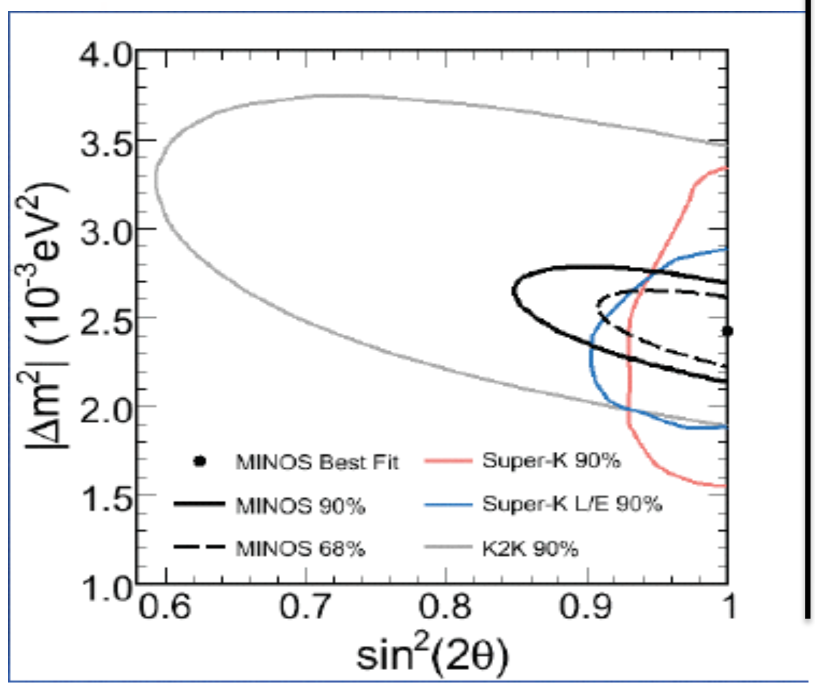


$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23}\ L/E)$$

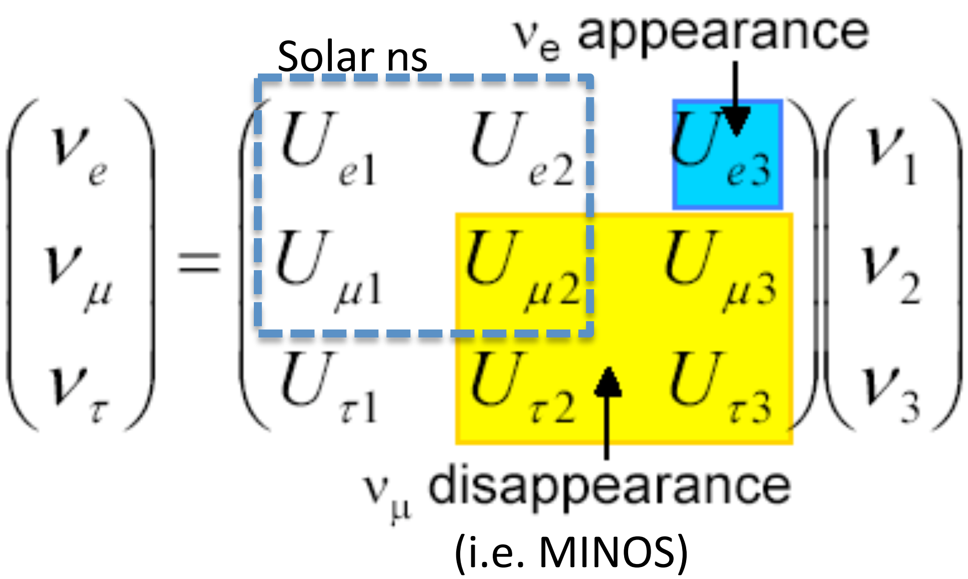
$$P(\nu_\mu \rightarrow \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23}\ L/E)$$

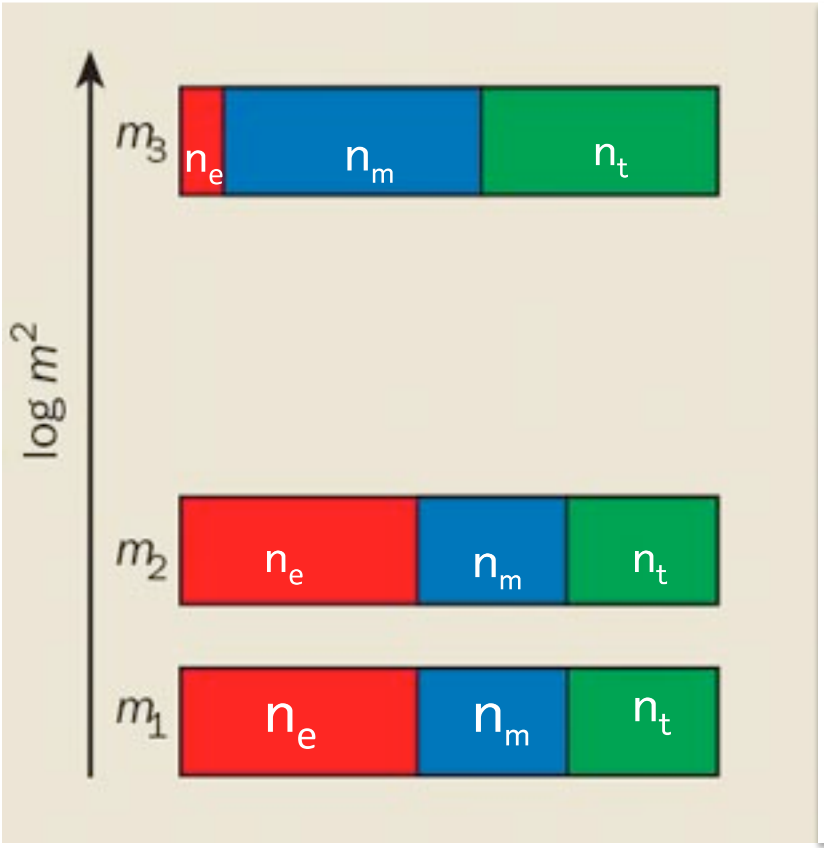
No oscillations – expect ~ 3 events/day; observe ~ 1- 2





Three neutrino mass and mixing





$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

To make matters more complicated, we don’t know the ordering of the neutrino mass states

This is known as the **“neutrino mass hierarchy”** question

Consider the Probability of

$$\nu_\mu \rightarrow \nu_e$$

For neutrinos travelling in a vacuum :

$$P(\nu_\mu \rightarrow \nu_e)_{vacuum} = f(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{12}, (sign)\Delta m^2_{23}, E_\nu, L)$$

If CP is conserved :

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

For neutrinos travelling through matter :

$$P(\nu_\mu \rightarrow \nu_e)_{matter} = f(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m^2_{12}, (sign)\Delta m^2_{23}, E_\nu, L, V_{matter})$$

$$V_{matter} = f(electron\ number\ density)$$

Why does it *matter*?

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

~ fake CP violation

If $m_3 > m_2$ (Normal mass hierarchy)

$$P(\nu_\mu \to \nu_e)_{matter} > P(\nu_\mu \to \nu_e)_{vacuum}$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e)_{matter} < P(\bar{\nu}_\mu \to \bar{\nu}_e)_{vacuum}$$

Neutrinos are enhanced and anti-neutrinos are suppressed

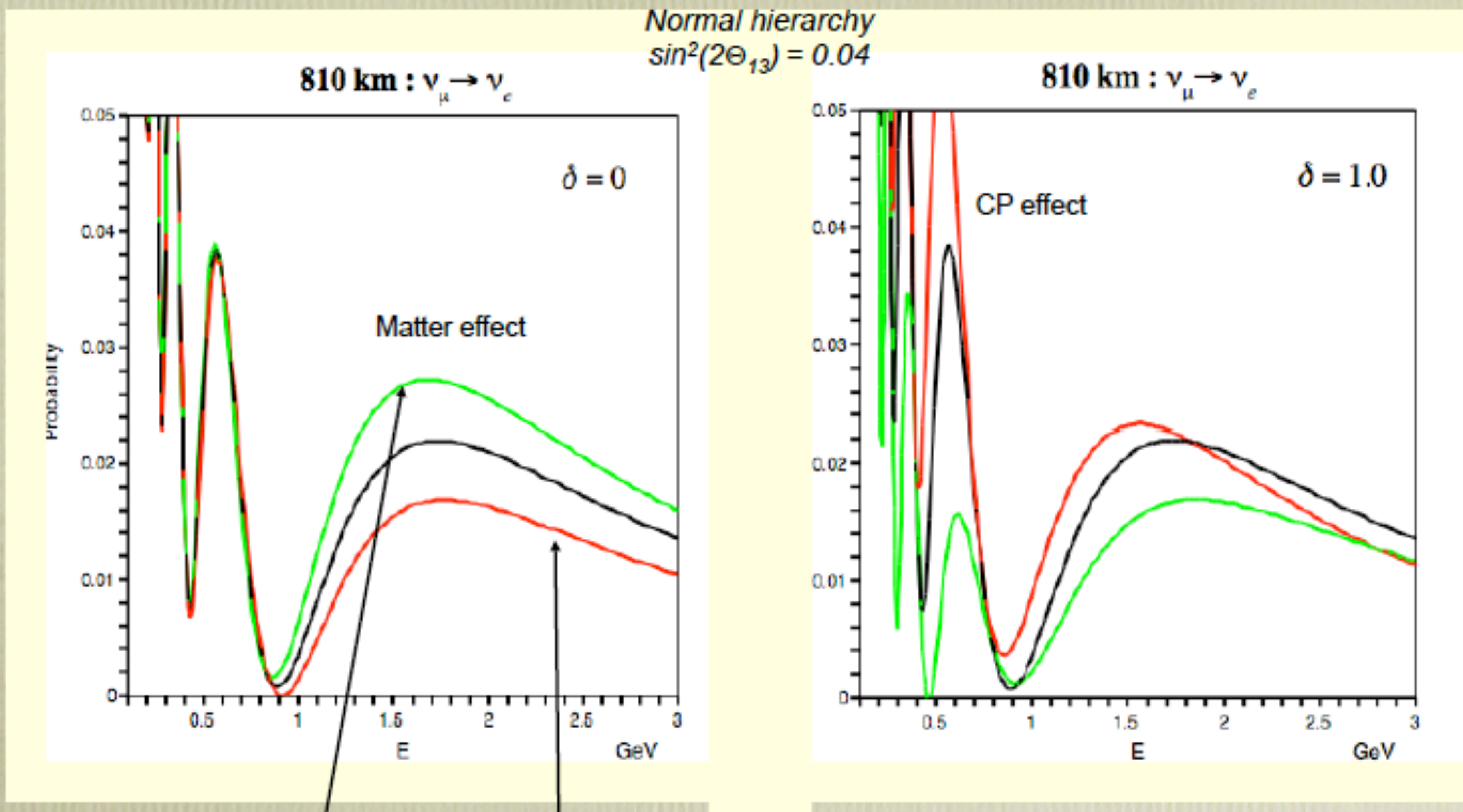
If $m_3 < m_2$ (Inverted mass hierarchy)

$$P(\nu_\mu \to \nu_e)_{matter} < P(\nu_\mu \to \nu_e)_{vacuum}$$
$$P(\bar{\nu}_\mu \to \bar{\nu}_e)_{matter} > P(\bar{\nu}_\mu \to \bar{\nu}_e)_{vacuum}$$

Anti-neutrinos are enhanced and neutrinos are suppressed

We can design experiments to try and tell these different situations apart!

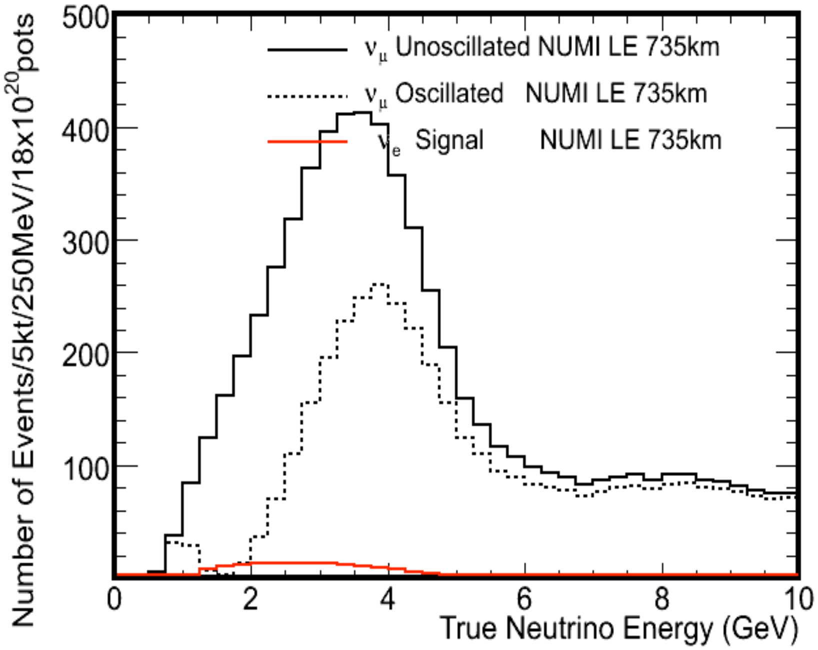
Matter Effects and CP violation



ν's and and anti-ν's have different oscillation probabilities

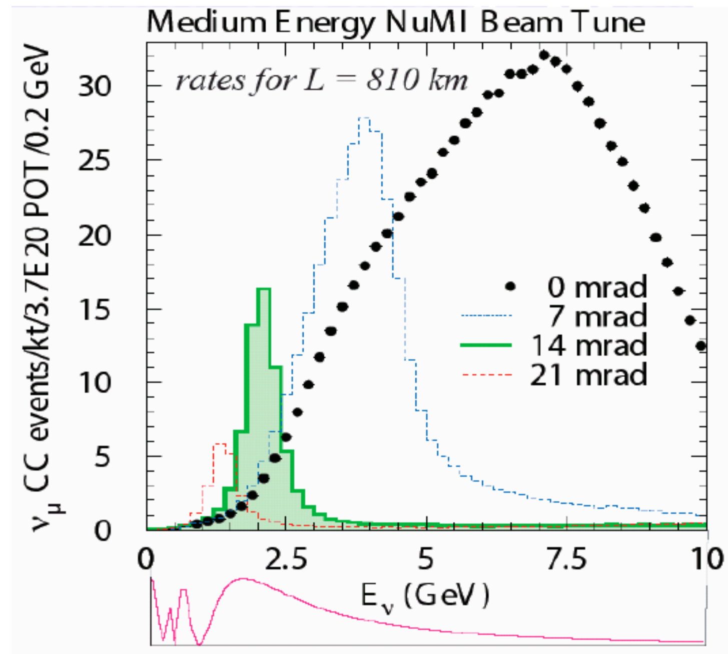
Optimizing an experimental configuration

MINOS



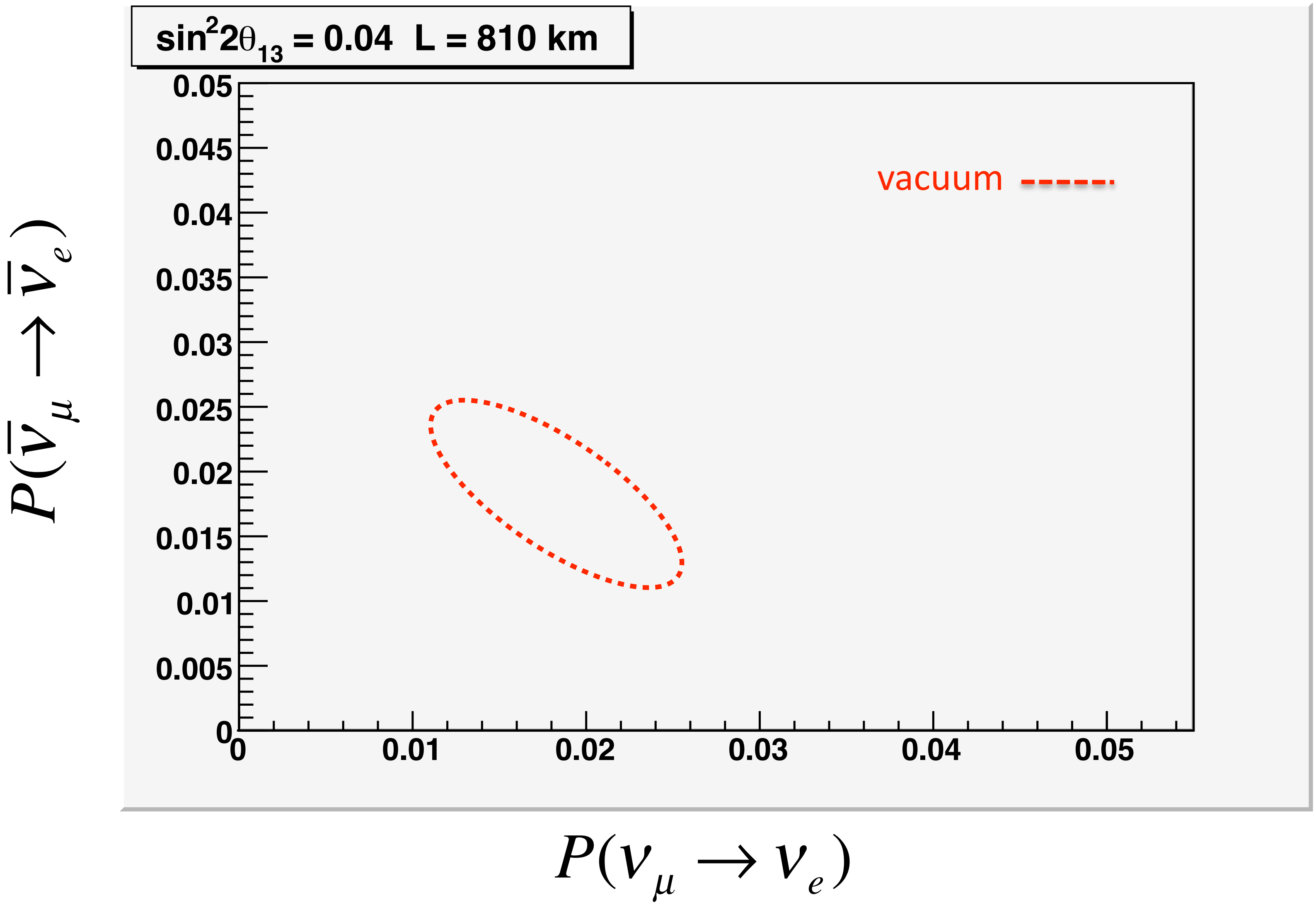
Must be able to detect muon neutrinos

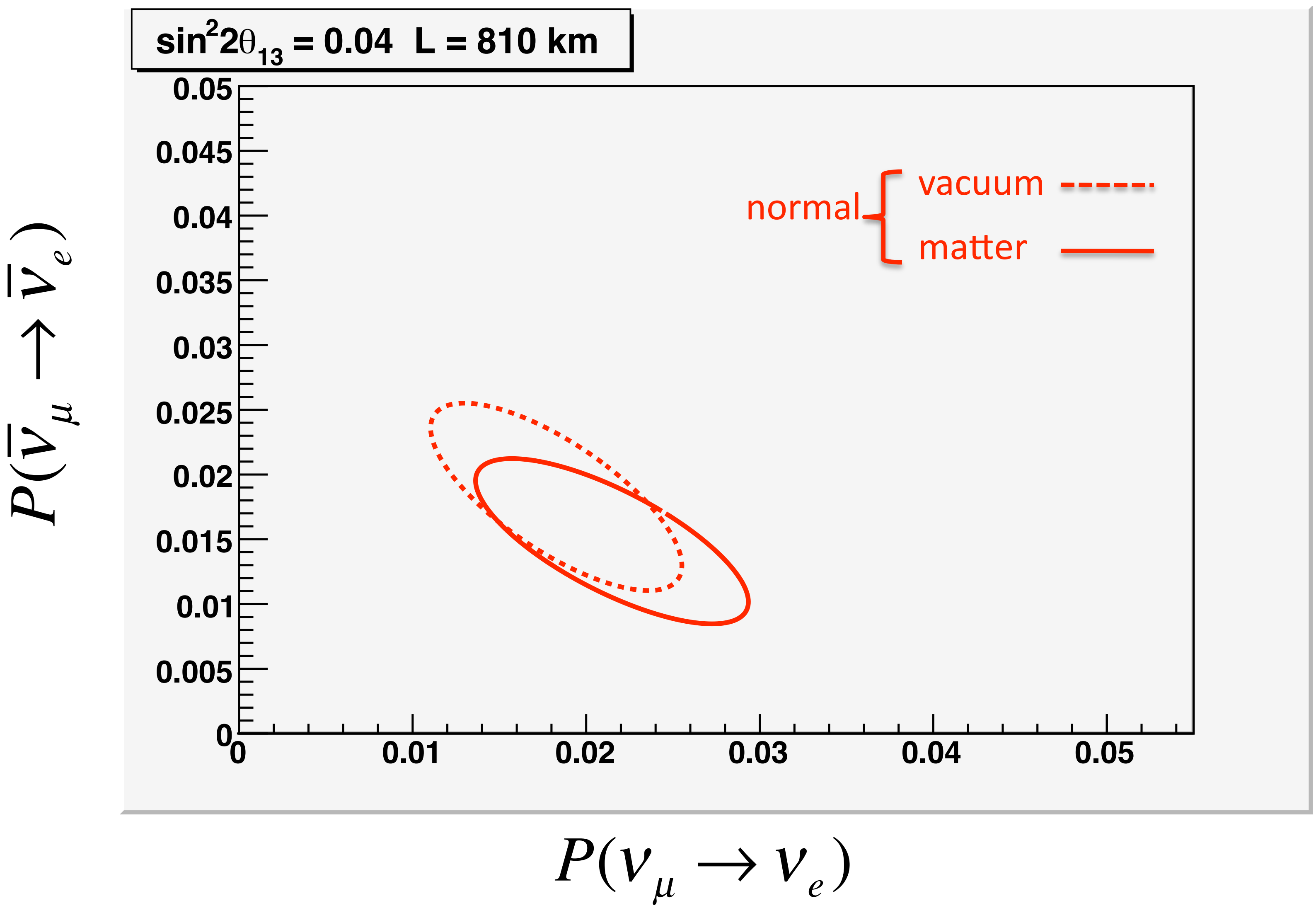
NOvA



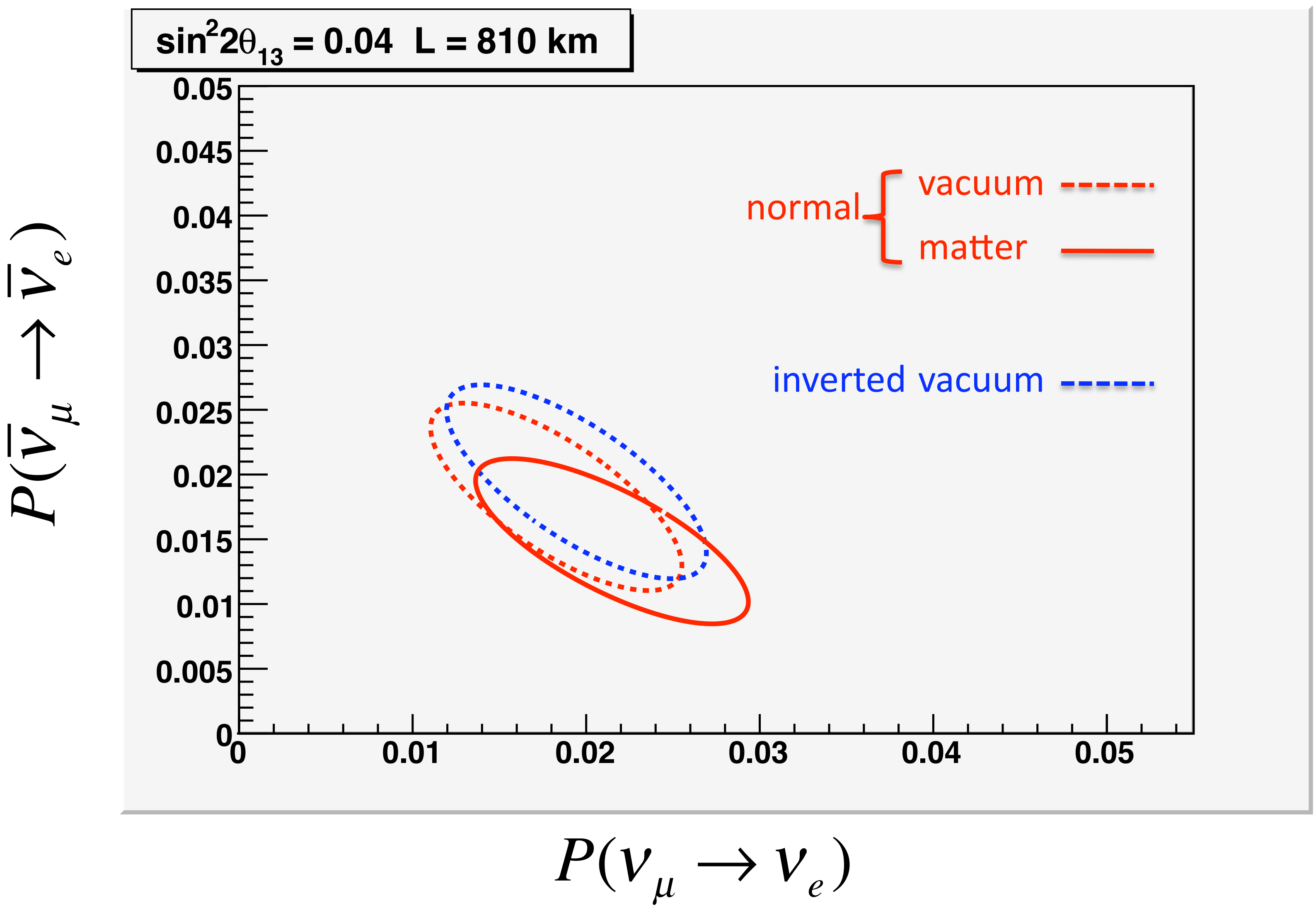
Must be able to detect electron neutrinos

Neutrino vs. anti-neutrino bi-probability plots

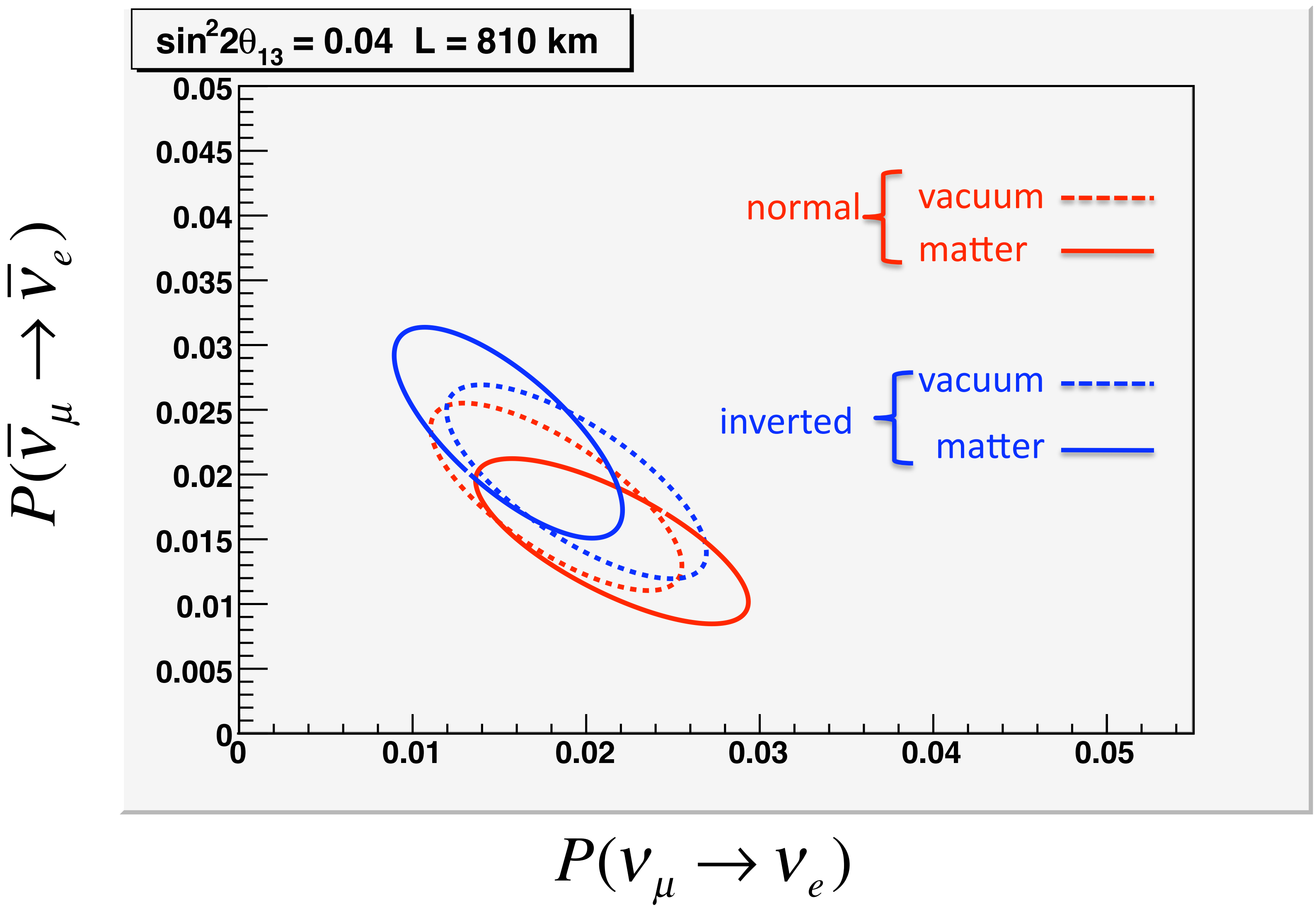




sin²2θ₁₃ = 0.04 L = 810 km
normal
vacuum
matter
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0.01
0.02
0.03
0.04
0.05
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
$P(\nu_\mu \rightarrow \nu_e)$

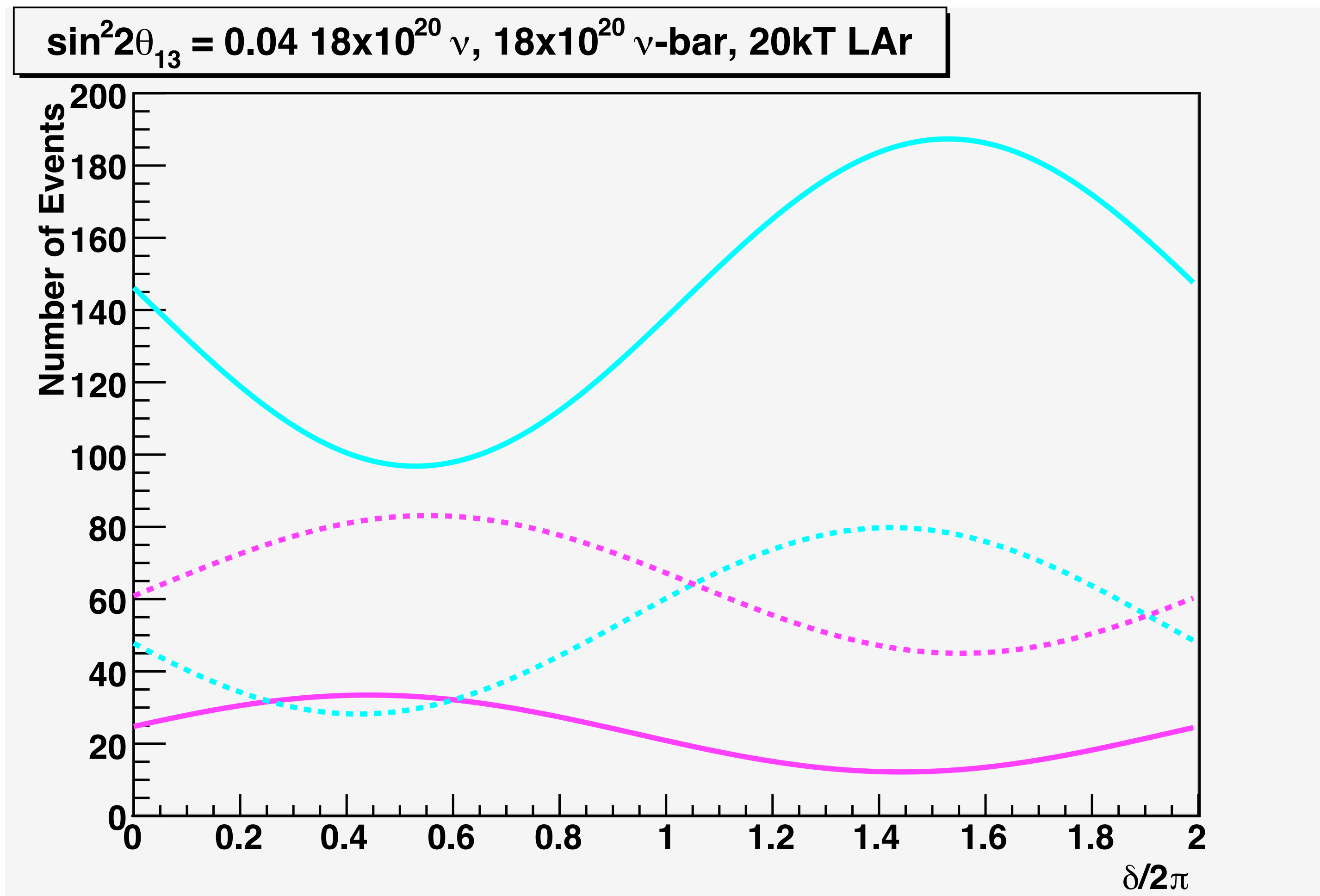


sin²2θ₁₃ = 0.04 L = 810 km
normal
vacuum
matter
inverted vacuum
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.01
0.02
0.03
0.04
0.05
$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
$P(\nu_\mu \rightarrow \nu_e)$

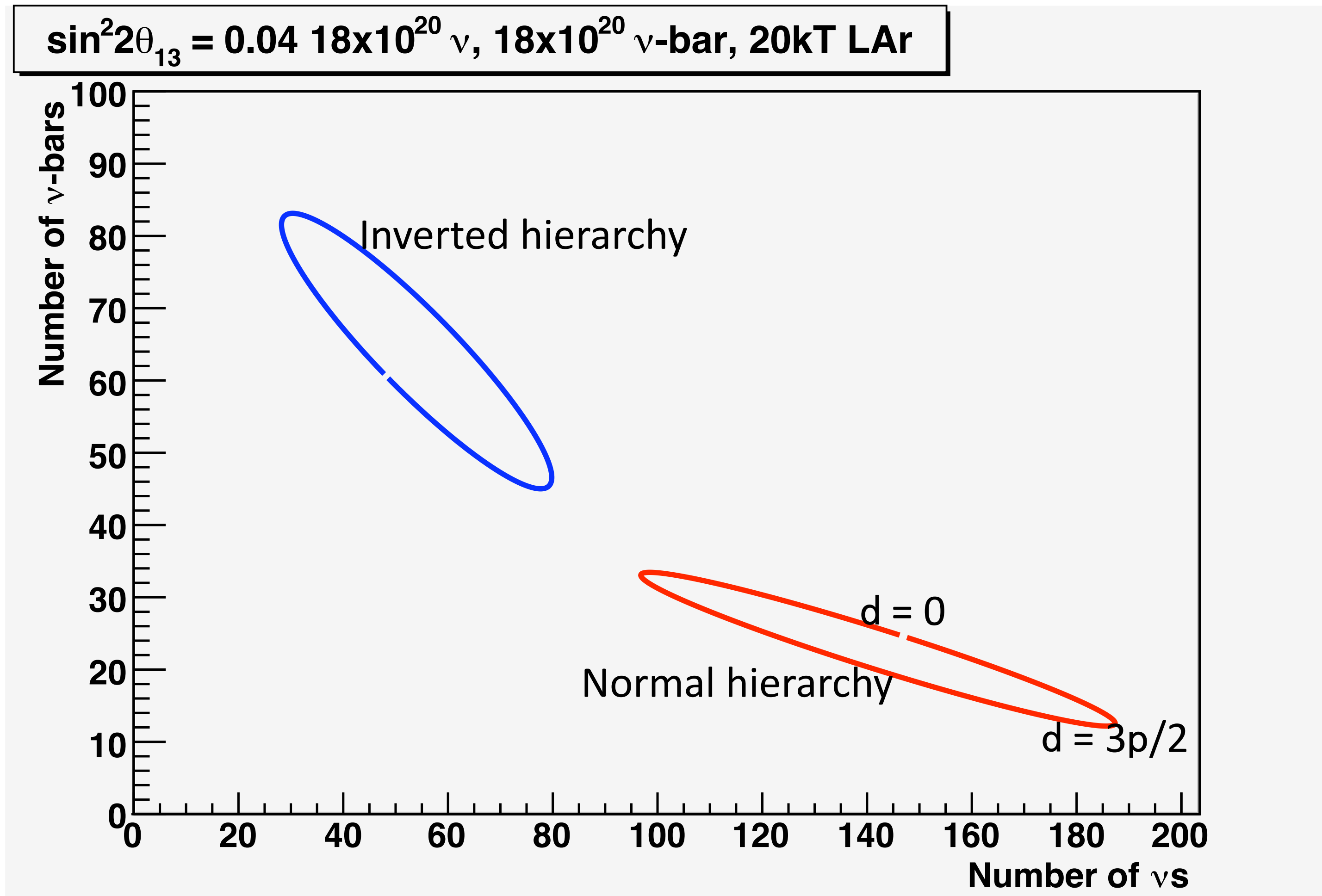


sin^{2}2θ_{13} = 0.04 L = 810 km
normal
vacuum
matter
inverted
vacuum
matter
0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
0.01
0.02
0.03
0.04
0.05
$P(\bar{\nu}_\mu \to \bar{\nu}_e)$
$P(\nu_\mu \to \nu_e)$

Why so large?



sin²2θ₁₃ = 0.04 18x10²⁰ ν, 18x10²⁰ ν-bar, 20kT LAr
Number of Events
200
180
160
140
120
100
80
60
40
20
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
δ/2π



sin²2θ13 = 0.04 18x10^20 ν, 18x10^20 ν-bar, 20kT LAr
Number of ν-bars
Number of νs
Inverted hierarchy
Normal hierarchy
d = 0
d = 3p/2
100
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
160
180
200