Accelerator Based Neutrino Experiments

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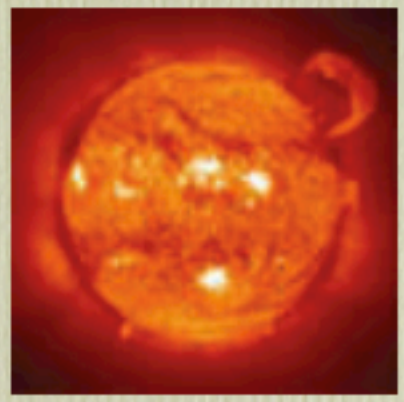
Topics

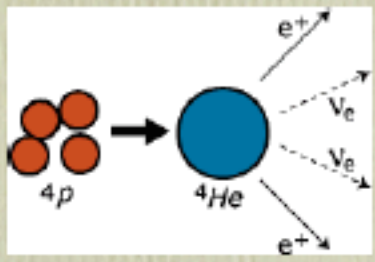
- Neutrino Properties
  - Neutrino Flavor Oscillations
  - Mass and Mixing
  - Mass hierarchy and CP-violation
- Neutrino Oscillation Experiments using Accelerators

Neutrinos are abundant in our universe

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

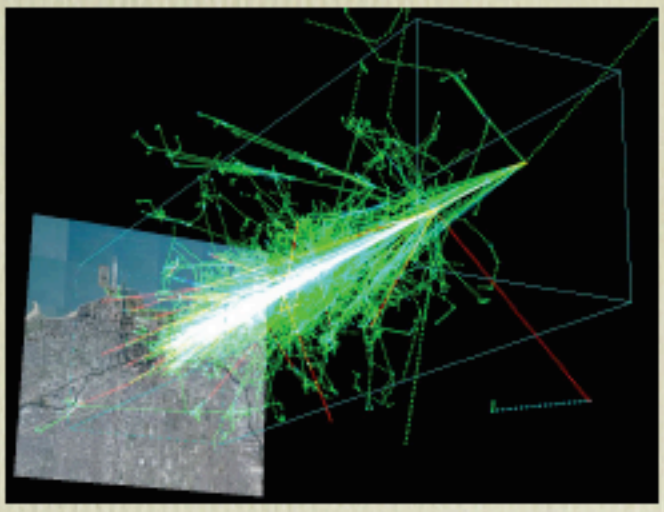
Our Sun is powered by nuclear reactions



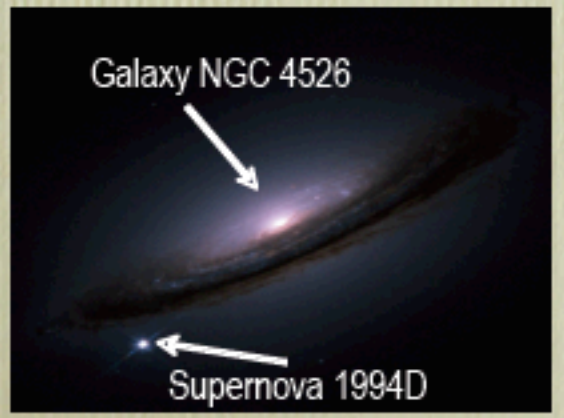


(100 billion per sq cm every second)

Cosmic ray interactions

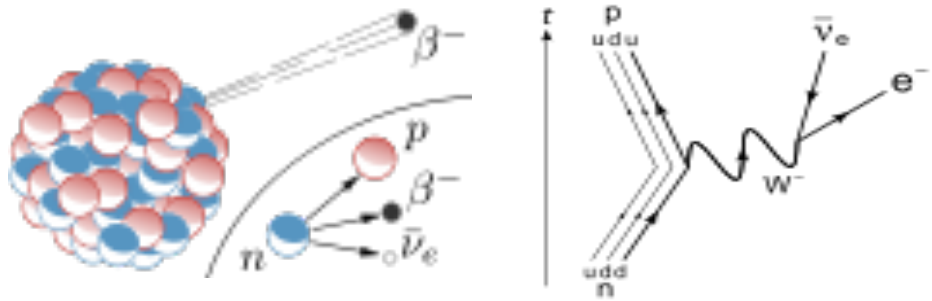


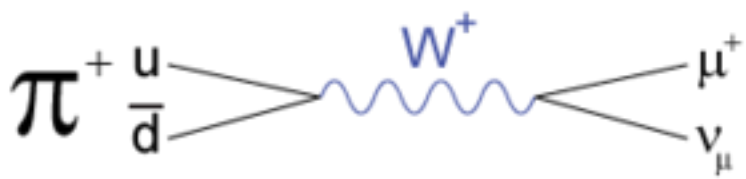
Supernovae (99% of energy is emitted as neutrinos)



Nuclear Power Plants

Neutrino Production



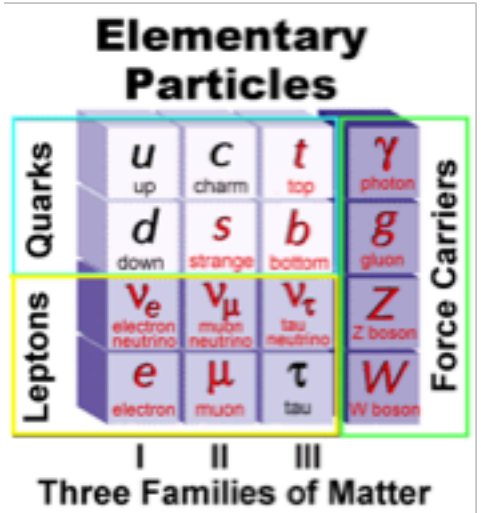


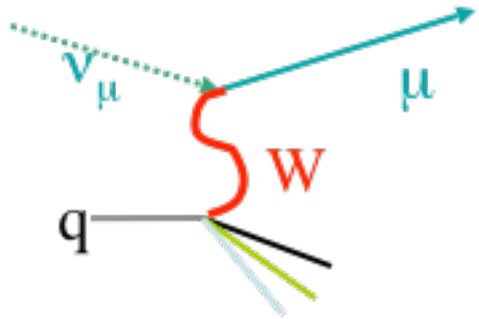
$$D_s^+ \rightarrow \tau + \nu_\tau$$

$$\downarrow$$

$$\mu + \nu_\mu + \nu_\tau$$

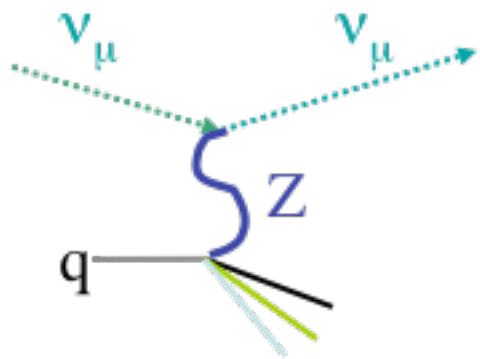
Neutrino Flavors & Interactions





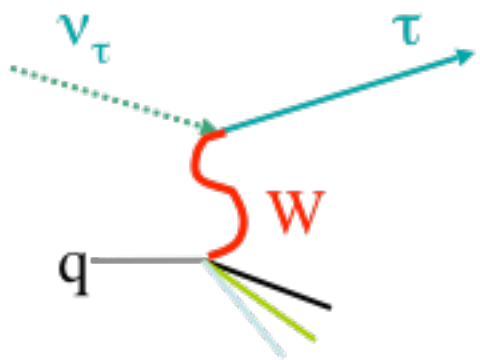
$$\nu_\mu + N \rightarrow \mu^- + X$$

Charged current



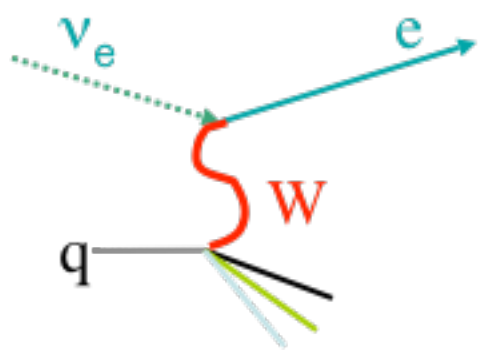
$$\nu_\mu + N \rightarrow \nu_\mu + X$$

Neutral current



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

Tau Charged current



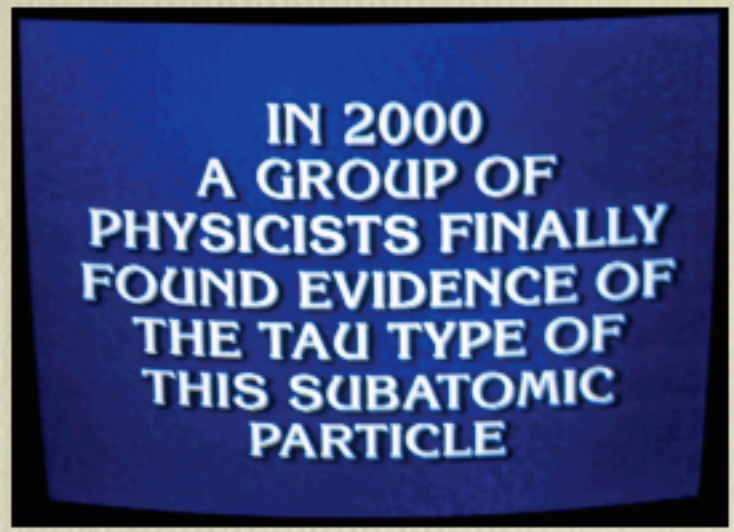
$$\nu_e + N \rightarrow e^- + X$$

Electron Charged current

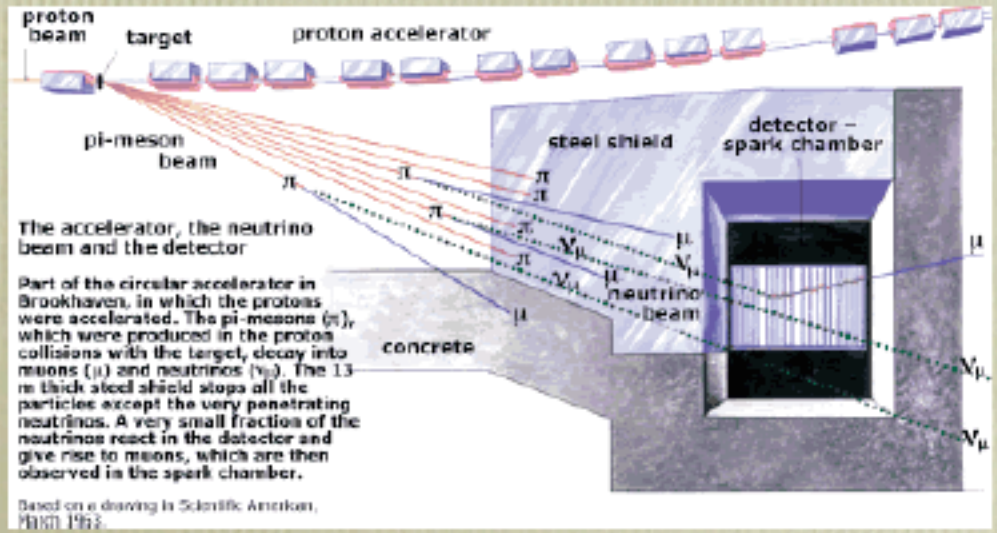
… but difficult to detect

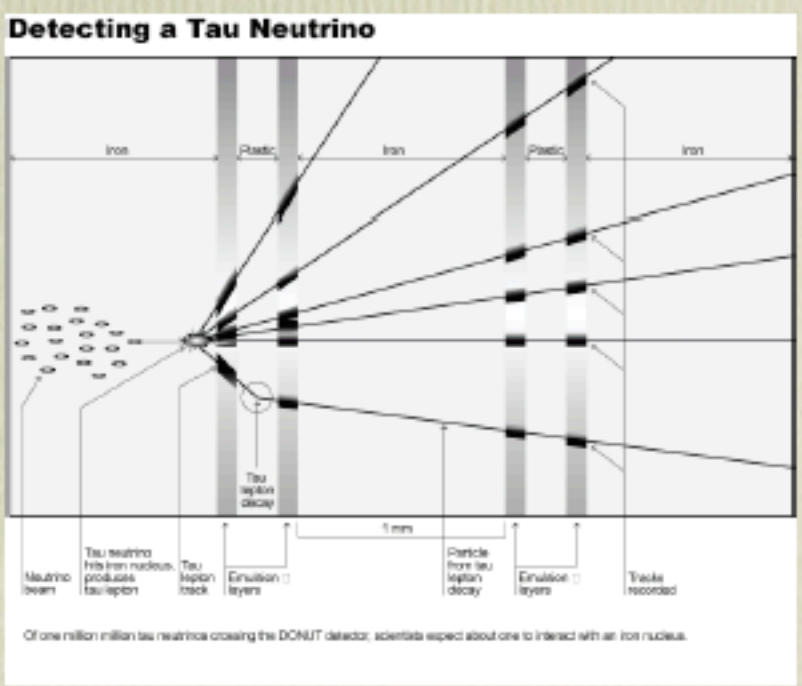
postulated in 1932

1st detected in 1956



2 neutrino hypothesis (-1947) confirmed in 1961





The Solar Neutrino Mystery

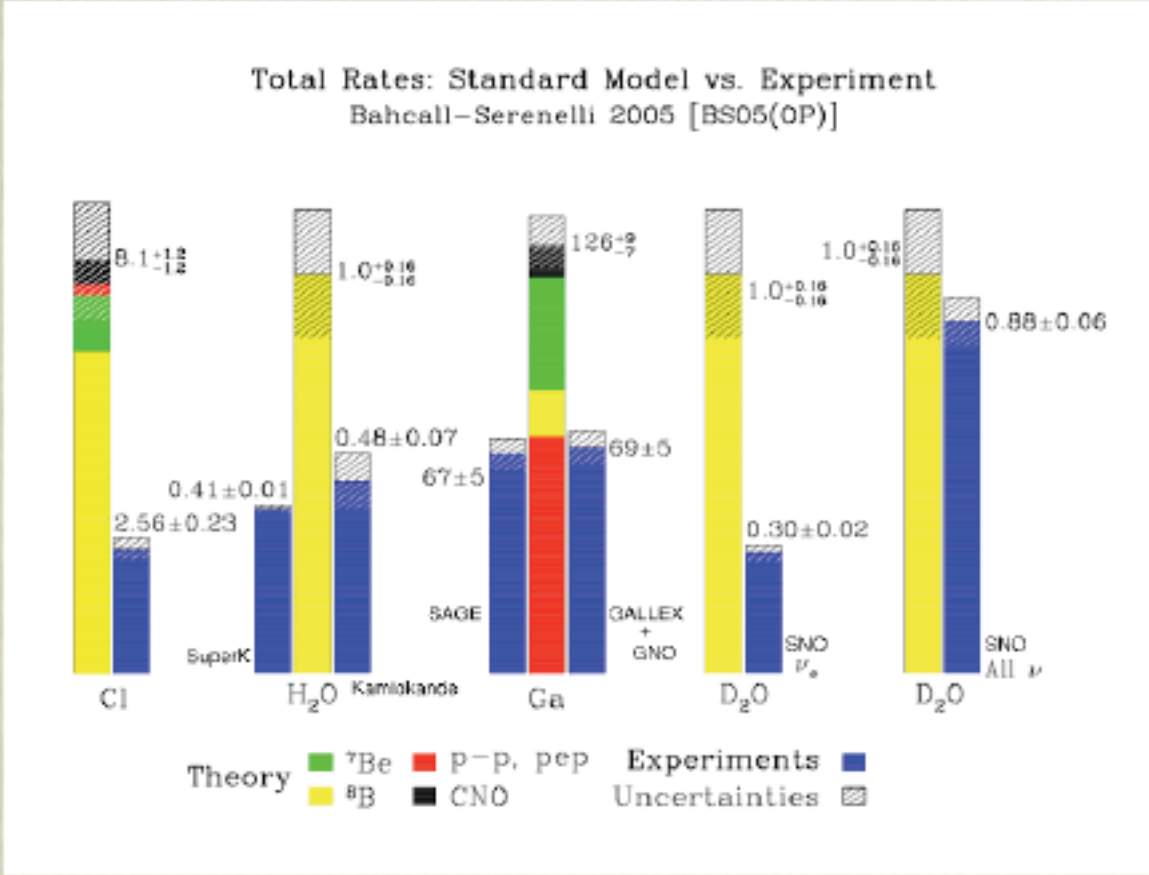
100,000 gallons of perchlorethylene
10^{30} atoms of chlorine

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

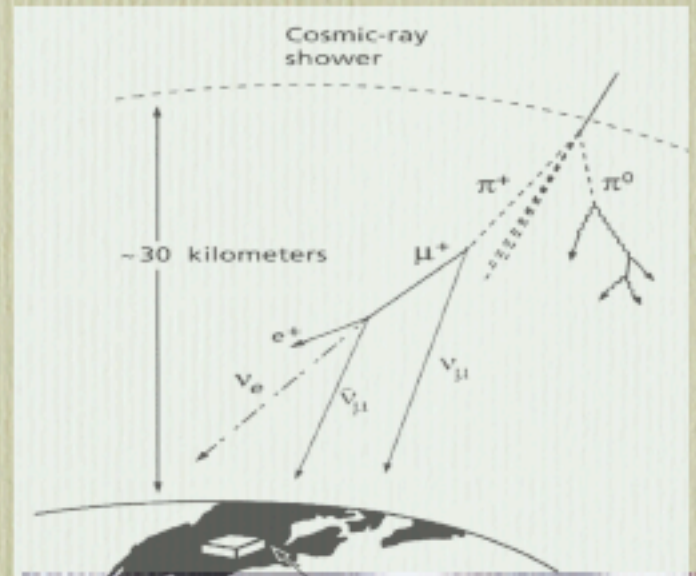
~1970 : detecting solar neutrinos via the inverse β-capture

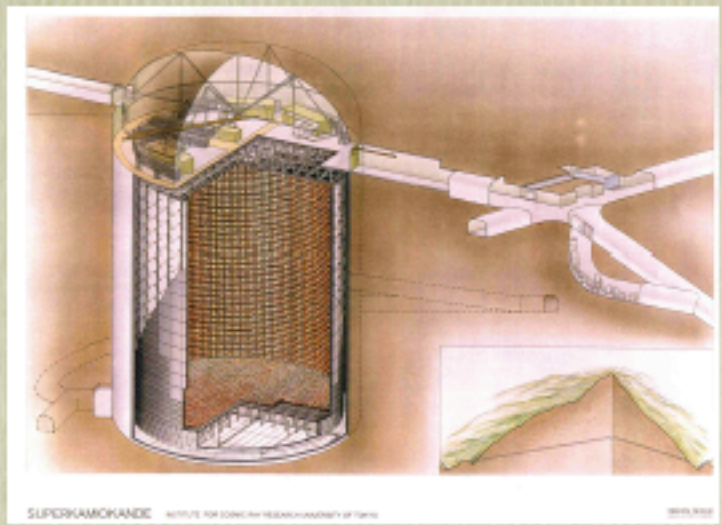
$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar$

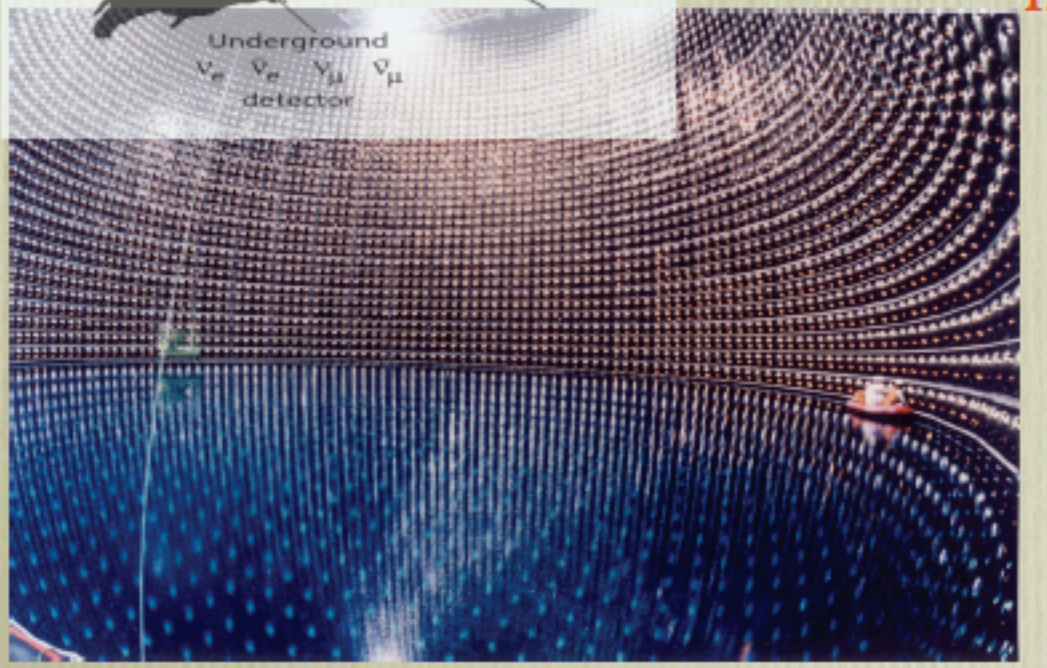
Only about 1/3 of the number expected were observed.



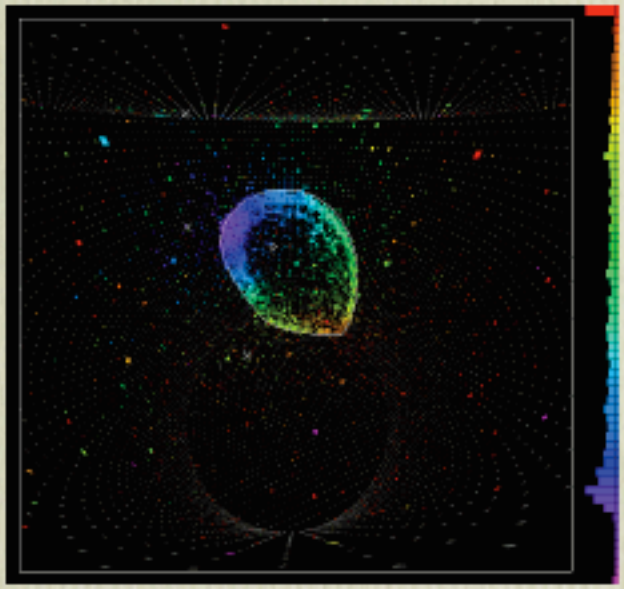
more "missing" neutrinos .....







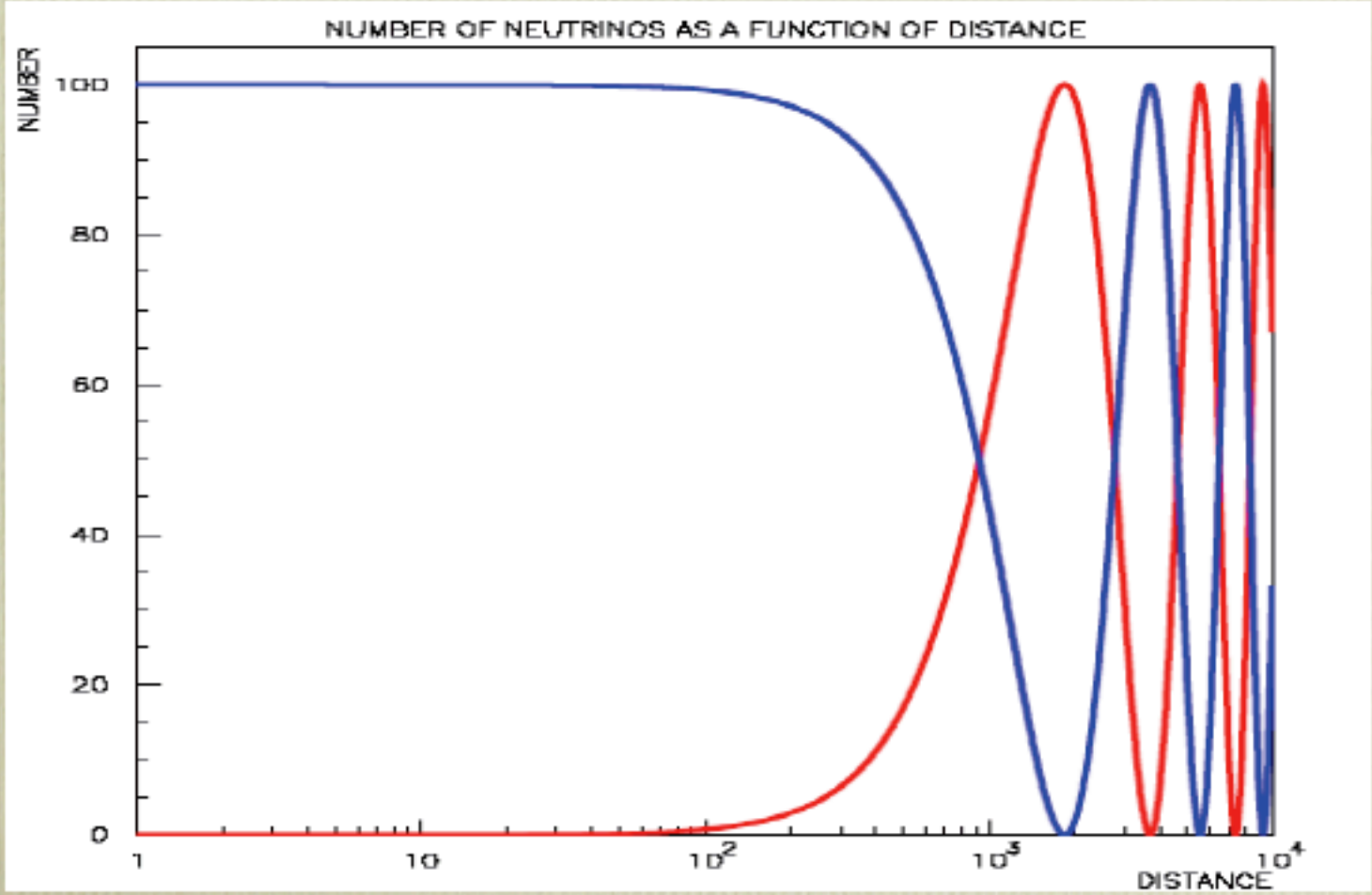
1/2 the predicted # of muon neutrinos are not detected



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 :

$$\Delta m^2_{12} \sim 8x10^{-5} \quad \Delta m^2_{23} \sim 3x10^{-3}$$

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

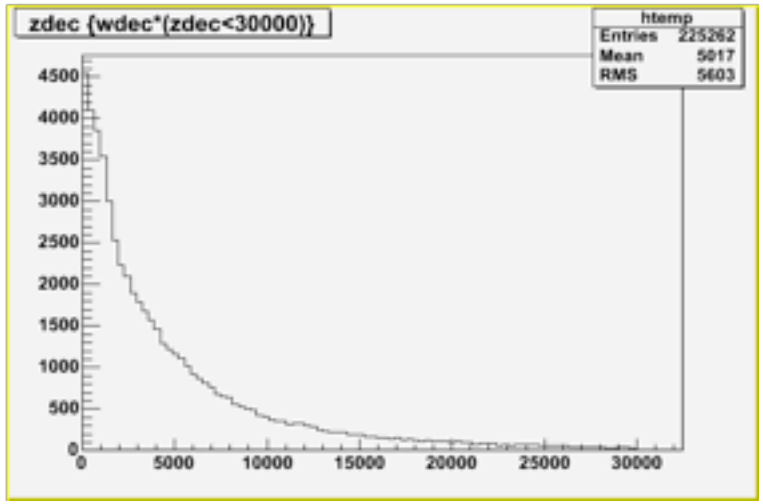
Neutrinos come from π decay

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

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

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

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

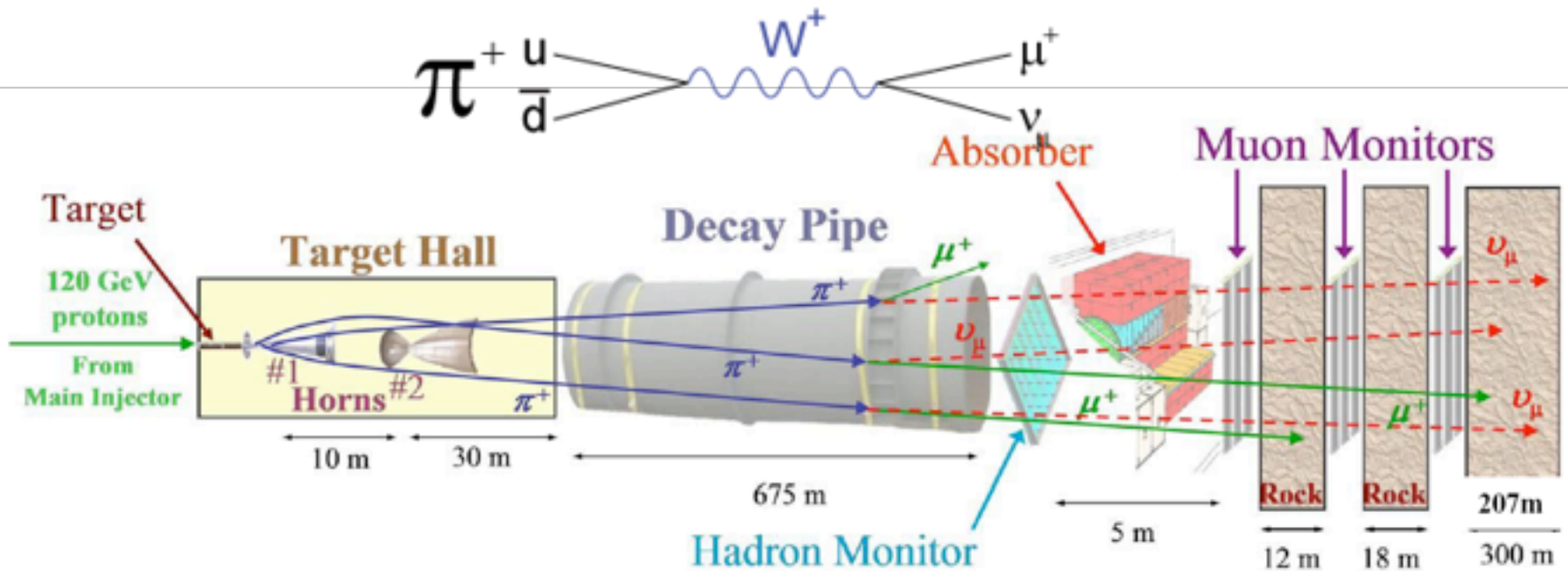


Pions (π) can be made at a proton accelerator :

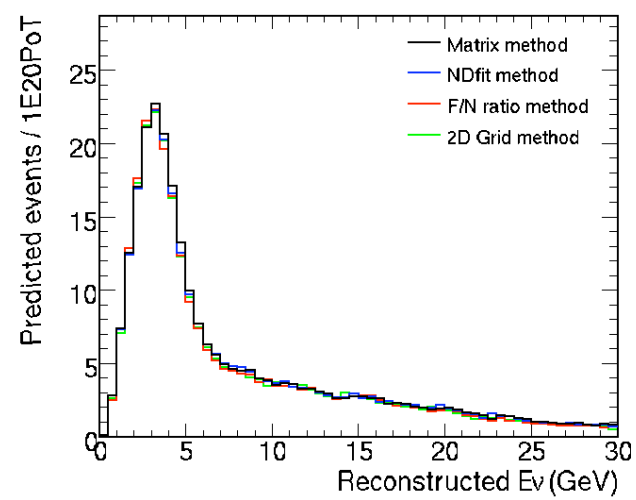
i.e. **Fermilab Main Injector**

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

Ingredients of a Neutrino Beam

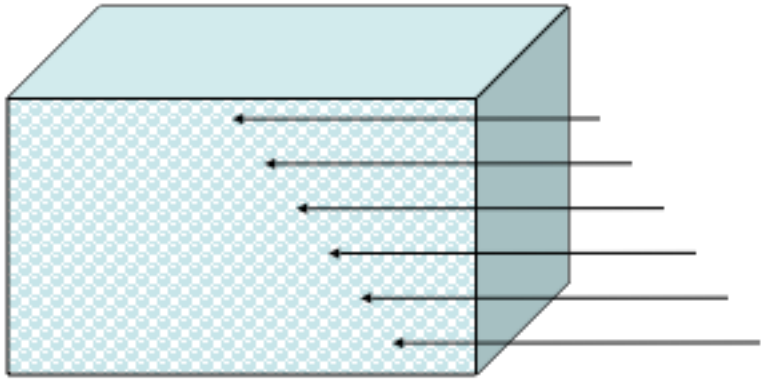


At Fermilab we can produce
~ 10^{11} neutrinos/m^2/10^{14} protons



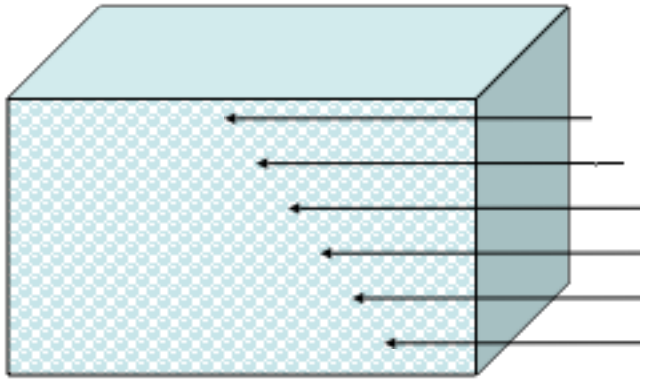
Why is it so difficult to detect neutrinos?

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

For a beam of neutrinos ……



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

$$\# \text{ of } \nu \text{ interactions} = \Phi \times \sigma/n \times N_n$$

Φ = neutrinos/unit area

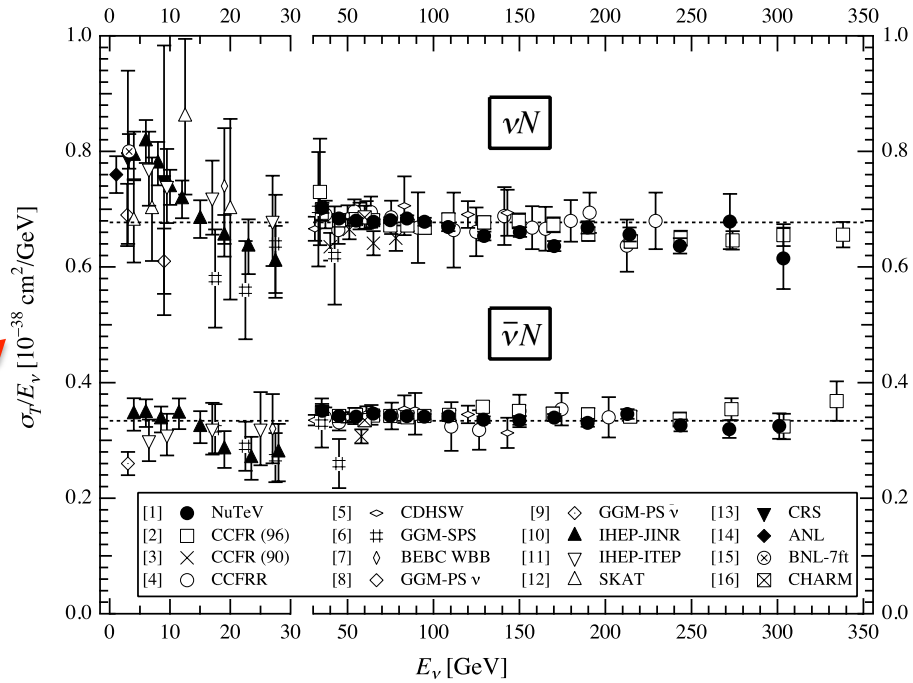
σ/n = cross section per nucleon (probability of interaction)

N_n = number of nuclei in the target

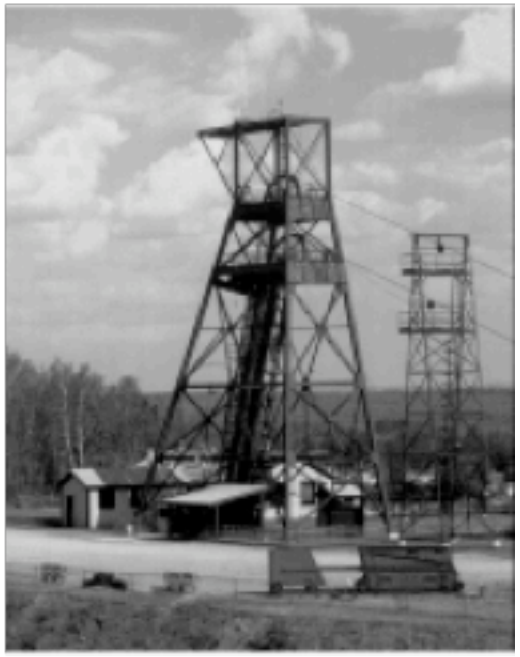
Recall our Φ is
~10^{11} neutrinos/m^2/10^{14} protons

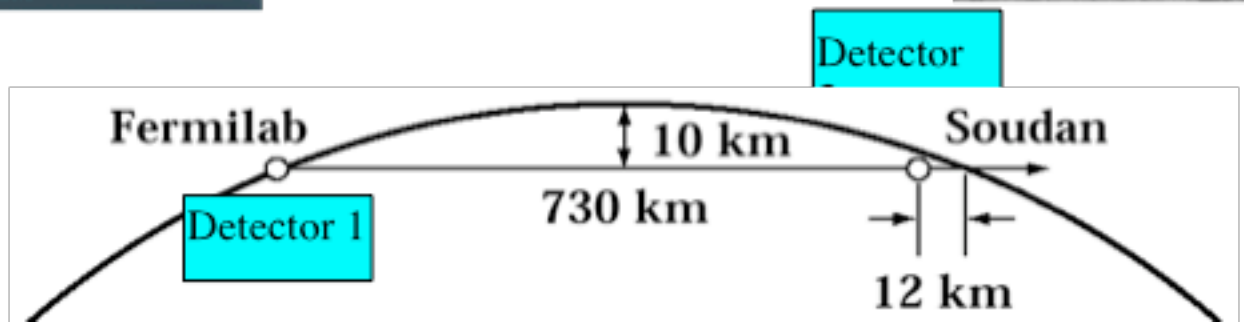
It takes a lot of neutrinos (protons), and target material to compensate for the very small cross section

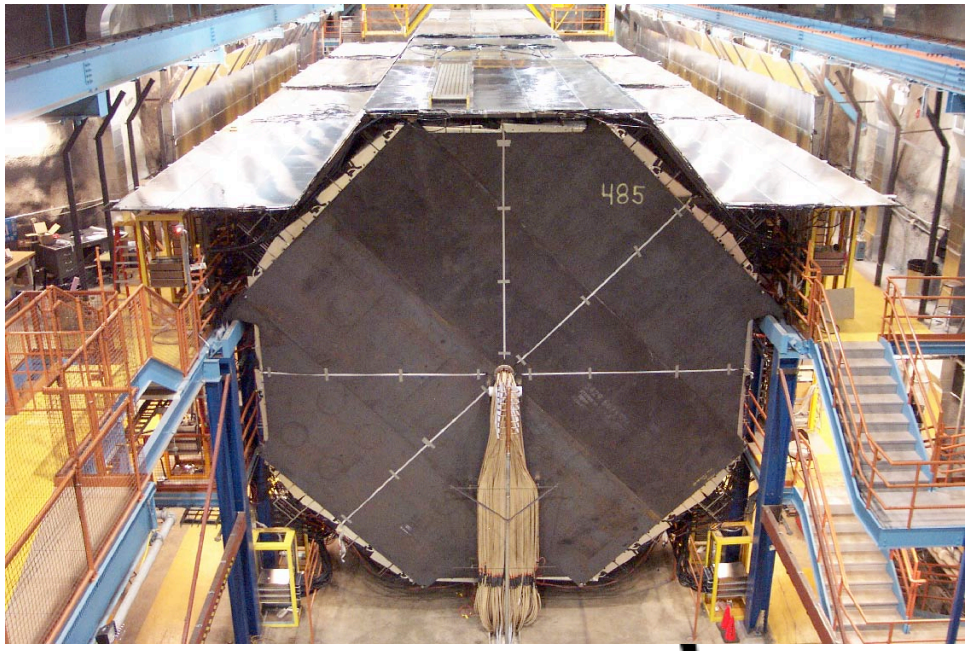
10^{-38}



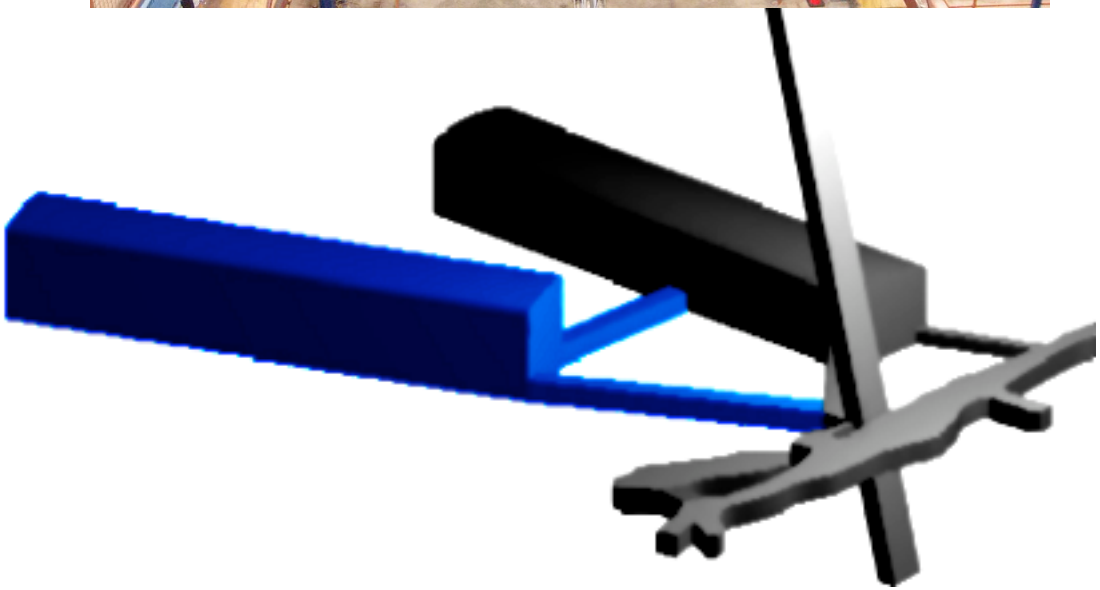
MINOS - Main Injector Neutrino Oscillation Search (Minnesota-Illinois)



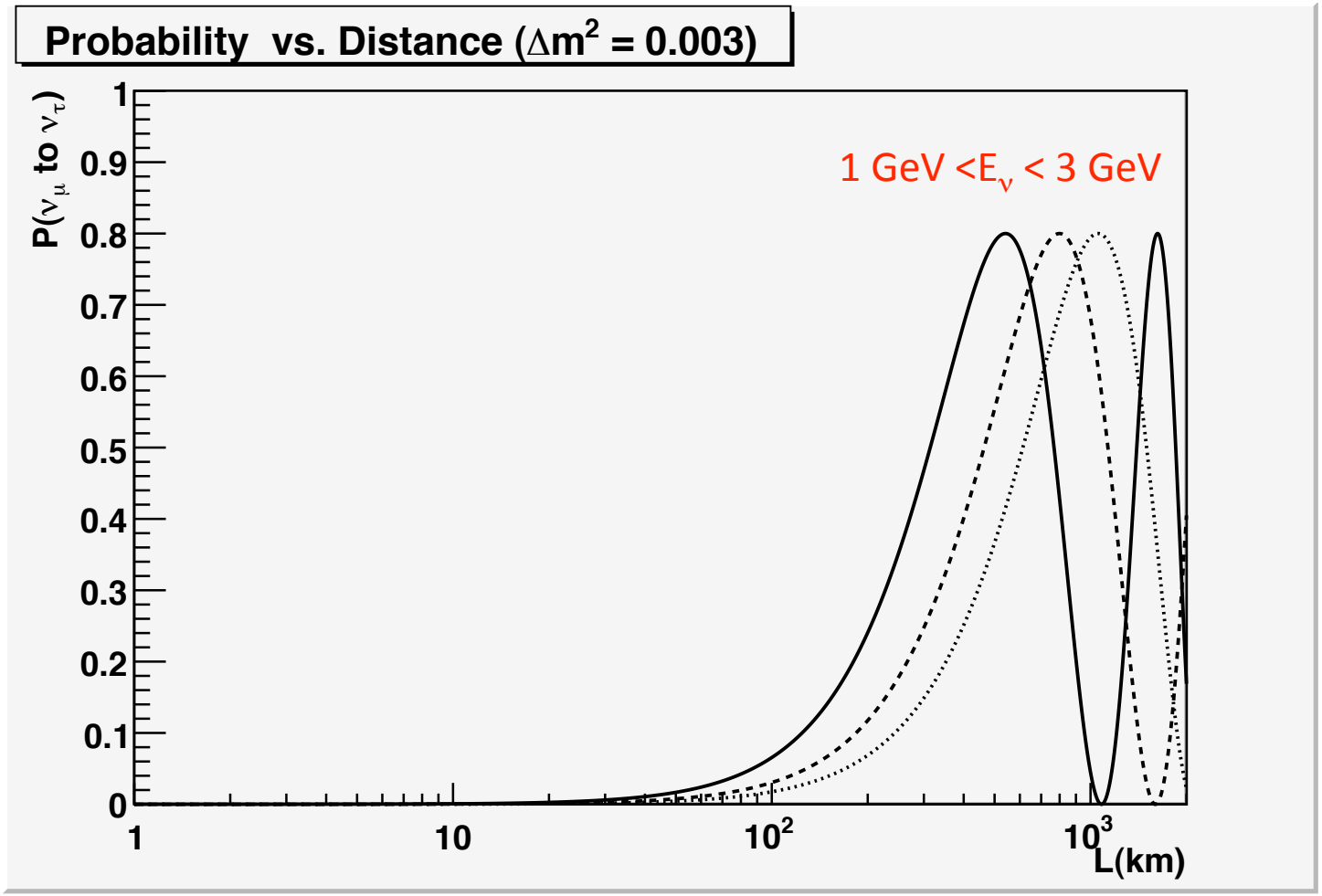



485

Charles W. Morgan



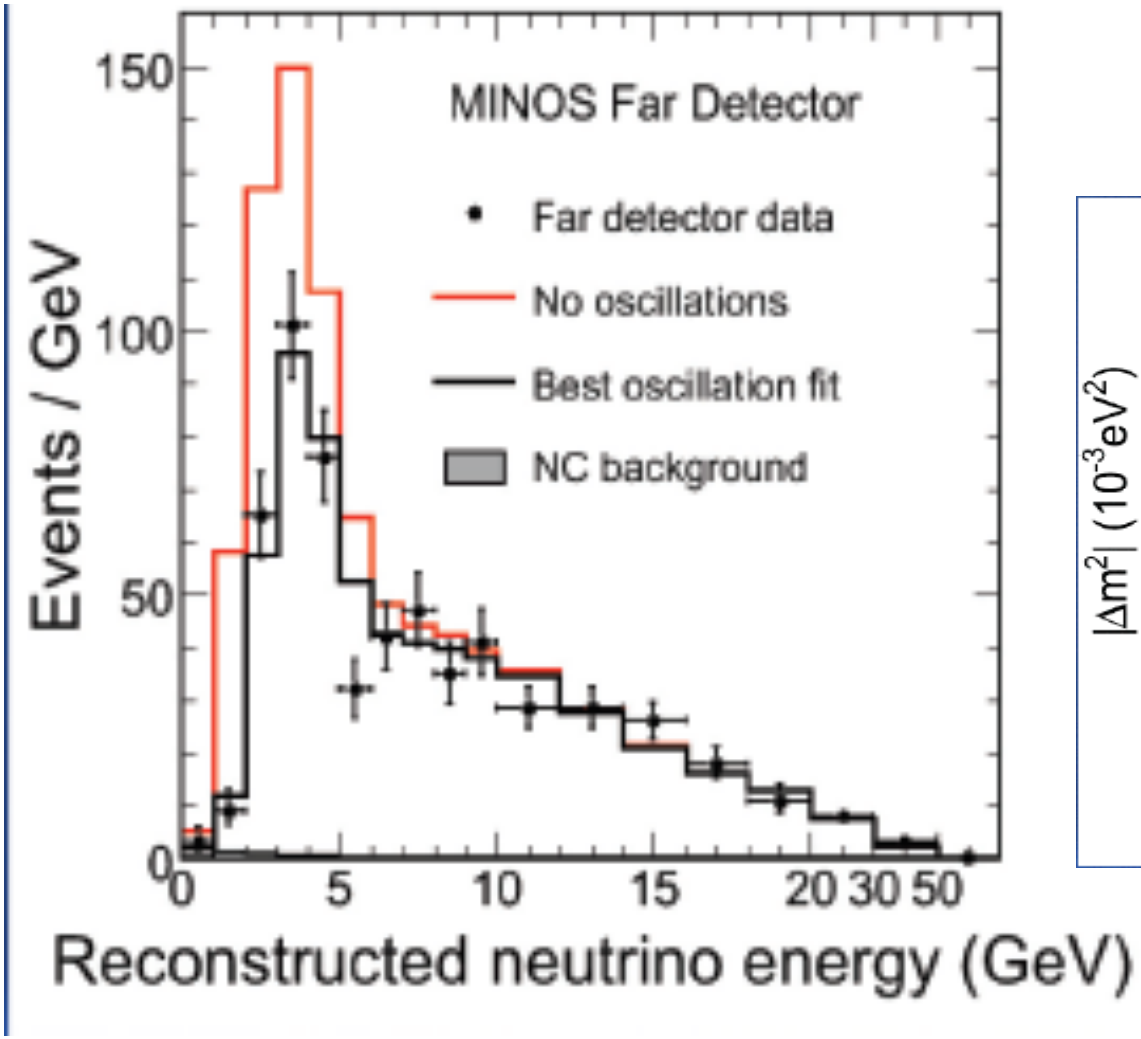
Why do we go over a “long baseline”?

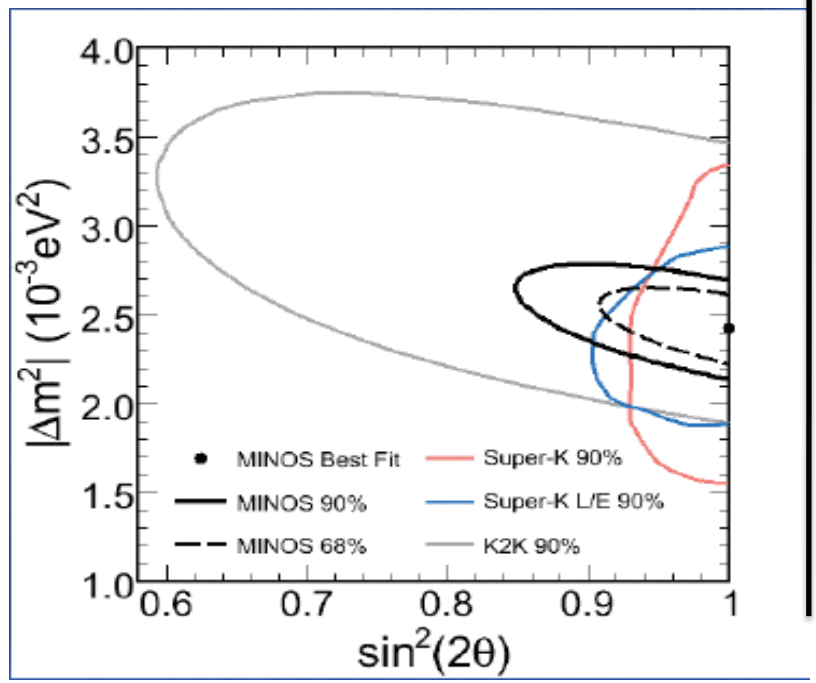


$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{23}\, L/E)$$

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

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





Three neutrino mass and mixing

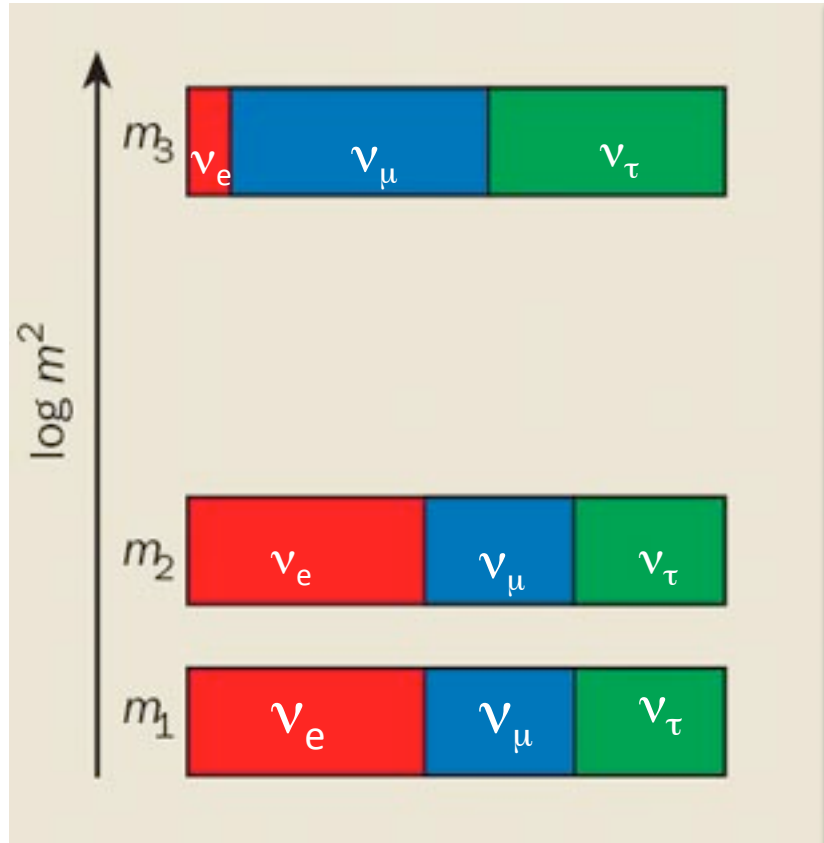
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Solar νs

ν_e appearance

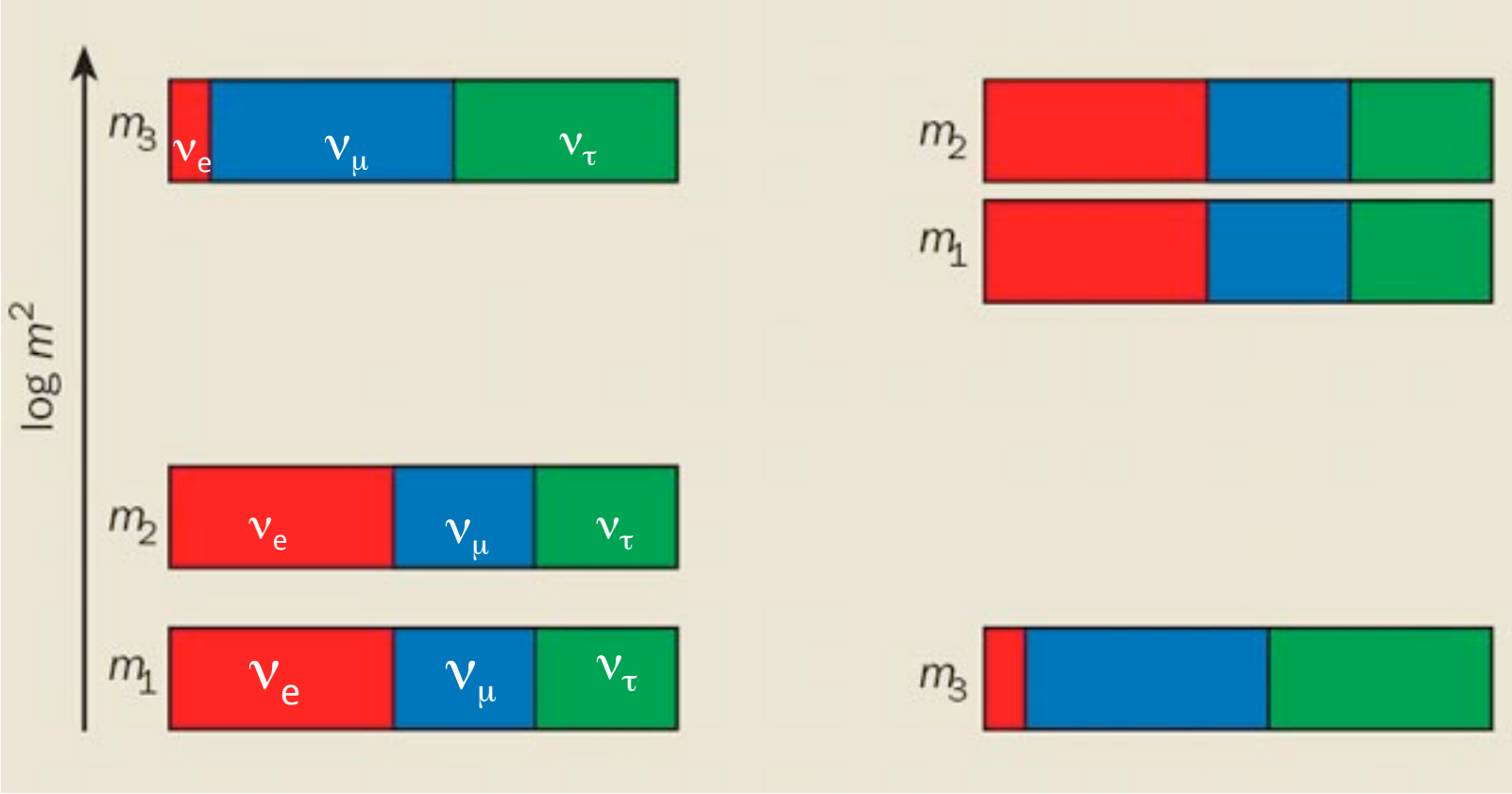
ν_μ disappearance

(i.e. MINOS)



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

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

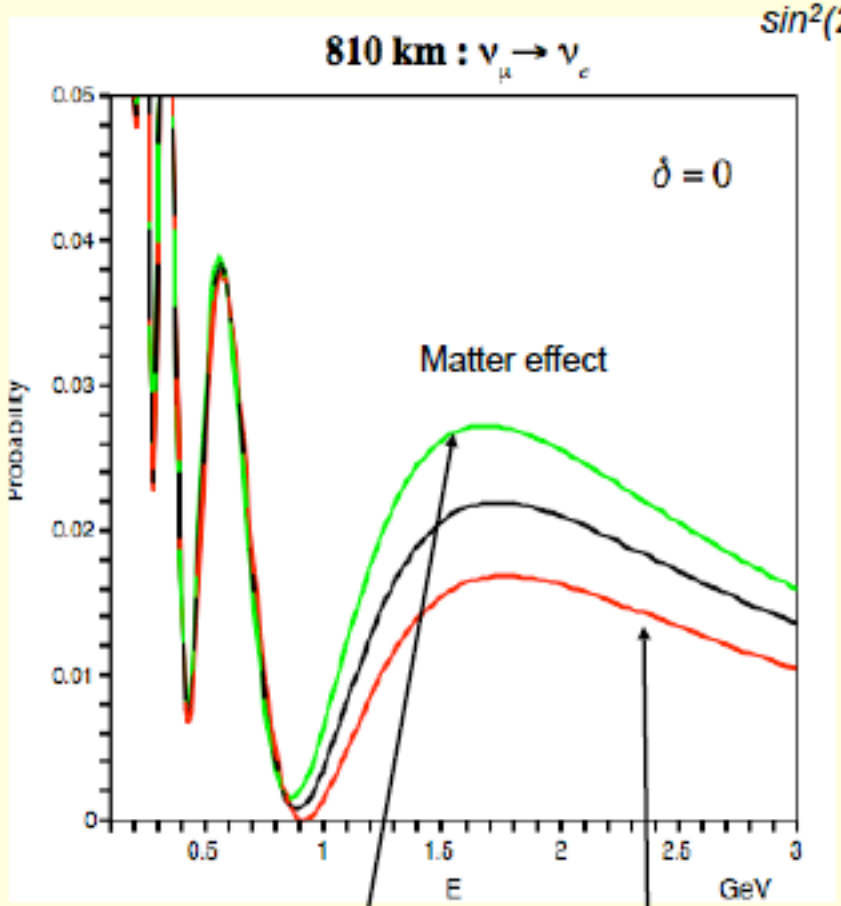
Probability of $\nu_\mu \rightarrow \nu_e$

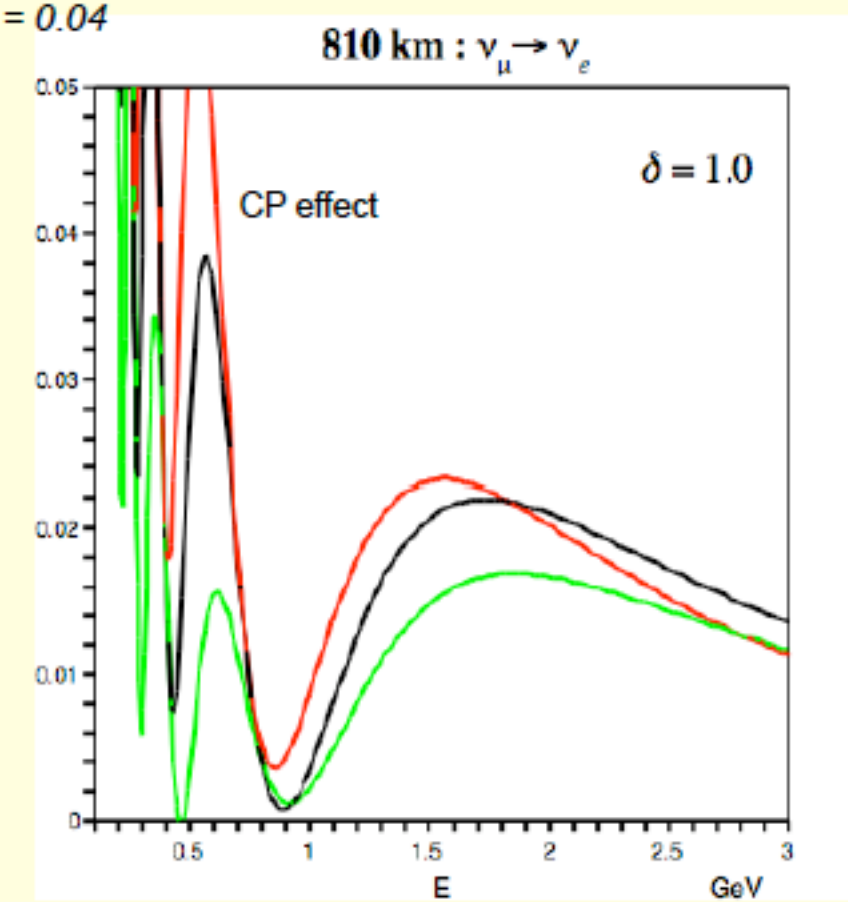
This is a series of “equations” and plots explaining mass hierarchy and CP violation.

Probably 2 slides…..

Matter Effects and CP violation

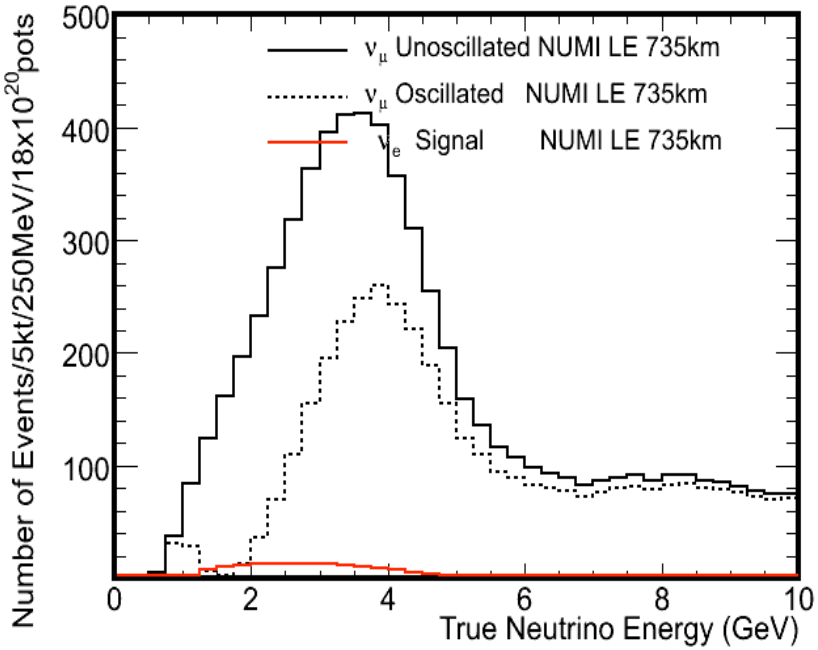
Normal hierarchy
$\sin^2(2\Theta_{13}) = 0.04$

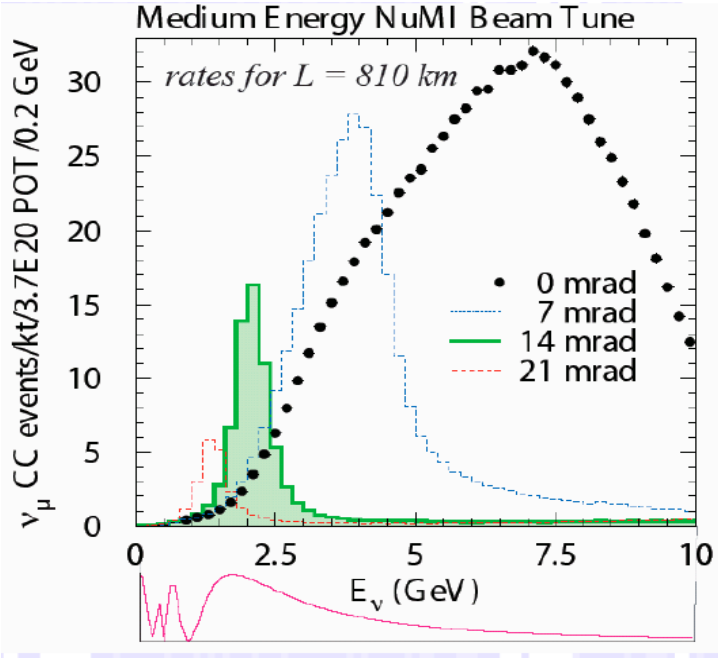




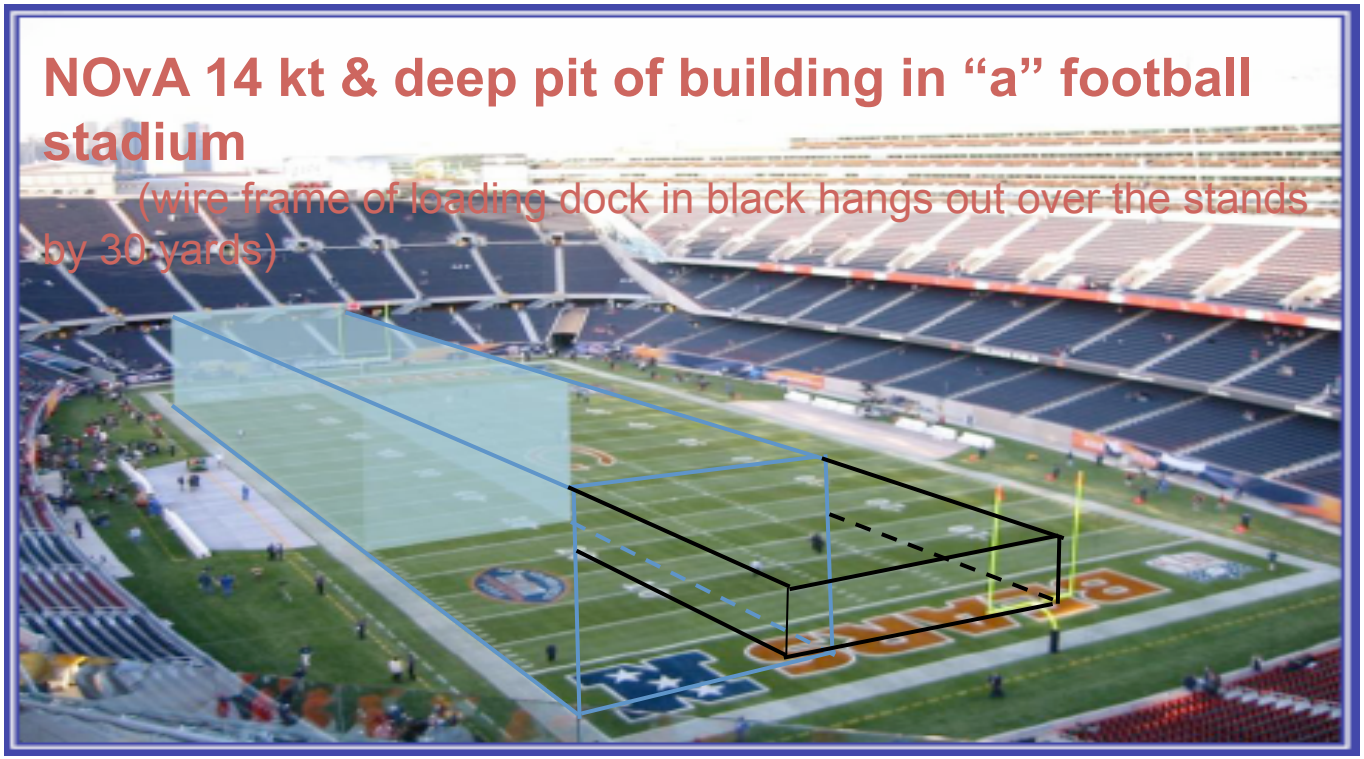
ν's and and anti-ν's have different oscillation probabilities

Optimizing an experimental configuration





NOνA : NuMI Off-Axis

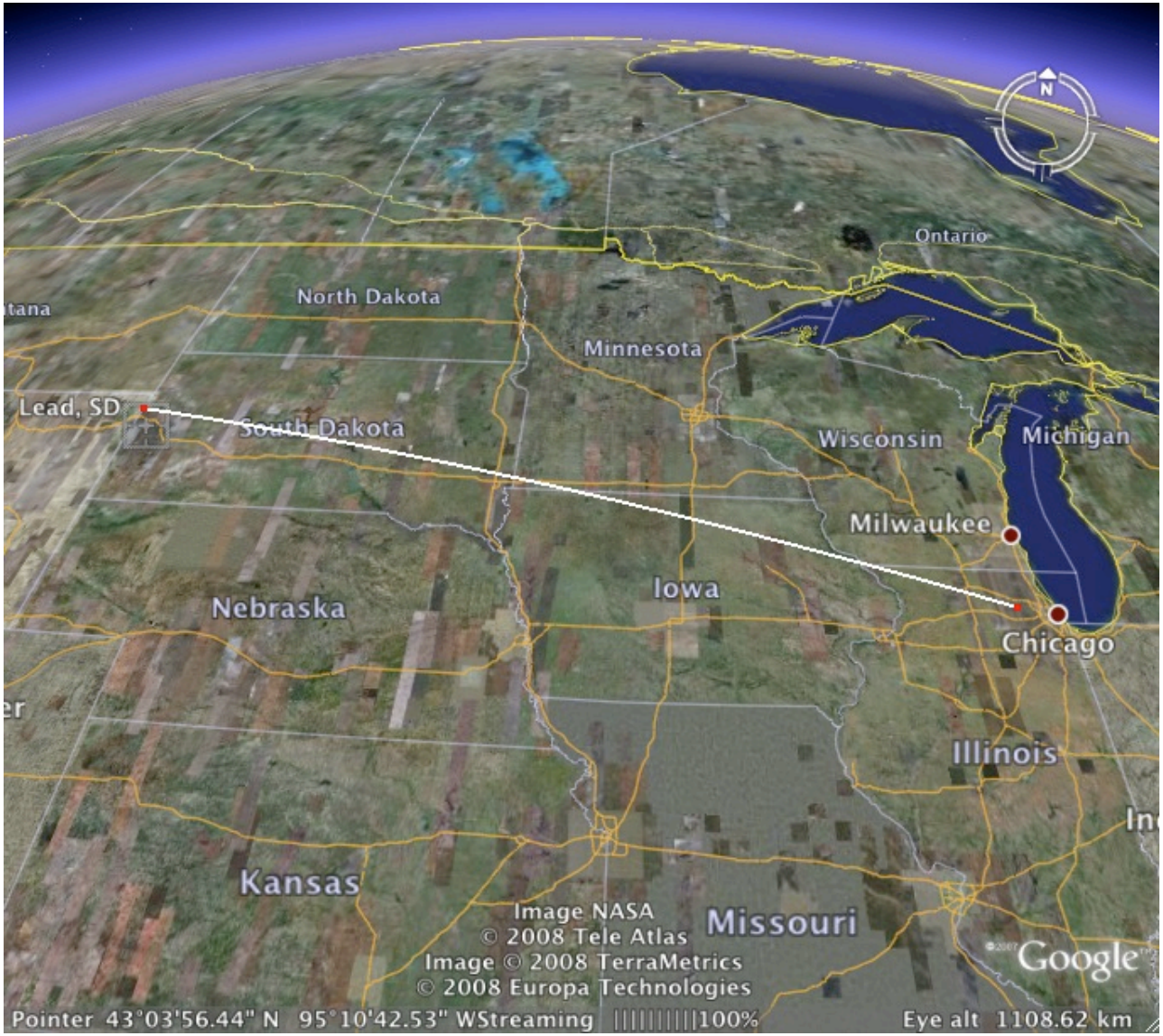


Start data taking with full detector in 2013 with 6×10^{20} POT/year

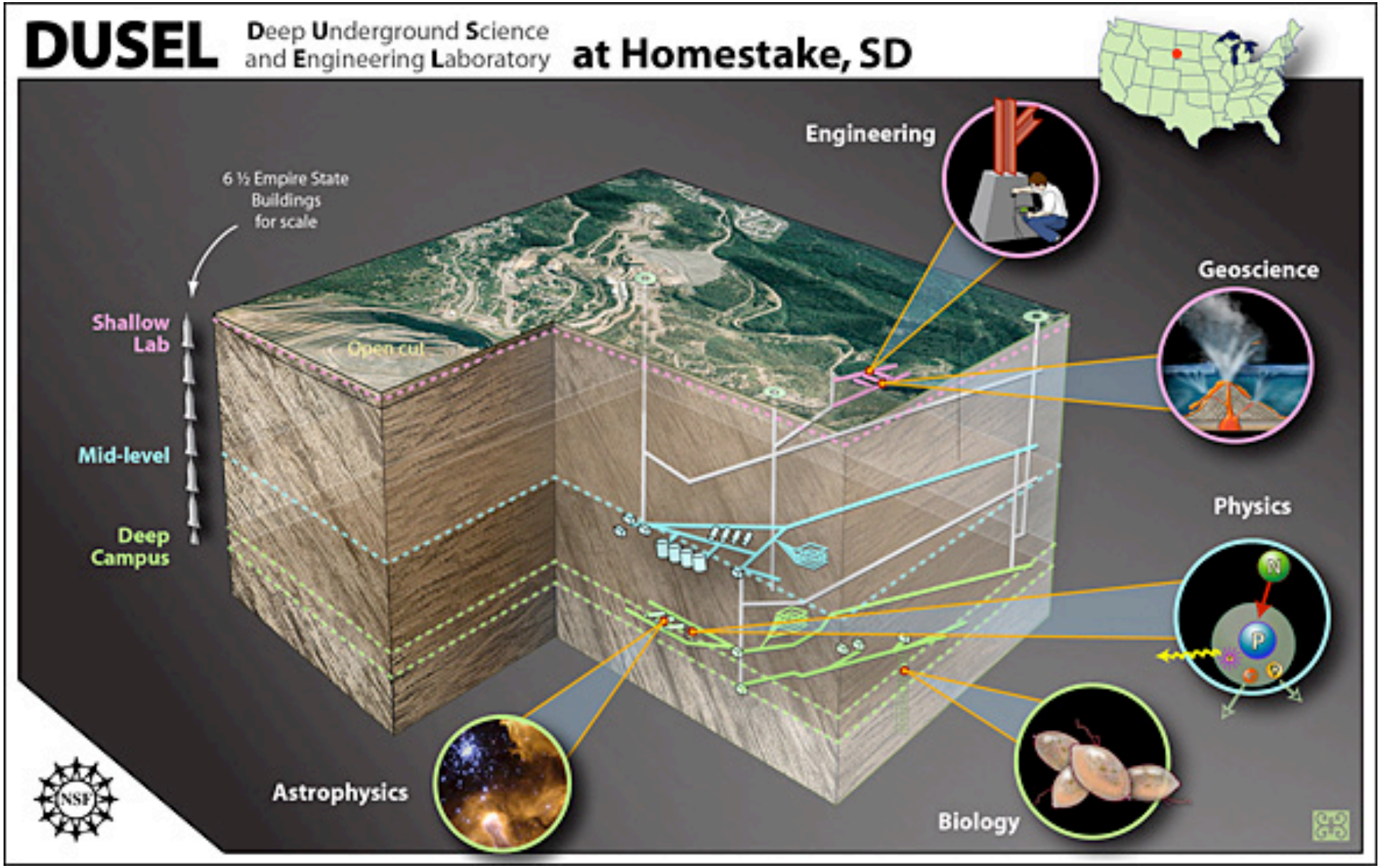
Run 3 years neutrino and 3 years anti-neutrino

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

Fermilab to Homestake DUSEL (1290km)

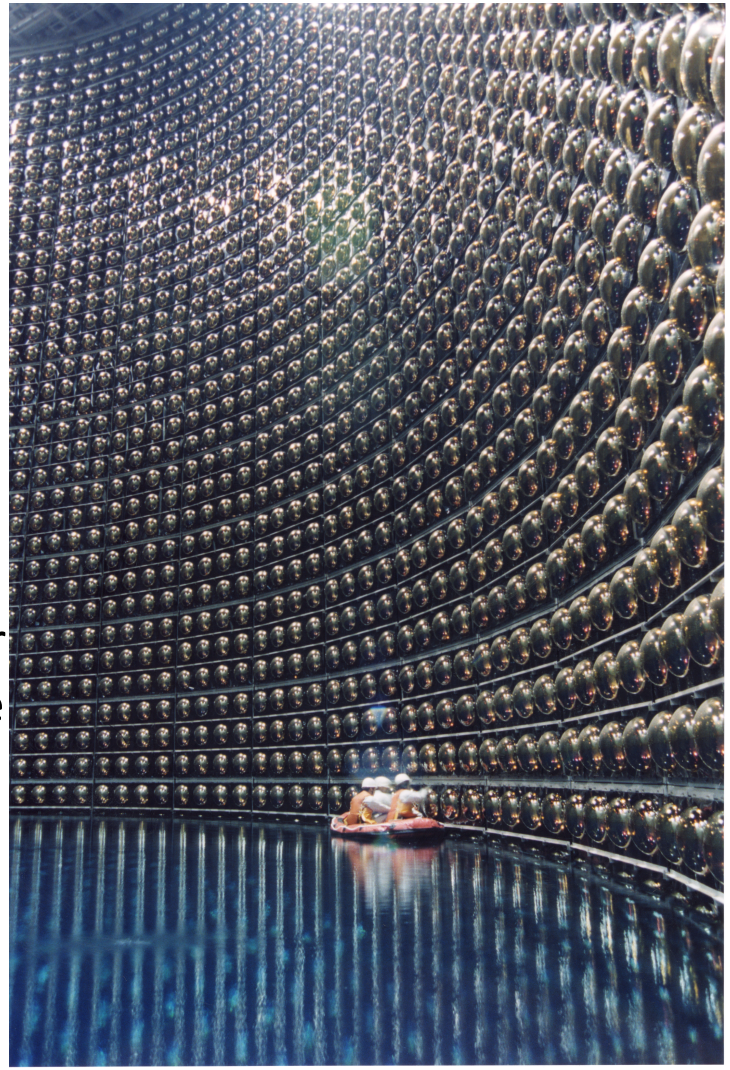


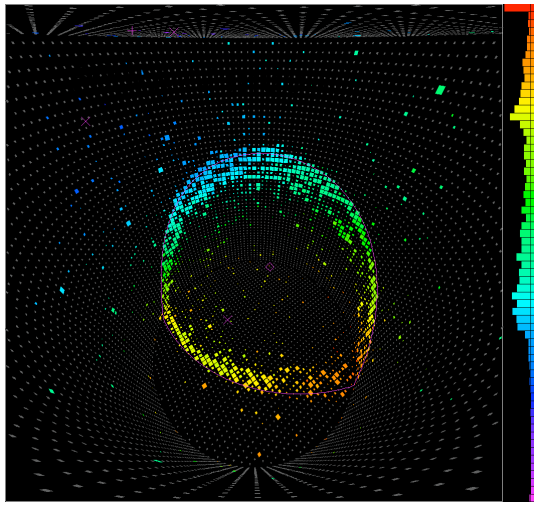
HOMESTAKE
Waste Water Treatment
Open Cut
Yates Complex
Town of Lead
~1km
Ross Complex
Kirk Canyon Adit

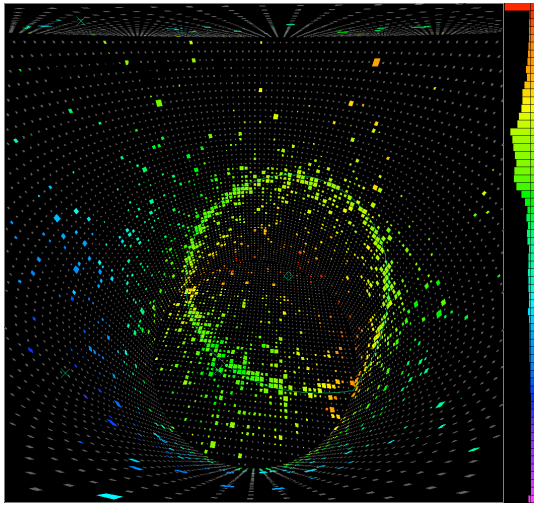

DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
6 ½ Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
Open cut
Engineering
Geoscience
Physics
Astrophysics
Biology
NSF

Why Underground?

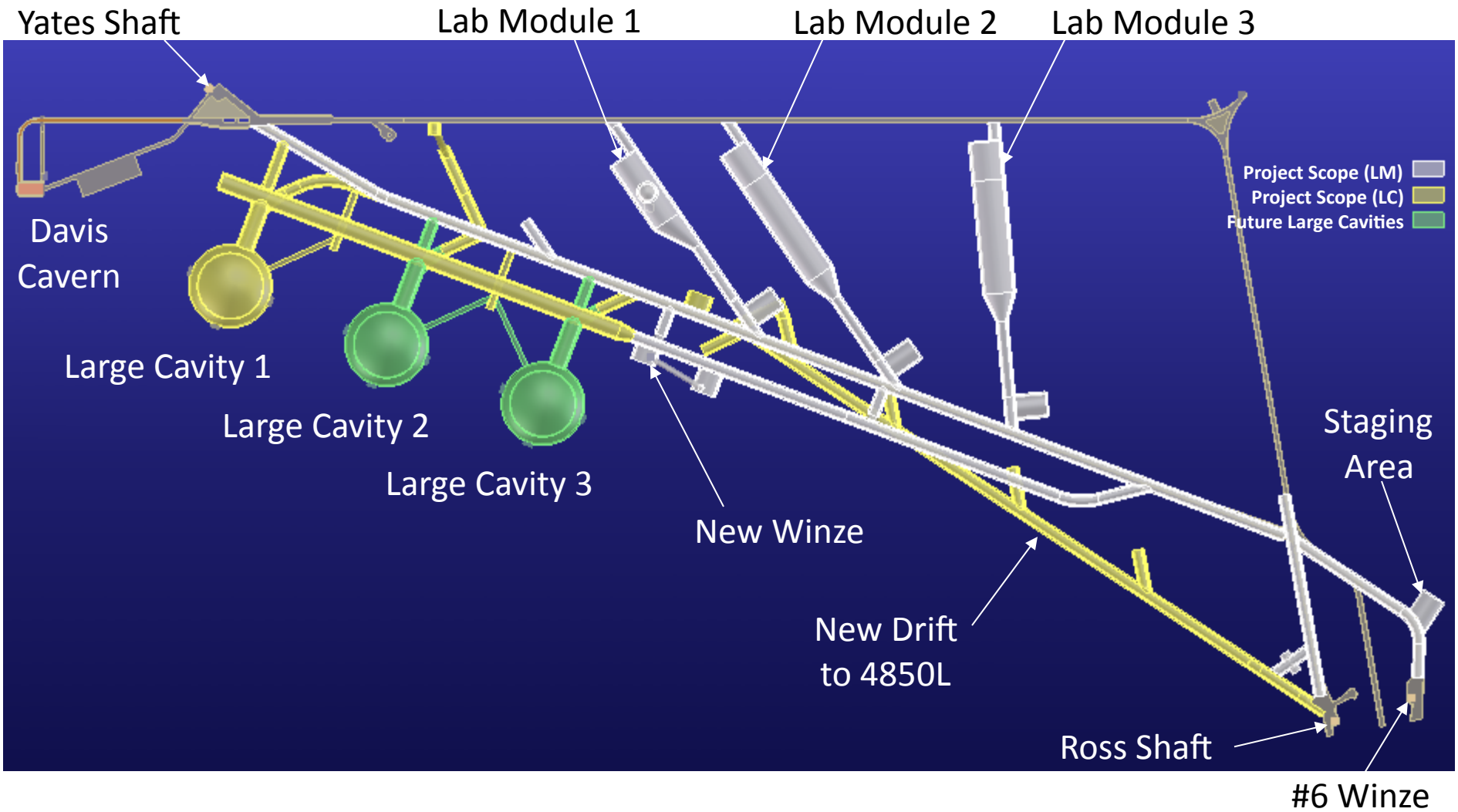
- Super-K
  - 13K 20” PMT
  - 40% coverage
  - 50 kT total mass
  - 39 m diameter
  - 42 m height
- LBNE
  - 60 K 10” PMT per 100kT FV module (25%)
  - ~55 m diameter
  - ~60 m height

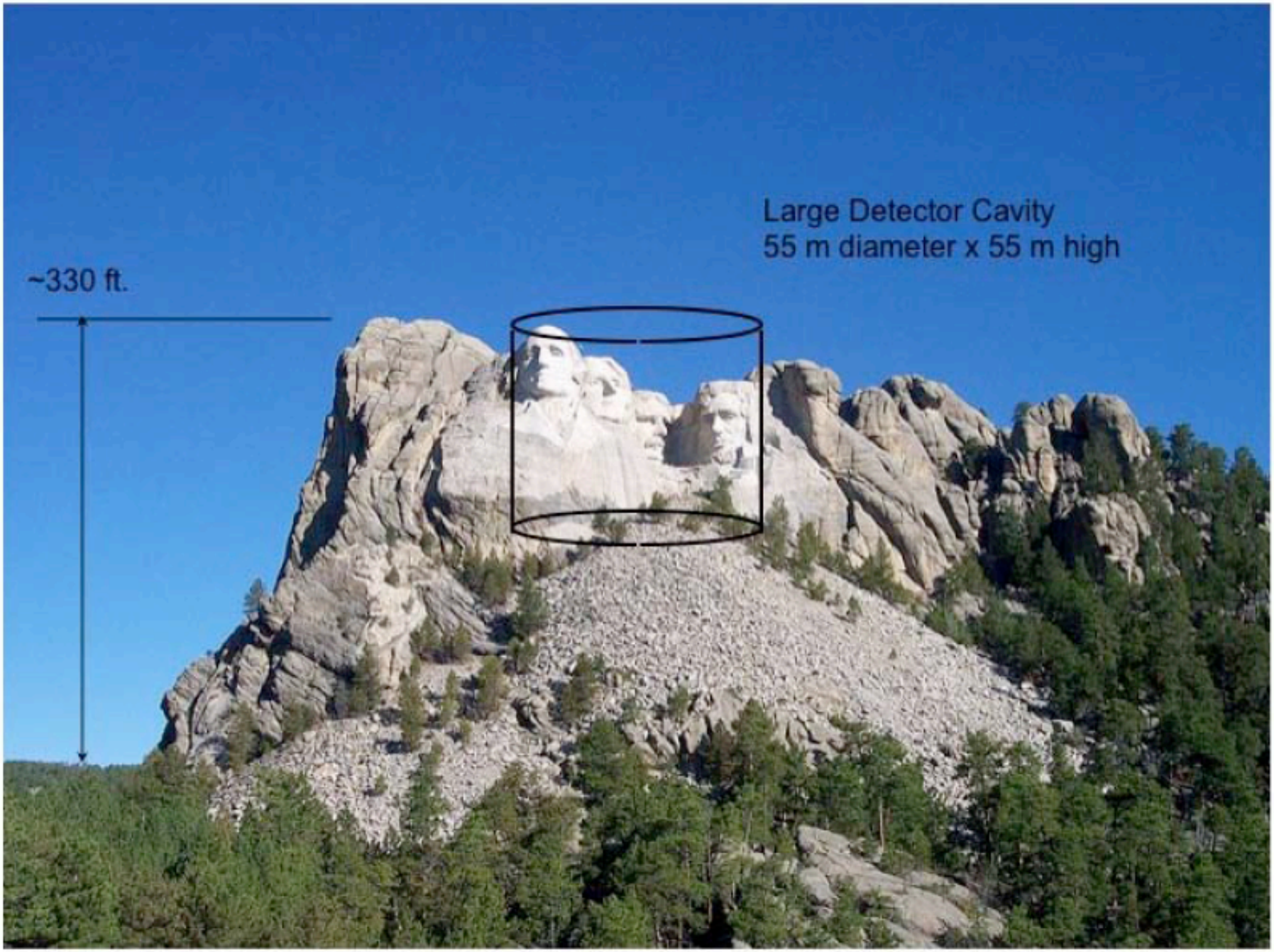






4850 Level Developmental Baseline for PDR:
Three Lab Modules & Three Large Cavities, Plan View




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

Summary

- Experiments to study nature's tiniest particles require tools of unprecedented scale.
- These experiments might possibly lead us to uncover one of the most compelling questions about our universe.

Thank you