Neutrino Physics II

CTEQ Summer School 2011

Madison, Wisconsin

July, 2011

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Fermilab

What's Our Plan?

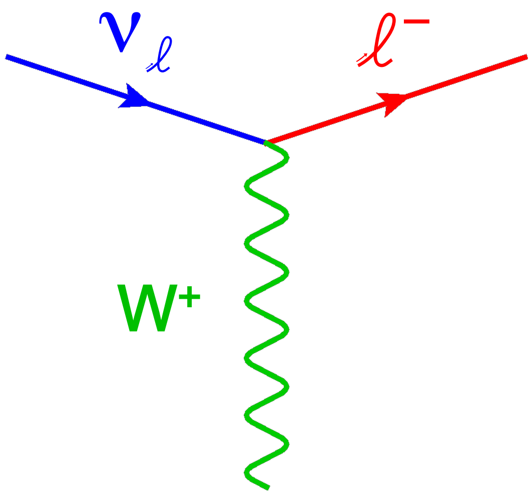
- Lecture I
  - Birth of Neutrino Physics
  - Some Basics of the Weak Interaction
  - Neutrinos as a Probe of Matter
- Lecture II
  - Early Experimental History – Big Challenges and Bigger Surprises
  - Neutrino Oscillations, Masses and Mixing
  - Open Questions in the Neutrino Sector

General Goal: To provide you an introduction to the basic vocabulary and concepts needed to understand current efforts and future results in neutrino physics

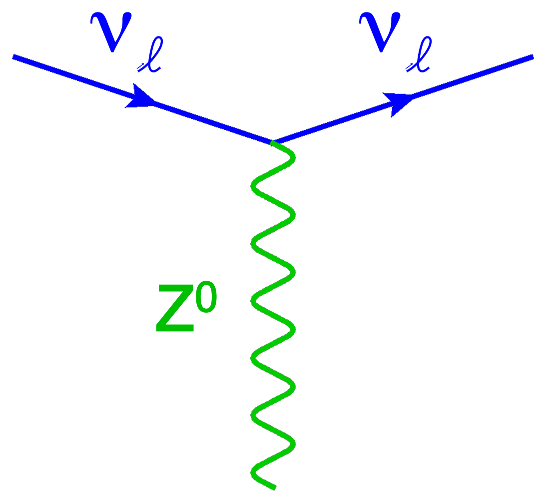
Two Types of Weak Interactions

$W^{\pm}$ exchange constitutes a "charged-current" interaction

Z^0 exchange constitutes a "neutral-current" interaction



Charged-Current (CC)

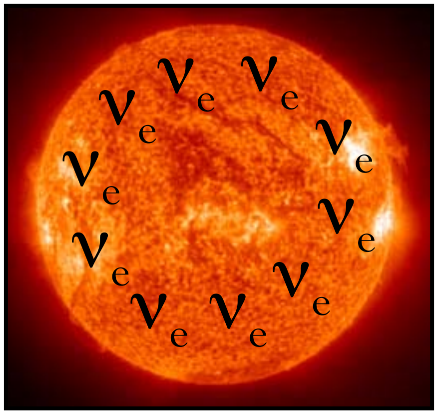


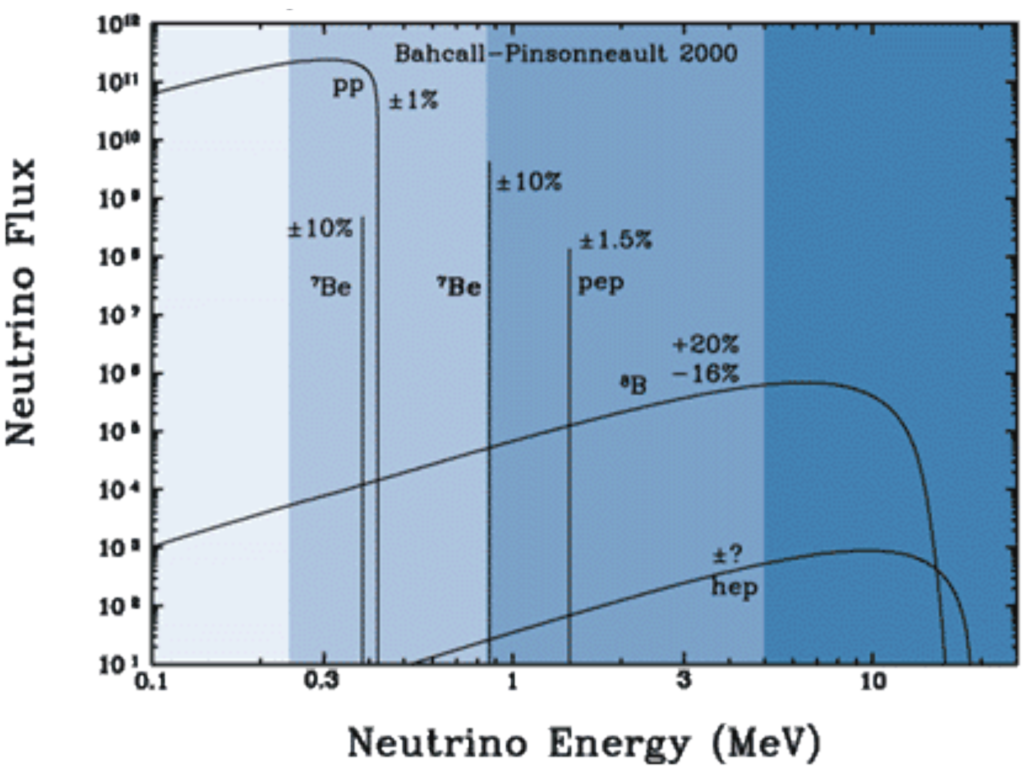
Neutral-Current (NC)

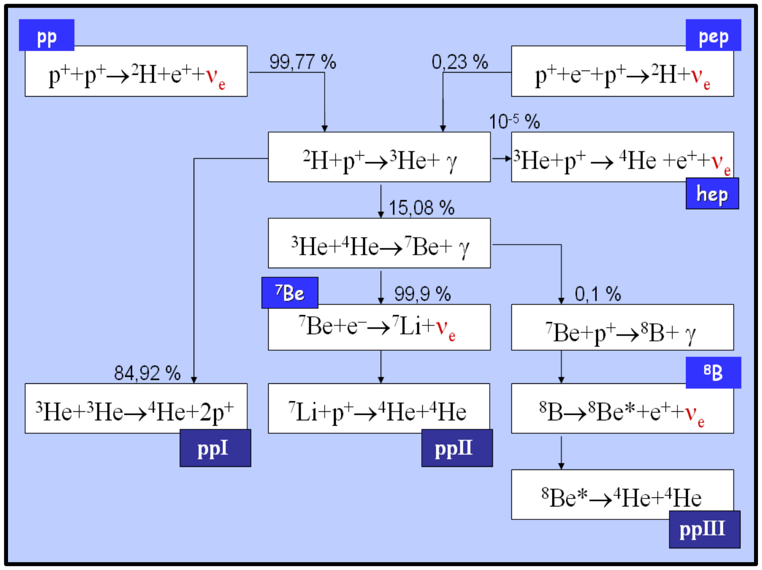
Can detect neutrinos through their CC and NC interactions

Let's Give it a Try: ν_e from the Sun

- Nuclear reactions in the sun produce electron neutrinos ONLY
- If can detect them, can test the model of the sun
  - Look deep into the sun using neutrinos!







Let's Give it a Try: ν_e from the Sun

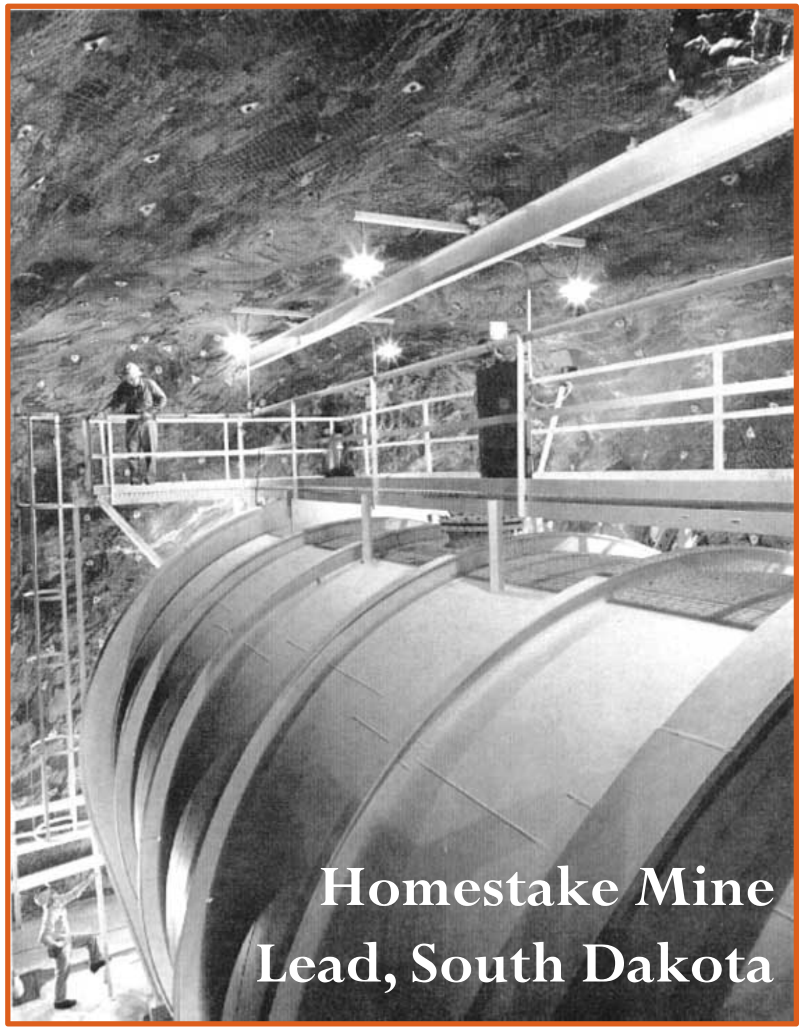
- Ray Davis set out to detect ν_e from the sun using a tank of cleaning fluid buried deep underground

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

- Every once in a while Davis would extract and count the number of argon atoms in the tank

- John Bahcall had calculated how many to expect:

$$\sim 36\ Ar\ atoms/month$$



Homestake Mine
Lead, South Dakota

Let's Give it a Try: ν_e from the Sun

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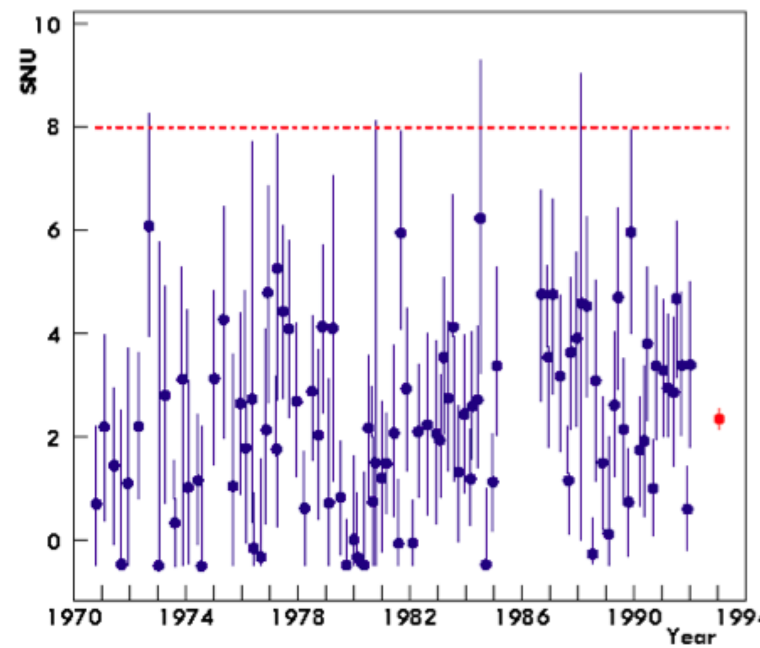


$$\frac{\phi_{\nu_e}(Homestake)}{\phi_{\nu_e}(Theory)} = 0.34 \pm 0.06$$

Let's Give it a Try: ν_e from the Sun

What could possibly explain this?

The theory was wrong

The experiment was wrong

They were both wrong

Let's Give it a Try: ν_e from the Sun

<u>What could possibly explain this?</u>

The theory was wrong

The experiment was wrong

They were both wrong

<u>But what if neither was wrong?</u>

Would imply ~2/3 of the solar ν_e flux "disappears" on the way to earth!

A Definitive Solar Neutrino Result

- Major drawback of Davis' experiment was could only see electron neutrino interactions. The Sudbury Neutrino Observatory (SNO) could see interactions involving all three flavors (ν_e, ν_μ, ν_τ)

$$\nu_e + d \rightarrow p + p + e^- \quad (CC)$$

CC interactions sample $\phi_{\nu e}$ only

$$\nu_x + d \rightarrow p + n + \nu_x \quad (NC)$$

$$\nu_x + e^- \rightarrow \nu_x + e^- \quad (ES)$$

NC interactions sample total $\phi_{\nu e} + \phi_{\nu\mu} + \phi_{\nu\tau}$

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.340 \pm 0.023(stat) \pm 0.030(syst)$$

ν_e fraction agrees with Davis!

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.21 \pm 0.36) \times 10^6 cm^{-2} s^{-1}$

Theory: $\phi_{total} = (5.69 \pm 0.91) \times 10^6 cm^{-2} s^{-1}$

Total flux agrees with Bahcall!

Try Again: ν_μ / ν_e from Atmosphere

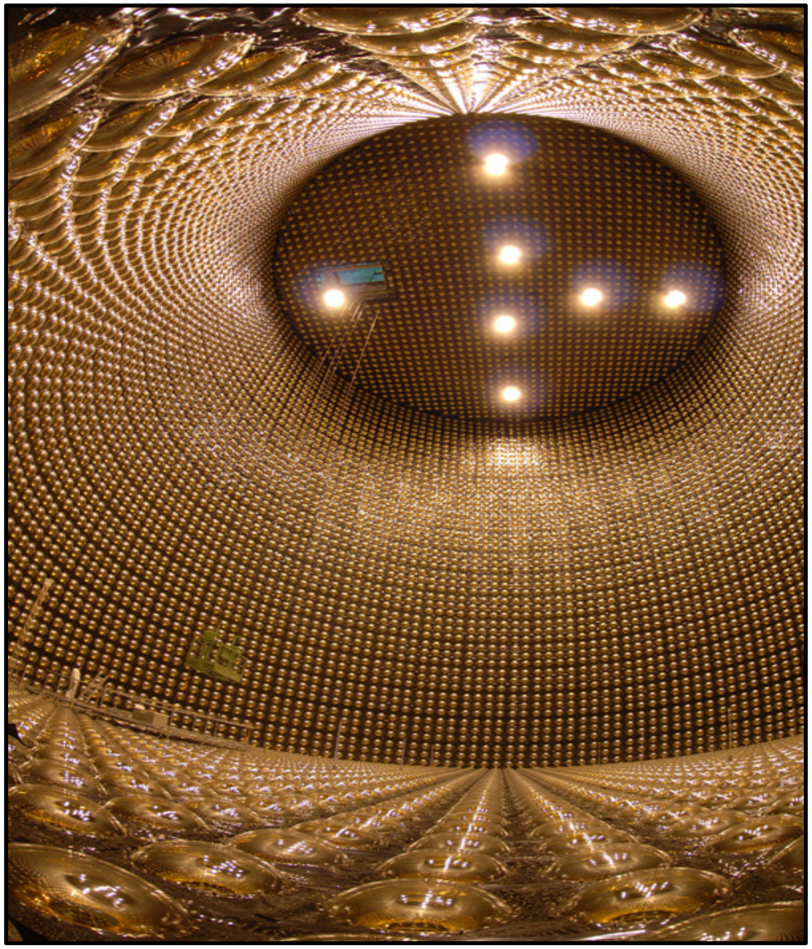
- Neutrinos created by decay of pions in particle showers initiated when energetic cosmic rays interact in the atmosphere

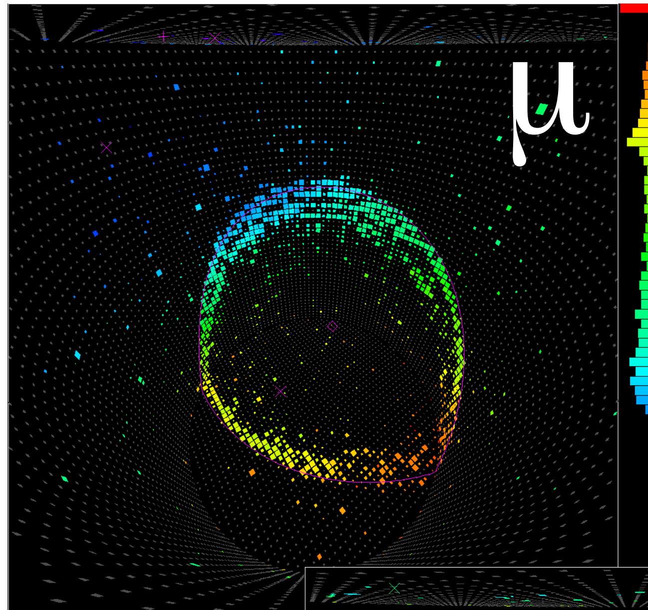
$$\text{Expect: } \frac{\phi_{\nu_\mu}}{\phi_{\nu_e}} \approx 2$$

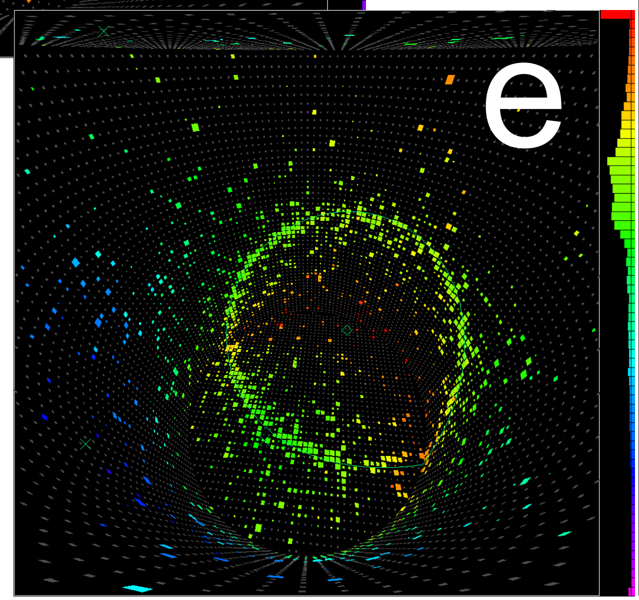
Try Again: ν_μ / ν_e from Atmosphere

Super-Kamiokande

50kT water Cherenkov detector



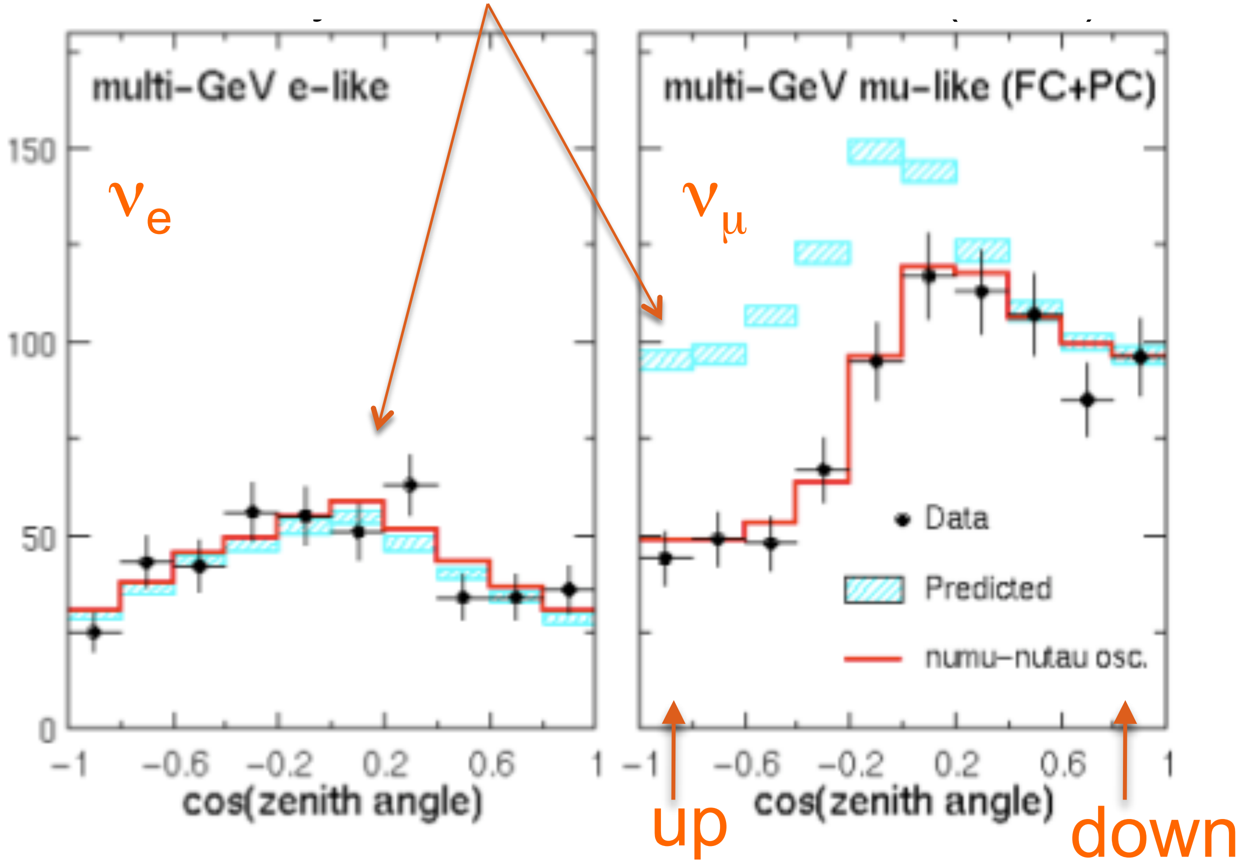


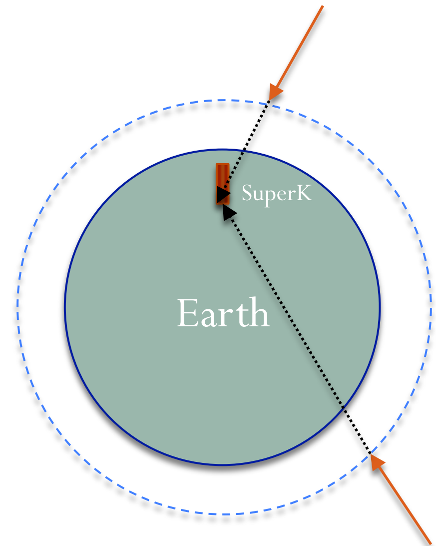


Originally built to search for proton decay. Still waiting for one of those, but won a Nobel Prize for study of atmospheric neutrinos in the mean time.

Try Again: ν_μ / ν_e from Atmosphere

Expect: $\frac{\phi_{\nu_\mu}}{\phi_{\nu_e}} \approx 2$





Expect:

$$\frac{\phi_{\nu_\mu}(Up)}{\phi_{\nu_\mu}(Down)} \approx 1$$

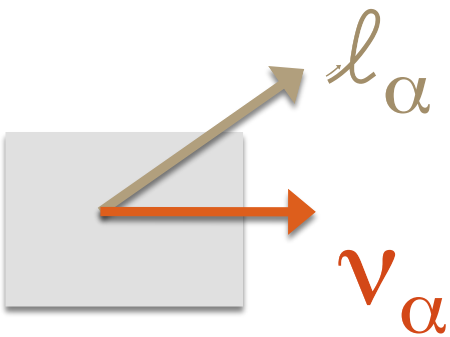
Another "Desperate Remedy"

Where are the disappearing neutrinos disappearing to? Another dilema that persisted for more than <u>two decades!</u>

- It was realized that if neutrinos indeed have small non-zero masses, then <u>quantum mechanics allows</u> that they could be disappearing into other kinds of neutrinos…
  - ν_e from the sun ➔ ν_μ / ν_τ
  - ν_μ from atmosphere ➔ ν_τ

and tiny masses can have HUGE effects

What is Neutrino Flavor?



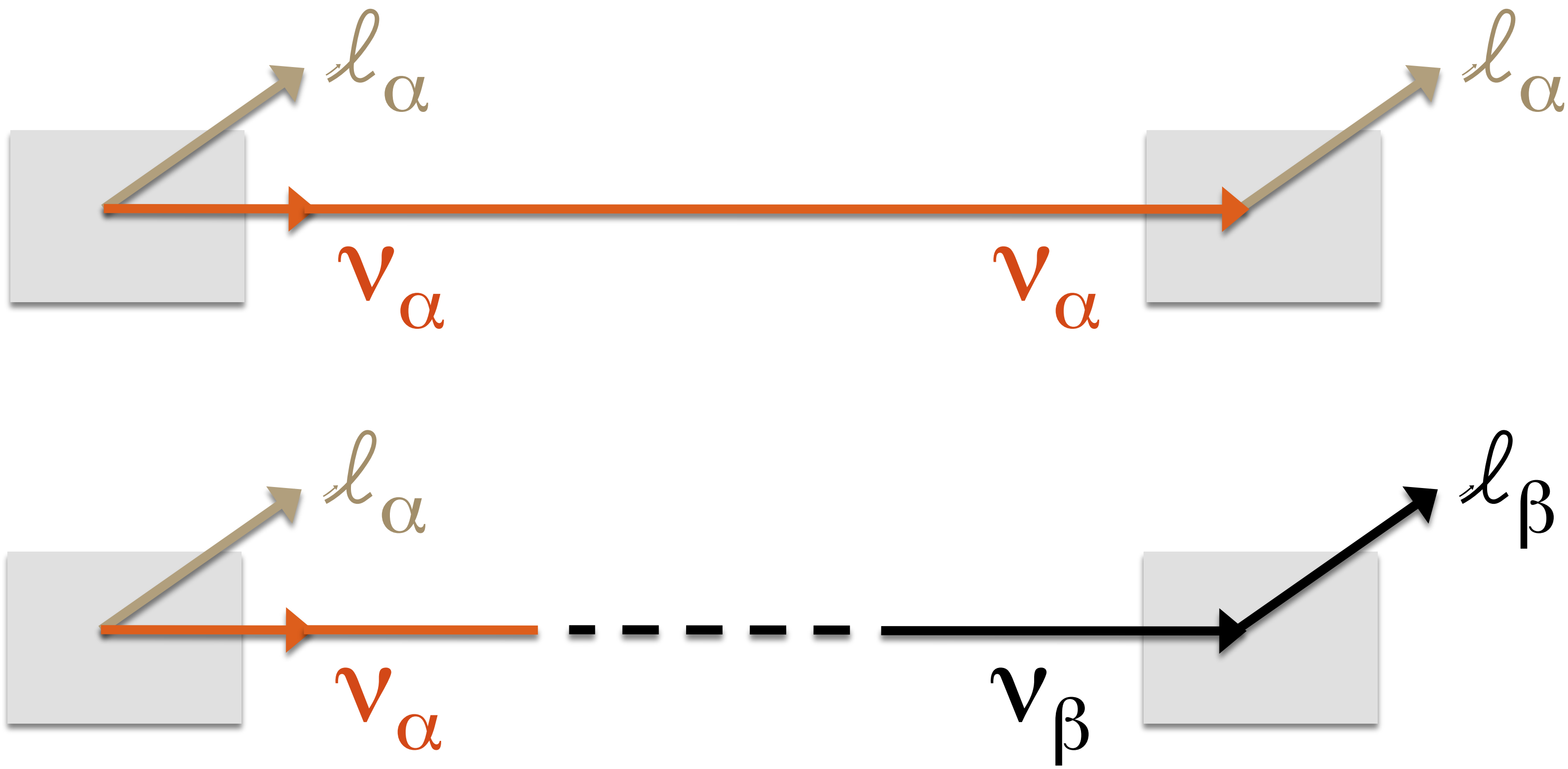
The neutrino of flavor α is the one created in W boson decay together with the charged lepton of flavor α

What is Neutrino Flavor?

The neutrino of flavor α is the one created in W boson decay together with the charged lepton of flavor α

And which creates a charged lepton of flavor α when it undergoes a charged-current interaction

What is Neutrino Flavor Change?

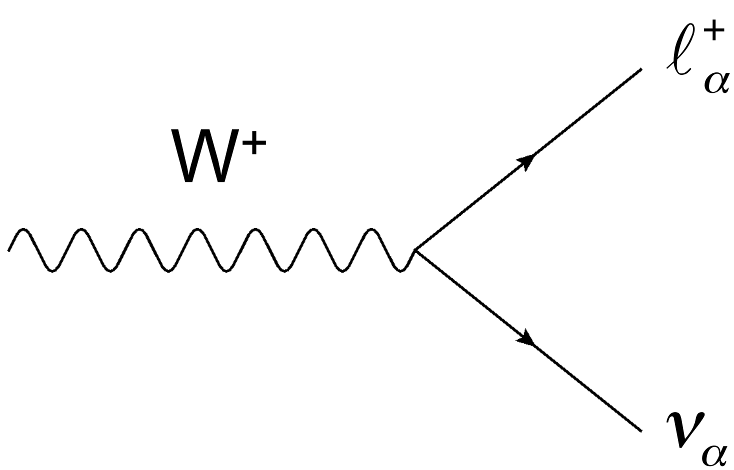


Which could be possible if
neutrinos have mass and leptons mix

Flavor ⟷ Mass

- We know the initial weak flavor, $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau, \ldots)$ through identification of the charged lepton partner $\ell_\alpha = (e, \mu, \tau, \ldots)$ when the neutrino is created

- But suppose that weak flavor eigenstate is actually a superposition of pure mass eigenstates



Mixing matrix describing mass state content of flavor states

$$\left|\nu_\alpha\right\rangle = \sum_i U_{\alpha i}^* \left|\nu_i\right\rangle$$

Neutrinos of definite flavor

Neutrinos of definite mass

Flavor ⟷ Mass

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

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

neutrino mass states

Flavor $\longleftrightarrow$ Mass

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

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

neutrino mass states

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

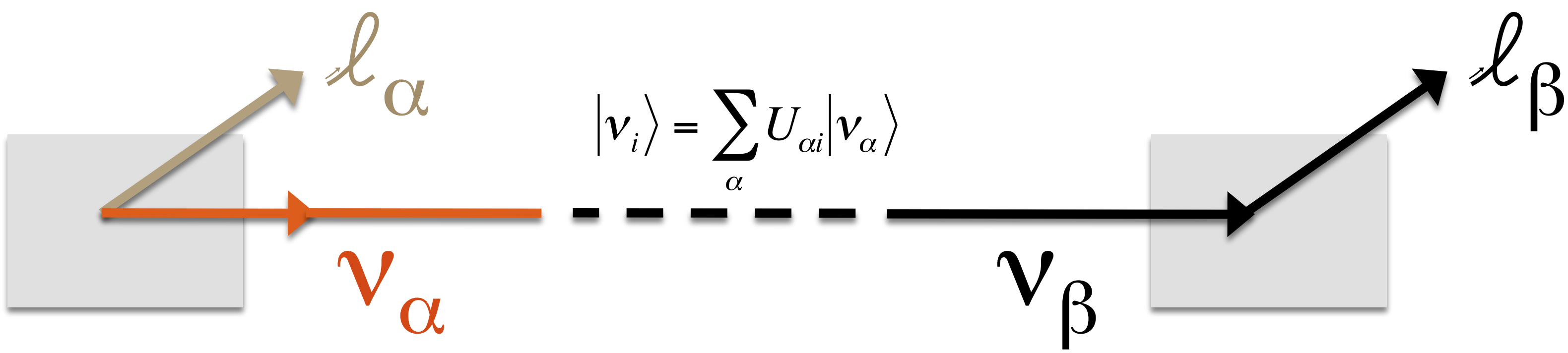
mass eigenstates == flavor eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 0.58 & 0.58 & 0.58 \\ 0.58 & 0.58 & 0.58 \\ 0.58 & 0.58 & 0.58 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates = equal mix of mass states

Flavor ⟷ Mass

- And a neutrino's propagation through space (from production to detection) is dictated by the free Hamiltonian whose eigenstates are the states of definite mass, $\nu_i = (\nu_1, \nu_2, \nu_3, \ldots)$, not flavor, and whose time evolution is described by the Schrodinger equation:



$$i\frac{\partial}{\partial t}|\nu_i(t)\rangle = E_i|\nu_i(t)\rangle \approx \left(E_i + \frac{m_i^2}{2E_i}\right)|\nu_i(t)\rangle$$

The Oscillation Formula

- The trivial solution to this Schrodinger equation tells us how the ν_i propagate in time:

$$\left|\nu_i(t)\right\rangle = e^{-i\left(E_i + m_i^2/2E_i\right)t}\left|\nu_i(0)\right\rangle$$

- The mass eigenstates which contribute coherently to an experimental beam are those with a common energy, E
- Since neutrino is ultra-relativistic, L ≈ t (for c = 1)

$$\left|\nu_\alpha\right\rangle \rightarrow \left|\nu(L)\right\rangle = \sum_i U_{\alpha i}^* e^{-i\left(m_i^2/2E\right)L}$$

at production point

after traveling a distance L

The Oscillation Formula

- The probability that a neutrino created as weak eigenstate α being detected as weak eigenstate β after traveling a distance L is:

$$P(\nu_\alpha \rightarrow \nu_\beta) = |\langle \nu_\beta | \nu \;\; (L) \rangle|^2 = \left| \sum_i U_{\alpha i}^* e^{-i(m_i^2 L/2E)} U_{\beta i} \right|^2$$

The Oscillation Formula

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$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu \ (L) \rangle|^2 = \left| \sum_i U^*_{\alpha i} e^{-i(m_i^2 L/2E)} U_{\beta i} \right|^2$$

$$= \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \right) \sin^2 \left(\Delta m^2_{ij} \frac{L}{4E} \right)$$

$$+ 2 \sum_{i>j} \Im \left(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} \right) \sin \left(\Delta m^2_{ij} \frac{L}{2E} \right)$$

$$\Delta m^2_{ij} \equiv m^2_j - m^2_i$$

mass-squared difference of two mass eigenstates

The Oscillation Formula

1. The periodic nature of the oscillation probability formula ($\sin^2\omega x$) has earned the phenomenon the name "neutrino oscillations".

2. If neutrinos do not have masses so that all $\Delta m^2 = 0$, then the probability reduces to $\delta_{\alpha\beta}$, and neutrinos cannot change flavor through oscillations. On the other hand, if neutrinos are found to oscillate, then one or more neutrino masses are necessarily non-zero and not identical.

3. If the mixing matrix is diagonal, such that eigenstates do not mix, then again the probability reduces to $\delta_{\alpha\beta}$, oscillations ➔ mixing

4. To determine the oscillation probability of antineutrinos, one must change the sign of the third term to (-). Because antineutrino transmutation is the CP mirror image of neutrino transmutation, evidence that $P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$ would be evidence of CP violation in the lepton sector.

The Mixing Matrix

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

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

neutrino mass states

By analogy with CKM matrix for quark mixing:

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

3 mixing angles and 1 CP violation phase $\quad c_{ij} \equiv \cos\theta_{ij} \quad s_{ij} \equiv \sin\theta_{ij}$

Verifying the Oscillation Explanation

- Recall, we laid out the oscillation scenario with neutrino masses and mixings as an explanation for the solar and atmospheric neutrino puzzles:
  - What happened to all the ν_e from the sun?
  - What happened to the ν_μ created in the atmosphere which traveled through the earth?

If this is the correct explanation, then we should be able to construct a set of laboratory experiments to test it and make precision measurements

The Mixing Matrix

Leptonic Mixing Matrix

flavor states participating in standard weak interactions

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

neutrino mass states

Very instructive to factorize matrix that we wrote down before:

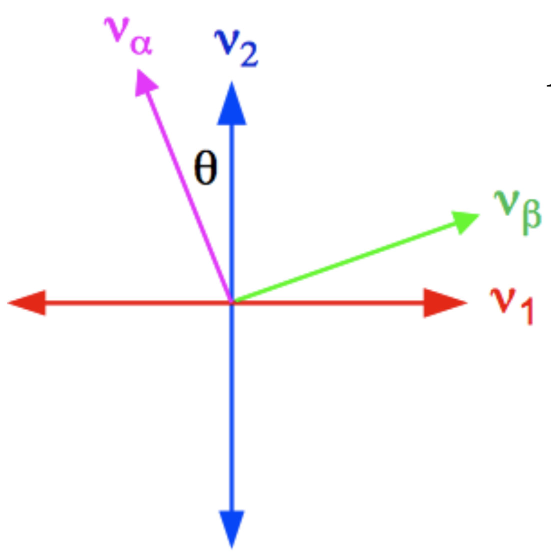
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{-i\delta} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

factor responsible for atmospheric neutrino anomaly ($\Delta m_{23}^2, \theta_{23}$)

Quasi 2-neutrino mixing

factor responsible for solar neutrino anomaly ($\Delta m_{12}^2, \theta_{12}$)

Two Neutrino Mixing



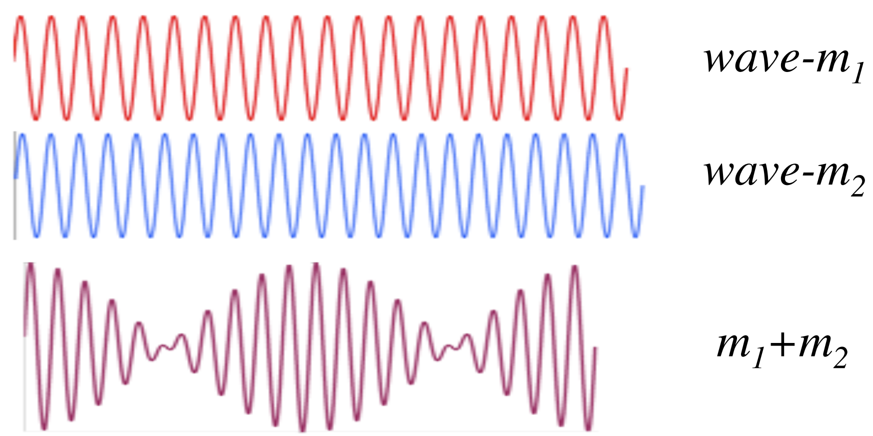
$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

The mixing angle, θ, determines the amplitude of the oscillation

Δm^2 determines the shape of the oscillation as a function of L (or E)

$$\Delta m_{ij}^2 \equiv m_j^2 - m_i^2$$

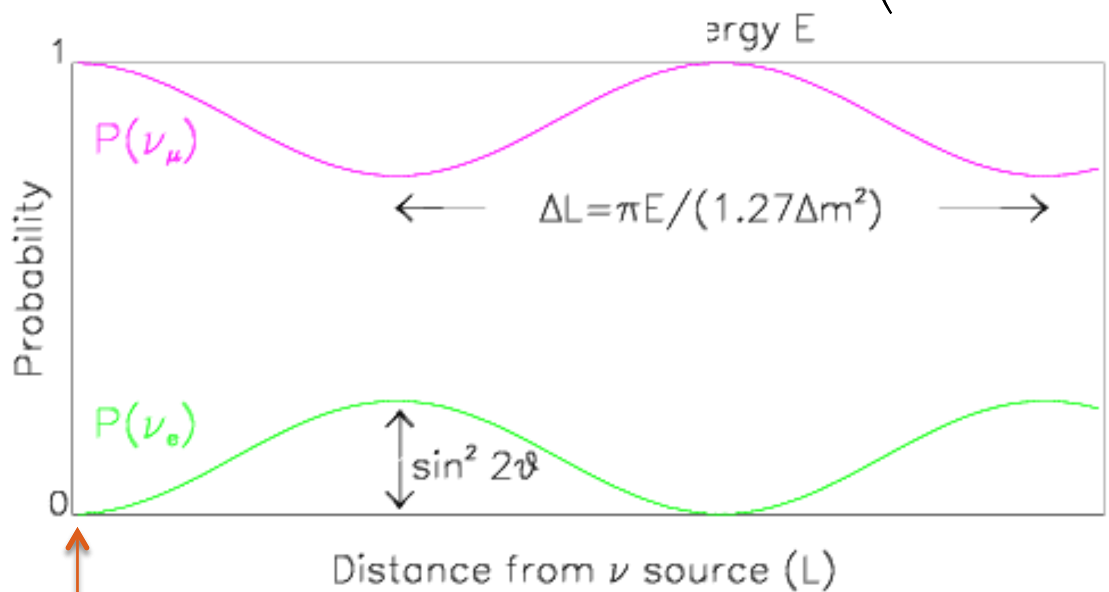
$$\begin{pmatrix} \nu_\alpha \\ \nu_\beta \end{pmatrix} = \begin{pmatrix} \cos\theta_{ij} & \sin\theta_{ij} \\ -\sin\theta_{ij} & \cos\theta_{ij} \end{pmatrix} \begin{pmatrix} \nu_i \\ \nu_j \end{pmatrix}$$



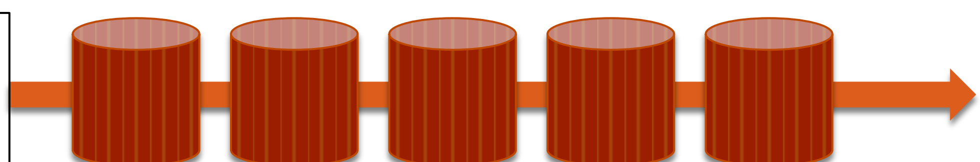
Two Neutrino Mixing

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\,\Delta m_{ij}^2 \frac{L}{E}\right)$$

Fixed E
Variable L



Begin with mono-energetic beam of ν_α



A bunch of detectors to measure ν_α / ν_β content along path

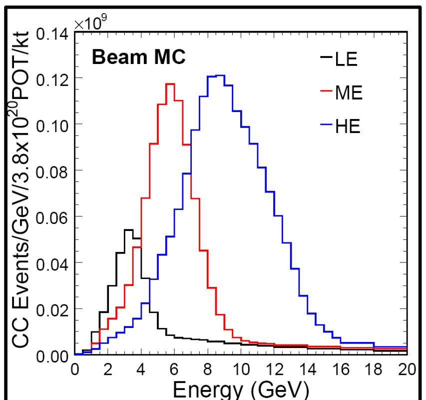
Wouldn't that be awesome!!
Alas…

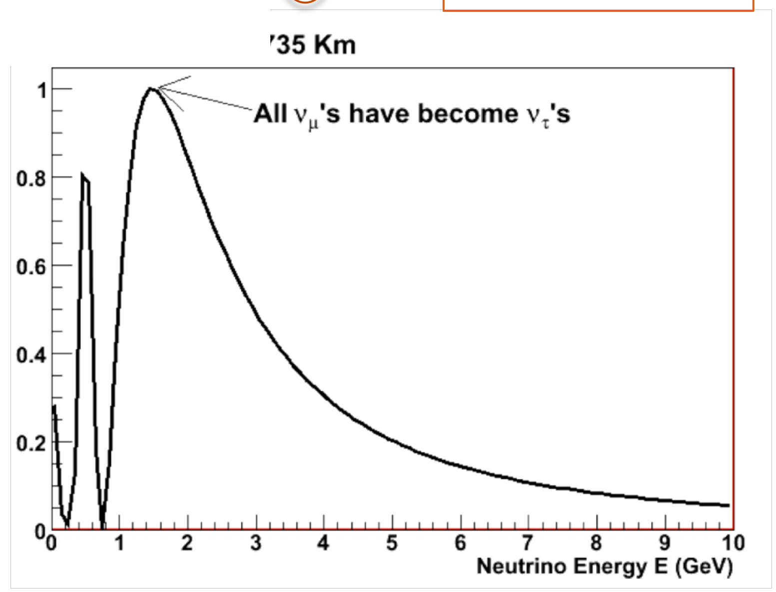
Two Neutrino Mixing

$$P(\nu_\alpha \rightarrow \nu_\beta) = \sin^2 2\theta_{ij} * \sin^2\left(1.27\Delta m^2_{ij}\frac{L}{E}\right)$$

Fixed L

Variable E

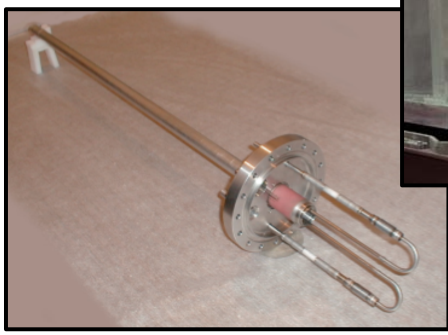


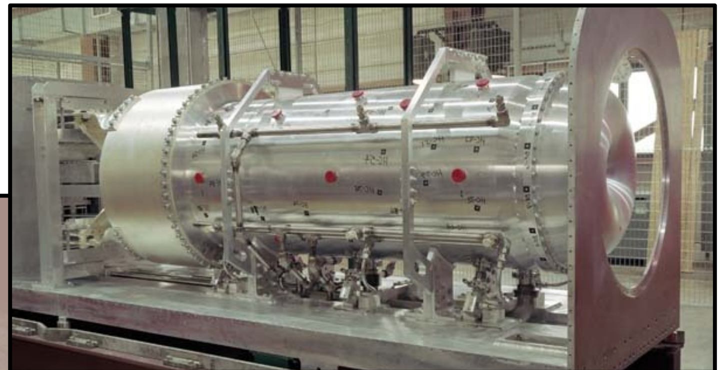


Begin with broad energy spectrum beam of ν_α

Measure ν_α / ν_β energy spectrum at origin and again after traveling distance L

Building a Neutrino Beam



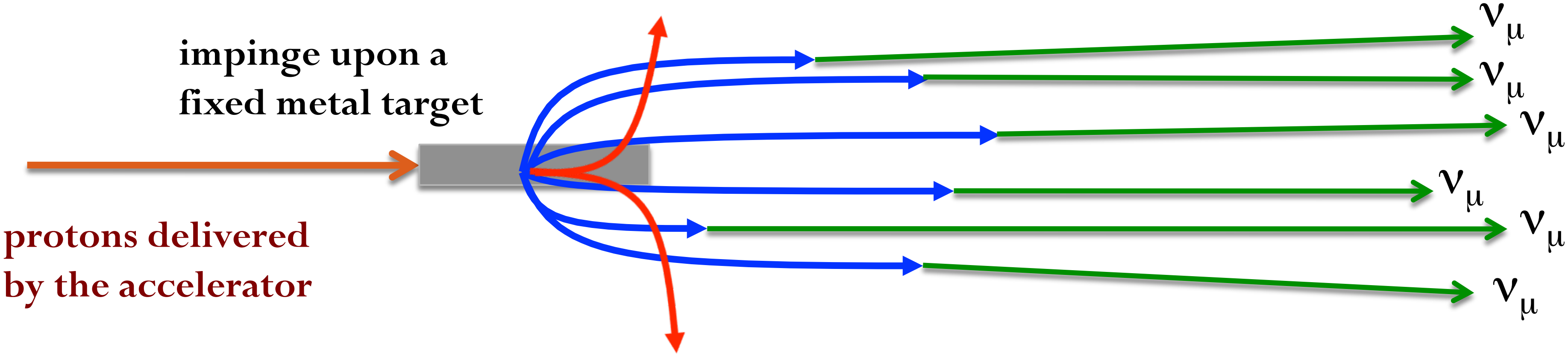


This is the basic concept first invented by Schwartz, Lederman and Steinberger when they discovered the ν_μ in 1962

pions decay into muon neutrinos

creates π/K mesons…

impinge upon a fixed metal target

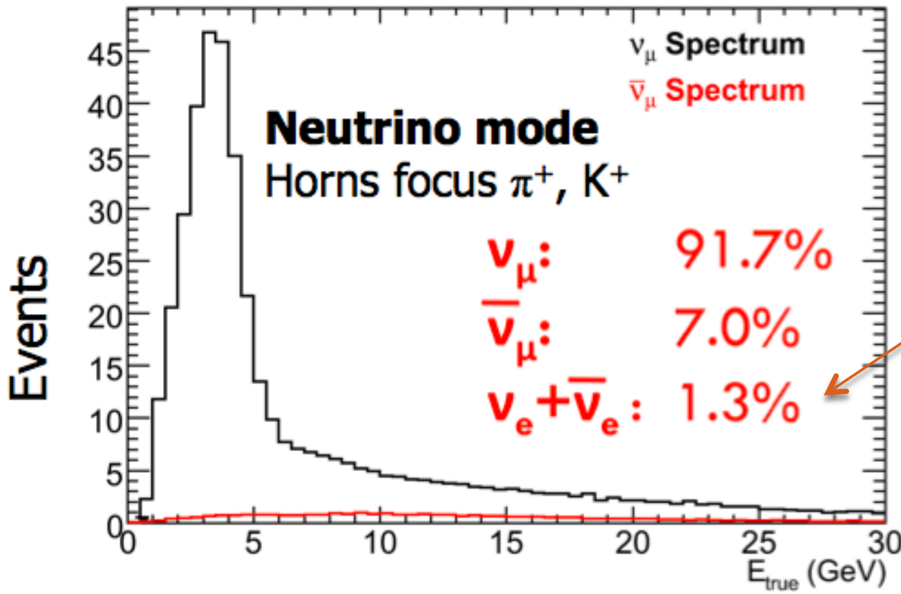


protons delivered by the accelerator

…which are focused (defocused) by a strong magnetic field created by a "focusing horn"

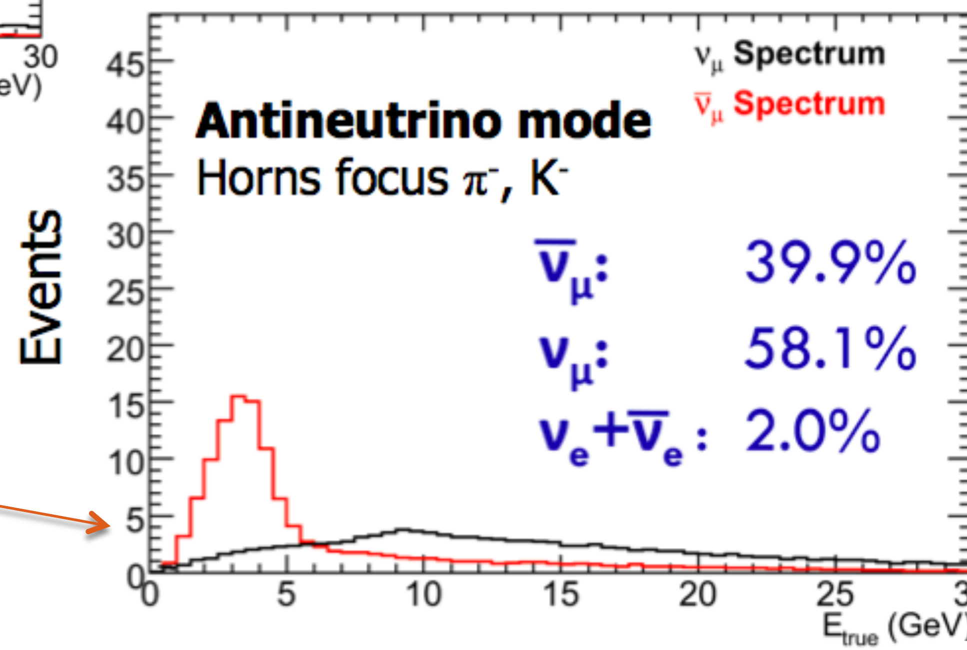
reversing current creates antineutrino beam

The NuMI Beamline at Fermilab



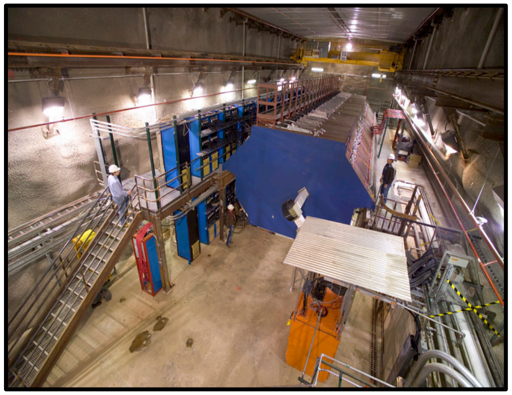
Beamline of the MINOS and MINERνA experiments

electron neutrinos from kaon and muon decays

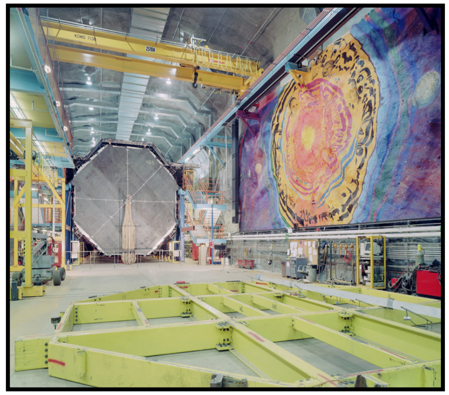


"wrong sign" contamination much worse in antineutrino mode due to differences in π^+/π^- spectra off target and neutrino/antineutrino cross sections

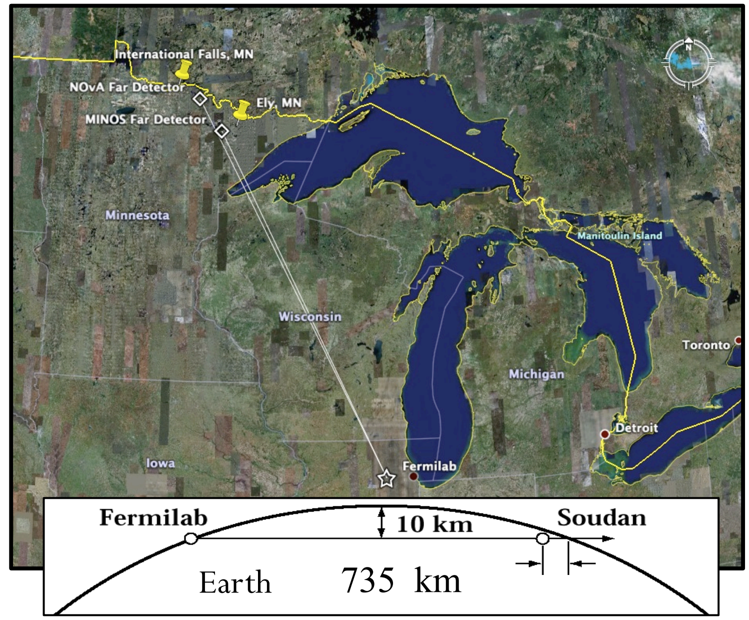
The MINOS Experiment

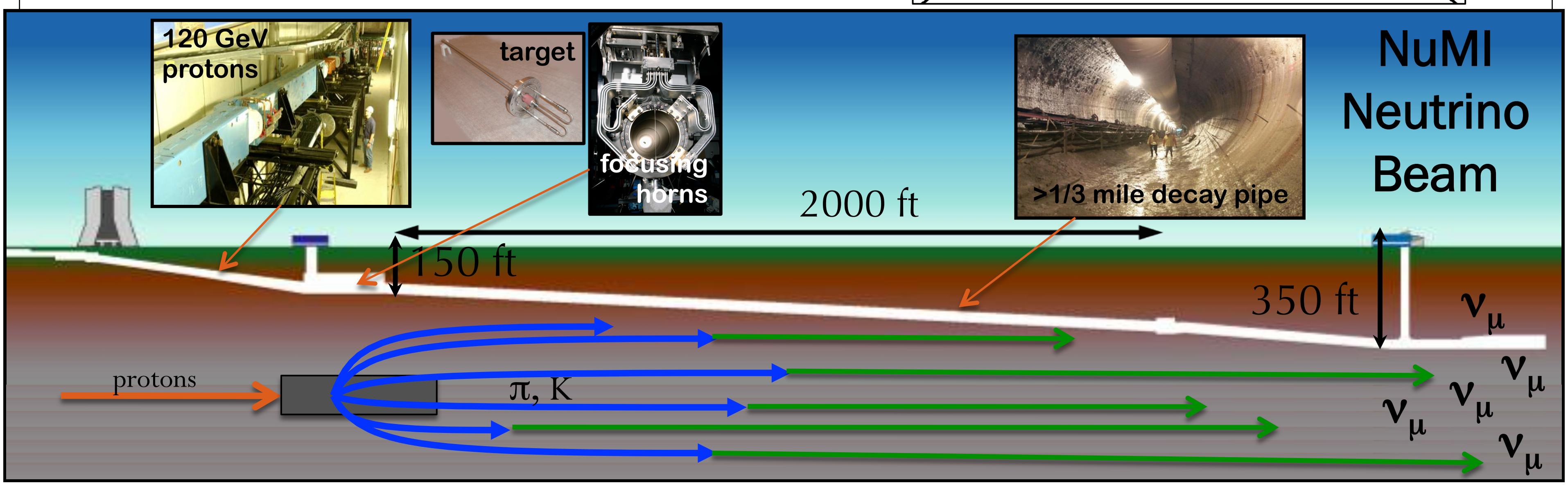


1k ton near detector
at Fermilab

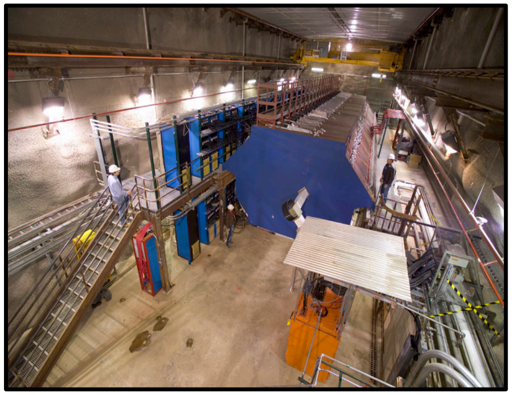


5 kton far detector
at Soudan, MN

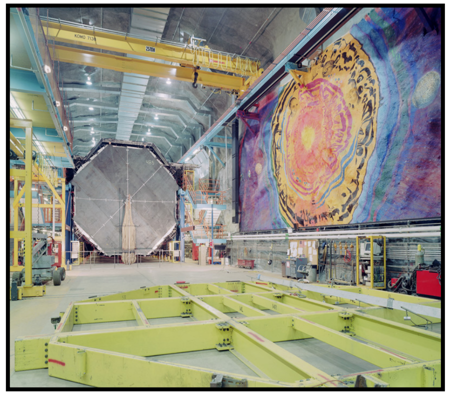




The MINOS Experiment



1k ton near detector
at Fermilab



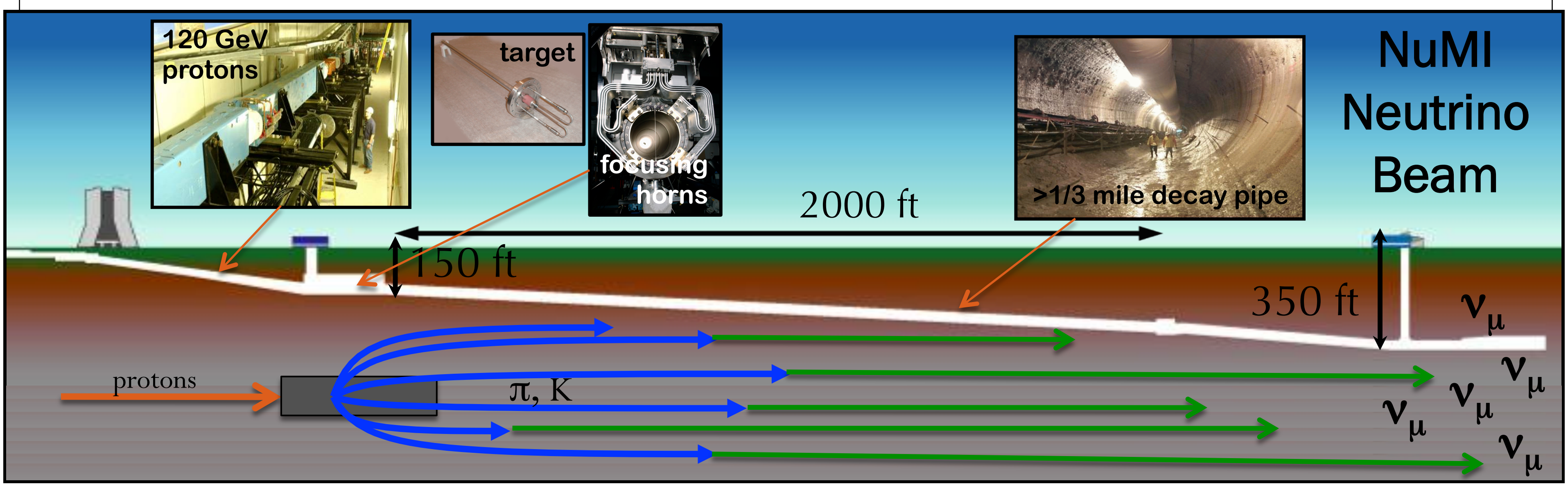
5 kton far detector
at Soudan, MN

$$\langle E \rangle_{MINOS} \approx 3\, GeV$$

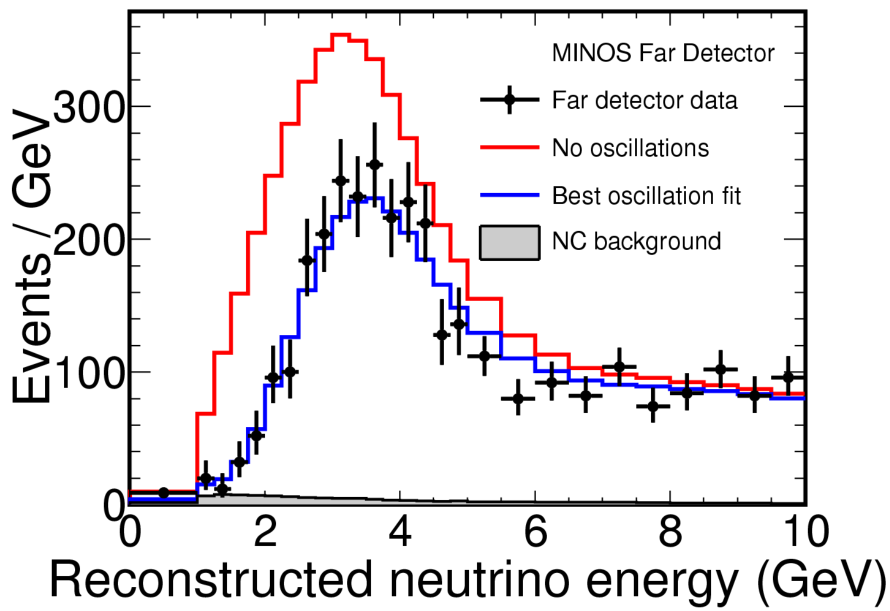
$$\langle L \rangle_{MINOS} \approx 735\ km$$

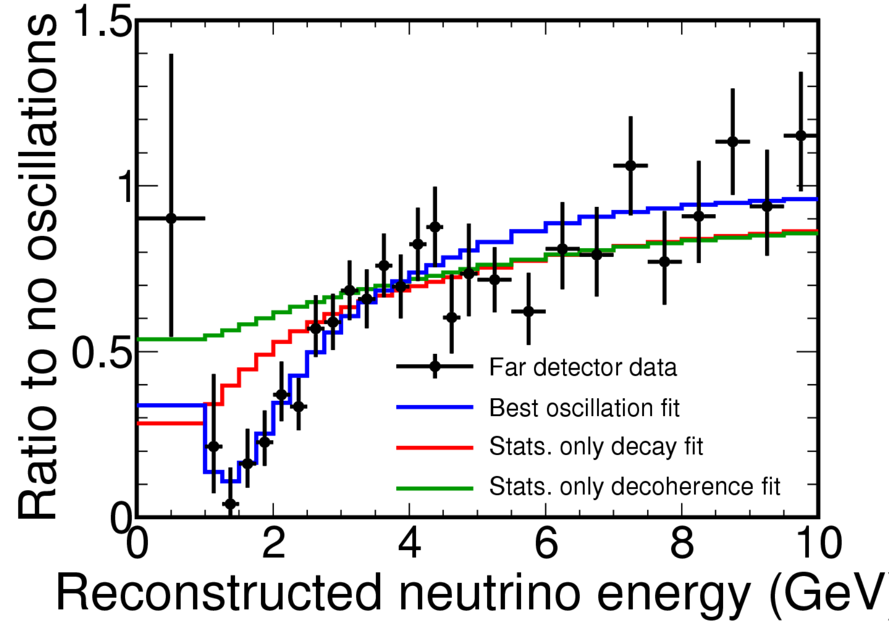
$$for\ \ \sin^2(x) \sim 1$$

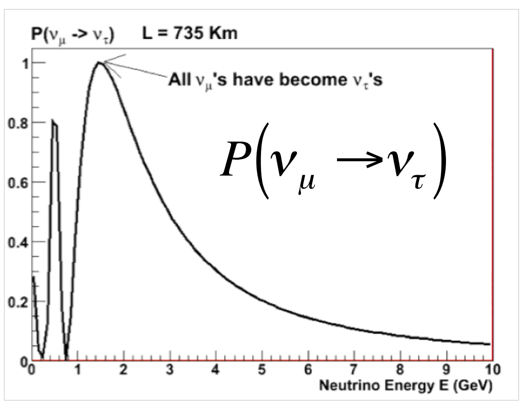
$$\Delta m^2 \geq 1 / \left(1.27 * \frac{735\ km}{3\, GeV} \right) \sim \underline{10^{-3}\, eV^2}$$



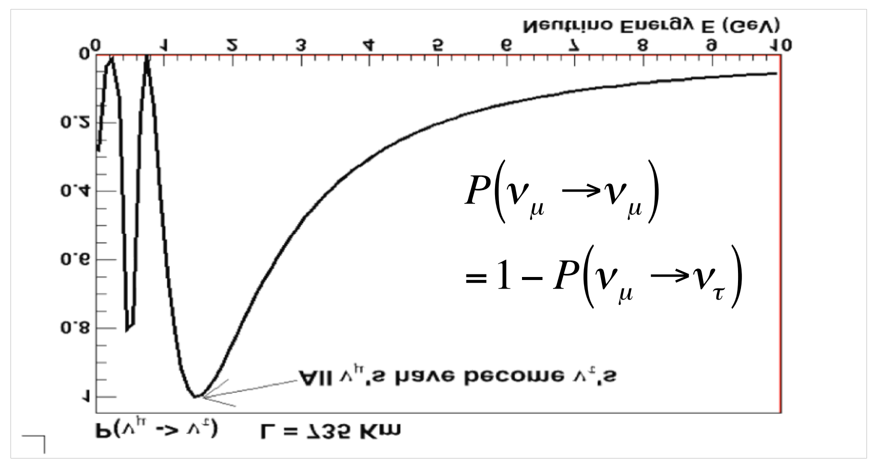
The MINOS Experiment



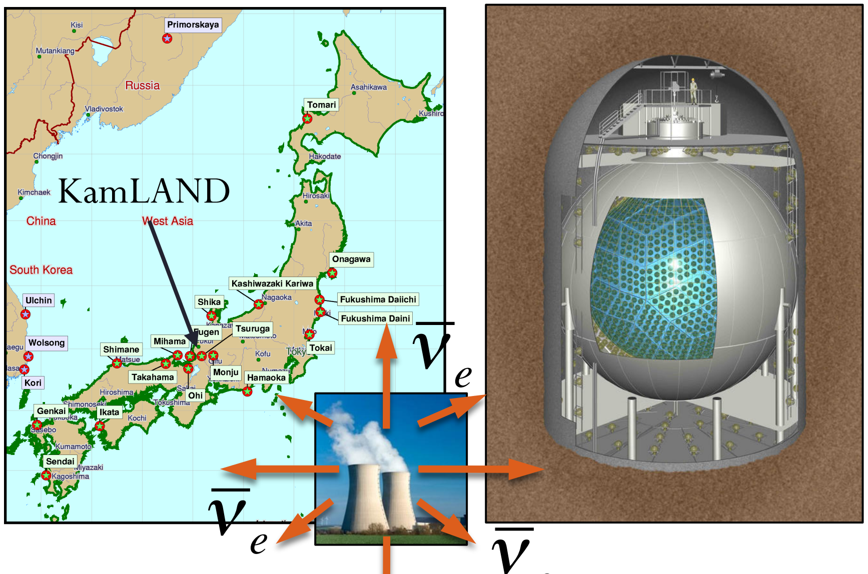




MINOS measures the <u>disappearance</u> of muon neutrinos



The KamLAND Experiment



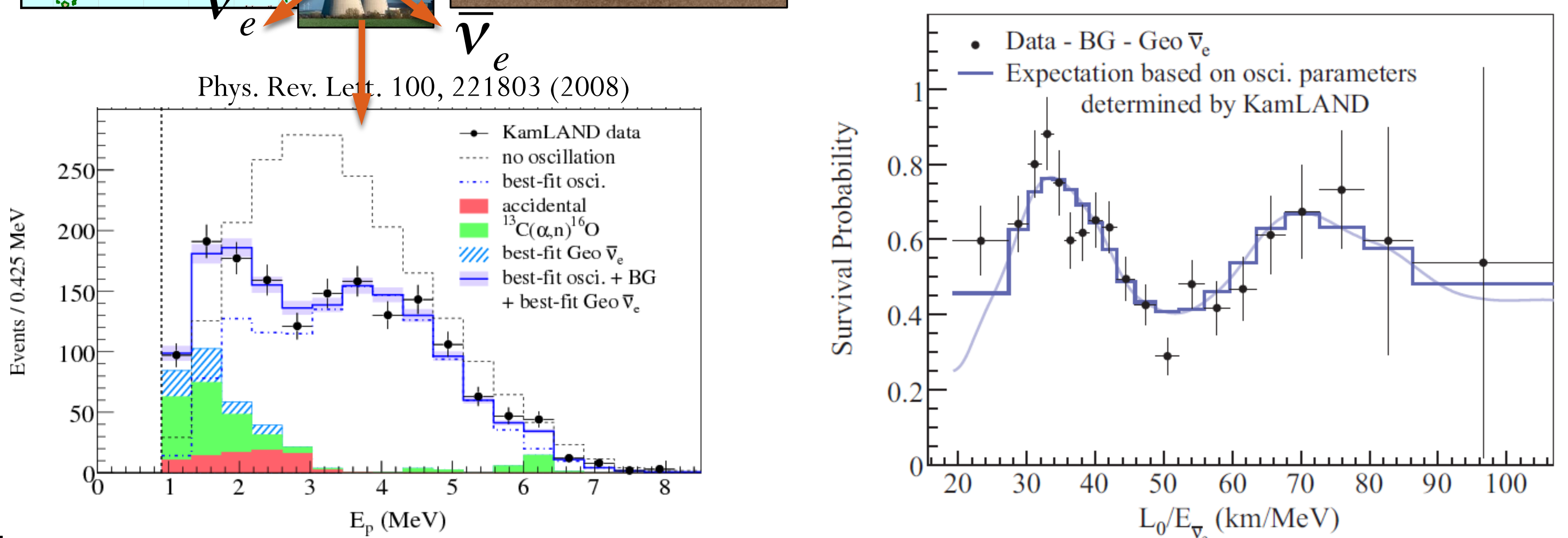
$$\langle E \rangle_{KamLAND} \approx 5\ MeV$$

$$\langle L \rangle_{KamLAND} \approx 180\ km$$

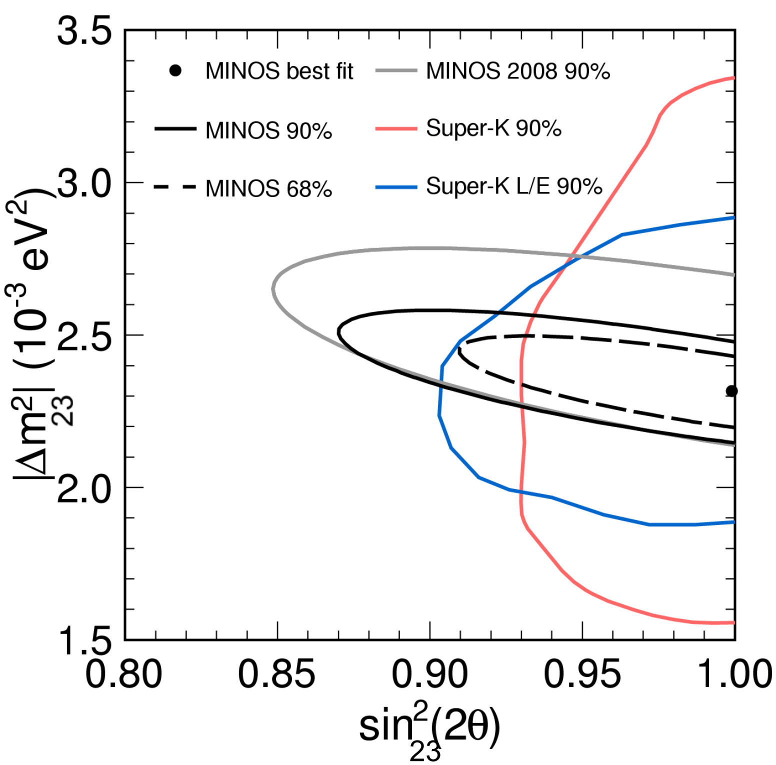
$$for\ \ \sin^2(x) \sim 1$$

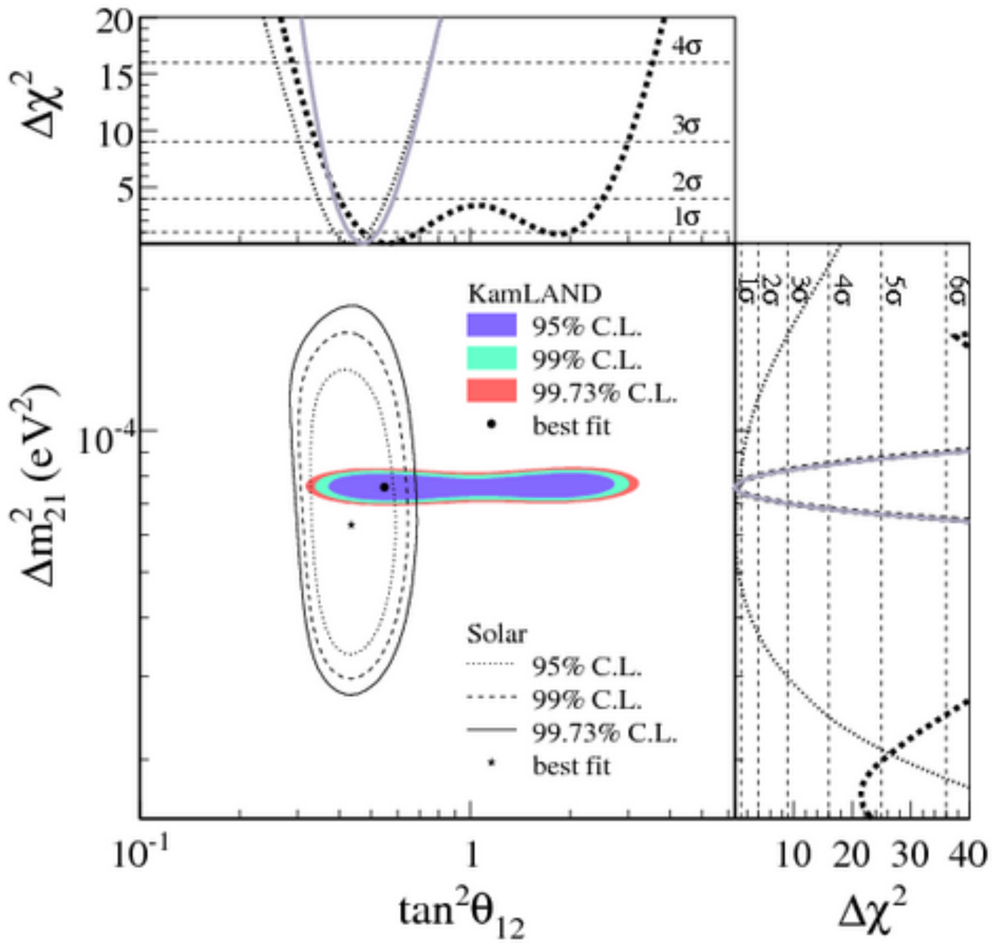
$$\Delta m^2 \geq 1 \Big/ \left(1.27 * \frac{180\ km}{0.005\ GeV}\right) \sim 10^{-5} eV^2$$

Phys. Rev. Lett. 100, 221803 (2008)



Presenting Oscillation Results





SuperK atmospheric data + MINOS

Solar data + KamLAND

Neutrino Mass and Mixing Summary

- "Atmospheric" Osc. Parameters

$$\Delta m^2_{23} = 2.51 \times 10^{-3} eV^2 \qquad (\pm 4.8\%)$$

$$\theta_{23} = 42.3^{\circ}{}^{+5.3}_{-2.8} \qquad (+12.5\%)$$

- "Solar" Osc. Parameters

$$\Delta m^2_{12} = 7.59 \times 10^{-5} eV^2 \qquad (\pm 2.6\%)$$

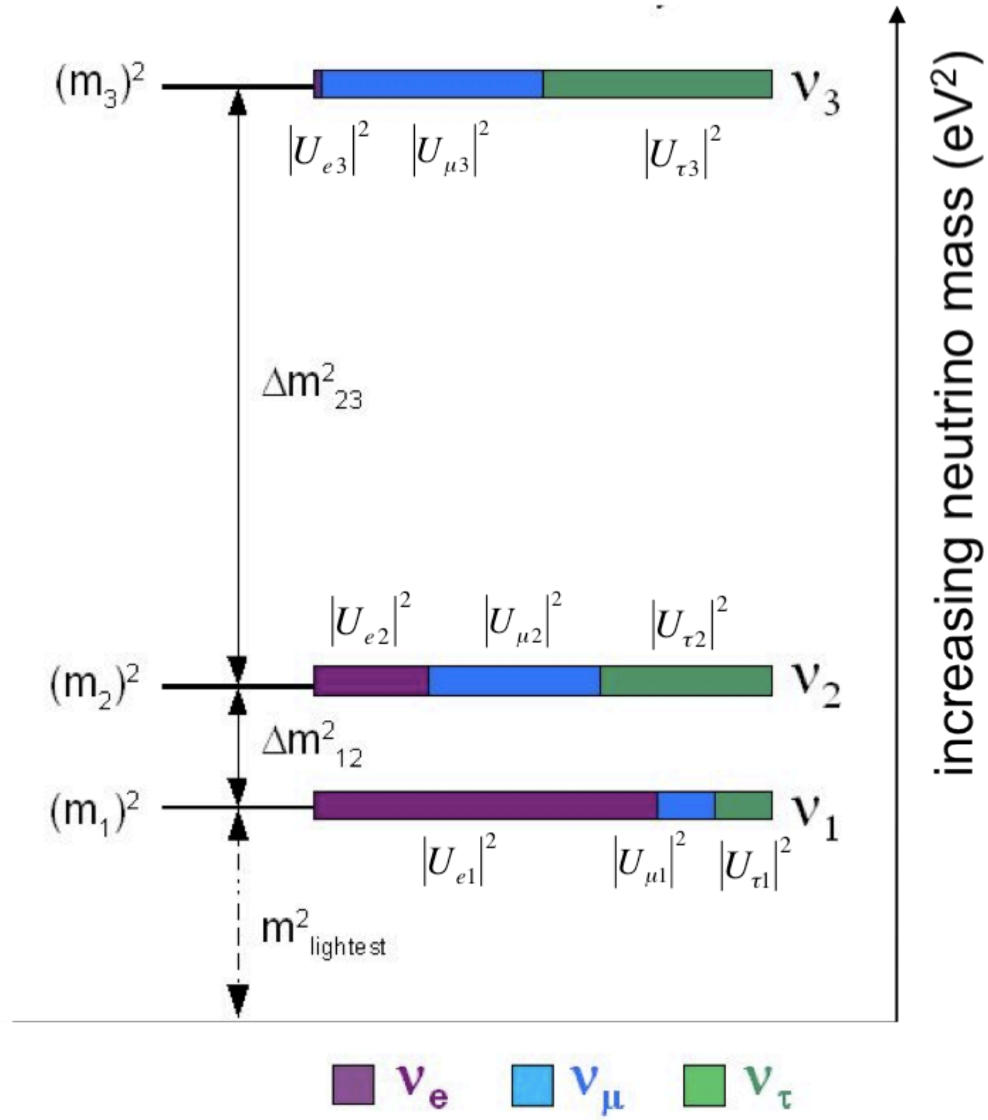
$$\theta_{23} = 34.4^{\circ}{}^{+1.0}_{-1.0} \qquad (\pm 2.9\%)$$

- Other Osc. Parameters

$$\theta_{13} < 9.4^{\circ} \qquad (1\sigma)$$

δ_{CP} unknown

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.6 & <0.1 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



* parameter values from global fits to data, hep-ph 1001.4524

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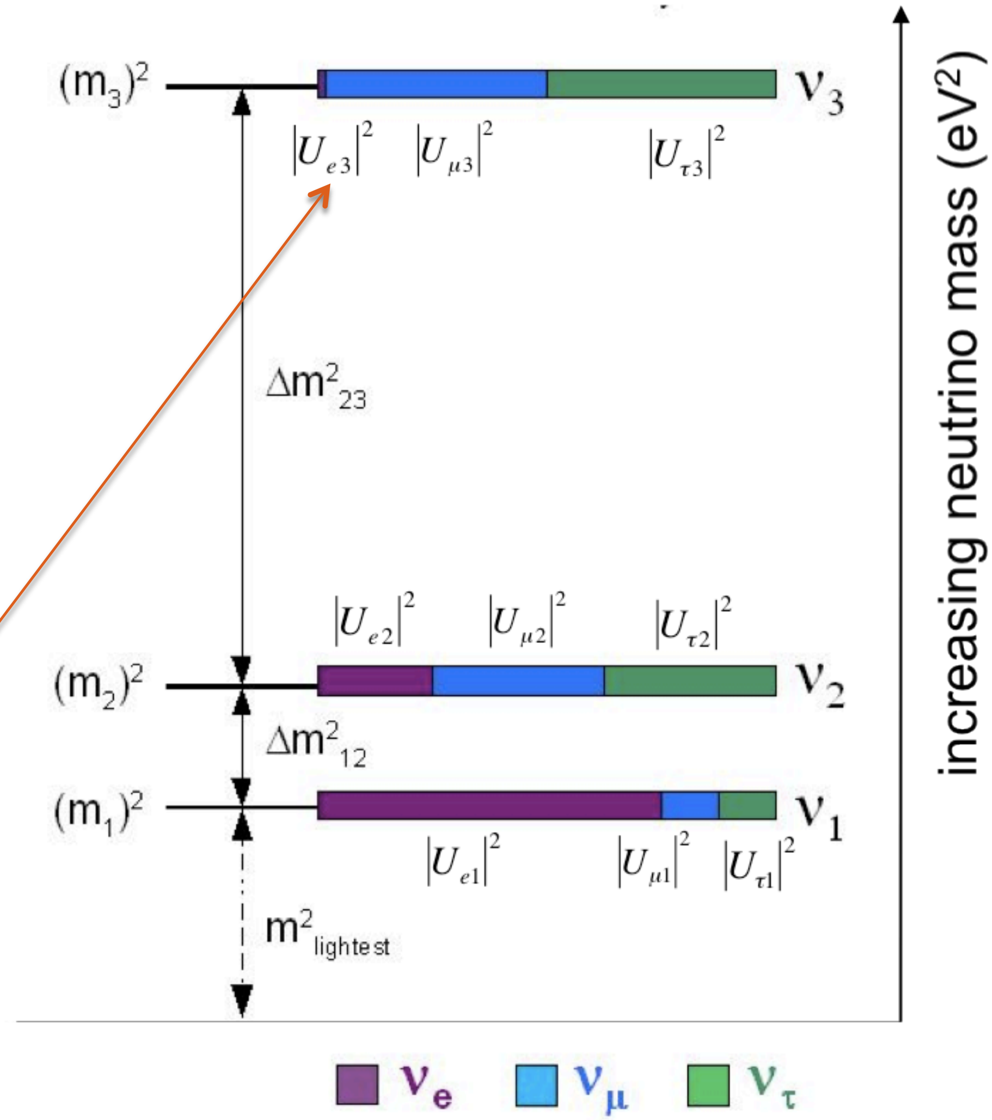


Still Many Open Questions

What is the absolute mass scale of the neutrinos?

What is the mass mechanism for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Are there additional neutrino states, or only three?

Why is neutrino mixing so different from quark mixing?

Is θ_{23} maximal?

What is θ_{13}? Why is it so small?

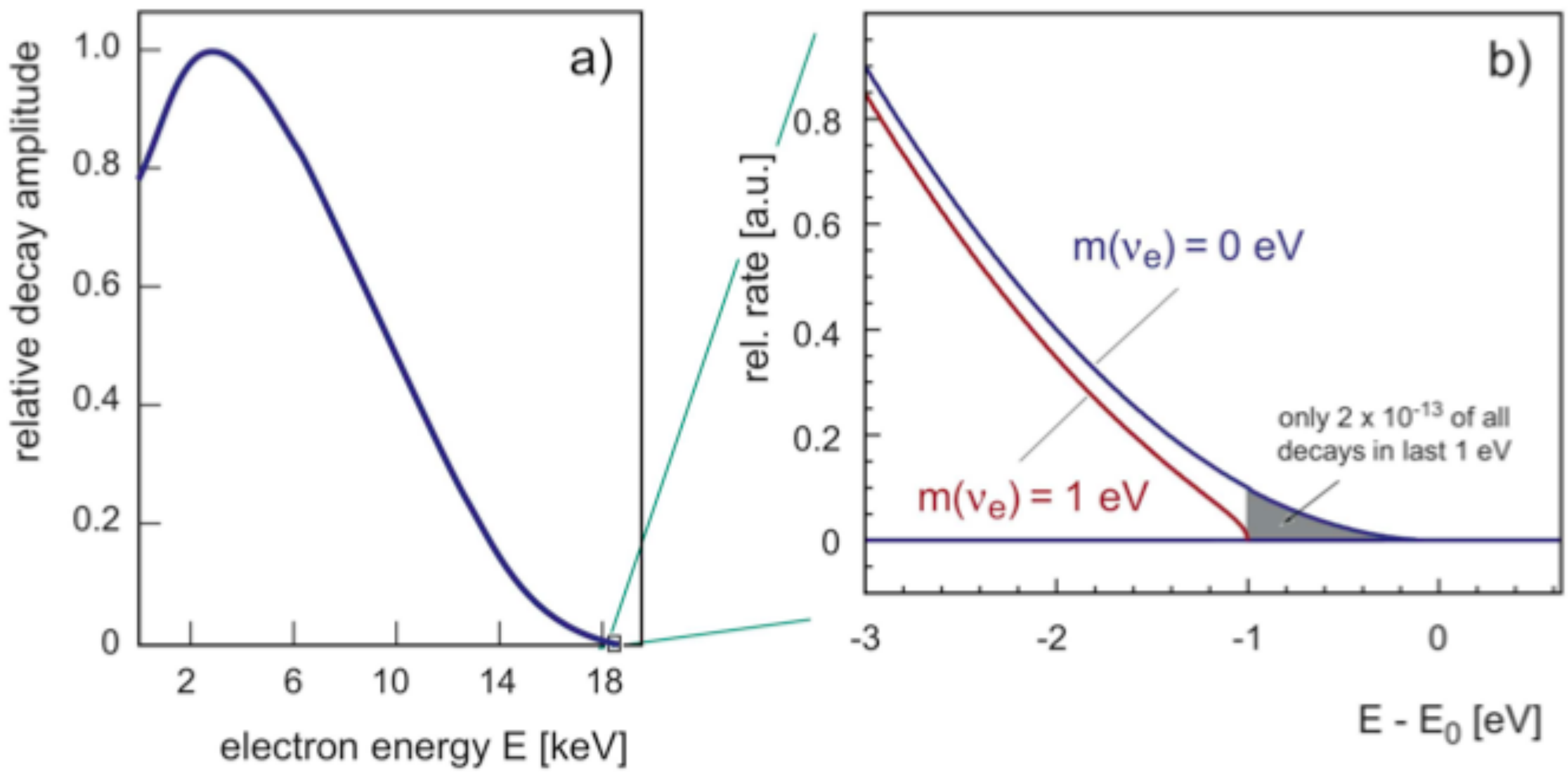
Is there CP violation in the neutrino sector (what is δ)?

What is the hierarchy of the neutrino masses (sign of Δm_{23}^2)?

Still Many Open Questions

What is the absolute mass scale of the neutrinos?

Best known laboratory method is to look at
endpoint of electron energy spectrum in tritium decay



Still Many Open Questions

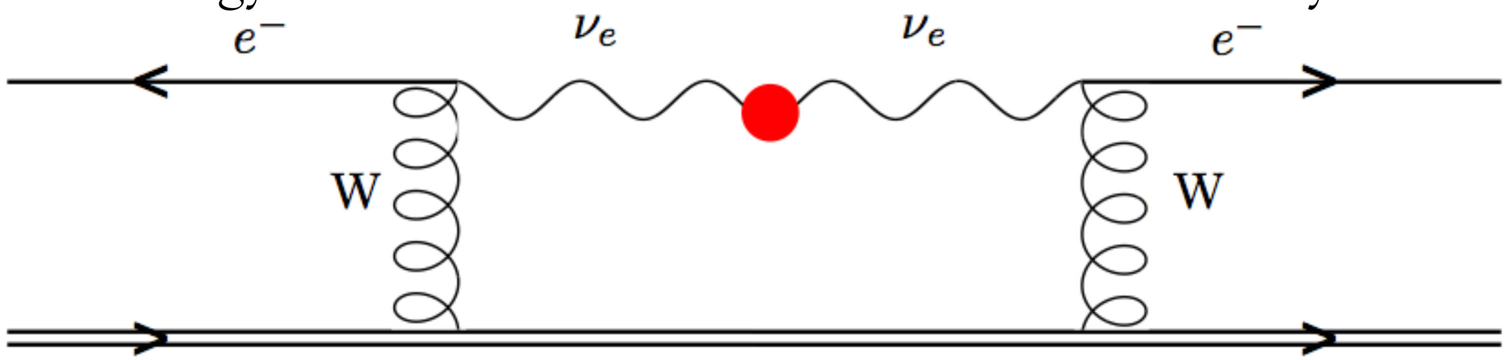
What is the absolute mass scale of the neutrinos?

KATRIN's goal is to reach 250 meV sensitivity

Still Many Open Questions

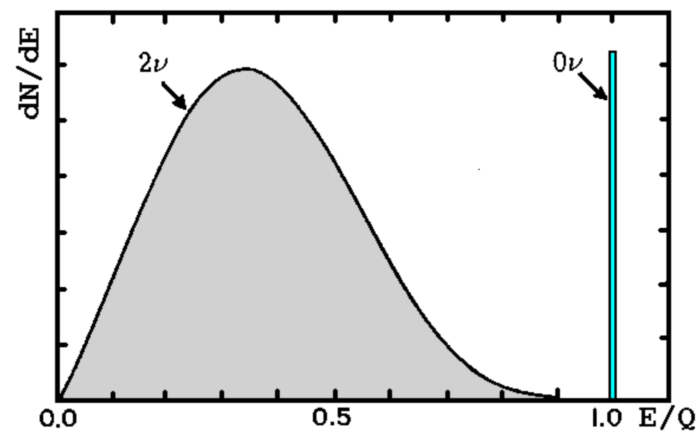
What is the mass mechanism for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Strategy is to search for neutrinoless double beta decay



Many experiments:

- CUORE (^{130}Te)
- GERDA (^{76}Ge)
- NEMO (^{100}Mo, ^{82}Se)
- . . .



Still Many Open Questions

What is the **absolute mass scale** of the neutrinos?

What is the **mass mechanism** for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Are there **additional neutrino** states, or only three?

Why is neutrino **mixing so different** from quark mixing?

accessible through oscillations

Is θ_{23} maximal?

What is θ_{13}? Why is it so small?

Is there **CP violation** in the neutrino sector (what is δ)?

What is the **hierarchy** of the neutrino masses (sign of Δm_{23}^2)?

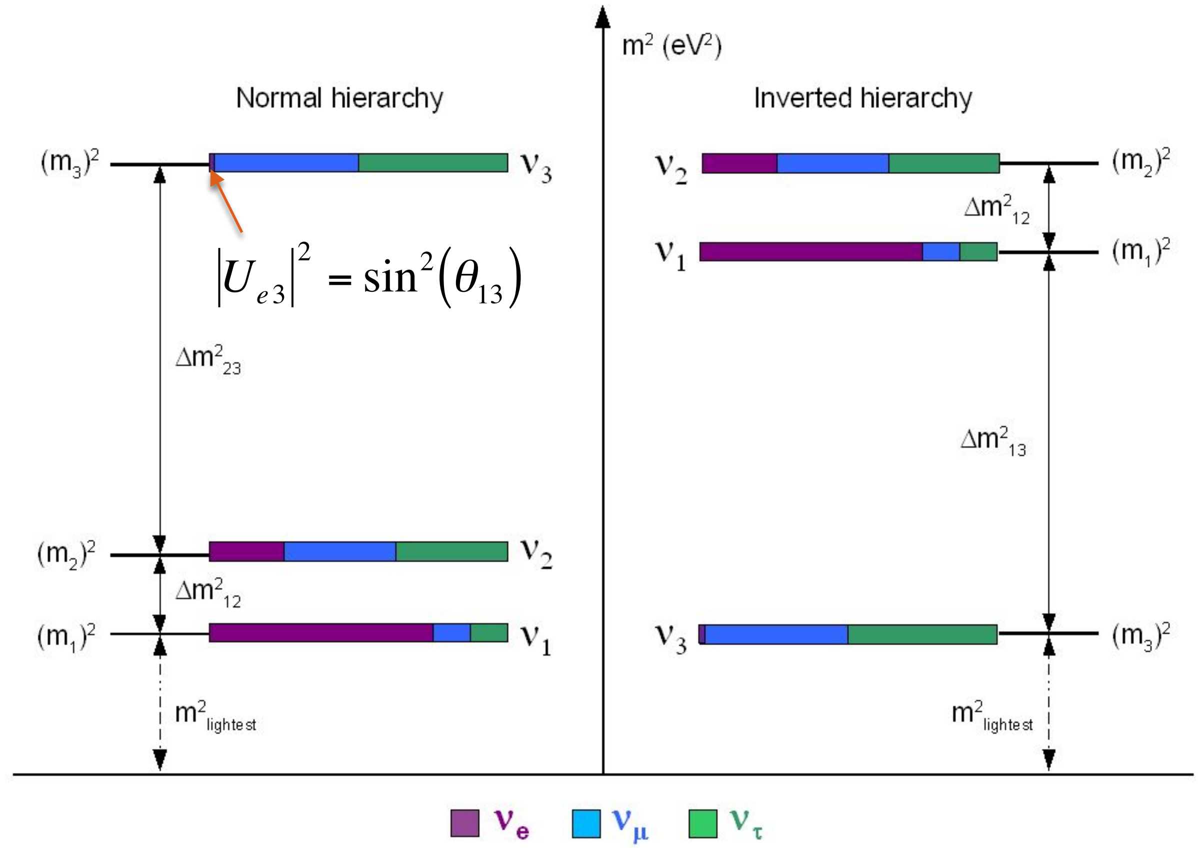
Still Many Open Questions

Quarks

$$U_{CKM} \sim \begin{pmatrix} 1 & 0.2 & 0 \\ 0.2 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Neutrinos

$$U_{MNS} \sim \begin{pmatrix} 0.8 & 0.6 & <0.1 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



Key to accessing the mass hierarchy and CP violation is $\nu_\mu \rightarrow \nu_e$ oscillations at the atmospheric (Δm_{23}^2) mass splitting

θ_{13} is the Gate Keeper

$$P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} T_1 - \alpha \sin 2\theta_{13} T_2 - \alpha \sin 2\theta_{13} T_3 + \alpha^2 T_4$$

$$\alpha = \frac{\Delta m^2{}_{21}}{\Delta m^2{}_{31}}$$

$$T_1 = \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2}$$

$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

CP Violating terms

$$T_3 = \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

$$\Delta = \frac{\Delta m^2{}_{31} L}{4E_\nu} \qquad x = \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2{}_{31}}$$

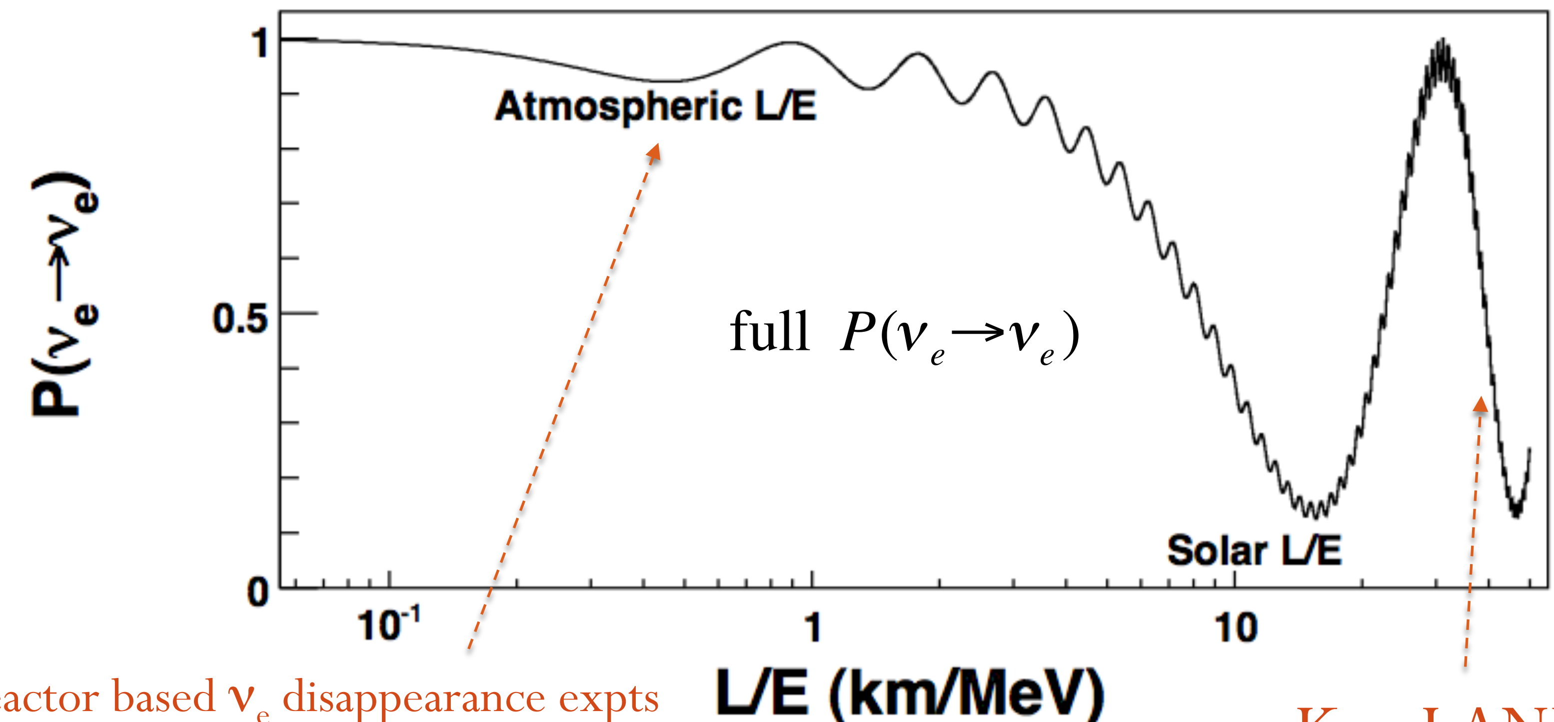
Matter Effects

Is there CP violation in the neutrino sector?

What is the mass hierarchy?

θ_{13} from ν_e Disappearance

- θ_{13} can be directly probed through ν_e disappearance at the right L/E
- Note, no sensitivity to mass hierarchy or CP violation



Reactor based ν_e disappearance expts such as Double Chooz and Daya Bay

KamLAND

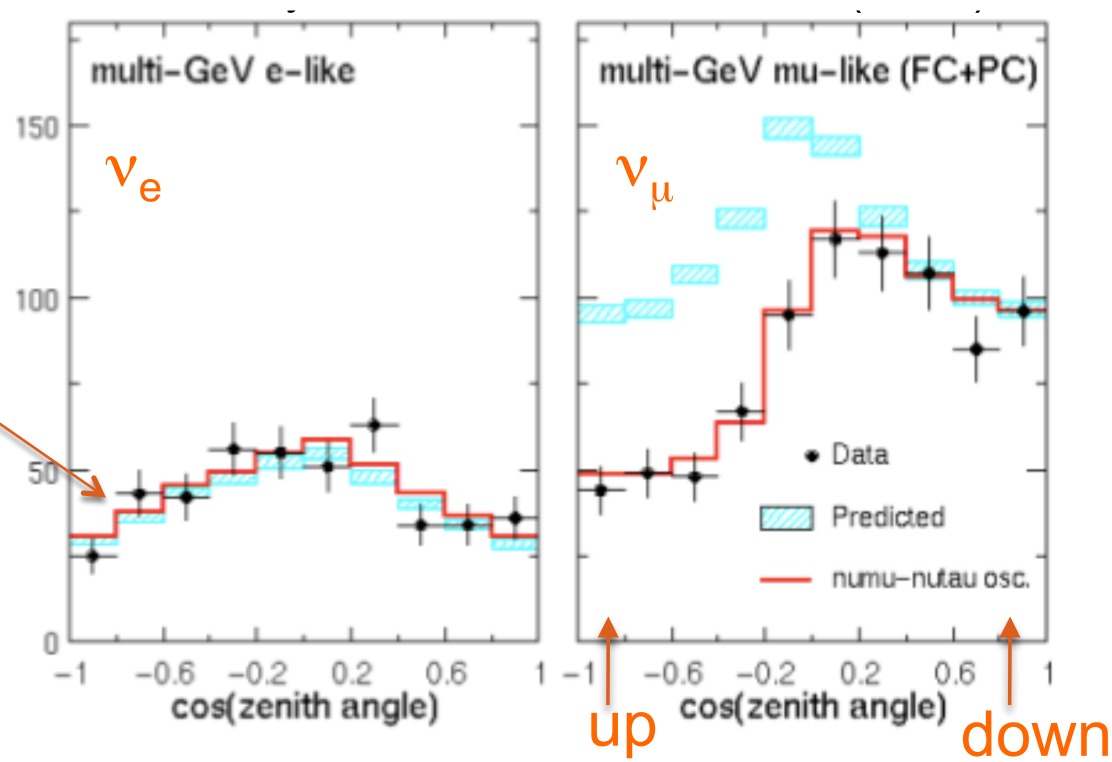
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \cdot \sin^2(1.27 \cdot \Delta m^2_{23} \cdot L/E)$$

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{12} \cdot \sin^2(1.27 \cdot \Delta m^2_{12} \cdot L/E)$$

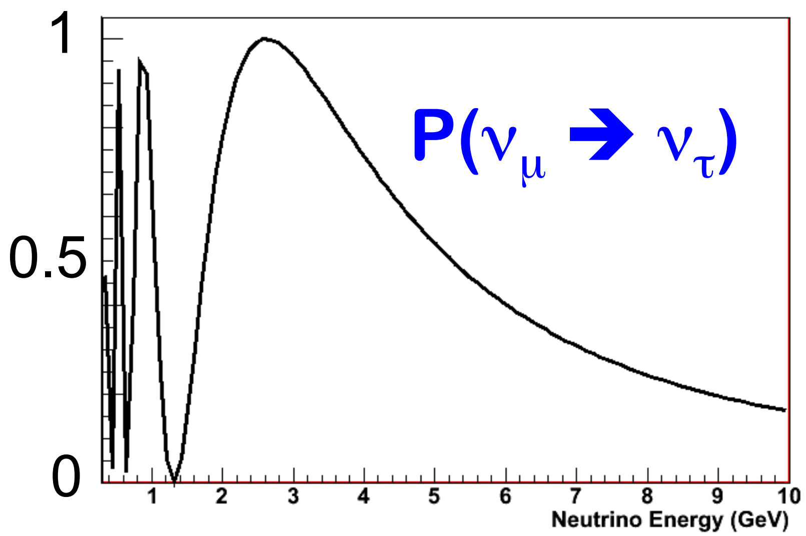
ν_μ Disappearance vs. ν_e Appearance

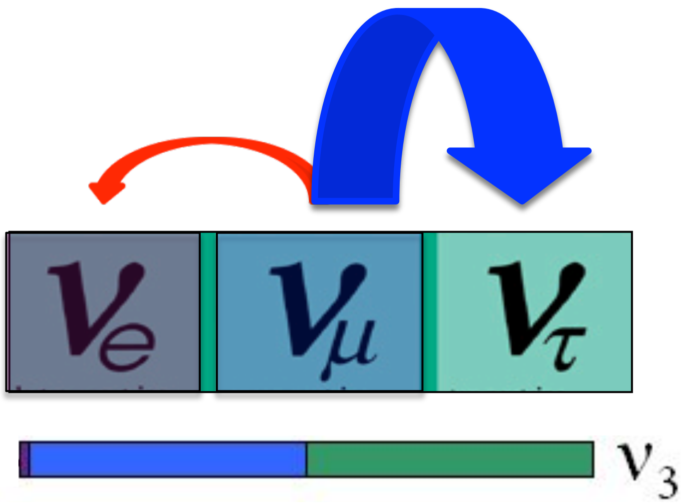
SuperK / MINOS ν_μ disappearance mostly due to $\nu_\mu \rightarrow \nu_\tau$

No noticeable excess of ν_e in upward direction in SuperK atmospheric data

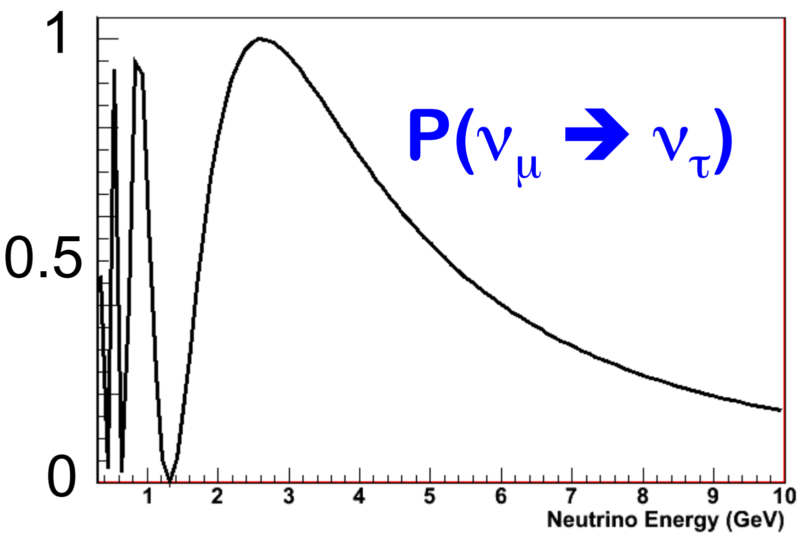


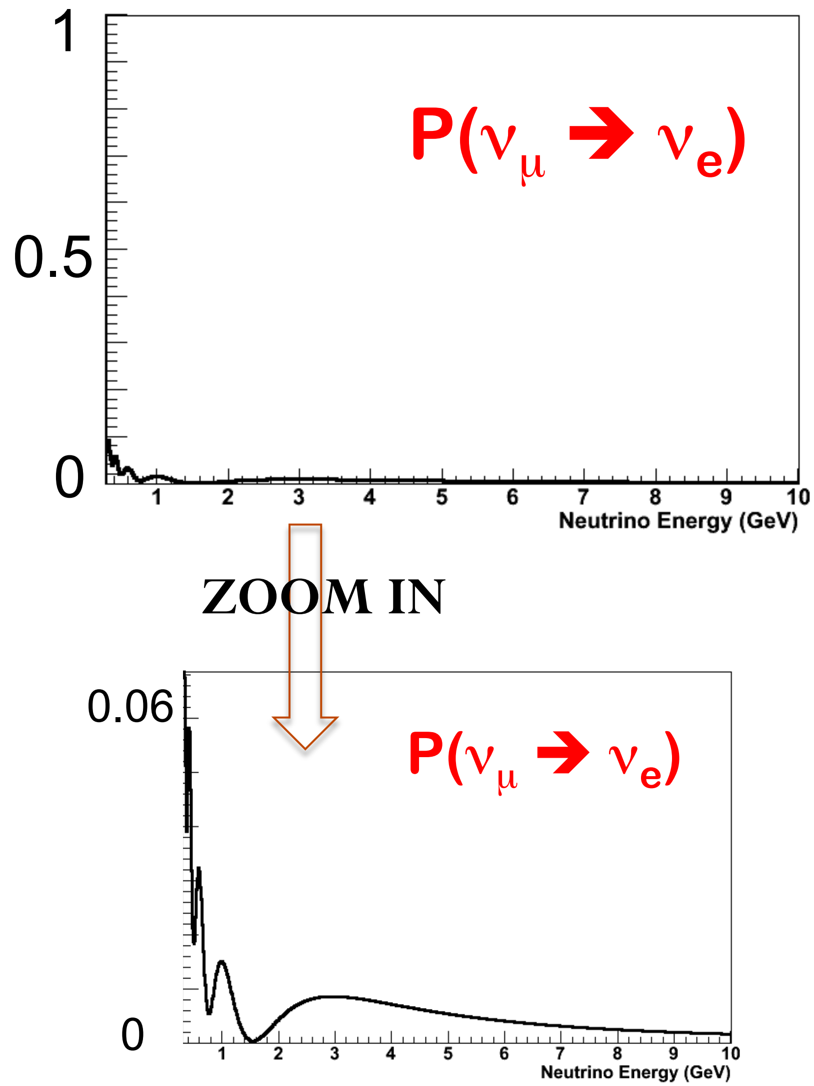
ν_μ Disappearance vs. ν_e Appearance

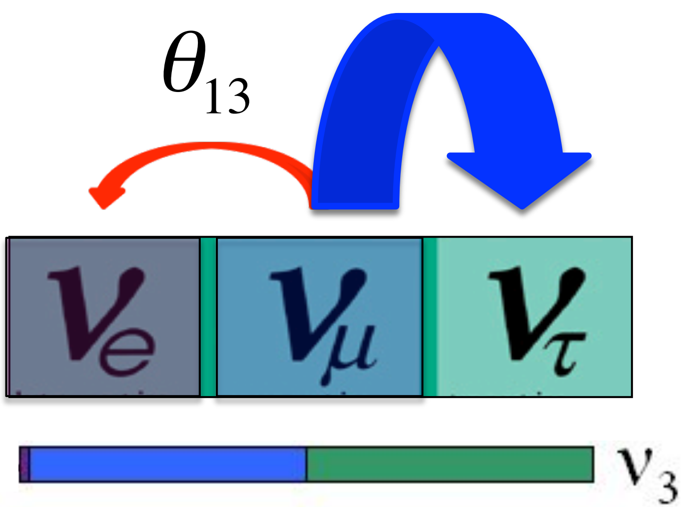




ν_μ Disappearance vs. ν_e Appearance

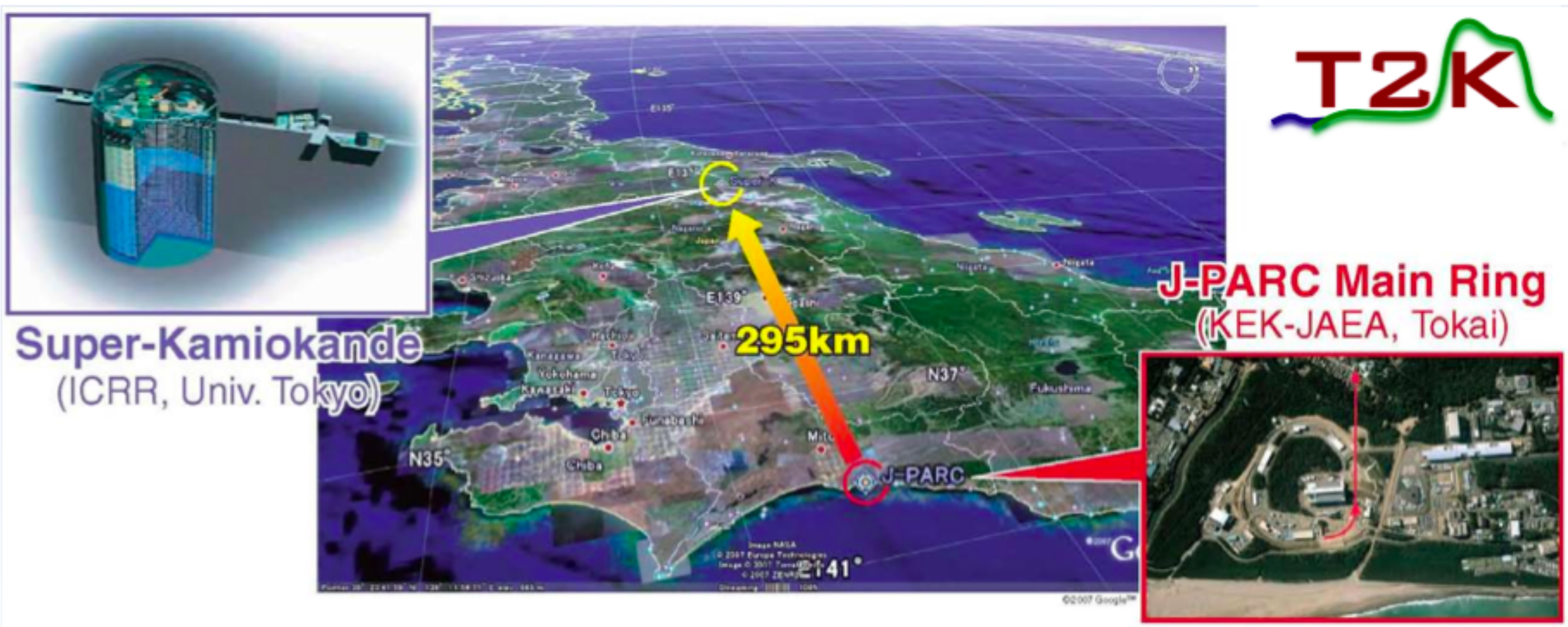






Long Baseline ν_e Appearance Searches

- MINOS detectors not optimized for electron detection, but have collected lots of data (8.2e20 POT)
- T2K uses Super Kamiokande detector with excellent electron reconstruction, but just started data collection (1.4e20 POT)



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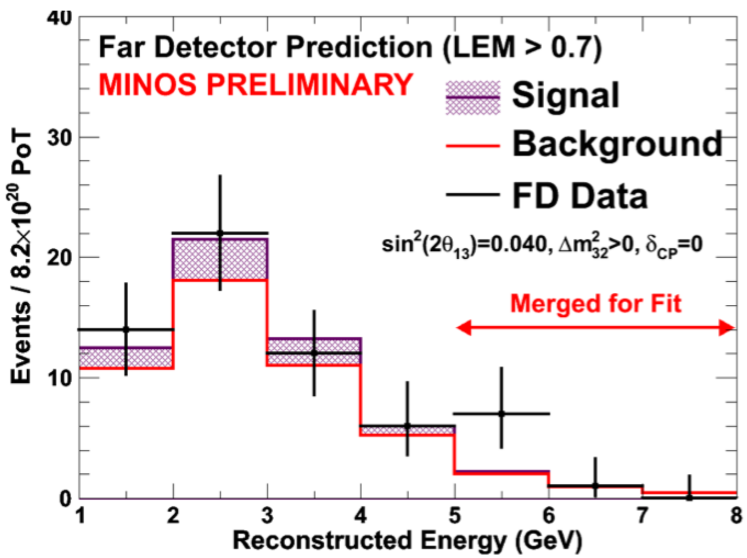
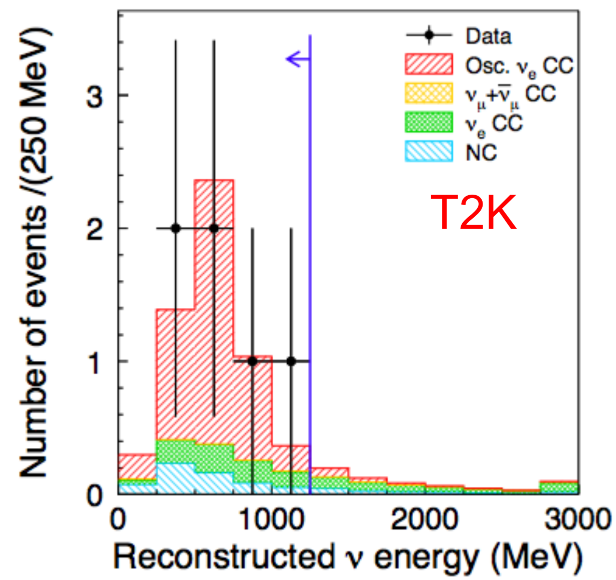




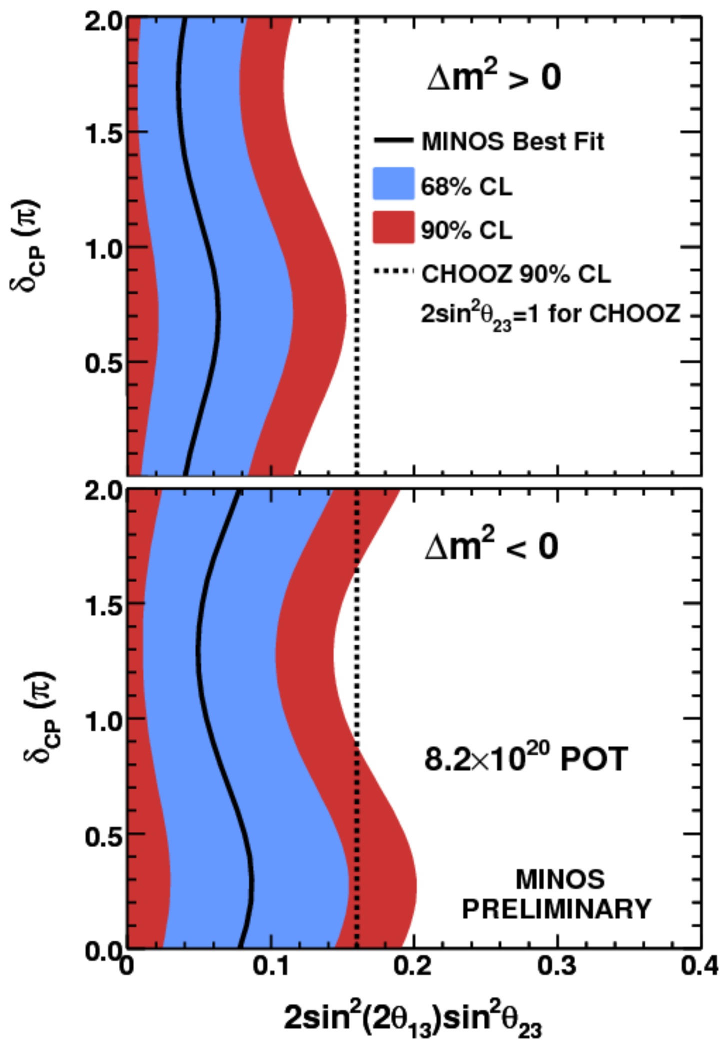
N_{ν_e} expected: $49.5 \pm 2.8(syst) \pm 7.0(stat)$

N_{ν_e} observed: 62

N_{ν_e} expected: $1.5 \pm 0.3(syst)$

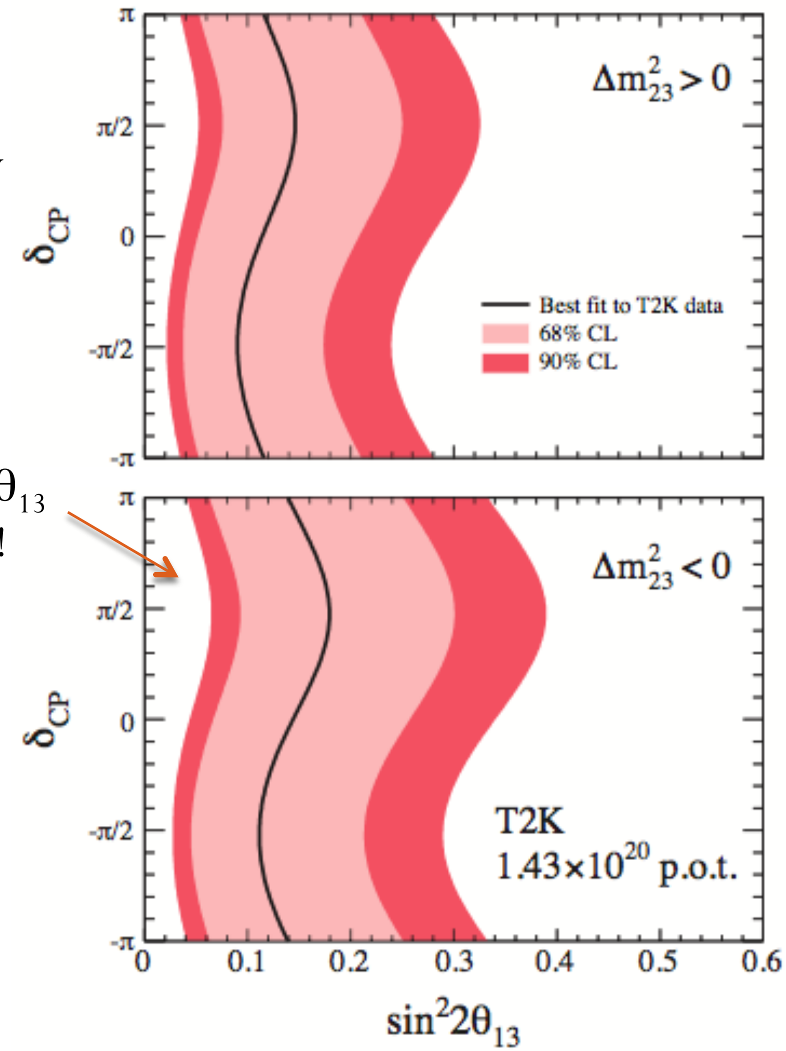
N_{ν_e} observed: 6

MINOS and T2K ν_e Results

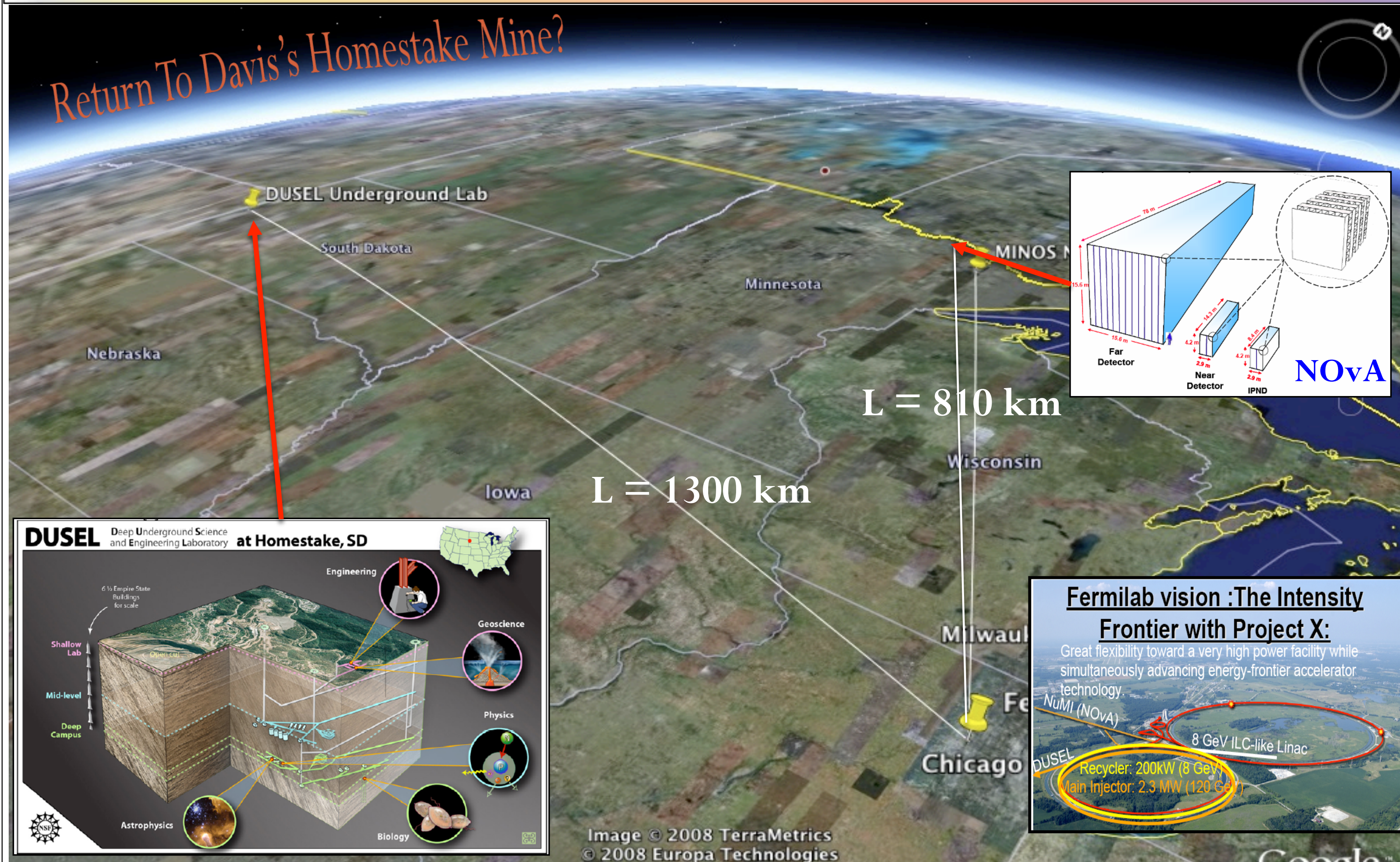


Value of θ_{13} depends on mass hierarchy and δ_{CP}

A hint at non-zero θ_{13} from T2K!



Future Long Baseline Experiments



Long Baseline Neutrino Experiment (LBNE)

- Baseline designs involve 100 kton water Cherenkov detector(s) AND/OR 17 kton liquid argon TPC neutrino detectors(s)

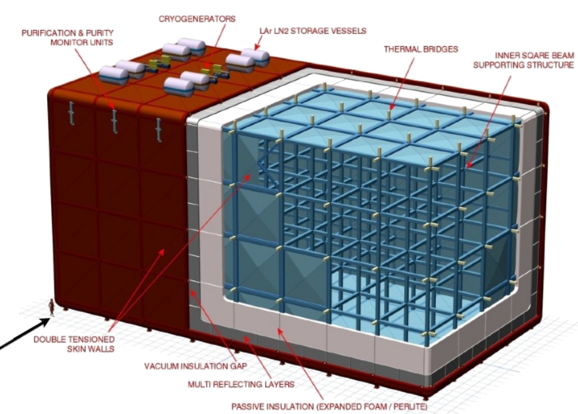
Long Baseline ν Physics
- θ_{13}, Mass Hierarchy, and CP violation
- Osc. parameters precision measurements

Proton Decay

Supernova Burst/Relic neutrinos

Atmospheric/Solar/UHE neutrinos

neutrino physicists



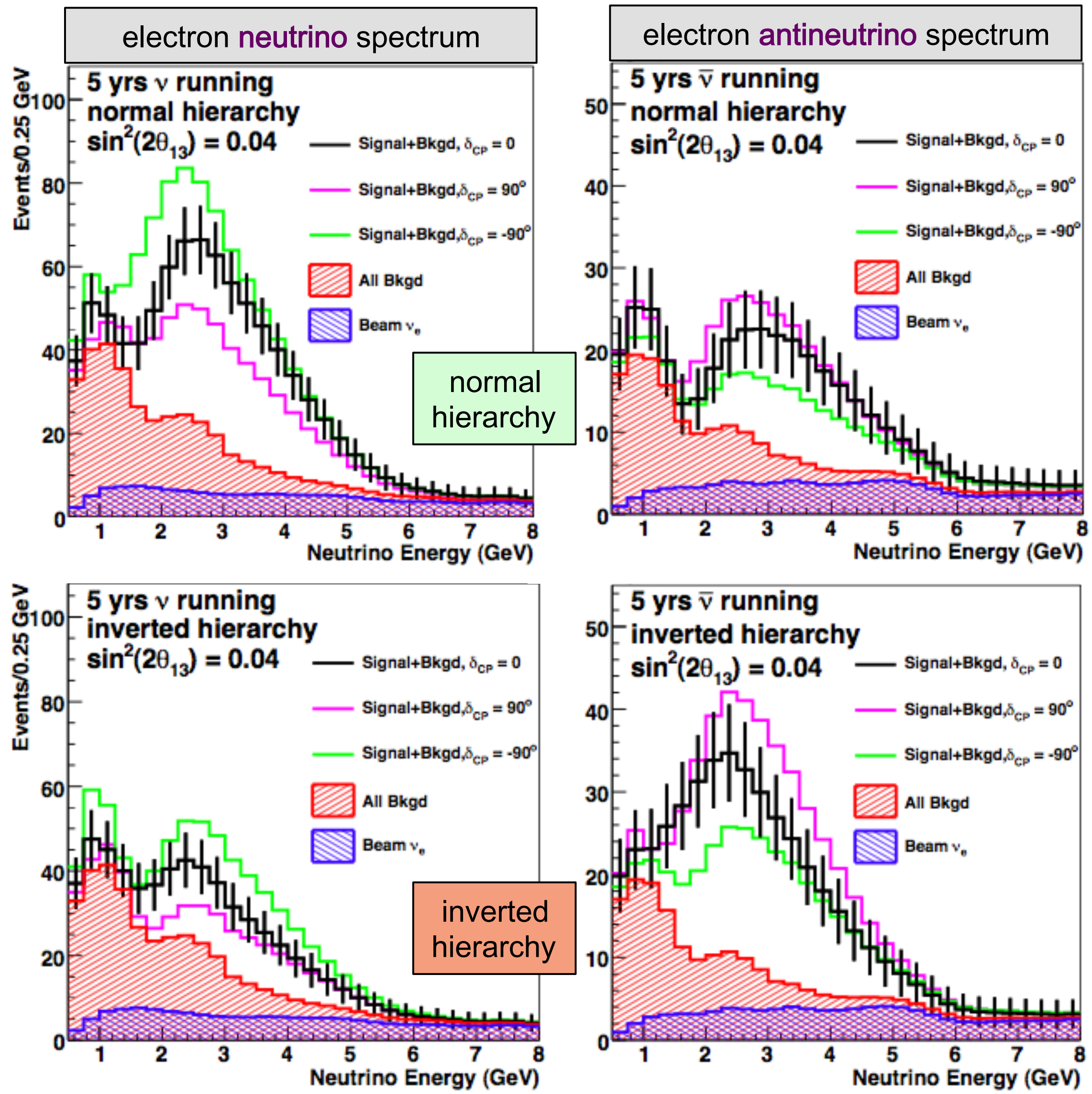
Long Baseline Neutrino Experiment (LBNE)

Comparison between neutrino and antineutrino oscillations is the key to extracting mass hierarchy and CP violation

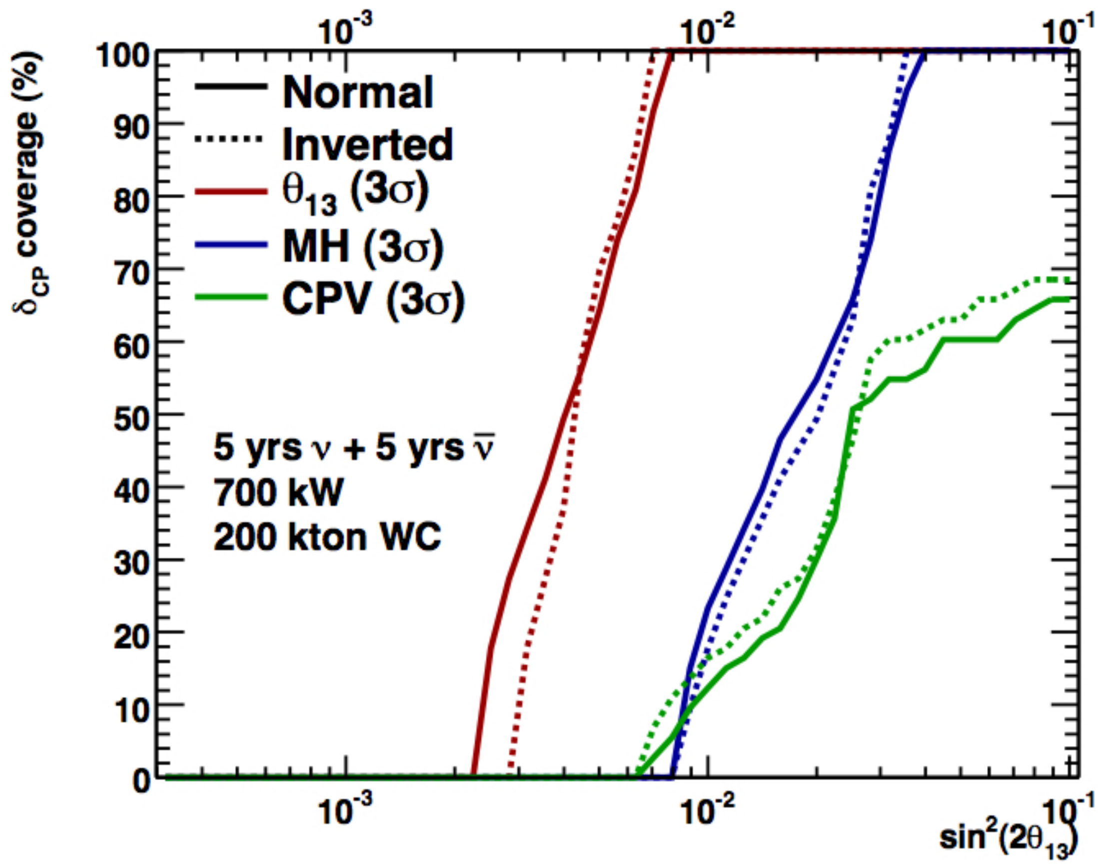
$$P(\nu_\mu \rightarrow \nu_e)$$

vs.

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



Long Baseline Neutrino Experiment (LBNE)



Right of red curve are values of δ_{CP} and $\sin^2(2\theta_{13})$ for which LBNE can resolve non-zero θ_{13} at 3σ

Right of blue curve are values of δ_{CP} and $\sin^2(2\theta_{13})$ for which LBNE can determine mass hierarchy at 3σ

Right of green curve are values of δ_{CP} and $\sin^2(2\theta_{13})$ for which LBNE can establish CP violation at 3σ

Summary II

- Neutrino mass and mixing has been firmly established as the solution to the solar and atmospheric neutrino puzzles
- However, still many open questions yet to answer:

What is the absolute mass scale of the neutrinos?

Heaviest one heavier than $\sqrt{\Delta m^2_{23}} \approx 50\ meV$

What is the mass mechanism for neutrinos? Dirac vs. Majorana particles. Are neutrinos their own antiparticles?

Are there additional neutrino states, or only three?

LSND and MiniBooNE

Why is neutrino mixing so different from quark mixing?

accessible through oscillations

Is θ_{23} maximal?

What is θ_{13}? Why is it so small?

Is there CP violation in the neutrino sector (what is δ)?

Could the leptons hold the key to understanding the matter dominated universe?

What is the hierarchy of the neutrino masses (sign of $\Delta m_{23}{}^2$)?

- Plus the unknown unknowns. Neutrinos have a reputation for surprises requiring "desperate remedies"!

Acknowledgements

- Many thanks to those from whom I liberally borrowed slides and ideas, especially:
  - Jorge Morfin (Fermilab)
  - Boris Kayser (Fermilab)
  - Stephen Parke (Fermilab)
  - Sam Zeller (Fermilab)
  - Kevin McFarland (University of Rochester)
  - Bonnie Fleming (Yale)
- Useful references for further reading:
  - K. Zuber, *Neutrino Physics*, 2004
  - J. Thomas, P. Vahle, *Neutrino Oscillations: Present Status and Future Plans*, 2008
  - F. Close, *Neutrino*, 2010
  - F. Halzen, *Quarks and Leptons*, 1984

Extras

MINOS Antineutrinos

Expect 156 events with no oscillations

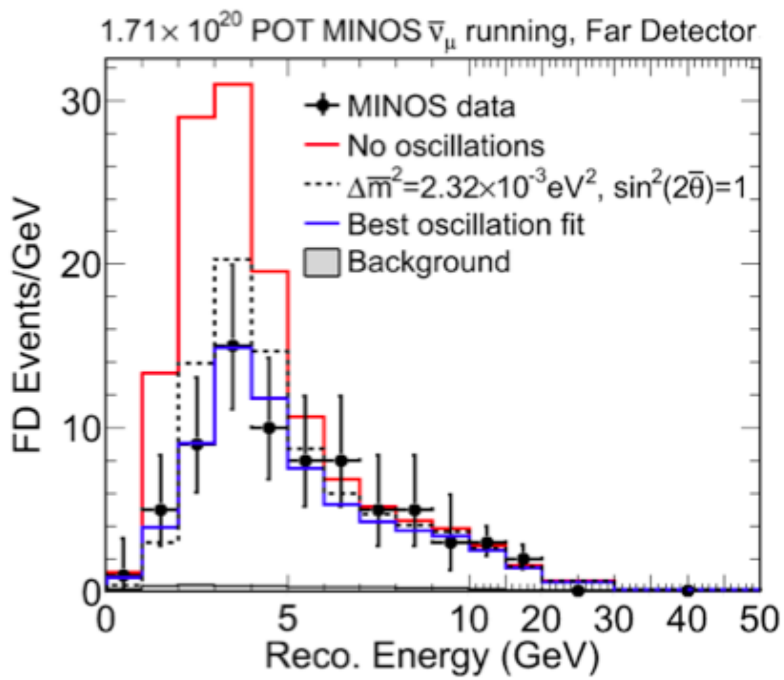
Observe 97 events

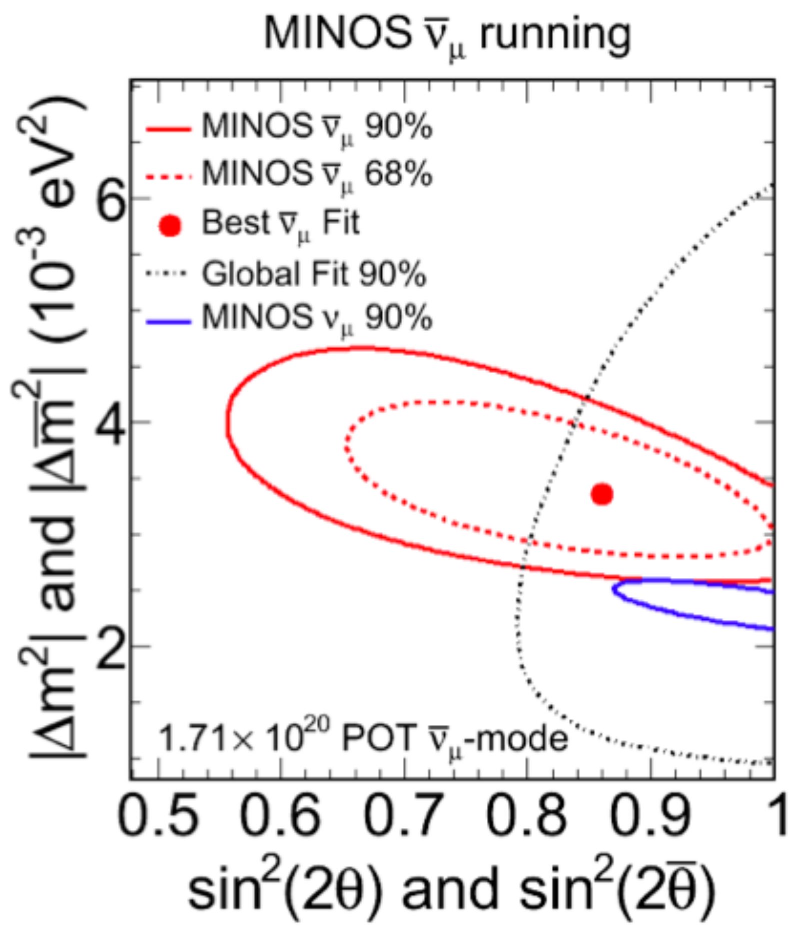
- No oscillations disfavoured at 6.3σ

Best fit to oscillations:

$$|\Delta\overline{m}^2| = (3.36^{+0.46}_{-0.40}(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}\,\text{eV}^2$$

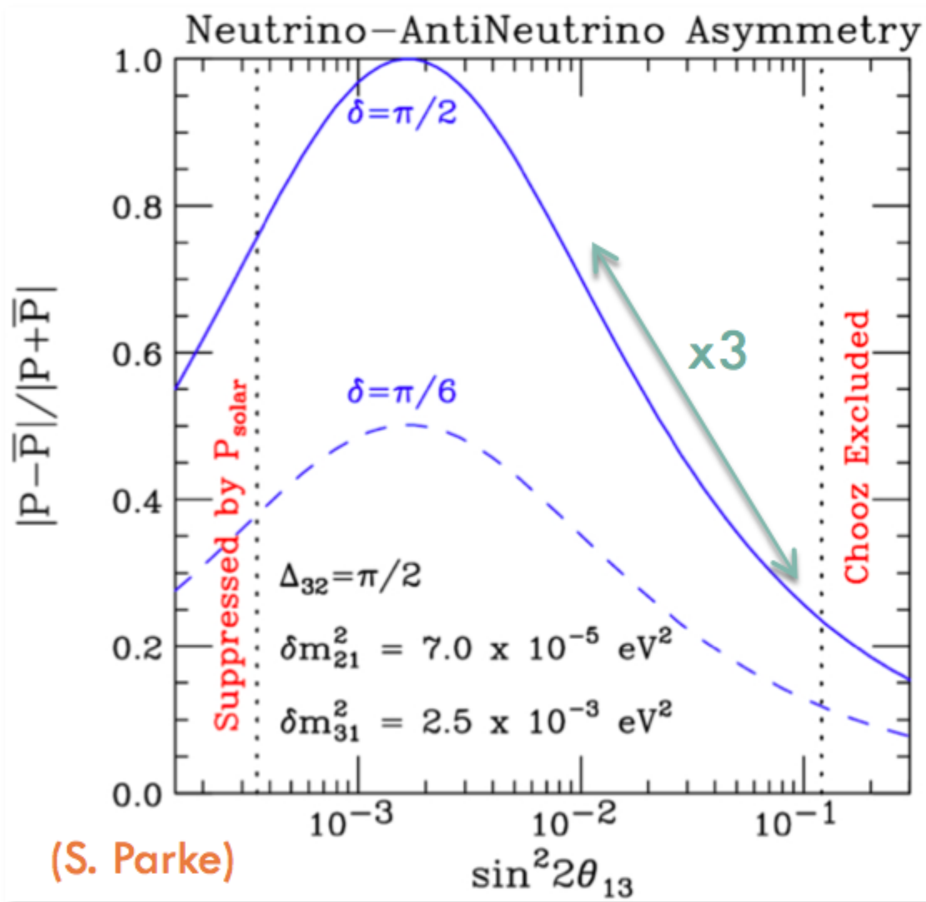
$$\sin^2(2\overline{\theta}) = 0.86^{+0.11}_{-0.12}(\text{stat.}) \pm 0.01(\text{syst.})$$





Global fit from Gonzalez-Garcia & Maltoni, *Phys. Rept.* 460 (2008), SK data dominates

$P(\nu) / P(\bar{\nu})$ Asymmetry



(ignoring matter effects & backgrounds for now)

- the asymmetry

$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

is proportional to $\sim 1/\sin\theta_{13}$

- **the asymmetry gets smaller as θ_{13} increases**

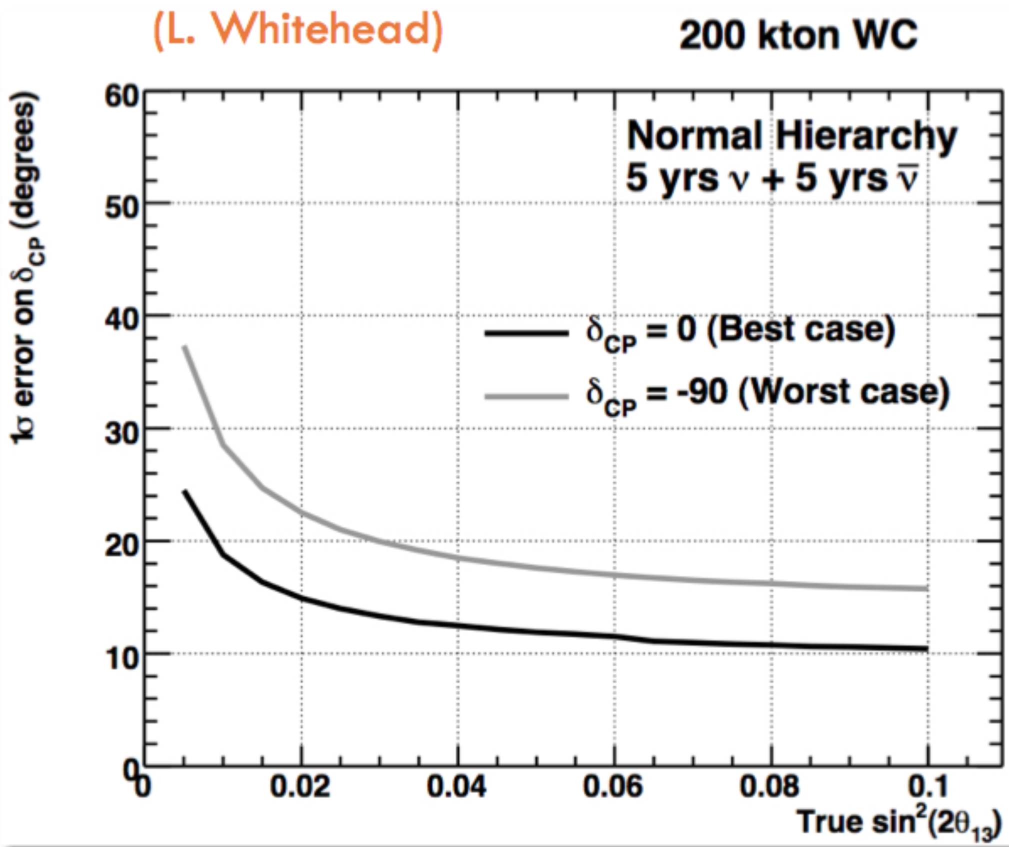
$$\left.\begin{array}{l} \sim 75\% \text{ for } \sin^2 2\theta_{13}=0.01 \\ \sim 25\% \text{ for } \sin^2 2\theta_{13}=0.10 \end{array}\right\} \delta_{CP}=\pi/2$$

factor ~3 reduction in CP asymmetry
(independent of baseline)

- **signal rate increases w/ θ_{13}**

factor ~10 increase from 0.01 to 0.1
so x3 improvement in stat sig of signal

$P(\nu)$ / $P(\bar{\nu})$ Asymmetry



(calculation includes backgrounds, background uncertainties, and matter effects)

- as a result, the error on the CP asymmetry and thus how well can measure δ_{CP} is essentially independent of the value of θ_{13}

- can provide an excellent measurement of δ_{CP} over a very broad range of θ_{13}

($10\text{-}20^0$ for $\sin^2 2\theta_{13}$~0.03-0.10; gets a little worse for smaller θ_{13})

$P(\nu)$ / $P(\bar{\nu})$ Asymmetry