Neutrino Oscillations and the Quest for CP-violation in the Neutrino Sector

University of Kansas

Department of Physics and Astronomy

Colloquium

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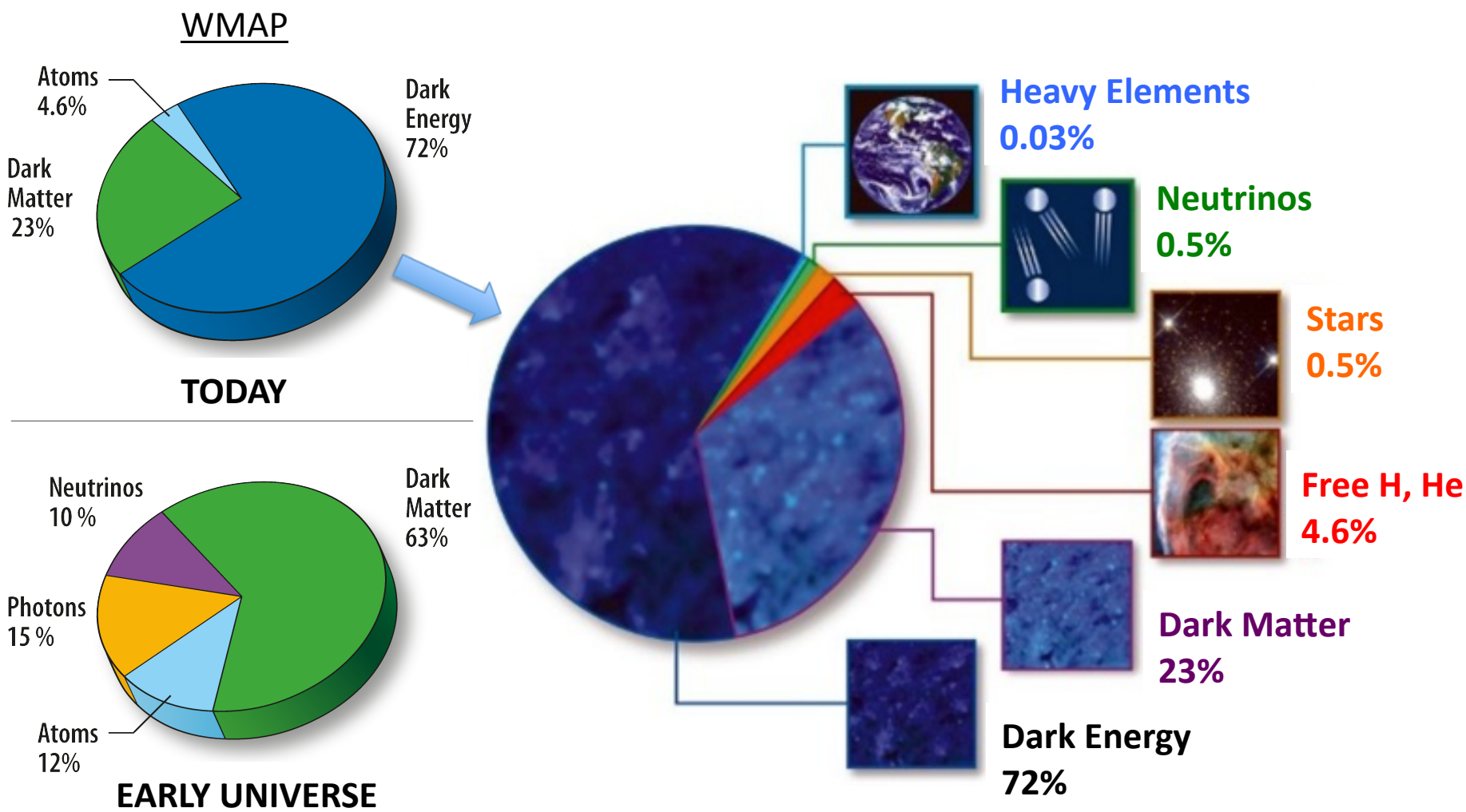
Why I may sound a little hoarse today

I appreciate the basketball team arranging the final four to coincide with my colloquium

Neutrinos matter in the universe



Neutrinos sources and energies

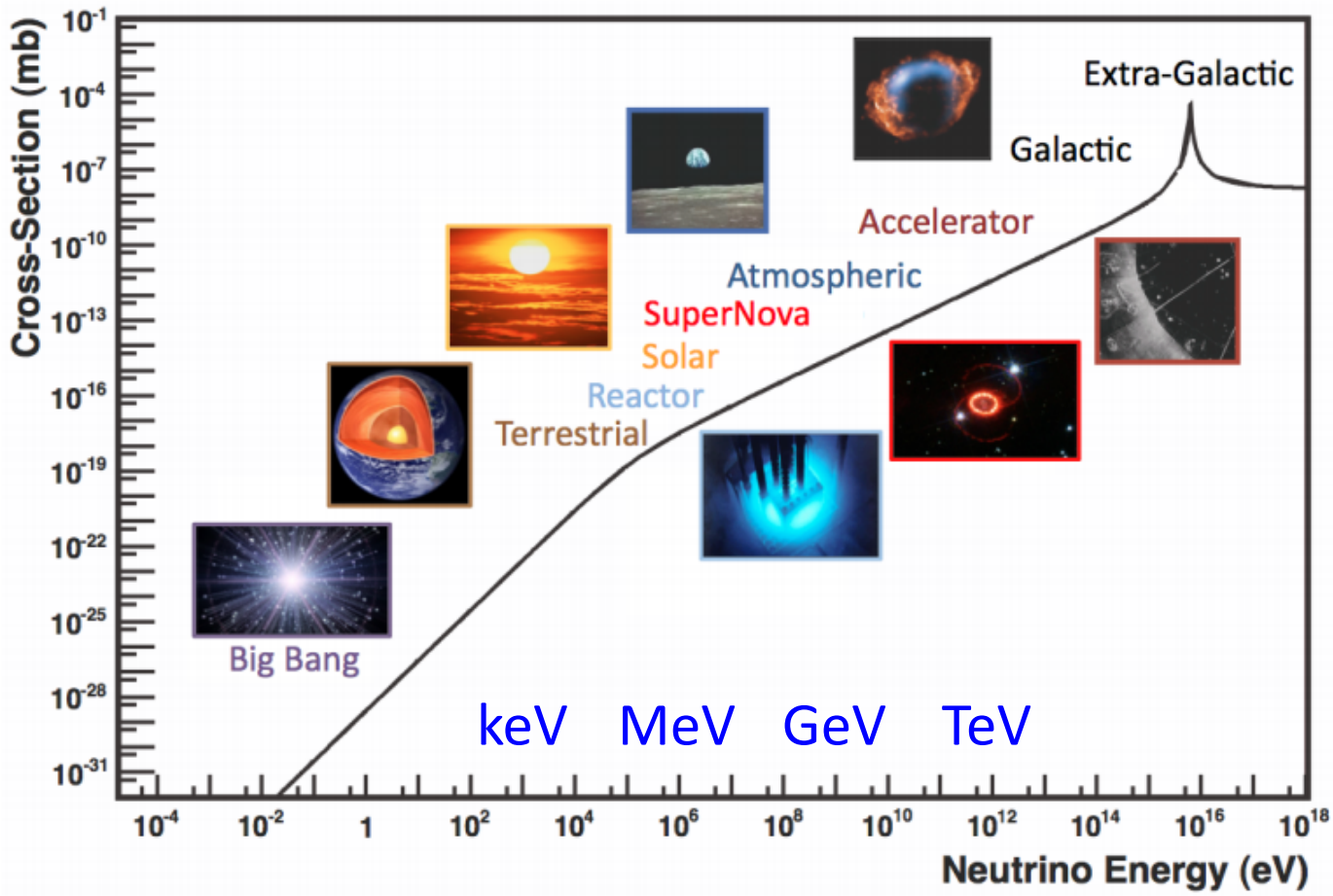


Figure 1-4. *Neutrino interaction cross section as a function of energy, showing typical energy regimes for different sources. The scattering cross section for $\bar{\nu}_e\, e^- \rightarrow e^-\, \bar{\nu}_e$ on free electrons is shown for comparison. Plot is reproduced from [50].*

Neutrinos sources and energies

A <u>banana</u> emits about **1 million neutrinos/day** from decays of the small number of naturally occurring <u>radioactive potassium atoms</u> they contain

Outline

- **The fascinating history of the neutrino:**
  - Early history, in brief
  - Neutrinos as a window on the universe, 20th century version
  - The remarkable discovery of neutrino oscillations, masses and mixing
  - A brief stop in Professor Shi's undergraduate QM course at U. of Kansas, circa 2000
  - The experimental evidence for the oscillation hypothesis
- **Neutrino physics at Fermilab, present and future**
  - Long-baseline oscillation program at Fermilab
  - Neutrinos as a window on the universe, 21st century version
  - Why the search for CP-violation in neutrinos represents a new paradigm in accelerator-based neutrino oscillation experiments
- **Summary**

Early history, in brief

Early milestones of the neutrino

- **1930 – It was well known that nuclei could change from one kind to another by emitting a beta (electron), but energy did not appear to be conserved in the process**
- **1931 – Pauli proposes his "desperate remedy", the 'neutron'**
- **1932 – Chadwick discovers the neutron, but it's too heavy**
- **1933 – Fermi saves the day with a new Italian name, 'neutrino'. Oh, and also a theory of weak interactions**
- **1934 – Bethe-Peierls calculate the expected cross section for neutrino inverse beta decay** $\sigma_{\bar{\nu}_e p \to n e^+} \approx 5 \times 10^{-44}\,\mathrm{cm}^2$
- **1956 – Reines and Cowen make the first experimental detection of a neutrino (actually, an electron antineutrino)**

Pauli's "desperate remedy"

Dear Radioactive Ladies and Gentlemen,

As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li6 nuclei and the continuous beta spectrum. I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy. Namely, the possibility that there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle and which further differ from light quanta in that they do not travel with the velocity of light. The mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses. The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant... ....

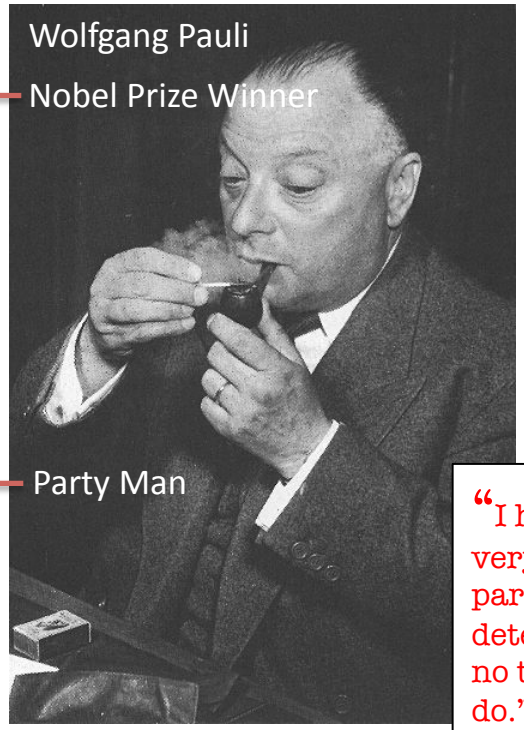
Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

W. Pauli

"wrong statistics" and "exchange theorem" refers to a second problem that:

$$n_{spin-1/2} \not\rightarrow p_{spin-1/2} + e_{spin-1/2}$$

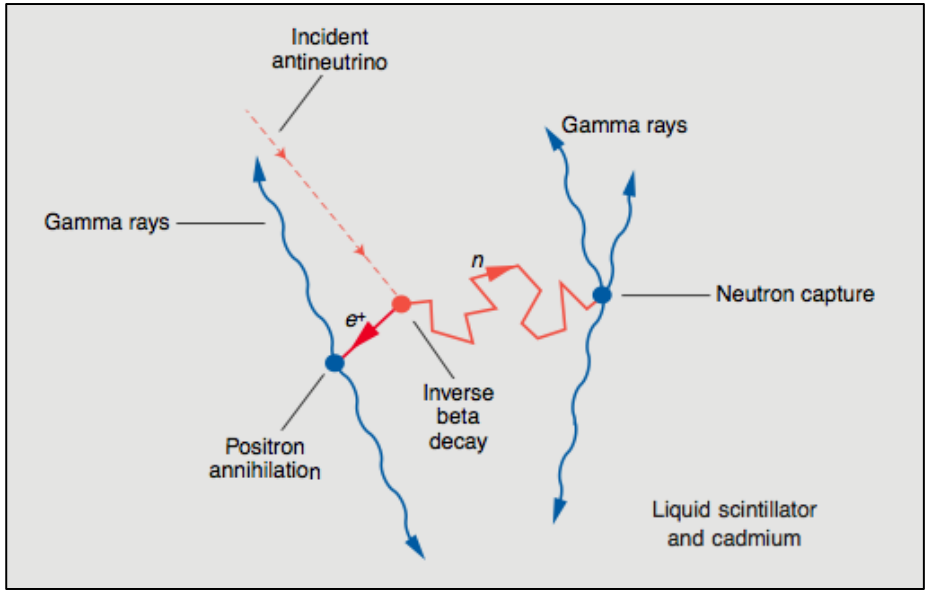


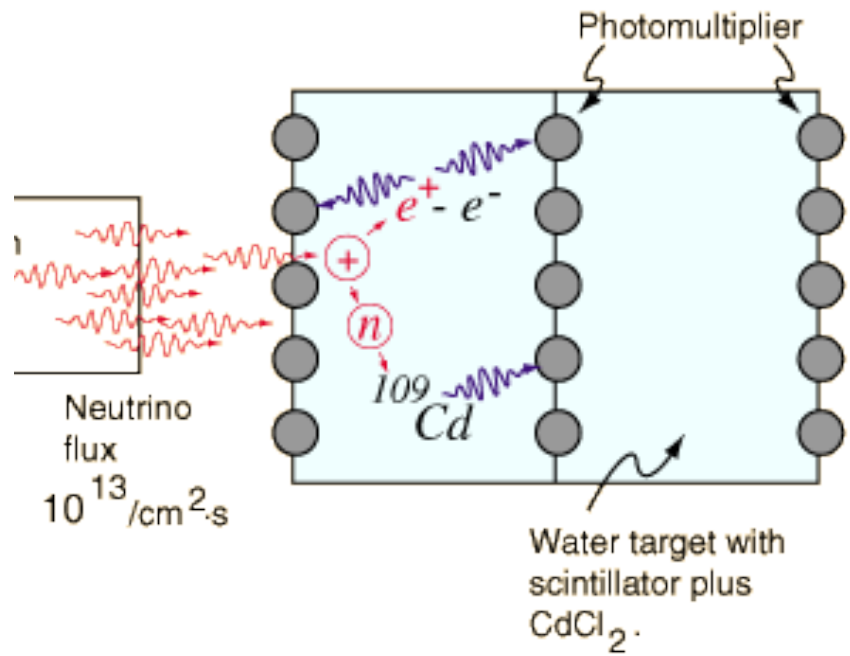
"I have done something very bad by proposing a particle that cannot be detected; it is something no theorist should ever do."

- Wolfgang Pauli (1931)

At long last, discovery

$$\bar{\nu}_e + p \rightarrow e^+ + n$$





Positron annihilates promptly on electron to produce two 0.5 MeV Gamma rays

Neutron gets captured by Cadmium nucleus after a delay of ~5 microseconds

A telegram 25 years in the making

"[Prof. Pauli], we are happy to inform you that we have definitely detected neutrinos from fission fragments by observing inverse beta decay of protons."

- Fred Reines and Clyde Cowan (1956)

"Everything comes to him who knows how to wait."

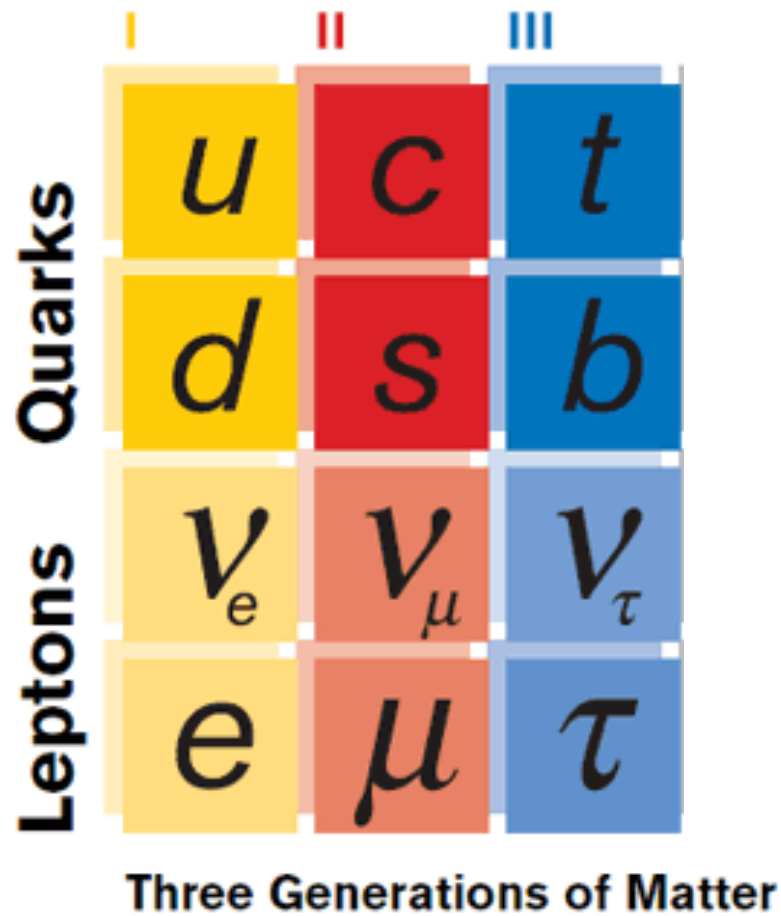
- Wolfgang Pauli (1956)

Flavor and Families in the Standard Model

- 1962 – Schwartz, Lederman and Steinberger established the existence of the second, distinct type of neutrino that made muons instead of electrons when they interact

- This discovery was really the first indication of the family structure in the Standard Model

- The third (and last?) neutrino was not directly detected until 2000 by the DONUT experiment at Fermilab (70 years after the Pauli hypothesis)



Neutrinos as a window on the universe: 20th century version

How can the sun shine for so long?

- **A burning question* in 19th century science:**
- **How old is the sun?**
  - 19th century physicists believed that gravitation was the source of the sun's energy
    - calculations based on this idea could give you about 20M years of solar energy
  - Geologists and biologists estimated that the earth was >300M years old in order to allow for observed geological change and the evolution of living things
- **While the debate raged, along came several key discoveries:**
  - nuclear radioactivity *(Rontgen, Bacquerel, 1896)* a new form of energy
  - $E = mc^2$ *(Einstein, 1905)* mass, energy equivalence
  - mass of 4 Hydrogen atoms > mass of 1 Helium atom *(Aston, 1920)* fusion releases energy
  - quantum mechanics allows two like-signed particles to come close together with small probability *(Gamow, 1928)* fusion is possible

*pun intended, if unfortunate

Energy Production in Stars

MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

Energy Production in Stars*

H. A. Bethe
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^{+}$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^{+}$, $N^{15}+H=C^{12}+He^{4}$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^{+}$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

It is shown further (§5–6) that *no elements heavier than* He^{4} *can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^{8} reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

§1. Introduction

THE progress of nuclear physics in the last few years makes it possible to decide rather

the amount of heavy matter, and therefore the opacity, does not change with time.

The combination of four protons and two electrons can occur essentially only in two ways

H. Bethe realized the connection between the CNO nuclear cycle and energy production by stars

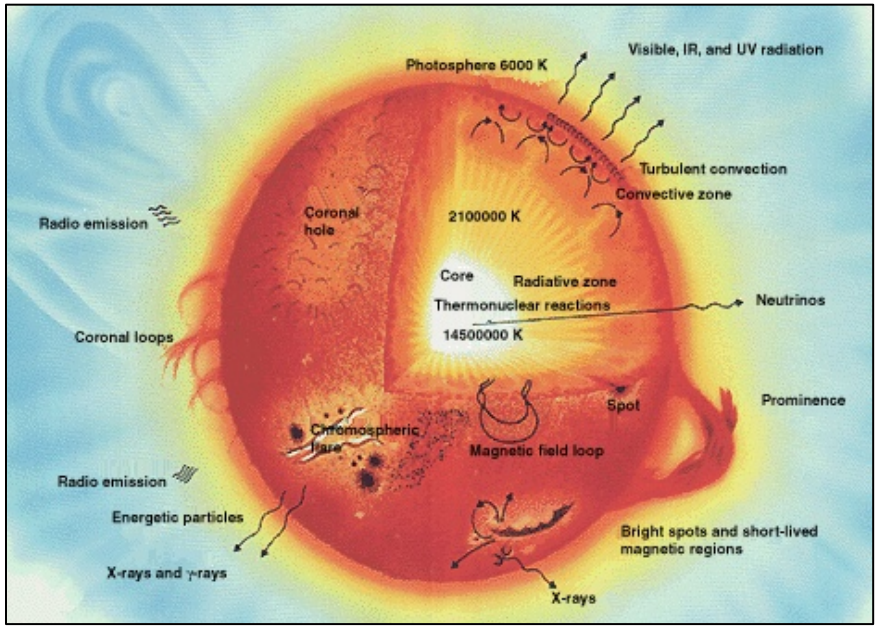
Crucial dependence on stellar temperature

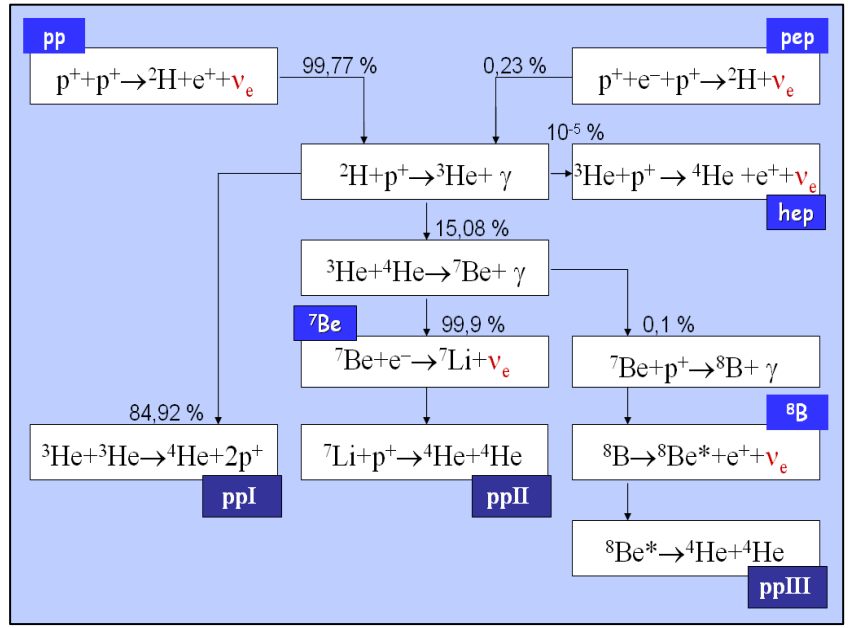
Bethe mentions throughout the paper the energy that would be carried away by neutrinos

(18 years before Reines and Cowen detected them)

Energy Production in Stars = neutrinos

$$4^1\mathrm{H} \rightarrow {}^4\mathrm{He} + 2e^+ + 2\nu_e + \mathrm{energy}$$





- **Only the neutrinos can escape the dense stellar core unscathed**
- **Order 100,000,000,000/cm²/s at earth**
- **Thus, neutrinos could provide a way to empirically test the theory of thermonuclear fusion as the source of the sun's energy**

Taking the sun's temperature

- **John Bahcall calculated the expected neutrino flux at the earth from the sun**

$$\Phi_\nu \sim T^{25} \text{ !!}$$

SOLAR NEUTRINOS*

John N. Bahcall

California Institute of Technology, Pasadena, California

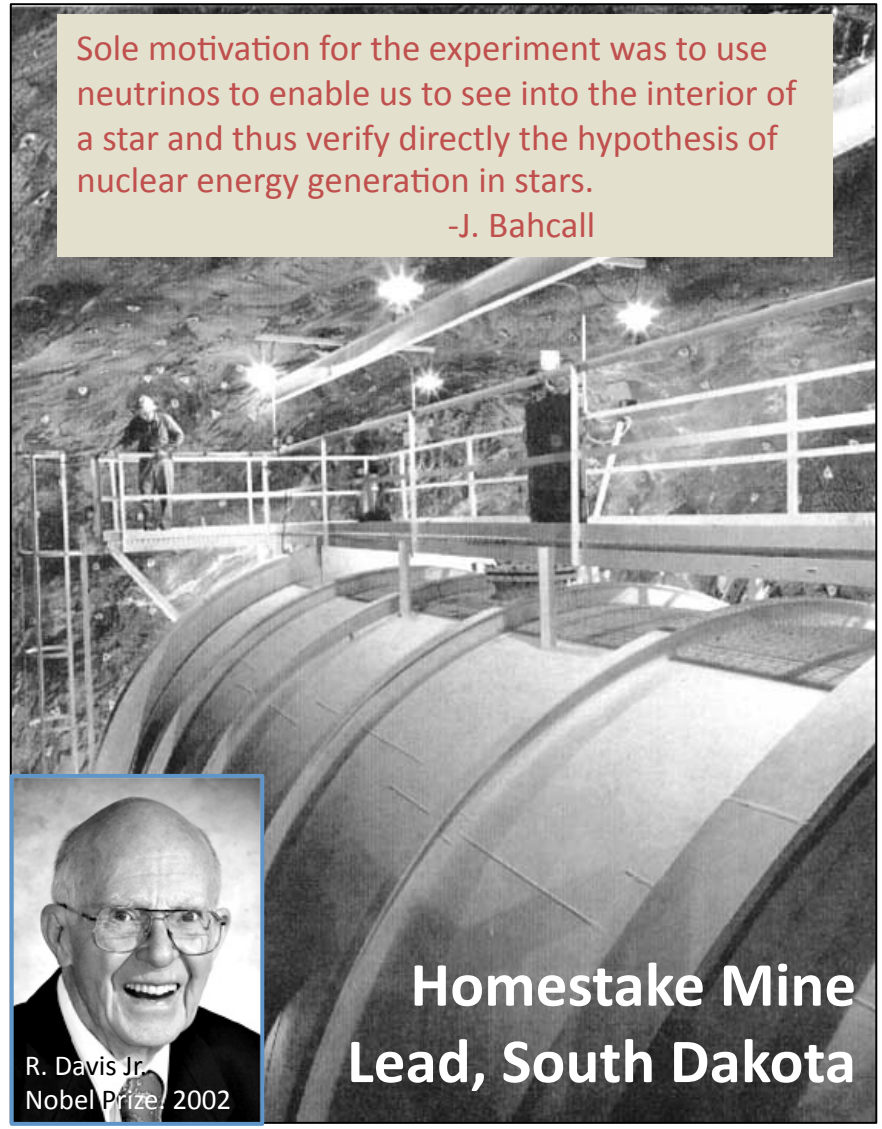
(Received 11 July 1966)

We find, using Eqs. (2) and (4) and previously published values for the neutrino fluxes[15,17,18] and absorption cross sections[4] for other neutrino sources, the following value for the sum of the fluxes times cross sections for all known sources of solar neutrinos:

$$\sum(\varphi_\nu \sigma) = (3.0^{+3}_{-1.5}) \times 10^{-35}$$

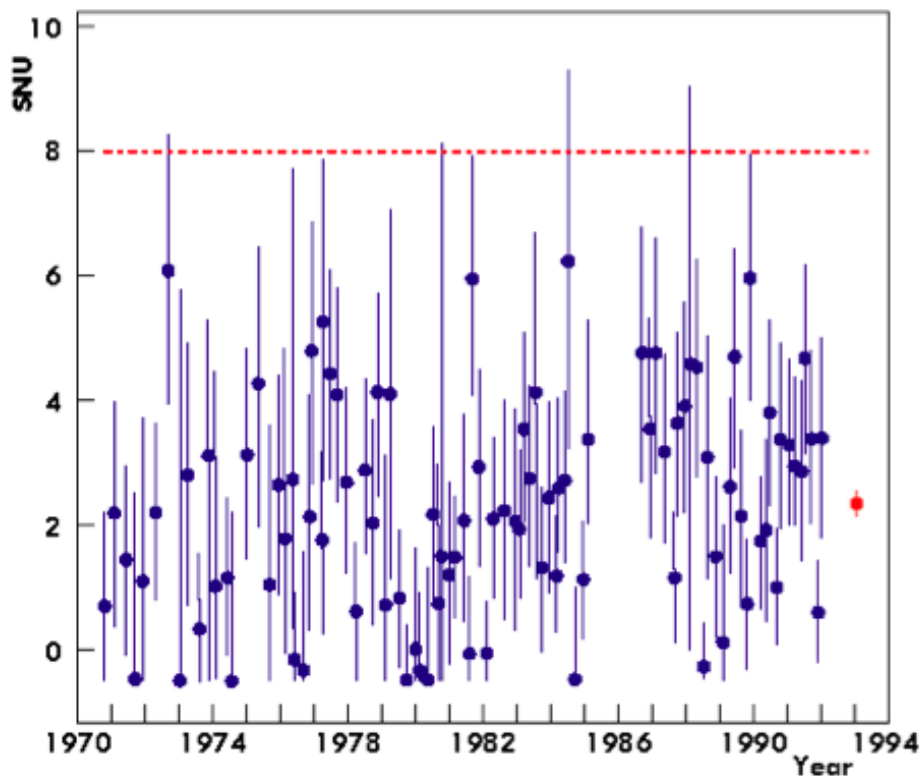
per Cl^{37} atom per second (5)

or six captures per day in the experiment, using 10^{+5} gal of C_2Cl_4, that is under way. After



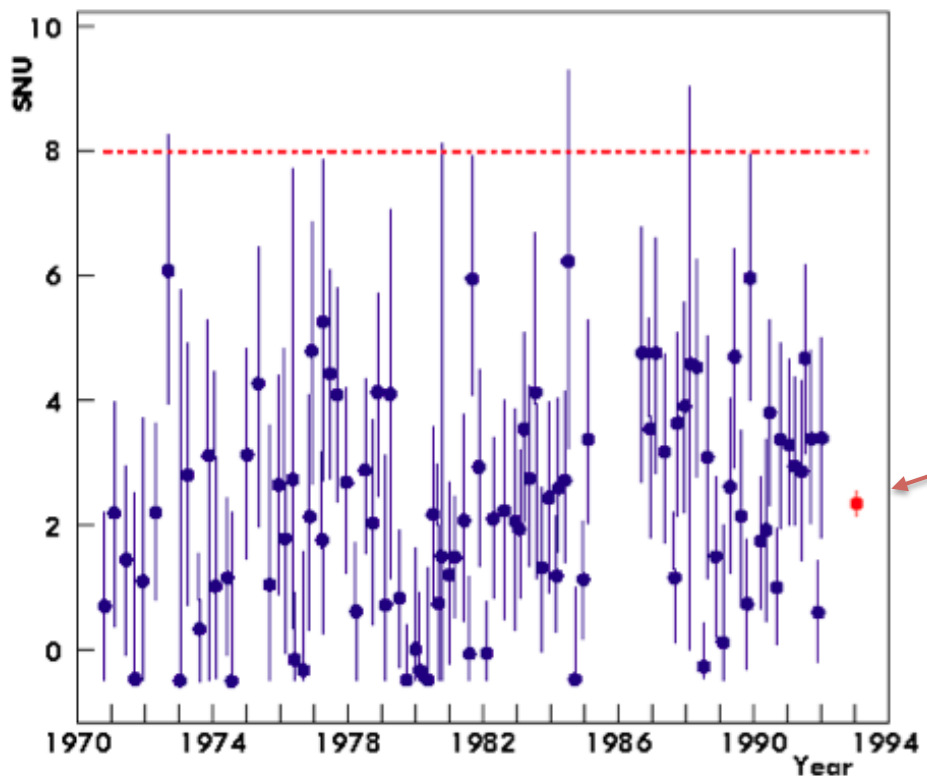
The solar neutrino success!

- **Because of the dependence on the 25th power of the sun's temperature, even agreement within a factor of three is a few percent confirmation of the temperature of the sun's core!**



The solar neutrino ~~success~~! anomaly!

- **Because of the dependence on the 25th power of the sun's temperature, even agreement within a factor of three is a few percent confirmation of the temperature of the sun's core!**



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

The remarkable discovery of neutrino oscillations, masses and mixings

Neutrino oscillations

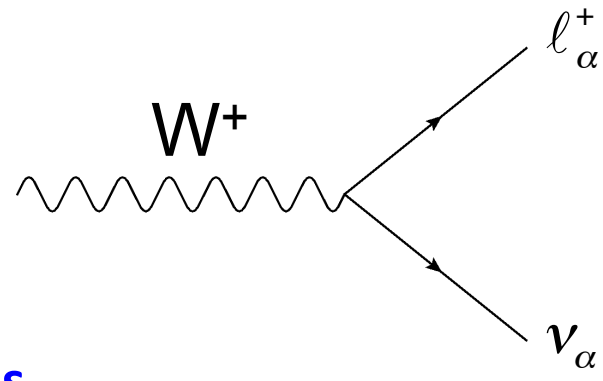
Neutrino Mixing Matrix

neutrino **flavor eigenstates** participate in 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 eigenstates**

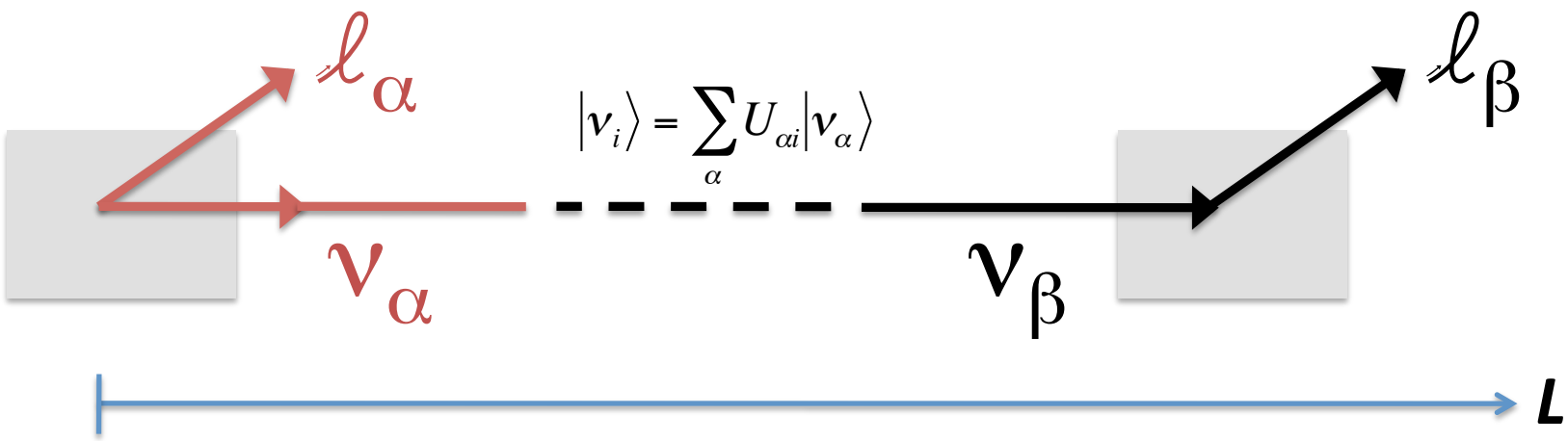
- **We know the weak flavor, $\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau, \ldots)$ only through identification of the charged lepton partner $\ell_\alpha = (e, \mu, \tau, \ldots)$ when a neutrino is created or destroyed through a W boson**



- **But suppose that weak flavor eigenstate is actually a superposition of pure mass eigenstates as shown above**

Neutrino oscillations

- A <u>neutrino's propagation through space</u> (from production to detection) is dictated by the free Hamiltonian whose eigenstates are the states of <u>definite mass</u>, $\nu_1 = (\nu_1, \nu_2, \nu_3, \ldots)$, not flavor



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

Parameterize the mixing matrix

Neutrino Mixing Matrix

neutrino **flavor eigenstates** participate in 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 eigenstates**

By analogy with CKM matrix for quark mixing:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

3 real angles and
1 CP-violating phase: $\theta_{13}, \theta_{12}, \theta_{23}, \delta_{CP}$

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

Factorize the mixing matrix

Neutrino Mixing Matrix

neutrino **flavor eigenstates** participate in weak interactions

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neutrino **mass eigenstates**

Very instructive to factorize the matrix :

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}_{0\nu\beta\beta}$$

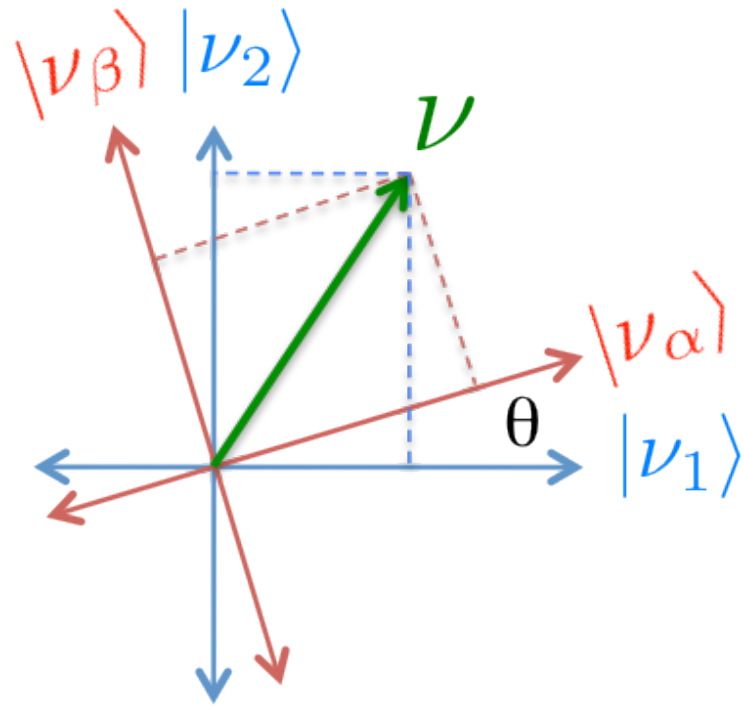
2-neutrino mixing

$0\nu\beta\beta$

does not contribue to oscillations

Two neutrino mixing

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



Two neutrino mixing

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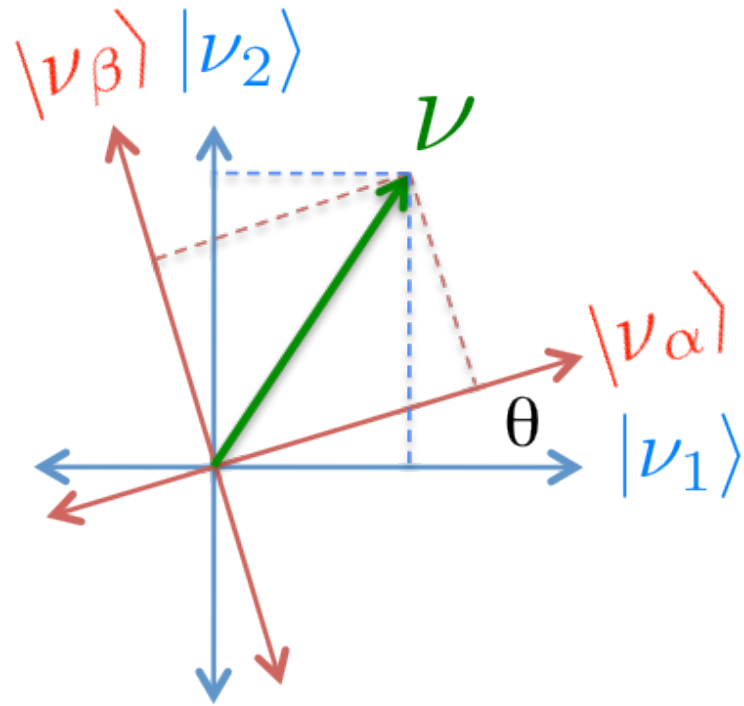
$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu \ (L) \rangle|^2 = \left| \sum_i U^*_{\alpha i} e^{-i(m_i^2 L/2E)} U_{\beta i} \right|^2$$

holds generally for any number of neutrinos,
but simplifies quite a bit for two



Two neutrino mixing

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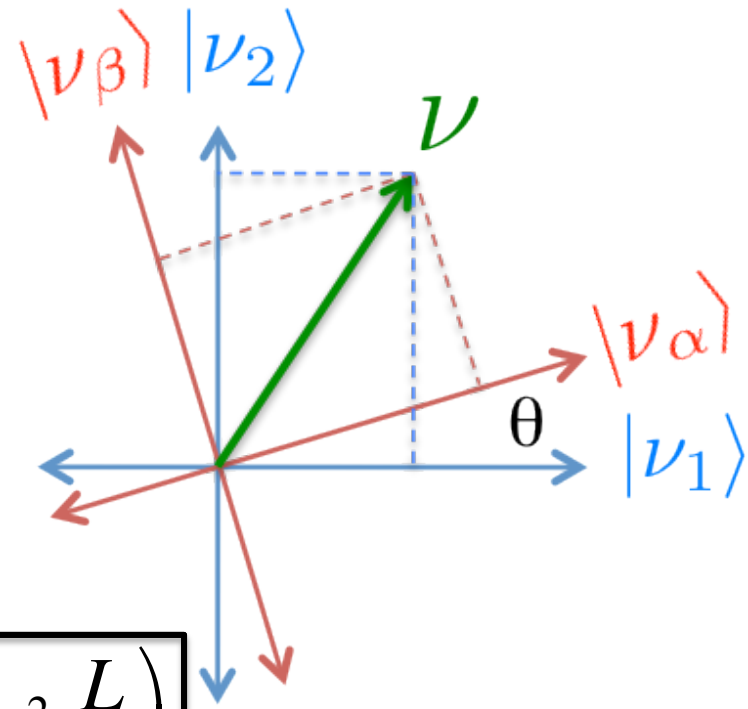


$$P(\nu_\alpha \to \nu_\beta) = |\langle \nu_\beta | \nu\ (L)\rangle|^2 = \left| \sum_i U^*_{\alpha i} e^{-i(m_i^2 L/2E)} U_{\beta i} \right|^2$$

If you begin at L=0 with ν_α …

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

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

Δm^2 determines the frequency of the oscillation as a function of L/E

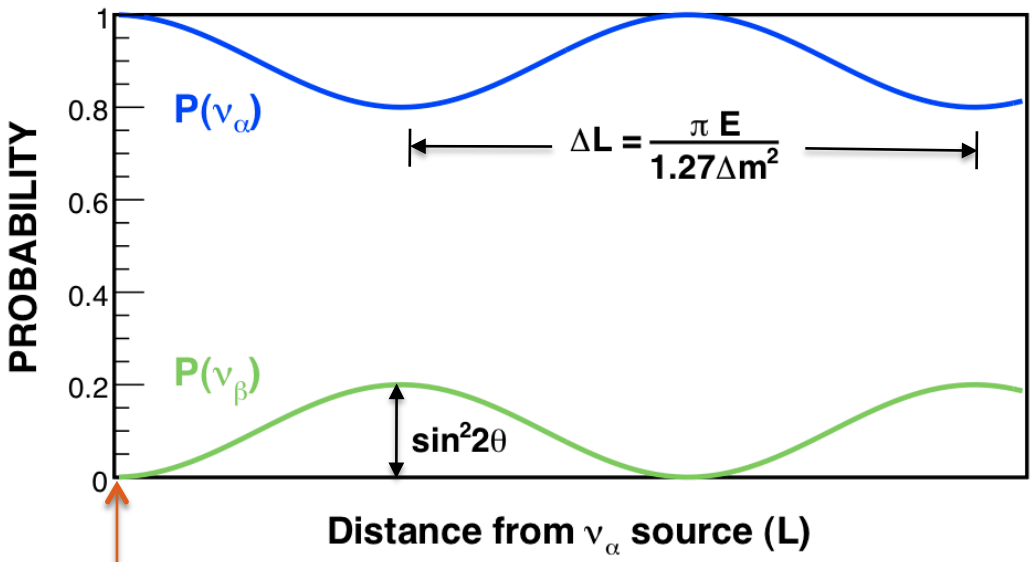
$$\Delta m^2_{ij} \equiv m_j^2 - m_i^2$$

probability depends on the mass-squared difference of the two mass eigenstates

The ultimate oscillation experiment

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

Fixed E
Variable L

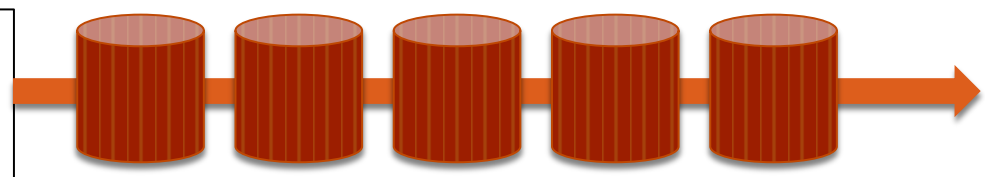


observe by ν_α **disappearance**

OR

observe by ν_β **appearance**

Begin with mono-energetic beam of ν_α

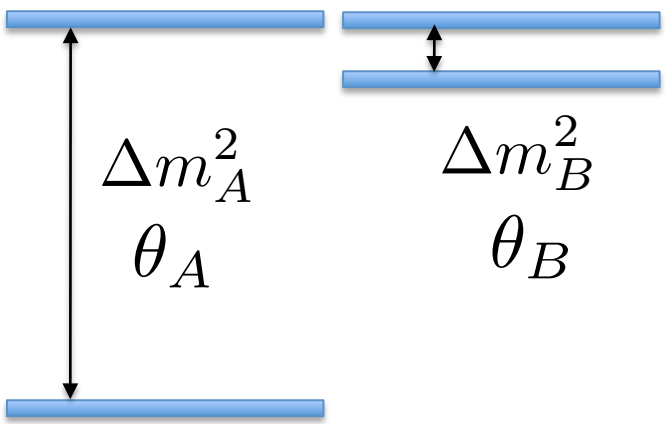


A bunch of detectors to measure ν_α / ν_β content along path

Wouldn't that be awesome!! Alas…$$$

Two neutrino mixing at two mass scales

- **Suppose a neutrino flavor can oscillate at two different mass scales (i.e. frequencies):**

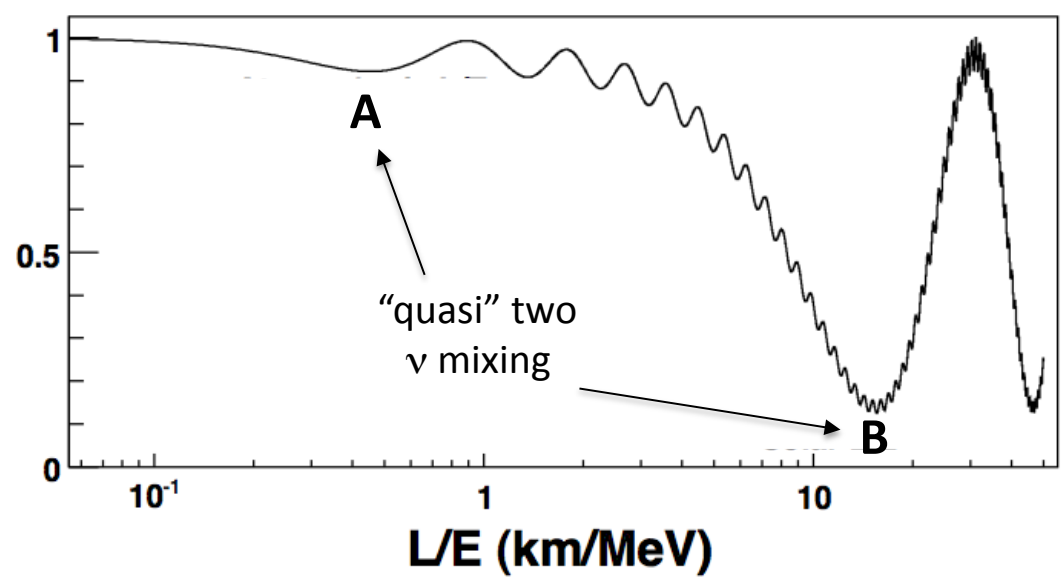


$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_A * \sin^2\left(1.27\Delta m_A^2 \frac{L}{E}\right)$$

$$P(\nu_\alpha \rightarrow \nu_\alpha) = 1 - \sin^2 2\theta_B * \sin^2\left(1.27\Delta m_B^2 \frac{L}{E}\right)$$

$$\Delta m_B^2 << \Delta m_A^2$$

$$\theta_A << \theta_B$$



A brief stop in
Professor Shi's undergraduate
Quantum Mechanics course,
circa 2000

Quantum mechanics homework

- **The calculation of the two-neutrino oscillation formula on the previous slides showed up in my undergraduate quantum mechanics textbook**

Problem 3.58:

"*Note:* This is about the simplest nontrivial quantum system conceivable. It is a crude model for neutrino oscillations…… At present this is highly speculative – there is no experimental evidence for neutrino oscillations; however, a very similar phenomenon does occur in the case of neutral K-mesons."

David J. Griffiths – *Introduction to Quantum Mechanics*, 1995

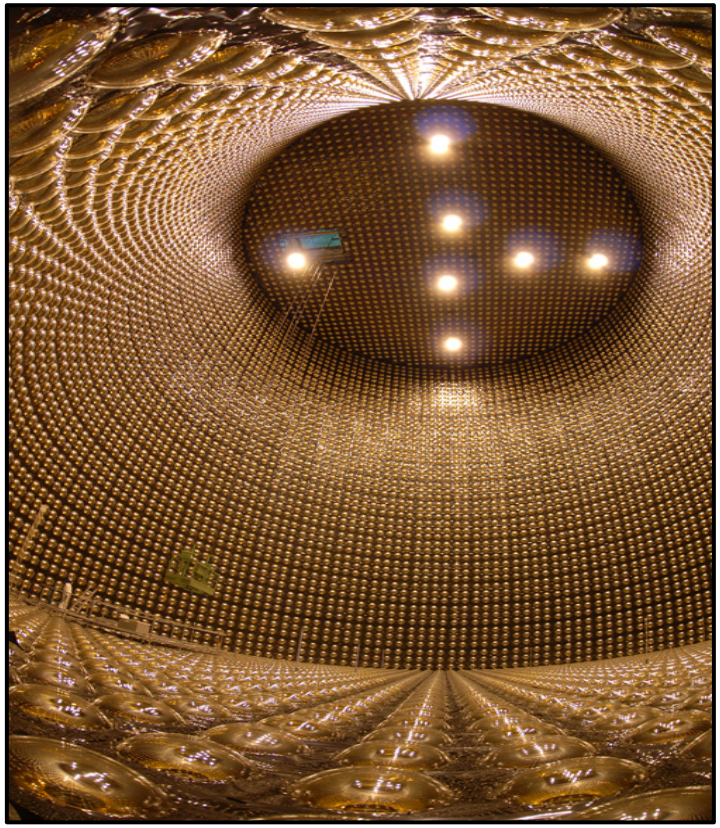
We'll see how the evidence has changed in the past 17 years…

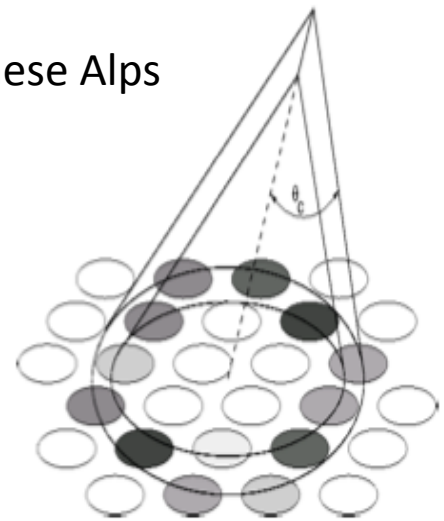
Experimental evidence* for the oscillation hypothesis

*the highlights at least. There are several wonderful experiments I have been forced to leave out for time

Super-K atmospheric neutrinos

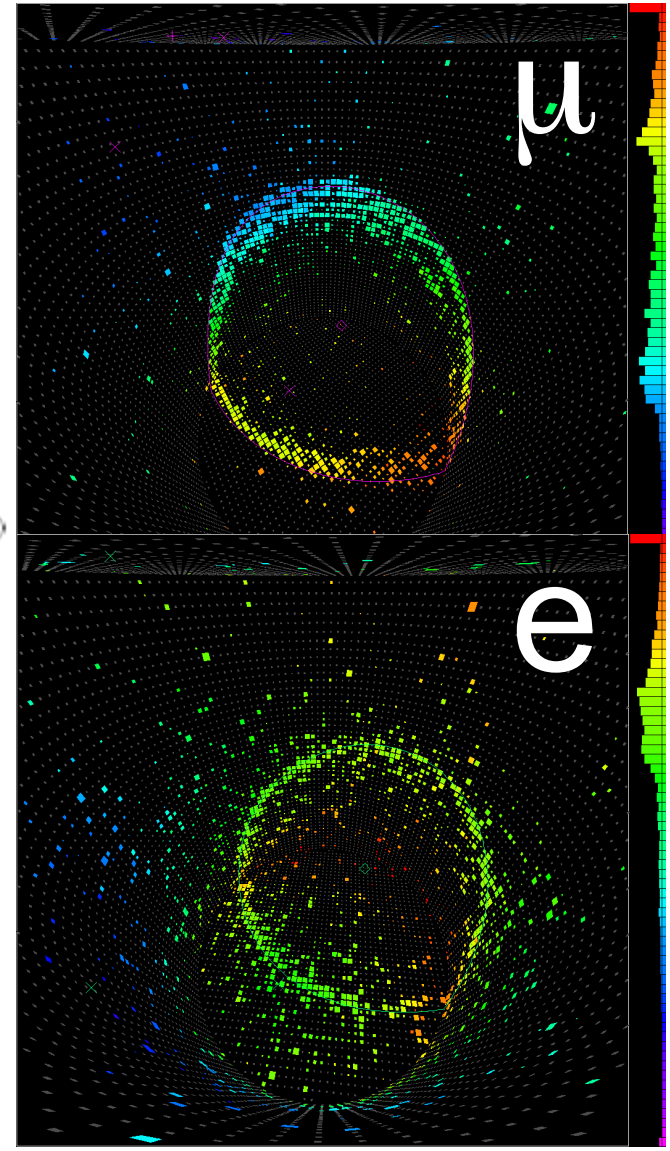
- **The Super-Kamiokande experiment in Japan**
  - 50 kT tank of ultra-pure water
  - Located 0.6 km under the Japanese Alps



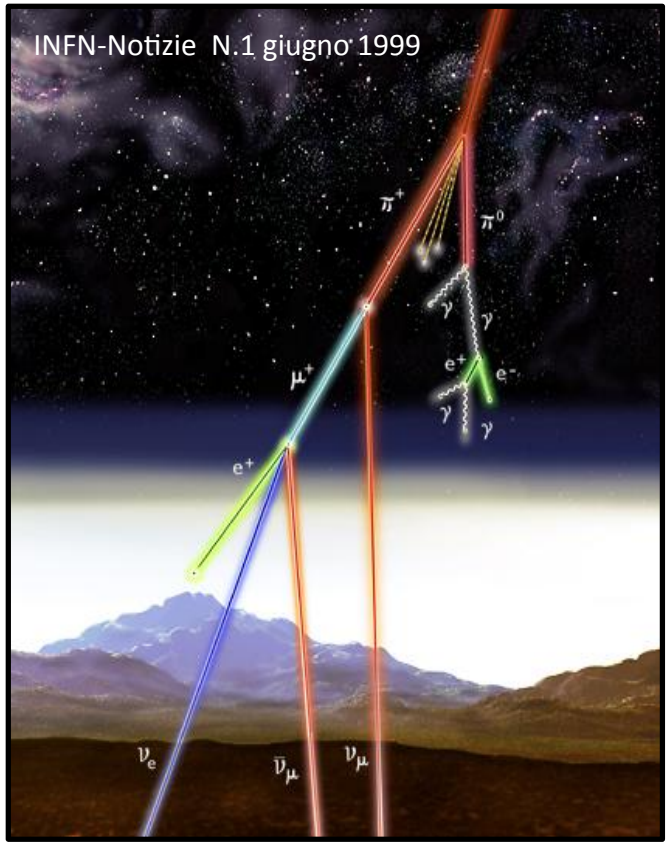


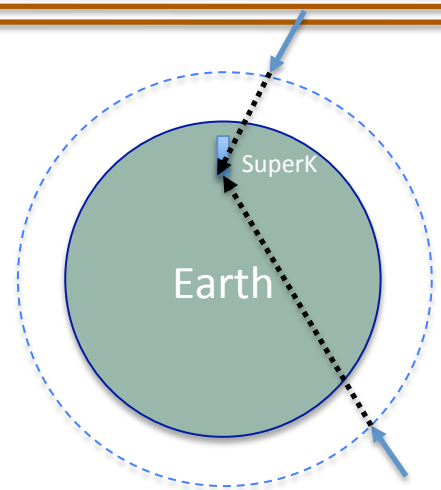
Originally built to search for proton decay.

Still waiting for one of those, but won a Nobel Prize for study of cosmic neutrinos in the mean time.



Super-K atmospheric neutrinos

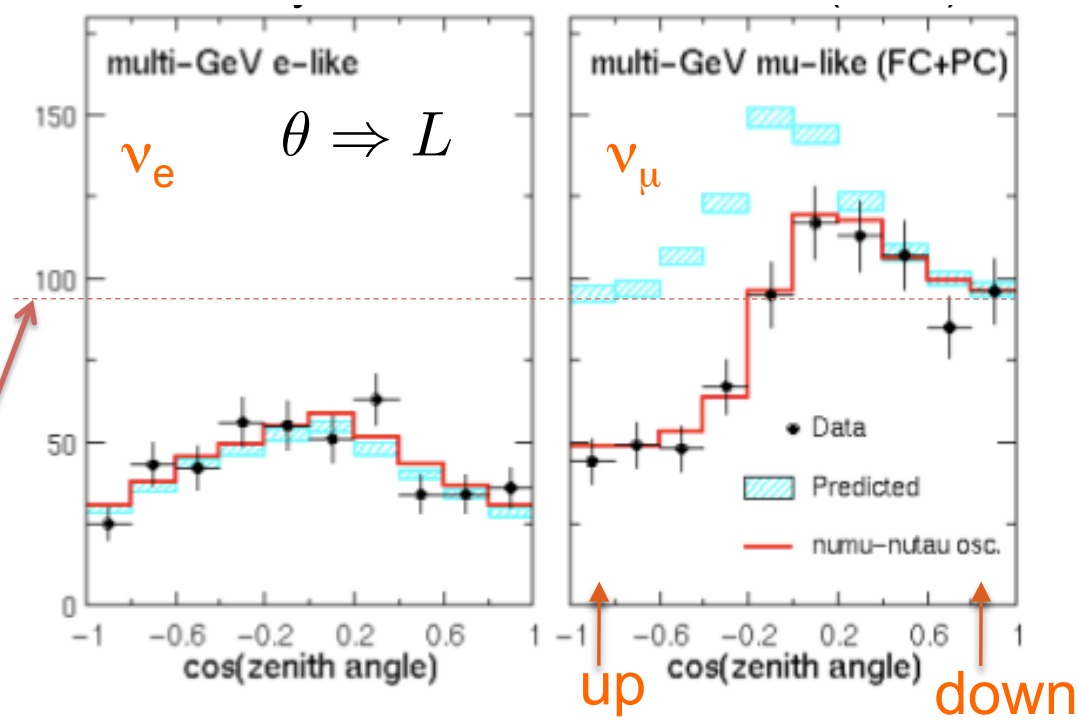




$$\langle E \rangle_{Super-K} \approx 1-10\ GeV$$

$$\langle L \rangle_{Super-K} \approx 10-10^4\ km$$

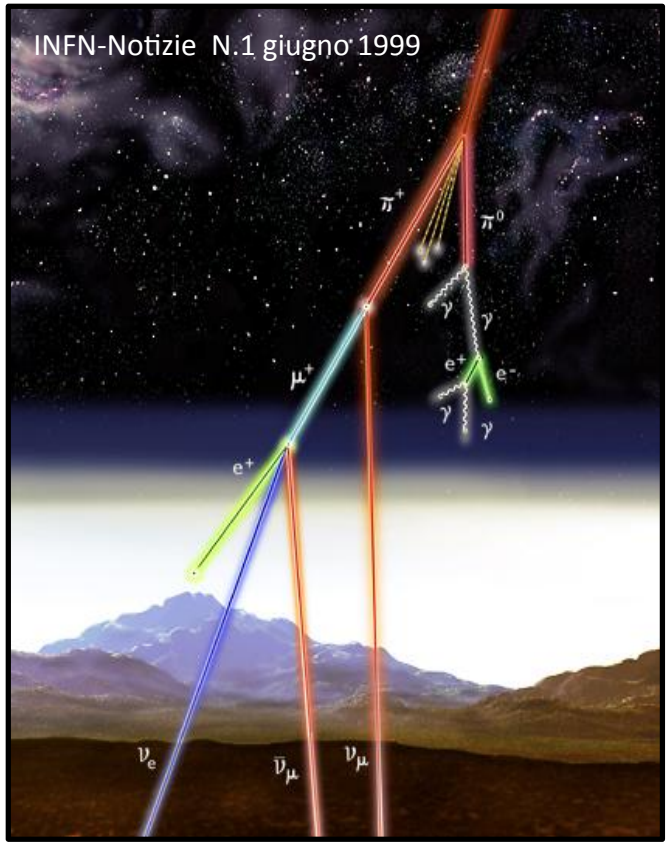
$$\Delta m^2 \sim 10^{-4} - 1\ eV^2$$

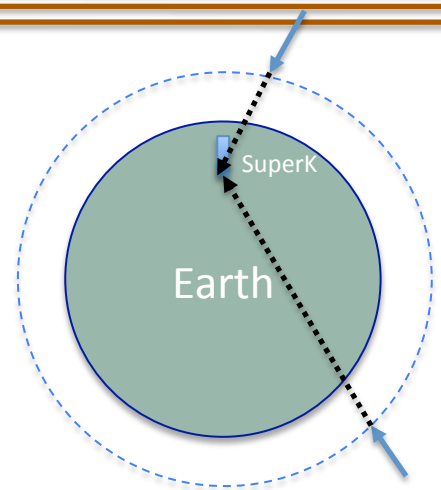


one expects:

$$\frac{\phi_{\nu_\mu}}{\phi_{\nu_e}} \approx 2 \qquad \frac{\phi_{\nu_\mu}(Up)}{\phi_{\nu_\mu}(Down)} \approx 1$$

Super-K atmospheric neutrinos





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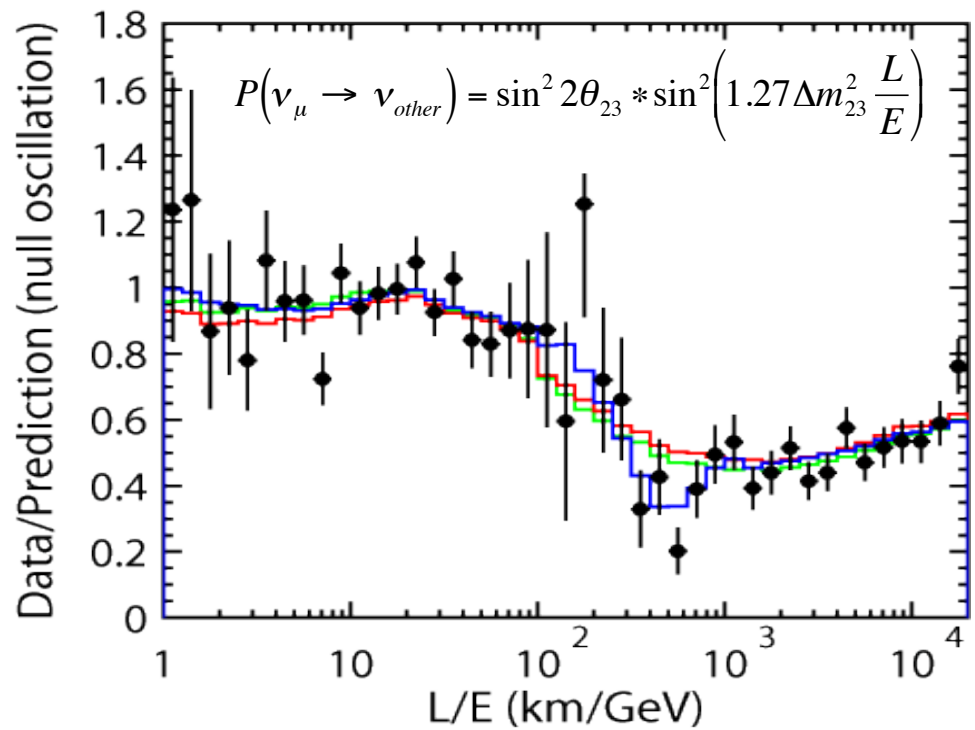
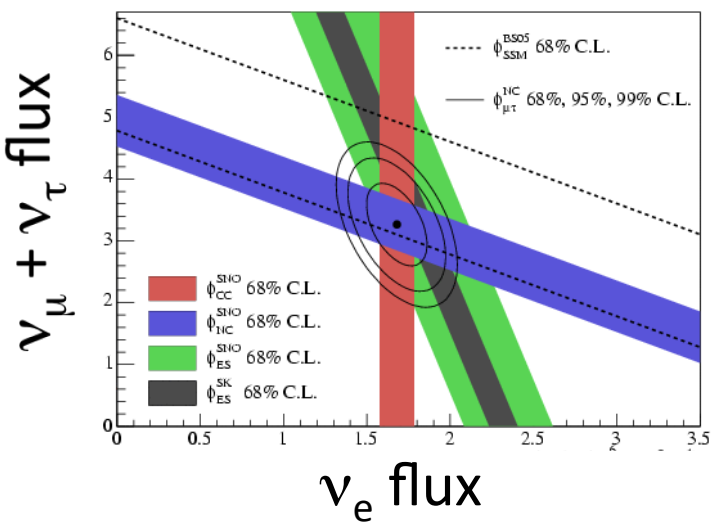


one expects:

$$\frac{\phi_{\nu_\mu}}{\phi_{\nu_e}} \approx 2 \qquad \frac{\phi_{\nu_\mu}(Up)}{\phi_{\nu_\mu}(Down)} \approx 1$$

Resolving the solar neutrino anomaly

- **Davis' experiment (and others) showed there were too few solar ν_e by factor 3**



$\nu_e + d \rightarrow p + p + e^-$ (CC) ← CC interactions sample $\phi_{\nu e}$ only

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

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

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

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

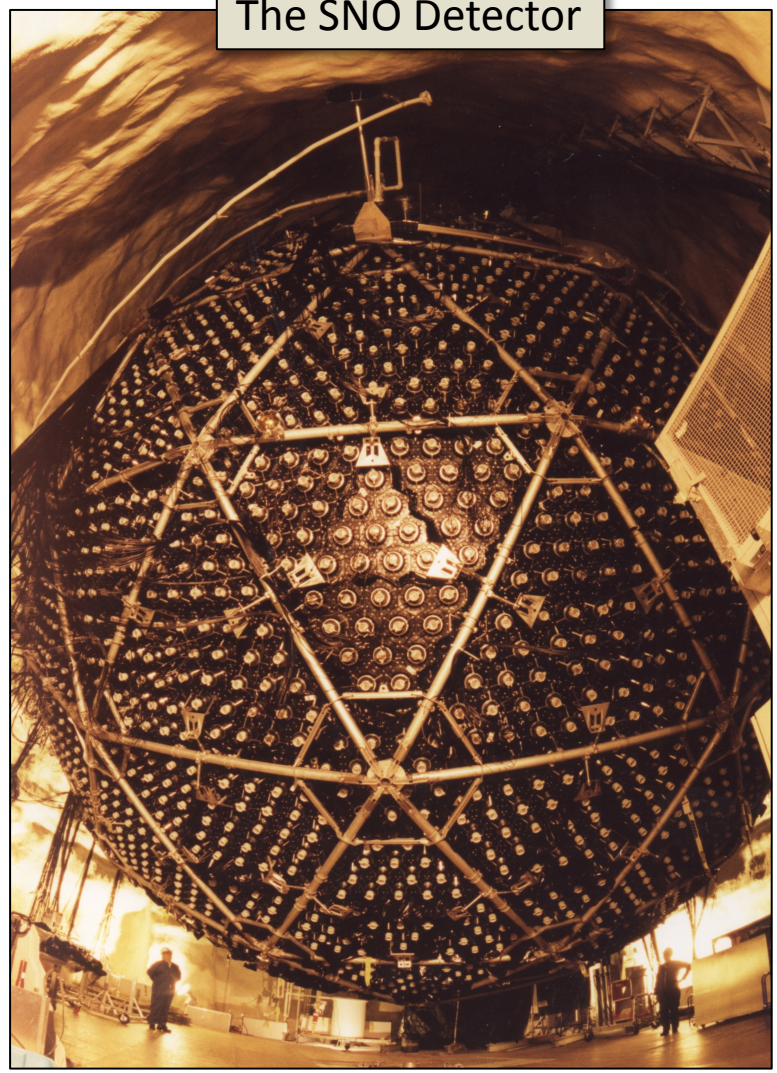
ν_e fraction agrees with Davis!

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

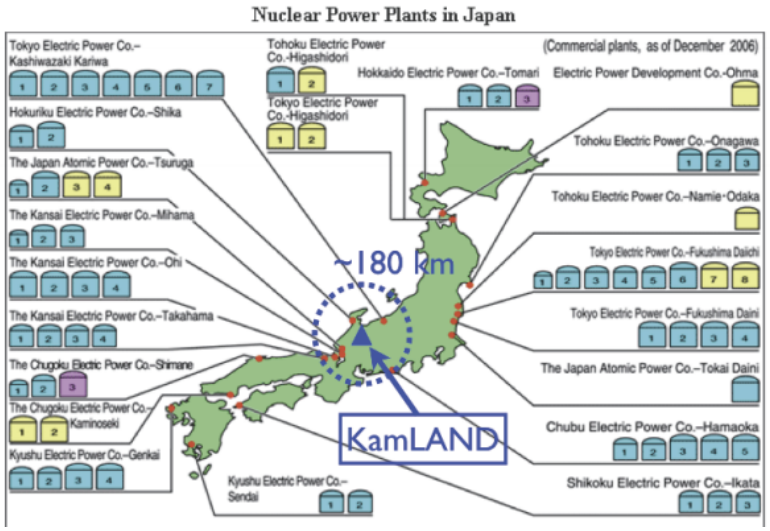
Theory: $\phi_{total} = (5.69 \pm 0.91) \times 10^6 cm^{-2} s^{-1}$

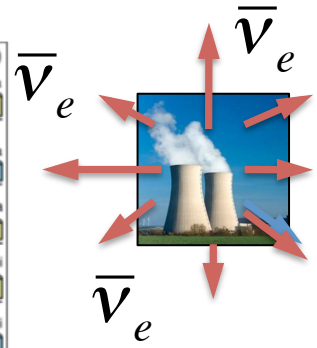
Total flux agrees with Bahcall!

The SNO Detector



The solar oscillation with reactor $\bar{\nu}_e$

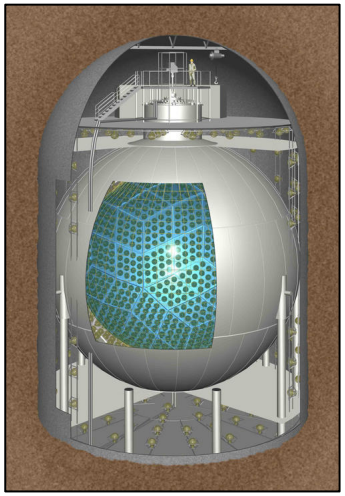


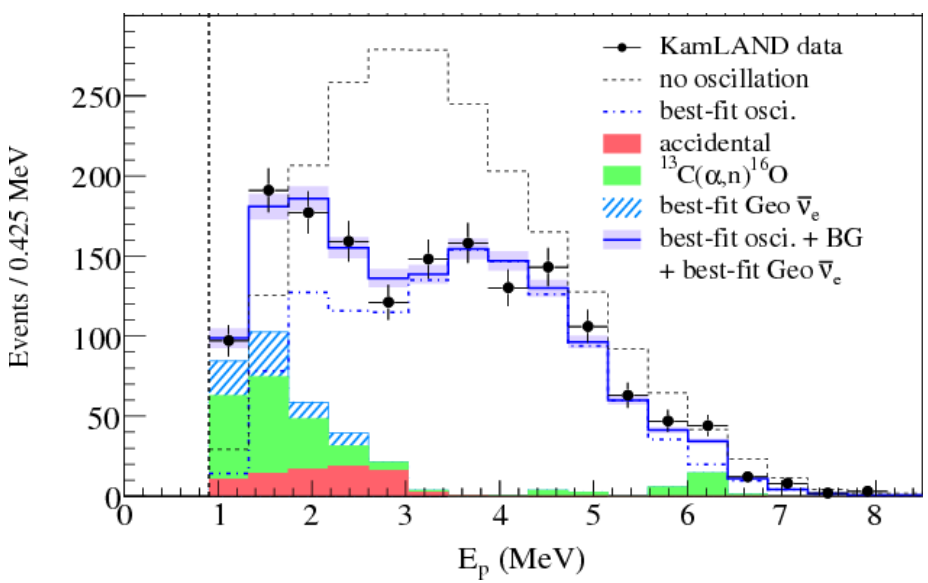


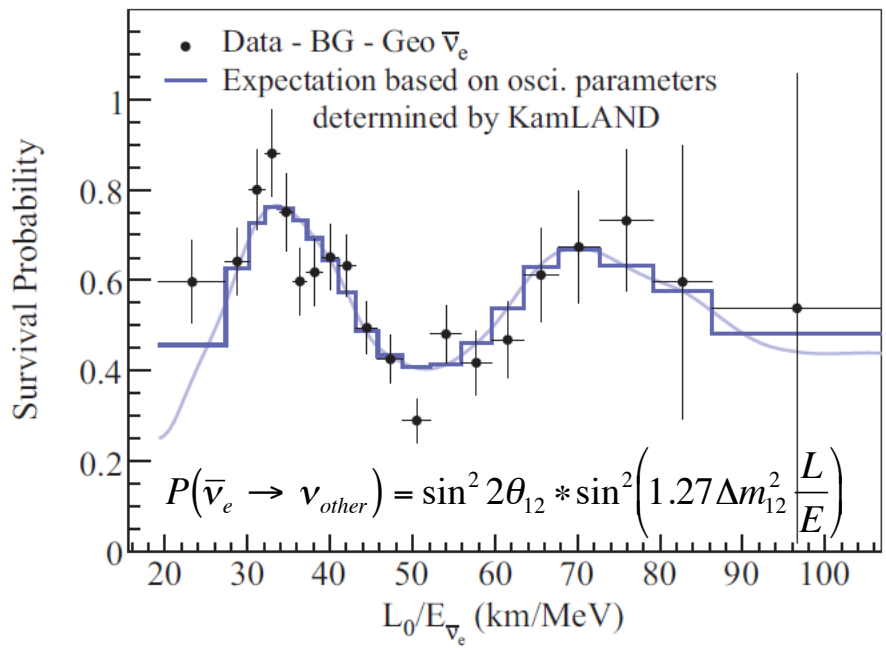
$$\langle E \rangle_{KamLAND} \approx 5\ MeV$$

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

$$\Delta m^2 \approx 10^{-5} eV^2$$







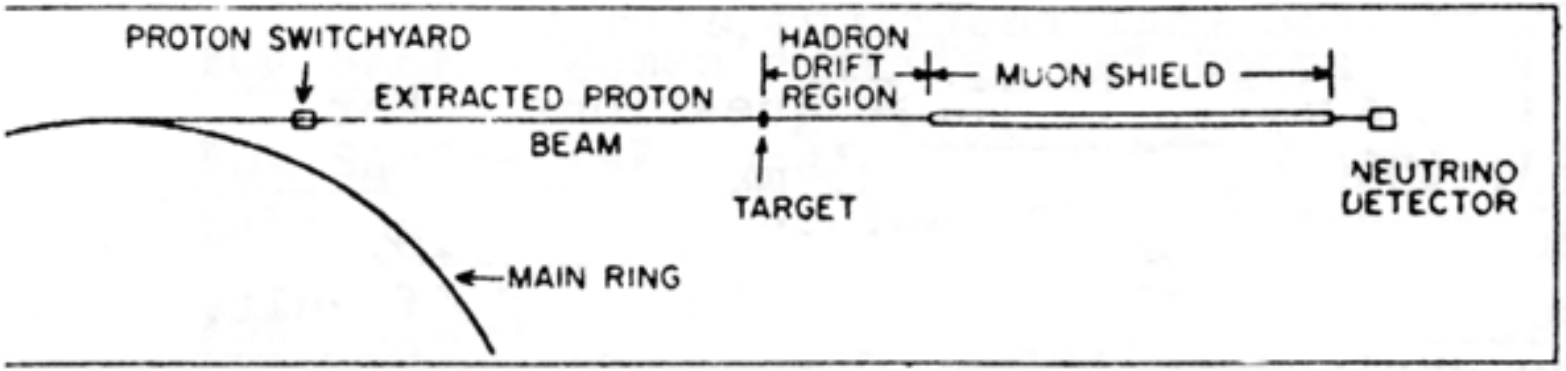
Neutrino Physics at Fermilab

Since the very beginning

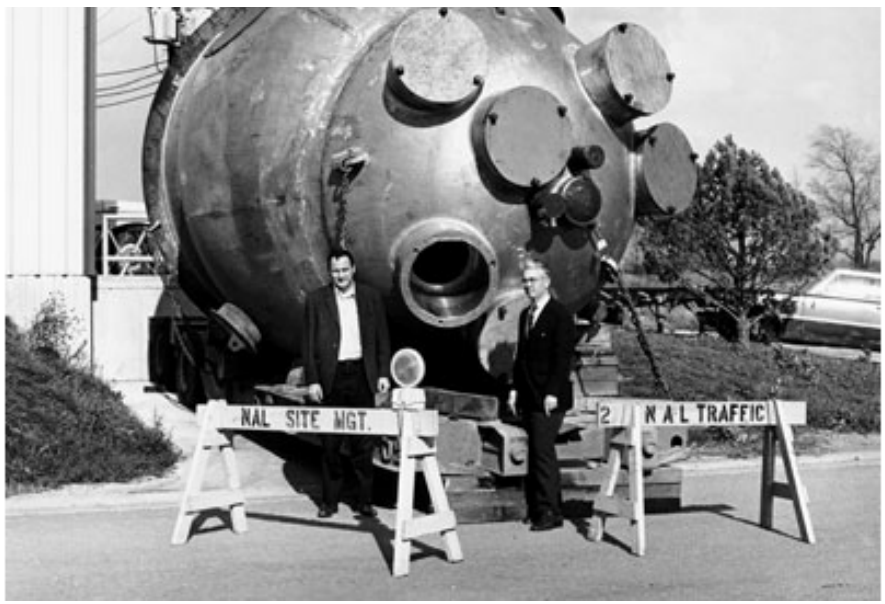
"One of the first aims of experiments on the NAL accelerator system will be the detection of the neutrino. I feel that we then will be in business to do experiments on our accelerator."

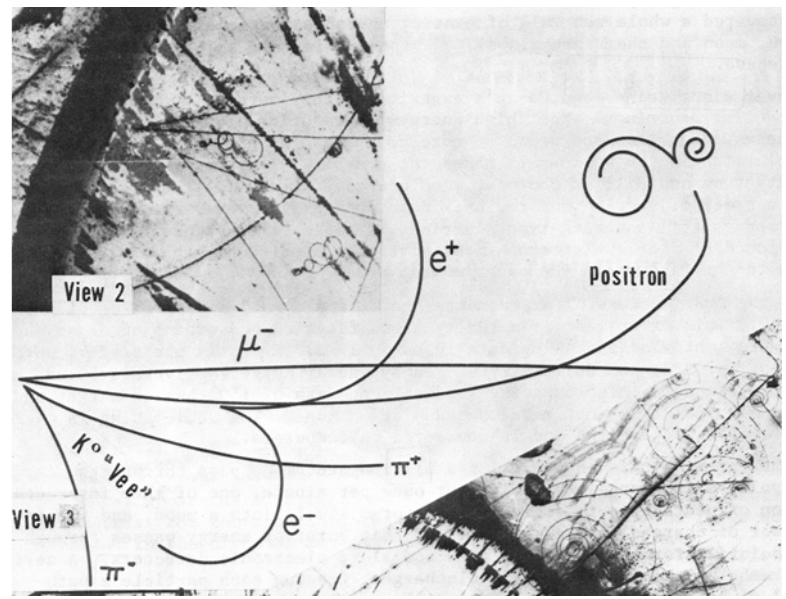
-Bob Wilson (1971)

Since the very beginning

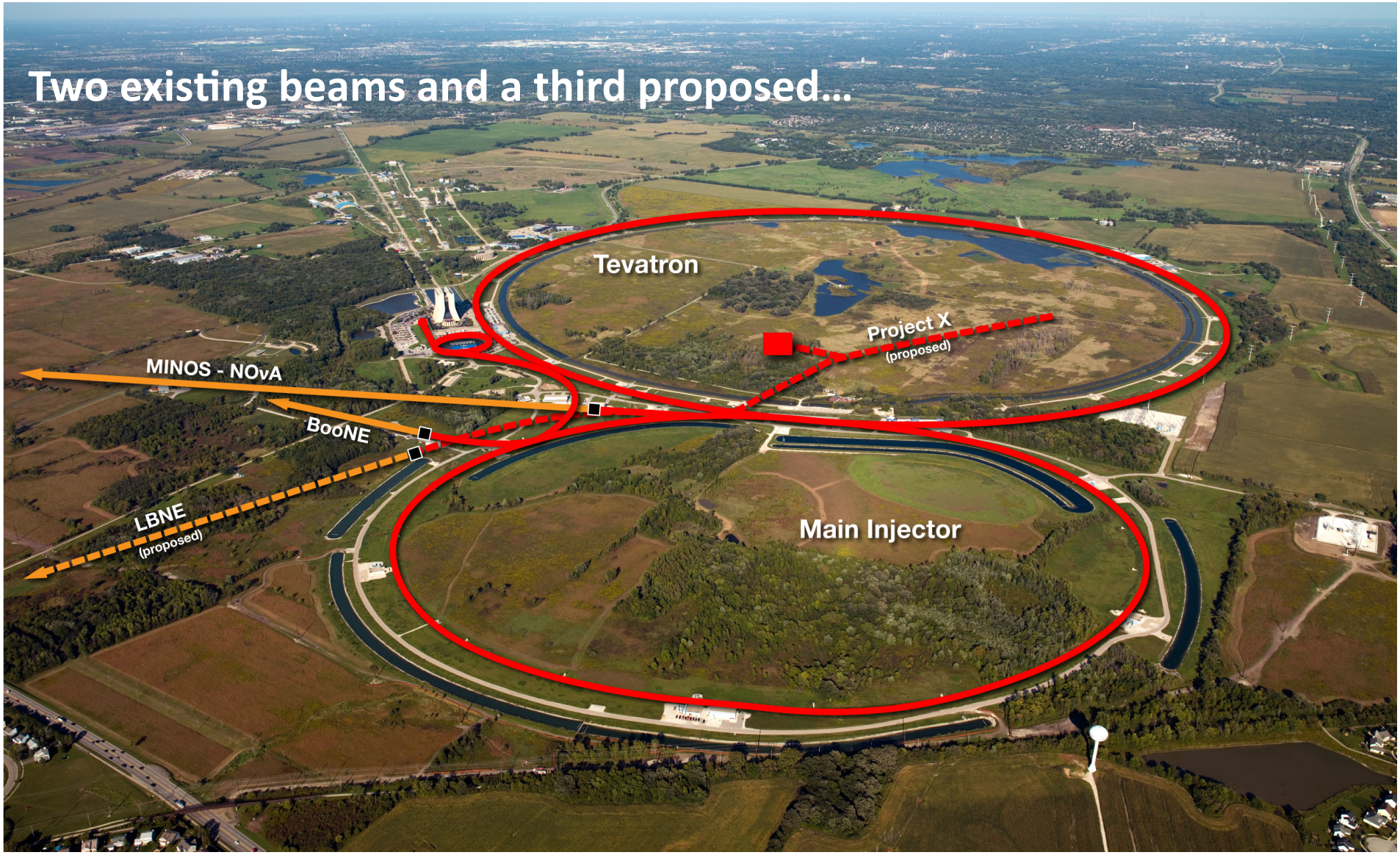


A schematic of the Neutrino Line at Fermilab where neutrinos are generated indirectly from protons. Protons from the accelerator strike a metal target, generating pions and kaons which then decay mainly into muons, neutrinos and antineutrinos. Muons and any remaining hadrons are filtered out as they pass through the mound of earth (muon shield); At the end of this process only neutrinos and anti-neutrinos remain. Detectors such as the 15-ft. Bubble Chamber and the equipment of other neutrino experiments are placed at this point to record neutrino activity in its purest form.





Modern accelerator neutrino beams

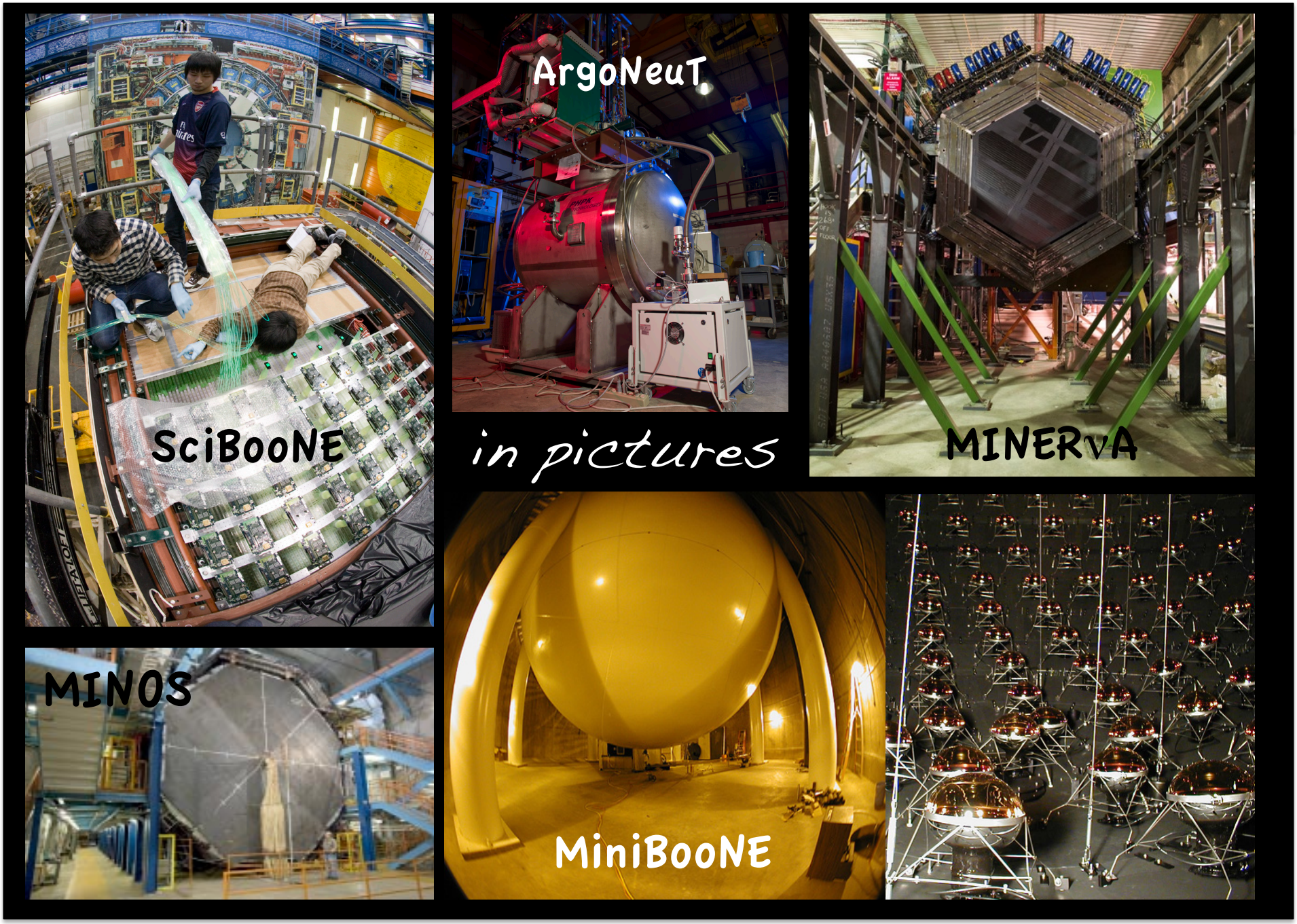


Modern neutrino experiments

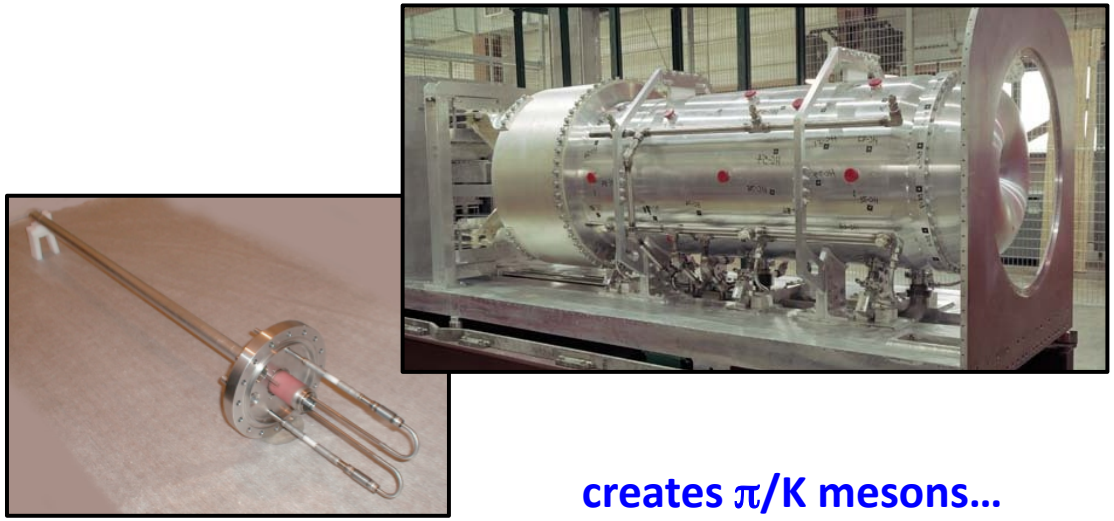
1. **Booster Neutrino Beam (BNB)** Lower mean energy, Lower intensity (30 kW)
   - **Short-baseline oscillations and neutrino cross sections experiments:**
     1. **MiniBooNE** (current) – 800 T mineral oil Cherenkov light
     2. **MicroBooNE** (future) – 170 T liquid argon time projection chamber (TPC) tracker
     3. **SciBooNE** (past) – solid scintillator tracker

2. **Main Injector Neutrino Beam (NuMI)** Adjustable mean energy, Higher intensity (350 kW now, 700 kW in 2013)
   - **Long-baseline oscillation experiments:**
     1. **MINOS** (current), **MINOS+** (future) – 5 kT iron + solid scintillator
     2. **NOvA** (future) – 15 kT liquid scintillator
   - **Short-baseline neutrino cross section experiments:**
     3. **MINERvA** (current) – finely segmented solid scintillator
     4. **ArgoNeuT** (past) – prototype liquid argon TPC tracker

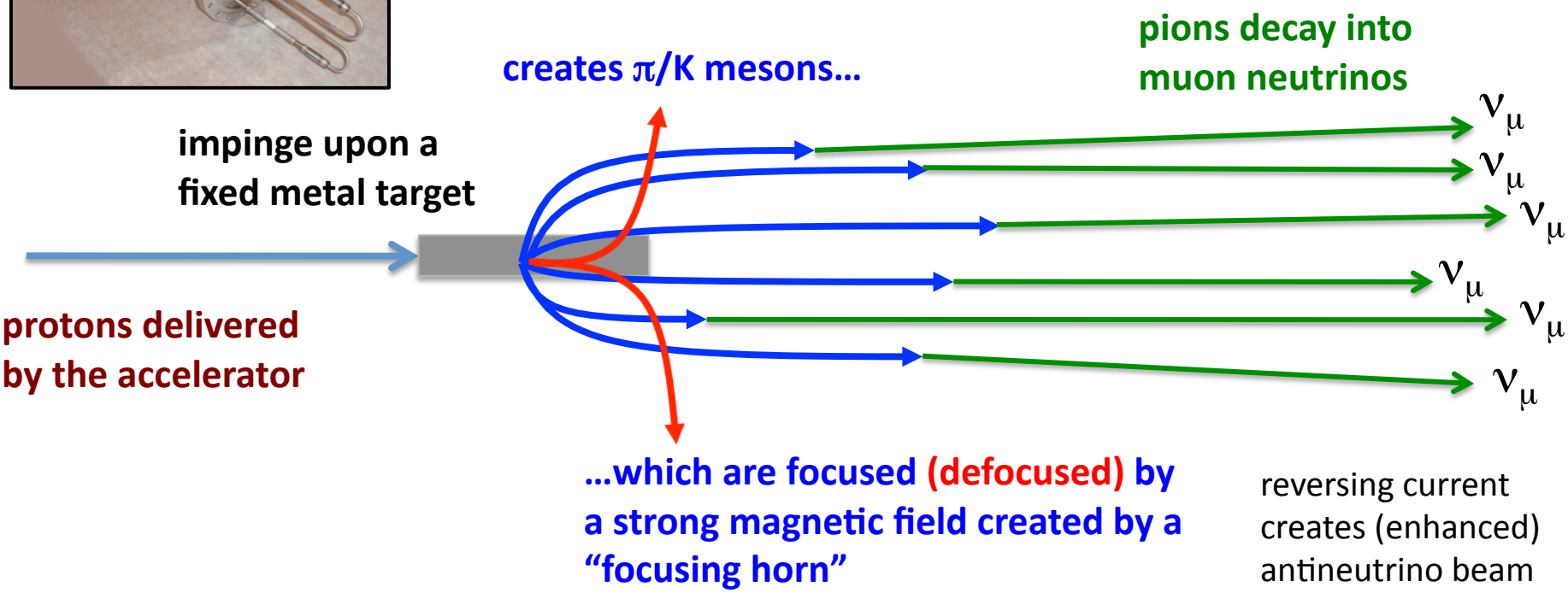
3. **LBNE Neutrino Beam** Wide band energy, Higher intensity (700 kW – 2.3 MW)
   - **Proposed for future long-baseline oscillation experiments:**
     1. **LBNE** (future) – 35 kT liquid argon TPC tracker


SciBooNE
ArgoNeuT
in pictures
MINERvA
MINOS
MiniBooNE

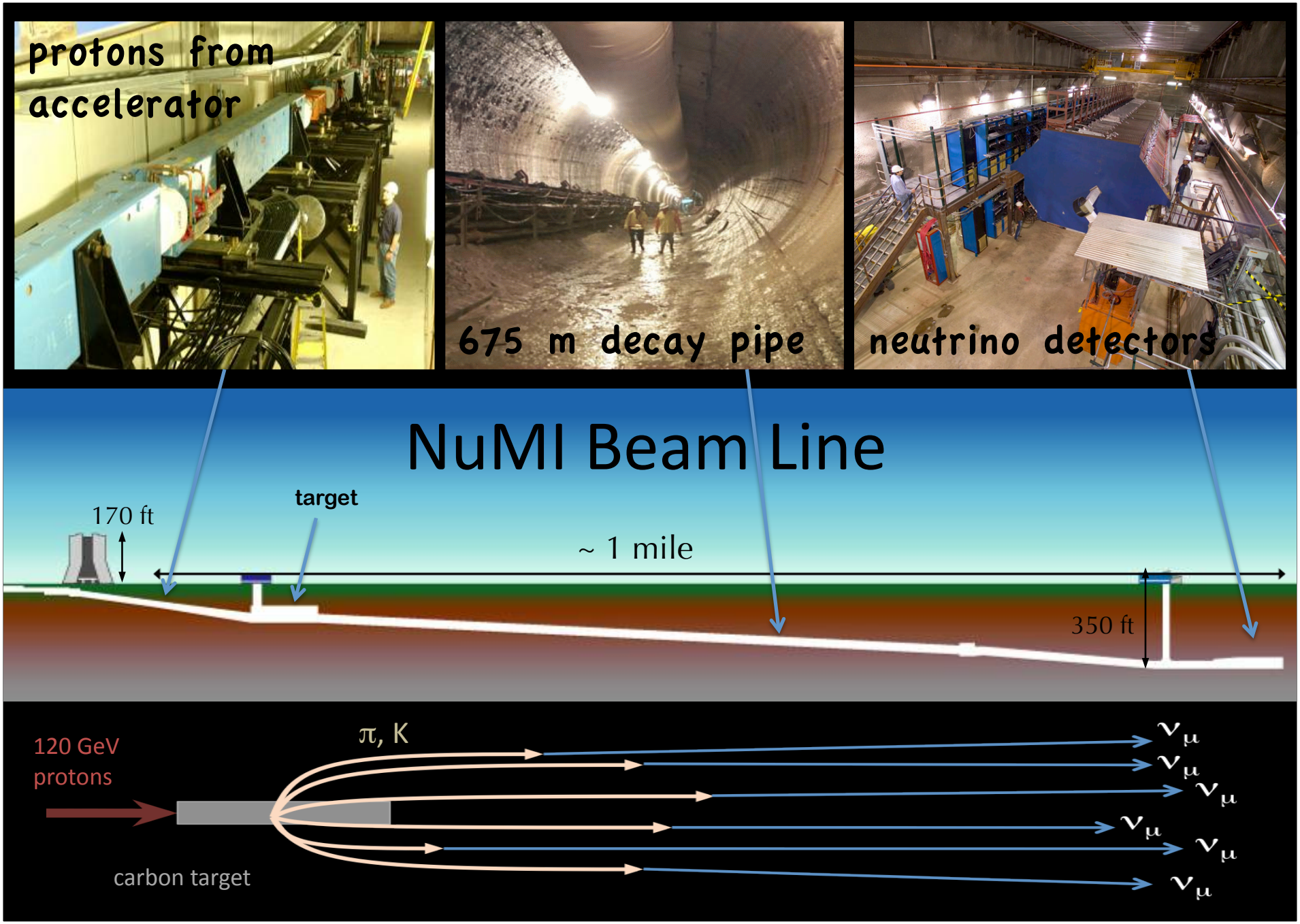
Making a neutrino beam



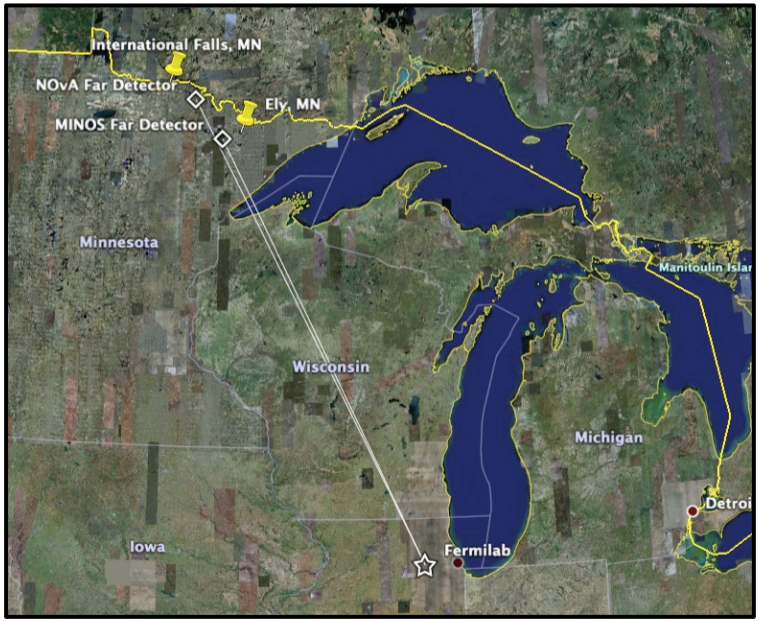
This is the basic concept first invented by Schwartz, Lederman and Steinberger when they discovered the ν_μ in 1962



reversing current creates (enhanced) antineutrino beam

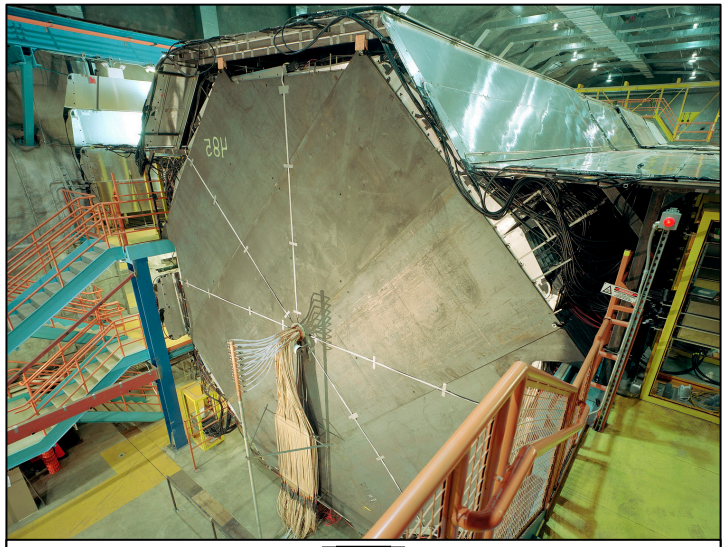

protons from accelerator
675 m decay pipe
neutrino detectors
NuMI Beam Line
target
170 ft
~ 1 mile
350 ft
120 GeV protons
π, K
carbon target
ν_μ
ν_μ
ν_μ
ν_μ
ν_μ
ν_μ

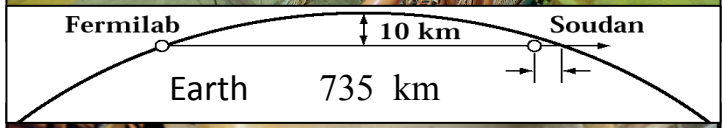
MINOS long-baseline oscillations



- **Running since 2005**
- **Magnetized steel and extruded scintillator bars**
- **1 kT near detector**
  - Detector response, sample unoscillated flux
- **5.4 kT far detector**

FAR DET (Soudan)



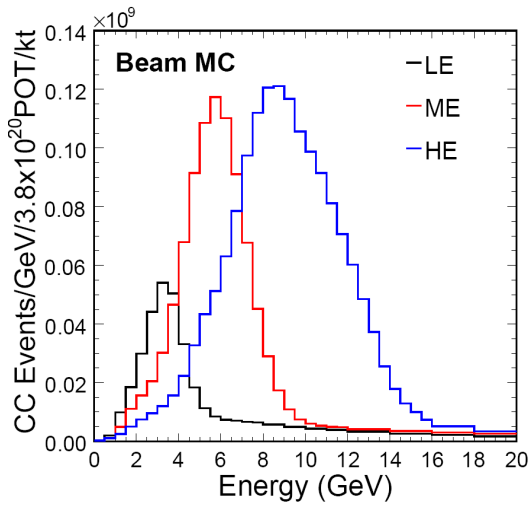


NEAR DET (Fermilab)

The atmo oscillation with accelerator ν_μ

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

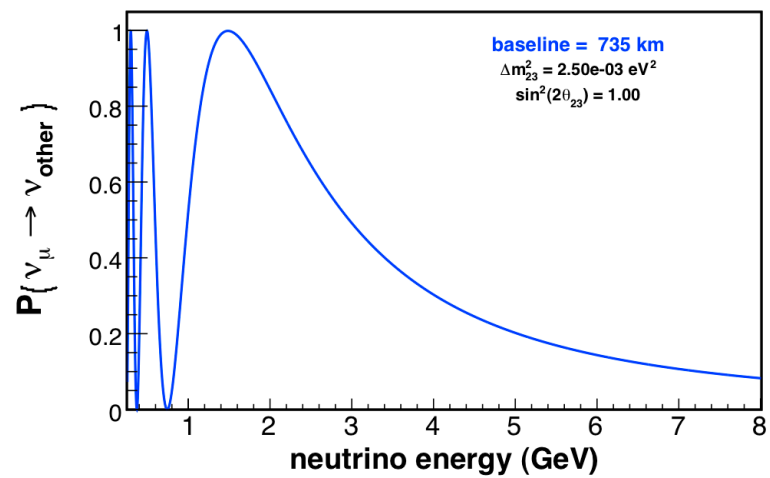
Fixed L
Variable E



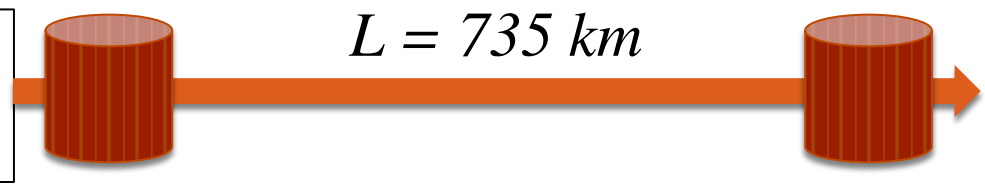
$$\langle E \rangle_{MINOS} \approx 3\ GeV$$

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

$$\Delta m^2 \approx 10^{-3} eV^2$$



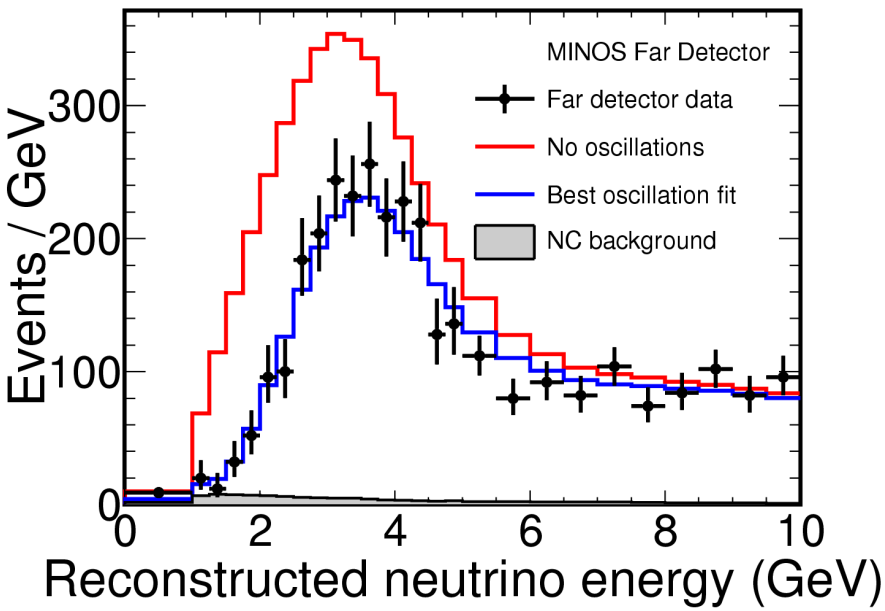
Begin with broad energy spectrum beam of ν_α

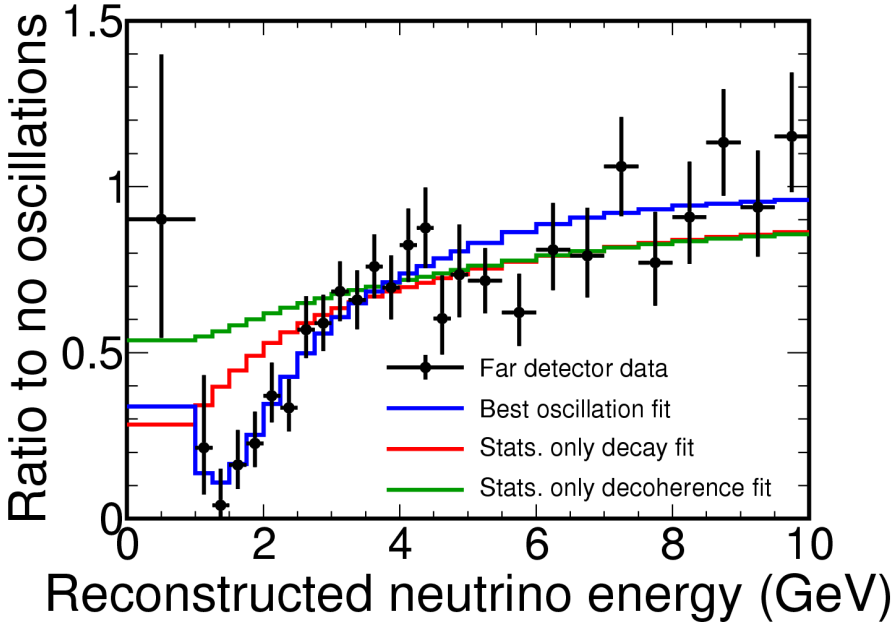


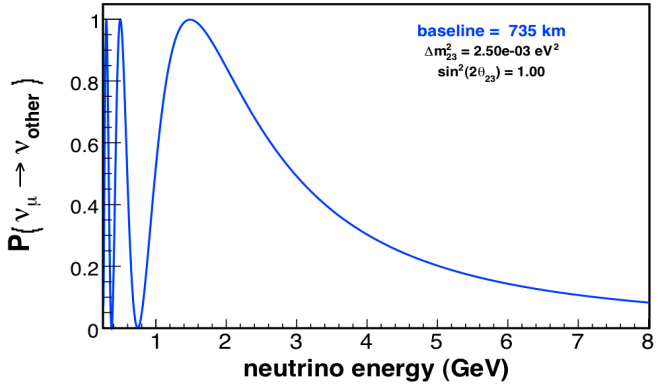
Measure ν_α / ν_β energy spectrum at origin and again after traveling distance L

The atmo oscillation with accelerator ν_μ

- **Use near detector event rate to predict far detector with no oscillations**

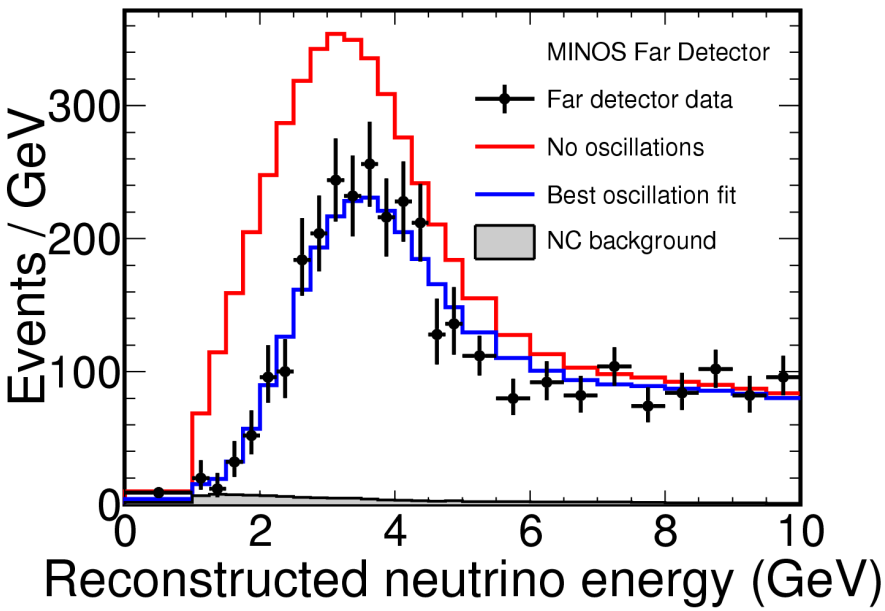


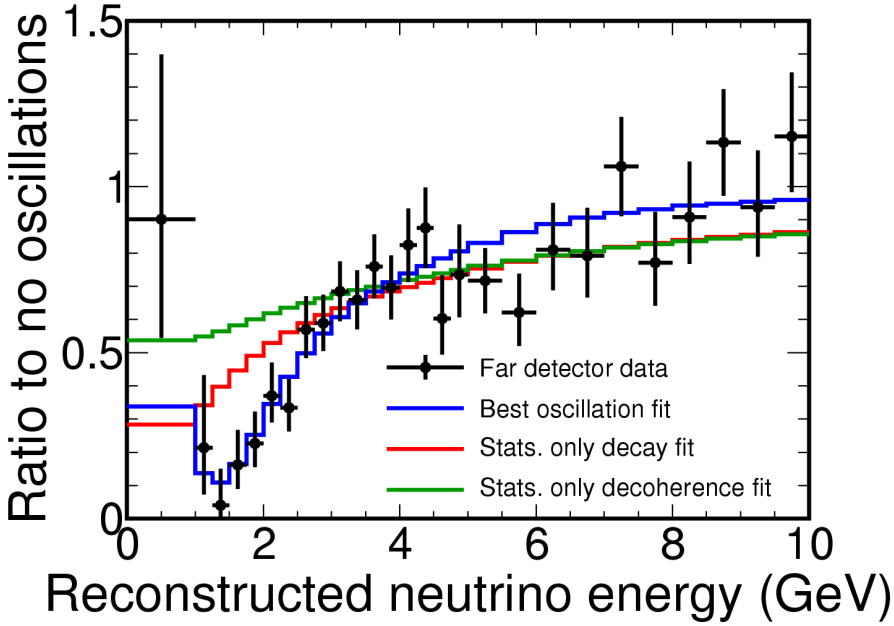




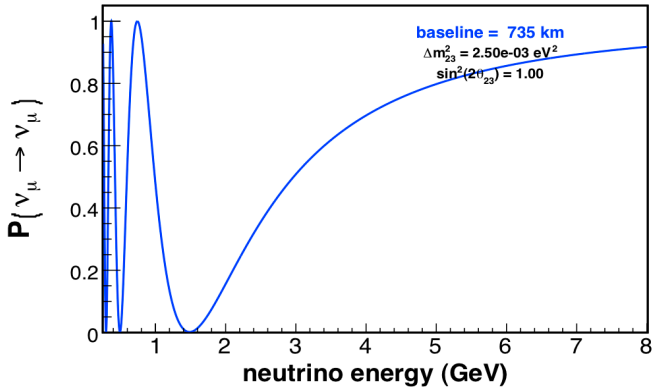
MINOS = ν_μ disappearance

- **Use near detector event rate to predict for far det. with no oscillations**





MINOS measures the
muon neutrino survival rate
(a disappearance measurement)



Let's review where we're at so far...

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \times \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}$$

atmospheric, accelerator neutrinos

solar, reactor neutrinos

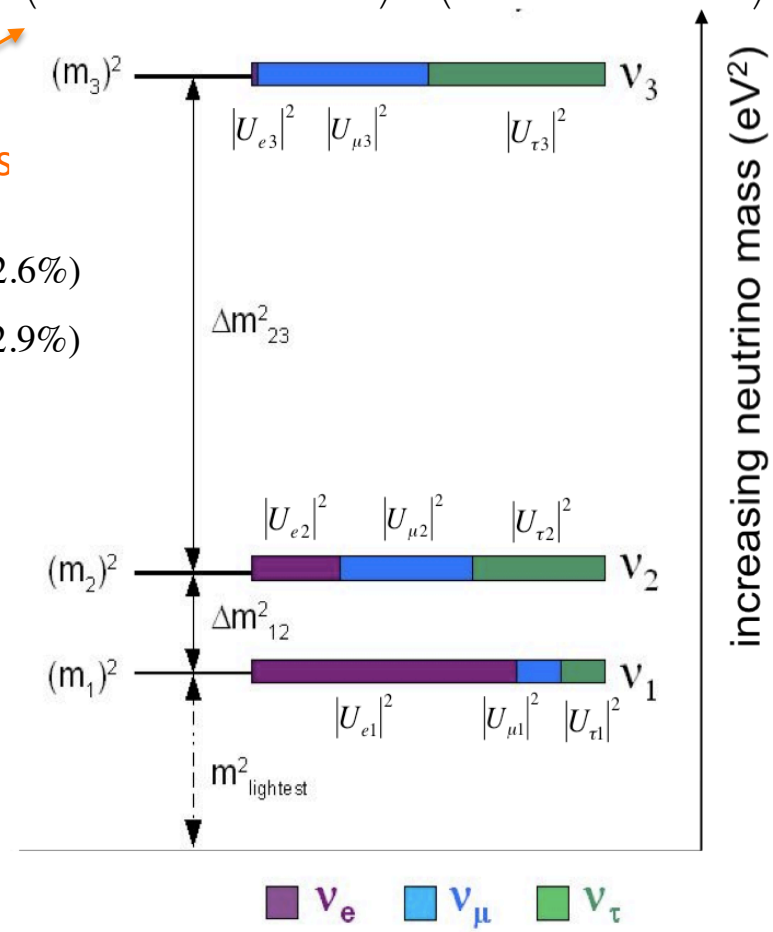
$\Delta m^2_{23} = 2.51 \times 10^{-3} eV^2 \quad (\pm 4.8\%)$

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

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

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

$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$



A few things to note...

Δm^2_{23}

Δm^2_{12}

$\Delta m^2_{13} \approx \Delta m^2_{23}$

θ_{12}

θ_{23}

θ_{13}

δ_{CP}

The two mass splittings, 2.5e-3 eV^2 and 7.6e-5 eV^2, differ by about a factor of 30

One mixing is large, 31°, but not maximal

One mixing is still consistent with maximal, $\pi/4$. Is it?

Until very recently, the third angle, θ_{13}, was completely unknown

Mixing in the neutrino sector is, in general, very different from that measured in the quark sector

The sign of Δm_{12}^2 is known, the sign of Δm_{23}^2 is not

The CP-violating phase, δ_{CP}, is completely unknown

neutrinos

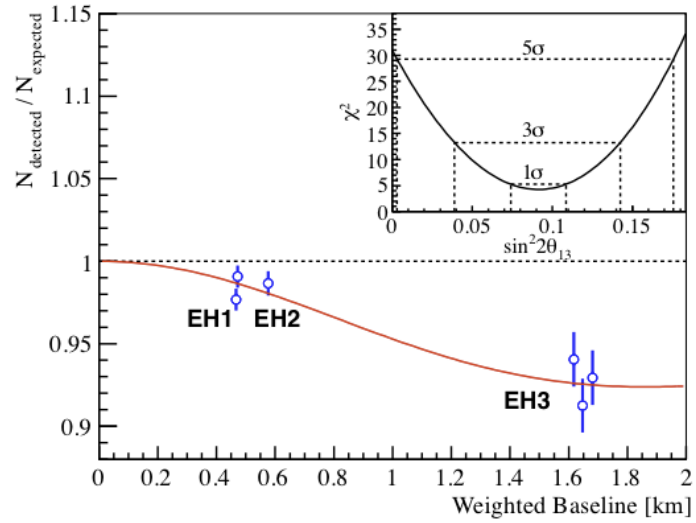
$$U_{MNSP} = \begin{pmatrix} 0.8 & 0.5 & 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

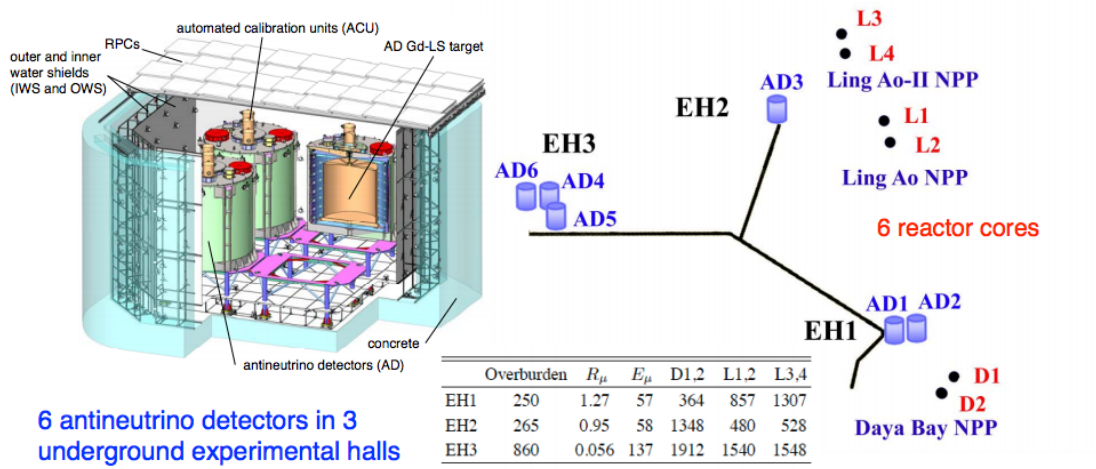
quarks

$$U_{CKM} = \begin{pmatrix} 1 & 0.2 & 0.004 \\ 0.2 & 1 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$

The race for the final angle, θ_{13}

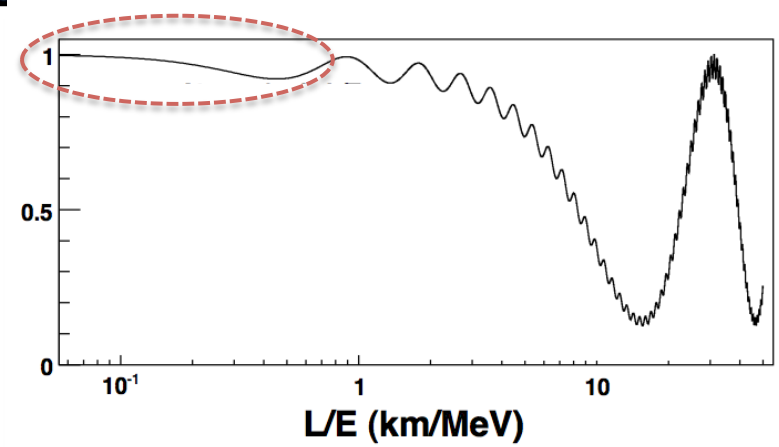
- **Possible to access through:**
  - short baseline $\overline{\nu}_e$ disappearance at nuclear reactors
  - long baseline ν_μ -> ν_e appearance using accelerators





	Overburden	R_μ	E_μ	D1,2	L1,2	L3,4
EH1	250	1.27	57	364	857	1307
EH2	265	0.95	58	1348	480	528
EH3	860	0.056	137	1912	1540	1548

Karsten Heeger, Univ. of Wisconsin EWNP Symposium, March 8, 2012 10



The race for the final angle, θ_{13}

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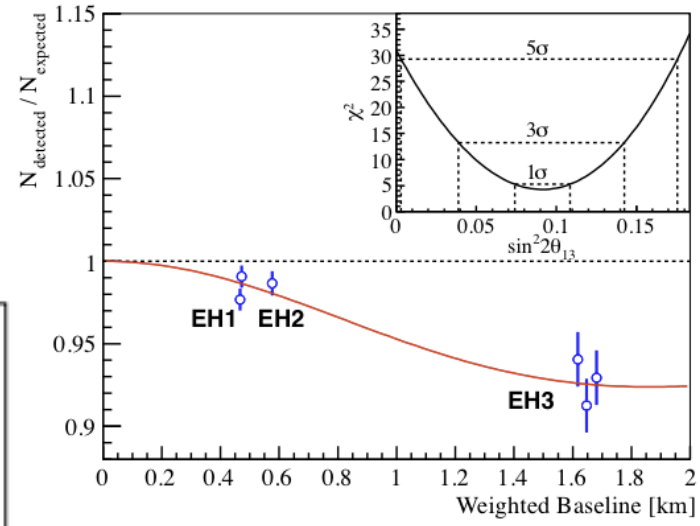
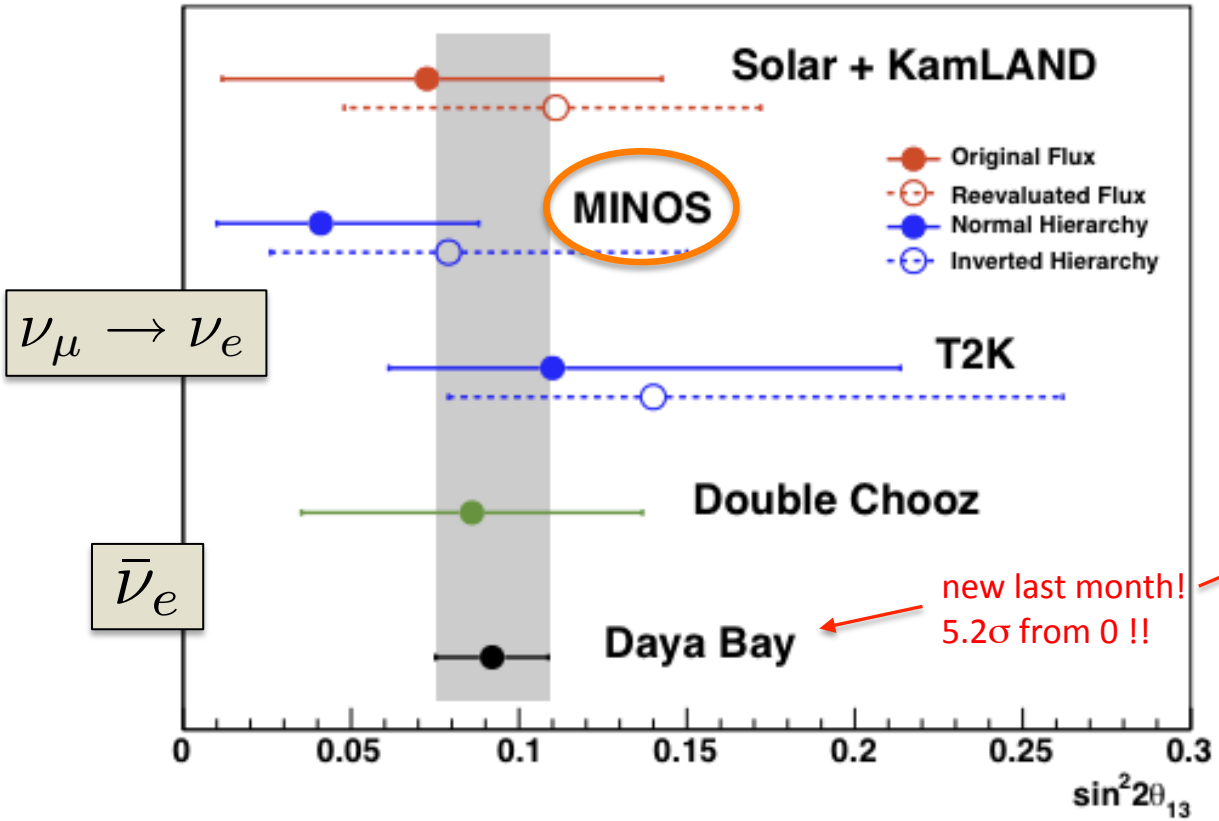
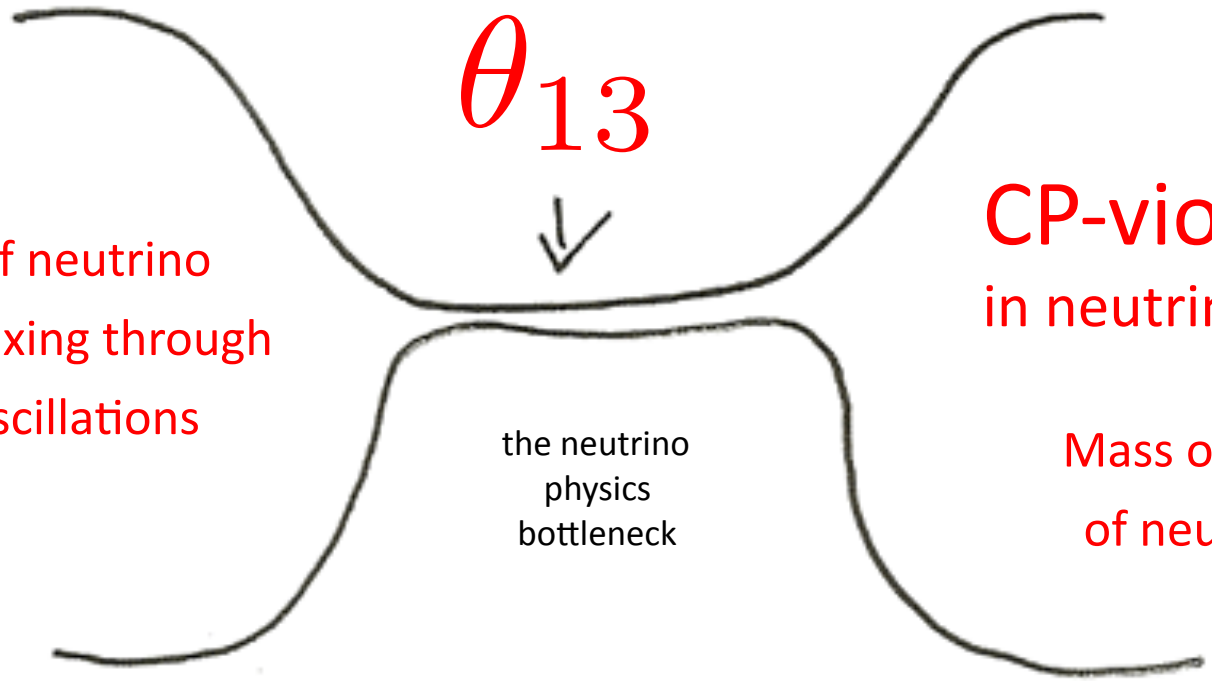




new last month!
5.2σ from 0 !!

$$\theta_{13} \approx 8.8^\circ$$

The meaning of large θ_{13}



Discovery of neutrino masses and mixing through neutrino oscillations

CP-violation in neutrino sector

Mass ordering of neutrinos

Neutrinos in the news

nature

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NATURE | FROM THE BLOG

Neutrino oscillat

Result improves prospects fo

Eugenie Samuel Reich

08 March 2012

An elusive parameter quantifyin
of ghostly subatomic neutrinos
another has been measured wit
time.

In a paper released online on 8
Reactor Neutrino Experiment in
a measurement of the disappea
produced in the world's fifth-larg
as they travelled about one kilo
of three 20-tonne, water-filled de
parameter known as $\sin^2(2\theta_{13})$
had speculated that the quantity
'mixing angles' that quantify rate

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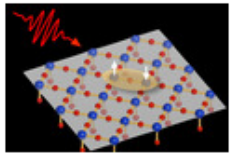

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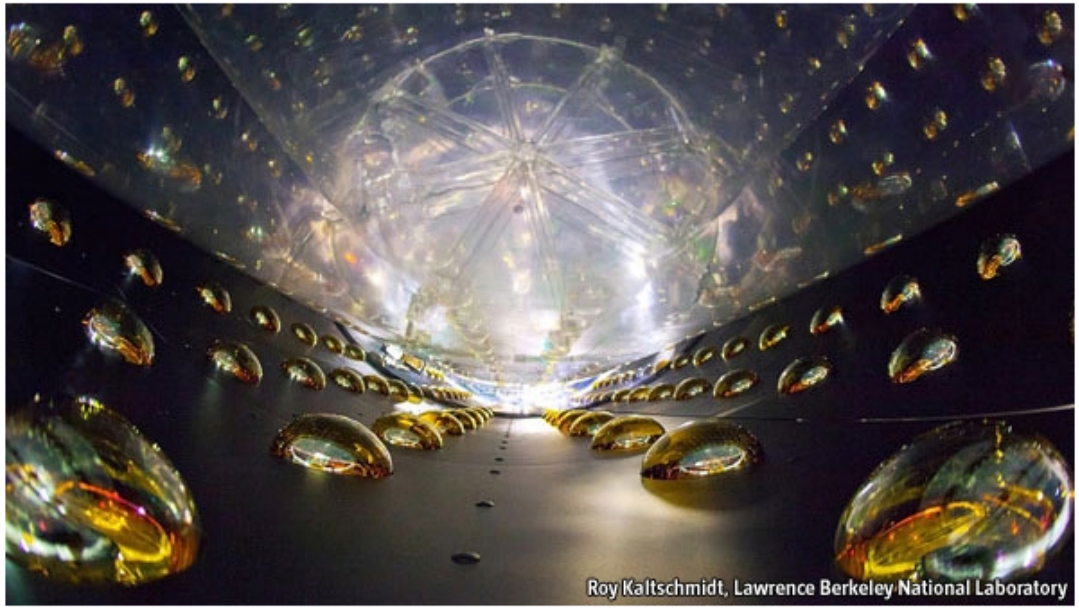

Roy Kaltschmidt, Lawrence Berkeley National Laboratory

HOT on the heels of results from Fermilab, in America, which reported last week on an esoteric phenomenon called charge-conjugation/parity (CP) violation involving equally

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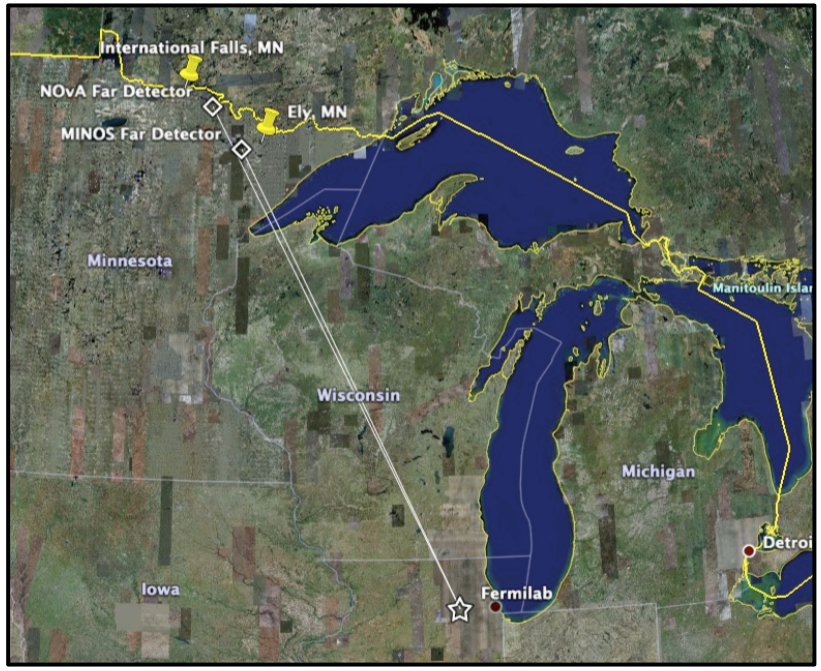
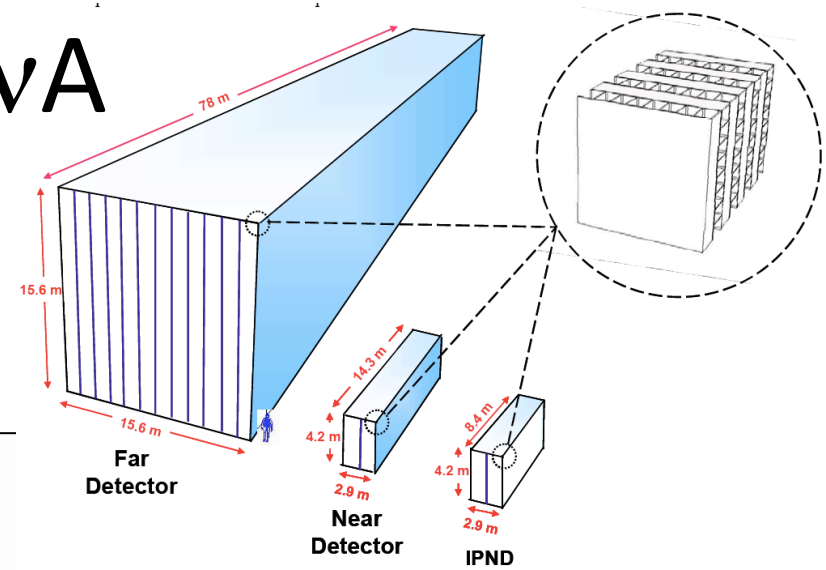
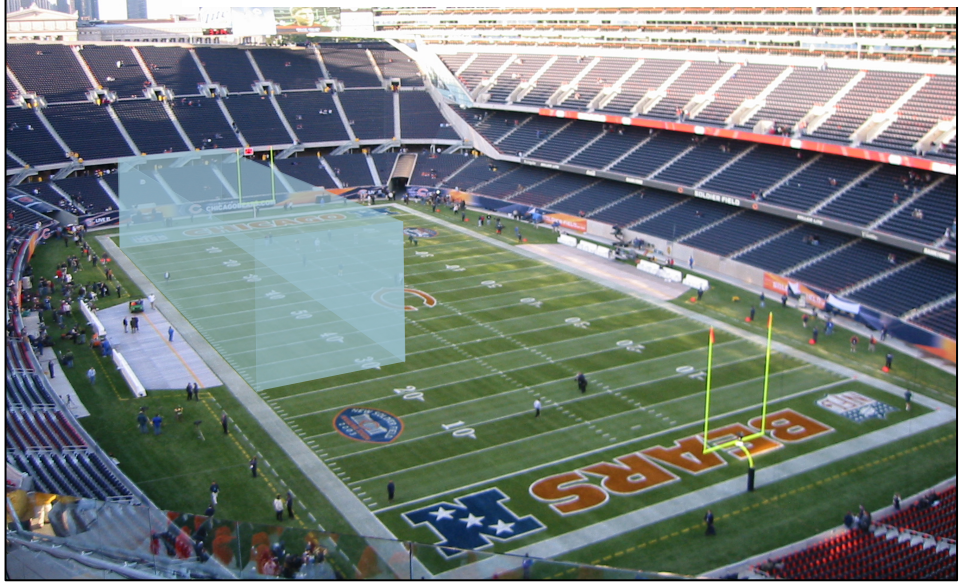
Going after θ_{13} with $\nu_\mu \to \nu_e$ appearance



NOνA





- **15 kT liquid scintillator far detector in Ash River, MN designed to detect ν_e**
- **810 km from the NuMI beamline, 2 mrad off-axis**
- **Begin running in 2013**

Neutrinos as a window on the universe: 21st century version

The need for more $\not{C}\not{P}$

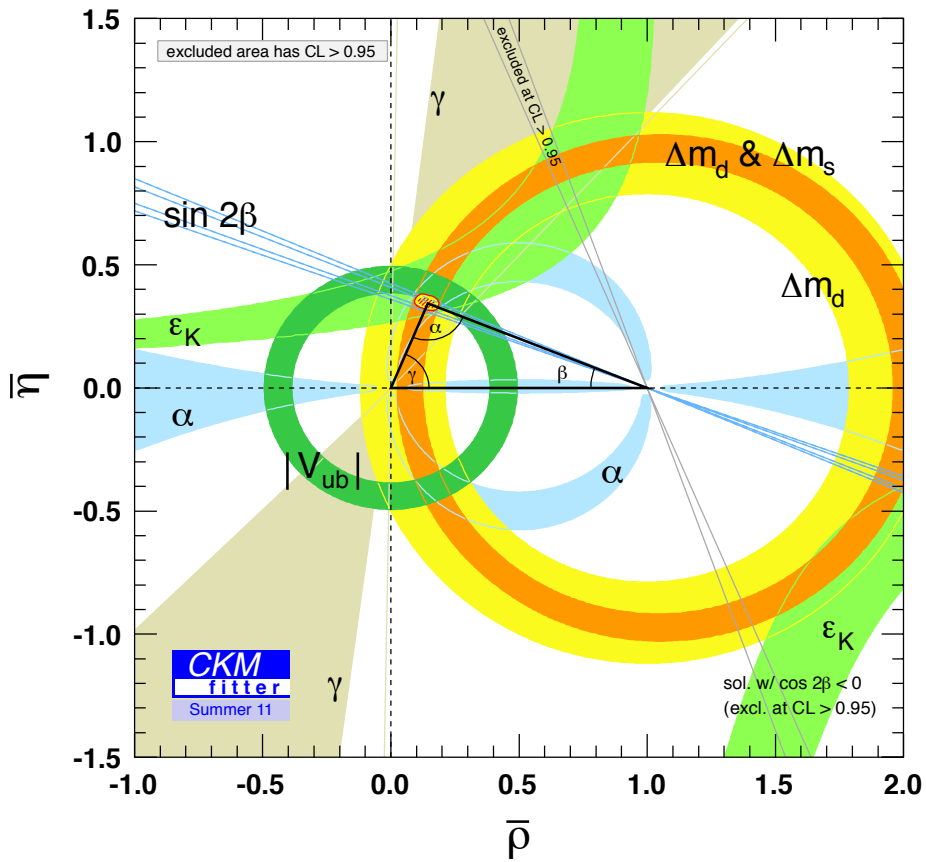
- **One of the great unanswered questions in physics and cosmology is how the universe came to contain so much matter as opposed to antimatter or instead didn't just reduce to a vast sea of photons**

- **There should be as-yet-unknown sources of CP-violation in the Standard Model in order to explain the matter/antimatter density difference observed in the universe**
  - Known CP-violations in the quark sector are all too small by many orders of magnitude to be the explanation
  - Work continues to search for new sources of CP-violation in the quark sector

- **Neutrino oscillations provide a unique opportunity to probe a brand new CP-violating sector of nature**

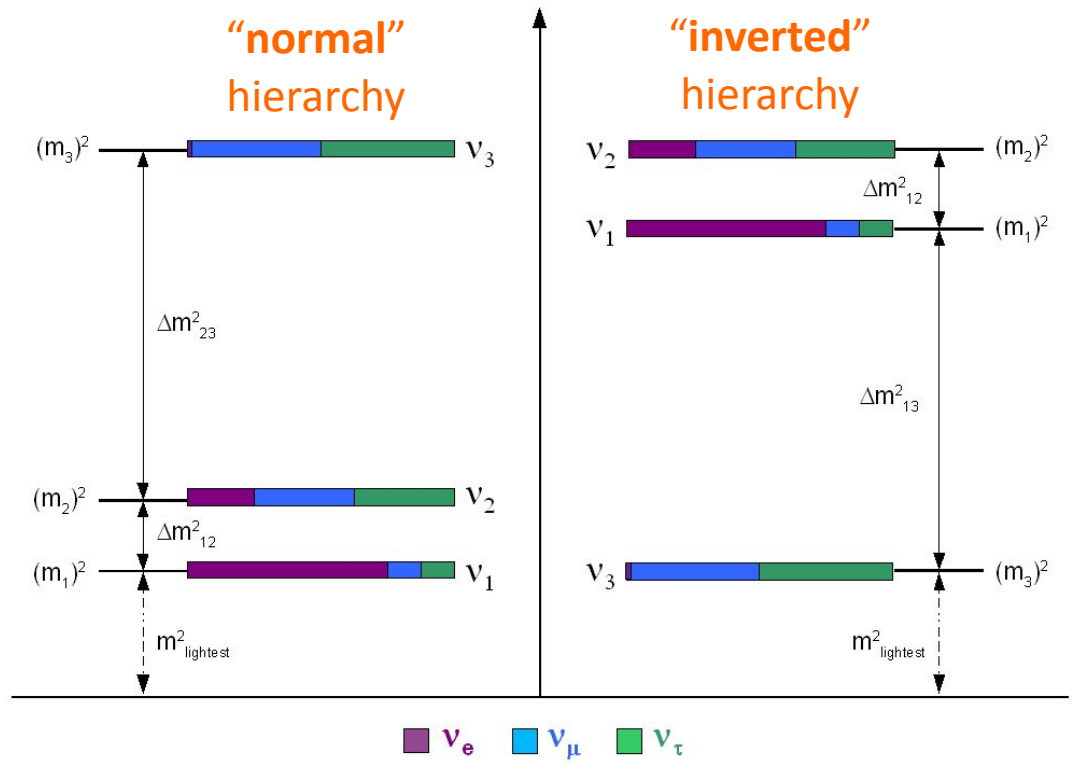
The need for more CP

- **This is what CP-violation looks like in the quark sector**
- **In leptons, we know nothing so far…**



The neutrino mass hierarchy

- **Oscillations are not sensitive to the absolute masses**
  - they do set a lower limit for $m_{heaviest} > 0.05$ eV
  - cosmology currently provides the best upper limit, $\Sigma m_i \sim 0.6$ eV
- **Nor are they inherently sensitive to the sign of mass differences, only $|\Delta m^2|$**
  - however, forward coherent scattering of neutrinos off electrons in matter changes the phase
  - different for neutrinos/antineutrinos since no positrons in the Earth
  - provides a way to determine sign(Δm^2) <u>if enough matter</u>



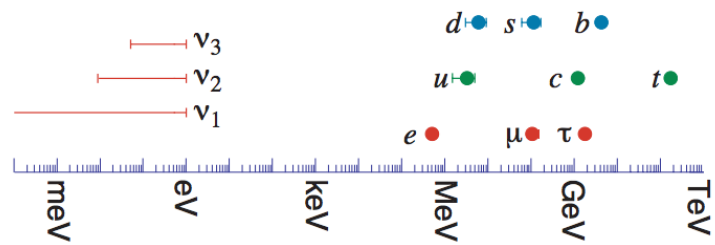
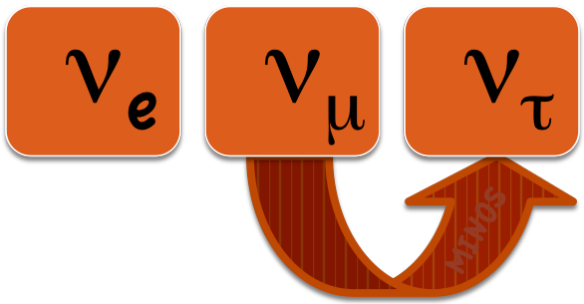


Figure 1-2. *Standard model fermion masses. For the neutrino masses, the normal mass hierarchy was assumed, and a loose upper bound $m_i < 1$ eV, for all $i = 1, 2, 3$ was imposed.*

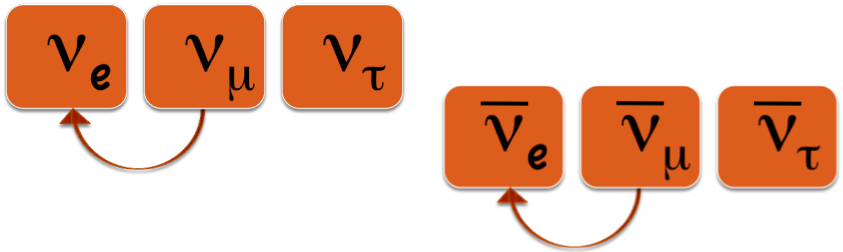
Why the search for CP-violation represents a new paradigm in accelerator-based long-baseline neutrino oscillation experiments

Searching for CP in neutrino oscillations

What MINOS has essentially done by measuring the large **disappearance** of muon neutrinos



Must measure $\nu_\mu \rightarrow \nu_e$ **appearance** in both neutrinos <u>and</u> antineutrinos to access CP-violating effects



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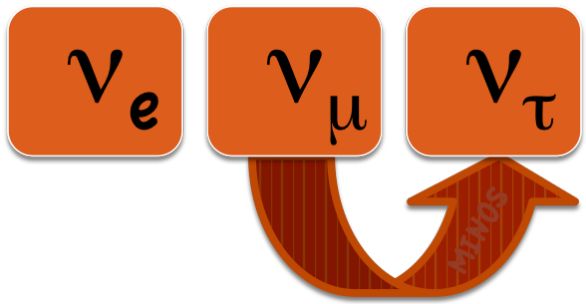
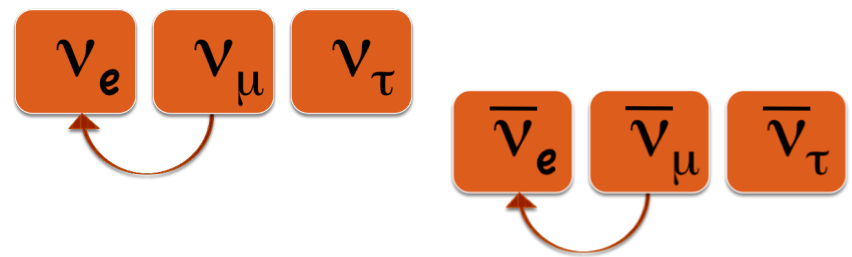


$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta_{23} \cdot \sin^2\left(\frac{1.27 \cdot \Delta m^2{}_{23} \cdot L}{E}\right)$$

Must measure $\nu_\mu \rightarrow \nu_e$ **appearance** in both neutrinos <u>and</u> antineutrinos to access CP-violating effects



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

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

CP Violating

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

CP Conserving

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

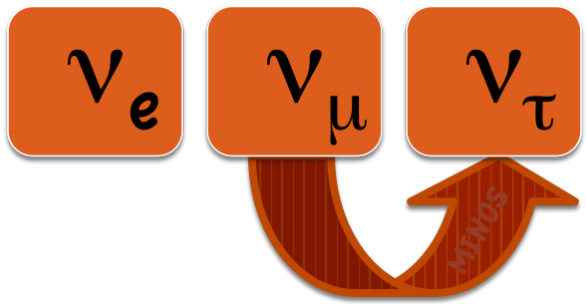
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

Matter Effects

$$\Delta \equiv \frac{\Delta m^2{}_{31} L}{4E_\nu} \qquad x \equiv \pm \frac{2\sqrt{2} G_F N_e E_\nu}{\Delta m^2{}_{31}} \qquad \alpha \equiv \frac{\Delta m^2{}_{21}}{\Delta m^2{}_{31}}$$

Searching for CP in neutrino oscillations

What MINOS has essentially done by measuring the large **disappearance** of muon neutrinos



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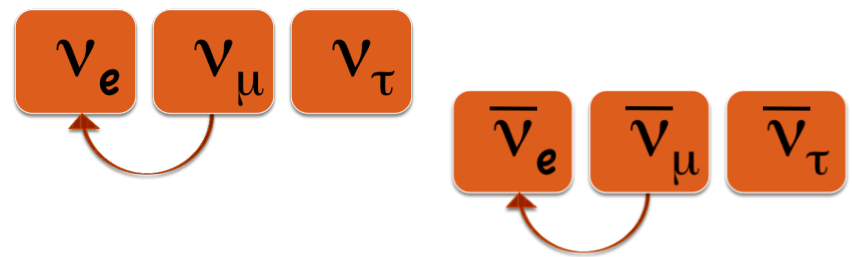
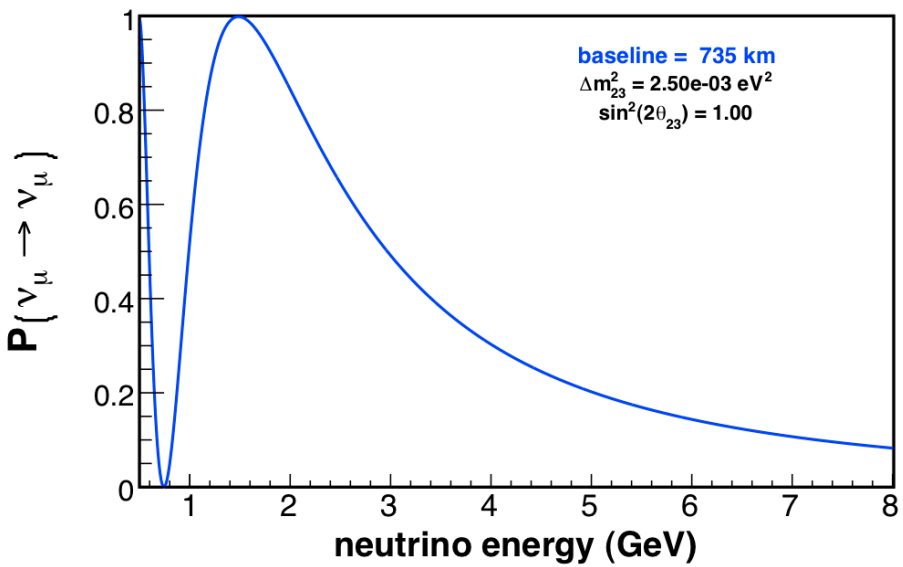
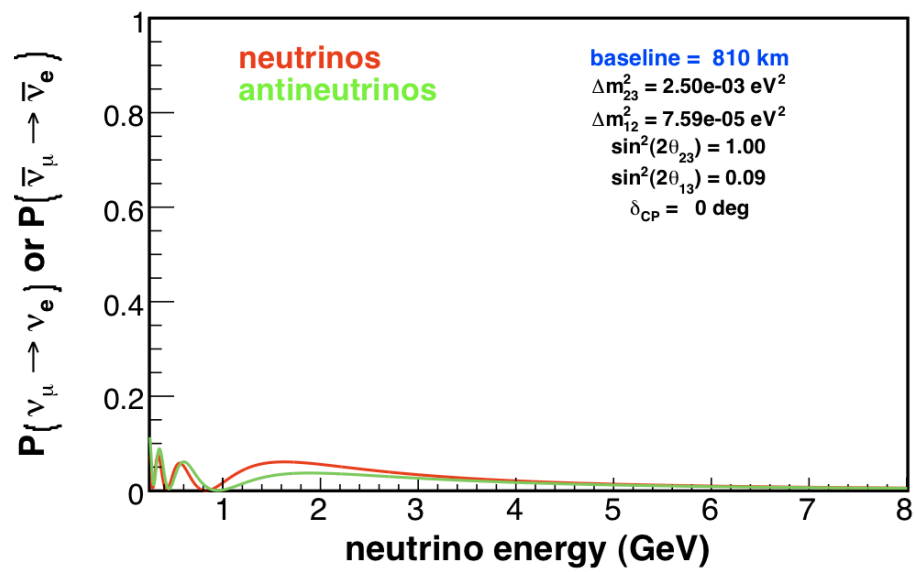
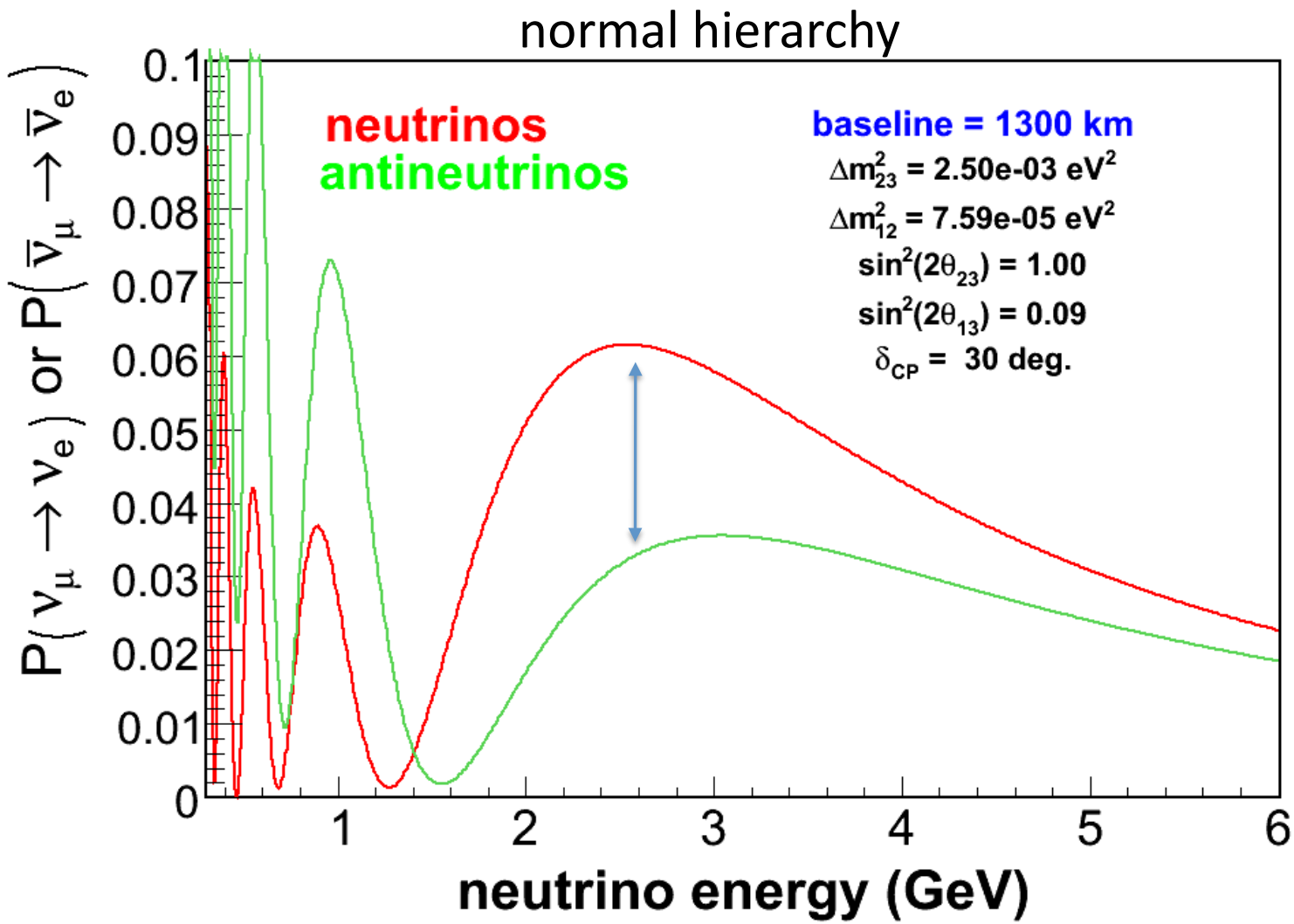






Searching for CP in neutrino oscillations



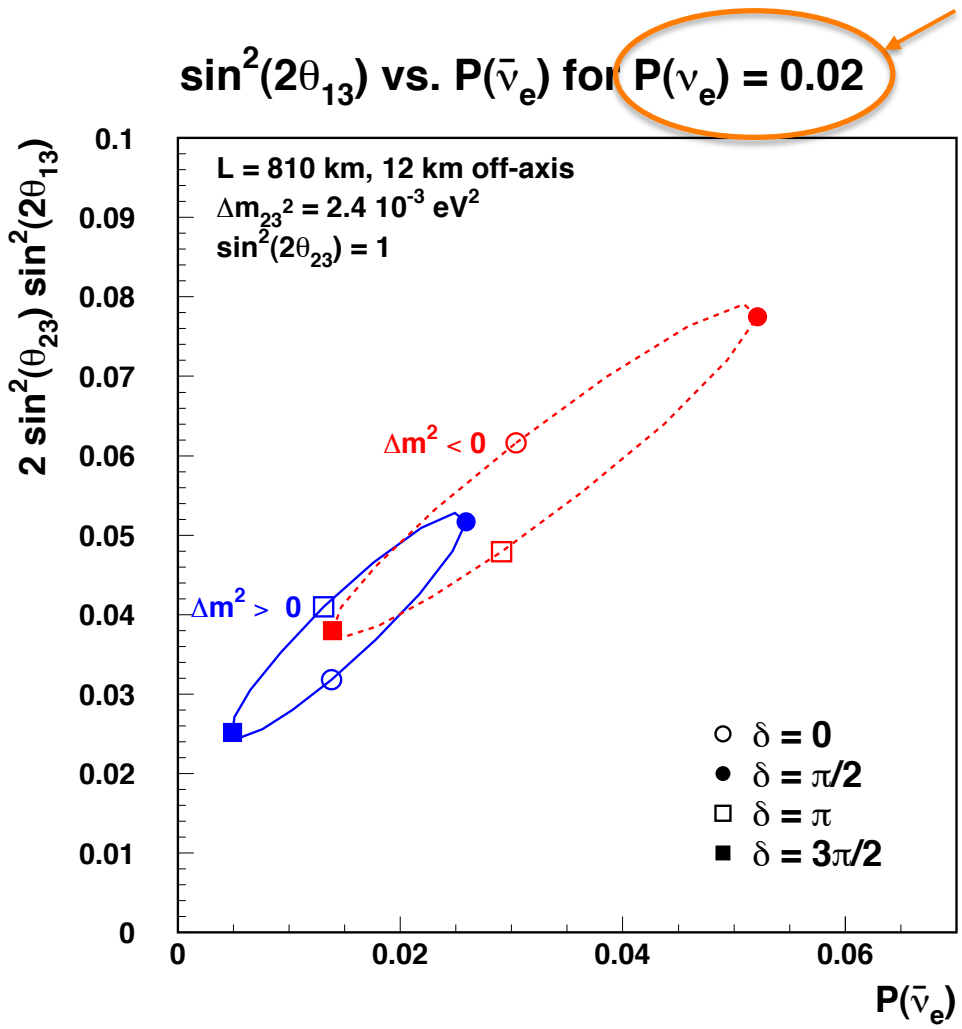
must precisely measure any asymmetry in the oscillation probabilities for neutrinos and antineutrinos

Searching for $\not{C}\not{P}$ in neutrino oscillations ν

- **Measure neutrino and antineutrino oscillations with high precision using accelerator-generated neutrino beams over very long baselines (order 1000 km)**
- **New experiments are being designed now to tackle this huge challenge**
- **Running / upcoming experiments make important steps along the path:**
  - precision measurements of θ_{13}
  - resolving the neutrino **mass hierarchy**
  - new measurements to get handles on **systematics** arising from neutrino/antineutrino fluxes, interaction cross sections, and nuclear medium effects
  - developing new **detector technologies** to improve signal / background separation and kinematic reconstruction

NOvA – going after the mass hierarchy

assuming this measured in neutrinos



NOvA – going after the mass hierarchy

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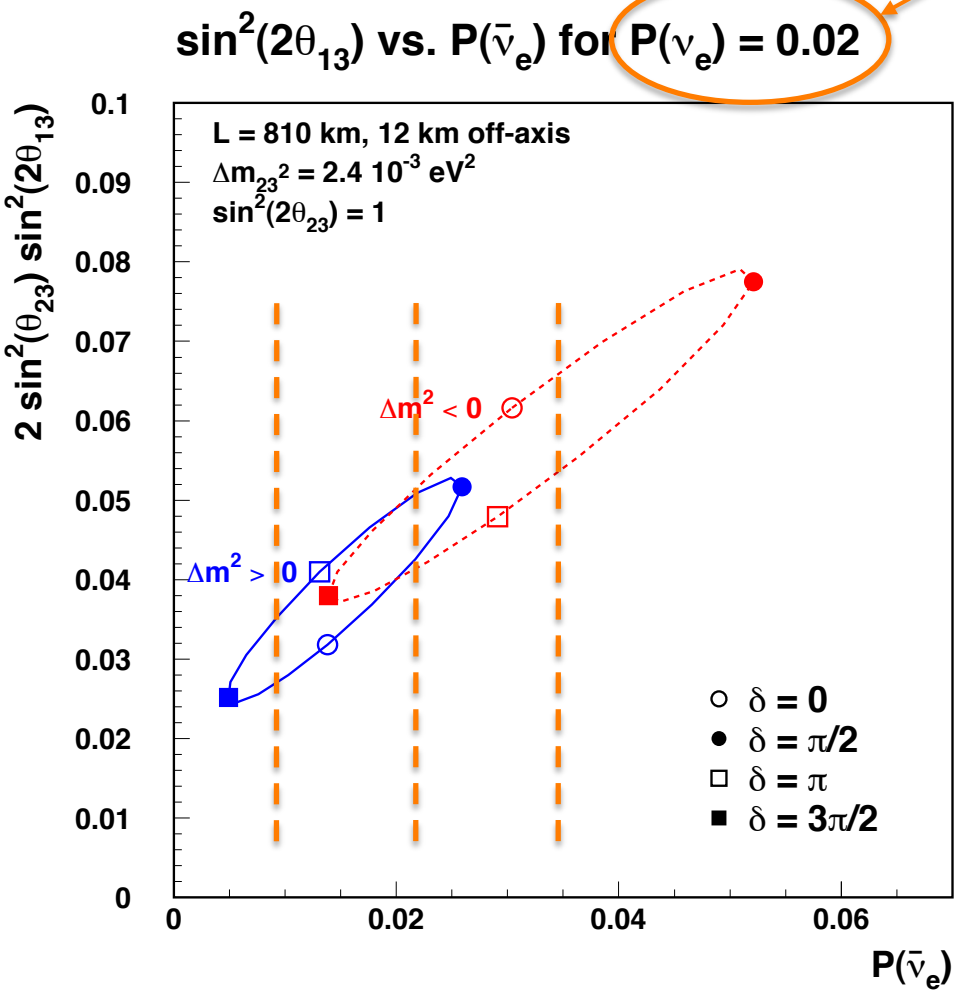
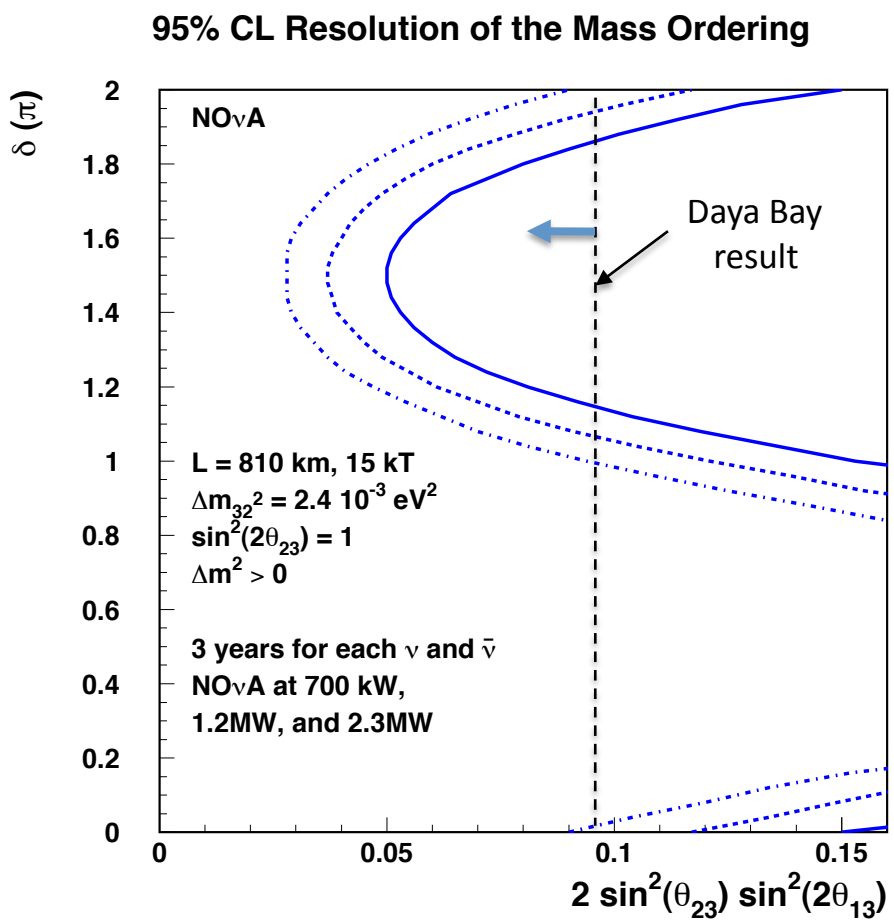
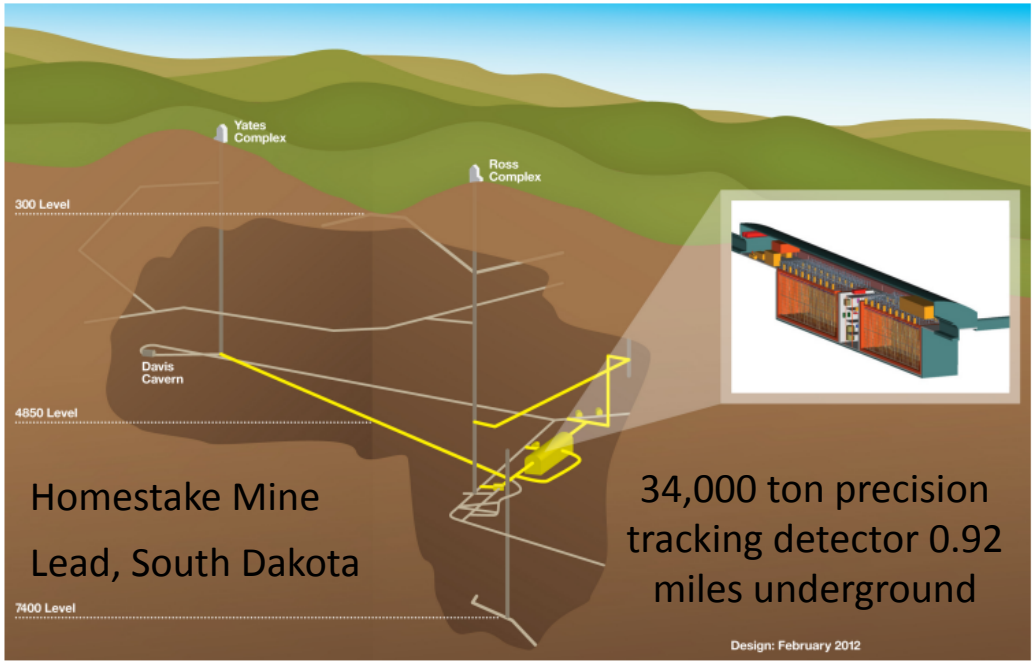




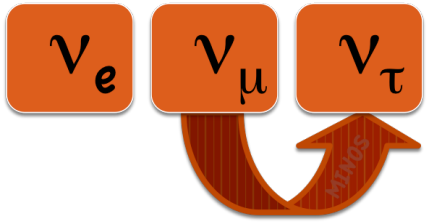
The Long-Baseline Neutrino Experiment

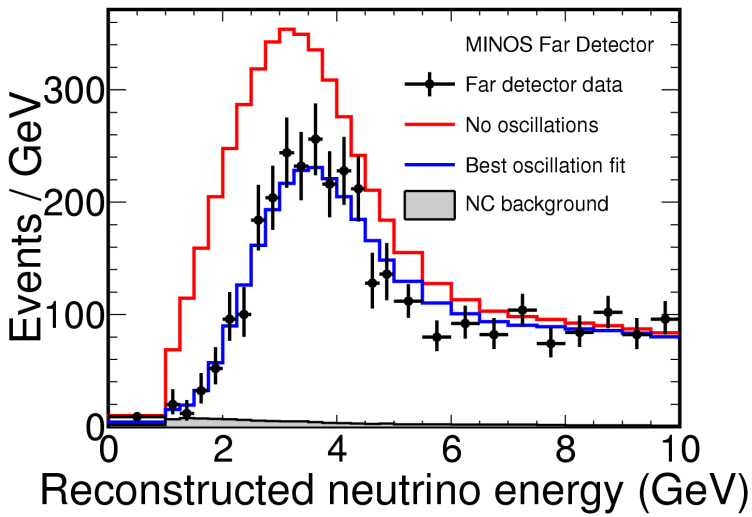
The Long-Baseline Neutrino Experiment

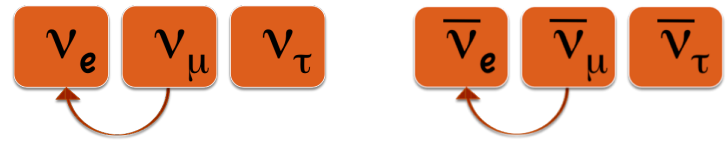


- **34 kT liquid argon time projection chamber (LArTPC) far detector**
- **LArTPC provides excellent signal (ν_e) from background separation (ν_μ NC interactions)**
- **1300 km from new, high-intensity wide-band beam from Fermilab**

The Long-Baseline Neutrino Experiment





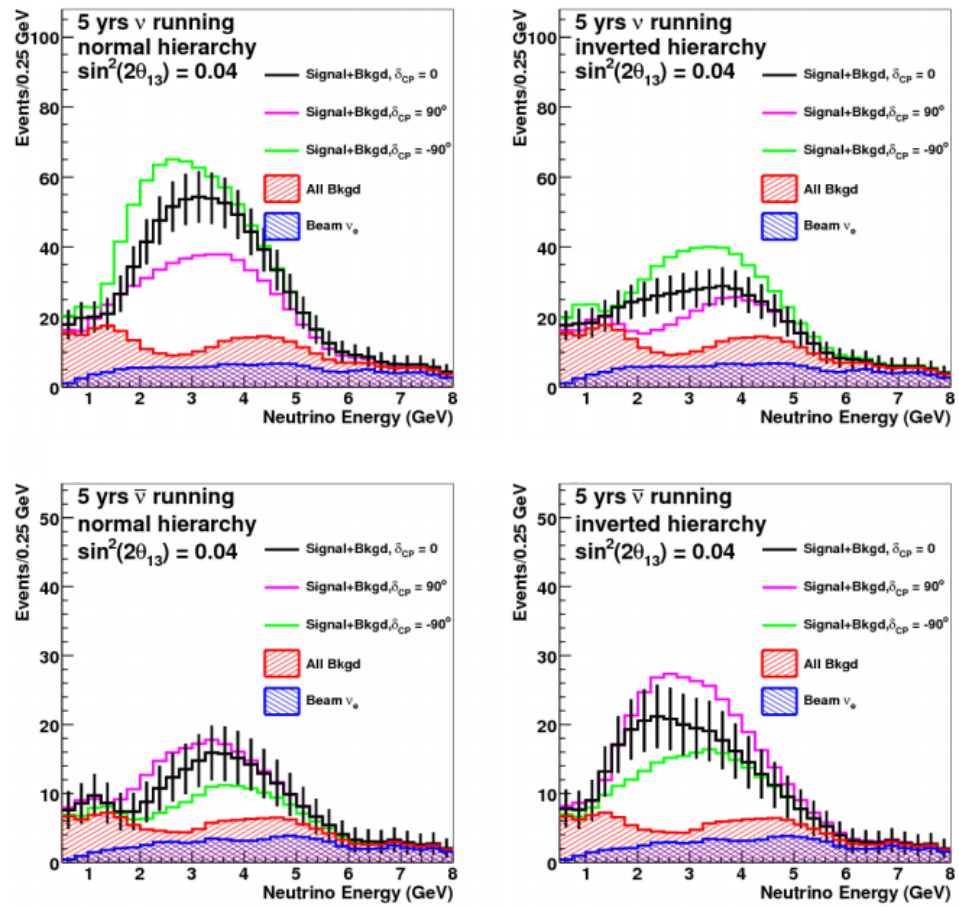


normal hierarchy

inverted hierarchy

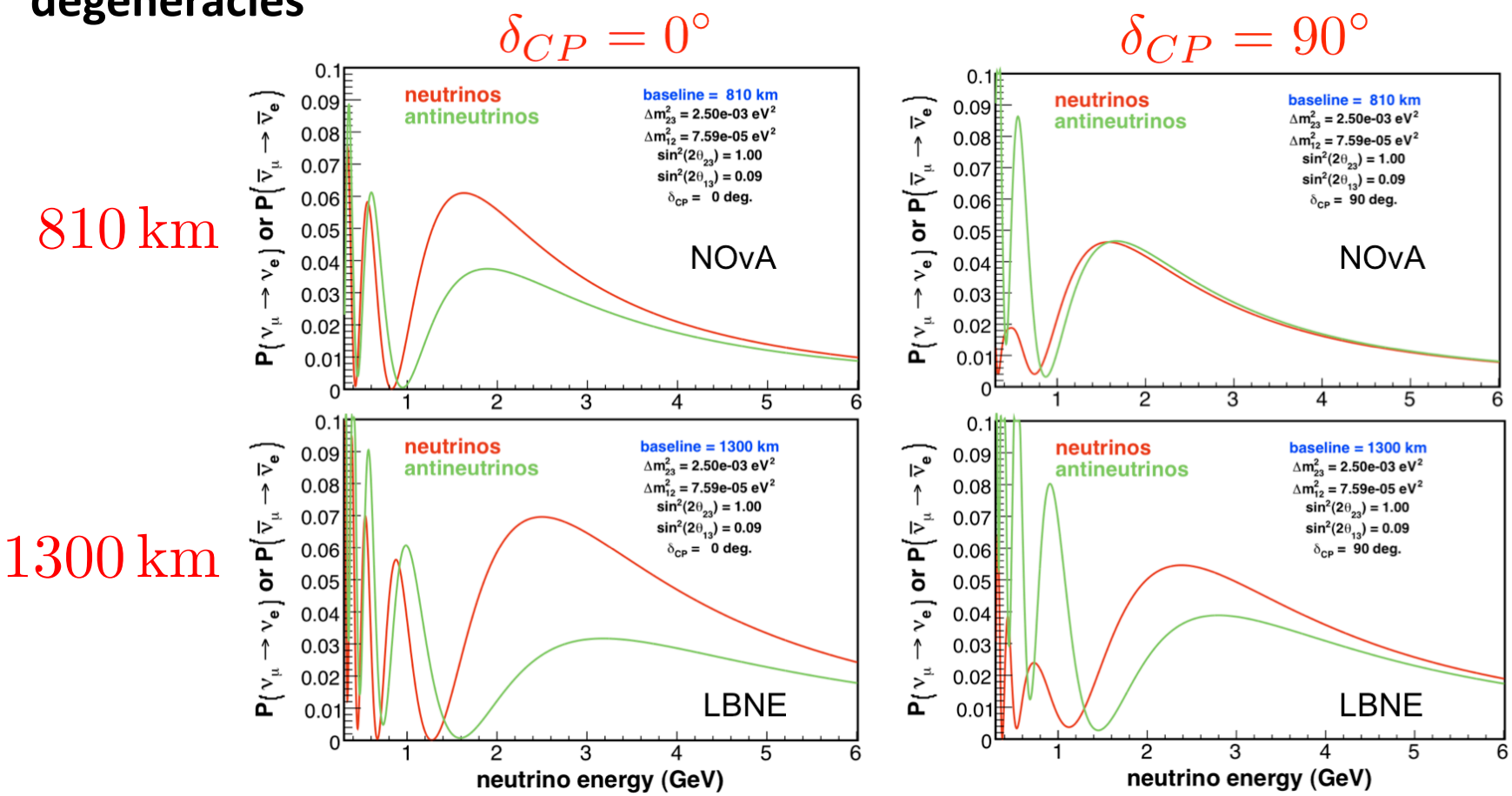
neutrinos

antineutrinos

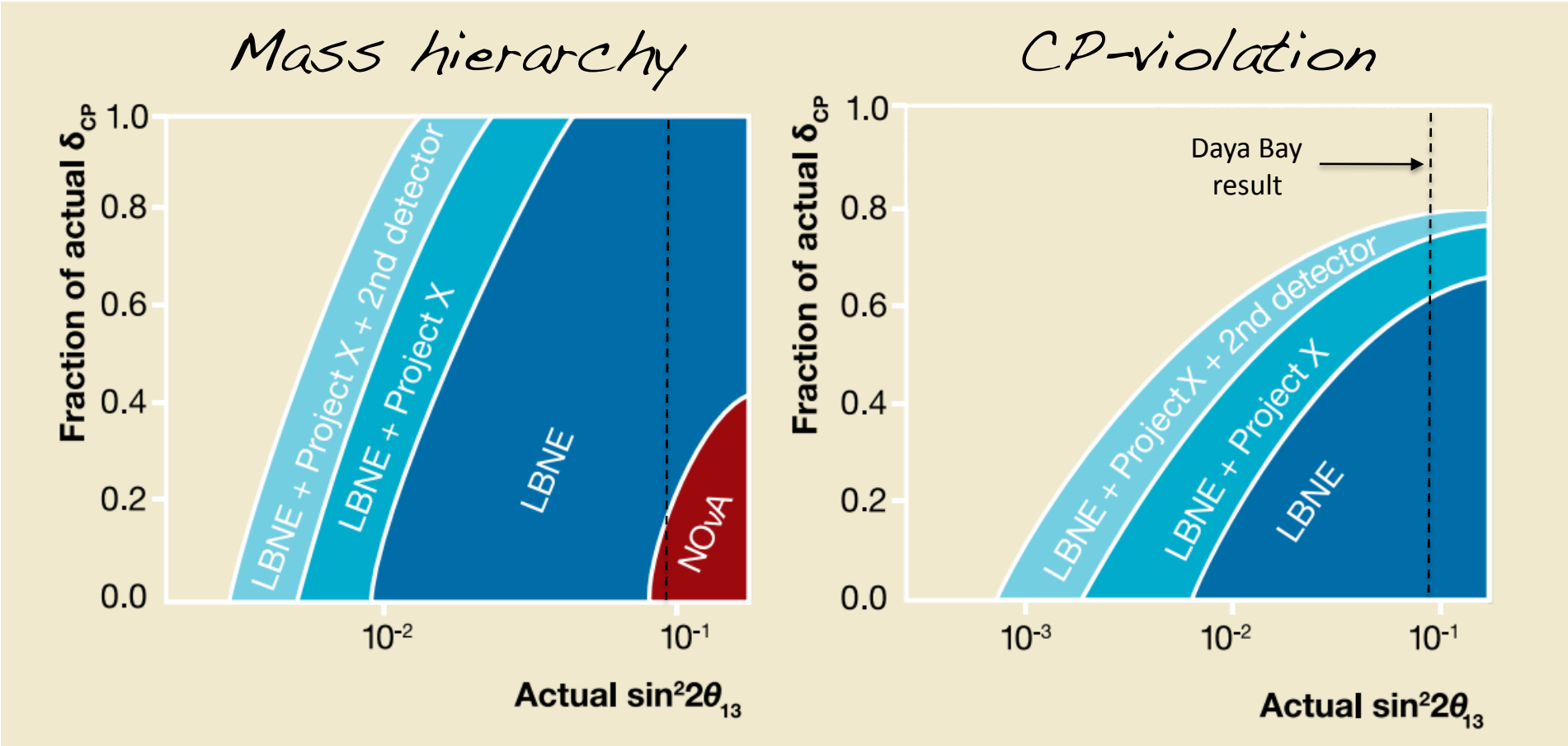


Why longer baseline?

- **Oscillation probabilities a convolution of matter effects and CP-violation**
- **Increased matter effect greatly improves one's ability to resolve degeneracies**



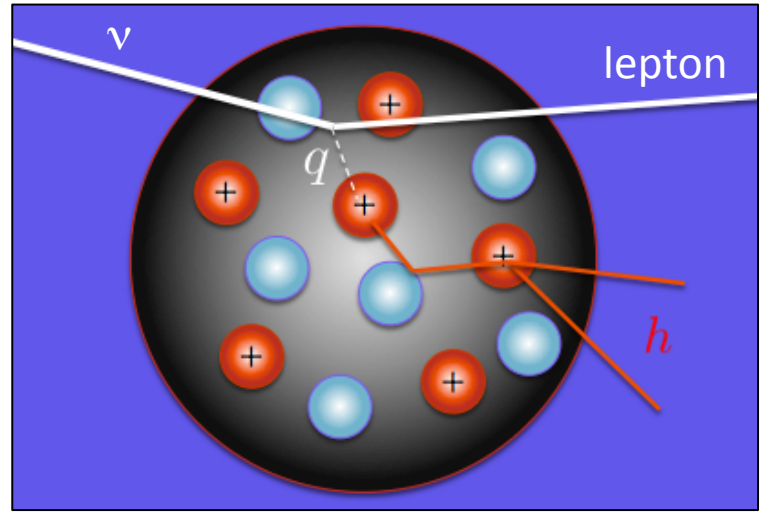
Hierarchy, CP sensitivities

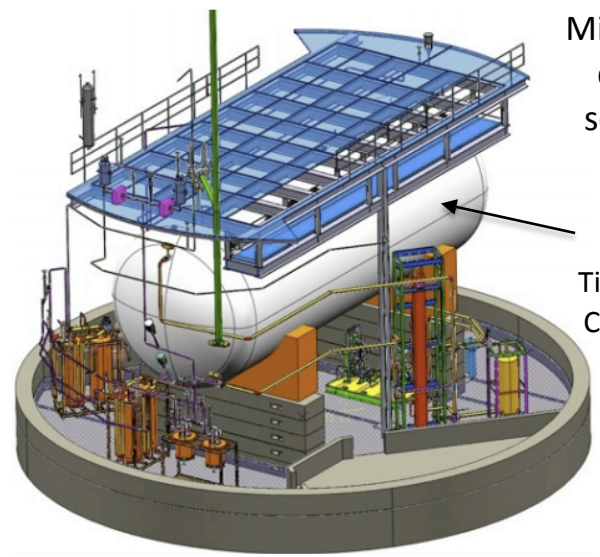


3σ sensitivity to the right of the curves

So many things I've left out...

- **Oscillation searches at short-baselines (high Δm^2) look for evidence of additional "sterile" neutrino states**
- **Detailed studies of neutrino-nucleus interactions**
  - High precision differential cross section measurements
  - Impacts of sizeable nuclear effects when scattering on nuclei at GeV energies
  - Using neutrinos as a weak force probe of the nucleus to extract nuclear PDFs
- **New detector technology development for neutrino physics**
- **All of these part of the Fermilab program**





MicroBooNE detector schematic (2013)

Liquid argon Time Projection Chamber (TPC)

Summary

- **Neutrino physics has already produced a rich history of exciting results**
- **While the experimental evidence for neutrino oscillations is now strong, there is much left to do:**

The main goal of next-generation neutrino oscillation experiments is to test whether the scenario outlined above, the standard three-massive-neutrinos paradigm, is correct and complete. This is to be achieved by not simply determining all of the parameters above, but "over-constraining" the parameter space in order to identify potential inconsistencies. This is not a simple task, and the data collected thus far, albeit invaluable, allow for only the simplest consistency checks. In the future, precision measurements, as will be discussed in Sec. 1.2, will be required.

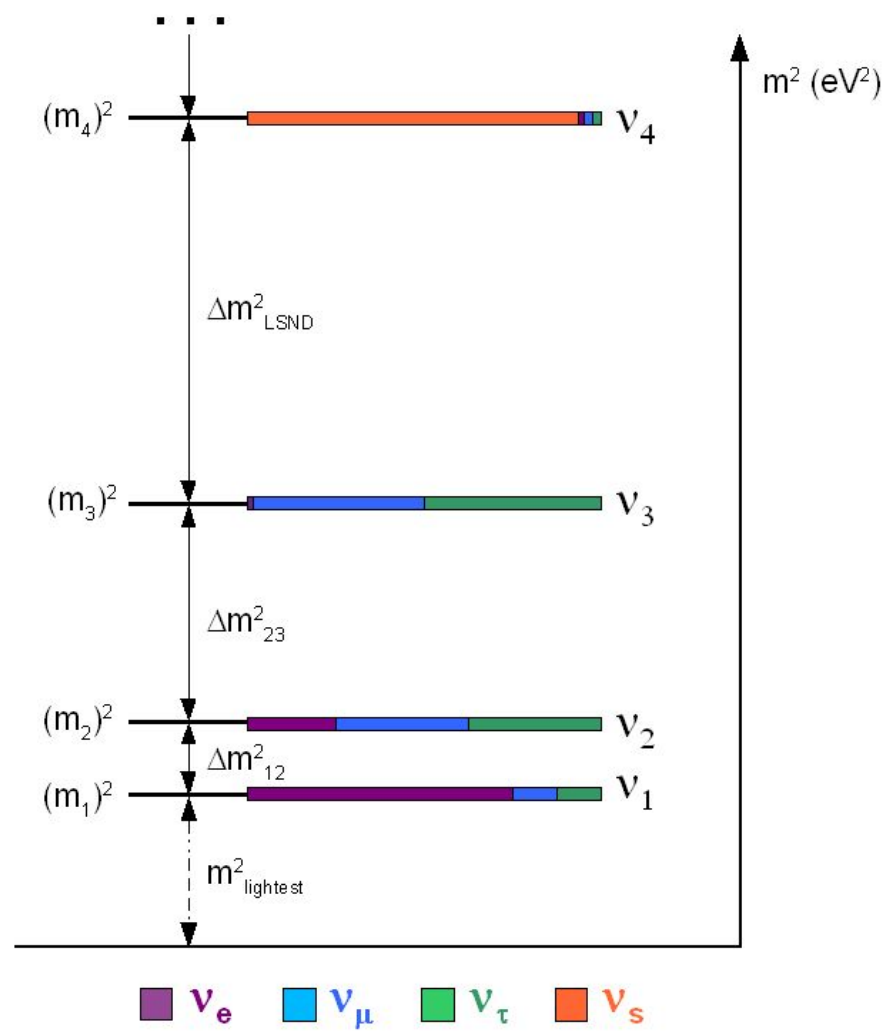
Intensity Frontier Workshop Report
November 30 – December 2, 2011, Rockville, MD

- **In particular, there now exists the exciting possibility to search for a new form of CP-violation in the neutrino sector**
- **An ambitious program of research is currently underway at Fermilab to make important advances in neutrino physics. Ultimate goal is a future facility with significant discovery potential for CP-violation in neutrinos.**

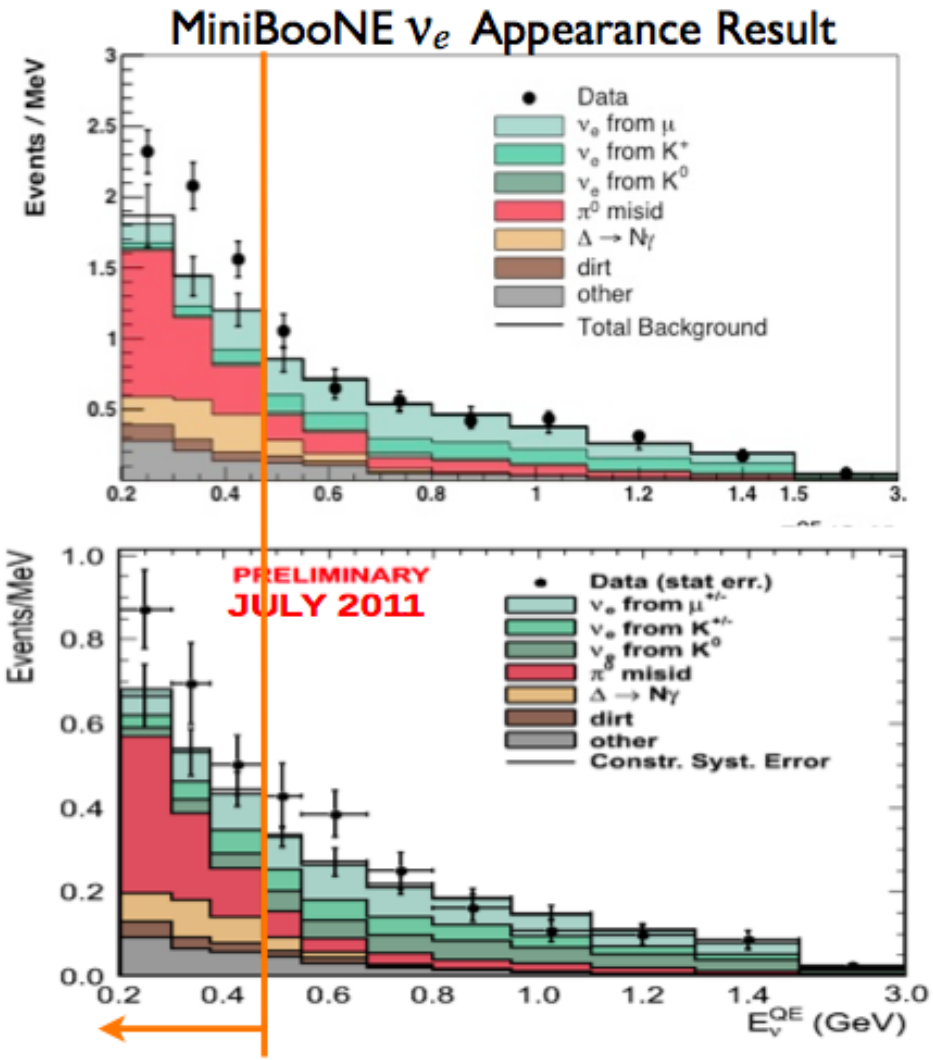
Thanks!

Oscillations at short-baselines (high Δm^2)

- **There is as yet unconfirmed evidence for additional oscillations consistent with a much larger mass-splitting of order 1 eV^2**
- **Typically interpreted as oscillations with one or more "sterile" neutrinos**



Oscillations at short-baselines (high Δm^2)

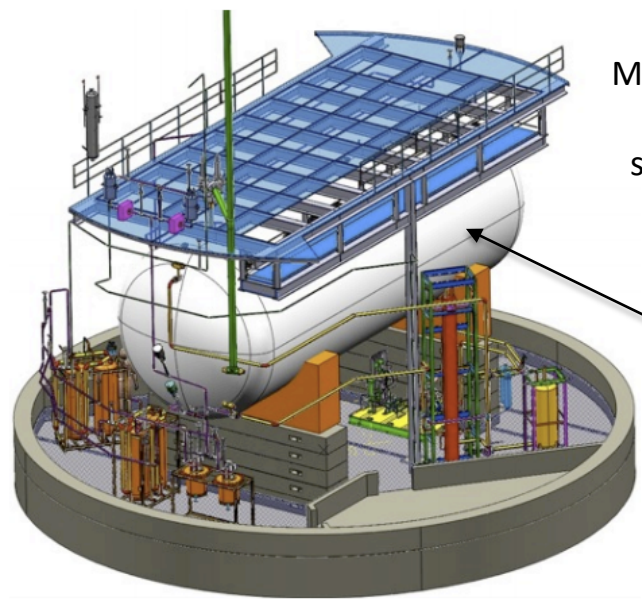


MiniBooNE Result Excess
(200-475 MeV)

Neutrino: 128.8±43.4 events

AntiNeutrino: 38.6±18.5 events

In neutrino mode, MicroBooNE will have ~5.5σ significance for electron-like excess, ~4σ for photon-like excess.

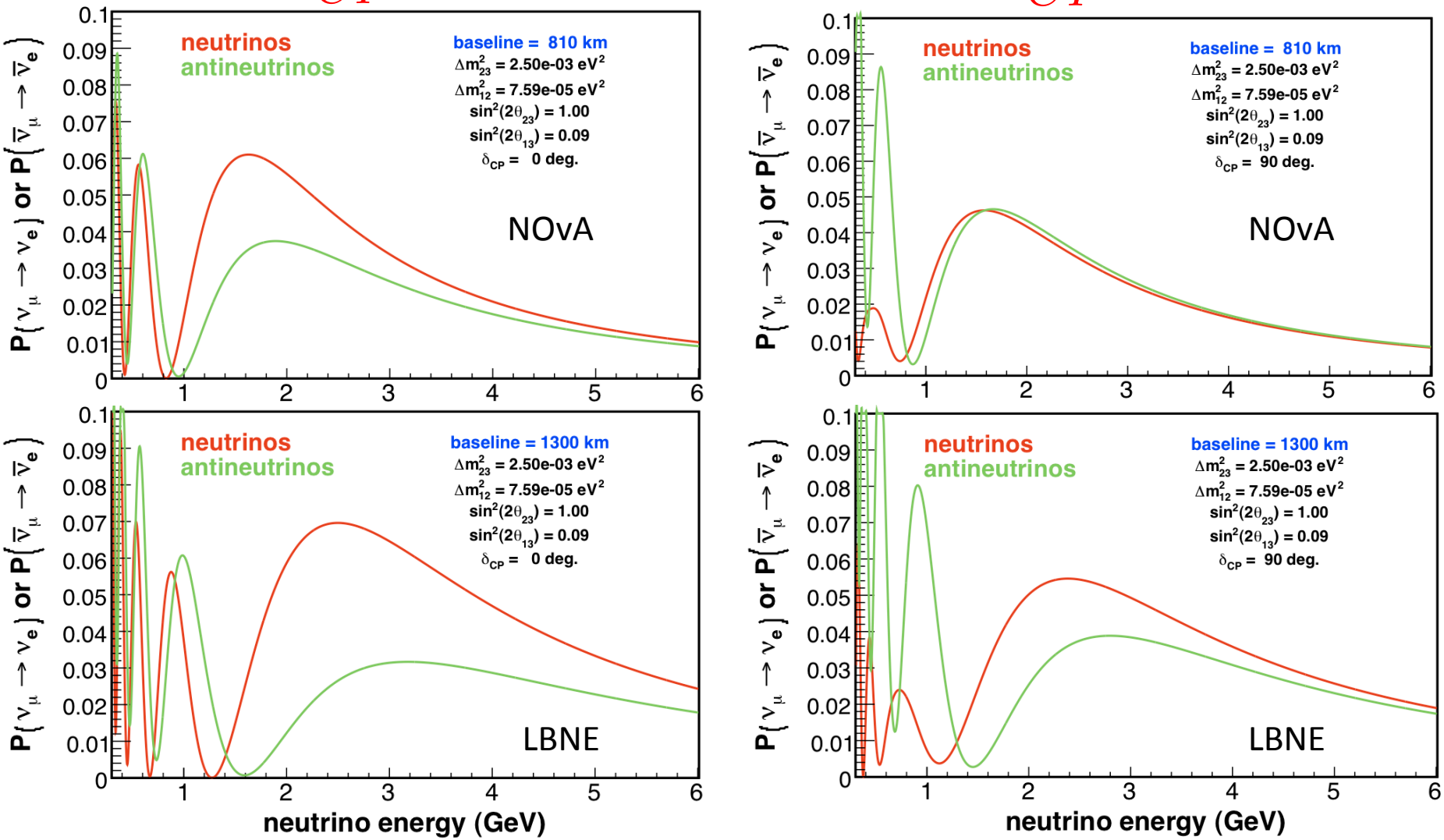


MicroBooNE detector schematic

Time Projection Chamber (TPC)

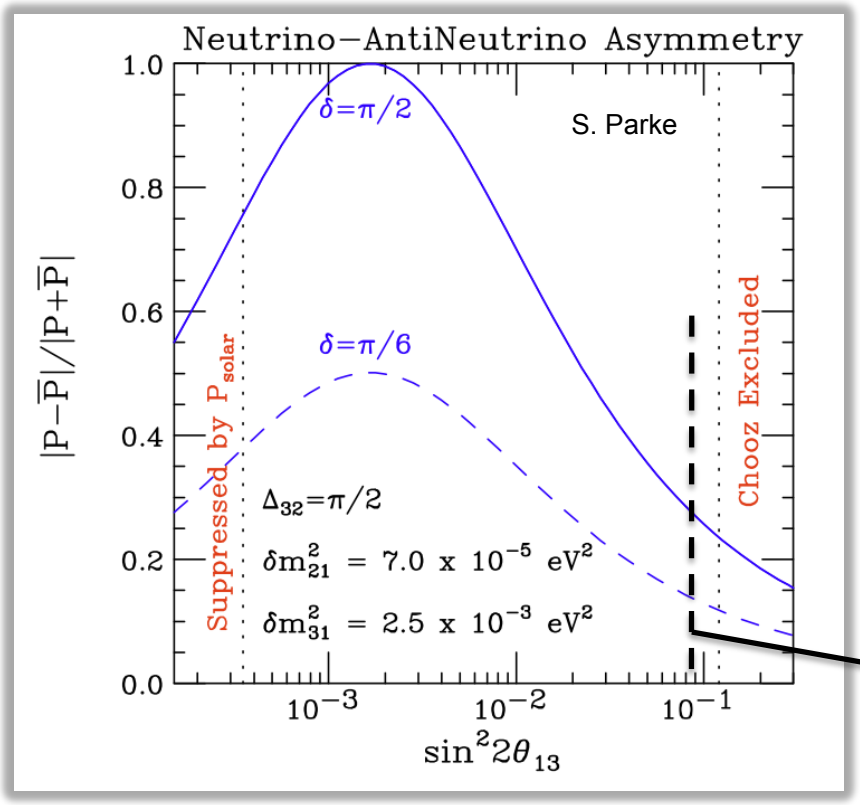
NOvA vs. LBNE

$\delta_{CP} = 0°$ $\delta_{CP} = 90°$



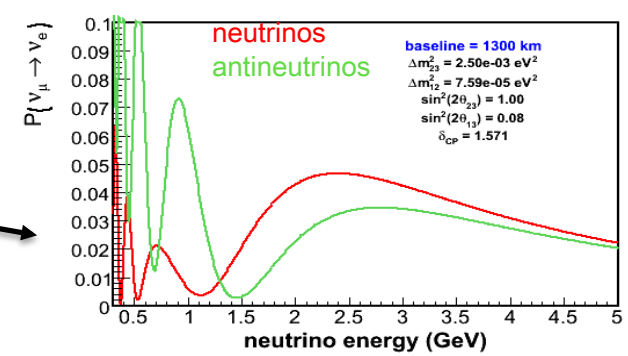
Oscillation asymmetry

- We've all been hoping for large θ_{13}, but may not make $\not{CP}$ any easier
- Discovery of $\not{CP}$ will require tight control of systematics
  - Comparing oscillations measured in different beams with very different spectra and different backgrounds (different systematics)

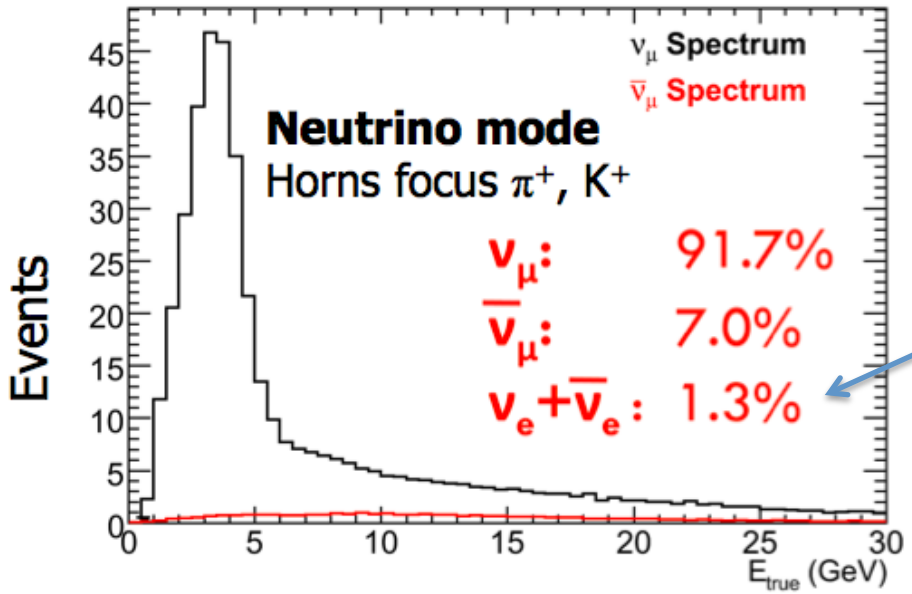


Need a detailed understanding of absolute effects, but especially any neutrino / antineutrino differences

- different fluxes ($\sigma \approx$7-25%)
- different cross sections ($\sigma \approx$20-50%)
- different nuclear effects ($\sigma \approx$20-50%)
- different backgrounds
- different E_ν -> $E_{visible}$

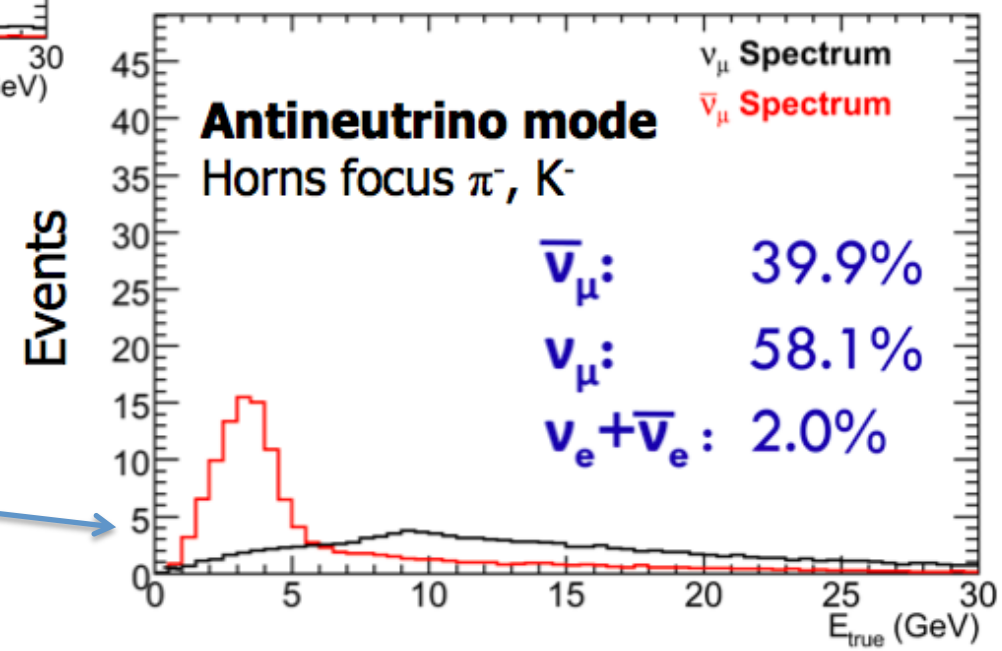


Accelerator neutrino beam composition



Beamline of the MINOS and MINERνA experiments

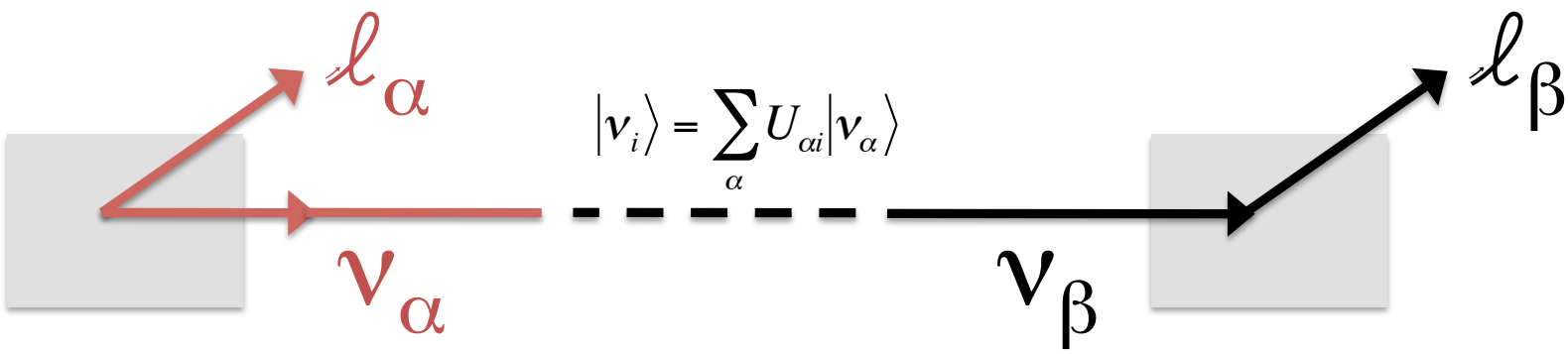
electron neutrinos from kaon and muon decays



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

Neutrino oscillations

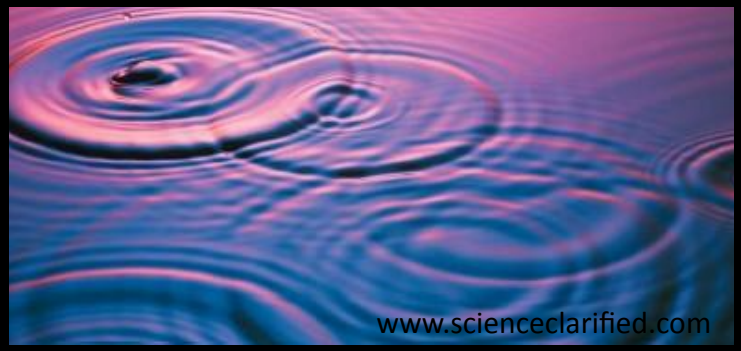
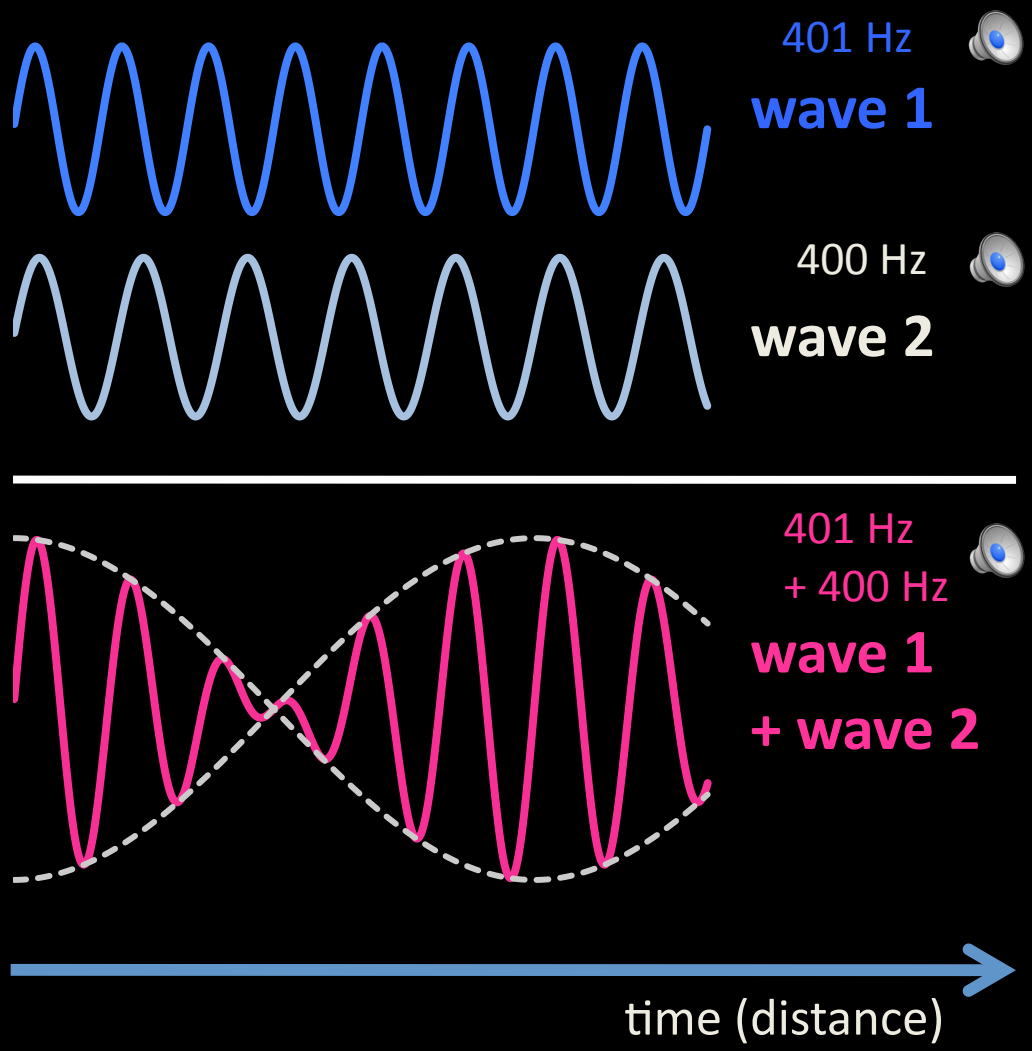
- **A <u>neutrino's propagation through space</u> (from production to detection) would be dictated by the free Hamiltonian whose eigenstates are the states of <u>definite mass</u>, $\nu_1 = (\nu_1, \nu_2, \nu_3, \ldots)$, not flavor**



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

neutrino oscillations

Quantum mechanics
particle ←→ wave
mass determines frequency

If neutrinos (ν_e,ν_μ,ν_τ) are *actually* mixtures of multiple waves with *different* frequencies (different masses)...

They can *interfere* like any waves and change the neutrino's flavor!