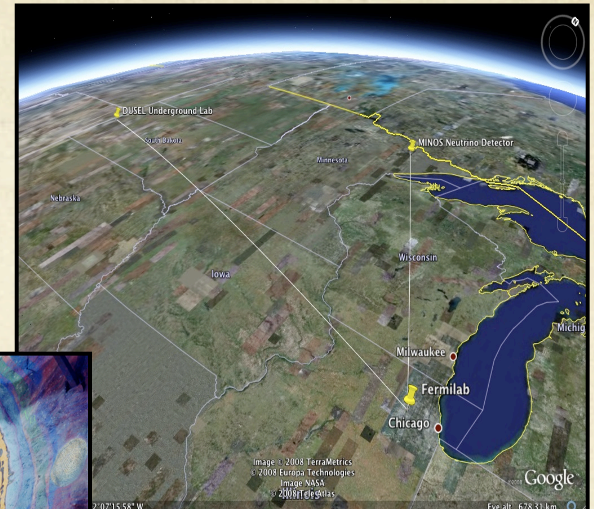
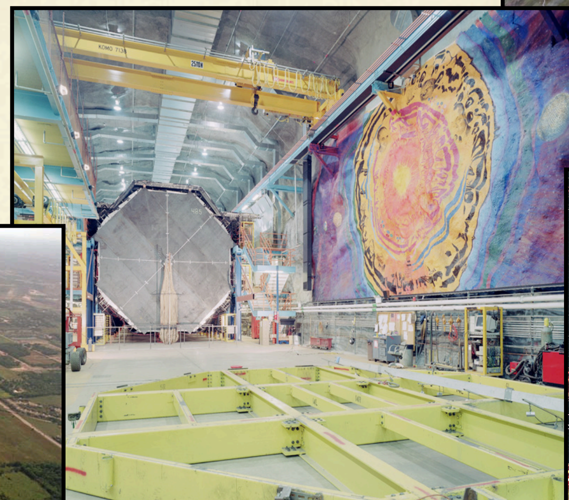
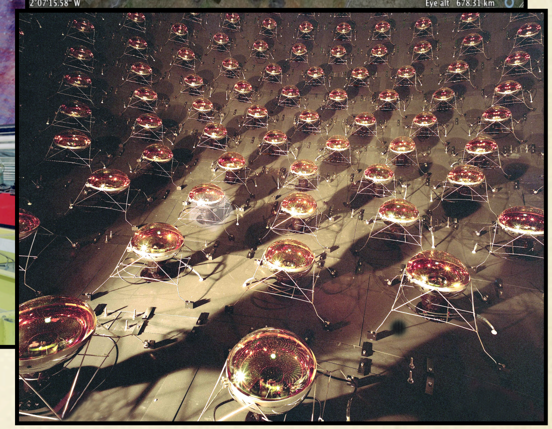
Neutrino Physics at Fermilab

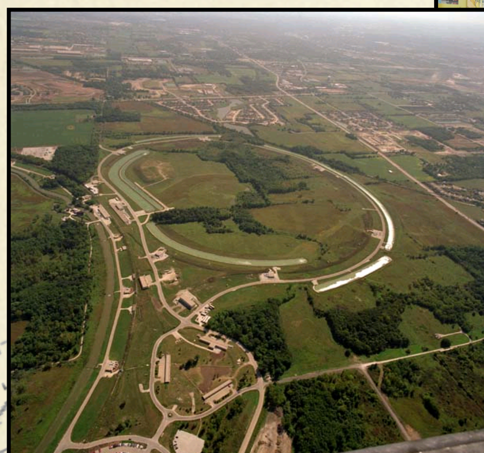
David Schmitz

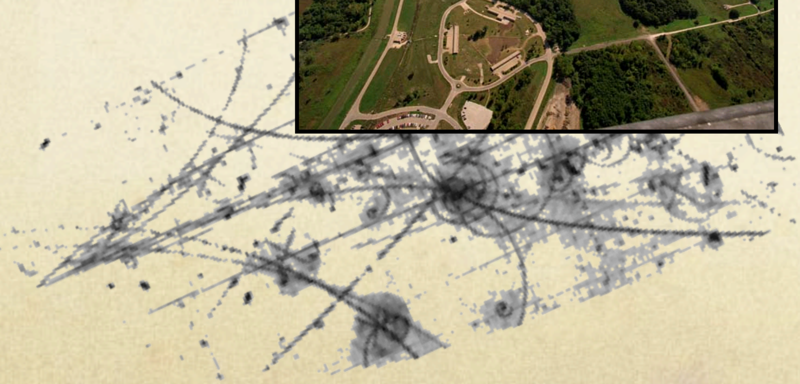
Fermi National Accelerator Laboratory







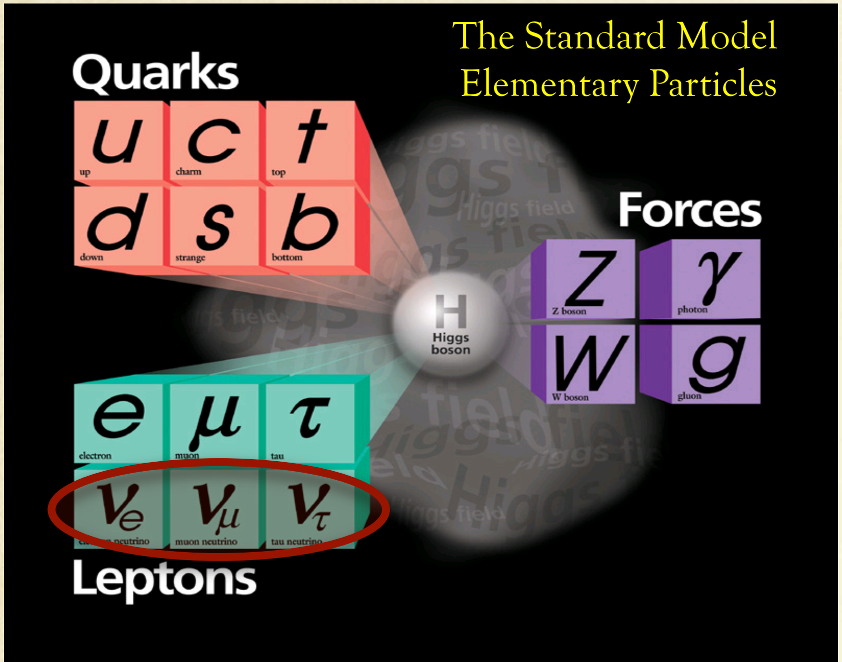


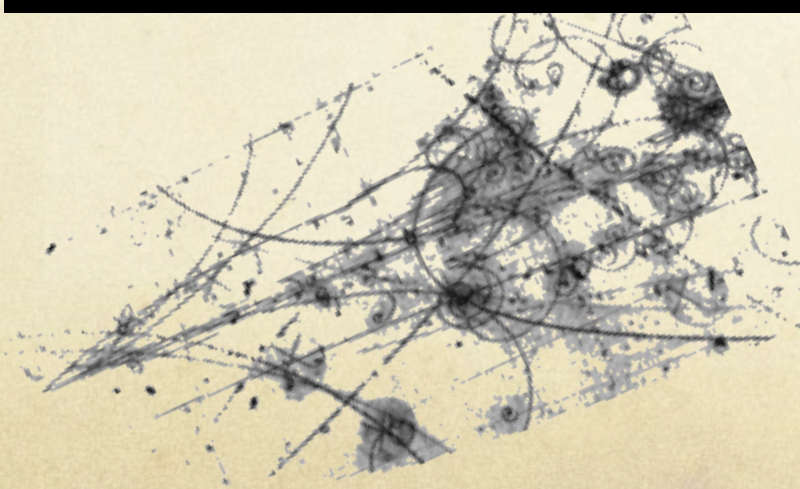


AAPT Winter Meeting
AAAS Annual Meeting

12–16 February , 2009 • Chicago, IL

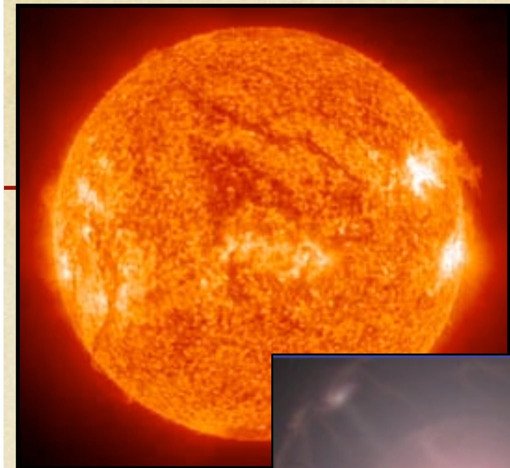
Neutrinos . . .





- come in three **“flavors”** and make up ¼ of the elementary matter particles
- but outnumber the others in the Universe by a factor of a **BILLION**
- are a critical component in nuclear processes that power stars
- large numbers formed at the time of the big bang are still whizzing around the Universe (“relic neutrinos”). ~400 / cm^3 of space, or about 25,000,000 in your space!
- carry most (~99%) of the energy from a Supernova explosion

Neutrinos . . .



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Neutrinos . . .

bananas emit about **1 million neutrinos/day**from decays of the small number of naturally occurring radioactive potassium atoms they contain

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- are a critical component in nuclear processes that power stars
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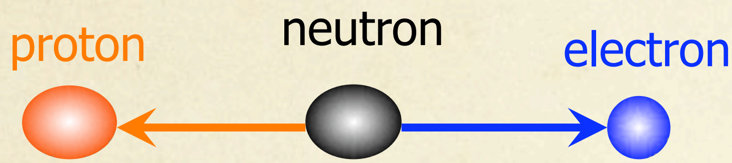
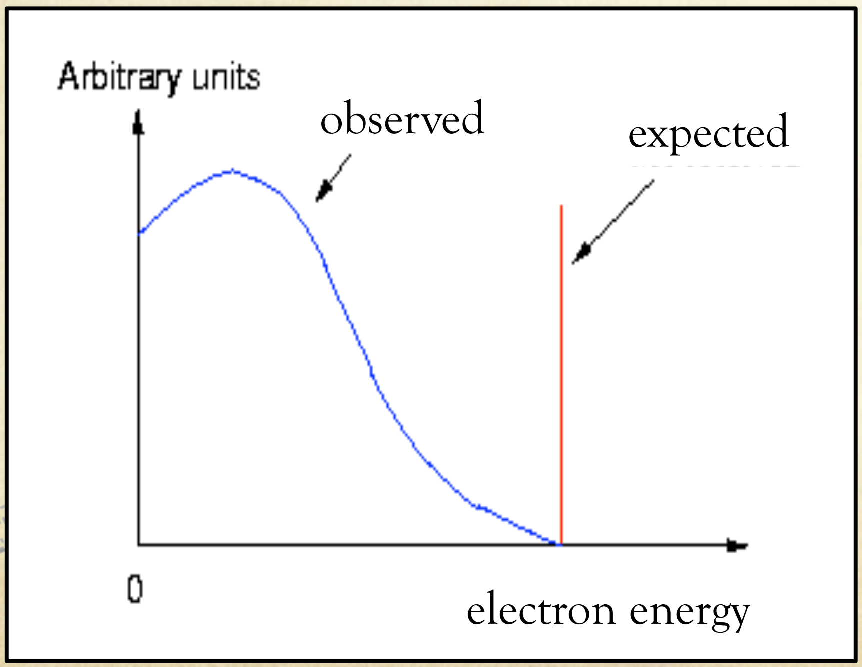
- carry most (~99%) of the energy from a Supernova explosion
- **come from bananas?! huh?**

The “desperate remedy”

- **in 1930 there was a crisis in particle physics!**



$(A, Z) \rightarrow (A, Z+1) + e^{-}$



It was well known that nuclei could change from one variety to another by emitting a **“beta”** (electron).

Some were ready to abandon **Conservation of Energy** to explain this missing energy phenomenon!

The "desperate remedy"

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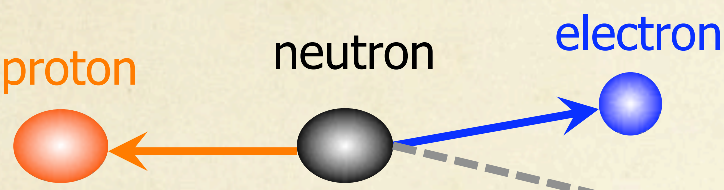
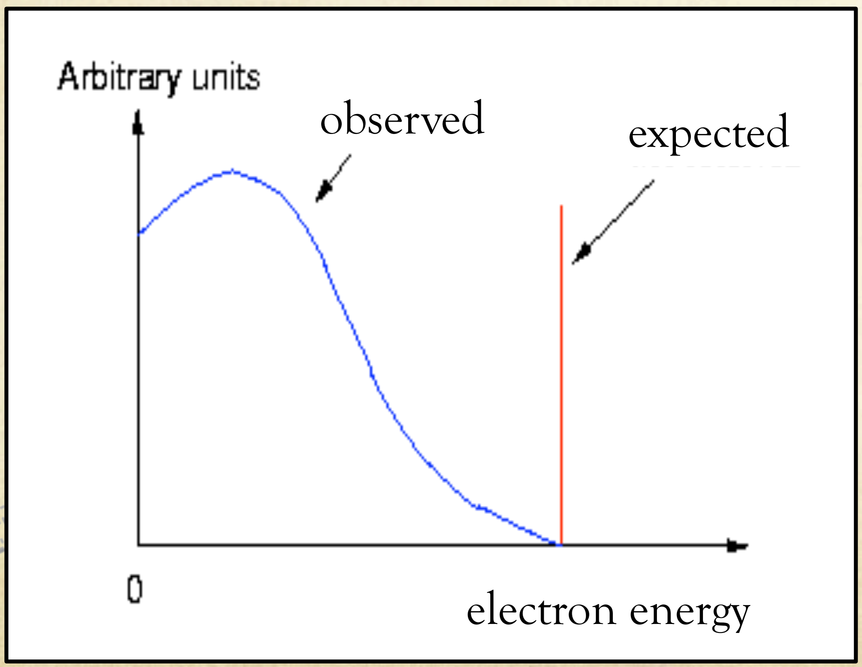


$$(A, Z) \rightarrow (A, Z+1) + e^{-} + \nu_e$$



It was well known that nuclei could change from one variety to another by emitting a **"beta"** (electron).

Some were ready to abandon **Conservation of Energy** to explain this missing energy phenomenon!

ν

. . . until W. Pauli proposed his **"desperate remedy"**,the neutrino, which invisibly carried away the missing energy – and the neutrino was born.

The "desperate remedy"

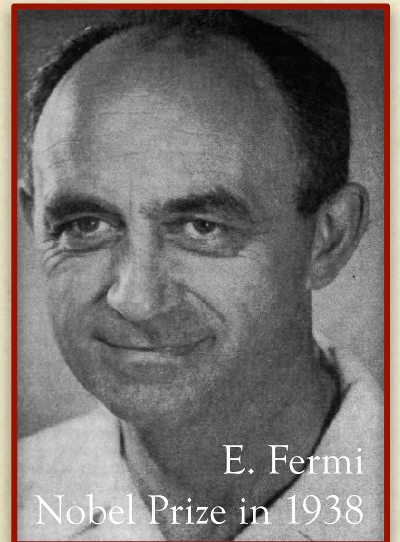
- the neutrino was thought to be a neutral, massless particle

W. Pauli
Nobel Prize in 1945

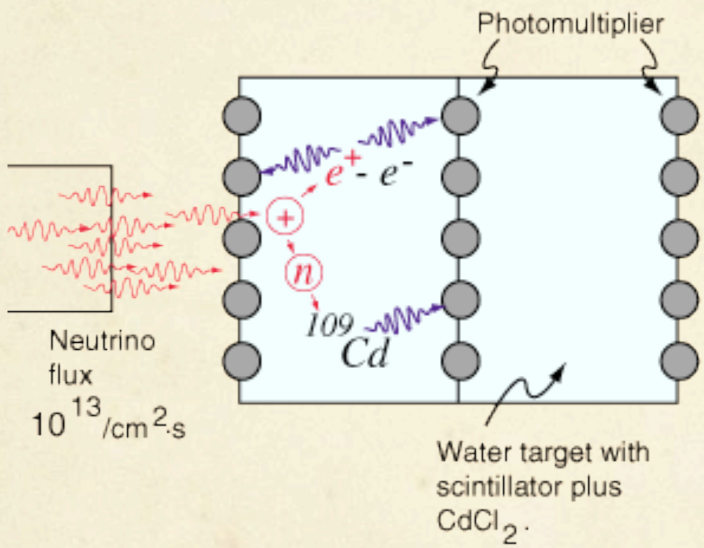
"I have done a terrible thing. I have postulated a particle that cannot be detected."

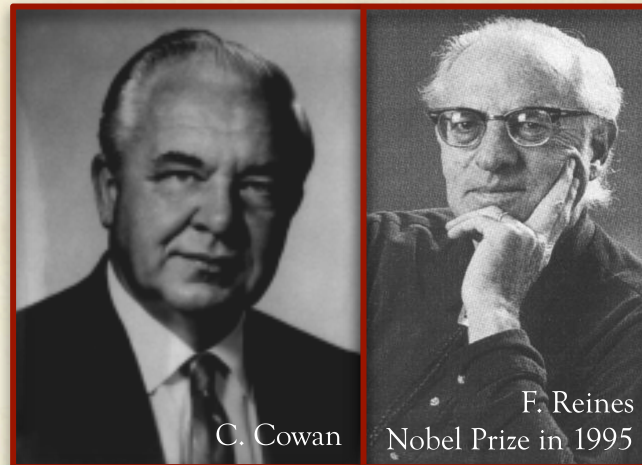
- W. Pauli (1931)

The Initial Discoveries



Enrico Fermi first developed the theory of the weak interaction in 1934 which describes how neutrinos interact with other matter





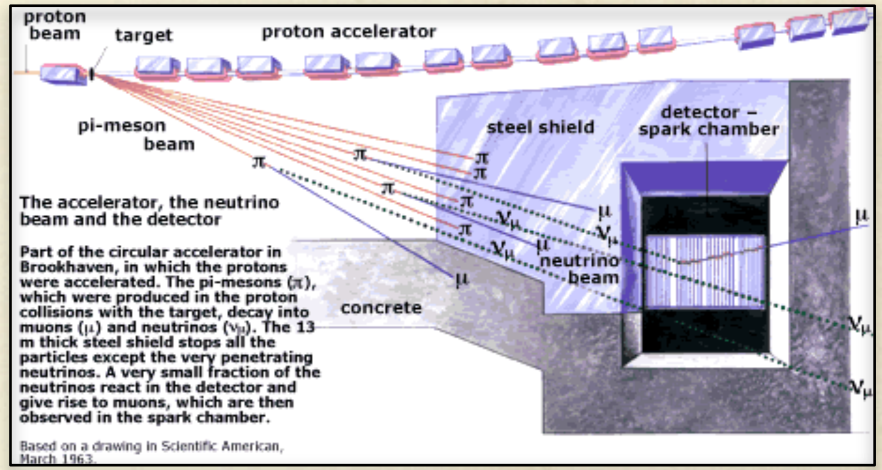
Fred Reines and Clyde Cowan finally detected a neutrino 25 years after Pauli's original proposal

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

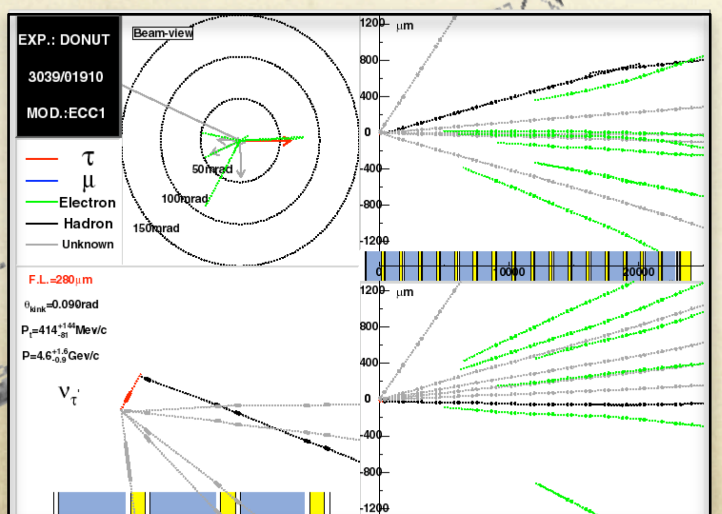
- F. Reines and C. Cowan (1956)

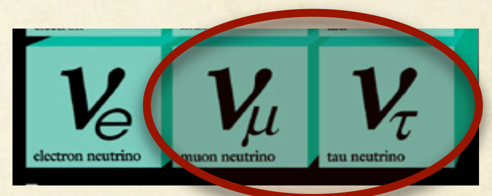
"Everything comes to him who knows how to wait."
- W. Pauli (1956)

The Initial Discoveries



Leon Lederman, Melvin Schwartz and Jack Steinberger made the surprising discovery of a second type of neutrino, the muon neutrino, in 1962





Finally, in 2000, 70 years after Pauli's idea, the Fermilab experiment DONUT directly detected a third kind of neutrino, the tau neutrino

An Aside : What took so long?

- **How weak *is* the weak interaction?**

compare a few mean free path estimates in solid lead – how far an average particle of a given type and energy travels before interacting

$$d_{lead} = \frac{1.66\text{x}10^{-27}\ \text{kg}}{(\sigma_{x\text{-}N}\ \text{m}^2)(11400\ \text{kg/m}^3)}$$

atomic mass unit

ν-N cross-section

density of lead

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1. <u>neutrinos produced by the sun</u> typically have a few MeV of energy

$$d \approx 1.5 \times 10^{16}\ \text{meters}$$

that's a bit over 1 light year (9.46×10^{15} m) of solid lead!!!!

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atomic mass unit (numerator); ν-N cross-section ($\sigma_{x\text{-}N}$); density of lead (11400 kg/m³)

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2. <u>neutrinos produced at an accelerator</u> typically have a few GeV of energy

$$d \approx 1.5 \text{ x } 10^{12} \text{ meters}$$

a little better, but still about 930 million miles. . .

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3. what about a proton with a few GeV in lead?

$$d \approx 10 \text{ centimeters } !!!!$$

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atomic mass unit

So to study neutrinos requires
intense neutrino sources
and
special detectors

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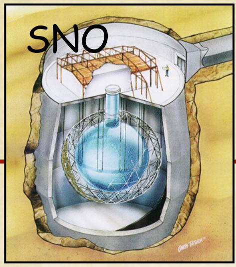
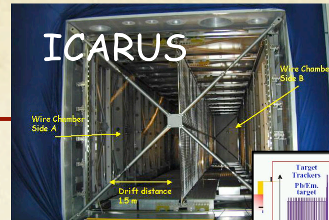
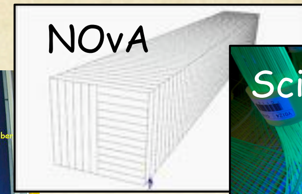
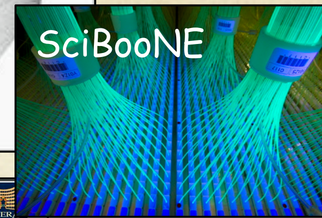
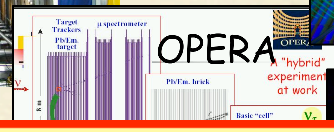
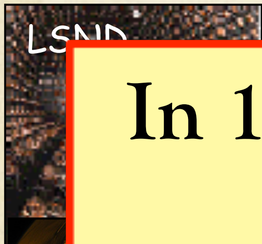


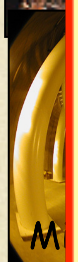










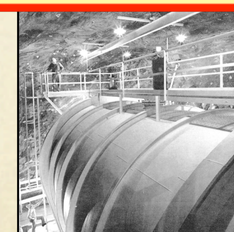


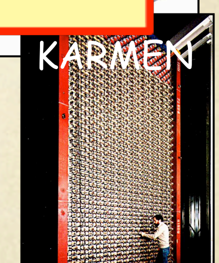
In 1971, Robert R. Wilson, the first director of Fermilab, told the lab users,

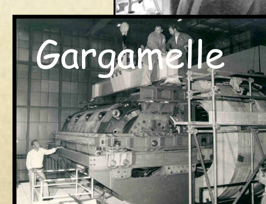
"One of the first aims of experiments on the NAL accelerator system will be the detection of the neutrino. I feel that we then will be in business to do experiments on our accelerator."

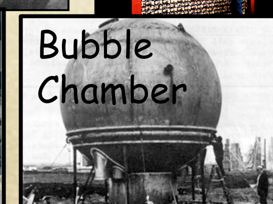
behavior and the profound implications for 75 years

- Fermilab has been near the forefront of this research for nearly 40 years since the lab first opened



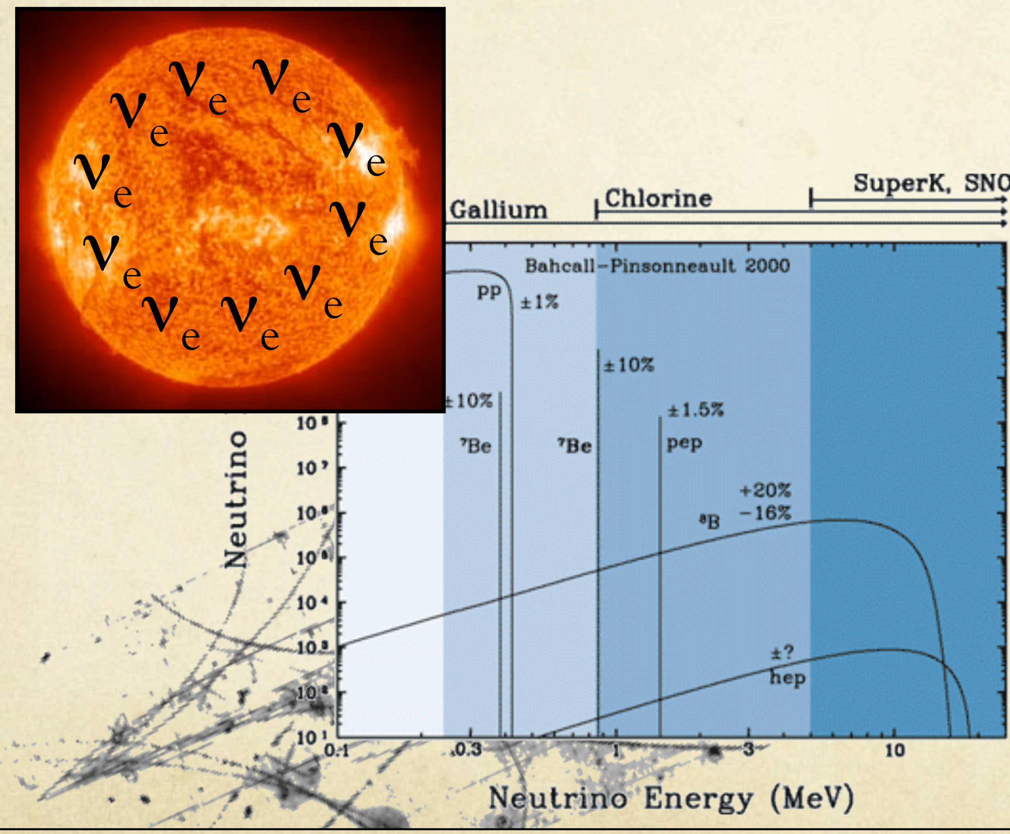


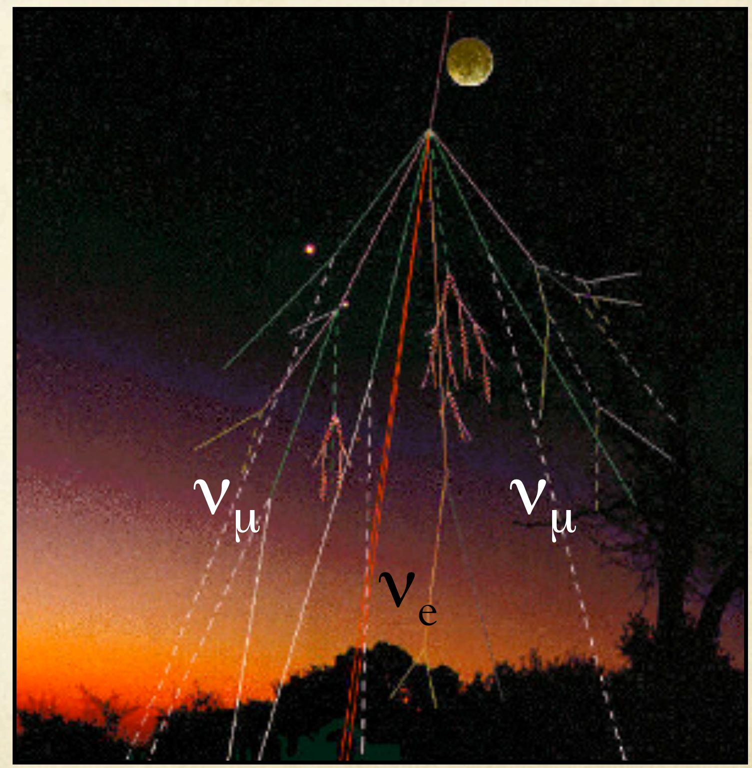




Neutrinos From the Cosmos

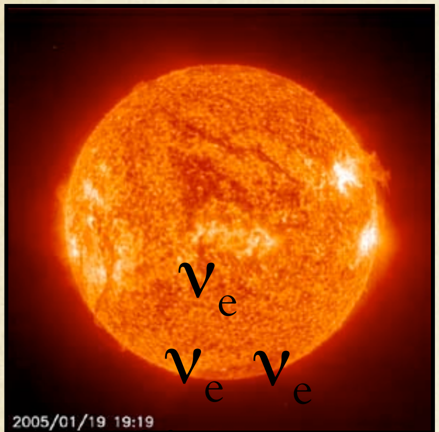
- the **Sun (huge numbers* of pure ν_e)**
  - neutrinos good probe of the processes deep inside the sun
- the **atmosphere (ν_μ and ν_e in a 2:1 ratio)**





*oh, about 60,000,000,000,000,000 will pass through your body during this talk.

Let the Surprises Begin

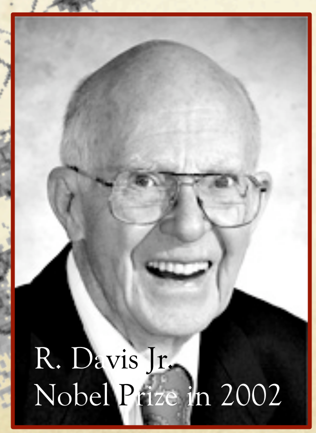


- **Only about 1/3** the expected number of ν_es from the sun were observed
- **less than the expected** 2:1 ν_μ:ν_e ratio of atmospheric neutrinos was observed (~1.3:1)

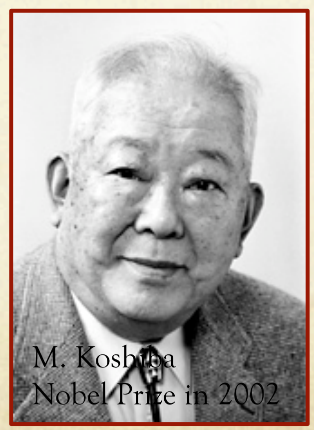
ν_e ν_e ν_e

ν_μ ν_e ν_μ

Homestake Mine
Lead, SD, USA



R. Davis Jr.
Nobel Prize in 2002



M. Koshiba
Nobel Prize in 2002

Super Kamiokande
Kamioka, Japan

Another desperate remedy?

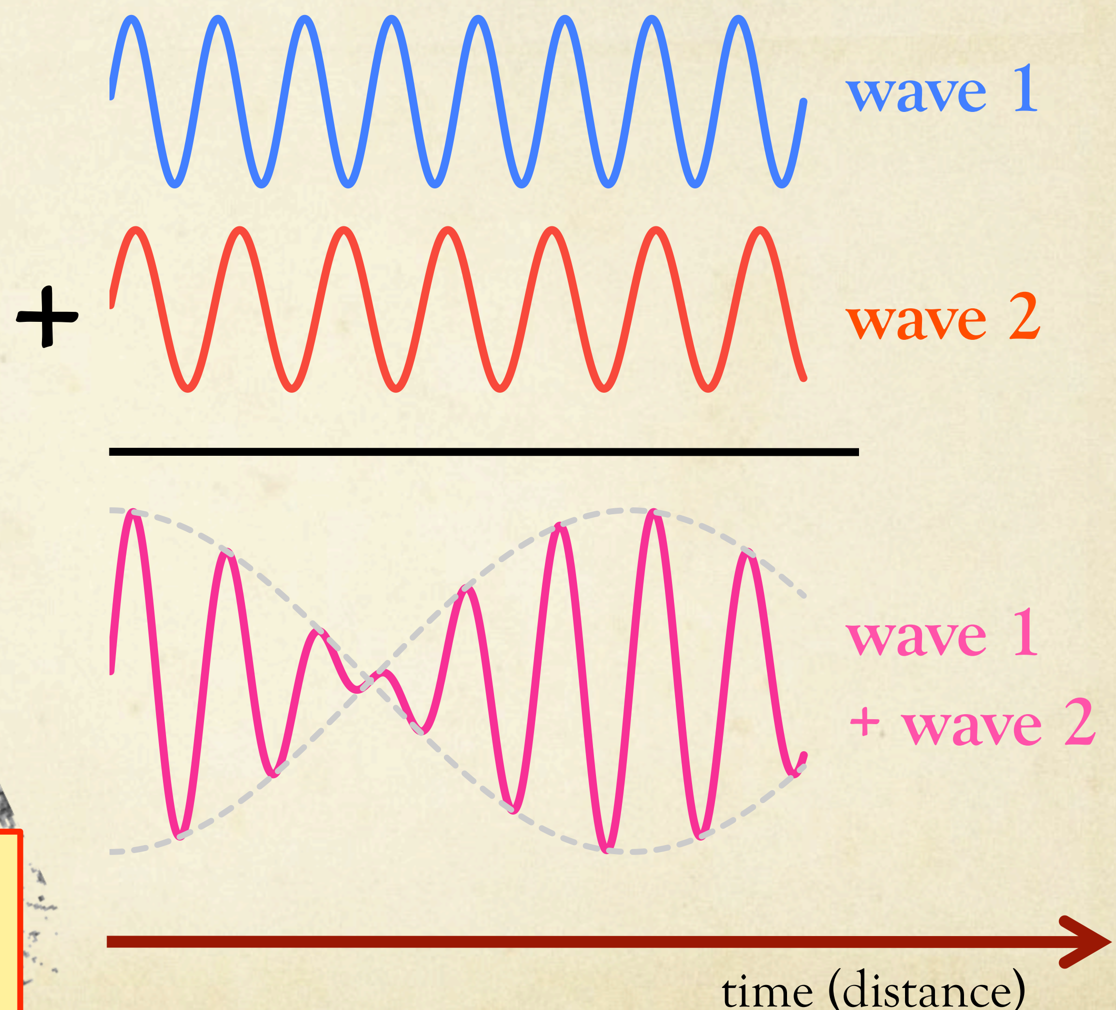
Where are the disappearing neutrinos disappearing to? Another dilema that persisted for more than two decades!

- **It was realized that if neutrinos indeed have small non-zero masses, then quantum mechanics allows that they could be disappearing into other kinds of neutrinos!**
  - ν_e **from sun** ➔ ν_μ/ν_τ **, which the Homestake detector could not see**
  - ν_μ **from atmosphere** ➔ ν_τ **, which Kamiokande detector could not see**

and tiny masses can have HUGE effects

Neutrino Oscillations

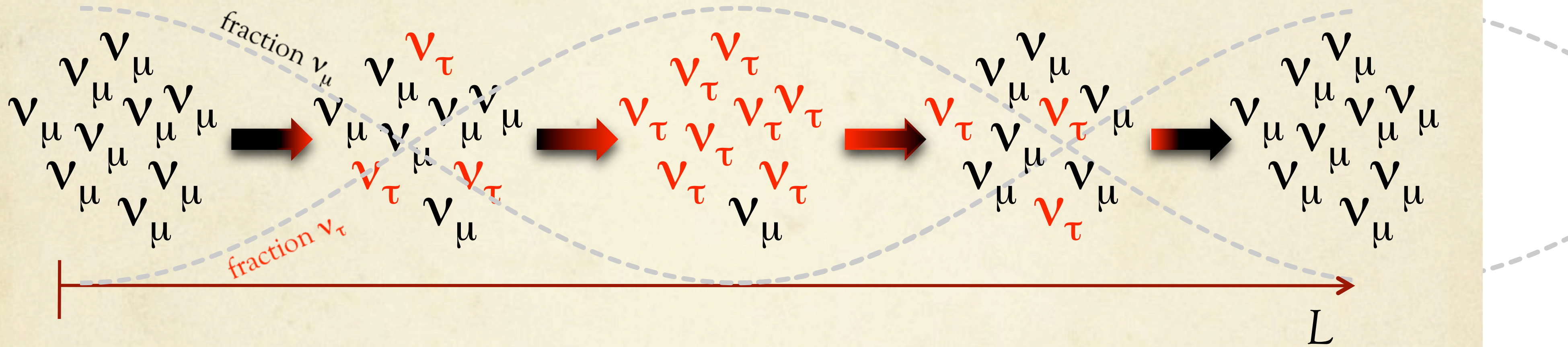
- Particles are like waves and particle mass determines the frequency
- If neutrinos (ν_e, ν_μ, ν_τ) are actually composed of multiple such waves with different frequencies (different masses) . . .
- Then they can interfere like any waves and change the neutrino's flavor composition in time!



The observation of neutrino "flavor oscillations", therefore, implies non-zero neutrino masses!

Neutrino Oscillations

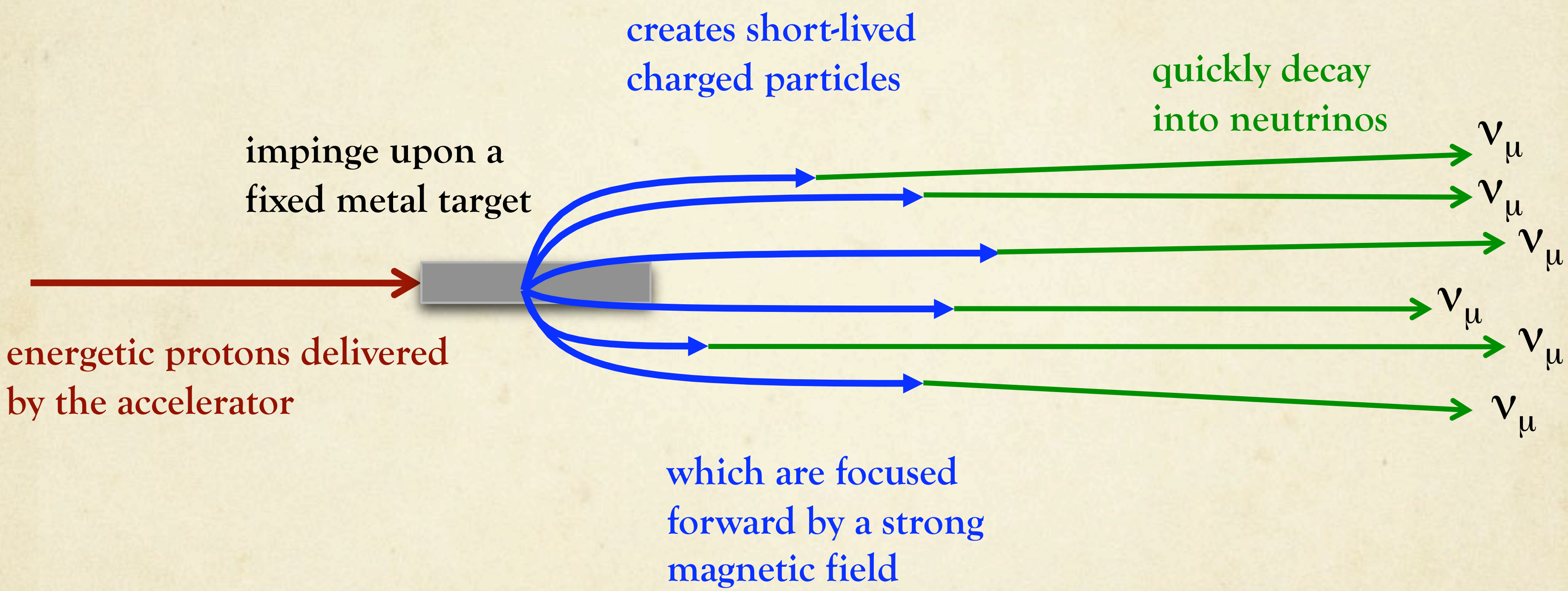
- this oscillation affects the *probability* that a neutrino is of type α as it travels



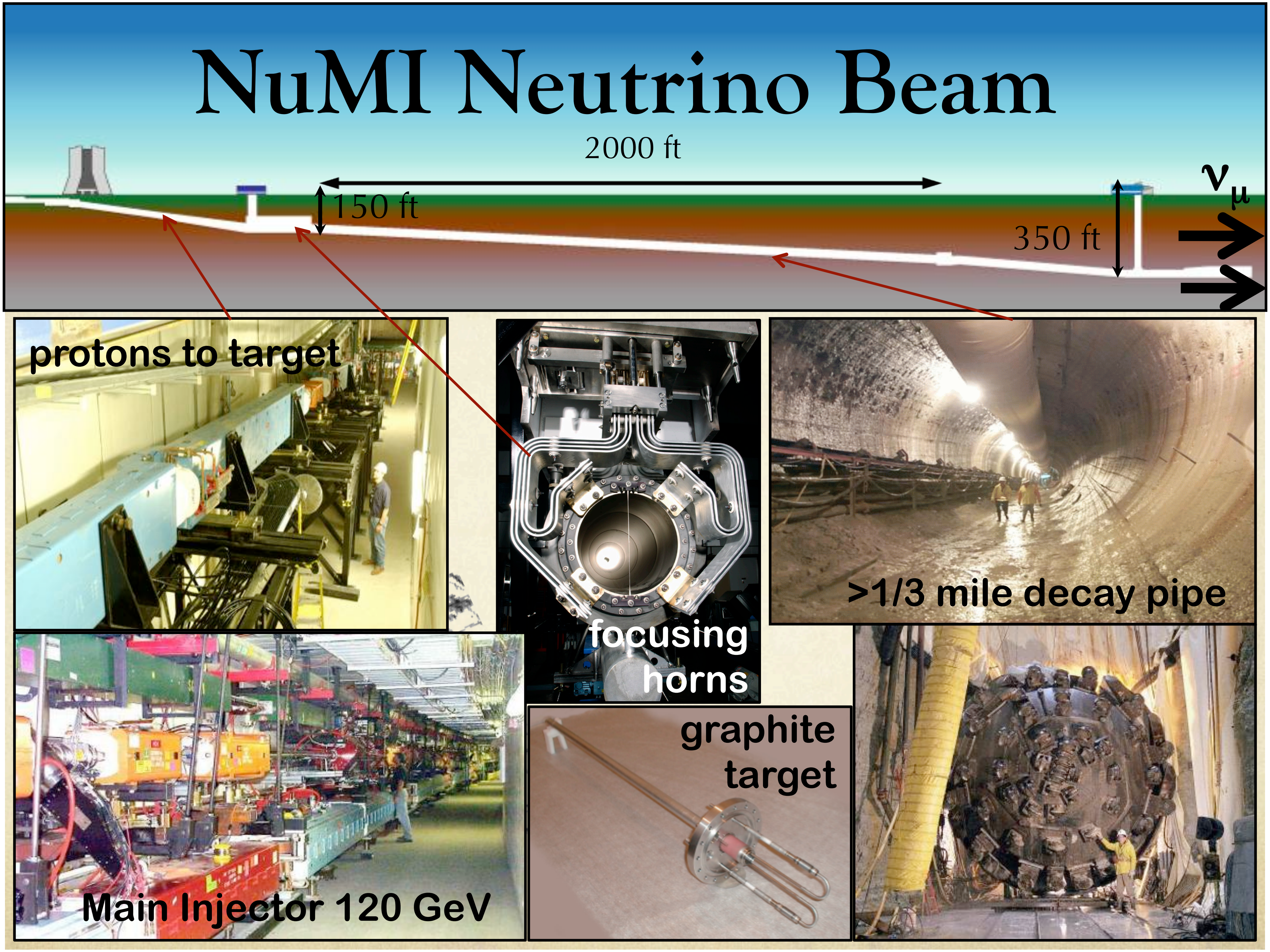
Important question : Can we reproduce the effect we believe we are seeing in neutrinos from the cosmos here on Earth in the laboratory?

Building A Neutrino Beam

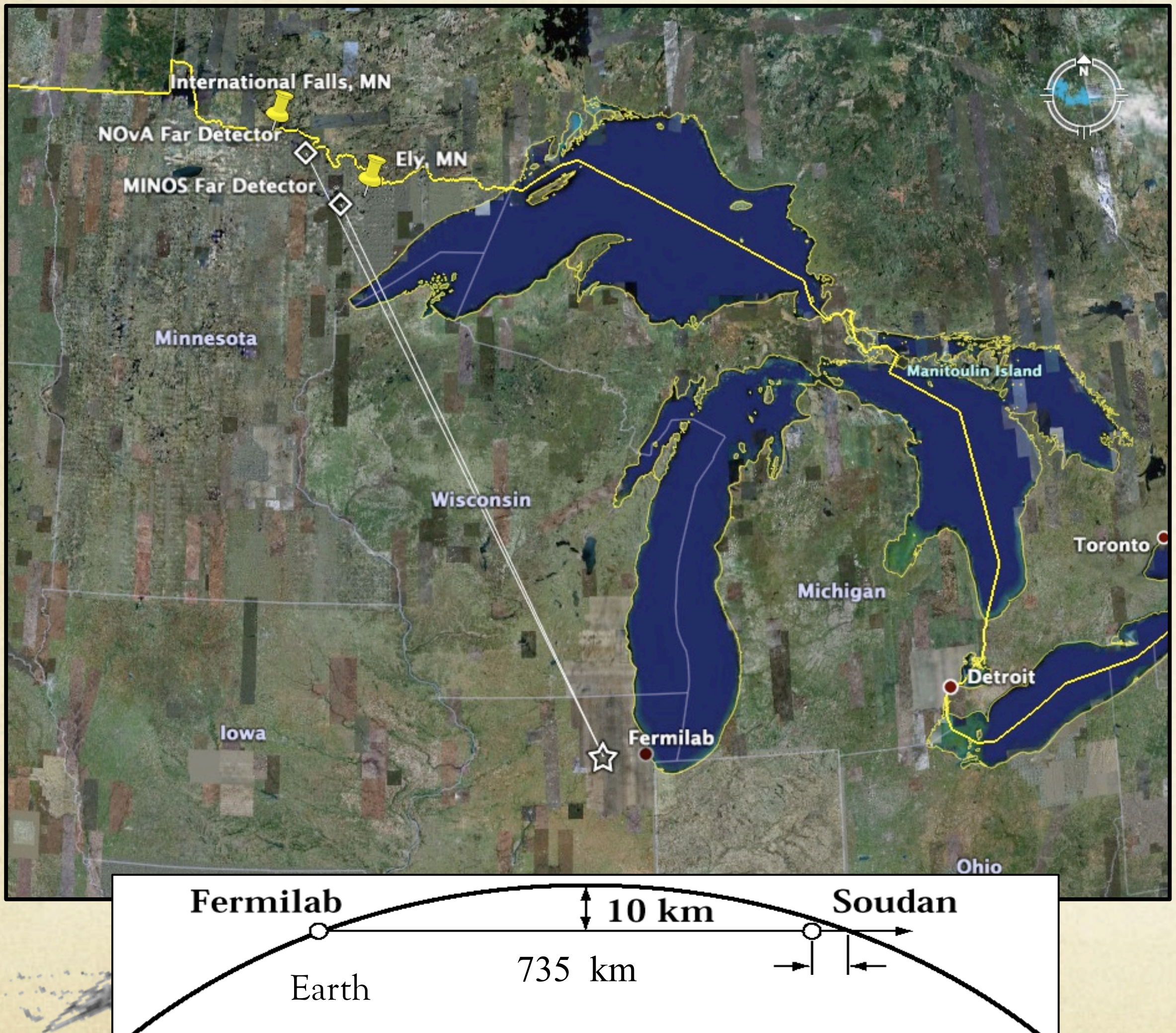
- **You can use a beam of protons to create an intense beam of neutrinos**



- In the last 10 years Fermilab has built two of the most intense neutrino sources in the world using its powerful proton accelerators in order to study neutrinos and oscillations
  - The Booster Neutrino Beam starts from 8 GeV protons from the Booster
  - The NuMI Neutrino Beam starts from 120 GeV protons from the Main Injector


NuMI Neutrino Beam
2000 ft
150 ft
350 ft
ν μ
protons to target
focusing horns
>1/3 mile decay pipe
graphite target
Main Injector 120 GeV

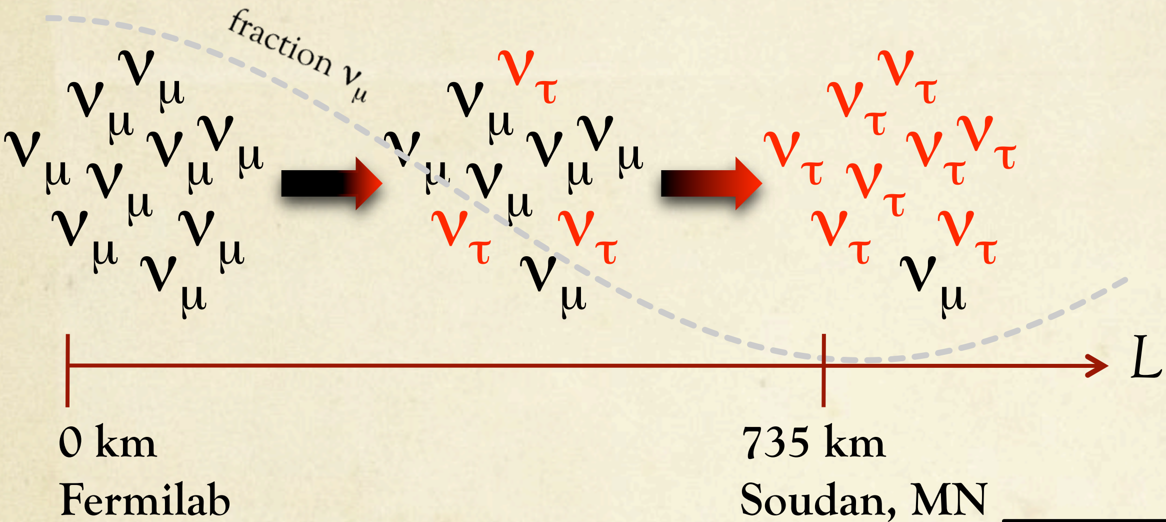
Where Are They Headed? North!



- The neutrinos make the 450 mile journey from Fermilab to northern Minnesota in 1/400th of a second.
- no tunnel required. recall, the Earth is like air to a neutrino!
- by comparing the number of muon neutrinos at both locations, one can look for them to disappear

Main **I**njector **N**eutrino **O**scillation **S**earch

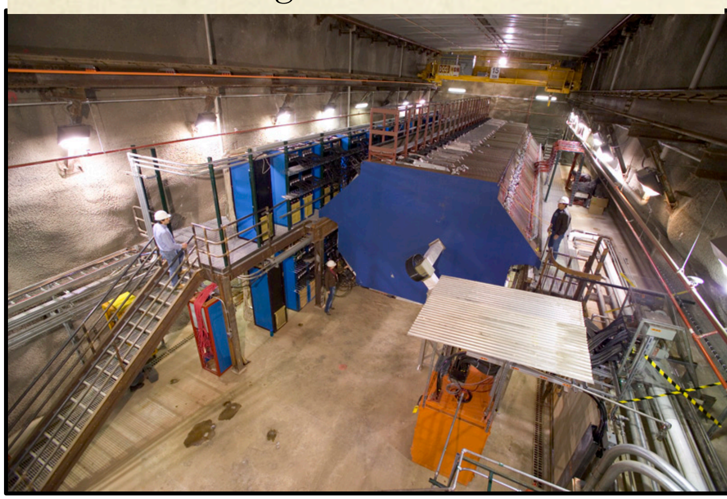
is a **two detector, long baseline** neutrino oscillation experiment.



The MINOS Experiment

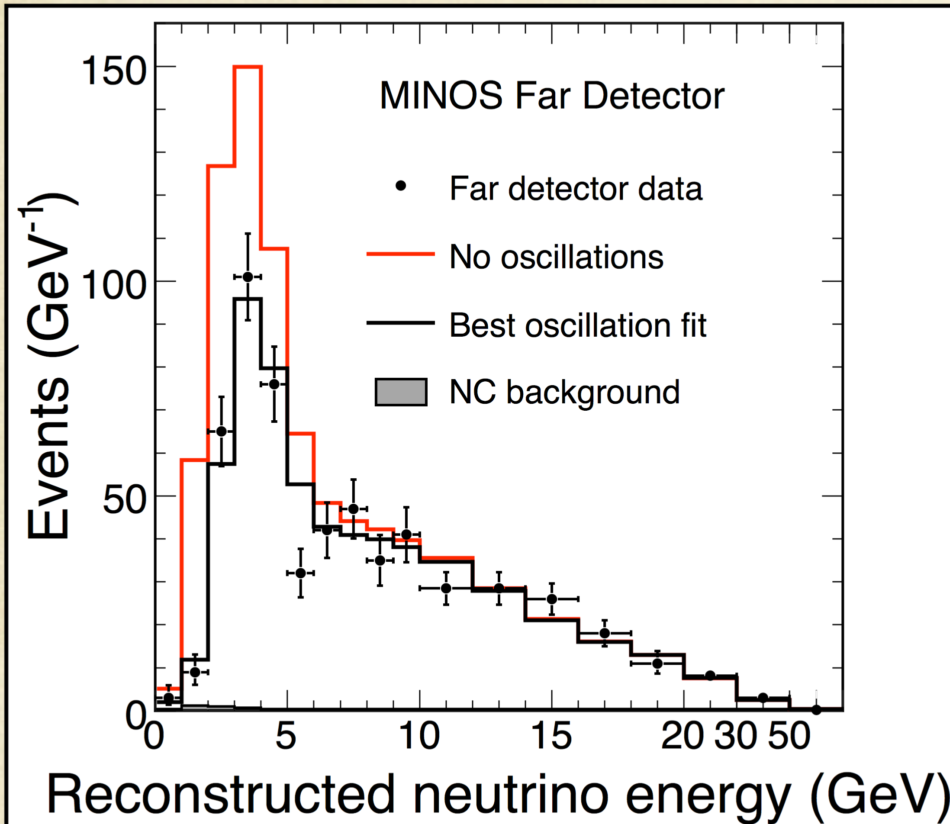
5400 tonneutrino detector 716 meters underground at the Soudan iron mine in Soudan, MN

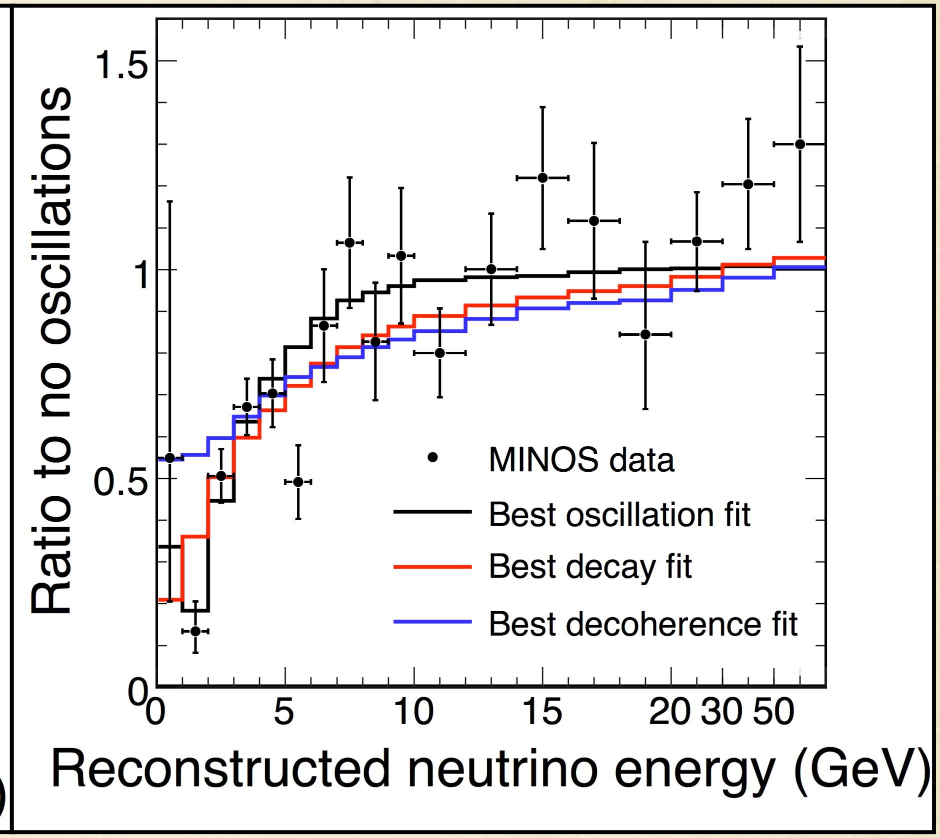
1000 ton neutrino detector 100 meters underground at Fermilab



both are specialized **muon neutrino** detectors

And They Do Disappear!!

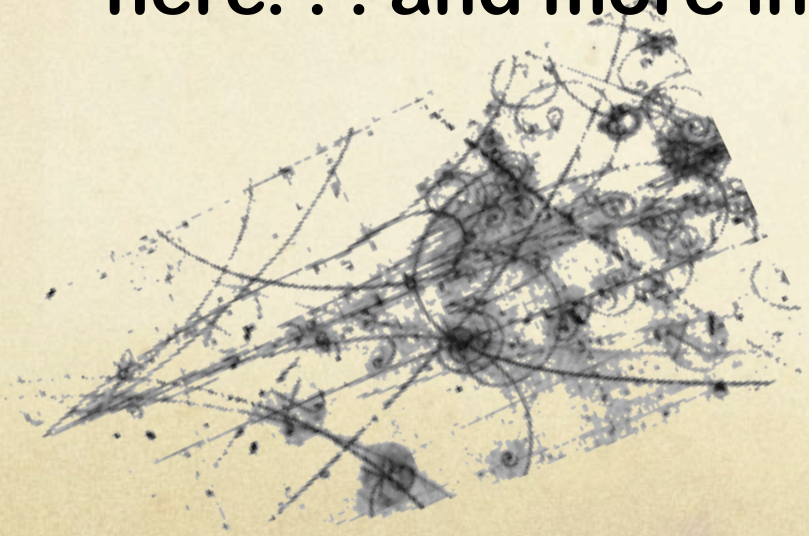




Comparison between Near/Far muon neutrino measurements establish the oscillation signal and characteristics!

Neutrino Oscillations

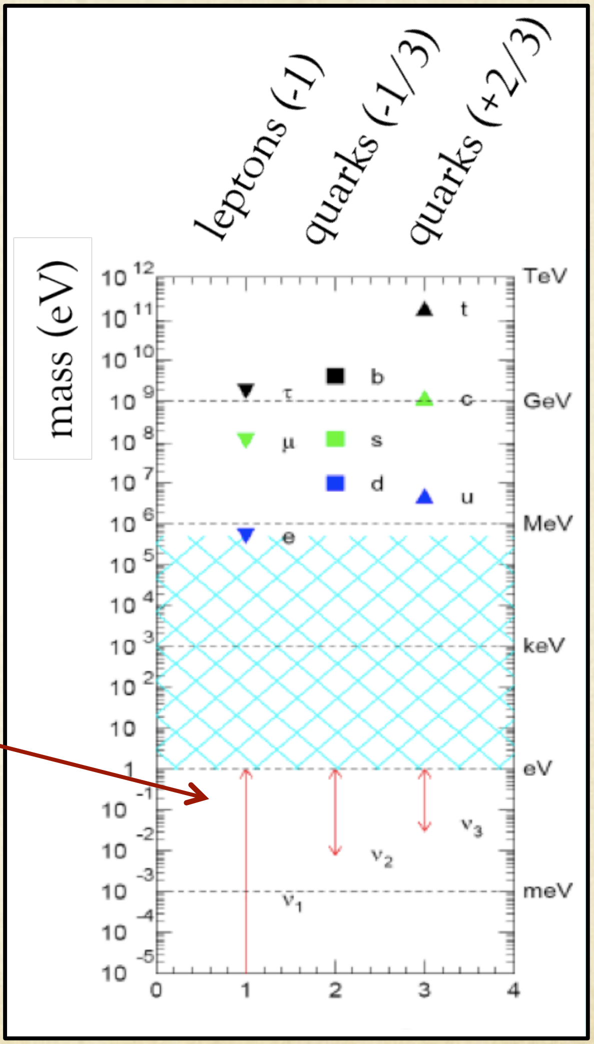
- **Experiments have provided incontrovertable evidence that neutrinos do change “flavor”**
- **neutrinos have mass!**
- **but the questions only get more difficult from here. . . and more interesting. . .**



Some Open Questions

- understanding the **masses of the elementary building blocks of matter** is one of the most fundamental problems in particle physics today

- neutrino oscillations is our only window onto mass for neutrinos
  - why are neutrino masses so small?
  - what is the hierarchy of the three known neutrino types?
  - are there more than three?

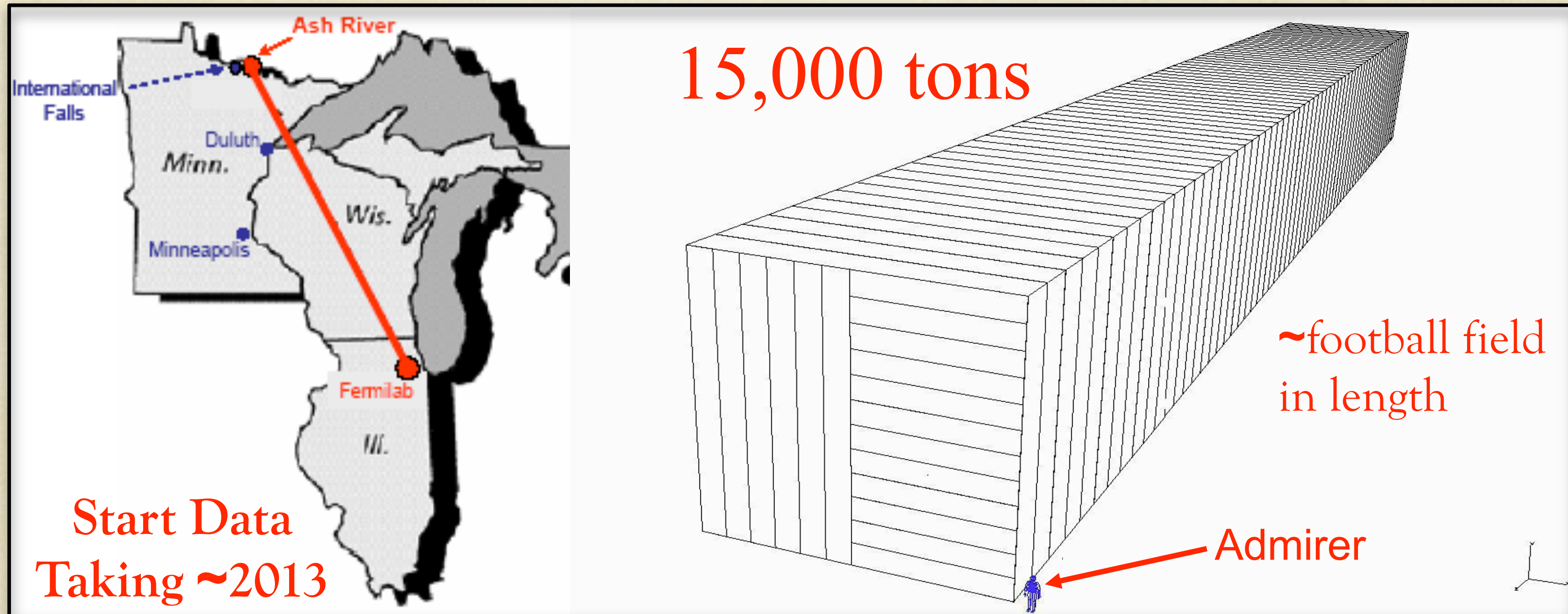


Some Open Questions

- there is a problem in our understanding of the Universe
- during the Big Bang, 14 billion years ago, equal amounts of matter and anti-matter would have been produced
- some fundamental difference in matter/anti-matter has (thankfully!!) led to the matter dominated Universe that we inhabit
- without it the Universe would be merely a sea of photons
- it's possible that the explanation lies with the neutrinos and the answer can be revealed in oscillation effects

- Fermilab is home to a very rich program of neutrino research includingexperiments running now, new detectors currently being constructed, and exciting plans for a world-class future programdesigned to find aswers to these questions

Future : The NOνA Experiment

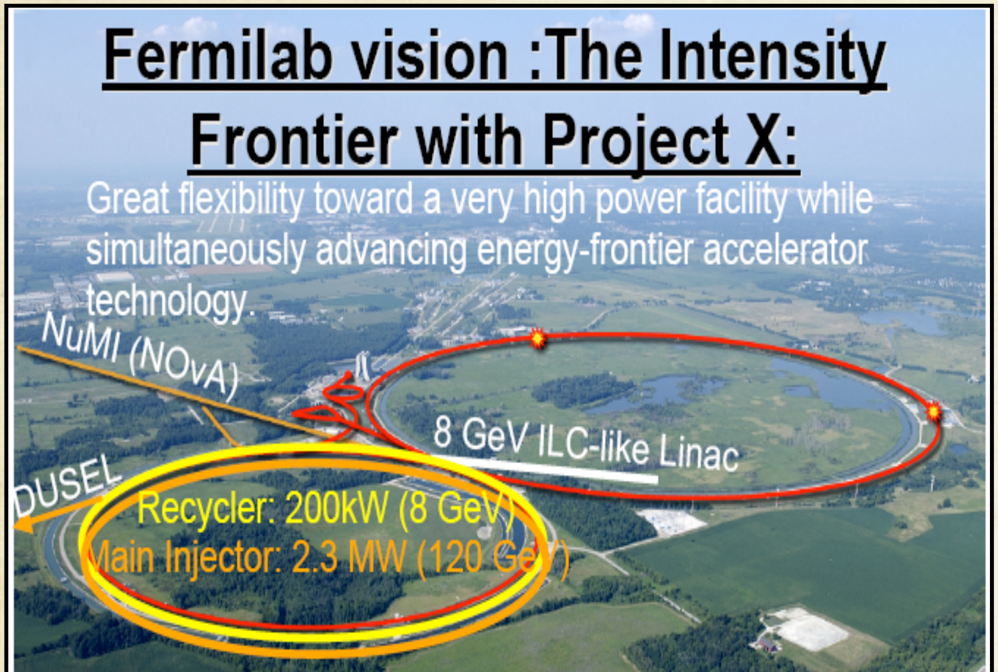


NOνA detector will be 3 times more massive than the MINOS detector

NOνA detector specially designed to detect electron neutrinos.

Makes continued use of the existing NuMI neutrino beam

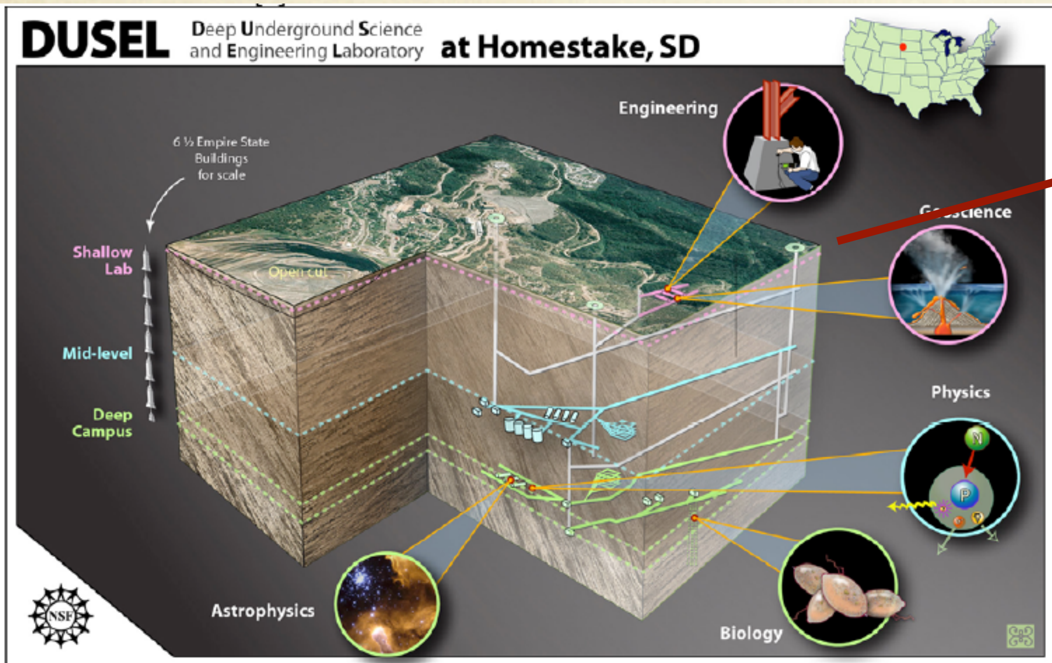
Future : Project-X to DUSEL



Currently planning a new high intensity neutrino source at Fermilab (Project-X)

Will involve the challenging development of cutting edge accelerator technologies

Future : Project-X to DUSEL



And a set of **extremely massive detectors** in the Deep Underground Science and Engineering Laboratory (DUSEL) in South Dakota

DUSEL is a multi-disciplinary science laboratory with a strong physics program

Conclusion

- Neutrinos are a fascinating and critical component of the Standard Model of Particle Physics
- Neutrinos have managed to surprise the particle physics community repeatedly over the past 75 years
- Fermilab will remain at the forefront of the efforts to explore this sector of the field and reveal what these tiny, ghost-like particles have to tell us about the Universe which we inhabit
  - building new experiments to reveal new discoveries
  - advancing the technology of creating intense neutrino sources
  - advancing the technology of detecting neutrinos
- And, hopefully, neutrinos will continue to spark the imagination of all. . .

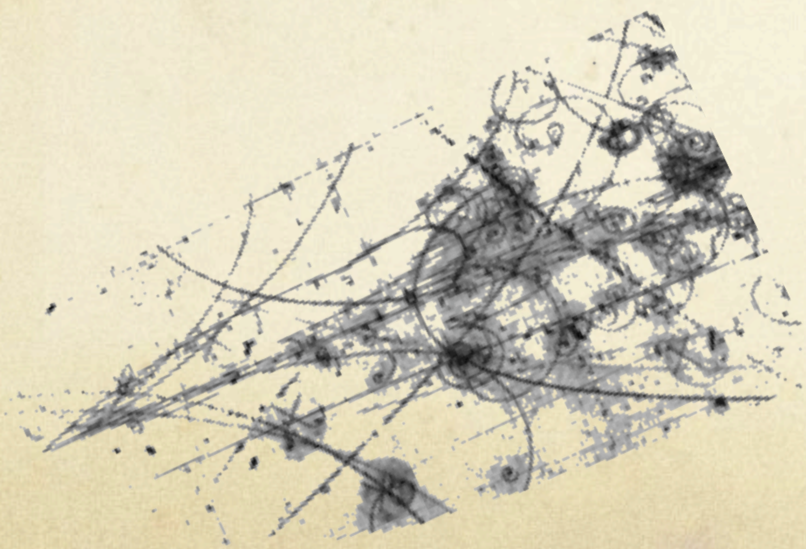
Neutrino Poetry

Cosmic Gall

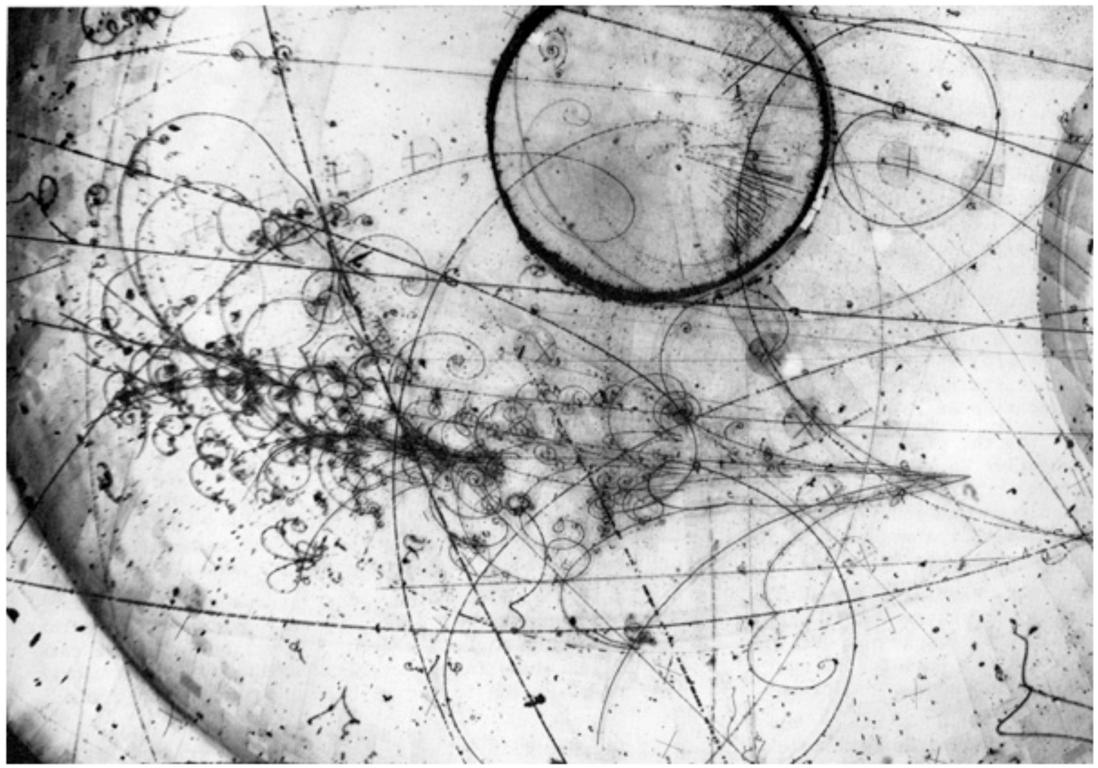
Neutrinos they are very small.
They have no charge and have no mass
And do not interact at all.
The earth is just a silly ball
To them, through which they simply pass,
Like dustmaids down a drafty hall
Or photons through a sheet of glass.
They snub the most exquisite gas,
Ignore the most substantial wall,
Cold-shoulder steel and sounding brass,
Insult the stallion in his stall,
And, scorning barriers of class,
Infiltrate you and me! Like tall
And painless guillotines, they fall
Down through our heads into the grass.
At night, they enter at Nepal
And pierce the lover and his lass
From underneath the bed – you call
It wonderful; I call it crass.

John Updike
(March 18, 1932 – January 27, 2009)

Thank You!



Fermilab 15-ft Bubble Chamber



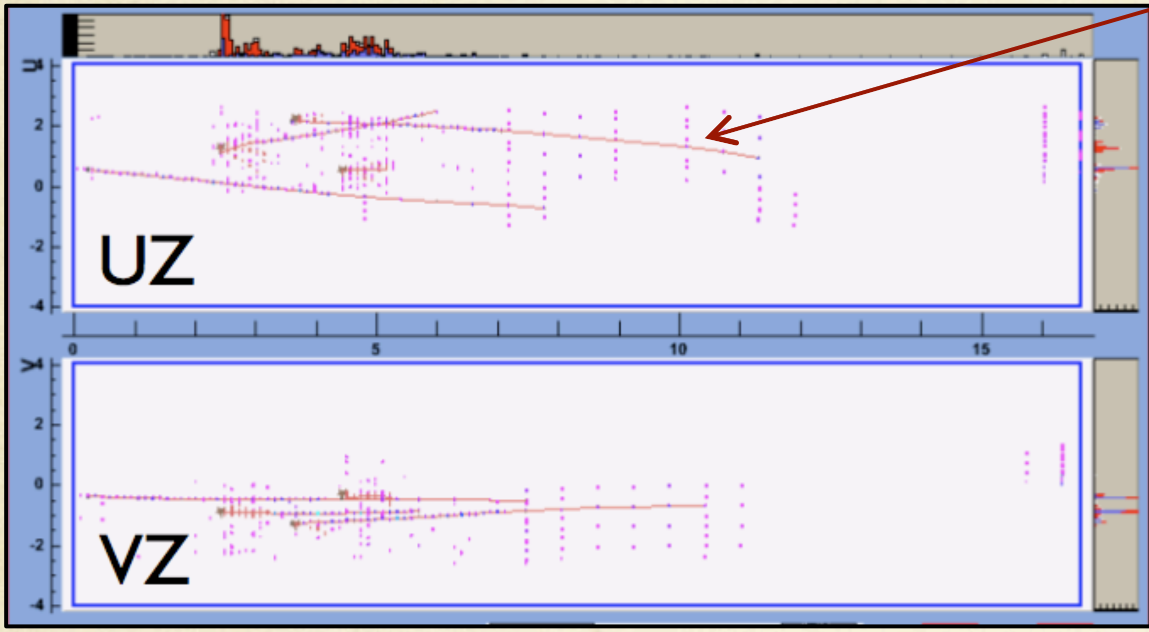
neutrino beam ←

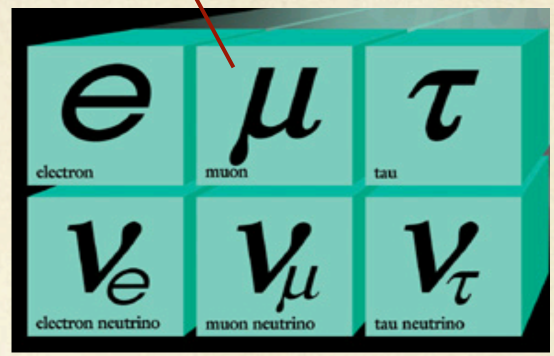
Picture of neutrino interaction in the Fermilab 15-foot Bubble Chamber with heavy neonhydrogen liquid mixture taken in April, 1976. Nearly one neutrino interaction per picture is found with the current run targeting 1013 protons at 400 GeV with the wide band - two horn system. Frequently the chamber is flooded with tracks from several neutrino interactions in the same exposure.

In addition to increasing the interaction rate, the heavy neon mixture allows many of the particles from neutrino interactions to be recognized by direct inspection of the track appearance: protons, charged pions and kaons produce secondary interactions; neutral pions are evidenced by their gamma rays converting to electron pairs; muons sail right through the liquid without interacting and direct electrons or positrons from the vertex are recognized by successive kinks and associated gamma ray conversions along their tracks. A major interest in the present experiment by a Columbia University-Brookhaven Laboratory collaboration is the study of "di-lepton" events in which two muons or a muon and an electron are produced in high energy neutrino interactions.

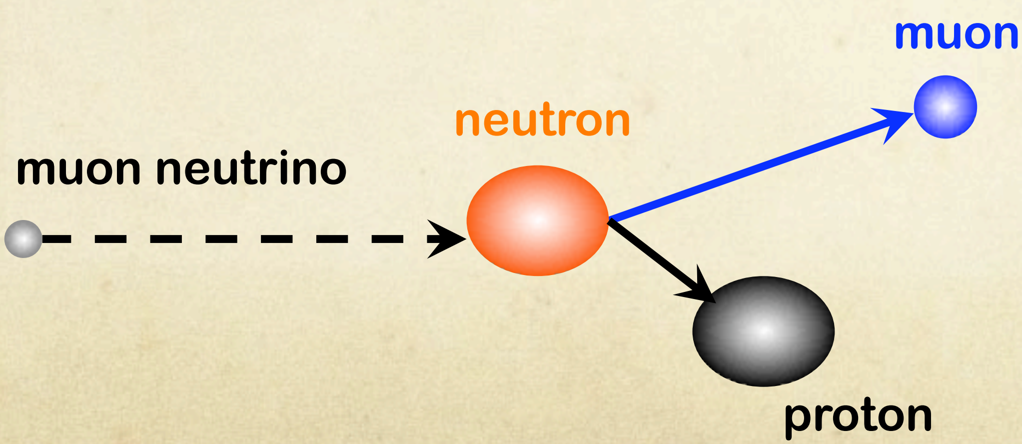
Source: The Village Crier Vol. 8 No. 18, May 6, 1976

Detecting Muon Neutrinos @ MINOS



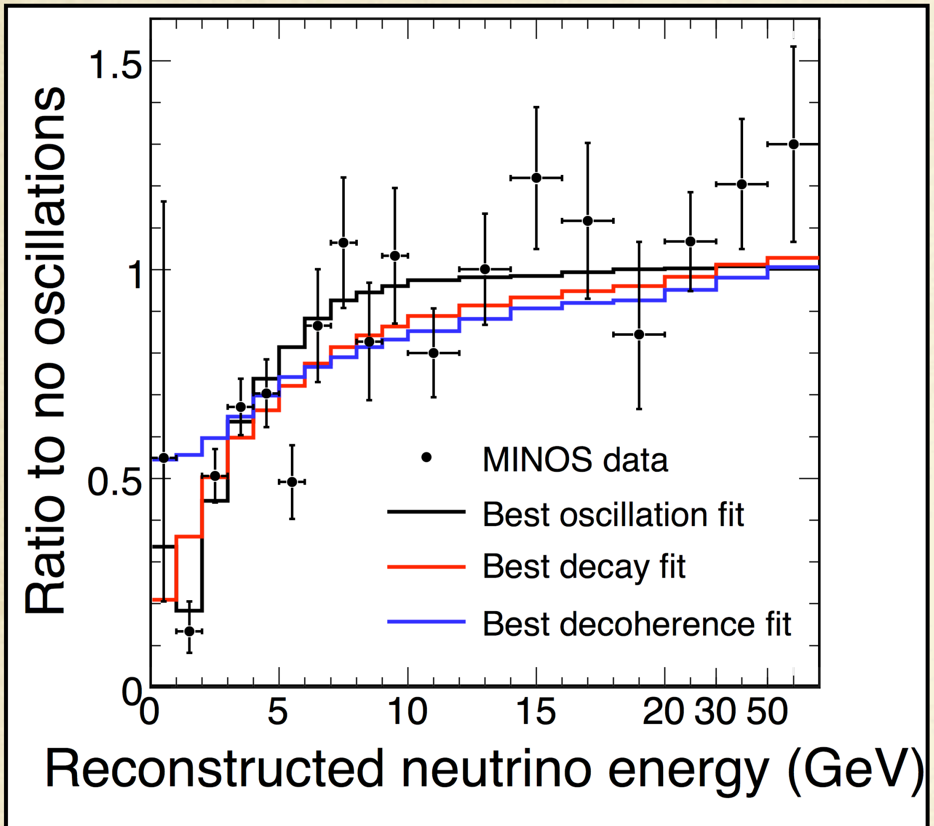


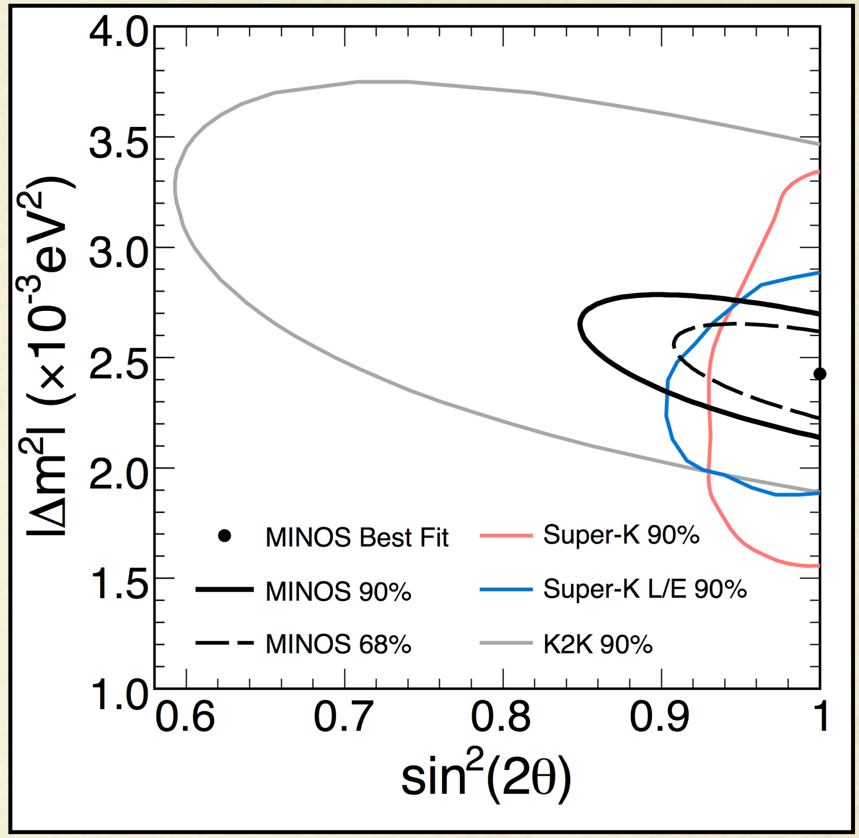
don’t see the neutrino directly, but when one interacts with a nucleus in the detector it creates its charged lepton partner



can distinguish the charged leptons in the detector

MINOS Results

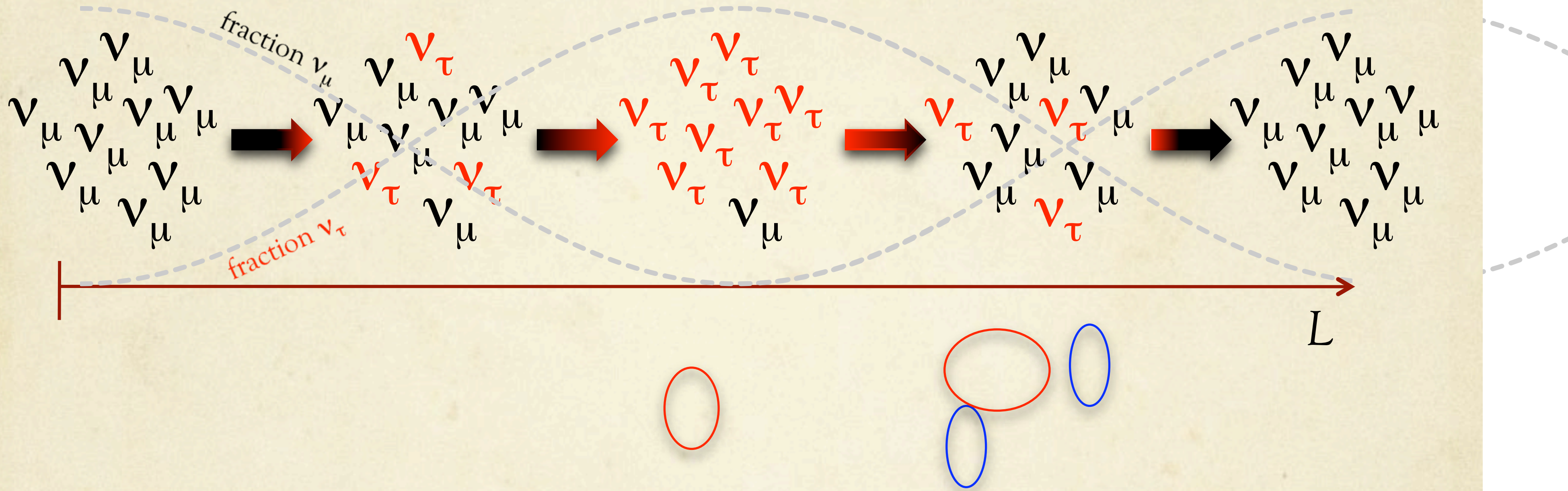




Comparison between Near/Far measurements establish the oscillation signal and characteristics!

Neutrino Oscillations

- this oscillation affects the *probability* that a neutrino is of type α as it travels



2 physics parameters we wish to measure:	
Δm^2	: mass difference between the neutrinos
θ	: how much they mix with each other

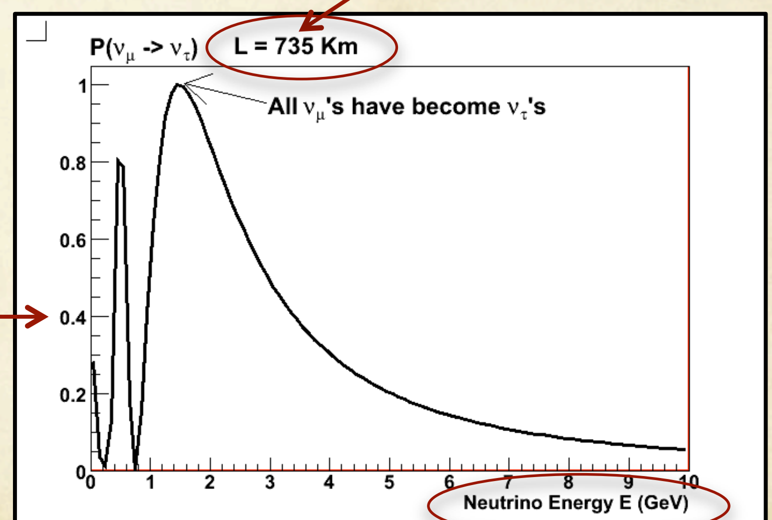
2 experimental parameters:	
L	: distance from source to detector
E	: energy of neutrino

Building a Neutrino Oscillator

- neutrino oscillations can explain the anomalies in solar and atmospheric neutrino data, but even better to create a controlled neutrino source and see if it oscillates
  - carefully control L and E in the oscillation formula
  - probe different values of mass difference (Δm^2) by changing L and E
  - measure the oscillation probability over a range of E

fixed L

measure oscillation probability P

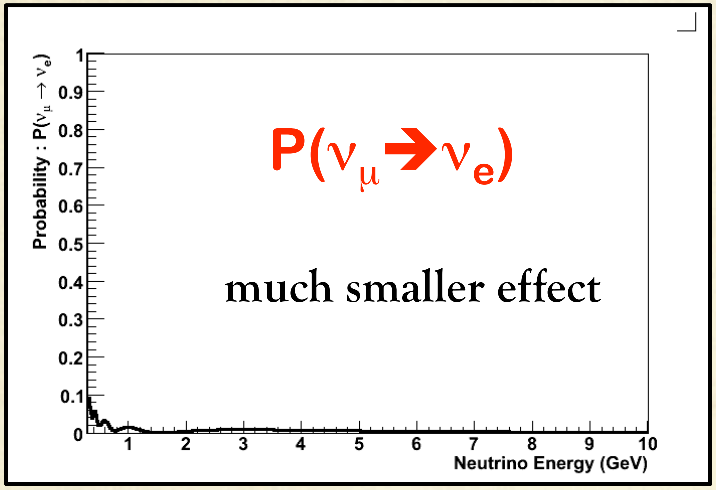


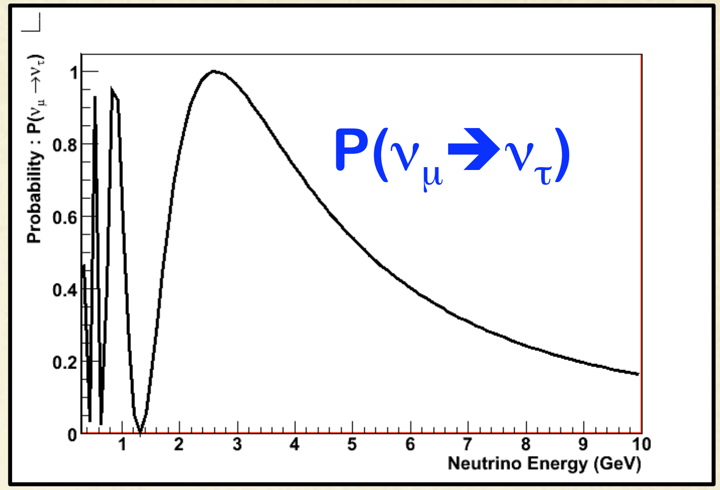
neutrino energy range E

Can we reproduce the effect we believe we are seeing in neutrinos from the cosmos here on Earth in the laboratory?

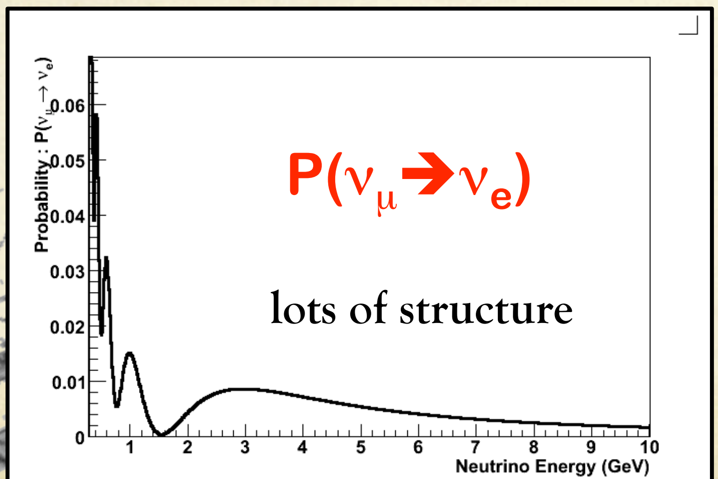
Moving Forward

$P(\nu_\mu \rightarrow \nu_e)$ not as simple as $P(\nu_\mu \rightarrow \nu_\tau)$...





ZOOM IN



Moving Forward

P(ν_μ→ν_e) not as simple as P(ν_μ→ν_τ)...

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

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

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

CP Violating

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

CP Conserving

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

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

Matter Effects

the matter/anti-matter asymmetric part!