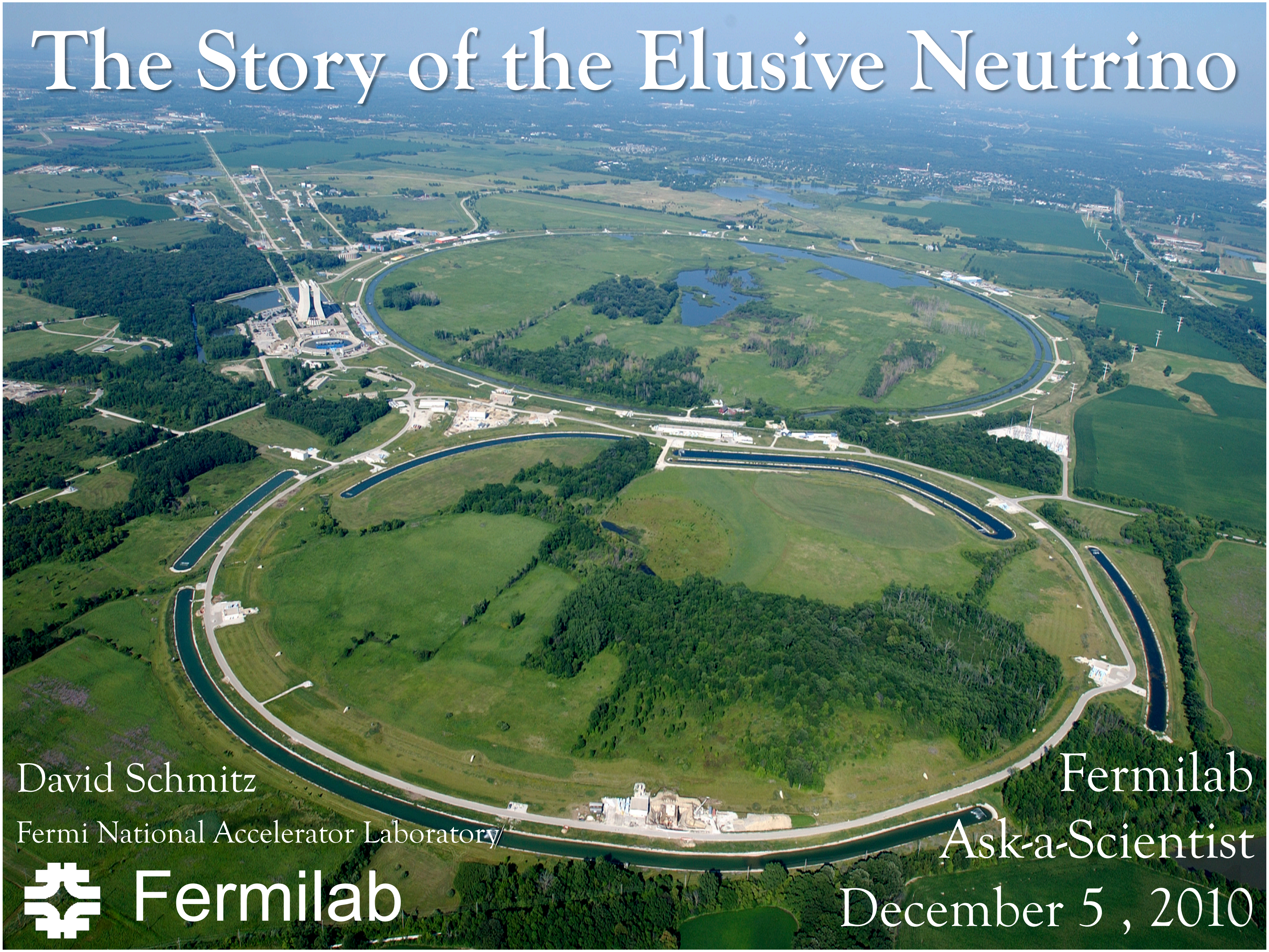
The Story of the Elusive Neutrino



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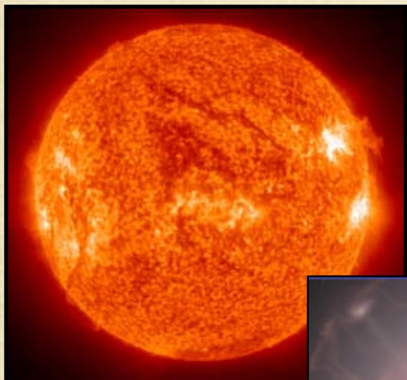
Fermilab

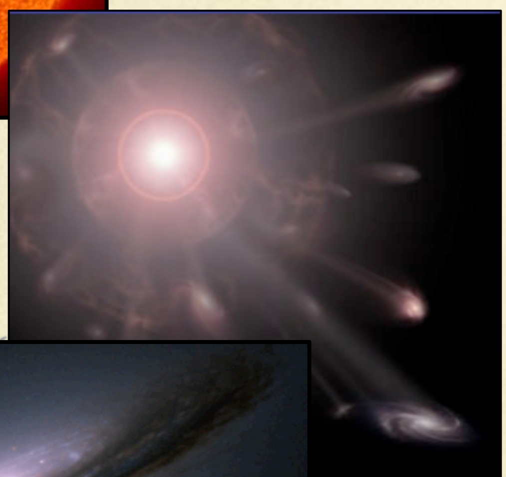
Fermilab
Ask-a-Scientist
December 5 , 2010

Neutrinos . . .

Are the <u>most abundant known matter particles</u> in the Universe, outnumbering all other particles by a factor of a BILLION



Are a critical component in nuclear processes that power stars. The Sun produces so many neutrinos that 100 billion are passing through your thumbnail *EACH SECOND!*



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 20,000,000 in *your space!*

Carry almost all (~99%) of the energy from a Supernova explosion, the most powerful explosions in the Universe

Neutrinos . . .

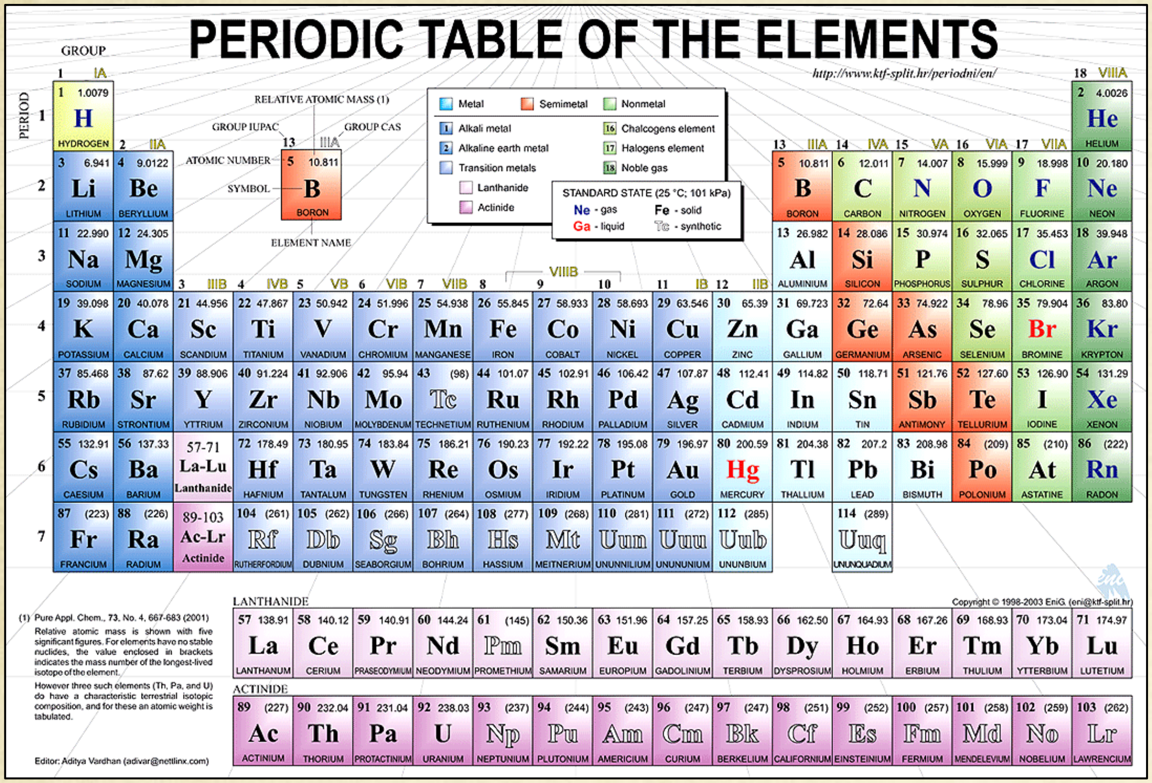
Come from bananas!?! huh?

We'll come back to this later…

Our Plan For Today

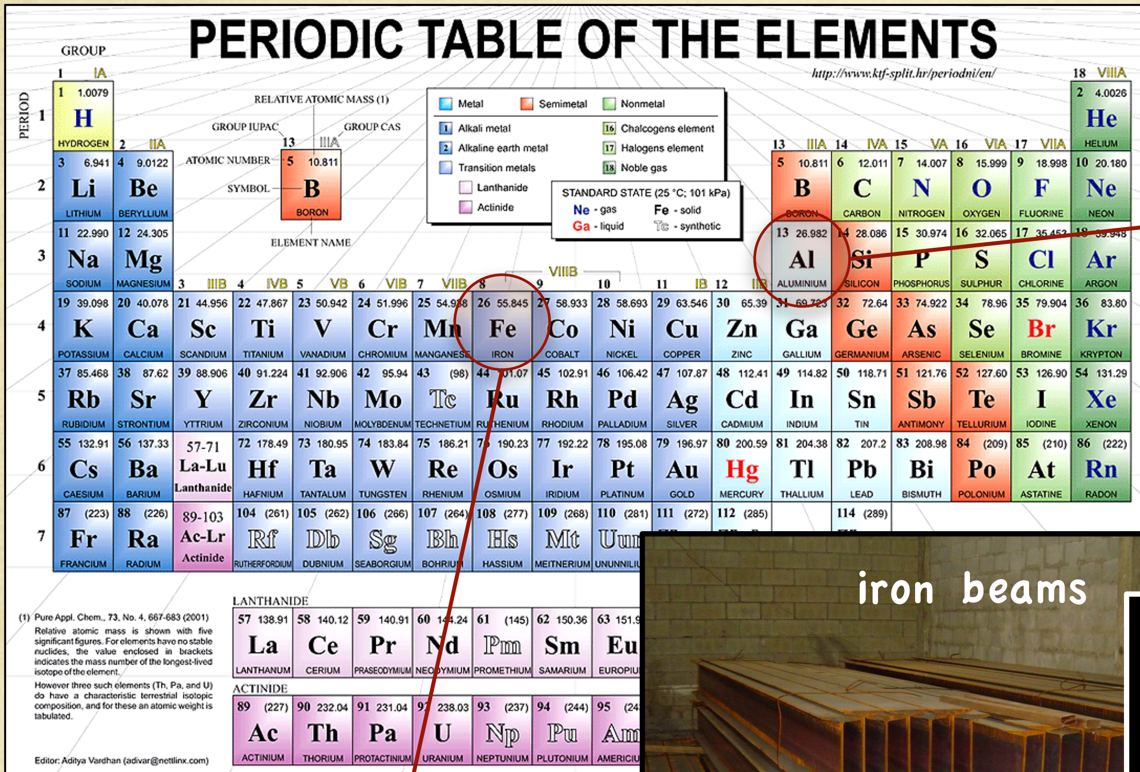
- First, we should take a quick look at particle physics as a whole to see where neutrinos fit into the picture
- Then, we'll explore the neutrino's history, full of surprises from the beginning
- Finally, we'll take a look at some experiments Fermilab is doing to find out what the neutrino might reveal about our Universe

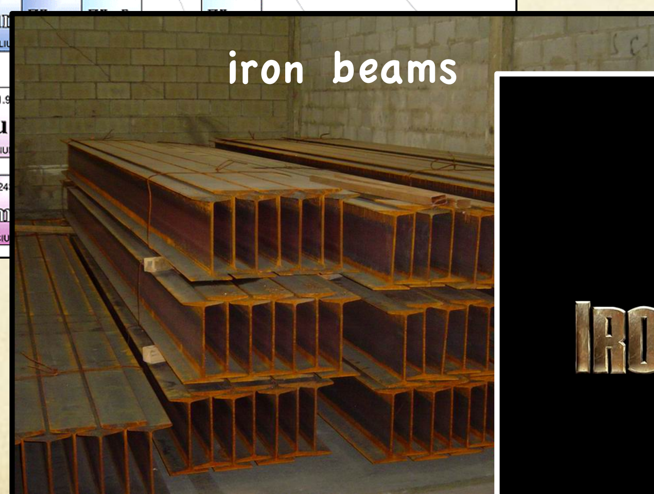
What is Particle Physics?



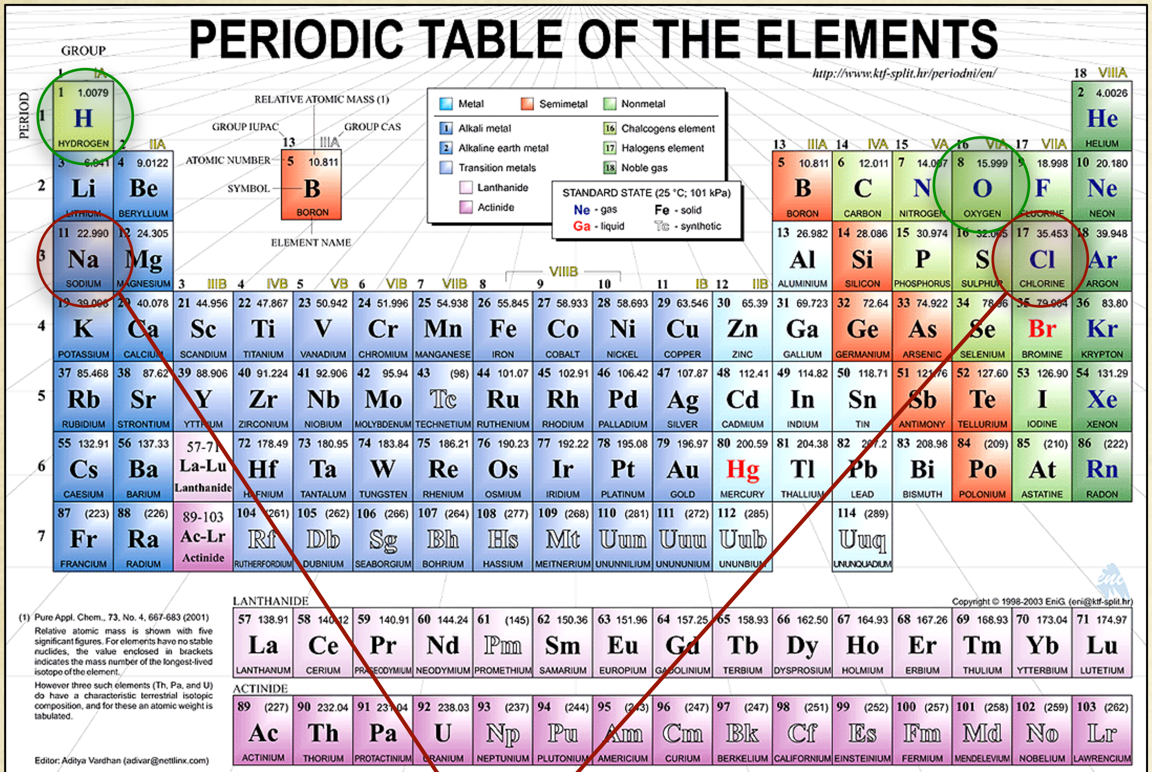
- **Let's start with chemistry, a science perhaps a bit more familiar**

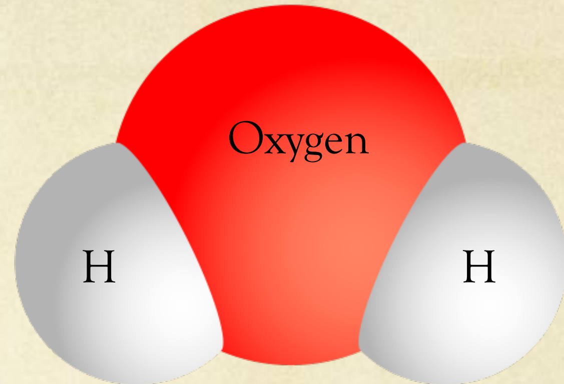
What is Particle Physics?





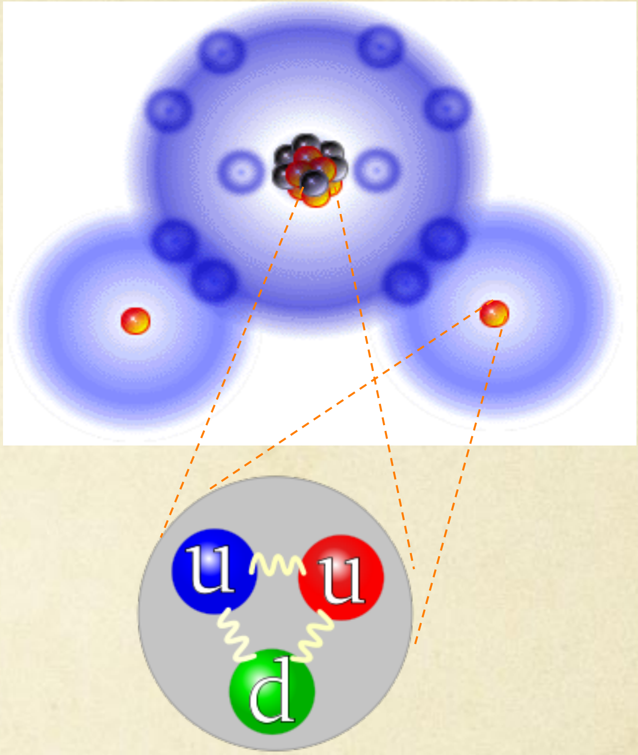
What is Particle Physics?





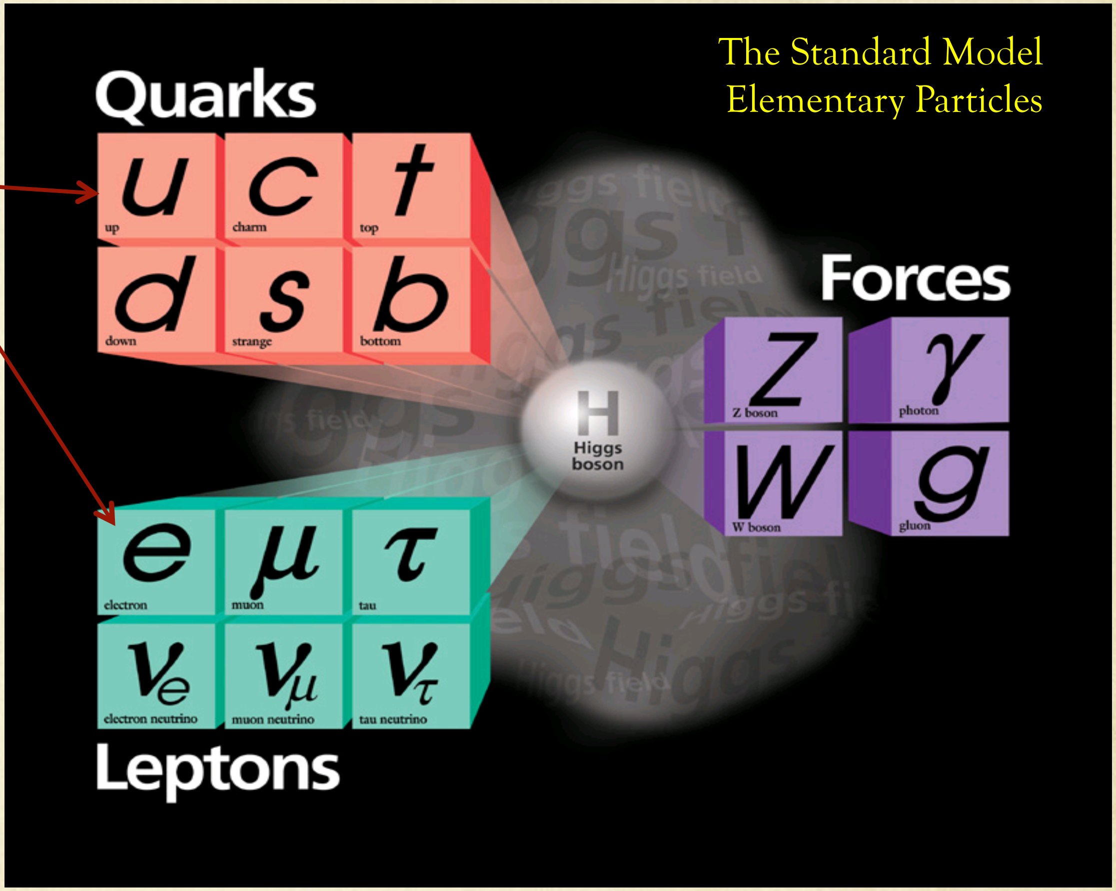
What is Particle Physics?

- What if, instead, we go the other way?
- It turns out that so much of the beautiful richness of our Universe can be elegantly explained by the "Periodic Table" of Particle Physics
- The Standard Model of Particle Physics

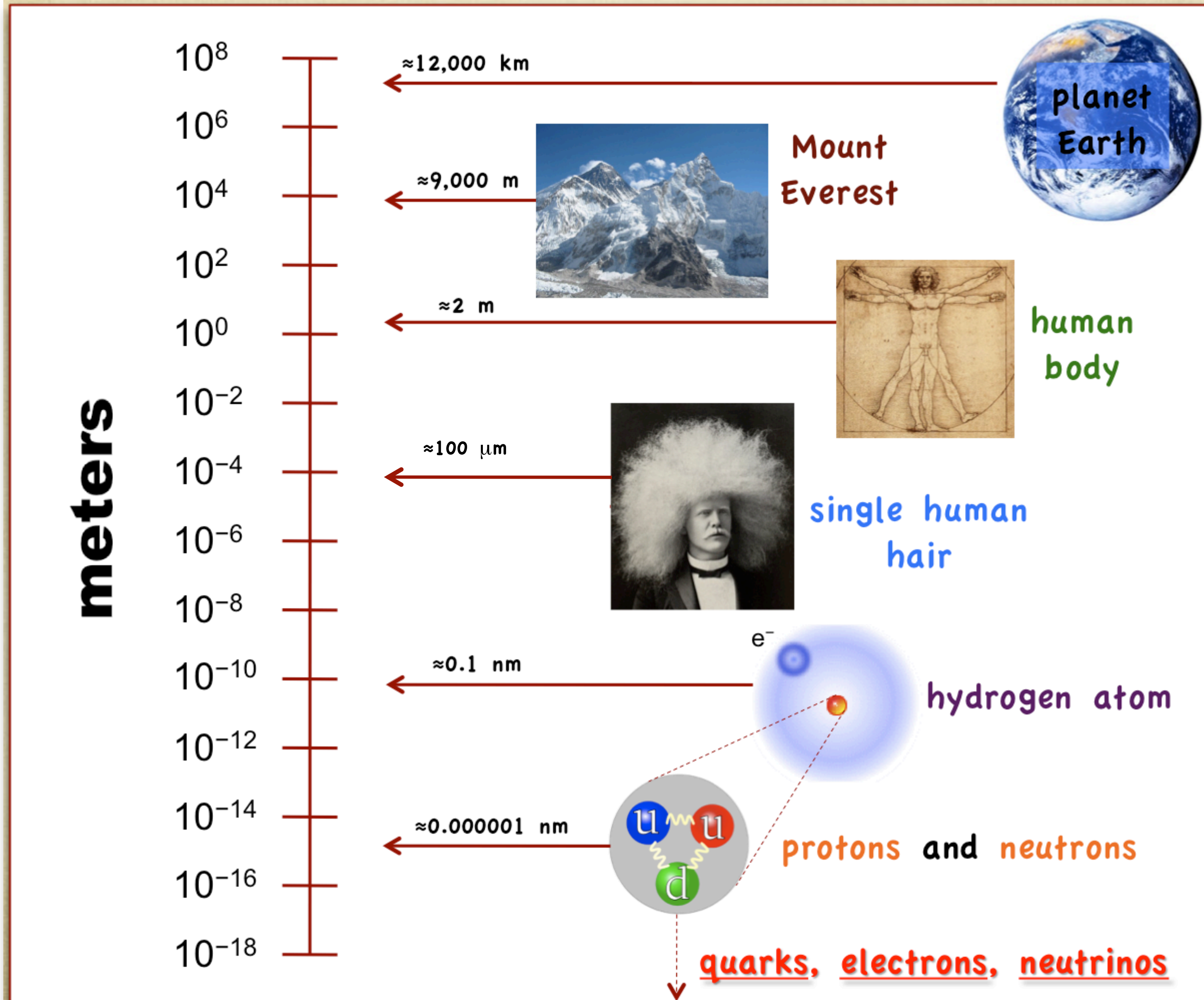


Standard Model of Particle Physics

- **12 matter particles**
  - 6 quarks
  - 6 leptons
  - these 12 building blocks make up all the varieties of “normal” matter in the Universe
- **4 forces**
  - gravitational force
  - electromagnetic force
  - strong nuclear force
  - weak nuclear force
  - these 4 ways for particles to interact with each other are the only ones we currently know about



A Sense of Scale – How Small is Small?



Each "order of magnitude" changes the value by a factor of 10, so the scale to the left represents a factor of 10^{26} = 100,000,000,000,000,000,000,000,000

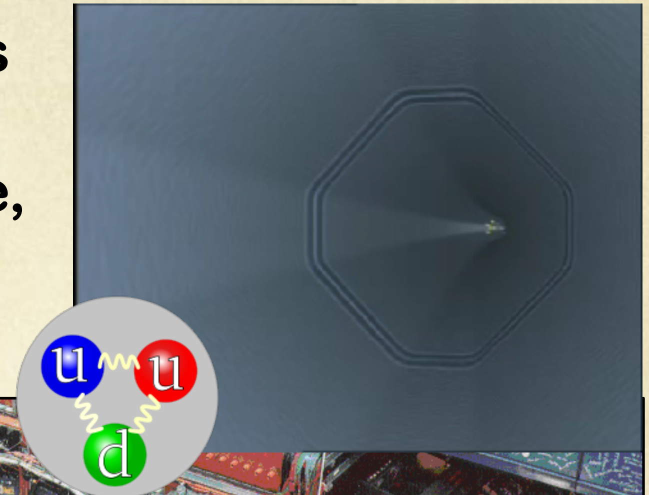
A proton is to one human hair

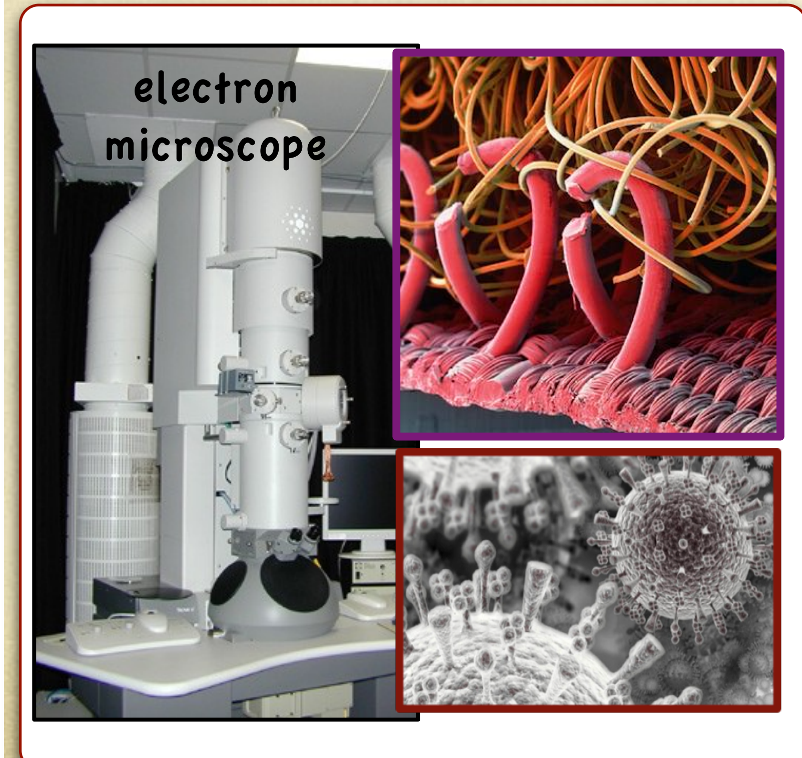
AS

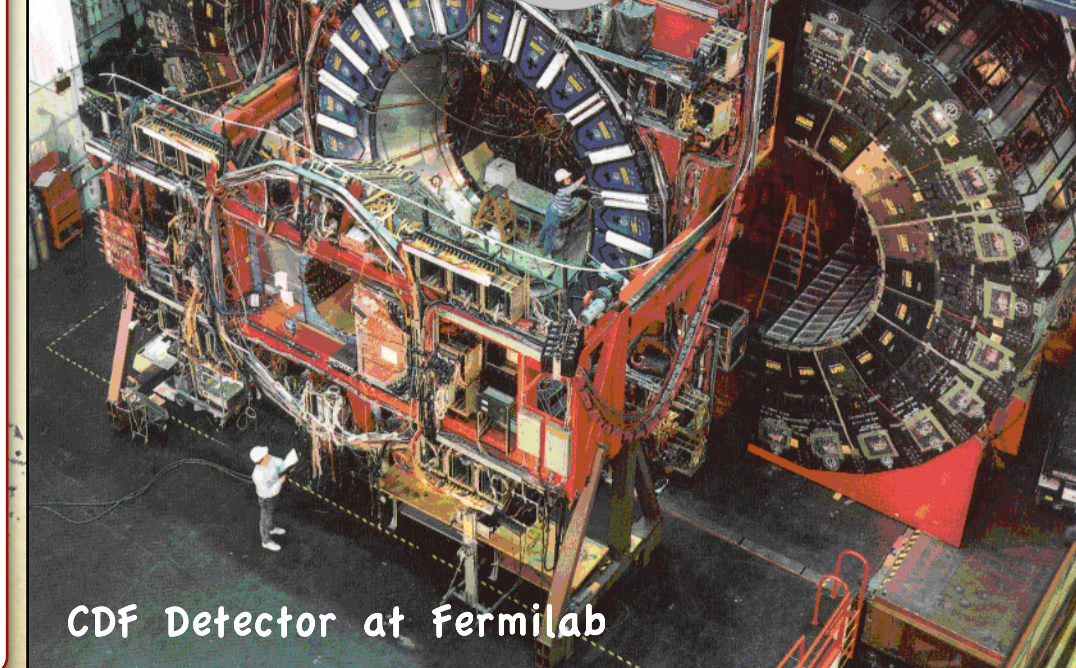
one human hair is to the diameter of the Earth

Seeing the Very Very Very Small

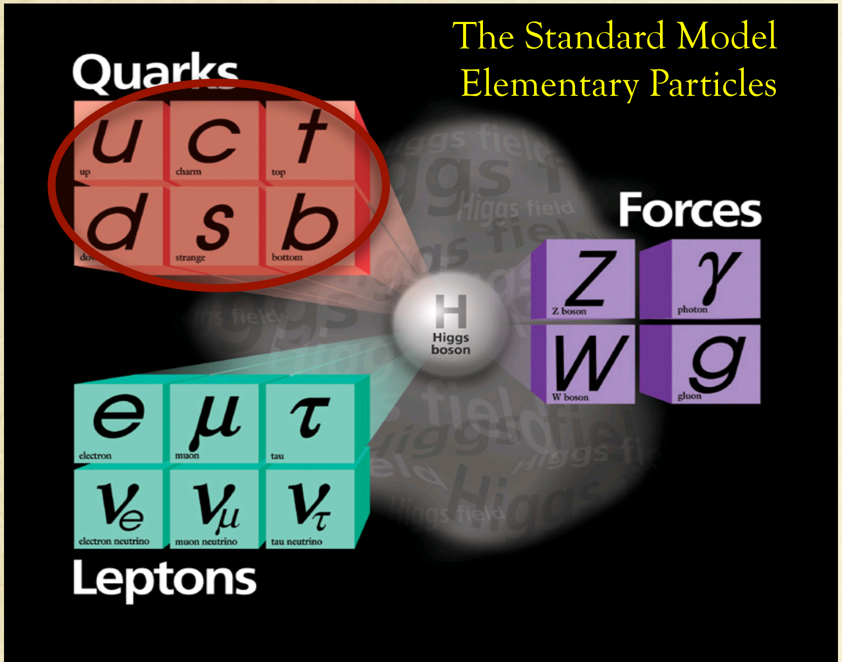
The great cosmic joke is that the <u>smaller</u> the object you want to probe, <u>the bigger your "microscope" must be</u>!!

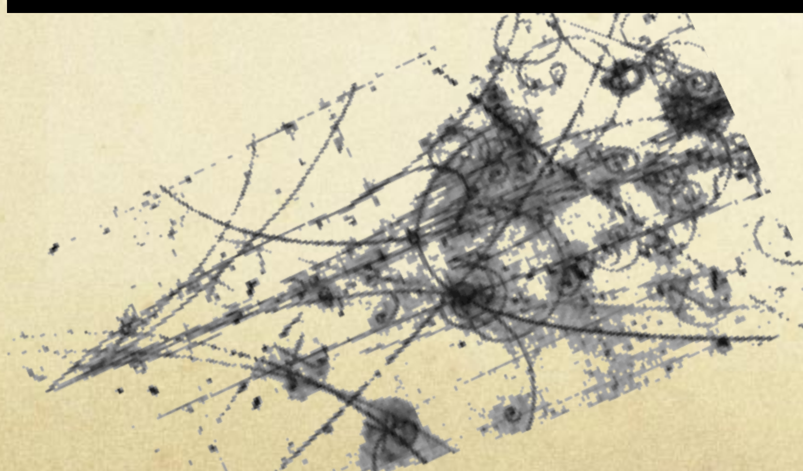




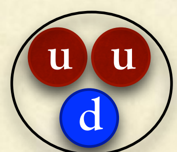


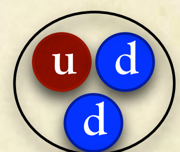
Quarks . . .

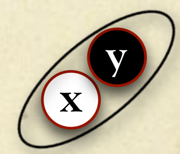




- Interact with other particles via the strong force, the weak force and the electromagnetic force
- Have fractional electric charge (+2/3 top row, -1/3 bottom)
- Strong force is attractive between quarks and holds them together in pairs or triplets





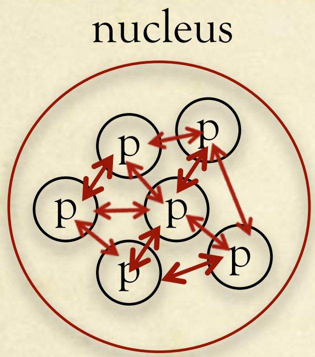


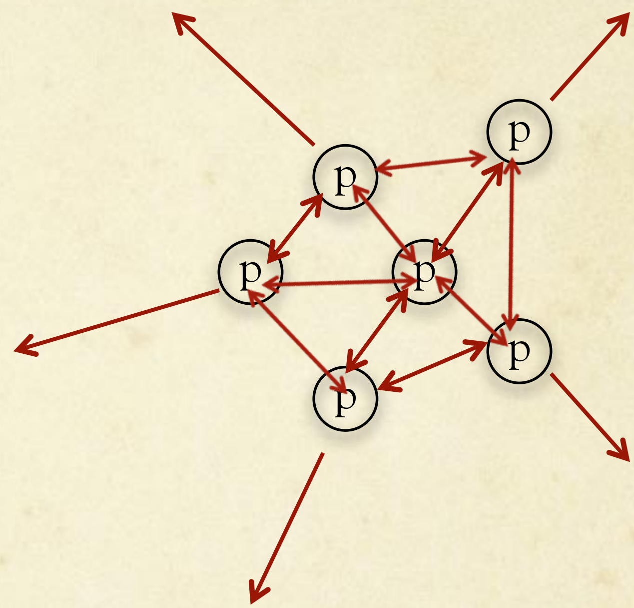
$$+\frac{2}{3}Q+\frac{2}{3}Q-\frac{1}{3}Q=+1Q$$

$$+\frac{2}{3}Q-\frac{1}{3}Q-\frac{1}{3}Q=0$$

Quarks . . .

- We know that like charges repel by the electromagnetic force, so why don't the positively charged protons in a tiny nucleus push apart from each other?





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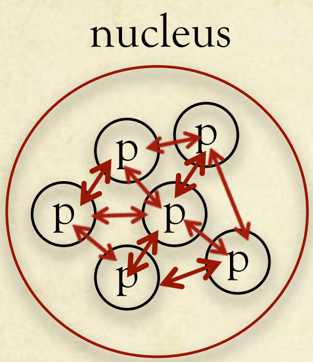
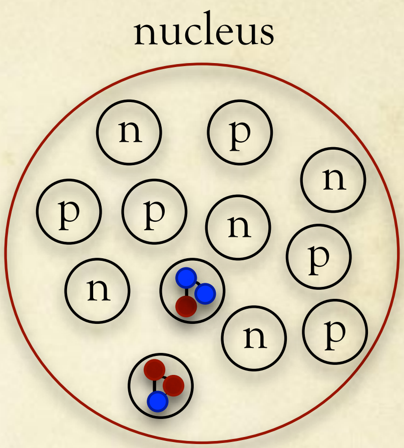
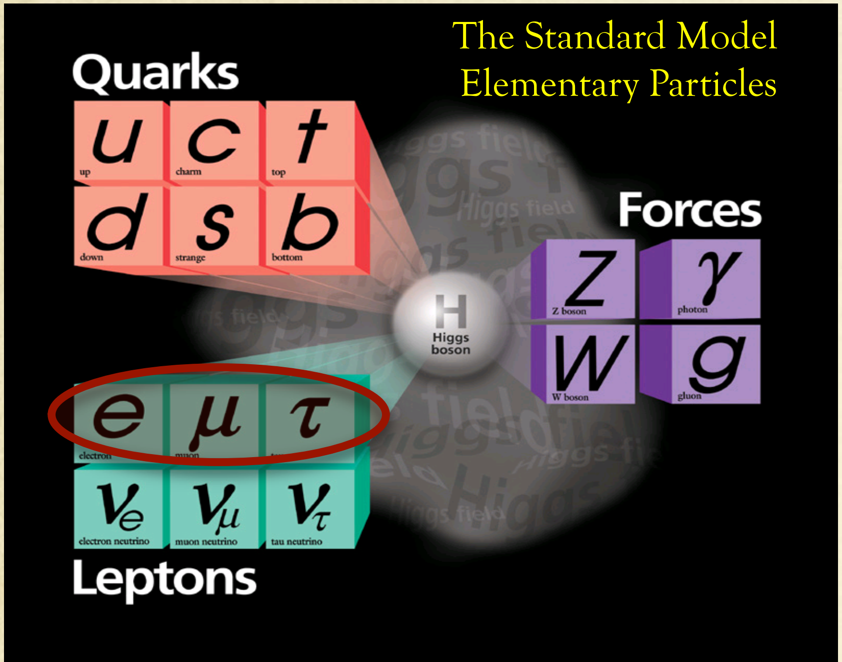


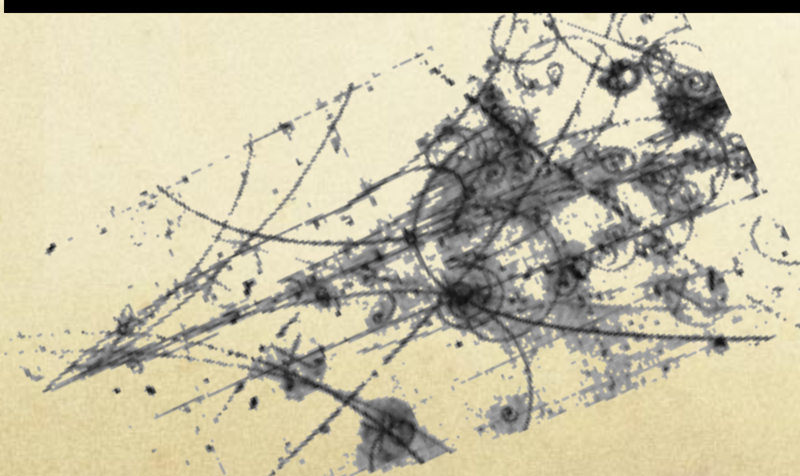


- Because the <u>attractive strong force</u> is stronger than the <u>repulsive electromagnetic force</u>

- Also neutrons help make a nucleus stable since they feel the strong force but are overall electrically neutral

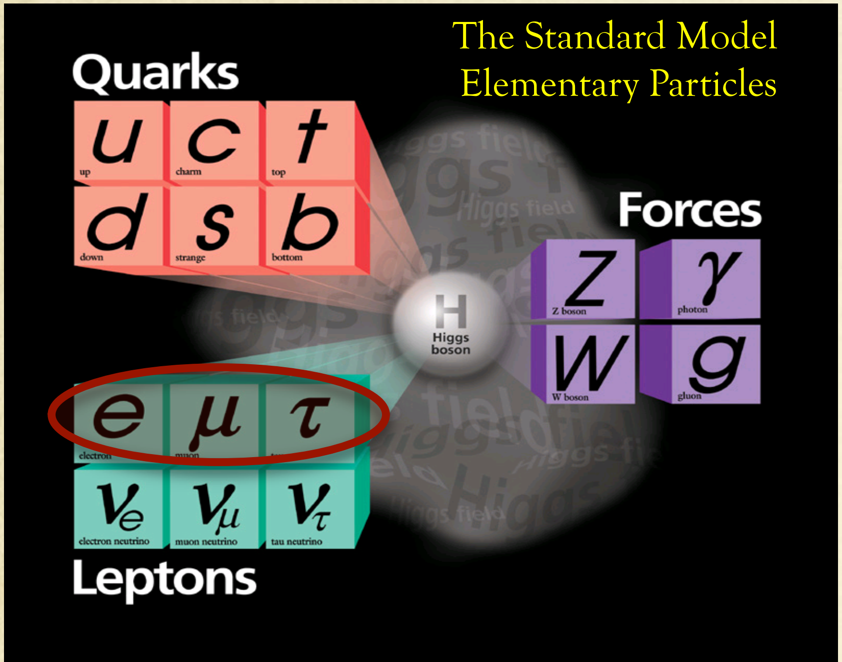
Charged Leptons . . .





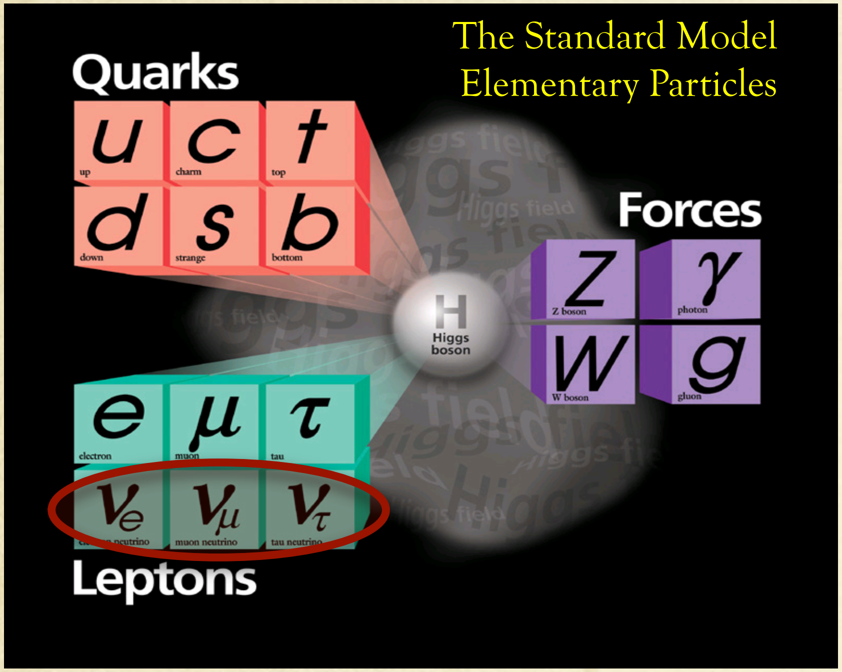
- Come in three **“flavors”**
  - electron
  - muon
  - tau
- Interact with other particles via the **weak** force and the **electromagnetic** force

Charged Leptons . . .



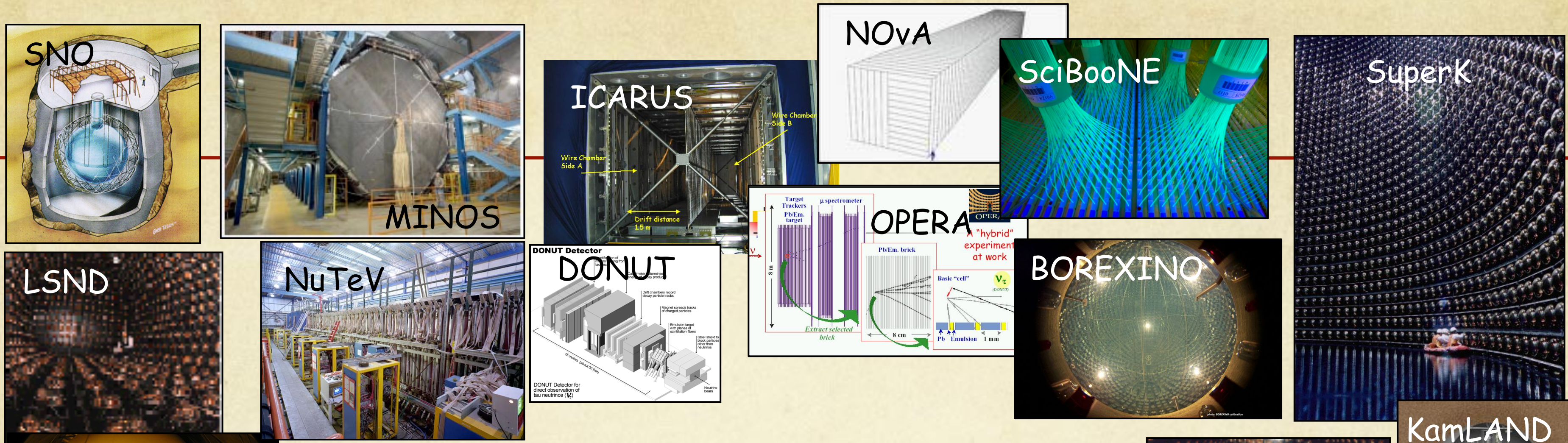
- Come in three "flavors"
  - electron
  - muon
  - tau
- Interact with other particles via the weak force and the electromagnetic force
- muons – main component of cosmic rays hitting the Earth
- electrons and electromagnetic forces responsible for a lot of "everyday" science affects
  - static electricity
  - fridge magnets

Neutrinos . . .



- Also come in three "flavors"
- Interact <u>ONLY</u> via the weak force
- Are assumed to be completely massless in the Standard Model
- Neutrinos make up ¼ of the elementary matter particles we know of, but outnumber the others in the Universe by a factor of a BILLION

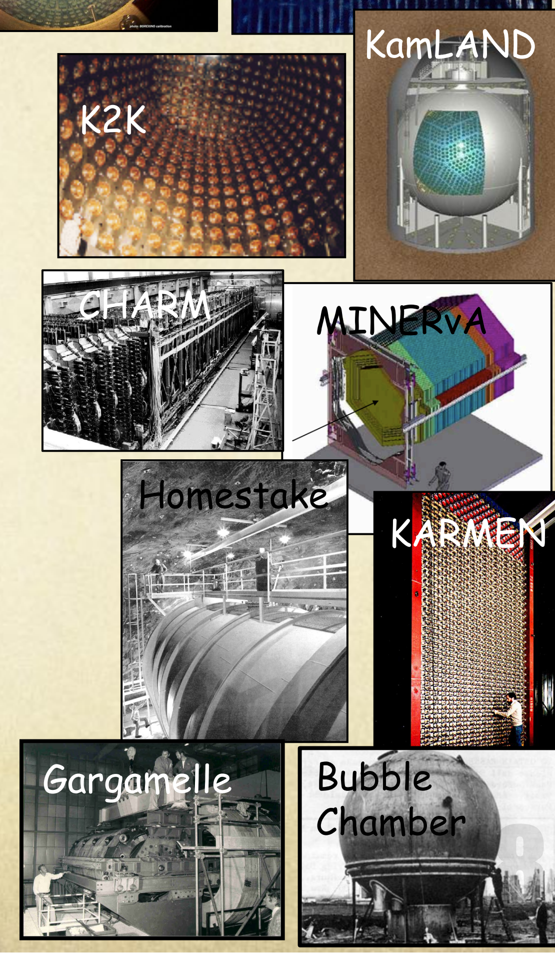
- So, to understand the nature of the Universe in which we live we must understand the properties of the neutrino!

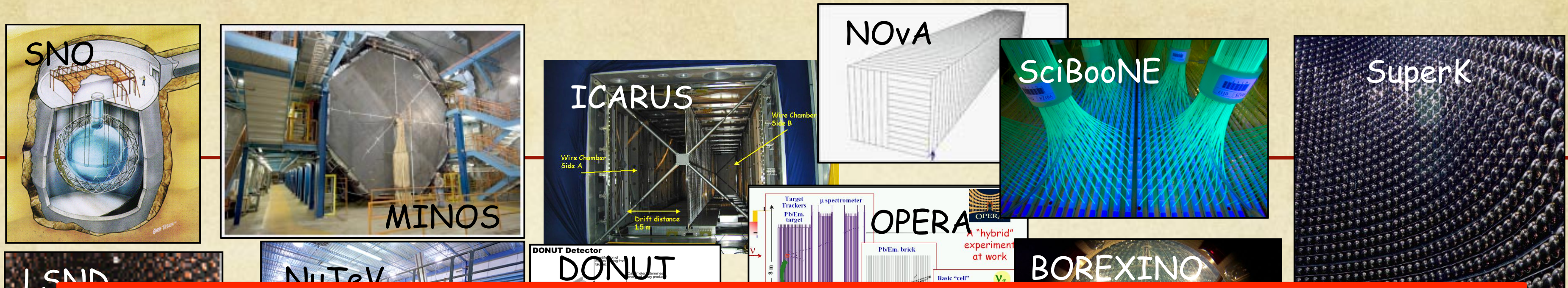


- Some of the many exciting experiments **around the world** that have been dedicated to studying the neutrino

- This little particle has continued to surprise us with its unexpected 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





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

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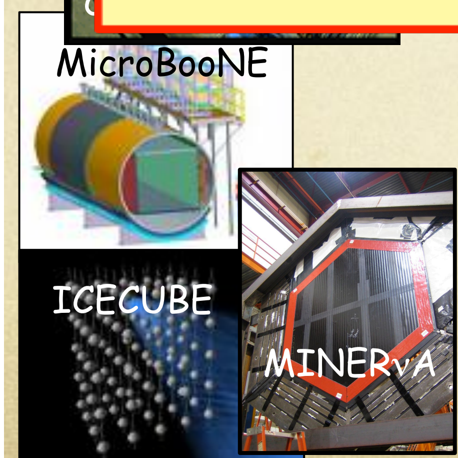
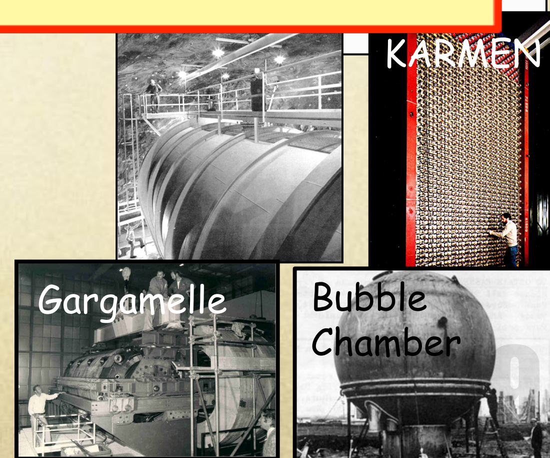




Neutrinos . . .

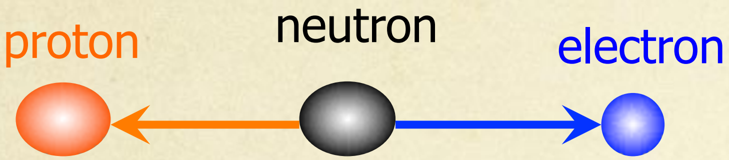
Come from bananas!?! huh?

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

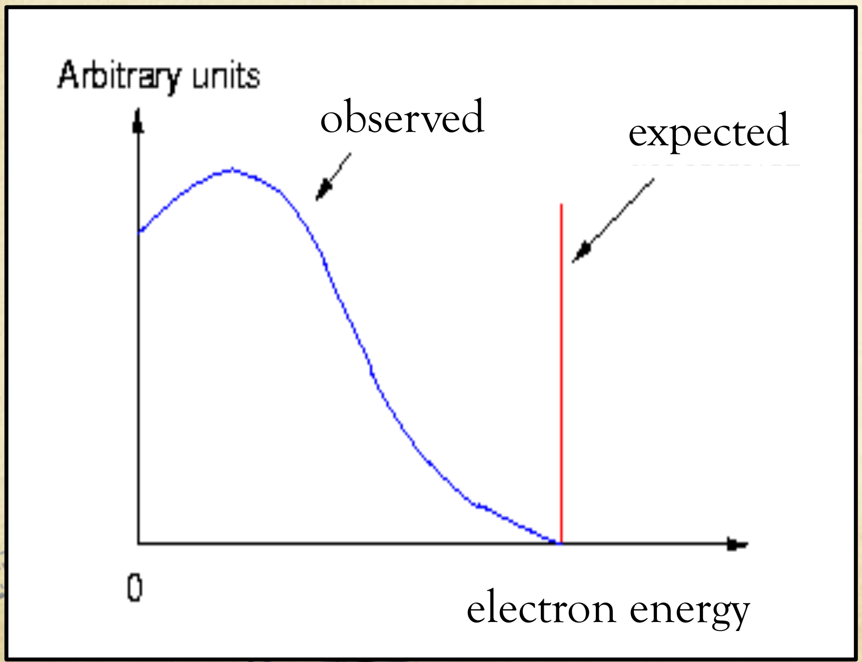
Related to how the neutrino was discovered in the first place
(not bananas, but radioactive decay)

The “desperate remedy”

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



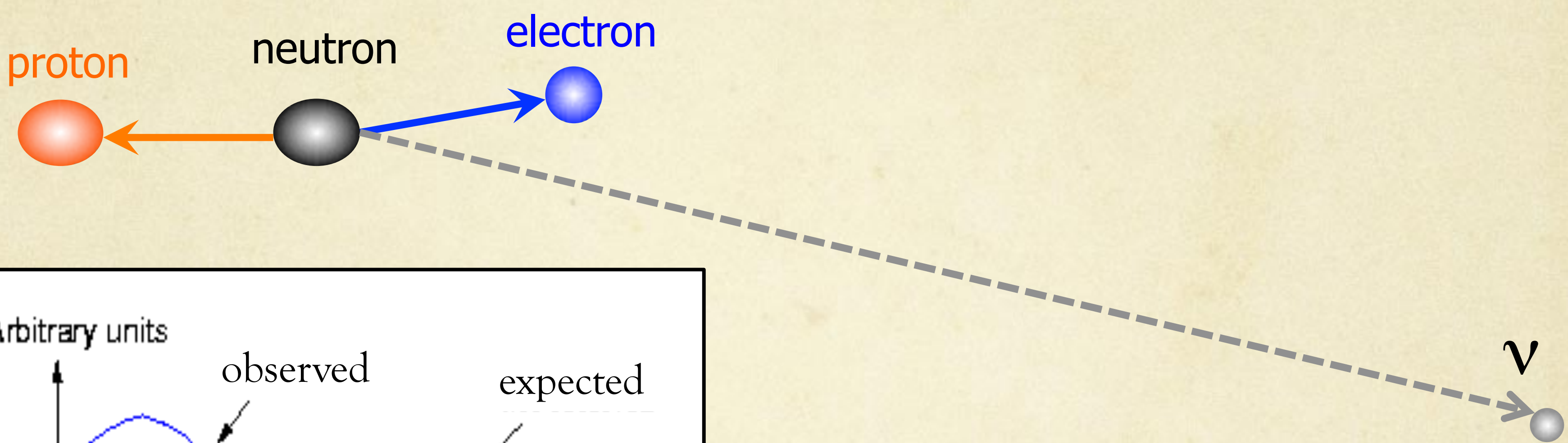
It was well known that nuclei
could change from one variety to another
by emitting a **“beta”** (electron).

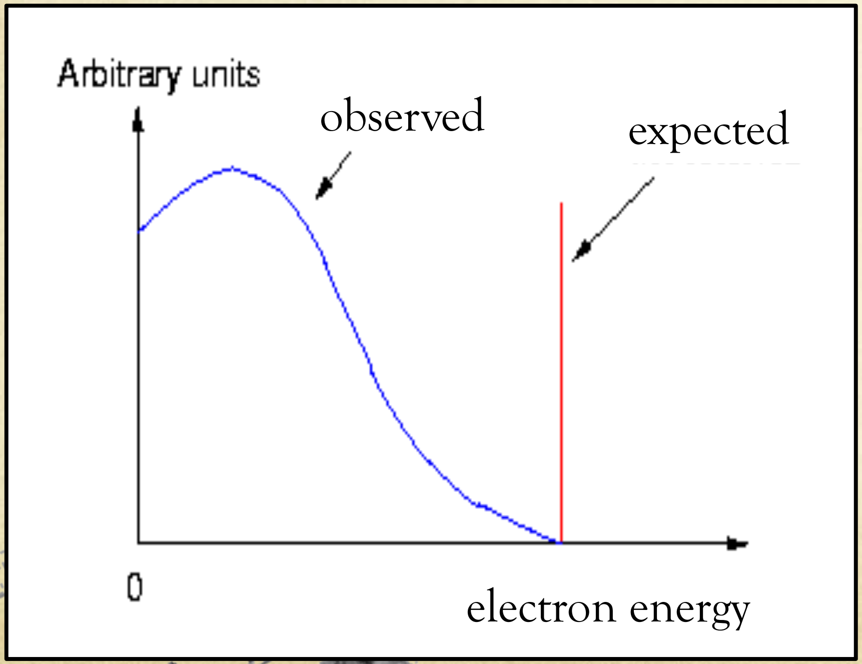


Some were ready to abandon
Conservation of Energy
to explain this missing energy
phenomenon!

The "desperate remedy"

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





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

The "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

W. Pauli
Nobel Prize in 1945

The “desperate remedy”

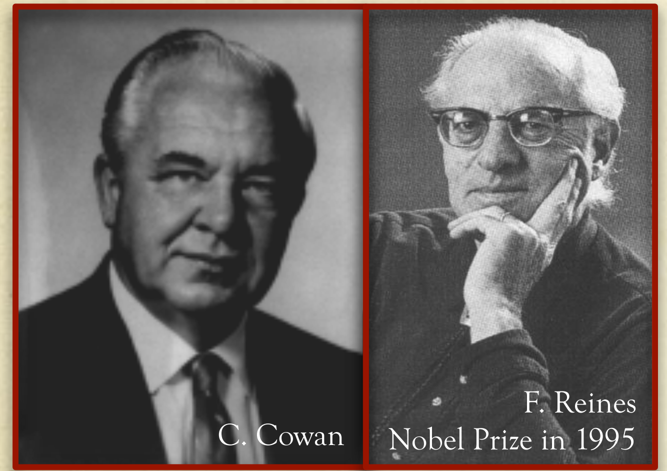
- the neutrino was thought to be a <u>neutral</u>, <u>massless</u> particle

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

- W. Pauli (1931)

W. Pauli
Nobel Prize in 1945

The Initial Discoveries



Finally, Fred Reines and Clyde Cowan managed to detect 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."

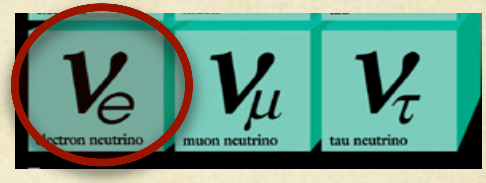
- F. Reines and C. Cowan (1956)

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

- W. Pauli (1956)

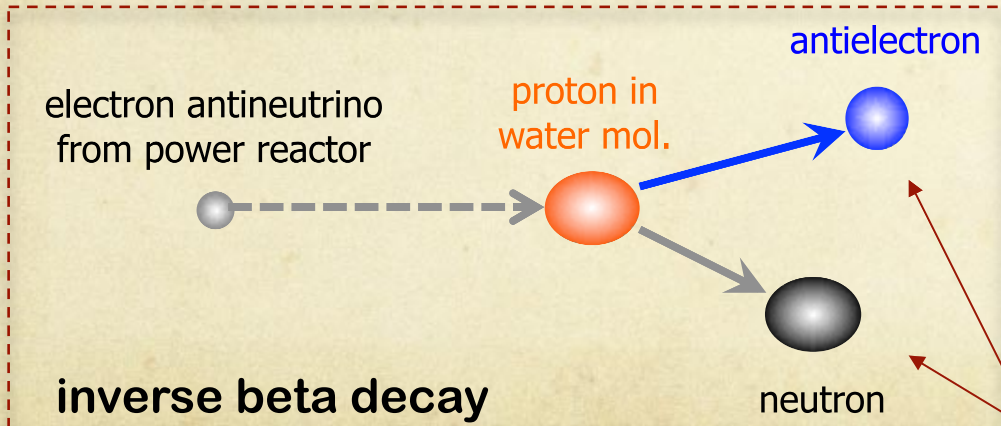
The Initial Discoveries

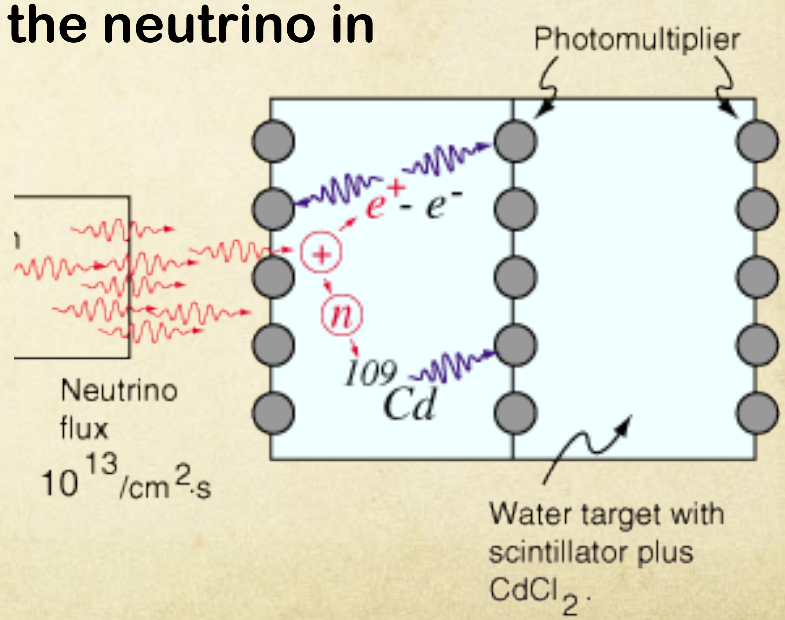
<u>**How did they do it?**</u>



You can't see a neutrino directly since all particle detectors are based on seeing *charged particles*

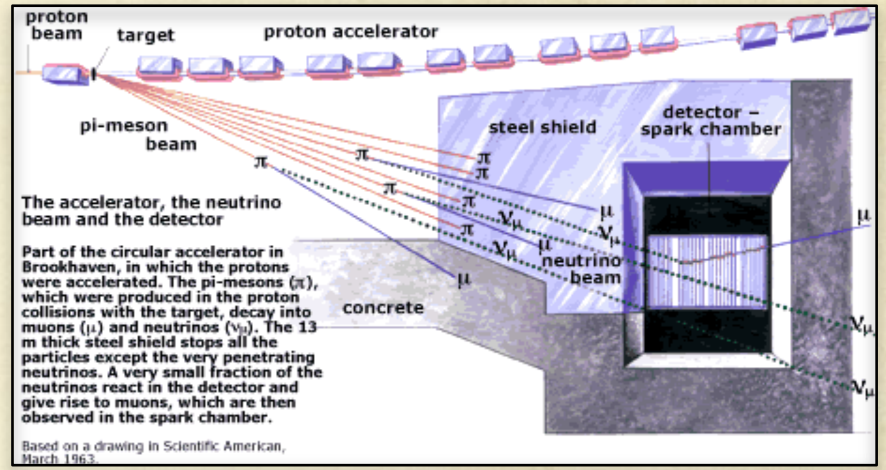
They looked for something called "inverse beta decay", the opposite of what made Pauli think of the neutrino in the first place



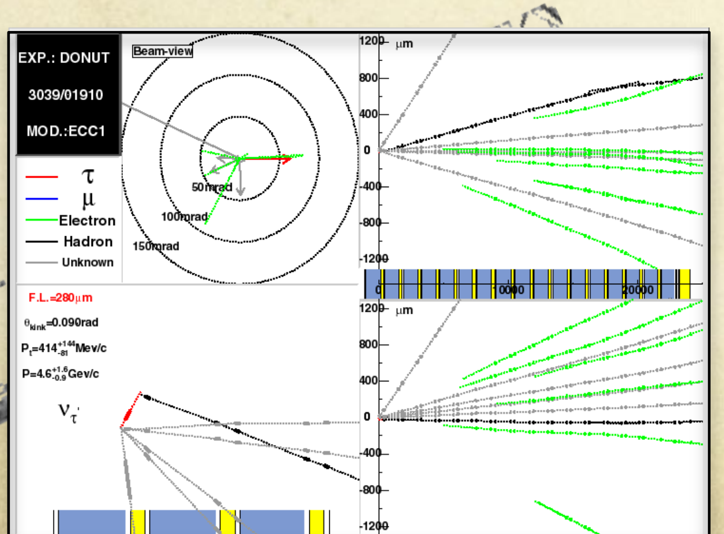


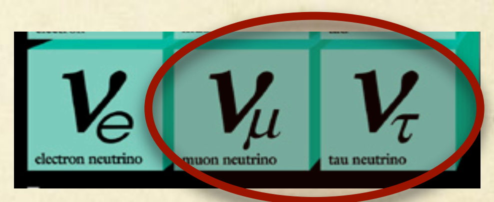
can see these

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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2. neutrinos produced at an accelerator 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?

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

An Aside : What took so long?

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

atomic mass unit

So to study neutrinos requires

intense neutrino sources

and

special detectors

2. neutrinos produced at an accelerator typically have a few GeV of energy

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

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

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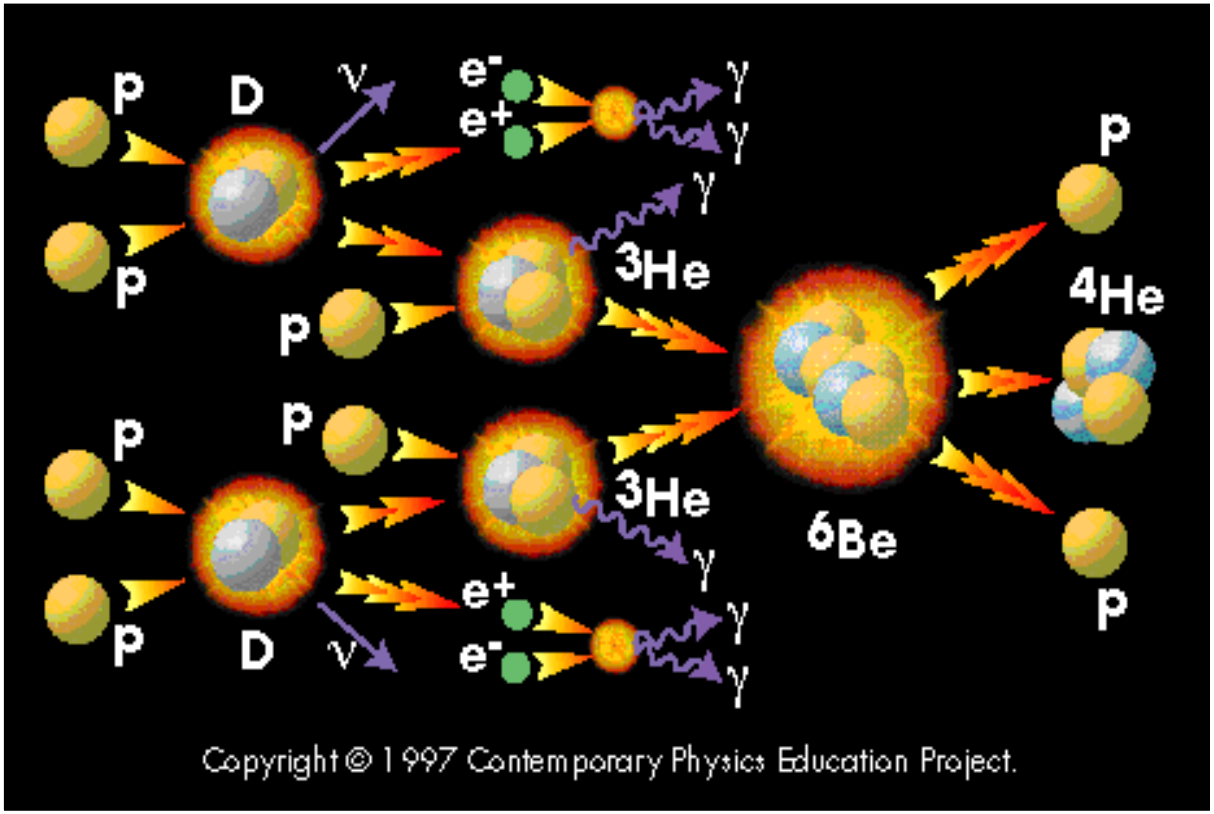
Neutrinos From the Cosmos

- the **Sun** produces huge numbers* of pure ν_e
  - the idea was that neutrinos would provide **a great probe of the complicated fusion processes** occuring deep inside the sun



*about 300,000,000,000,000,000 will pass through your body during this talk.

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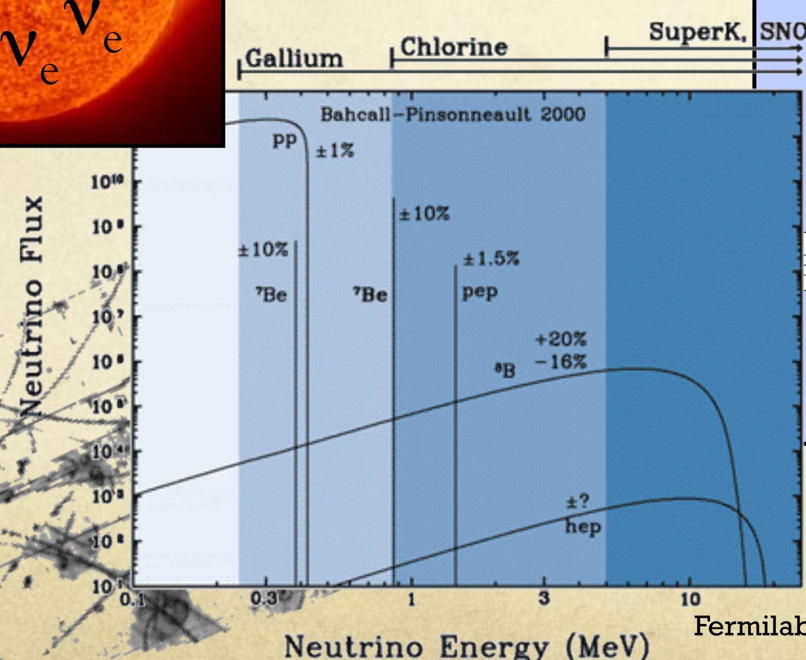
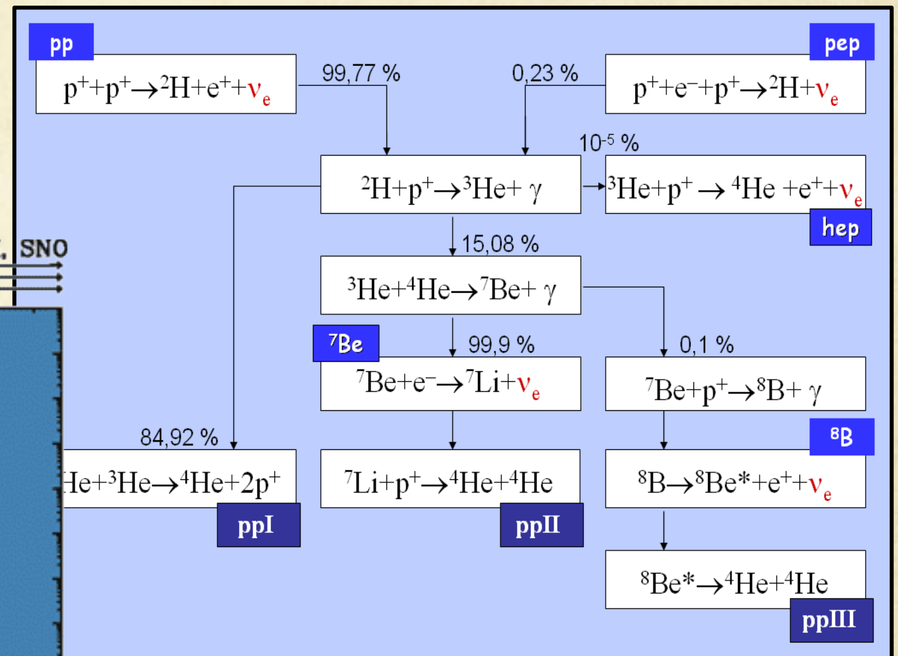
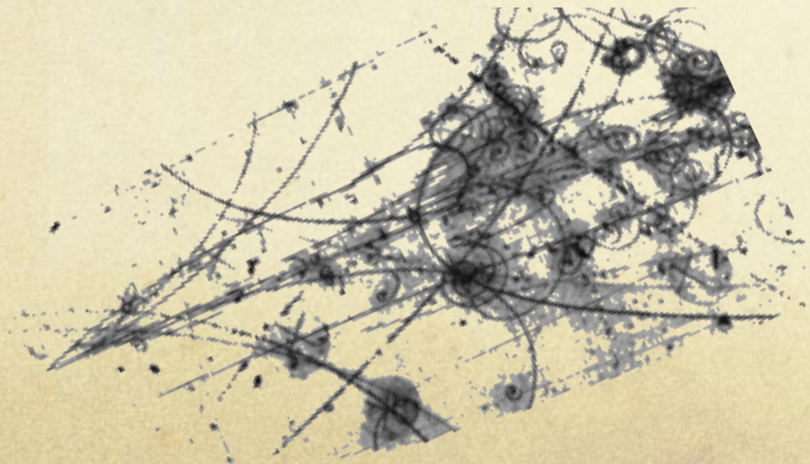
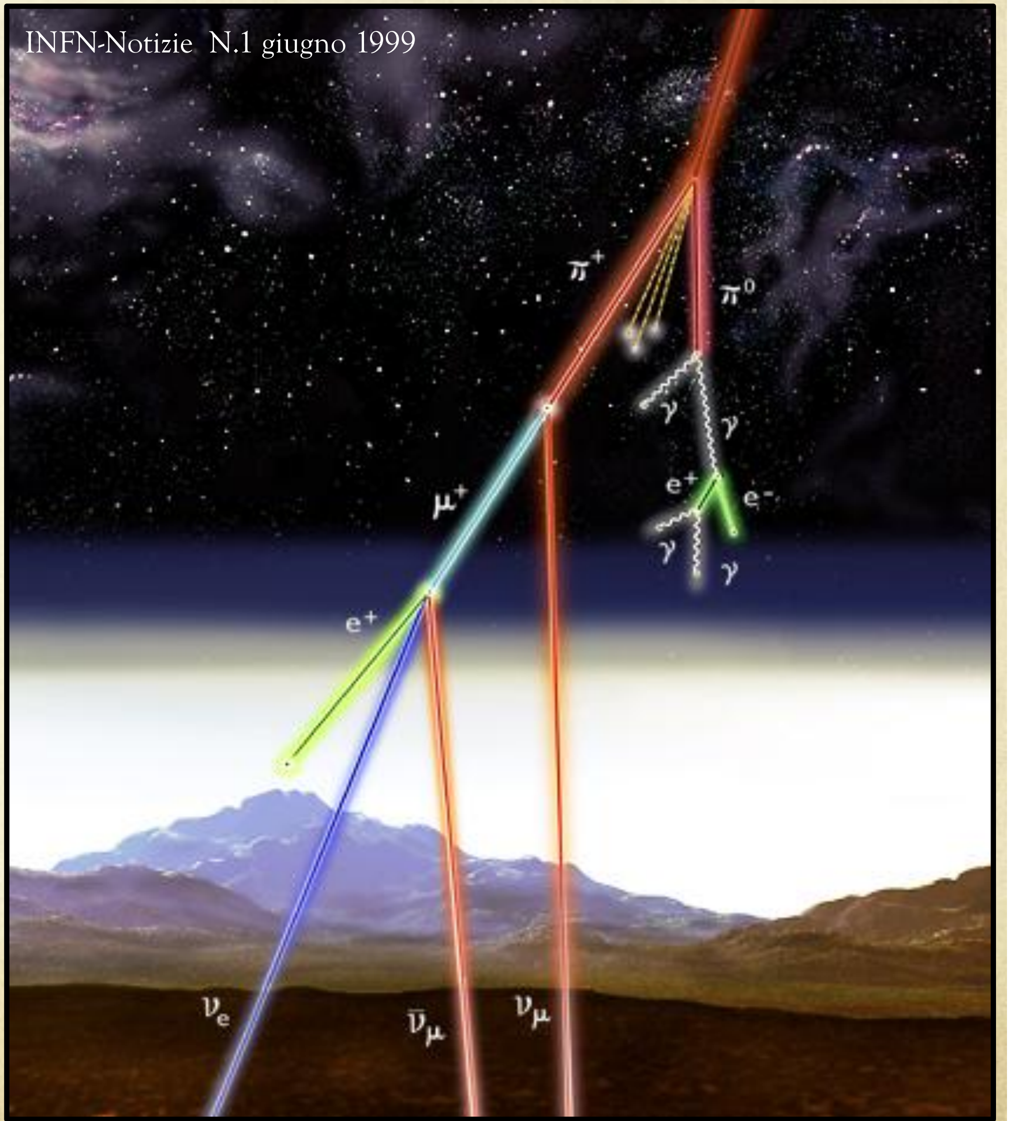




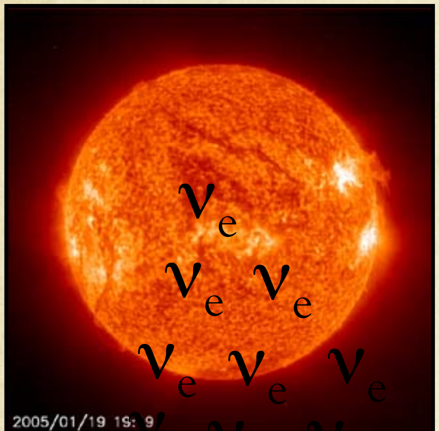
Neutrinos From the Cosmos

- neutrinos are produced in the atmosphere by cosmic rays colliding with air molecules
- should reach Earth with ν_μ and ν_e in a 2:1 ratio

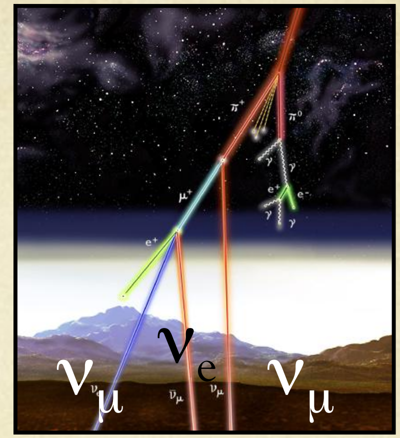


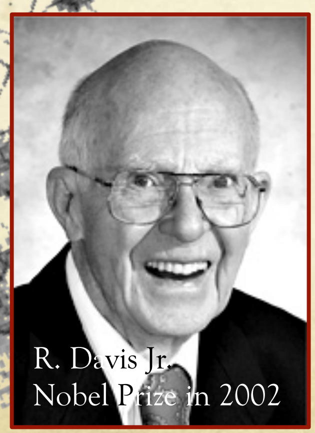


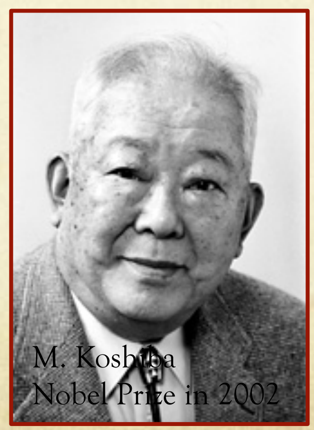
Let the Surprises Begin

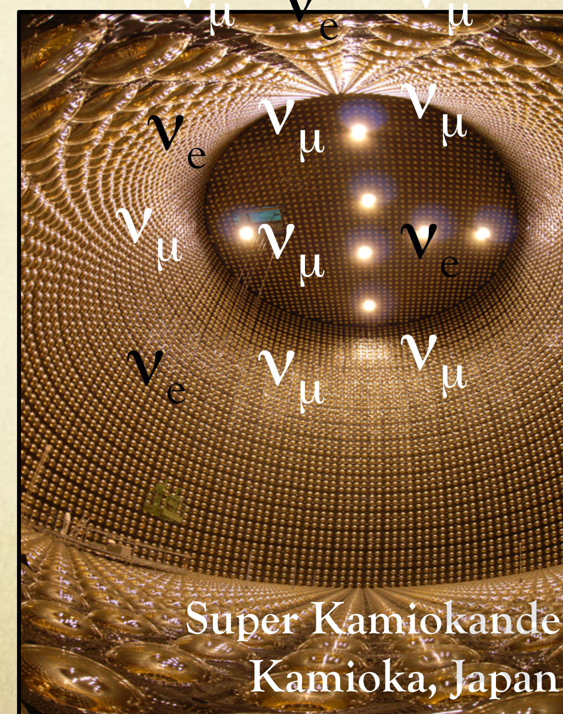


- **Only about 1/3 the expected number of ν_es from the sun were observed**
- **Less than the expected 2:1 $\nu_\mu:\nu_e$ ratio of atmospheric neutrinos was observed (~1.3:1)**









Another desperate remedy?

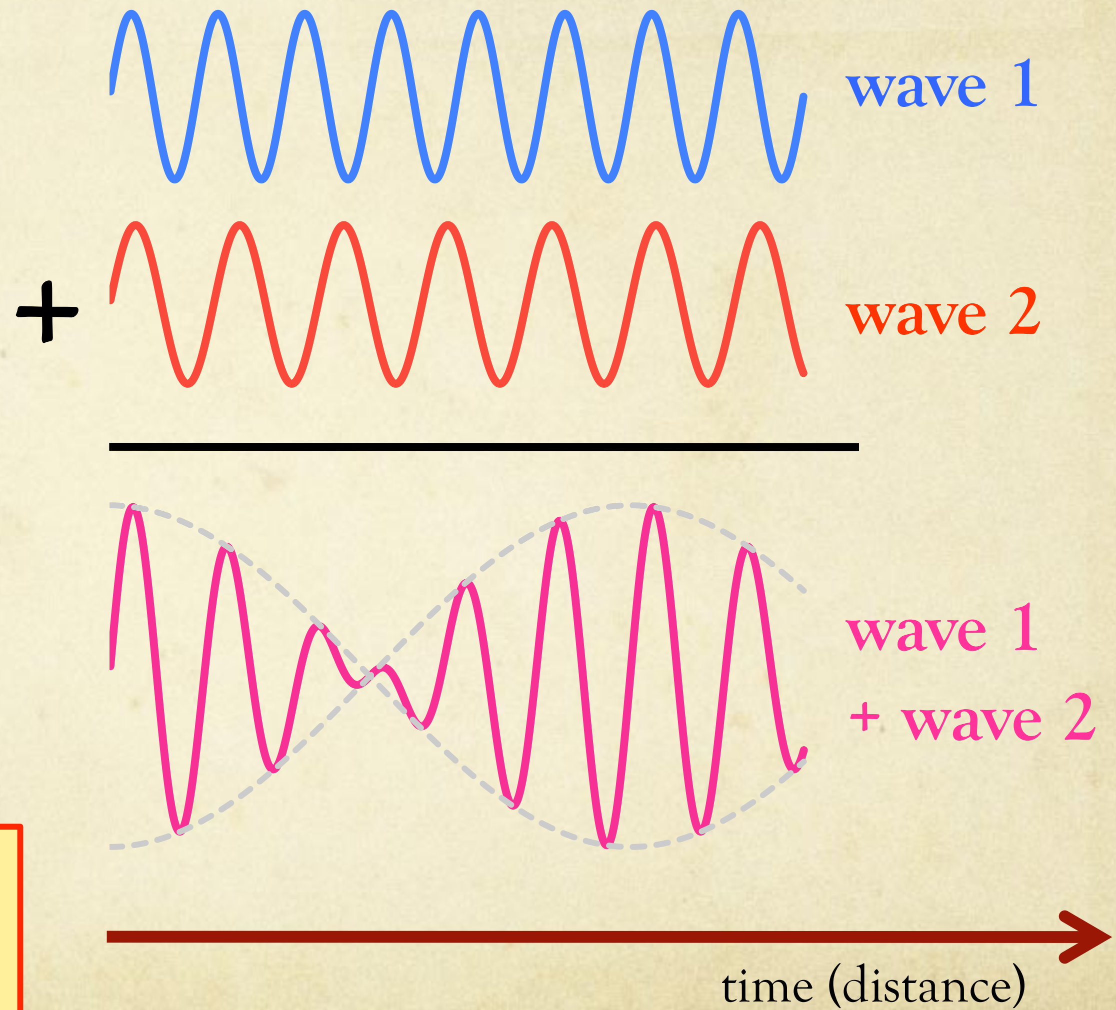
Where are the disappearing neutrinos disappearing to? Another dilema that persisted for more than two decades!

- 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

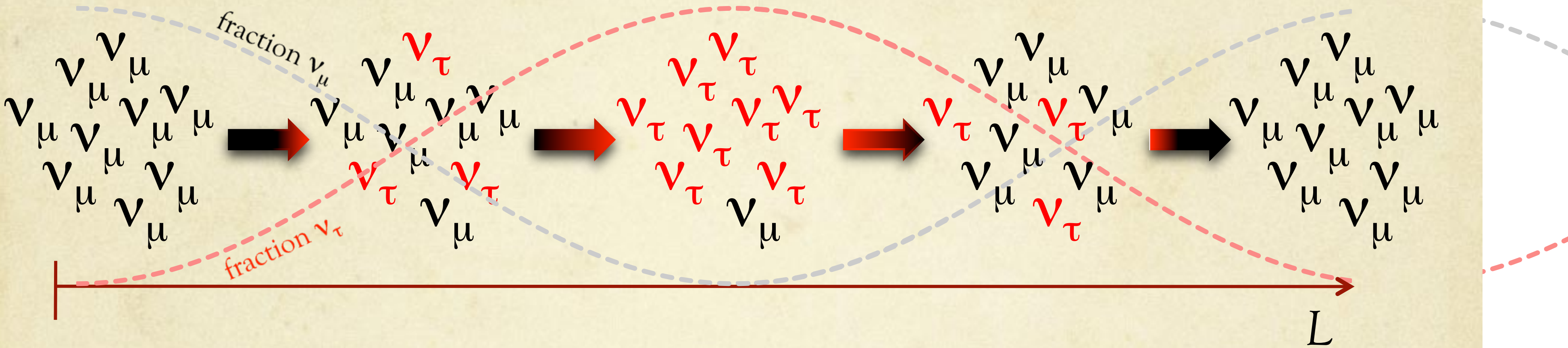
- Quantum Mechanics tells us that particles can be like waves and particle mass determines the frequency
- If neutrinos (ν_e, ν_μ, ν_τ) are actually composed of multiple such waves with different frequencies (different masses) . . .
- Then they can interfere like any waves can and change the neutrino's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



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

Neutrino Oscillations

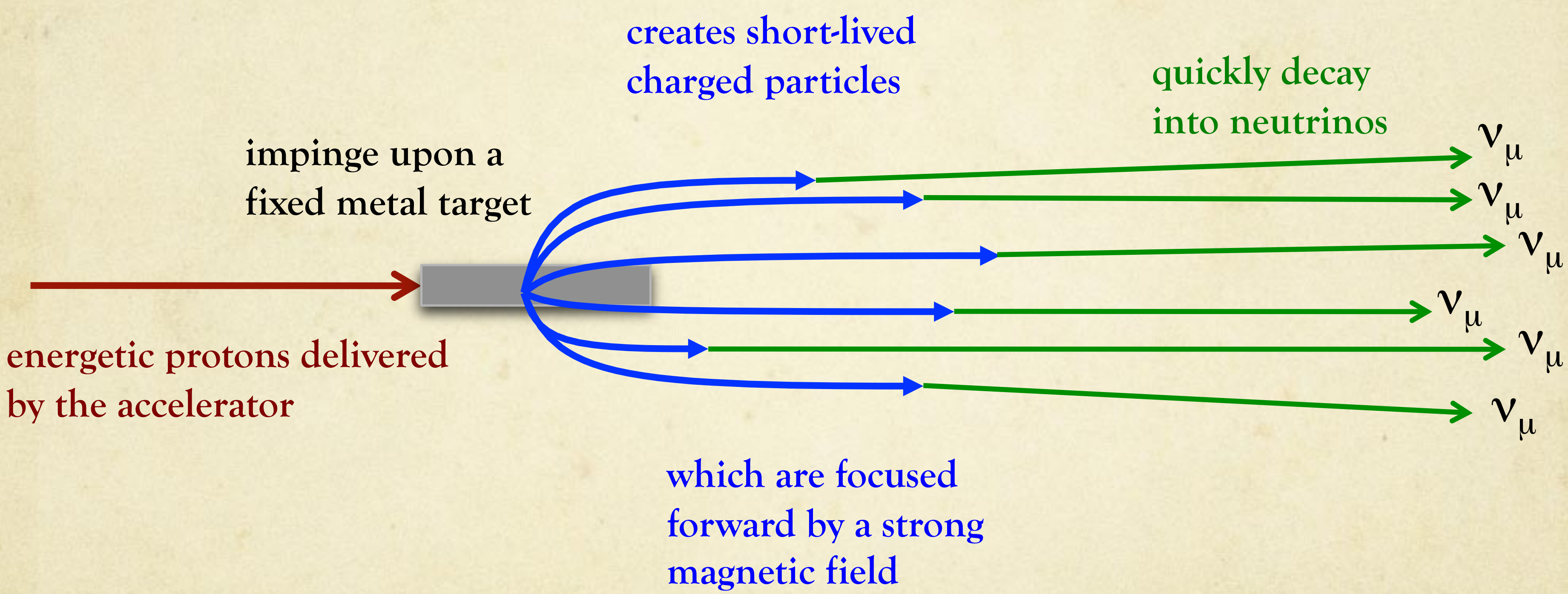
- This oscillation affects the ***probability*** that a neutrino is of a particular type as it travels



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

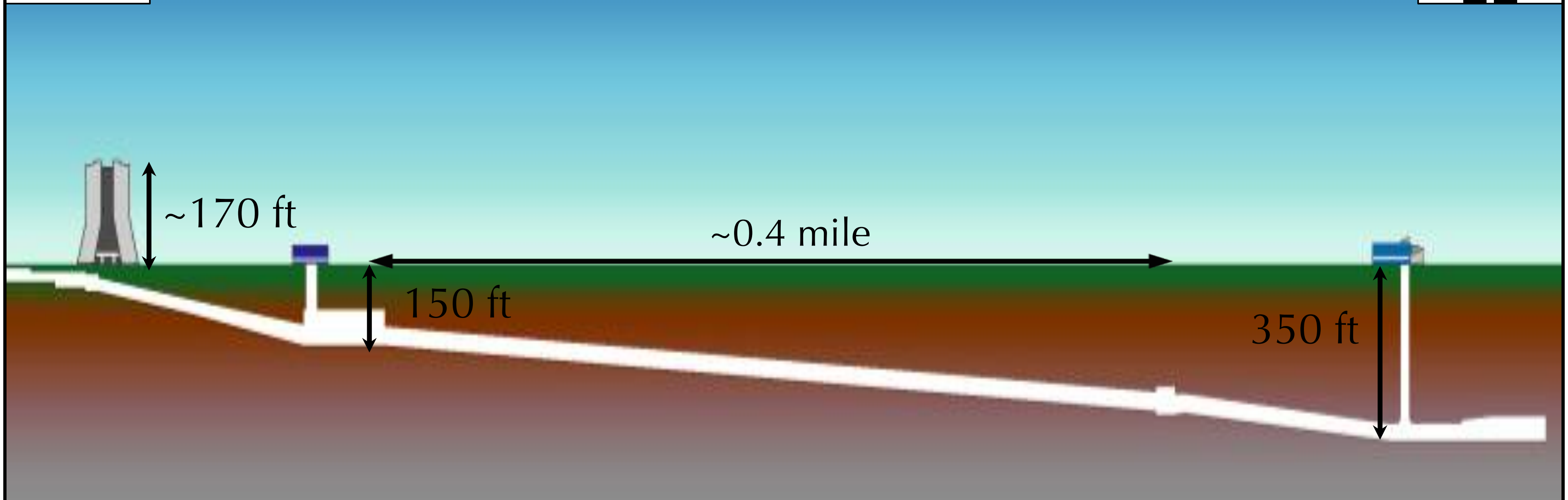
Building A Neutrino Beam

- Turns out, you can use an intense beam of protons to create an intense beam of neutrinos

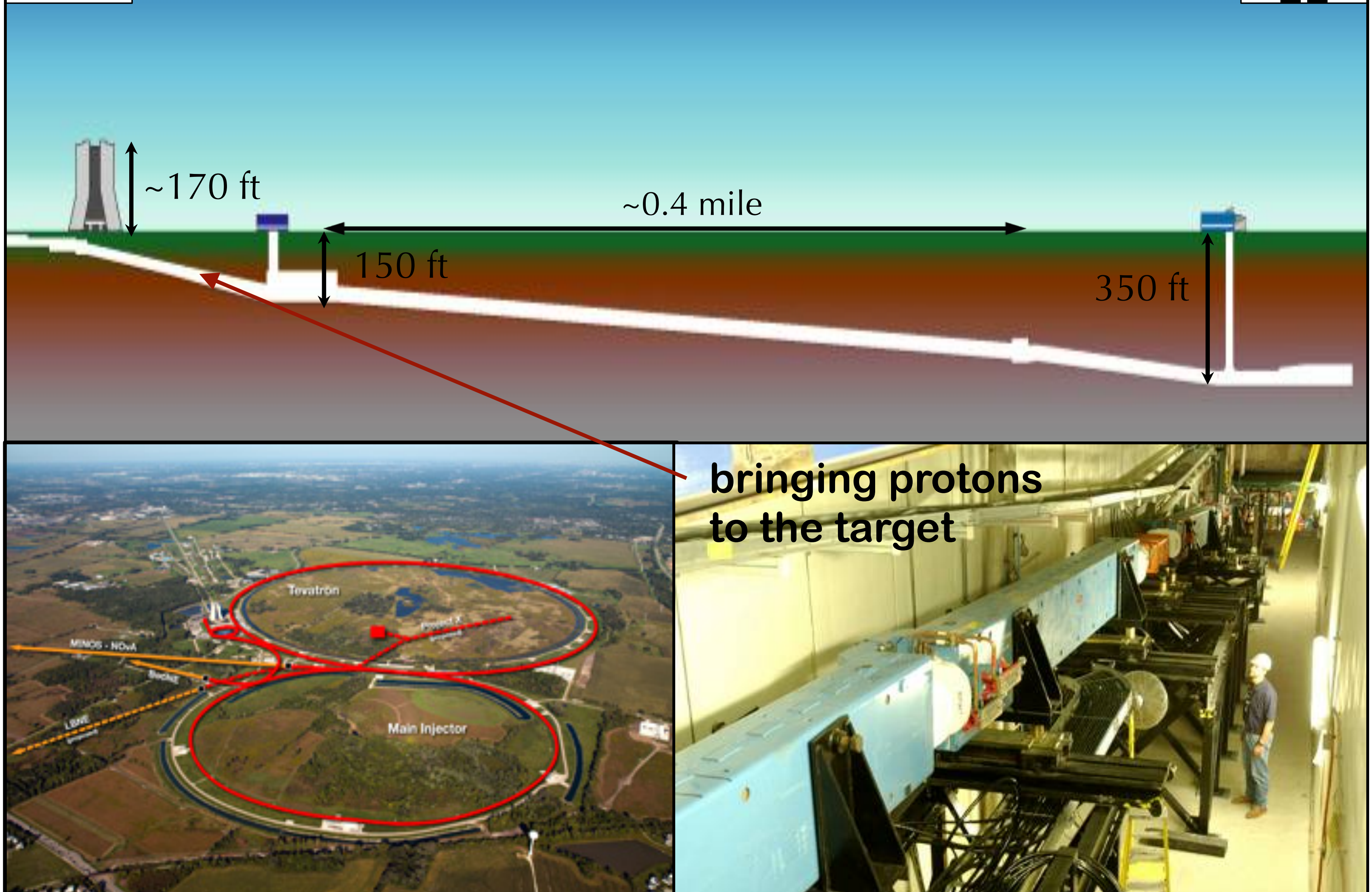


- In the last 10 years Fermilab has built two of the most intense neutrino sources in the world using its powerful proton accelerators in order to study neutrinos and oscillations
  - The Booster Neutrino Beam starts from 8 GeV protons from the Booster
  - The NuMI Neutrino Beam starts from 120 GeV protons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

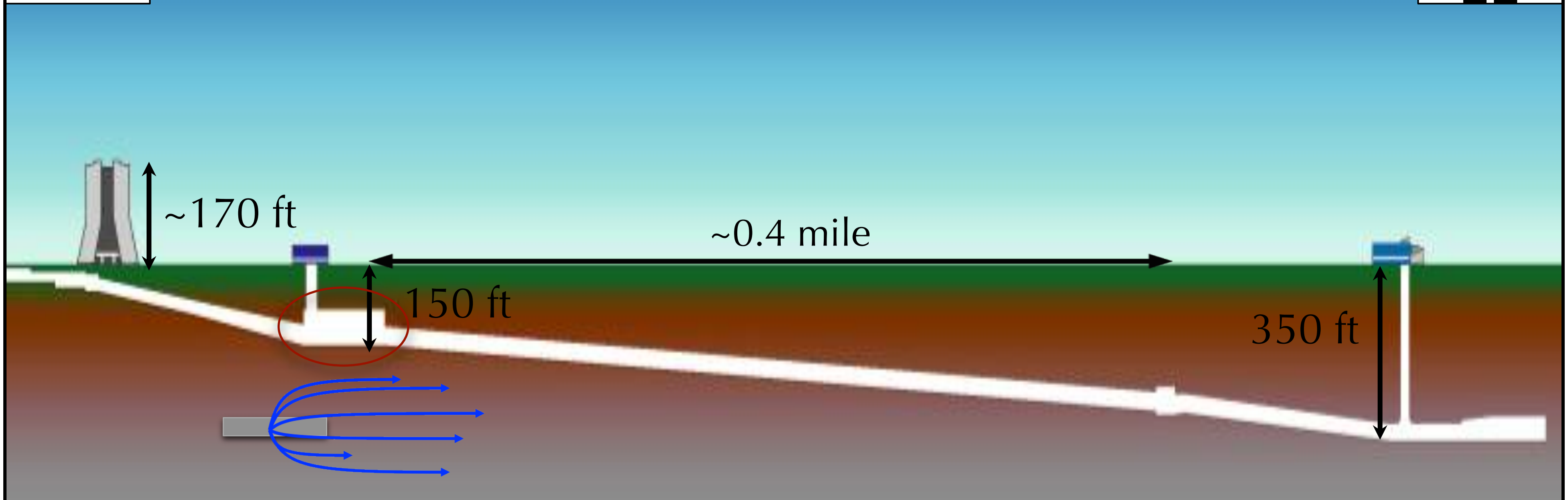
NuMI Neutrino Beam

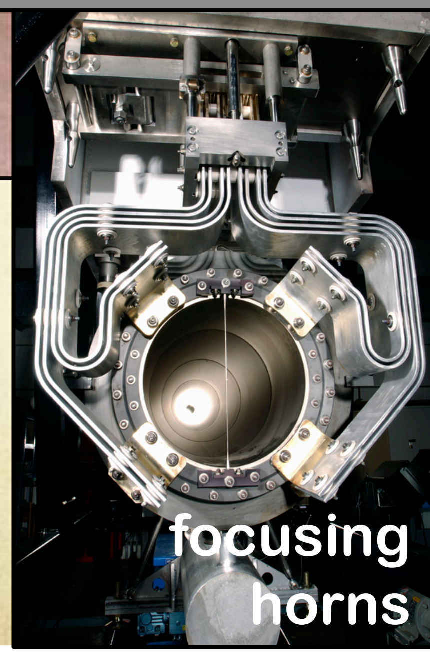


NuMI Neutrino Beam



NuMI Neutrino Beam

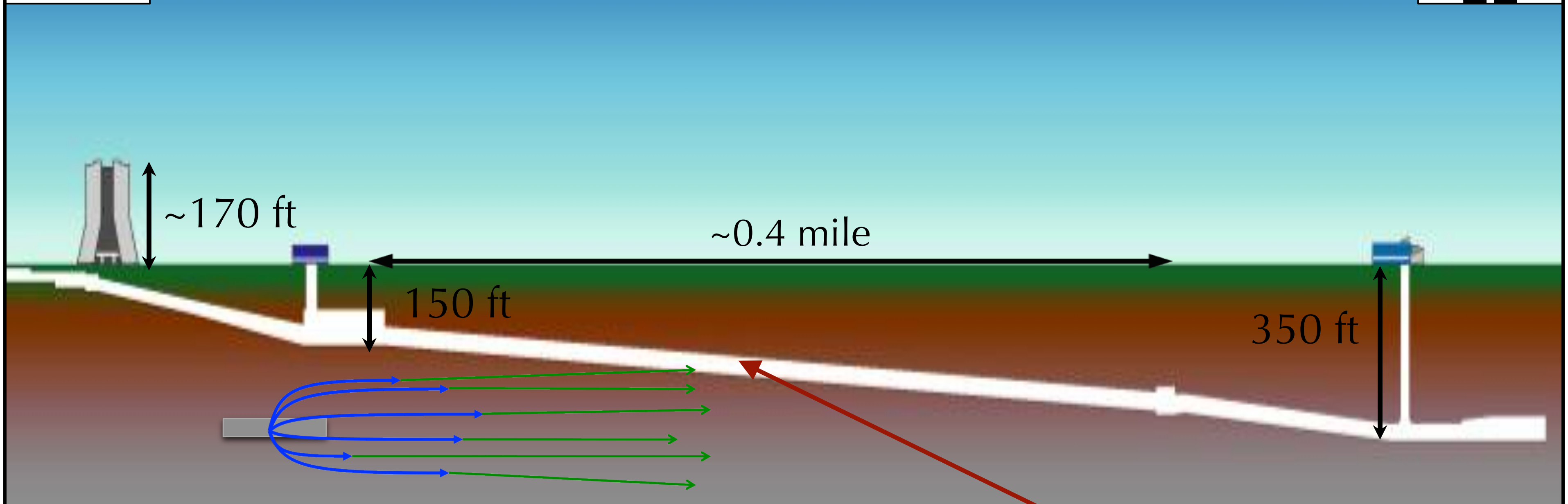


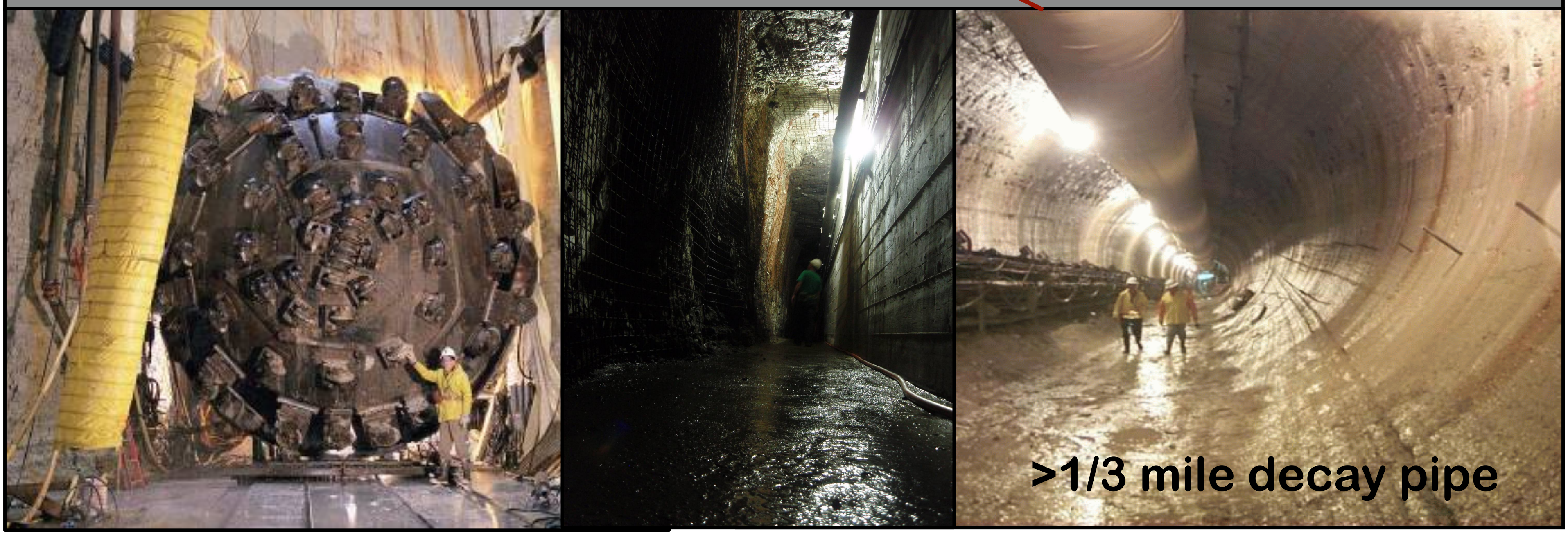


- Graphite target is hit with ~30 trillion protons every 2 seconds 24 hours a day. That's about 350,000 Watts of power.

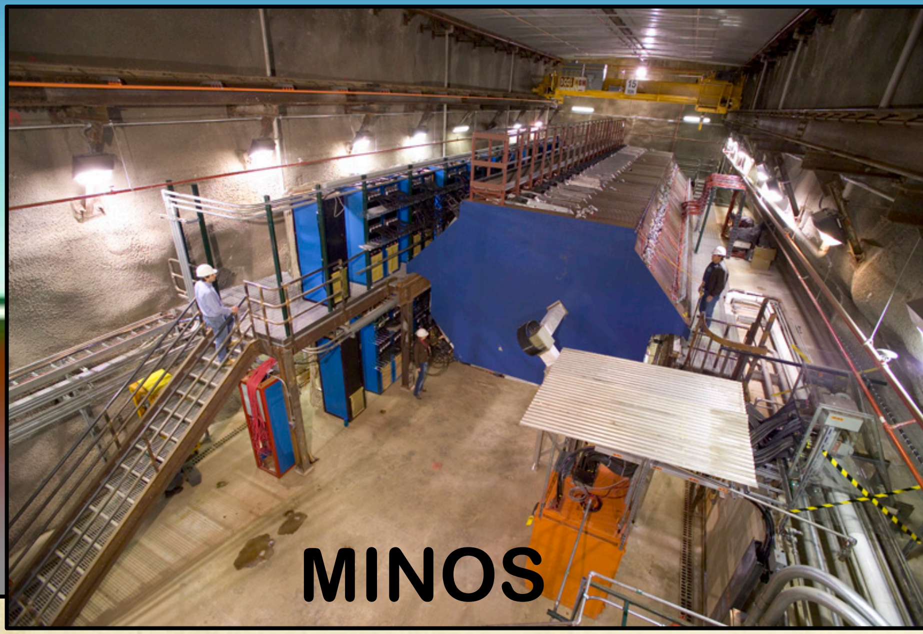
- 2 aluminum focusing "horns" are pulsed with 200,000 Amps of current every 2 seconds to create the magnetic field

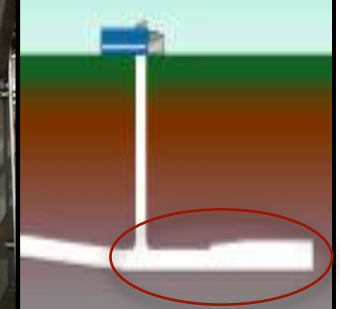
NuMI Neutrino Beam

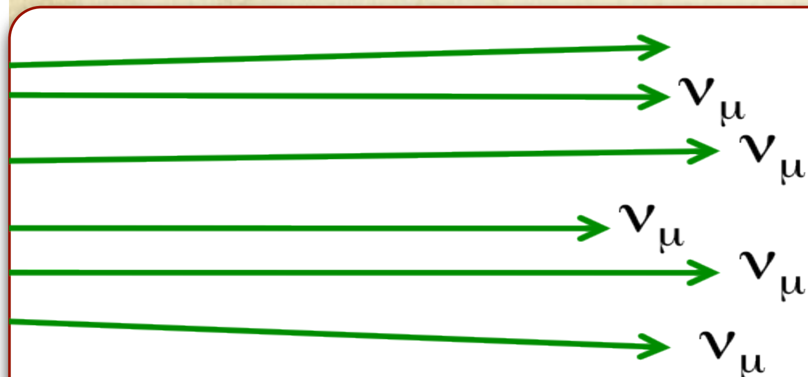




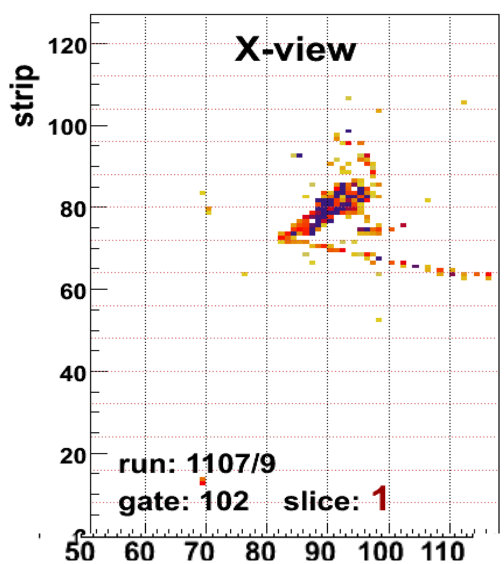
NuMI Neutrino Beam

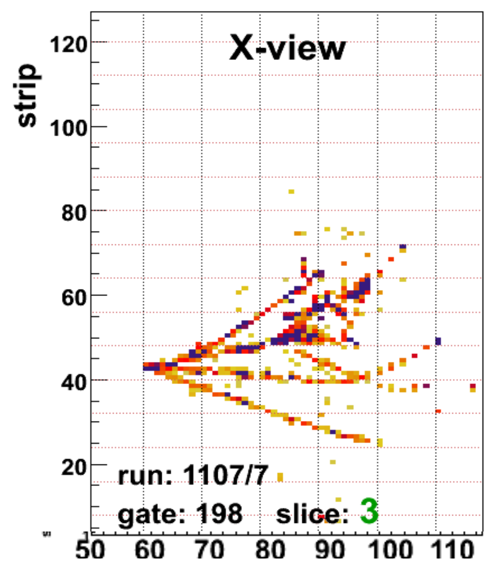




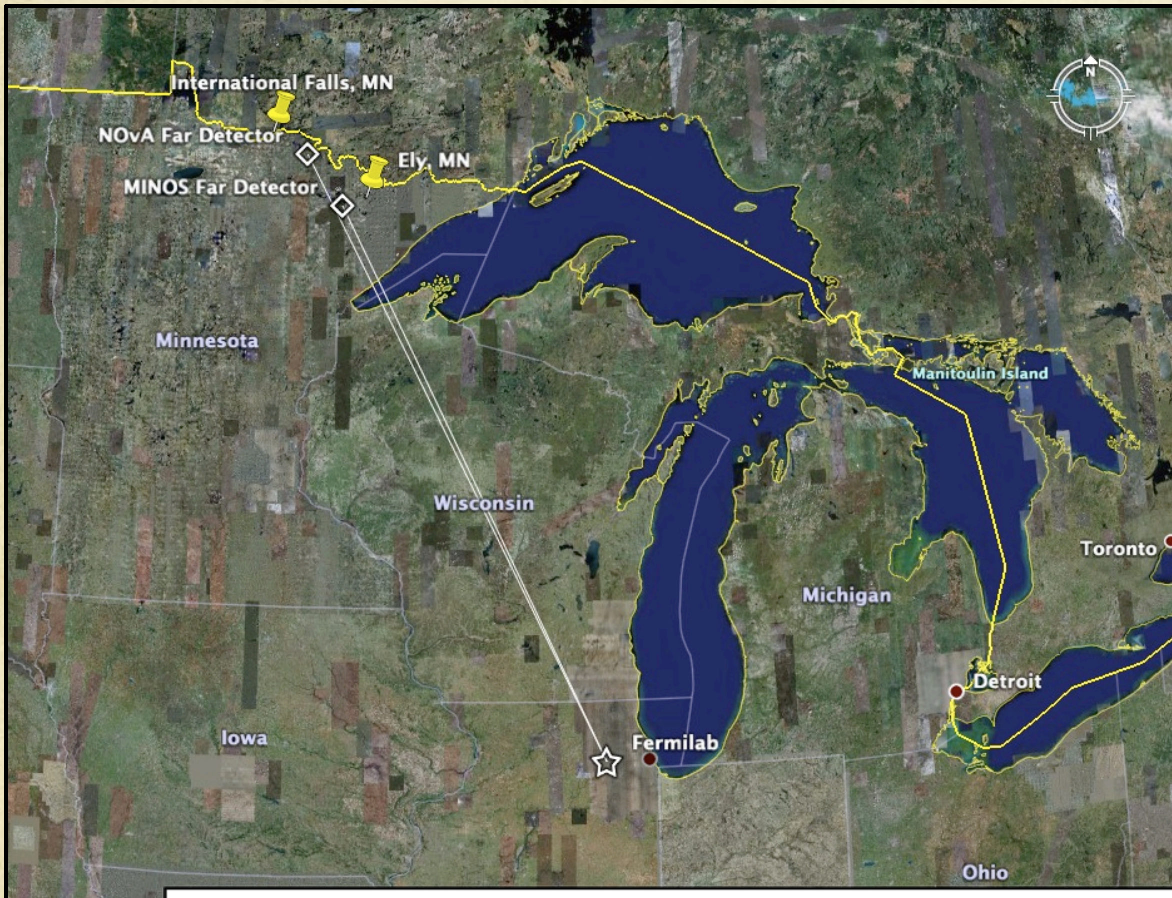


- A few neutrinos interact spectacularly in the detectors. Of course, most pass right by…

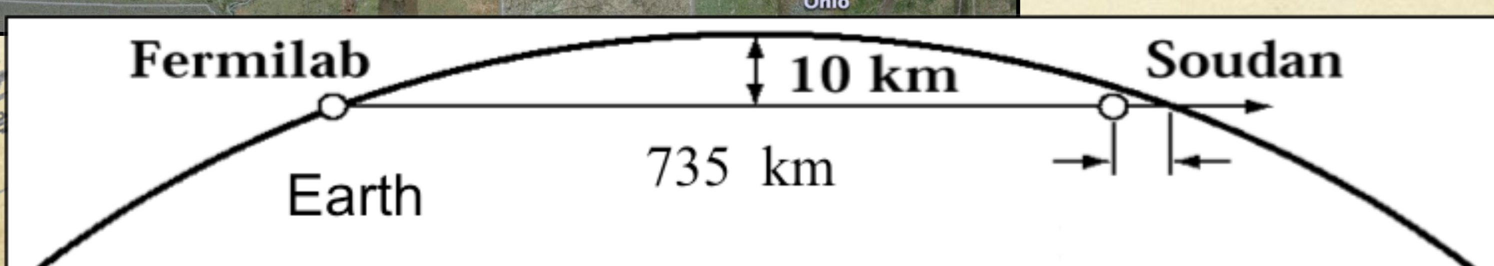




Where Are They Headed? North!

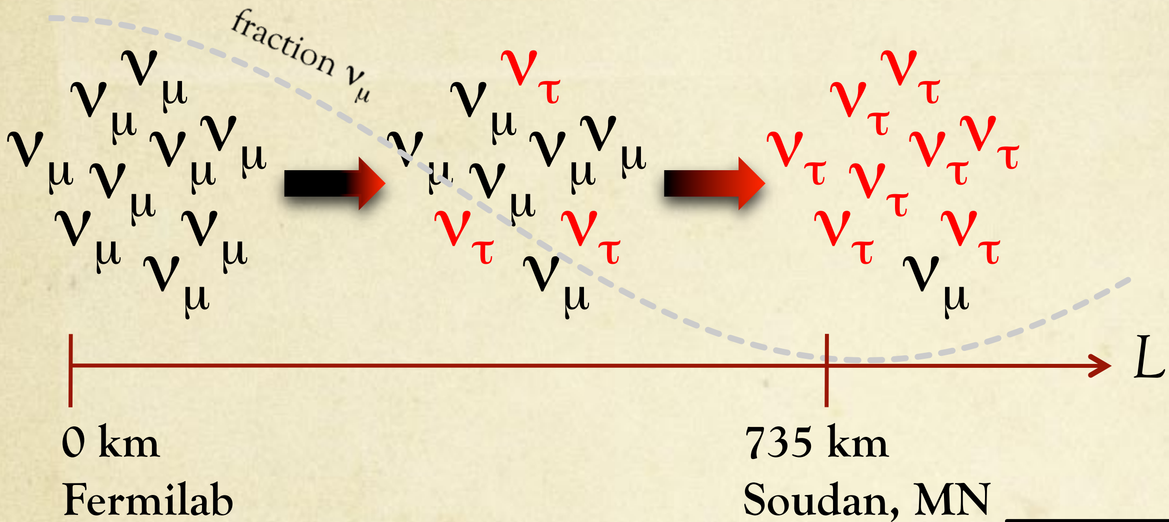


- The neutrinos make the 450 mile journey from Fermilab to northern Minnesota in 1/400th of a second
- No tunnel required. recall, the Earth is like air to a neutrino!
- By comparing the number of muon neutrinos at both locations, one can look for them to disappear



Main Injector Neutrino Oscillation Search

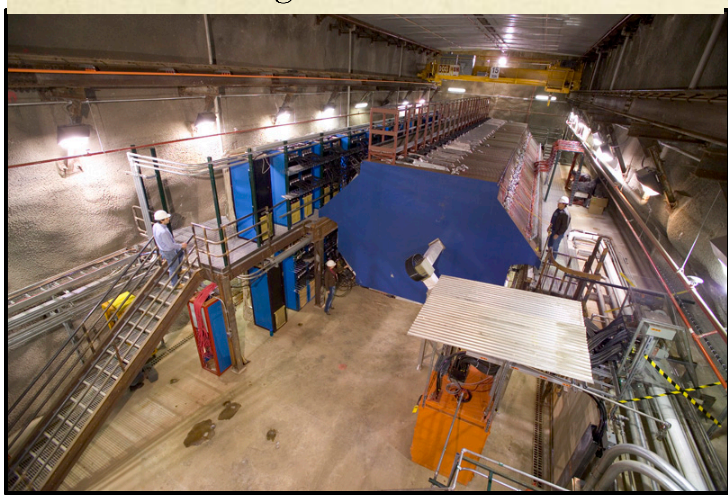
is a **two detector, long baseline** neutrino oscillation experiment.



The MINOS Experiment

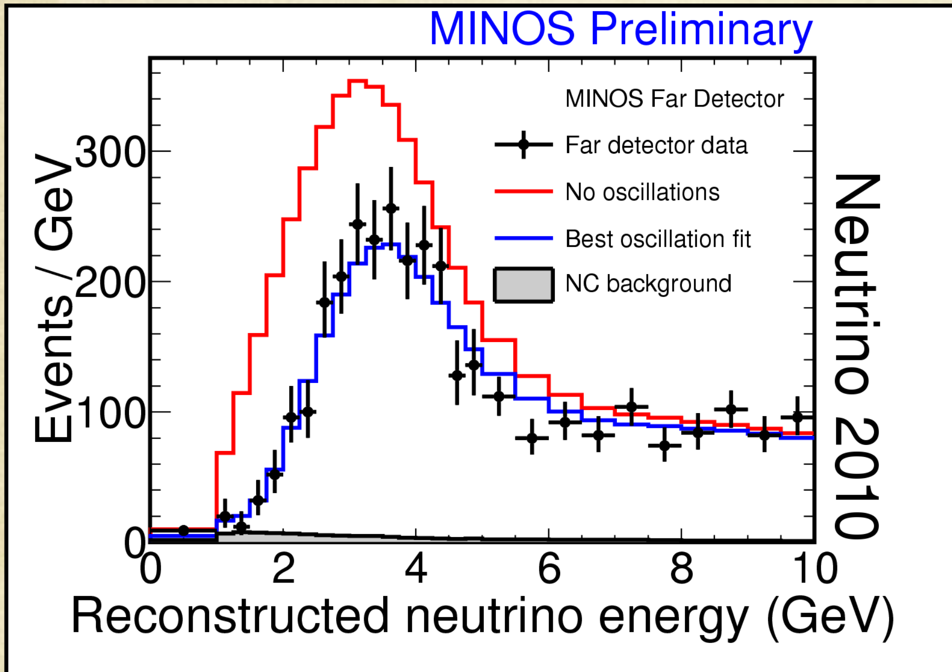
5400 ton neutrino detector 716 meters underground at the Soudan iron mine in Soudan, MN

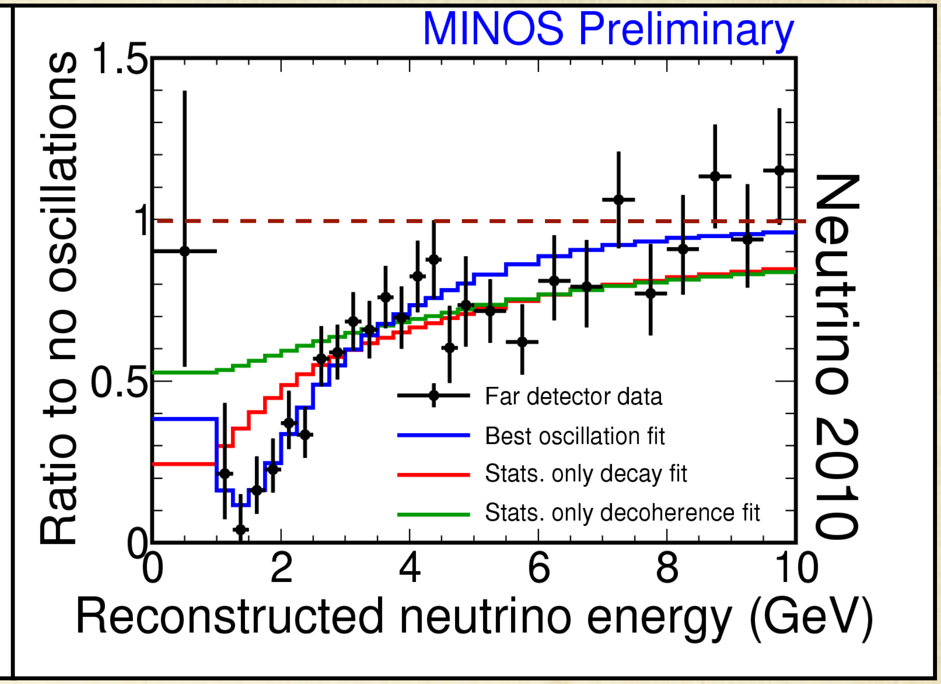
1000 ton neutrino detector 100 meters underground at Fermilab



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 currently 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?

1 sunflower seed is a trillion trillion (10^24) protons

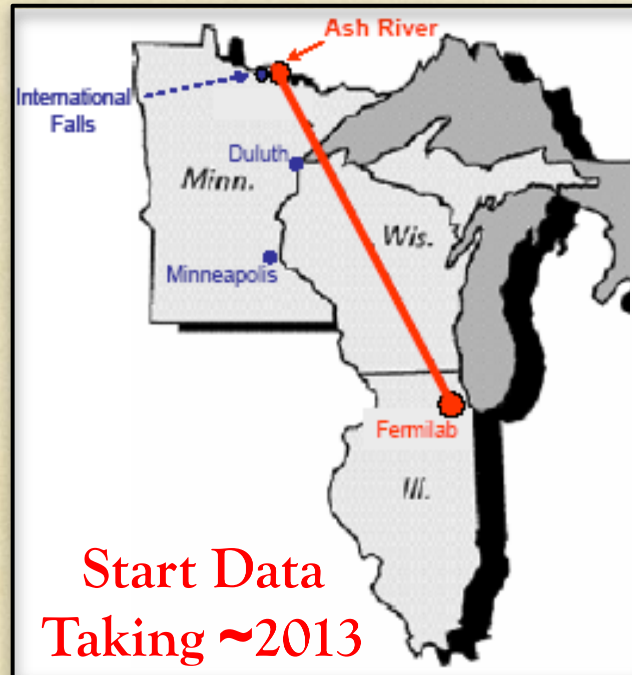
mass of electron
≈ 1/2000th mass of proton

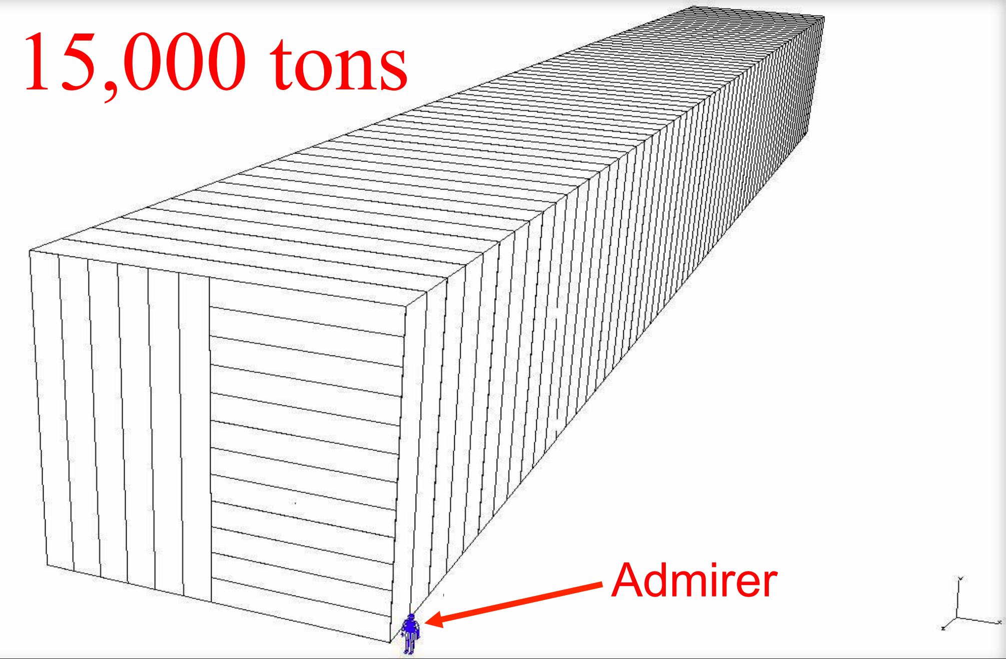
mass of neutrino
< 1/1,000,000th mass of electron

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
- To continue this search we will need a next generation of powerful neutrino beams and massive detectors

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 : The NOνA Experiment

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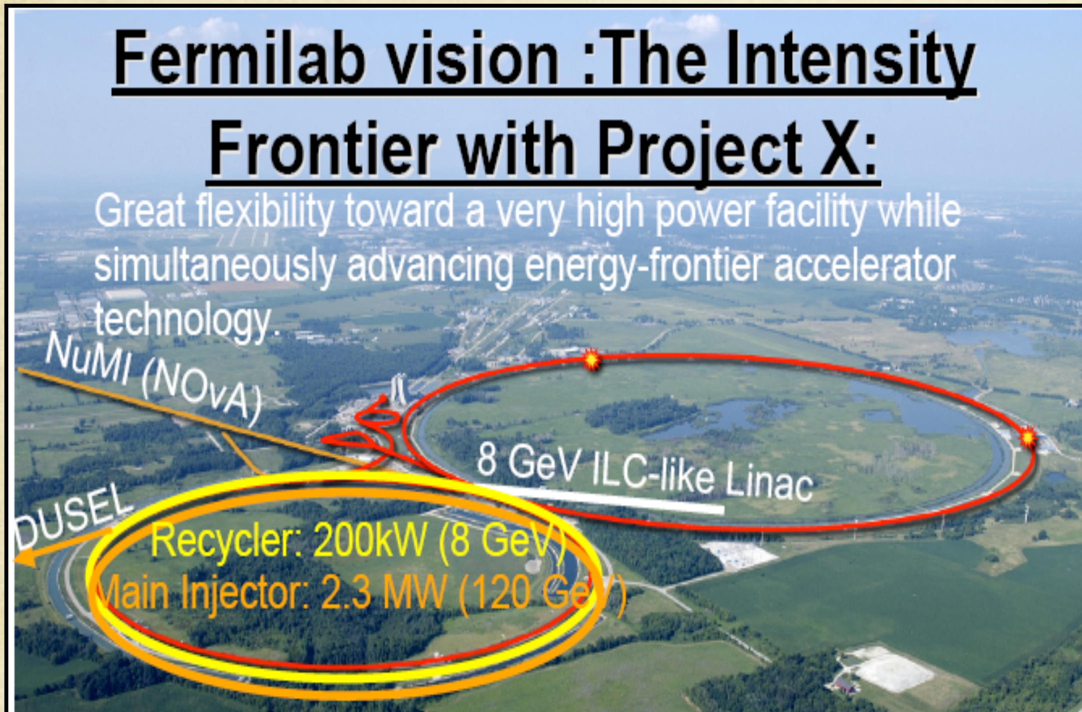
Future : The NOνA Experiment

Future : Project-X to DUSEL



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

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

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
  - many, many efforts I did not have the time to discuss
- 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)