

The Story of the Elusive Neutrino

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Fermi National Accelerator Laboratory



Fermilab

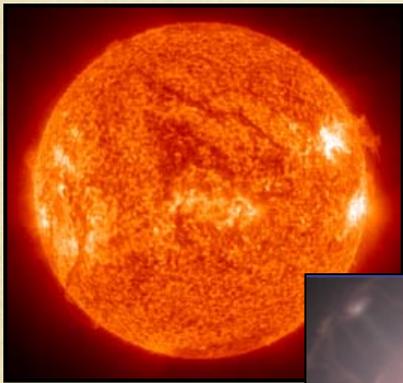
Fermilab

Ask-a-Scientist

December 5, 2010

Neutrinos . . .

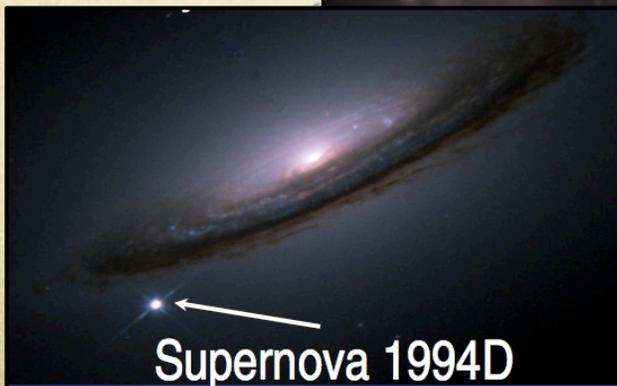
Are the most abundant known matter particles in the Universe, outnumbering all other particles by a factor of a **BILLION**



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 / cm³ 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?

PERIODIC TABLE OF THE ELEMENTS
<http://www.ktf-split.hr/periodni/en/>

PERIOD 1 2 3 4 5 6 7

GROUP I IA 2 IIA 3 IIIB 4 IVB 5 VB 6 VIB 7 VIIB 8 VIIIIB 9 10 IB 11 IIB 12 IIIB 13 IIIA 14 IVA 15 VA 16 VIA 17 VIIA 18 VIIIA

RELATIVE ATOMIC MASS (A)

GROUP IUPAC **GROUP CAS**

ATOMIC NUMBER **SYMBOL** **ELEMENT NAME**

Legend:
 Metal (blue), Alkali metal (light blue), Alkaline earth metal (yellow), Transition metals (orange), Semimetal (red), Nonmetal (green), Chalcogens element (light green), Halogens element (dark green), Noble gas (grey), Lanthanide (pink), Actinide (purple)
STANDARD STATE (25 °C, 101 kPa):
 Ne - gas, Fe - solid, Ga - liquid, Hg - synthetic

LANTHANIDE
 57 138.91 La Lanthanum, 58 140.12 Ce Cerium, 59 140.91 Pr Praseodymium, 60 144.24 Nd Neodymium, 61 (145) Pm Promethium, 62 150.36 Sm Samarium, 63 151.96 Eu Europium, 64 157.25 Gd Gadolinium, 65 158.93 Tb Terbium, 66 162.50 Dy Dysprosium, 67 164.93 Ho Holmium, 68 167.26 Er Erbium, 69 168.93 Tm Thulium, 70 173.04 Yb Ytterbium, 71 174.97 Lu Lutetium

ACTINIDE
 89 (227) Ac Actinium, 90 232.04 Th Thorium, 91 231.04 Pa Protactinium, 92 238.03 U Uranium, 93 (237) Np Neptunium, 94 (244) Pu Plutonium, 95 (243) Am Americium, 96 (247) Cm Curium, 97 (247) Bk Berkelium, 98 (251) Cf Californium, 99 (252) Es Einsteinium, 100 (257) Fm Fermium, 101 (258) Md Mendelevium, 102 (259) No Nobelium, 103 (262) Lr Lawrencium

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
 Relative atomic mass is shown with five significant figures. For elements with no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
 However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (advvar@netlinx.com)

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

What is Particle Physics?

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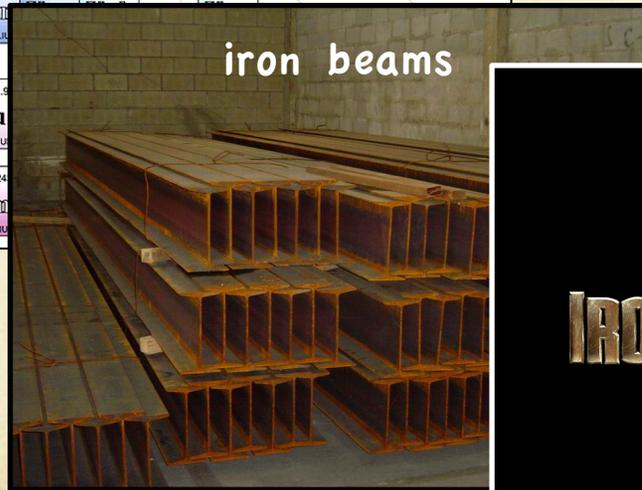
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4	4	4	4	10	18	18	18	10	8	6	10	18	18	10	8	6	10	18	18
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6	6	6	6	10	18	18	18	10	8	6	10	18	18	10	8	6	10	18	18
7	7	7	7	10	18	18	18	10	8	6	10	18	18	10	8	6	10	18	18

Legend:
 Metal (blue), Semimetal (orange), Nonmetal (green)
 1 Alkali metal, 2 Alkaline earth metal, 3 Transition metals, 4 Lanthanide, 5 Actinide
 16 Chalcogens element, 17 Halogens element, 18 Noble gas
 STANDARD STATE (25 °C, 101 kPa):
 Ne - gas, Ga - liquid, Fe - solid, Ts - synthetic

LANTHANIDE:
 57 La, 58 Ce, 59 Pr, 60 Nd, 61 Pm, 62 Sm, 63 Eu, 64 Gd, 65 Tb, 66 Dy, 67 Ho, 68 Er, 69 Tm, 70 Yb, 71 Lu

ACTINIDE:
 89 Ac, 90 Th, 91 Pa, 92 U, 93 Np, 94 Pu, 95 Am, 96 Cm, 97 Bk, 98 Cf, 99 Es, 100 Fm, 101 Md, 102 No, 103 Lr

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What is Particle Physics?

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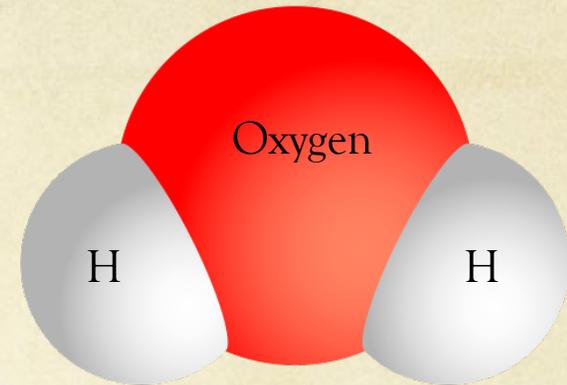
GROUP I II III IV V VI VII VIII
 PERIOD 1 2 3 4 5 6 7

RELATIVE ATOMIC MASS (A)
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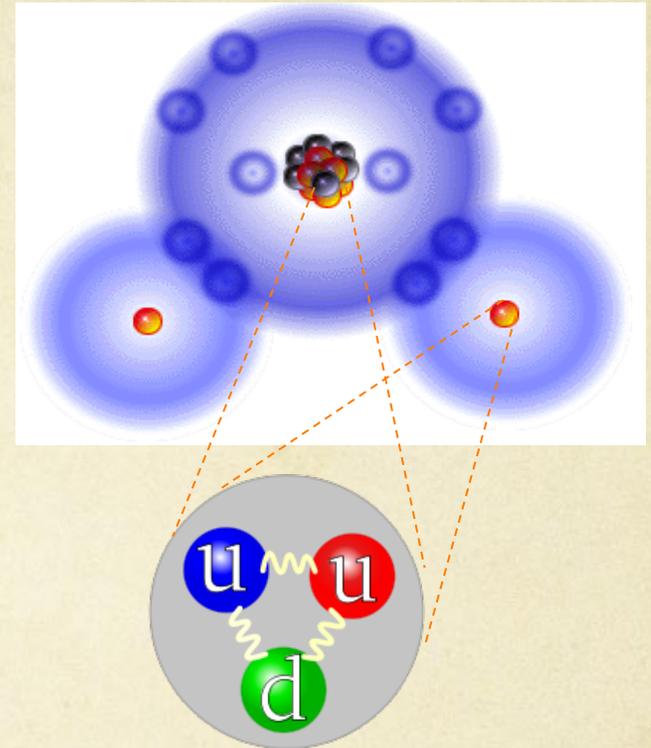
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995	996	997	998	999	1000	1001	1002

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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**



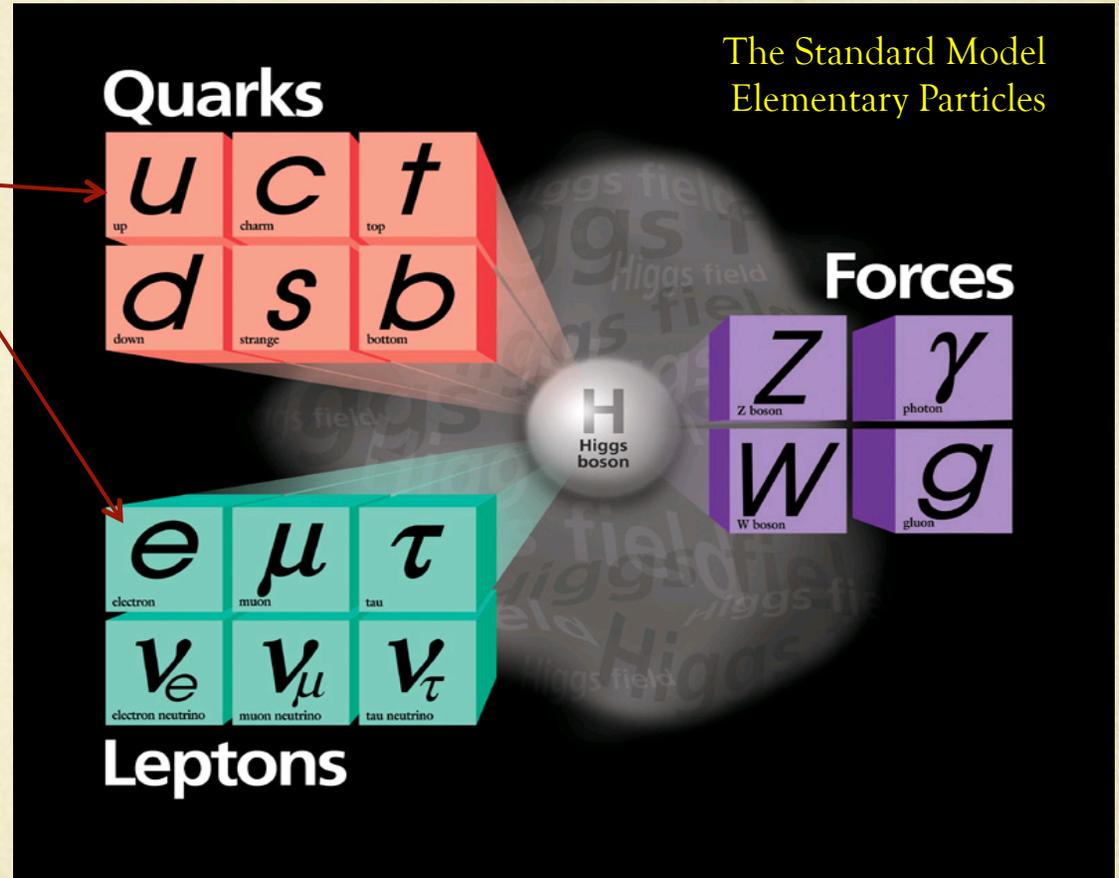
Standard Model of Particle Physics

○ 12 matter particles

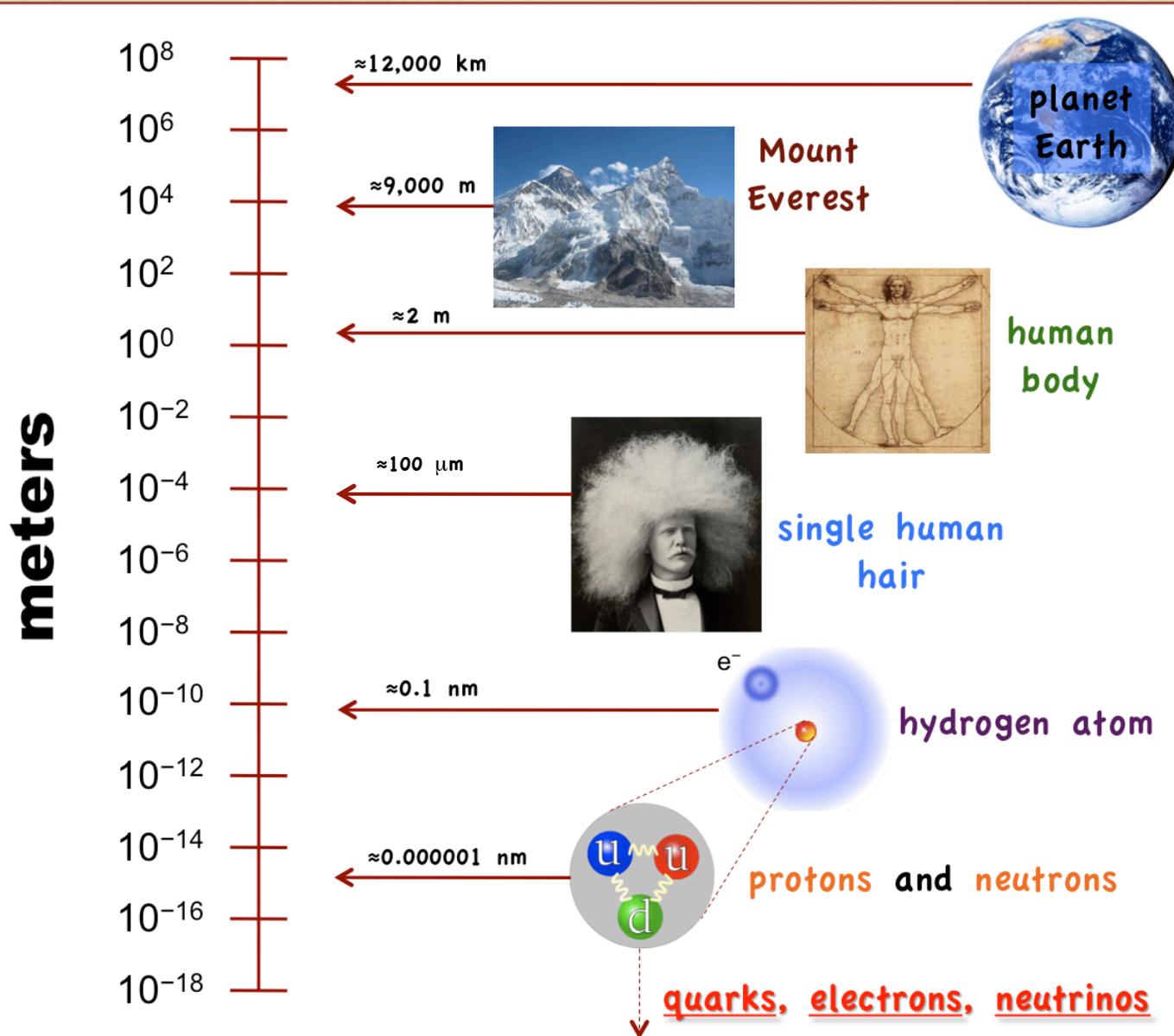
- **6 quarks**
- **6 leptons**
- these 12 building blocks make up all the varieties of “normal” matter in the Universe

○ 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?



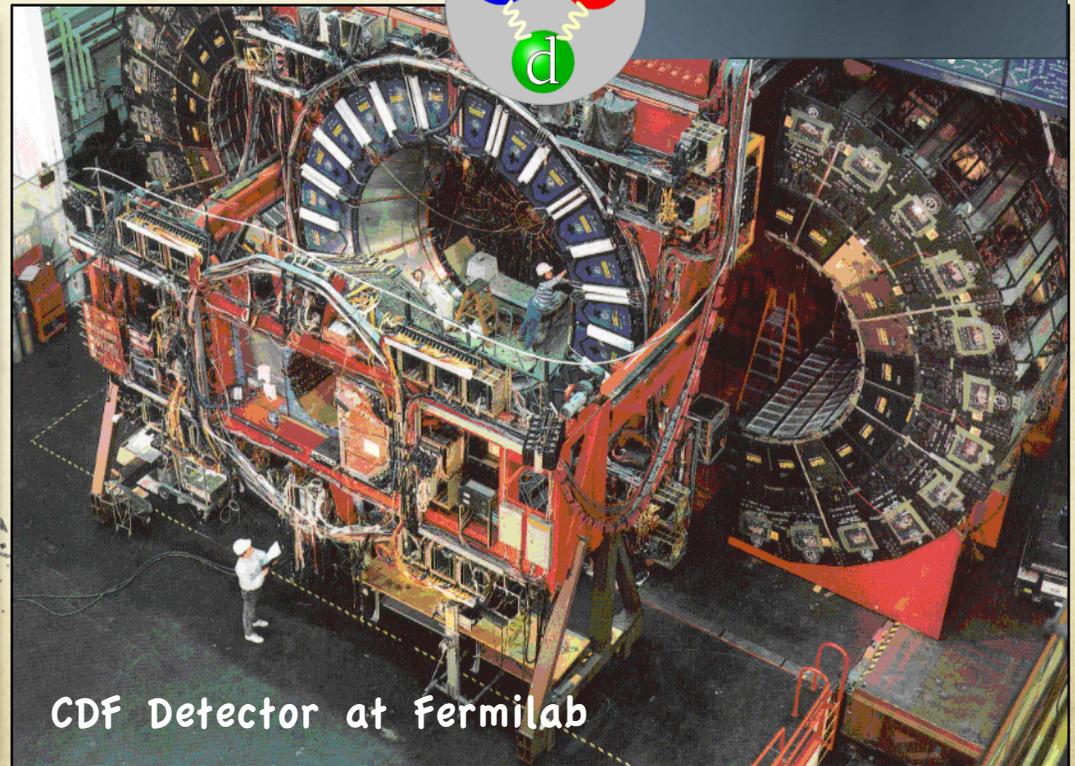
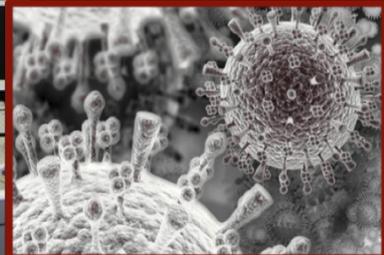
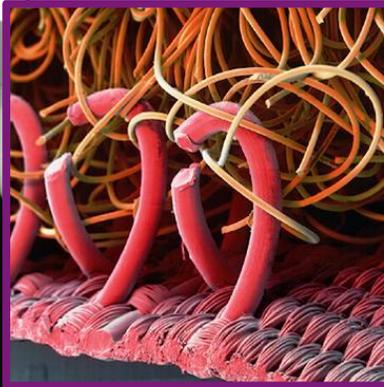
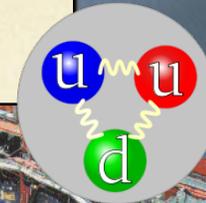
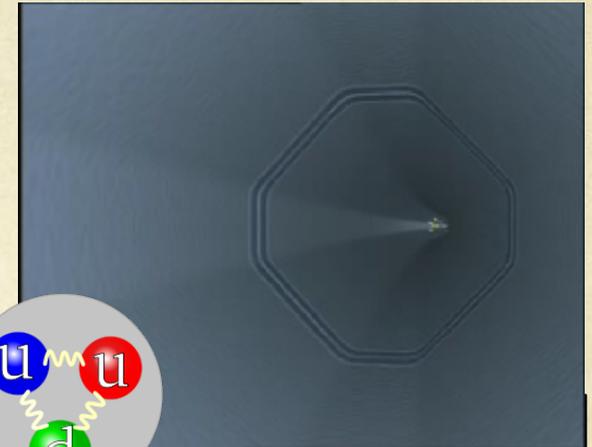
Each “order of magnitude” changes the value by a factor of 10, so the scale to the left represents a factor of $10^{26} =$
 100,000,000,000,000,000,000,000,000

A proton is to one human hair AS one human hair is to the diameter of the Earth

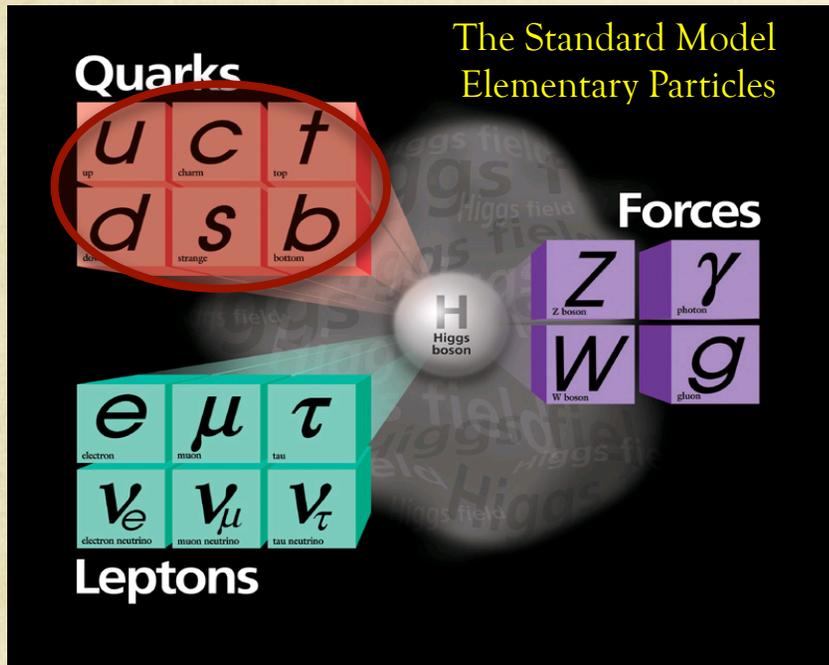
Seeing the Very Very Very Small



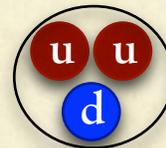
The great cosmic joke is that the smaller the object you want to probe, the bigger your “microscope” must be!!



Quarks . . .

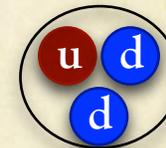


- Interact with other particles via the **strong** force, the **weak** force and the **electromagnetic** force
- Have **fractional electric charge** (+2/3 top row, -1/3 bottom)
- Strong force is attractive between quarks and holds them together in **pairs** or **triplets**



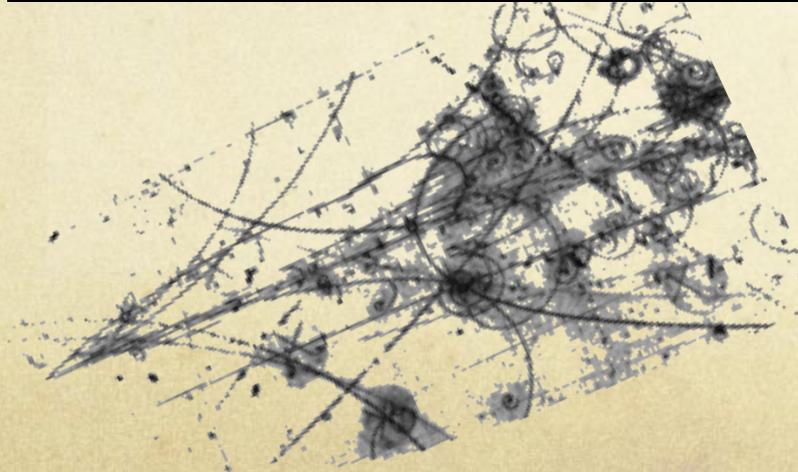
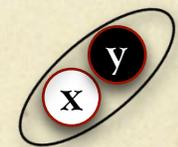
proton

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



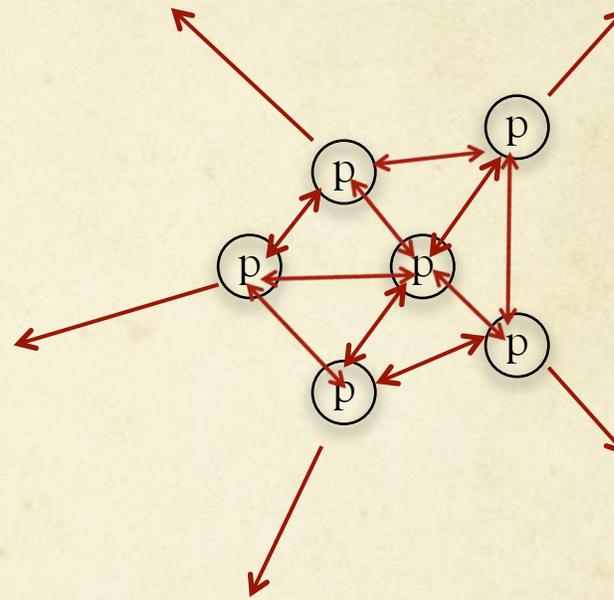
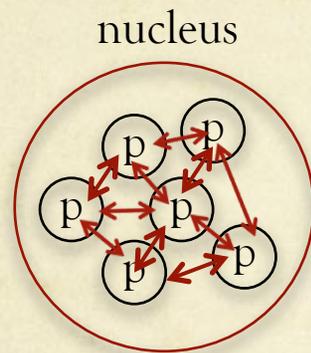
neutron

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



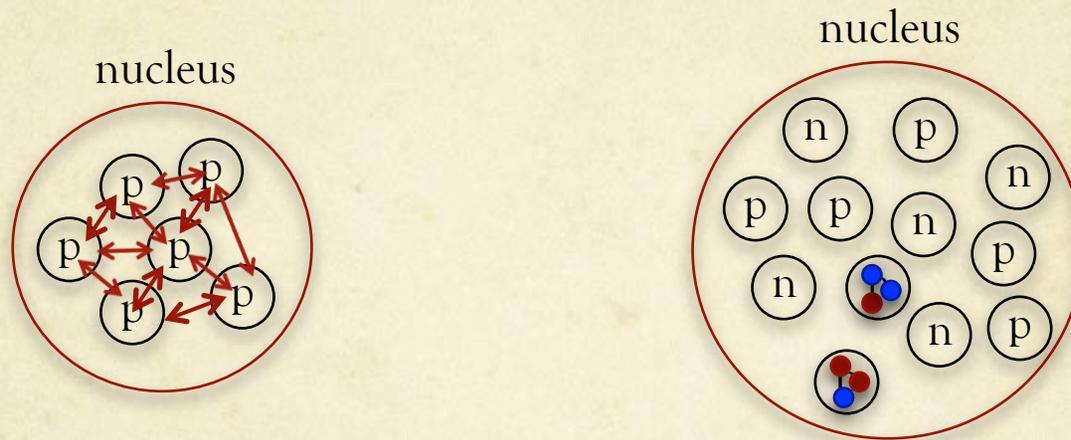
Quarks . . .

- 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?



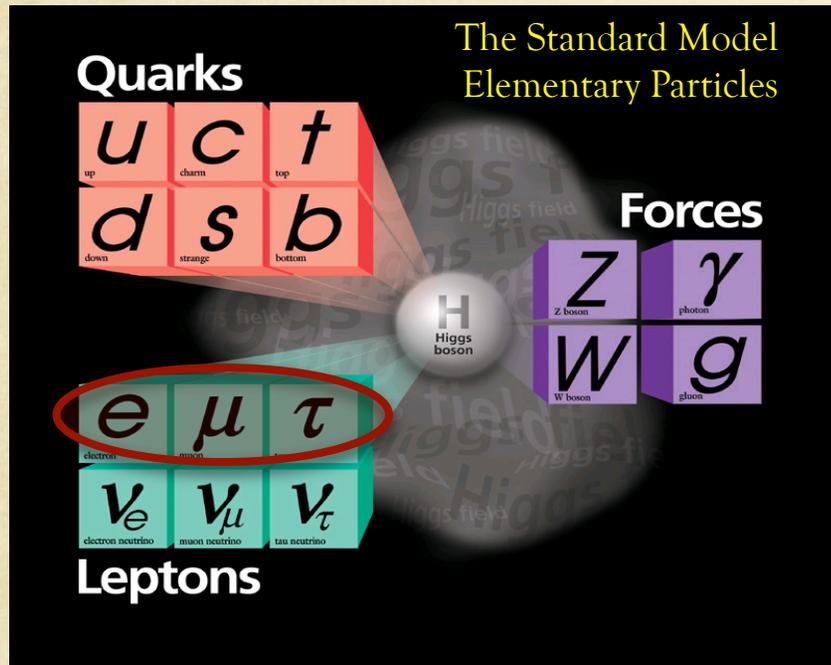
Quarks . . .

- 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?



- Because the attractive strong force is **stronger** than the repulsive electromagnetic force
- Also **neutrons** help make a nucleus stable since they feel the strong force but are overall electrically neutral

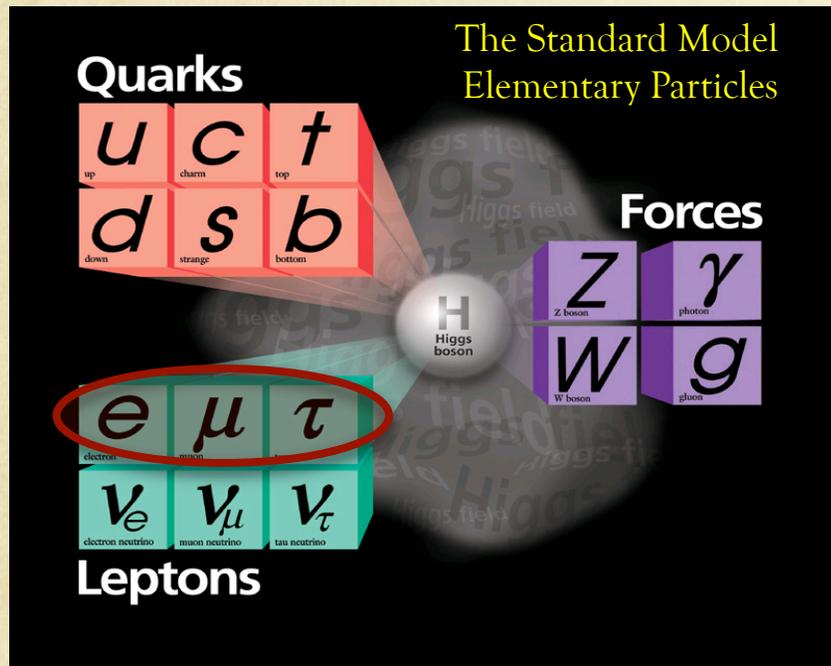
Charged Leptons . . .



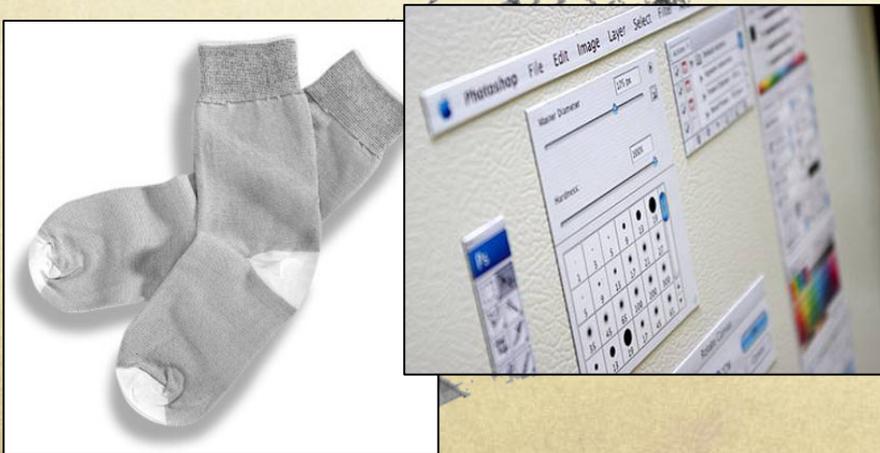
- Come in three “flavors”
 - electron
 - muon
 - tau
- Interact with other particles via the **weak** force and the **electromagnetic** force



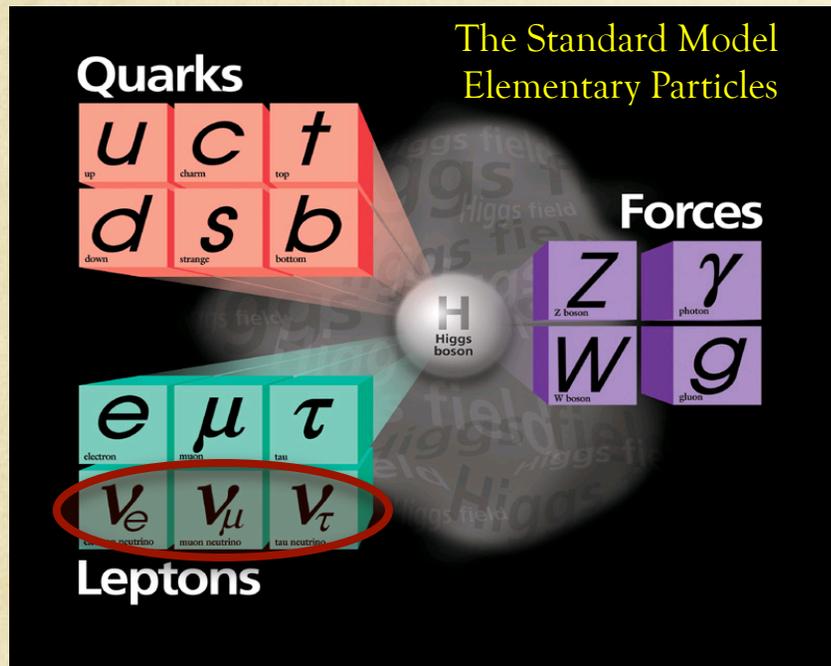
Charged Leptons . . .



- 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

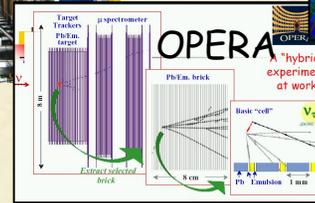
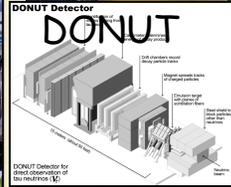
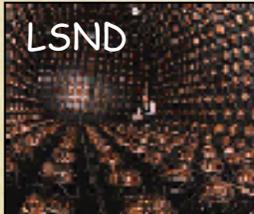
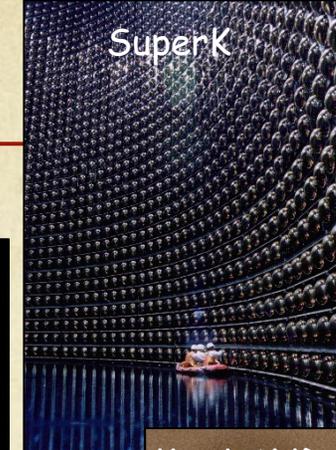
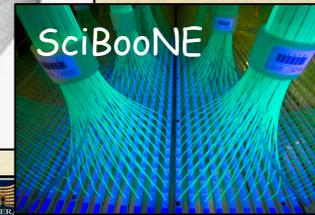
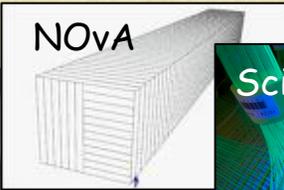
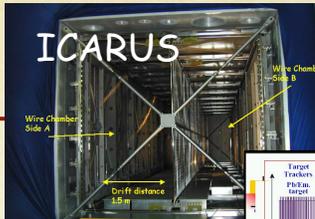


Neutrinos . . .

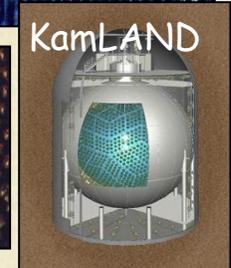


- Also come in three “flavors”
- Interact ONLY via the **weak** force
- Are assumed to be completely **massless in the Standard Model**
- **Neutrinos** make up $\frac{1}{4}$ of the elementary matter particles we know of, but outnumber the others in the Universe by a factor of a **BILLION**

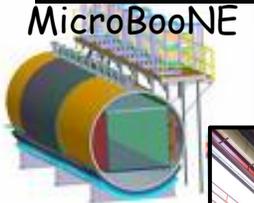
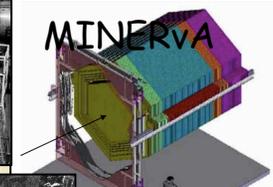
○ So, to understand the nature of the Universe in which we live we must understand the properties of the neutrino!



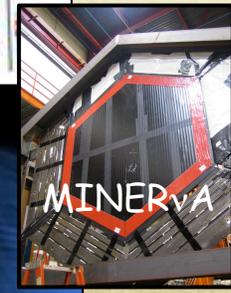
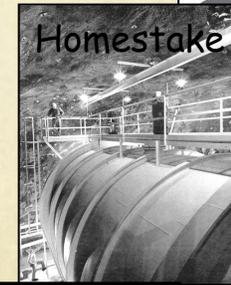
• Some of the many exciting experiments **around the world** that have been dedicated to studying the neutrino

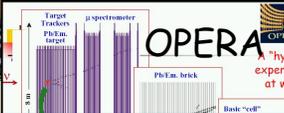
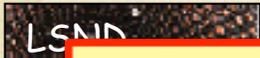
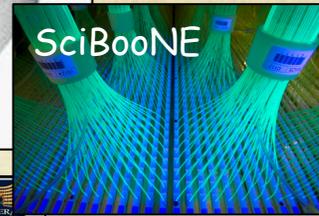
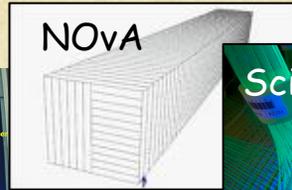
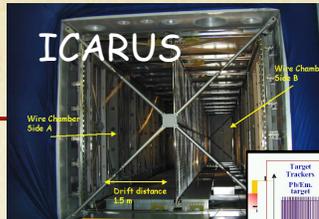
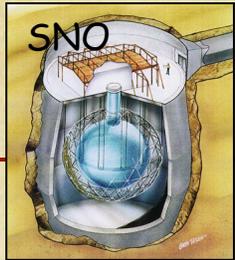


• This little particle has continued to surprise us with its unexpected behavior and the profound implications for 75 years



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



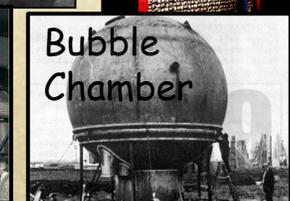
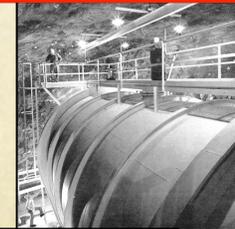
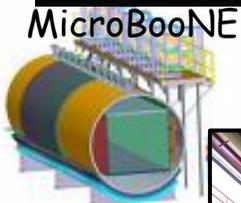


In 1971, Robert R. Wilson, the first director of Fermilab, told the lab users,

“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

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



Neutrinos . . .



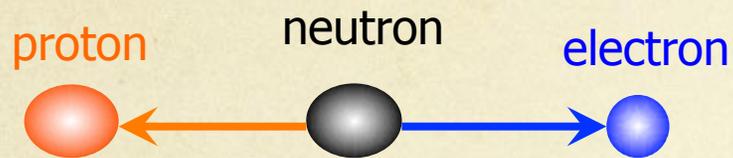
Come from **bananas!?! huh?**

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

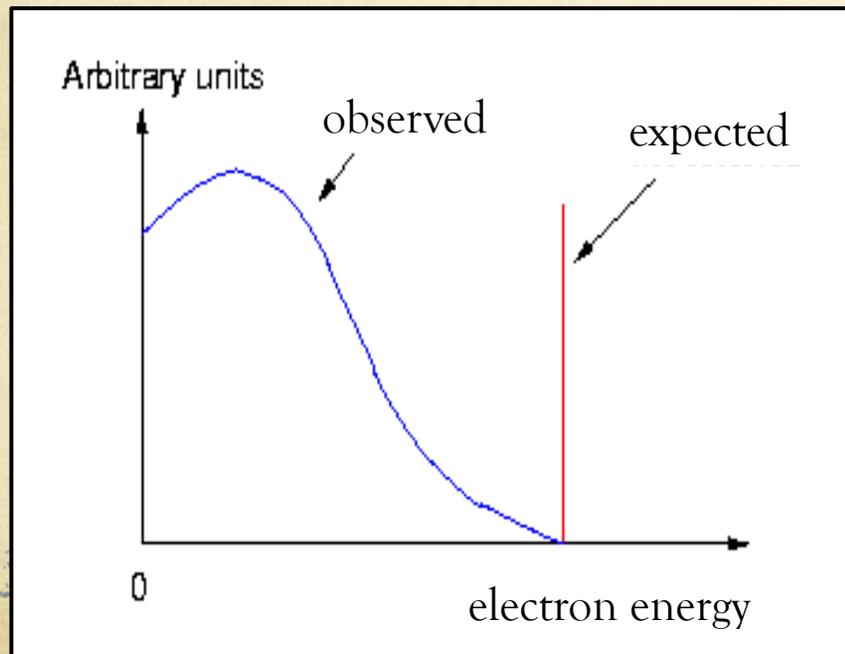
Related to how the neutrino was discovered in the first place (not bananas, but radioactive decay)

The “desperate remedy”

- In 1930 there was a crisis in particle physics!



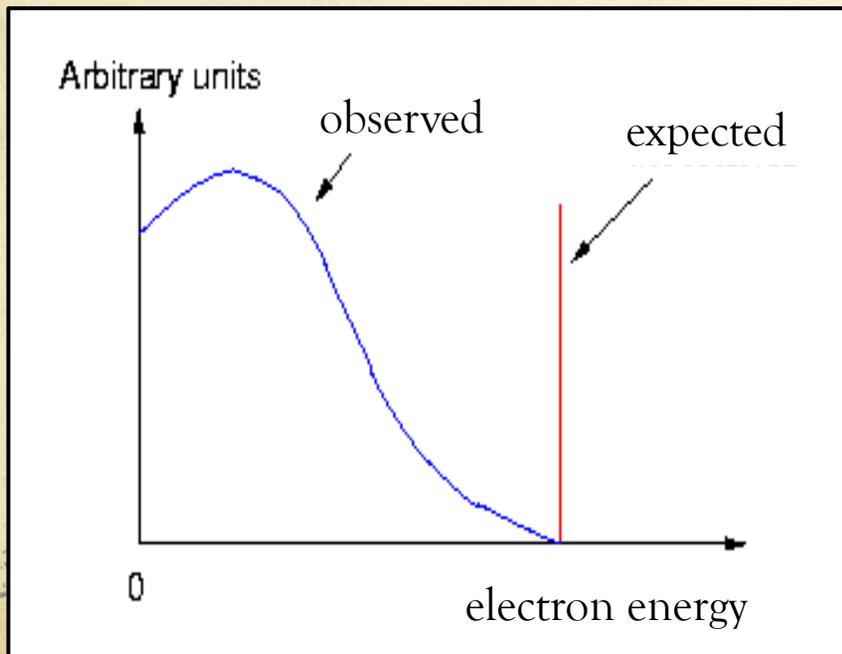
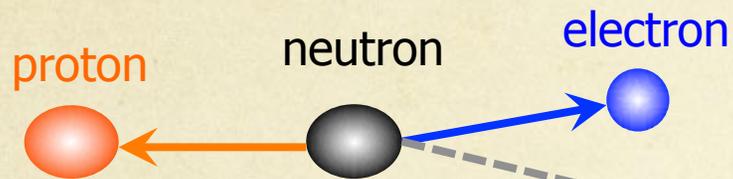
It was well known that nuclei could change from one variety to another by emitting a “beta” (electron).



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”

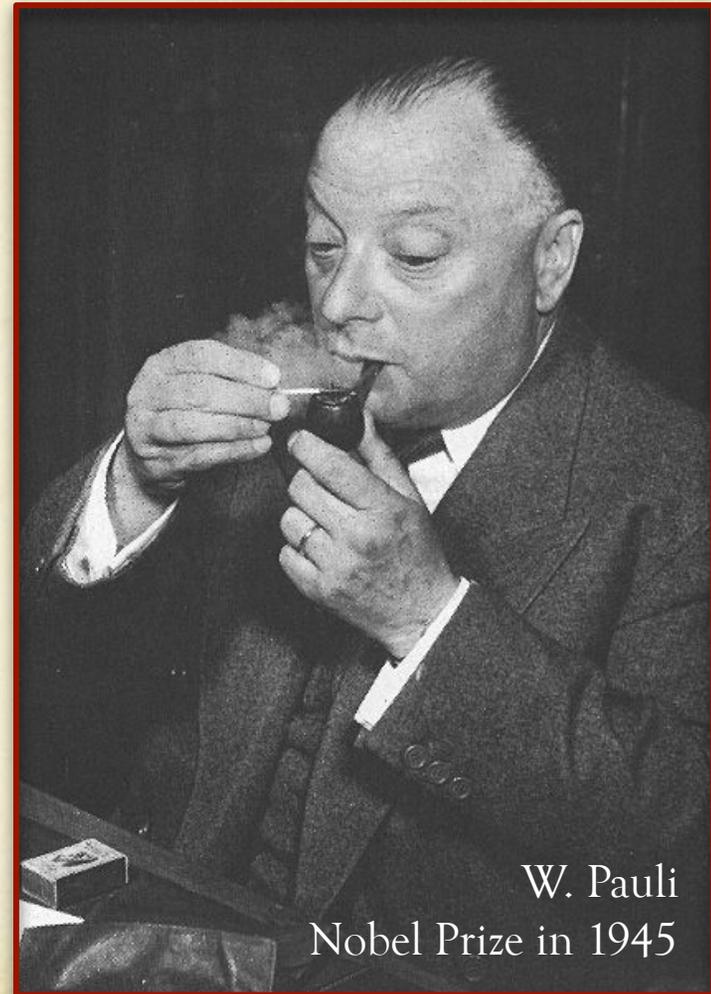
Dear Radioactive Ladies and Gentlemen,

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 Tübingen 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 neutral, massless particle

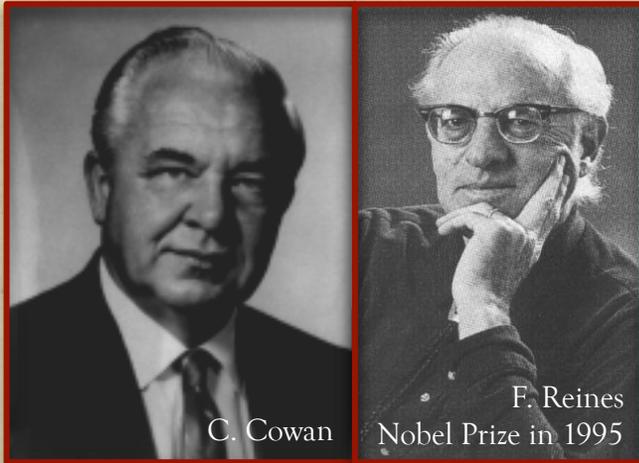
“I have done a terrible thing. I have postulated a particle that cannot be detected.”

- 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)

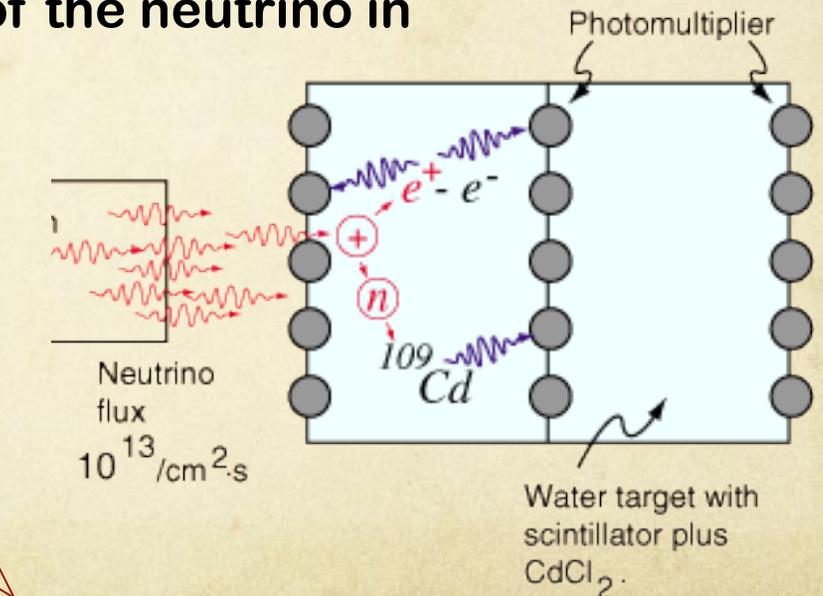
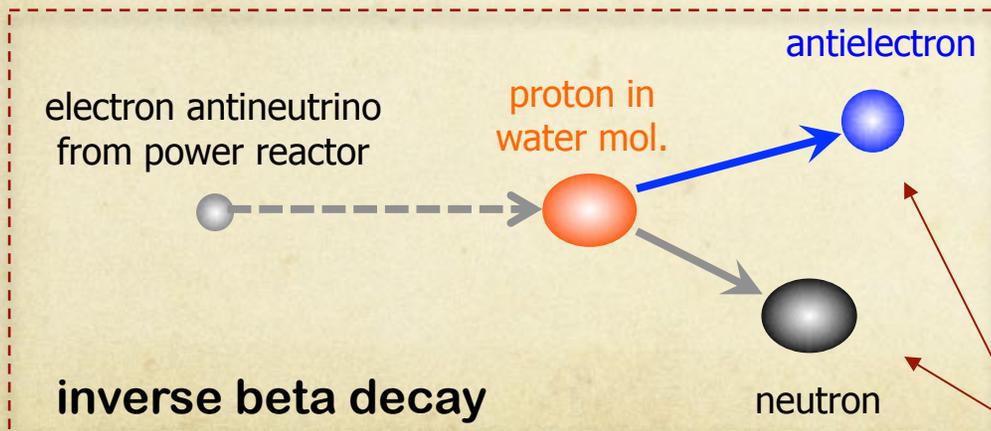
The Initial Discoveries

How did they do it?

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

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

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

atomic mass unit

ν -N cross-section

density of lead

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atomic mass unit

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density of lead

1. neutrinos produced by the sun typically have a few MeV of energy

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

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

An Aside : What took so long?

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1. neutrinos produced by the sun typically have a few MeV of energy

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

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

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

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

An Aside : What took so long?

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

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

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

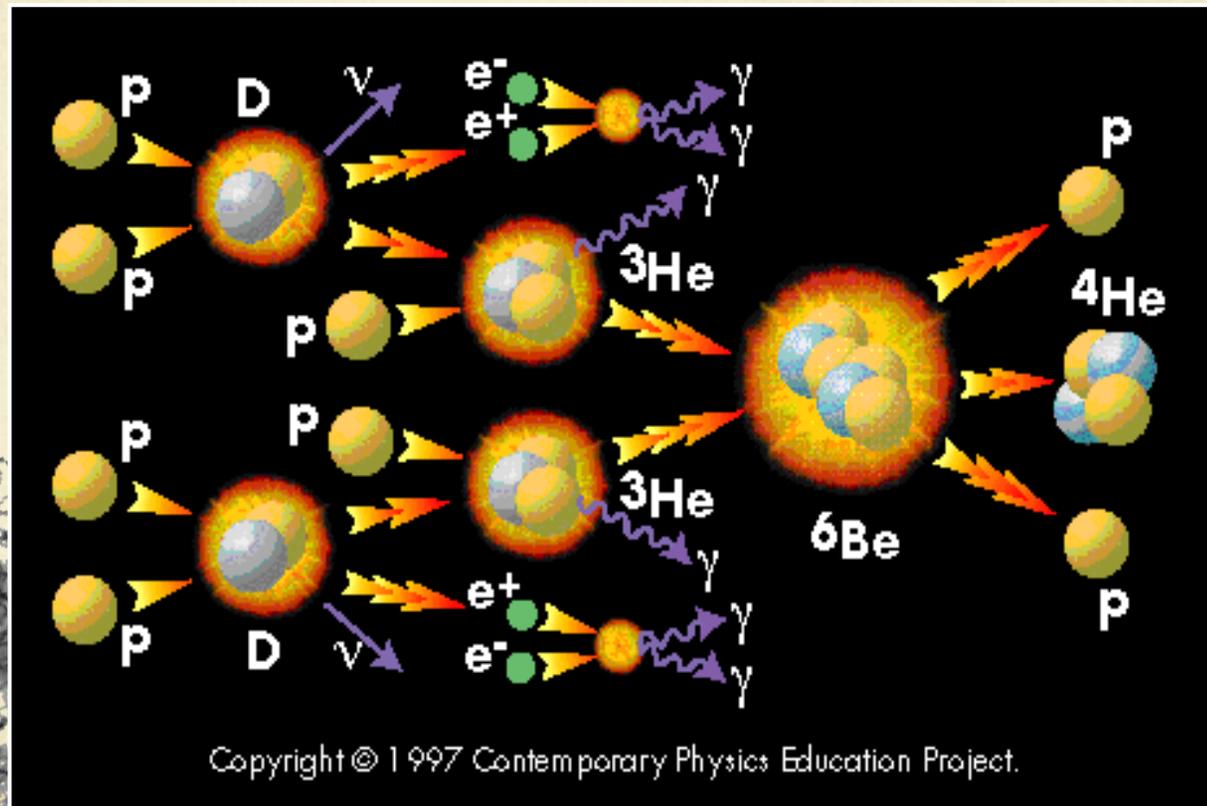
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Neutrinos From the Cosmos

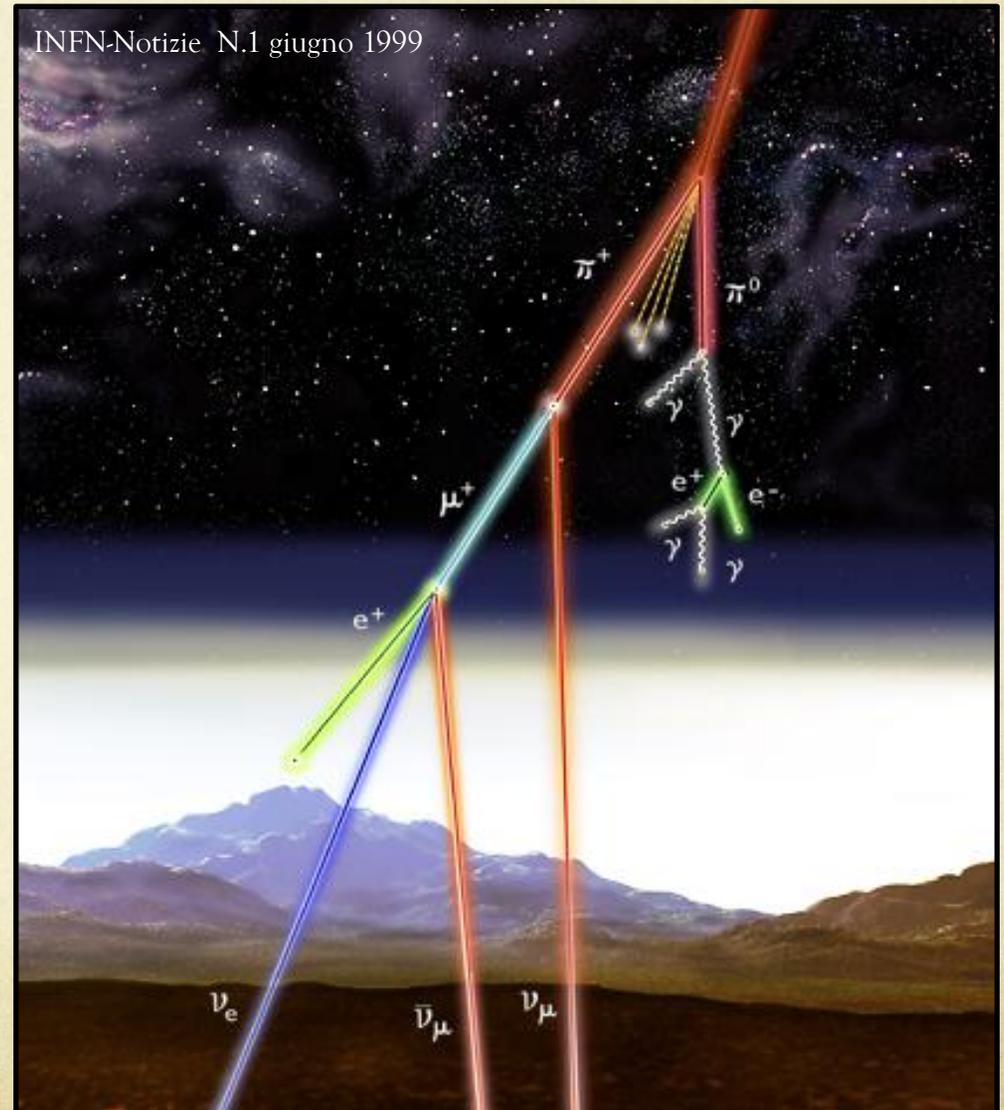
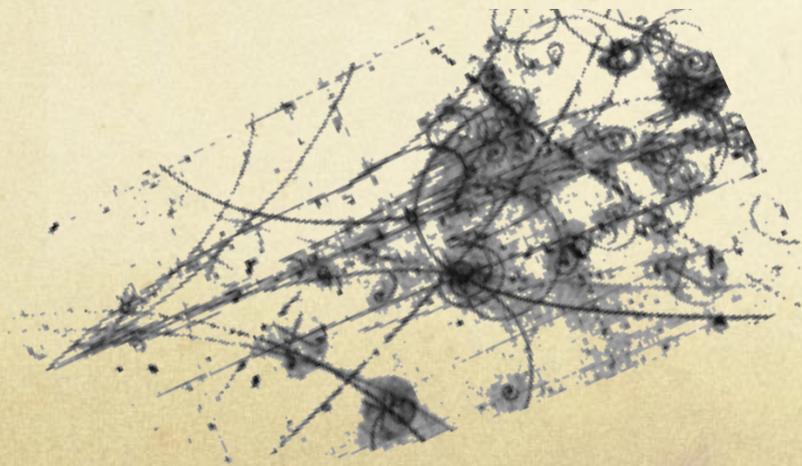
- the **Sun** produces huge numbers* of pure ν_e
 - the idea was that neutrinos would provide **a great probe of the complicated fusion processes** occurring deep inside the sun



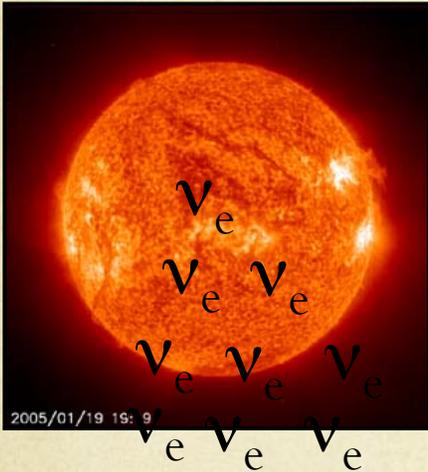
*about 300,000,000,000,000,000 will pass through your body during this talk.

Neutrinos From the Cosmos

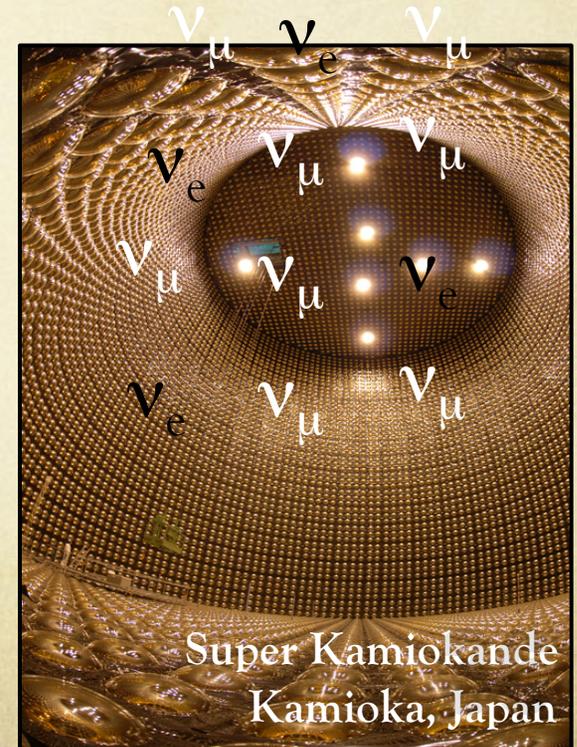
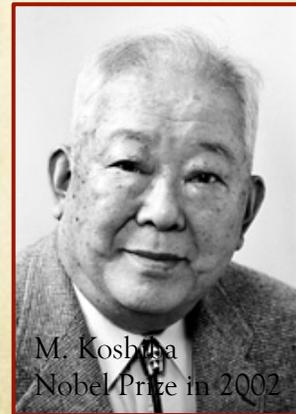
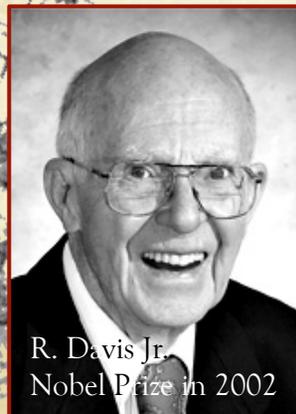
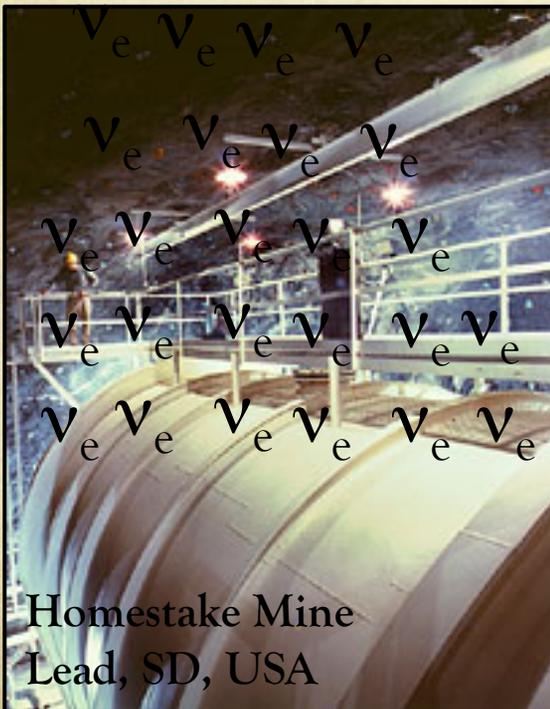
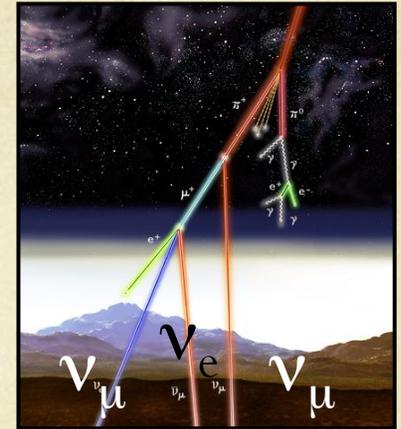
- neutrinos are produced in the **atmosphere** by cosmic rays colliding with air molecules
- **should reach Earth with ν_μ and ν_e in a 2:1 ratio**



Let the Surprises Begin



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



Another desperate remedy?

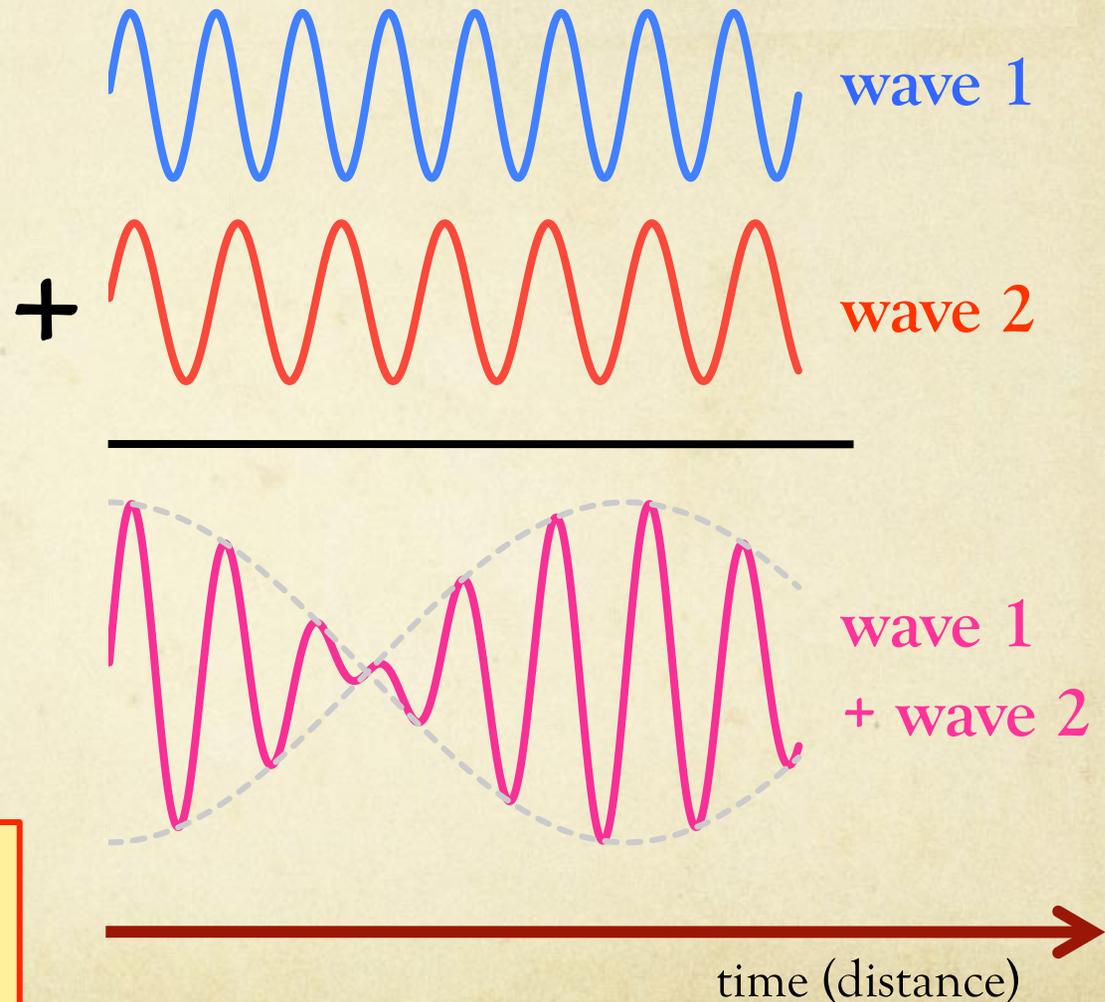
Where are the disappearing neutrinos disappearing to? Another dilemma that persisted for more than two decades!

- 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 $\rightarrow \nu_\mu/\nu_\tau$, which the Homestake detector could not see
 - ν_μ from atmosphere $\rightarrow \nu_\tau$, which Kamiokande detector could not see

and **tiny** masses can have **HUGE** effects

Neutrino Oscillations

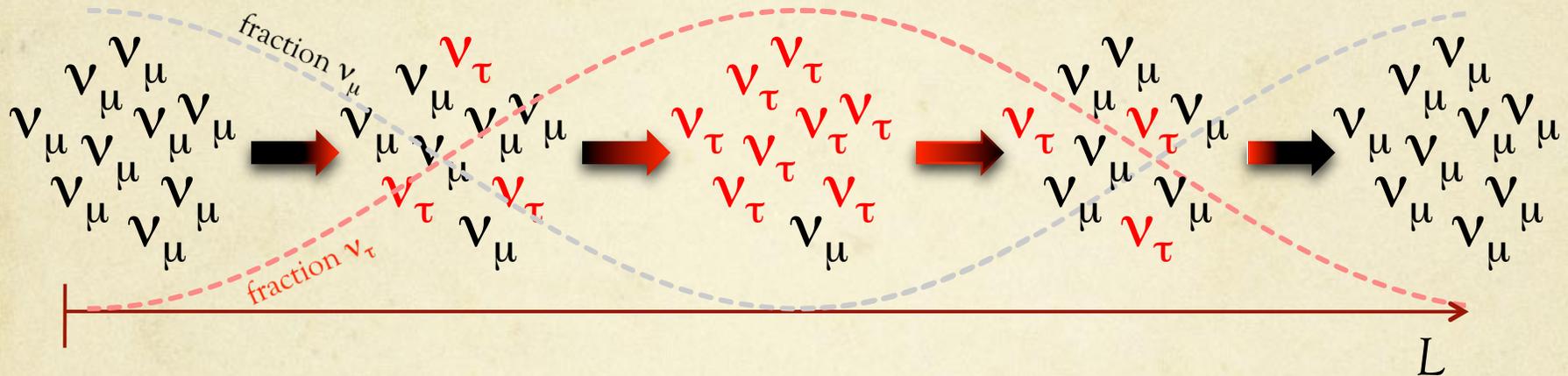
- Quantum Mechanics tells us that particles can be like waves and particle **mass determines the frequency**
- If neutrinos (ν_e, ν_μ, ν_τ) are actually composed of **multiple such waves with different frequencies** (different masses) . . .
- Then they can **interfere like any waves can** and change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



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

Neutrino Oscillations

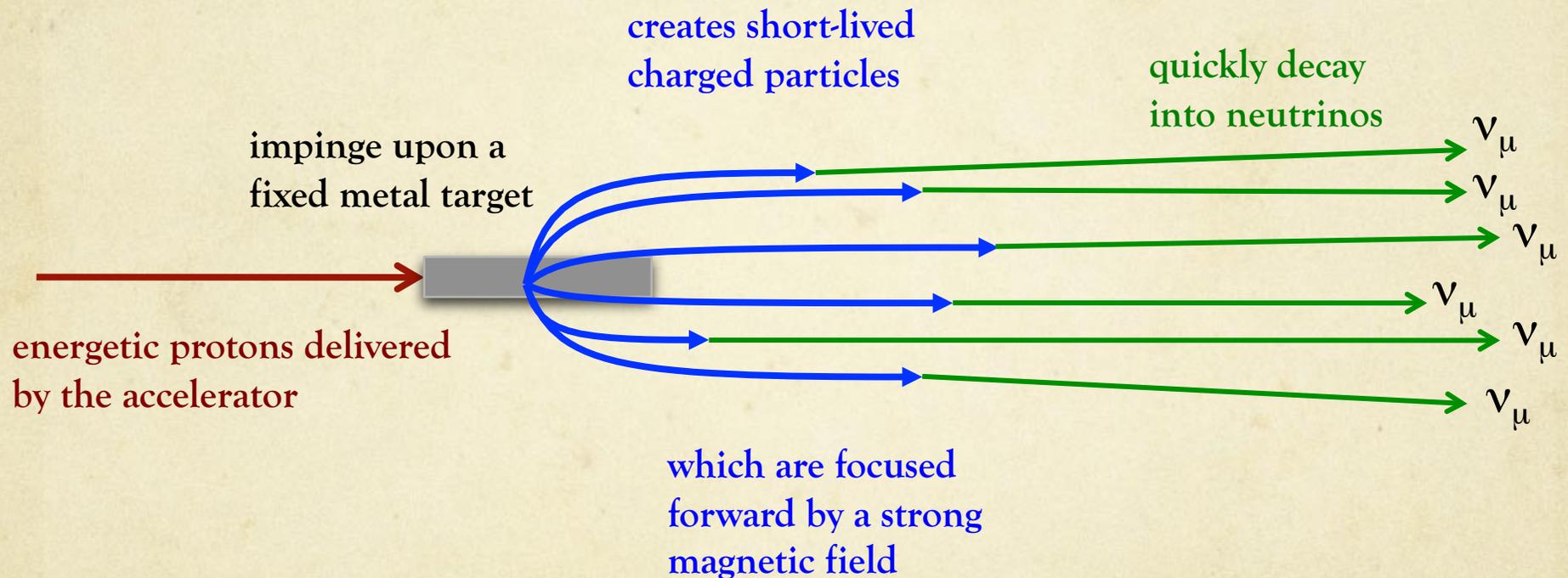
- This oscillation affects the *probability* that a neutrino is of a particular type as it travels



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

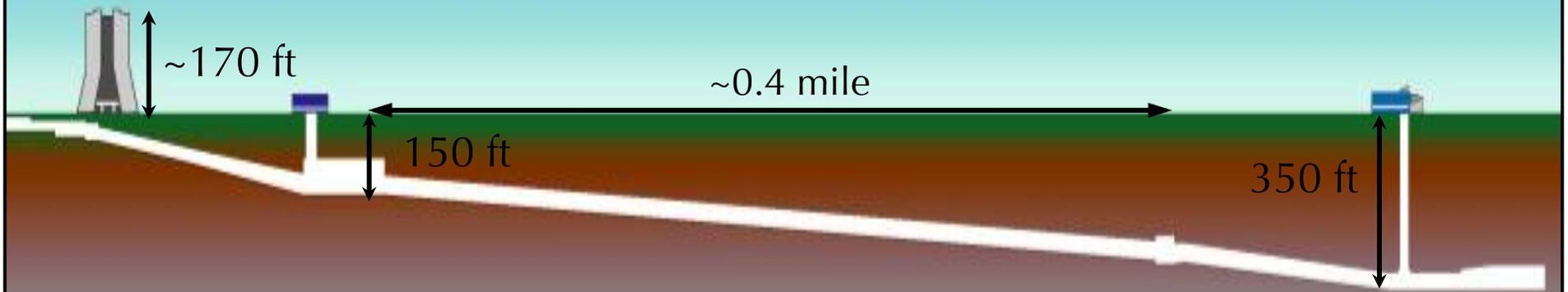
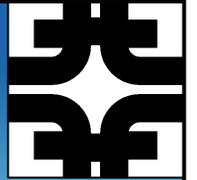


- In the last 10 years Fermilab has built **two of the most intense neutrino sources in the world** using its powerful proton accelerators in order to study neutrinos and oscillations
 - The **Booster Neutrino Beam** starts from 8 GeV protons from the Booster
 - The **NuMI Neutrino Beam** starts from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





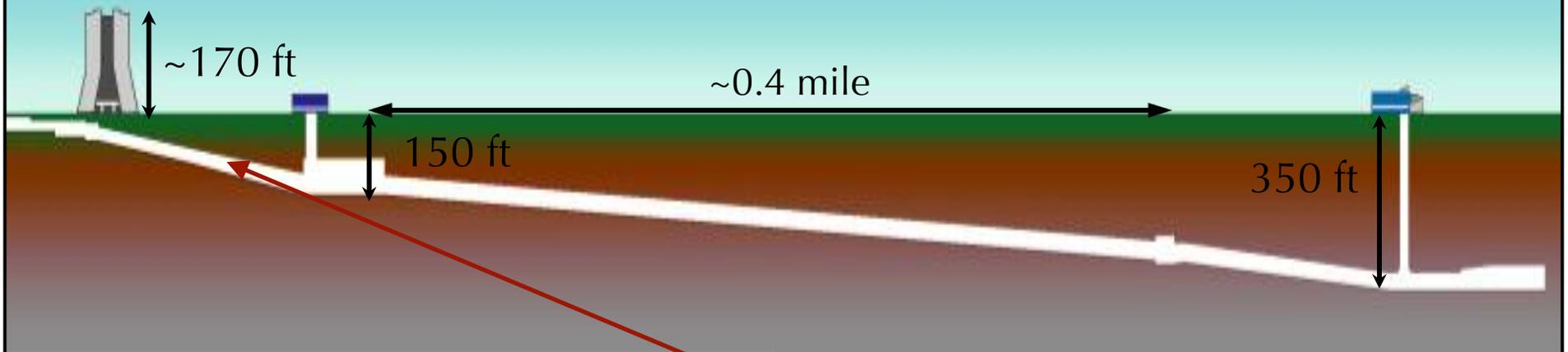
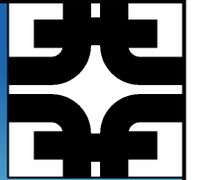
NuMI Neutrino Beam



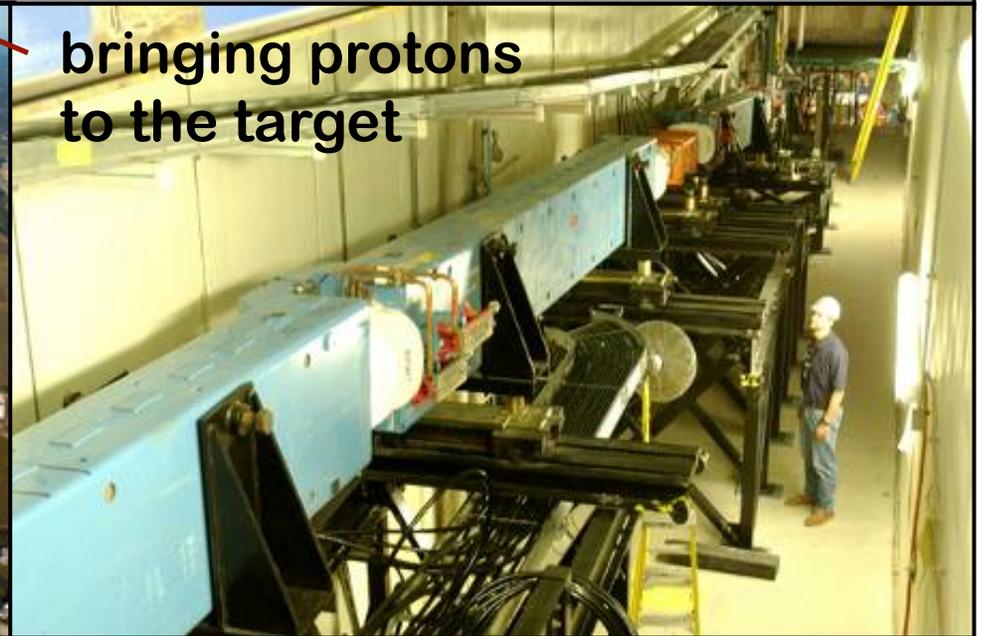
Main Injector 120 GeV



NuMI Neutrino Beam

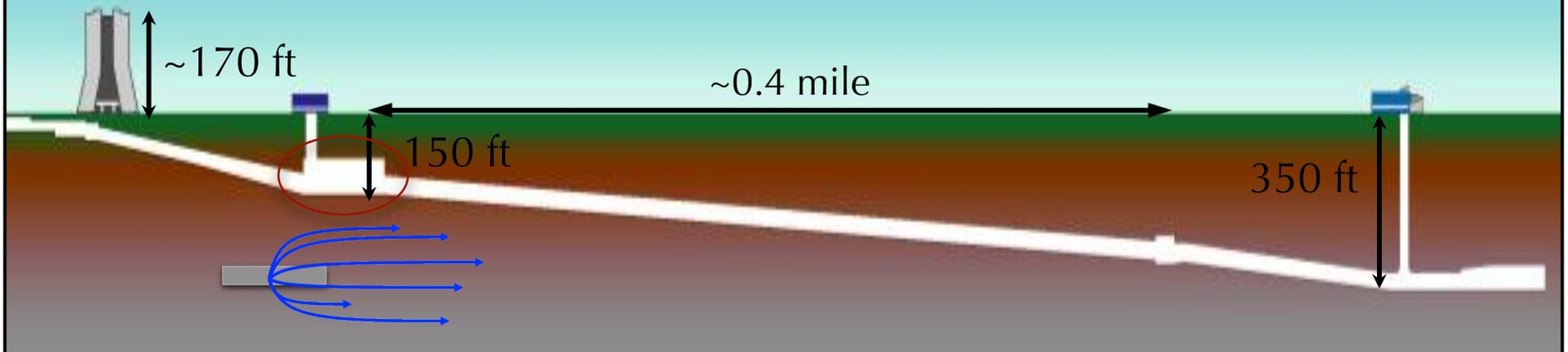
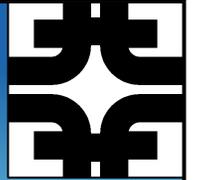


bringing protons
to the target



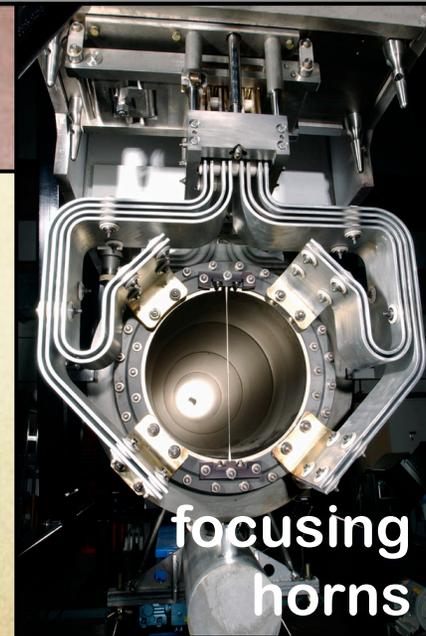


NuMI Neutrino Beam



- 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

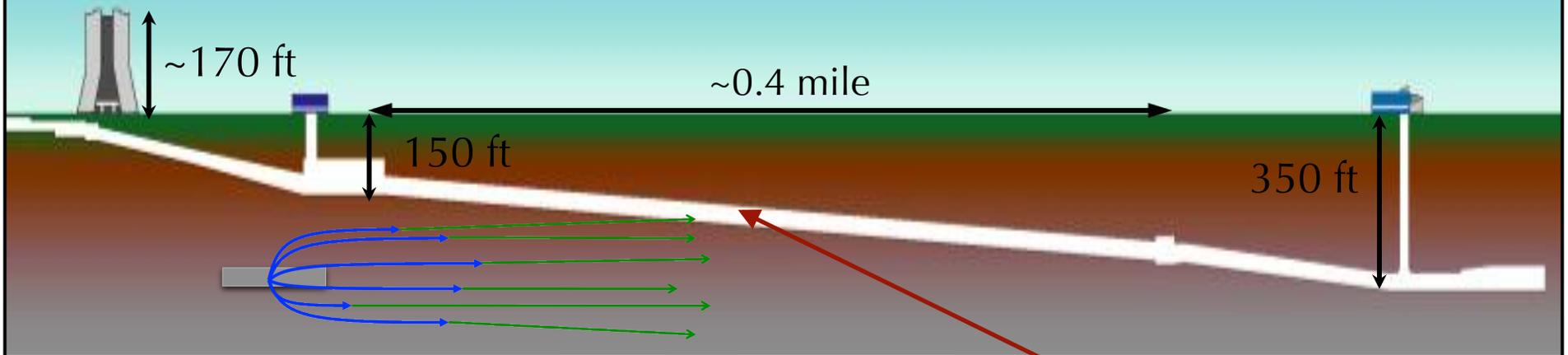
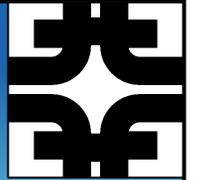


focusing horns



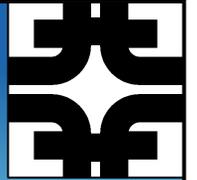


NuMI Neutrino Beam





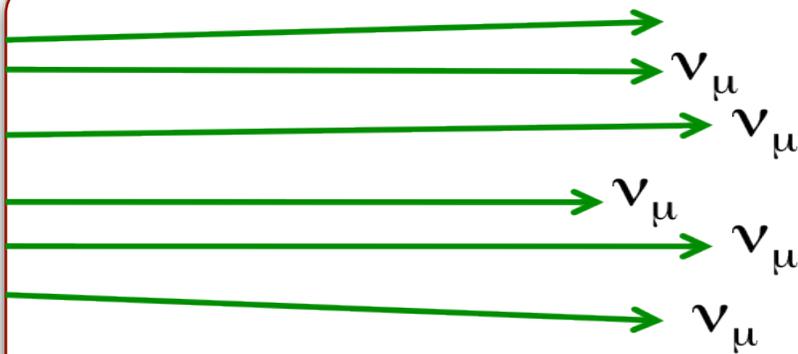
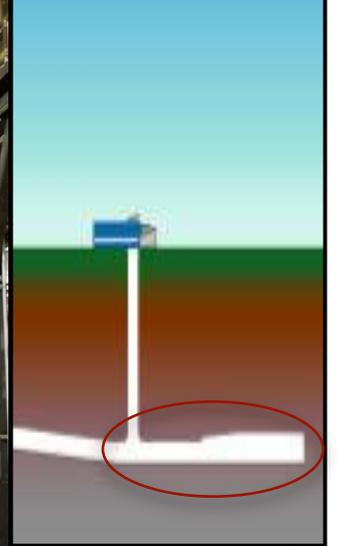
NuMI Neutrino Beam



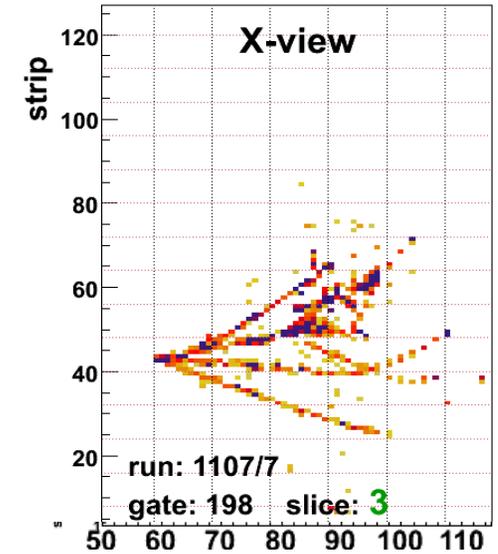
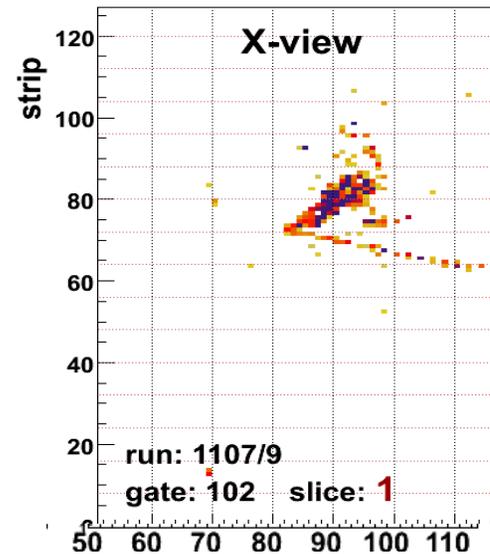
MINOS



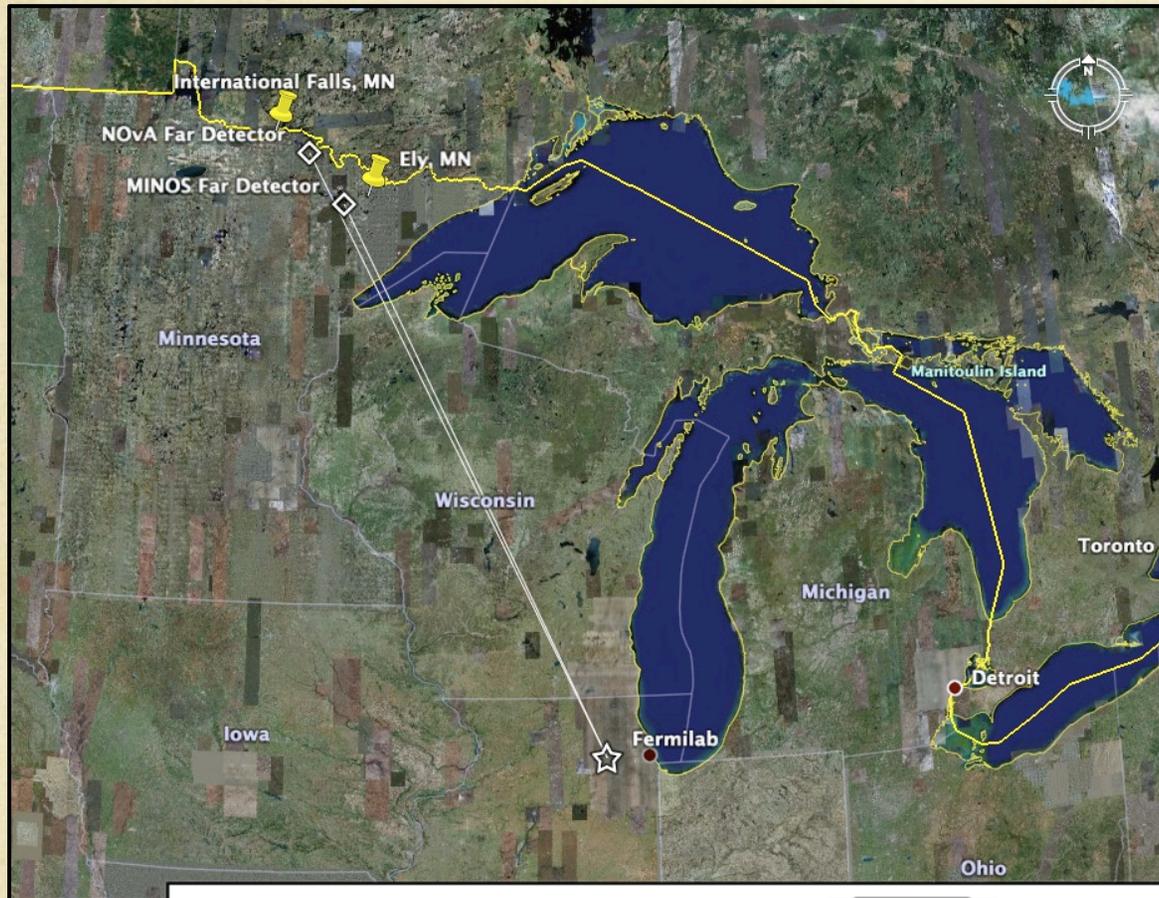
MINERvA



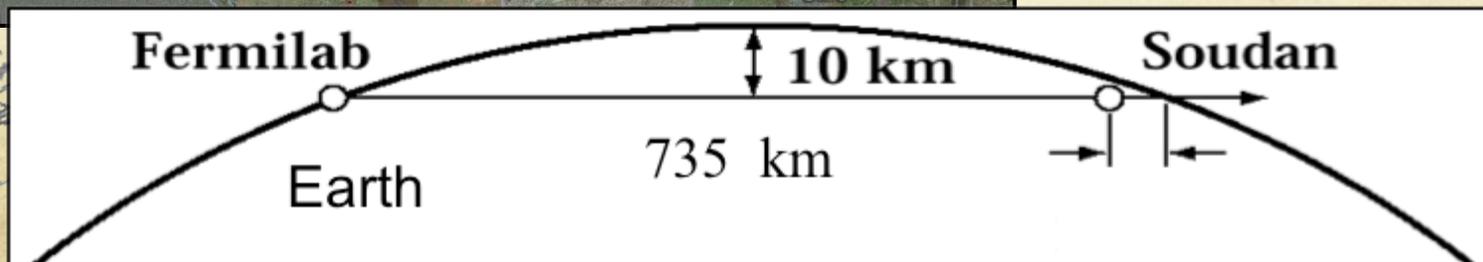
• A few neutrinos interact spectacularly in the detectors. Of course, most pass right by...



Where Are They Headed? North!

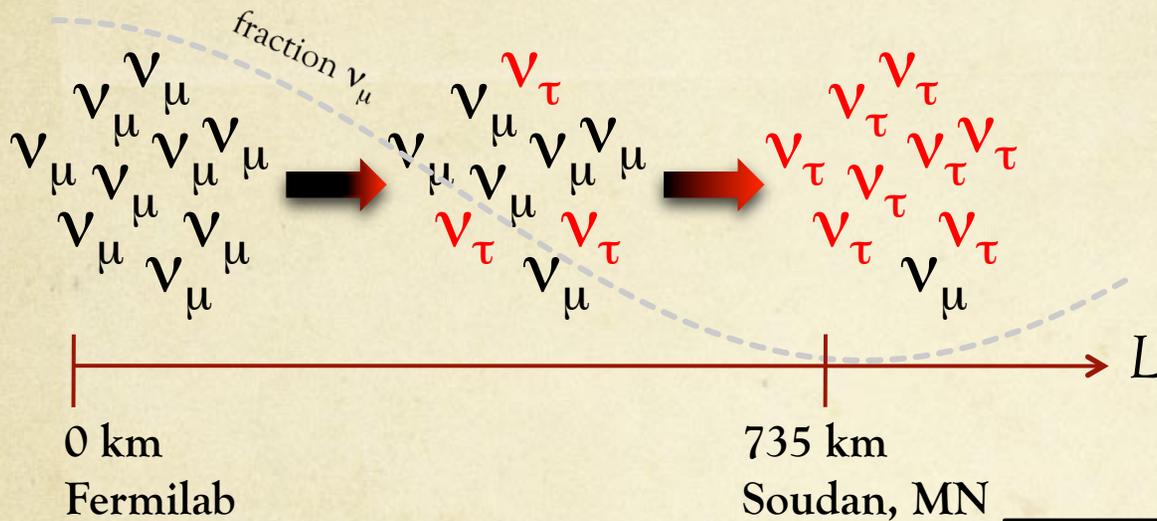


- The neutrinos make the 450 mile journey from Fermilab to northern Minnesota in **1/400th of a second**
- **No tunnel required.** recall, the Earth is like air to a neutrino!
- By comparing the number of muon neutrinos at both locations, one can **look for them to disappear**



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

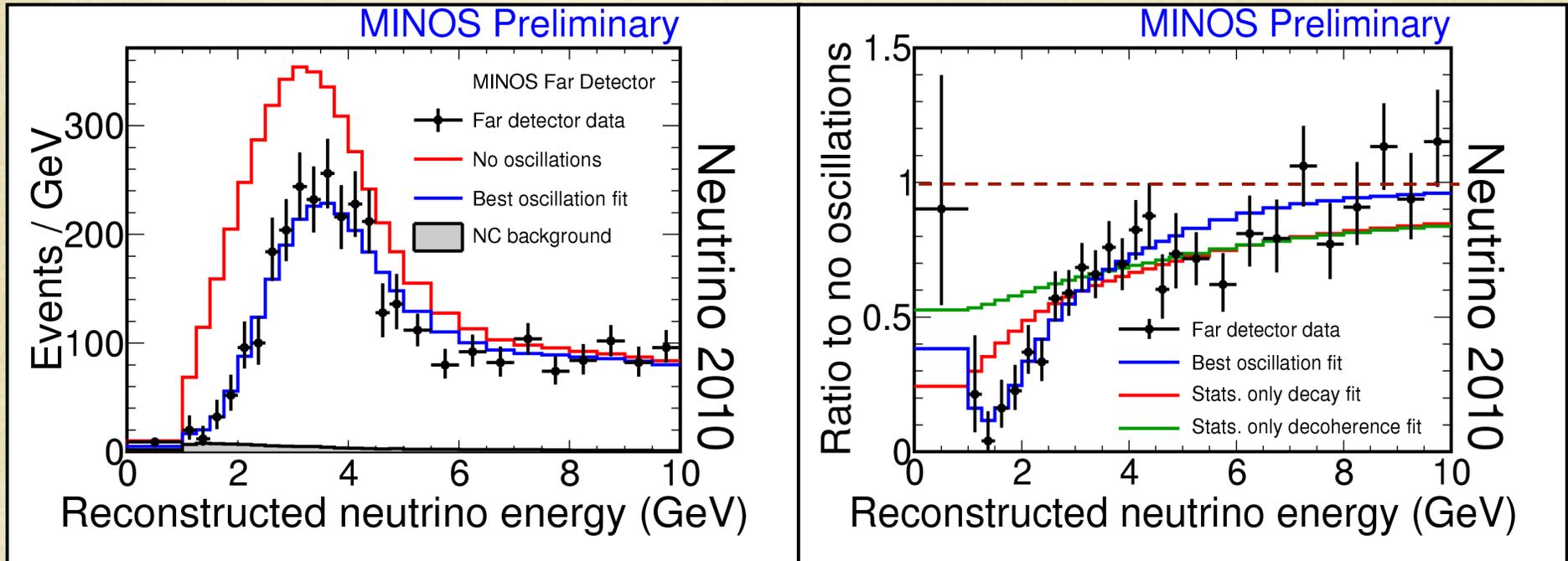


both are
specialized
muon
neutrino
detectors



Fermilab Ask-a-Scientist - Neutrinos! December 5, 2010

And They Do Disappear!!



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

Neutrino Oscillations

- Experiments have provided incontrovertible 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
 $\approx 1/2000^{\text{th}}$ mass of proton



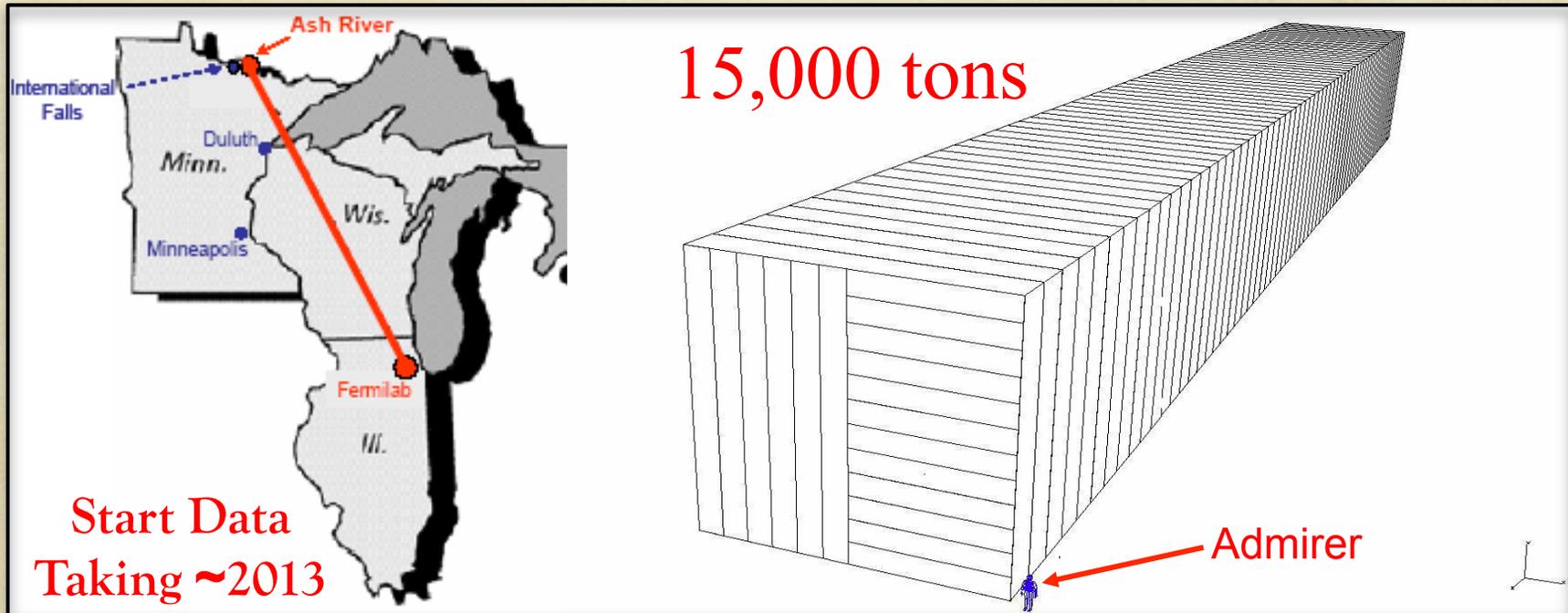
mass of neutrino
 $< 1/1,000,000^{\text{th}}$ mass of electron



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 NO ν A Experiment



NO ν A detector will be **3 times more massive** than the MINOS detector
NO ν A detector specially **designed to detect electron neutrinos**.
Makes continued **use of the existing NuMI neutrino beam**

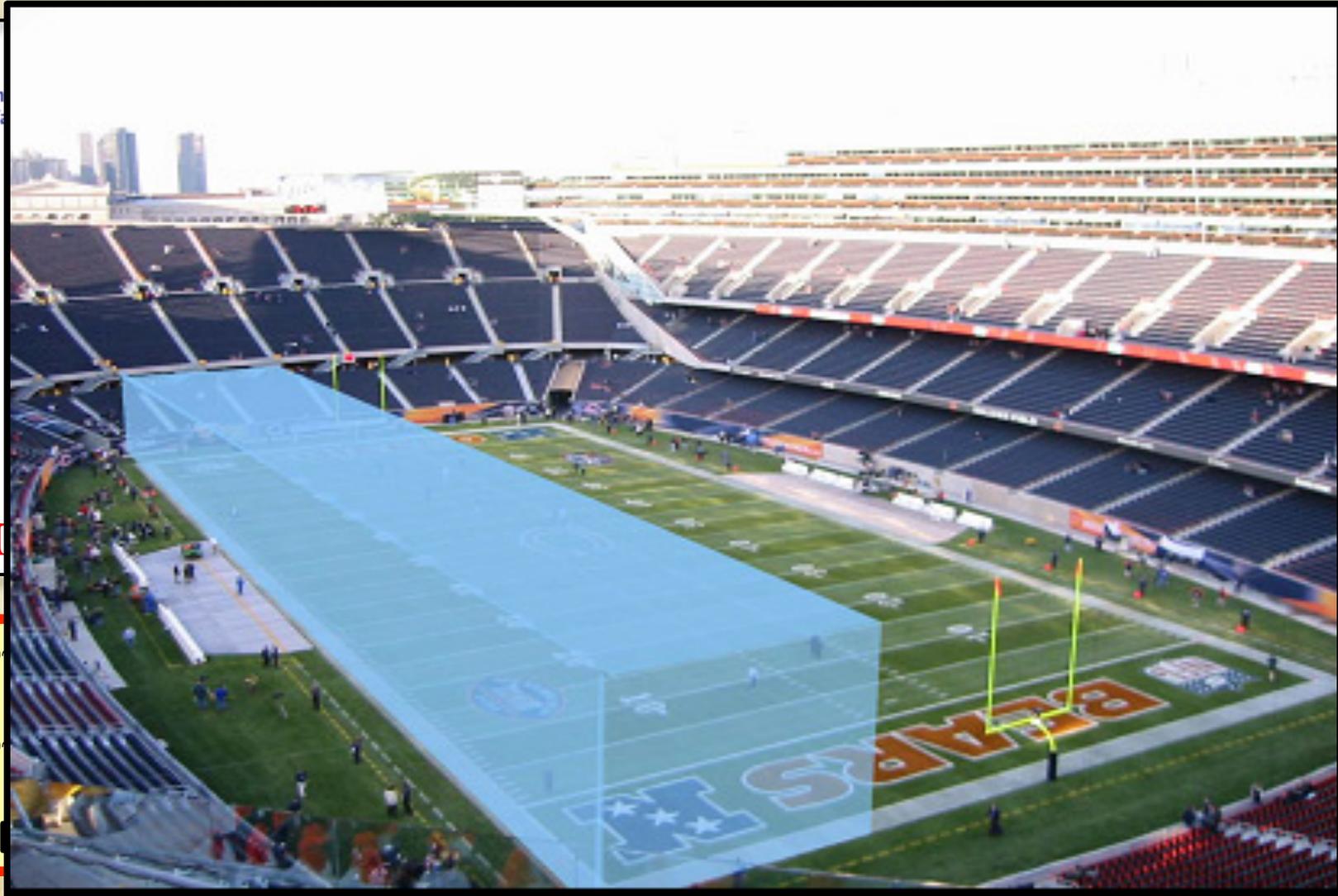
Future : The NOvA Experiment



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Future : The NOvA Experiment



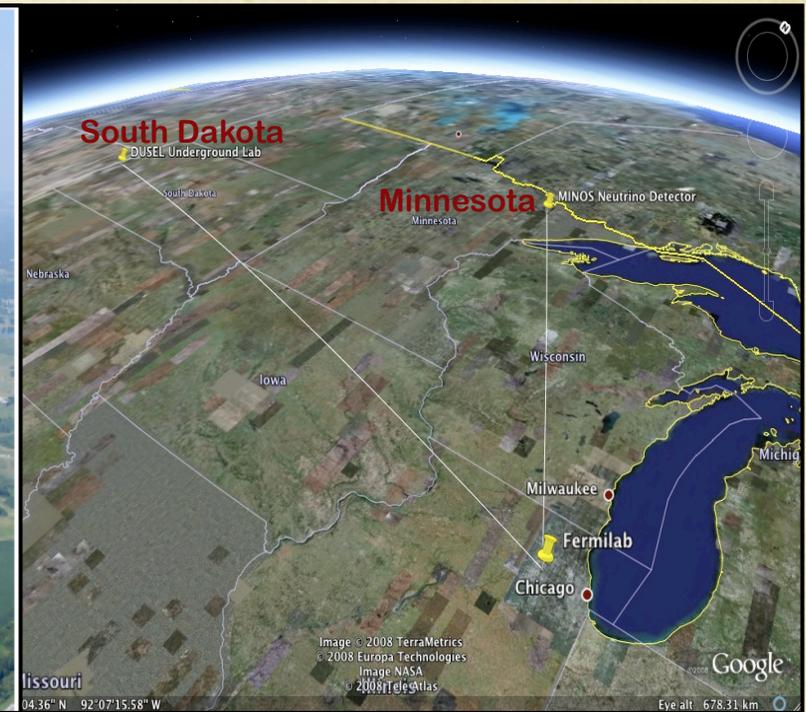
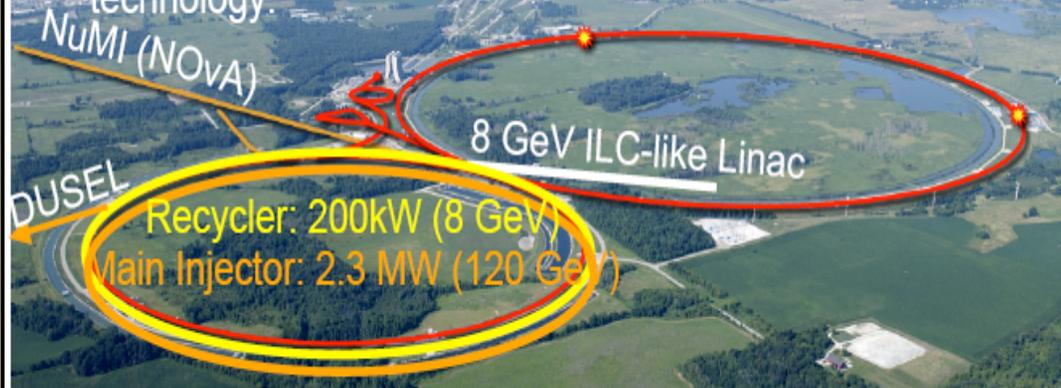
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Future : Project-X to DUSEL

Fermilab vision :The Intensity Frontier with Project X:

Great flexibility toward a very high power facility while simultaneously advancing energy-frontier accelerator technology.



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)