In One Ear … Out the Other

A Talk About Neutrinos

Physics for Everyone Lecture Series
Fermi National Accelerator Laboratory
April 6, 2011

David Schmitz, Fermilab

What are neutrinos?

Where do they come from?

Why are they important?

to a particle physicist?

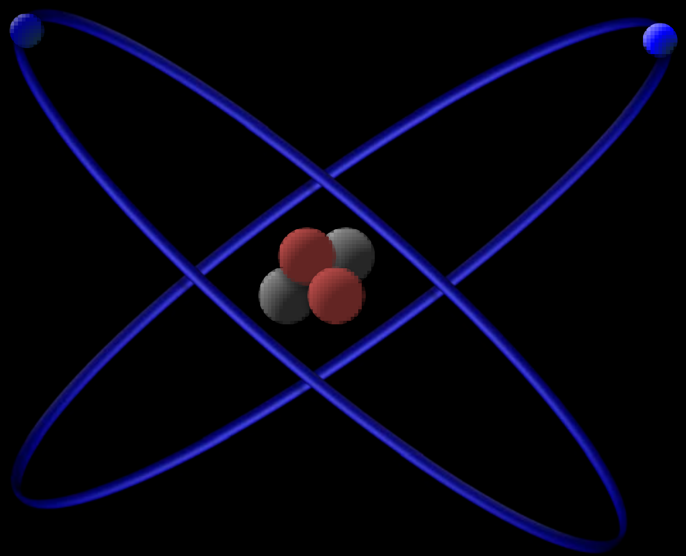
to the Universe?

to you?

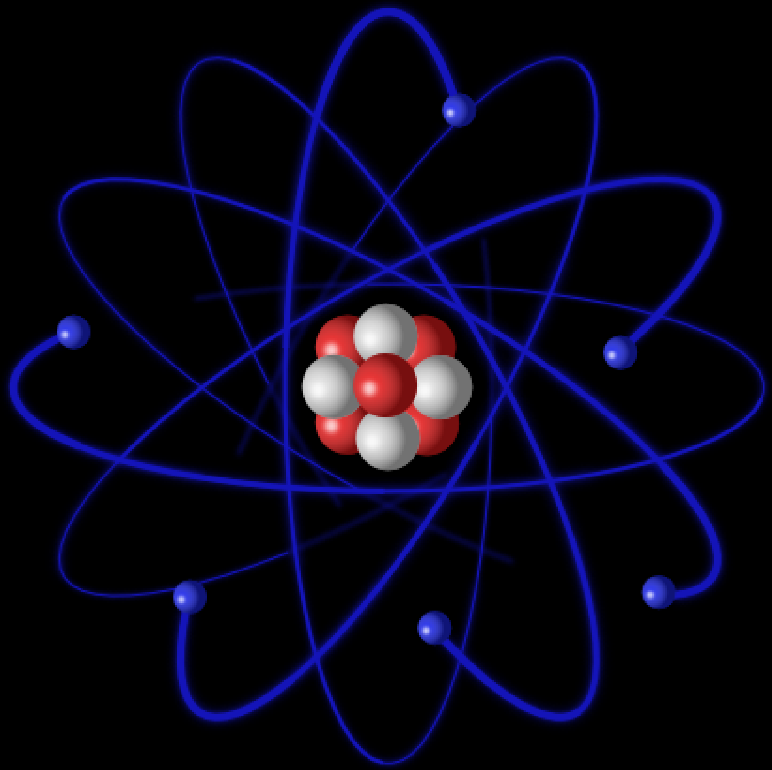
And where in the world did the silly title of this talk come from?

Everything we see around us is made of only three particles:

protons neutrons electrons



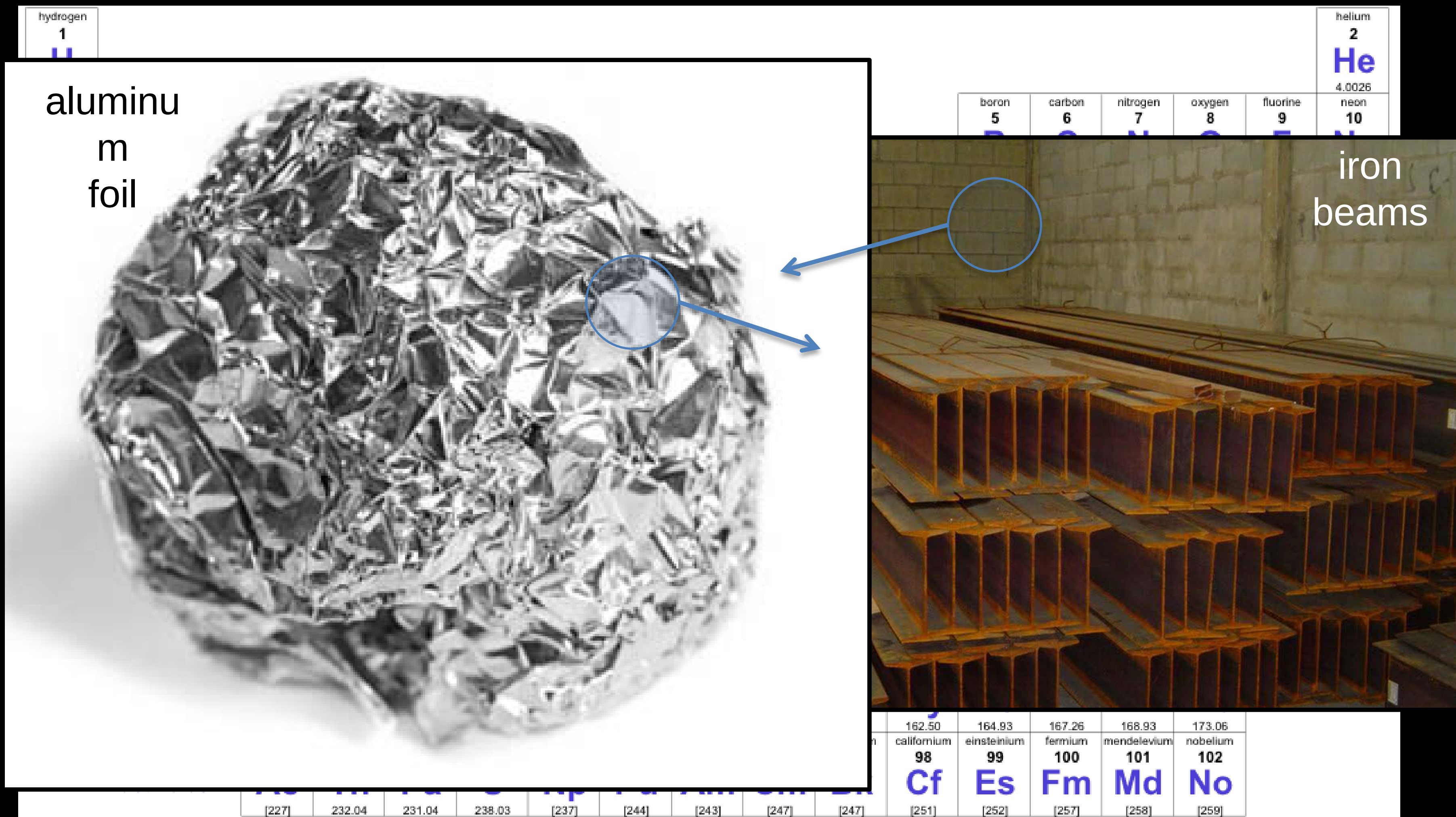
Helium Atom



Carbon Atom

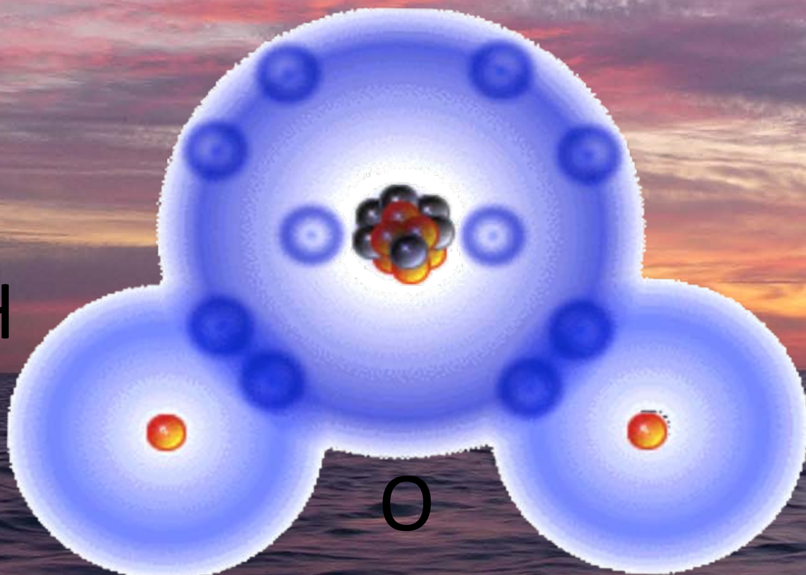
Everything we see around us is made of <u>only three particles</u>:

protons neutrons electrons



Everything we see around us is made of <u>only three particles</u>:

protons neutrons electrons



Lake Michigan

Everything we see around us is made of <u>only three particles</u>:

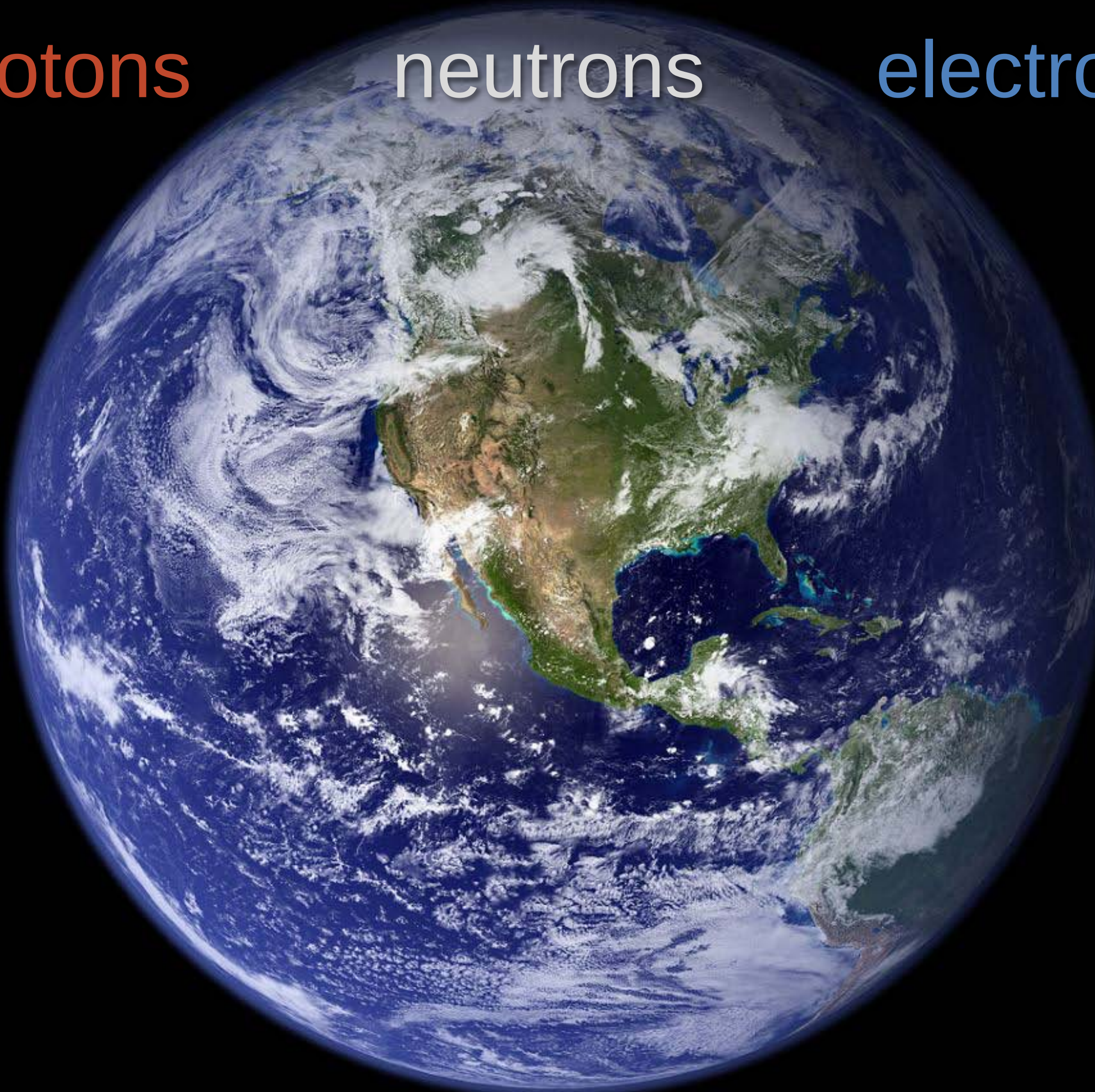
protons neutrons electrons

ople

!

Everything we see around us is made of <u>only three particles</u>:

protons neutrons electrons



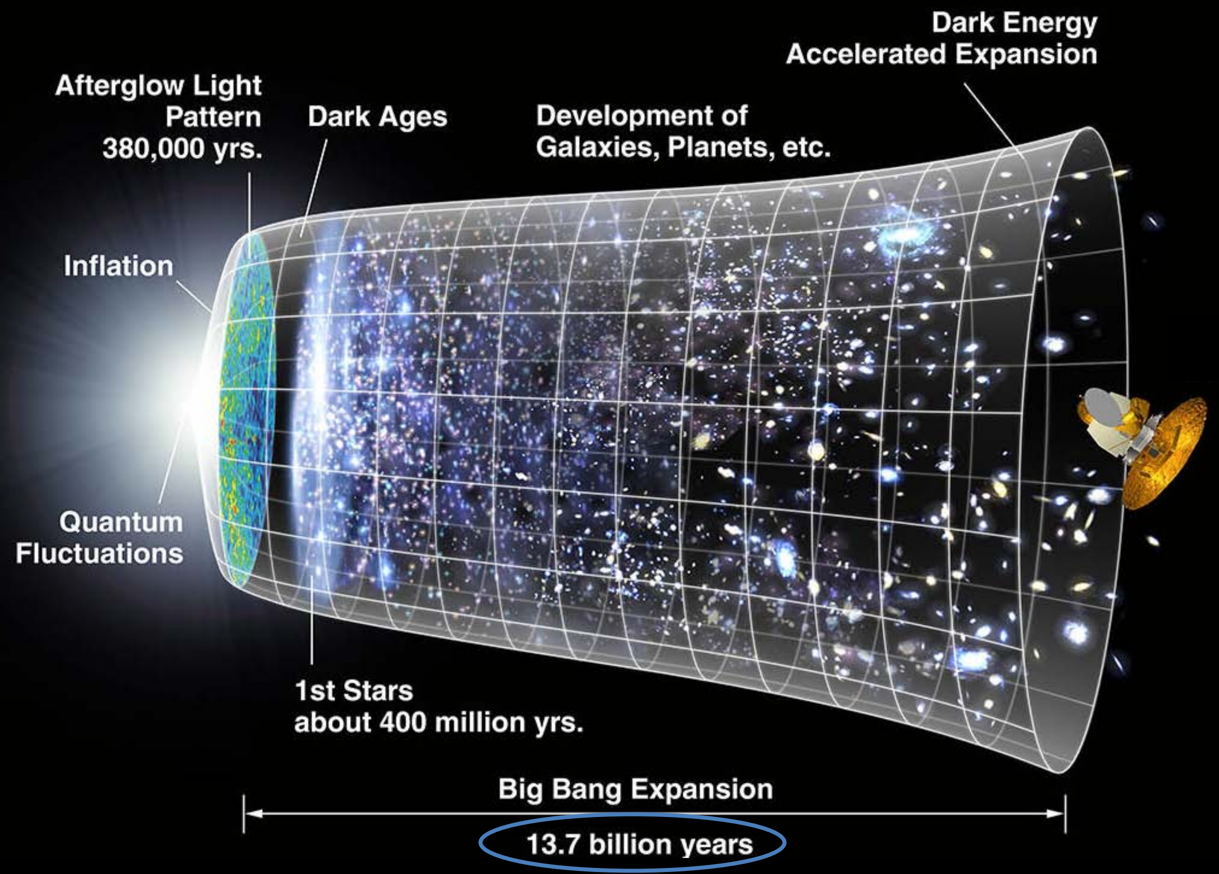
So… is the entire Universe made of these three particles?

protons neutrons electrons

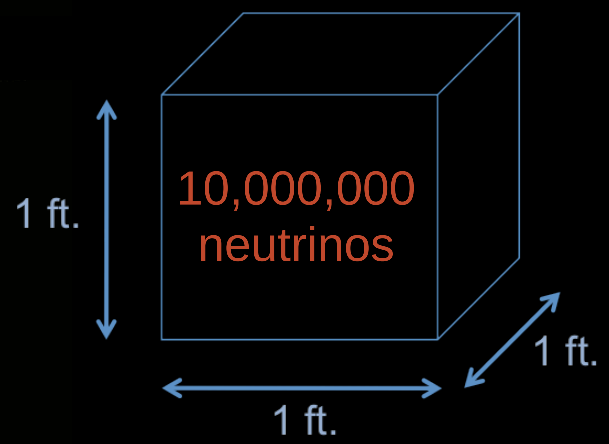
NOT EVEN CLOSE!!

In fact, we now know that for every proton, neutron or electron, the Universe contains

A BILLION neutrinos!



"Relic" Neutrinos



In every cubic foot of space in the Universe, there are 10,000,000 neutrinos which were created in the Big Bang and are still zooming around!

Whenever a star explodes as a Supernova,

the most powerful explosions in the Universe,

99% of the energy is carried off by neutrinos!

In fact, every star is an incredible neutrino factory throughout its lifetime, including our star, the Sun.

Stars are the raw materials manufacturing plants of the Universe, where all elements heavier than hydrogen are made

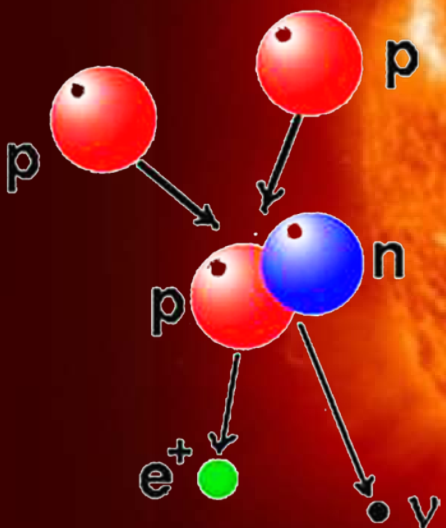
No neutrinos would mean that
stars couldn't burn

no carbon

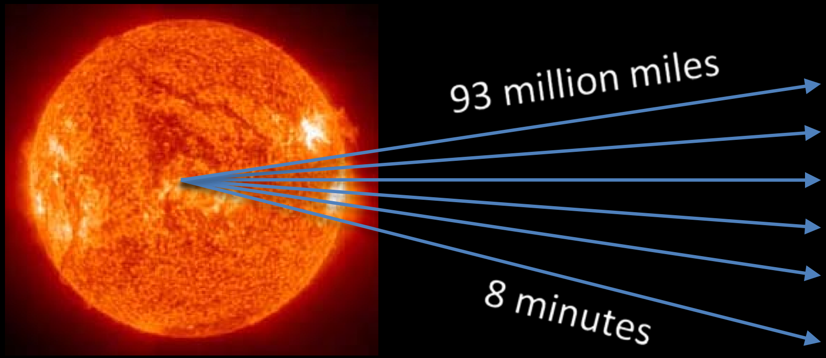
no oxygen

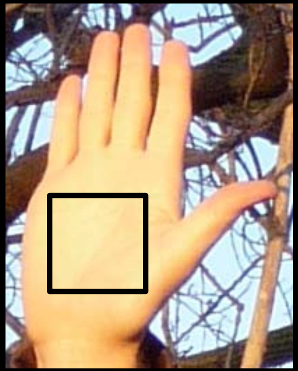
no water

nothing much at all, really ☹



The complicated chain of reactions couldn't even get started without neutrinos

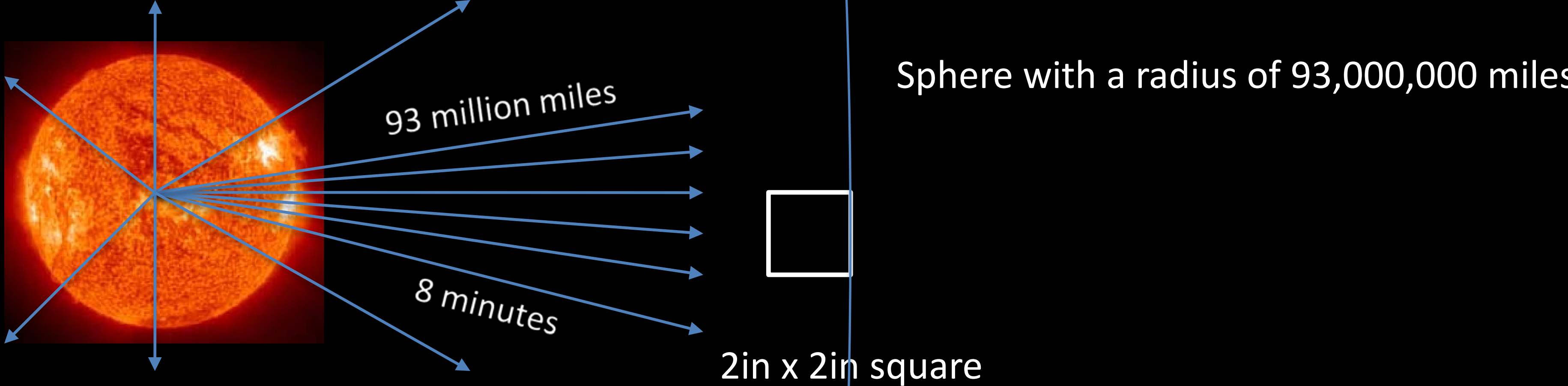




2in x 2in square

How many neutrinos in 10 seconds?

0 sec.	0
2 sec.	3,400,000,000,000
4 sec.	6,800,000,000,000
6 sec.	10,200,000,000,000
8 sec.	13,600,000,000,000
10 sec.	17,000,000,000,000 !!

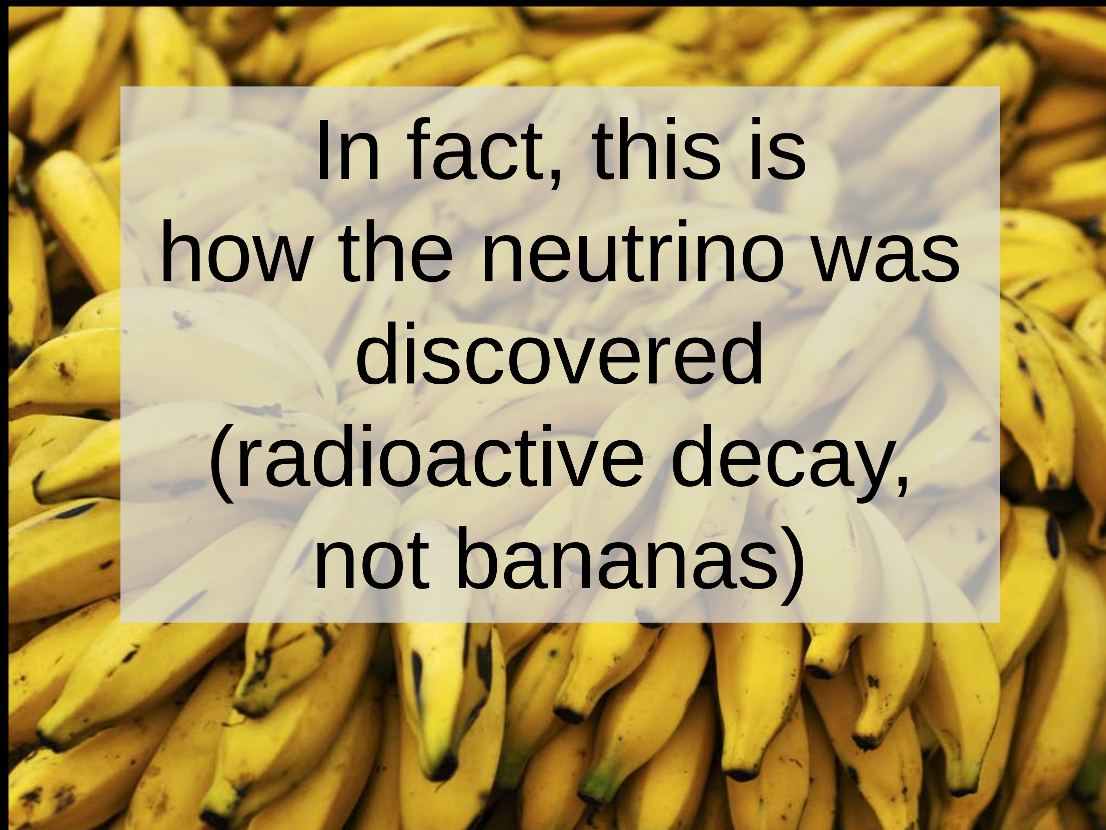


How many neutrinos is the Sun producing per second TOTAL?

≈20,000,000,000,000,000,000,000,000,000,000,000,000,000

= 2 x 10^{38} neutrinos/second!!

You don't have to look to the cosmos to find neutrinos. For example:



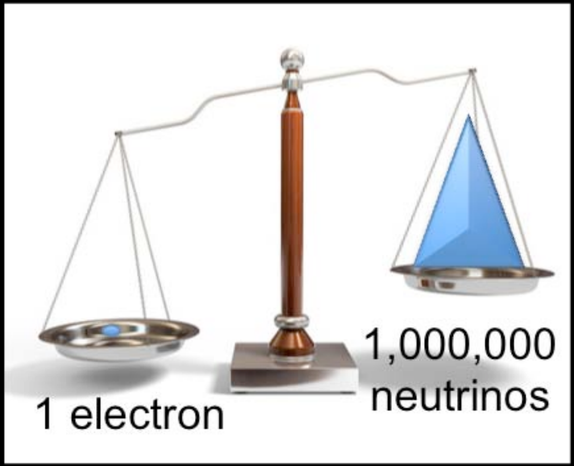
A banana emits about **1 million neutrinos/day** from decays of the small number of naturally occurring radioactive potassium atoms they contain!

It would seem that to understand
the Universe that we live in,
we will need to

understand

neutrinos

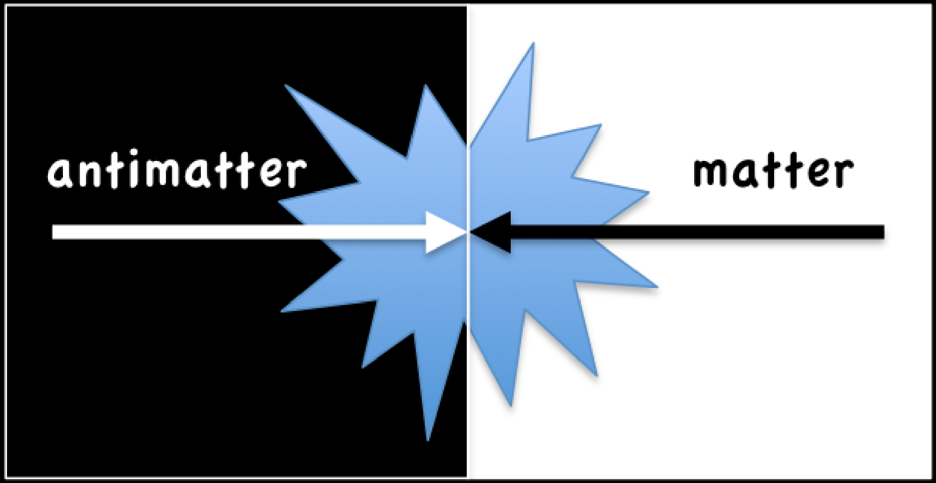
So what might they tell us?



Neutrinos are very very very light

Why?

How is it
that we exist,
anyway?



So what might they tell us?

New detectors to look for neutrinos from:

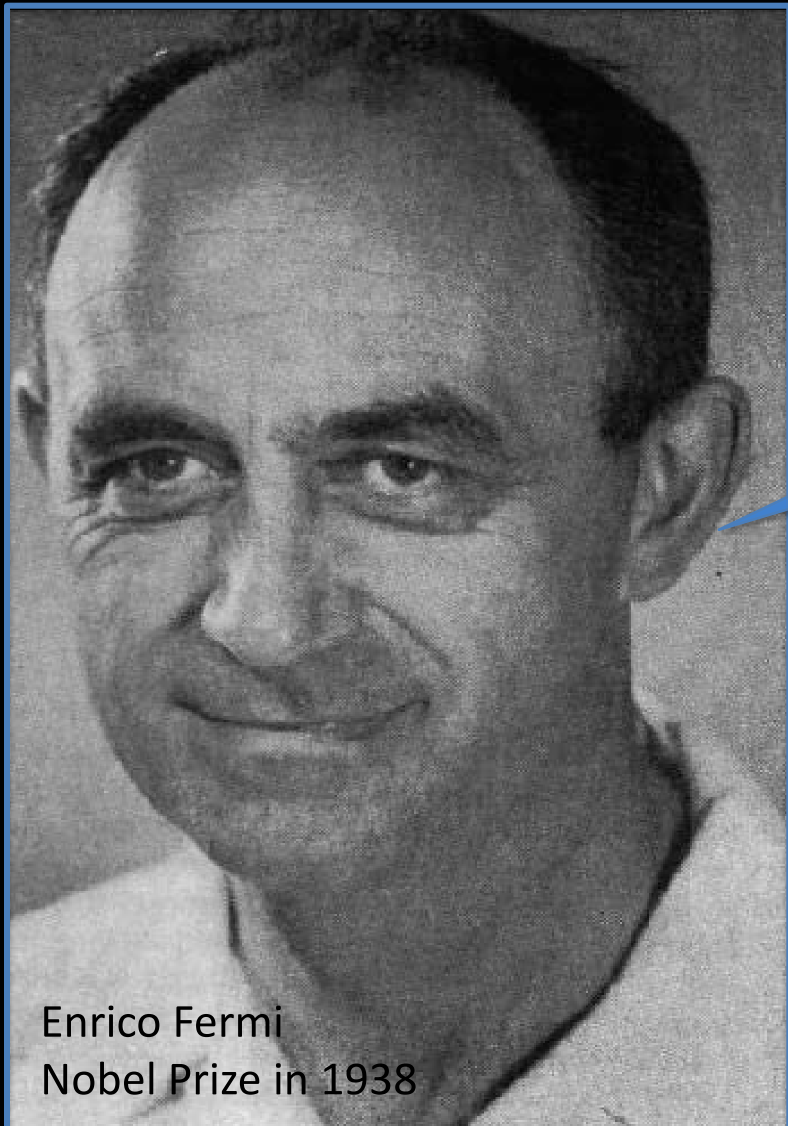
The Sun

Supernovae explosions

Ultra-high-energy neutrino sources

Big Bang relic neutrinos

Center of the Earth


Enrico Fermi
Nobel Prize in 1938

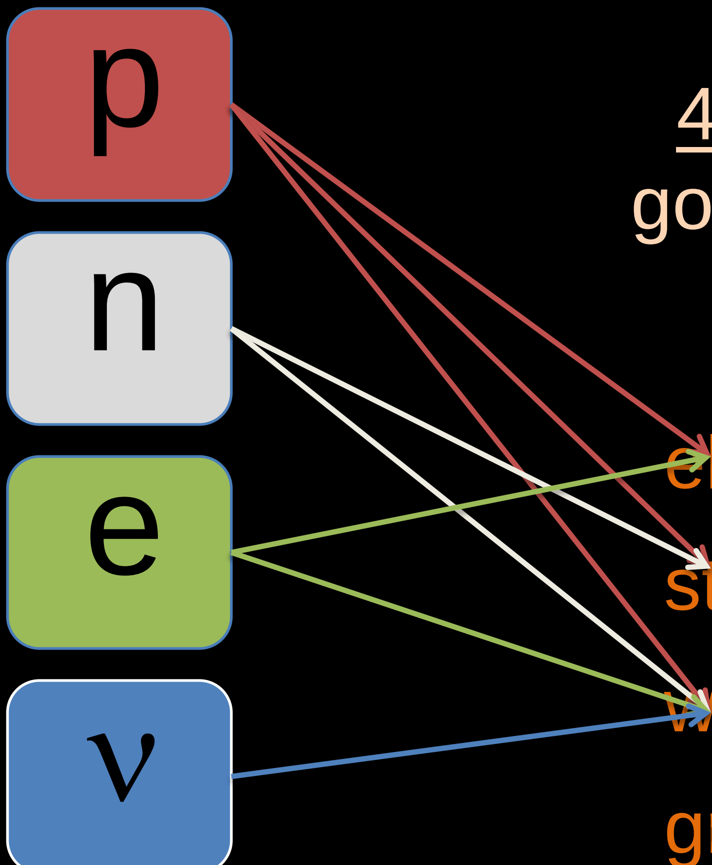
<u>neutrino</u>: ORIGIN mid 20th cent.: from Italian, diminutive of ***neutro.***

Little, neutral object.

It was Enrico Fermi who first calculated the mechanism for detecting a neutrino in 1934

ANSWER: It would be very difficult. In fact, it would take more than 20 years.

What in the world took so long?



The answer lies in the 4 fundamental forces that govern the interactions of all matter in the Universe:

electromagnetic force

strong nuclear force

weak nuclear force

~~gravitational force~~

What in the world took so long?

From Fermi's theory, one can calculate how far an average neutrino of a given energy travels before interacting

Neutrinos produced by the Sun are pretty low energy:

d ≈ 1.5 x 10^{16} meters in lead

that's over 1.5 light years of solid lead!!!

Neutrinos
(and hopefully not this talk)
really do go In One Ear and Out the Other!

A typical neutrino

from the Sun would pass right through

10,000,000,000,000,000,000

(10 Quintillion) people in a line and not interact with any of them!

What in the world took so long?

From Fermi's theory, one can calculate how far an average neutrino of a given energy travels before interacting

Neutrinos produced at Fermilab ~1000 times more energy:

d ≈ 1.5 x 10^{12} meters in lead

a bit better, but still

≈930,000,000 miles of lead

What in the world took so long?

From Fermi's theory, one can calculate how far an average neutrino of a given energy travels before interacting

For comparison, a proton from the Fermilab Booster:

d ≈ 10 centimeters in lead !!!!

To overcome the incredibly FEEBLE interaction of the neutrino with matter,

studying neutrinos requires

very intense neutrino sources

and

special detectors

Ray Davis
knew this well

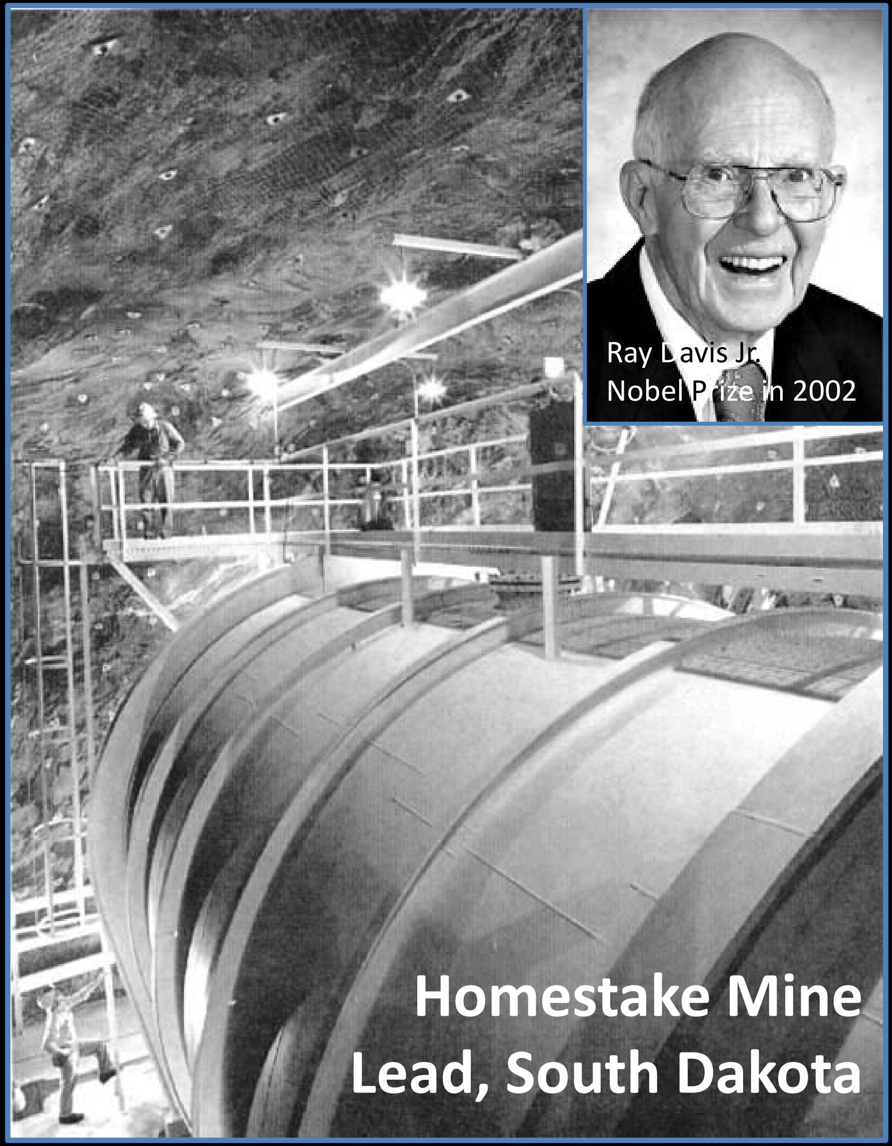
615 tons of cleaning fluid

4,850 ft. below ground
in Homestake Mine in
South Dakota

late 1960s – 1970s

solar neutrino + Chlorine atom

→ electron + Argon atom



After two months, Davis would need to extract about

30 atoms of Argon

from a tank with

10,000,000,000,000,000,000,000,000,000,000 total atoms!!

What he found was about 1/3 of the total number of argon atoms as was expected

This discrepancy would go without explanation for more than 30 years

The electron’s big brother, the muon, was discovered way back in 1936, but seemed to not fit in at the time

p

n

e

ν

μ

Identical to the electon
except 200x heavier

“Who ordered that?” -I.I. Rabi

The electron’s big brother, the muon, was discovered way back in 1936, but seemed to not fit in at the time

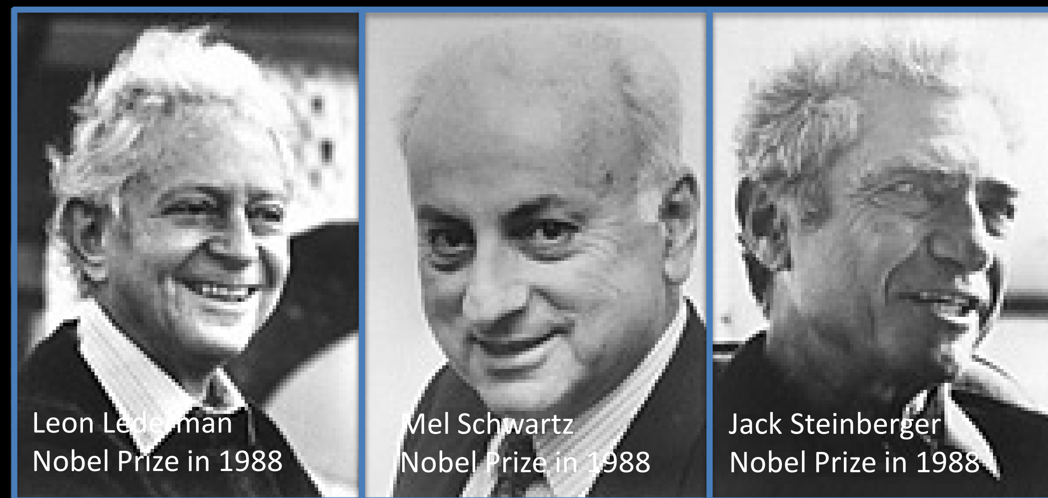
p

n

e μ

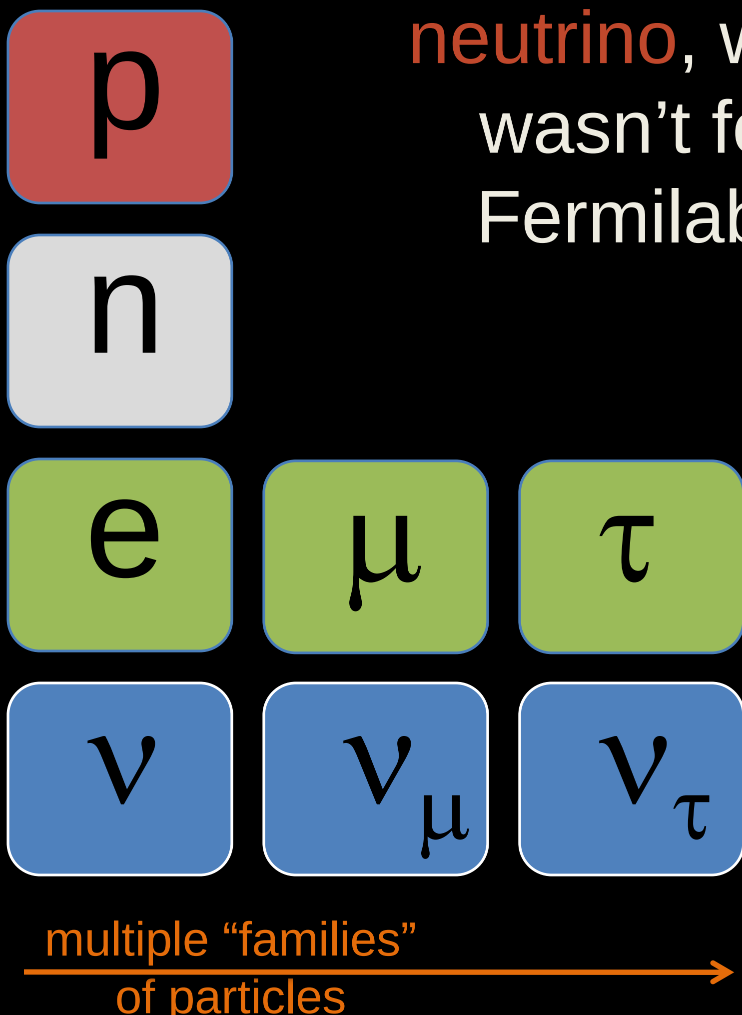
ν ν_μ

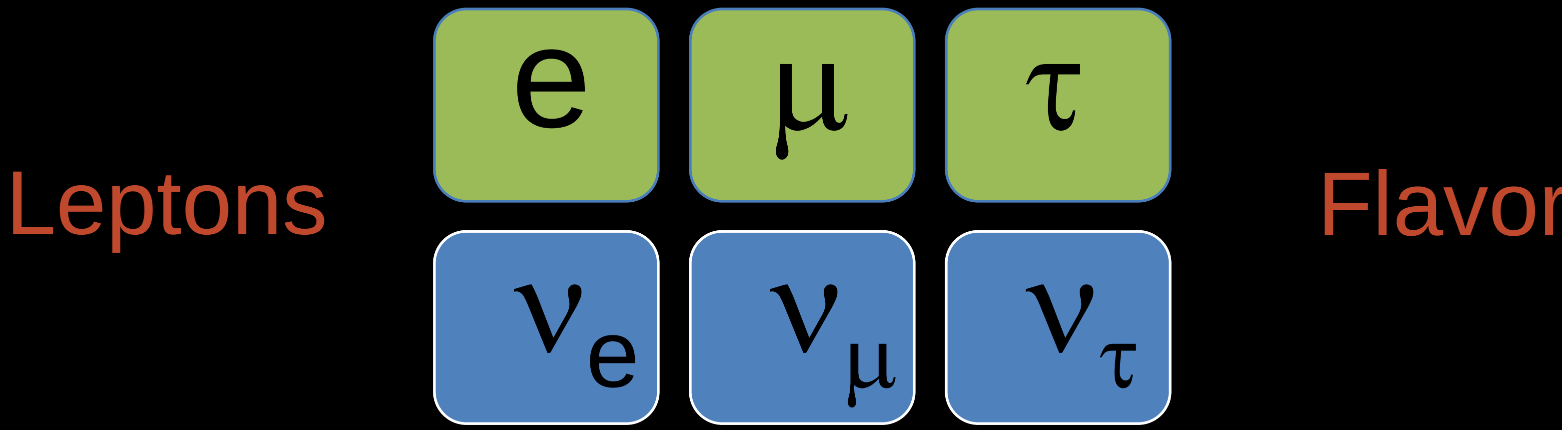
multiple “families” of particles



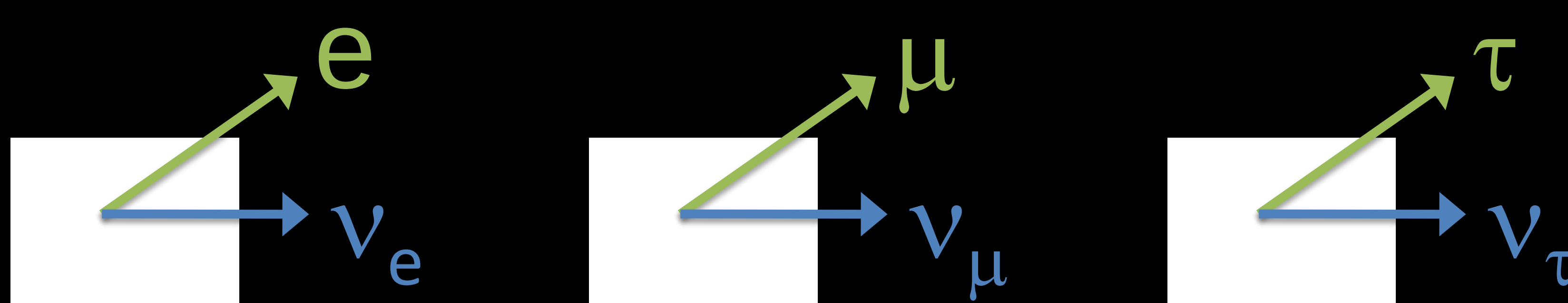
Leon Lederman, Melvin Schwartz and Jack Steinberger made the surprising discovery of a second type of neutrino, the muon neutrino, in 1962

The third type of neutrino, the tau neutrino, was so difficult to detect, that it wasn't found until 2000 right here at Fermilab by the DONUT experiment



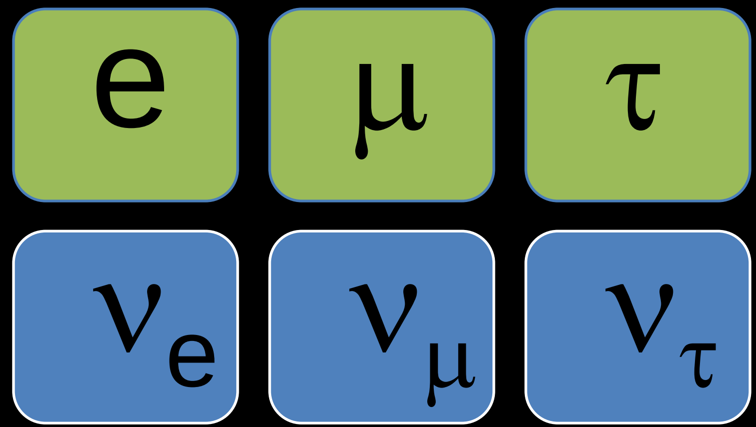


Neutrinos ONLY interact with members of their own family



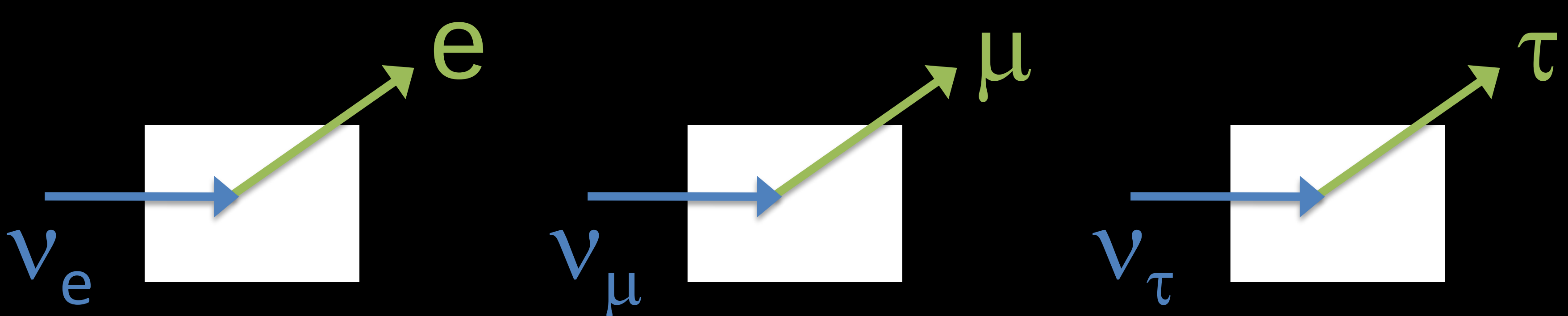
Neutrino is created

Leptons



Flavor

Neutrinos <u>ONLY</u> interact with members of their own family



Neutrino is destroyed

The next search…

neutrinos from the atmosphere

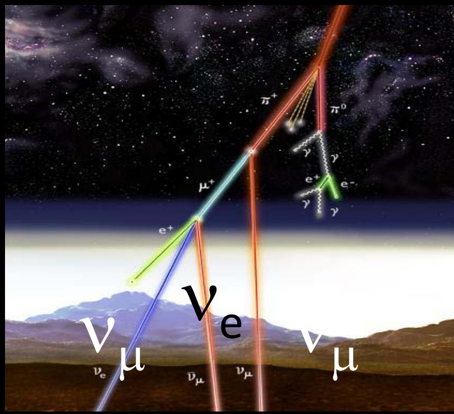
expect 2 times more ν_μ than ν_e

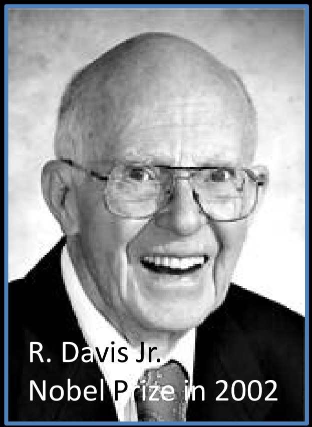
found $\nu_\mu \sim \nu_e$

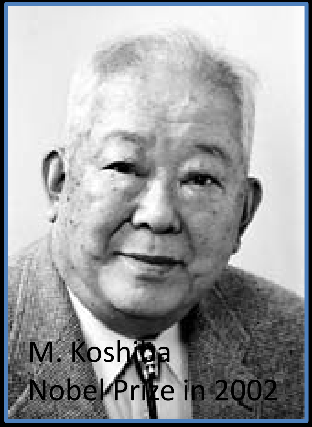
Where are all the neutrinos going?!?

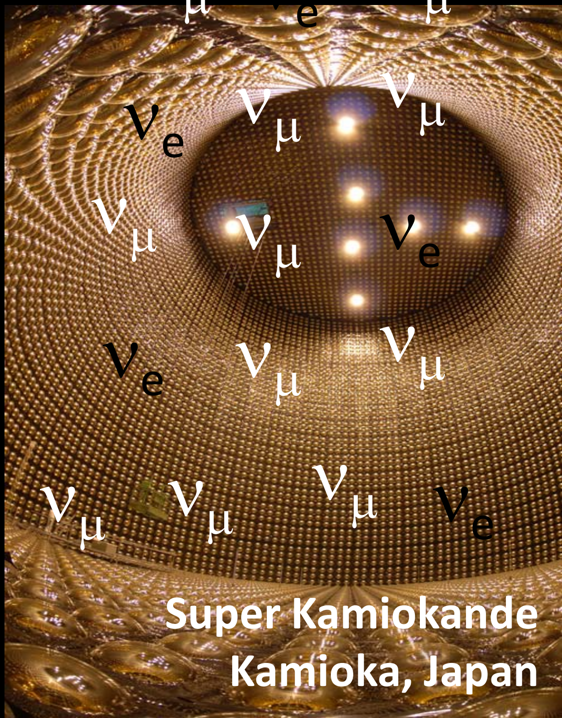
Not seeing enough electron neutrinos from the Sun

Not seeing enough muon neutrinos from the atmosphere









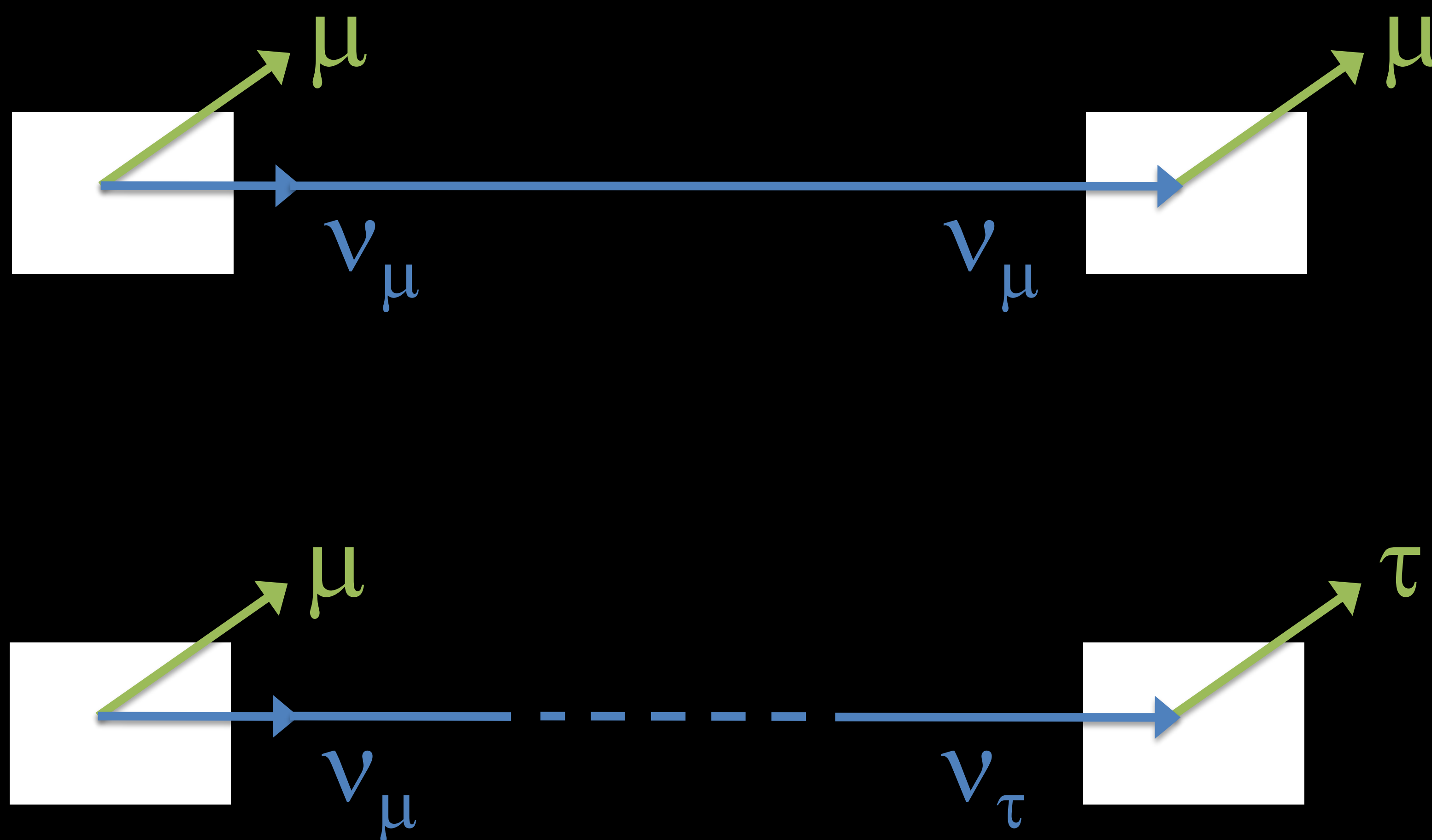
Where are all the neutrinos going?!?

Not seeing enough electron neutrinos from the Sun

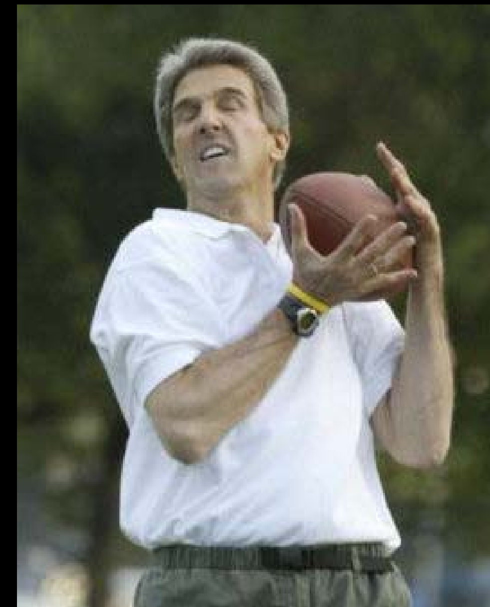
Not seeing enough muon neutrinos from the atmosphere

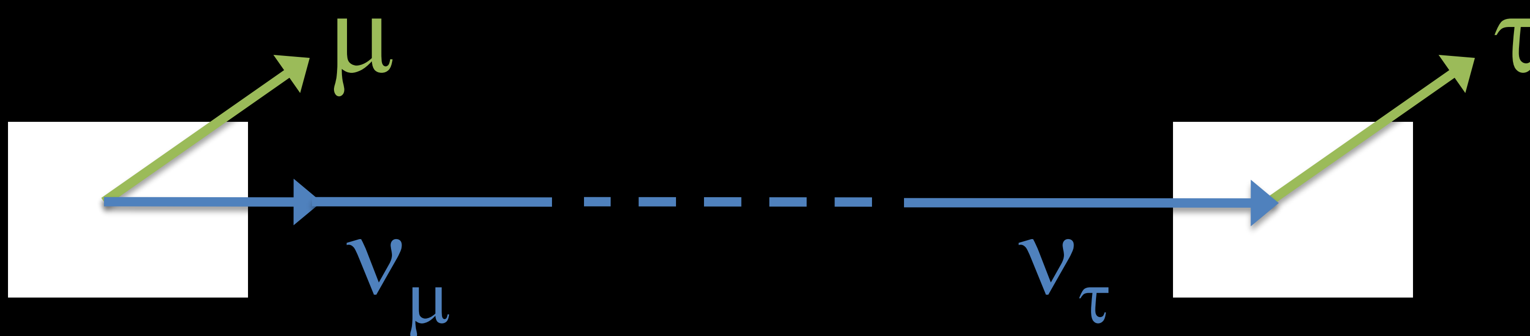
Enter the idea of

neutrino oscillations



μ
μ
ν
μ
ν
μ
μ
τ
ν
μ
ν
τ





μ
τ
ν_μ
ν_τ

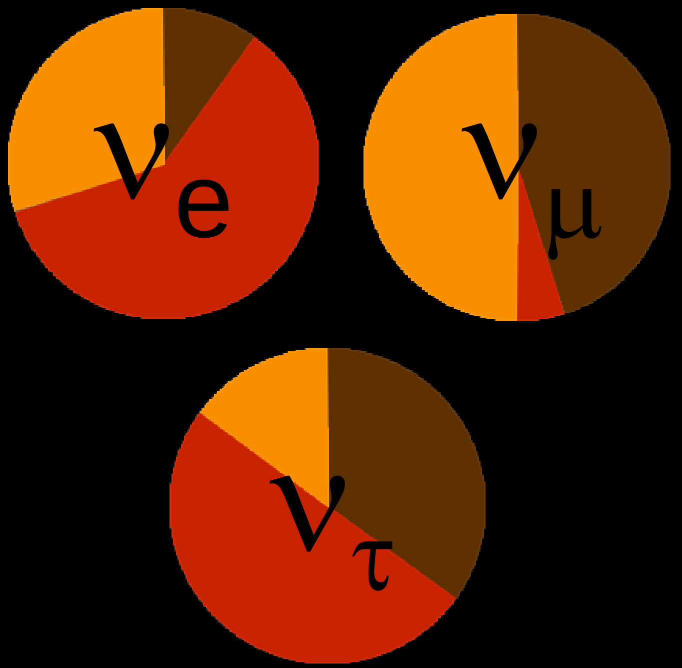
This could be possible if:

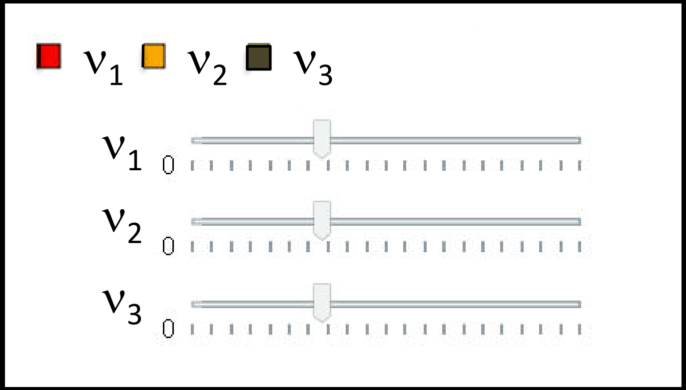
The ν_e, ν_μ and ν_τ are not the real particles!

but

The real neutrinos mix together to makeup ν_e, ν_μ and ν_τ

and these real neutrinos have different masses



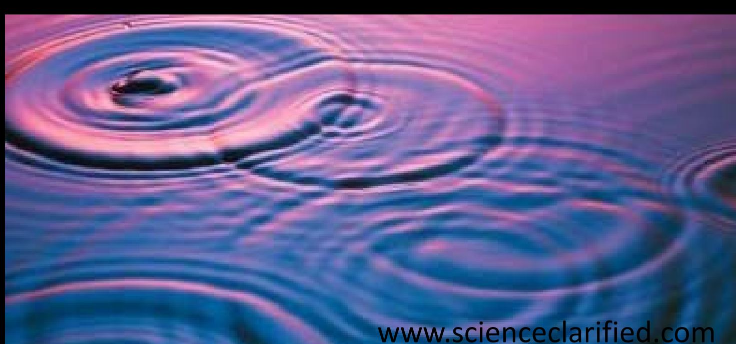


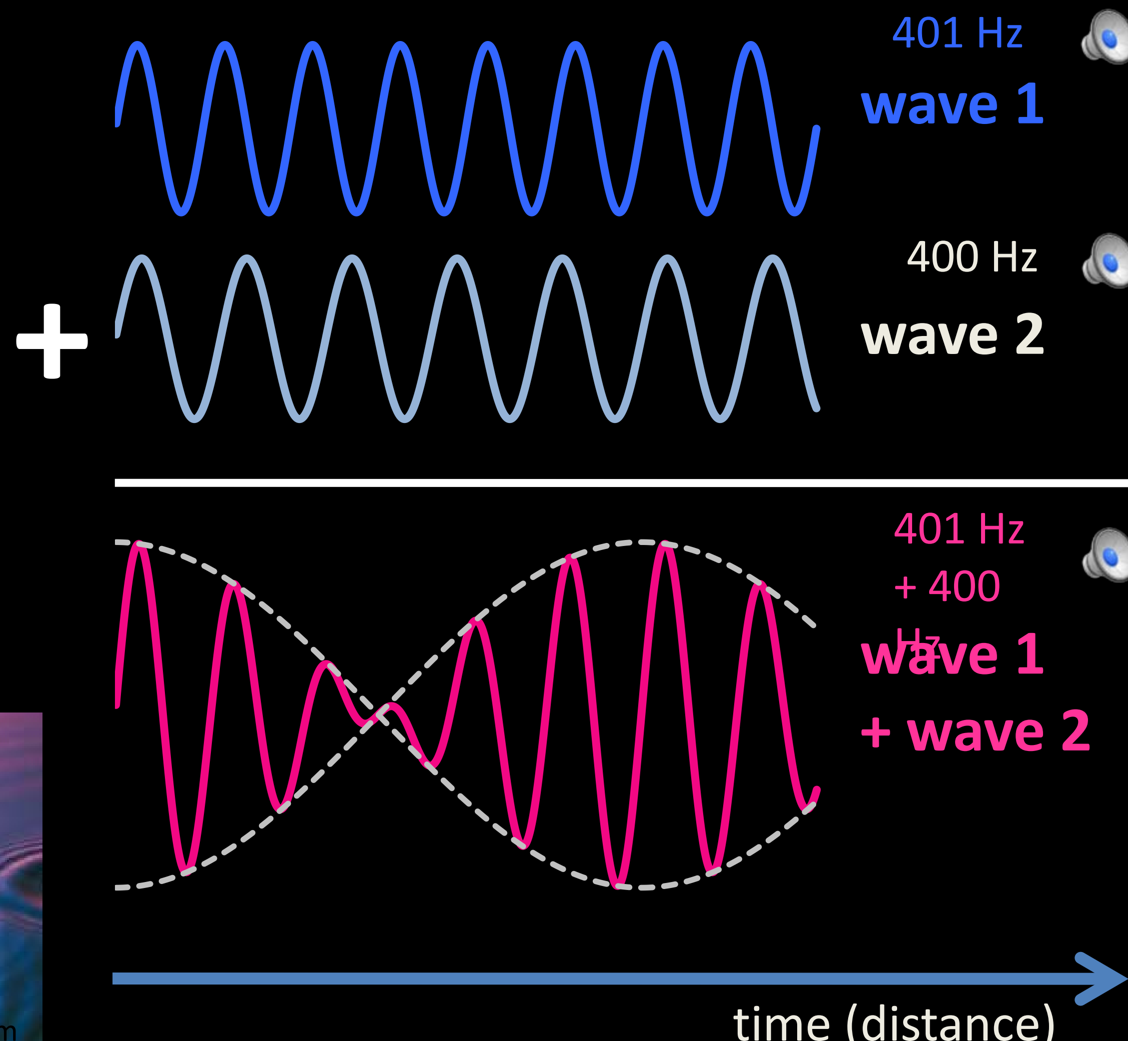
neutrino oscillations

Quantum mechanics
particle ←→ wave
mass determines frequency

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

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





Important Question:

Can we reproduce

the effect we are seeing in

neutrinos from the cosmos

here on Earth

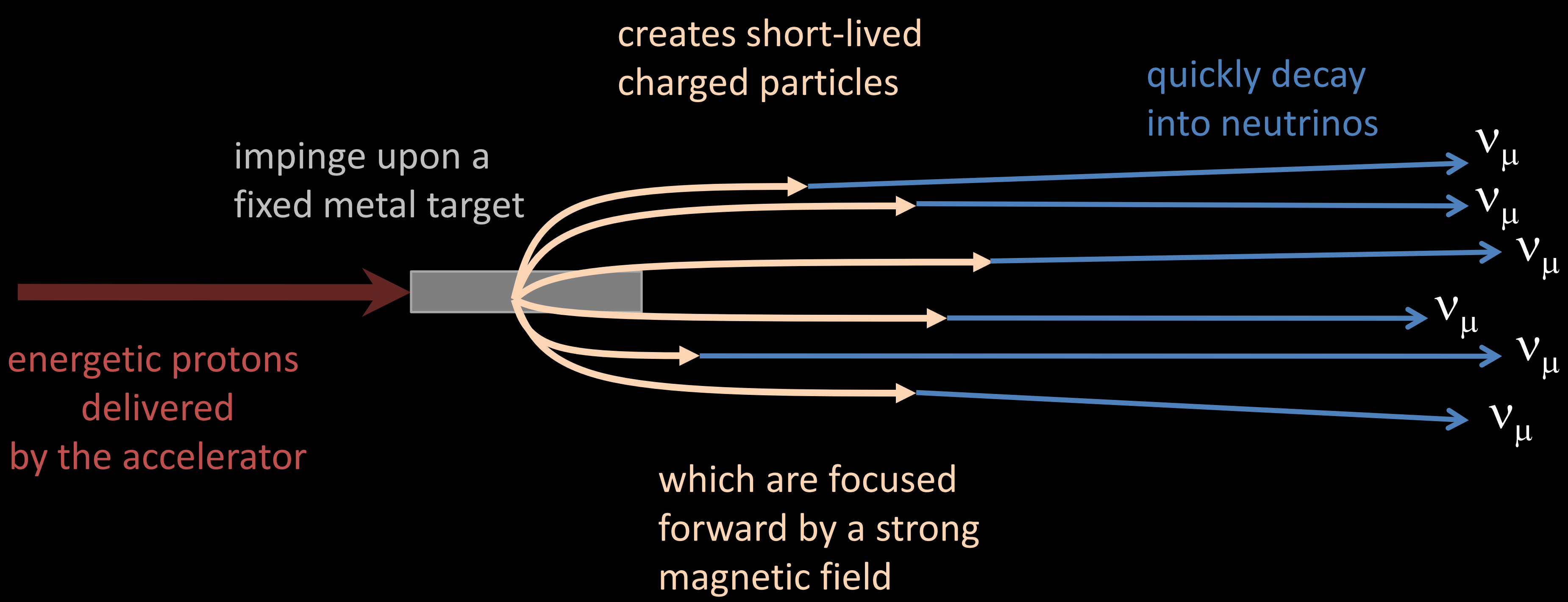
in the laboratory?

Turns out that you can use an

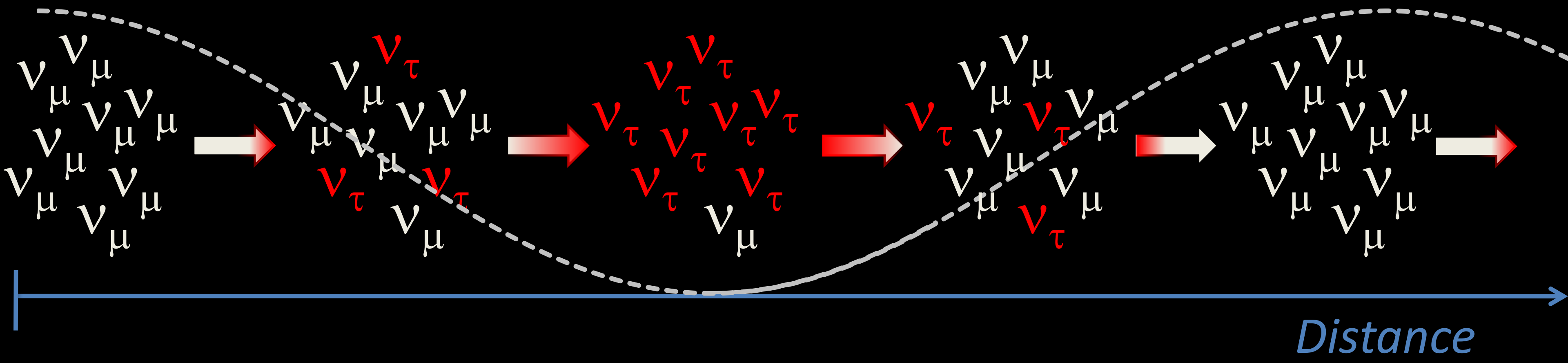
intense beam of protons

to create an

intense beam of neutrinos



And look for them to oscillate



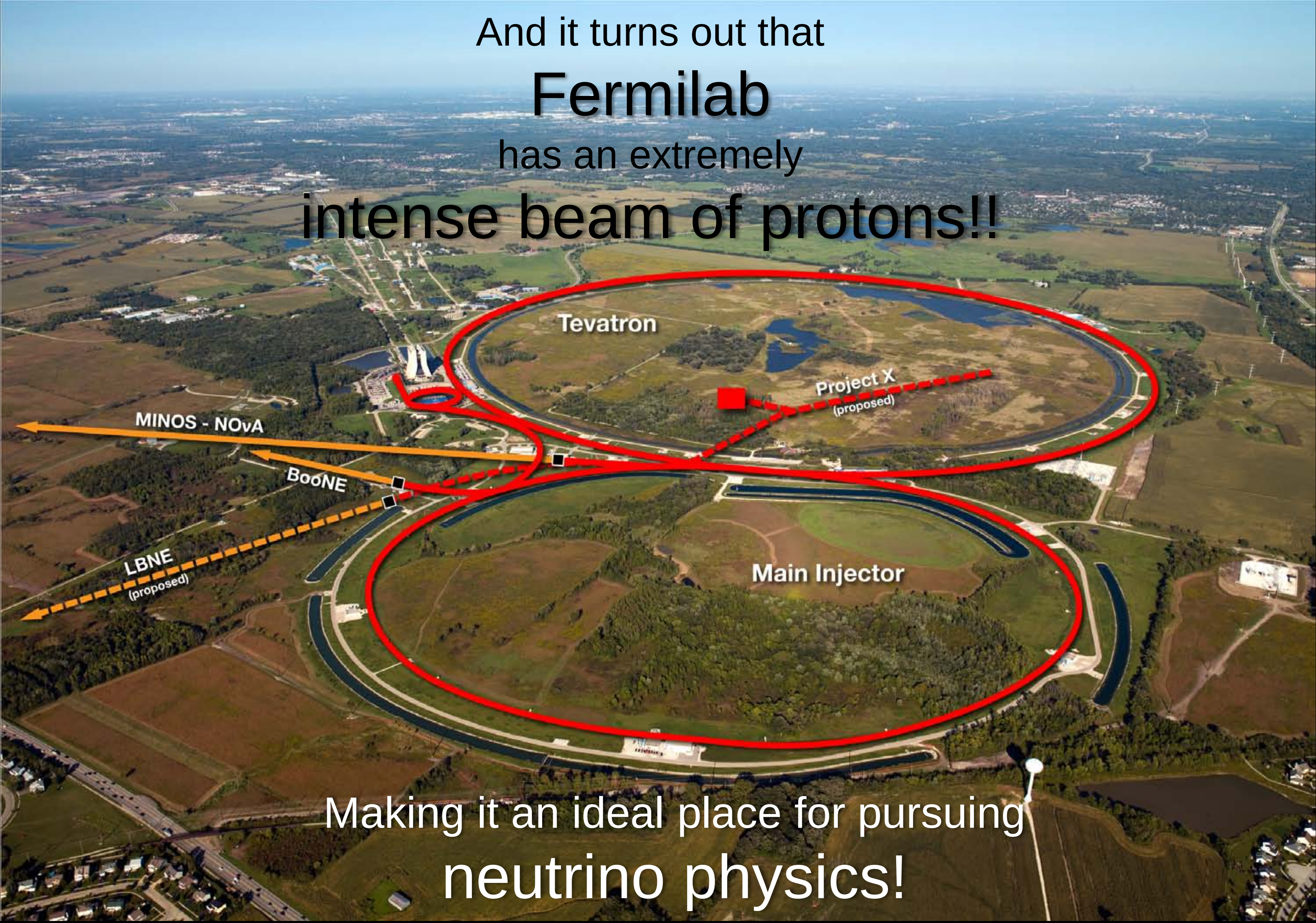
But you need a LOT of neutrinos because of how feebly they interact

And it turns out that

Fermilab

has an extremely

intense beam of protons!!



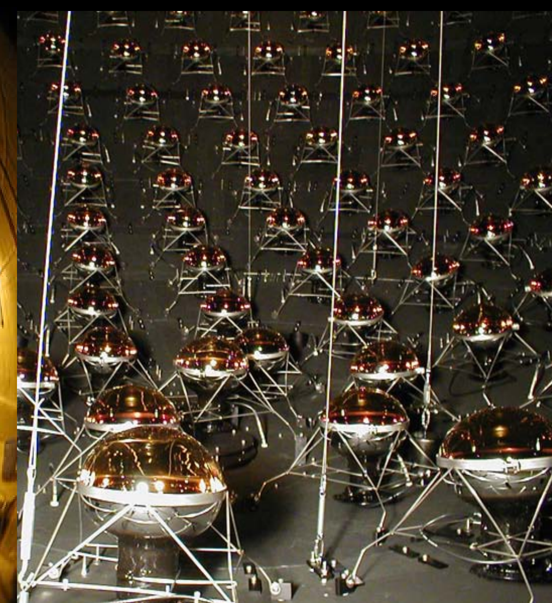
Making it an ideal place for pursuing

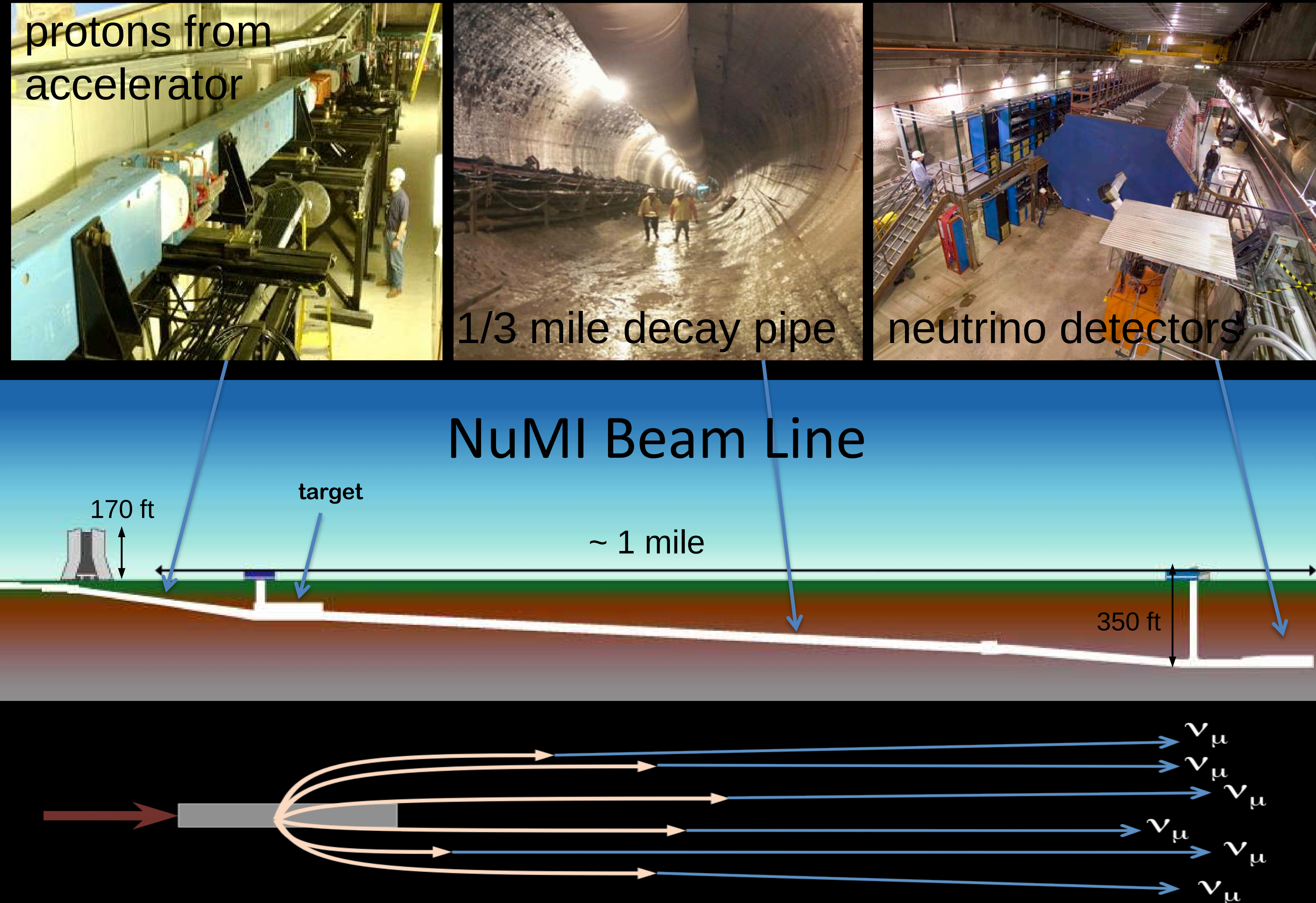
neutrino physics!

From the beginning…

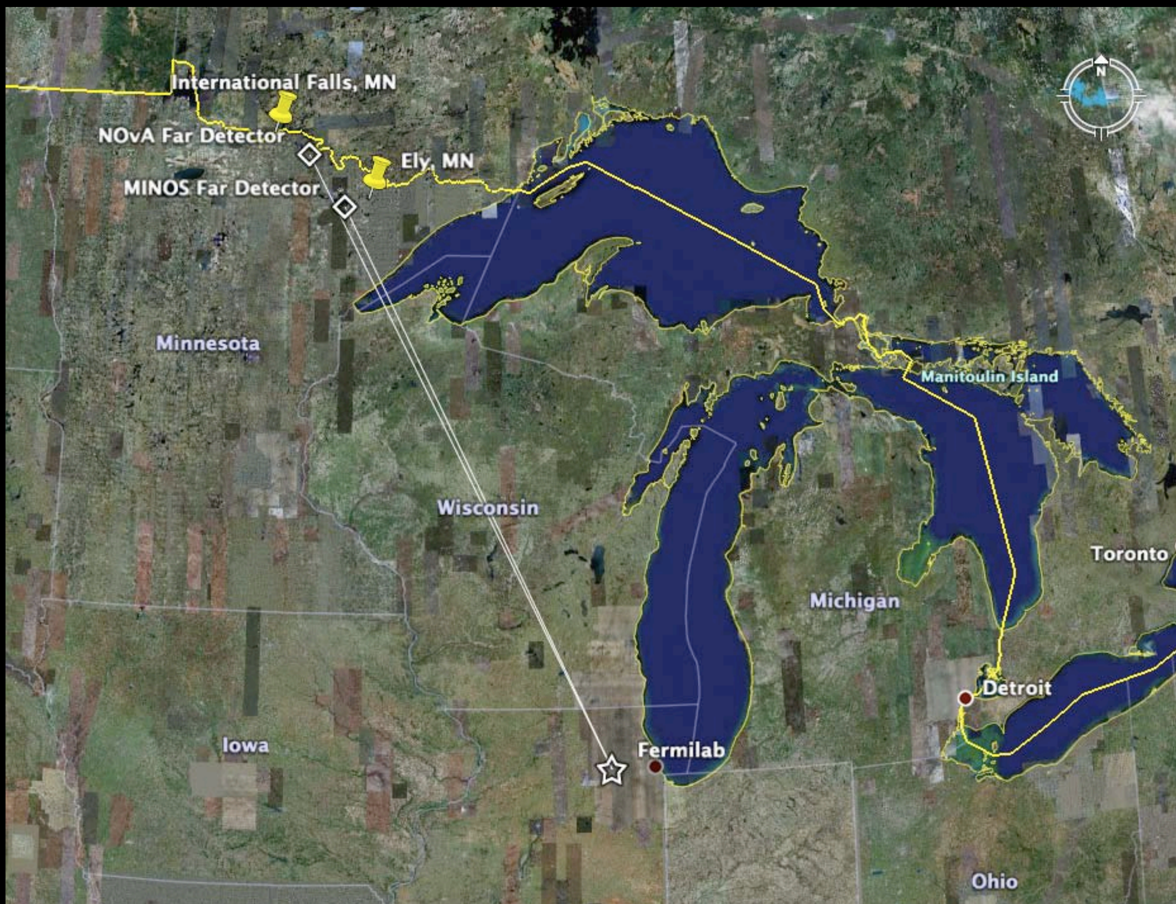
"One of the first aims of experiments on the NAL accelerator system will be the detection of the neutrino. I feel that we then will be in business to do experiments on our accelerator."
-Bob Wilson (1971)

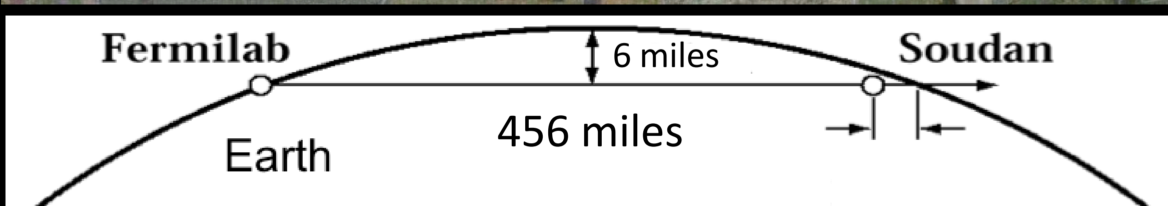
To Today…




protons from accelerator
1/3 mile decay pipe
neutrino detectors
NuMI Beam Line
target
170 ft
~ 1 mile
350 ft
νμ
νμ
νμ
νμ
νμ
νμ

Where are all those neutrinos headed?

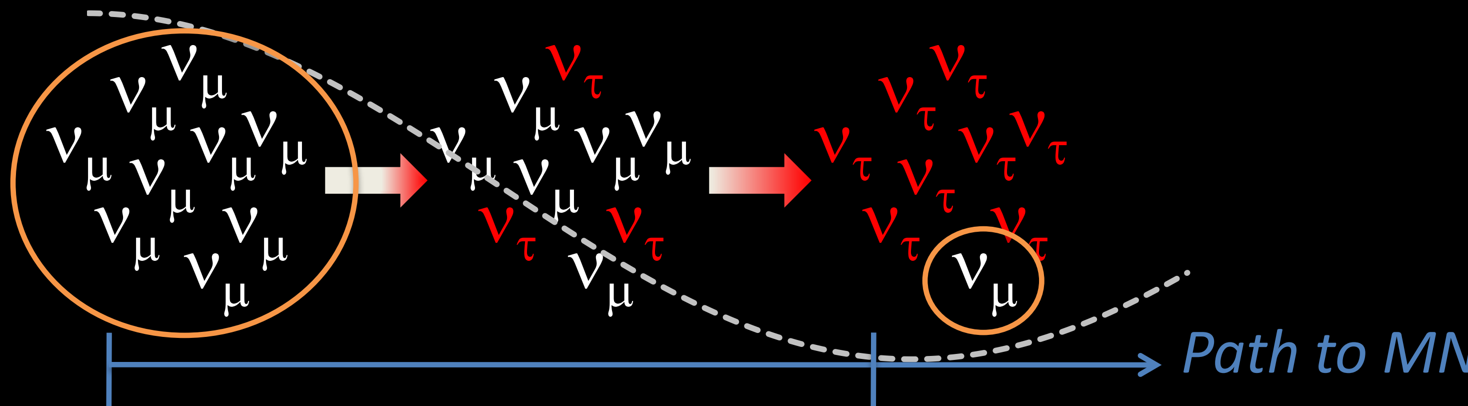




North!

And they make the journey from Fermilab to northern Minnesota in 1/400th of a second!

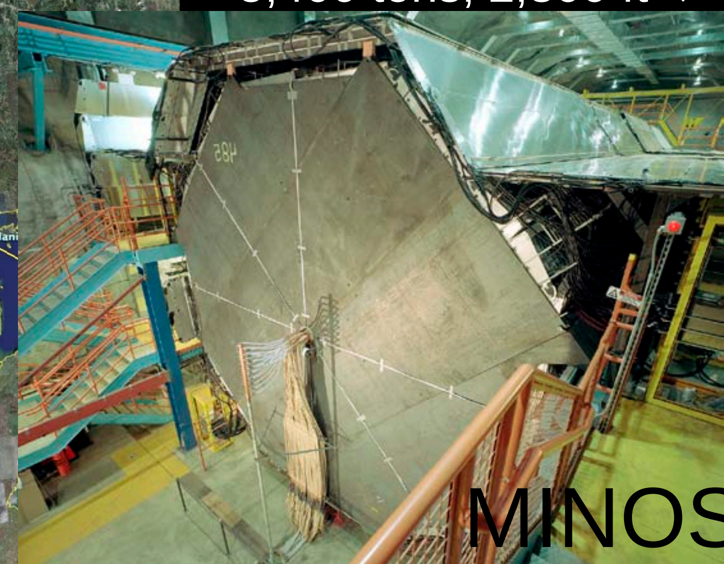
But will they change their flavor?!?



0 miles
Fermilab

456 miles
Soudan, MN

5,400 tons, 2,300 ft ↓

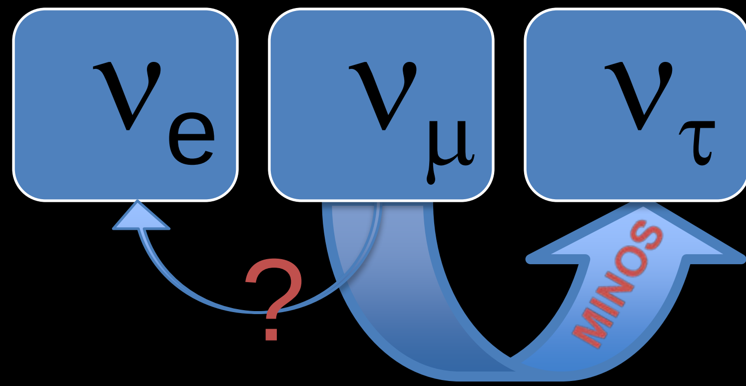


Neutrino oscillations are a very recent discovery in the world of modern particle physics

my undergraduate textbook

“This is about the simplest nontrivial quantum system conceivable. It is a crude model for neutrino oscillations. . . . . At present this is highly speculative – there is no experimental evidence for neutrino oscillations”

David J. Griffiths – *Introduction to Quantum Mechanics* (Problem 3.58) 1995



ν_e
ν_μ
ν_τ
?
MINOS

Rich physics in this next stage!!

ν_e ν_μ ν_τ

This is why to keep going!

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

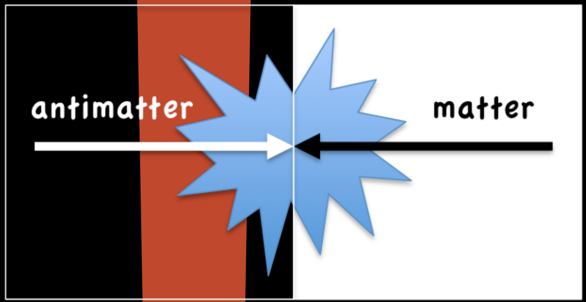
$$T_2 = \sin\delta_{CP}\sin 2\theta_{12}\sin 2\theta_{23}\sin\Delta\frac{\sin(x\Delta)}{x}\frac{\sin[(1-x)\Delta]}{(1-x)}$$

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

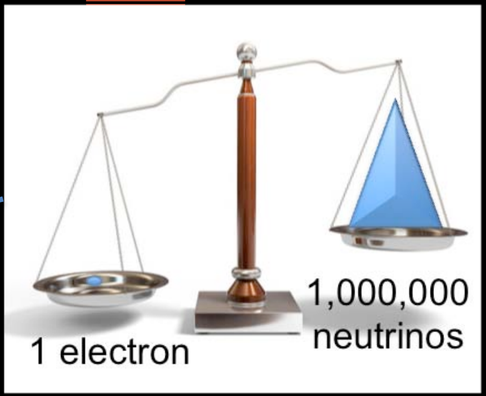
$$T_4 = \cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2(x\Delta)}{x^2}$$

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

matter/antimatter parts



mass ordering parts

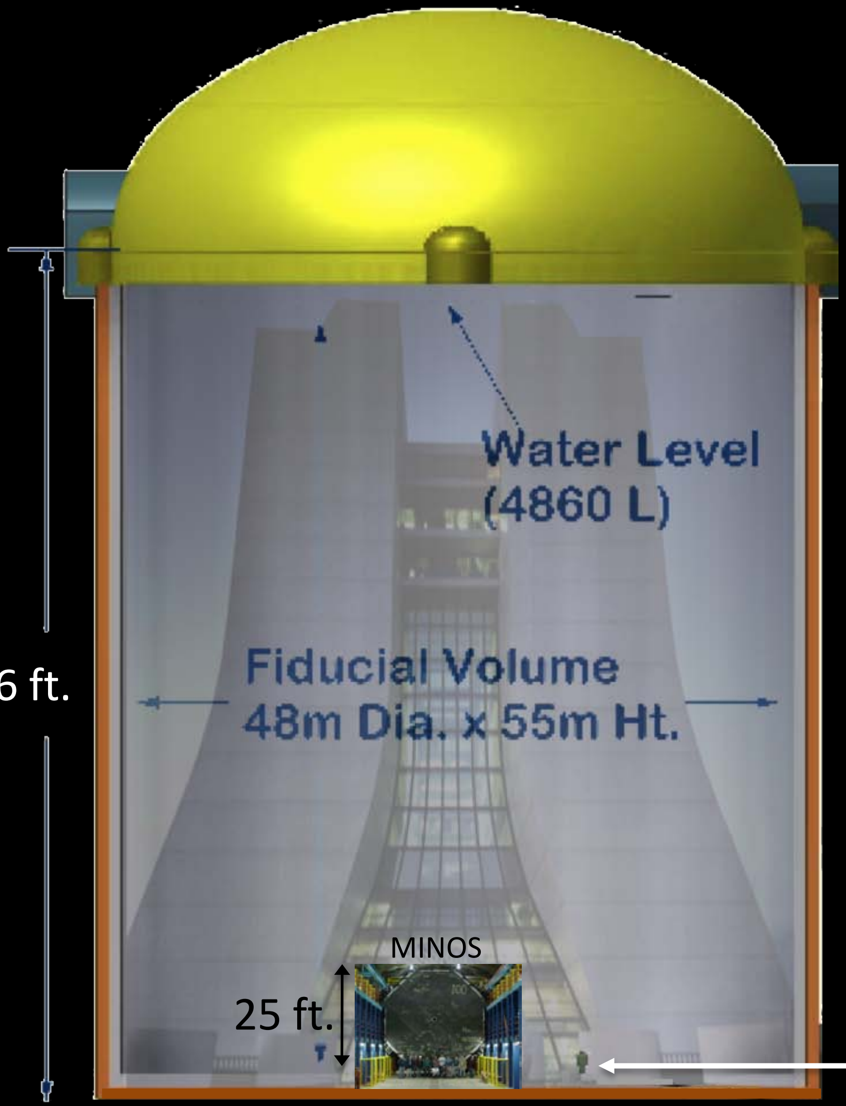


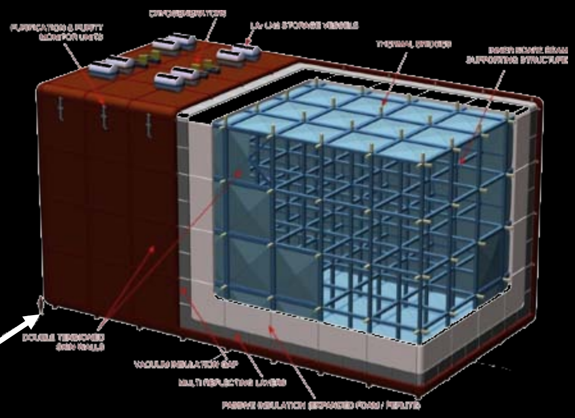

Return To Davis's Homestake Mine?
DUSEL Underground Lab
South Dakota
Minnesota
MINOS Neutrino Detector
Nebraska
800 miles
450 miles
Wisconsin
Iowa
Michig
Milwaukee
Fermilab
Chicago
Image © 2008 TerraMetrics
© 2008 Europa Technologies
Image NASA
© 2008 Tele Atlas
Google
Missouri
43°14'04.36" N 92°07'15.58" W
Eye alt 678.31 km

Long Baseline Neutrino Experiment (LBNE)

the next big thing ☺

206 ft.





neutrino physicists

Neutrinos have taught us a lot about themselves and about the Universe (like how the Sun shines, oscillations…)

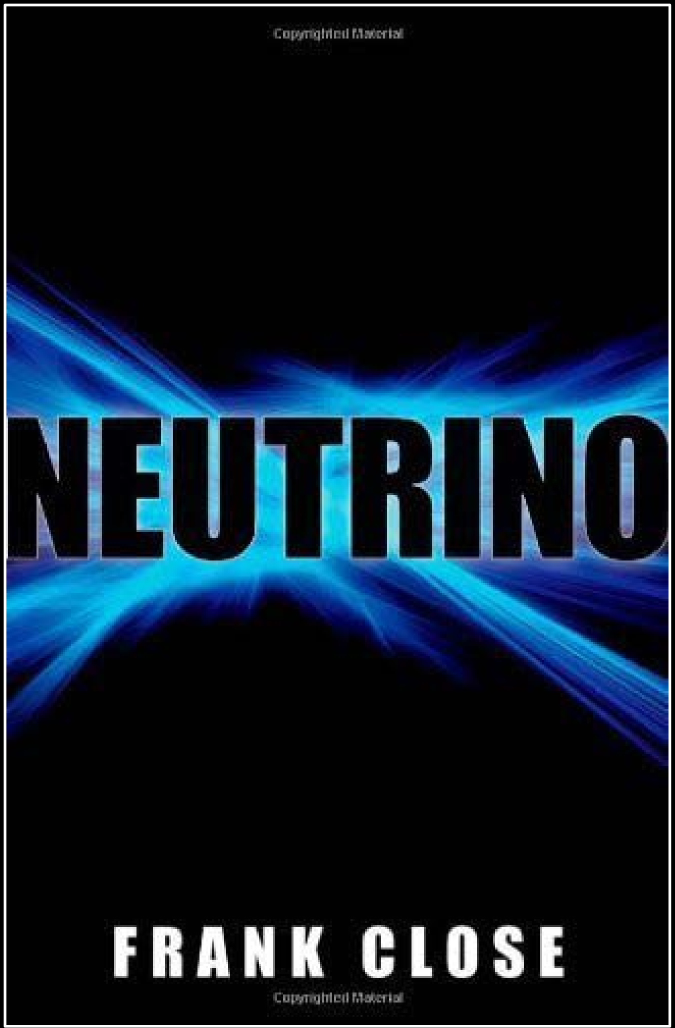
Feels like the tip of the iceberg
What else will the neutrino reveal to us about matter and the workings of the Universe?

So we push ahead to see where the neutrino leads us!

And hopefully, these littlest of little, ghost-like particles will continue to inspire the imaginations of us all…

Interested in more?

YouTube: Boris Kayser
Neutrinos Get Under Your Skin



Thank you very much!

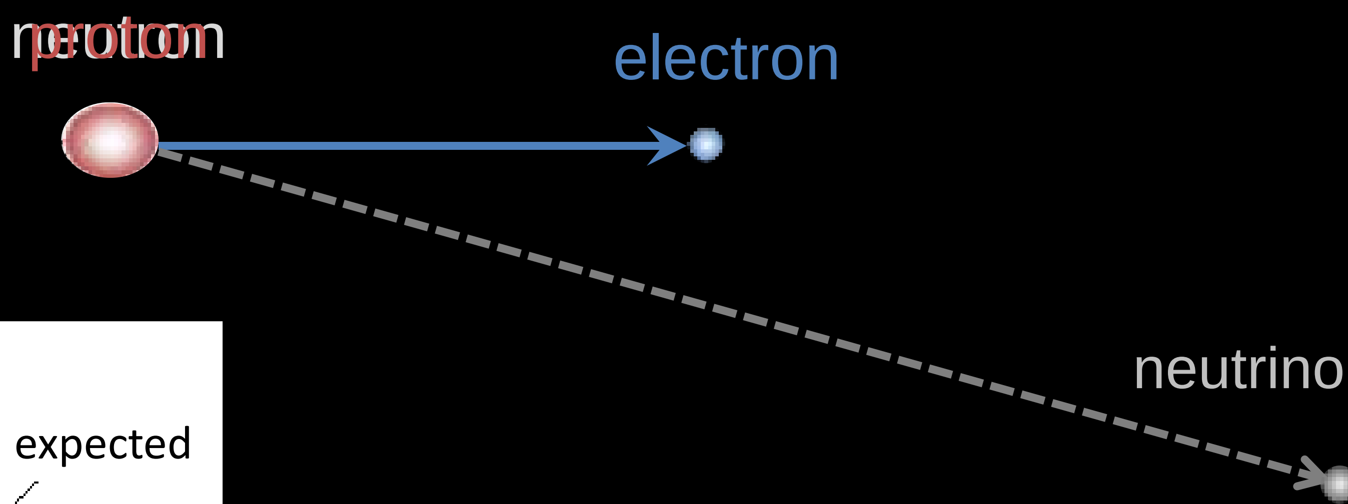
extras

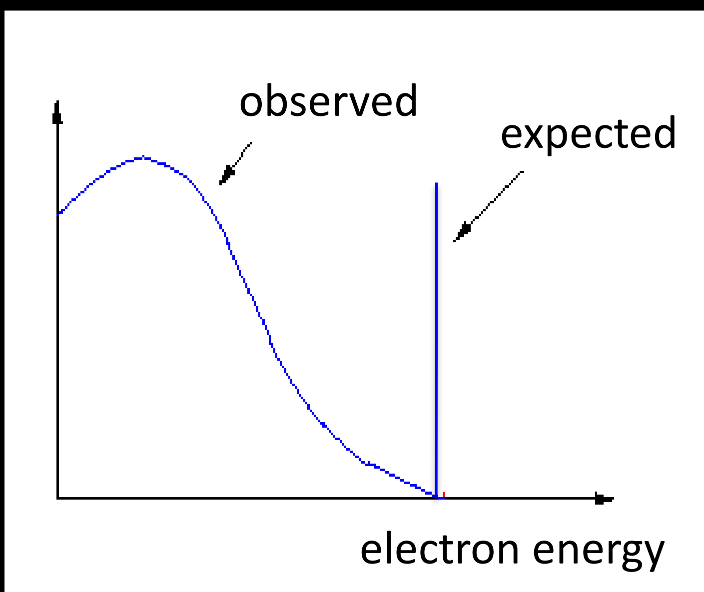
Cosmic Gall

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)

By 1931, it was well known that an atom could change from one variety into another when a neutron converts to a proton by emitting a “beta” particle (electron)





Wolfgang Pauli’s
“Desperate remedy”

Dear Radioactive Ladies and Gentlemen,

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

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

Your humble servant,

W. Pauli

Wolfgang Pauli
Nobel Prize in 1945

Setting out to detect the first neutrino

Fred Reines & Clyde Cowen   Project Poltergeist (1950's)

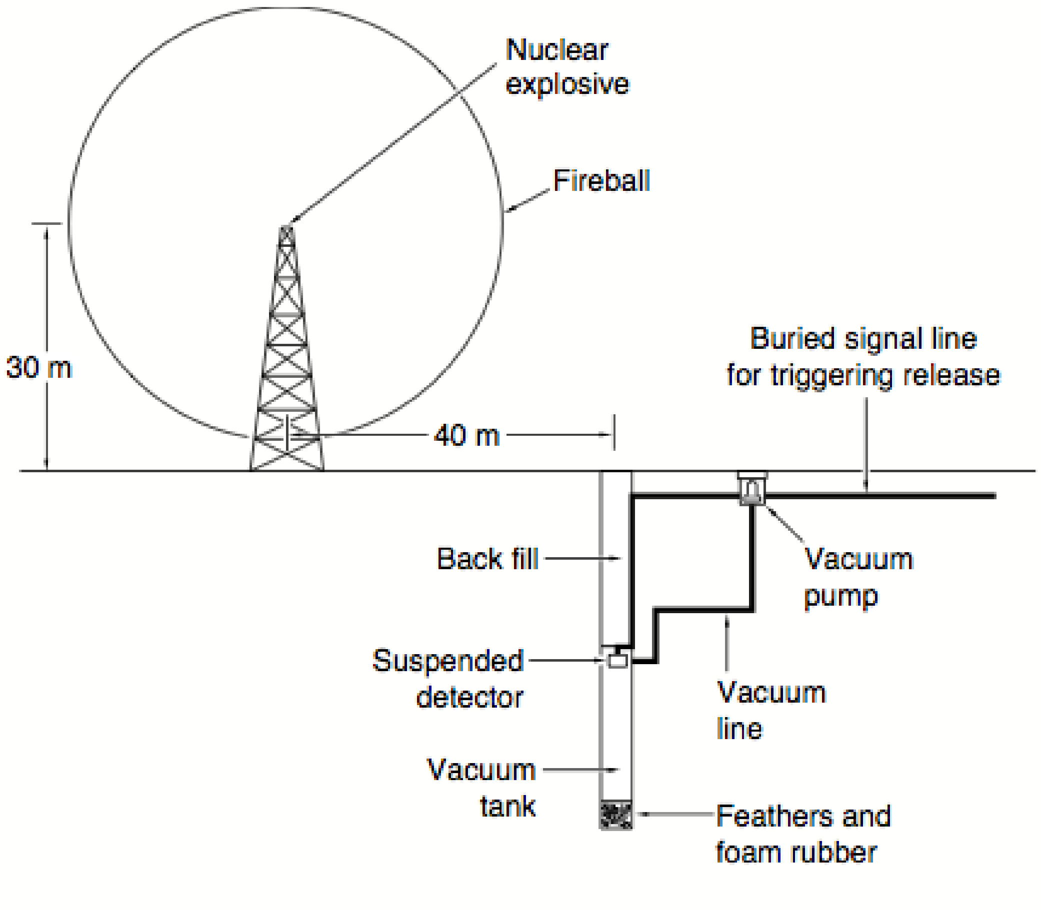
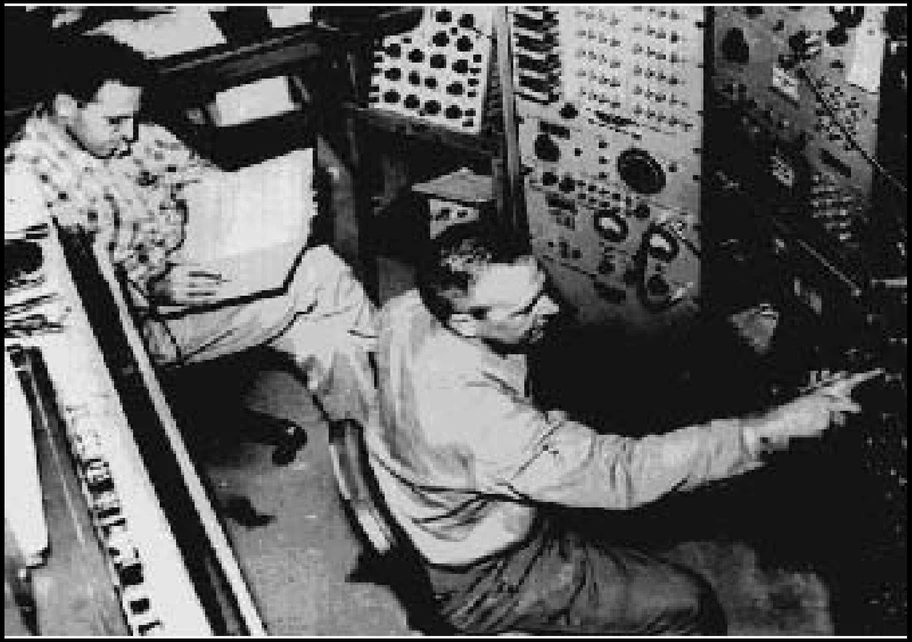
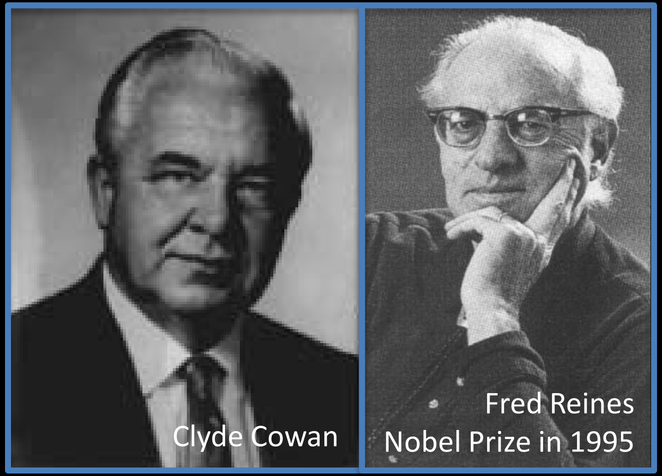
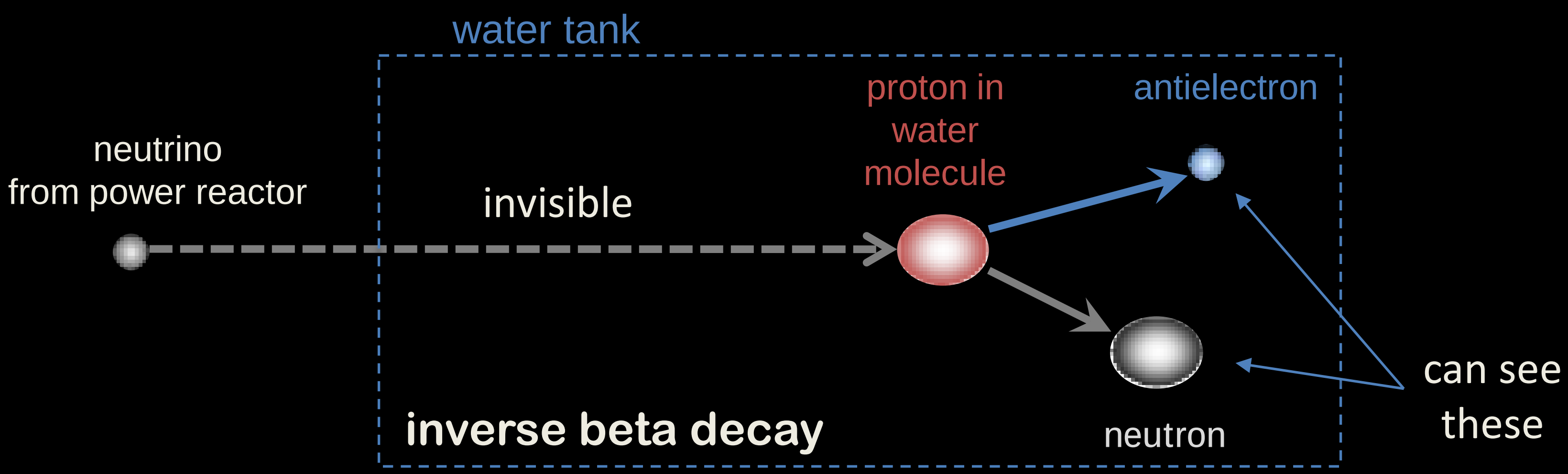


Figure 1. Detecting Neutrinos from a Nuclear Explosion

Project Poltergeist (1956)







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

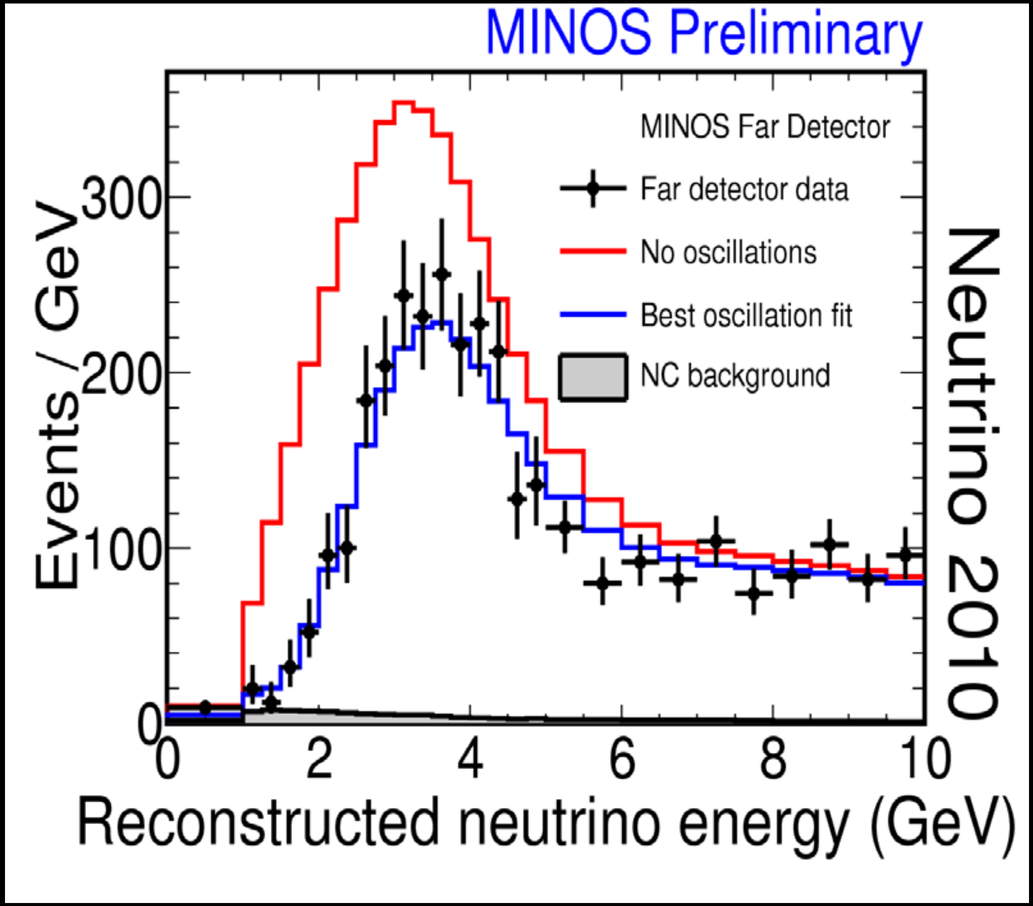
- Fred Reines and Clyde Cowan (1956)

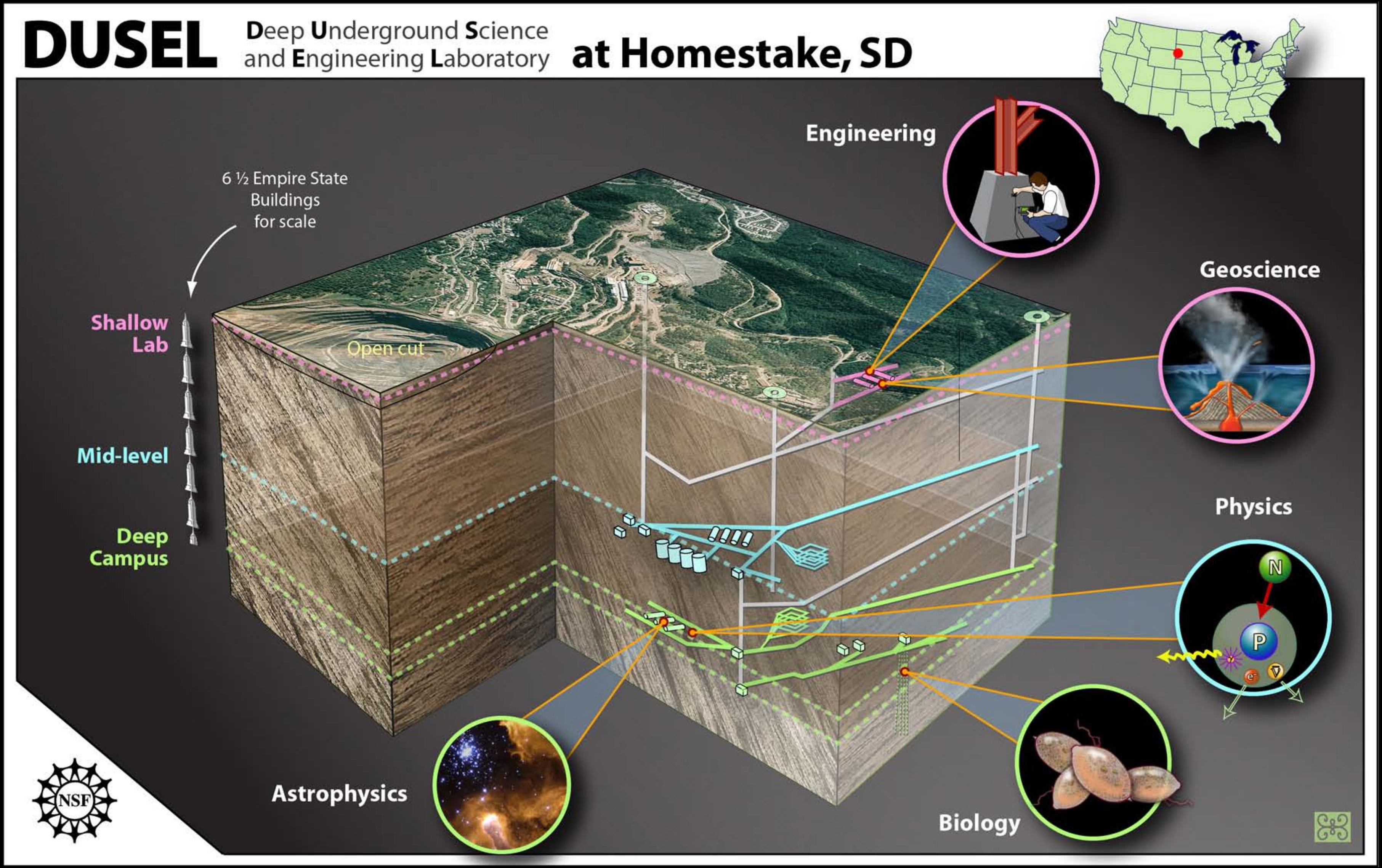
"Everything comes to him who knows how to wait."

- Wolfgang Pauli

It had taken 25 years to detect the first of Pauli's neutrino!

The muon neutrinos disappeared just like the ones in the atmosphere!!




DUSEL
Deep Underground Science and Engineering Laboratory
at Homestake, SD
Engineering
6 ½ Empire State Buildings for scale
Geoscience
Shallow Lab
Open cut
Mid-level
Physics
Deep Campus
N
P
e
Astrophysics
Biology
NSF