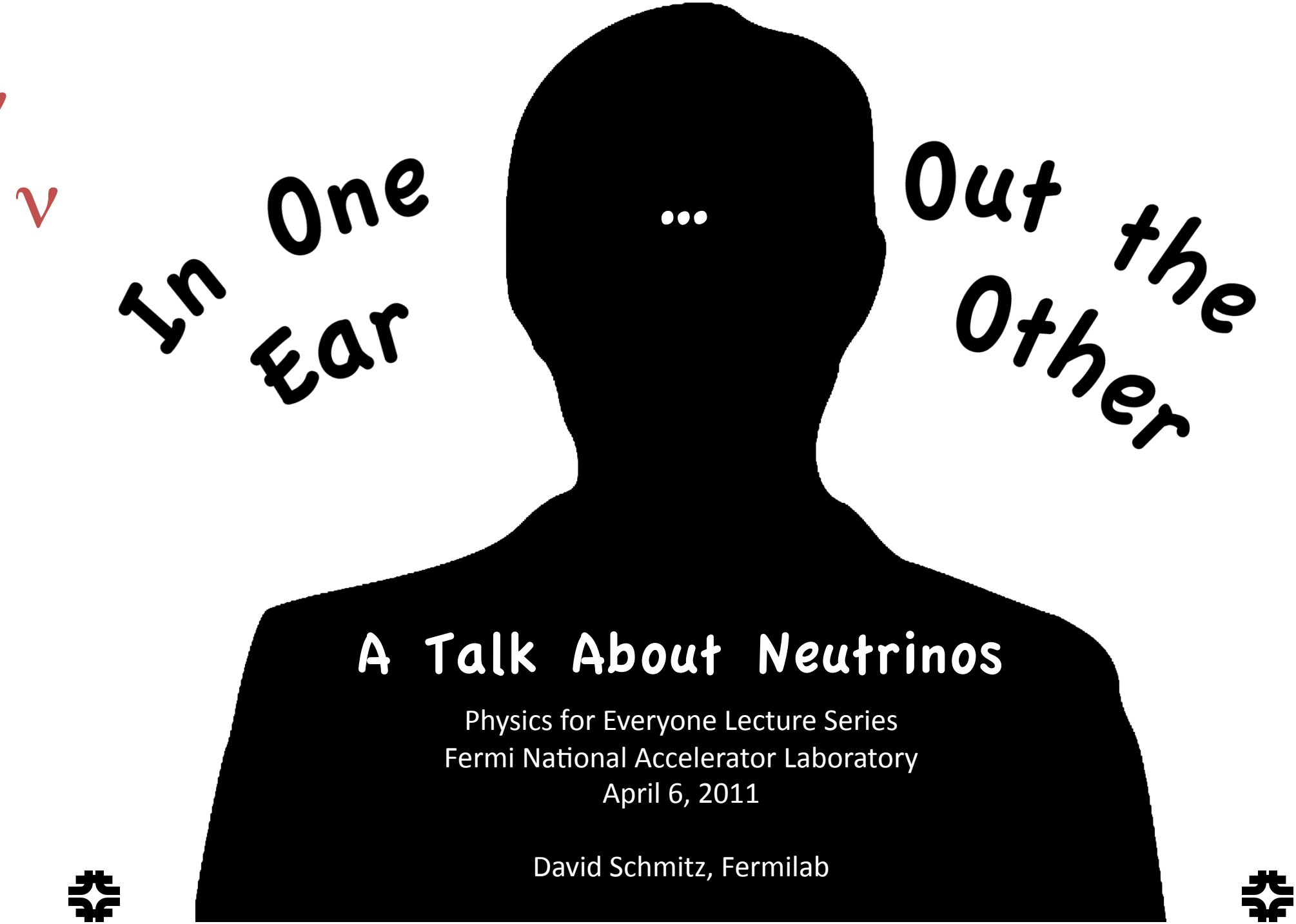


A Talk About Neutrinos

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?

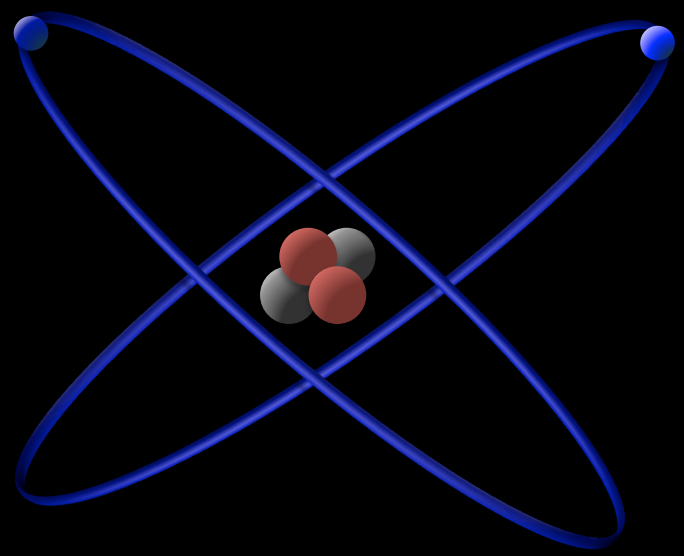
to the Universe?

to you?

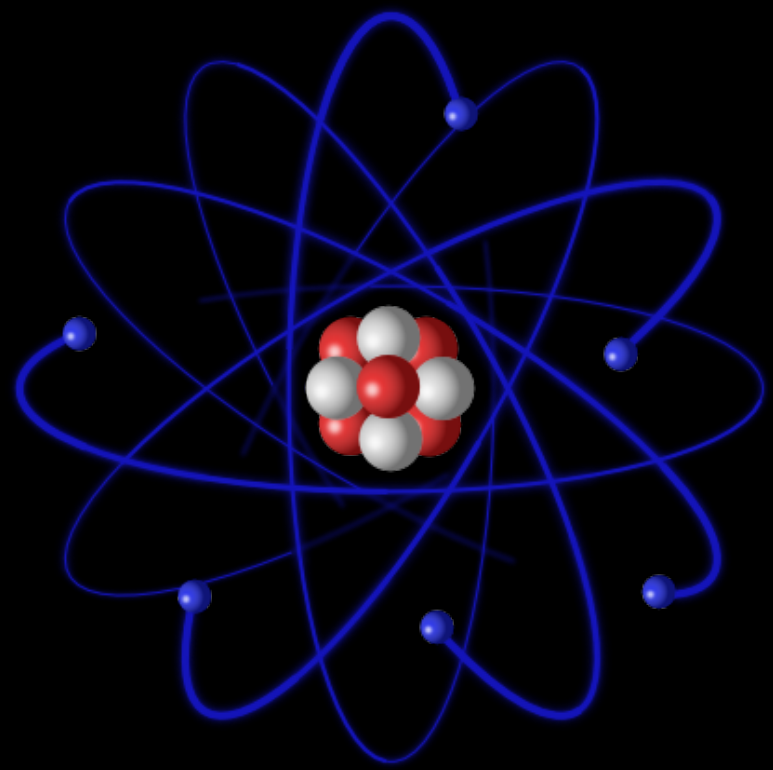
And where in the world did the silly title of this talk come from?

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>:

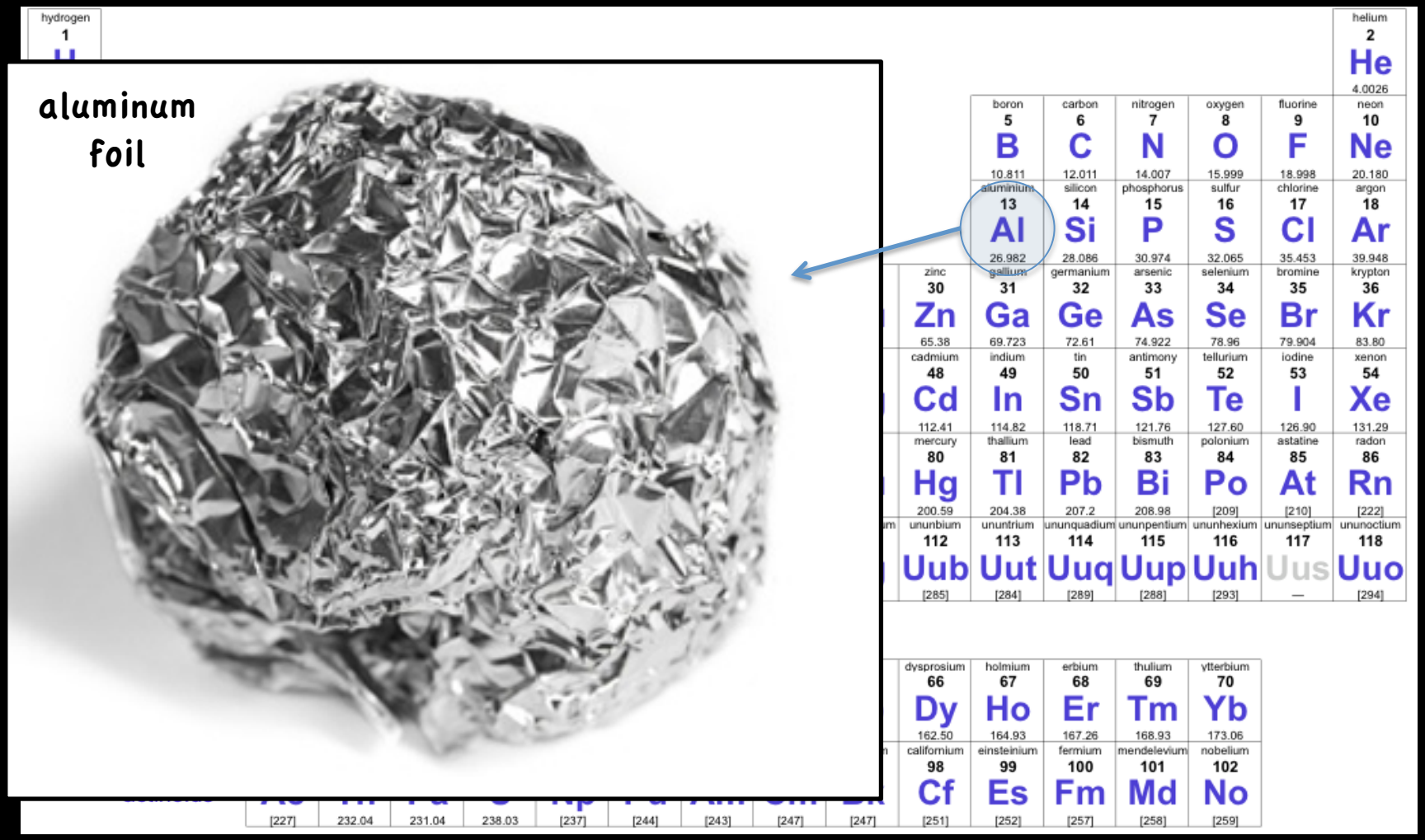
protons **neutrons** **electrons**

hydrogen 1 H 1.0079																		helium 2 He 4.0026
lithium 3 Li 6.941	beryllium 4 Be 9.0122												boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998	neon 10 Ne 20.180
sodium 11 Na 22.990	magnesium 12 Mg 24.305												aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453	argon 18 Ar 39.948
potassium 19 K 39.098	calcium 20 Ca 40.078		scandium 21 Sc 44.956	titanium 22 Ti 47.867	vanadium 23 V 50.942	chromium 24 Cr 51.996	manganese 25 Mn 54.938	iron 26 Fe 55.845	cobalt 27 Co 58.933	nickel 28 Ni 58.693	copper 29 Cu 63.546	zinc 30 Zn 65.38	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904	krypton 36 Kr 83.80
rubidium 37 Rb 85.468	strontium 38 Sr 87.62		yttrium 39 Y 88.906	zirconium 40 Zr 91.224	niobium 41 Nb 92.906	molybdenum 42 Mo 95.96	technetium 43 Tc [98]	ruthenium 44 Ru 101.07	rhodium 45 Rh 102.91	palladium 46 Pd 106.42	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90	xenon 54 Xe 131.29
caesium 55 Cs 132.91	barium 56 Ba 137.33	57-70 *	lutetium 71 Lu 174.97	hafnium 72 Hf 178.49	tantalum 73 Ta 180.95	tungsten 74 W 183.84	rhenium 75 Re 186.21	osmium 76 Os 190.23	iridium 77 Ir 192.22	platinum 78 Pt 195.08	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]	radon 86 Rn [222]
francium 87 Fr [223]	radium 88 Ra [226]	89-102 **	lawrencium 103 Lr [262]	rutherfordium 104 Rf [267]	dubnium 105 Db [268]	seaborgium 106 Sg [271]	bohrium 107 Bh [272]	hassium 108 Hs [270]	meitnerium 109 Mt [276]	darmstadtium 110 Ds [281]	roentgenium 111 Rg [280]	ununbium 112 Uub [285]	ununtrium 113 Uut [284]	ununquadium 114 Uuq [289]	ununpentium 115 Uup [288]	ununhexium 116 Uuh [293]	ununseptium 117 Uus —	ununoctium 118 Uuo [294]

*lanthanoids	lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70 Yb 173.06
**actinoids	actinium 89 Ac [227]	thorium 90 Th 232.04	protactinium 91 Pa 231.04	uranium 92 U 238.03	neptunium 93 Np [237]	plutonium 94 Pu [244]	americium 95 Am [243]	curium 96 Cm [247]	berkelium 97 Bk [247]	californium 98 Cf [251]	einsteinium 99 Es [252]	fermium 100 Fm [257]	mendelevium 101 Md [258]	nobelium 102 No [259]

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

protons **neutrons** **electrons**



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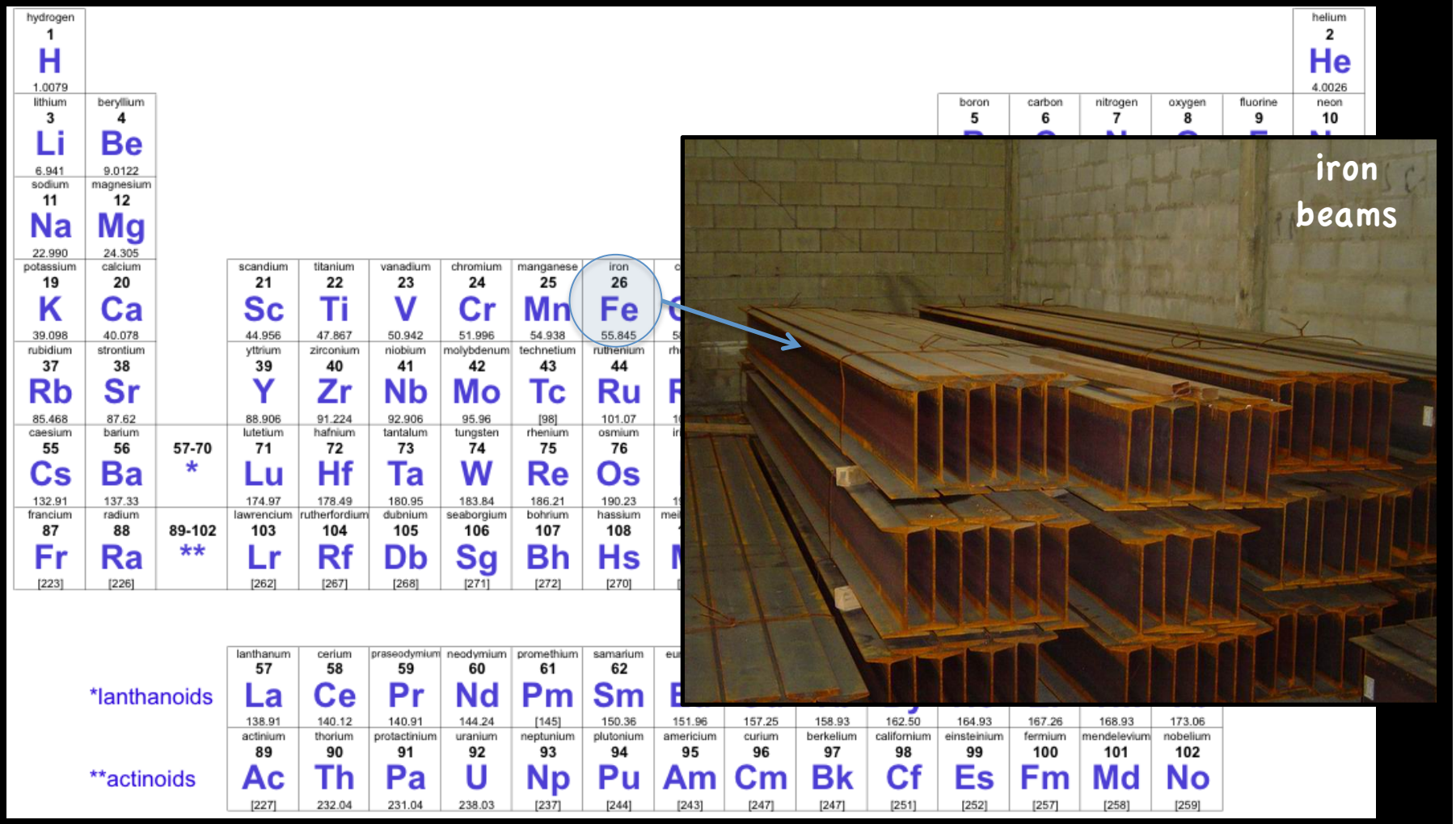
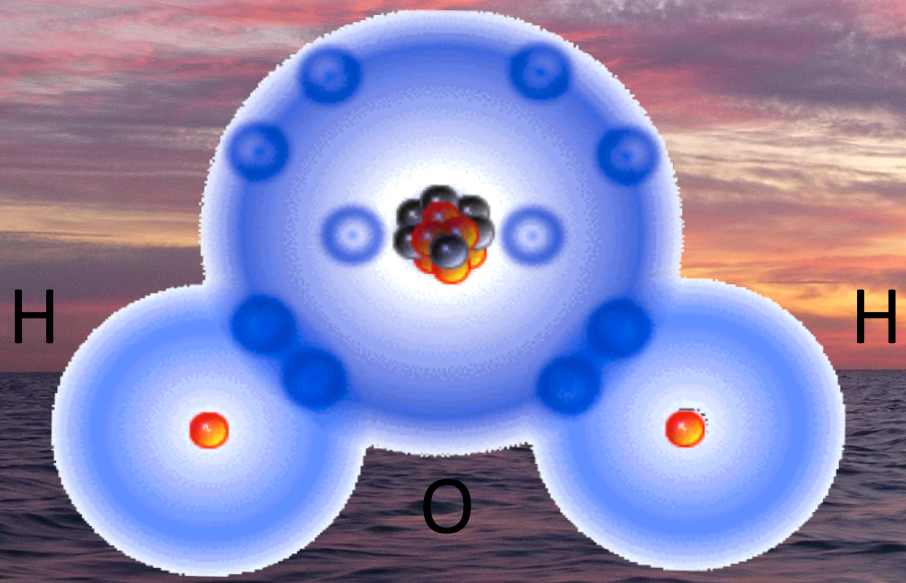


Everything we see around us is made of <u>only three particles</u>:

protons neutrons electrons



Lake Michigan

Everything we see around us is made of only three particles:
protons
neutrons
electrons
People!

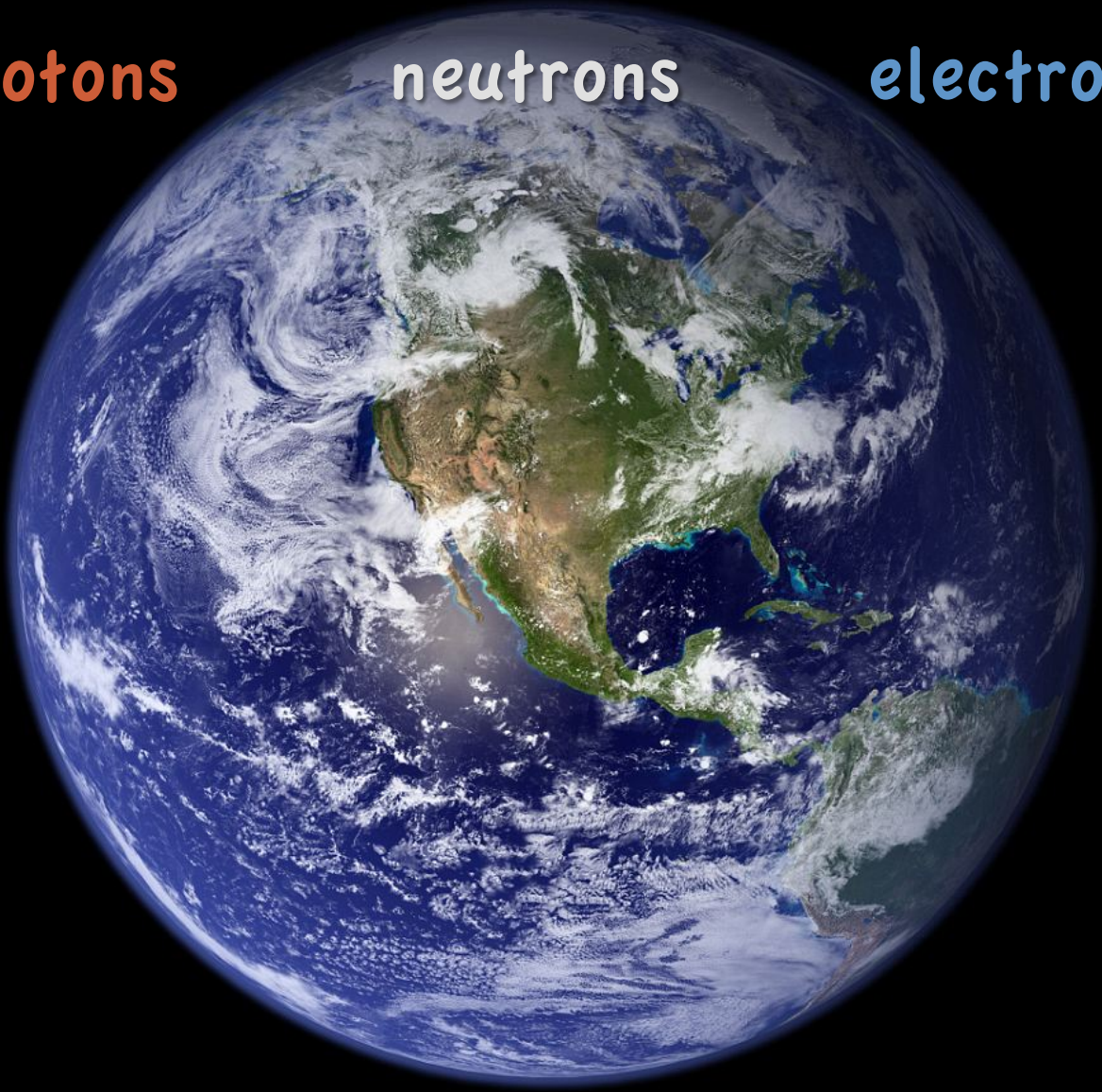
Everything we see around us is made of only three particles:

protons neutrons electrons

ple!

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

protons neutrons electrons



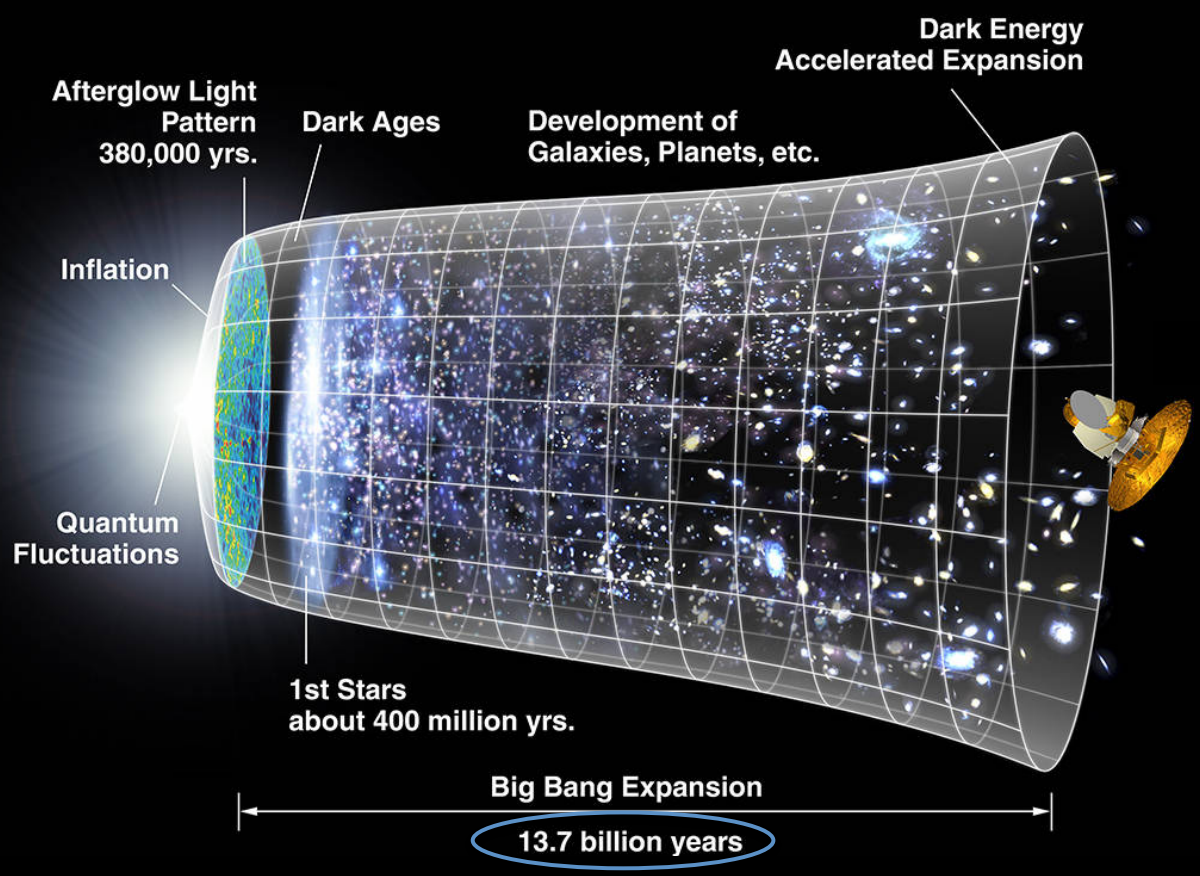
So… is the entire Universe made of these three particles?

protons neutrons electrons

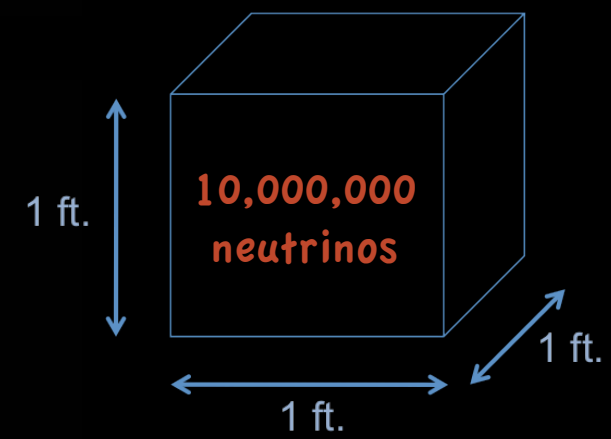
NOT EVEN CLOSE!!

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

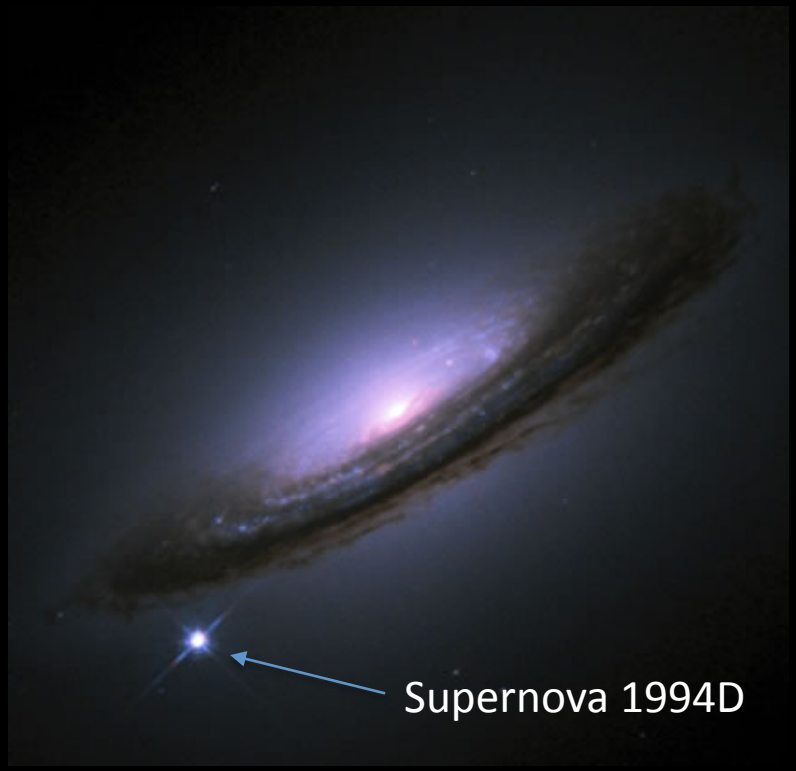
A BILLION neutrinos!

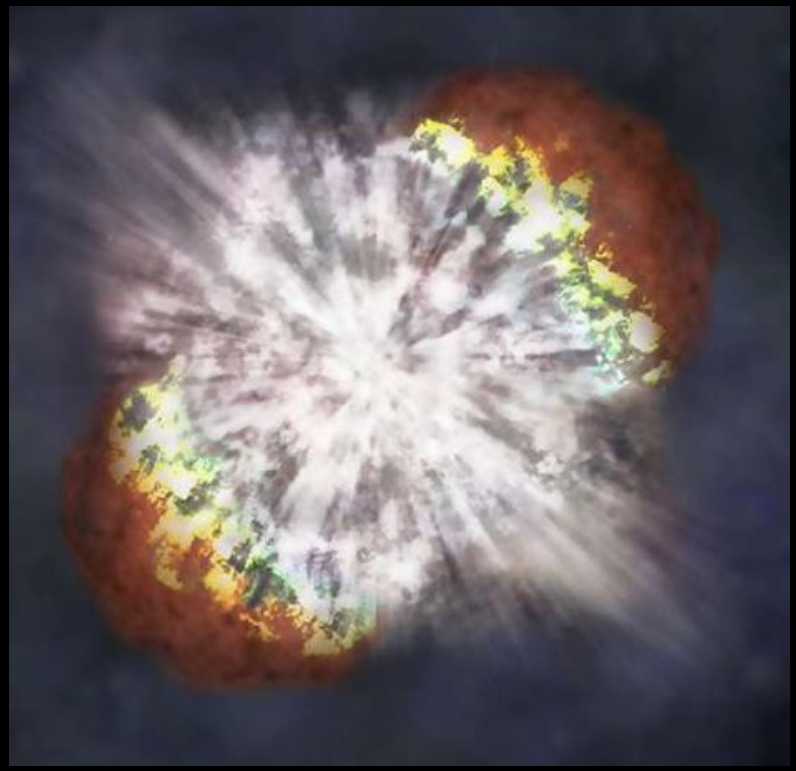


"Relic" Neutrinos



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!

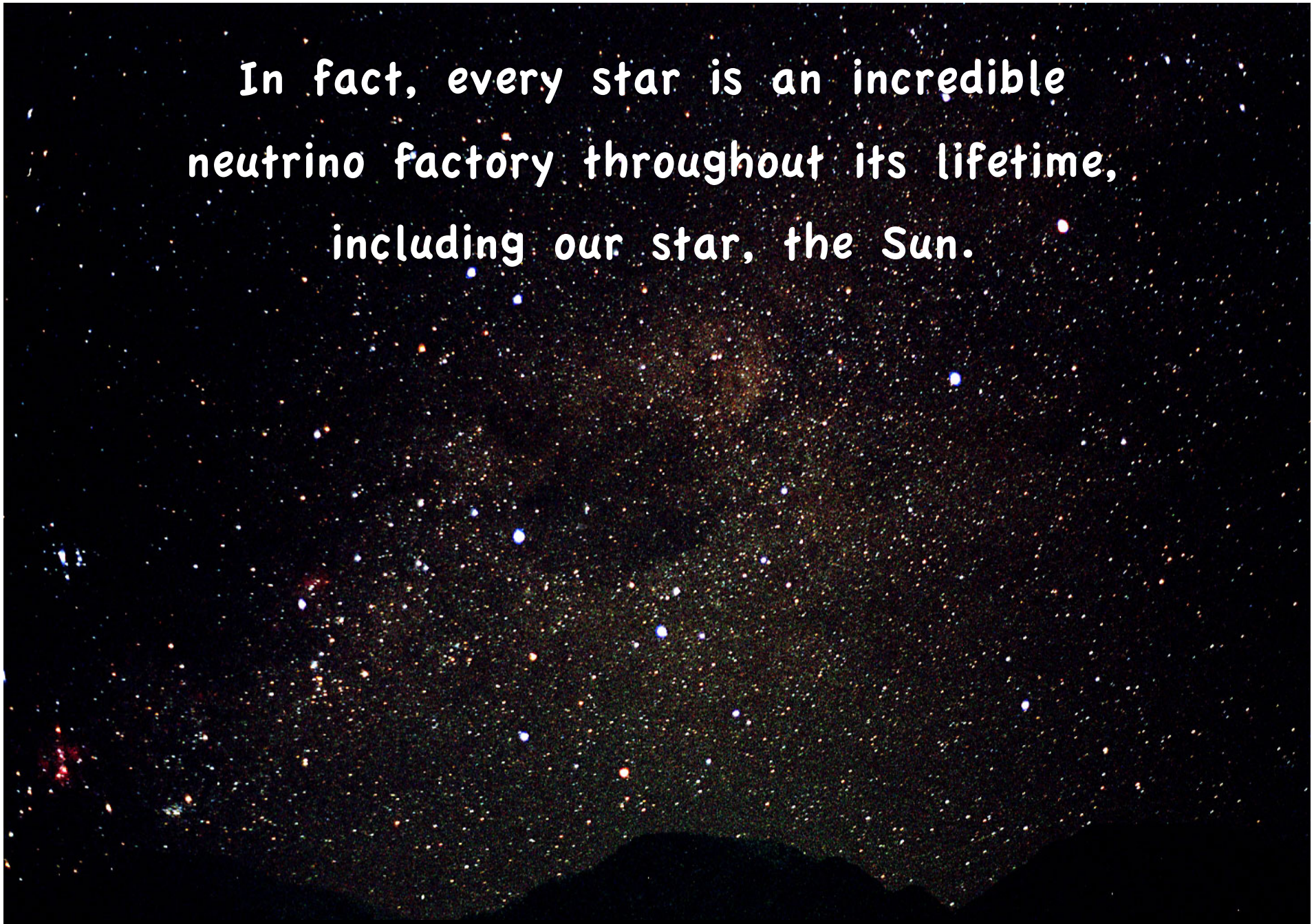




Whenever a star explodes as a Supernova,

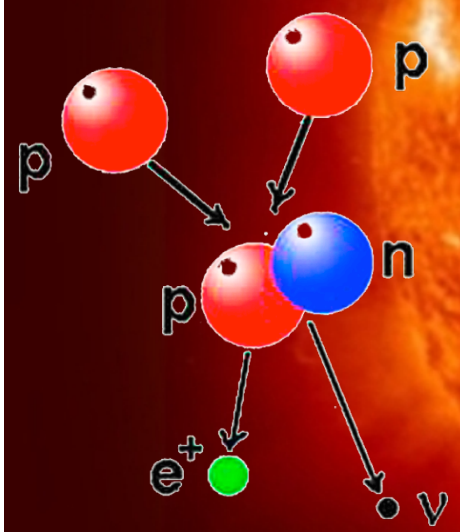
the most powerful explosions in the Universe,

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



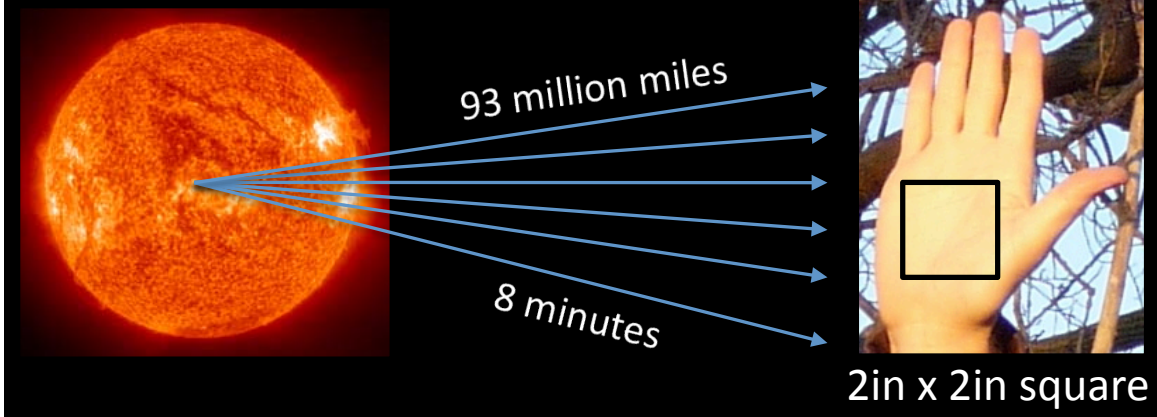
no carbon

no oxygen

no water

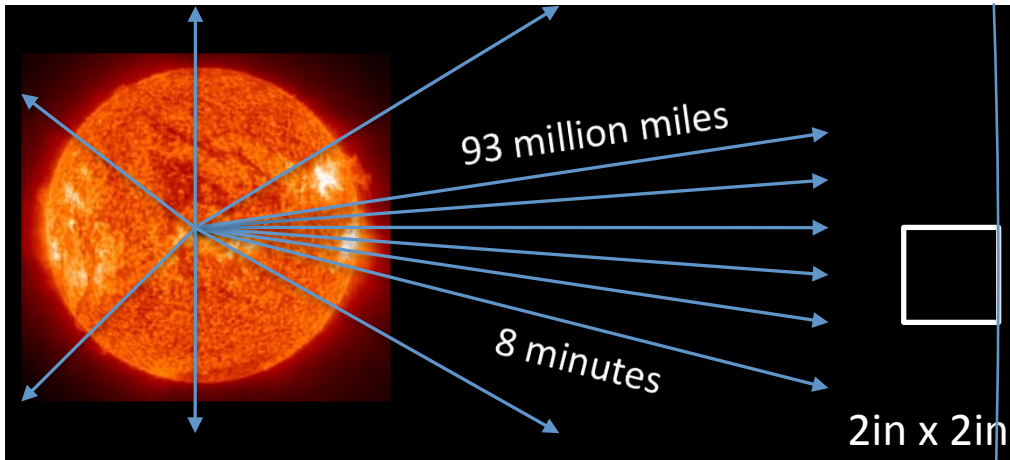
nothing much at all, really ☹

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



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 !!



Sphere with a radius of 93,000,000 miles

How many neutrinos is the Sun producing per second TOTAL?

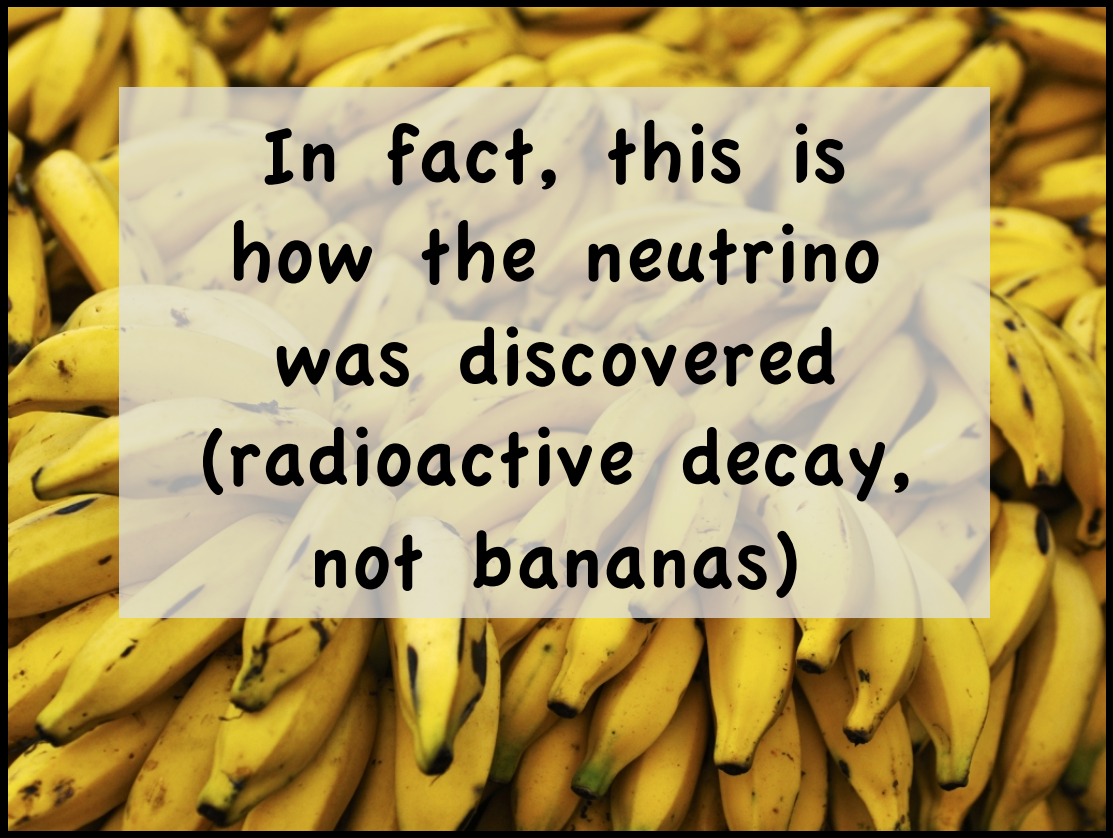
≈20,000,000,000,000,000,000,000,000,000,000,000,000,000,000,000

= 2×10^{38} neutrinos/second!!

You don't <u>have</u> to look to the cosmos to find neutrinos. For example:

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

You don't <u>have</u> to look to the cosmos to find neutrinos. For example:



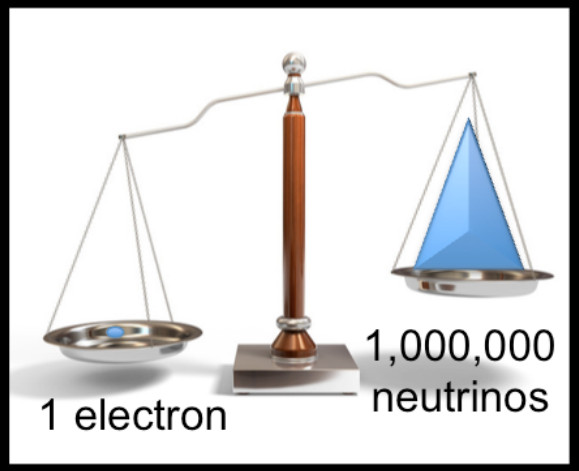
A <u>banana</u> emits about **1 million neutrinos/day** from decays of the small number of naturally occurring <u>radioactive potassium atoms</u> they contain!

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

understand

neutrinos

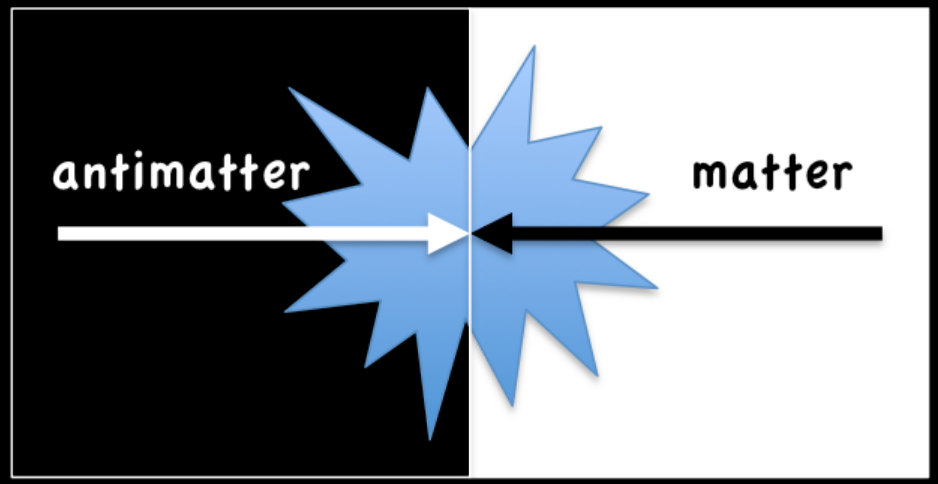
So what might they tell us?



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:

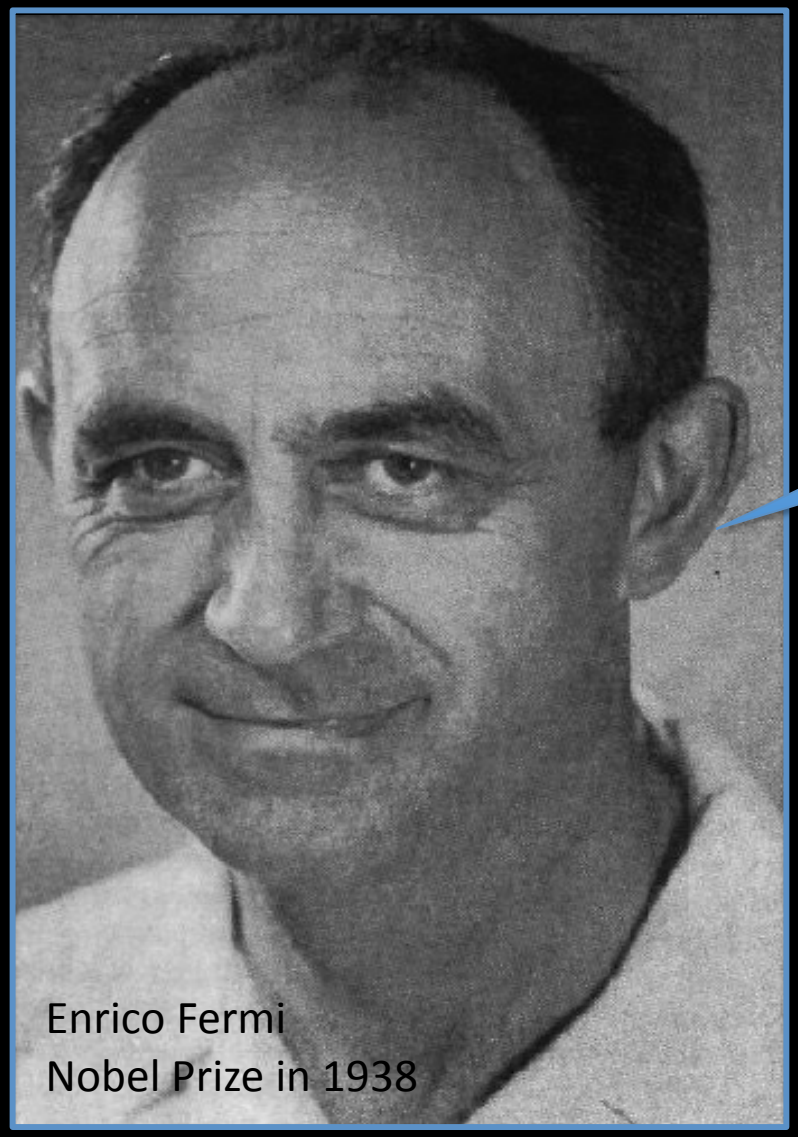
The Sun

Supernovae explosions

Ultra-high-energy neutrino sources

Big Bang relic neutrinos

Center of the Earth



Enrico Fermi
Nobel Prize in 1938

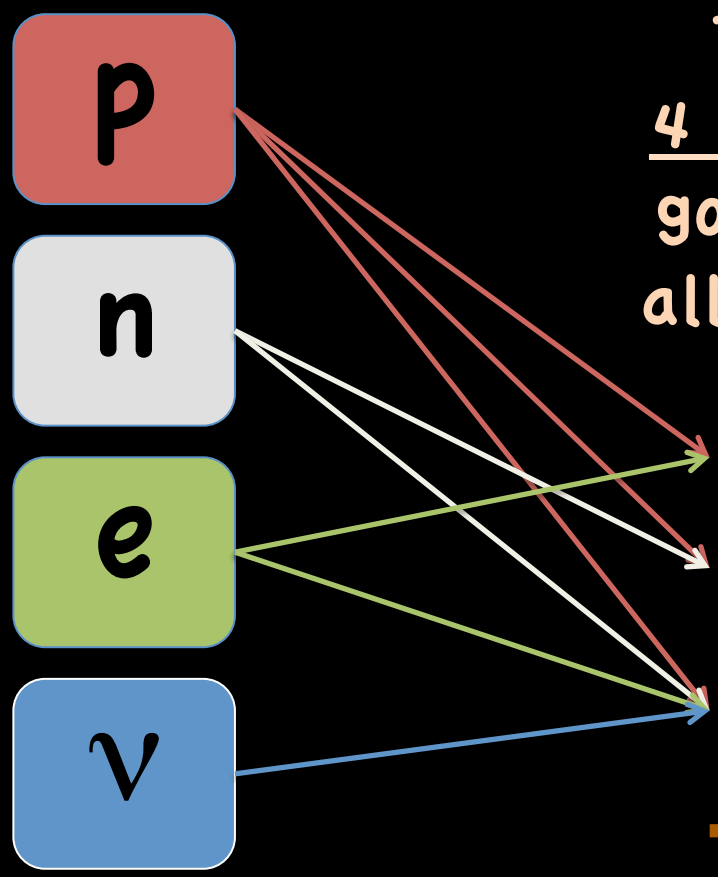
neutrino: ORIGIN mid 20th cent.: from Italian, diminutive of ***neutro.***

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 <u>4 fundamental forces</u> 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?

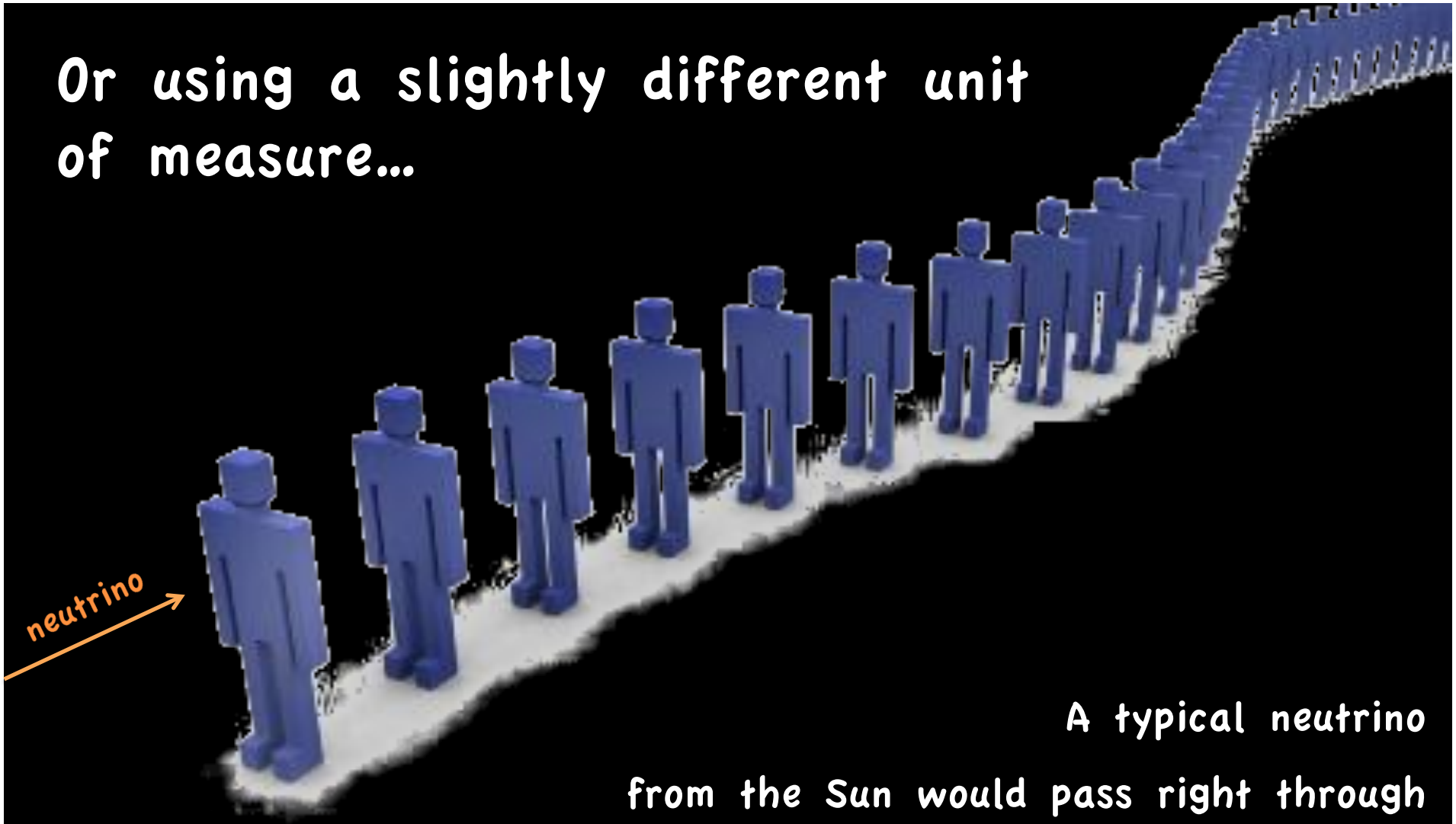
From Fermi's theory, one can calculate how far an average neutrino of a given energy travels before interacting

Neutrinos <u>produced by the Sun</u> are pretty low energy:

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

that's over <u>1.5 light years</u> of solid lead!!!

Or using a slightly different unit of measure…



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!

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 <u>produced at Fermilab</u> ~1000 times more energy:

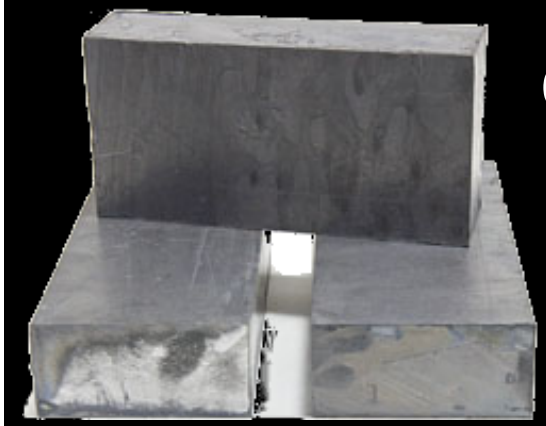
$$d \approx 1.5 \times 10^{12} \text{ meters in lead}$$

a bit better, but still ≈930,000,000 <u>miles</u> 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 <u>proton</u> from the Fermilab Booster:



d ≈ <u>10 centimeters</u> 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

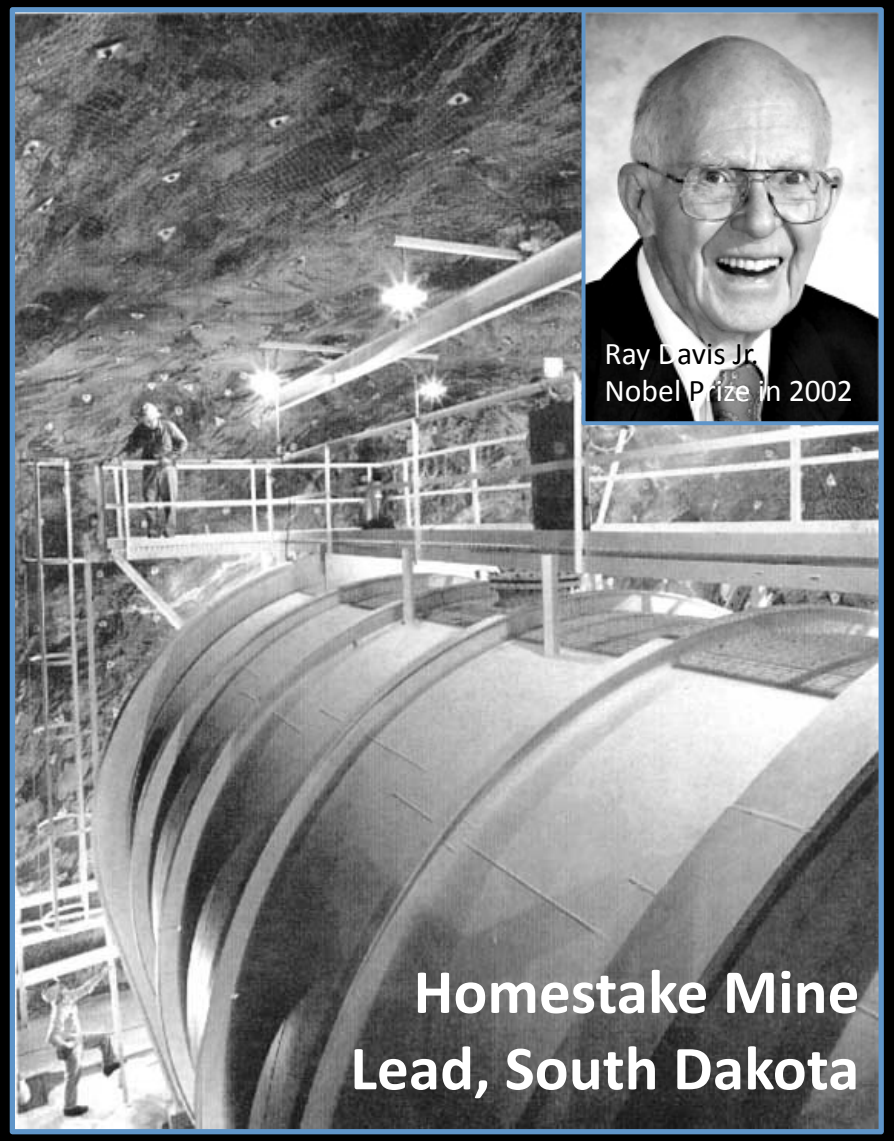
615 tons of cleaning fluid

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

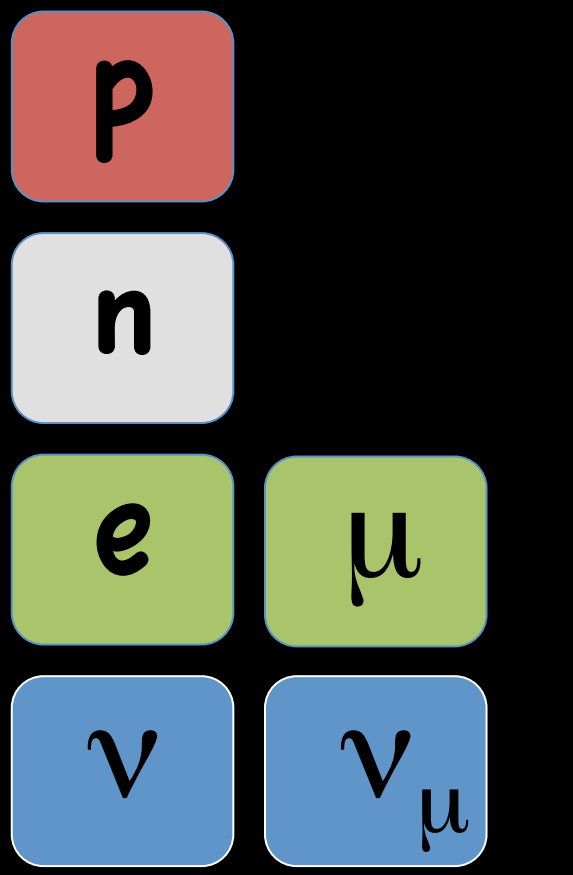
ν

μ

Identical to the electon except 200x heavier

"Who ordered that?" -I.I. Rabi

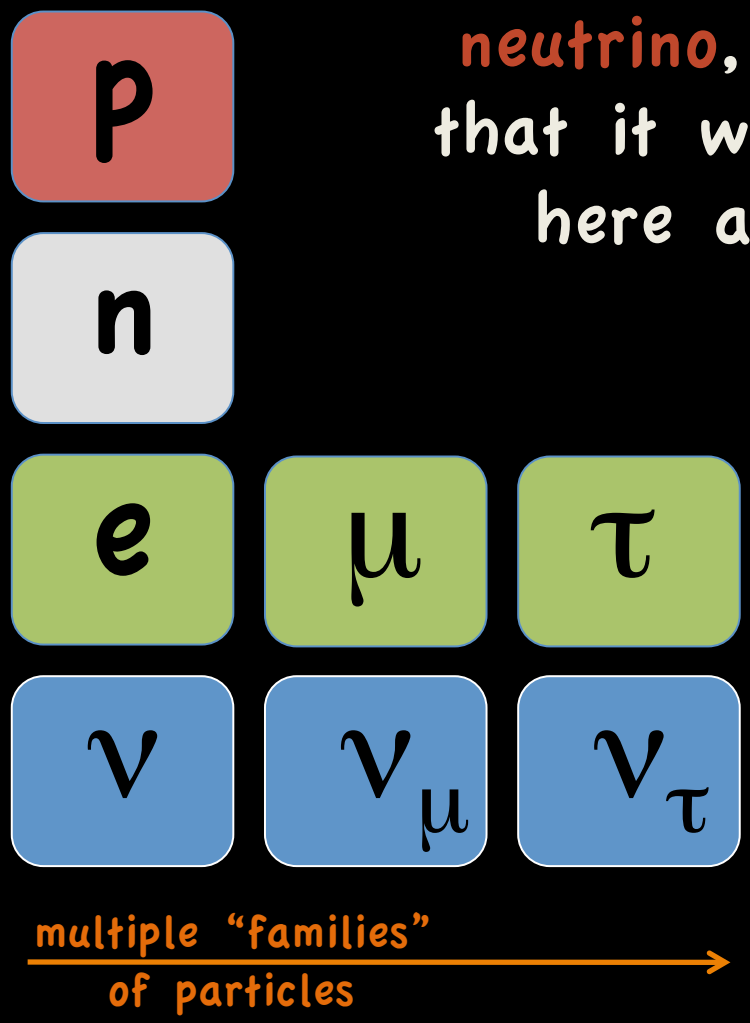
The electron's big brother, the muon, was discovered way back in 1936, but seemed to not fit in at the time



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

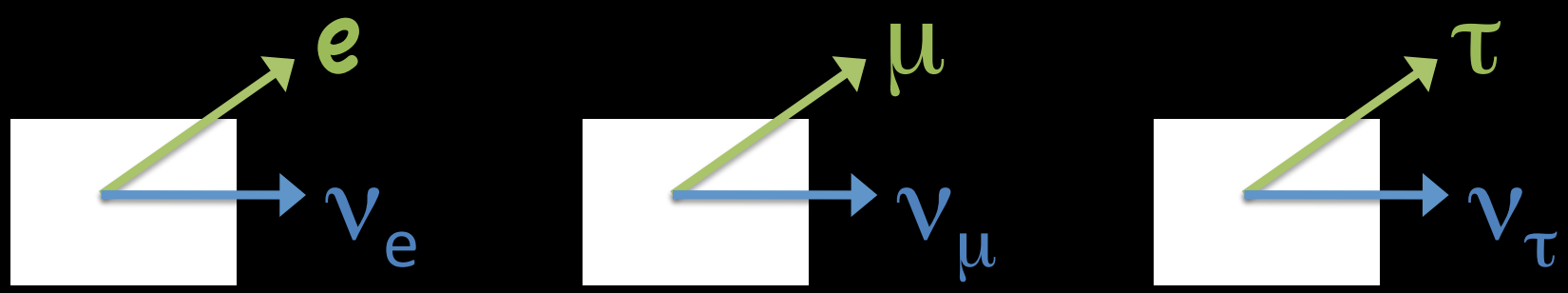


Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

Flavor

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



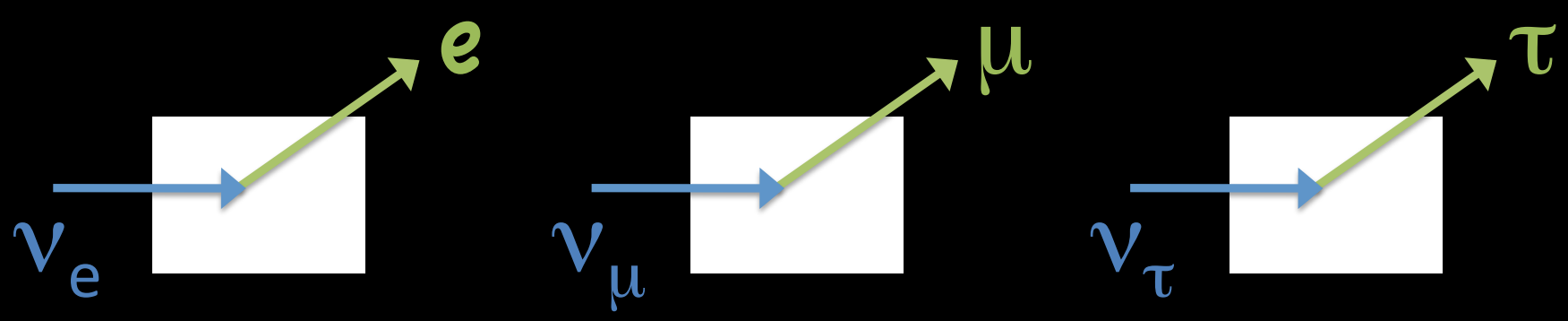
Neutrino is created

Leptons

e	μ	τ
ν_e	ν_μ	ν_τ

Flavor

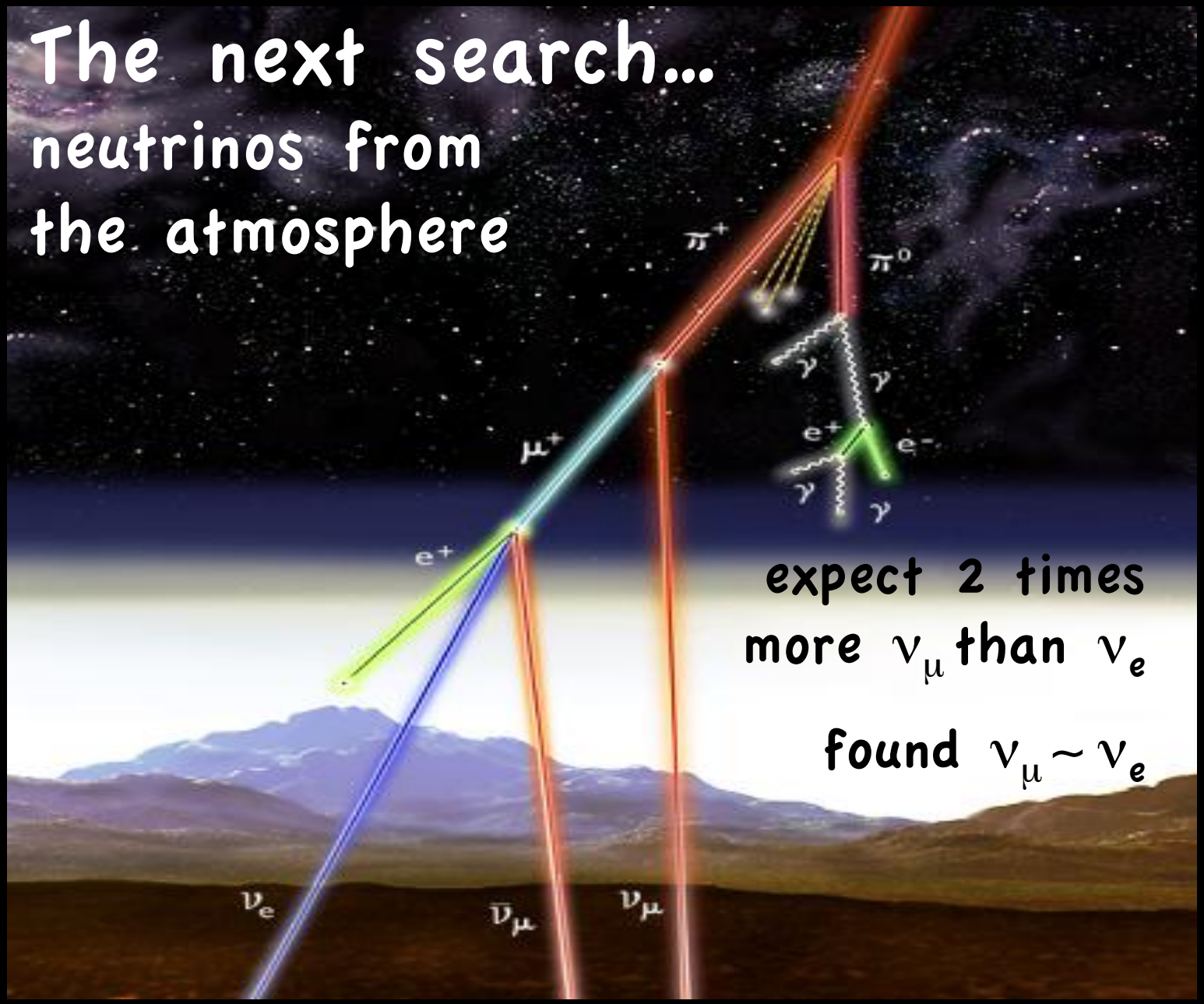
Neutrinos <u>ONLY</u> interact with members of their own family



Neutrino is destroyed

The next search…

neutrinos from the atmosphere



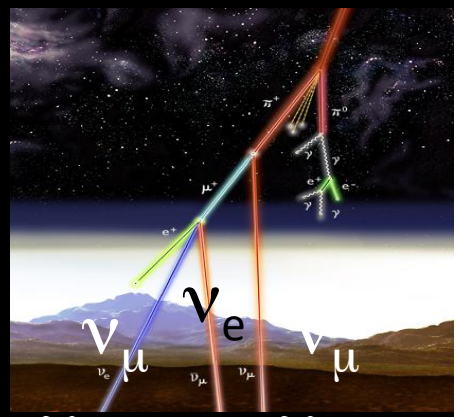
expect 2 times more ν_μ than ν_e

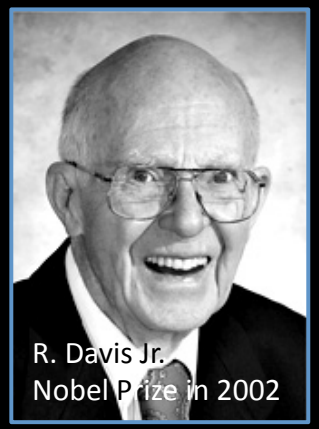
found $\nu_\mu \sim \nu_e$

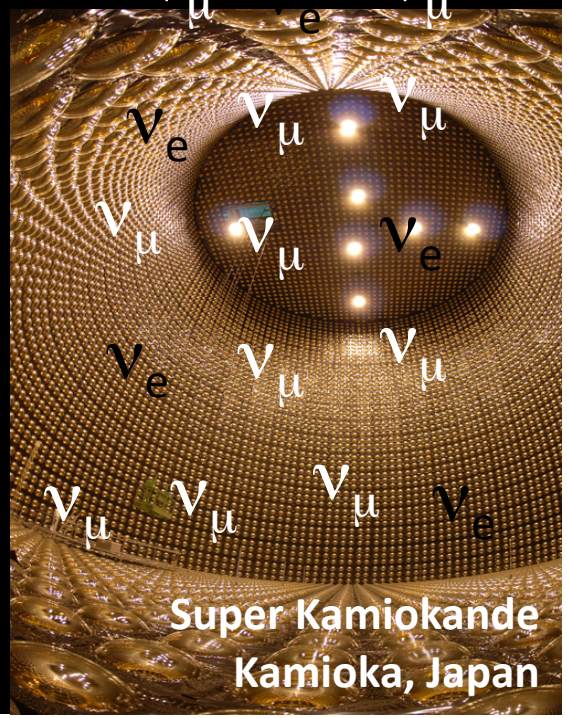
Where are all the neutrinos going?!?

Not seeing enough electron neutrinos from the Sun

Not seeing enough muon neutrinos from the atmosphere







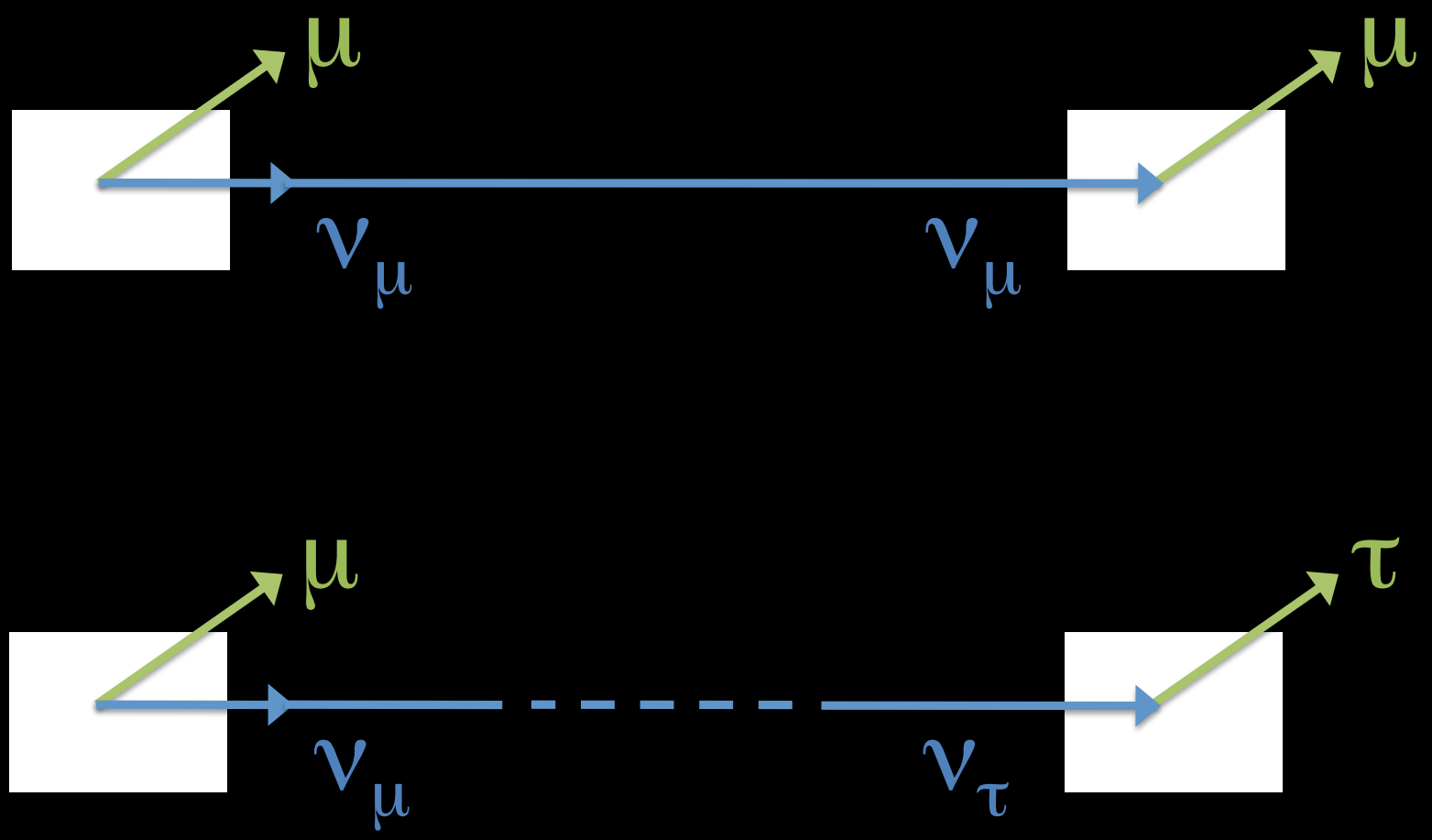
Where are all the neutrinos going?!?

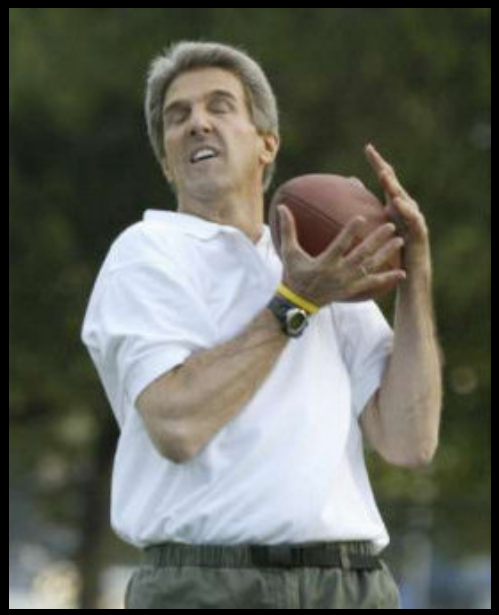
Not seeing enough electron neutrinos from the Sun

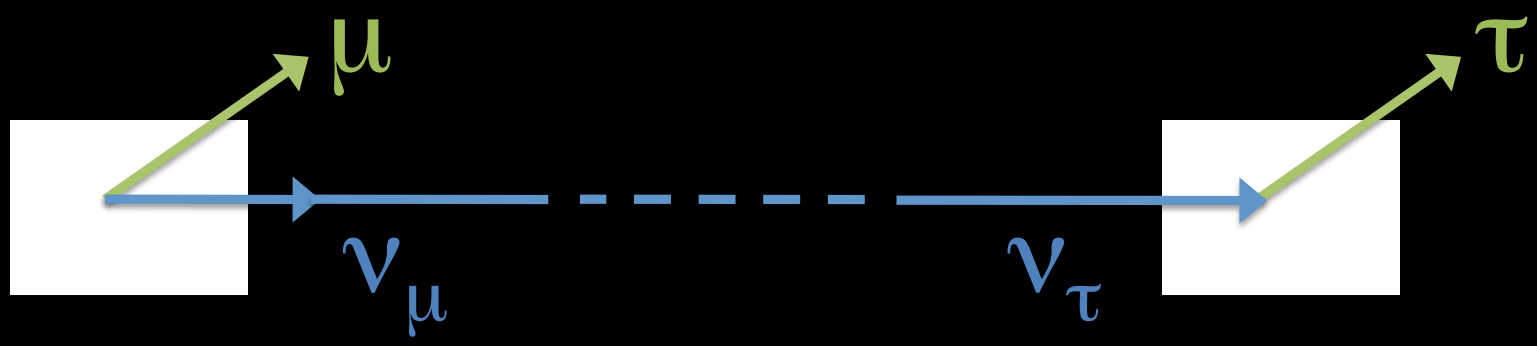
Not seeing enough muon neutrinos from the atmosphere

Enter the idea of

neutrino oscillations

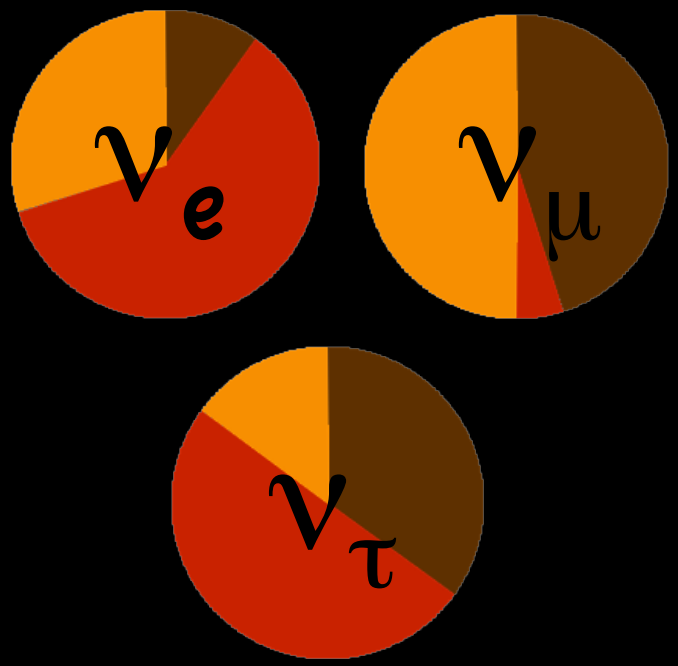

μ
μ
ν_μ
ν_μ
μ
τ
ν_μ
ν_τ




μ
τ
ν_μ
ν_τ

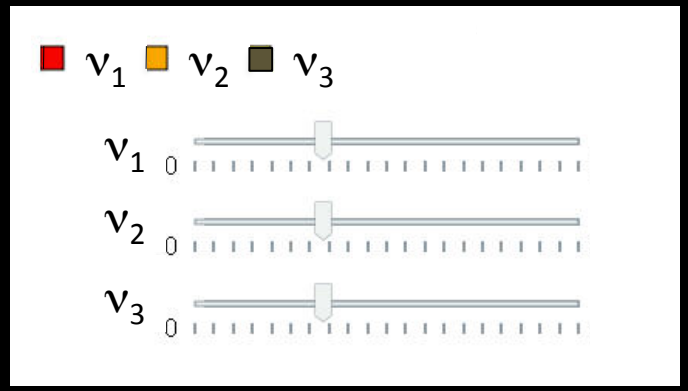
This could be possible if:

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

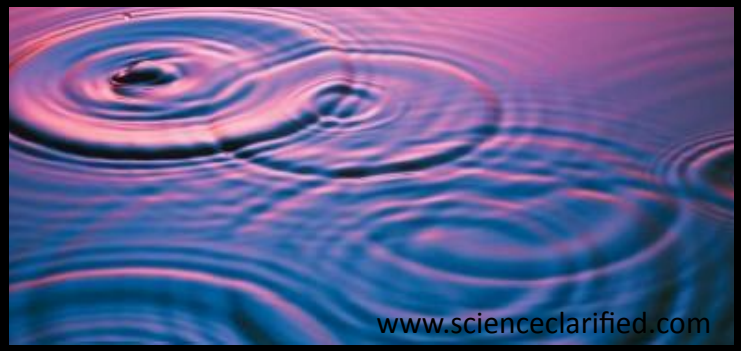


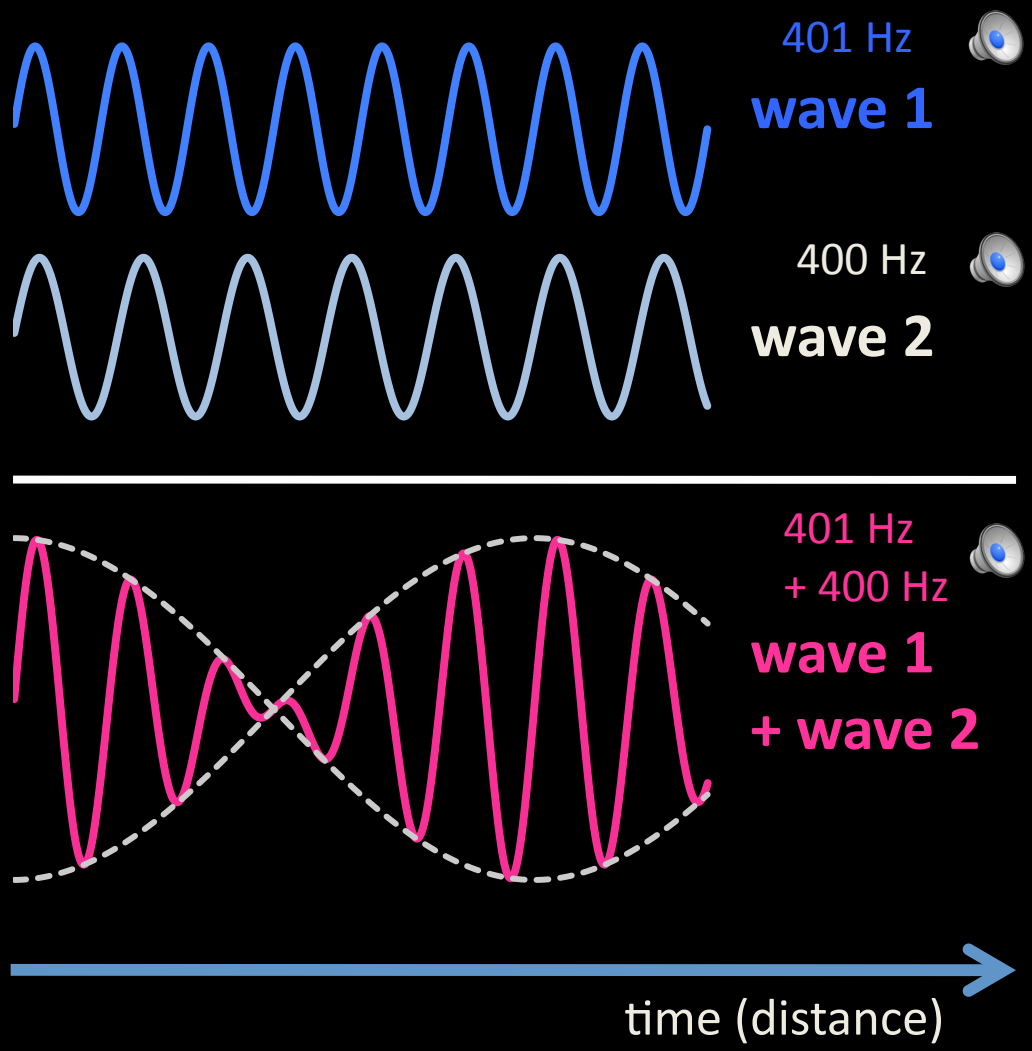
neutrino oscillations

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

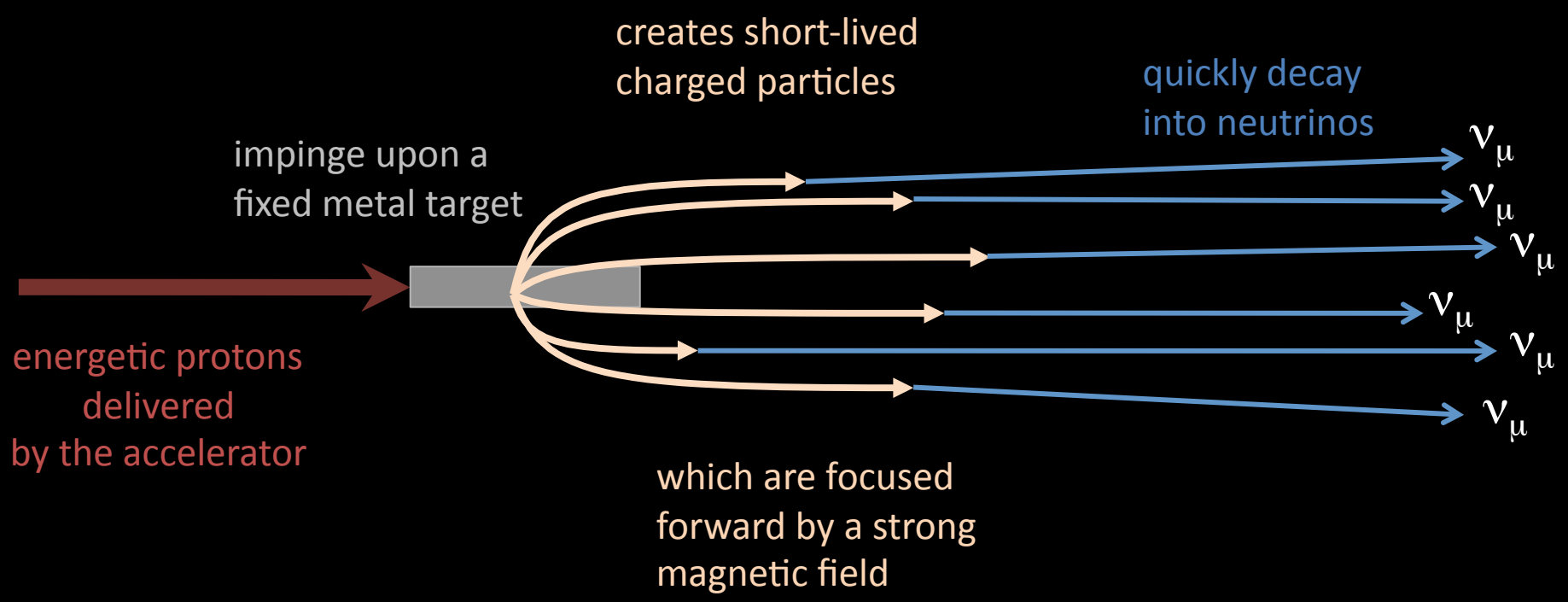
in the laboratory?

Turns out that you can use an

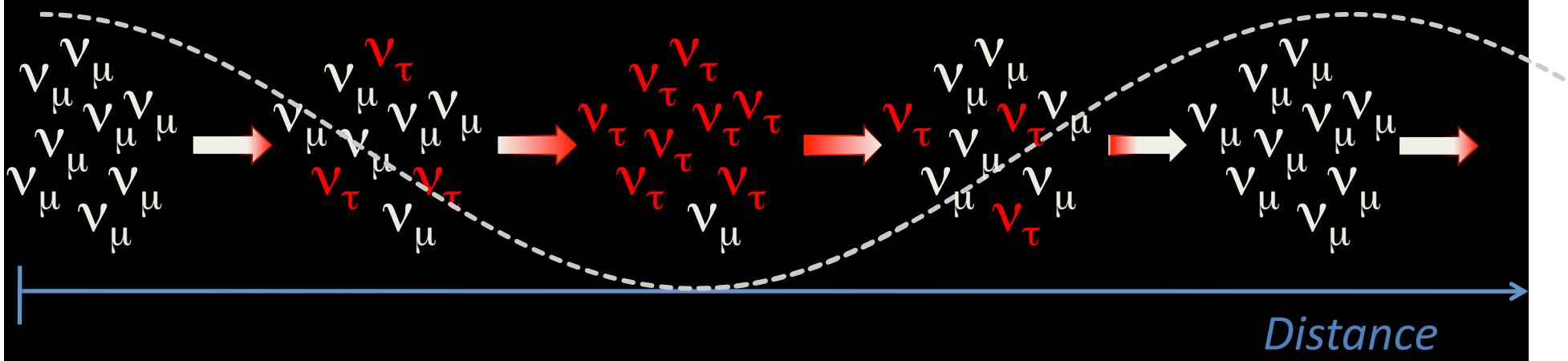
intense beam of protons

to create an

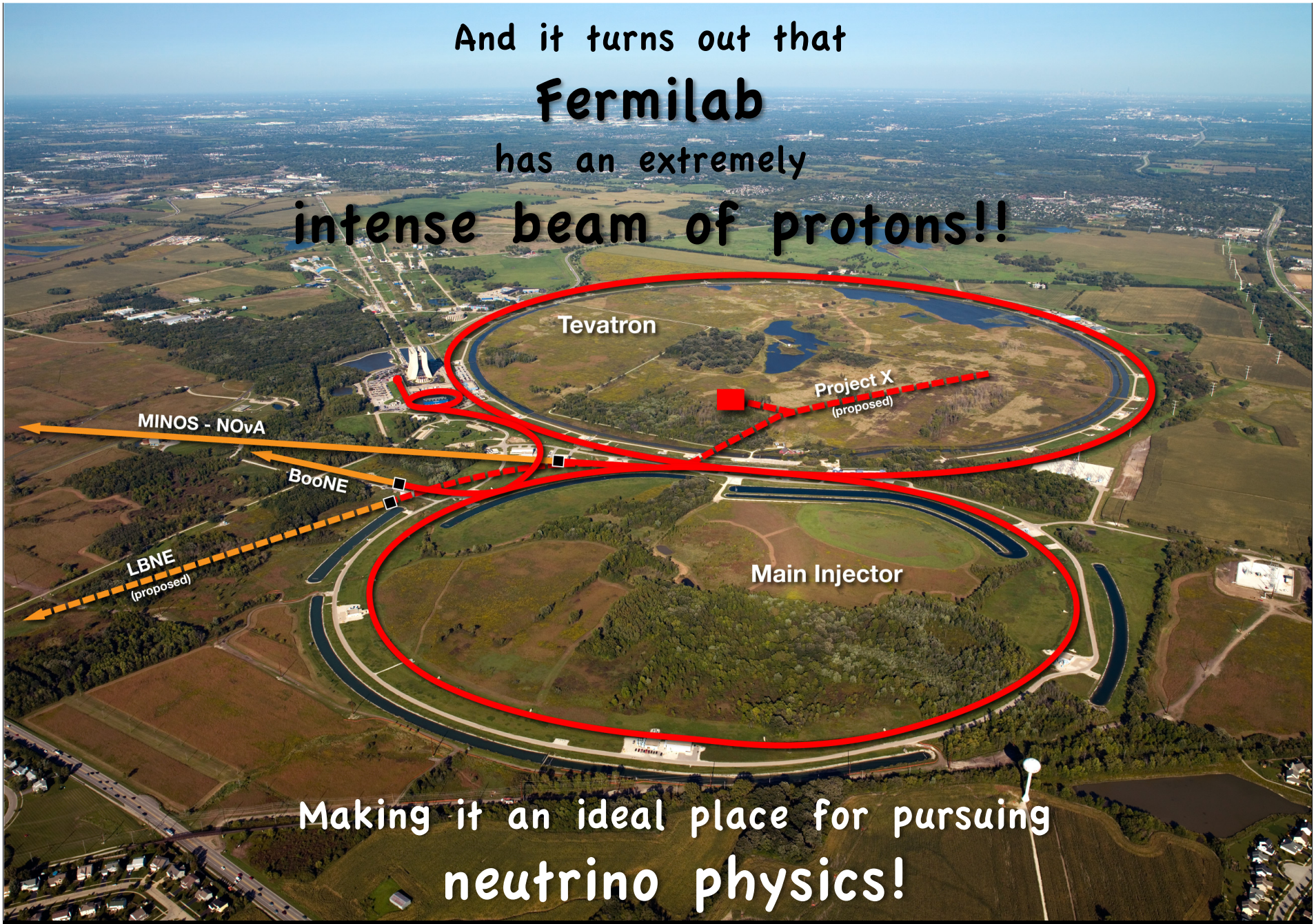
intense beam of neutrinos



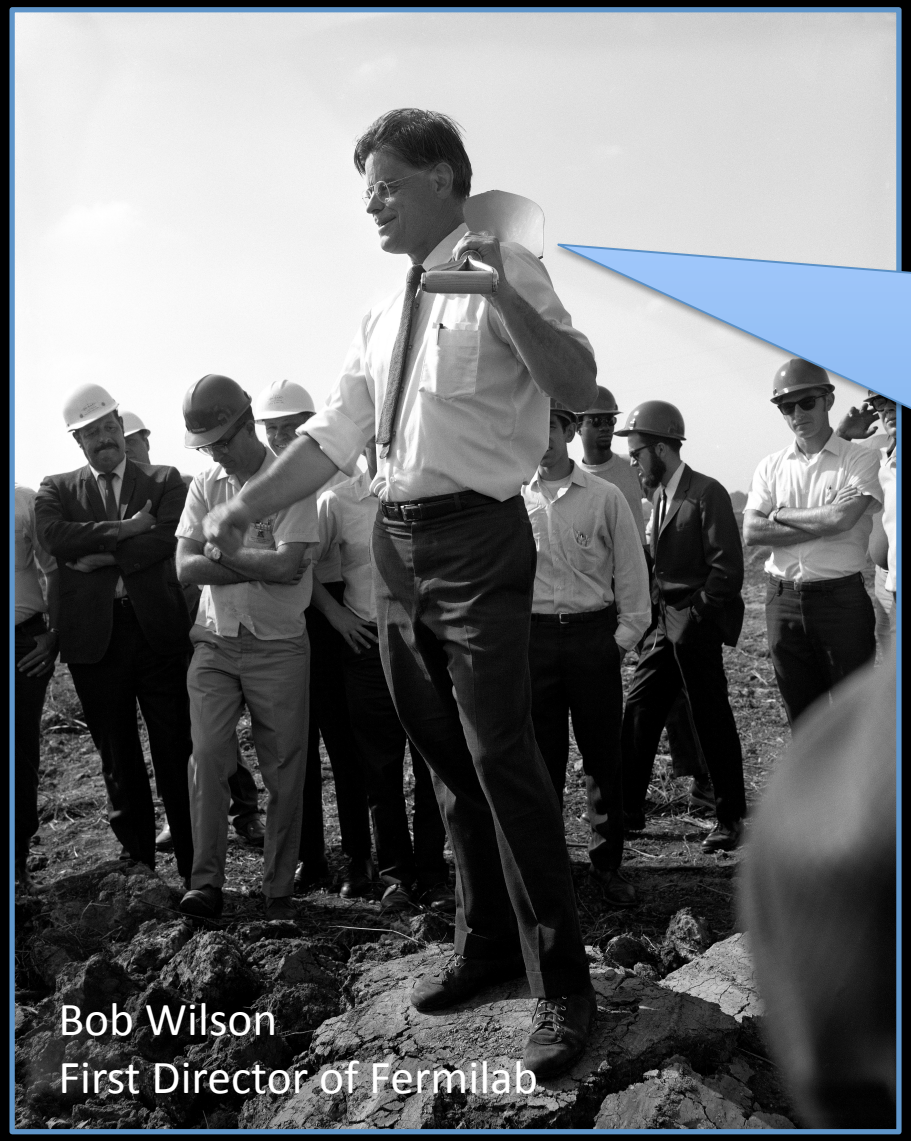
And look for them to oscillate



But you need a <u>LOT of neutrinos</u> because of how feebly they interact

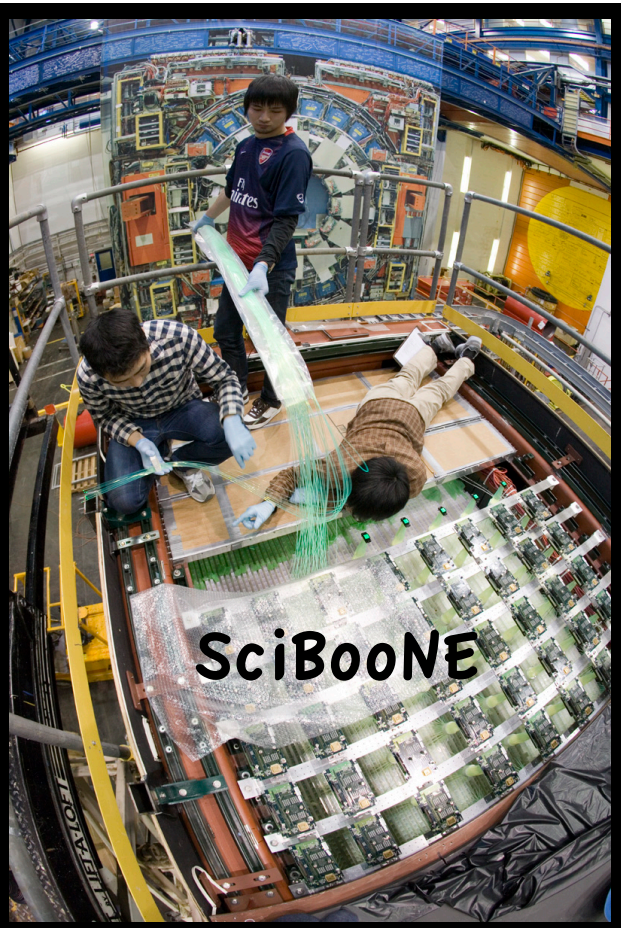

And it turns out that
Fermilab
has an extremely
intense beam of protons!!
Tevatron
Project X
(proposed)
MINOS - NOvA
BooNE
LBNE
(proposed)
Main Injector
Making it an ideal place for pursuing
neutrino physics!

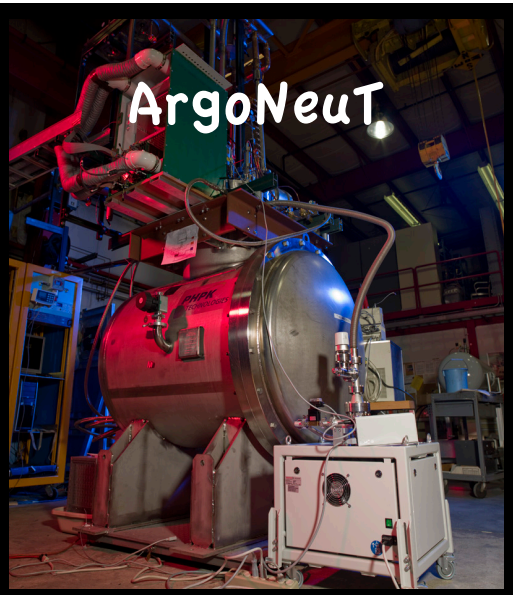
From the beginning…



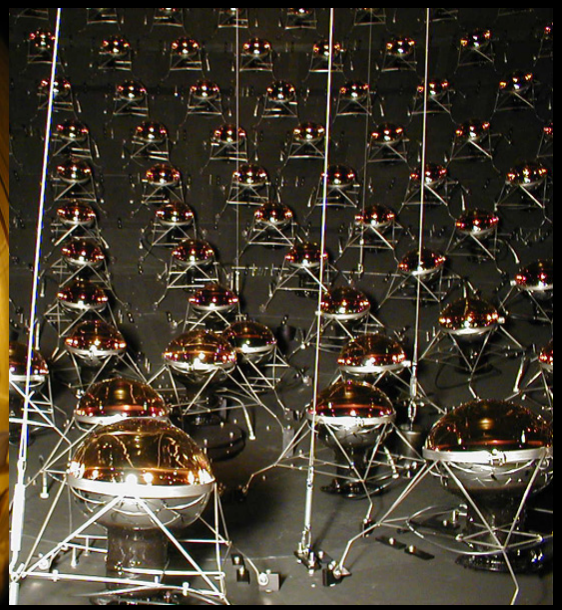
"One of the first aims of experiments on the NAL accelerator system will be the detection of the neutrino. I feel that we then will be in business to do experiments on our accelerator."

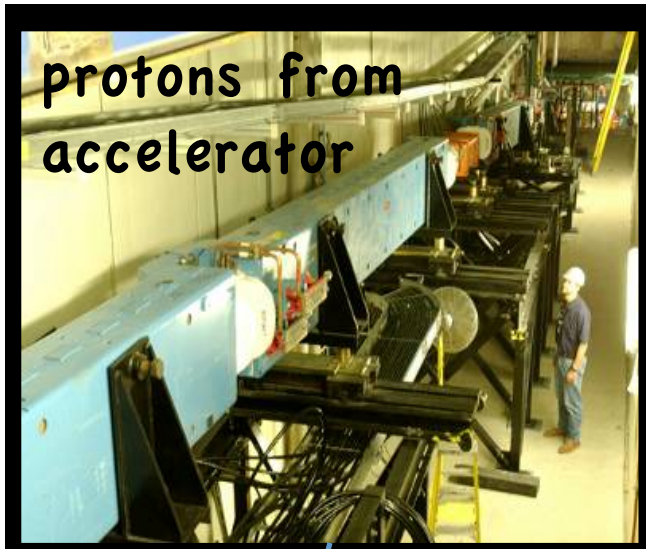
-Bob Wilson (1971)





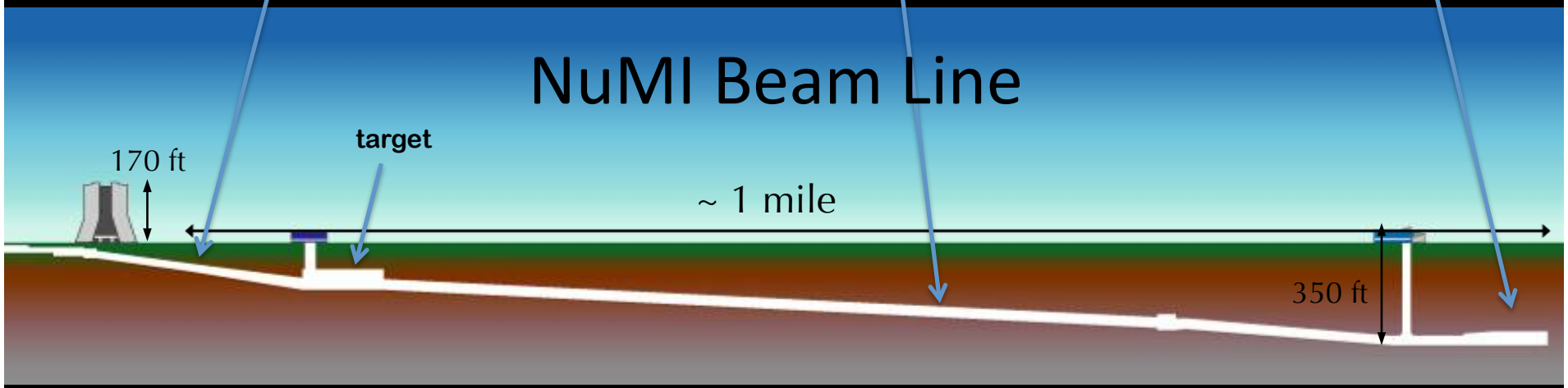
To Today…

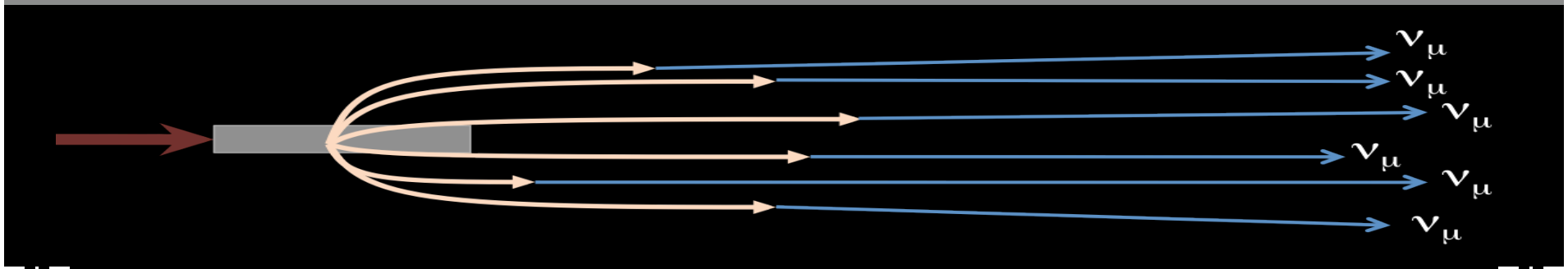



protons from
accelerator

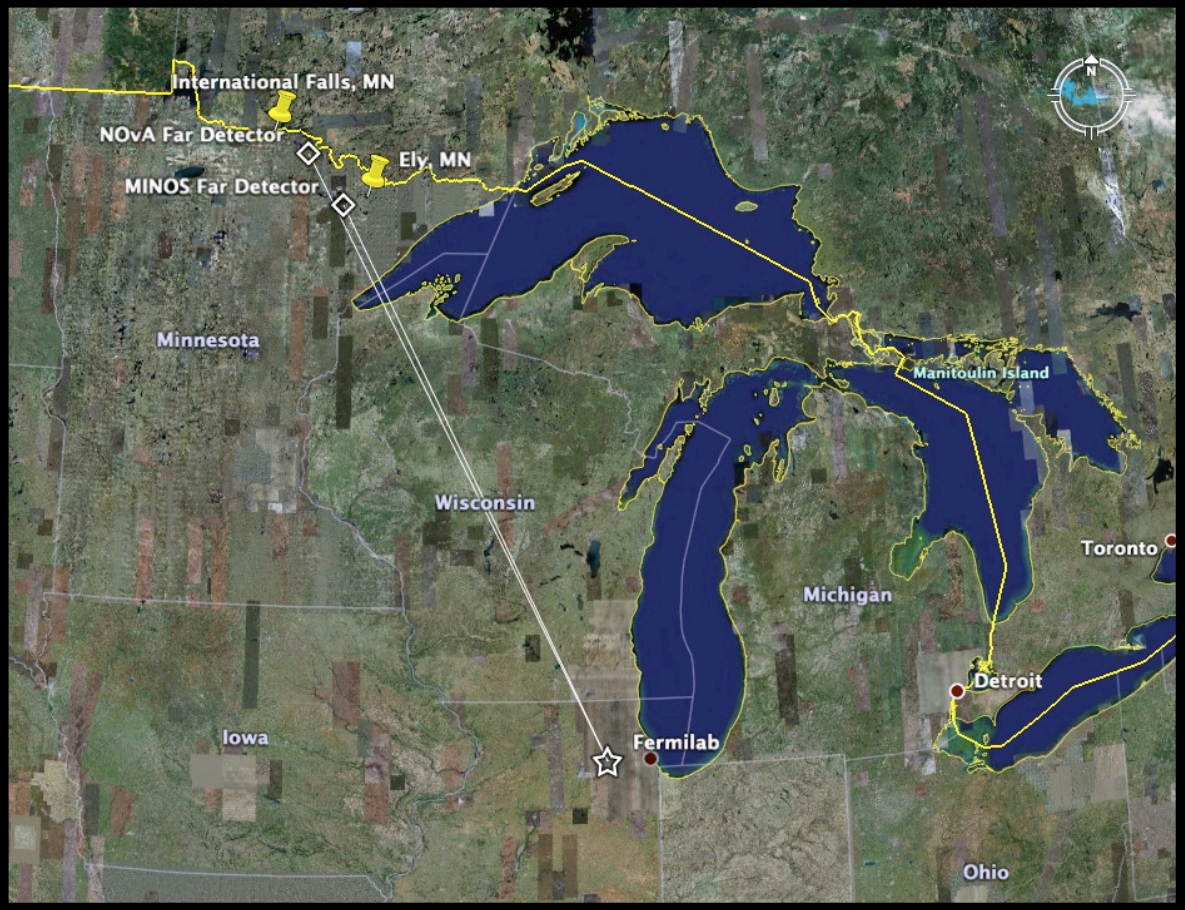
1/3 mile decay pipe

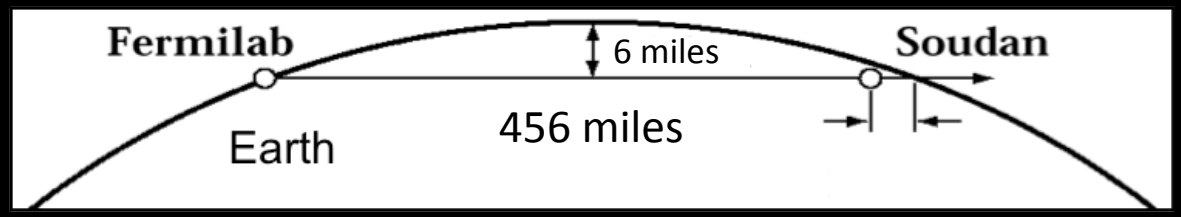
neutrino detectors


NuMI Beam Line
170 ft
target
~ 1 mile
350 ft


ν_μ
ν_μ
ν_μ
ν_μ
ν_μ
ν_μ

Where are all those neutrinos headed?

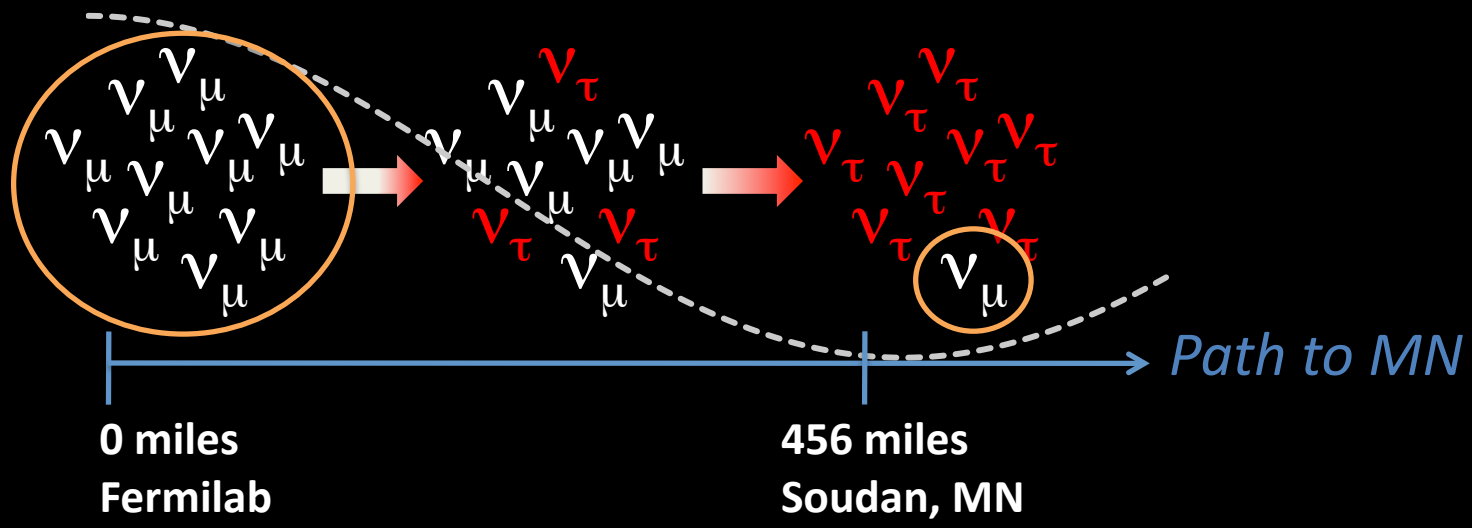




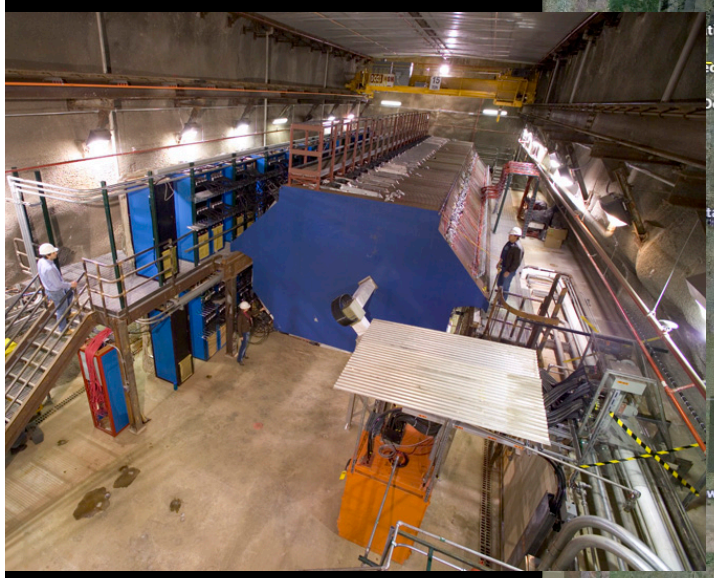
North!

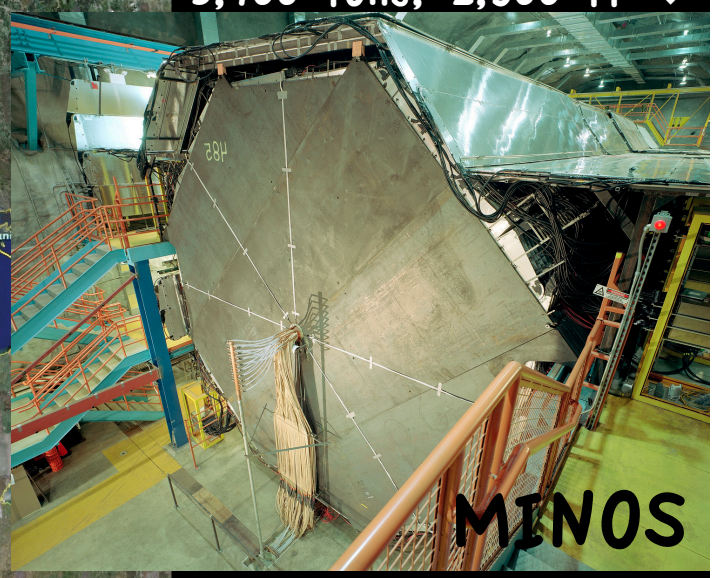
And they make the journey from Fermilab to northern Minnesota in 1/400th of a second!

But will they change their flavor?!?



5,400 tons, 2,300 ft



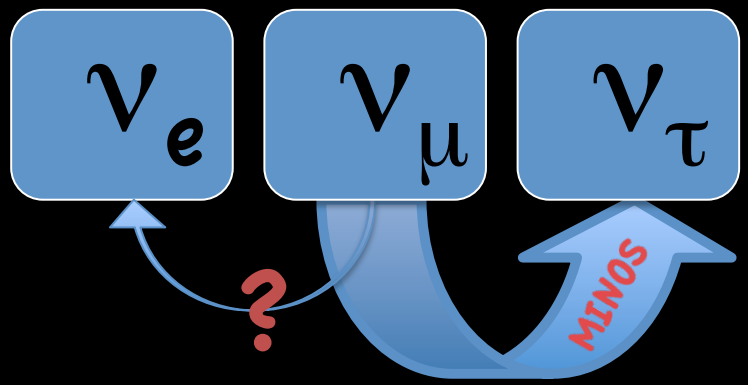


Neutrino oscillations are a very recent discovery in the world of modern particle physics

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



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

Rich physics in this next stage!!

ν_e ν_μ ν_τ

This is why to keep going!

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

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

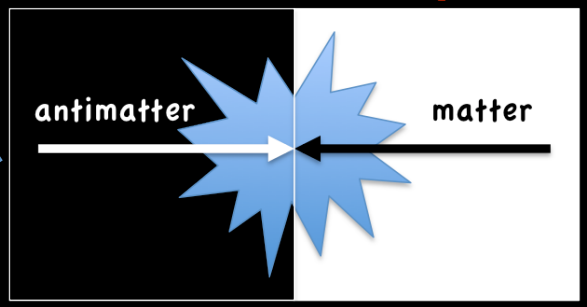
$$T_2 = \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)}$$

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

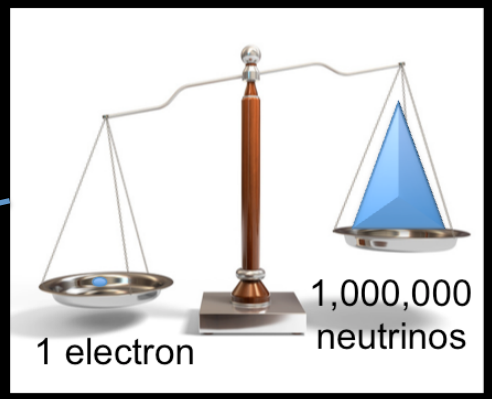
$$T_4 = \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2}$$

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

matter/antimatter parts



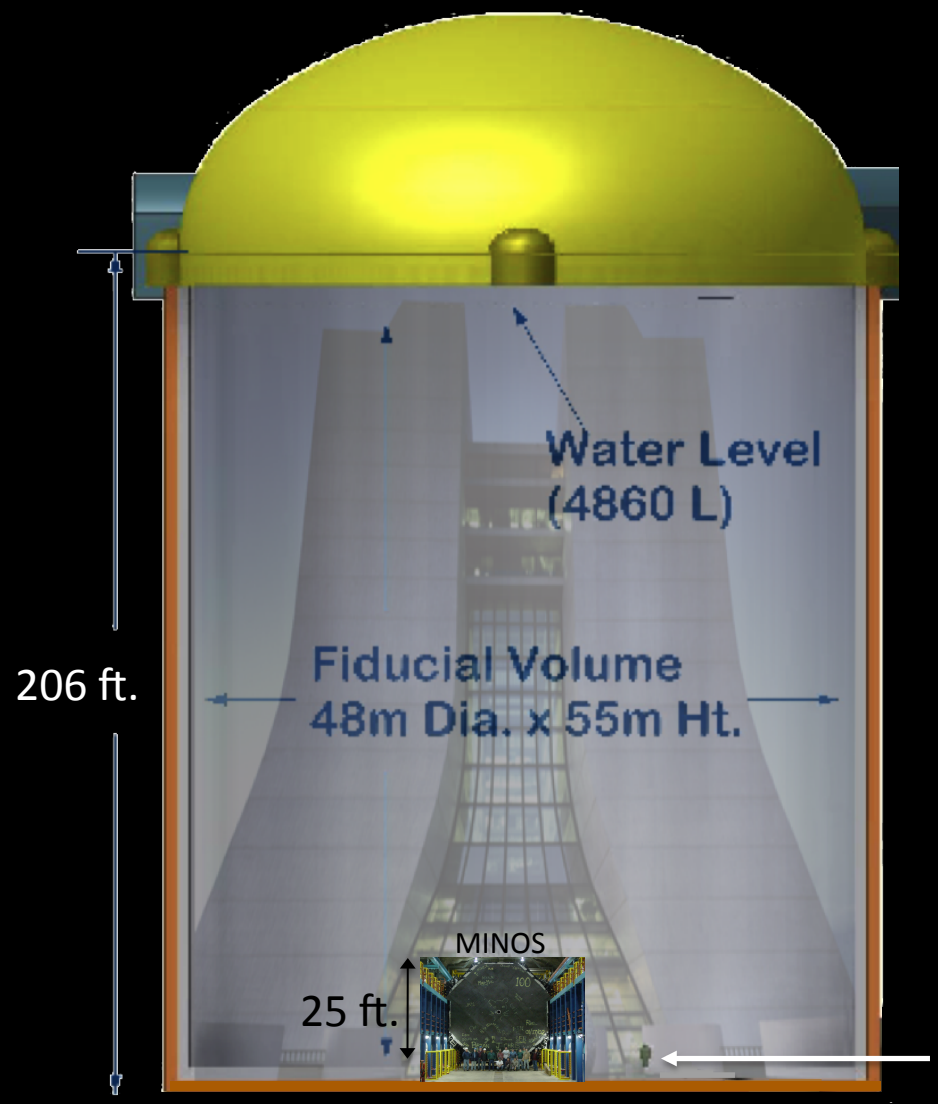
mass ordering parts

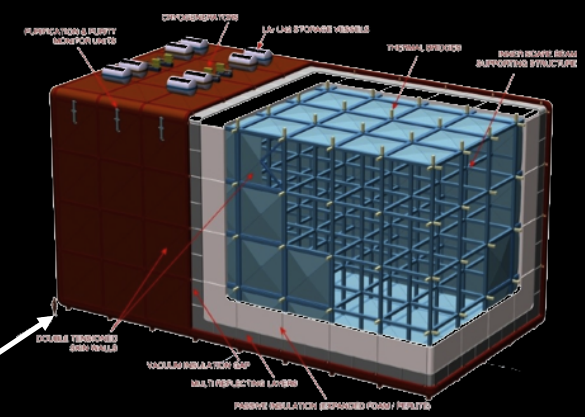


Return To Davis's Homestake Mine?

Long Baseline Neutrino Experiment (LBNE)

the next big thing ☺





neutrino physicists

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

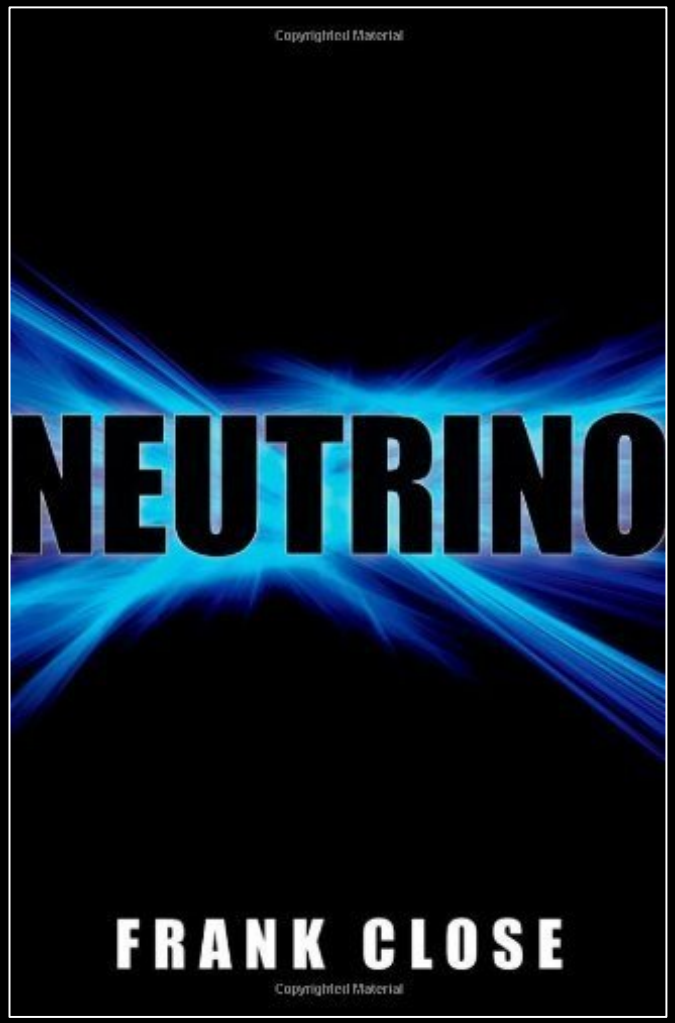
Feels like the tip of the iceberg
What else will the neutrino reveal to us about matter and the workings of the Universe?

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!

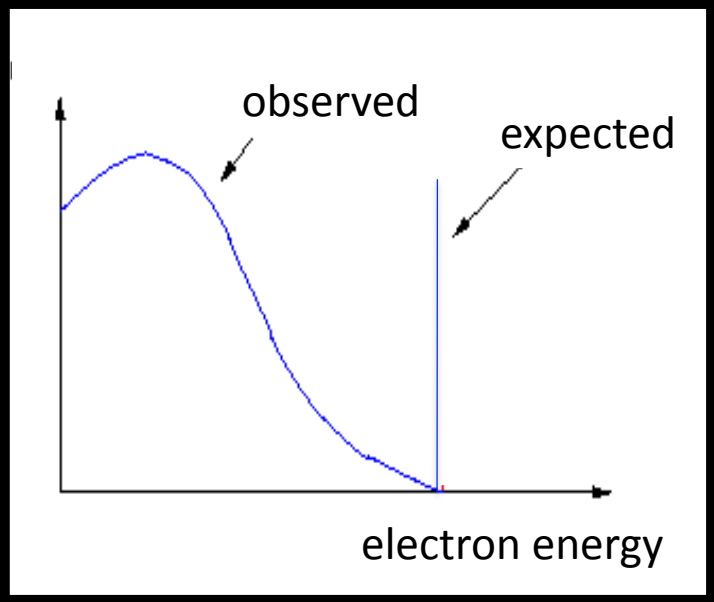
extras

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.

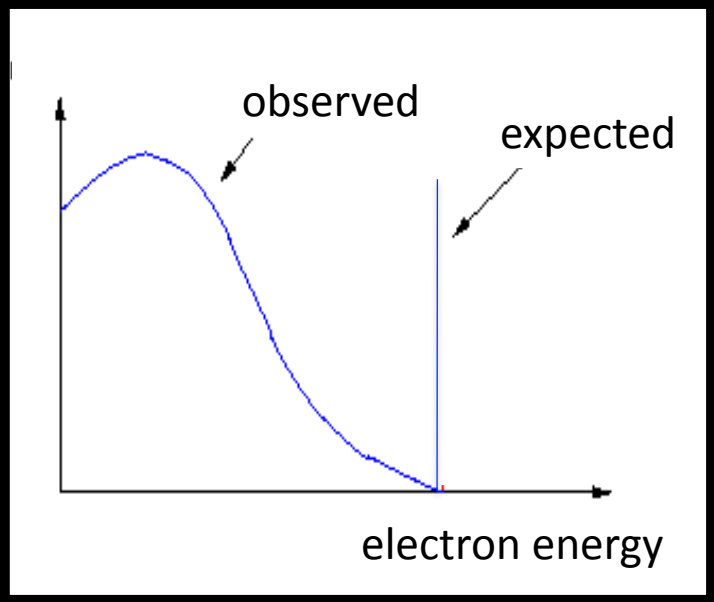
John Updike
(March 18, 1932 – January 27, 2009)

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"

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
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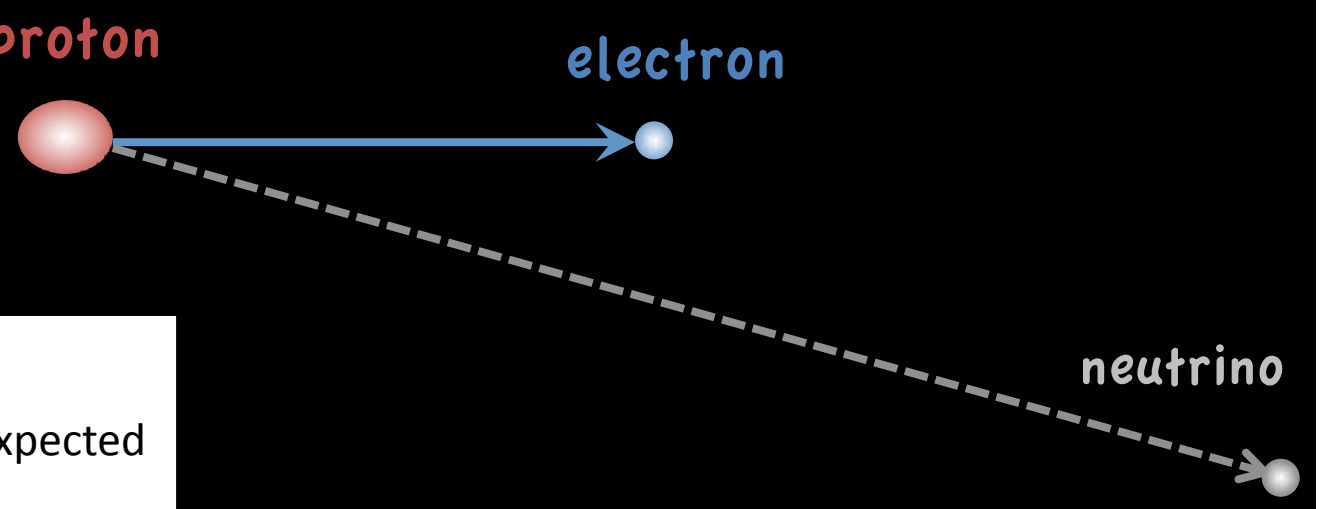
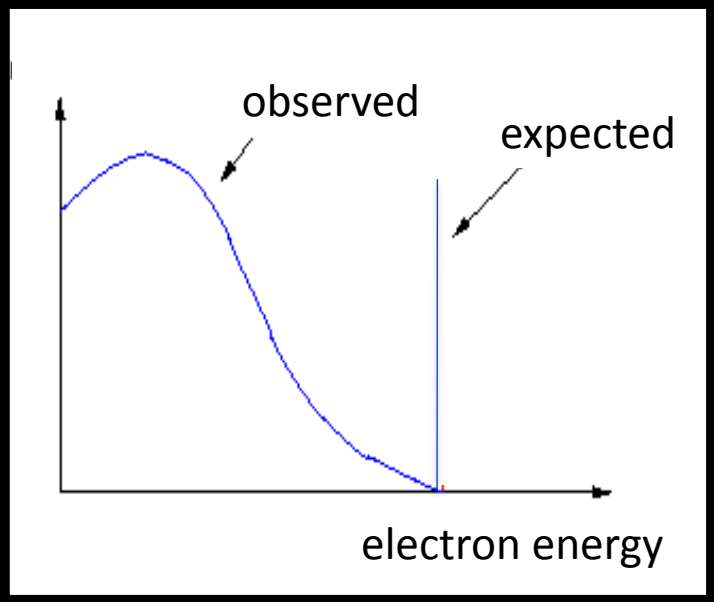




Wolfgang Pauli's
"Desperate remedy"

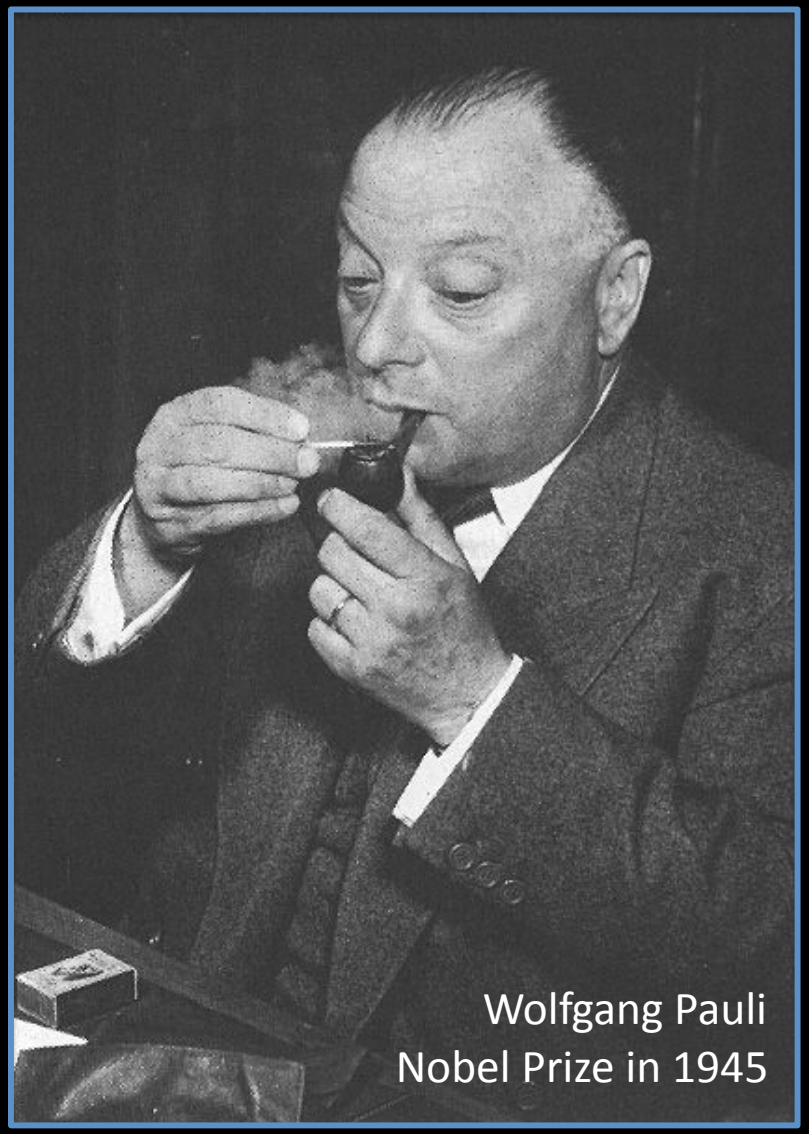
Dear Radioactive Ladies and Gentlemen,

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



Setting out to detect the first neutrino

Fred Reines & Clyde Cowen

Project Poltergeist (1950's)

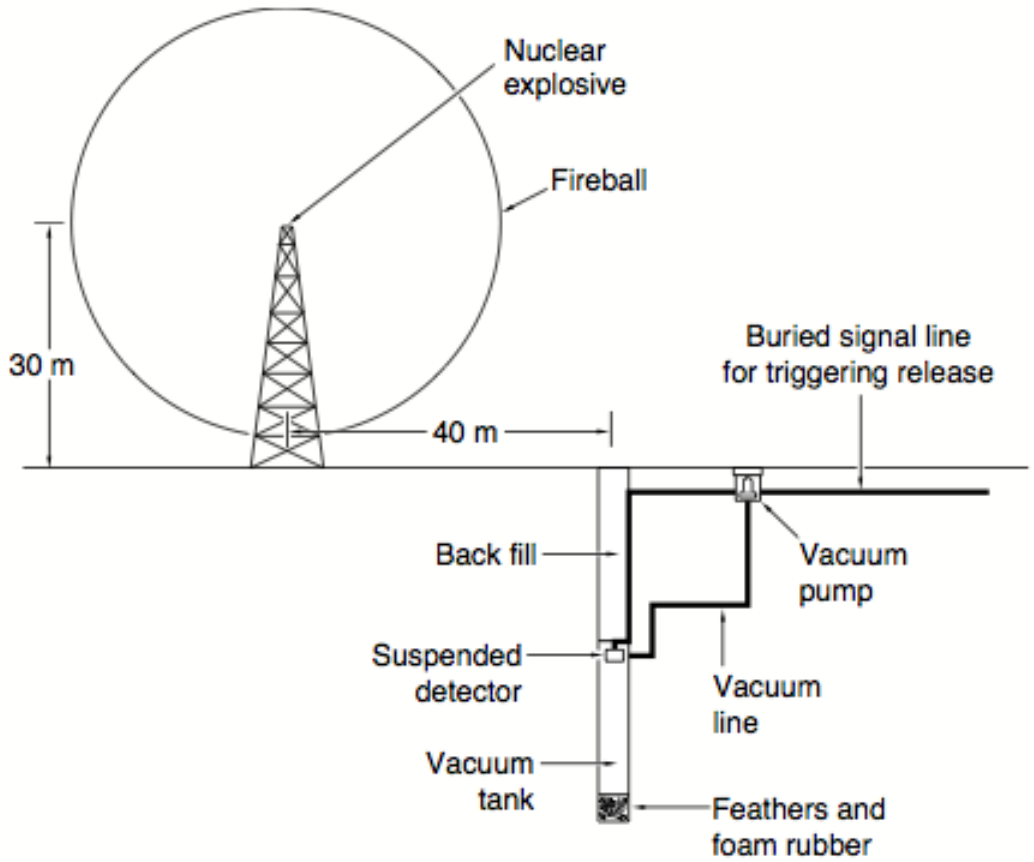
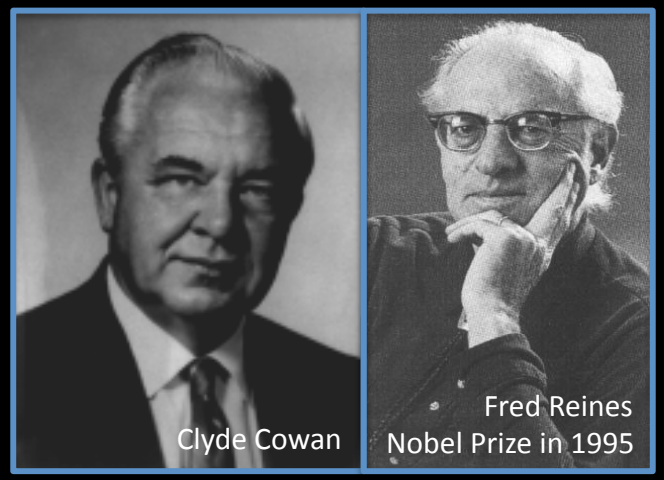
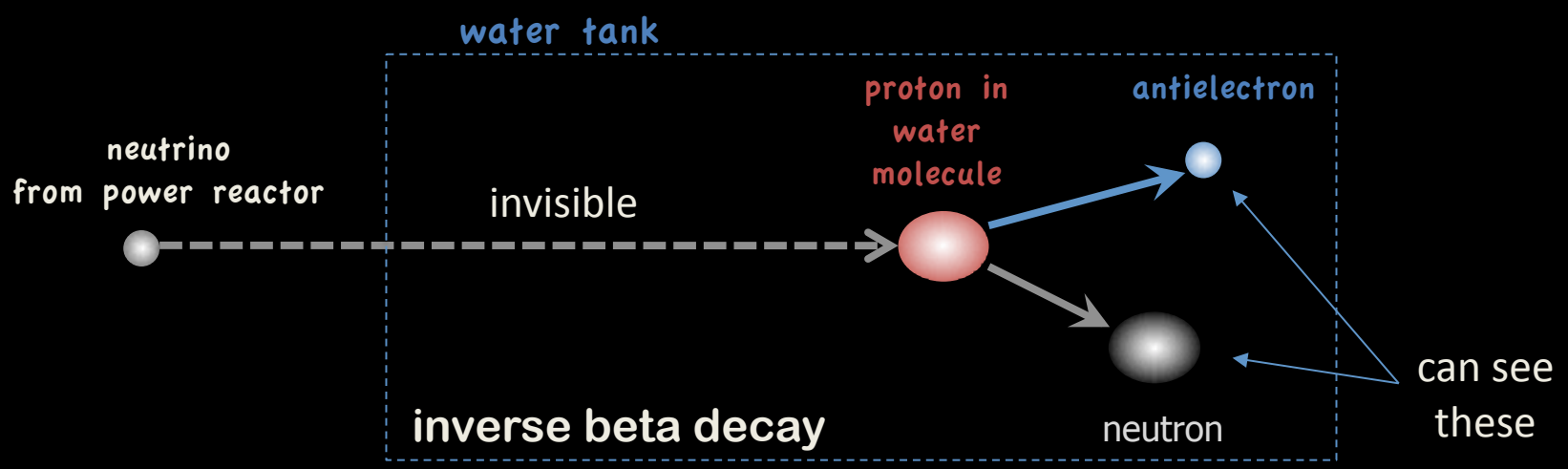


Figure 1. Detecting Neutrinos from a Nuclear Explosion

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."

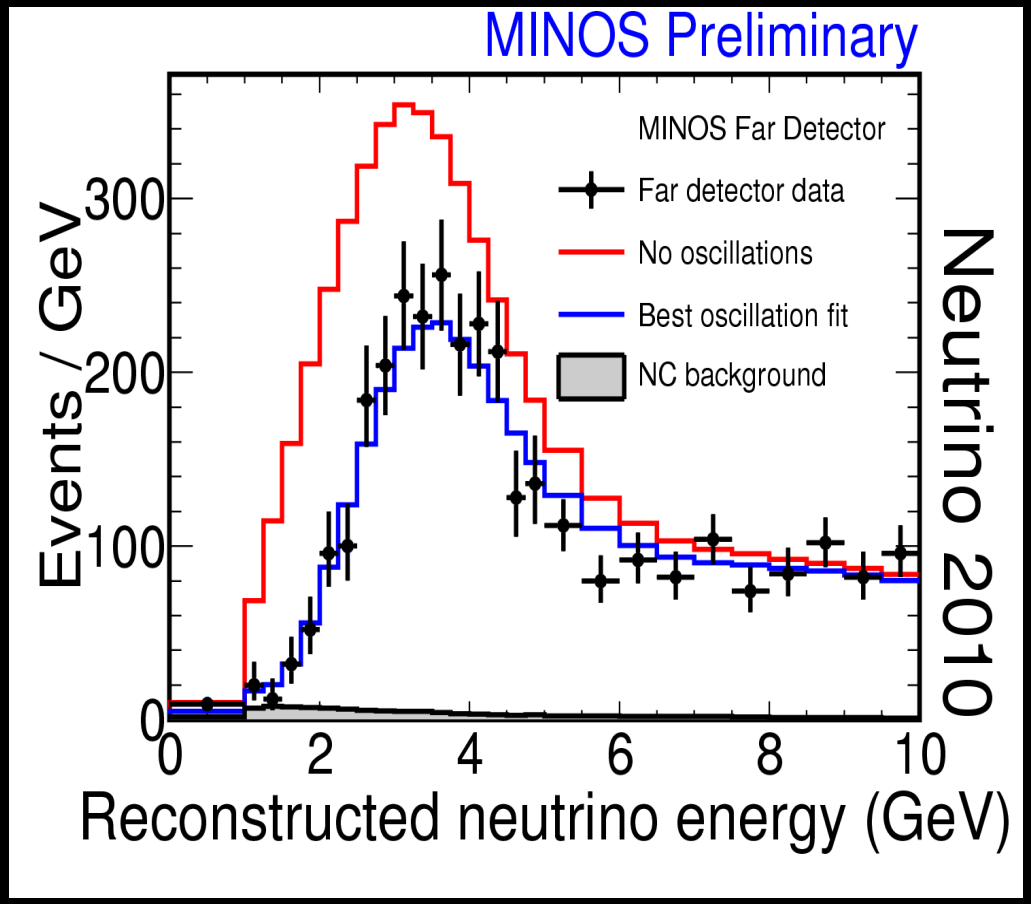
- Fred Reines and Clyde Cowan (1956)

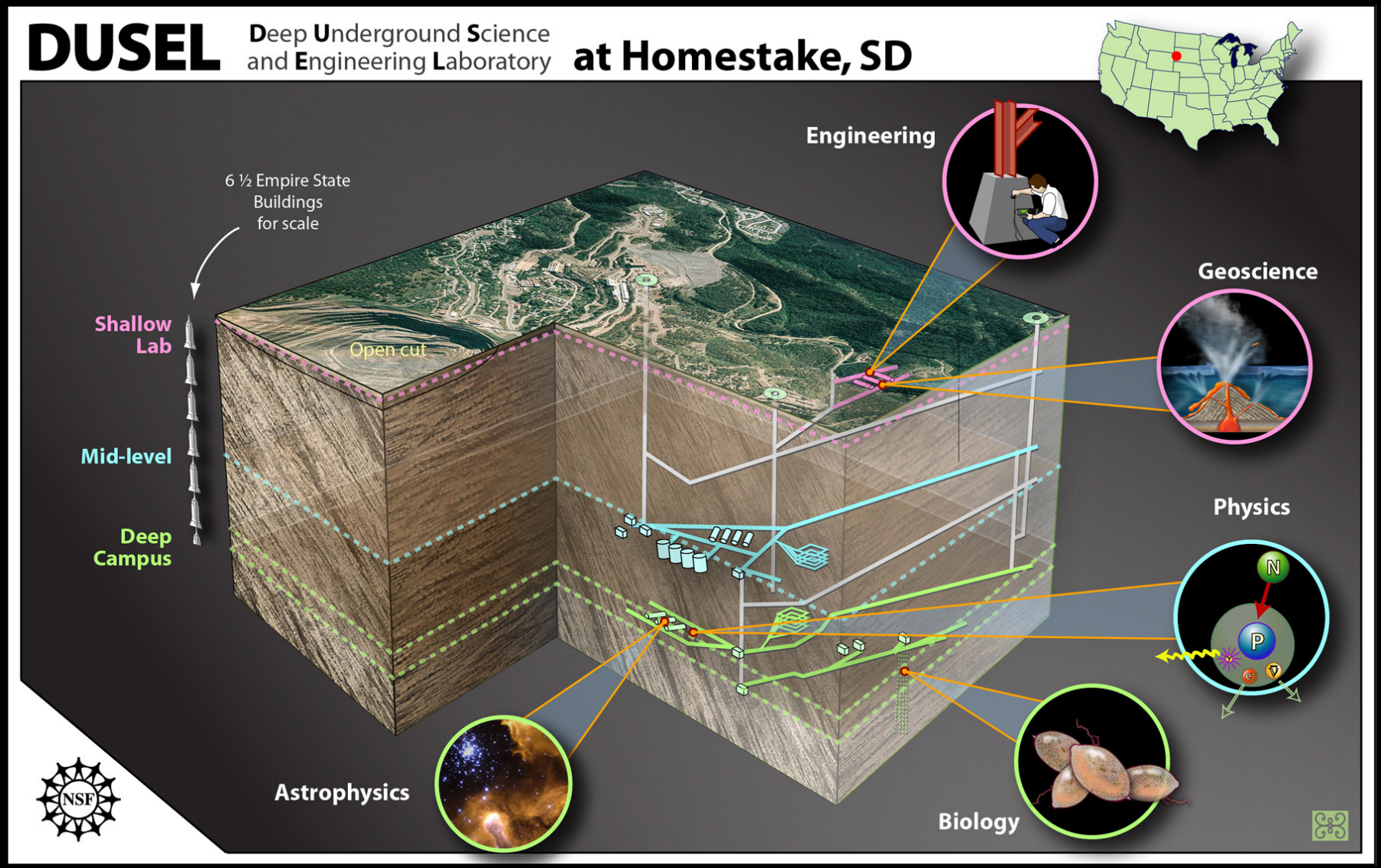
"Everything comes to him who knows how to wait."

- 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
6 ½ Empire State Buildings for scale
Shallow Lab
Mid-level
Deep Campus
Open cut
Engineering
Geoscience
Physics
N
P
Astrophysics
Biology
NSF