Neutrinos

...

Saturday Morning Physics

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Fermilab
November 4, 2017

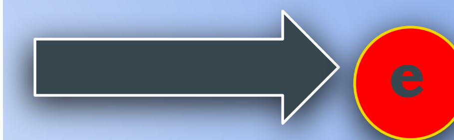
Standard Model and Neutrinos

Elementary Particles

What does elementary mean?

Leptons

e — electron — *charge: -1*

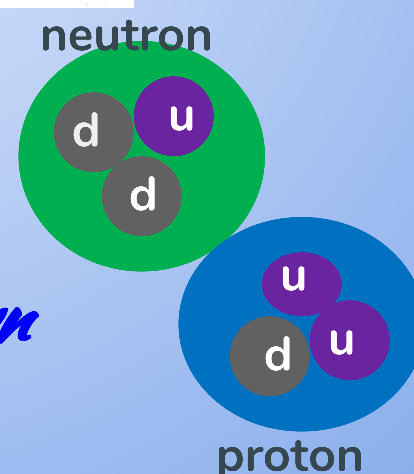


Quarks

u — up — *charge: +2/3*

d — down — *charge: -1/3*

→ *protons = 2 up and 1 down*

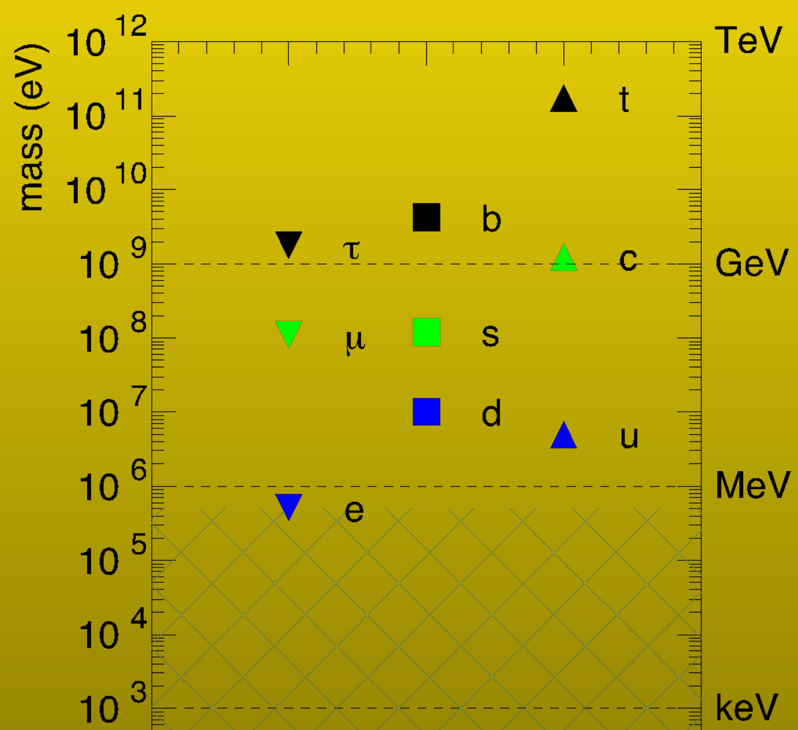


Partial Standard Model of Elementary Particles

Leptons

Quarks

The difference between the generations is the MASS!



The Fundamental Forces of the Universe **Influence** the Behavior of Particles!

Thanks to the electromagnetic force, we can't walk through walls!

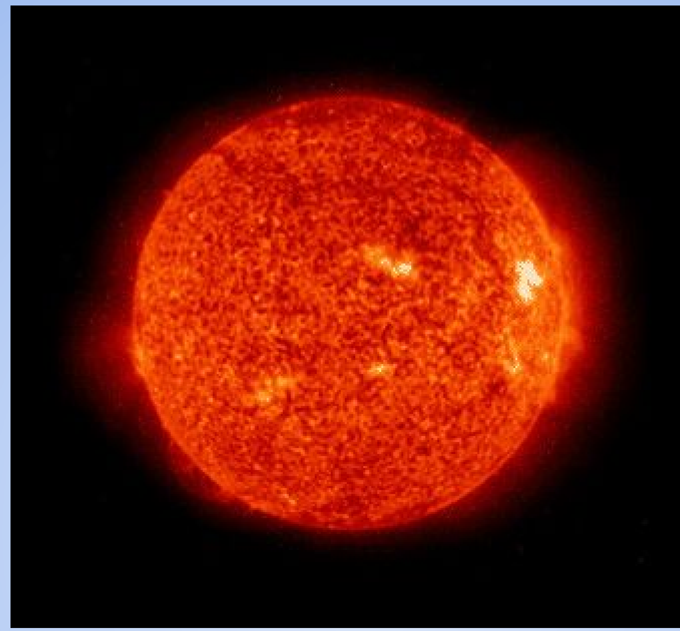
The Fundamental Forces of the Universe **Influence** the Behavior of Particles!

How about the weak force?

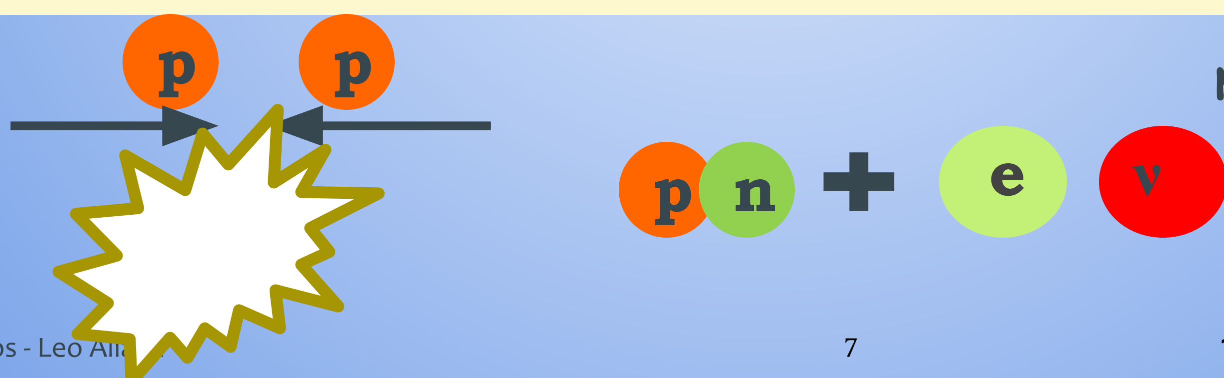
Let's take a detour first....

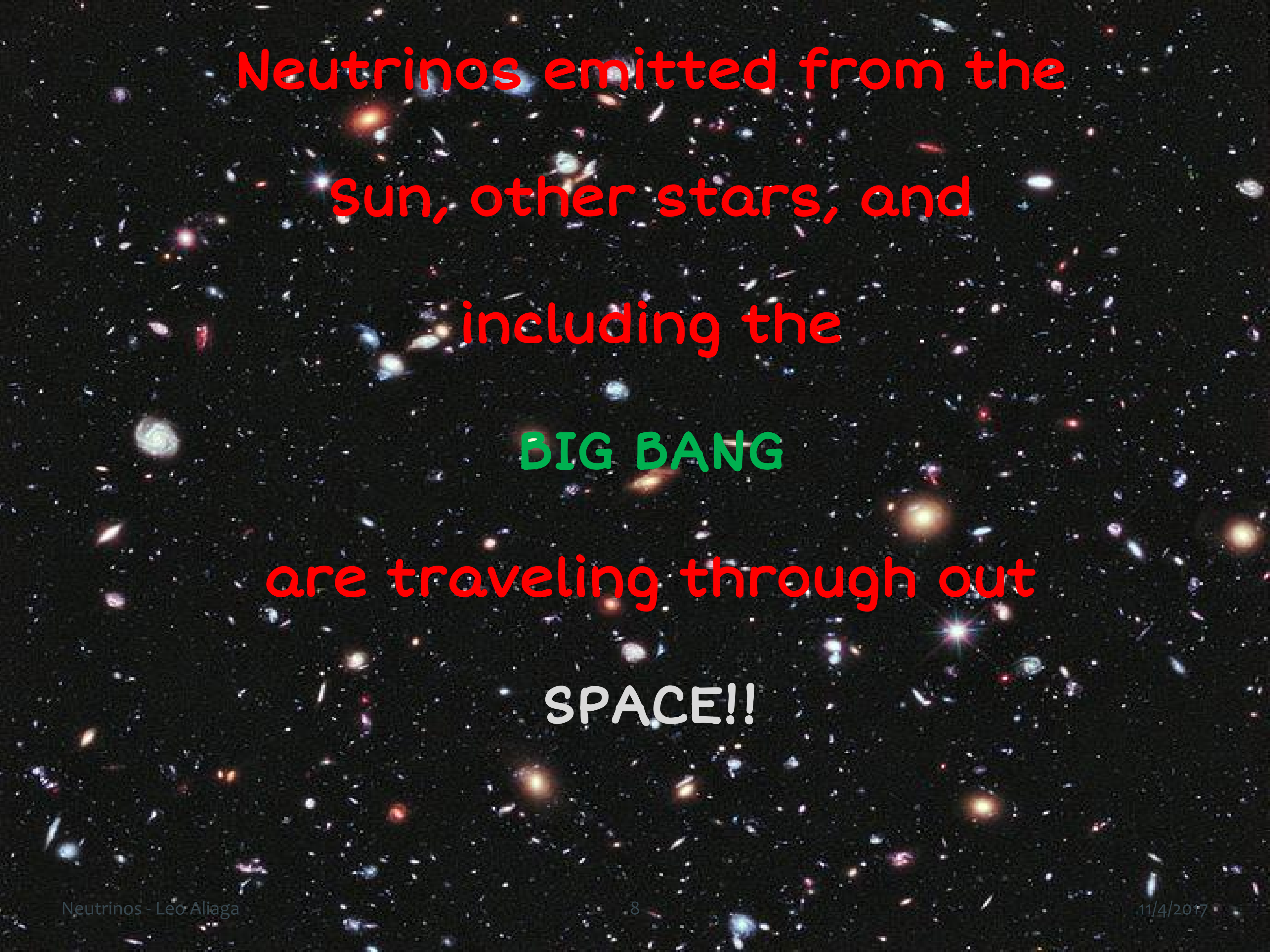
Nature Can Produce Particles!!!

The sun is an ultimate nuclear fusion reactor!



Nuclear Fusion





Neutrinos emitted from the

Sun, other stars, and

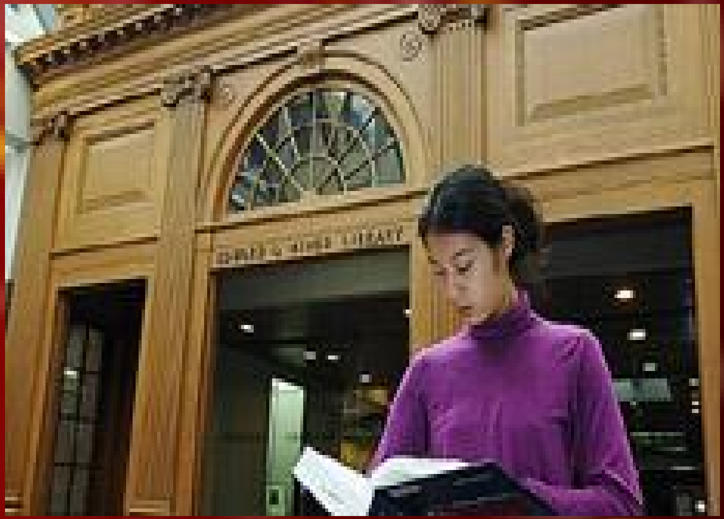
including the

BIG BANG

are traveling through out

SPACE!!

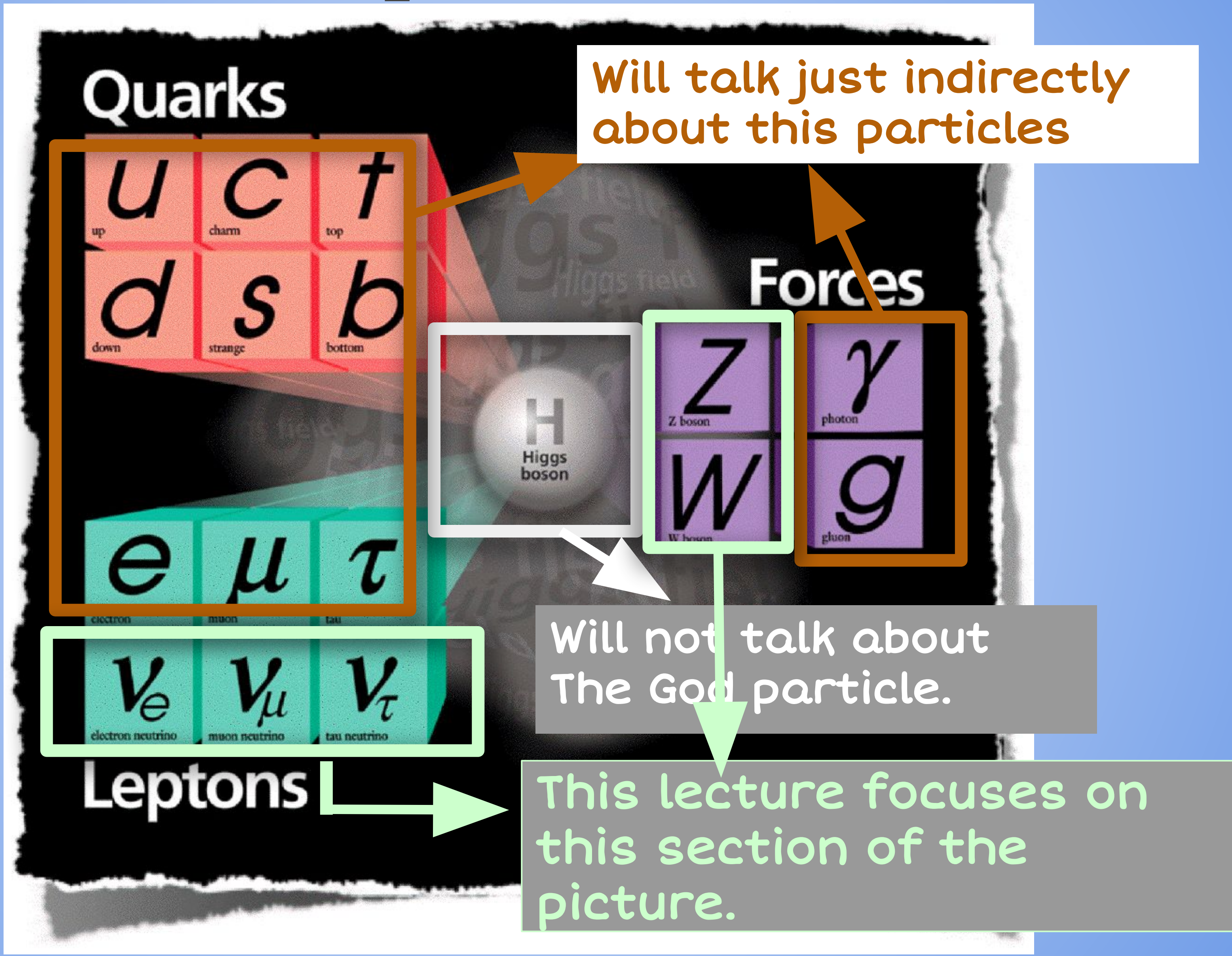
Millions and millions and millions of neutrinos are also passing through YOU at this very MOMENT!



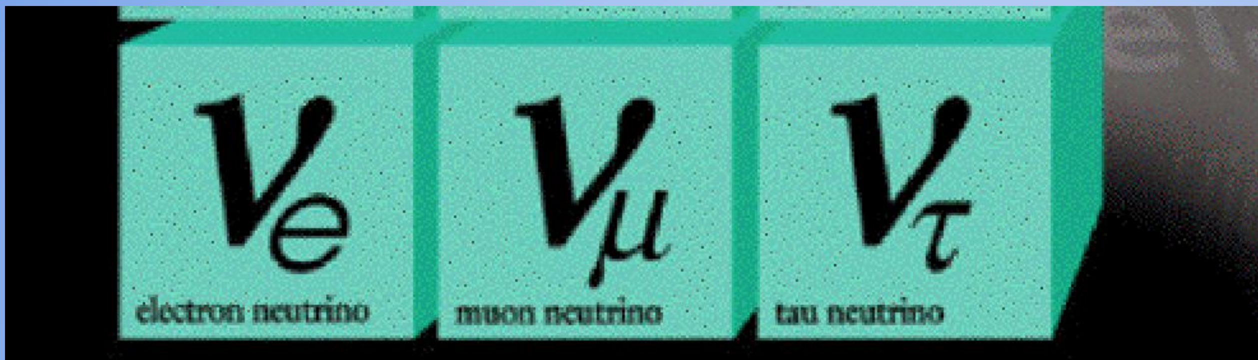
~ 65 billion of neutrinos / cm^2 / sec from the Sun.

Neutrino flux: ν/ cm2 / sec

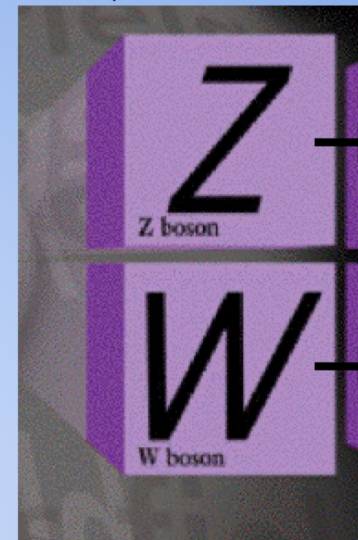
The Complete Picture



3 neutrinos types (flavors):
no charge, only interact by
weak force



2 mediators of
weak force



charge: 0

charge: +-1

What are neutrinos?

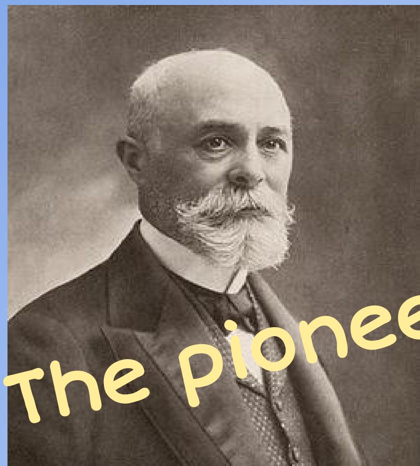
What is the **Weak force** that influences the nature of neutrinos?

Why are neutrinos ***SO*** important?

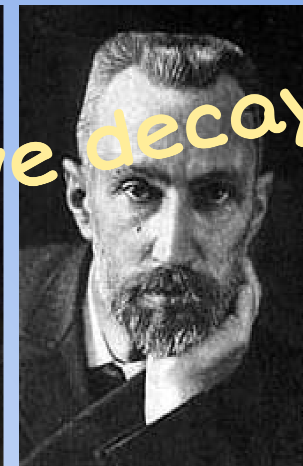
The Discovery of the Neutrino

The pioneers of radioactive decay

Antoine Henri Becquerel



Marie Curie and Pierre Curie

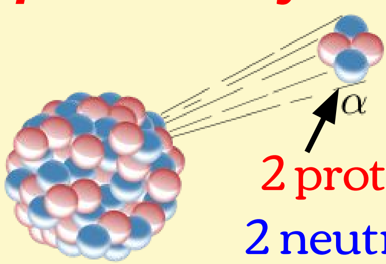


Radioactive Decay

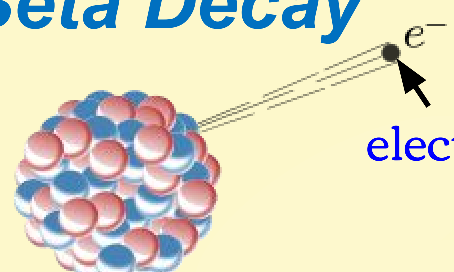
unstable atomic nucleus loses energy by emitting particles

transforms an atom into a different type of atom or into a lower energy

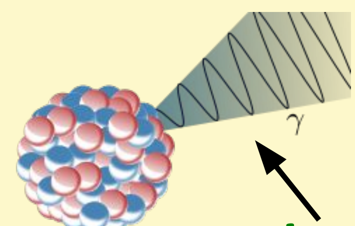
Alpha Decay



Beta Decay



Gamma Decay

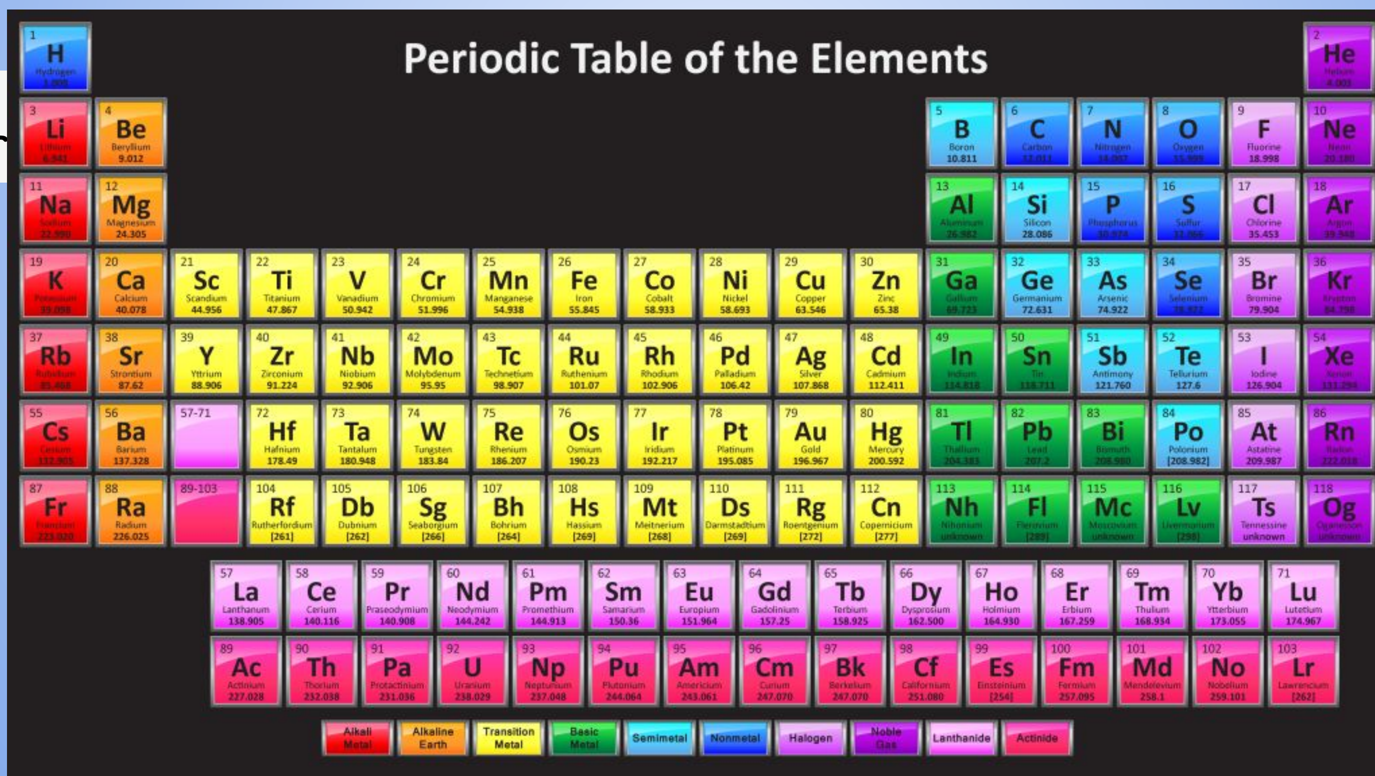


Studying Beta Decay

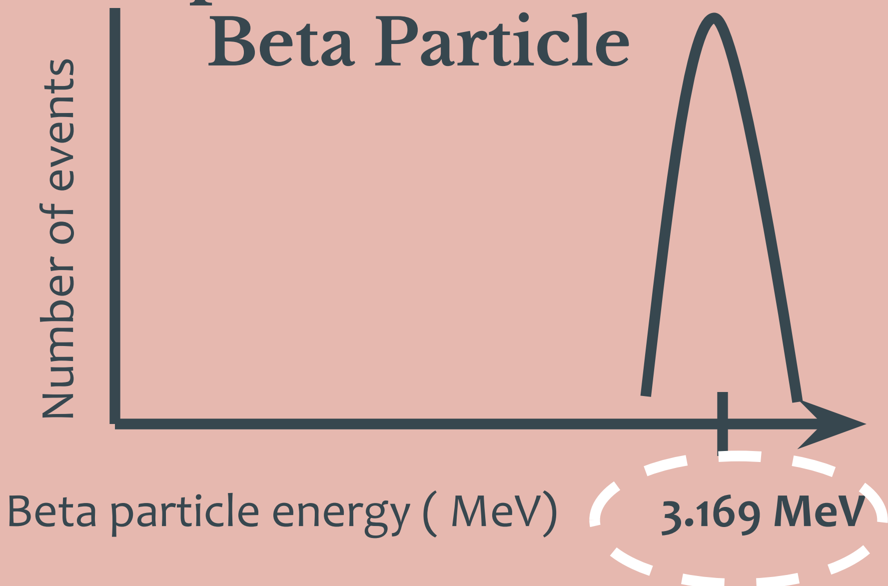
Rhodium → **Palladium** + **Electron (Beta Particle)**

Rhodium	Palladium	Electron (Beta Particle)
98,652.876 MeV/c²	**98,649.196 MeV/c²**	**0.511 MeV/c²**

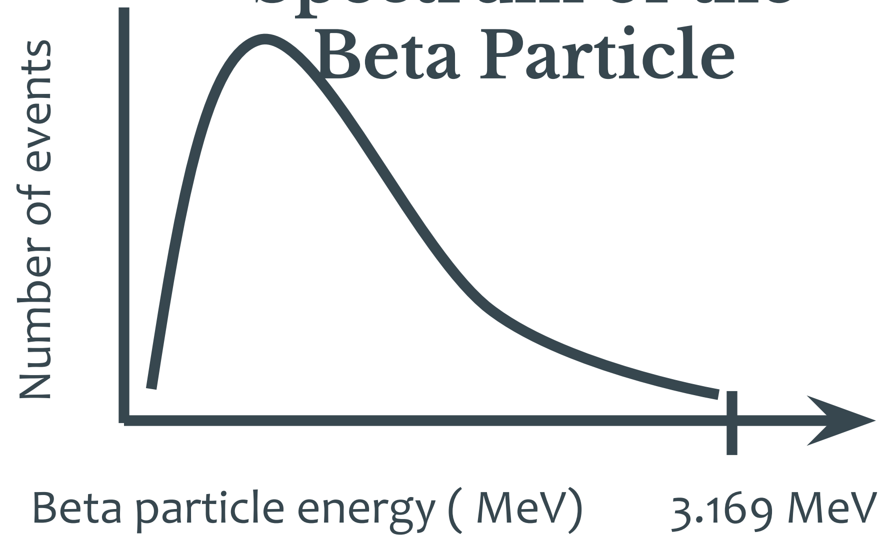
electr… …69 MeV.



Expected Energy Spectrum of the Beta Particle



Measured Energy Spectrum of the Beta Particle



Could it be possible?

Does the Beta Decay Violate the Law of Energy Conservation?

In 1930, Wolfgang Pauli proposed that another particle (**a neutral particle, a particle that can not be detected**) is emitted along with the electron.

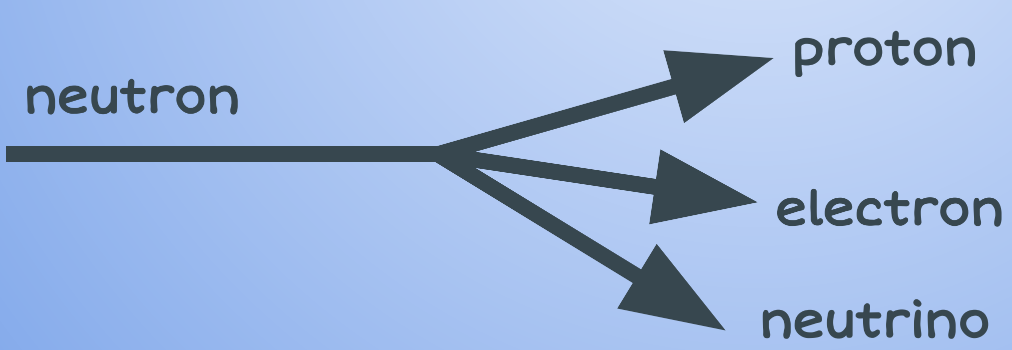
However, Pauli was skeptical about the proposal.

In fact, on Dec. 4, 1930, Pauli wrote a letter to a conference organizer proposing the idea of a neutral particle.

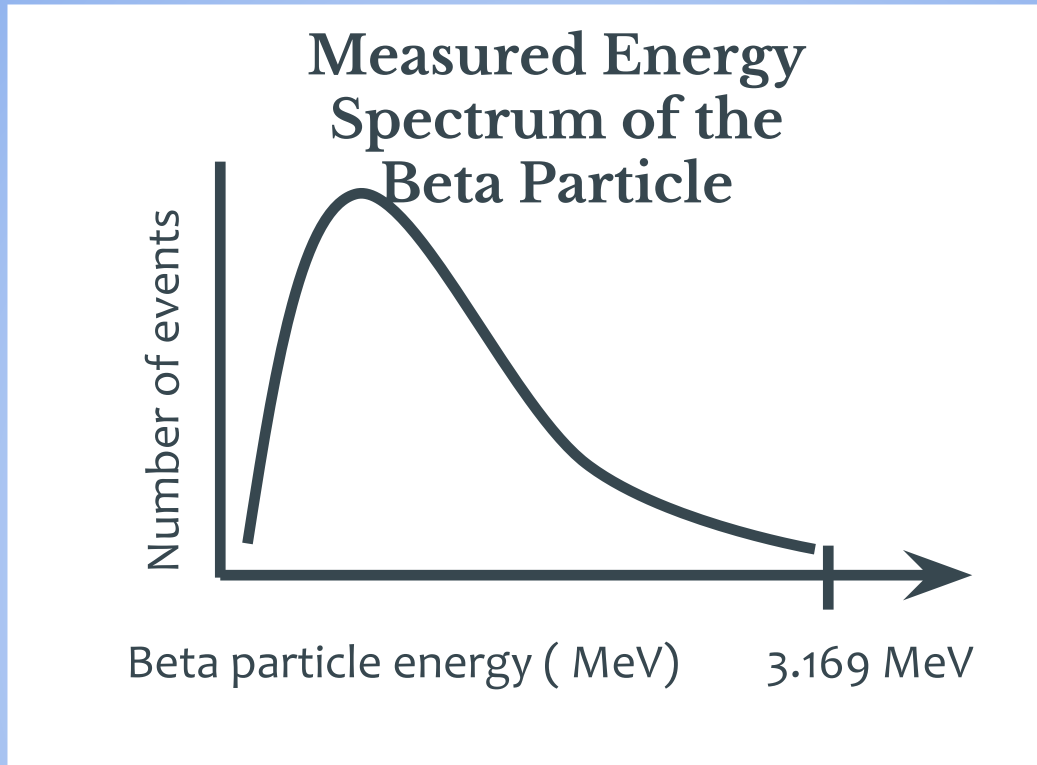
In 1933, Enrico Fermi brought the particle into reality.

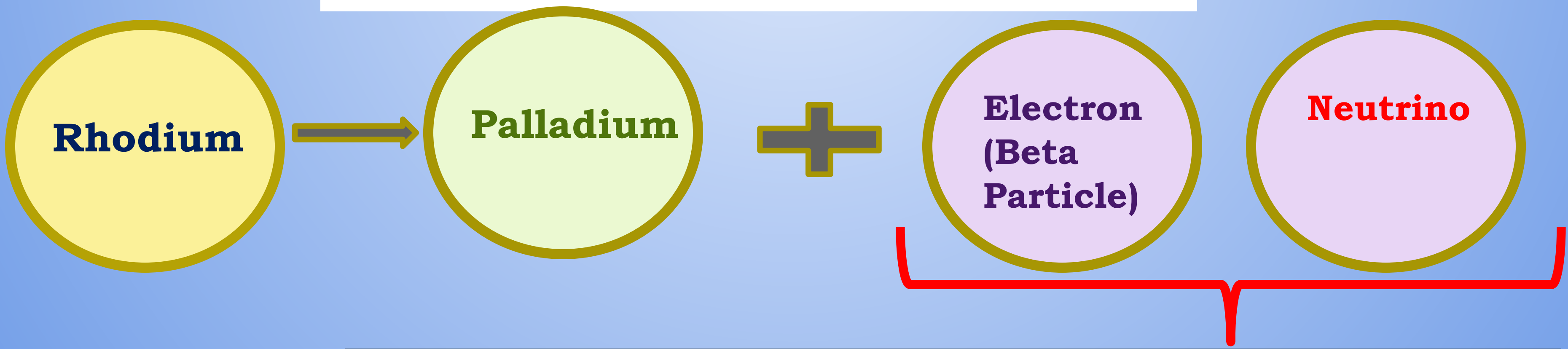
Fermi's theory showed that the neutron (also bound in the nucleus) decays into a proton and simultaneously emits an electron and a ***neutrino***.

The **WEAK FORCE** turns the neutron into a proton.



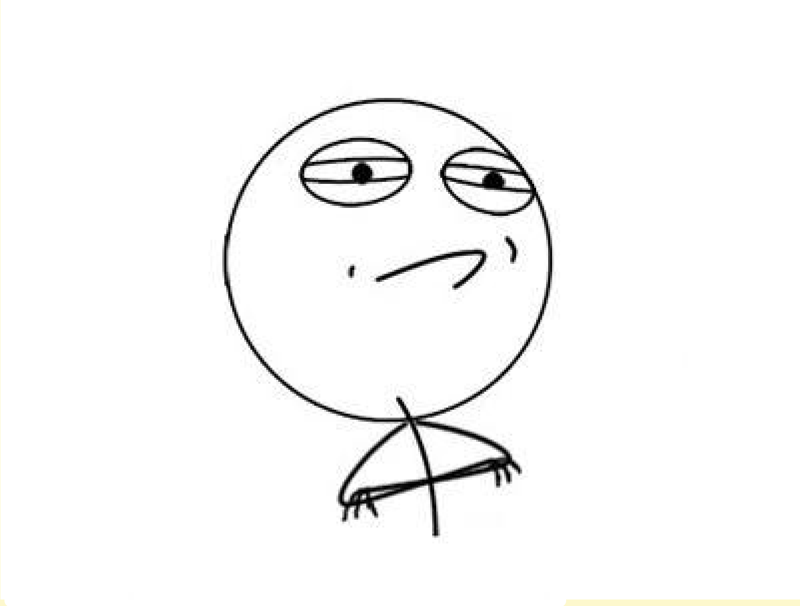
Back to the Beta Decay





Energy is shared between the particles.

- Fermi's theory of energy remains conserved.

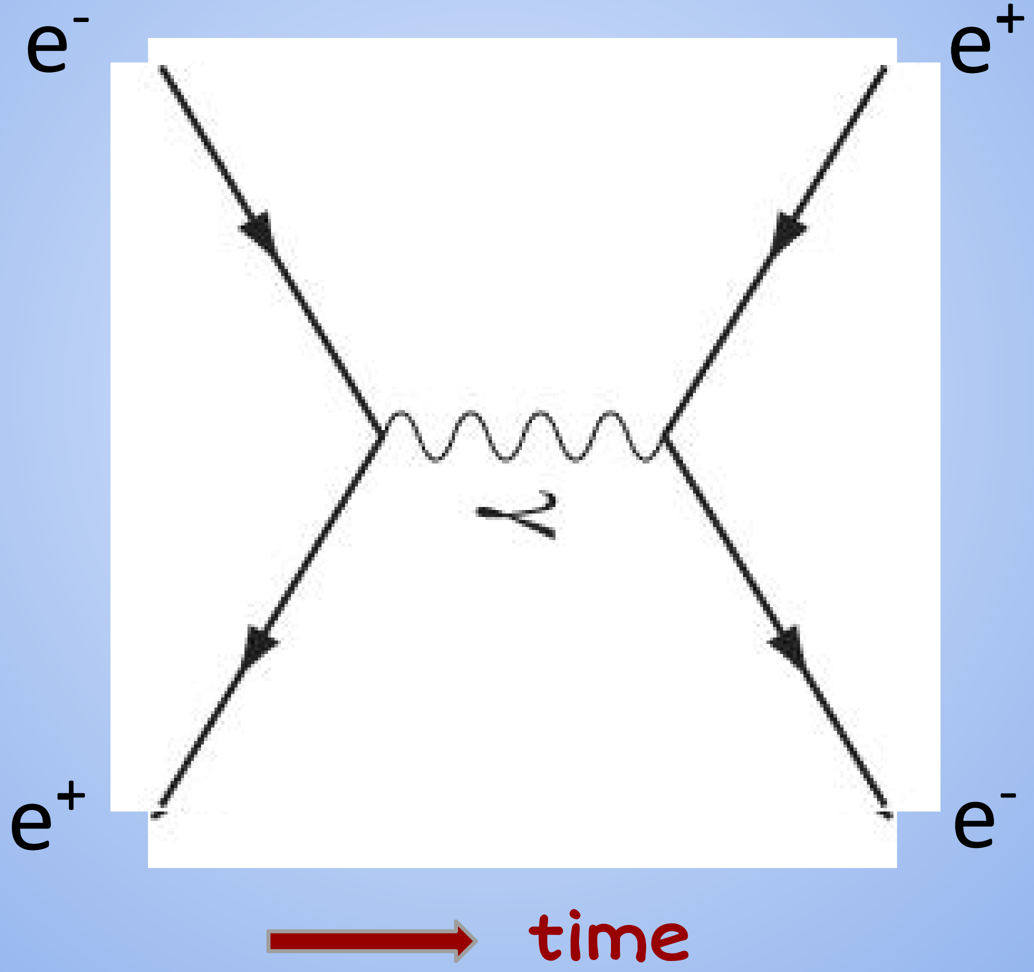


- A new particle, the neutrino, is proposed.
- Next step is to detect the neutrino.

Finding the Neutrino

Nature has many symmetries

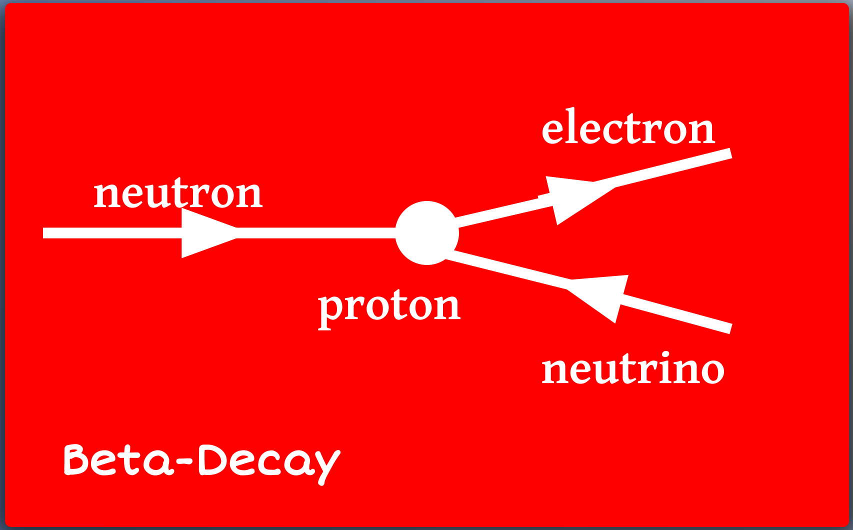
Symmetry in Interactions

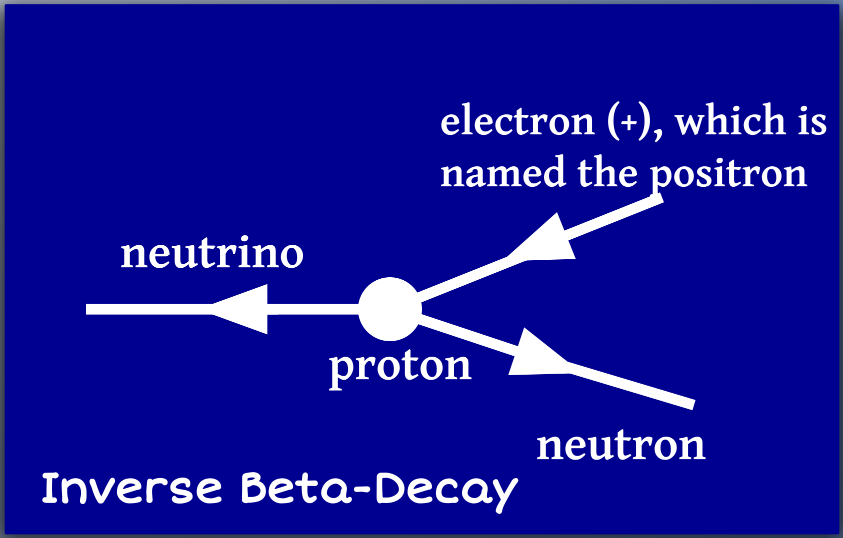


Symmetry Plays a Fundamental Role in Particle Physics

Time Reversal

Any particle interaction that occurs forward in time can also occur backwards.



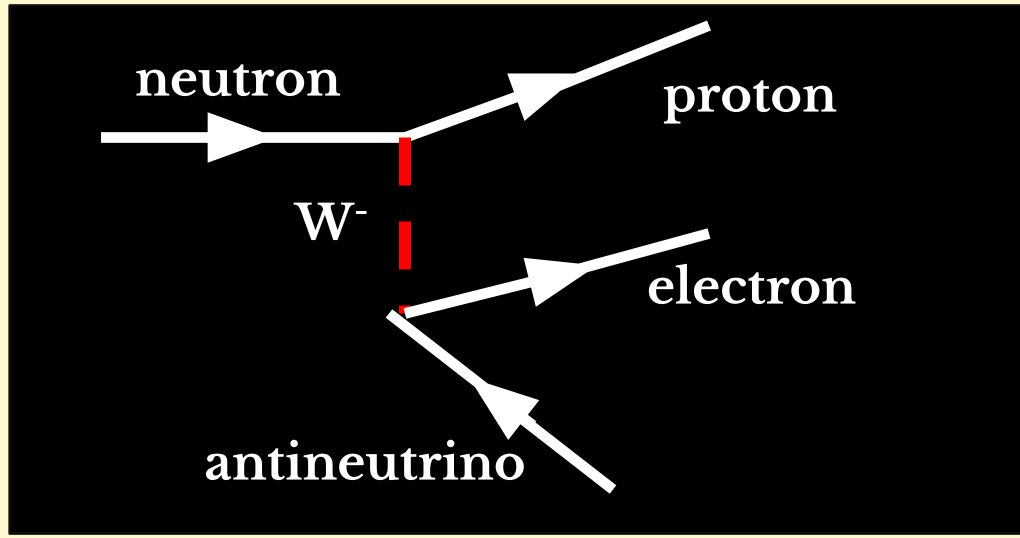


We can **DETECT** the neutrino by the inverse beta-decay.

The weak force and neutrinos

In 1936, Yukawa proposed the **W boson**.

The carrier of the **WEAK FORCE**.



The weak force is one of the four fundamental forces of nature.

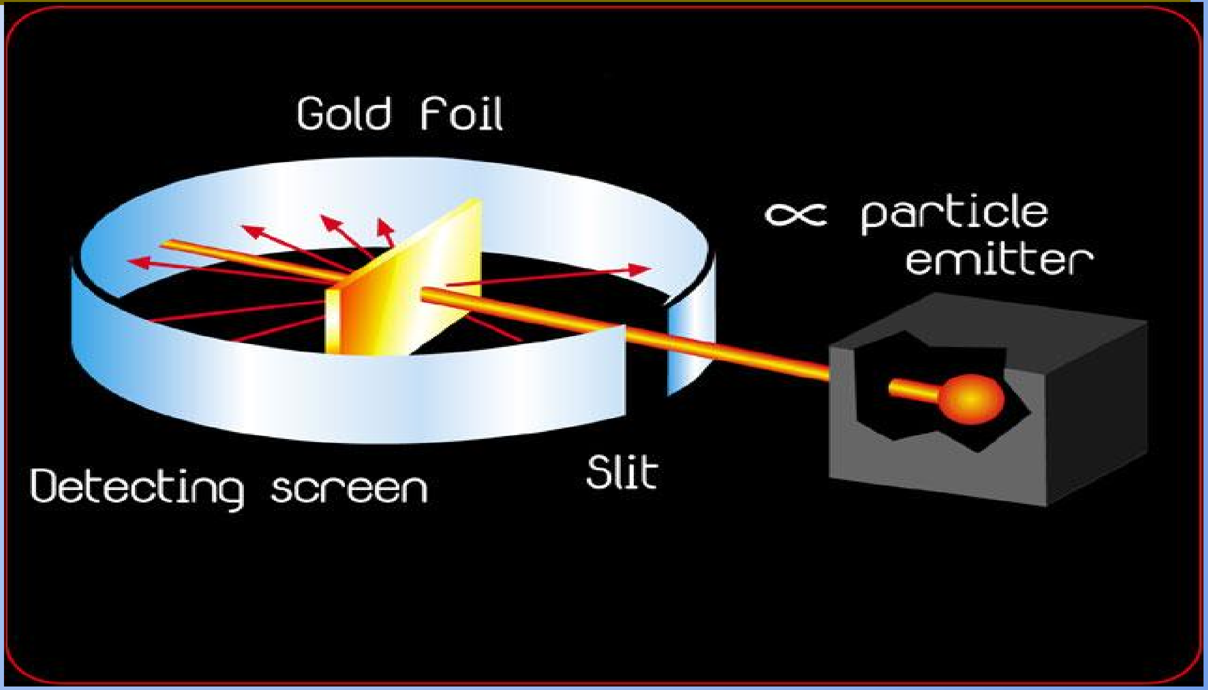
Weak force is **10,000 times** weaker than the electromagnetic force.

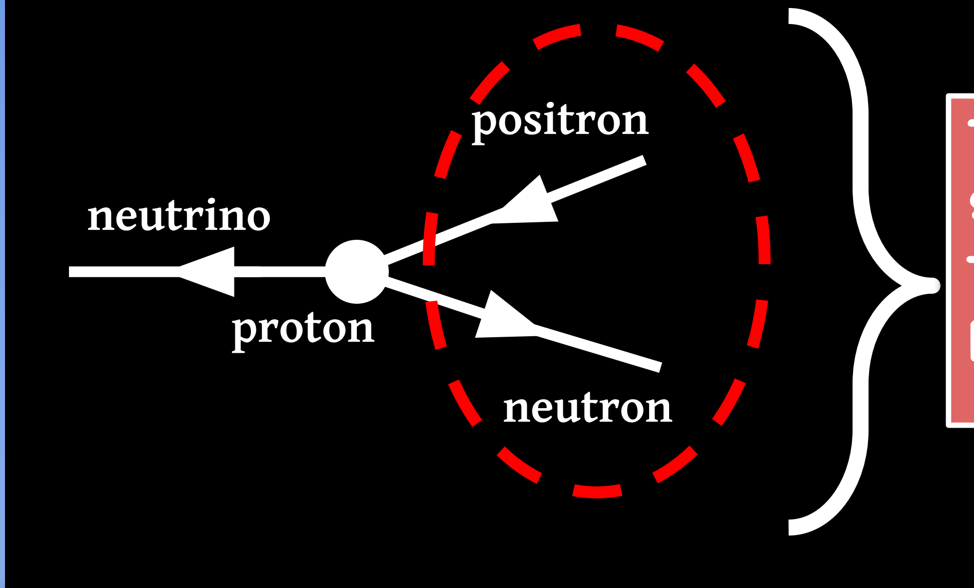
Physicists Use Scattering Experiments to Understand and Discover Particles

Scattering experiments measure the cross section of a particle interaction.

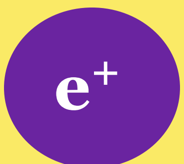
Cross-section is the number of counts in which the particle interacts with another particle.

Units of cross-section: **area (cm^2)**



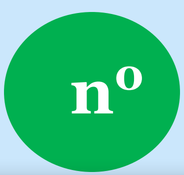


To observe the neutrino, scientists needed to detect the signatures of the positron and neutron.



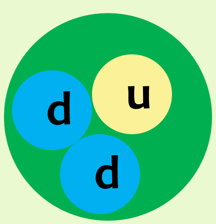
positron

is a positive charged electron → interacts via the electromagnetic force → interaction results in emission of gamma rays

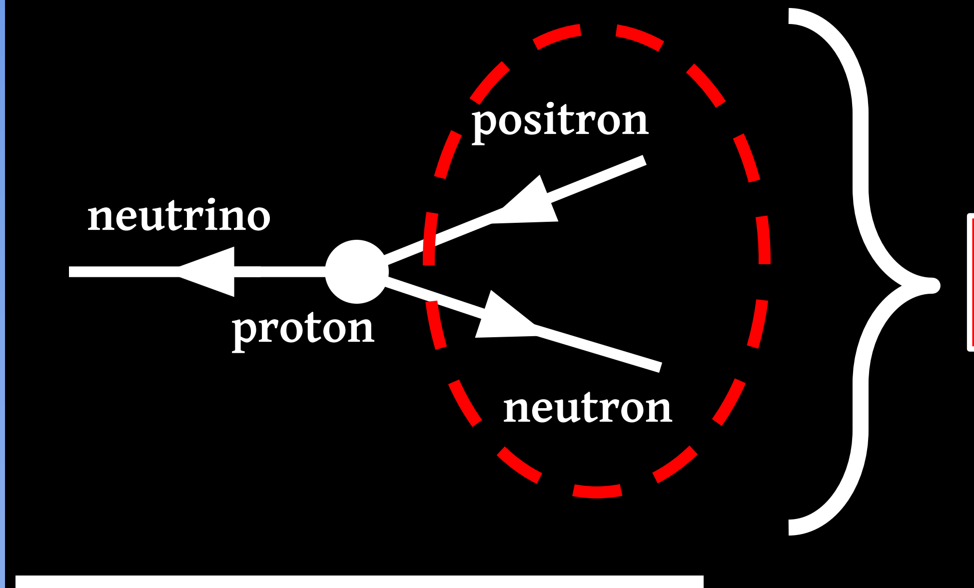


neutron

looking inside the neutron

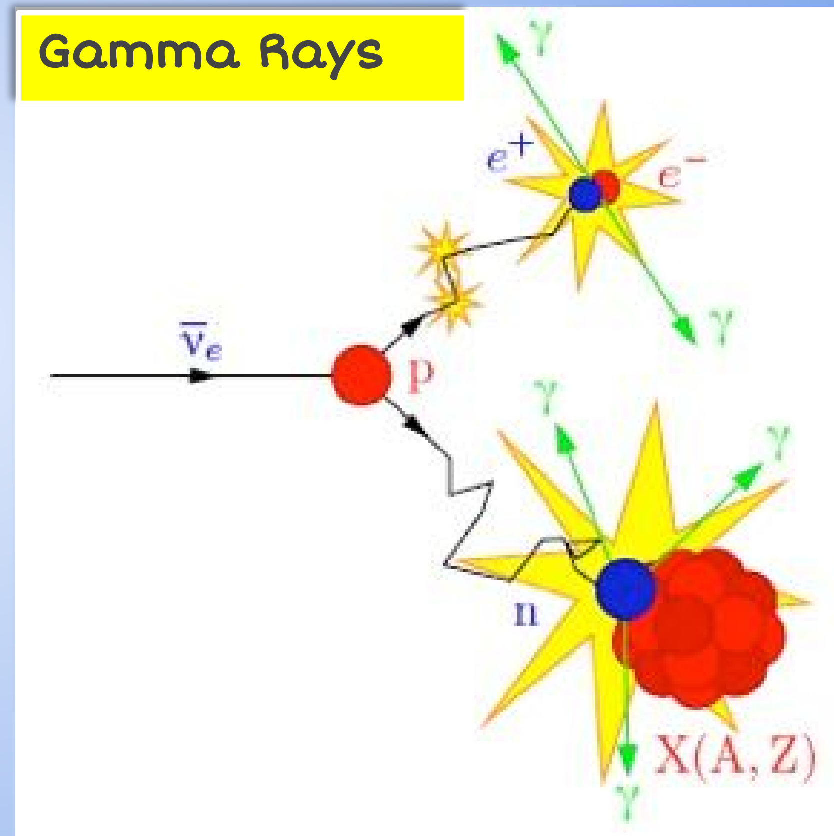


an atomic nucleus can capture a neutron → strong force binds the neutron in the nucleus to create a heavier particle → the heavier particle is unstable → emits gamma rays to become stable



signature of the inverse beta decay

Gamma Rays



The HULK is unstable.
Bruce Banner is stable.

One would think that finding the signature of the neutrino will be easy.

Physicists calculated the cross-section of the inverse beta-decay to be less than 10^{-44} m^2.

What does that mean? What is the rate?

Solar Neutrinos can travel up to a light year of lead before interacting (MeV scale).

Neutrinos at Fermilab can travel up to 200 earths before interacting(GeV scale)

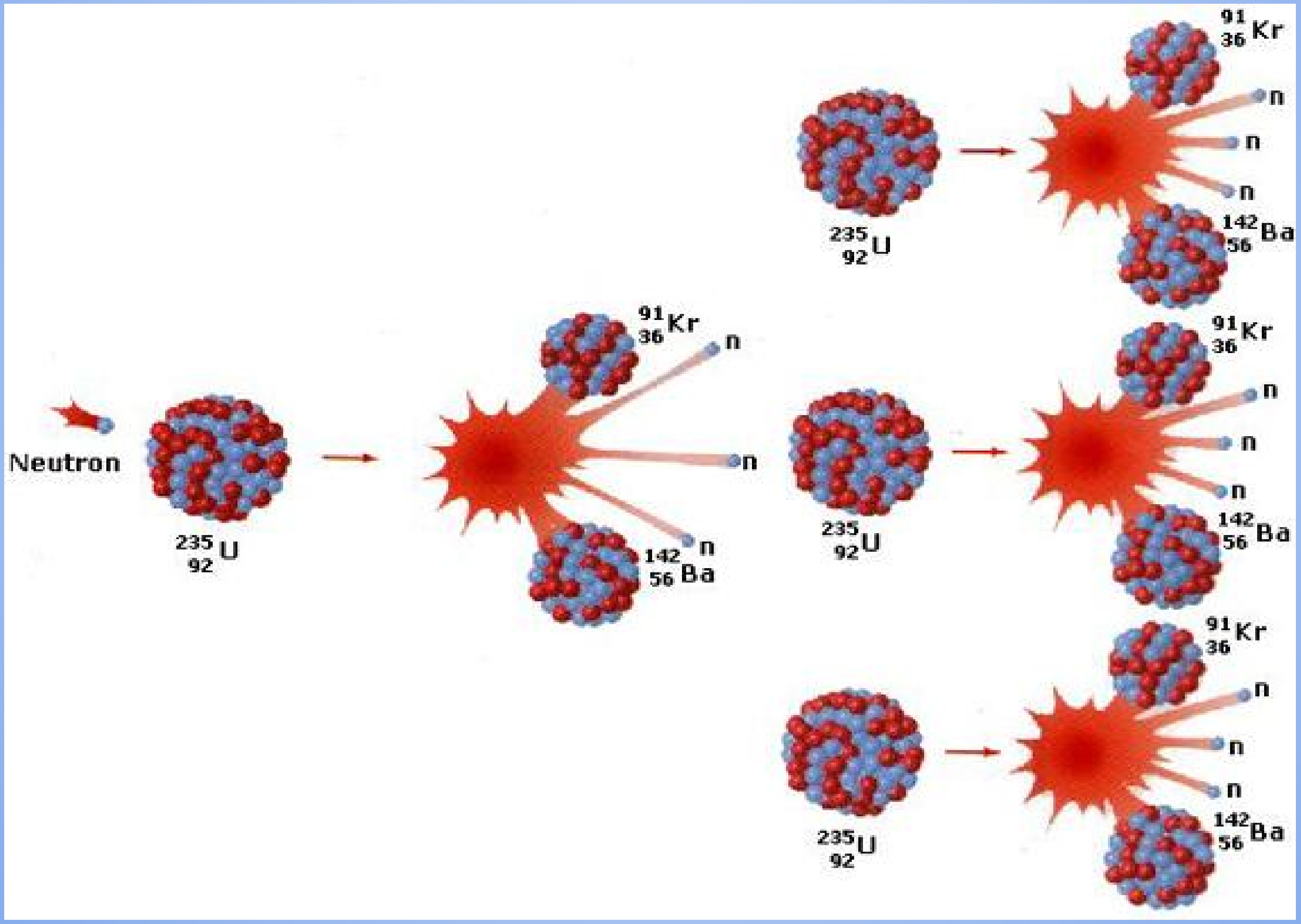
1GeV = 10^3 MeV
= 10^9eV

Neutrino interactions are extremely rare !

Need an intense source of neutrinos!

(more neutrino per area per time, higher flux)

In 1934, Fermi was developing nuclear fission, artificial radioactivity. He bombarded heavy elements with slow neutrons.

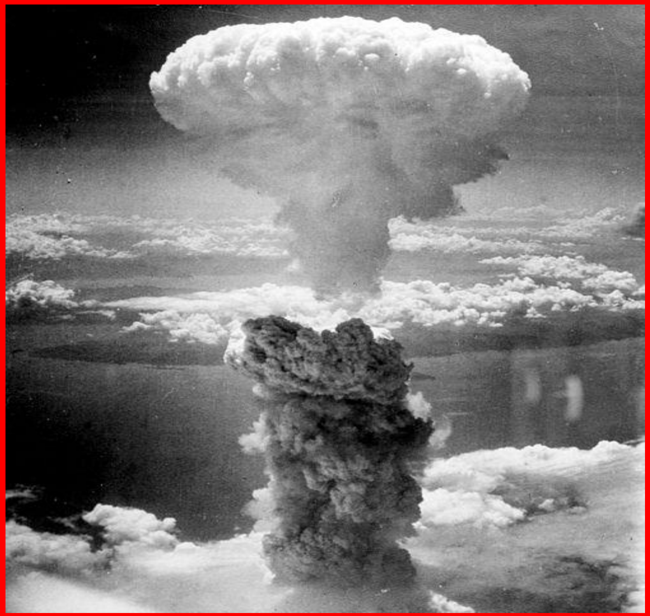


Fermi's colleague Leo Szilard understood the military application of nuclear fission.

Both Fermi and Szilard recruited Albert Einstein to write a letter to President Franklin D. Roosevelt to encourage him to fund their work.

The Manhattan Project was put into action in 1942.

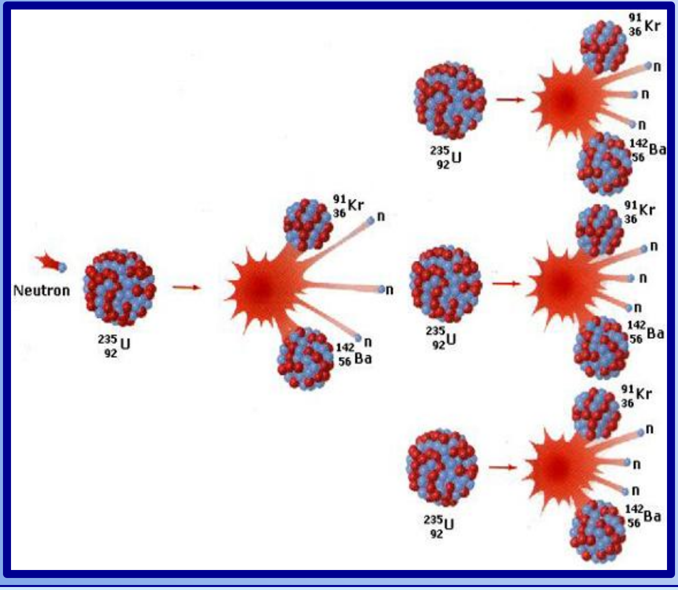
The most brilliant physicists of the era working together constructed the first atomic bomb!

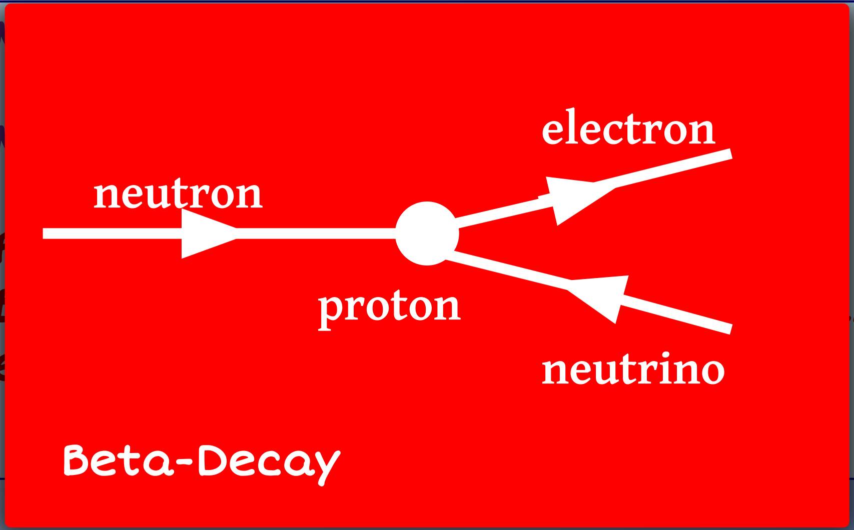


After World War II, scientists aim to extend the knowledge of frontier particle physics.

From the explosion products of the nuclear bomb, scientists were given a manufactured nuclear reactor.

Lets do some Science!!!

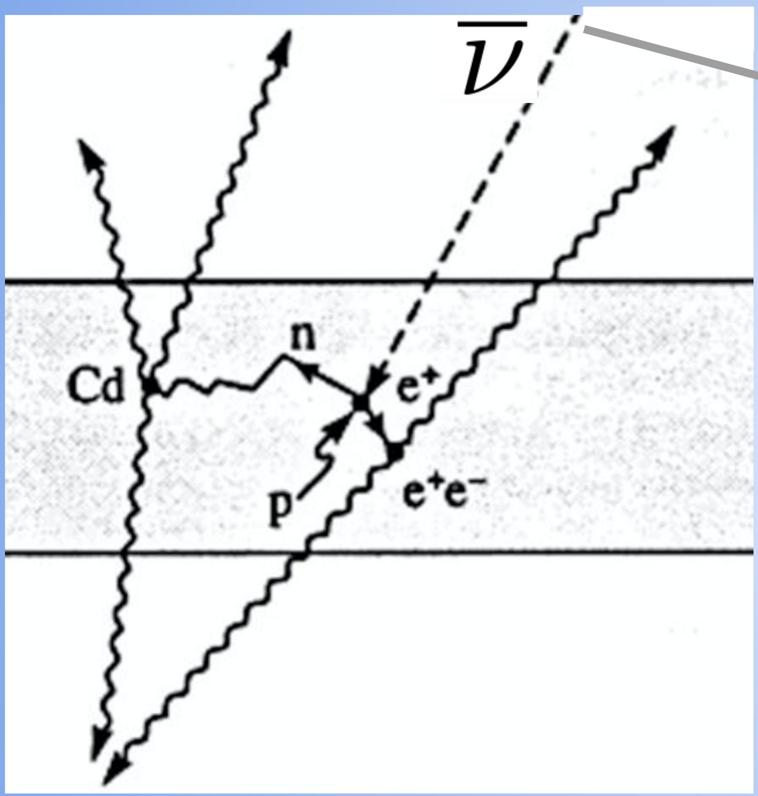




Nuclear reactors were expected to produce neutrino beams on the order of 10^{12}-10^{13} neutrino / sec / cm^2 .

Project Poltergeist

Two decades later, a team lead by Clyde L. Cowan and Frederick Reines designed an experiment to detect neutrinos.



Uses neutrinos from nuclear fission.

Neutrinos interact with a proton via inverse beta decay

Detects the outgoing particles from the neutrino interaction.

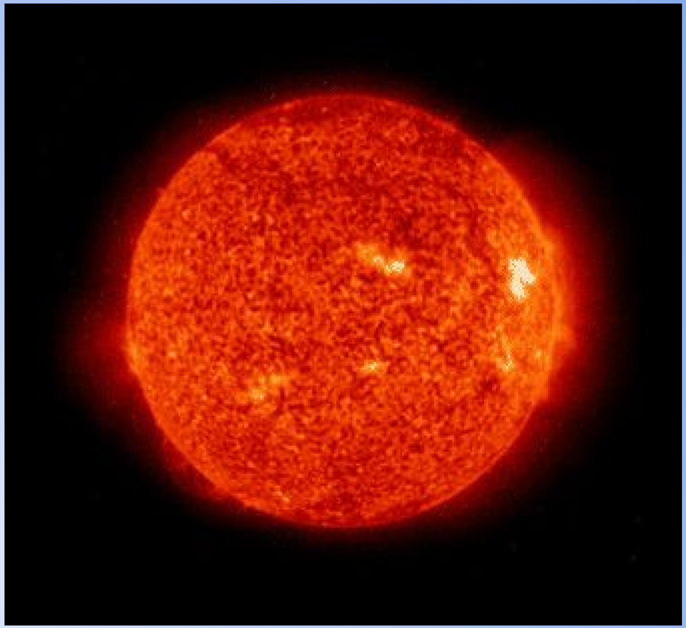
Project Poltergeist

Results (1956)

Neutrinos are observed at a rate of 0.56 counts per hour!

We were able to produce and measure neutrinos here, on Earth!!!

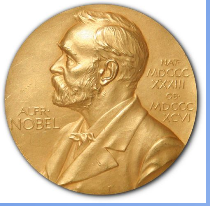
What about using neutrinos emitted from the Sun…



In the late 1930s, physicists developed the solar model.

The solar model mathematically describes the nuclear fusion reactions that are occurring in the Sun's core.

30 years after neutrinos were postulated...

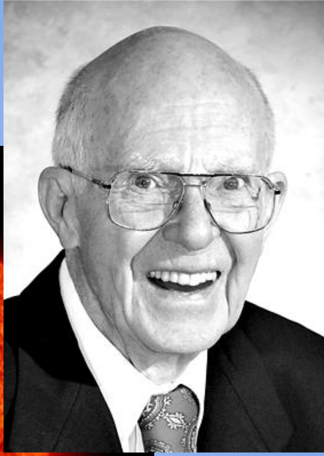


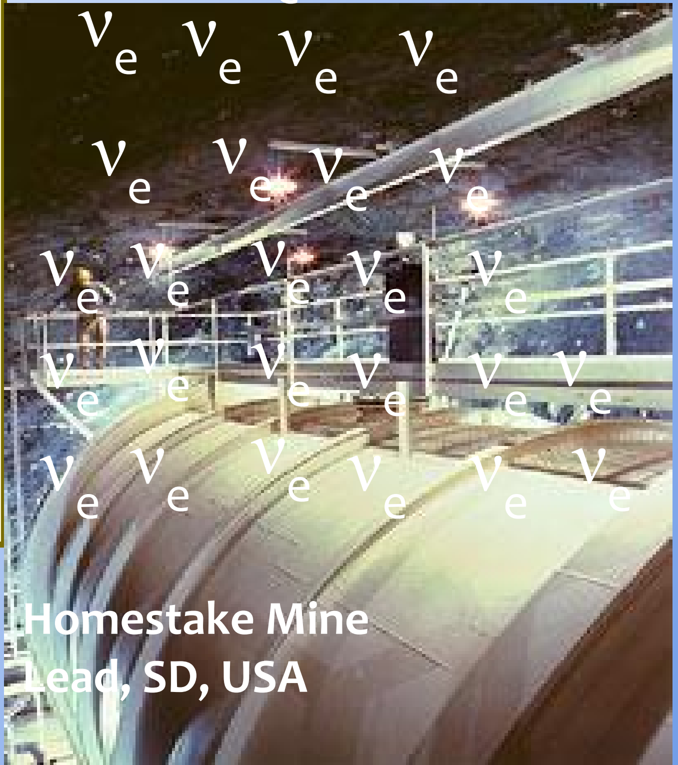
In 1961, Ray Davis confirmed the detection of solar neutrinos. The **Homestake Experiment** used solar neutrino interactions to convert Chlorine-37 into radioactive Argon-37.

Where did all of the neutrinos go?

After correcting for detector effects and using the Solar Model prediction, the Davis' group expected to see *one solar neutrino per day*.

However, they only saw *one solar neutrino every fourth day.*





Our measurement is wrong

Our understanding of how our detector behaves is wrong

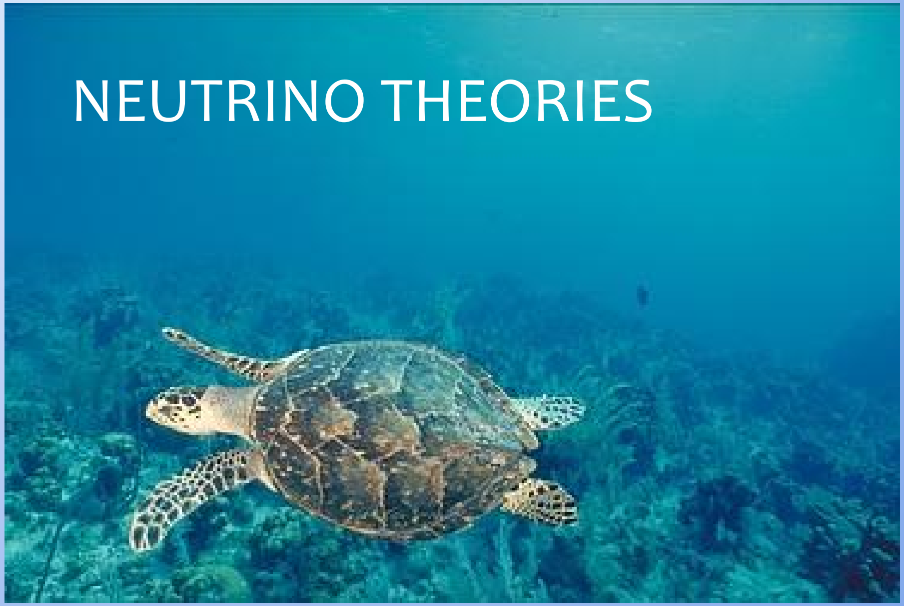
Where did all of the neutrinos go?

Our understanding of how neutrinos behave is wrong

Our understanding of the way neutrinos are created in the sun is wrong

The Mysteries of Neutrinos


NEUTRINO EXPERIMENTS


NEUTRINO THEORIES

The muon was discovered (1936) before the muon neutrino.

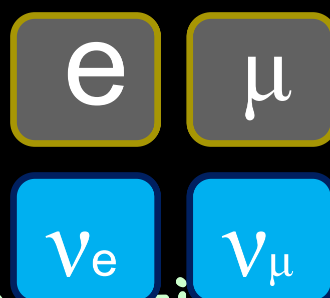
?

$$\pi \to \mu \, \nu$$

muon is a 2nd generation of the electron

There must be a 2nd generation of the neutrino.

Eventually, physicists discovered that there exist two types of neutrinos.

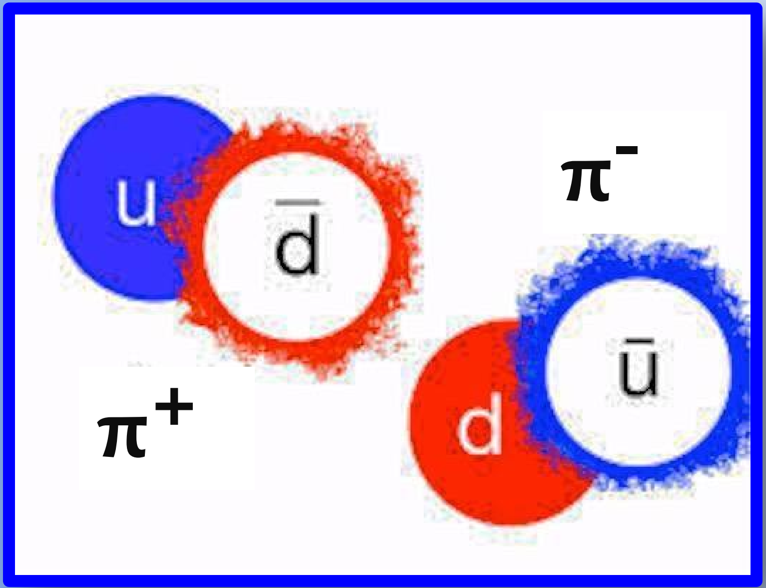


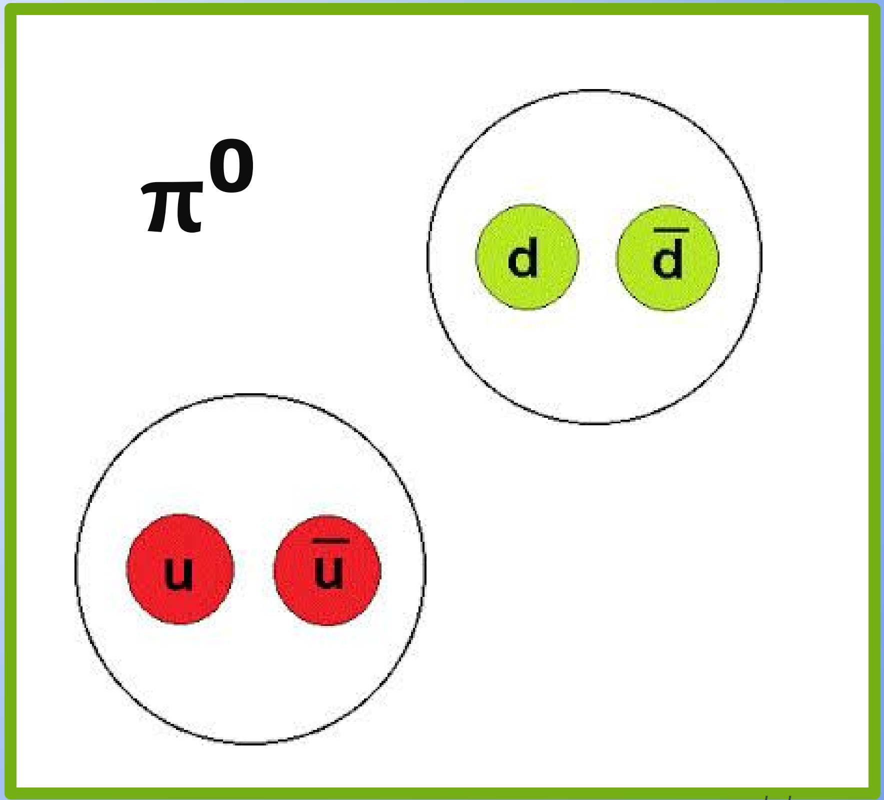
So, how many generations of neutrinos do exist?

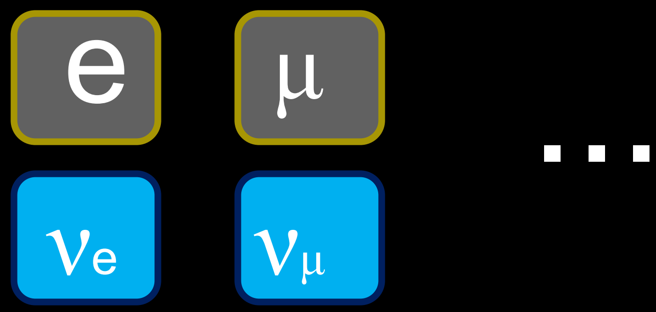
Pions

A particle made from a quark and anti-quark pair.

There are three types of pions.



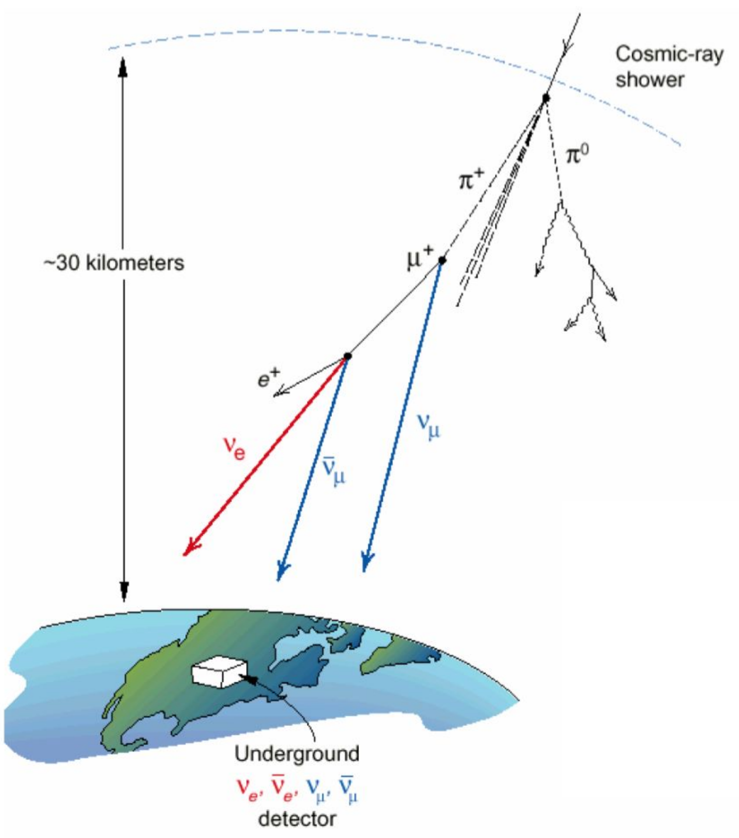




So, how many generations of neutrinos do exist?

Atmospheric Neutrinos

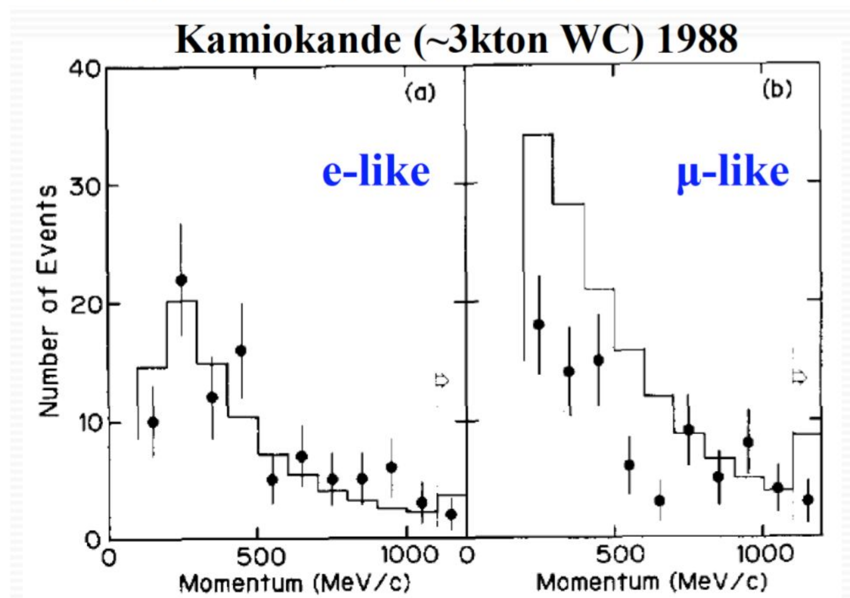
- Cosmic rays (mostly protons) interact in the upper atmosphere creating hadronic showers (mostly pions).



- Roughly 2:1 muon neutrinos to electron neutrinos expected:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

- Events found in Kamiokande:

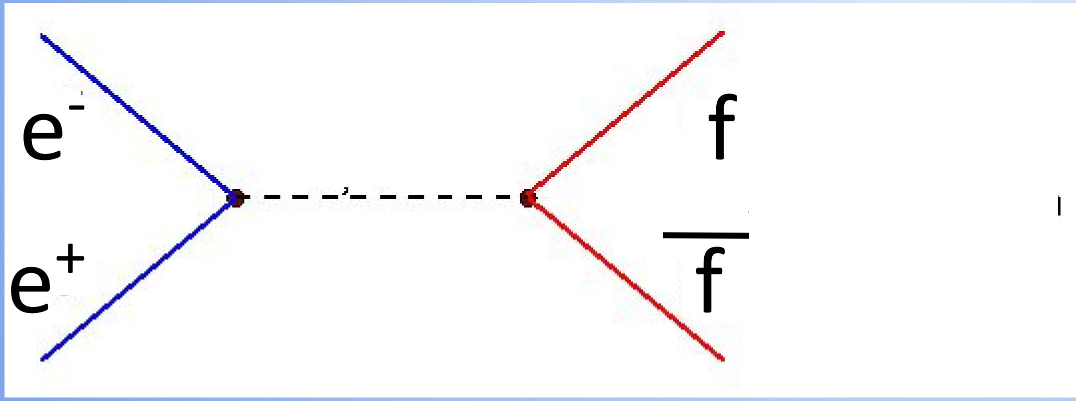


Why?

Physicists worried about the number of generations.

The best measurement comes from studying **the decay of Z boson**

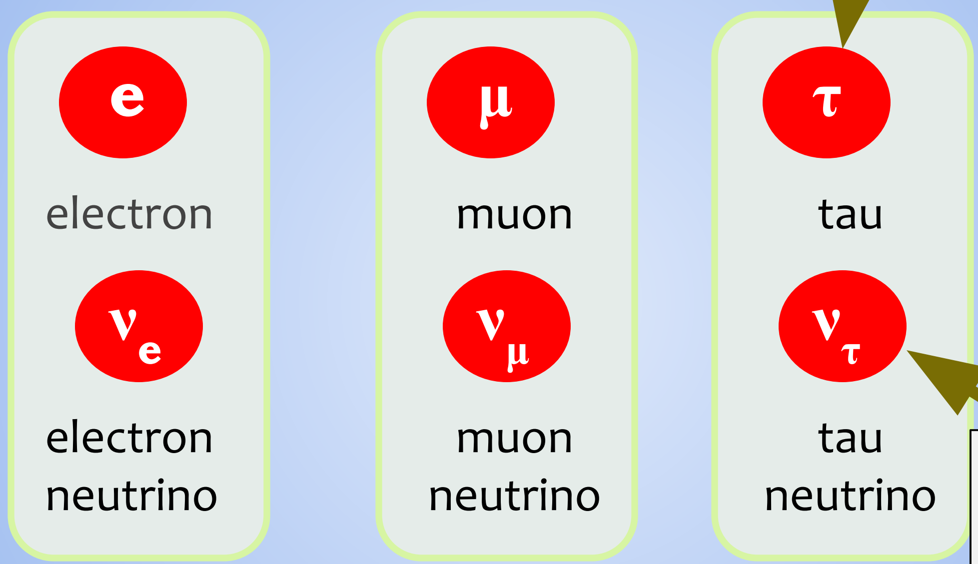
→ measured 3 generations



Where f = quarks, leptons, neutrinos.

Recap: Leptons

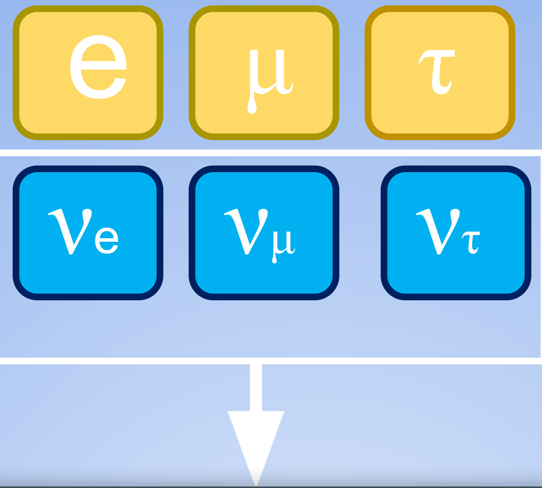
Discovered in the mid 1970s



Discovered in 2000 at Fermilab DONUT experiment

3rd generation!!!!

OK! do we have everything??



Particle physics proposed that the measured neutrinos are NOT REAL particles!

In fact, the real neutrinos ν_1, ν_2, ν_3 mix to create the flavor neutrinos, ν_e, ν_μ, ν_τ !

The real neutrinos, ν_1, ν_2, ν_3 have a well defined mass.

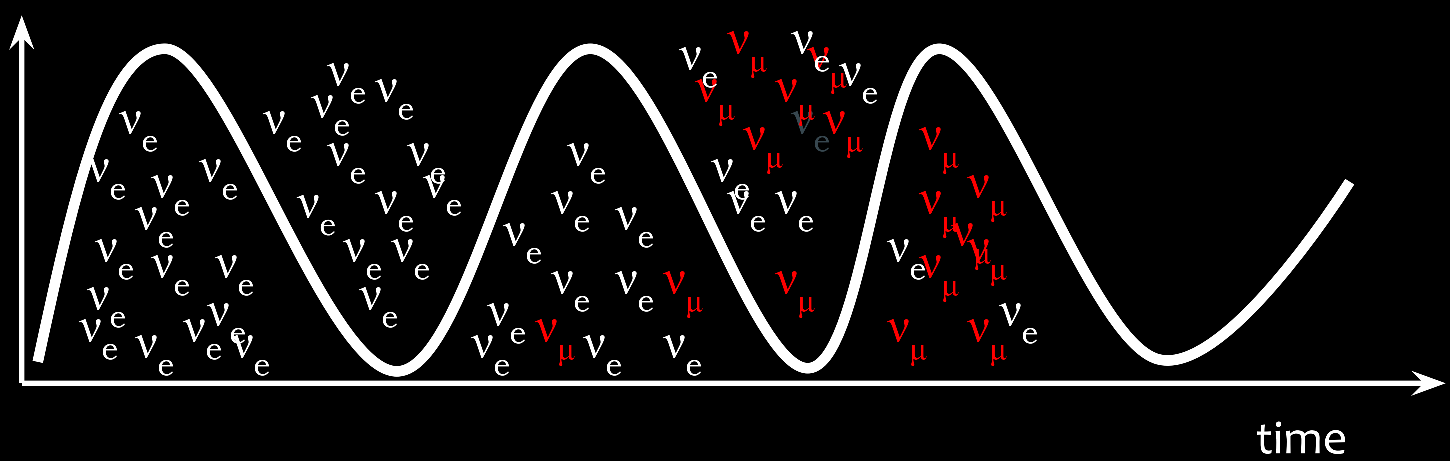
Wait….

So, the neutrinos that scientists have detected are a mixture of real neutrinos?

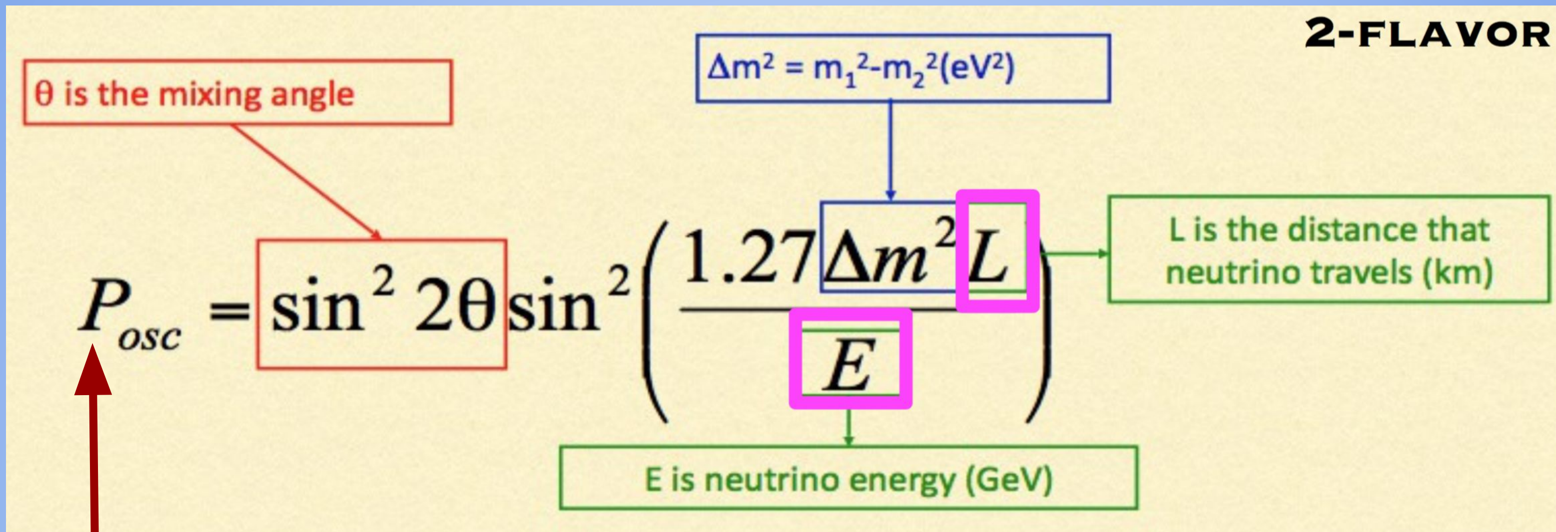
Neutrino Oscillations

Neutrinos created with a specific flavor can evolve into a different flavor at a later time.

Diagram shows the probability of changing to another type of neutrino as a function of time.

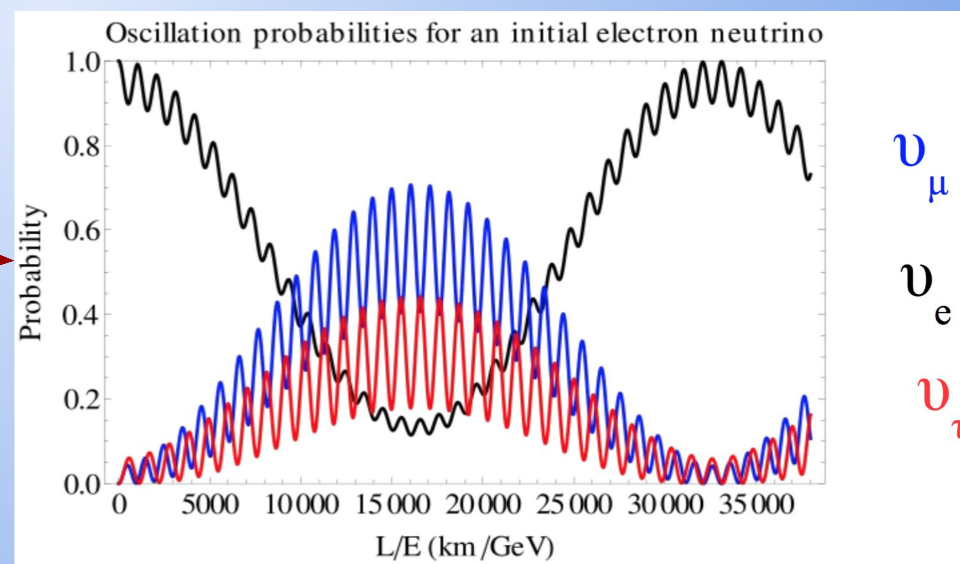


Neutrino Oscillations



Oscillation probability

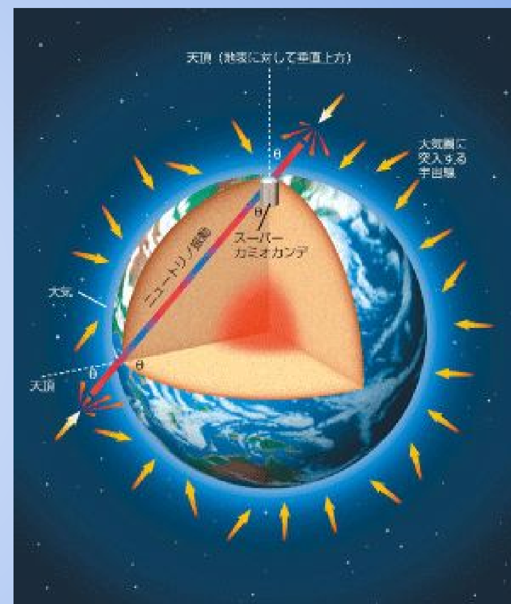
f(L/E)



Understanding the Behavior of Neutrinos

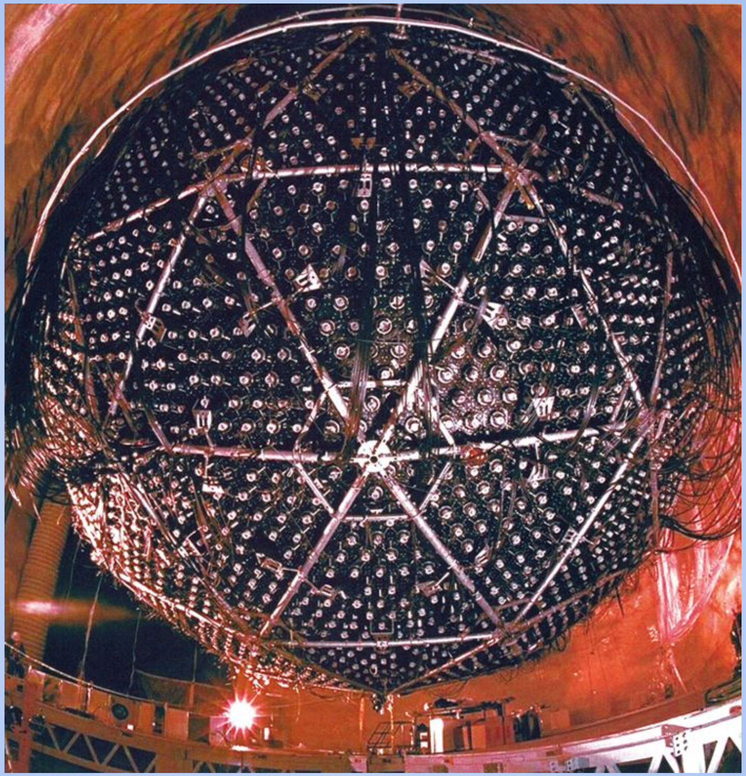
In 1998, Super-Kamiokande (Japan) announced the finding of neutrinos with non-zero mass.

Study neutrino oscillations using atmospheric neutrinos.



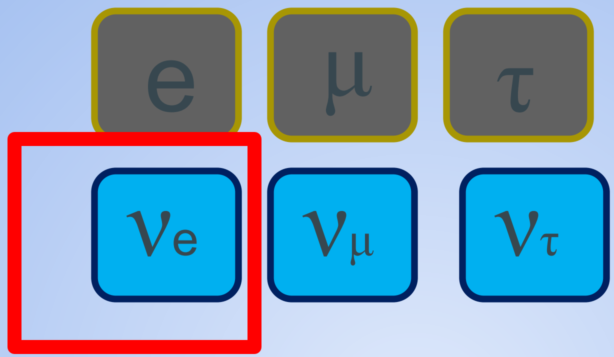
Atmospheric neutrinos produced by the decay of particles resulting from interaction of particles with the Earth's atmosphere.

In 2001, the results from Sudbury Neutrino Observatory (Canada) solved the mystery of the missing solar neutrinos puzzle.



SNO announced that the total number of all neutrino flavour agrees with the Solar model.

What is the Source of the Missing Solar Neutrinos?



Can neutrino oscillations explain the missing solar neutrinos?

By the time the neutrinos enter the Earth's atmosphere, the electron neutrinos COULD BE changing flavour.

40-year Puzzle Solved

Neutrino experiments.

So far, there are 4 types/sources of experiments:

- Solar
- Atmospheric

Natural sources

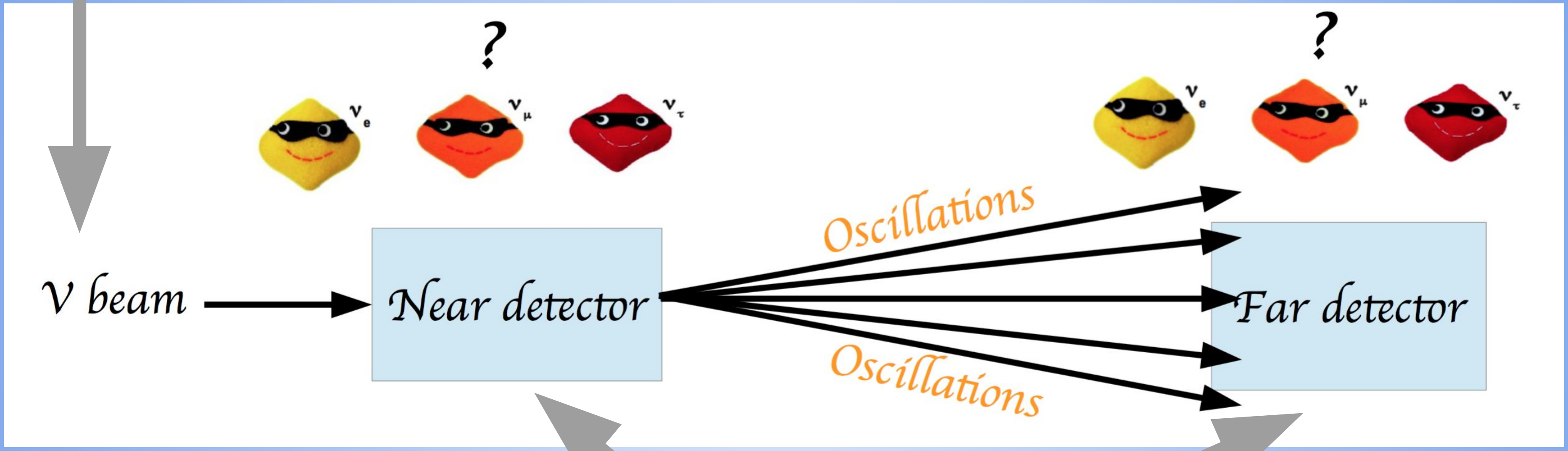
- Reactor
- Accelerator

Artificial sources

Let's talk about it

Accelerator Neutrinos Strategy

Generate neutrinos from accelerators



To have two functionally identical detectors

Oscillation probability = differences between measured and expected without oscillation

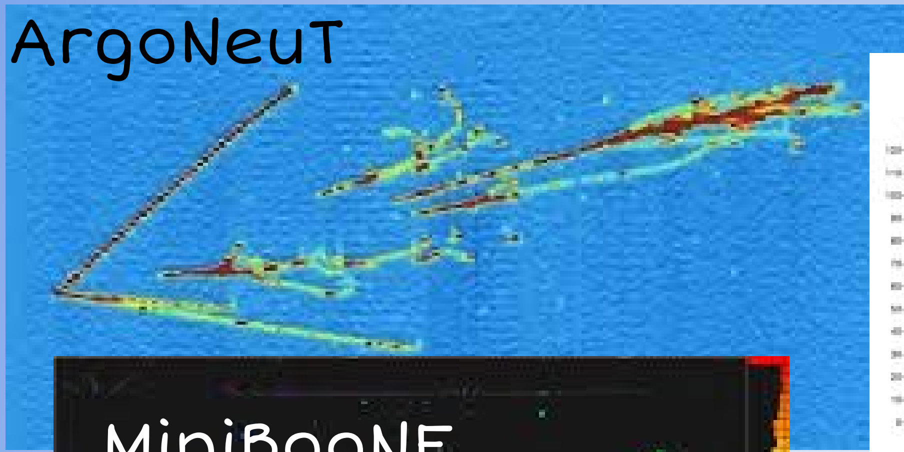
Fermilab Accelerator Complex

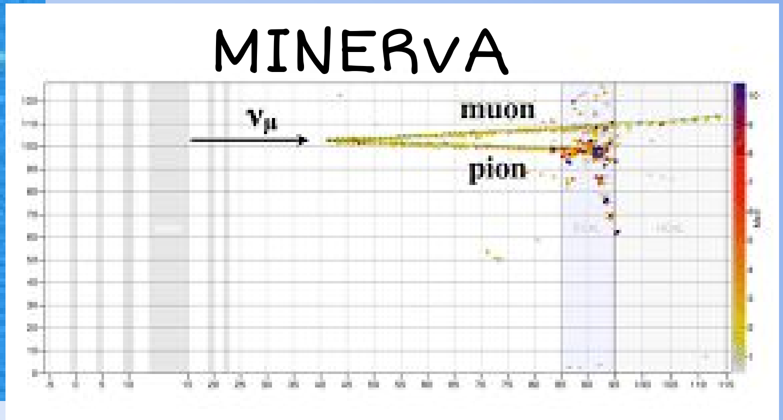
Neutrino beams:
- BNB
- NuMI

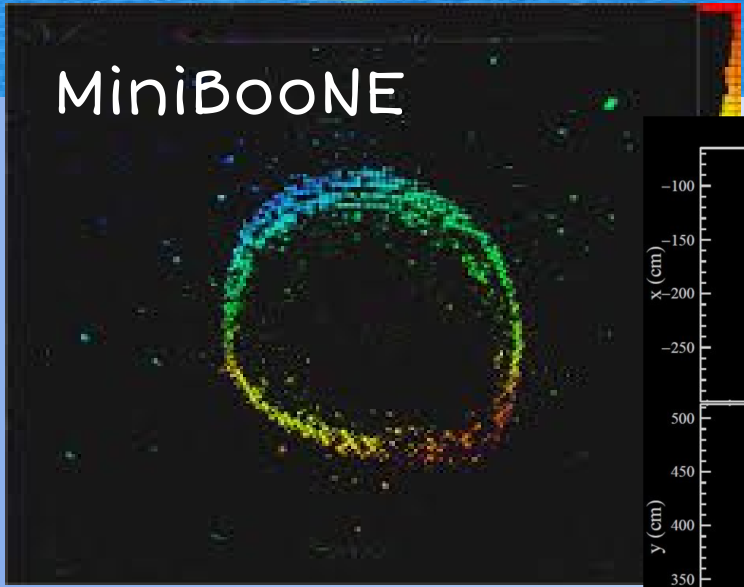
Future: LBNE

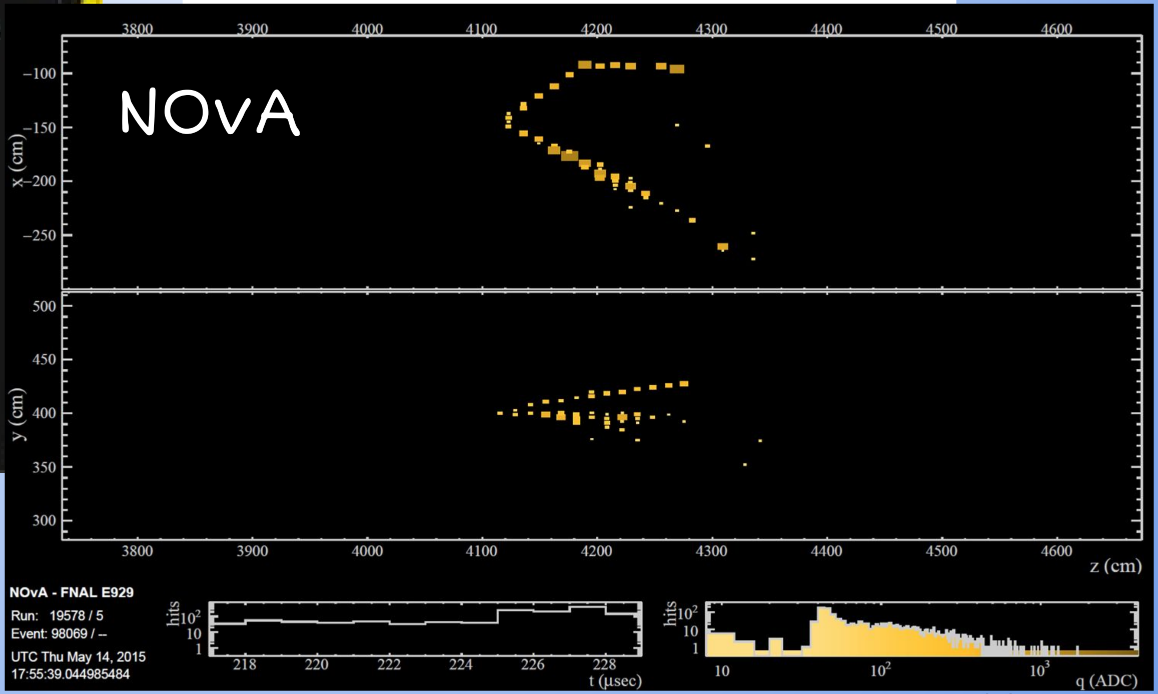
Several Neutrino experiments at Fermilab...

What do the detectors see?

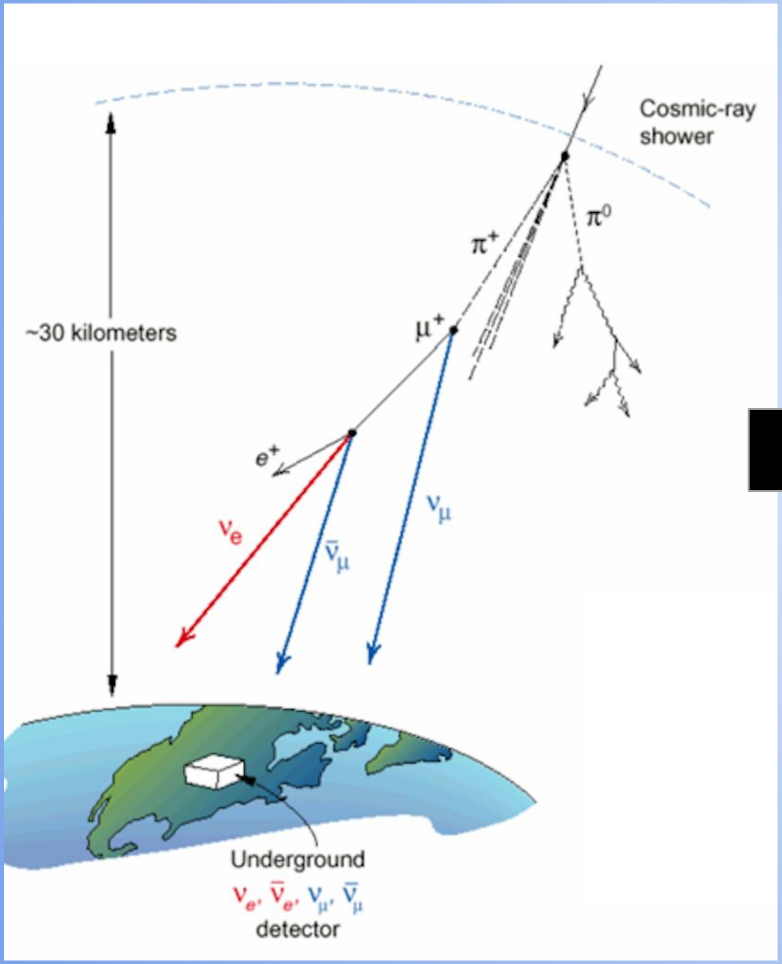


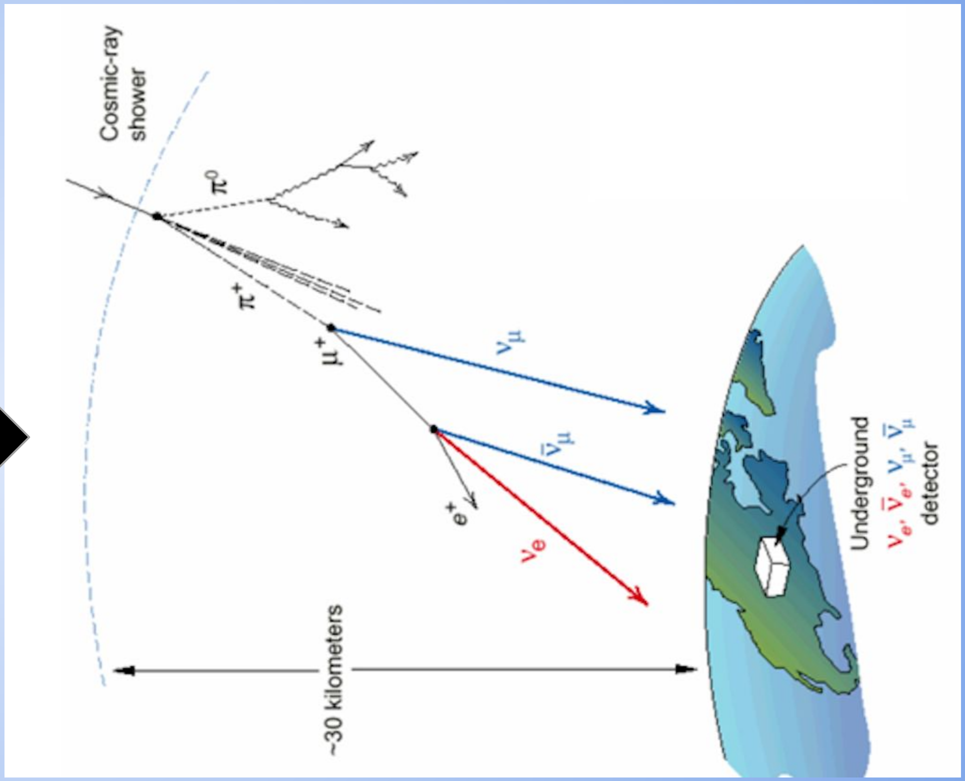


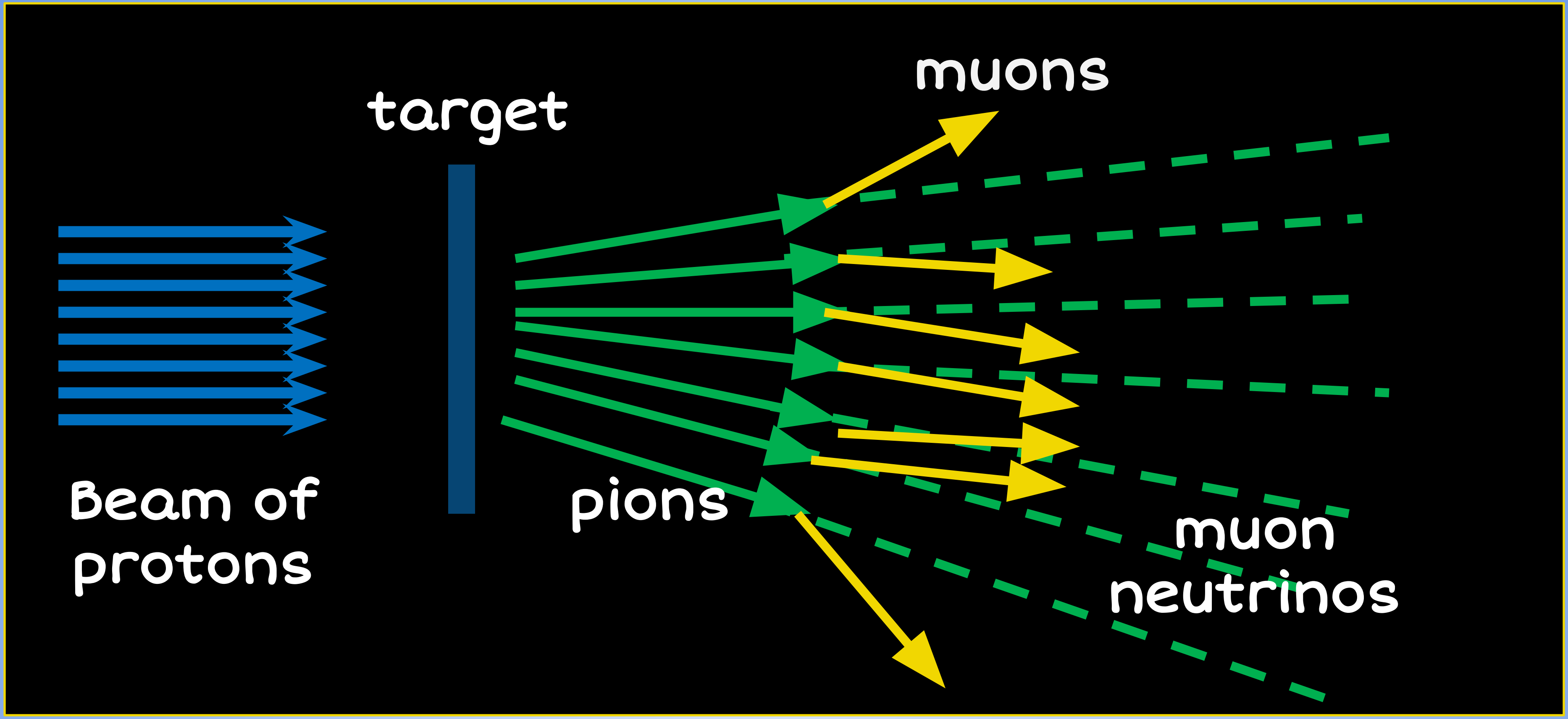


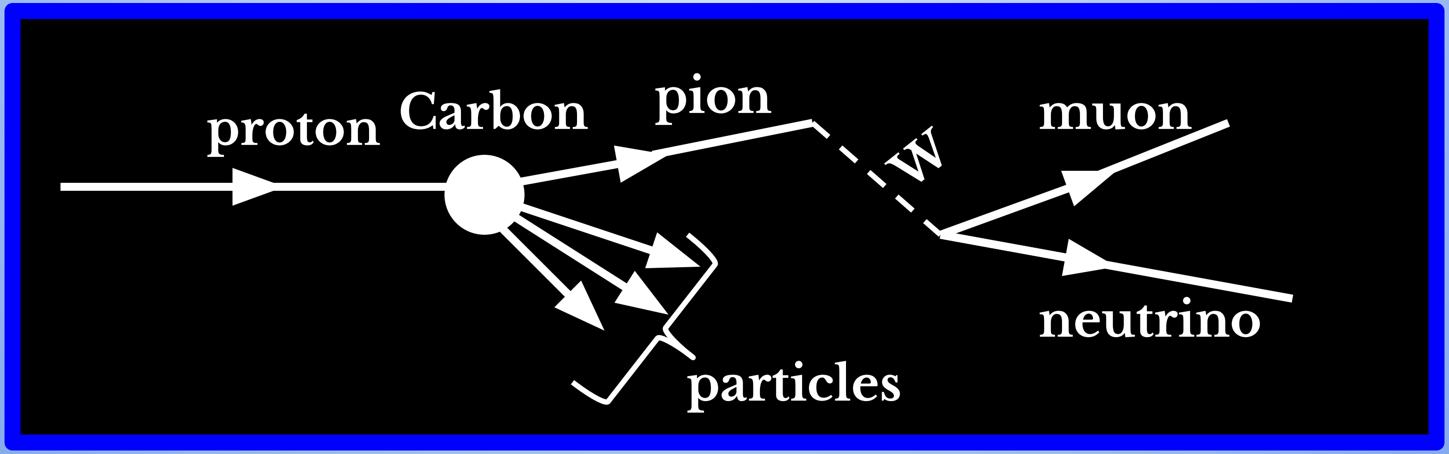


We use the same principle of the atmospheric neutrinos





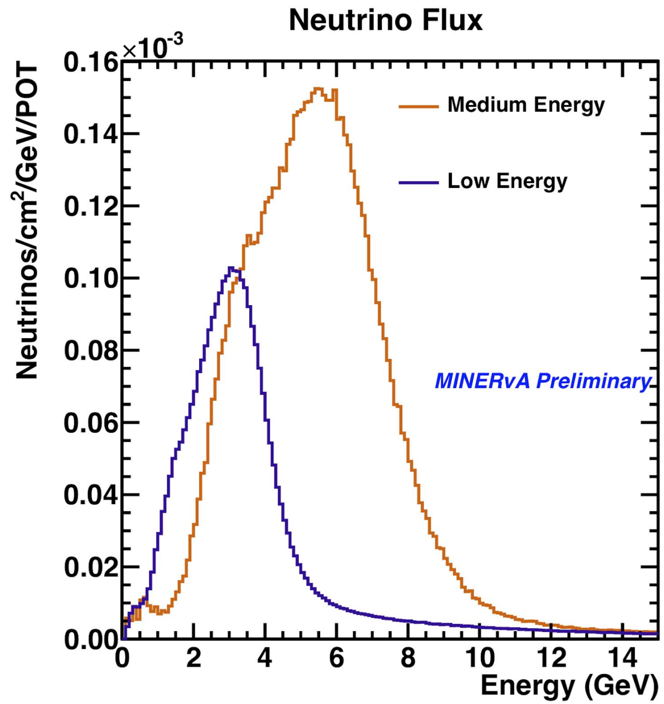

muons
target
Beam of protons
pions
muon neutrinos

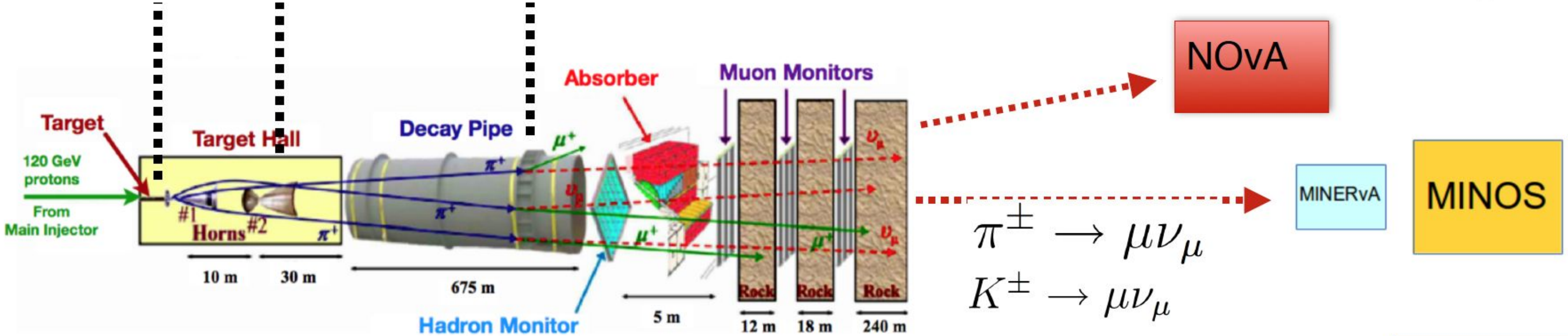

proton
Carbon
pion
W
muon
neutrino
particles

NeUtrinos at the Main Injector

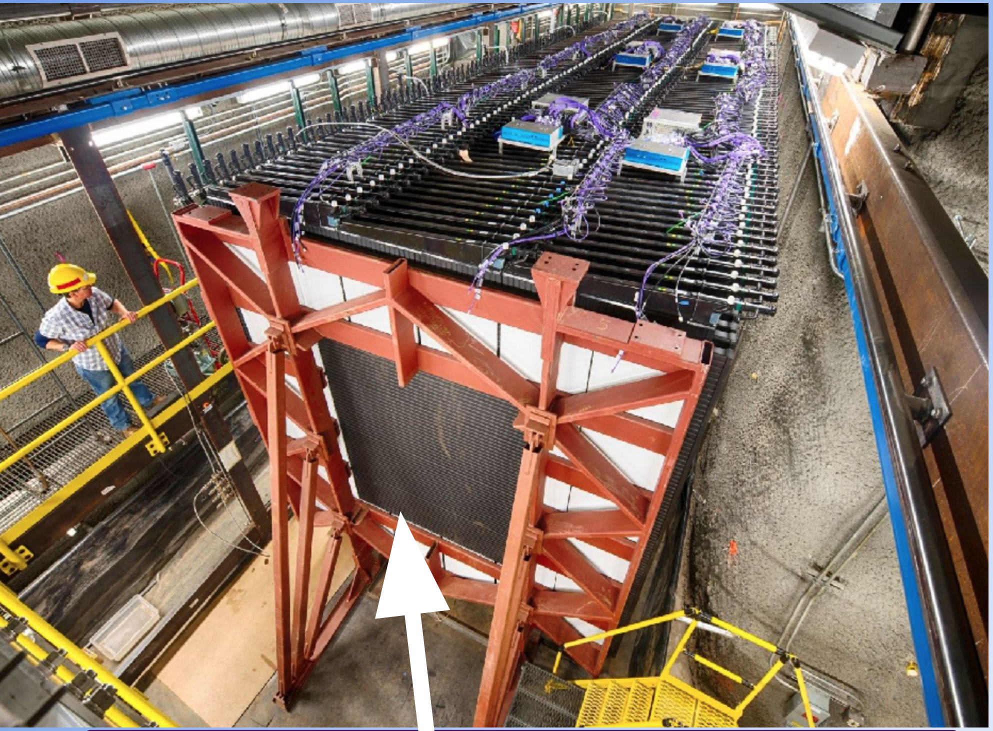
Currently, 5×10^{13} protons on target (POT) every 1.3 sec

~ same amount of neutrinos





$$\pi^{\pm} \rightarrow \mu\nu_{\mu}$$
$$K^{\pm} \rightarrow \mu\nu_{\mu}$$

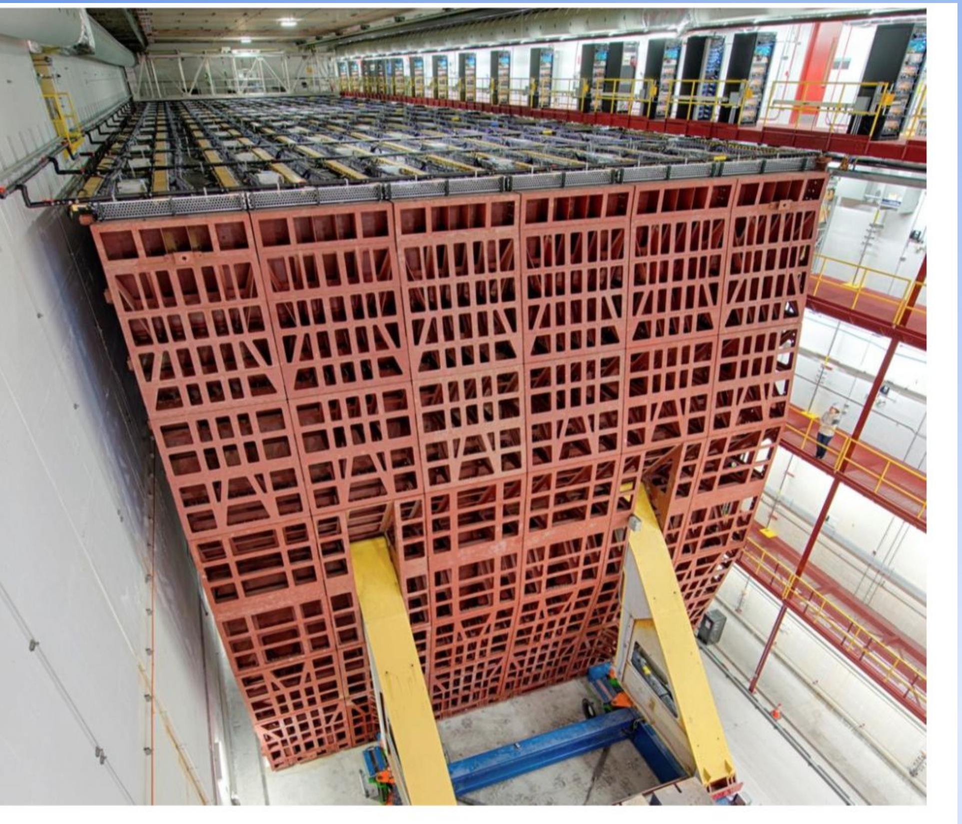


The detector records information about the particles from neutrino interactions.

NOvA Near Detector

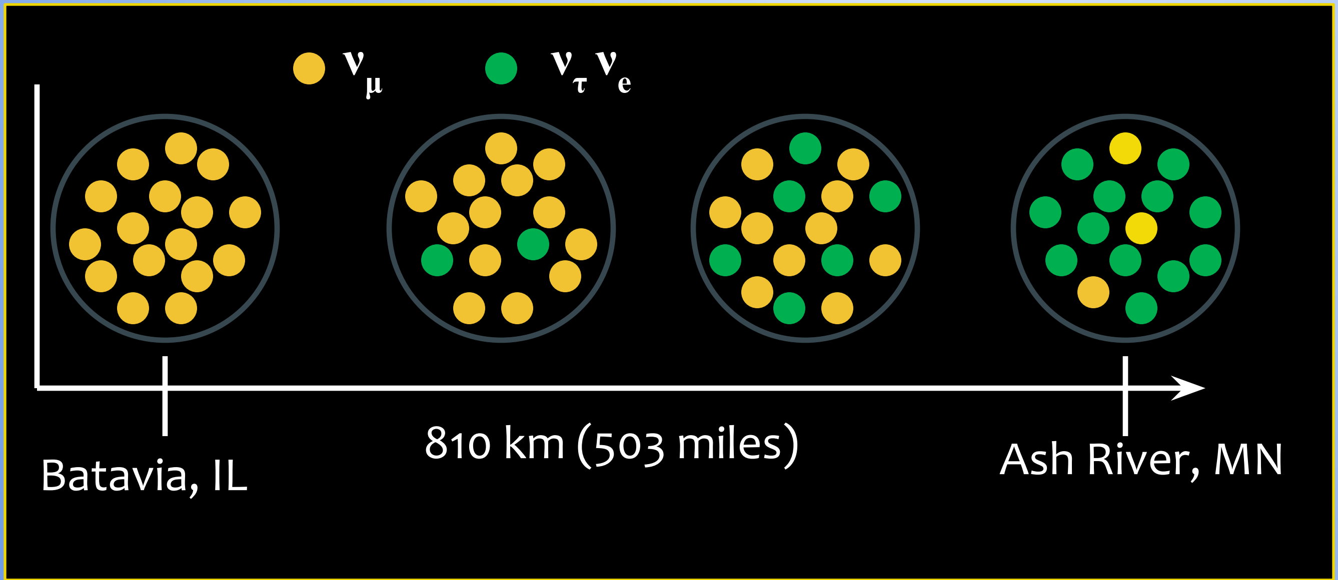
100 meters underground

ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ ν_μ

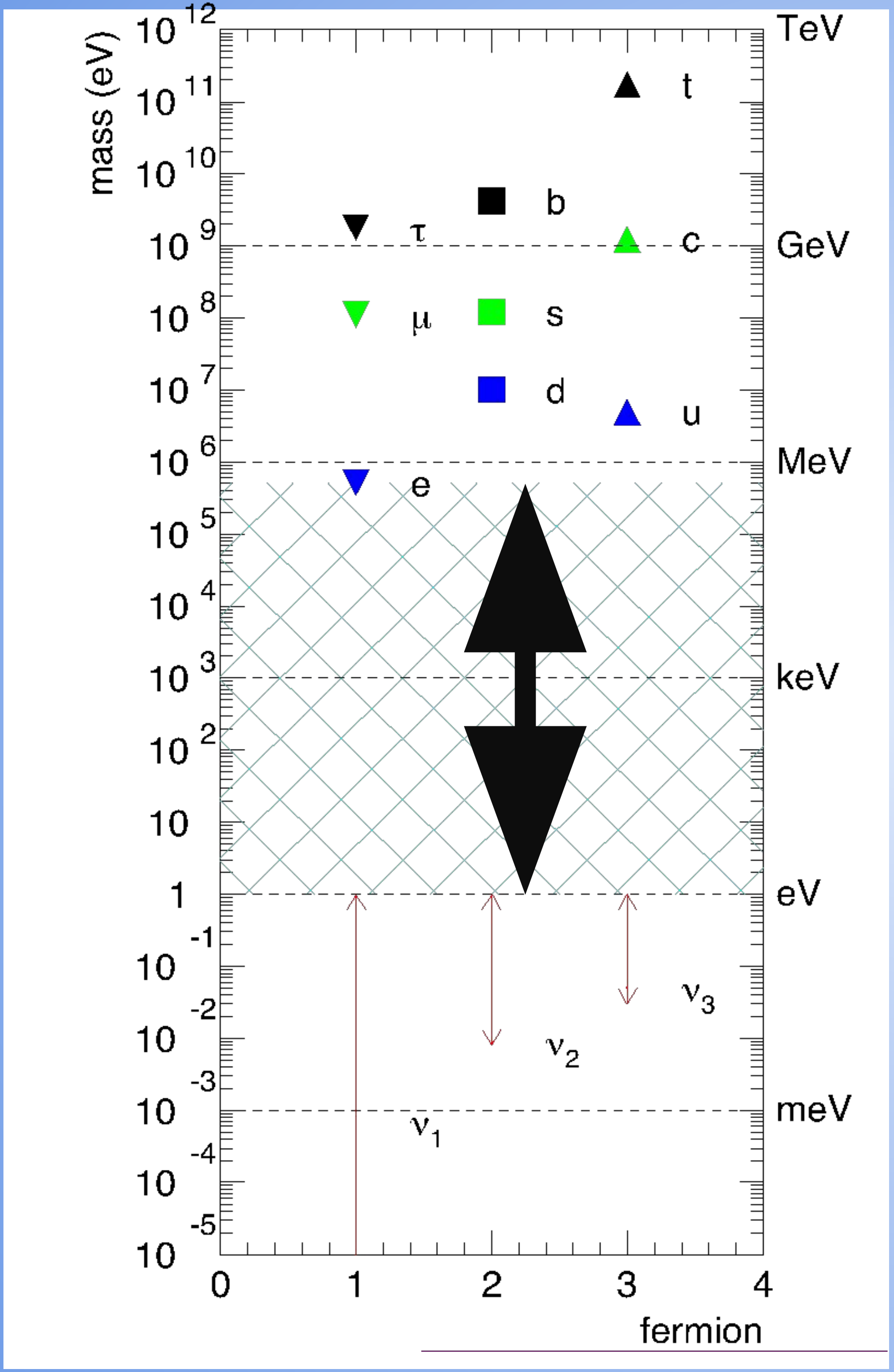


NOvA Far Detector

on surface



Why is it important for physicists to build more large detectors to understand neutrinos?



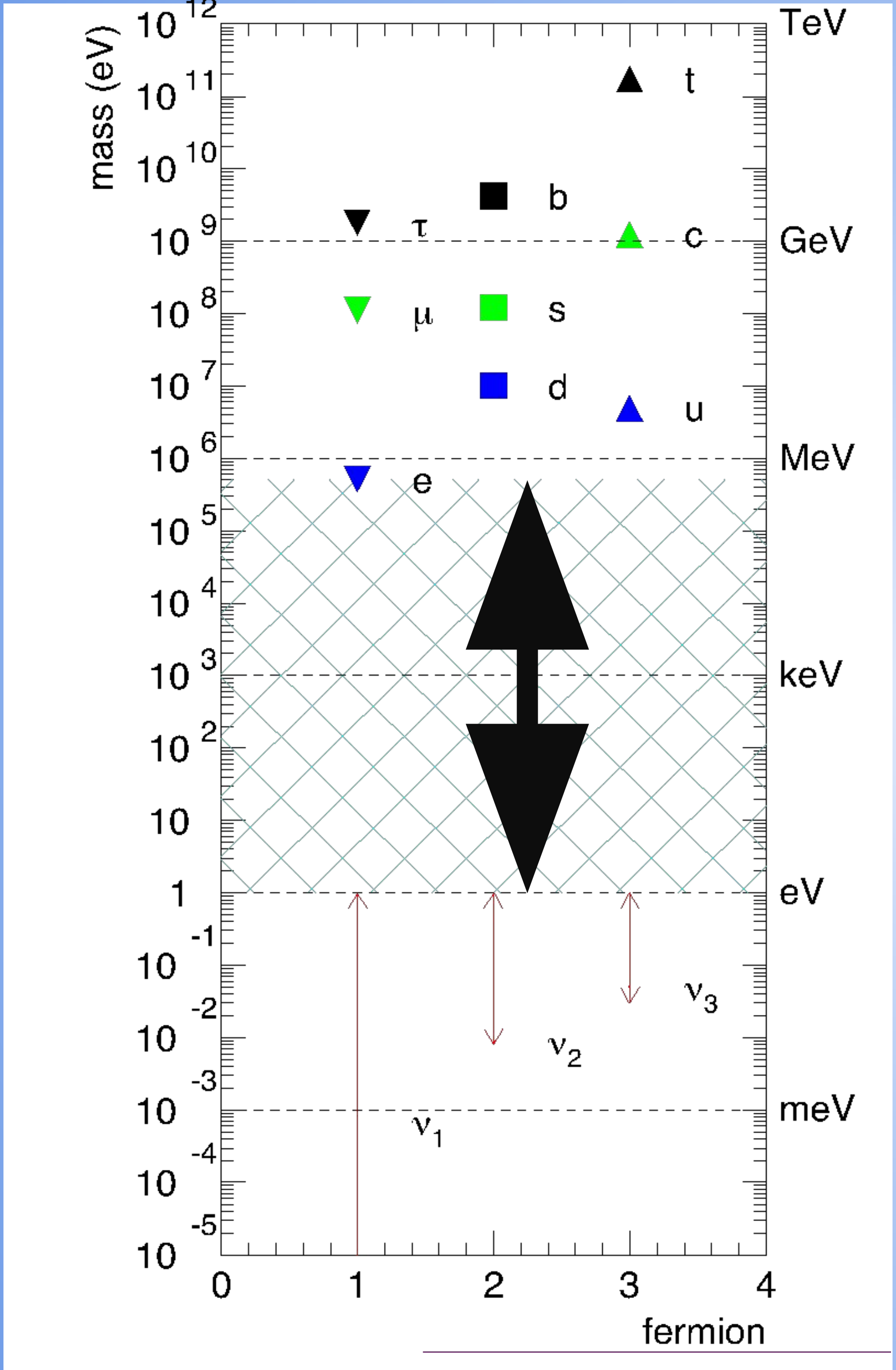
Neutrinos have mass.

BUT.. Why are the neutrinos SO light?

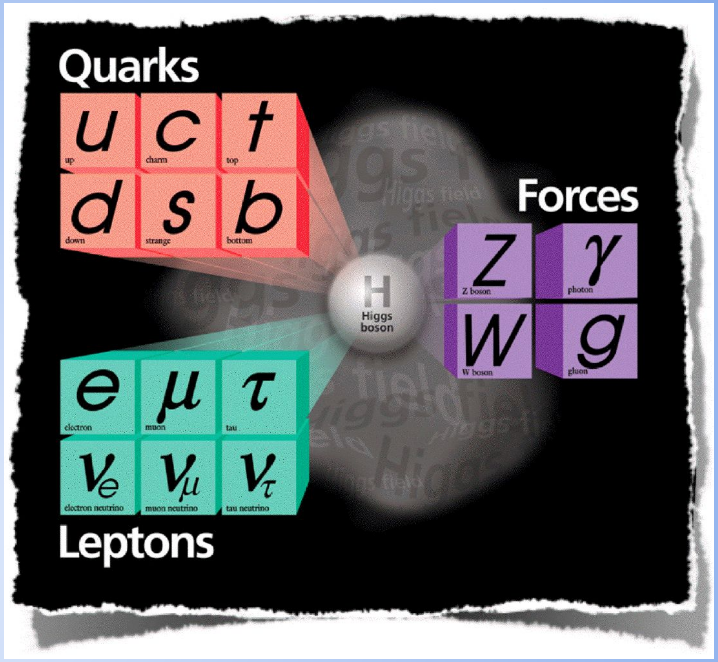
There is a very popular theory floating around.

BUT REALLY...

We do NOT know!



Neutrinos have mass.



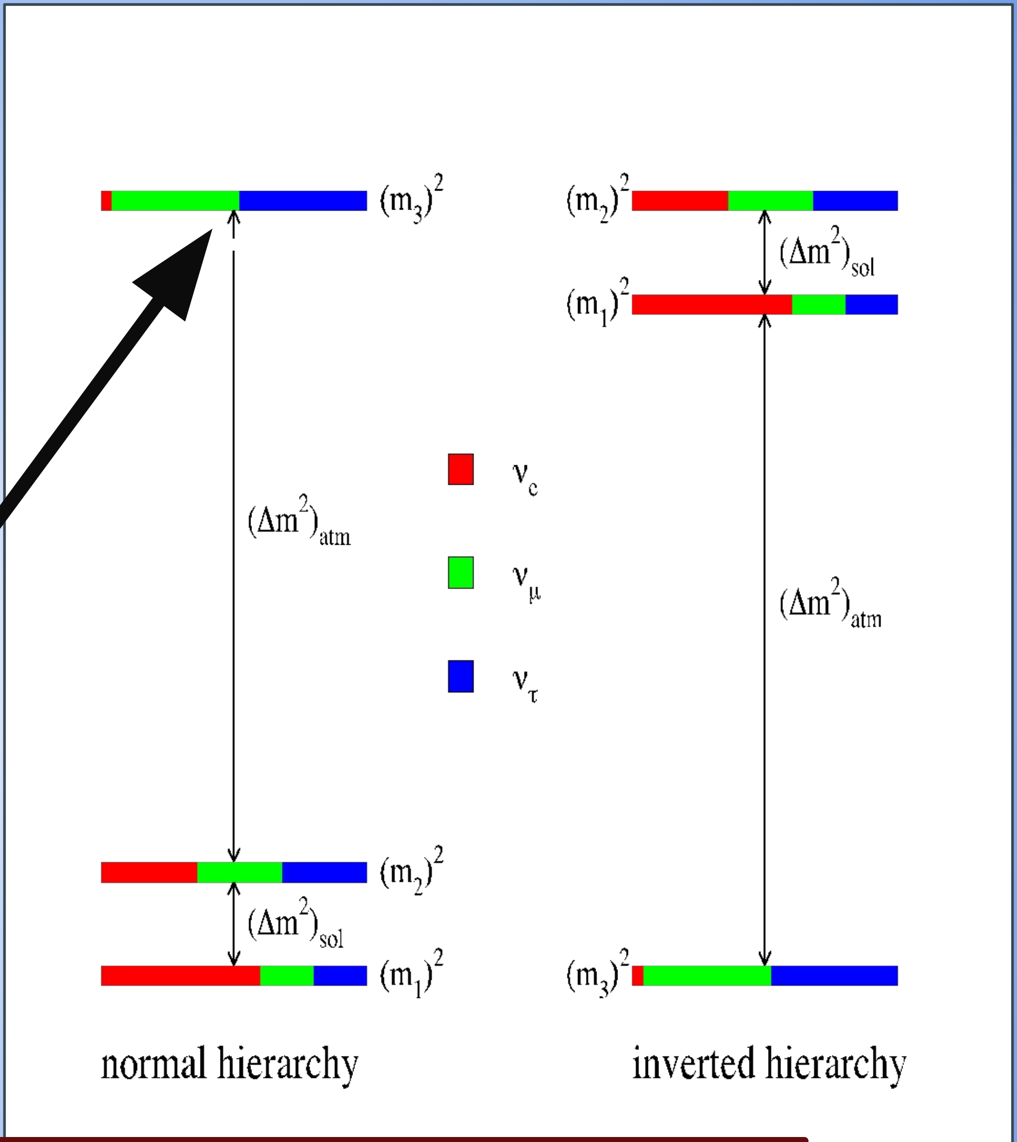
The Standard Model is not complete

Evidence that there are MANY behaviors in nature that we do not understand.

Remember, the neutrinos that scientists have detected are a mixture of real particles...

Do not know the ordering of the masses?

We do not know if the real neutrino ν_3 consists of more ν_μ or ν_τ.



All we know is the difference between the masses.

Why matter dominates over antimatter in the universe?

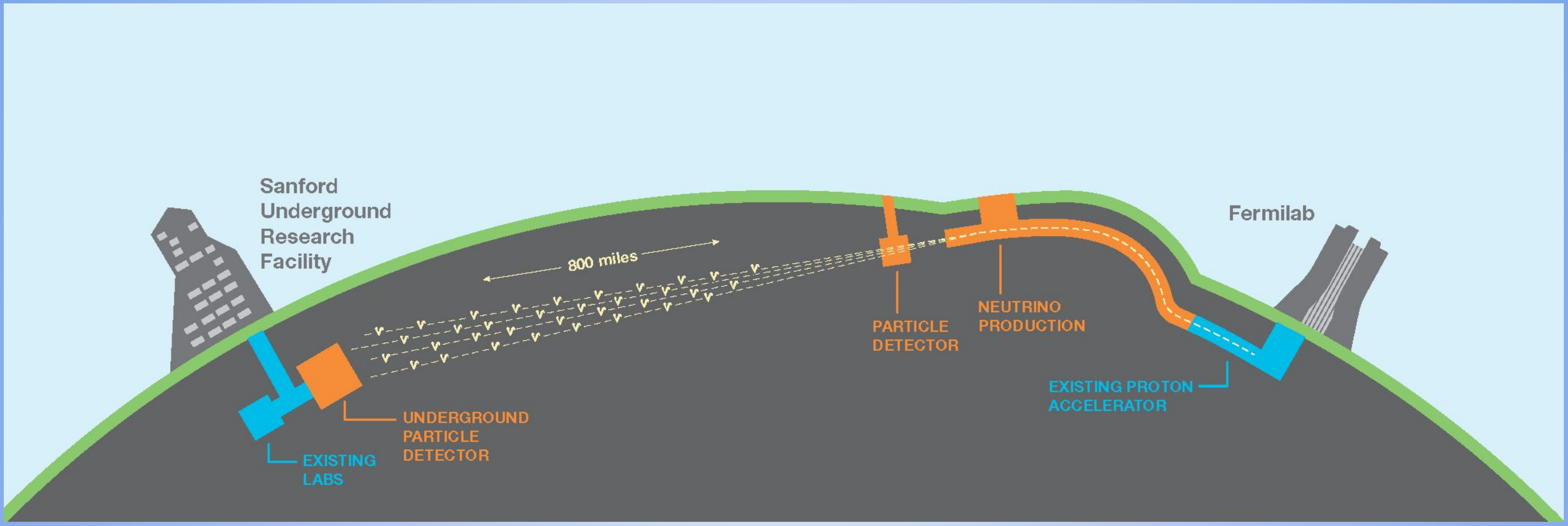
(Olena Shmahalo / Quanta Magazine)

Detecting a difference in the behaviour of the neutrinos and antineutrinos

we do not fully understand the universe.

There exists new detector technology to answer many of the unknown questions.

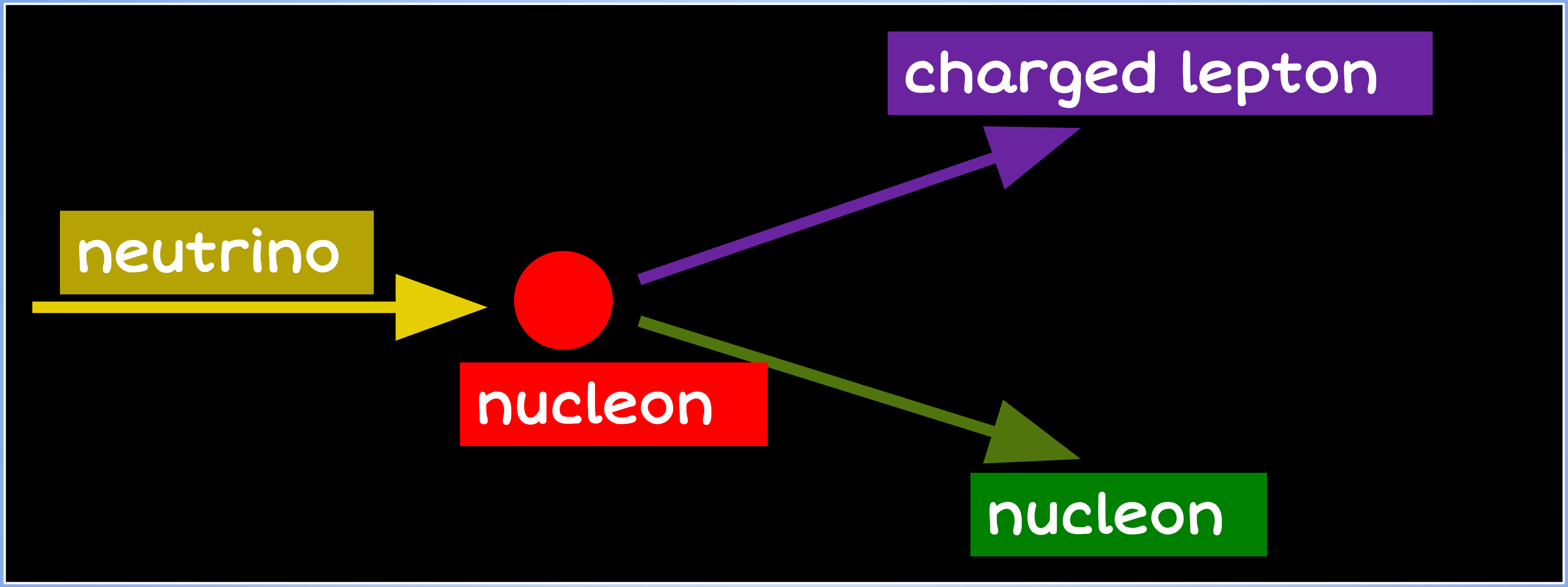
with new technology comes new challenges



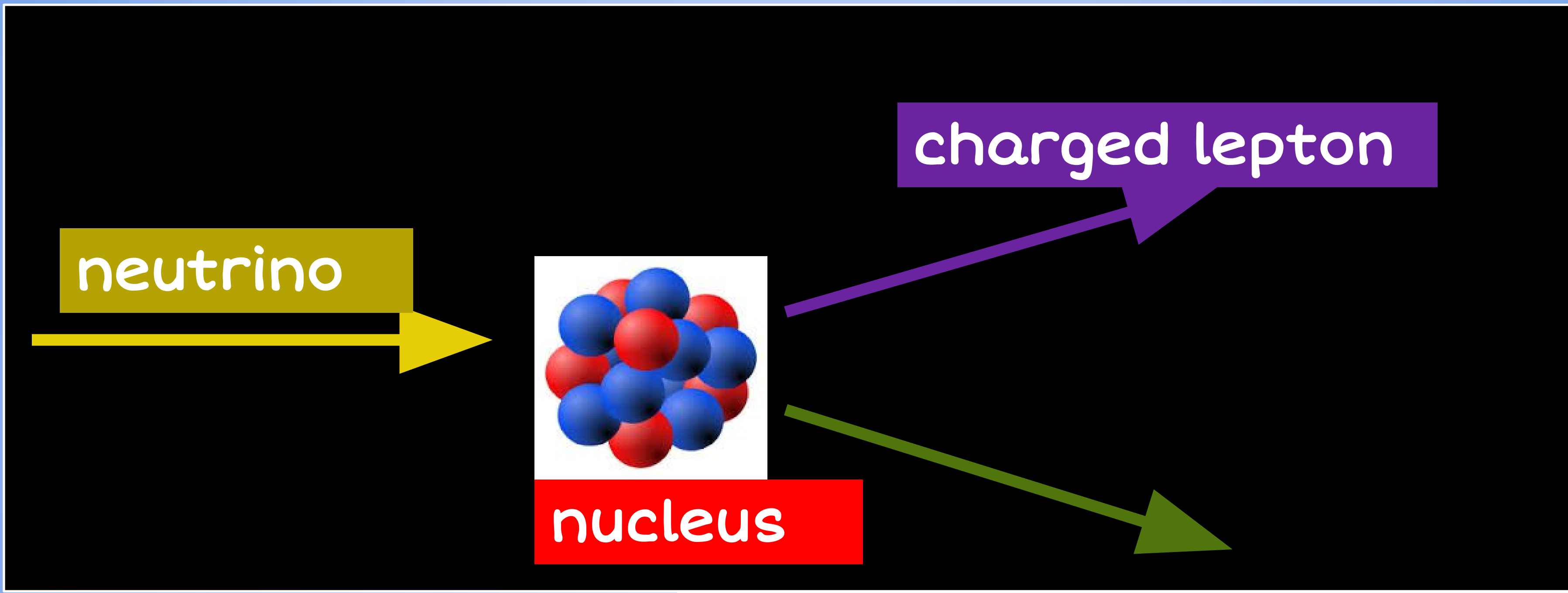
Some challenges:

neutrino flux determination, reconstruction, incomplete theoretical models, **cross-sections**, etc..

What do neutrino physicists want?



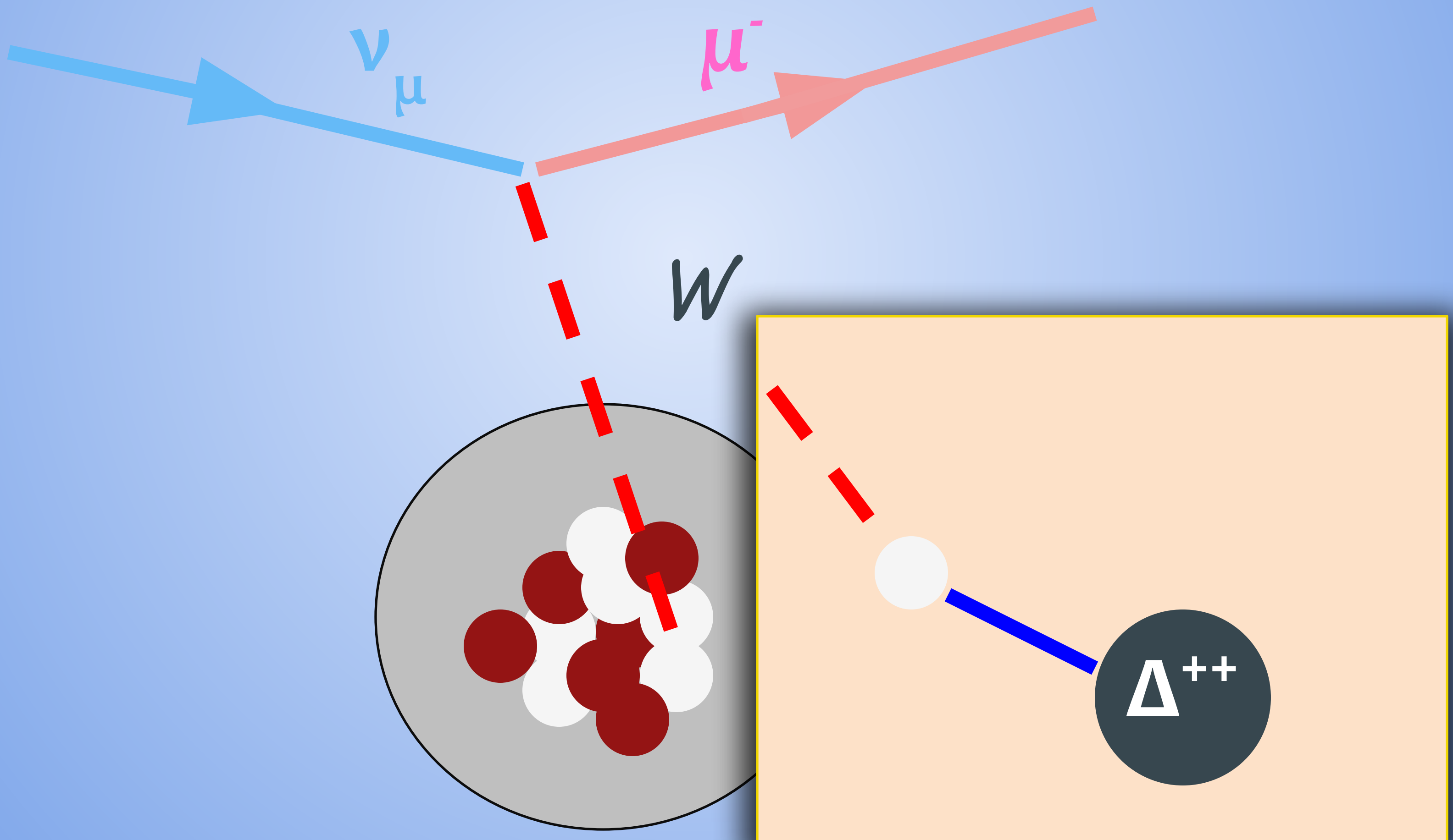
What do neutrino physicists have?



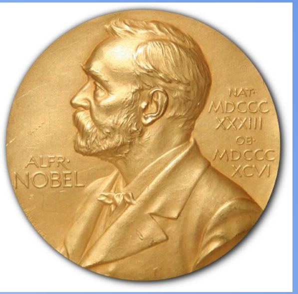
- nucleon
- many nucleons
- nucleon and pions
- nucleon and many pions
- nucleon and many other type of particles
- nothing

Very difficult to calculate

An Example of a Neutrino Interaction



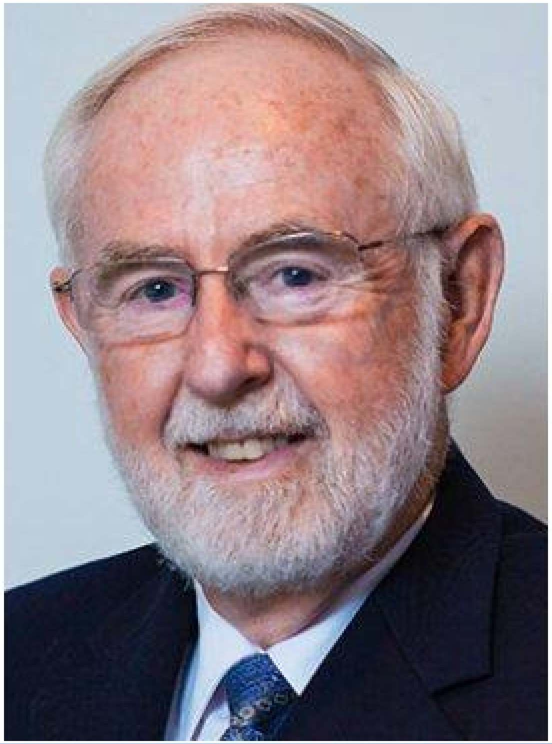
Nobel Prize in 2015 for Discovering Neutrino Oscillations



Takaaki Kajita

Super - Kamiokande

Arthur B. McDonald



SNO

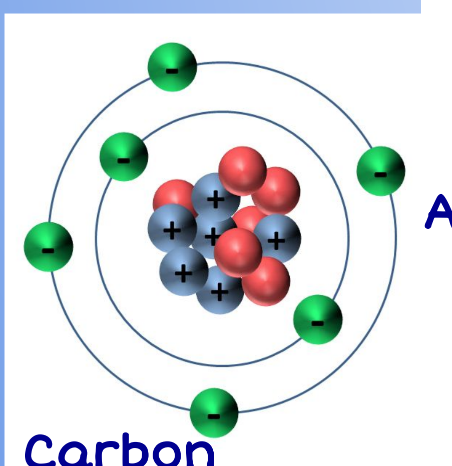
Thanks for your attention....

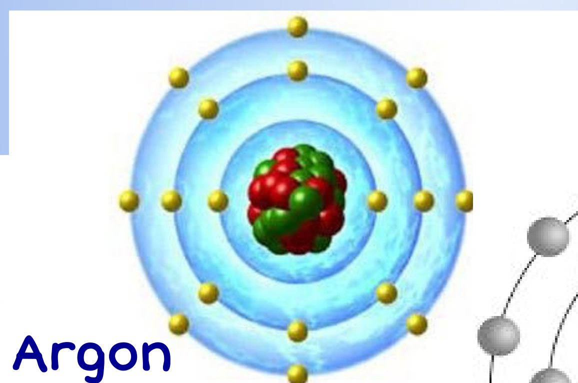
any question?

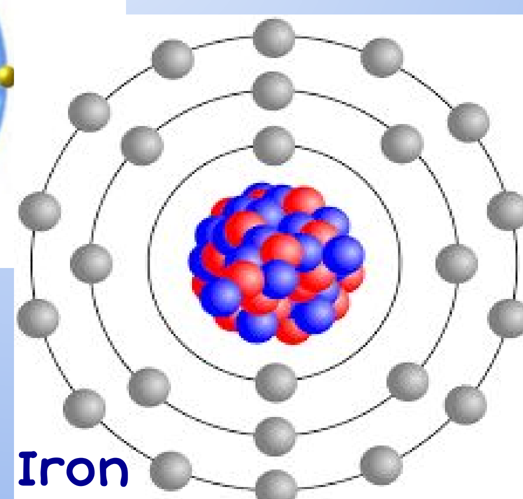
Backup

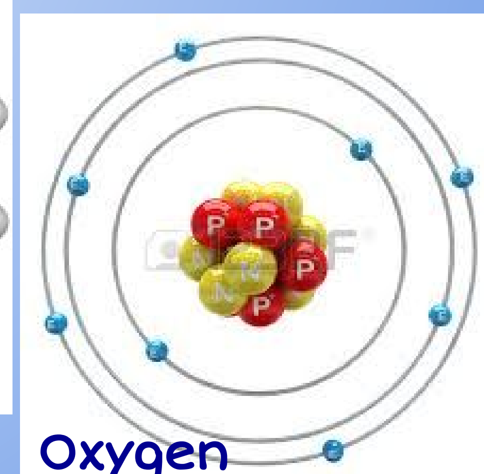
The rate of neutrino interactions is **SO** small.

Therefore, large detectors composed of heavy atoms are needed.

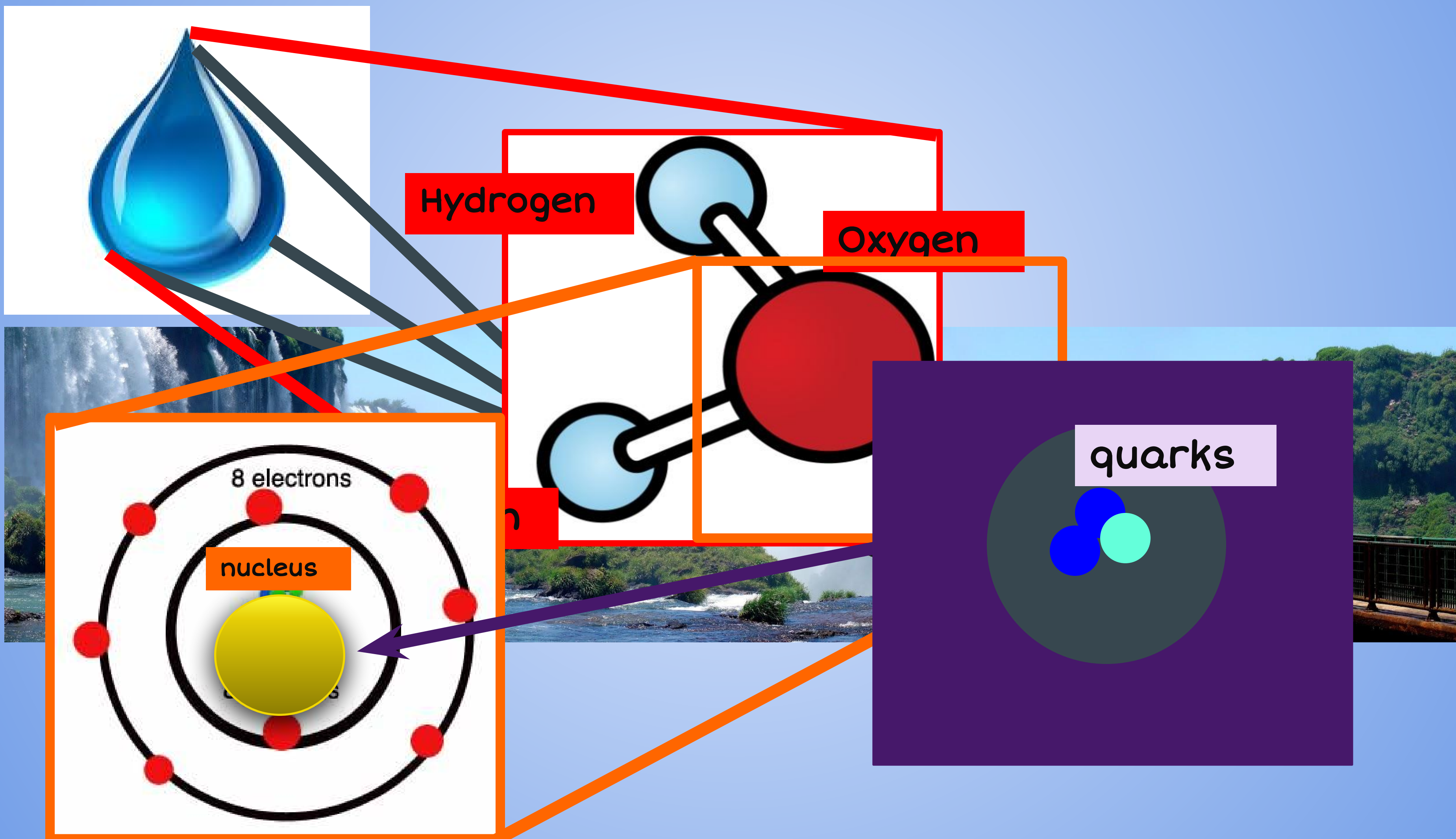








Everything is Composed of Particles!

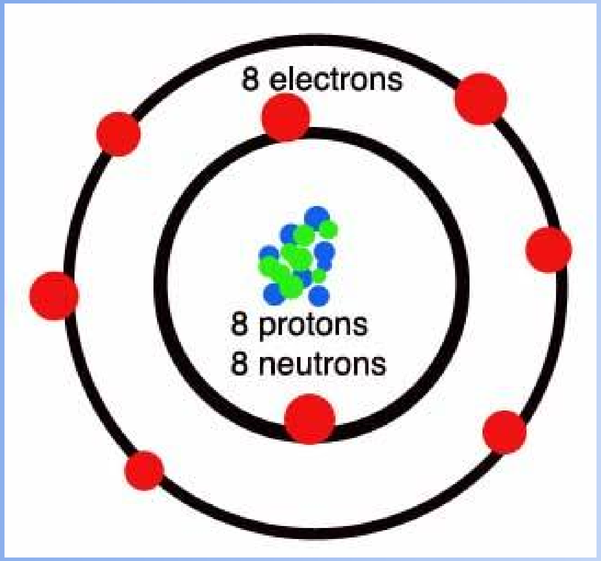


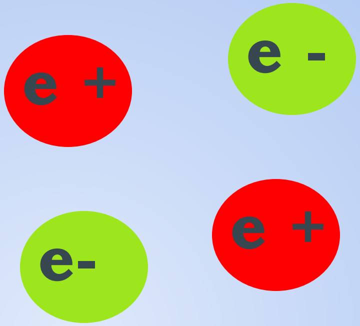
The Fundamental Forces of the Universe **Influence** the Behavior of Particles!

- *Electromagnetic.*
- *Strong.*
- *Weak.*
- *Gravitational.*

Not part of the Standard Model…

The Fundamental Forces of the Universe **Influence** the Behavior of Particles!





Mediator:
gamma (γ)

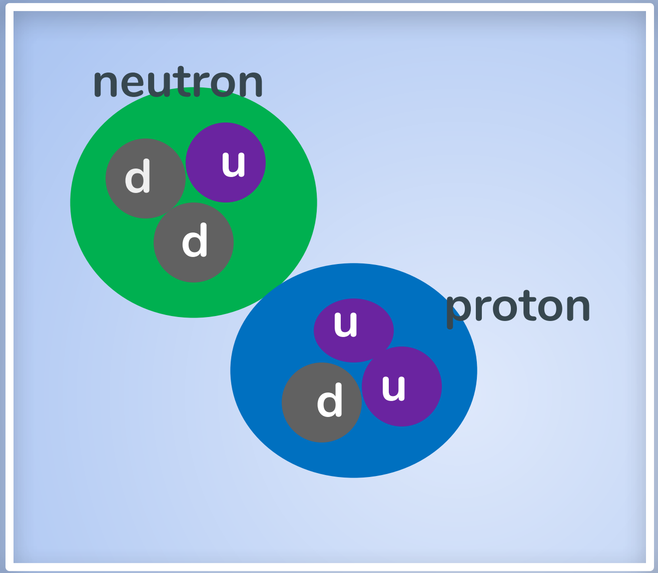
The electromagnetic force

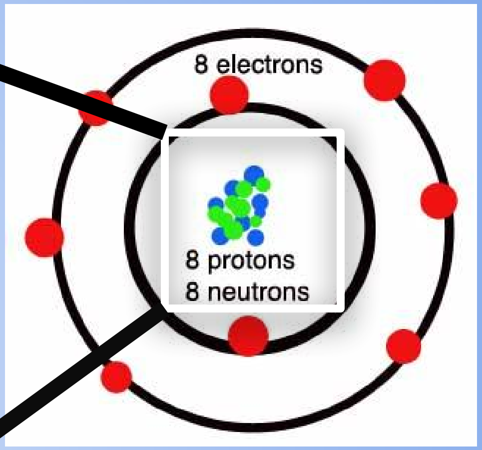
Acts upon electrically charged particles

Keeps the electrons bound and orbiting around the atomic nucleus

The Fundamental Forces of the Universe **Influence** the Behavior of Particles!

Mediator: gluon (g)





The strong nuclear force

Holds the nucleus together

Range of the force is 0.000000000000001 meters

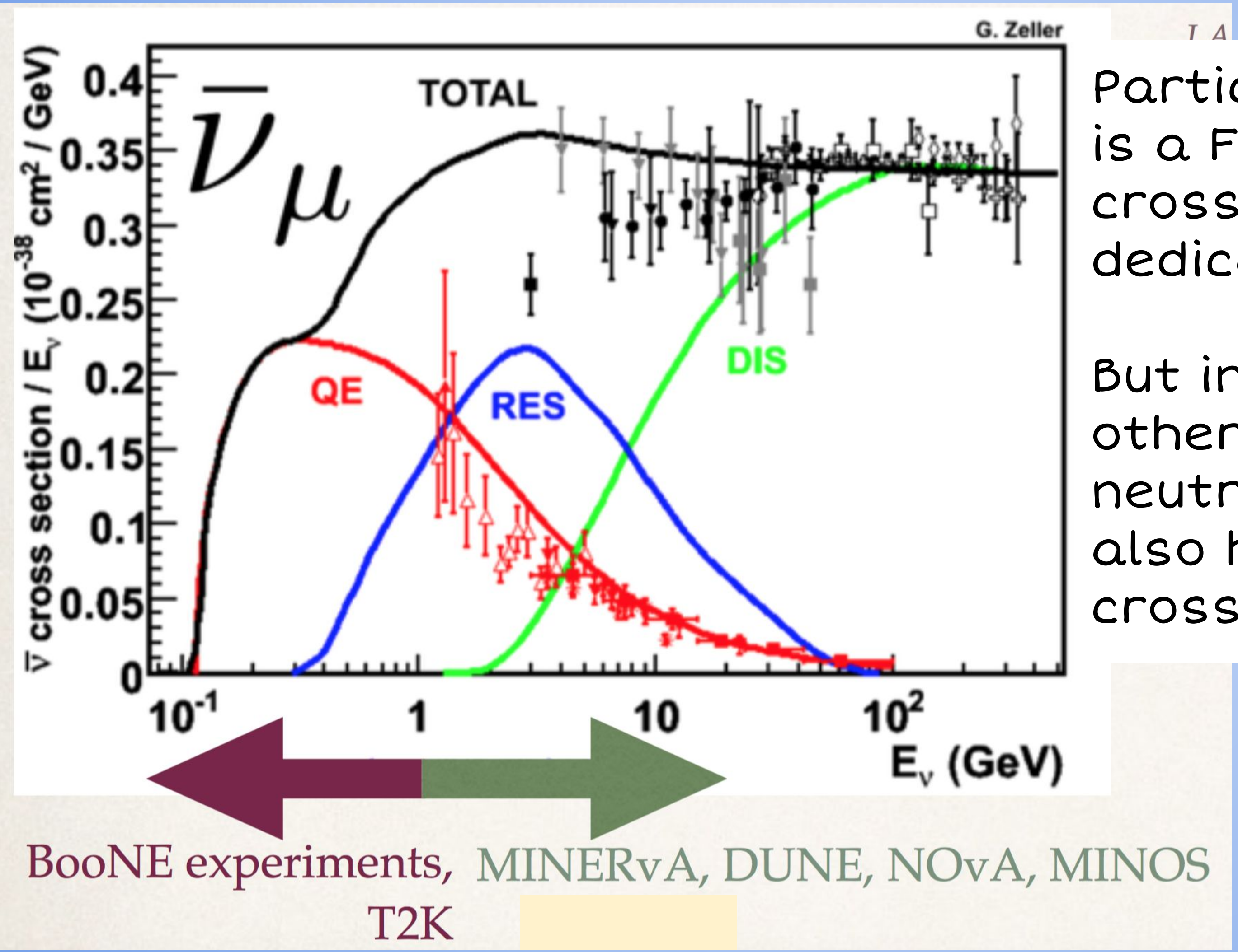
What is the energy of 1 MeV?

The energy of a flying mosquito is 1,000,000,000,000 electron volts,

where 1 MeV = 1,000,000 electron volts.
= 1.6×10^{-13} Joules.

It is high energy for an elementary: for an electron at rest, it will make it to move at 0.94c .

Neutrino - nucleus cross-section needs to be accurately determined

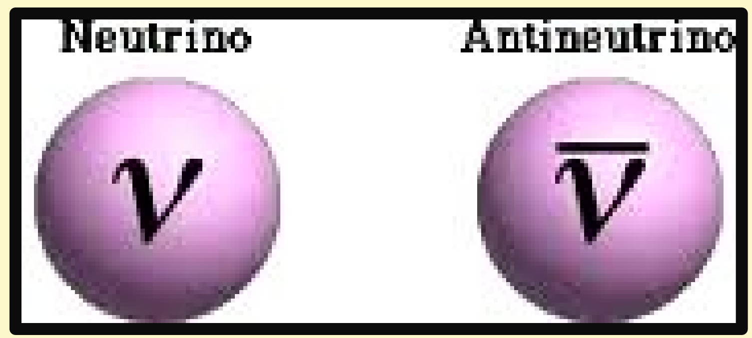


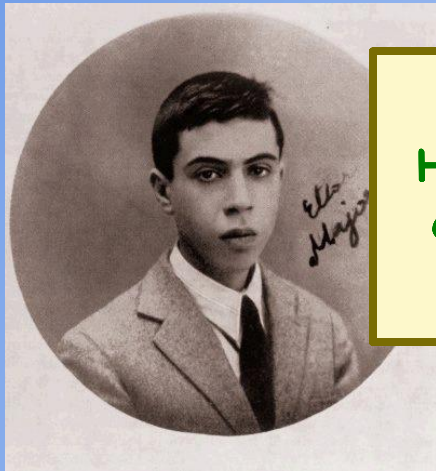
Particularly MINERvA is a Fermilab cross-section dedicated experiment.

But in general all other Fermilab neutrino experiment also have cross-section studies.

Another mystery

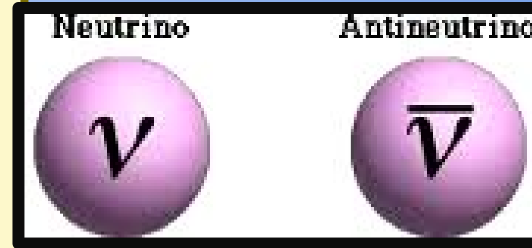
After Fermi published his beta-decay theory, Ettore Majorana derived a theory to suggest that the neutrino may be its own anti-particle. Means that the neutrino and anti-neutrino are the same.



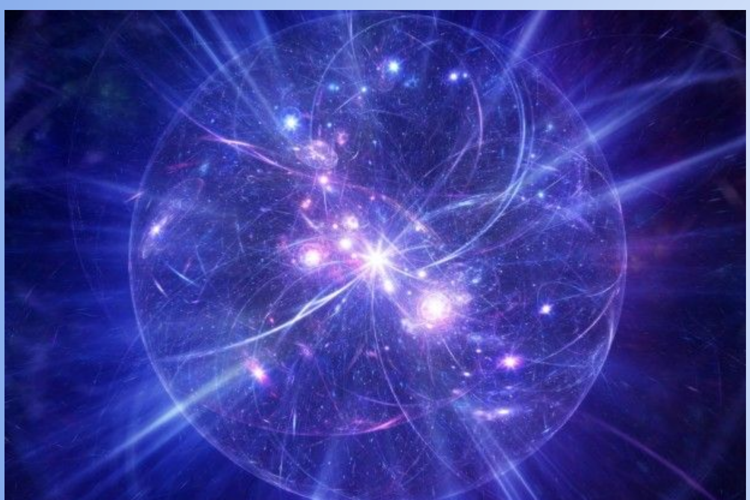


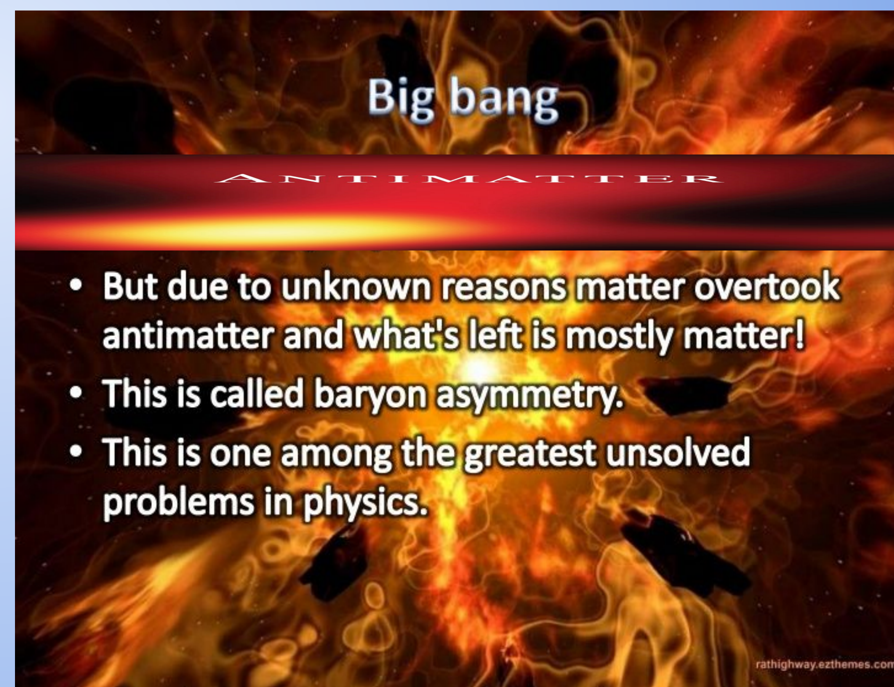
Remember THIS Guy!

He predicted that the neutrino and anti-neutrino are exactly the same.

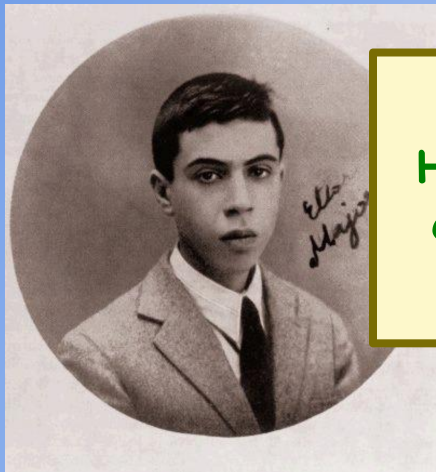


This is important because …





Big Bang created equal amount of matter and anti-matter.



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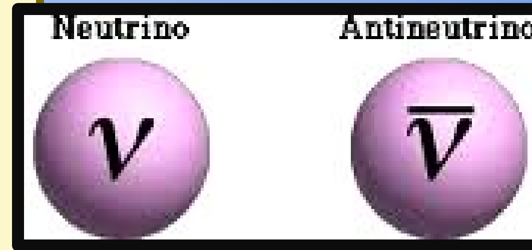
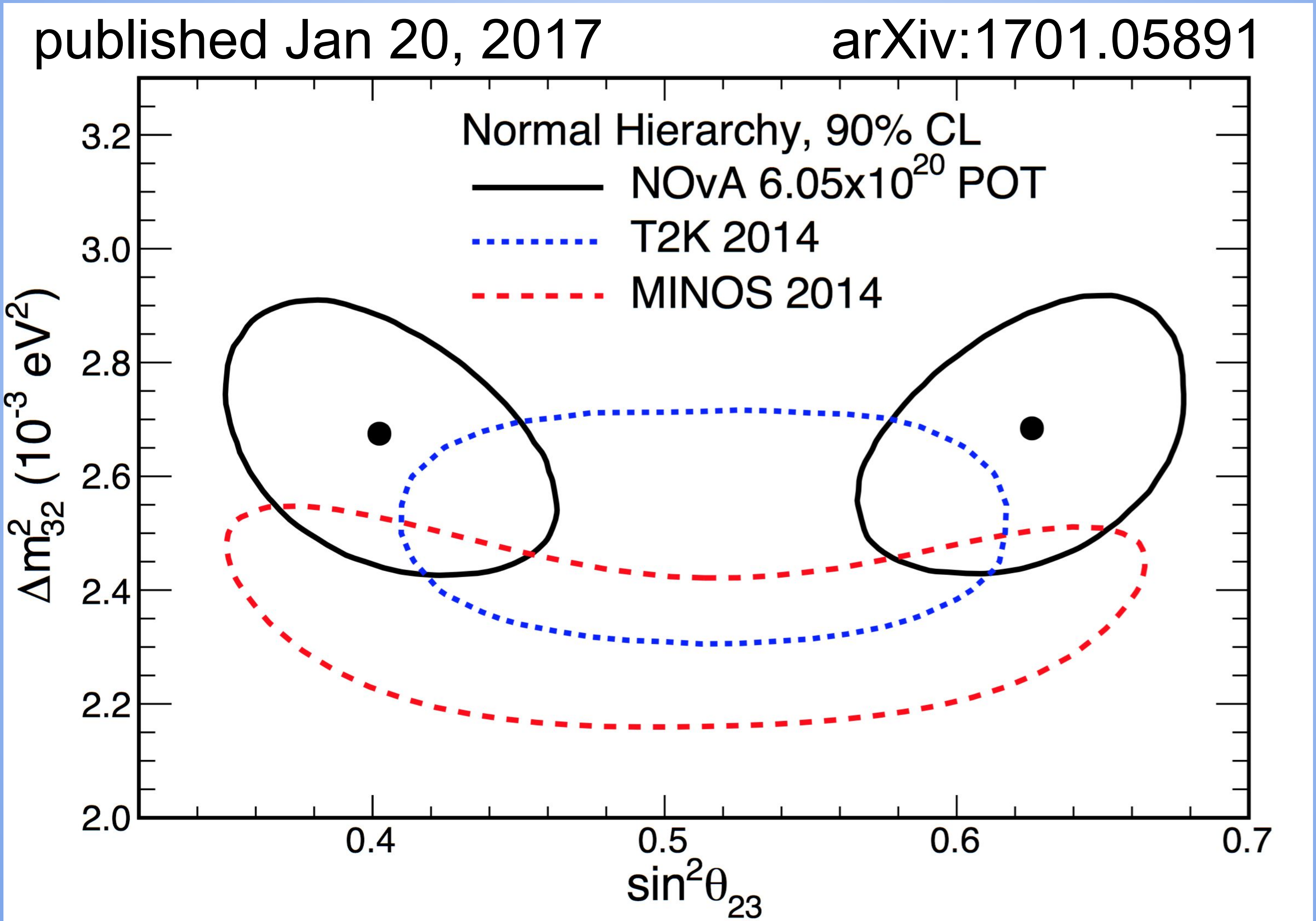


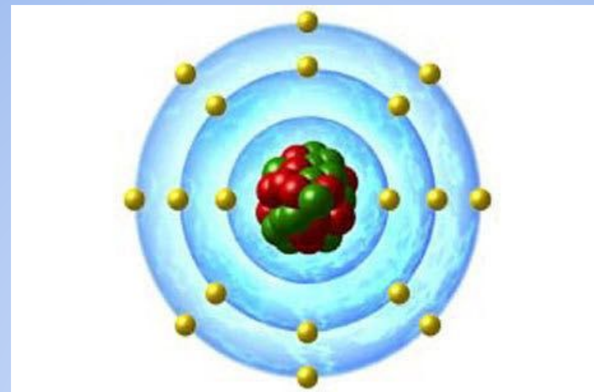
Making precision measurements of the properties of neutrinos bring us a step closer to uncovering the biggest mysteries of the universe!

We are in a new ERA of Neutrino Detectors

This measurements is happening right now…

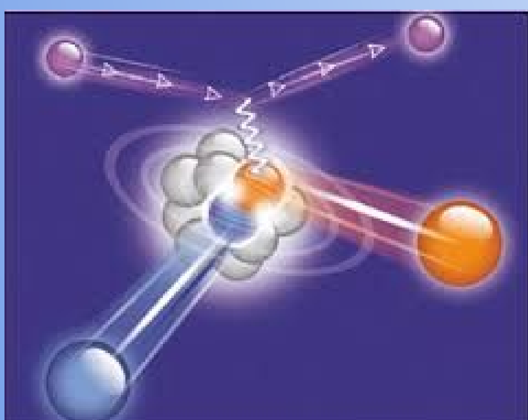


Why is it so complicated?

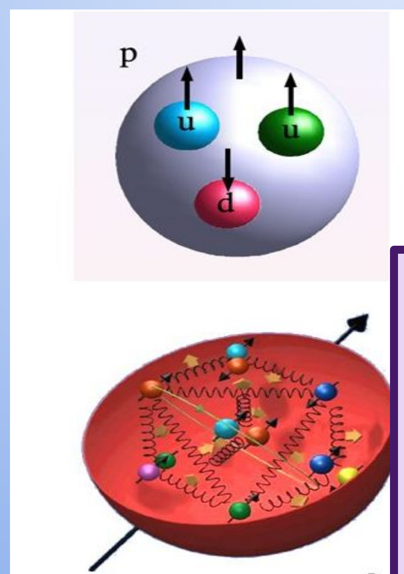


The neutrino has to collide with a nucleon under various scenarios.....

Also, there is a pion cloud surrounding the nucleus.



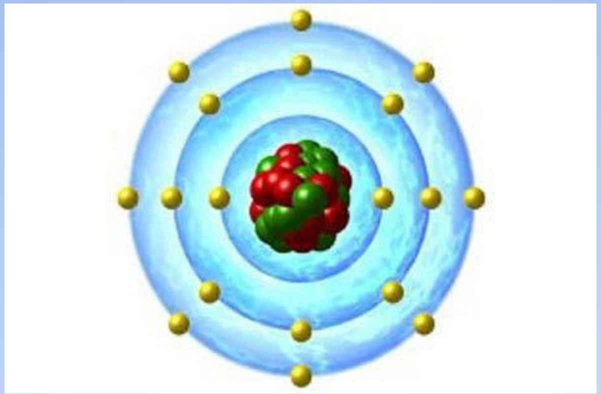
nucleon bound with another nucleon



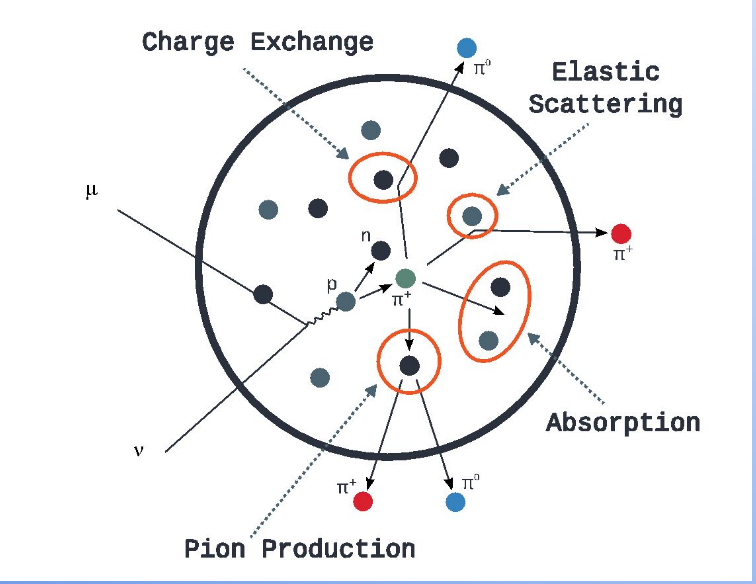
The inside of
looks li

3 valence q
quarks, and p
gluons holding

Why is it so complicated?



The outgoing hadrons have to exit this complicated environment.



On the way out of the nucleus, the hadron can undergo various interactions with spectator nucleons.

The detector will see many, one, or no hadrons.