

Neutrinos



Saturday Morning Physics

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Fermilab
November 4, 2017

Standard Model and Neutrinos

Elementary Particles

What does elementary mean?

Leptons



charge: -1

electron



Quarks



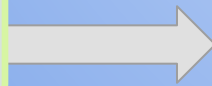
charge: +2/3

up



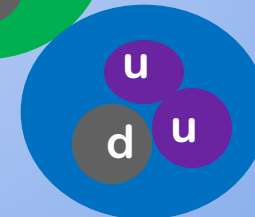
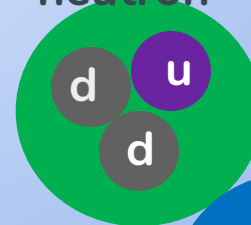
charge: -1/3

down



protons = 2 up and 1 down

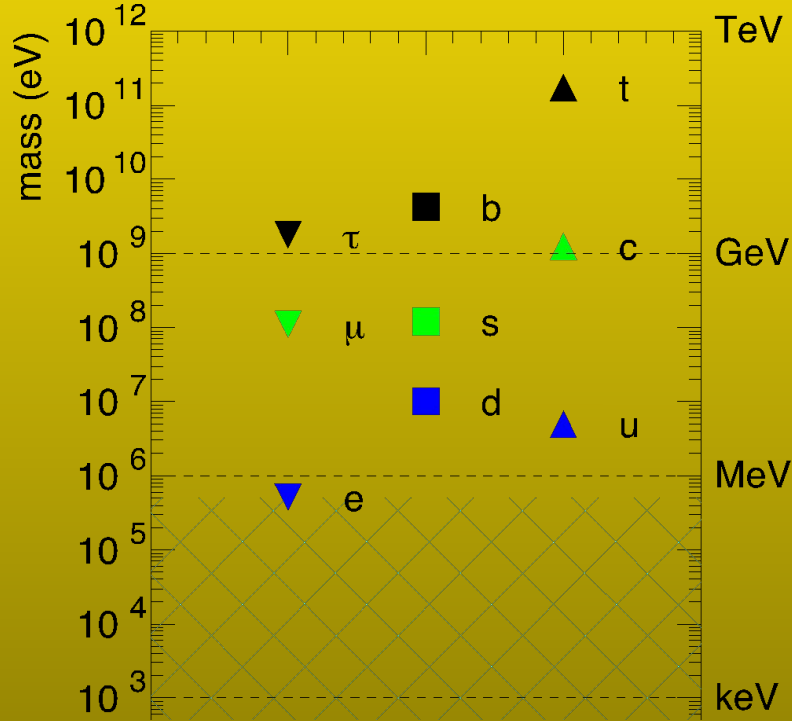
neutron



proton

Partial Standard Model of Elementary Particles

The difference between the generations is the MASS!



Leptons

1ST G

Quarks

ION

m

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



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

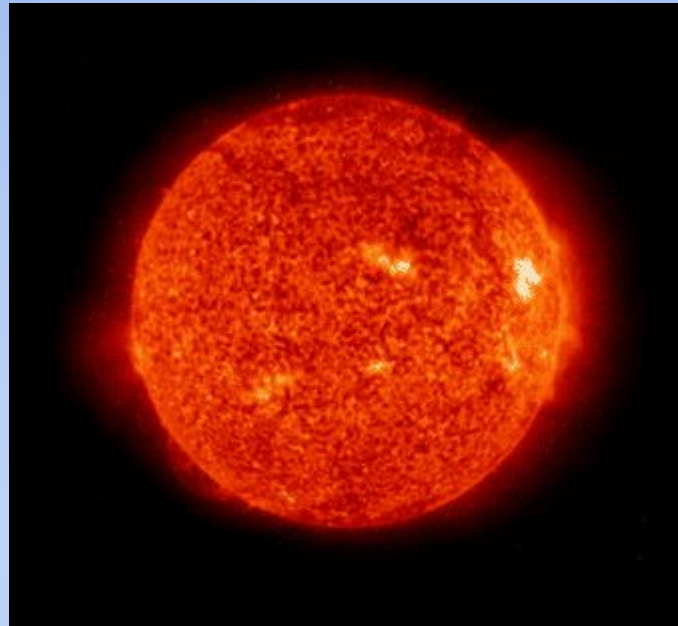
The Fundamental Forces of the Universe **Influence** the Behavior of Particles!

How about the weak force?

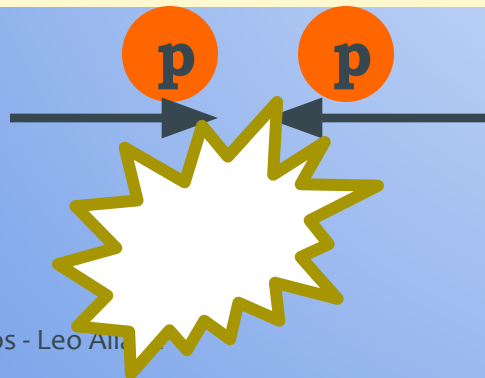
Let's take a detour first....

**Nature Can Produce
Particles!!!**

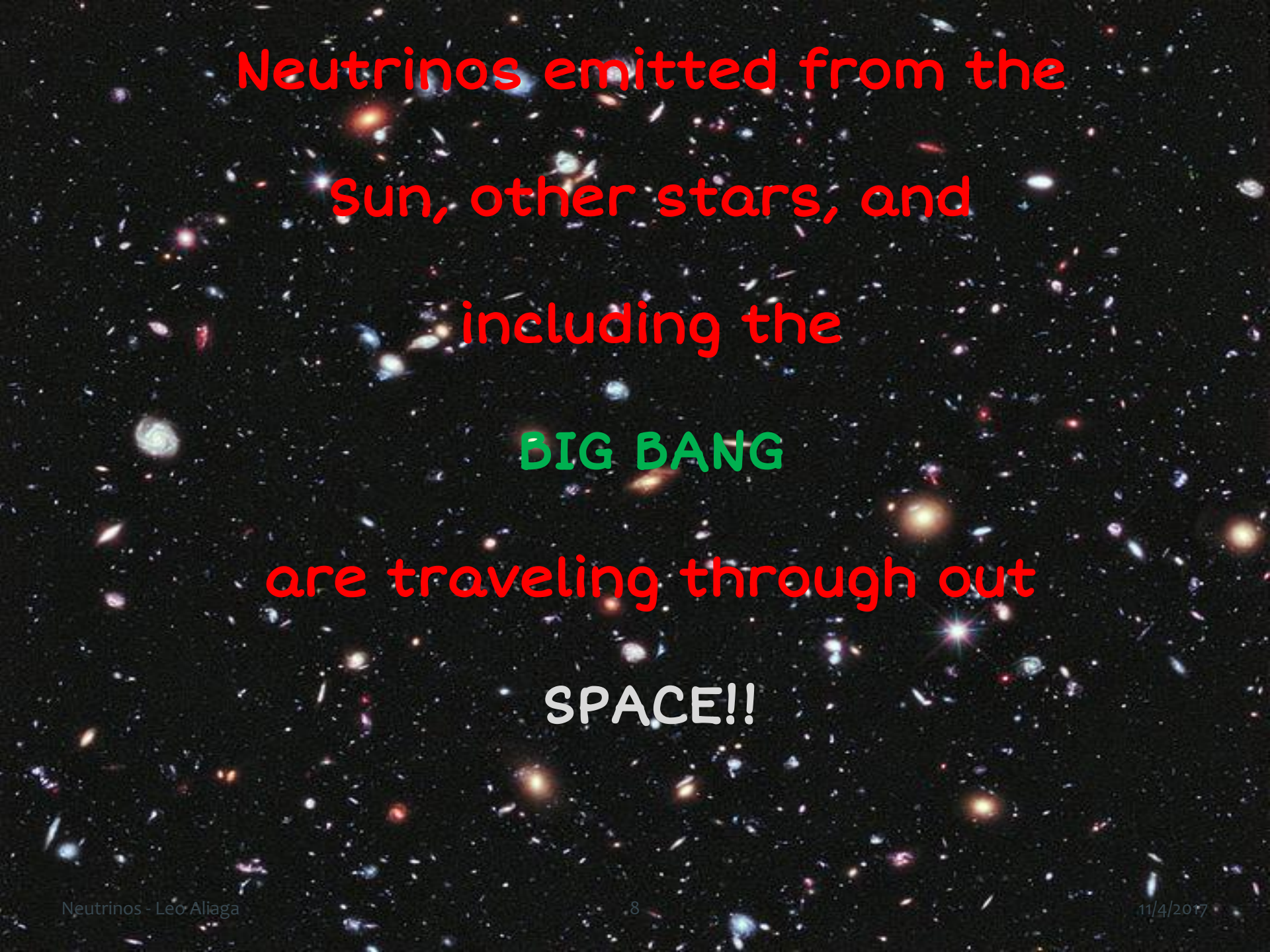
The sun is an ultimate nuclear fusion reactor!



Nuclear Fusion



NEUTRINOS



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!

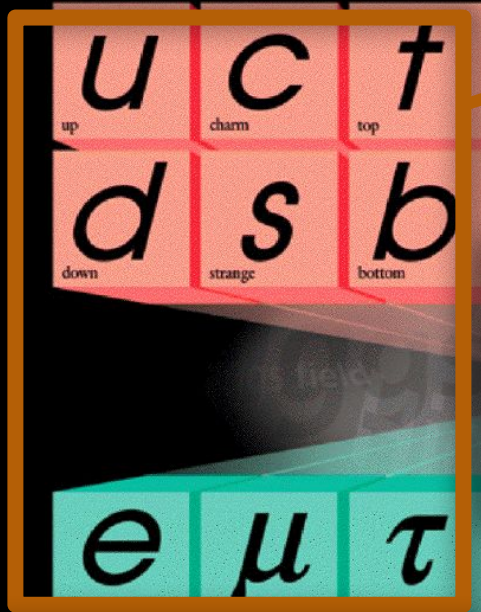


~ 65 billion of neutrinos / cm² / sec from
the Sun.

Neutrino flux: ν / cm² / sec

The Complete Picture

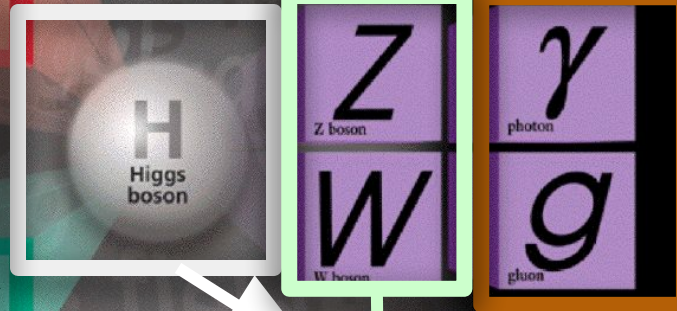
Quarks



Leptons

Will talk just indirectly about this particles

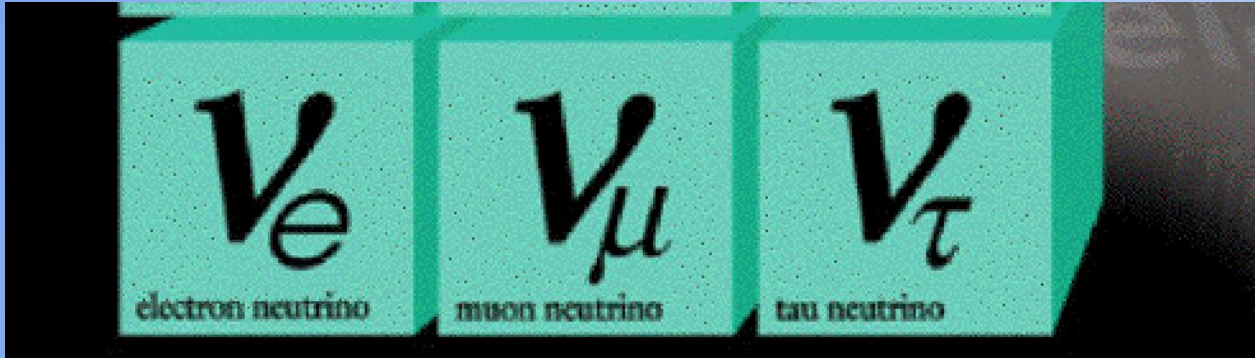
Forces



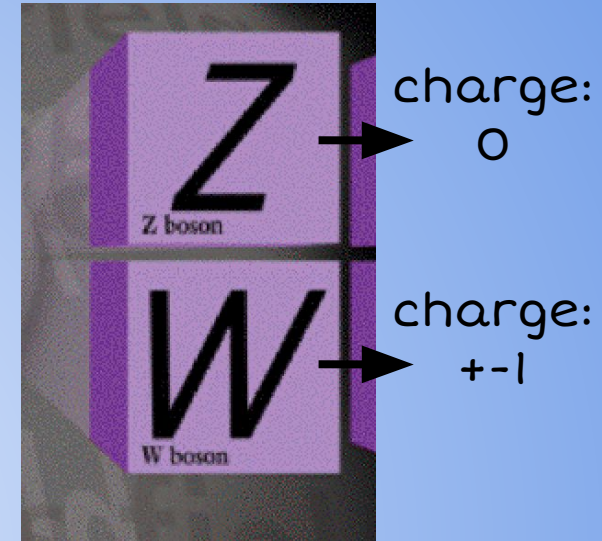
Will not talk about The God particle.

This lecture focuses on this section of the picture.

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



2 mediators of
weak force



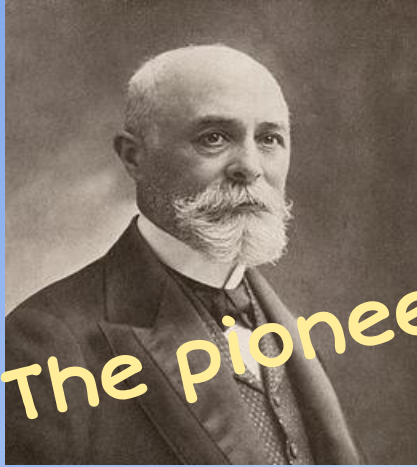
What are neutrinos?

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

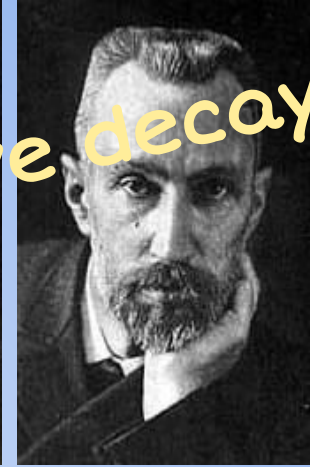
Why are neutrinos **SO** important?

The Discovery of the Neutrino

Antoine Henri Becquerel



Marie Curie and Pierre Curie

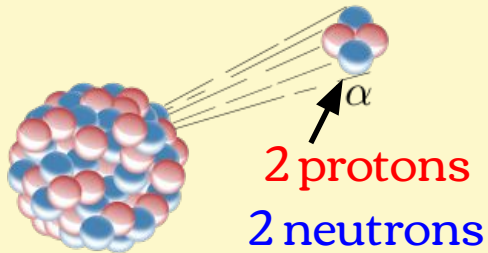


The pioneers of radioactive decay

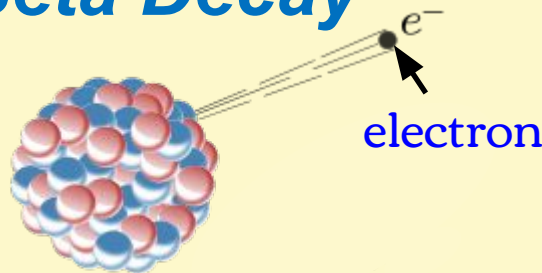
Radioactive Decay

unstable atomic nucleus loses energy by emitting particles
transforms an atom into a different type of atom or into a lower energy

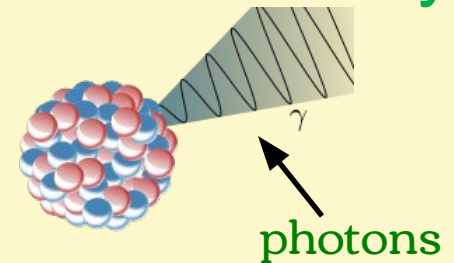
Alpha Decay



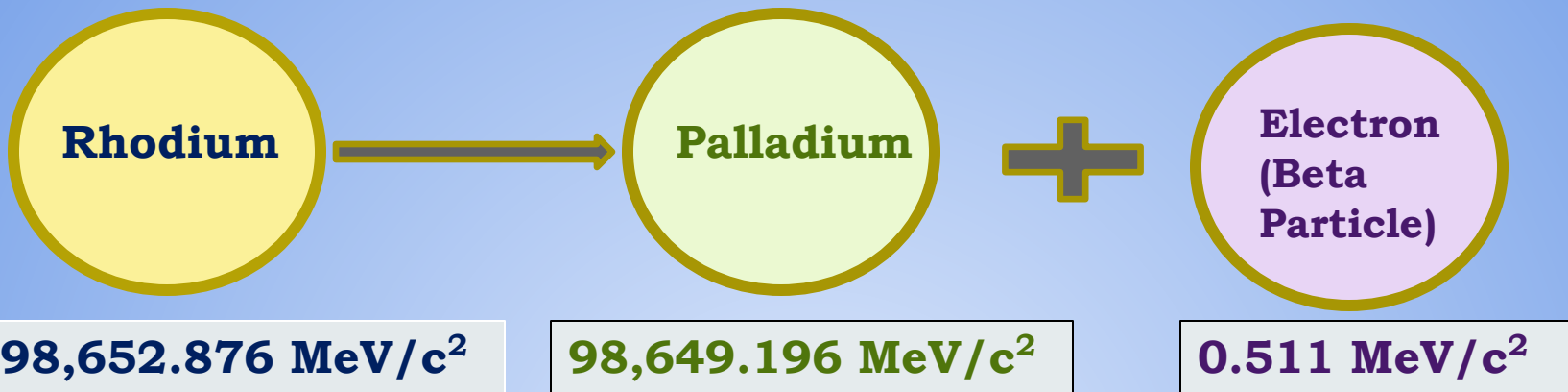
Beta Decay



Gamma Decay



Studying Beta Decay



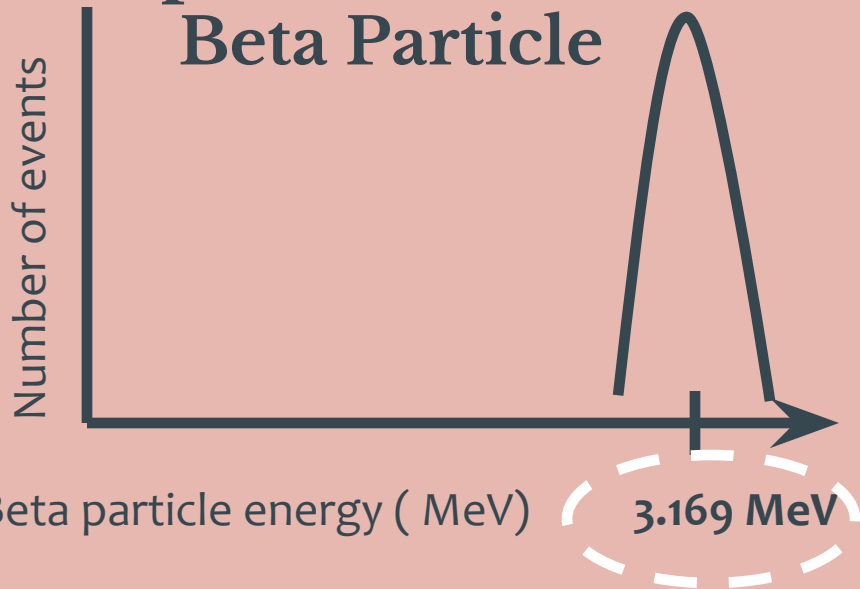
Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.002
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.065	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 83.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.227	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [209]	86 Rn Radon [222]
87 Fr Francium [223]	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Mc Moscovium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]
57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967			
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [259]	103 Lr Lawrencium [262]			
Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide								

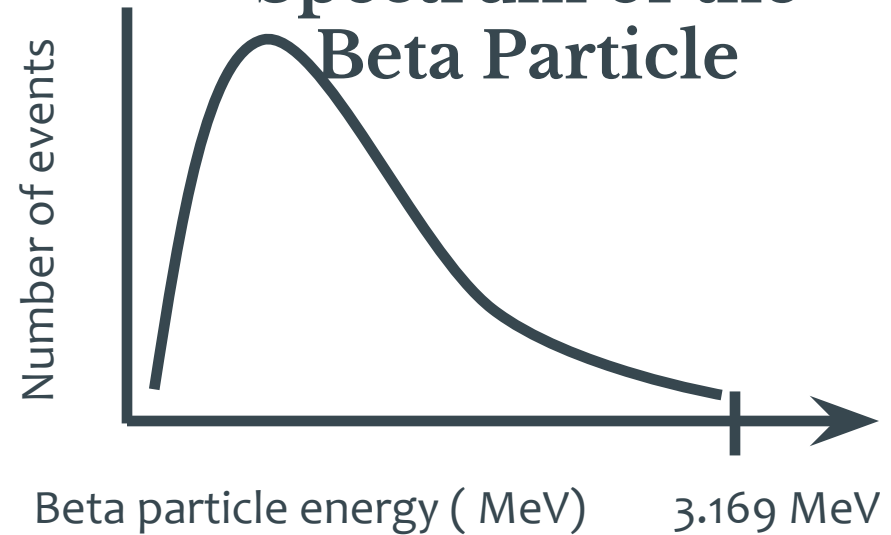
electron

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.

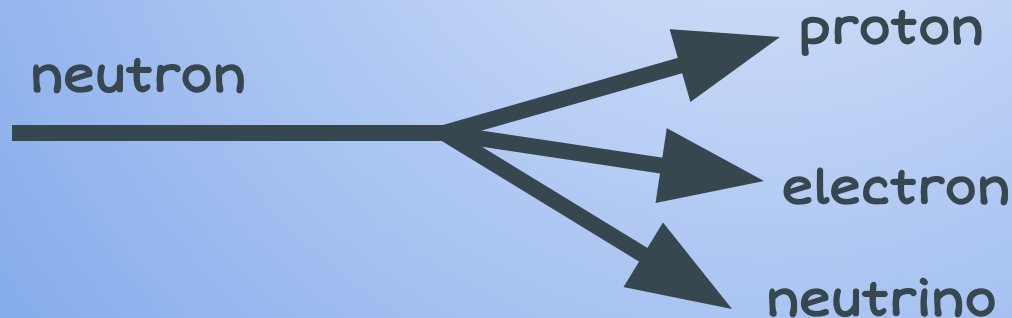
However, Pauli was skeptical about the proposal.

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

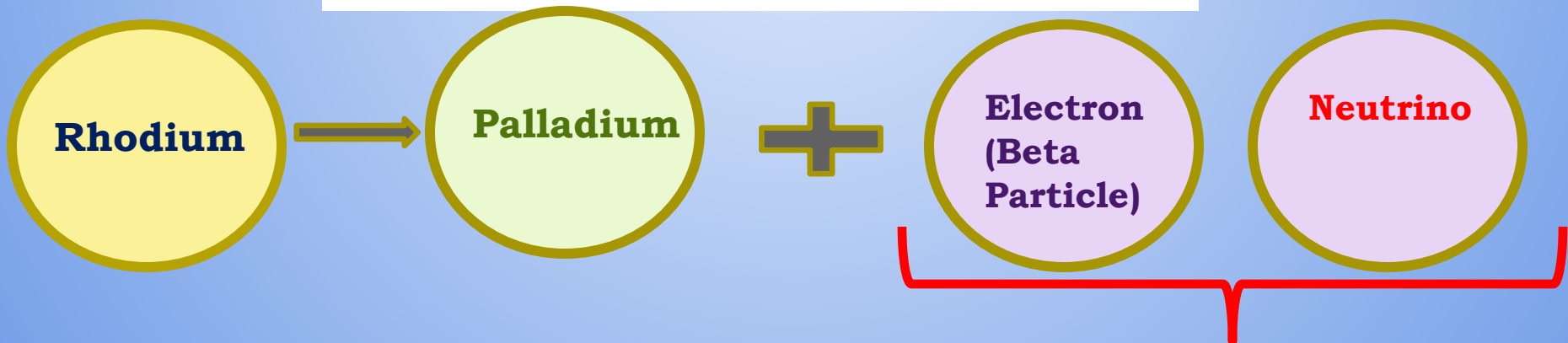
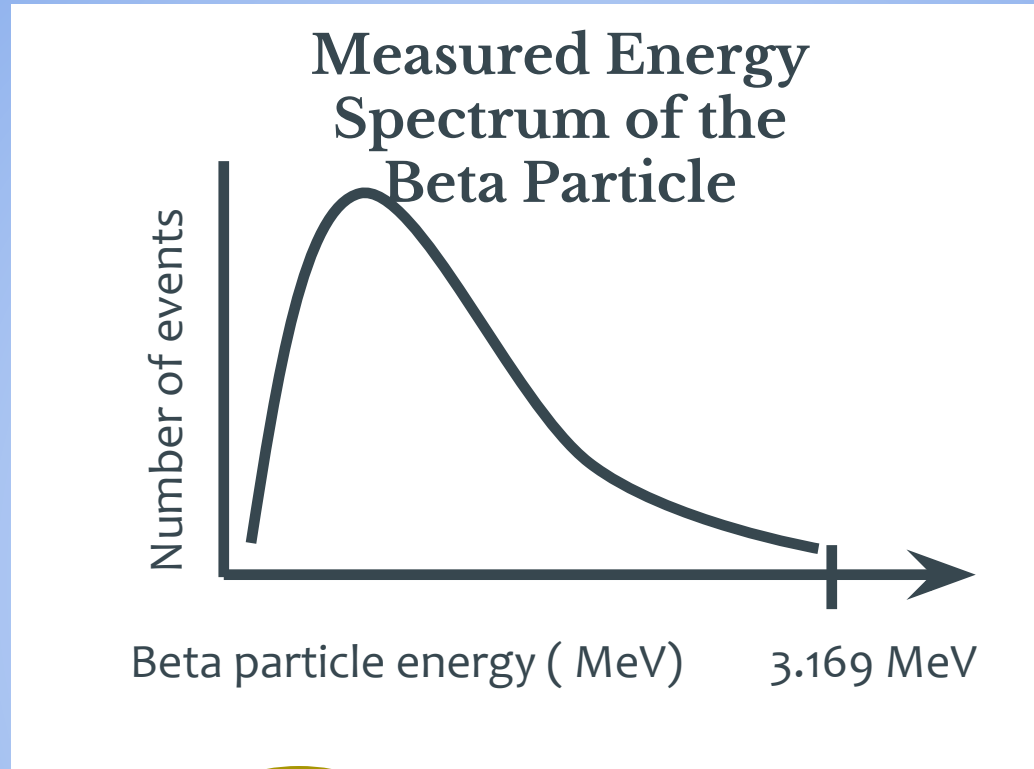
In 1933, Enrico Fermi brought the particle into reality.

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.



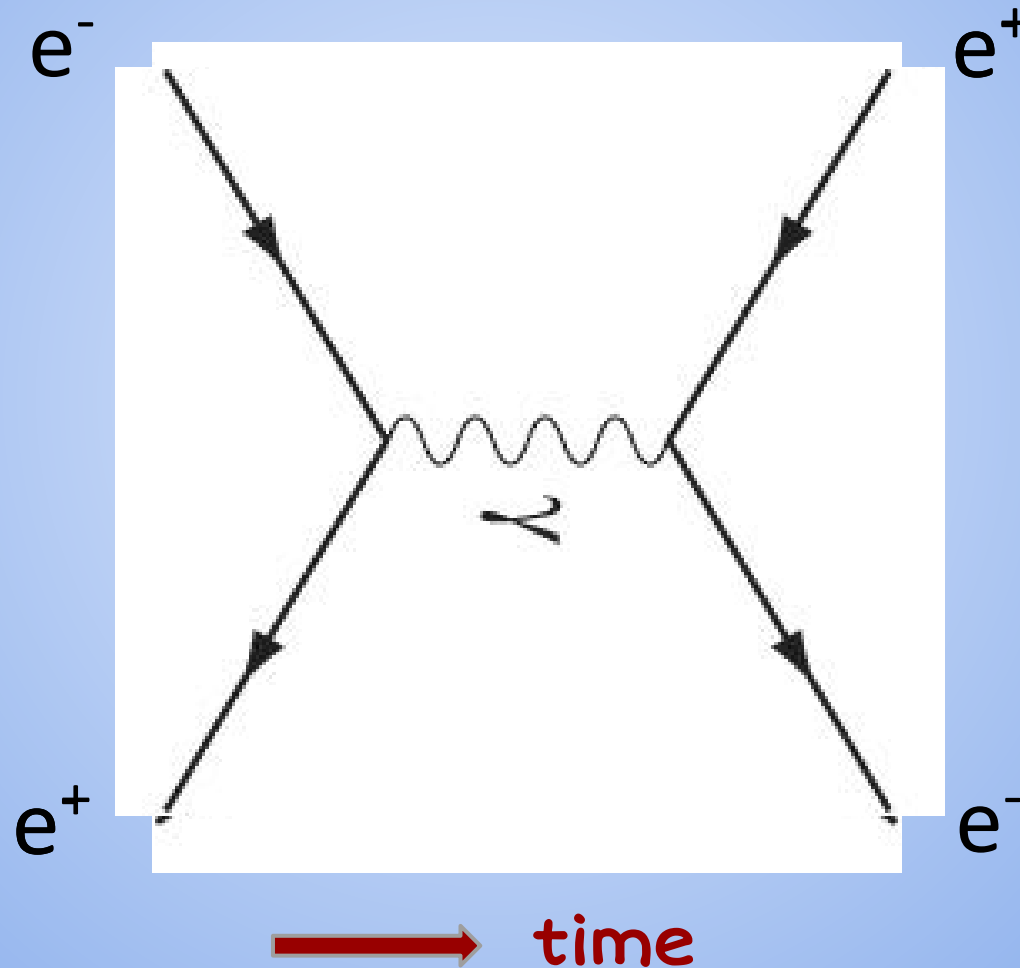
- A new particle, the neutrino, is proposed.
- Next step is to detect the neutrino.

Finding the Neutrino

Nature has many symmetries



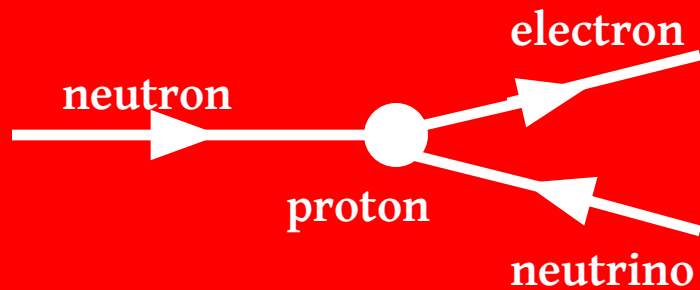
Symmetry in Interactions



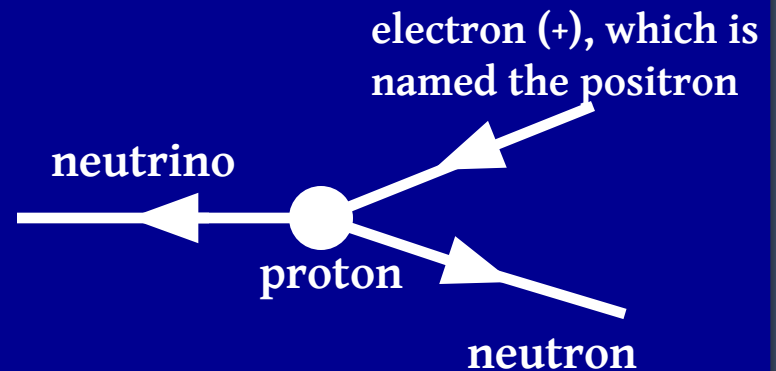
Symmetry Plays a Fundamental Role in Particle Physics

Time Reversal

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



Beta-Decay



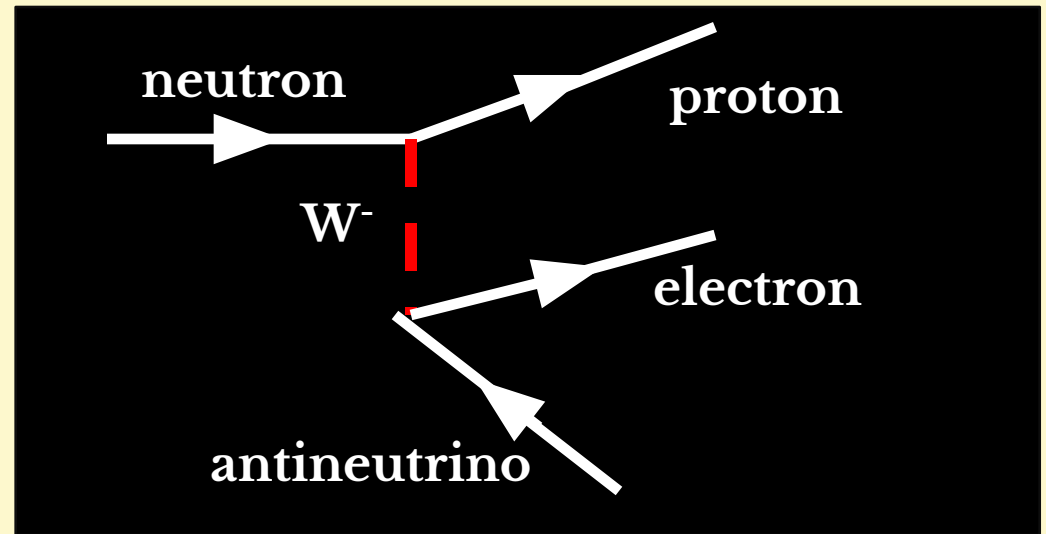
Inverse Beta-Decay

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

The weak force and neutrinos

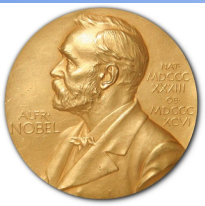
In 1936, Yukawa proposed the **W boson**.

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.



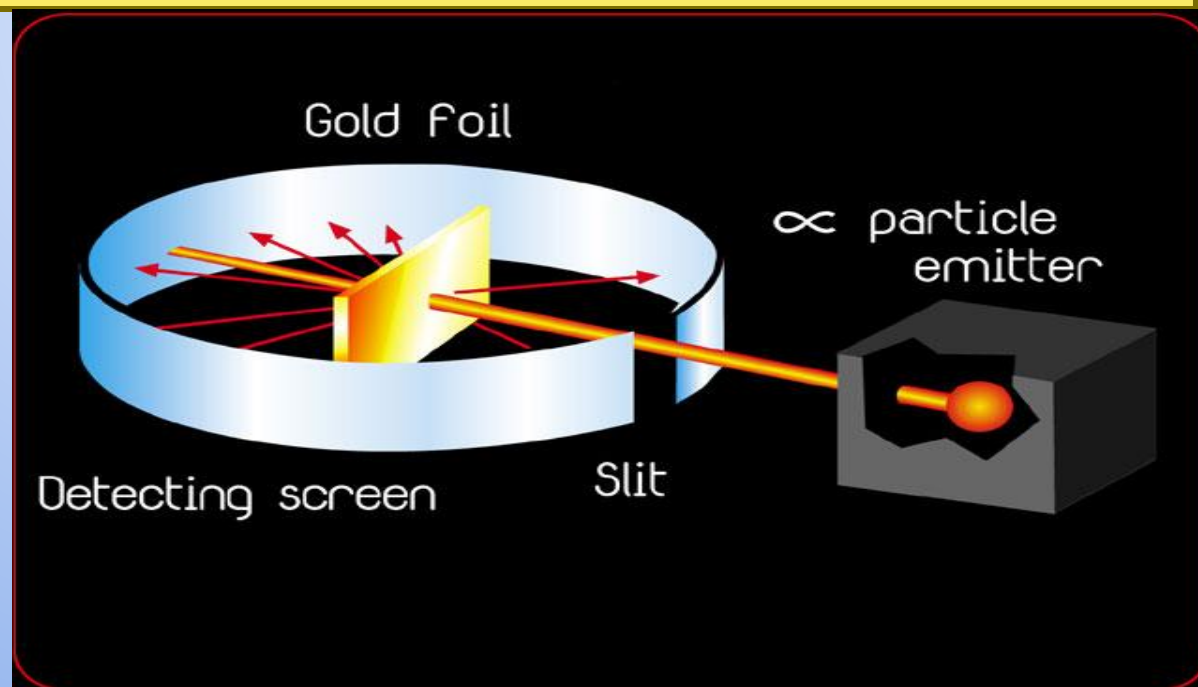
Neutrinos - Leo Aliaga

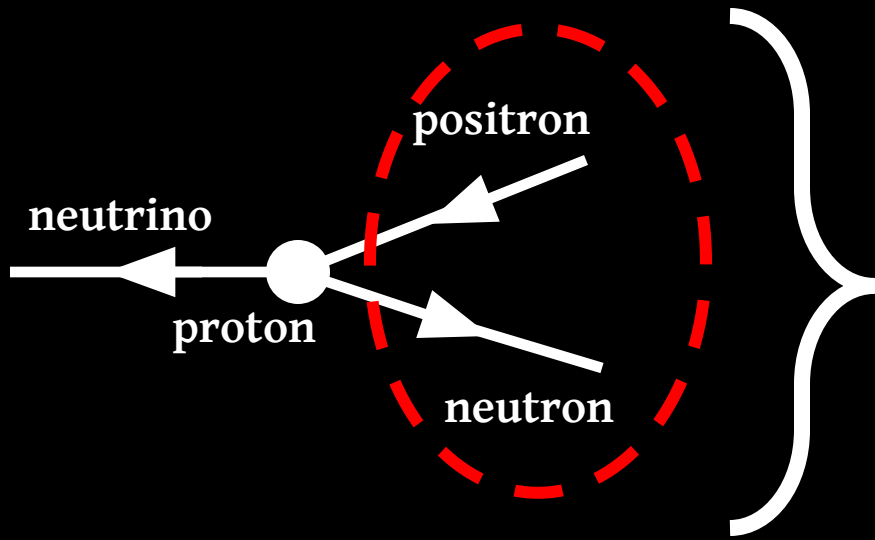
Physicists Use Scattering Experiments to Understand and Discover Particles

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.



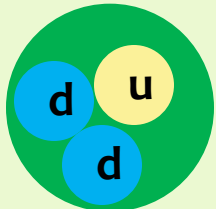
positron

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

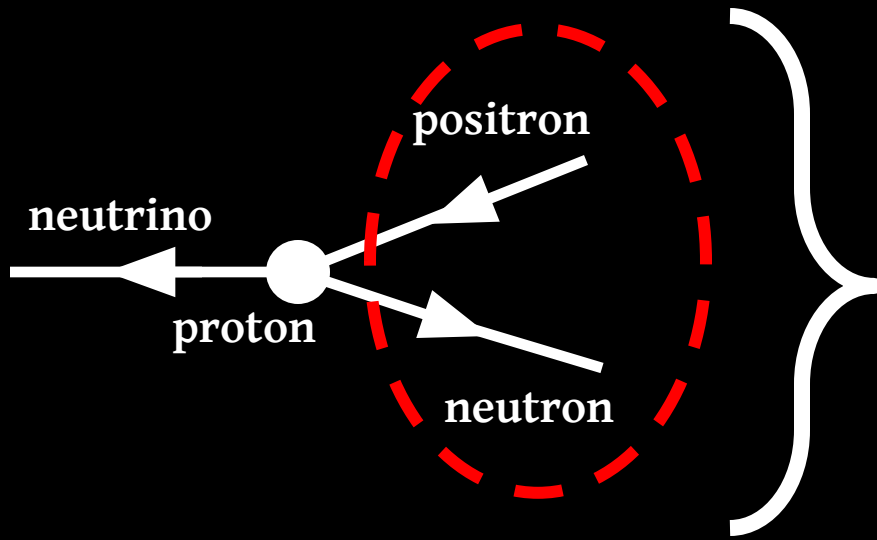


neutron

looking inside the neutron



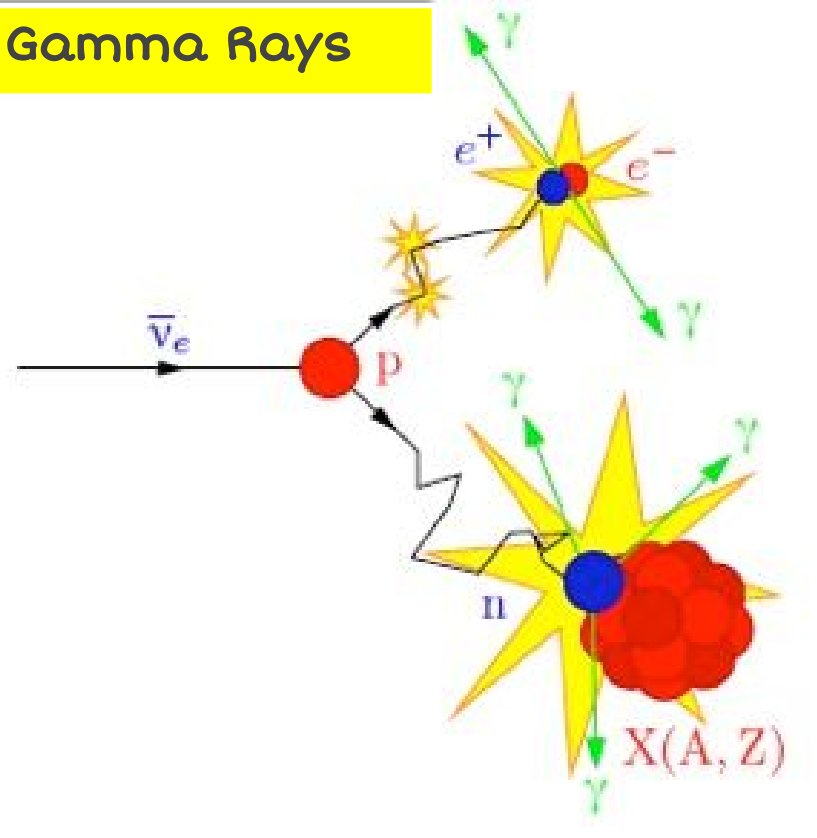
an atomic nucleus can capture a neutron → strong force binds the neutron in the nucleus to create a heavier particle → the heavier particle is unstable → emits gamma rays to become stable



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)

$$1\text{GeV} = 10^3 \text{ MeV} \\ = 10^9 \text{ eV}$$

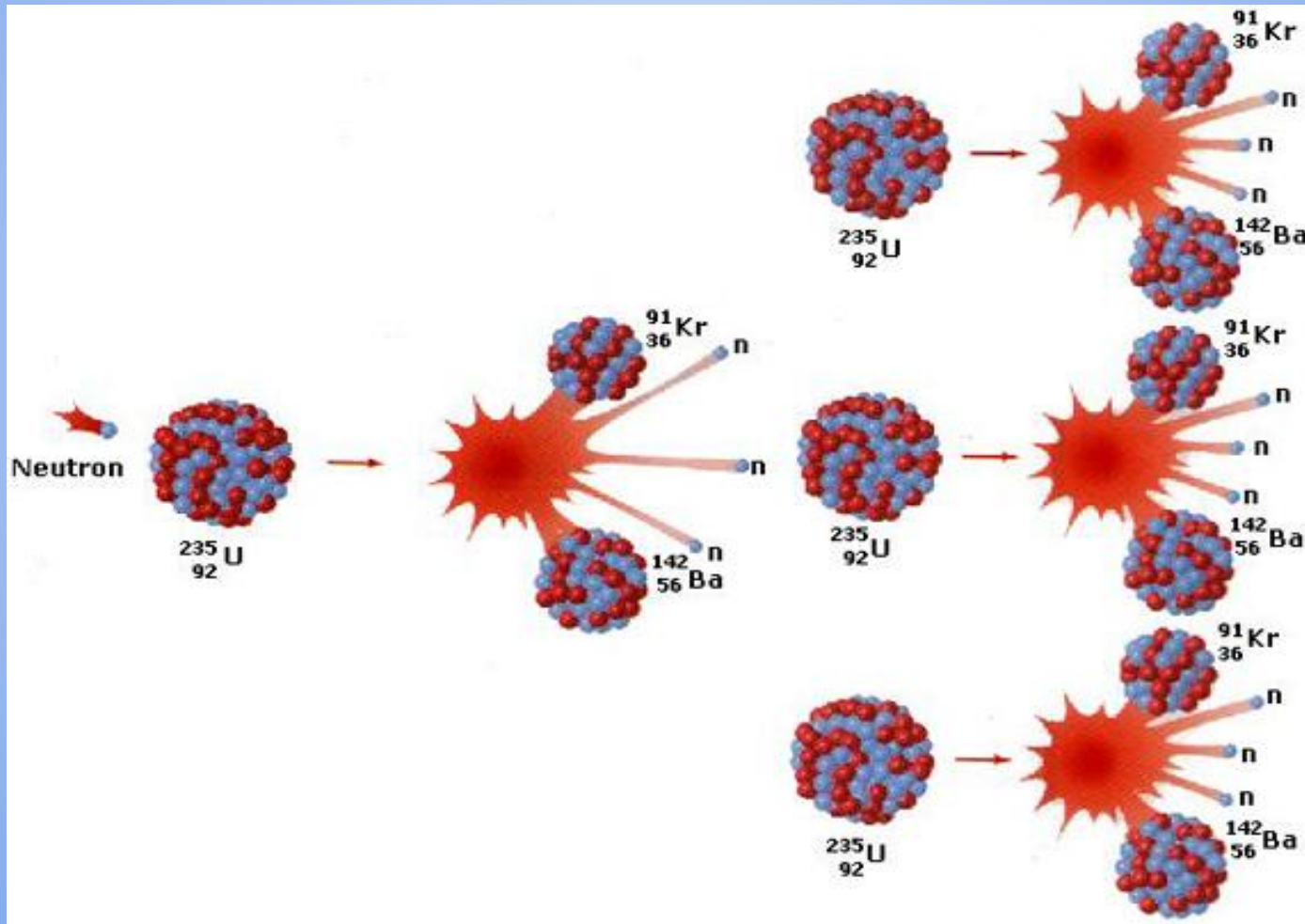


Neutrino interactions are extremely rare !

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.

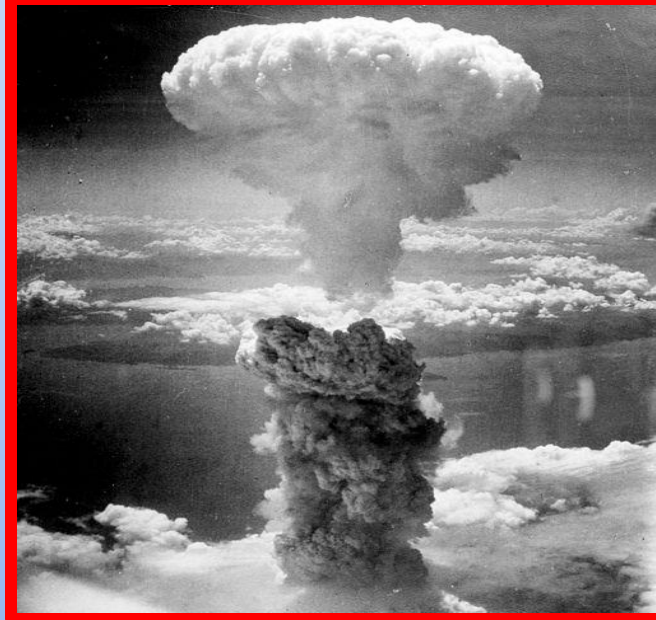


Fermi's colleague Leo Szilard understood the **military** application of nuclear fission.

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.

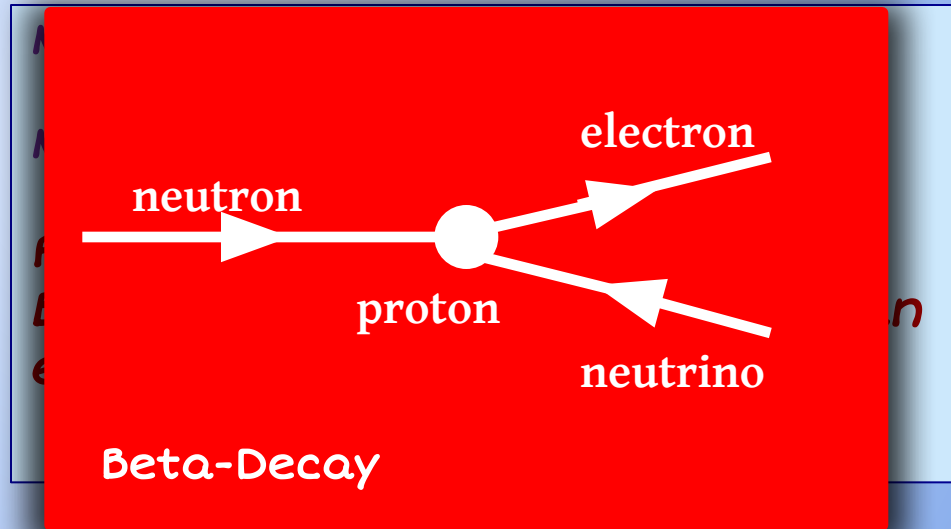
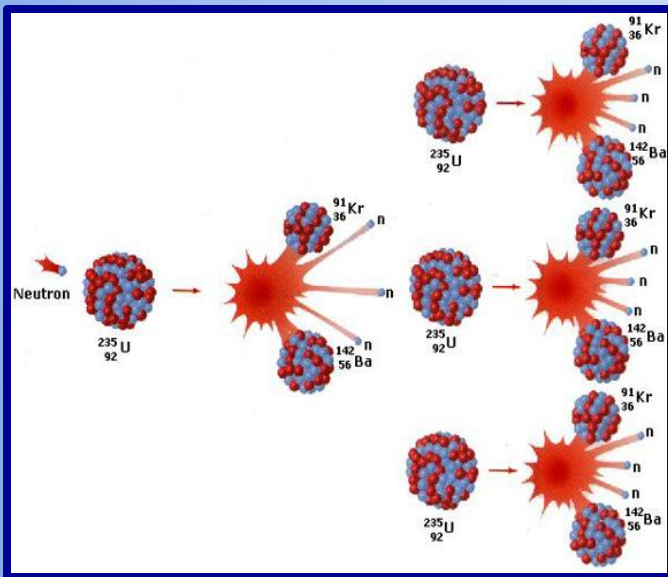
The most brilliant physicists of the era working together constructed the first **atomic bomb!**



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**.

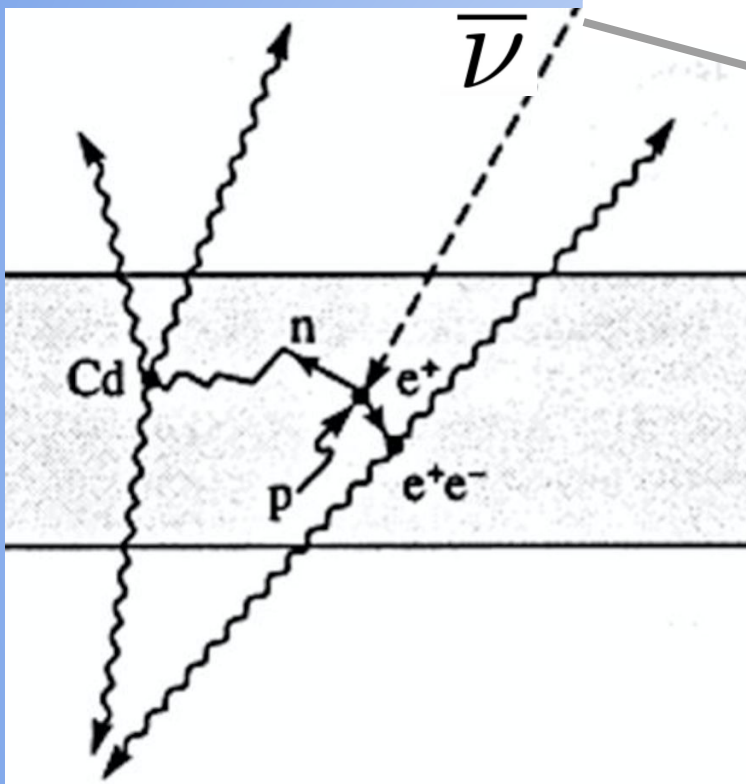
Lets do some Science!!!



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



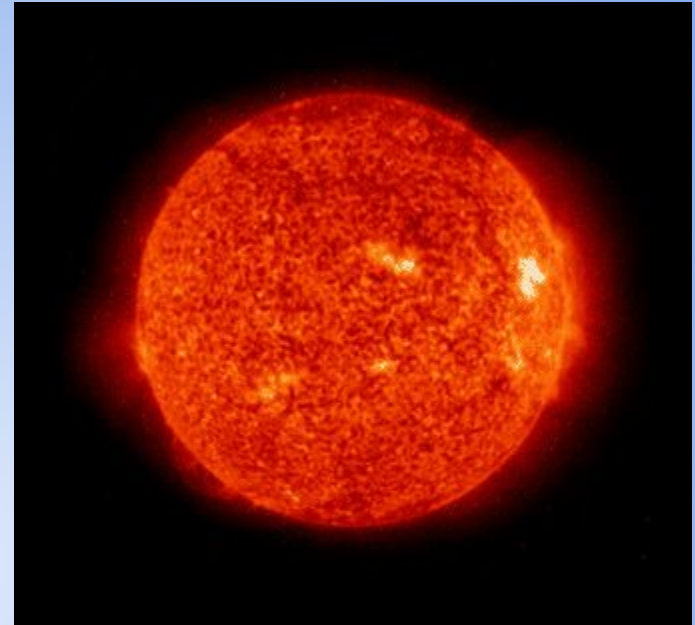
Results (1956)

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



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

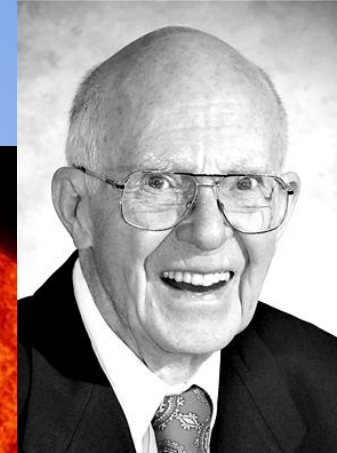
***What about using
neutrinos emitted from
the Sun...***



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**.

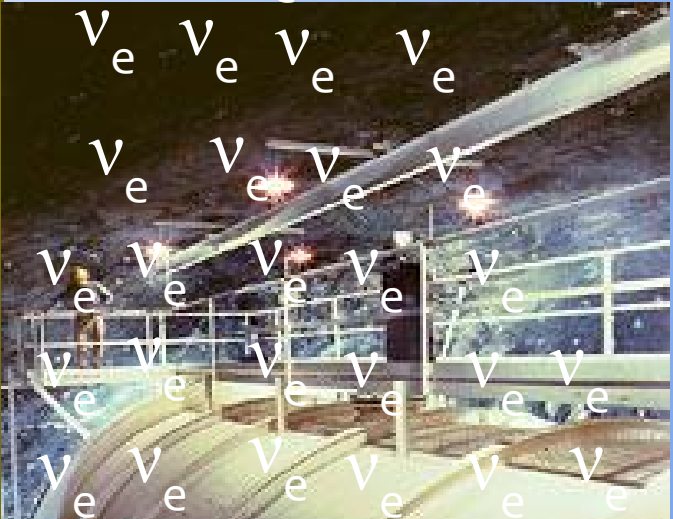
*30 years after neutrinos were
postulated...*



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**.

Homestake Mine
Lead, SD, USA

Our measurement
is wrong

Our understanding of
how our detector
behaves is wrong

Where did all of the neutrinos go?

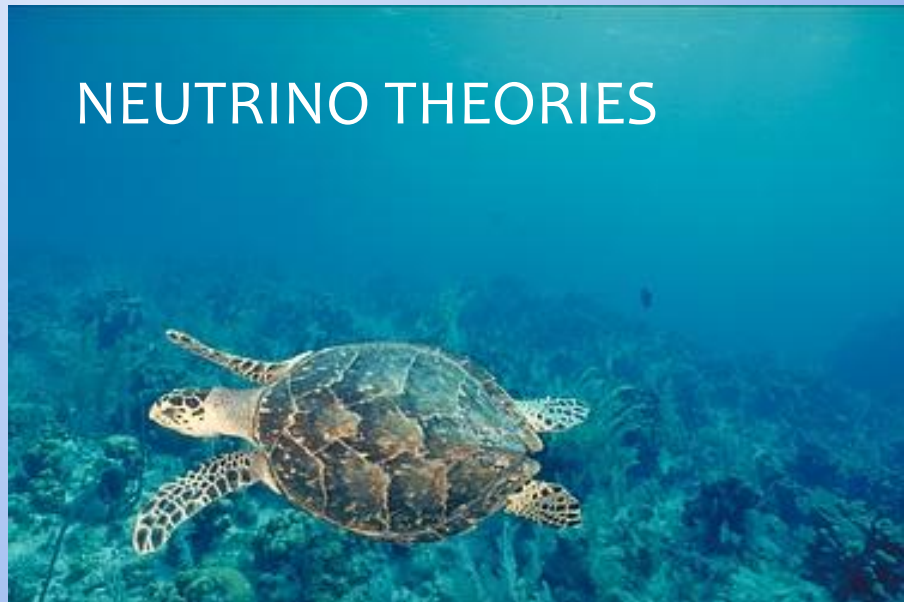
Our understanding of
how neutrinos behave
is wrong

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

The Mysteries of Neutrinos

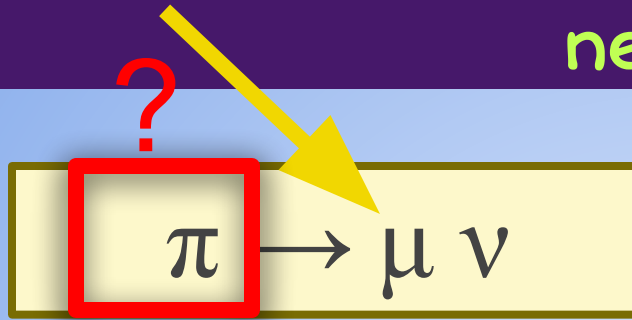


NEUTRINO EXPERIMENTS



NEUTRINO THEORIES

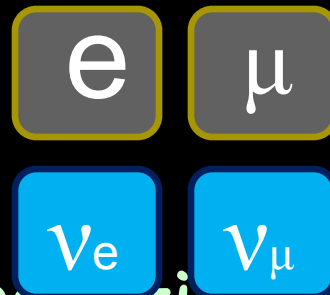
The muon was discovered (1936) before the muon neutrino.



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.

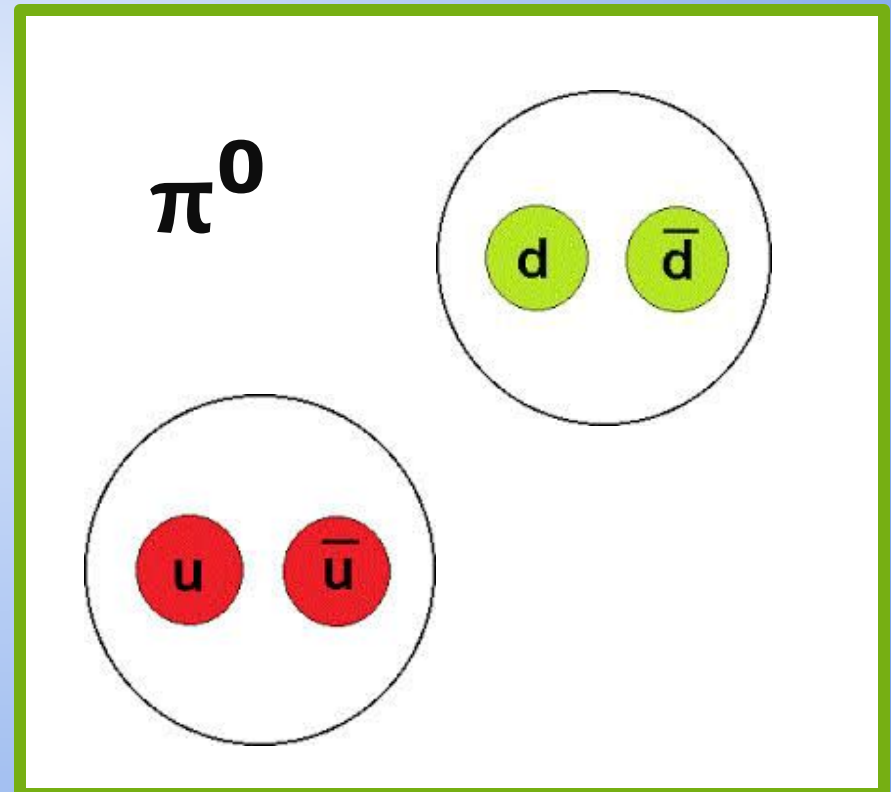
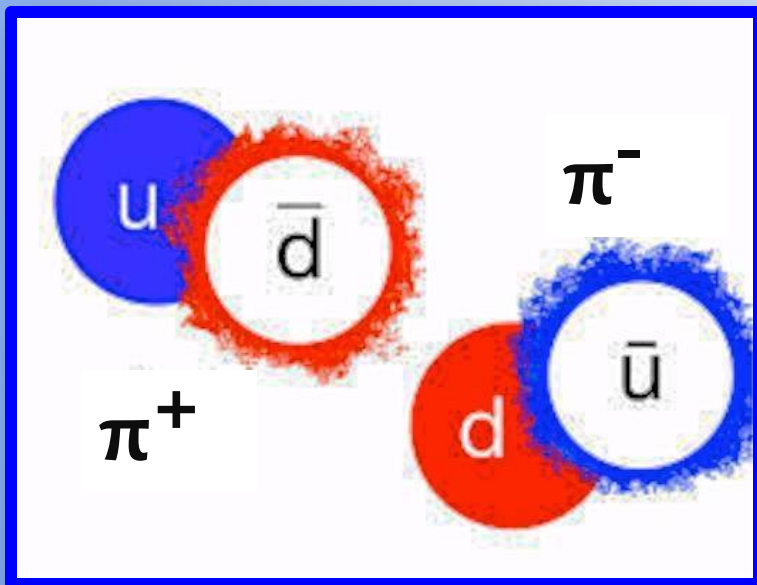


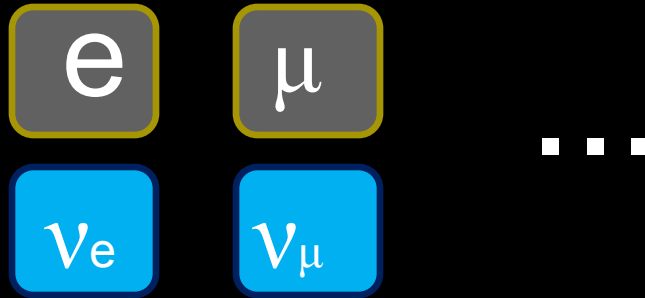
So, how many generations of neutrinos do exist?

Pions

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

There are three types of pions.

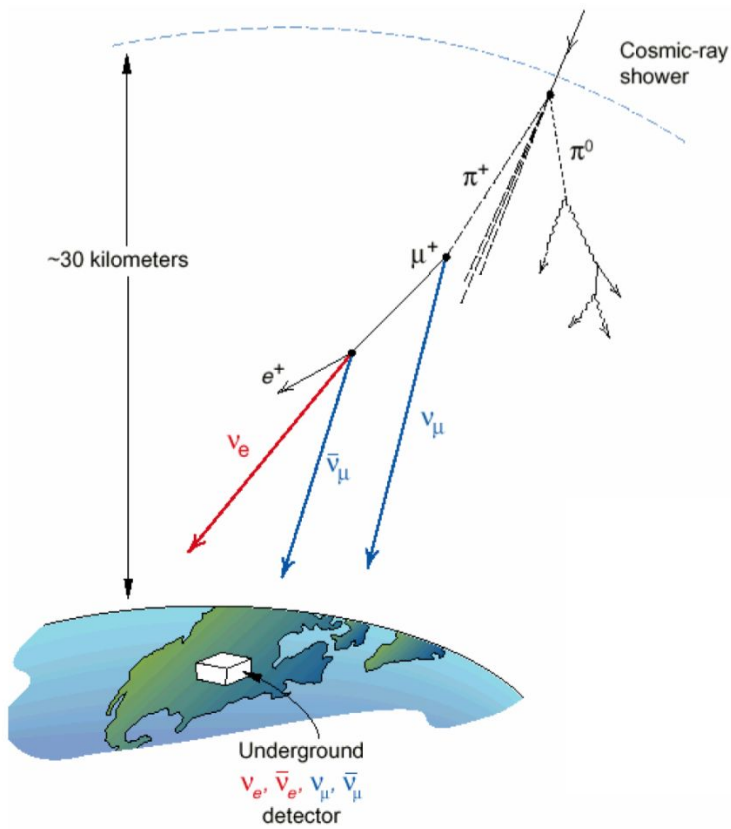




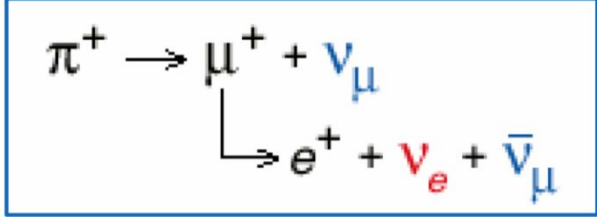
So, how many generations of neutrinos do exist?

Atmospheric Neutrinos

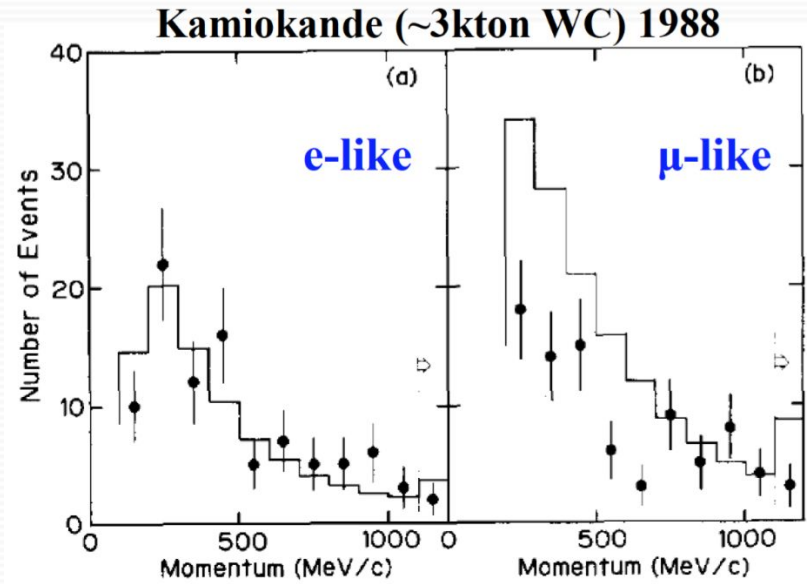
- Cosmic rays (mostly protons) interact in the upper atmosphere creating hadronic showers (mostly pions).



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



- Events found in Kamiokande:

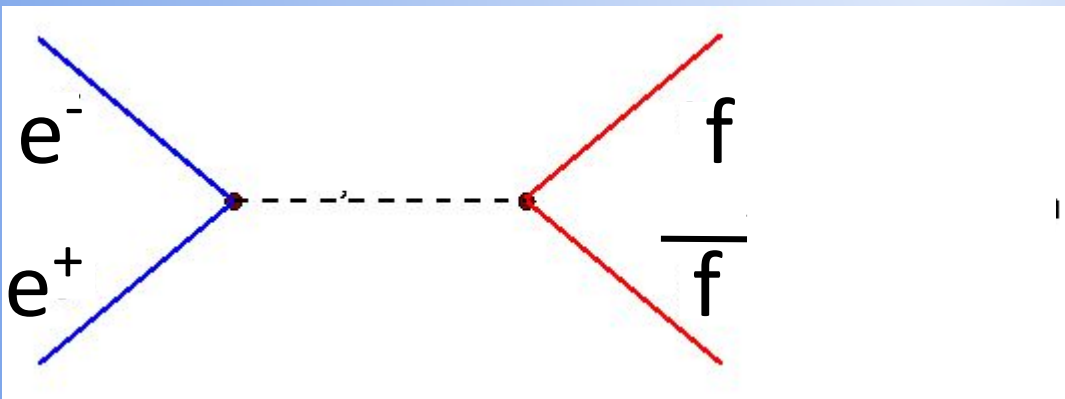


Why?

Physicists worried about the number of generations.

The best measurement comes from studying the decay of Z boson

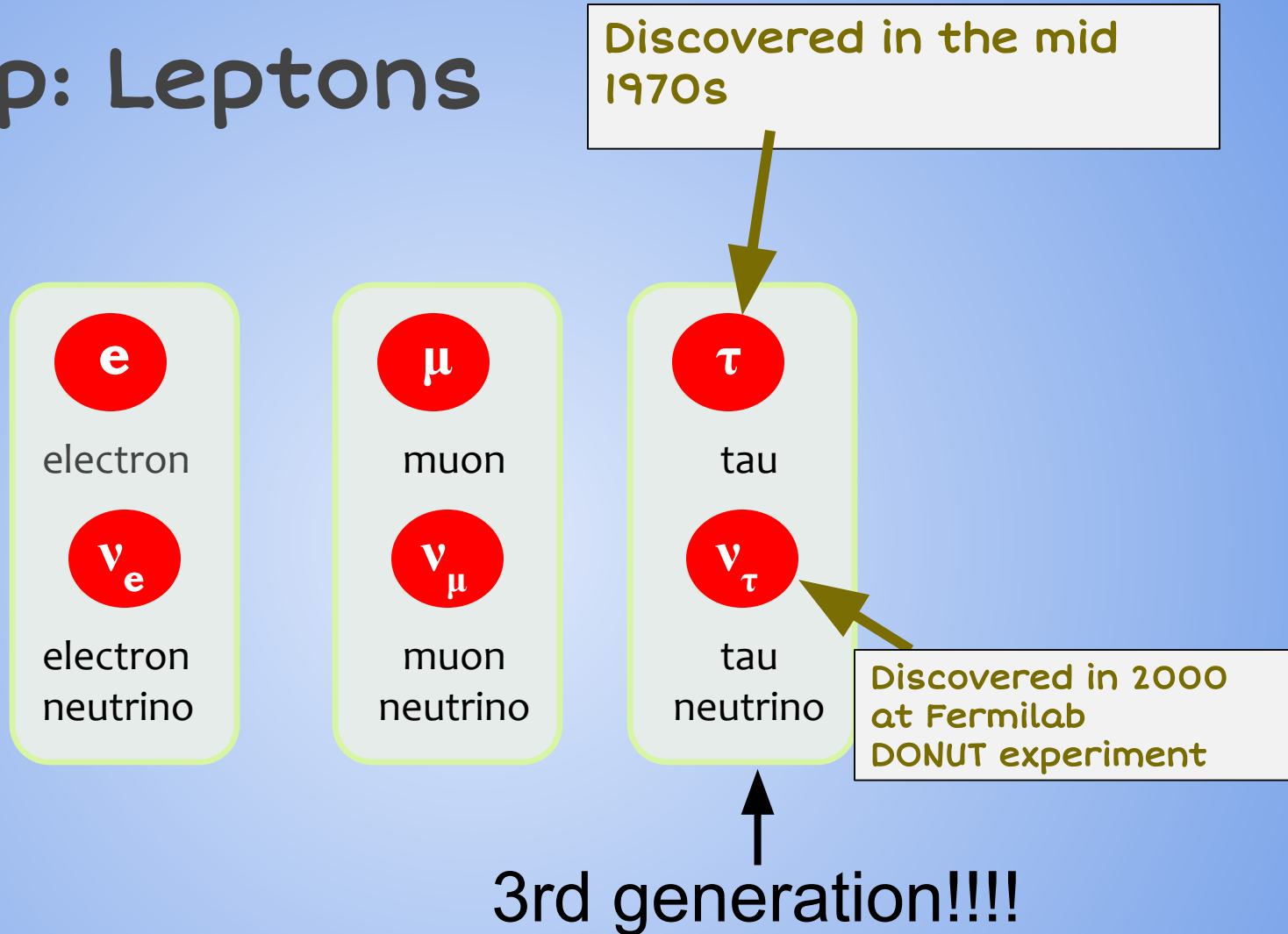
→ measured 3 generations



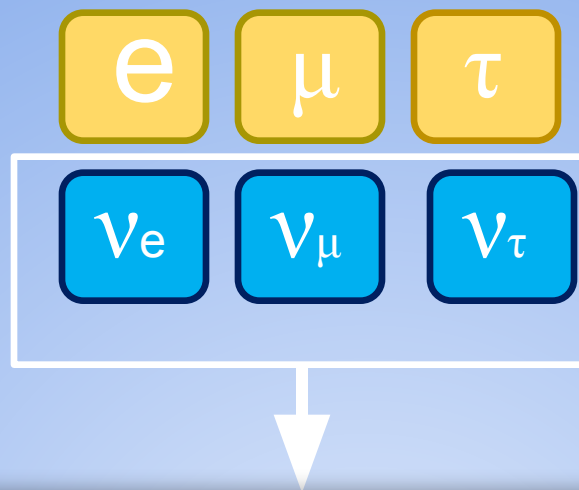
Where f = quarks, leptons, neutrinos.



Recap: Leptons



OK! do we have everything??



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

In fact, the real neutrinos $\nu_{1'}$ $\nu_{2'}$ $\nu_{3'}$ mix to create the flavor neutrinos, ν_e ν_μ ν_τ !

The real neutrinos, $\nu_{1'}$ $\nu_{2'}$ $\nu_{3'}$ have a well defined mass.

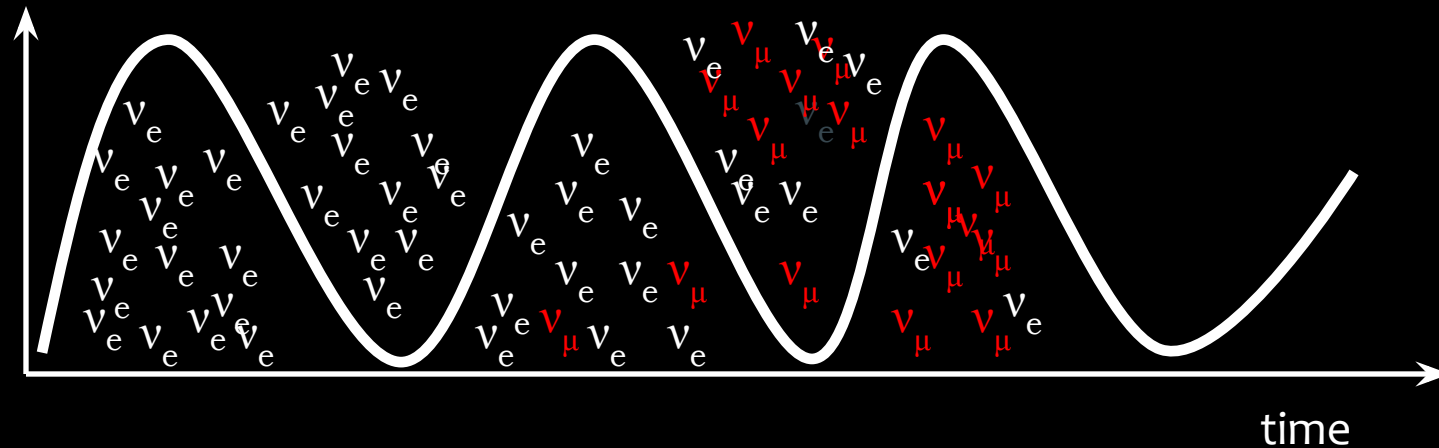
Wait...

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

2-FLAVOR

θ is the mixing angle

$$P_{osc} = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E} \right)$$

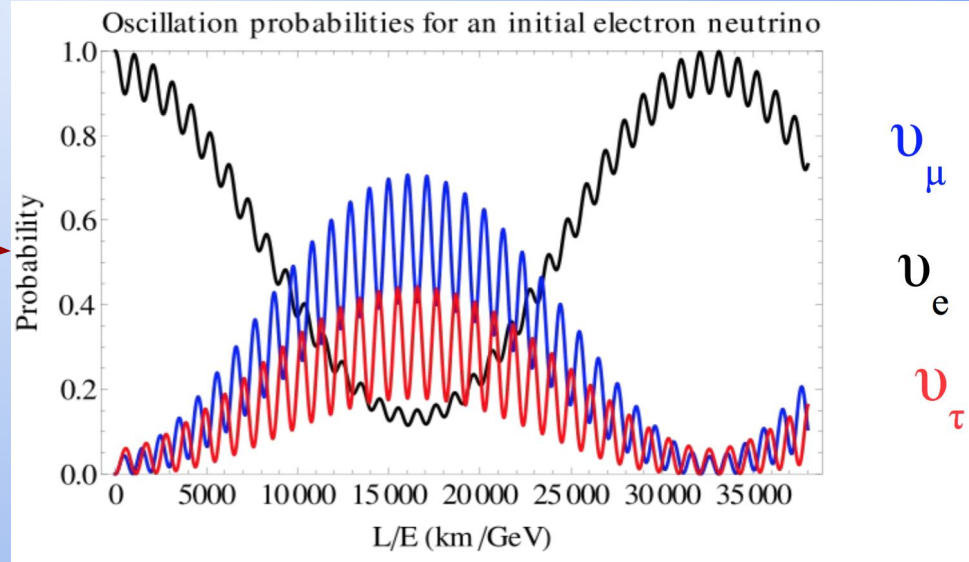
$\Delta m^2 = m_1^2 - m_2^2 (\text{eV}^2)$

L is the distance that neutrino travels (km)

E is neutrino energy (GeV)

Oscillation probability

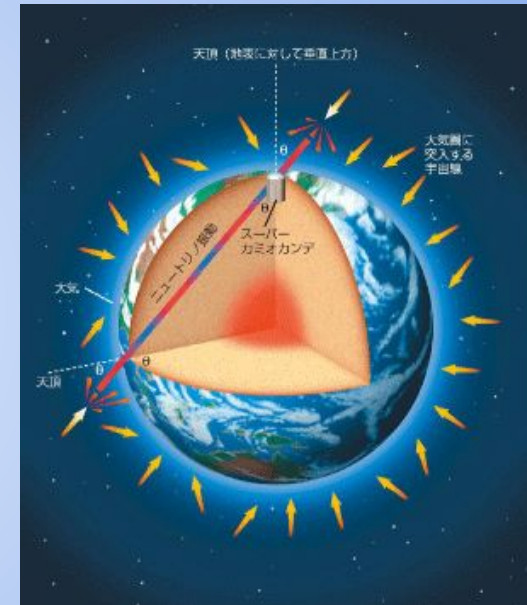
f(L/E)



*Understanding the Behavior
of Neutrinos*

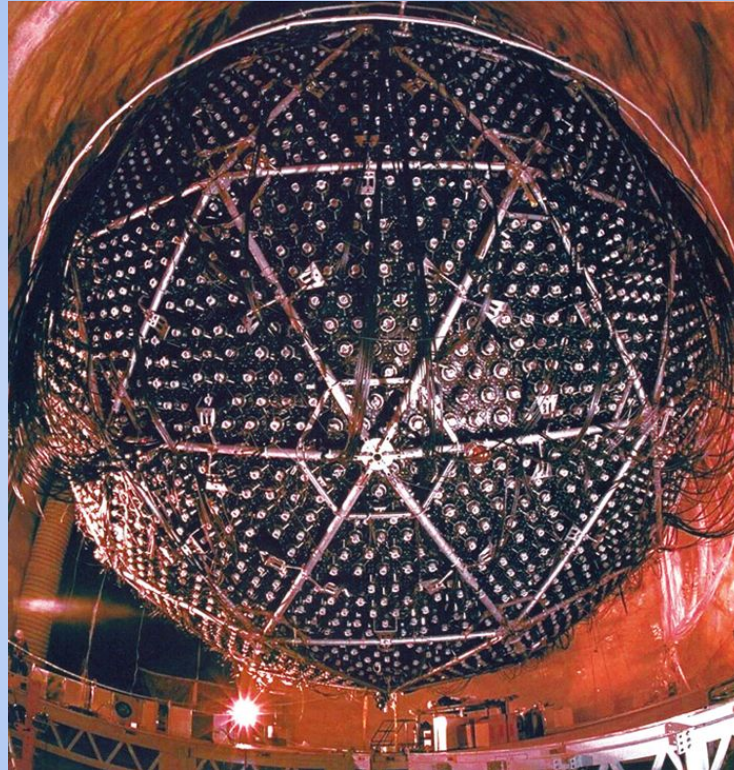
In 1998, Super-Kamiokande (Japan) announced the finding of neutrinos with **non-zero mass**.

Study neutrino oscillations using atmospheric neutrinos.



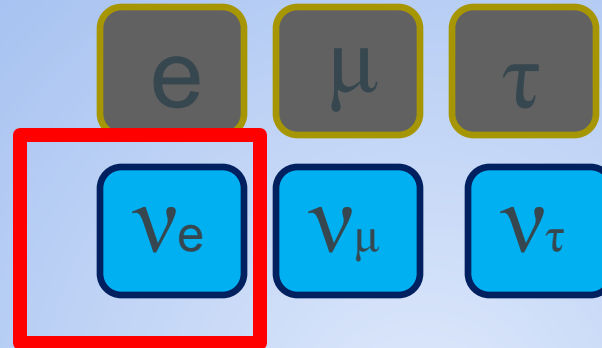
Atmospheric neutrinos produced by the decay of particles resulting from interaction of particles with the Earth's atmosphere.

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

- Reactor

- Accelerator

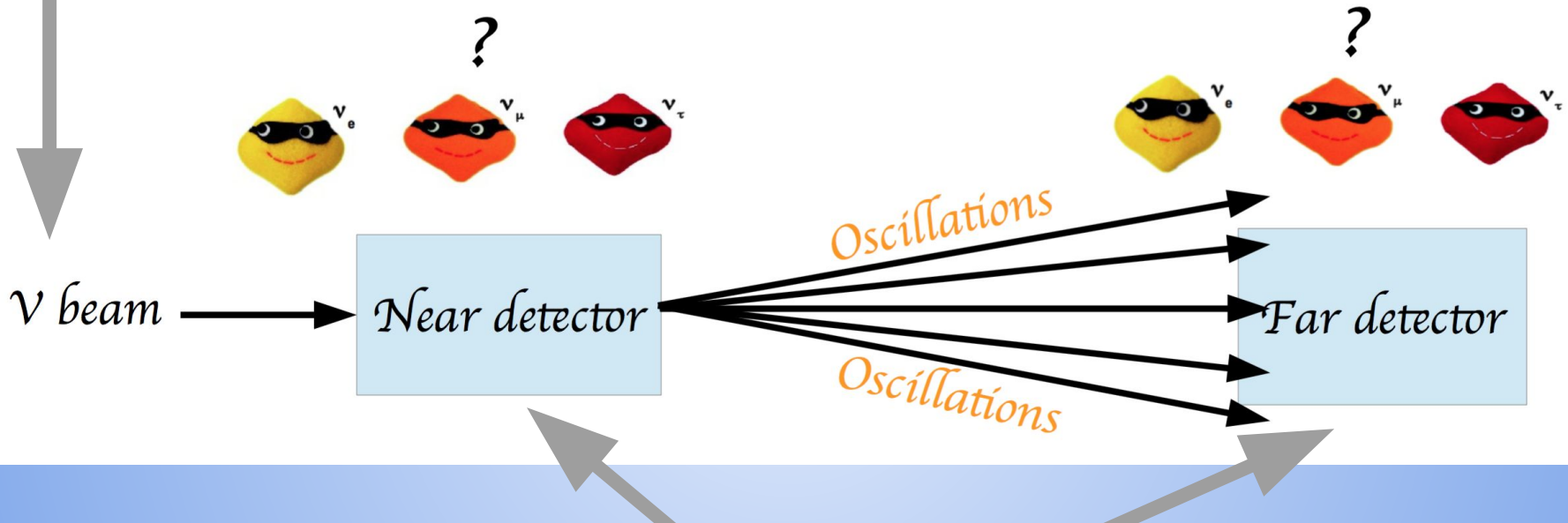
Natural sources

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



Tevatron

LINAC

Booster

Project X
(proposed)

MINOS - NOvA

BooNE

LBNE
(proposed)

Main Injector

Neutrino beams:

- BNB
- NuMI

Future: LBNE

Several Neutrino experiments at Fermilab...



MINERvA



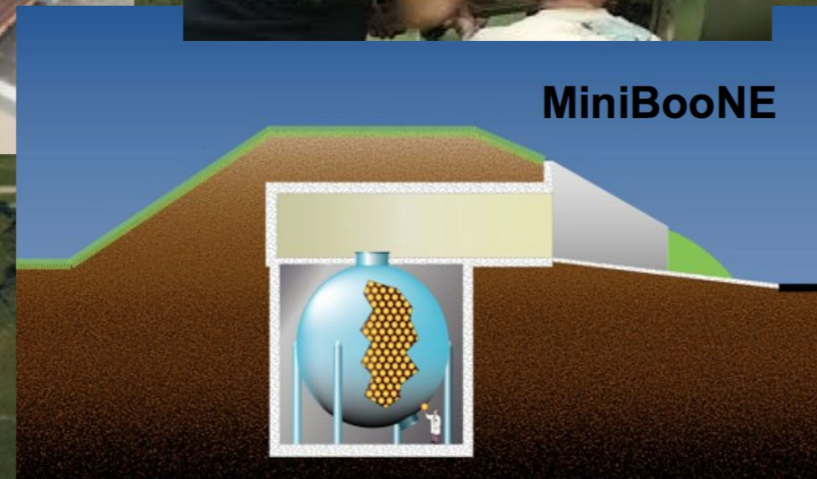
MicroBooNE



LArIAT



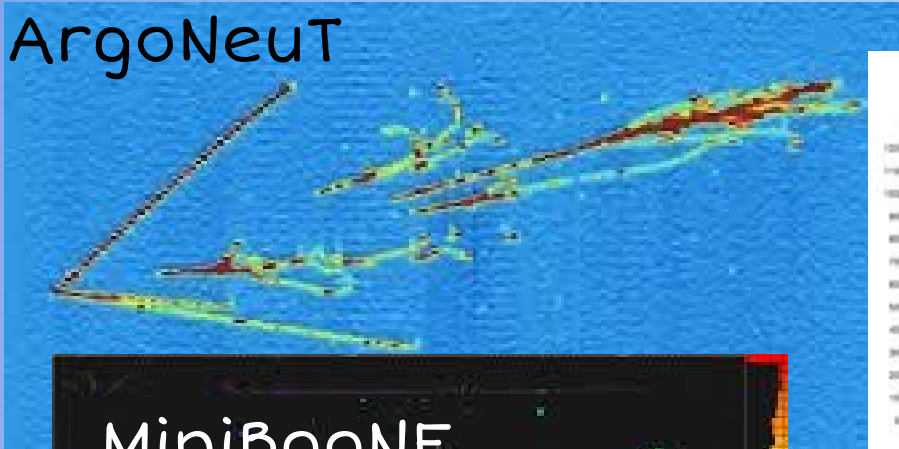
ArgoNeuT



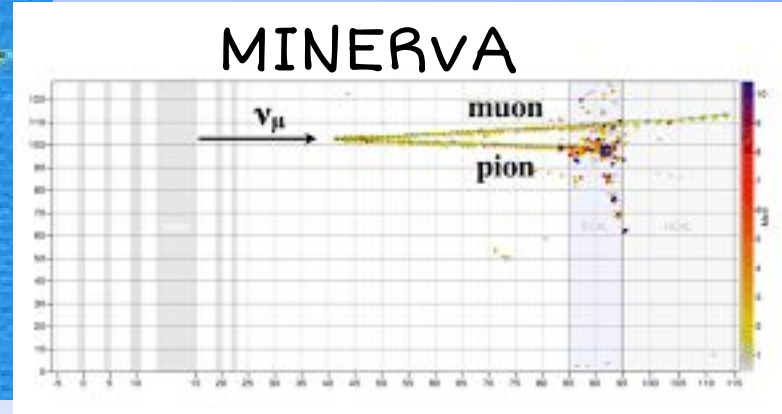
MiniBooNE

What do the detectors see?

ArgoNeuT



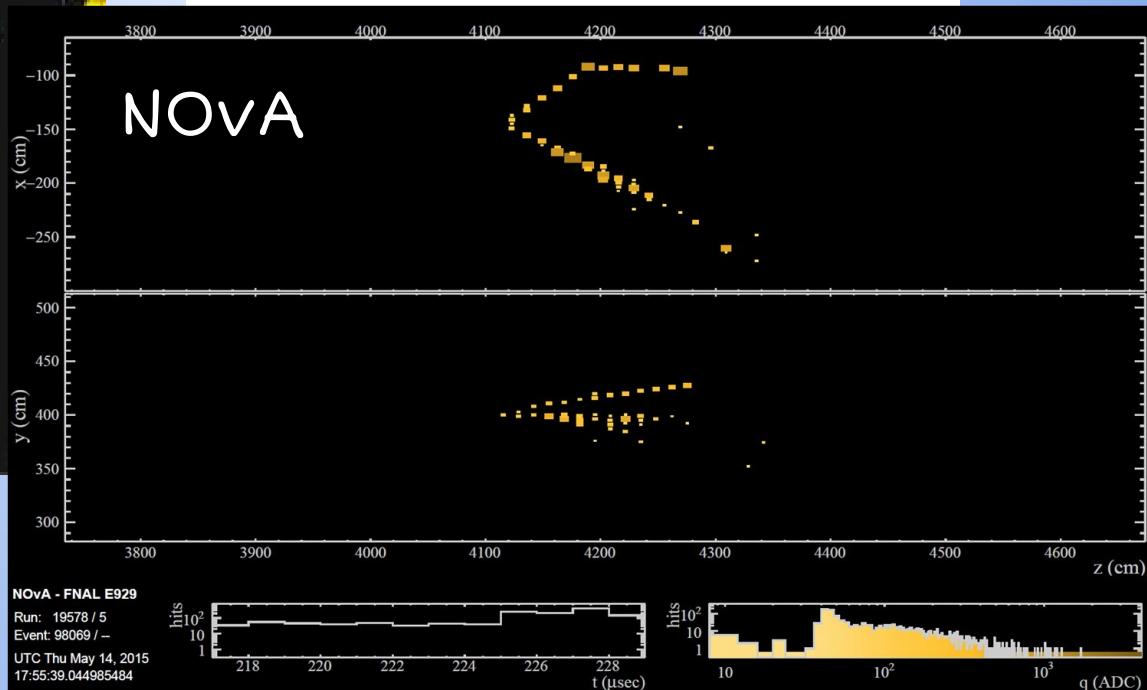
MINERvA



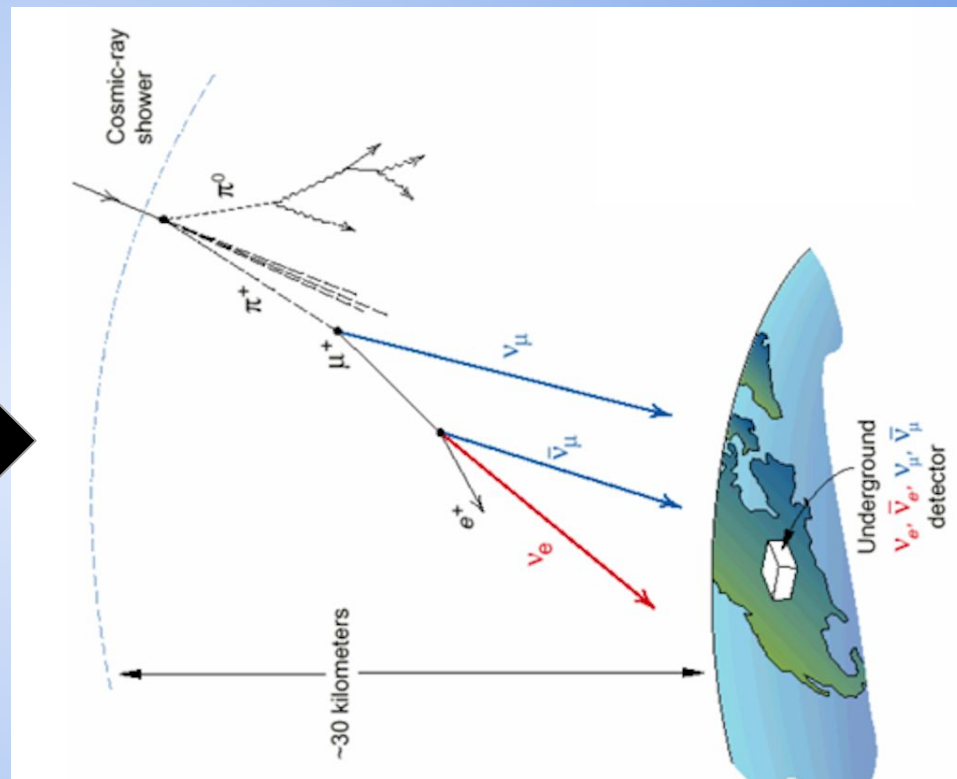
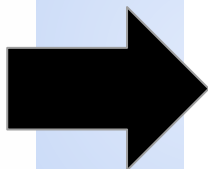
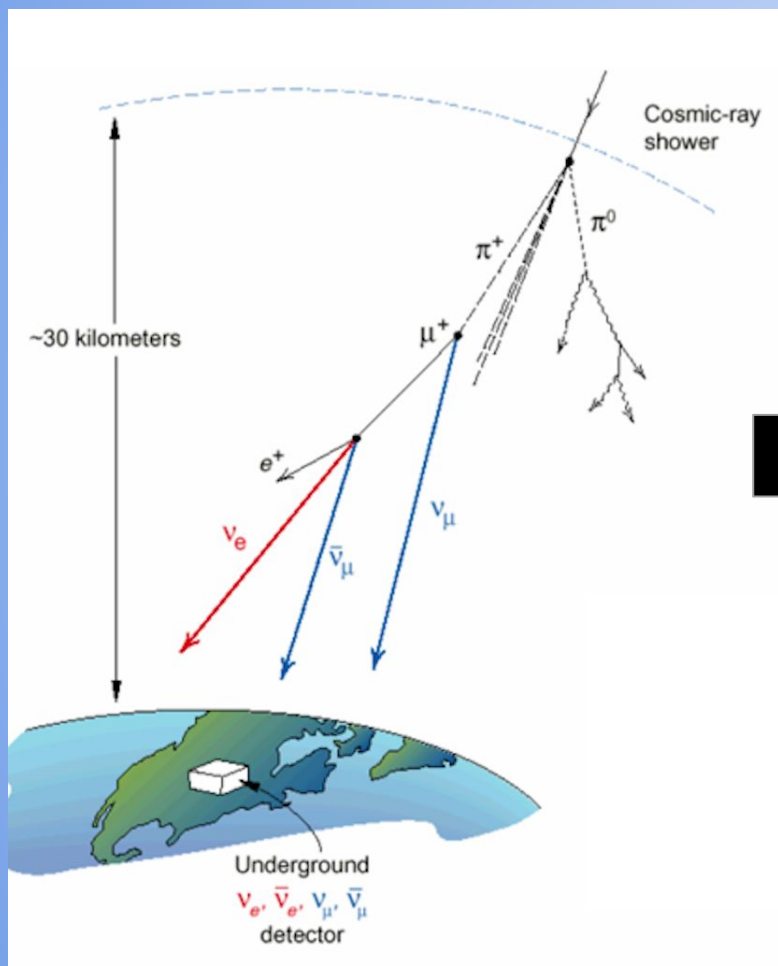
MiniBooNE

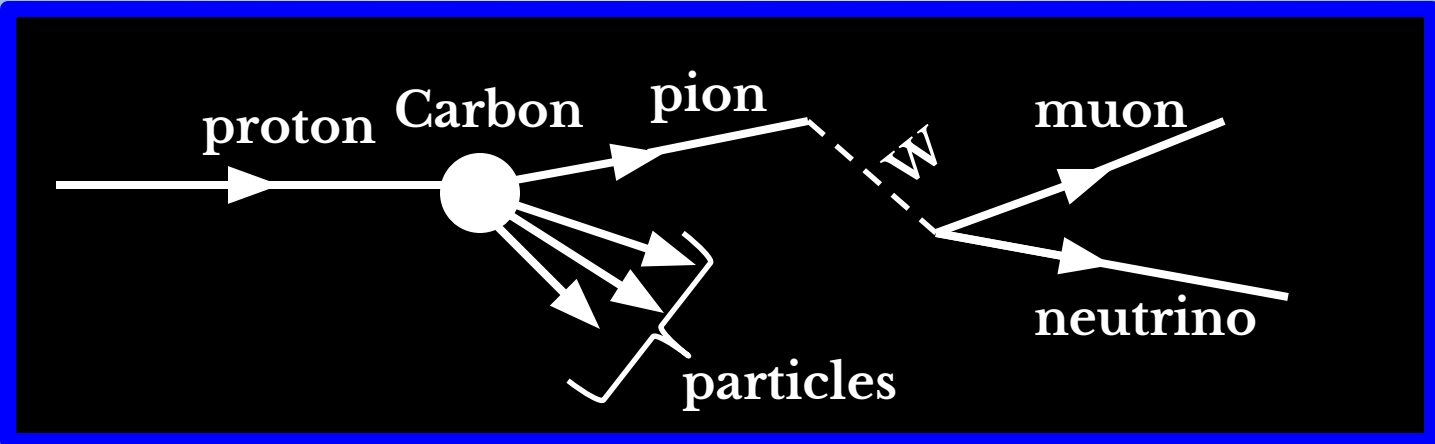
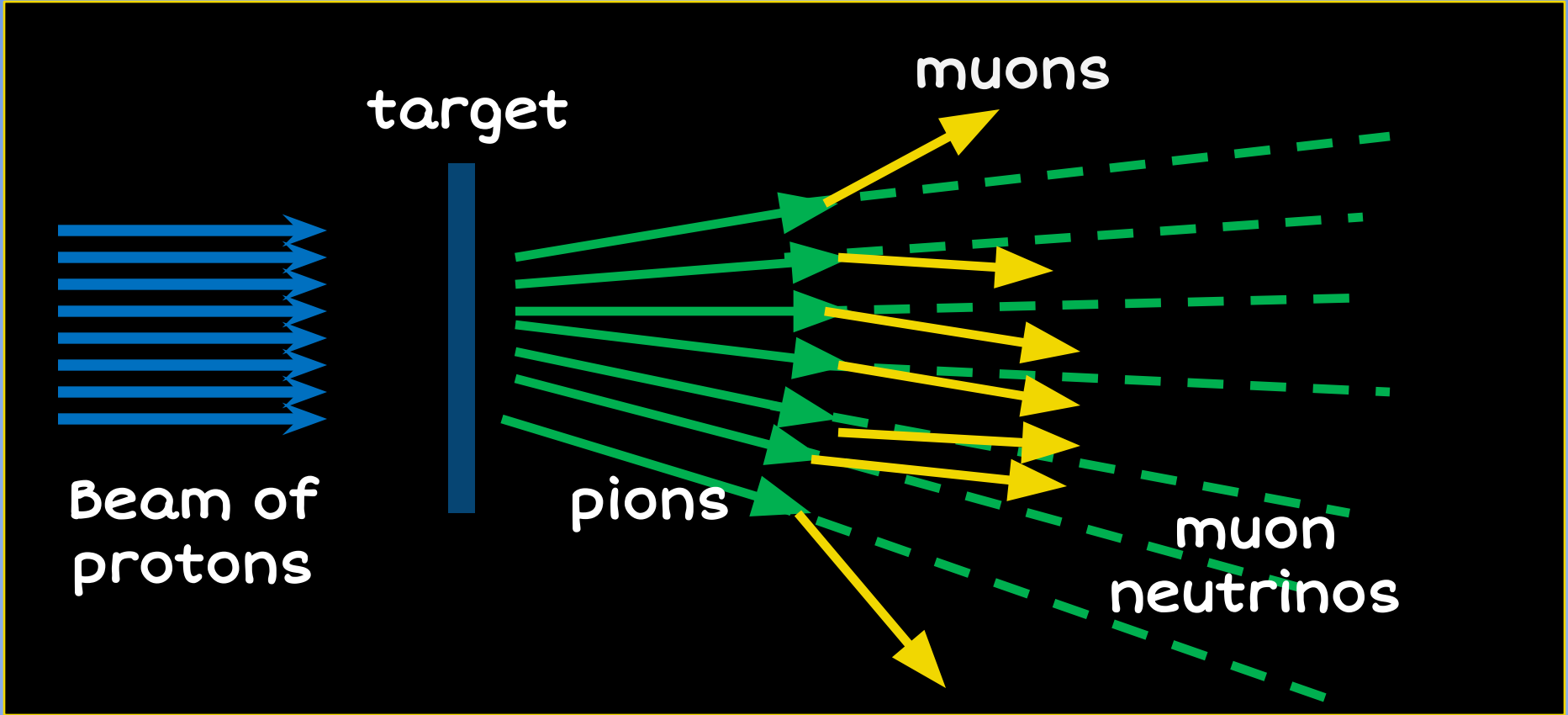


NOvA



We use the same principle of the atmospheric neutrinos

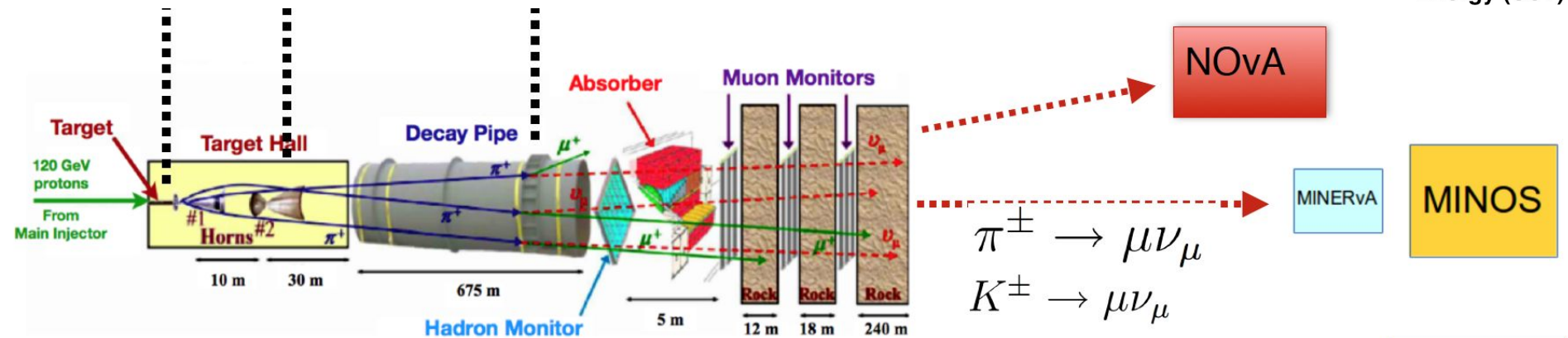
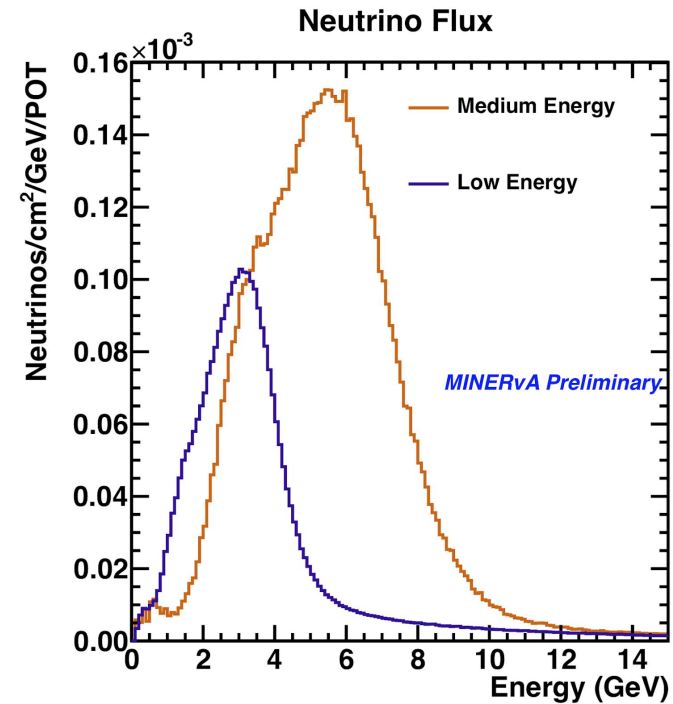


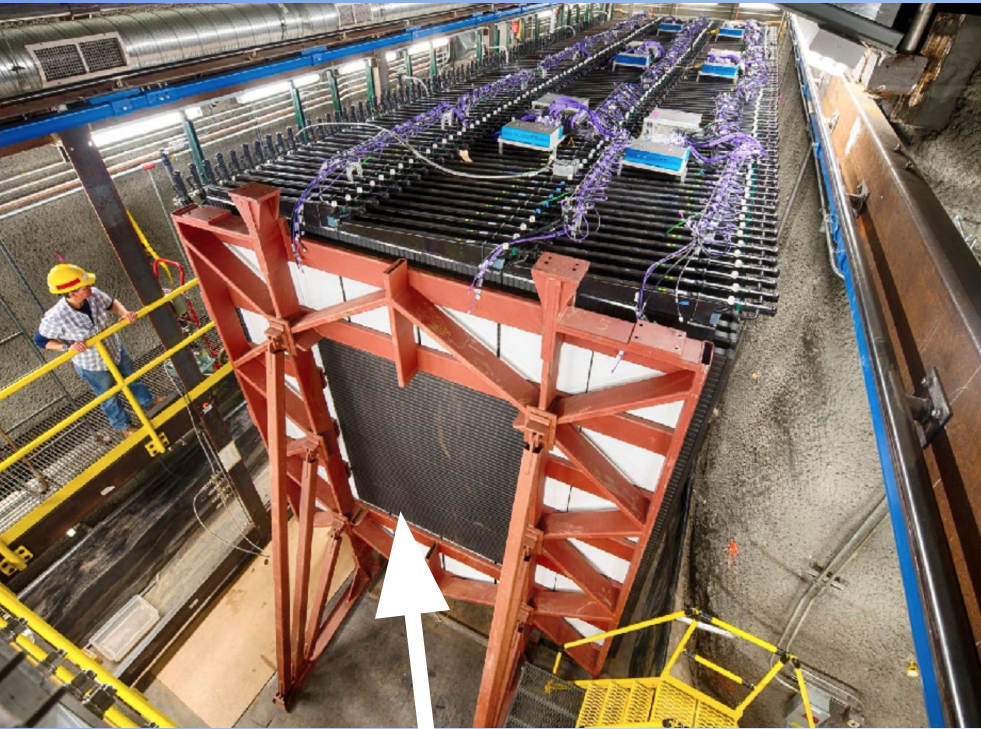


Neutrinos at the Main Injector

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

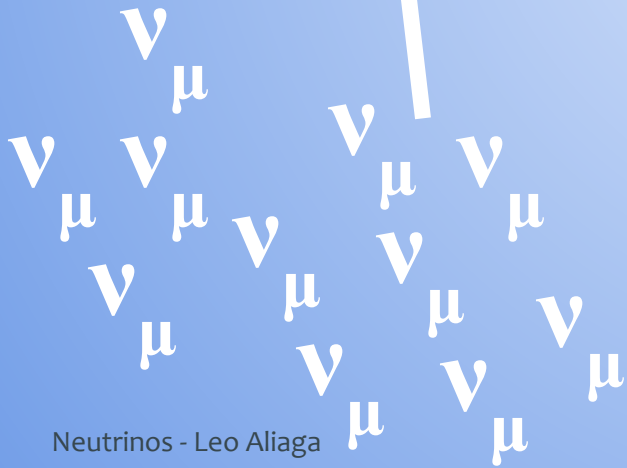
~ same amount of neutrinos





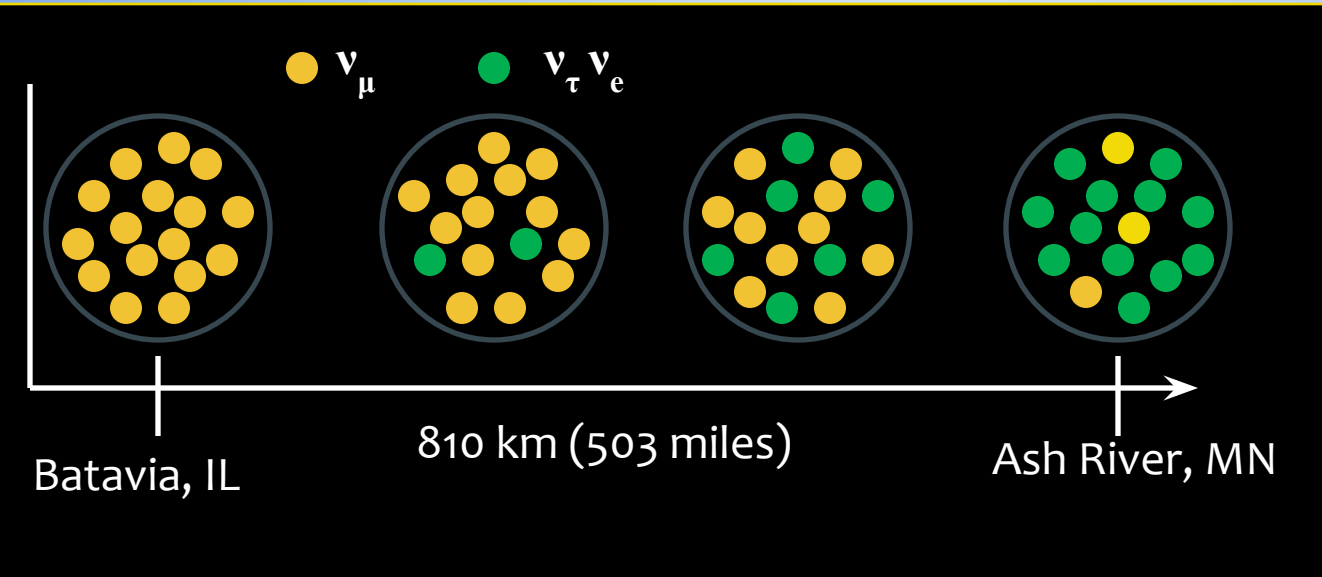
The detector records information about the particles from neutrino interactions.

NOvA Near Detector
100 meters underground

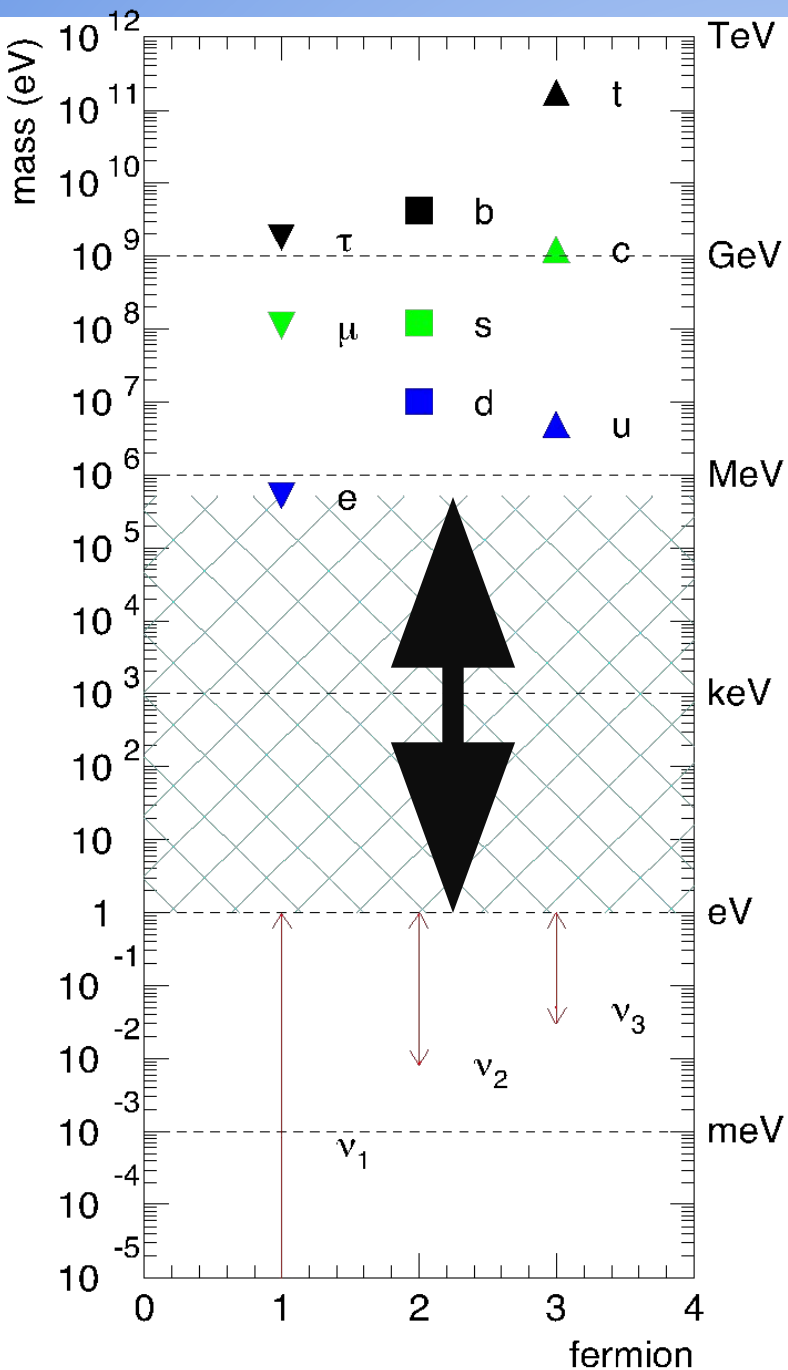




*NOvA Far Detector
on surface*



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



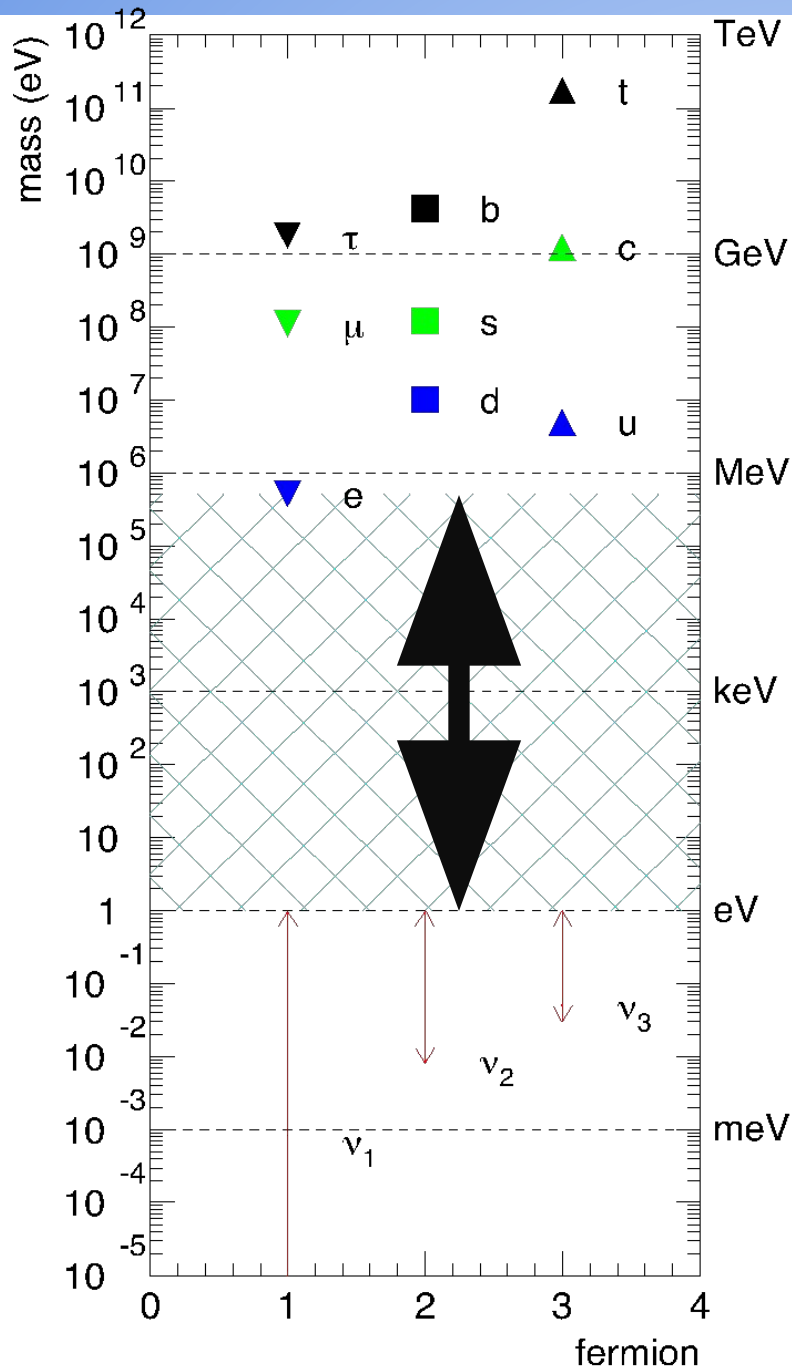
Neutrinos have mass.

BUT.. Why are the neutrinos SO light?

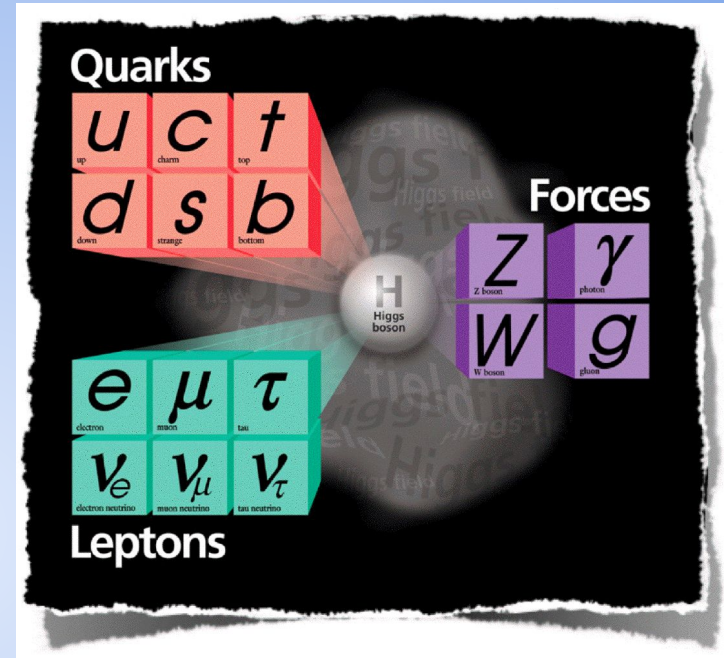
There is a very popular theory floating around.

BUT REALLY...

We do NOT know!



Neutrinos have mass.



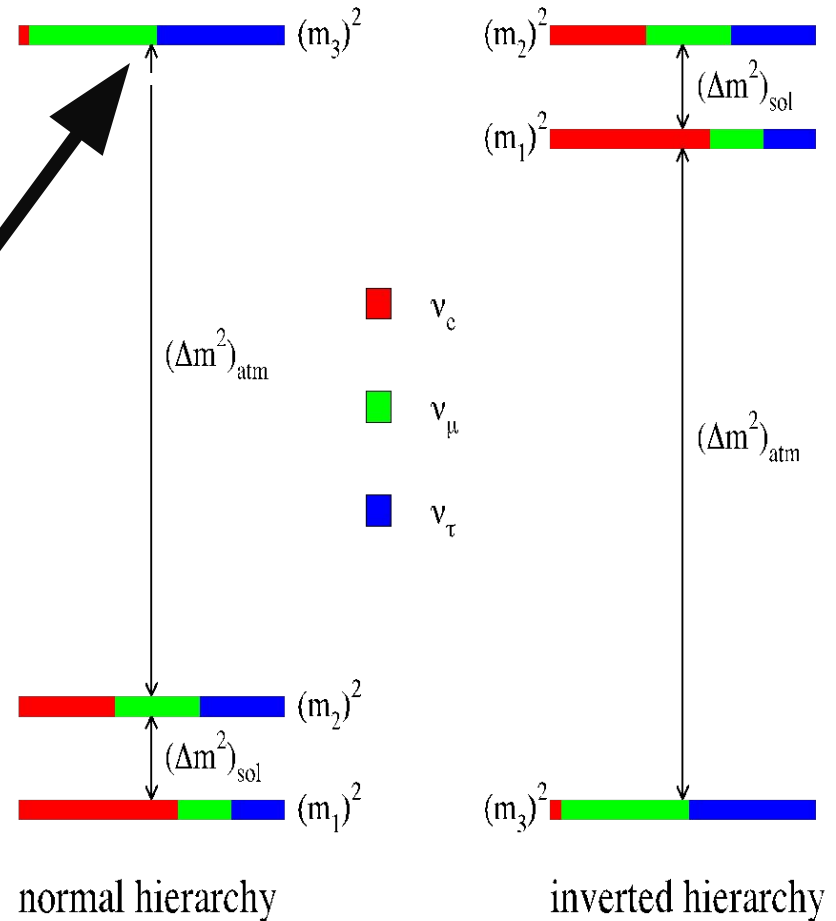
The Standard Model is not complete

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?



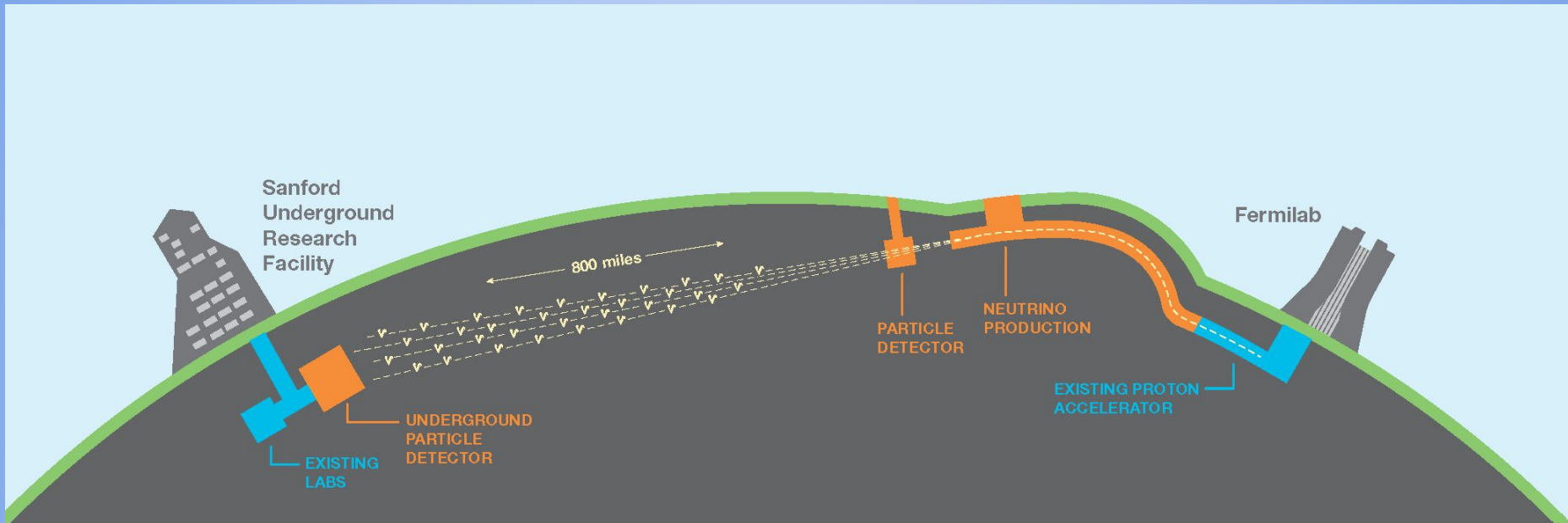
(Olena Shmahalo / Quanta Magazine)

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.

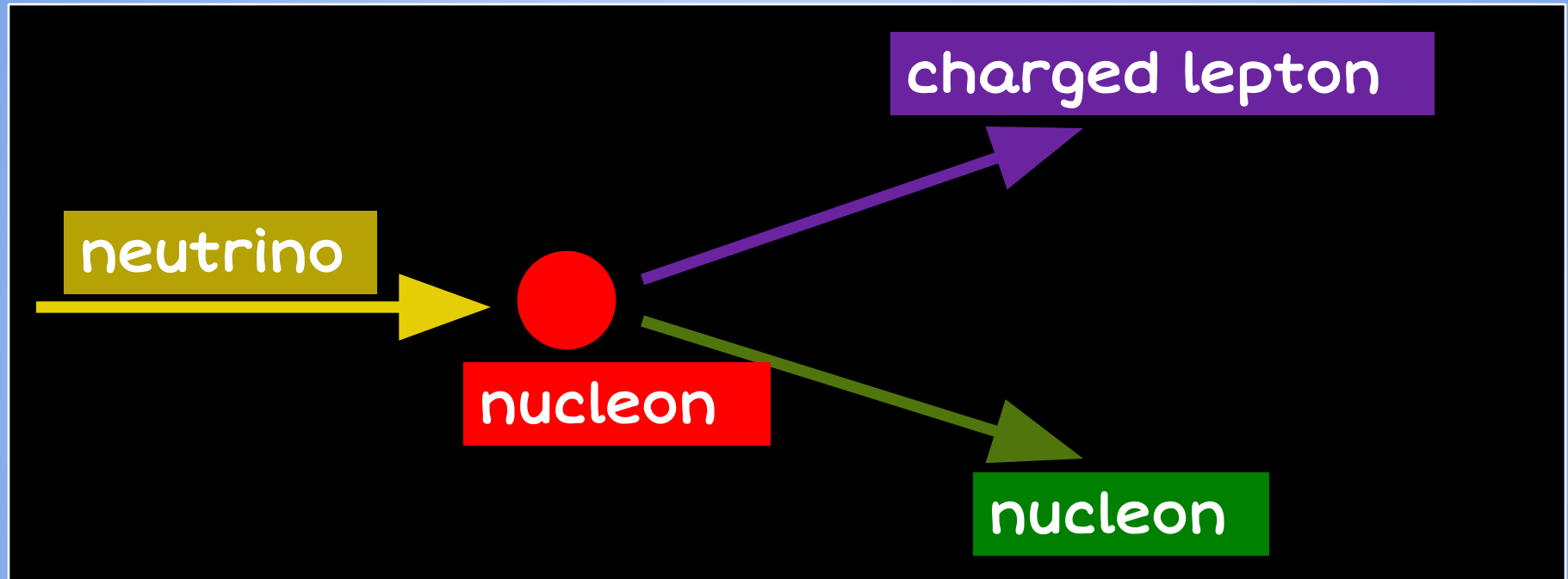
with new technology comes new challenges



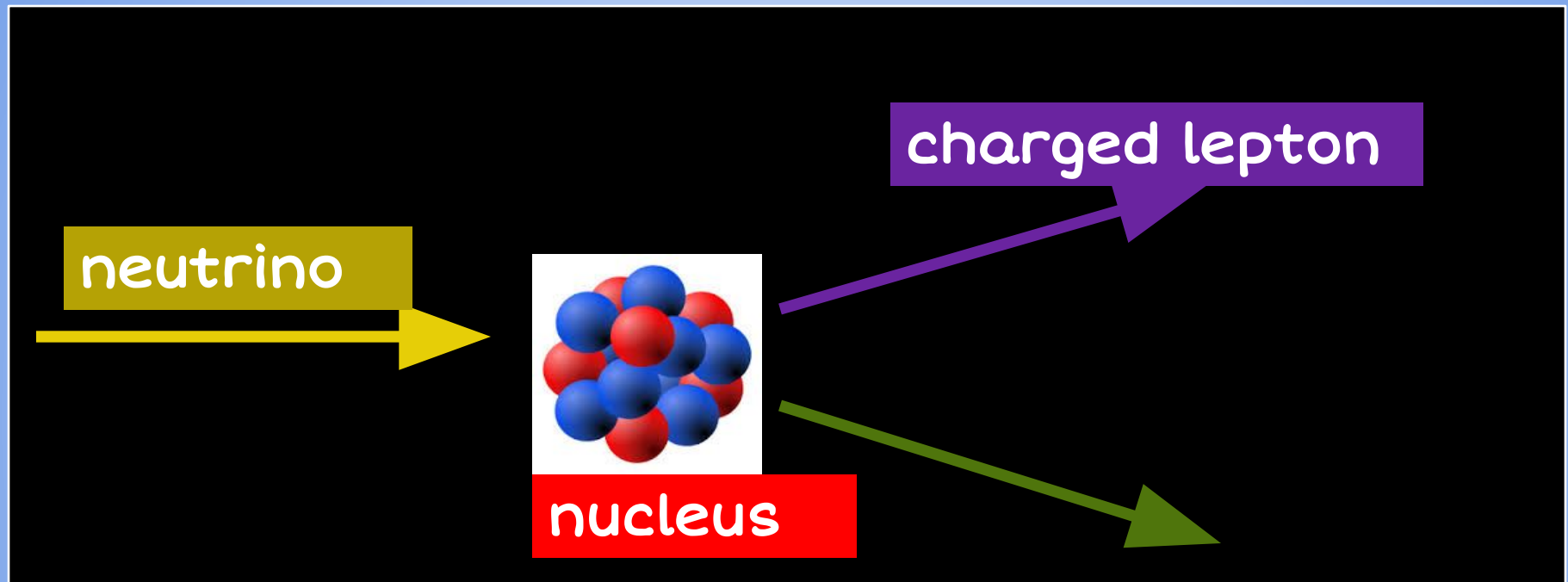
Some challenges:

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

What do neutrino physicists want?



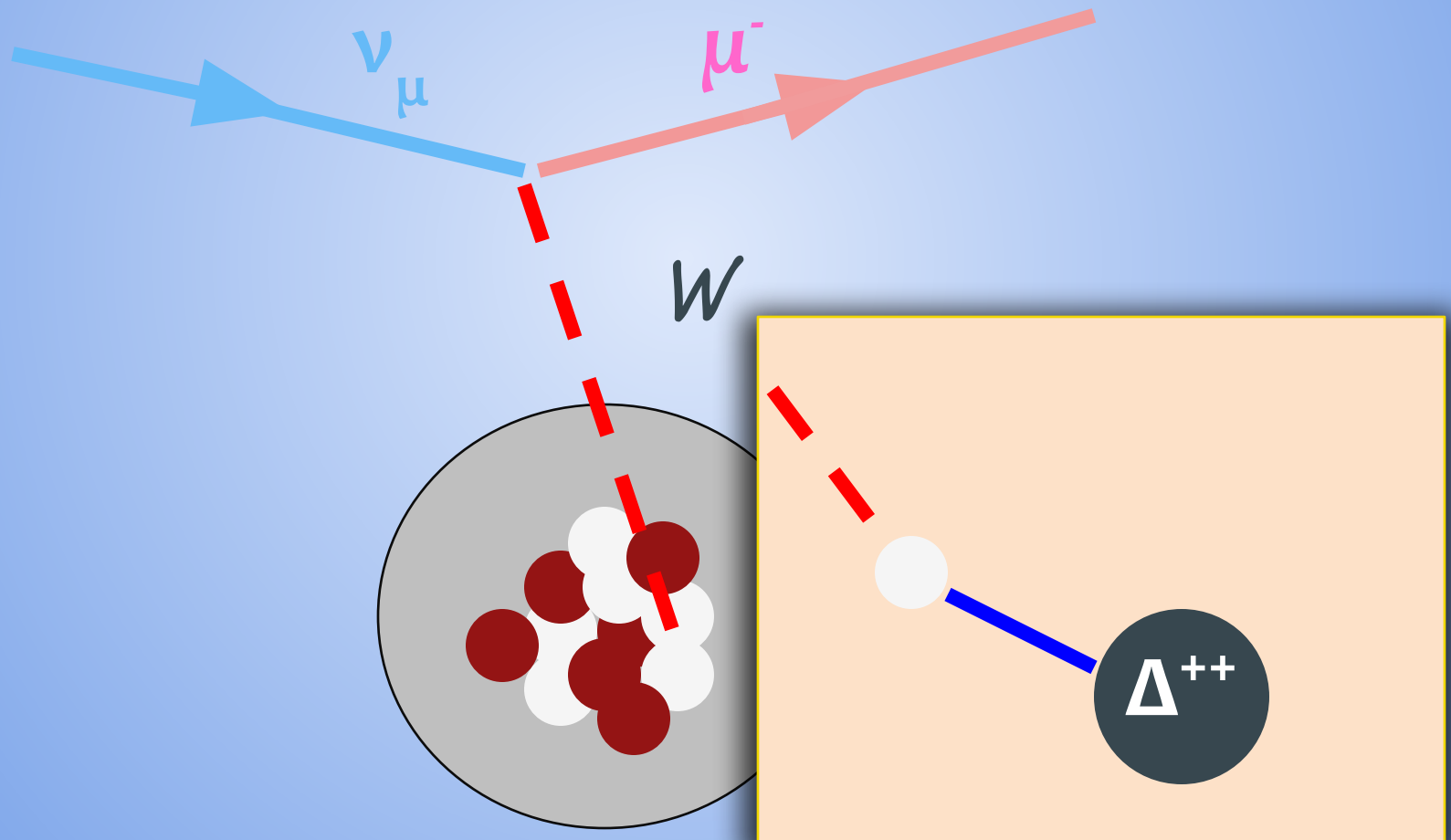
What do neutrino physicists have?



Very difficult to calculate

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

An Example of a Neutrino Interaction



Nobel Prize in 2015 for Discovering Neutrino Oscillations



Takaaki Kajita



**Super -
Kamiokande**

Arthur B. McDonald



SNO

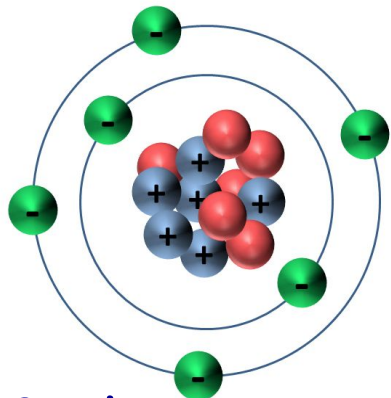
Thanks for your attention...

any question?

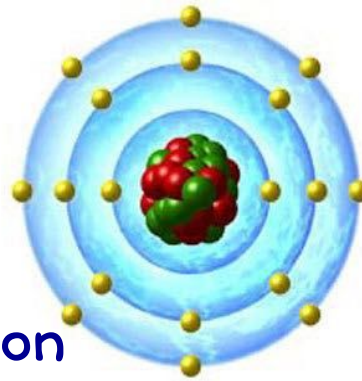
Backup

The rate of neutrino interactions is
SO small.

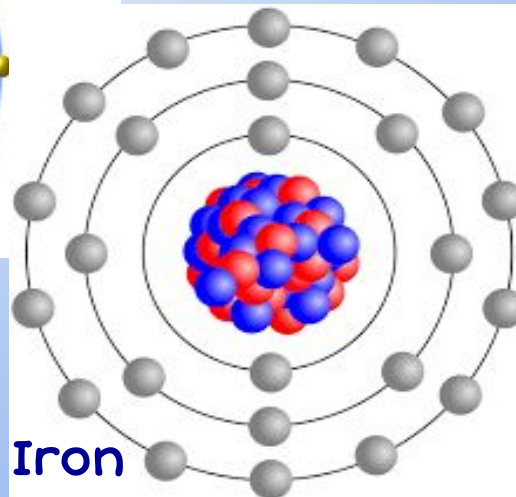
Therefore, large detectors composed of
heavy atoms are needed.



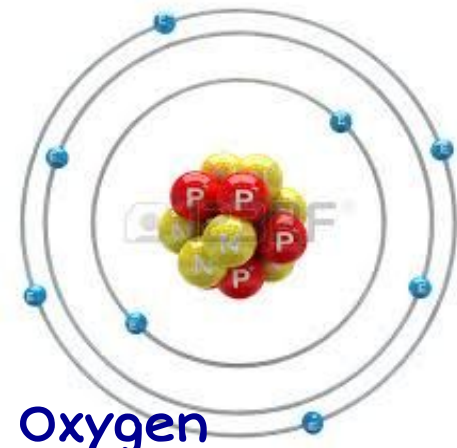
Carbon



Argon

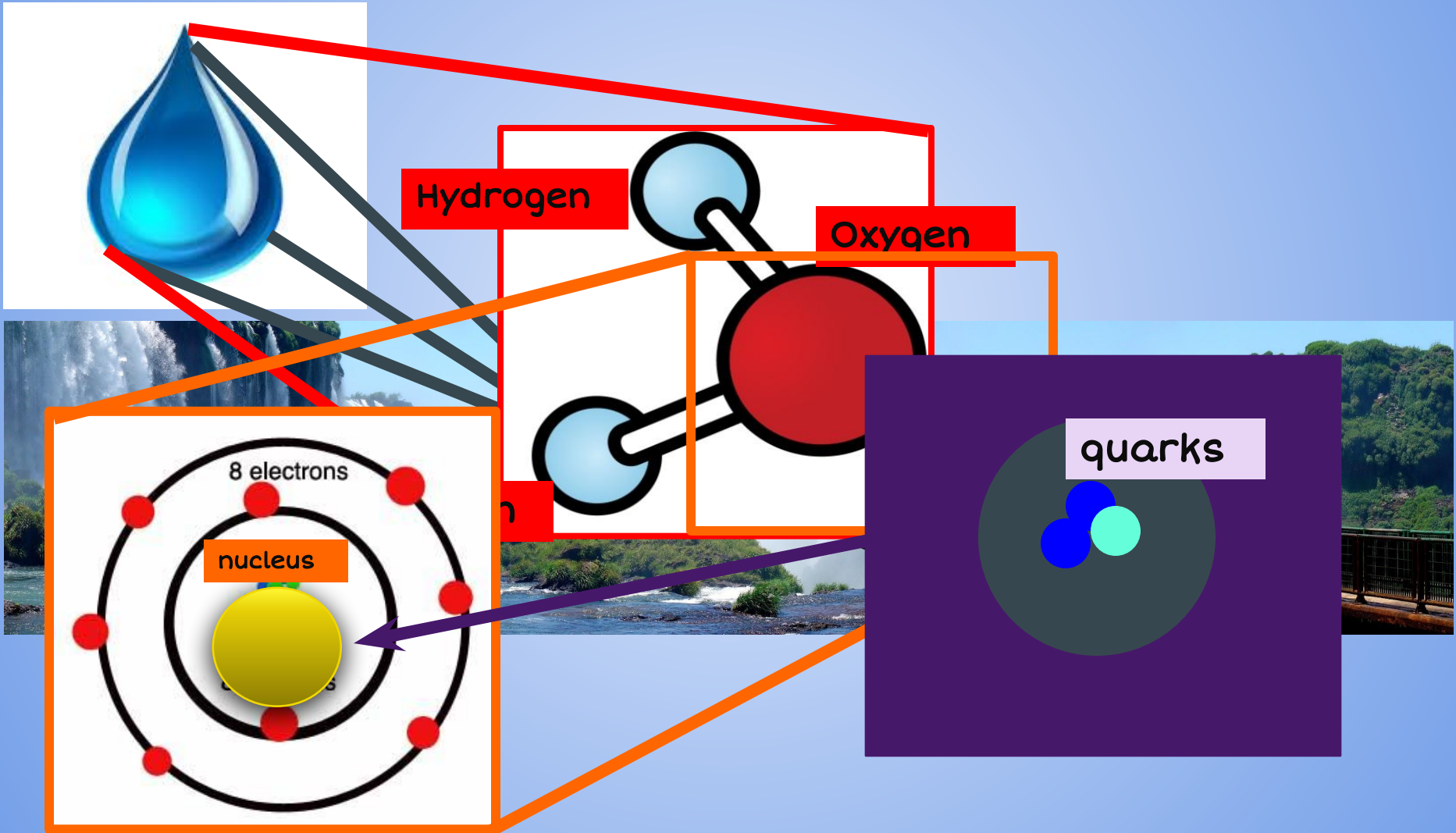


Iron



Oxygen

Everything is Composed of Particles!



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

→ *Electromagnetic.*

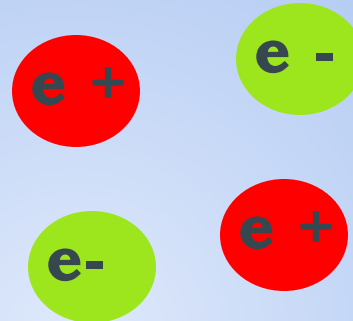
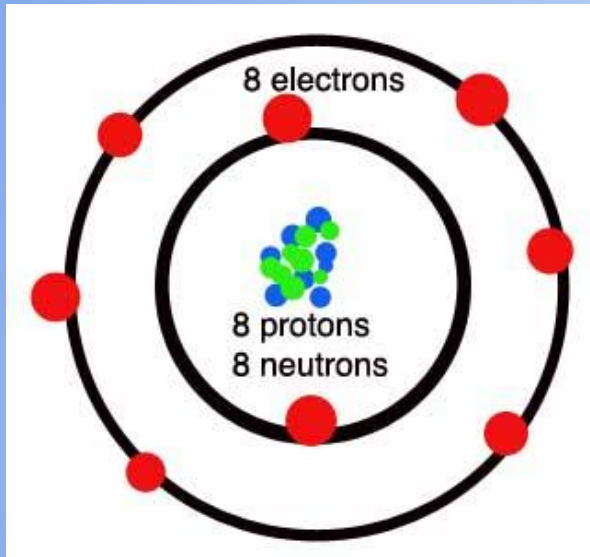
→ *Strong.*

→ *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

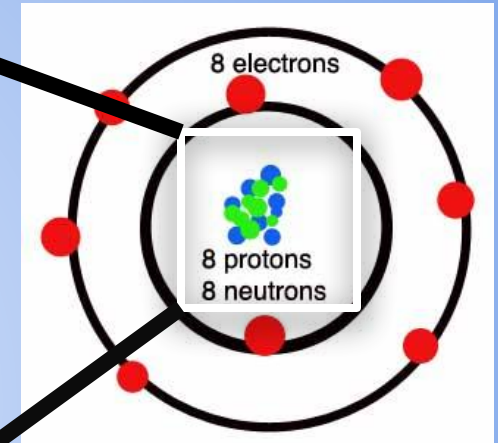
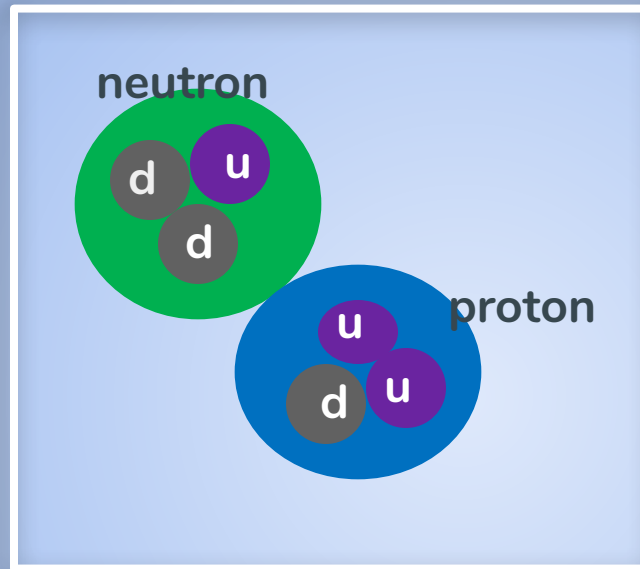
Acts upon electrically charged particles

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 0.000000000000000001 meters

What is the energy of 1 MeV?

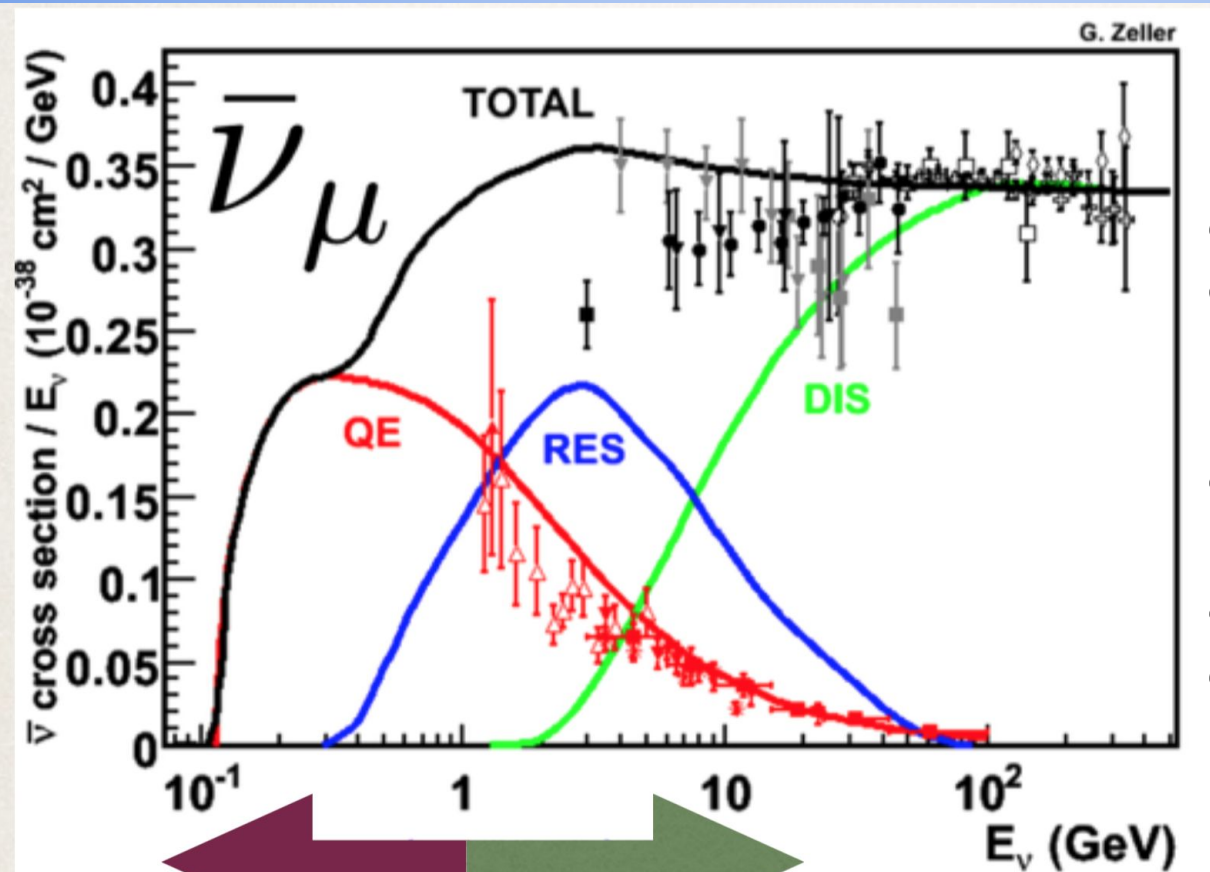
The energy of a flying mosquito is
1,000,000,000,000 electron volts,



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.

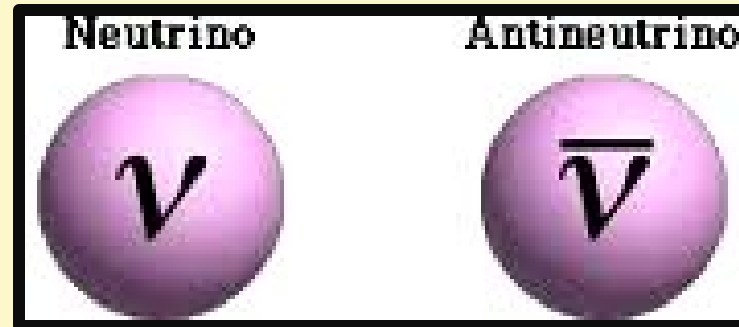
But in general all other Fermilab neutrino experiment also have cross-section studies.

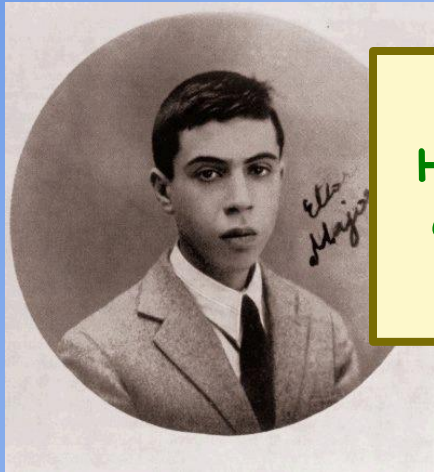
BooNE experiments, MINERvA, DUNE, NOvA, MINOS
T2K

Another mystery

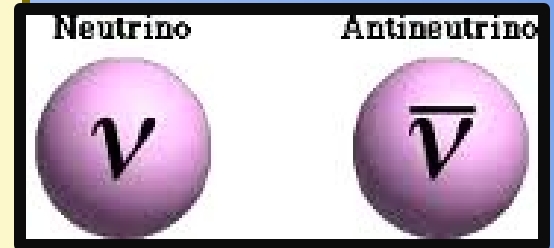


After Fermi published his beta-decay theory, Ettore Majorana derived a theory to suggest that the neutrino may be its own anti-particle. Means that the neutrino and anti-neutrino are the same.

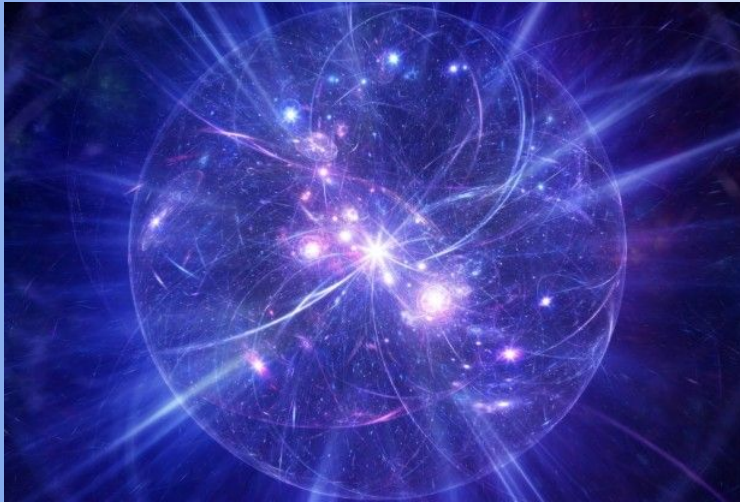




Remember THIS Guy!
He predicted that the neutrino
and anti-neutrino are exactly
the same.



This is important because ...



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

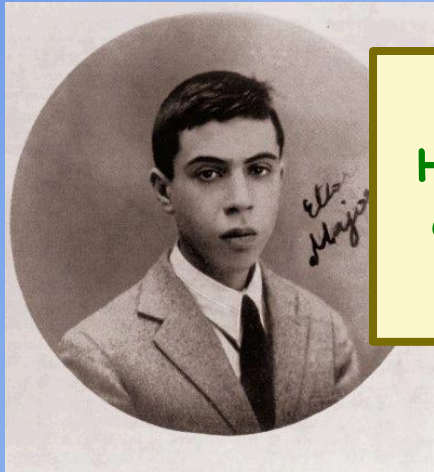
A background image for a slide about antimatter, featuring a fiery, orange and red cosmic scene with the text 'Big bang' and 'ANTIMATTER' overlaid.

Big bang

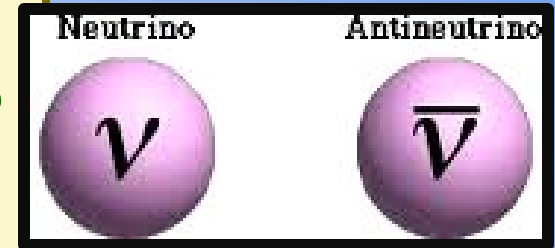
ANTIMATTER

- But due to unknown reasons matter overtook antimatter and what's left is mostly matter!
- This is called baryon asymmetry.
- This is one among the greatest unsolved problems in physics.

rathighway.ezthemes.com



Remember THIS Guy!
He predicted that the neutrino
and anti-neutrino are exactly
the same.



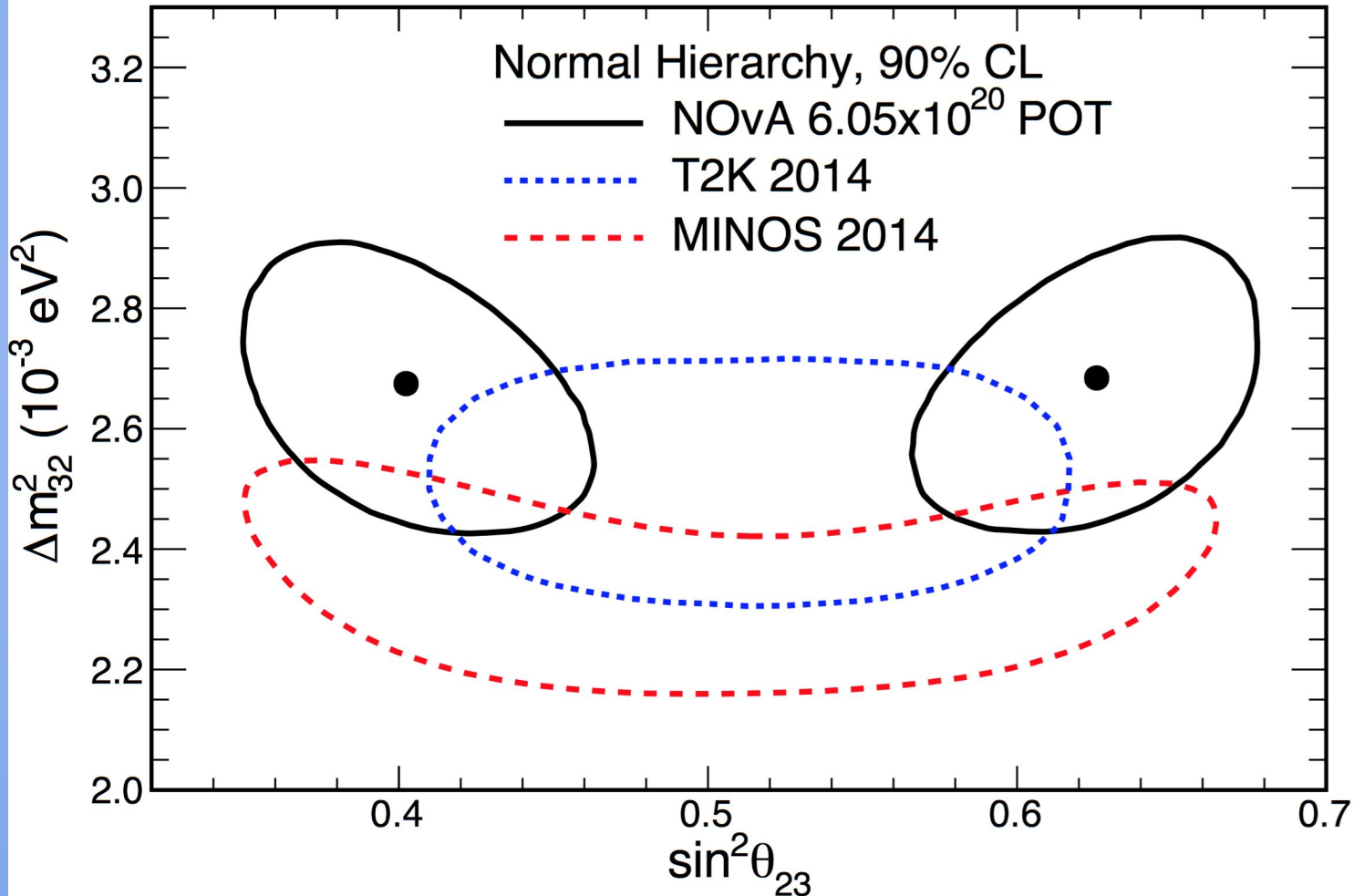
Making precision measurements of the
properties of neutrinos bring us a step
closer to uncovering the biggest mysteries
of the universe!

**We are in a new ERA of
Neutrino Detectors**

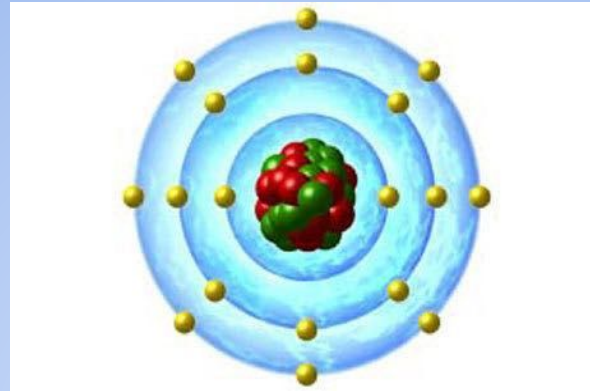
This measurements is happening right now...

published Jan 20, 2017

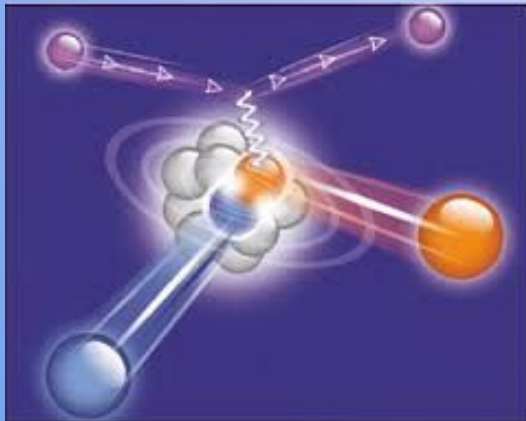
arXiv:1701.05891



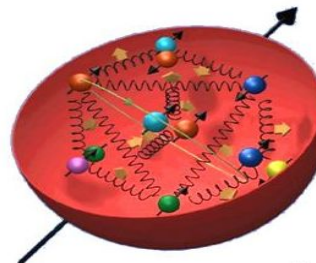
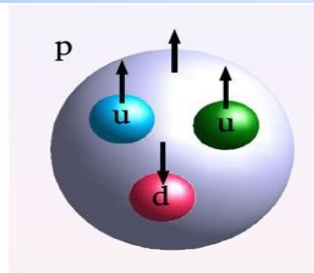
Why is it so complicated?



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



nucleon bound with another nucleon

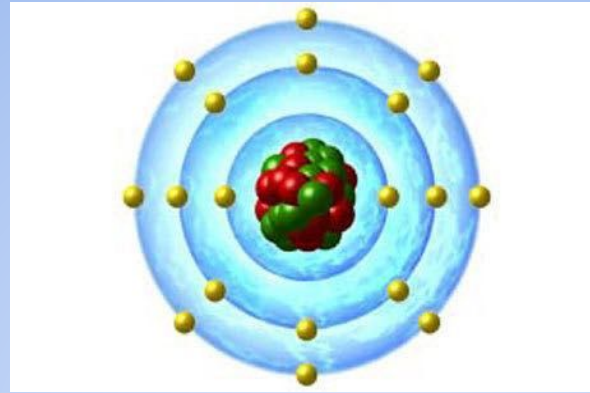


The inside of
looks like
3 valence quarks, and gluons holding

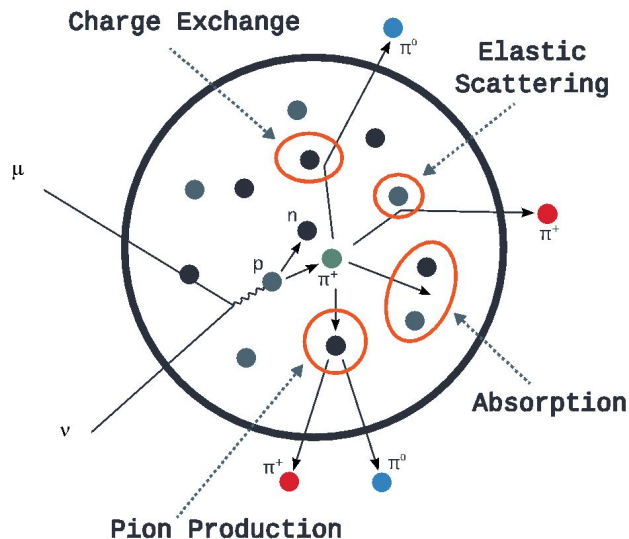
Also, there is a pion cloud surrounding the nucleus.



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.