Introduction to All the Small Stuff that Makes Up Matter

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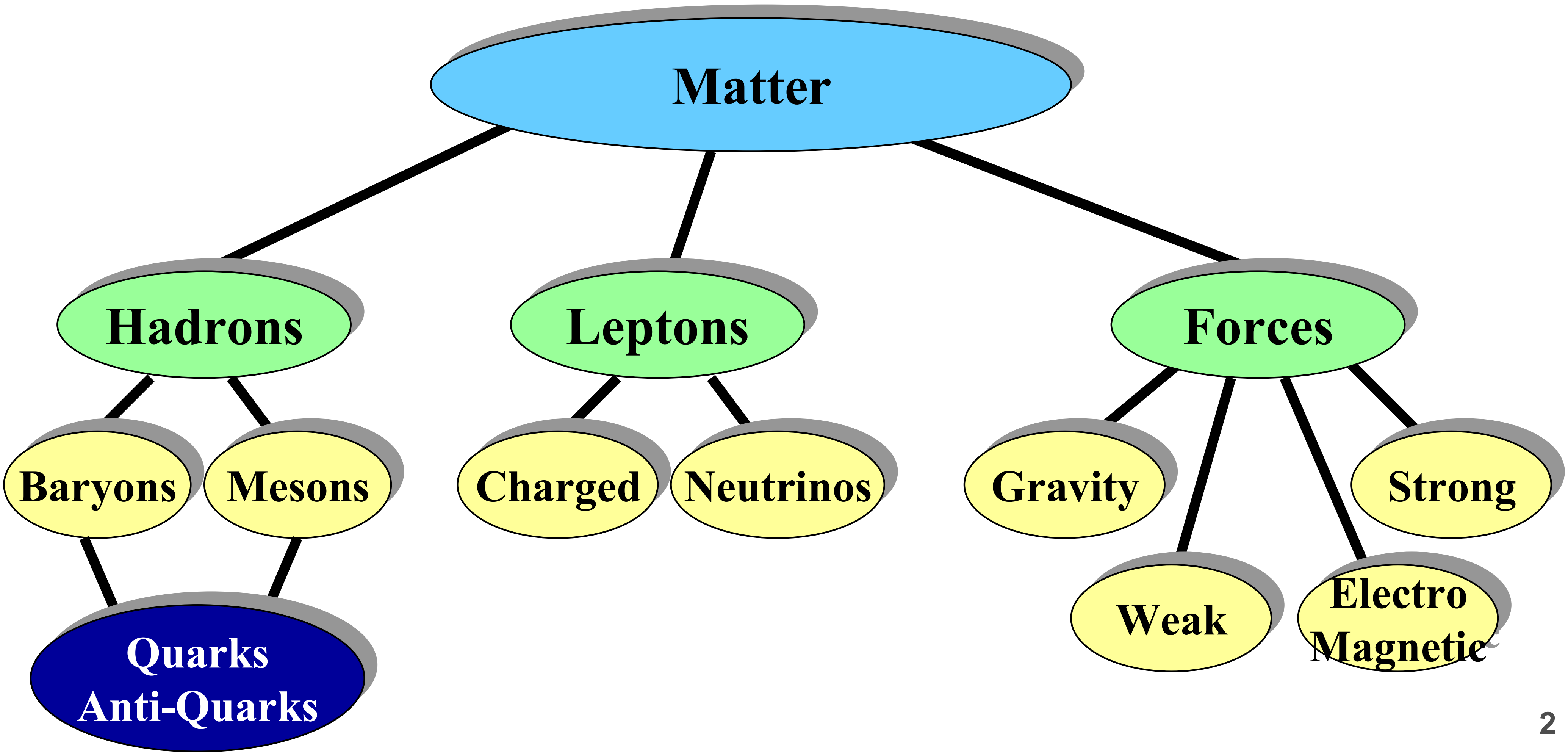
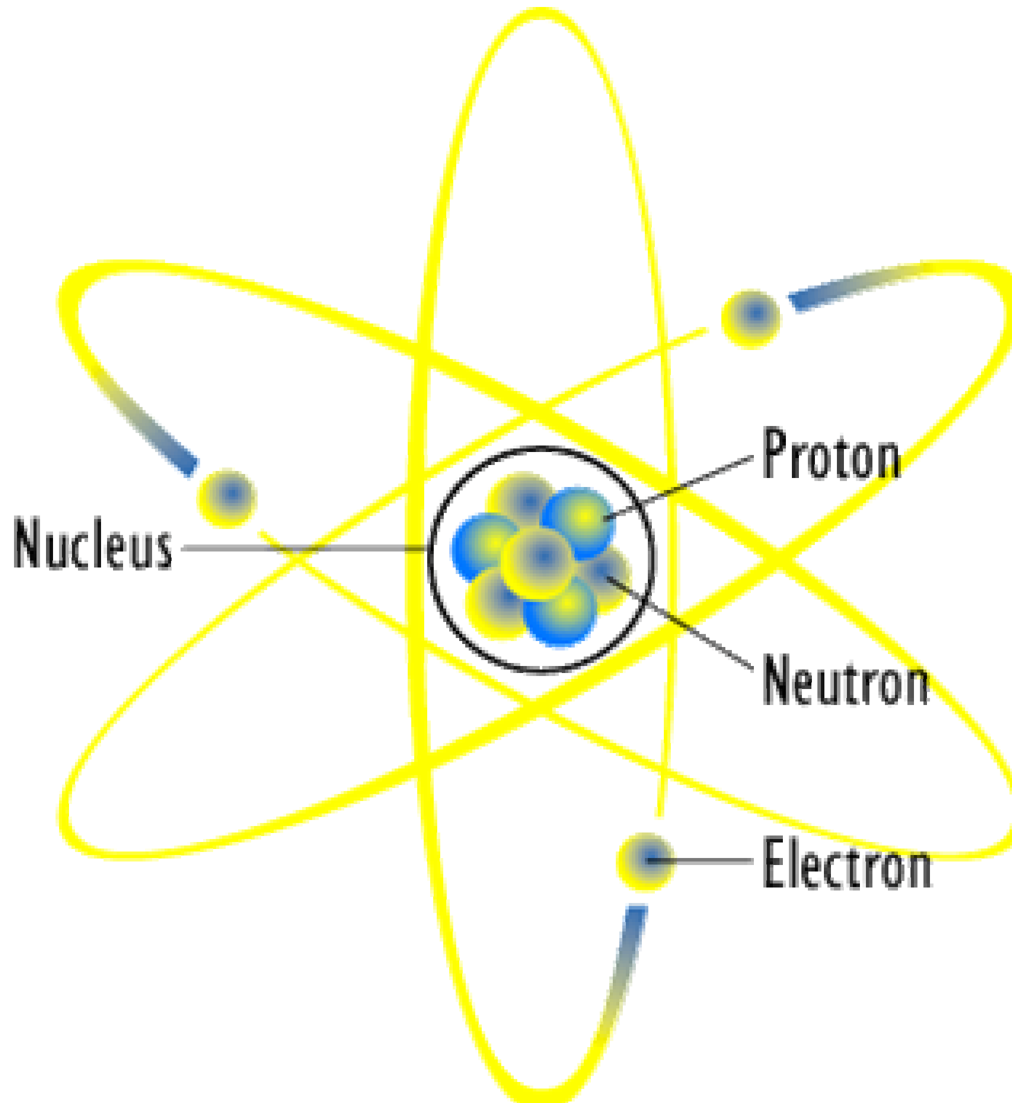
What IS Matter ?

- Matter is all the “stuff” around you!



Every atom holds mysteries

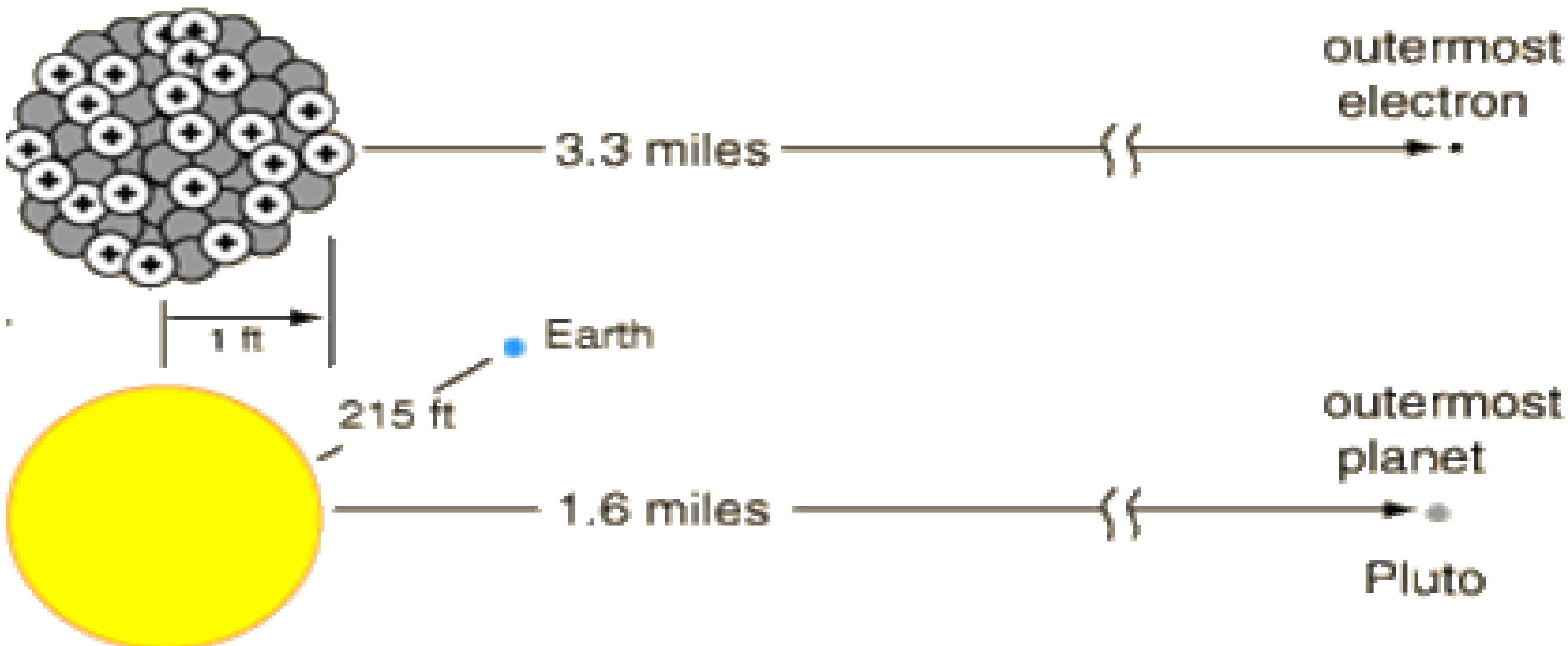
Inside of every atom is a nucleus.
Nuclear Physicists investigate these nuclei to help shape the modern world.



Nuclei are unimaginably small!

If Nucleus, Sun were ~1 foot

http://hyperphysics.phy-astr.gsu.edu/hbase/nuclear/nucuni.html#c2



Atoms and Space

- Approximately what fraction of the volume of an atom does the nucleus consume?

  Assume that the nucleus and the atom can be approximated via spheres with the radii given below.

  Use the following data:

- The radius of the nucleus is ~ 5×10^{-15} [m].
- The electrons orbits at a radius of ~ 2×10^{-10} [m]
- Ignore the electrons size, as it is unimportant.
- The volume of a sphere is $(4/3)\pi R^3$.

Answer…

a) First find the volume of the entire atom

Volume = $(4/3)*\pi*(2\text{x}10^{-10})^3 = 3.4 \text{ x } 10^{-29}$ [m^3]

b) Now find the volume which contains the nucleus.

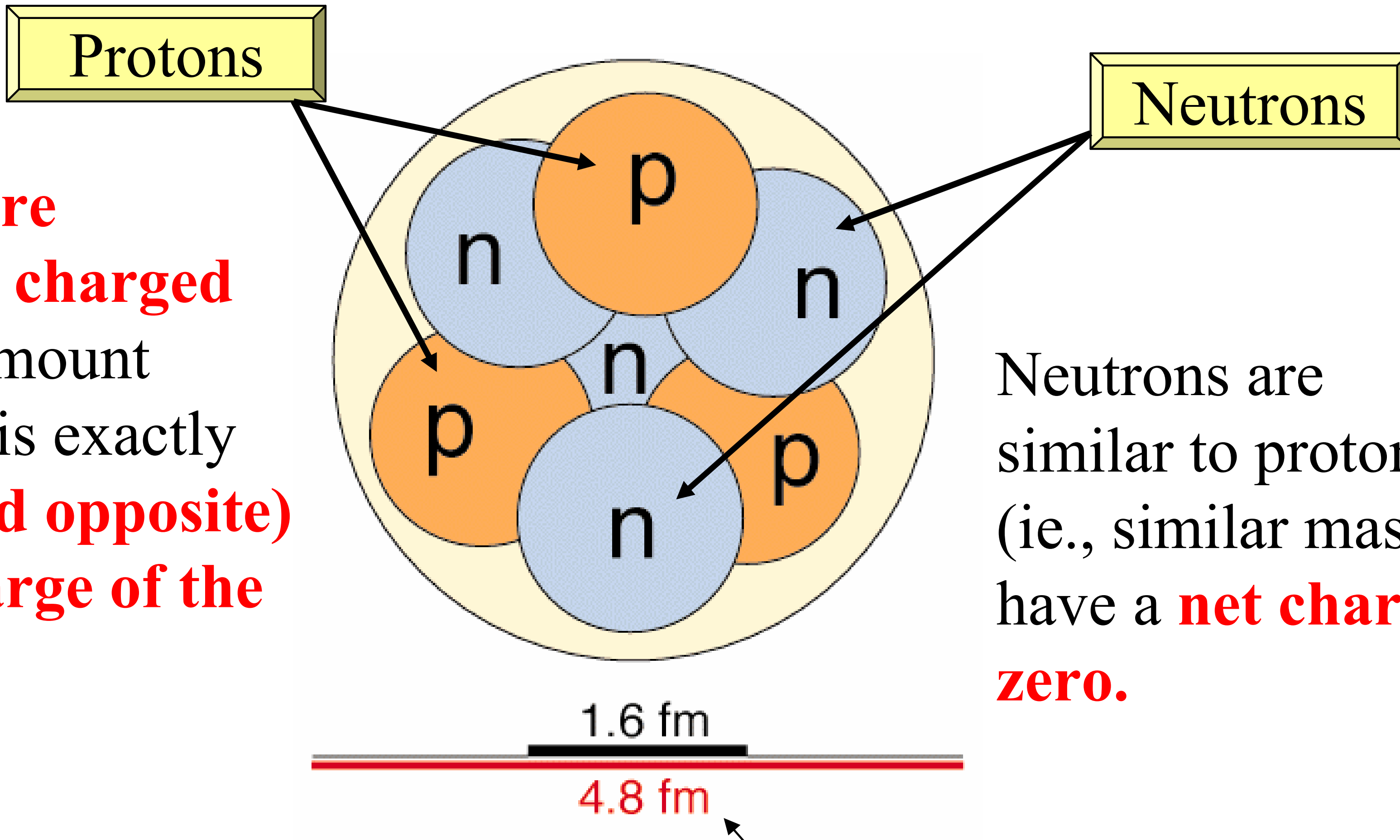
Volume = $(4/3)*\pi*(5\text{x}10^{-15})^3 = 5.2 \text{ x } 10^{-43}$ [m^3]

c) Now compute the fraction:

Fraction = $(5.2 \text{ x } 10^{-43} / 3.4 \text{ x } 10^{-29}) = 0.0000000000000015$

In other words, more than 99.9999999% of an atom is empty space !!!

What's in the Nucleus?



Protons are positively charged and that amount of charge is exactly **equal (and opposite) to the charge of the electron**

Neutrons are similar to protons (ie., similar mass), but have a **net charge of zero.**

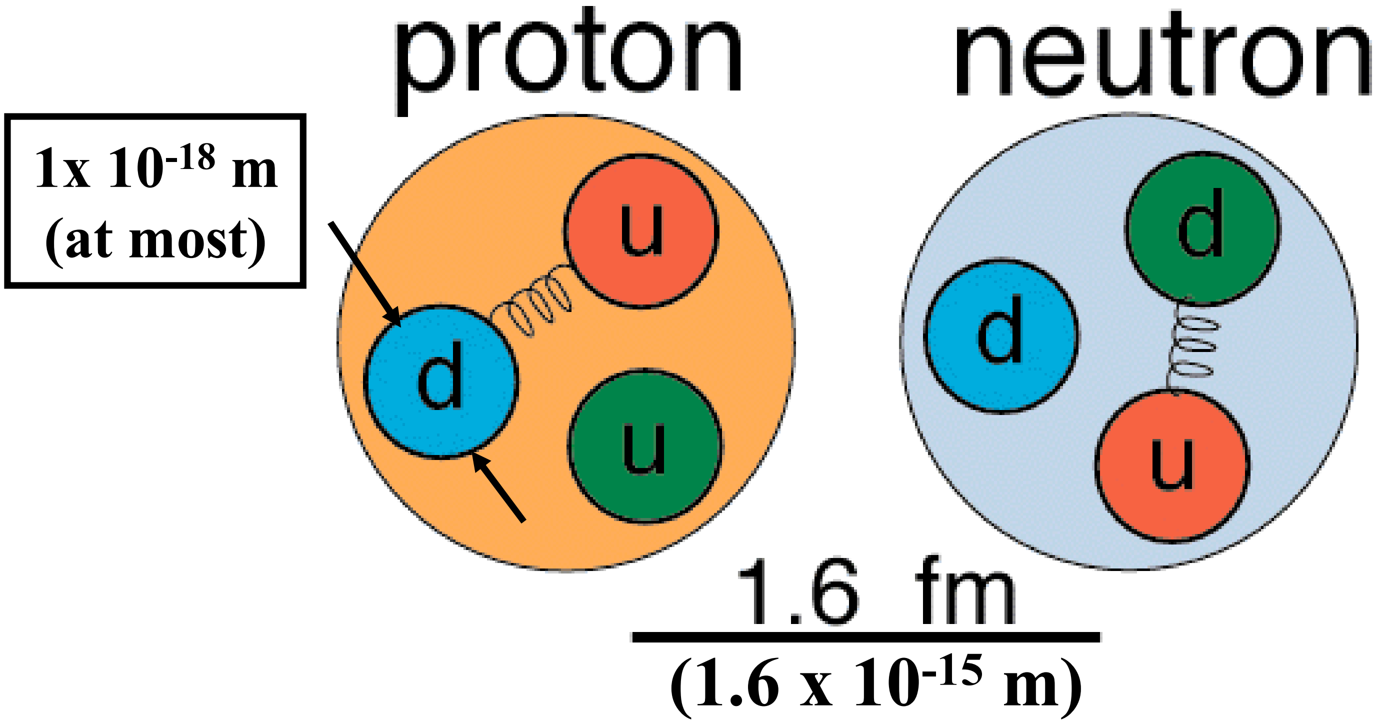
Recall: 1 [fm] = 10^{-15} [m]

Are protons and neutrons fundamental?

(By fundamental, I mean are they indivisible?)

The answer is NO !

Protons and neutrons are made of smaller objects called quarks!



- Protons
  - 2 **"up"** quarks
  - 1 **"down"** quark
- Neutrons
  - 1 **"up"** quark
  - 2 **"down"** quarks

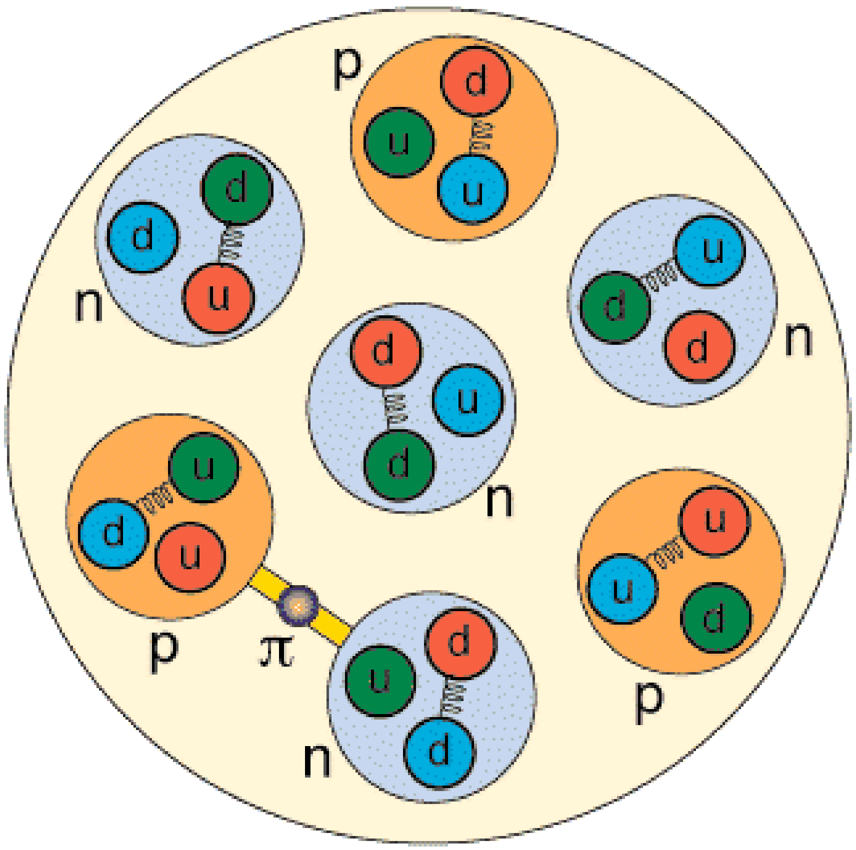
Three Families of Quarks

Woohhh, fractionally charged particles?

	Generations (Increasing mass →)		
	I	**II**	**III**
Charge = **+2/3**	**u** **(up)**	**c** **(charm)**	**t** **(top)**
Charge = **-1/3**	**d** **(down)**	**s** **(strange)**	**b** **(bottom)**

Also, each quark has a corresponding antiquark.
The **antiquarks** have **opposite charge** to the quarks

Protons & Neutrons



To make a proton:

We bind **2 up quarks** of **Q = +2/3** and **1 down quark** of **Q = -1/3**. The total charge is

2/3 + 2/3 + (-1/3) = +1 !

To make a neutron:

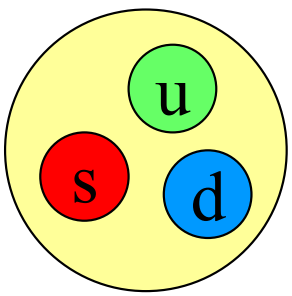
We bind **2 down quarks of Q= -1/3** with **1 up quark of Q = +2/3** to get:

(-1/3) + (-1/3) + (2/3) = 0 !

⇨ So, it all works out ! But, yes, we have **FRACTIONALLY CHARGED QUARKS**!

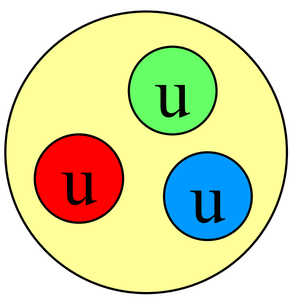
Are there baryons other than protons and neutrons?

- Good question, my dear Watson…
- The answer is a resounding **YES !**
- Other quarks can combine to form other baryons. For example:



This combination is called a Lambda baryon, or Λ^0 for short

CHARGE: 2/3 + (-1/3) + (-1/3) = 0



This combination is called a Delta baryon, or Δ^{++} for short

CHARGE: 2/3 + 2/3 + 2/3 = +2

Quark Confinement

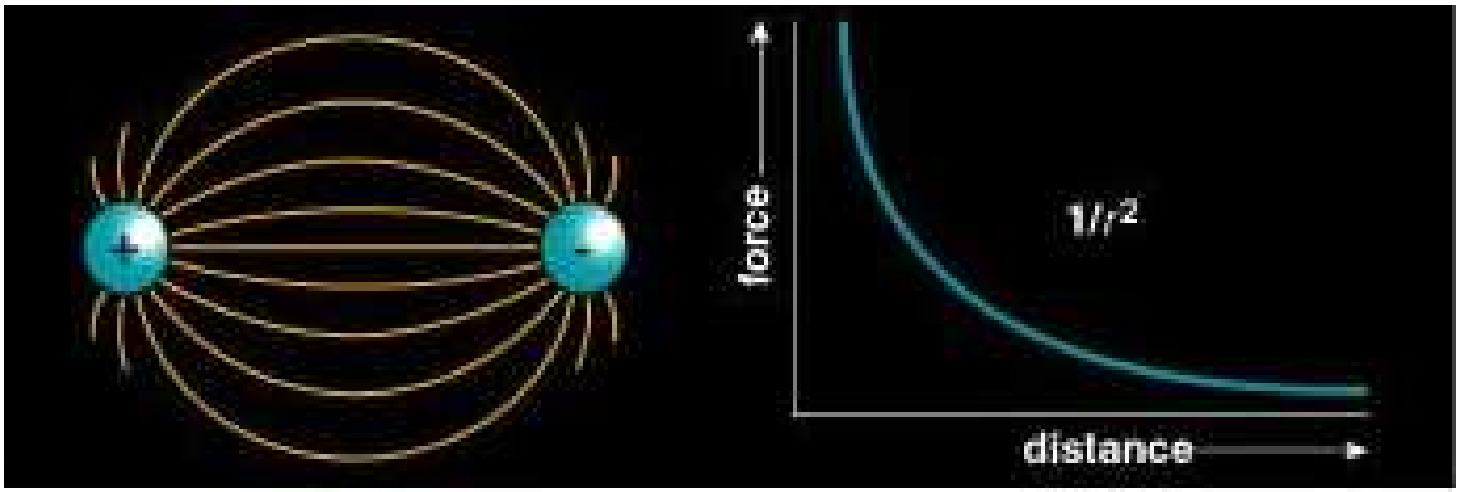
- Quarks are "**confined**" inside **hadrons** (baryons or mesons). We do not see them as "free" particles (like electrons, for example).

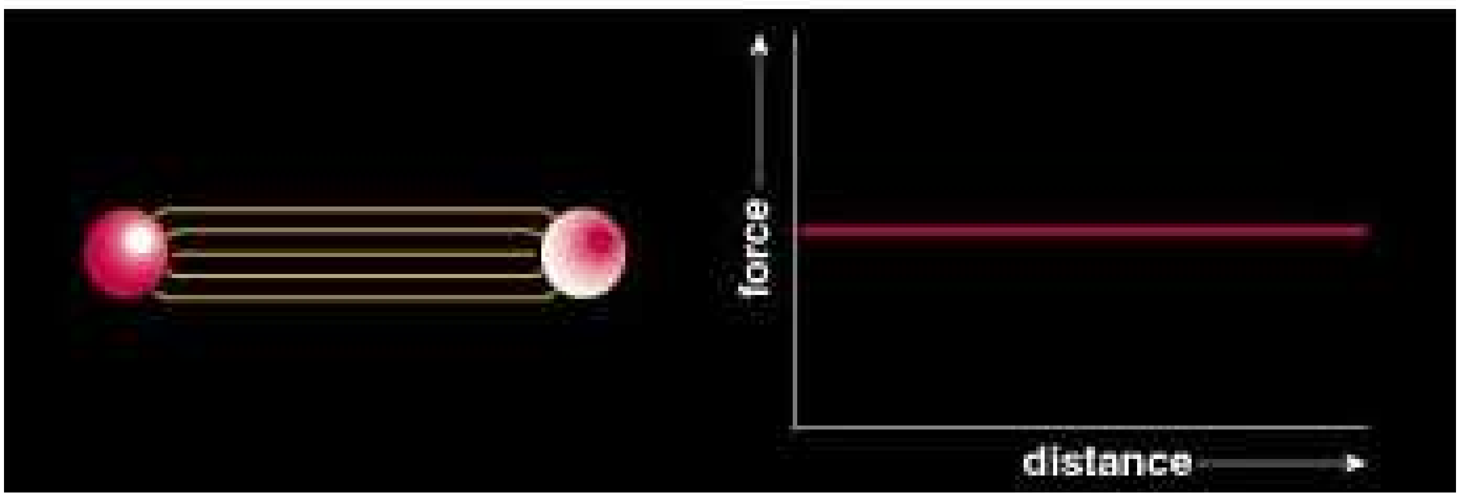
- This is a result of the "**strong force**".

Electric Force between Charges

vs.

Strong Force between Quarks





Color

- I have been showing quarks as being either **RED**, **GREEN** or **BLUE**.

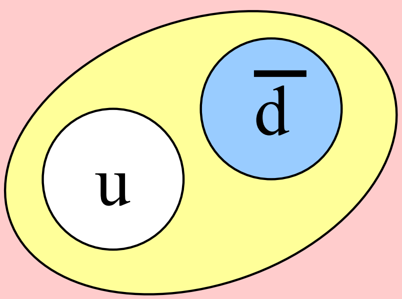
- It turns out that quarks have a property called "**COLOR**". This property is as intrinsic to the quarks as "*electric charge*".

- This intrinsic property is not really a visible color, but it helps to visualize the property, which can have 3 values.

- A consequence of "quark confinement" is that all hadrons must be color-neutral (i.e. white).

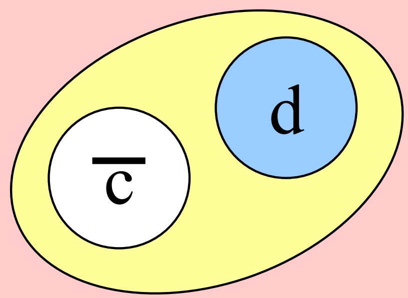
Mesons

- **Mesons** are also in the **hadron family**.
- They are formed when a **quark** and an **anti-quark** "bind" together.
- Because they are hadrons, they must be colorless. So, the quark has color, and the antiquark has "anticolor".



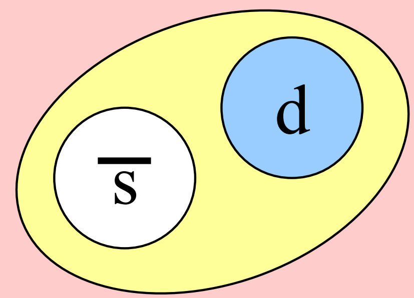
Called a π^+ meson (or pion)

$Q = 2/3 + 1/3$
$= +1$



Called a D^- charm meson

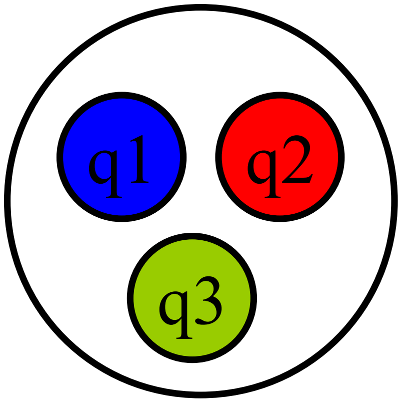
$Q = (-2/3) + (-1/3)$
$= -1$



Called a K^0 strange meson (or kaon)

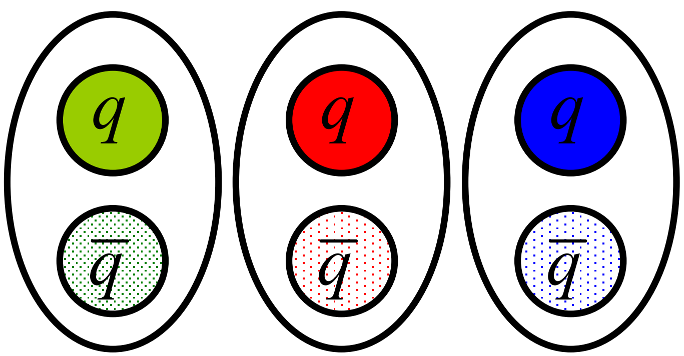
$Q = 1/3 + (-1/3)$
$= 0$

Color of Hadrons



BARYONS

RED + BLUE + GREEN = "WHITE"
or "COLORLESS"

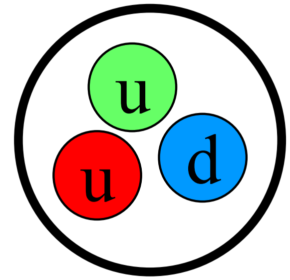


MESONS

GREEN + ANTIGREEN = "COLORLESS"
RED + ANTIRED = "COLORLESS"
BLUE + ANTIBLUE = "COLORLESS"

The Quarks – a Recap

Quarks		Antiquarks	
Q = +2/3	Q = -1/3	Q = -2/3	Q = +1/3
u	d	$\bar{u}$	$\bar{d}$
c	s	$\bar{c}$	$\bar{s}$
t	b	$\bar{t}$	$\bar{b}$



Proton

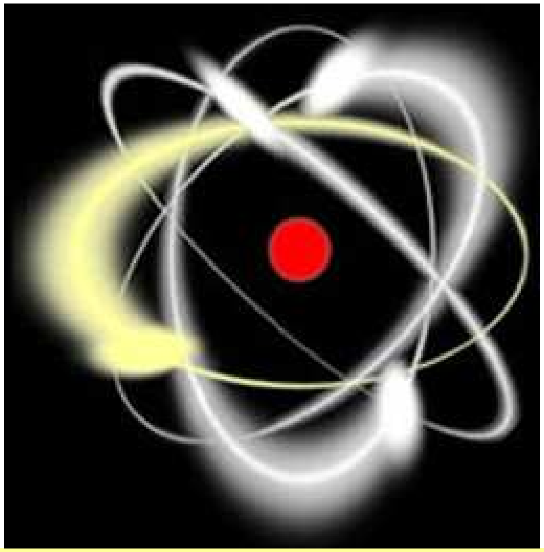
- **Quarks can have 3 color values: red, green & blue**
- **Quarks have total spin S = ½ (S_Z = -½ or +½)**
- **Anti-quarks have the same mass as their quark does.**

- **Hadrons = Baryons + Mesons**
- **Baryons (antibaryons) contain 3 quarks (3 antiquarks)**
- **Mesons contain a quark and an antiquark**

If neutrons & protons are not fundamental, what about electrons?

Are they made up of smaller constituents also ?

As far as we can tell, electrons appear to be indivisible.



Leptons

- **Electrons belong to a general class of particles, called "Leptons."**

- **As far as we can tell, the leptons are "fundamental".**

- **Each charged lepton has an uncharged partner called the "neutrino."**

- **The leptons behave quite differently than the quarks.**

  - They don't form hadrons (no binding between leptons).

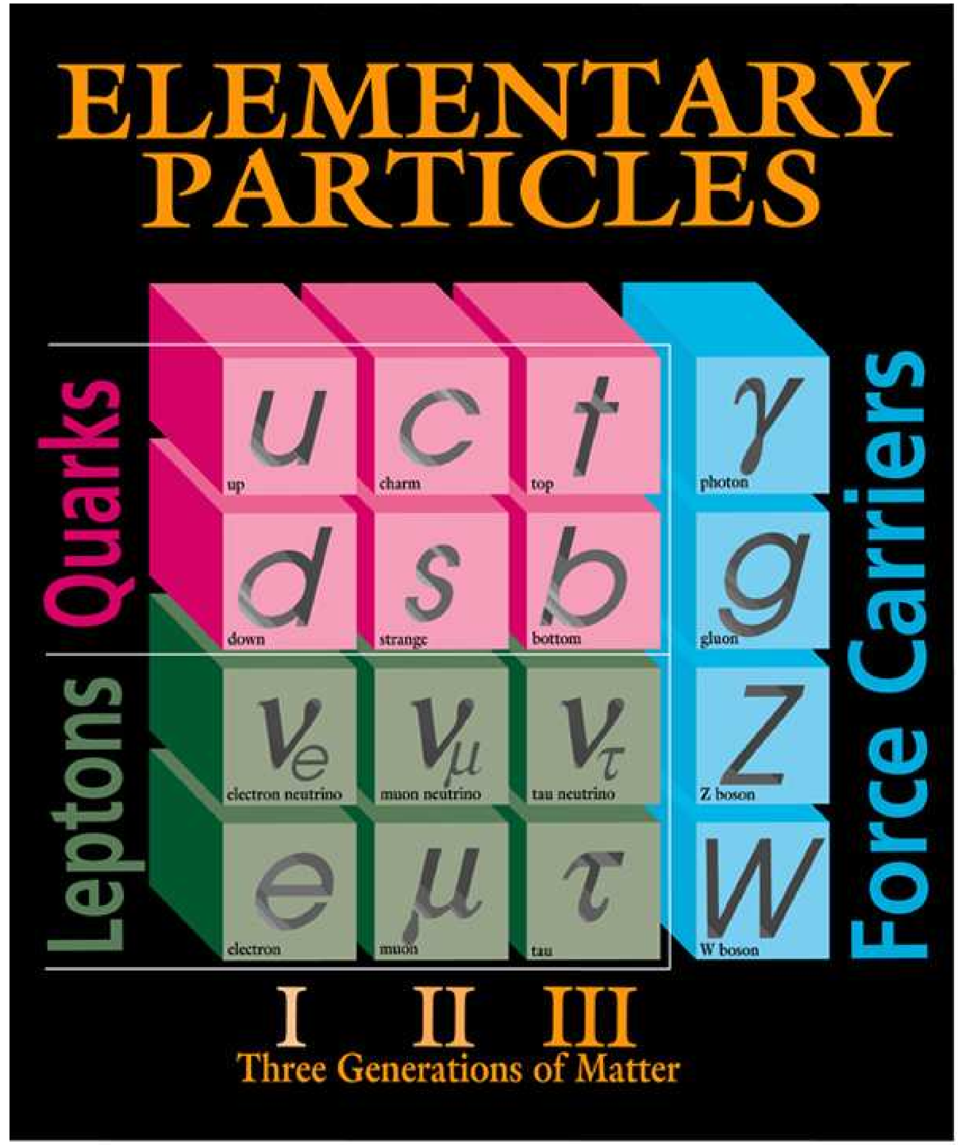
So here's the big picture

- **Quarks** and **leptons** are the most fundamental particles of nature that we know about.

- **Up** & **down quarks** and **electrons** are the constituents of ordinary matter.

- The other quarks and leptons can be produced in cosmic ray showers or in high energy particle accelerators.

- Each particle has a corresponding antiparticle.



Fermilab 95-759

How do we know any of this?

"Particles, particles, particles."

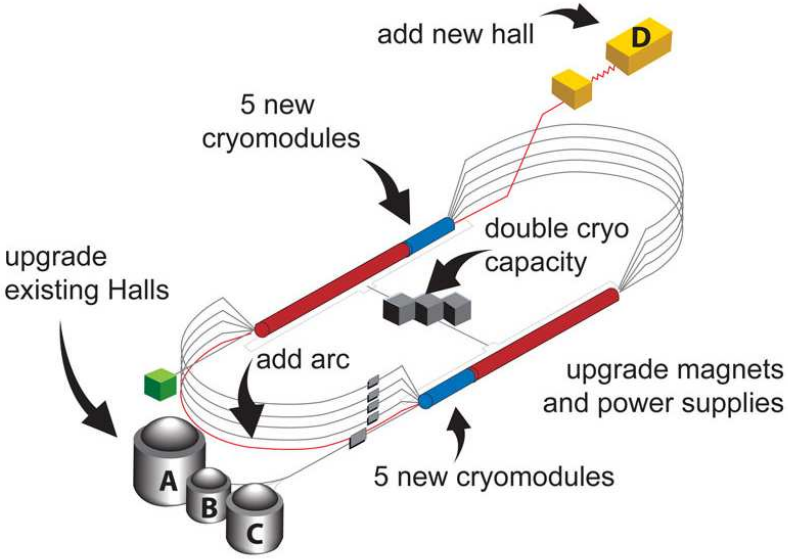
❑ High energy particles provide a way to probe, or "see" matter at the very smallest sizes. (e.g. Electron microscope).

❑ Today, particle accelerators produce energetic beams which allow us to probe matter at its most fundamental level.

❑ As we go to higher energy particle collisions:

1) Wavelength probe is smaller ➔ **see finer detail**
2) Can produce more **massive objects**, via $\mathbf{E=mc^2}$

Jefferson Lab
Thomas Jefferson National Accelerator Facility



- U.Regina researchers travel to Jefferson Lab to do studies of the quark structure of matter.
- The electron accelerator produces a very intense beam able to probe distances $<10^{-15}$m.
- Analogous to a very powerful electron microscope!

Are there other types of charged leptons (like the electron) ?

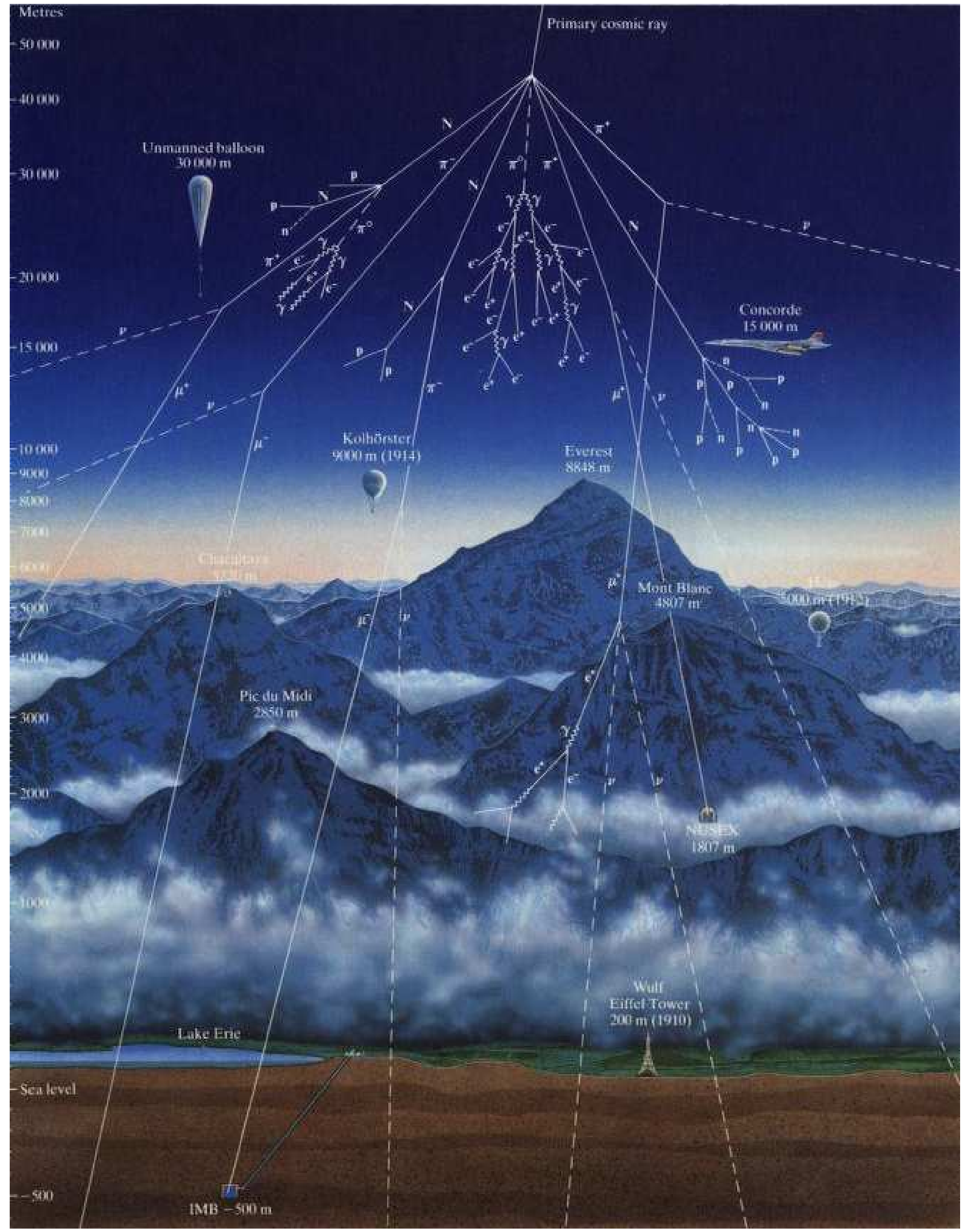
- **1932**: Discovery of the positron, the "anti-particle" of the electron.

Anti-particles really exist !!!!!

- **1937** – Muons (μ^+ and μ^-) discovered in cosmic rays.

$$M(\mu) \sim 200{*}M(e)$$

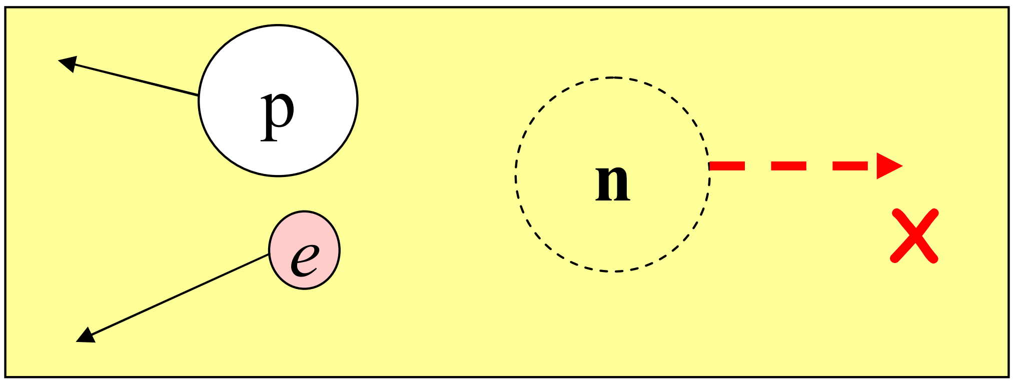
- The muon behaves very similarly to the electron (i.e., it's a lepton).

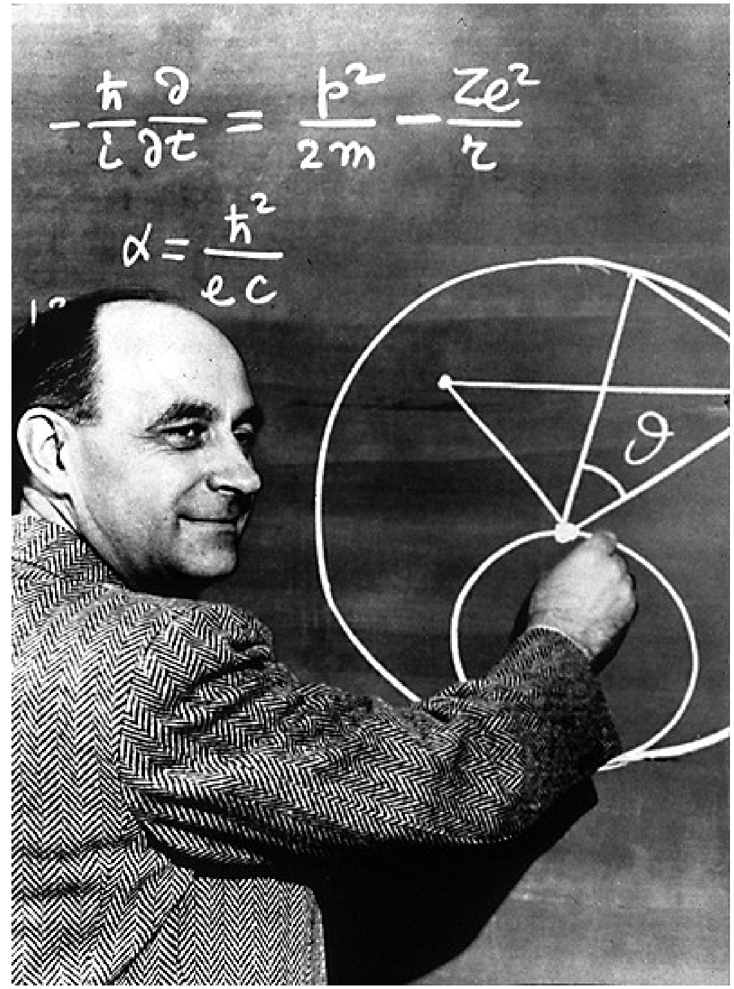


Neutrinos

1934: To account for the “unseen” momentum in the reaction (decay):

$$n \rightarrow p + e^{-} + X$$





Nobel Laureate: Enrico Fermi

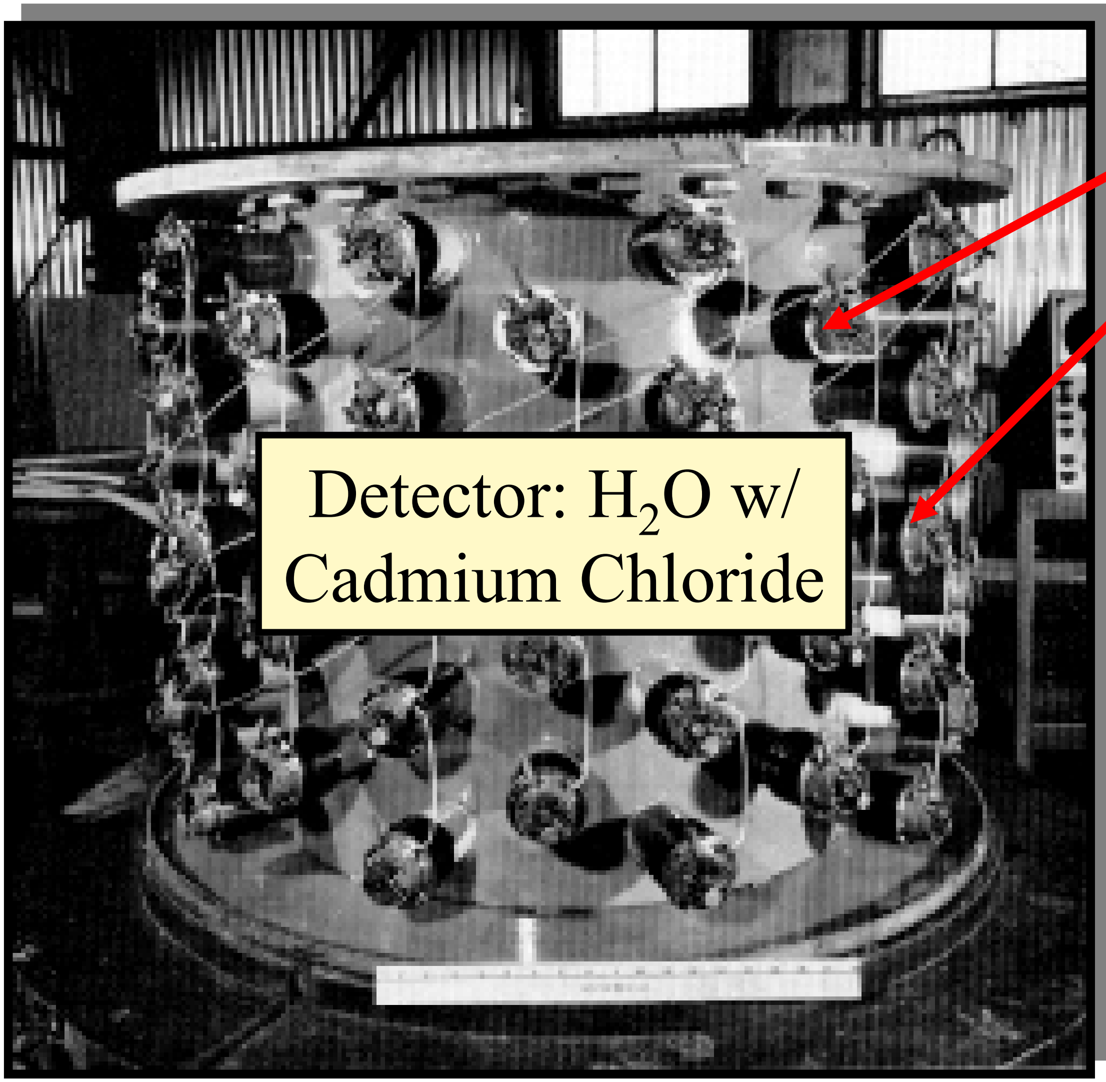
Fermi proposed that the unseen momentum (X) was carried off by a particle dubbed the *neutrino (n).*

(means “*little neutral one*”)

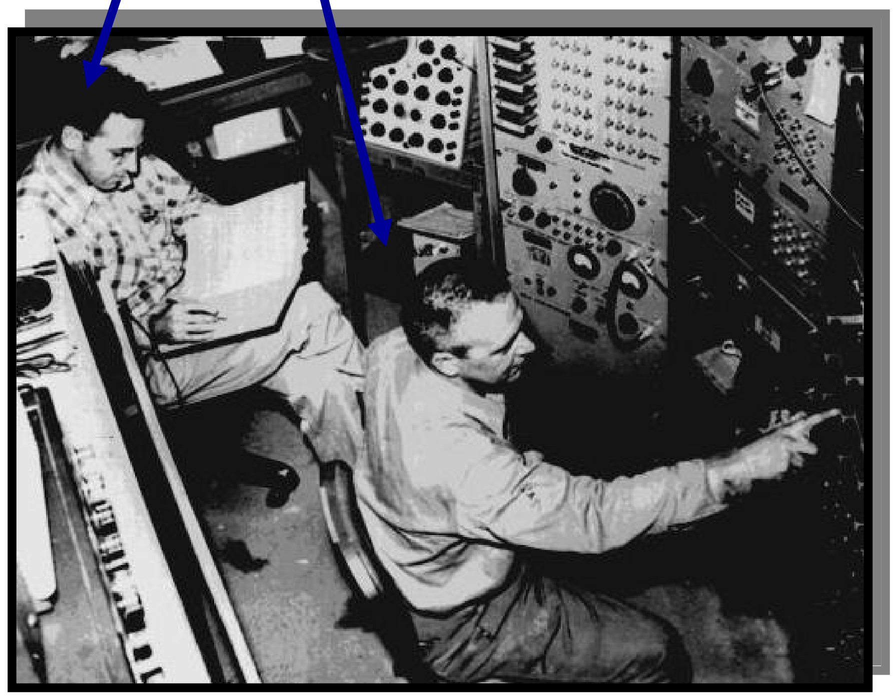
Discovery of the neutrino

❑ **1956**: Existence of the neutrino confirmed at a nuclear reactor. (Nobel Prize)

Photon detectors



Fred Reines and
Clyde Cowan, 1956



This all looks Greek to me ?

Lepton (particle)

e^-	electron
μ^-	muon-minus
τ^-	tau-minus
ν_e	electron neutrino
ν_μ	muon neutrino
ν_τ	tau neutrino

Anti-lepton (anti-particle)

e^+	positron
μ^+	muon-plus
τ^+	tau-plus
$\bar{\nu}_e$	electron anti-neutrino
$\bar{\nu}_\mu$	muon anti-neutrino
$\bar{\nu}_\tau$	tau anti-neutrino

Three happy families…

Family	Leptons		Antileptons	
	Q = -1	Q = 0	Q = +1	Q = 0
1	e^-	ν_e	e^+	ν_e
2	μ^-	ν_μ	μ^+	ν_μ
3	τ^-	ν_τ	τ^+	ν_τ

3 families, just like the quarks… interesting !!!