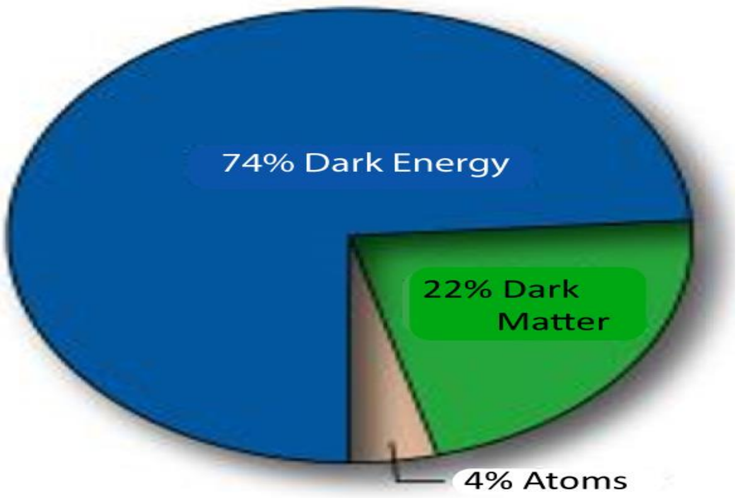
Building Blocks of the Universe



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Dec. 20, 2022

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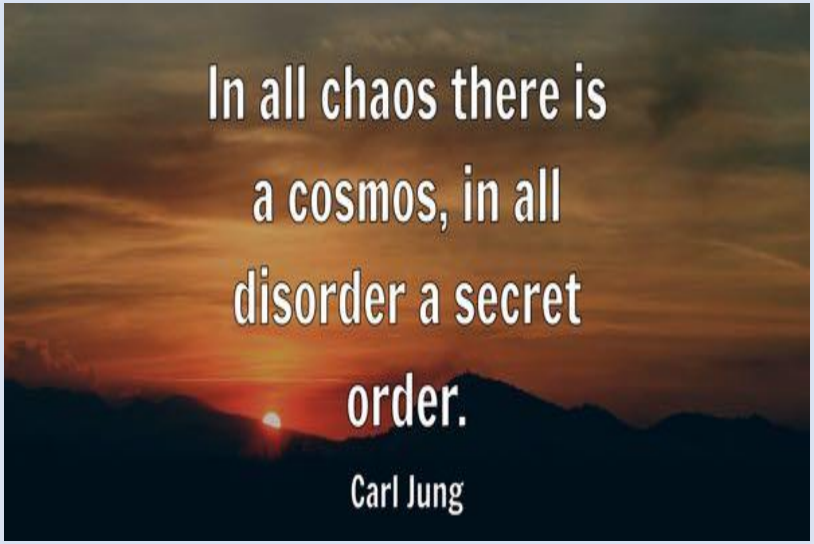
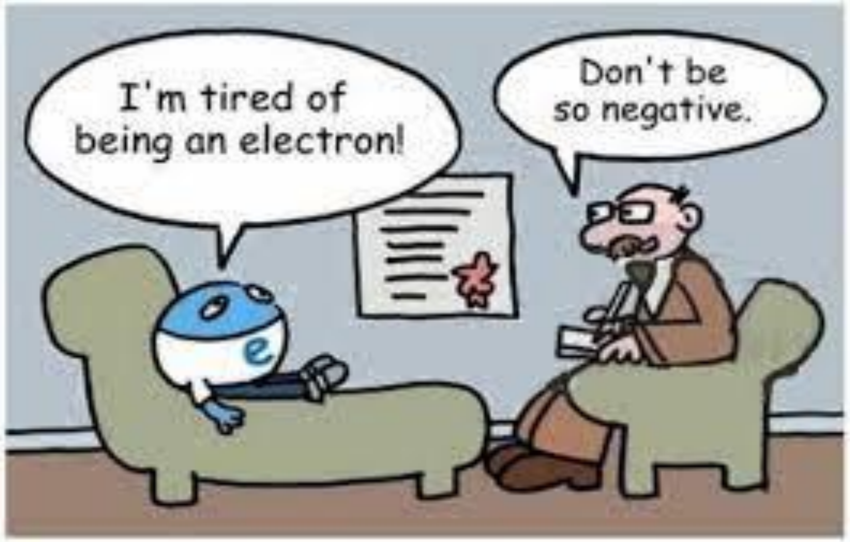
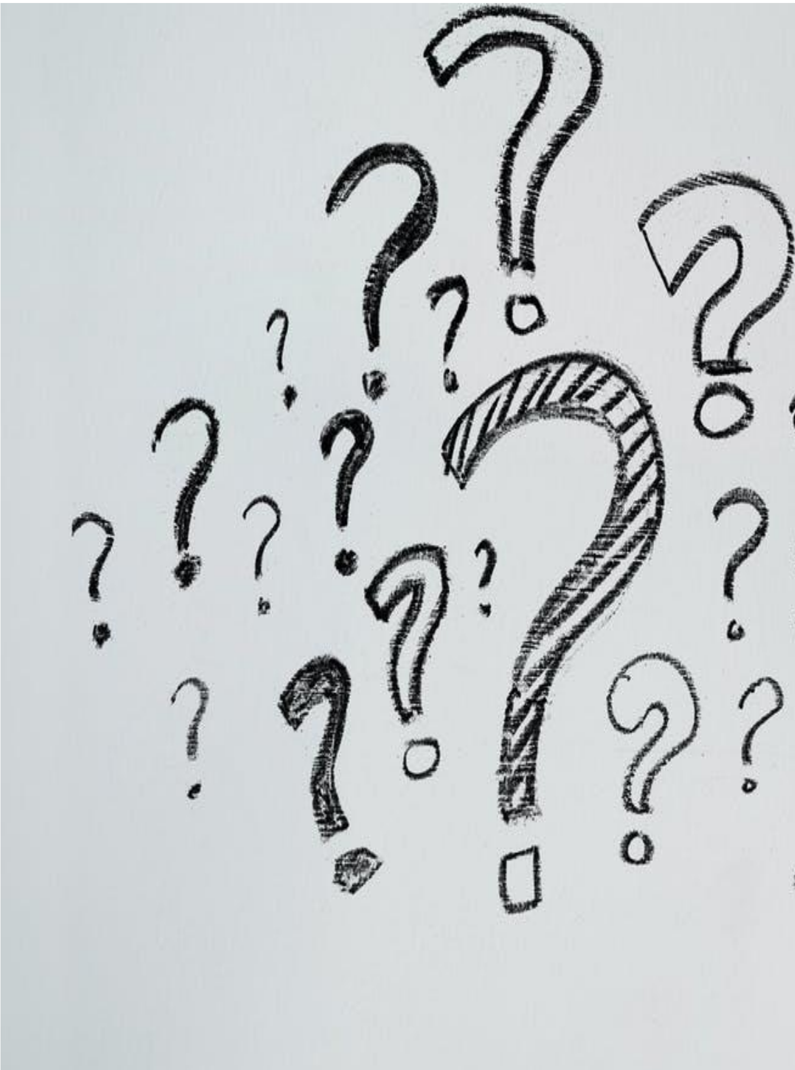
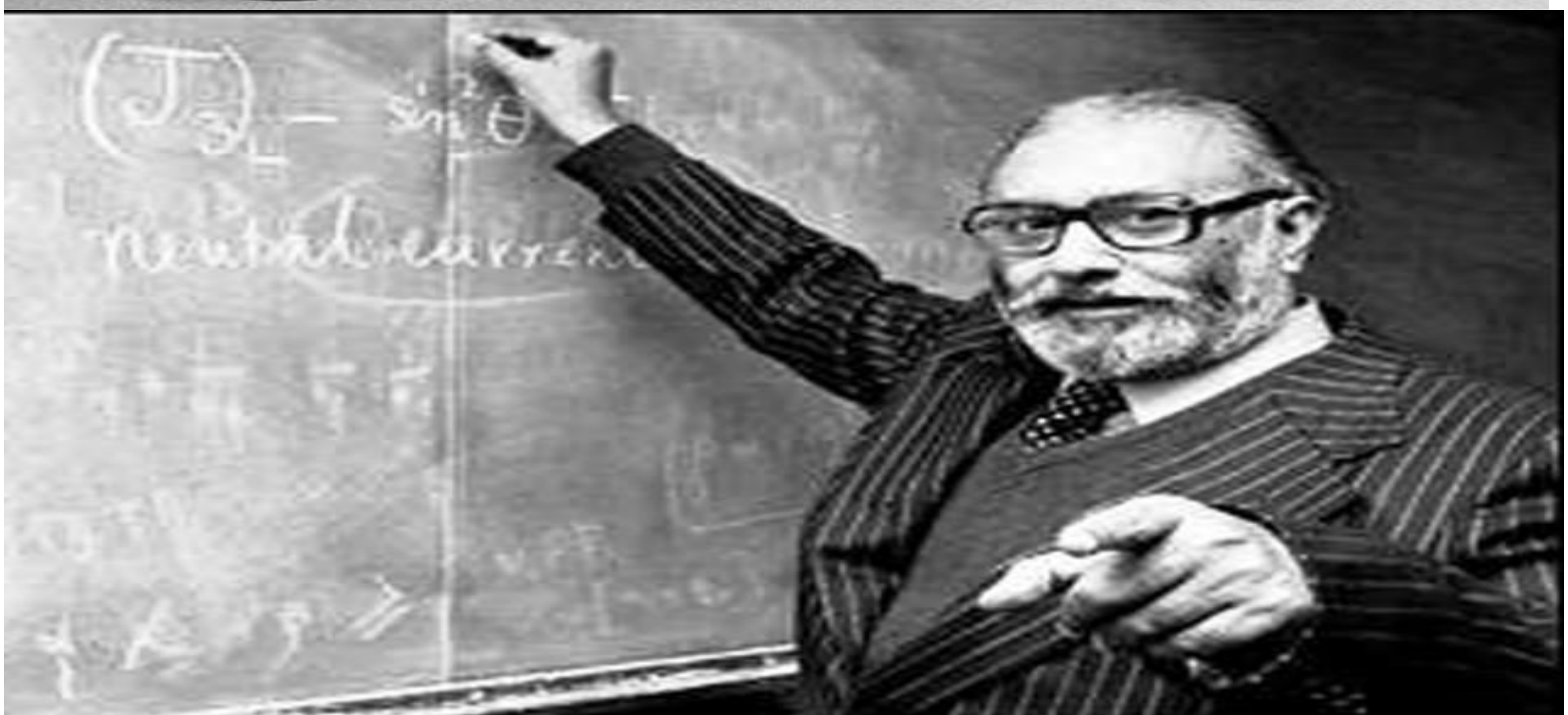


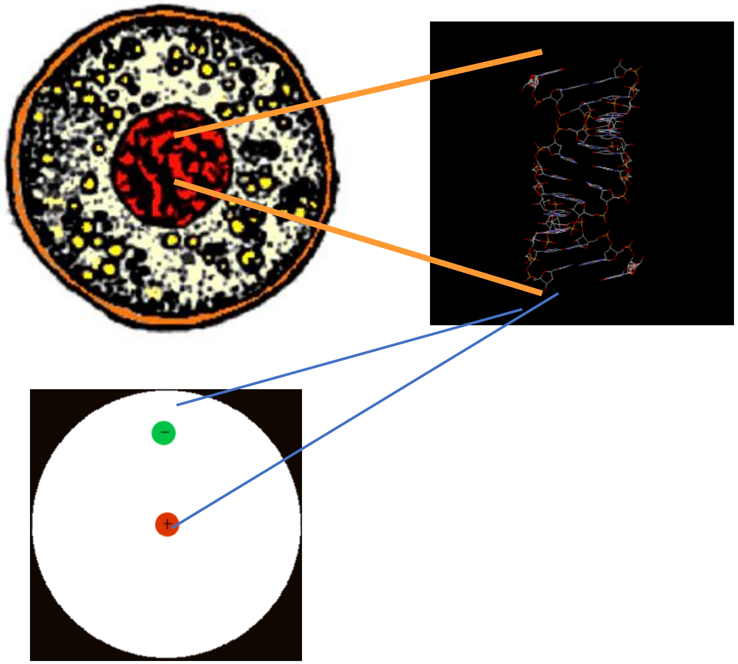




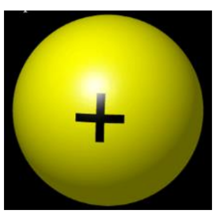
- Introduction
- The Standard Model:
  - The cast of characters
  - The Forces
  - The new periodic table
- Mysteries of the Standard Model

The Subatomic World

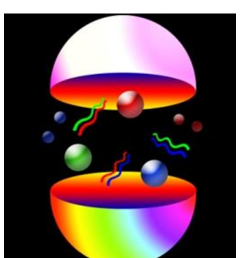


Cellular Biology ~10^{-5} m

Chemistry ~10^{-8}-10^{-10} m

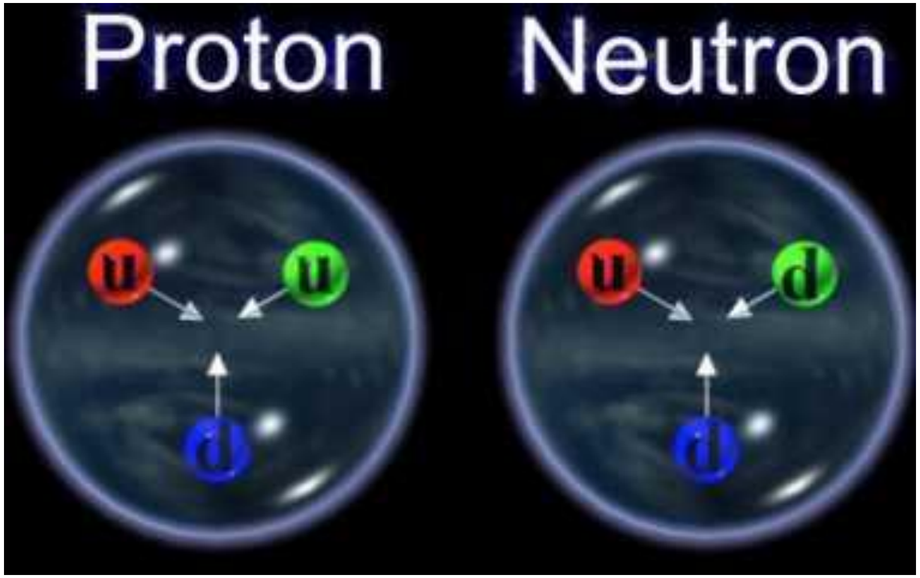


Nuclear Physics ~10^{-15} m



Particle Physics ~10^{-18} m

Under closer examination of atoms…



- There is overwhelming evidence that protons and neutrons are not "fundamental".

- They are in fact made up of smaller objects, called quarks.

- Like an atom has valence electrons, a proton (or neutron) also contain "valence" quarks of two types: up($Q=+2/3e$) and down ($Q=-1/3e$)

- We know this by smashing particles together at high energy (momentum), as

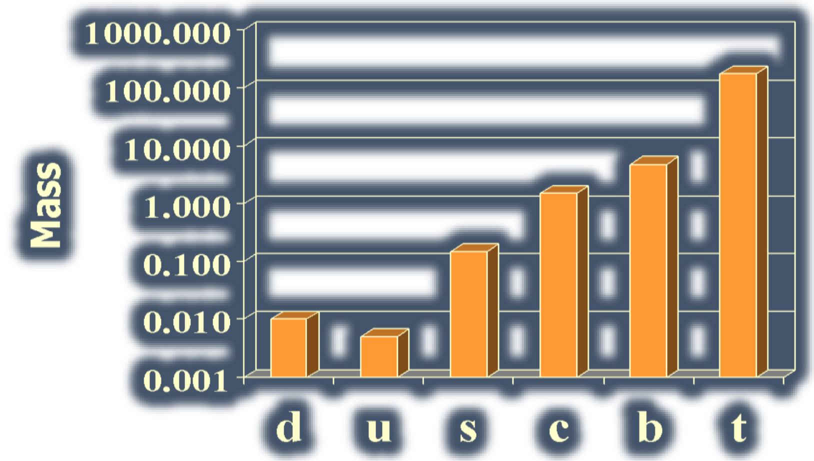
$$\lambda = h / p$$

- The smaller the deBroglie wavelength better "resolution" to "see" internal structure

The Cast of Characters

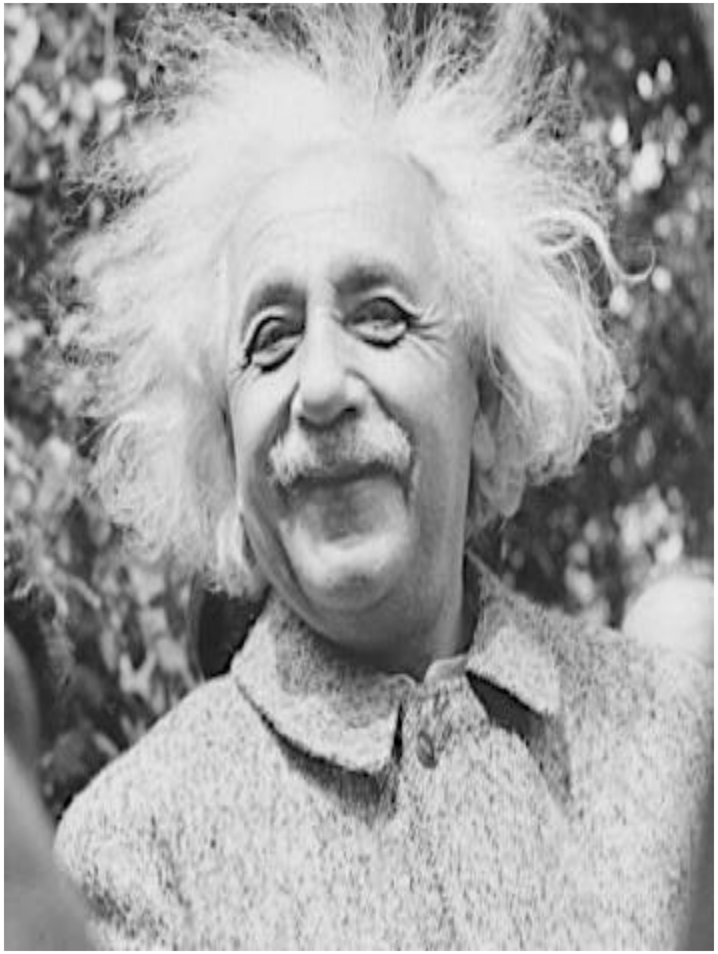
Many experiments have shown that there in fact more than just two types of quarks. In fact, experiments have shown that:

	1	2	3
+2/3*e*	u	c	t
-1/3*e*	d	s	b

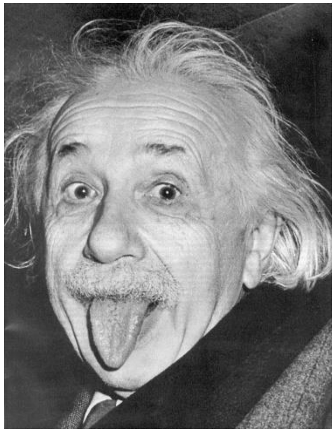


- 3 families of quarks… why?
- Ordinary matter is made of only the lightest quarks (u & d)….Why?
- How do we know about the heavier quarks, if they're not contained in ordinary matter?

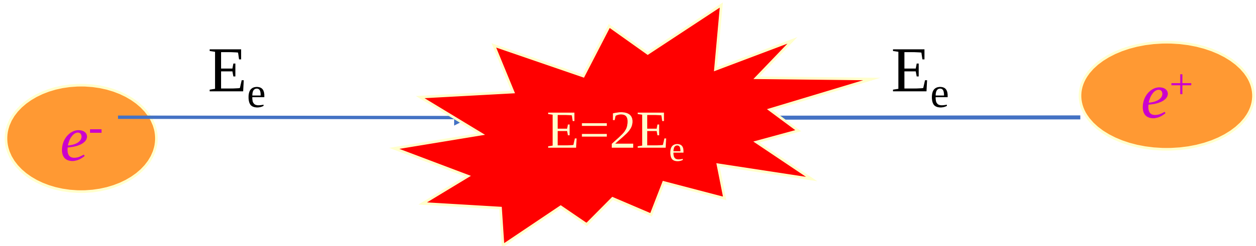
How do we produce the heavier quarks



How do we produce the heavier quarks



$$E = mc^2$$

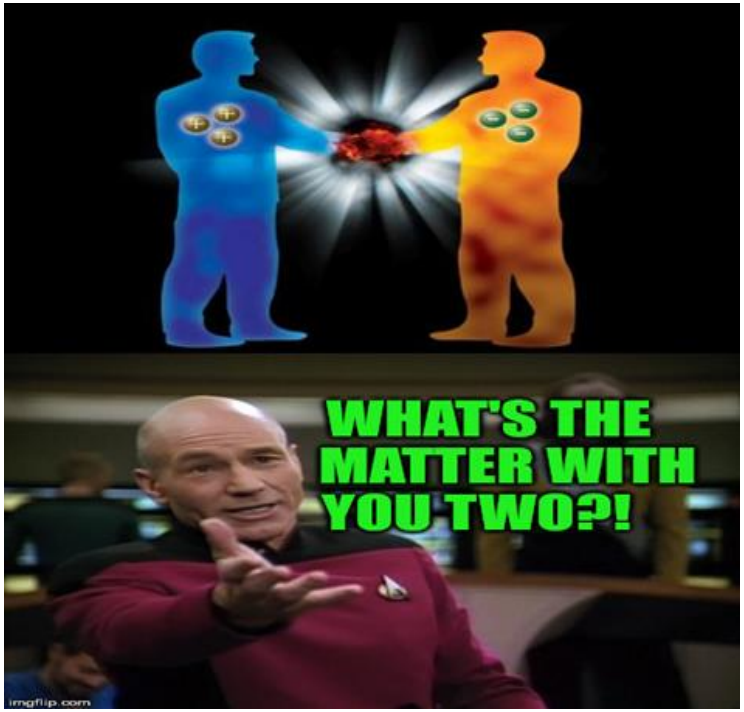


- The electron and anti-electron (positron) can annihilate into pure energy (*i.e.*, a photon)

- This energy then can "re-emerge" in the form of any particle-antiparticle which:
  - satisfies energy conservation
  - Carry electric charge

Did you say anti-electron?

- Antimatter is just as real as matter
- Every particle has an antiparticle?
- The anti-particle has exactly the same mass as the particle but opposite charge (or does it?)



"50,000 atoms of anti-hydrogen made"

Physicists have made 50,000 atoms of anti-hydrogen, the antimatter counterpart of normal hydrogen. This new substance will enable them to test one of the fundamental assumptions of modern physics - the Standard Model…

Nature: Sept. 2002

Are there more fundamental particles?

- Quarks from one class of particles. e^- μ^- τ^-

- How does the electron fit into the big picture?
  Like quarks, years of experiments have shown that there are 3 "*electron-like*" charged particles: $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$.

- Many experiments have shown that apart from their masses, the "*muon*" and "*tau*" behave identically to the electron. Again 3 families…

- A third type of massless, zero-charge particle, called the neutrino, was hypothesized to exist by Fermi based on the apparent failure of momentum conservation in the decay:

$$n \rightarrow p + e^- \quad (+ \nu)$$

Neutrino was not detected

In 1956, Reines and Cowan discovered this elusive particle.

- In fact, over the last few decades, we've learned that there are 3 types of neutrinos. ν_e ν_μ ν_τ

The full cast of particles

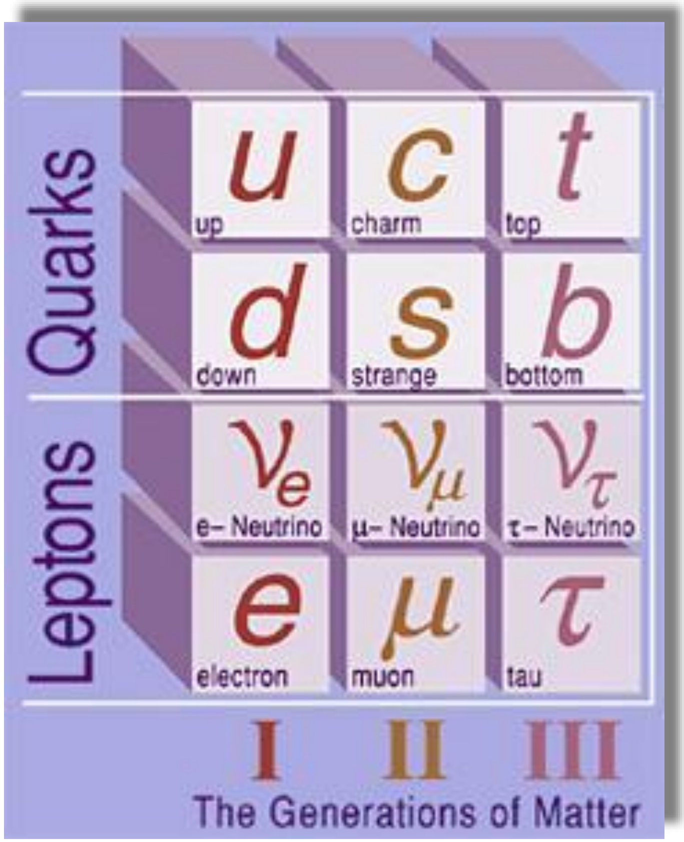
Electric
Charge

+2/3

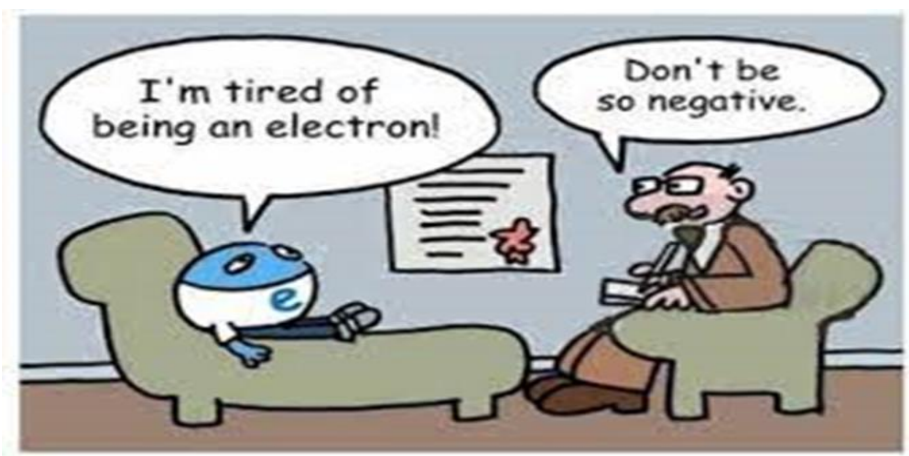
-1/3

0

-1



- 3 families of quarks
- 3 familes of "leptons"
- All these particles have corresponding antiparticles



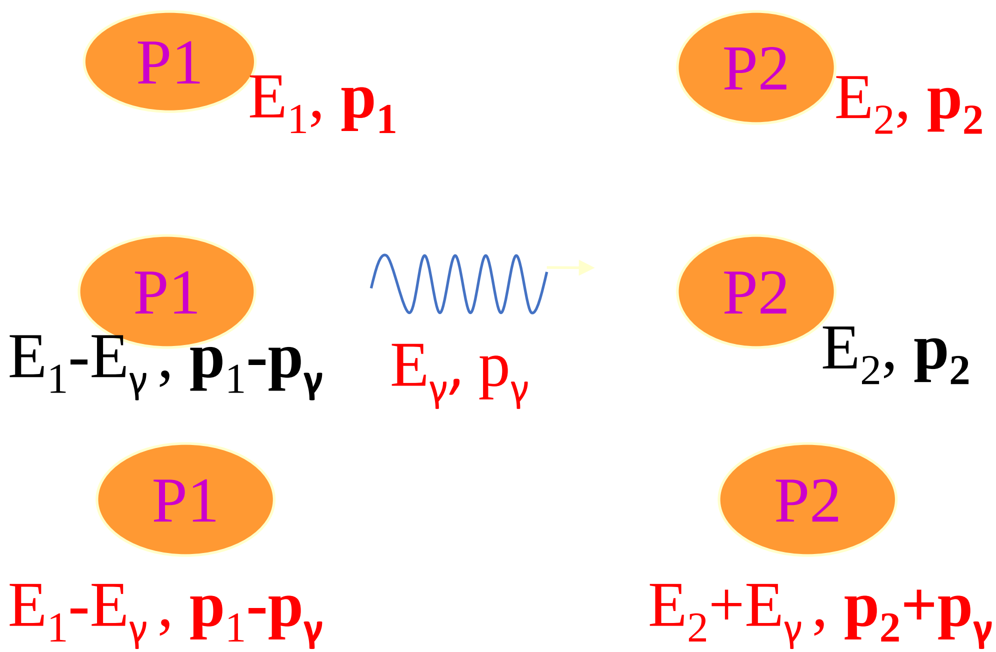
How do particles interact with one another?

The Quantum View of Forces

- Forces are the result of an <u>INTERACTION</u> between two objects

- Interaction occurs via the exchange of a "*force carrier*" or "*mediator*".

- The basic idea is as follows



- Particles 1 and 2 exchange energy and momentum
- Bang! An interaction !!

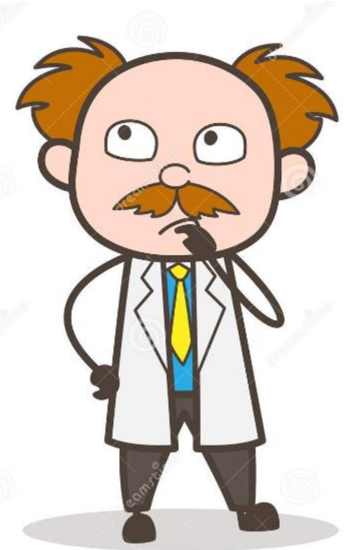
Force Carriers

<u>Basic underlying concepts</u>:

- Each fundamental force has an associated force carrier.
- The force carrier can only interact with particles which have the *intrinsic charge* associated with that force.
  - For EM:
    - the force carrier is the photon (γ).
    - the intrinsic charge is electric charge.
    - the photon cannot "see" particles which have $q_e = 0$.

Question:

So which particles can interact electromagnetically????



Quarks and charged leptons (but not neutrinos)

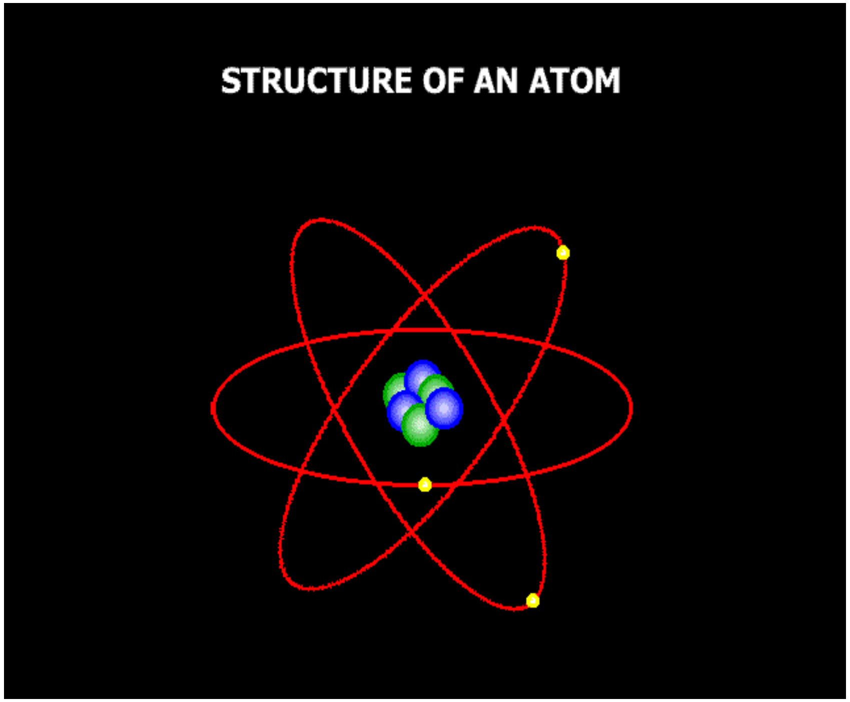
Strong Force

The electrons stay bound to the nucleus via the continual exchange of (virtual) photons between the protons and electrons.

But why does the nucleus stay together ???

The protons should repel and the nucleus should not stay intact if they only interacted via EM !

There must be a much stronger force at work here !! The STRONG FORCE!!!



Strong Force (QCD):

Force carrier: "Gluon"

Intrinsic Charge: Color (r, g, b)

Only quarks have color.

Only quarks may participate in the strong interaction !

Self Interactions

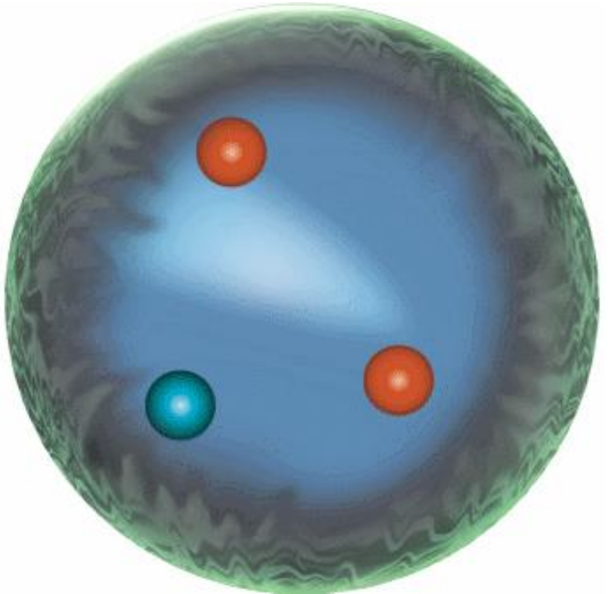
A photon can only interact with objects which carry electric charge.

Since $Q_\gamma=0$, it cannot interact with other photons

BUT, gluons DO CARRY COLOR CHARGE, and therefore

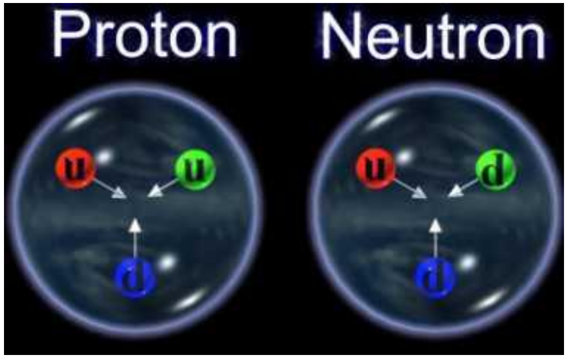
Gluons can interact with other gluons via the strong force

This is a dramatic difference
between EM and the STRONG force,
which is the root of the
short range of the strong force.



The results of this is that the proton is
a complicated bag of valence quark, gluons
and even virtual quark+antiquarks

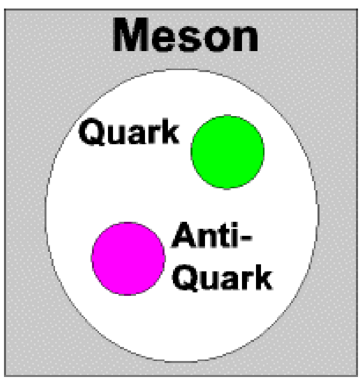
Quarks, Baryons & Mesons



- Also Quarks are always confined in "color neutral" particles:

1 RED + 1 BLUE + 1 GREEN = COLORLESS

When combined this way → baryons



- Mesons contain 1 quark + 1 antiquark

The quark has "color" and the antiquark has "anti-color"

Gluons interact with quarks b/c they have color charge.

Weak Force

Earlier, we mentioned that there exist heavy quarks, such as strange (s), charm (c), bottom (b) and top (t).

Why don't we see them around today?

They're unstable and decay rapidly (~10^{-9}–10^{-12} s)

How does this happen?

Here, a third force is at work:

WEAK INTERACTION

What are the force carriers and the "intrinsic charge"?

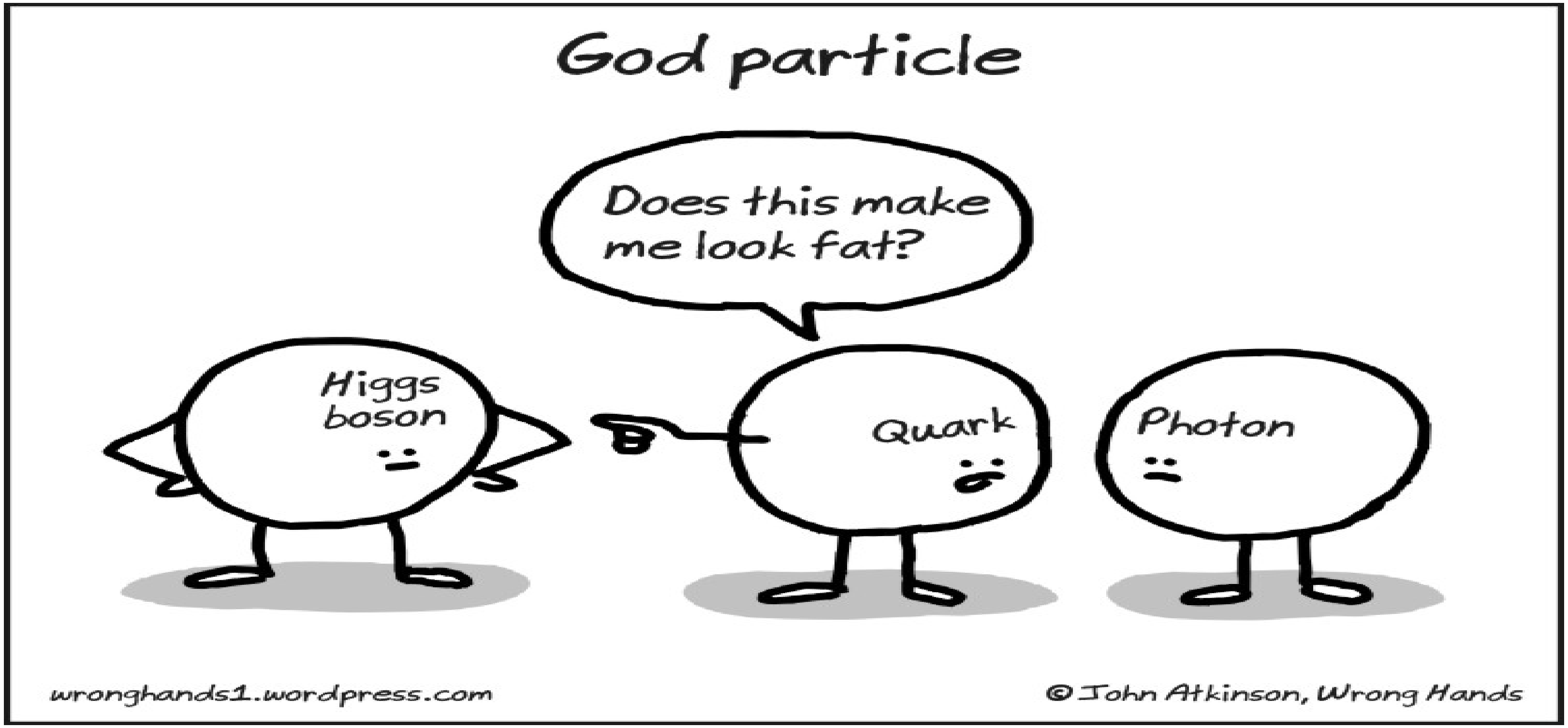
There are **3 force carriers:** **W^+, W^- and Z^0**

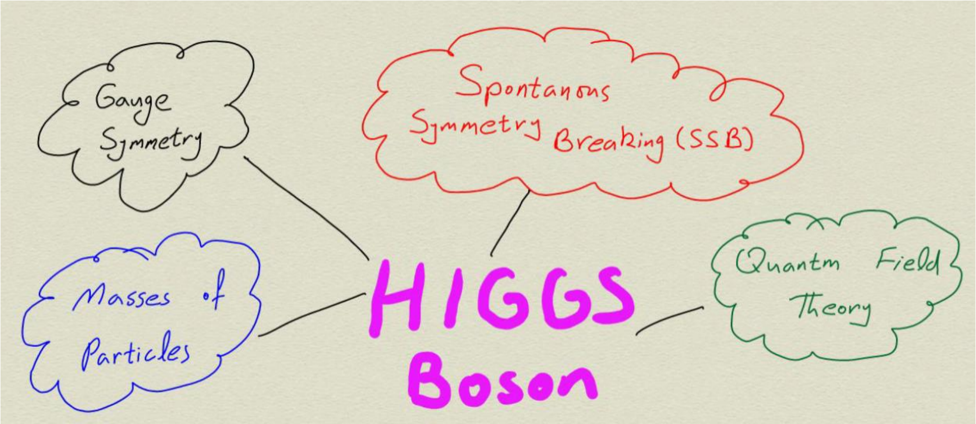
Unlike the photon and gluon, these force carriers are very massive (~$100*m_P$)

It is this very large mass which accounts for the "weakness" of the weak force

- Has Disparity in Matter and Anti-Matter
- Responsible for Radioactivity and Burning of the Sun (as well as Nuclear energy).

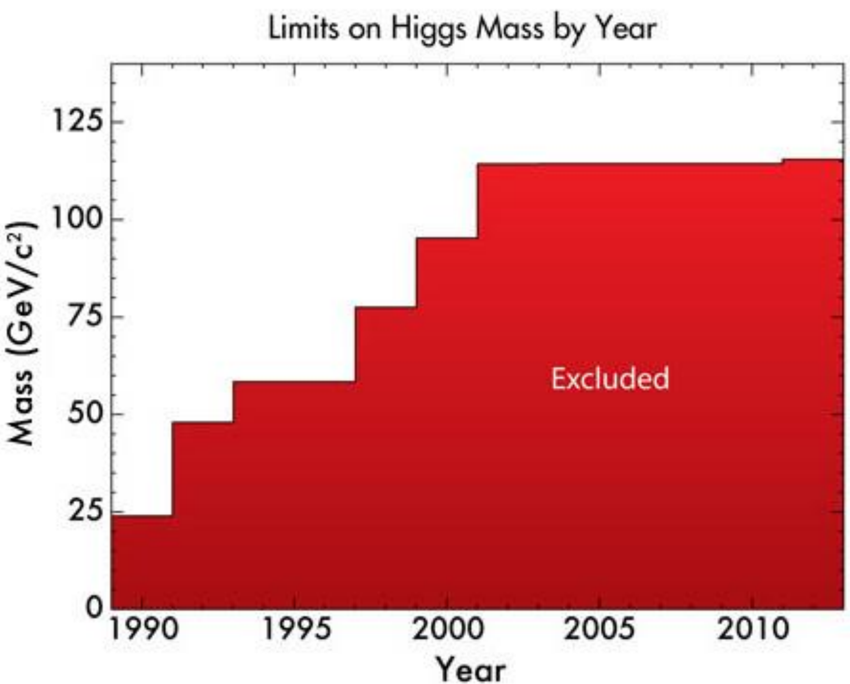
The Origin of Mass

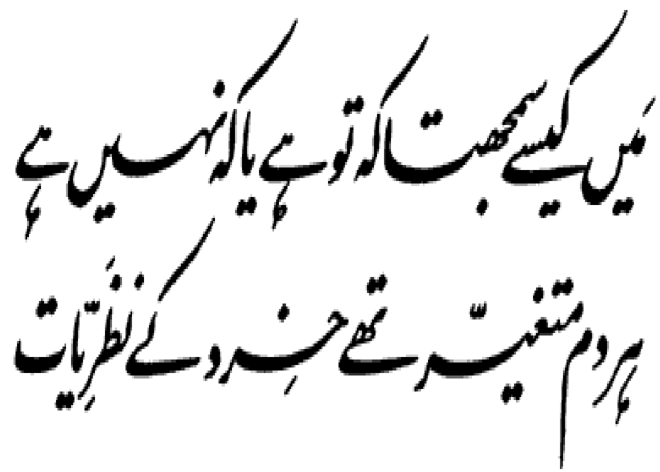




The Higgs Boson

- The whole theoretical edifice of Standard Model of particle physics is based on gauge theories and the symmetries involved are held together via Higgs boson. Without Higgs, SM makes no theoretical sense. Its discovery helps confirm the mechanism by which fundamental particles get mass.
- Higgs Boson was the most important prediction of the Standard Model, which was finally discovered at the LHC in 2012.





The Higgs Boson

In July 2012, after half a century of waiting, the drama was intense. Physicists slept overnight outside the auditorium to get seats for the seminar at the CERN lab in Geneva, Switzerland.

Not Everyone was happy!

The Nobel prize cost him $100."

Why we have matter in the world?

Does matter differ from antimatter?

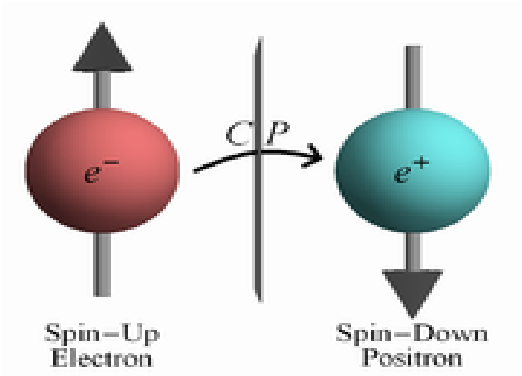
From Big Bang, we expect:

$N_{matter} = N_{antimatter}$

Then why is our Universe matter-dominated?
The answer must involve breaking of a symmetry called CP (Changing all the particles by anti-particles, and looking at the situation in a mirror (reflection through center in fact))

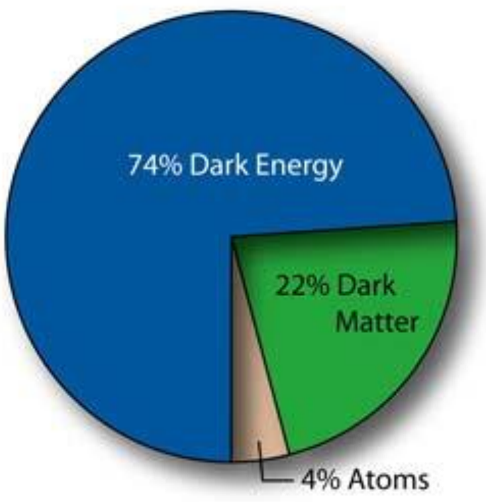
Can weak interactions provide enough of this breaking?

Are there new forces involved which cause CP violation?

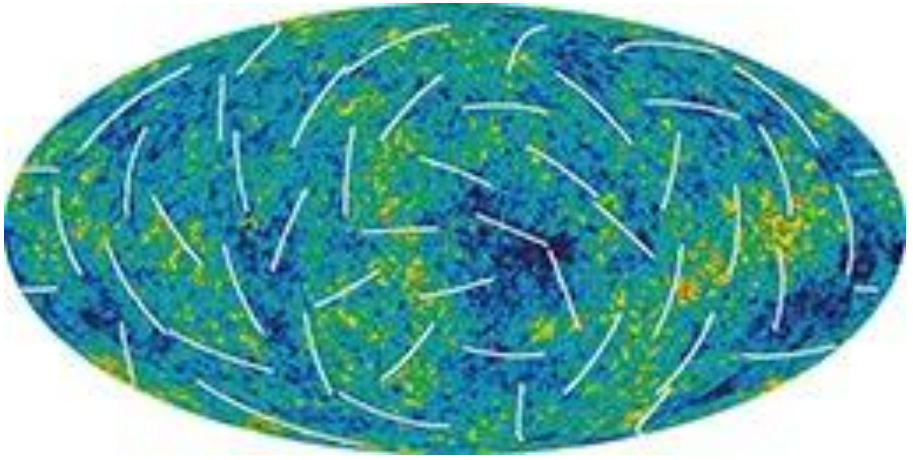


What is Dark Matter?

A lot of recent excitement over our new view of the Universe



WMAP Data: Cosmic Microwave Background



The tools are sophisticated telescopes which look at EM waves in the microwave region.
The CMB is a fundamental prediction of ~any Big Bang Model

Doppler shifting of atomic spectral lines indicate galaxies are rotating faster than they should based on the "visible mass" → Dark Matter ??

Beyond the Standard Model

- Why do we observe matter and almost no antimatter?
- What is this dark matter?
- SM doesn't predict the value of particles masses?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- Why are there exactly three generations of quarks and leptons?
- How does gravity fit into all of this?

New Physics

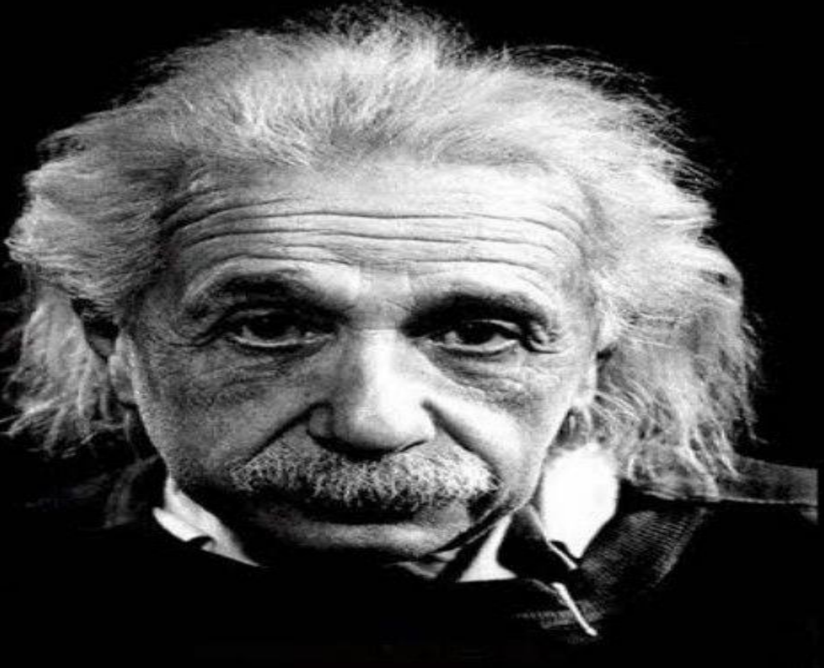
Is there something else going on at higher energies??

Due to various theoretical reasons, scientists believe in various new physics scenarios that may be found at LHC.

These include:

Supersymmetry. (relates fermions and bosons, in this case the particle content of standard model will be doubled, with a super partner for each standard model particle with a different Spin

Extra Dimensions.(this will typically show up as partners of particles with same spin , called KK modes)



“If you want to live a happy life, tie it to goals, not to people.”

ALBERT EINSTEIN