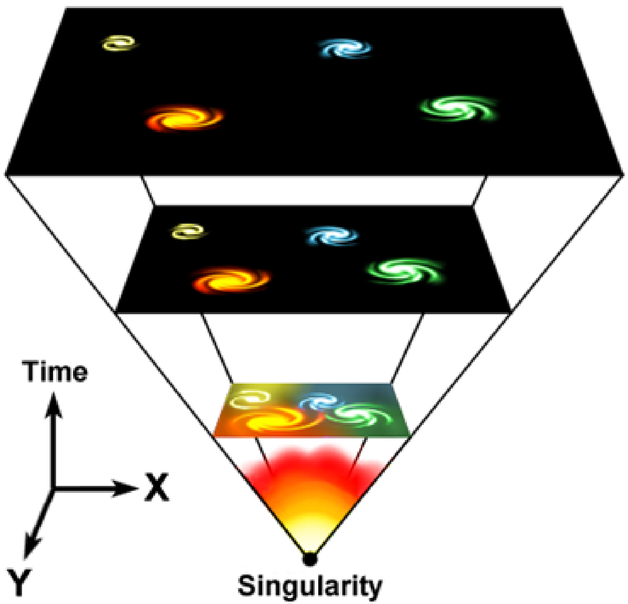
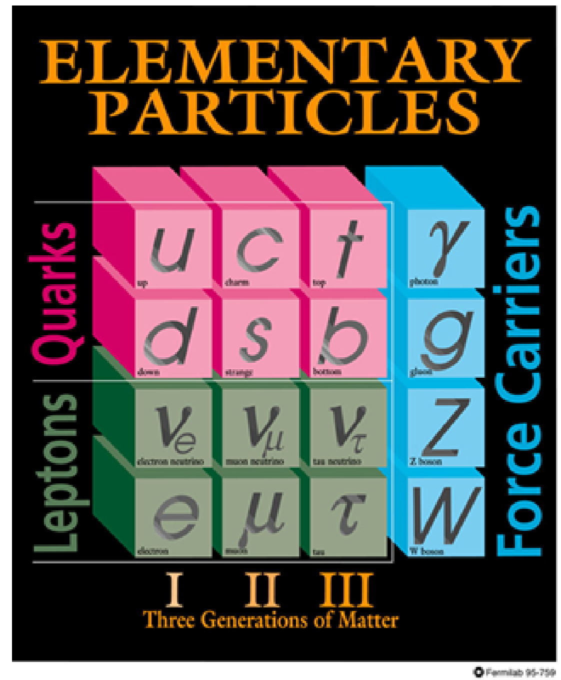
The Early Universe, fundamental forces, and the origin of matter

reading: "State of the Universe", Ch. 9, pp 154-169





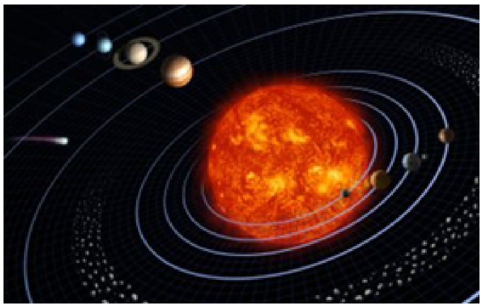
In the Big Bang model
the universe was (very) hot and dense
in the first few stages of its evolution

- We have discussed how Einstein's theory of general relativity (GR) is used to model expansion of the Universe
- Dynamical nature of the equations and expansion of space imply existence of very dense and very hot initial state of the Universe:
  - *Support for this is the existence of the relic Cosmic Microwave Background radiation with a black body spectrum*
  - *Models for nucleosynthesis of hydrogen, helium, and lithium during the first three minutes explain why most of the normal matter in the Universe is ~75% hydrogen, and ~24% helium by mass*
  - *but the normal matter is not the most fundamental and not the only constituent of the Universe…*

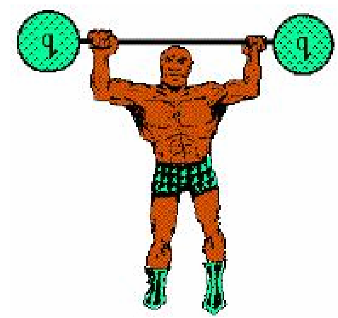
Fundamental forces

the constituents of the Universe can be described in terms of a menagerie of particles and four fundamental forces

Q: what is a force?



gravity



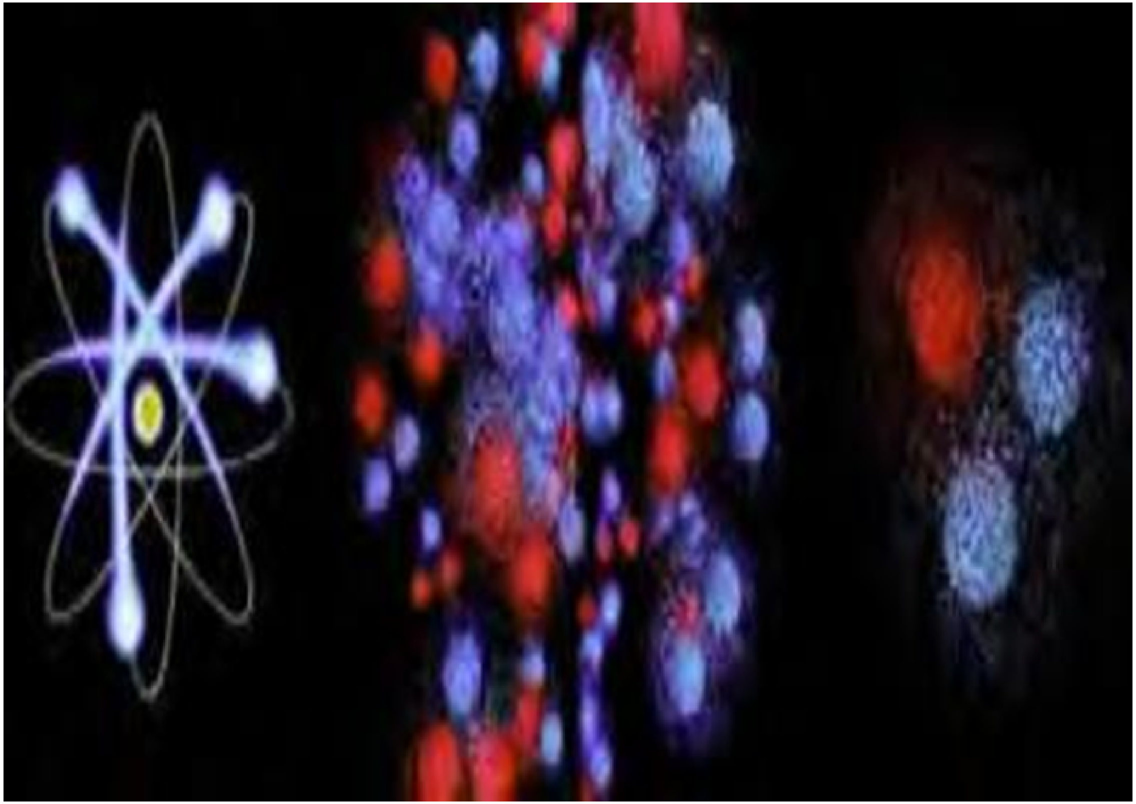
Strong force

electromagnetic force

weak force

Electromagnetic, strong, and weak forces are governing the structure and properties of atoms and atomic nuclei

these three forces can all be described in a very similar way



atom

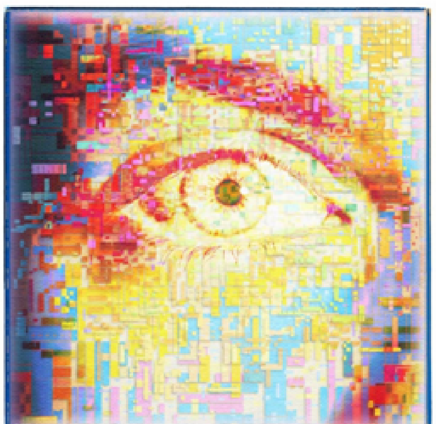
proton or neutron

atomic nucleus

Electromagnetic (EM) force

the most familiar and extremely important force:

- we perceive the word the way it is because of it (not only the fact that we can see things, but also the fact that things appear material to us)
- the fact that we can touch, push, and simply walk the ground is due to the EM force



Daniel Bernoulli

Charles-Augustin
de Coulomb

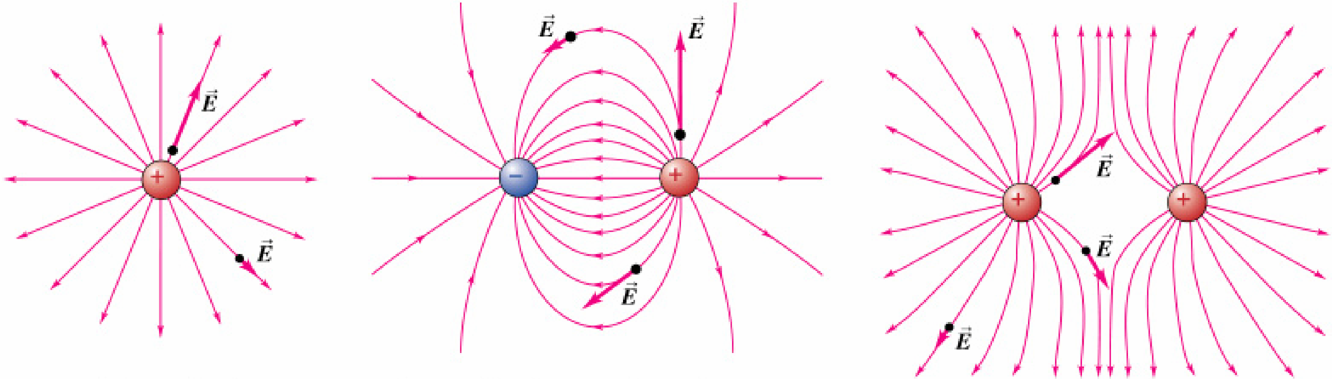
$$|F| = k_C \frac{|q_1||q_2|}{r^2}$$

Coulomb's law.
Looks familiar?

Force field

Michael Faraday

Michael Faraday introduced the concept of electric *force field* – a field that emanates from each electric charge into space. If another charge is placed in the field, it feels the electric force and the force fields of two particles interact. Force field is simply a mathematical concept used to describe what experiments indicated…



(a) A single positive charge (compare Figure 21.16)

(b) A positive charge and a negative charge of equal magnitude (an electric dipole)

(c) Two equal positive charges

Michael Faraday

Connection of electric and magnetic forces

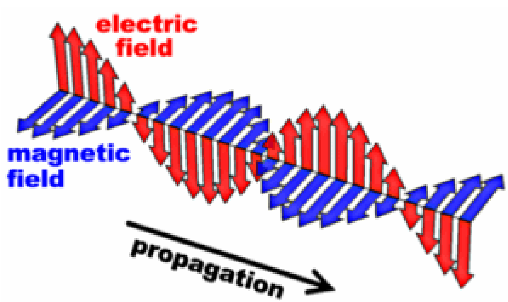
Michael Faraday used experiments to show that *electricity and magnetism are connected.*

For example, moving electric charges influenced magnets, and moving a magnet though a coil of wire generates electric current in the wire.

This was interpreted as an indication that *electricity and magnetism are a manifestation of the same underlying electromagnetic force*

Theory of Electromagnetism

James Clerk Maxwell



Electro-magnetic radiation

In 1864, James Clerk Maxwell came up with a set of differential equations that described the empirical data on the electric and magnetic forces/fields and their relation to each other

- equations described how perturbances in electric and magnetic fields propagate in space and time
- according to this theory, such perturbances or waves are propagating with the speed of light (this directly implies that light itself is an electromagnetic wave)
- at the same time, quantum mechanics developed in the beginning of the 20th century indicated that light and radiation in general came in discrete parcels, called *quanta*

Theory of Electromagnetism and failure of the galilean transformations

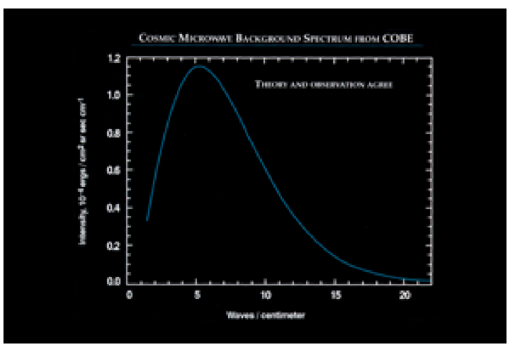
James Clerk Maxwell

In his theory Maxwell had to assume that Galilean transformations (v'=v+u, and absolute time) are wrong, otherwise his equations would change form in different uniformly moving frames of reference

- this was first indication that something was amiss in the standard view of space and time
- later this was tackled by Einstein and led to the development of special theory of relativity

Electromagnetic radiation and quantum mechanics

Max Planck



spectrum of black body radiation

In late 19th century, Max Planck tried to explain the shape of the spectrum of the black body radiation observed in laboratory, and came up with an idea that electromagnetic waves come in discrete parcels of energy – *quanta*

this proved to be a very fundamental paradigm shift and changed understanding of the laws governing microscopic physics profoundly. However, quantum mechanics developed before 1930 did not satisfy the revised view of space-time of special theory of relativity

Development of the quantum field theory

Paul Dirac

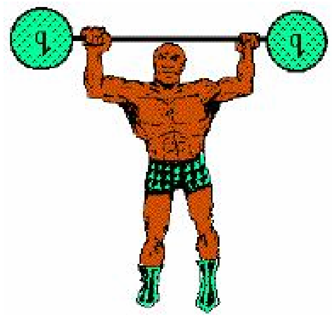
In 1928 Paul Dirac formulated equation describing quantum behavior of electron which satisfied transformations of special theory of relativity.

- the equation describes probability of finding an electron or photon at a given time in a given location of space
- Dirac's equations showed that particles and forces can be described with the same mathematical language of fields
- The equation also suggested existence of an electron's twin – a positron, particle with similar properties but positive charge. Such particles are called anti-particles. Later it was realized that all fundamental particles have anti-particle twins…

quantum field theory

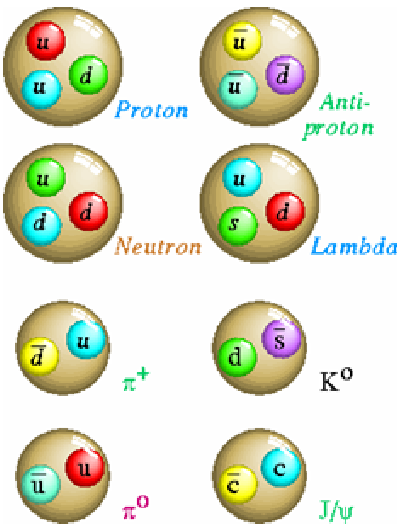
- Particles and forces between them can mathematically be described as fields – functions defined as a function of time and spatial coordinates.
- Forces are mediated by special particles (e.g., EM by photons) and propagate at the speed of light.
- Particles have different properties in addition to charge and mass, such as "spin"
  - *particles with integral spin (e.g., 1, -1) are called <u>bosons</u> (photons, gravitons)*
  - *particles with half-integral spin (e.g., ½) are called <u>fermions</u> (electrons, protons, neutrons)*
  - *fermions are particles which interact via exchange of bosons, the mediators of forces (i.e., EM, strong, weak, gravity forces)*

Strong force

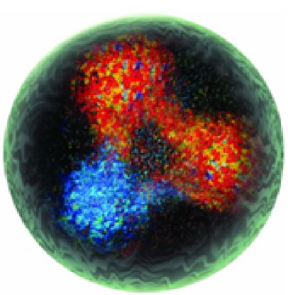


- Much stronger than the EM force but is only strong at small separations (comparable to the size of atomic nuclei),

  this force can overcome repulsive force between positively charged protons binding them in nuclei

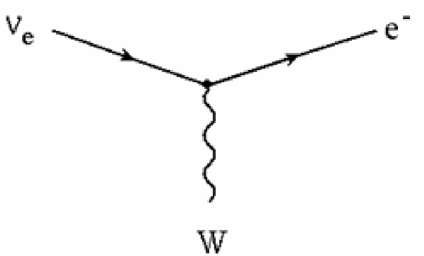


- at larger separations EM force is stronger.
- Protons and neutrons are actually made up from more fundamental particles, called *quarks*
  - *quarks have spins of ½ like fermions, but charges of 2/3 and -1/3. They also have other properties which distinguishes different types of quarks.*
  - *triplets of quarks are bound in protons and neutrons by the strong force.*
  - *quarks interact via mediator particles of strong force called gluons*



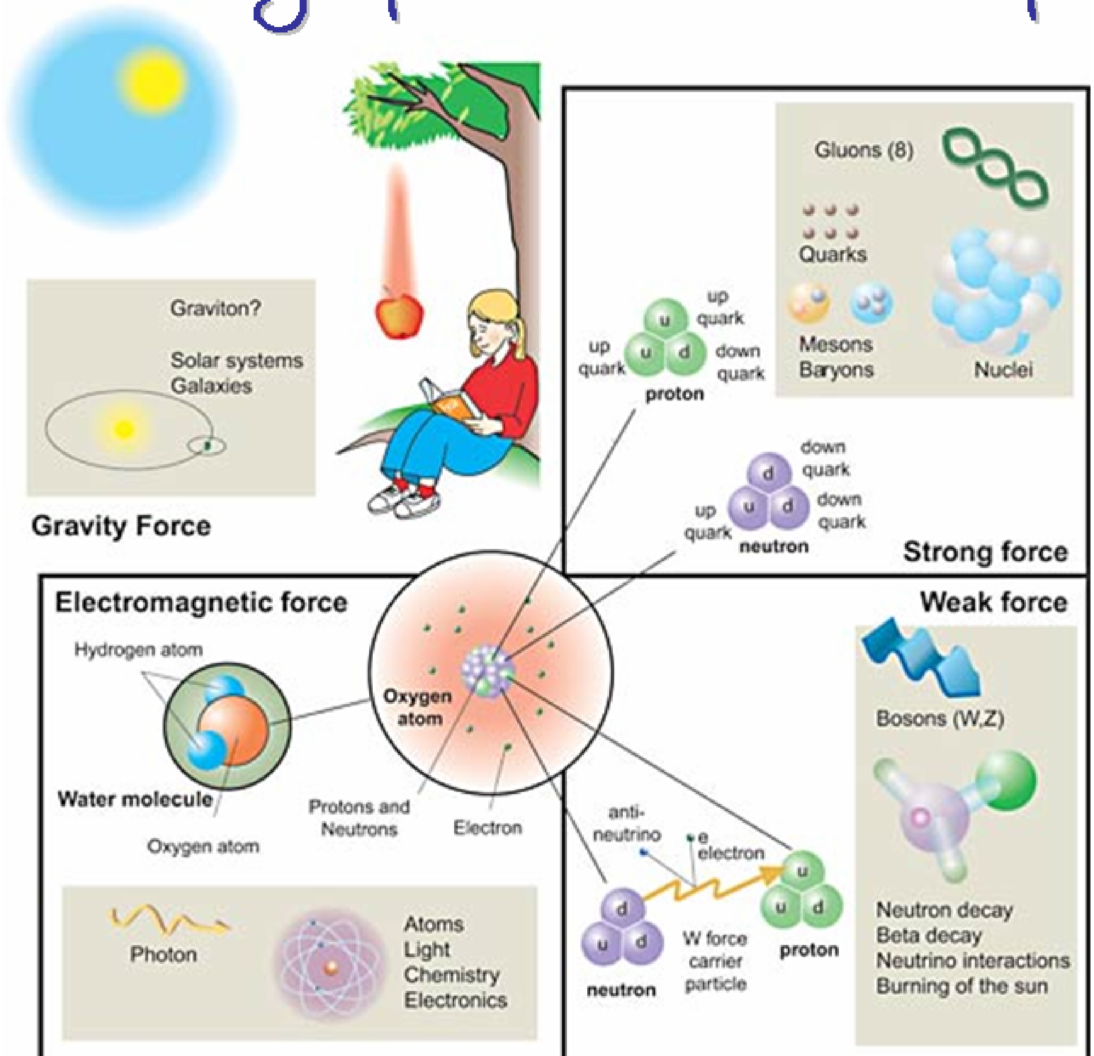
Weak force

- As the strong force, weak force also acts only at small nuclear scales
- Unlike other forces it can change the nature of interacting particles (i.e., interacting particles can be transformed into different particles by this force)
- There are particles, neutrinos, that interact with other particles only via weak force. Because of this, it is very difficult to detect them, but there are ~ten billion neutrinos generated by nuclear reactions in the Sun passing through your bodies every second!
- Enrico Fermi formulated a theory of weak interactions and postulated existence of neutrinos



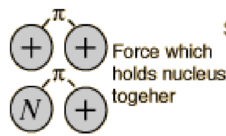
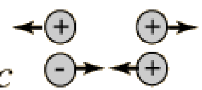
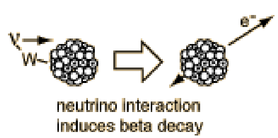
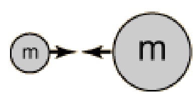
"The chances of a neutrino actually hitting something as it travels through all this howling emptiness are roughly comparable to that of dropping a ball bearing at random from a cruising 747 and hitting, say, an egg sandwich." – Douglas Adams

Summary: fundamental forces



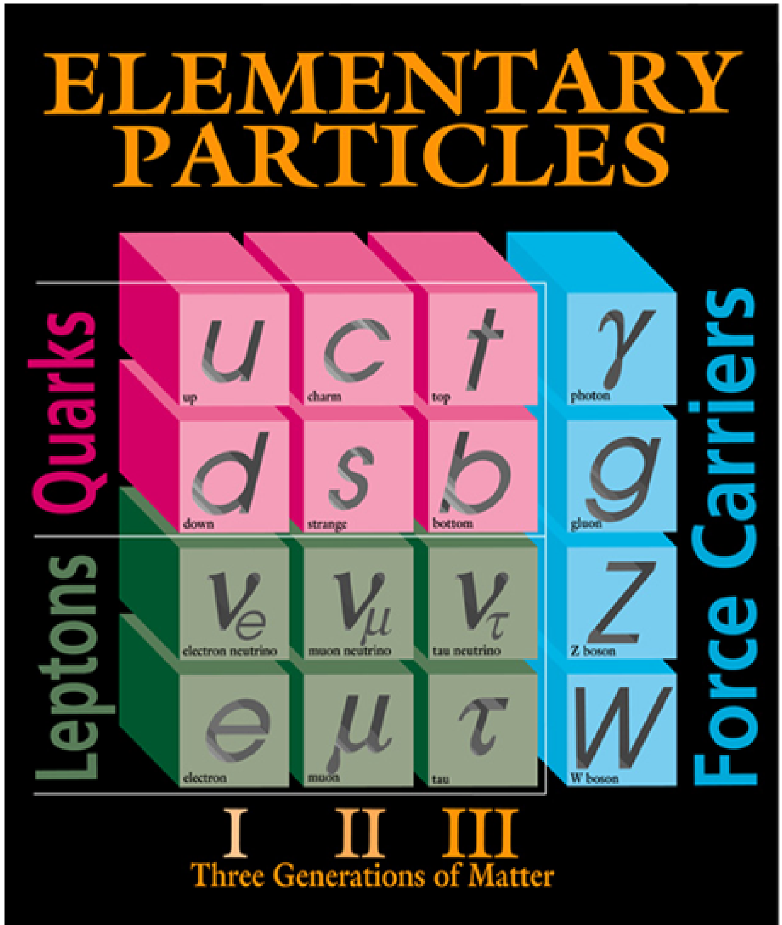
The hierarchy puzzle: very different relative strengths of the four fundamental forces

Fundamental Forces

Force		Strength	Range (m)	Particle
Strong		1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak		10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM!"

Despite the apparent complexity and large variety of particles there are simple foundations and underlying summetries



+ graviton

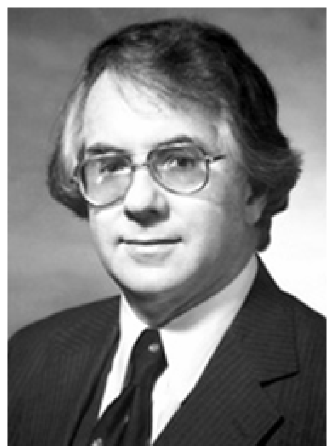
These symmetries imply deep connections between different particles and different forces in nature

This gives motivation to the idea that there is one unifying explanation for all the forces and particles (the grand unification)

Unification of electromagnetic and weak forces

- In 1960s, Glashow, Salam, and Weinberg came up with a theory which explained both EM and weak force as a manifestation of a single unified force
- This worked if one assumed that quarks and leptons have negligible mass, which would be true if all of their energy was in the form of energy of their motions and their rest mass is not important.
- This is true if particles have a lot of kinetic energy of motions and move with velocities close to the speed of light

Steven Weinberg



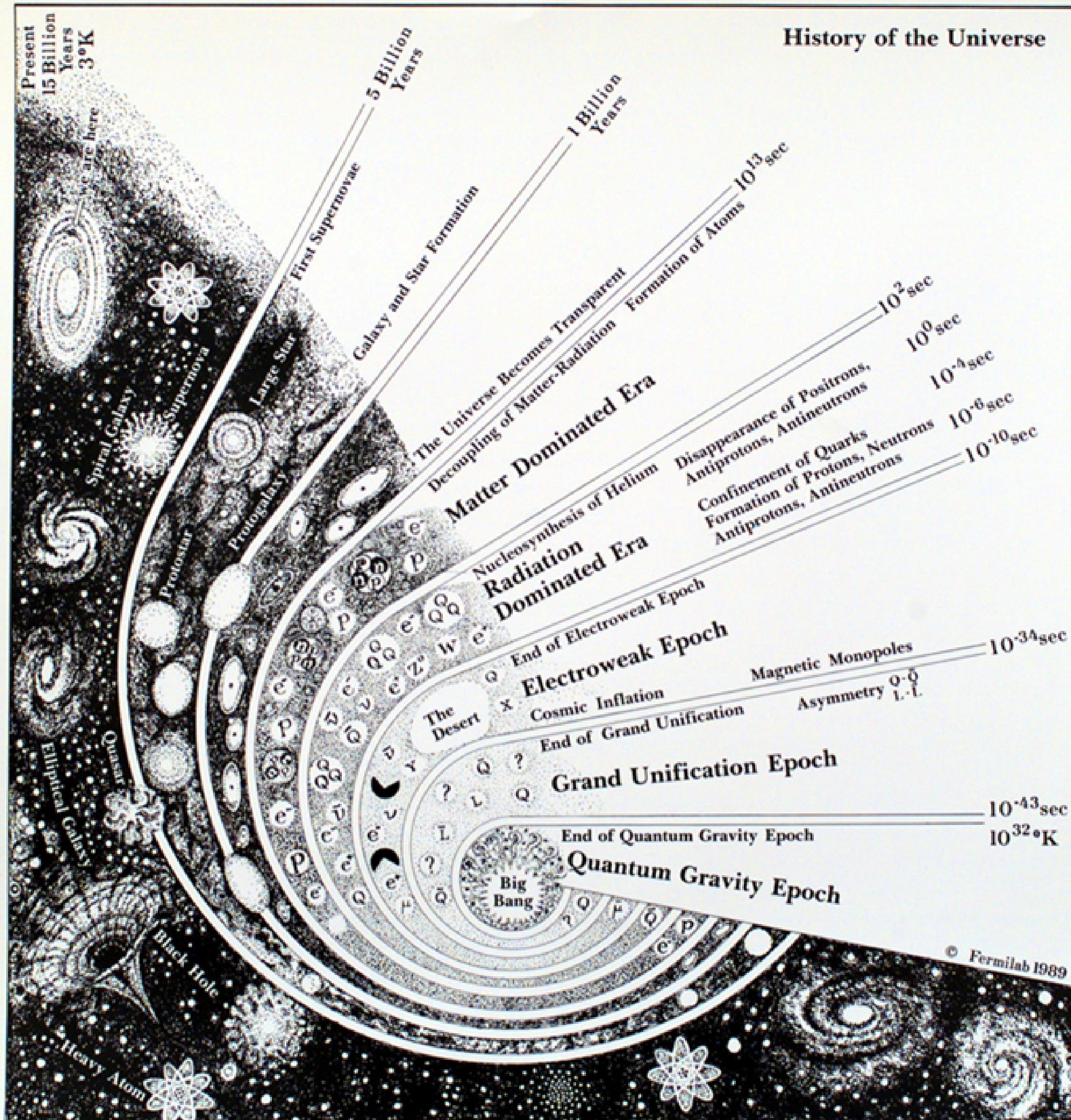
Sheldon Glashow

Abdus Salam

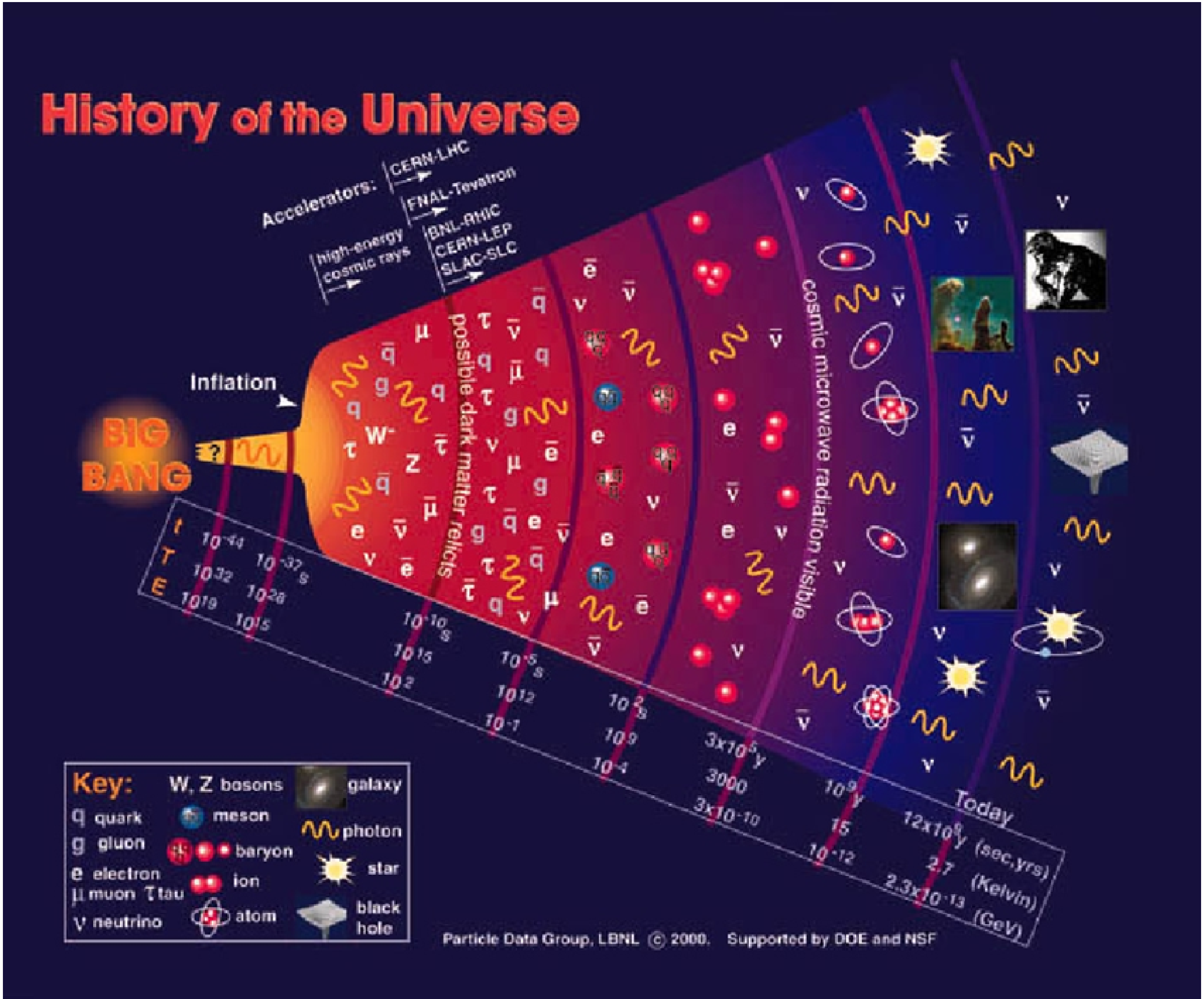
Unification of electromagnetic and weak forces

- The electroweak theory postulated that two new particles – W and Z gauge bosons, mediated interactions of the new unified force.
- These particles were later discovered in the CERN laboratory experiments in 1979
- EM and weak forces are thought to have been unified early in the evolution of the Universe when all particles were “hotter” – or had more kinetic energy, and thus closer to the conditions of unification

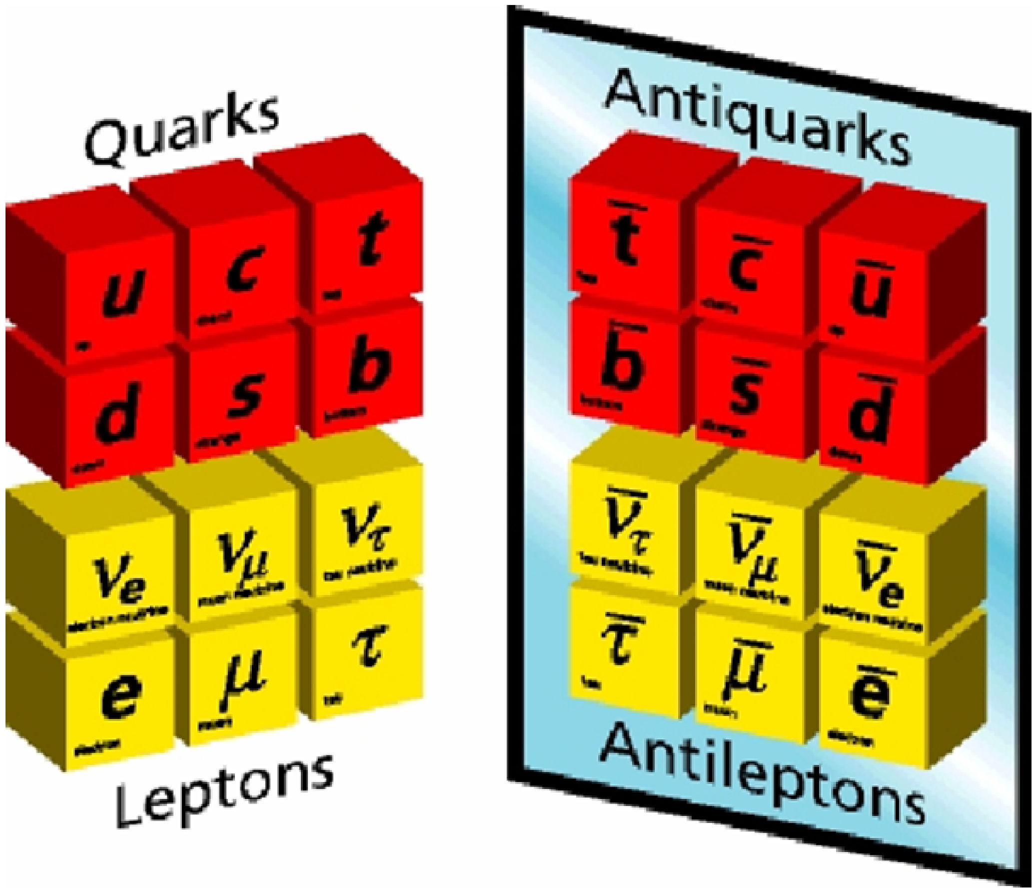
Aerial view of the CERN laboratory



History of the Universe
Present
15 Billion Years
3°K
5 Billion Years
1 Billion Years
10^{13} sec
10^{2} sec
10^{0} sec
10^{-4} sec
10^{-6} sec
10^{-10} sec
10^{-34} sec
10^{-43} sec
10^{32} °K
First Supernovae
Galaxy and Star Formation
The Universe Becomes Transparent
Decoupling of Matter-Radiation
Formation of Atoms
Matter Dominated Era
Nucleosynthesis of Helium
Disappearance of Positrons, Antiprotons, Antineutrons
Confinement of Quarks
Formation of Protons, Neutrons
Antiprotons, Antineutrons
Radiation Dominated Era
End of Electroweak Epoch
Electroweak Epoch
Magnetic Monopoles
Cosmic Inflation
Asymmetry
The Desert
End of Grand Unification
Grand Unification Epoch
End of Quantum Gravity Epoch
Quantum Gravity Epoch
Big Bang
Spiral Galaxy
Supernova
Large Star
Protogalaxy
Protostar
Quasar
Elliptical Galaxy
Black Hole
Heavy Atom
© Fermilab 1989


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relics
cosmic microwave radiation visible
t
T
E
Today
(sec,yrs)
(Kelvin)
(GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole
Particle Data Group, LBNL © 2000. Supported by DOE and NSF

Symmetry between matter and anti-matter?



Most of the observed matter in the Universe is of the usual kind (i.e, not anti-matter). Why?

- if islands of anti-matter existed, we should have detected copious amounts of radiation coming from the boundaries with normal matter, where matter and anti-matter would be annihilating
- plus, any such arrangement would imply strong inhomogeneities in the early universe, thereby violating one of the most fundamental tenets of the Big Bang model.
- one idea: assymetry in the initial amounts of matter and anti-matter due to some assymetry of forces and interactions in the early universe
- photons leftover from the annihilation of matter and anti-matter are the photons we now observe as the Cosmic Microwave Background

These symmetries imply deep connections between different particles and different forces in nature

This gives motivation to the idea that there is one unifying explanation for all the forces and particles (the grand unification)