If it is so hard to push quarks together (to overcome the EM repulsion), how do quarks in my body come together?

All these energy spent to push quarks together, where does it go?

quarks: strong, EM, weak, gravity
electrons: EM, weak, gravity
neutrinos: weak, gravity(?)

Properties of Leptons

Charge	1st generation	2nd generation	3rd generation
-1	electron $5.45 \times 10^{-4}\ M_p$ 5.11×10^{-4} GeV/c^2	muon $0.113\ M_p$ 0.106 GeV/c^2	tau $1.90\ M_p$ 1.78 GeV/c^2
0	electron ne[illegible] $<1.07 \times 10$[illegible] $<1.14 \times 10^{-8}$ GeV/c^2	[illegible] $<2.85 \times 10^{-4}$ GeV/c^2	tau neutrino $<0.075\ M_p$ <0.080 GeV/c^2

Only upper limits!

- Note how the first row increases in mass along generations
- Do neutrinos have mass? This would have a big impact on cosmology if they do. SNO EXPERIMENT STRONGLY SUGGESTS THEY HAVE MASS!
- If neutrinos have mass, then they may contribute significantly to the dark matter component of our universe (since there are so many of them around!)
- If neutrinos have no mass, the only way they can interact is via the weak force. A block of lead 100 trillion km thick would be needed to significantly reduce the number of neutrinos passing through your body

The Sun generates neutrinos copiously (nuclear reactions). 10^{12} of these pass through your body every second.

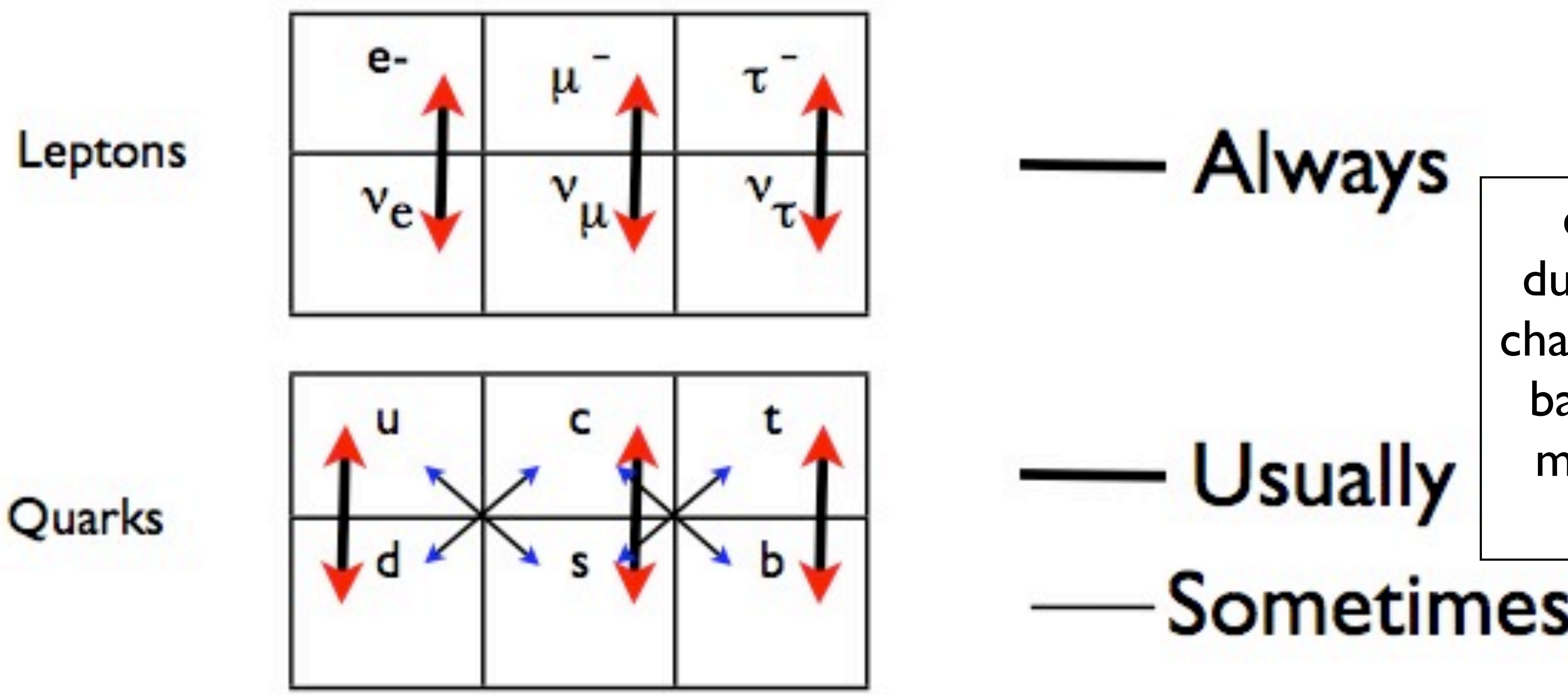
The Weak Force (or 'weak interaction')

Weak	10^{-5}	10^{-17} m	Breaks atoms apart

- Most difficult of the forces to describe: it is unlike our concept of conventional force.
    - it is neither attractive nor repulsive, but rather it changes particles from one type to another.
- It's felt by both leptons and quarks.
- It is associated with the generational structure of quarks and leptons.

- It is weak.
- It acts over a distance ~ 1% of a proton size.

Weak interactions transmute fundamental particles ('flavour changes')

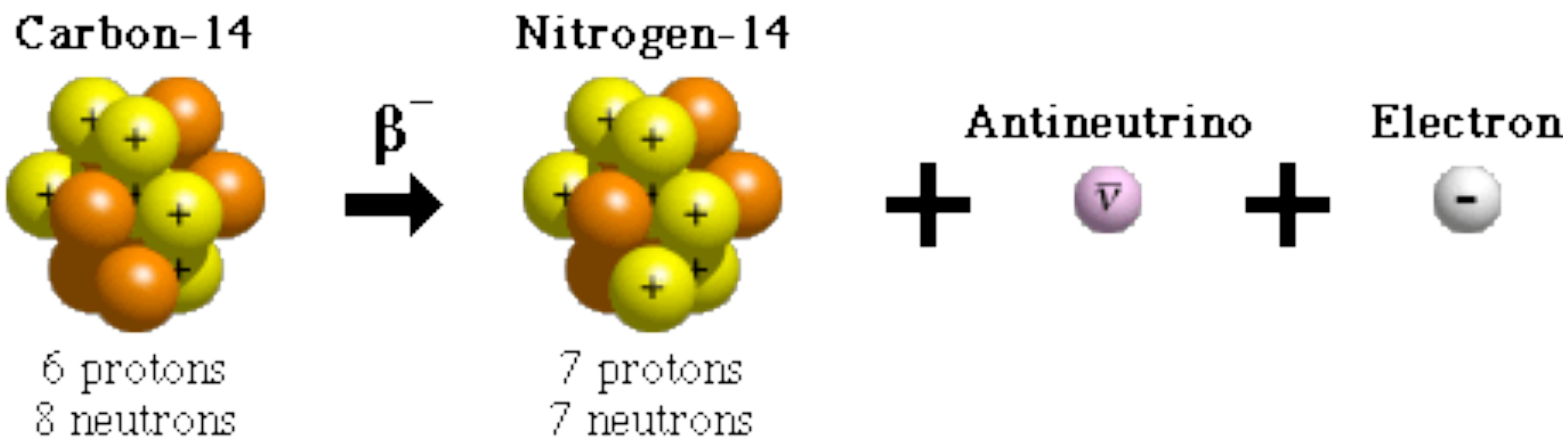


conservation rules during transformation: charges, lepton numbers, baryon numbers... but may be broken in the early universe

The "generation gap" appears to be larger for leptons! They don't appear to be able to move across generations.

But news from Sudbury Neutrino observatory....

An important weak force interaction --- beta decay



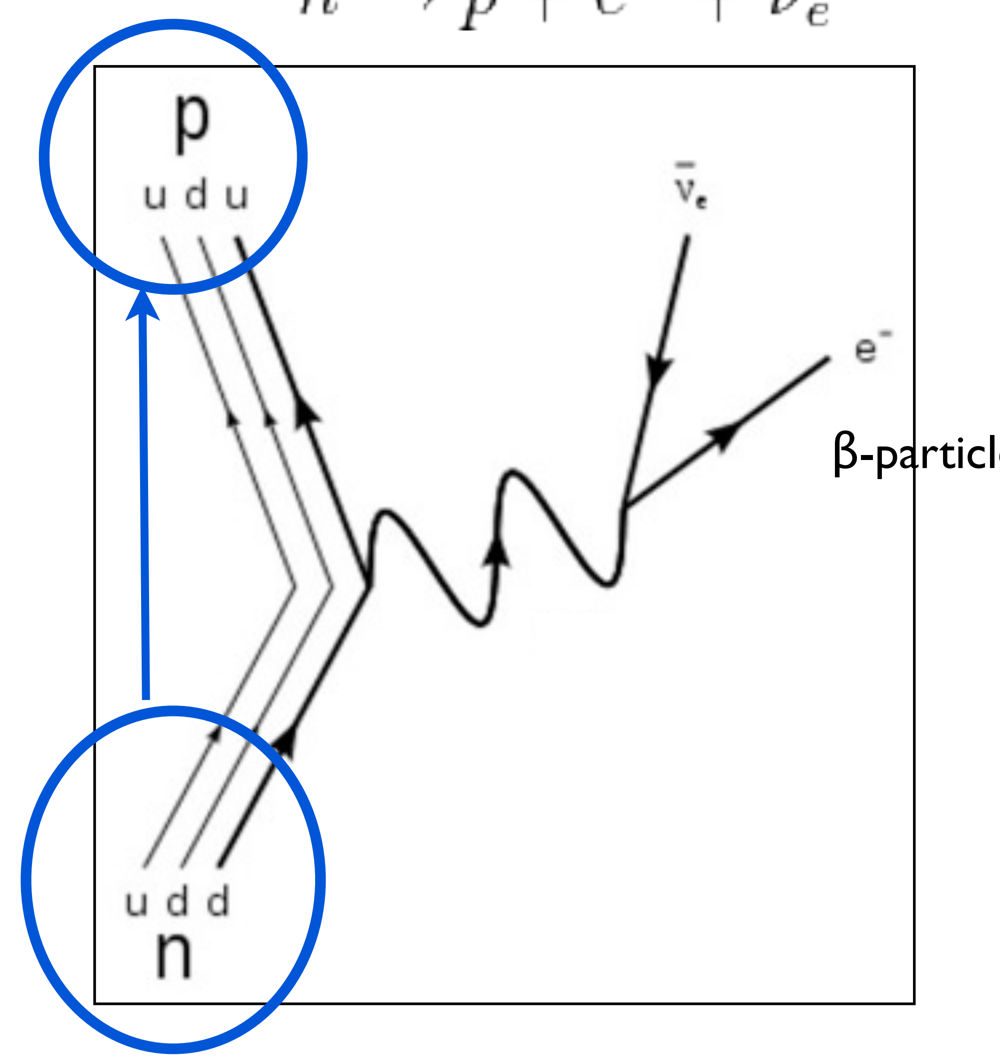
Nucleus (A,Z)
less stable

Nucleus (A,Z+1)
more stable

$$n \rightarrow p + e^- + \bar{\nu}_e$$

Alchemy

Radioactivity



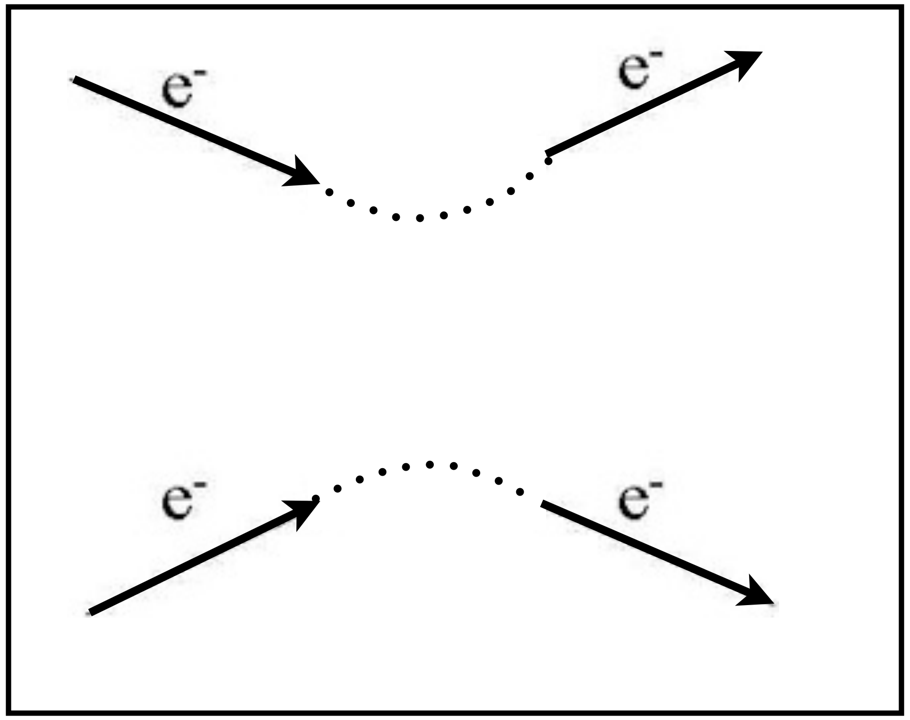
A modern understanding of 'force' (Allday §11)

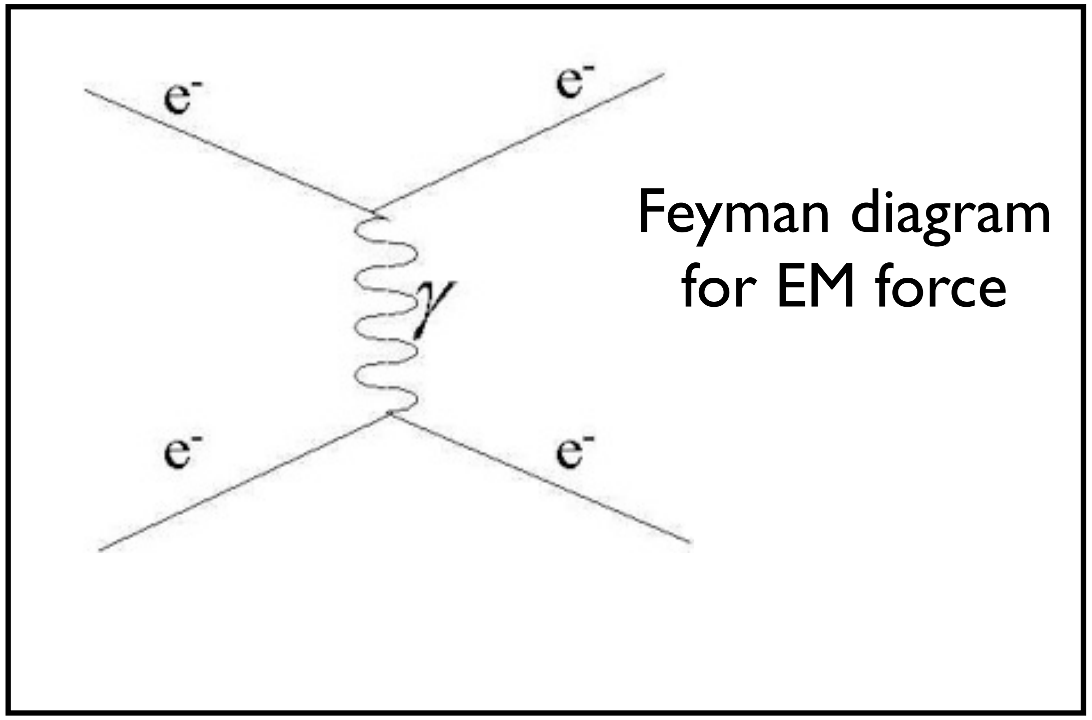
Electron scattering (repulsion between two approaching electrons).

Classically, the repulsive force felt by one electron is exerted by the other.
Standard Model, force arises due to exchange of the force carrier particles (bosons) between interacting quarks and leptons (fermions).

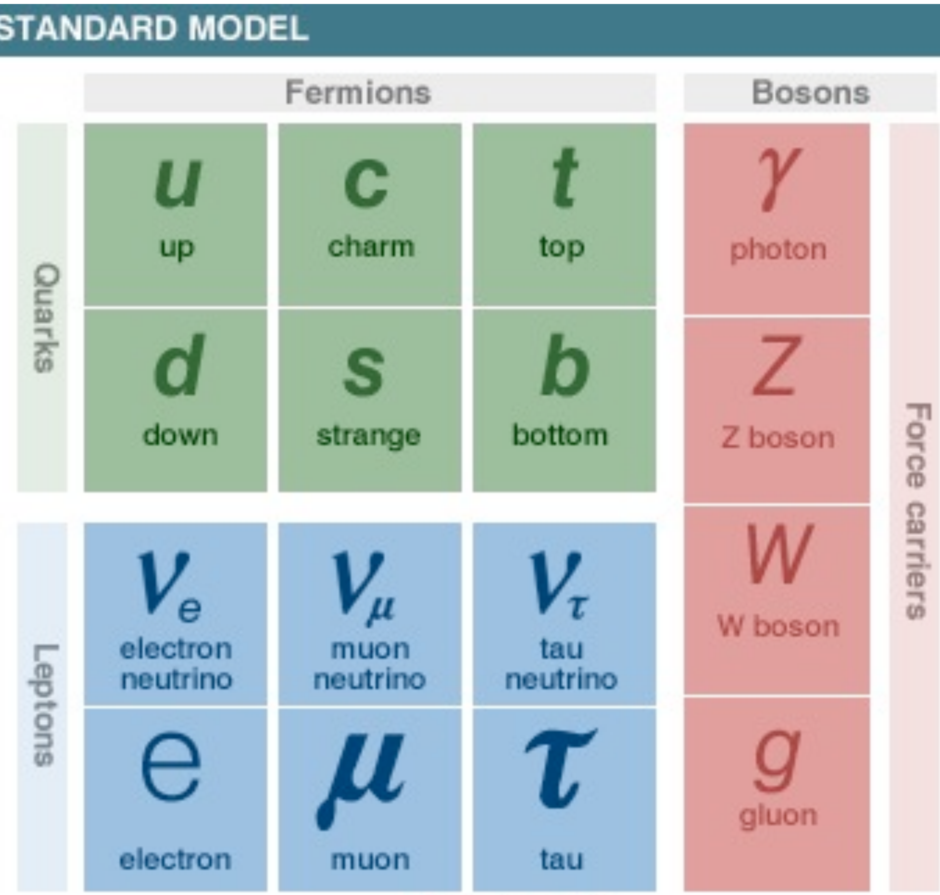
Scattering re-interpreted: two electrons exchange photon on close-passage, since photon transports energy and angular momentum from one to the other, trajectories of both electrons modified -- appear to run away from each other.

A casual (classical) observer would remark: aha, two electrons repel each other.

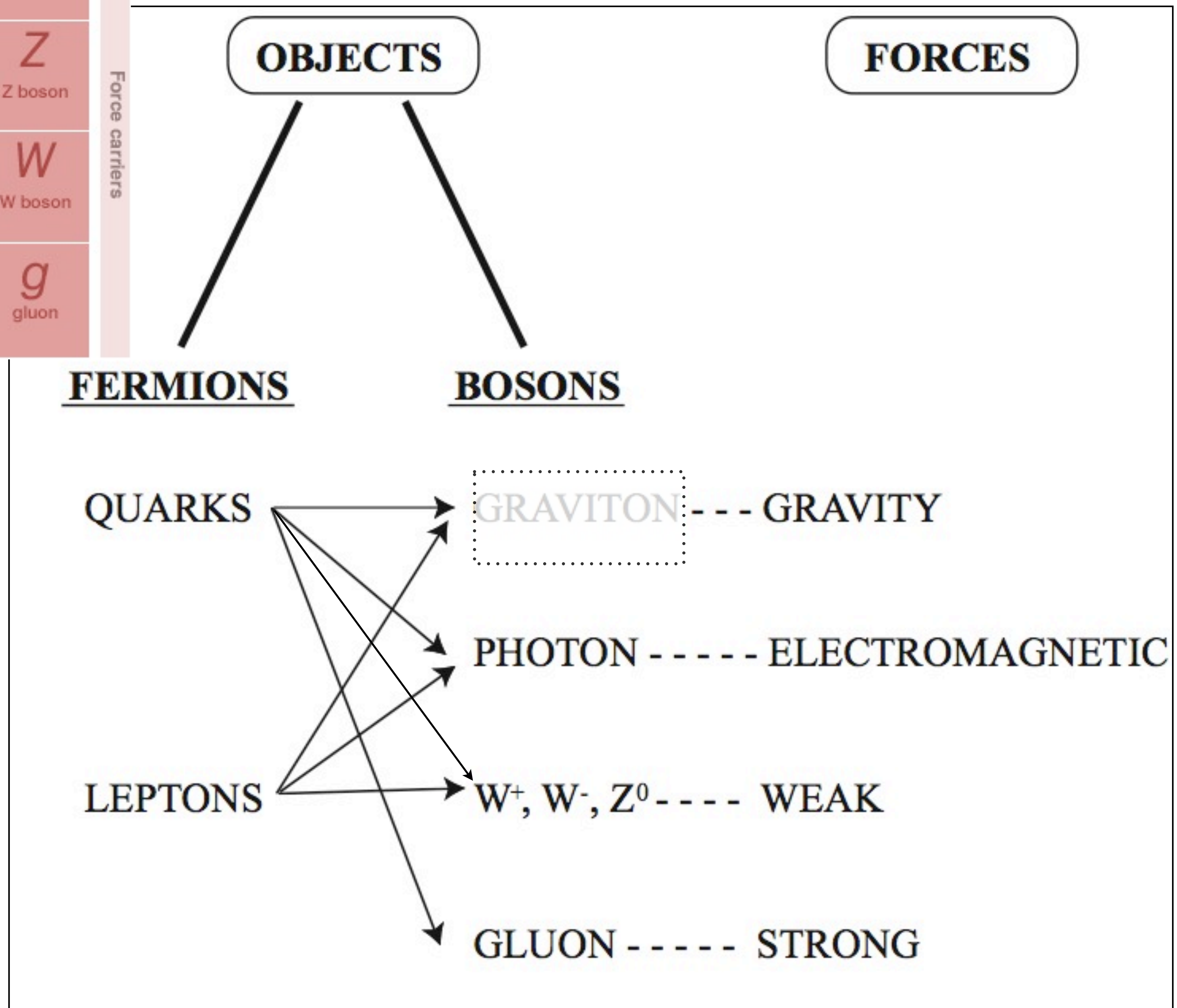


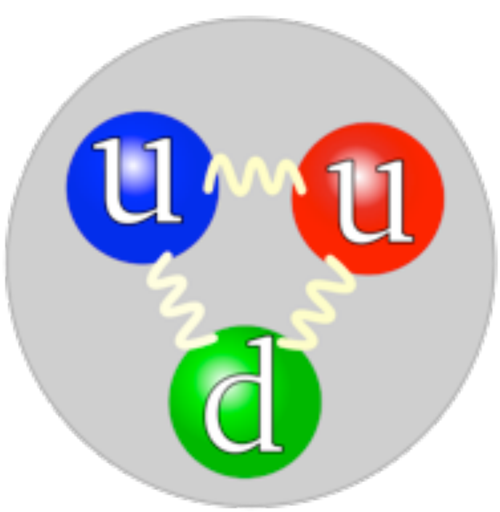


force = exchange of 'force carriers' (bosons)



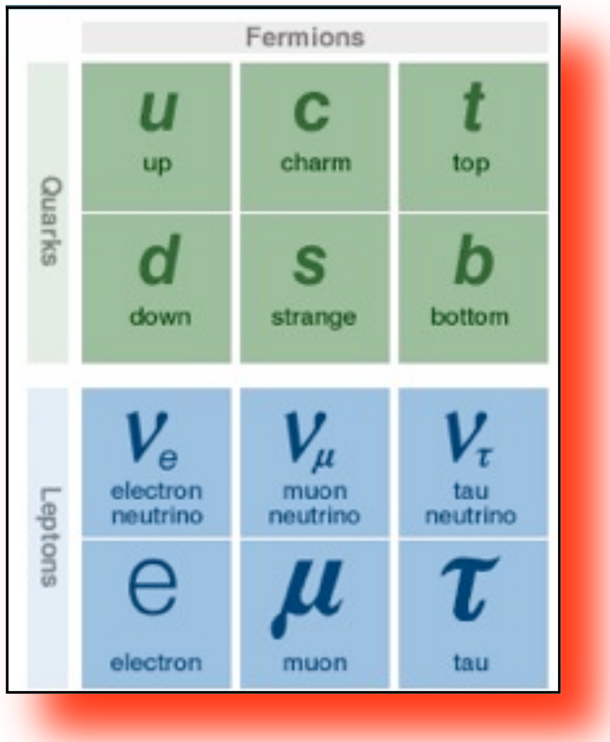
Bosons are “force carriers”





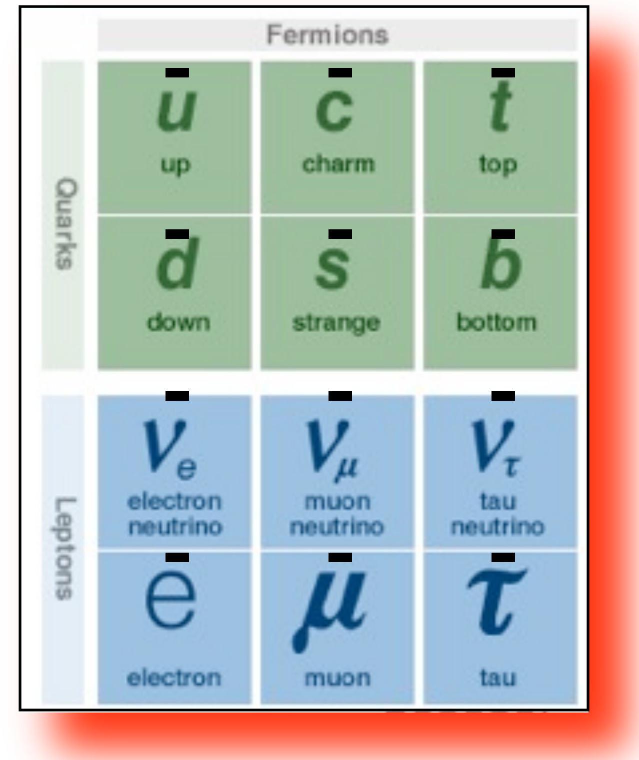
Proton mass ~ 1 Gev/c^2
>> quark masses

6 quarks + 6 leptons, that's it?



"MIRROR"

"mirror" (symmetry, super-symmetry...)
generates a new set of particles
-- anti-quarks & anti-leptons



Identical particles except for charge,
baryon number/lepton number....
anti-matter particles

u & u: identical mass
opposite charge/baryon #
when they meet, 'annihilate'

- When a particle and an antiparticle interact, they annihilate each other and give off other particles and/or photons.
  - in an annihilation reaction $2mc^2$ energy is released into creating other particles or photons (=gamma rays). The inverse is true also: you can also create a particle-antiparticle pair by interacting γ–rays.

!!!! *THIS IS THE ENGINE FOR CREATION* !!!!

$$E = m\,c^2$$

Hiroshima bomb

=

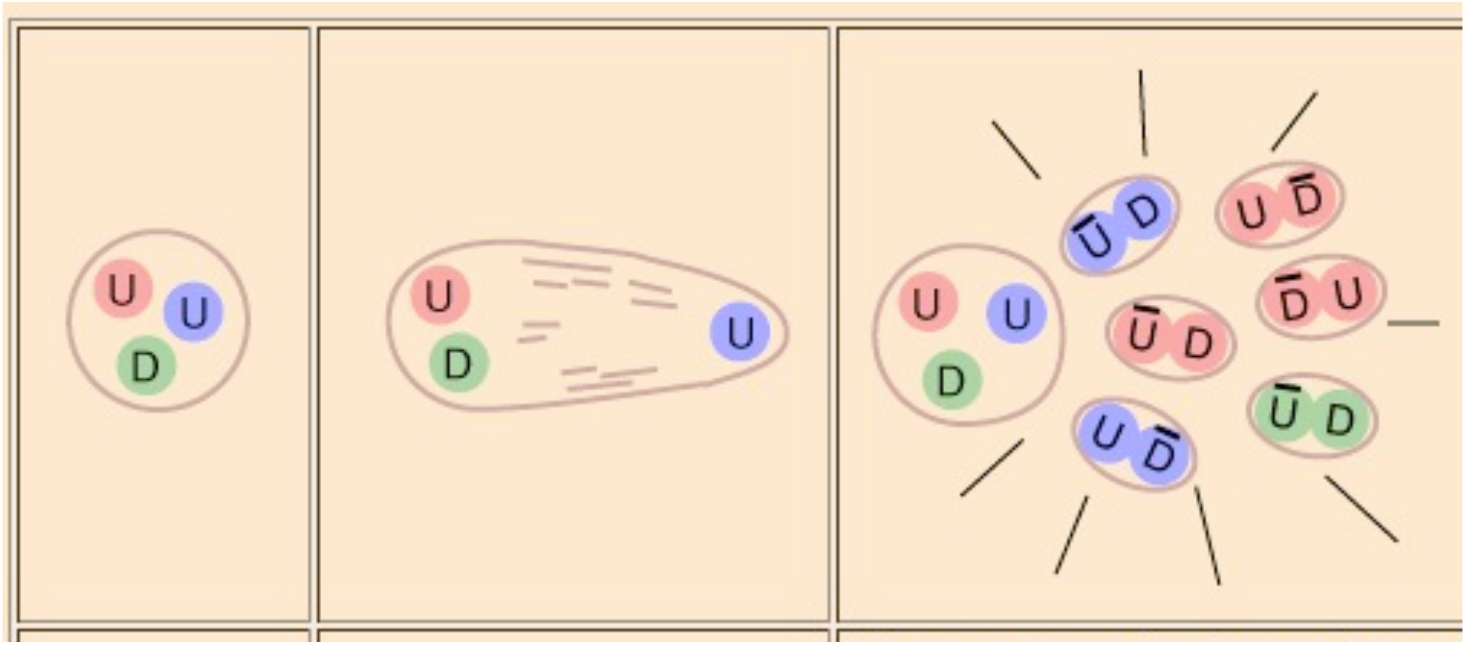
0.2 g matter

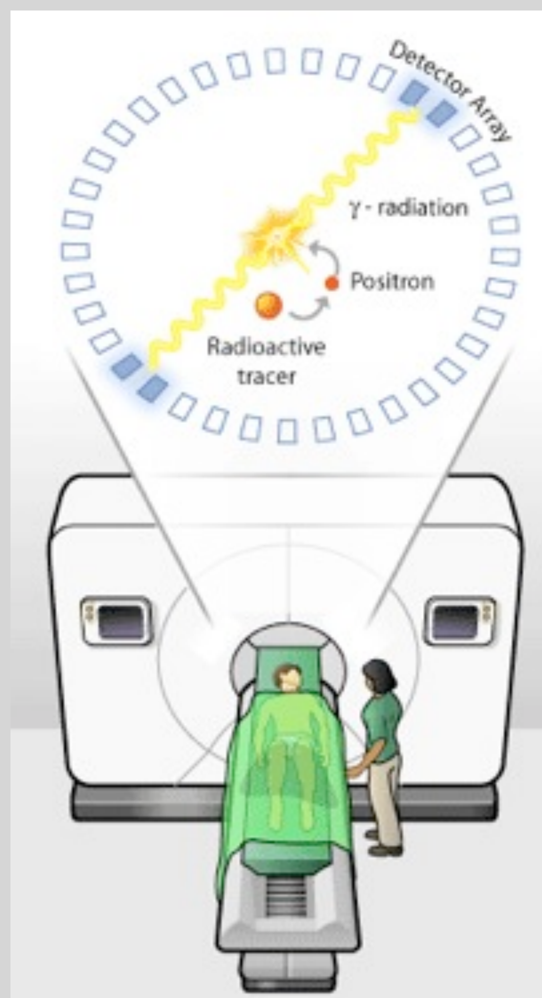
+

0.2 g anti-matter

- Our universe is predominately made of matter. How would an anti-matter universe look like?
- When universe was just born, photons produce ~ equal amounts of matter & anti-matter.
- For some reason, a very small, inexplicable asymmetry.

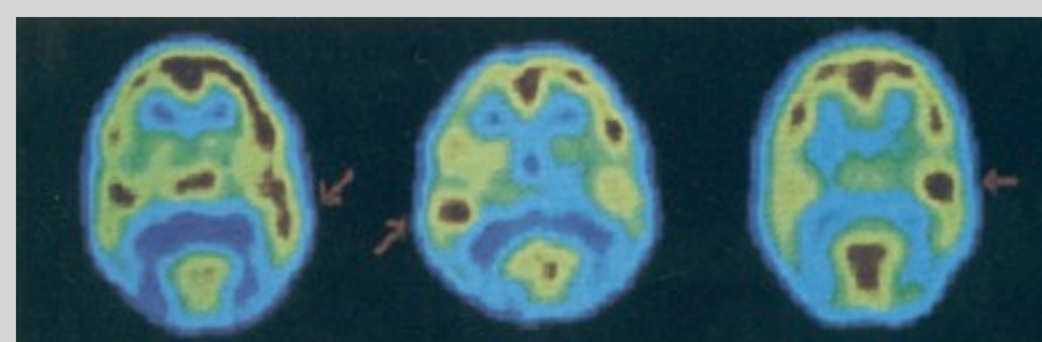
“Anti-matter is science-fiction. There is only matter on Earth” ...?





P(ositron)E(mission)T(omography)

Positron = anti-electron



cancerous cells absorbs e+-containing sugar, annihilation generates gamma-ray, pinpointing the cells

Vacuum is continuously bubbling with... matter-antimatter pairs

Heisenberg's uncertainty principle (1927)

$$\Delta x \, \Delta p \gtrsim h$$

Position and momentum, cannot be simultaneously known to arbitrarily high precision. The more precisely one property is measured, the less precisely the other can be measured

$$\Delta E \Delta t \gtrsim h,$$

A state that only exists for a short time cannot have a definite energy. To have a definite energy, the frequency of the state must accurately be defined, and this requires the state to hang around for many cycles, the reciprocal of the required accuracy

- matter-antimatter pairs continuously pop in and out of vacuum, for a short spurt of time; "energy" not accurately defined in this duration

an anti-proton can pop up around you, but lasts for a time as short as 10^{-24} sec

- these are 'virtual particles'. Empty space bubbles with virtual particles. This is important in the early universe.

Why are strong force and weak force so short-ranged?

Name	Strength	Range
Strong	1	10^{-15} m
Electromagnetism	1/137	Infinite
Weak	10^{-5}	10^{-17} m
Gravity	10^{-39}	Infinite

$$\Delta E \Delta t \gtrsim h,$$

- The maximum range of an exchange force is limited by the uncertainty principle:
- The force carrier particle has to ‘get back home before it is missed’.
- They are ‘virtual’ particles: created and exist only during the exchange process.
- More massive exchange particles (gluons, W & Z bosons): smaller range for the force: virtual particles can exist for a shorter amount of time and therefore travel a shorter distance.

- EM force & gravity have infinite reach -- because photons and gravitons are massless.

The 100 years' experimental efforts on understanding the nature of elementary particles are summarized in Table 15-01a below:

Date	Detection	Discovery	Credit	Nature
1895	Cathod-ray tube	X-ray	W. Rontgen	High energy photon
1897	Cathod-ray tube	Electron	J. J. Thomson	Electric charge carrier
1898	Photographic plate	Radioactive elements	P. and M. Curie	Unstable nuclei
1911	α particle scattering	Atomic nucleus	E. Rutherford	Modern atomic model
1932	Cloud Chamber	Neutron	J. Chadwick	Neutral constituent of nuclei
1932	Bubble Chamber	Positron	C. Anderson	Anti-matter
1956	Anti-neutrino detector	Anti-neutrino	Cowan and Reines	Weak interaction
1964	UA1 detector	Quarks	CERN	Strong interaction
1979	JADE detector	Gluons	DESY	Force carriers for strong interaction
1983	UA1 detector	W boson	CERN	Force carriers for weak interaction
1995	CDF detector	Top quark	Fermilab	Third generation quark
2000	DONUT detector	Tau neutrino	Fermilab	Third generation lepton

Table 15-01a Major Discoveries of Elementary Particles

CERN: European Organization for Nuclear Research

1. world's largest
2. founded 1954, to boost post-war European science, and to share cost of large experiments, signed by 12 countries
3. great contributions: neutral currents, W&Z particles, anti-hydrogen..., and multiple Nobel prizes
4. annual budget: Euro $700 Million = 0.004% of European Union GDP ($2/pp)
5. ~10,000 scientists from 80 nations.

the Large Hadron Collider Experiment

- world's largest, most energetic (and also most expensive) particle accelerator , 20 years since conception
- current cost ~ US$10 billions, much cost overruns and delays, first beam 2009

University of Toronto
ATLAS Group

Department of Physics
60 St. George St., Toronto
Ontario, Canada, M5S 1A7
Tel:(416) 978-1543
Fax: (416) 978-8221

Goals of LHC:

High speed collision generates high temperature and density; protons and neutrons dissolving into quark-gluon plasma, last 'seen' at 10^{-6} sec after big-bang;

LHC energy: proton-proton ~10 Tev = 10^{13} ev = a mosquito@1mile/h

lead ion 575Tev ~ 10^{6} proton mass

1) the resultant debris reveals nature of strong force

2) matter and anti-matter may decay differently?

3) Higgs boson: the hypothesized Higgs field which gives mass to some particles

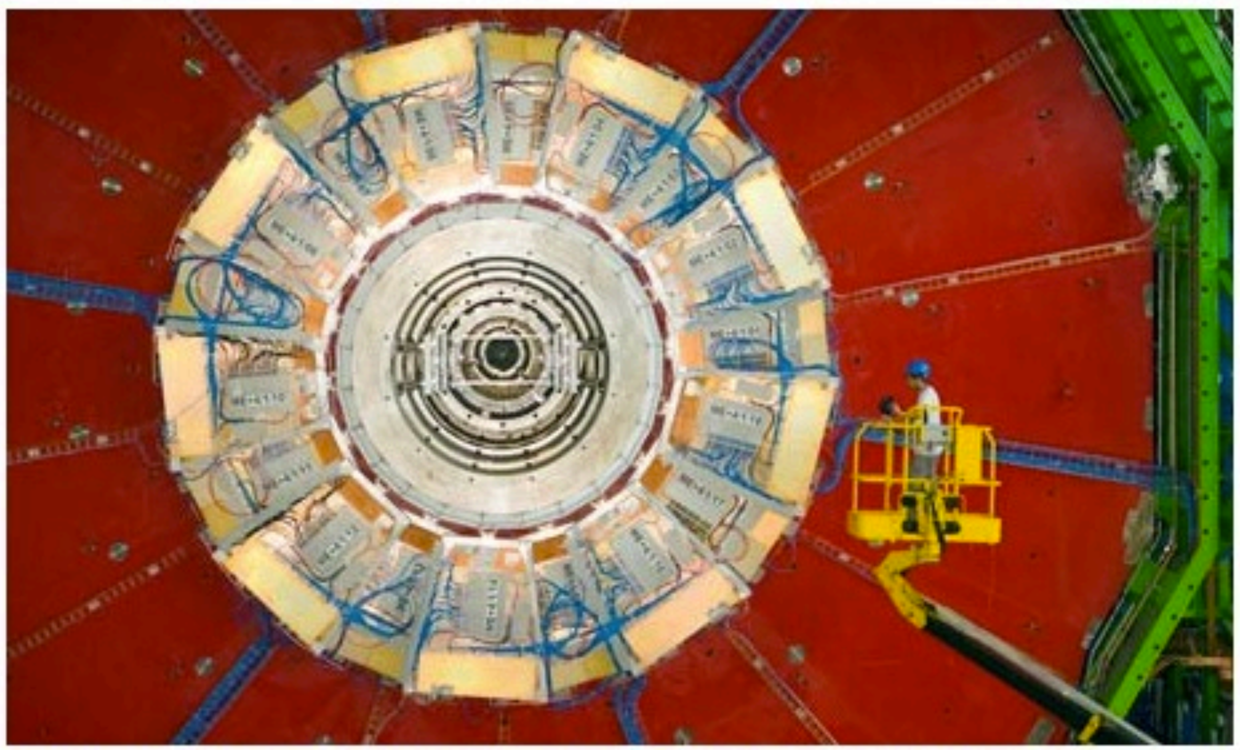
4) super-symmetrical particles, dark matter candidates?

News › Science › AAAS

Discovery of Higgs Boson rated year's top scientific achievement by Science

Other discoveries include sequencing DNA from extinct humans, turning stem cells into egg cells and landing Curiosity on Mars

Robert Booth
The Guardian, Thursday 20 December 2012 19.34 GMT



The Large Hadron Collider at Cern. The discovery of the Higgs Boson was hailed as an 'intellectual, technological and organisational triumph'. Photograph: Mark Thiessen/National Geographic Society/Corbis

From landing the Curiosity rover on Mars after a 350m-mile journey, to the discovery of the world's most wanted sub-atomic particle, the top 10

hypothesized in 1970s (Higgs +)

Higgs boson permeate the universe soon after formation,

particles that feel Higgs gets a 'mass'

photons do not interact with Higgs

first evidences: LHC, July 31, 2012

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Switzerland: Physics

PHY398Y0: Independent Experiential Study Project

Students will be required to complete an analysis project, document the results and give periodic oral reports to the group. The final report will be completed at the end of summer in Toronto. The grade will be determined based on the final report (60%) and an assessment of the oral reports (40%) -- at least two presentations will be required.

Students will work on a project analyzing LHC data under the supervision of one of the senior scientists in the group.

India: Astrophysics

AST398H0: Independent Experiential Study Project

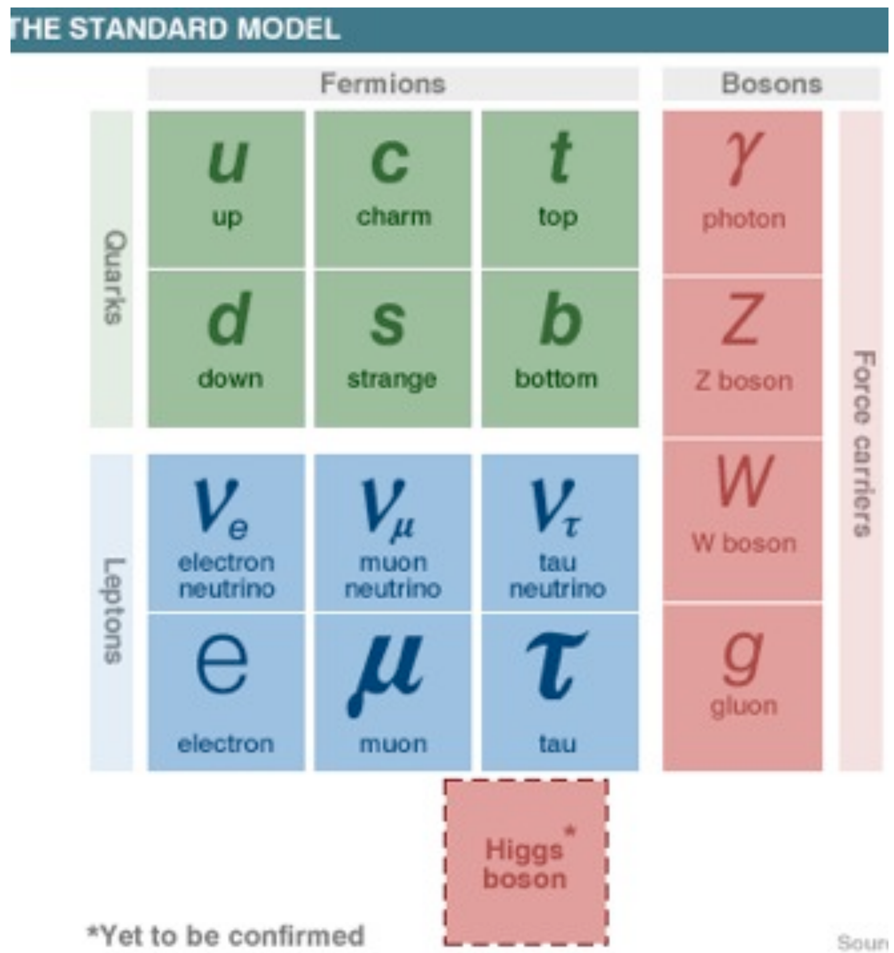
Students will be required to do readings and take part in discussions, and submit an introductory assignment summarizing the project and plan of action before traveling to the GMRT. While in India, weekly progress reports (about 1 page) should be submitted, including enough detailed information to serve as a record for any follow-up research. At the end of the project, students will collaborate to write a single group paper, due approximately 2 weeks after returning from India. This group paper may be distributed to collaborators and used as a basis for published work. Finally, students will have individual oral exams after submitting the final report to gauge their

The Fore-Front of Physics

the 'Standard Model' of particle physics accommodates all known subatomic particles and their interactions (forces). Much successes in the past few decades.

However, the 'Standard Model' is now seriously challenged.

What are the dark matter particles?
why is gravity so much weaker?
why do we have a 'matter-only' universe?
what is dark energy?
what gives rise to the physical constants?
……



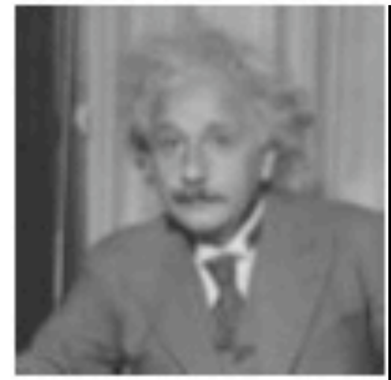
Luminous matter - Part III: unification of forces

Physicists' dream: Unification of All Forces

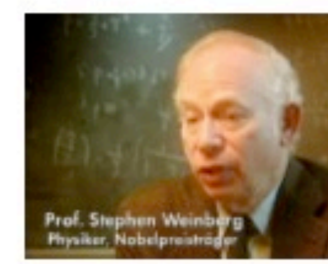
Friction, wind force, chemical binding, nuclear reaction... every process in nature is whittled down to just 4 forces.

But why 4? why not 3 or 5?

Only one answer is good enough.

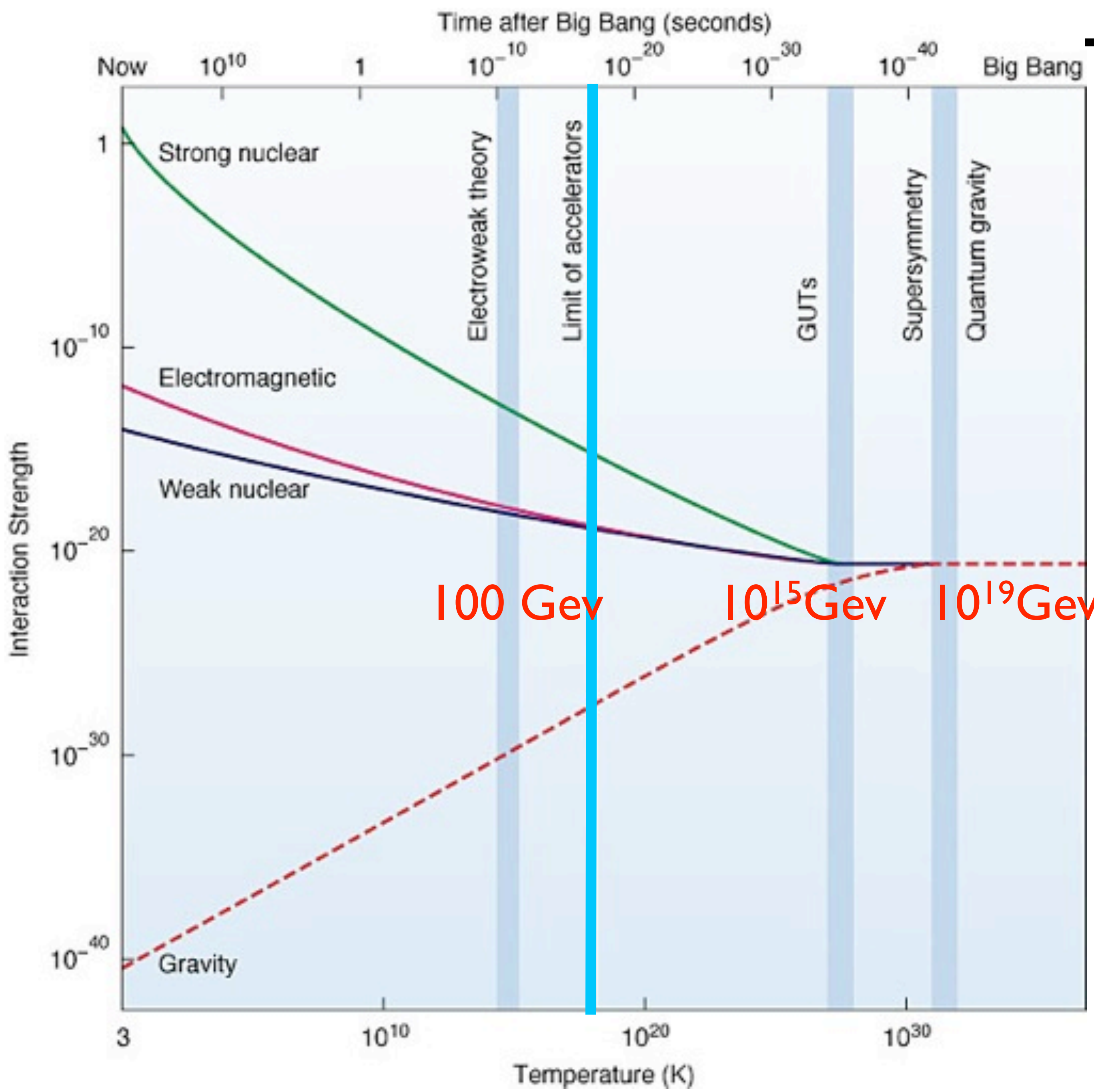


Step I: 1905, Einstein unified the forces of electricity and magnetism... the force is now called *Electromagnetism*



Step II: 1960s, Glashow, Salam & Weinberg showed that the Weak force and Electromagnetism unify at high energies into the *Electroweak* force.

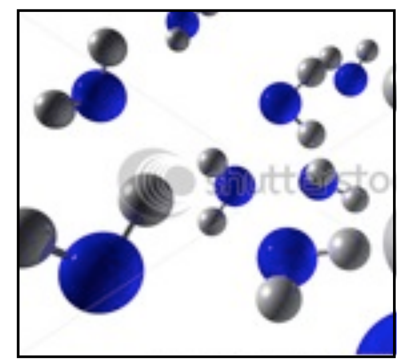
All forces unite, at high enough energies, to one grand force

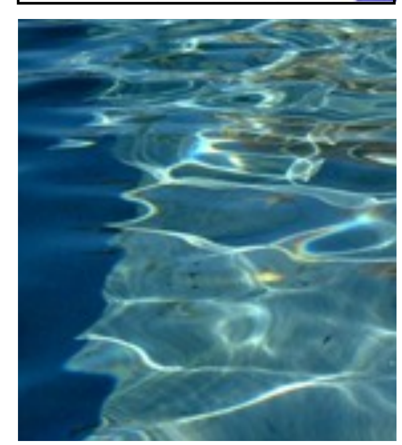


Temperature

Quarks

protons +
neutrons + e-





15 known phases of ice

Specificity

We think: All forces unite, at high enough energies, to one grand force

- However, even unifying strong force with electroweak force (step III) has turned out difficult, best theory going is (arguably) supersymmetry.

- Theory to unify gravity with other forces, ‘quantum gravity’, (step IV) is elusive. Would it also explain the origin of fundamental constants? a ‘theory of everything’. String theory is a candidate, though we are ludicrously far from any remotely believable theory.

- The high energy condition for force unification is unreachable in any earth-based accelerators. The last time it occurred in nature was during the BIG BANG.

- some unknown particles may be required in unification theories, and act as dark matter in the universe.

- Connection between nature of matter and the universe runs deep.

Nature of Matter (recap)

- All matter is made of quarks and leptons. Fundamental particles.

- Atomic nuclei: protons and neutrons bound together by the nuclear force (spill-over strong force).
  - Radioactivity (of unstable isotopes, weak force) and fission (of large nuclei) spontaneously break up nuclei into fragments
  - Fusion (small nuclei) binding together to build larger ones, contributing nuclear energy along the way (how stars shine)

- Atoms and molecules: atomic number (# of protons) of an element determines its chemical property. Electron clouds interact by EM force, electronic transitions and molecular bonds (chemistry)

- Large scale structure in the universe: gravity