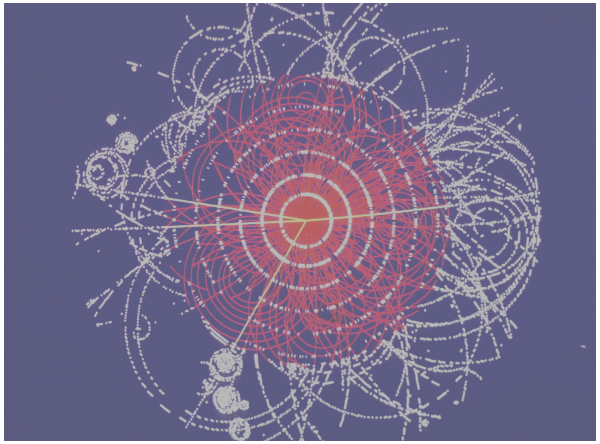
Particles and Interactions



Prof. Marina Cobal
Giancarlo Panizzo

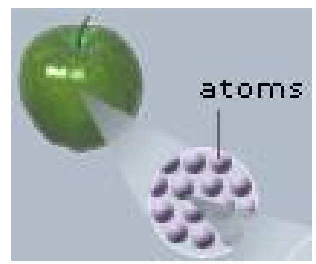
Summer School on Particle Physics

We and all things around us are made of atoms

Human Hair

~ 50 μm = 50 10^{-6} m

= 0.000050 m



Atom ~ 10^{-10} m

= 0.0000000001 m

What is the world made of?

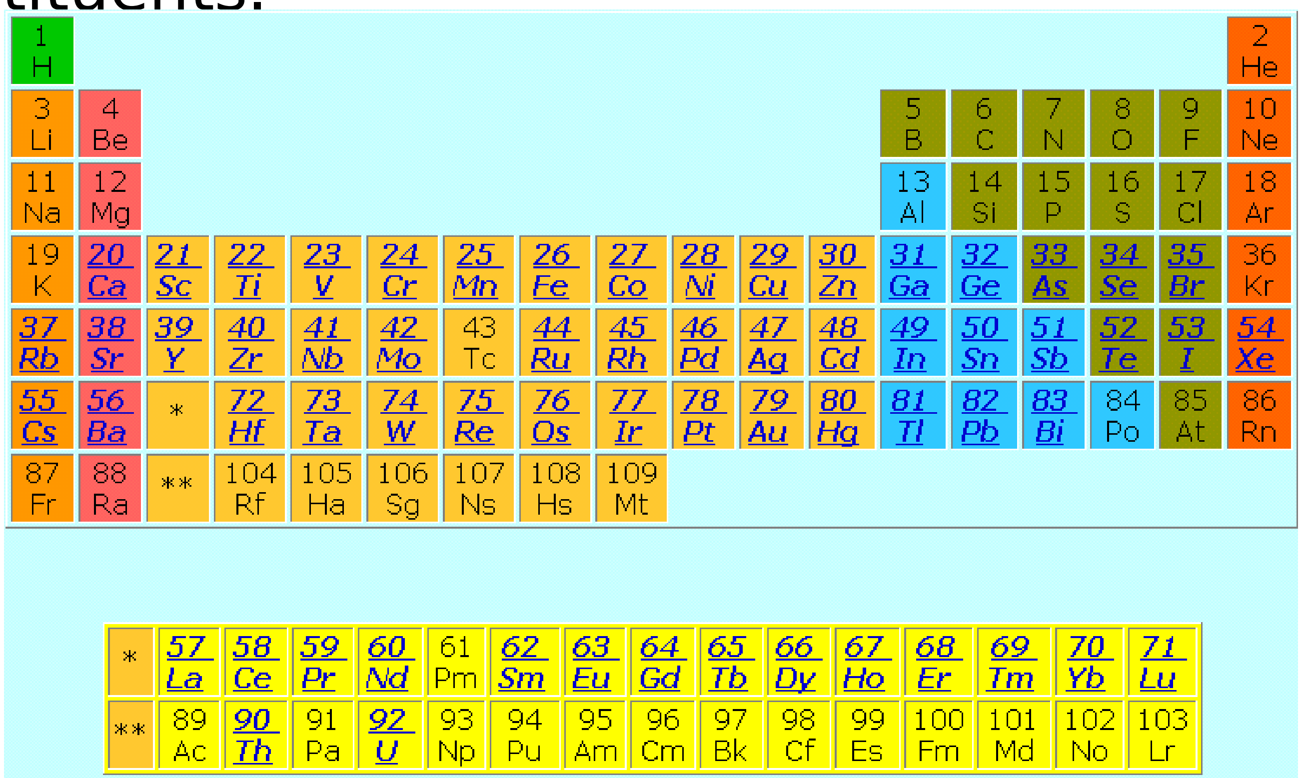
- In the ancient time: 4 elements
- 19° century– atoms
- Beginning 20th century – electrons, protons, neutrons
- Today – quarks and leptons

The atom in the 20th century…

- Atoms reacts through chemical reactions
- More than 100 atoms known (H, He, Fe
- The internal structure is not well known

Table of elemens

- Atoms are grouped in families which present similar properties The elements table is done
- This symmetry suggests a structure with simpler constituents.

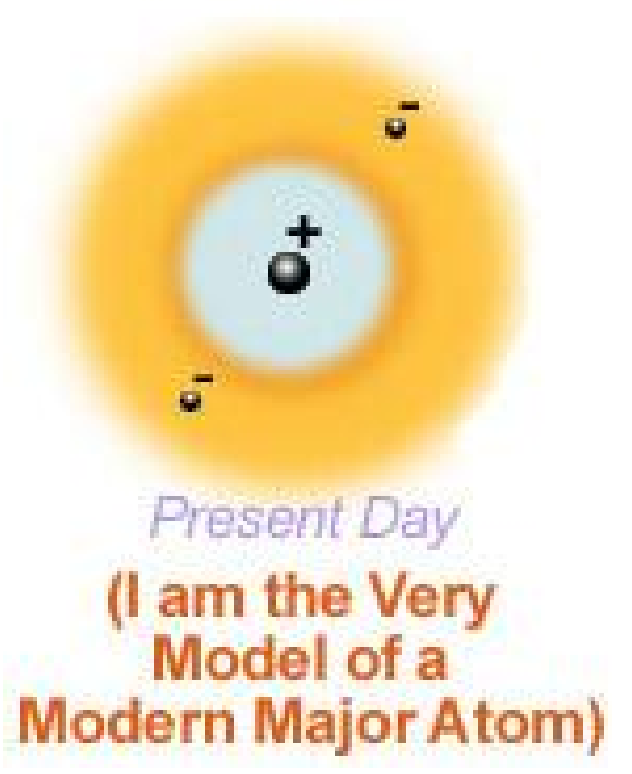


1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	**	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt									

*	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
**	89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Atomic Model

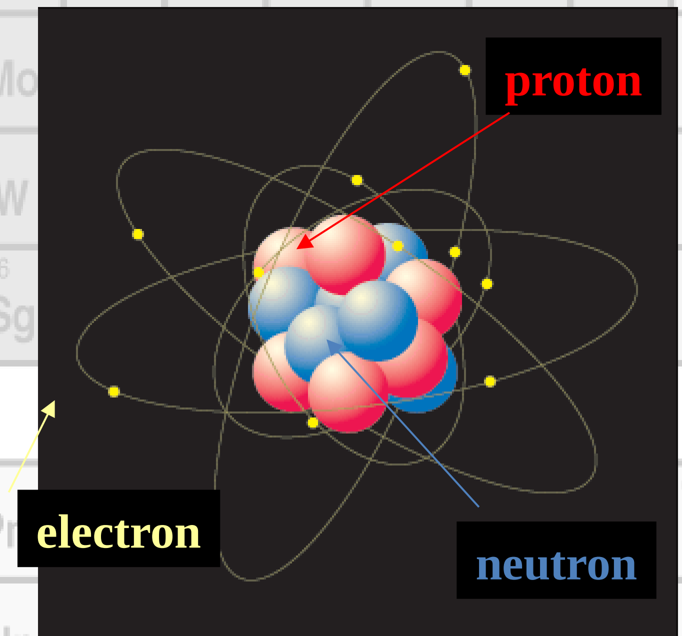
- With the experiments now we are able to “break up” atoms
- Light particles (electrons) with negative charge around a positive and heavy nucleus
- Practically, the atom is empty!



Atoms

Atoms are all similarly made of:
- protons and neutrons in the nucleus
- electrons orbiting around

The electron was the first elementary particle to be discovered
(JJ Thomson 1897)



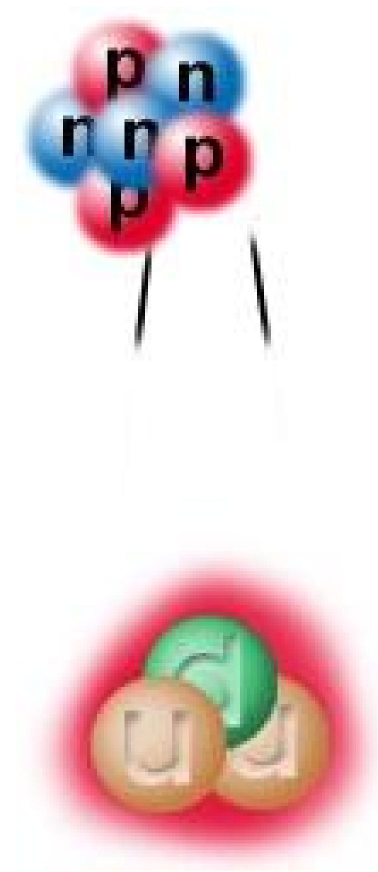
Protons, neutrons are made up of quarks

Nucleus

- The nucleus is small and dense. For a while it was thought to be point-like.
- However, there were so many different nuclea as many atoms
- Simplification: all nuclea are made of neutrons and protons!

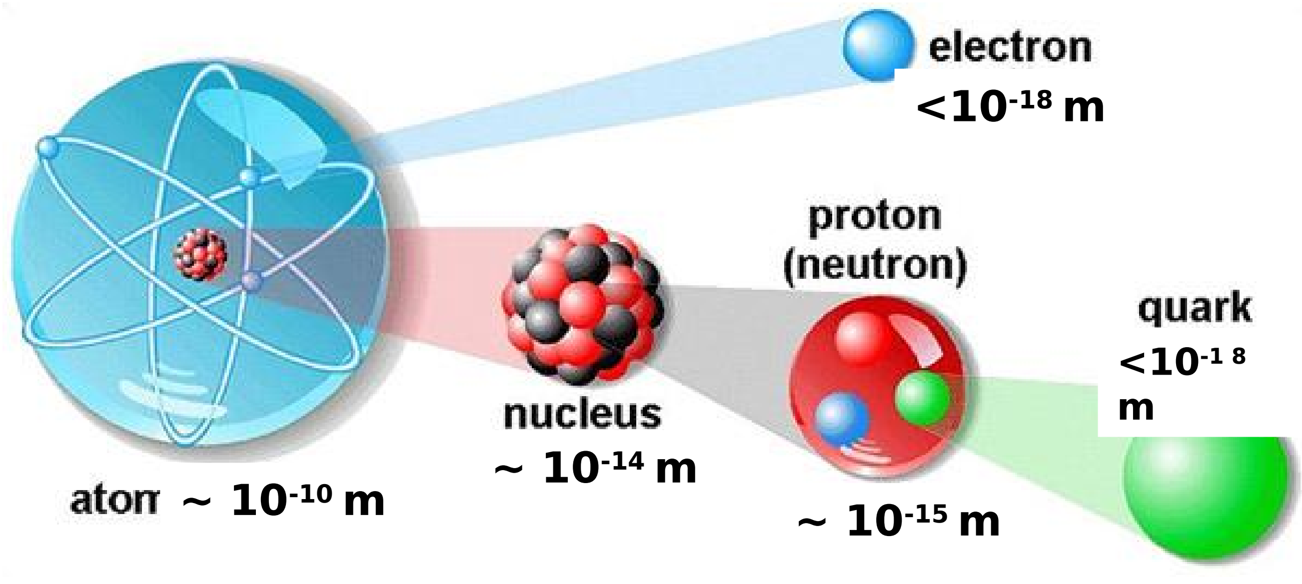
Quarks

- Today we know that also protons and neutrons are not fundamental units.
- They are made of smaller particles called **quarks**
- For the moment looks like quarks are pointlike



From the atom to the quark

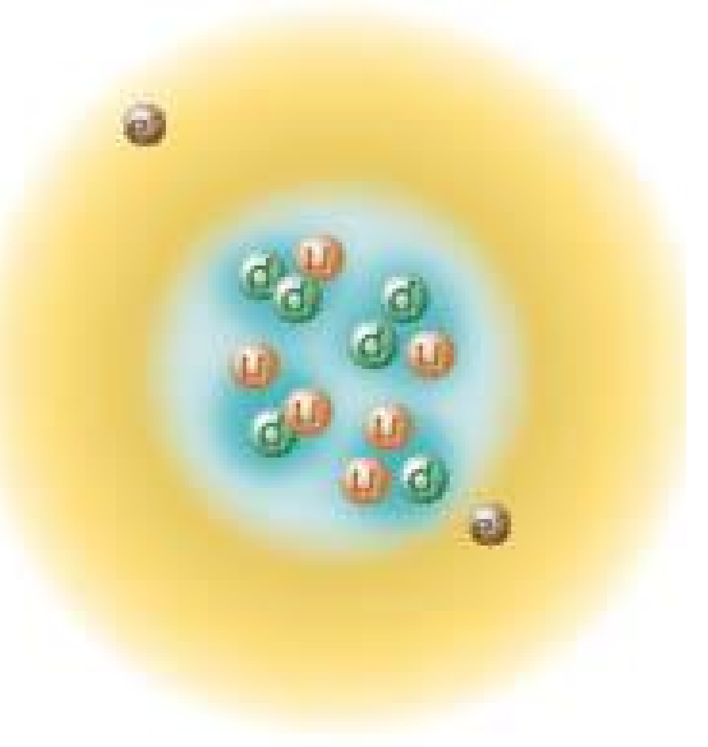
How small are the smallest constituents of matter?



Atoms and sub-atomic particles are much smaller than visible light wave-length
Therefore, we cannot really "see" them (all graphics are artist's impressions)
To learn about the sub-atomic structure we need particle accelerators

The Modern Atom

- A cloud of electrons moving constantly around the nucleus
- Protons and neutrons moving in the nucleus
- Quarks moving in protons and neutrons



Sub-atomic dimensions

Everyday Objects are made of Molecules.

Molecules are made of Atoms.

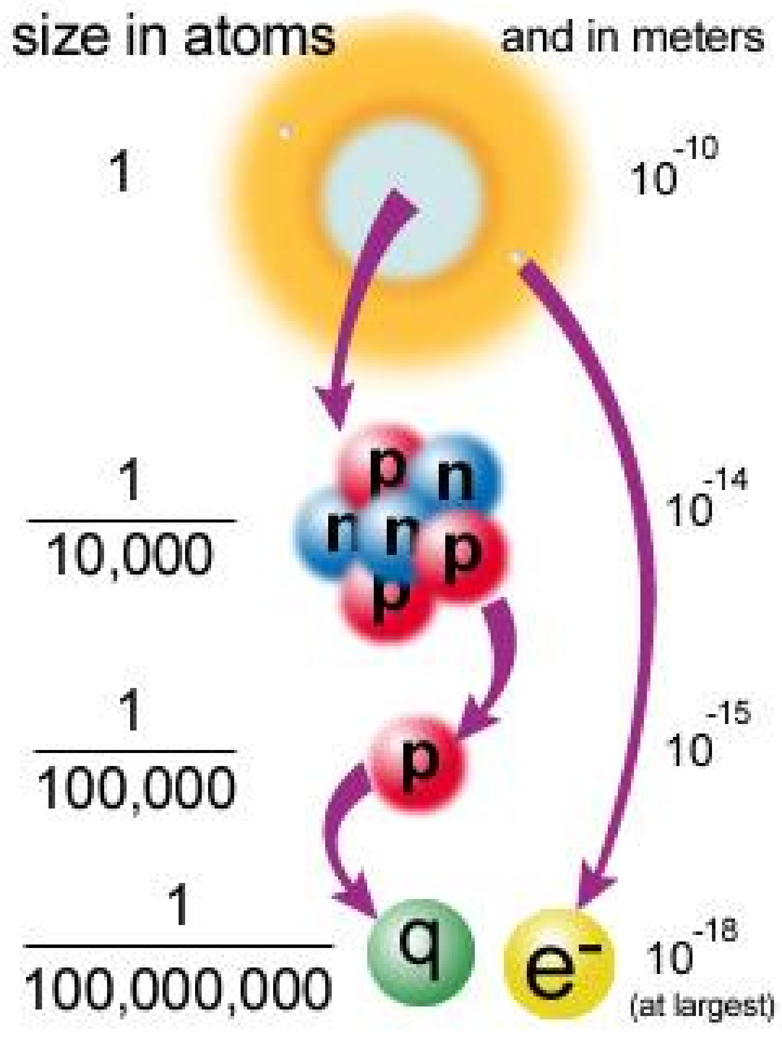
Atoms are made of Nuclei and Electrons.

Nuclei are made of Protons and Neutrons.

Protons and Neutrons are made of Quarks.

Quarks and Electrons are made of ???

Quarks and Electrons are "Elementary Particles"



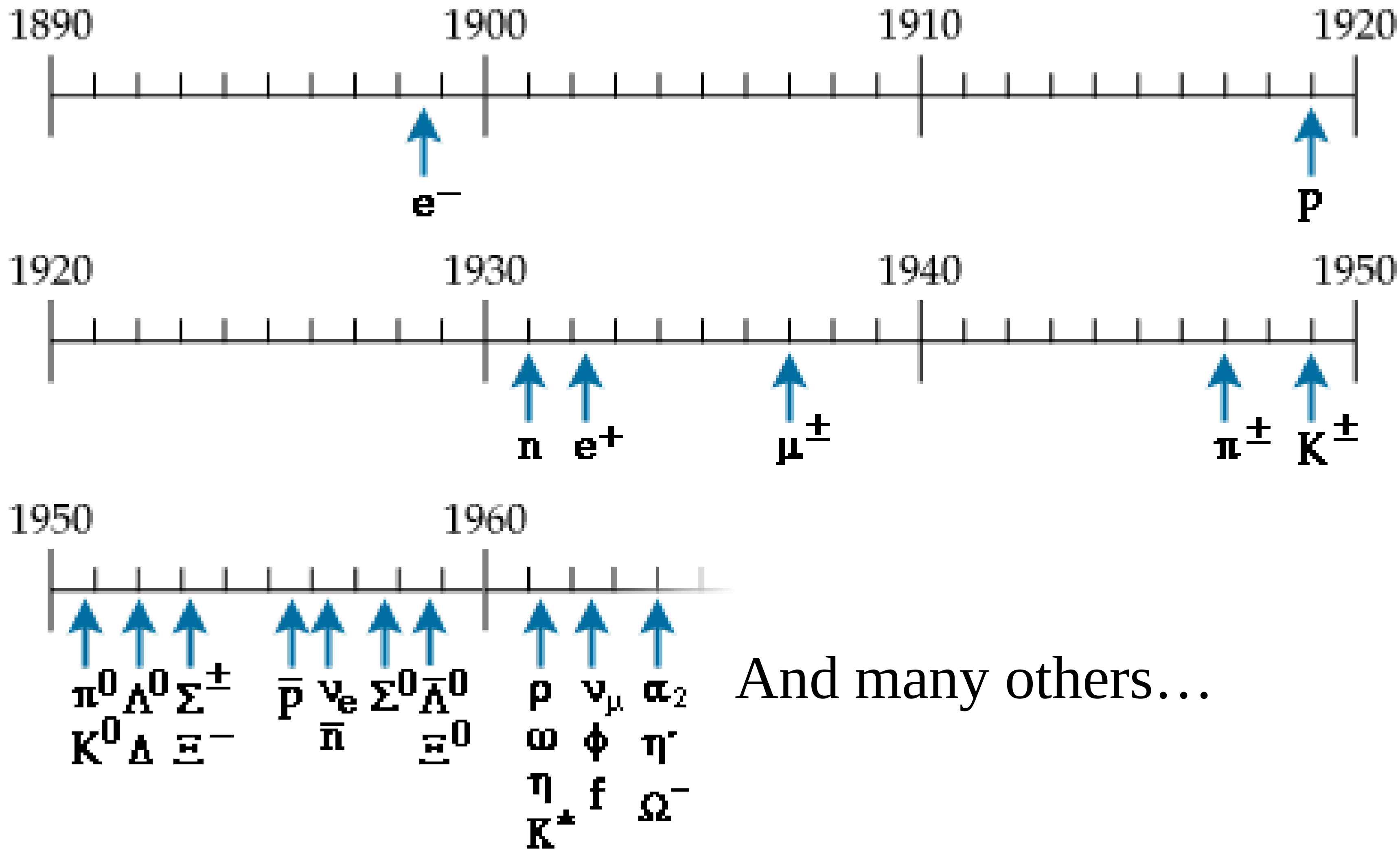
New Particles

- Collisions of elettrons and nuclea in the cosmic rays and in the particle accelerators at the beginning of the 30ies, brought to the discovery of many other particles.

- Some of them were predicted, other were discovered as surprises, being completely unexpected.

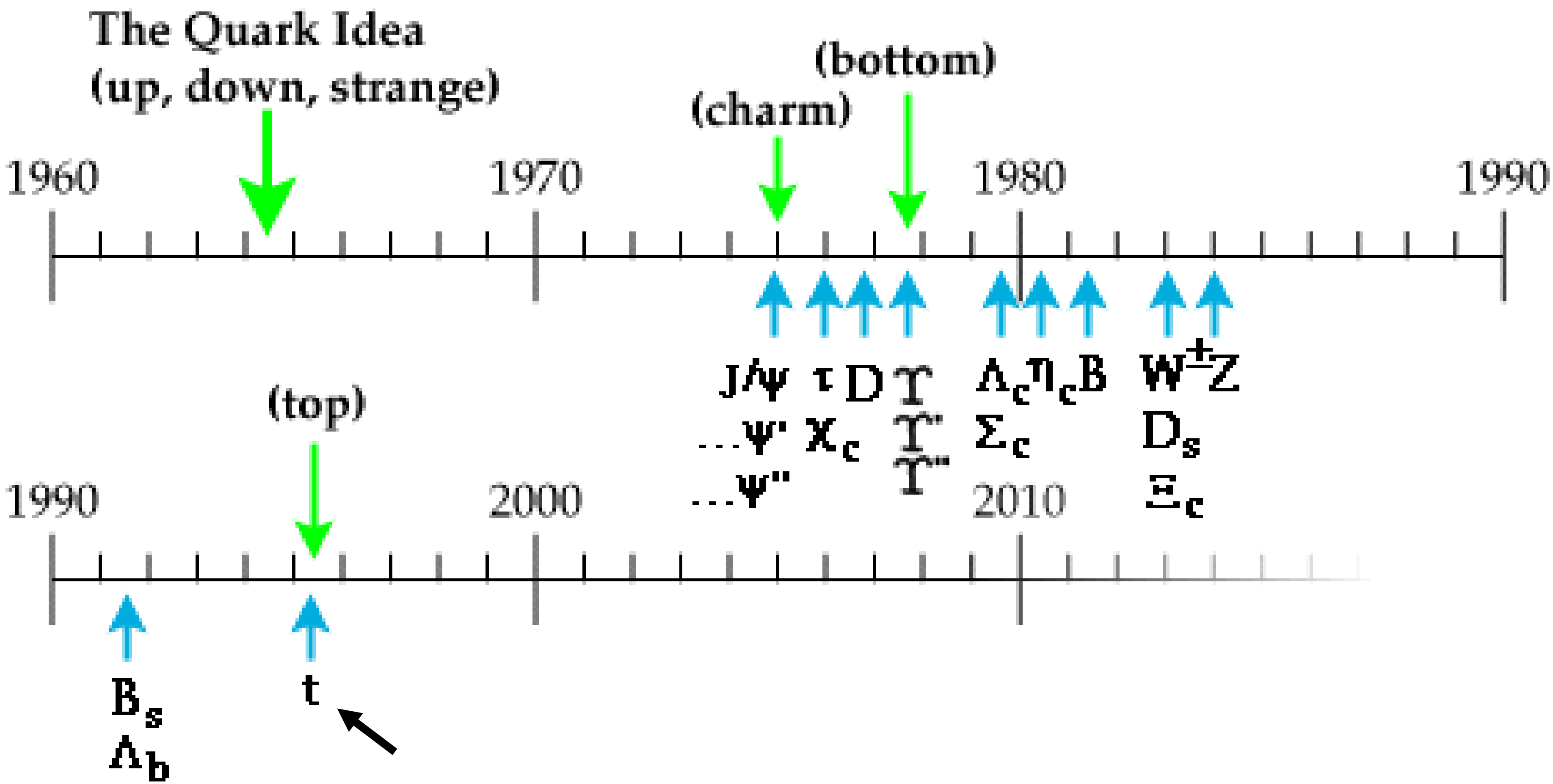
- At the beginning it was thought that all these particles were fundamentals.

At the beginning just a few…



And many others…

Introducing the quarks..



"***Young man, if I could remember the names of these particles, I would have been a botanist!***"

E.Fermi to his student L. Lederman (both Nobel laureates)

The Particle Physicist's Bible: Particle Data Book https://pdg.lbl.gov

STRANGE MESONS	
K_L^0	130
K_S^0	310
K^0	
K^+	
$K_0^*(800)^0$	
$K_0^*(800)^+$	
$K_0^*(1430)^0$	
$K_0^*(1430)^+$	
$K(1460)^0$	
$K(1460)^+$	
$K(1830)^0$	
$K(1830)^+$	
$K_0^*(1950)^0$	
$K_0^*(1950)^+$	
$K^*(892)^0$	
$K^*(892)^+$	323
$K_1(1270)^0$	10313
$K_1(1270)^+$	10323
$K_1(1400)^0$	20313
$K_1(1400)^+$	20323
$K^*(1410)^0$	100313
$K^*(1410)^+$	100323
$K_1(1650)^0$	9000313*
$K_1(1650)^+$	9000323*
$K^*(1680)^0$	30313

CHARMED MESONS	
D^+	411
D^0	421
$D_0^*(2400)^+$	10411
$D_{s1}(2536)^+$	10433
$D_{s1}(2460)^+$	20433

$c\bar{c}$ MESONS	
$\eta_c(1S)$	441
$\chi_{c0}(1P)$	10441
$\chi_{b0}(1P)$	10551
$\Upsilon(1S)$	553
$\Upsilon_1(1D)$	30553

BOTTOM MESONS	
B^+	521
B^{*0}	513

LIGHT BARYONS	
p	2212
n	2112
Δ^{++}	2224

CHARMED BARYONS	
Λ_c^+	4122
Σ_c^{++}	4222
Σ_c^+	4212
Σ_c^0	4112
Σ_c^{*++}	4224

BOTTOM BARYONS	
Λ_b^0	5122
Σ_b^-	5112
Ω_b^-	5332
Ω_b^{*-}	5334
Ξ_{bc}^0	5142
Ξ_{bc}^+	5242
$\Xi_{bc}'^0$	5412
$\Xi_{bc}'^+$	5422
Ξ_{bc}^{*0}	5414
Ξ_{bc}^{*+}	5424
Ω_{bc}^0	5342
$\Omega_{bc}'^0$	5432

Most particles are not stable and can decay to lighter particles..

What is fundamental?

- Physicists have found hundreds of new particles.
- Today we know that most of them are not fundamental
- A theory has been developed that seems to explain quite well what we do observe in nature: the theory is called **Standard Model**
- This model includes 6 quarks, 6 leptons and 13 particles which carry the force in between quarks and leptons.

Fundamental Constituents of Matter: Quarks and Leptons

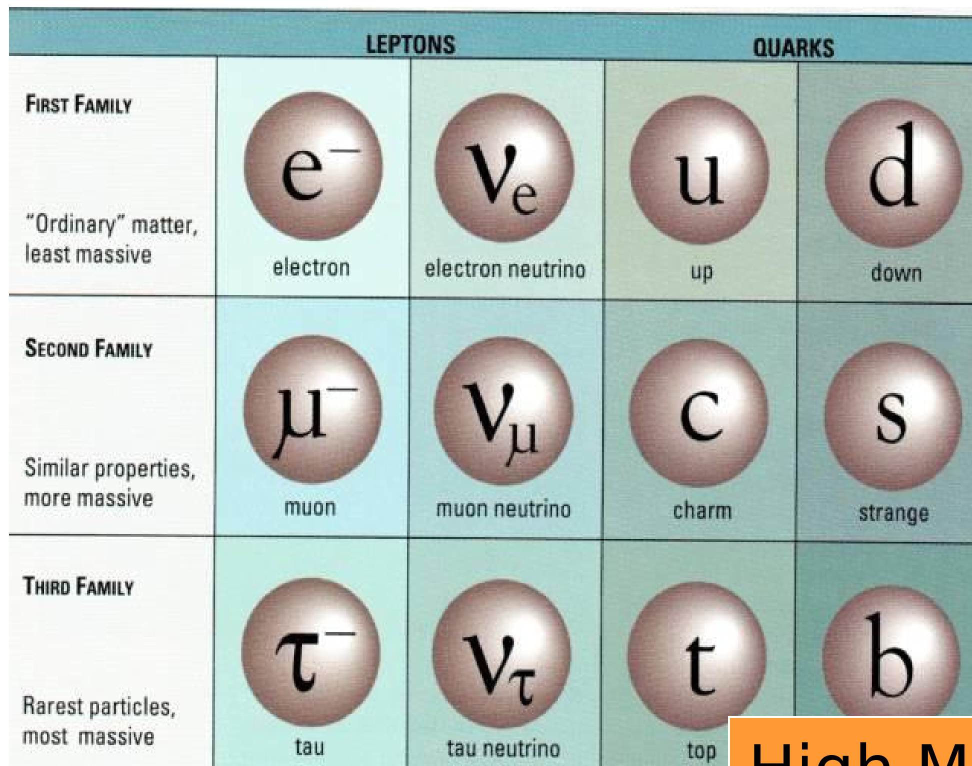
Structureless building blocks down to a spatial extension of 10^{-18} m

Well defined spin and charge

Matter Constituents under ordinary conditions (low energy/T)

Constituents of unstable particle (produced at high energy, in astrophysical systems). They decay to lower mass particles

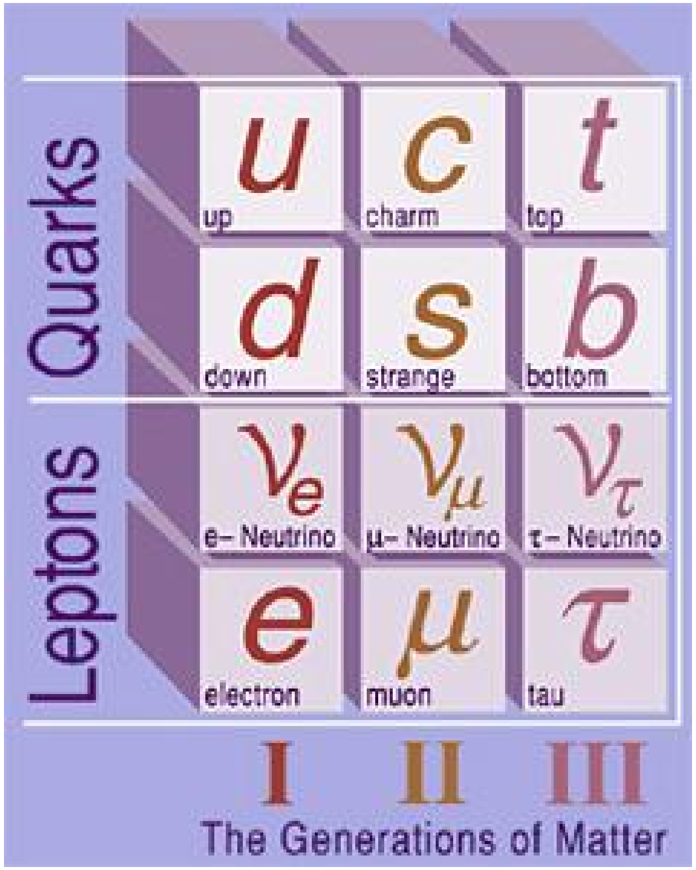
Low Mass



High Mass

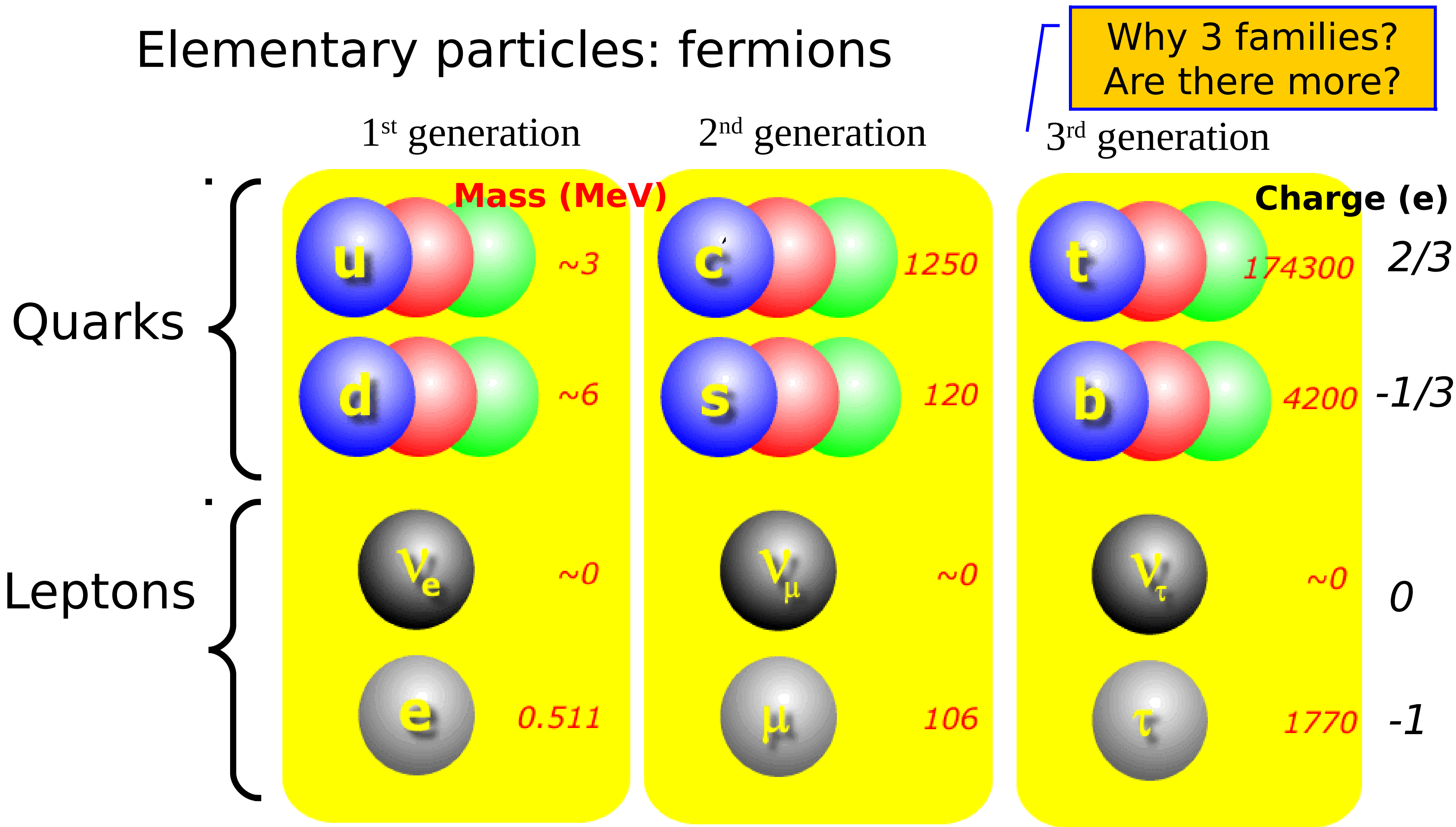
Families

- The 6 quarks and leptons are organized in families
- The 3 families have analogies
- Quarks have charge +2/3 e -1/3. Leptons have charge -1 and 0.



Fermions:
the fundamental components

Elementary particles: fermions



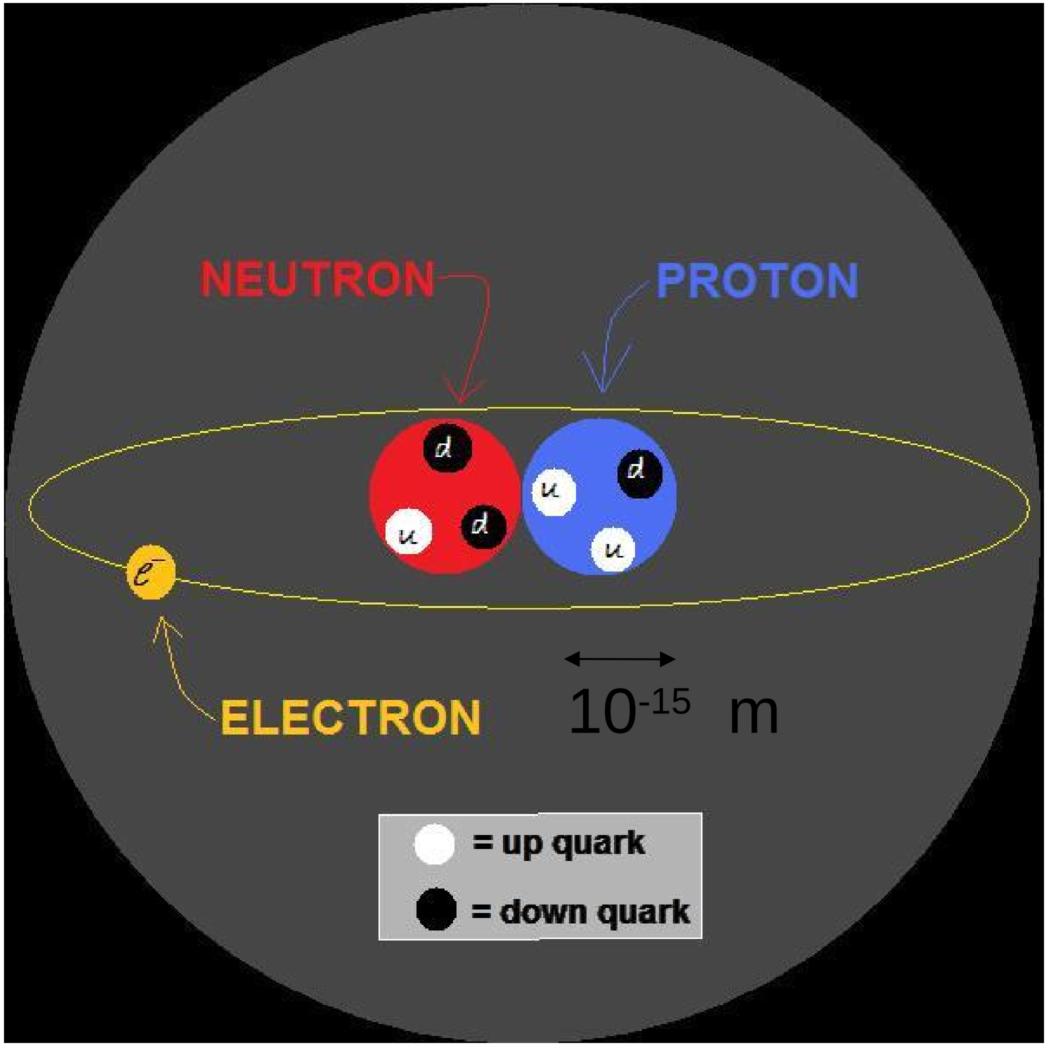
What is the world made of?

- Real world is not done by single quarks
- Quarks exist only in groups, to form the so-called hadrons (protons and neutrons are hadrons)
- Example: a proton is made of two quarks of up type and one quark of type down.
- The matter around, and even each of us, is made of quarks up and down and of electrons.

A reductionist example: the Deuterium Atom

$$p = (u, u, d)$$

$$n = (u, d, d)$$

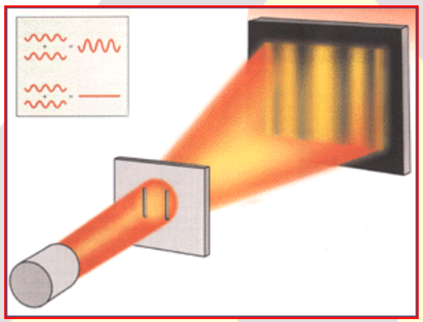


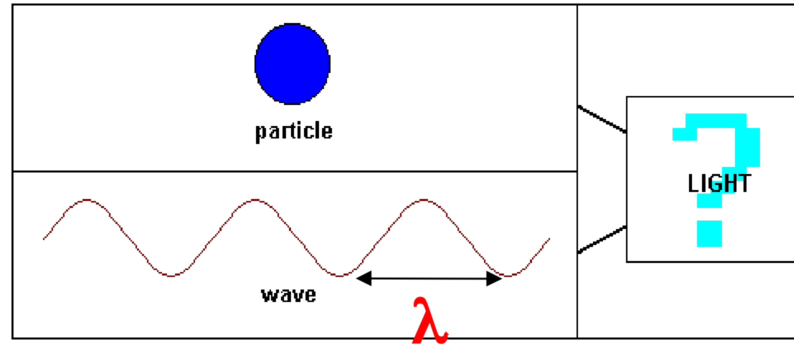
And the leptons?

- There are 6 leptons: 3 charged and 3 neutral.
- They look like pointlike particle without an internal structure.
- Electrons are the most common and are found in the ordinary matter.
- Muons (μ) and taus (τ) are heavier and charged as the electrons.
- Neutrinos (ν) have no charge and they have an extremely small mass.

Wave-particle duality of Nature

Central concept of quantum mechanics:
all particles present wave-like properties





How to imagine the wave-particle duality.

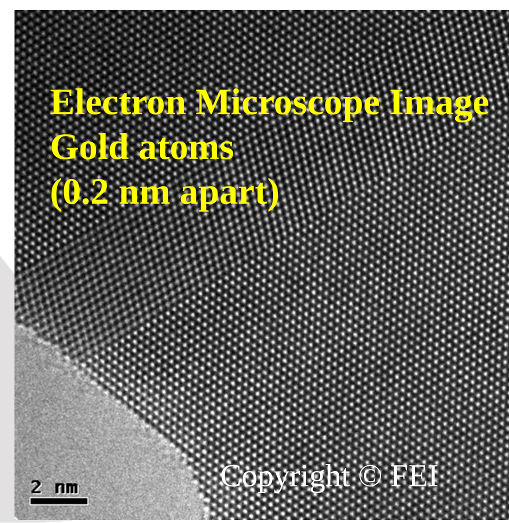
Not only light has a dual nature

De Broglie showed that moving particles have an equivalent wavelength λ

$$\lambda \propto \frac{1}{p}$$

So high momentum gives us short wavelengths so we can make out small details

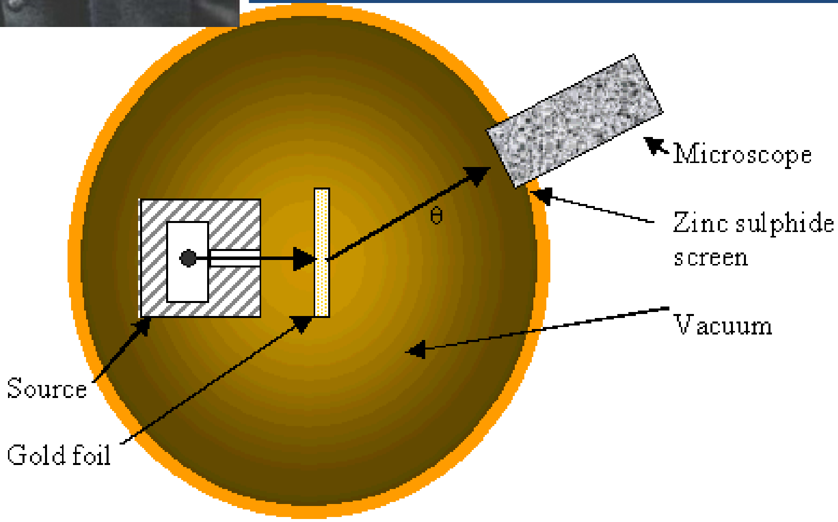
Example: electron microscope

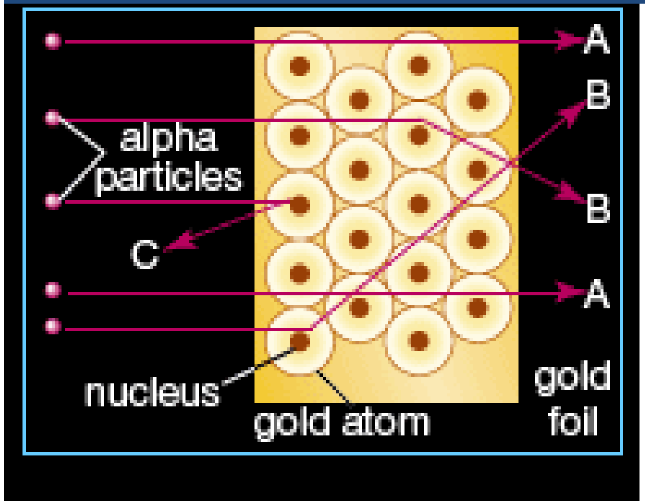


Rutherford:
atoms are not elementary particles!

1911

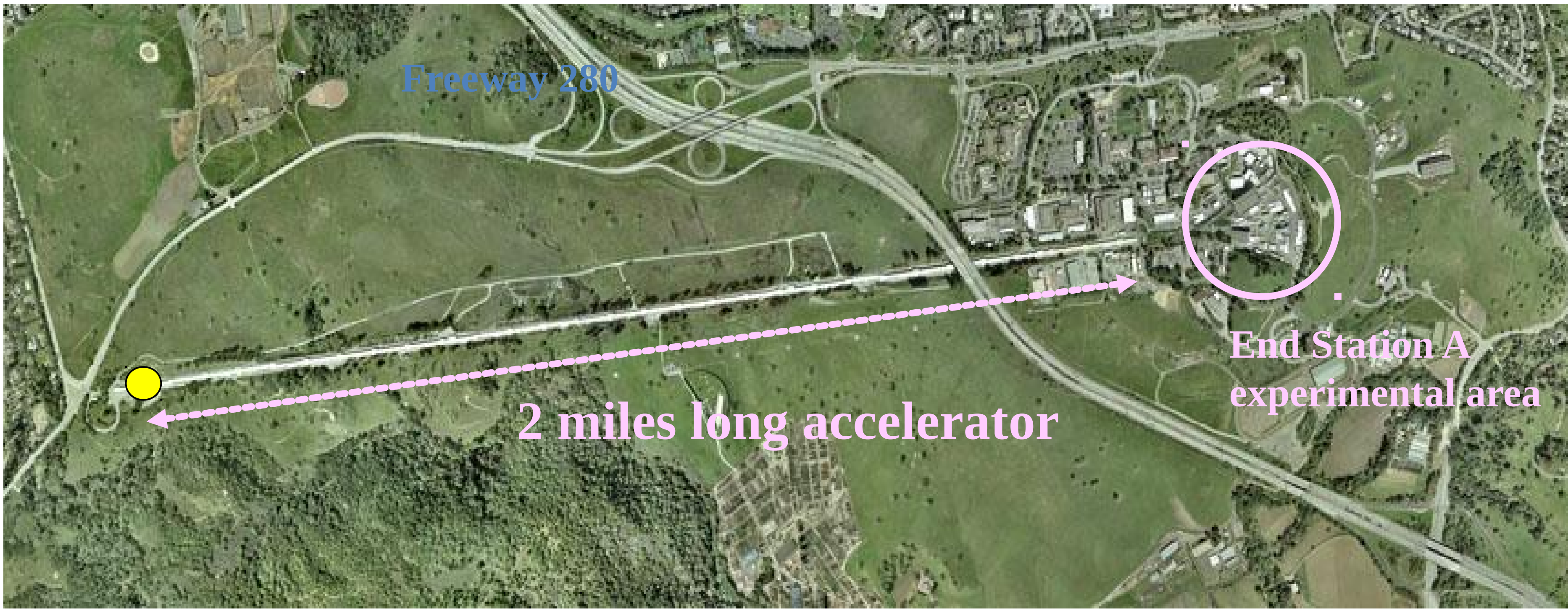
Rutherford found a nucleus in the atom by firing alpha particles at gold and observing them bounce back





Precursor of modern scattering experiments at accelerator

Quarks detected within protons



Stanford (SLAC), California, late 1960s

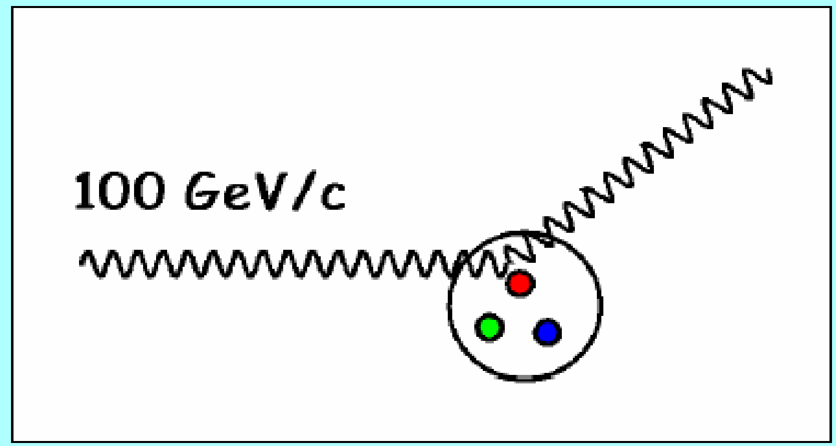
Fire electrons at proton: big deflections seen!

Probing the proton

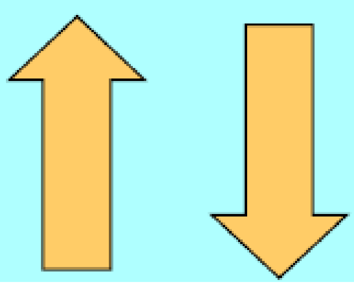
For an electron with p = 100 GeV/c

$\lambda = 2\pi \times 197/10^5 = 0.012$ fm
or 1.2 10^{-17}m

A 100 GeV electron will be able to probe inside the proton and scatter off the quarks inside.



Increasing Energy



Decreasing distance probed

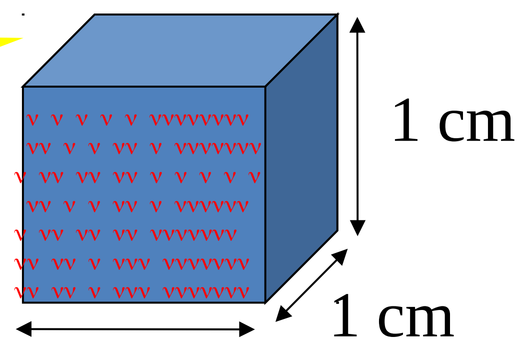
Is the whole Universe made only of quarks and electrons?

No! There are also neutrinos! ν

Electron, proton and neutrons are rarities!
For each of them in the Universe there is 1 billion neutrinos

Neutrinos are the most abundant matter-particles in the Universe!

Within each cm^3 of space: ~300 neutrinos from Big Bang

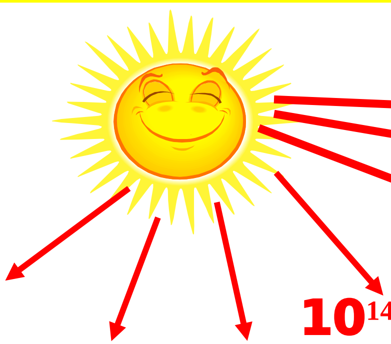


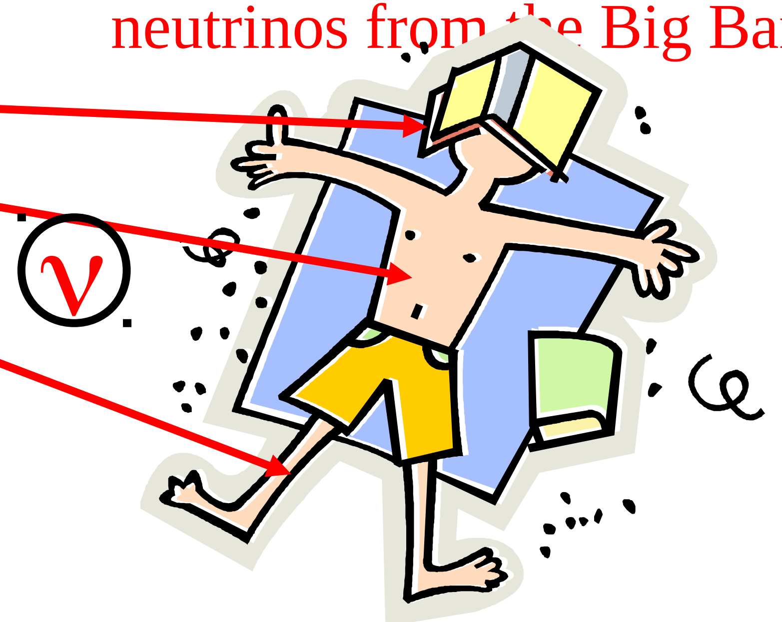
Neutrinos are everywhere!
in the outer space, on Earth, in our bodies..

Neutrinos get under your skin!

Every cm^2 of Earth surface is crossed every second by more than 10 billion (10^{10}) neutrinos produced in the Sun

Within your body at any instant: roughly 30 million neutrinos from the Big Bang



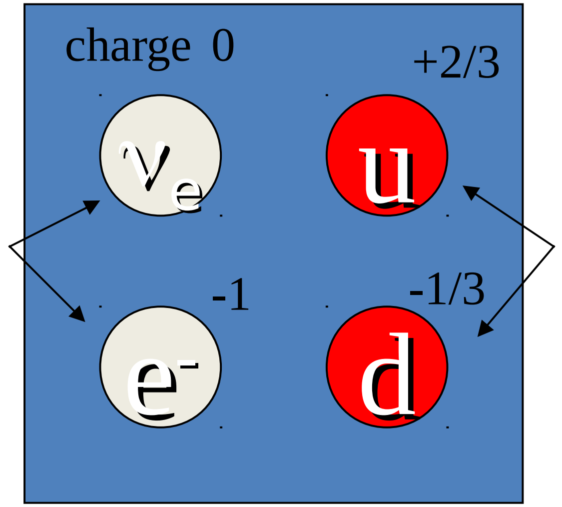


10^{14} neutrinos per second from Sun are zipping through you

No worries!
Neutrinos do not harm us.
Our bodies are transparent to neutrinos

The particles of ordinary matter

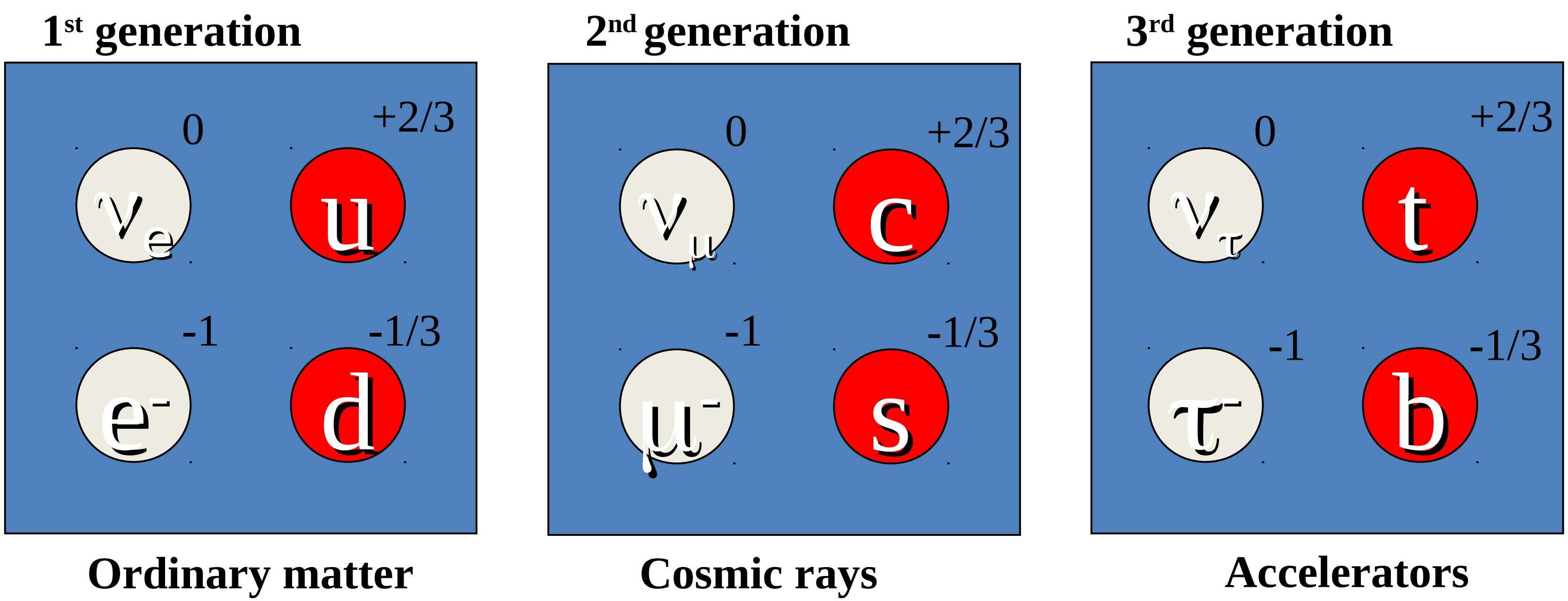
Leptons:
ν = neutrino
e = electron



Quarks:
u = up
d = down

All stable matter around us
can be described using
electrons, neutrinos, u and d “quarks”

3 Families (or Generations)



3 generations in everything similar but the mass

We believe these to be the fundamental building blocks of matter

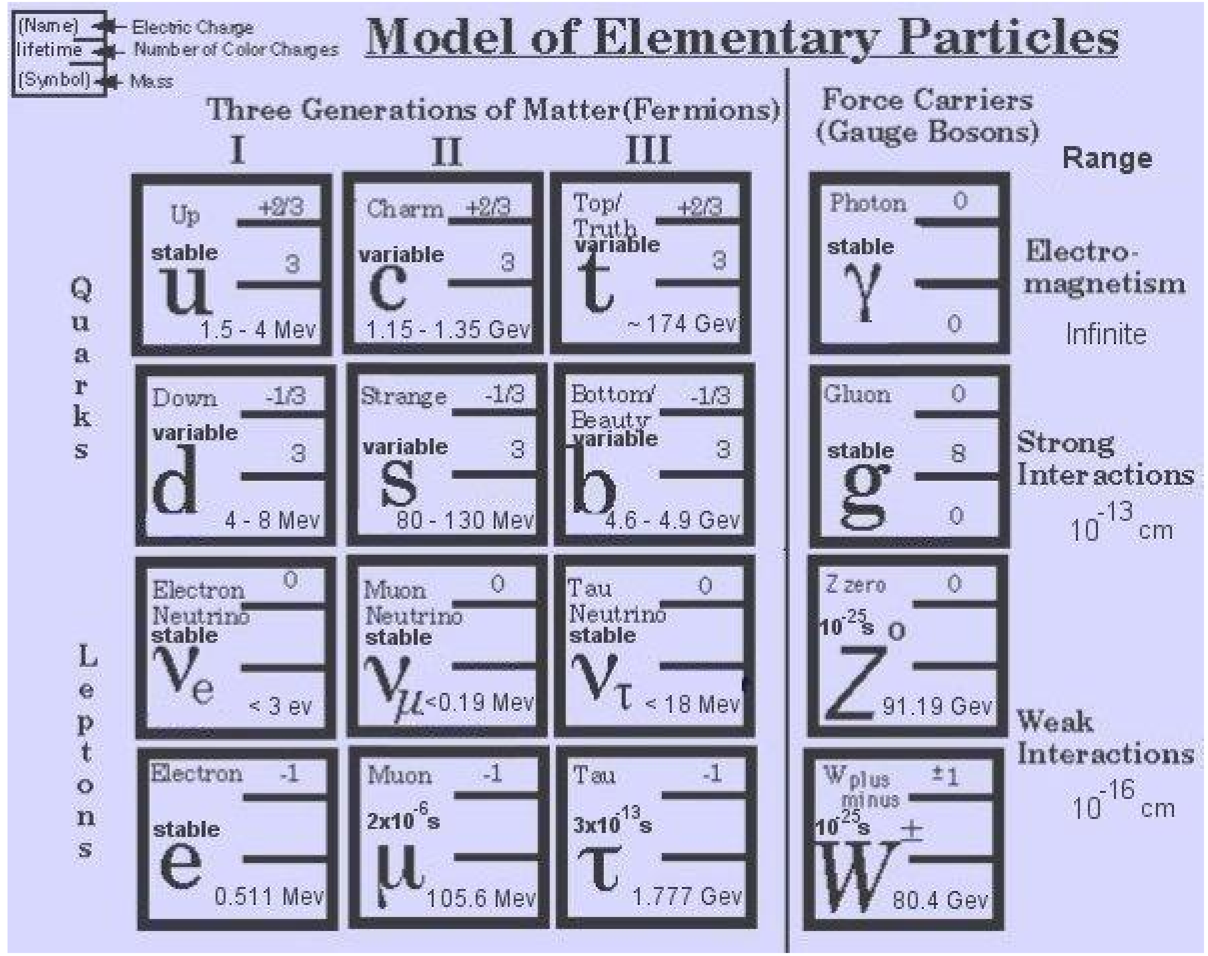
Constituents properties:

Quarks:

- Electric charge
- Color
- Effective mass
- Spin (1/2)

Leptons:

- Electric charge
- Mass
- Spin (1/2)



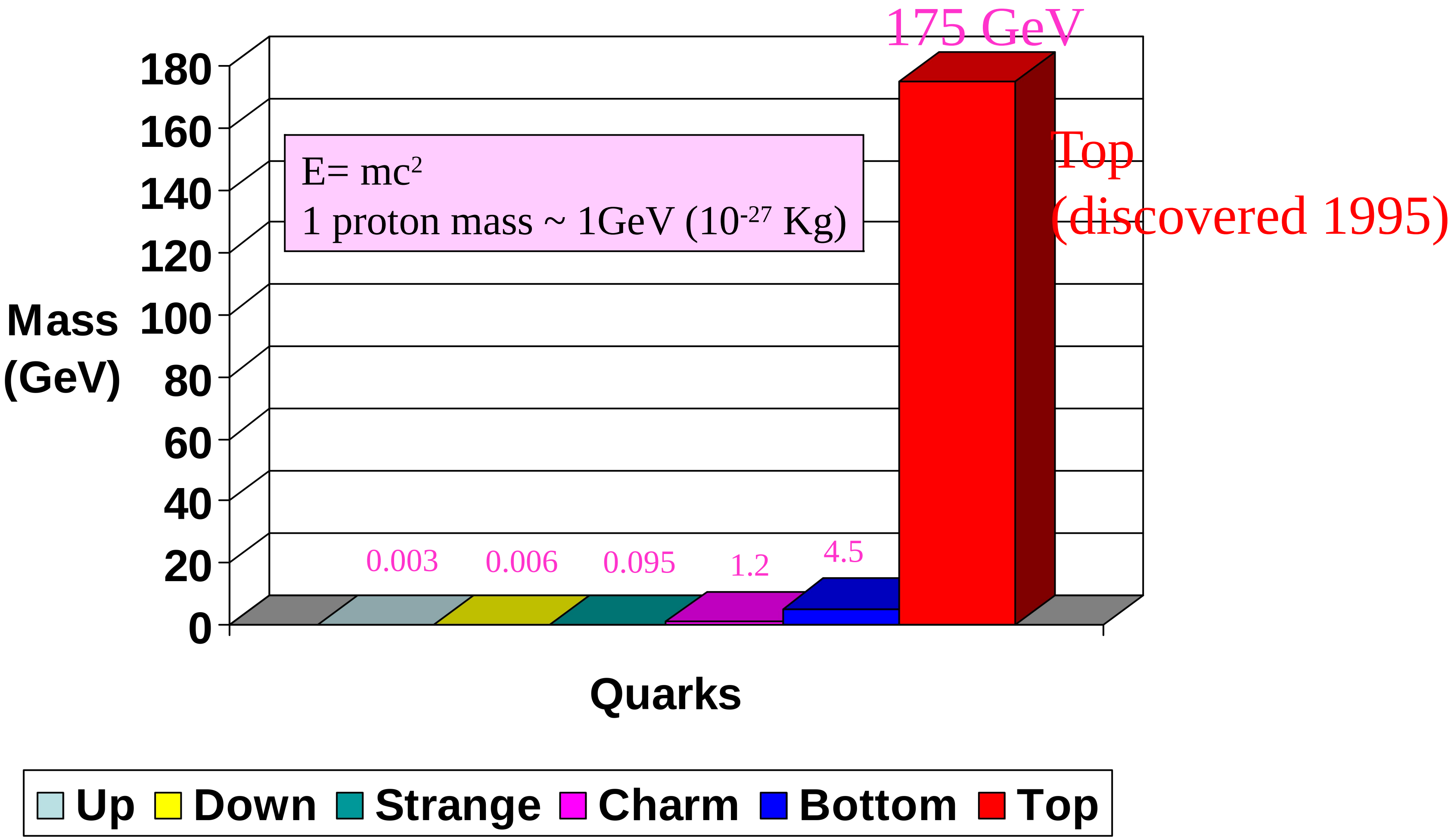
3 families

Costituents of Matter

Force Carriers

All Contituents (Quarks, Leptons) are Fermions.

Quark masses



The mass grows larger in each successive family

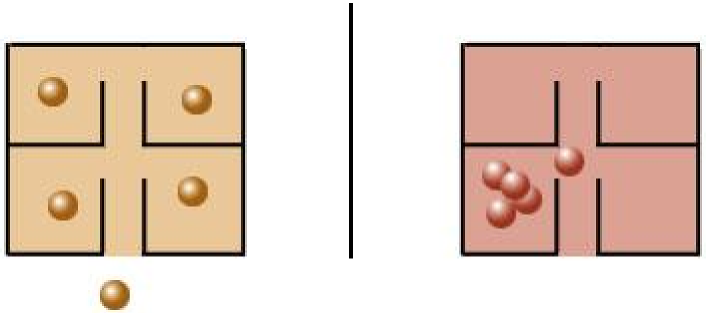
Quantum Mechanics

- Atoms and particles behavior is described by the Quantum Mechanics
- Some properties, like energy for example, can only assume some discrete values, they don’t belong to a continuum
- Particle properties are described by these values (quantum numbers). Some examples:
  - Electric charge
  - Colour charge
  - Flavour
  - Spin

Pauli principle

- We can use the particle quantistic properties to classify them

- Some particles, called fermions, obey to the Pauli principle. While some others – the bosons – do not.



Costituents and Force Carriers: the Spin/Statistics Theorem

(W. Pauli, 1940)

$\frac{1}{2}\hbar\,,\ \frac{3}{2}\hbar\,,\ \ldots.$ **Fermions**

Fermi-Dirac Statistics

Bose-Einstein Statistics

$0,\ \hbar\,,\ 2\,\hbar\,,\ \ldots.$ **Bosons**

Integer Spin
Particles

Consequences of the Spin/Statistics Theorem:
- formal: wave functions, field operators commutation rules
- experimental: nuclear and atomic structure, Bose-Einstein condensates

Fermions and Bosons

Fermions		Bosons	
Leptons and Quarks	Spin = $\frac{1}{2}$	Spin = 1*	Force Carrier Particles
Baryons (qqq)	Spin = $\frac{1}{2}, \frac{3}{2}, \frac{5}{2} \ldots$	Spin = 0, 1, 2…	Mesons ($q\bar{q}$)

The Wave Function must have the correct symmetry under interchange of identical particles. If 1, 2 are identical particles :

$$|\psi(x_1,x_2)|^2 = |\psi(x_2,x_1)|^2$$

$$\psi = \pm\ \psi(1 \leftrightarrow 2)$$

(probability must be conserved upon excange of identical particle)

Identical Bosons (symmetric)

Identical Fermions (antisymm.)

A consequence of the Spin/Statistics Theorem: for two identical Fermions 1,2 in the same quantum state x:

$$\psi(x_1,x_2) = \psi(x_2,x_1) = -\ \psi(x_1,x_2) \Rightarrow \psi(x_1,x_2)=0$$

Pauli Exclusion Principle!

Particles/Antiparticles: the "birth" of Particle Physics

1928: Dirac Equation, merging Special Relativity and Quantum Mech.
A relativistic invariant Equation for spin ½ particles. E.g. the electron

$$\left(i\,\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$

- E>0, s=+1/2
- E>0, s=-1/2
- E<0, s= +1/2
- E<0, s= -1/2

Upon reinterpretation of negative-energy states as antiparticles of the electron:

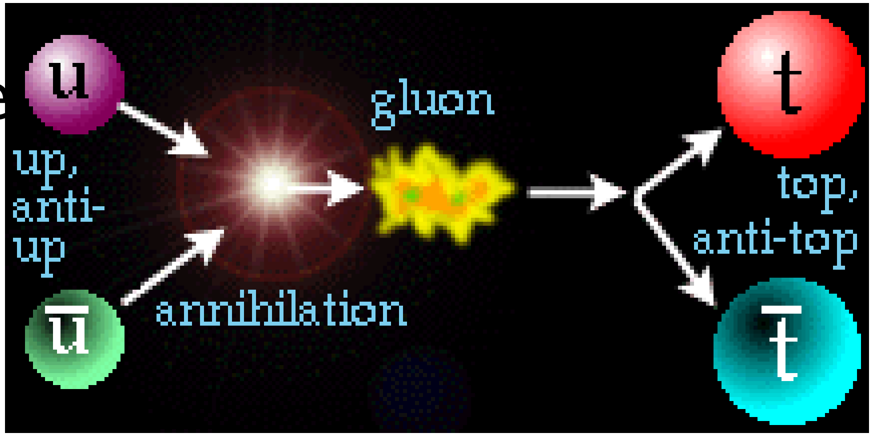
The positron, a particle identical to the electron e^- but with a positive charge: e^+. The first prediction of the relativistic quantum theory.

Electron, s=+1/2
Electron, s=-1/2

Positron, s=1/2
Positron, s=-1/2

Matter and Anti-matter

- For every particles there is a corresponding particle of anti-matter, or anti-particle



- These particles appear to be as their sisters of matter, but with opposite charge

- Particles are created or destroyed with their antiparticles.

Antiparticles

All quarks and leptons have antiparticle partners, with all quantum numbers reversed, but with the same masses.

Put a bar over the symbol

Antiquarks: $\bar{u}, \bar{d}, \bar{s}, \bar{c}, \bar{b}, \bar{t}$

Charge + rather than -

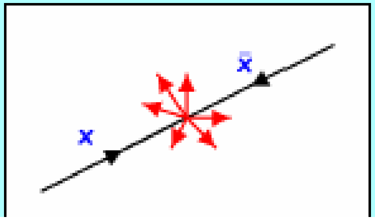
Antileptons: $e^{+}, \mu^{+}, \tau^{+}, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$

The anti-electron is known as the positron.

Antiquarks have anticolour.

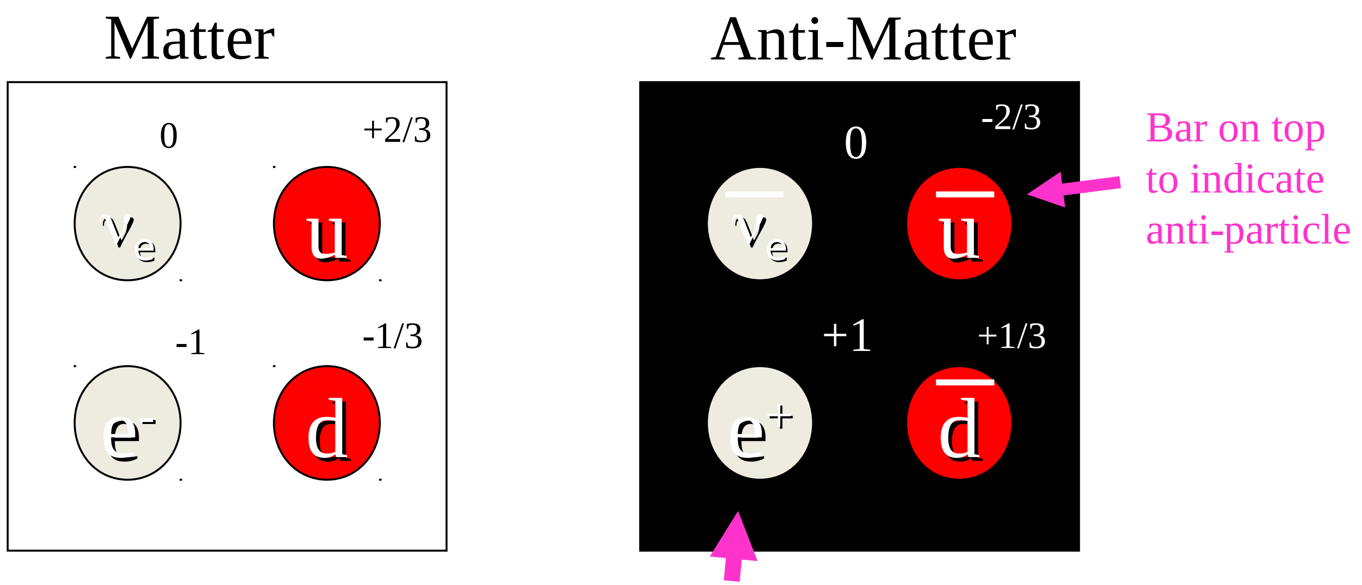
Note:	Electric Charge has values +, - , 0
	Colour Charge has values r, g, b, $\bar{r}$, $\bar{g}$, $\bar{b}$

When particle and antiparticle meet they annihilate to give energy with all quantum numbers zero (usually as photons).



Anti-matter

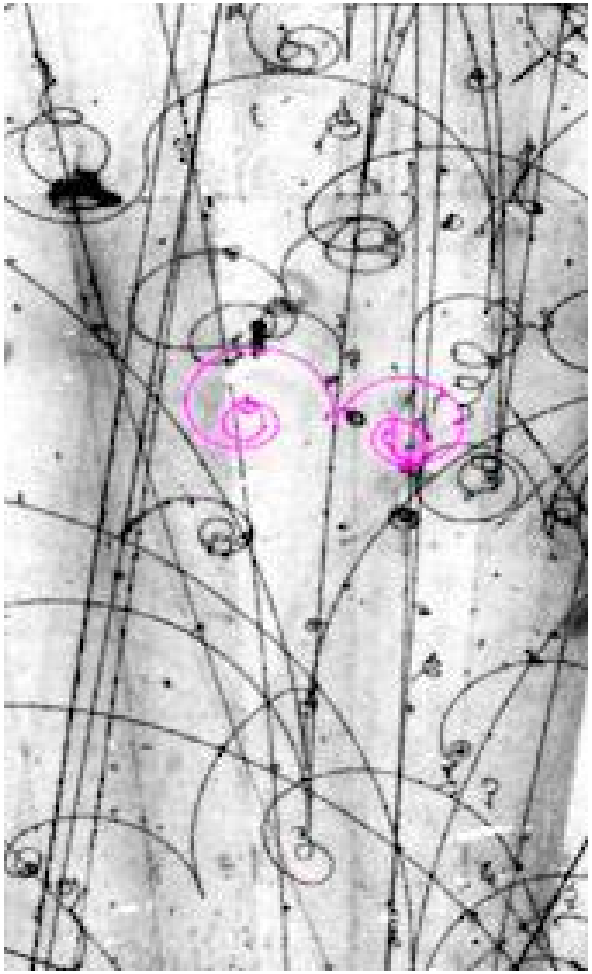
- For every fundamental <u>particle</u> of matter there is an <u>anti-particle</u> with same mass and properties but opposite charge



positron

- Correspondent anti-particles exist for all three families
- Anti-matter can be produced using accelerators

Matter-antimatter pair creation



- •Electron-positron pair created out of photons hitting the bubble-chamber liquid
- •Example of conversion of photon energy into matter and anti-matter
- •Matter and anti-matter spiral in opposite directions in the magnetic field due to the opposite charge
- •Energy and momentum is conserved

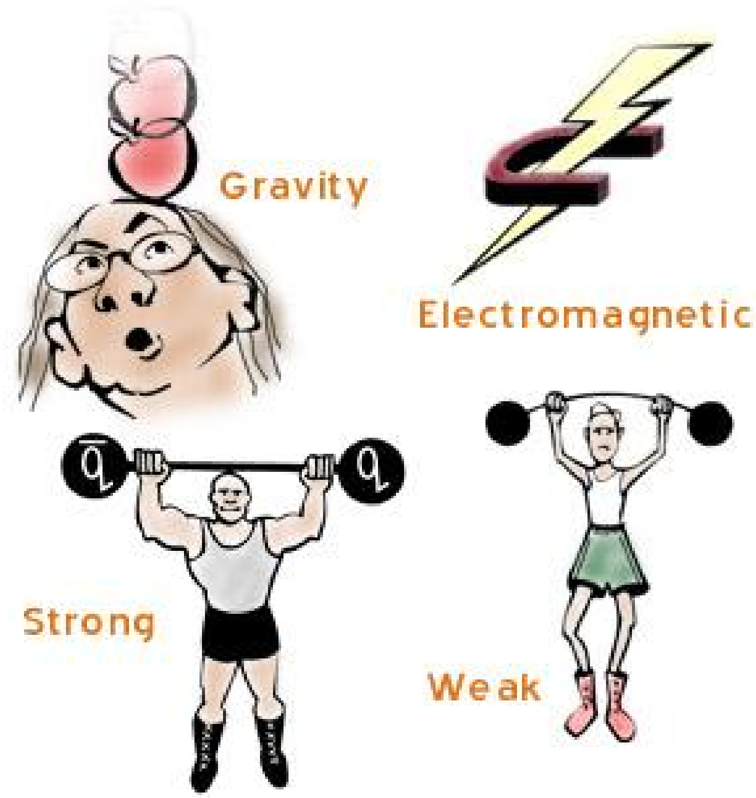
4 Forces

- There are 4 fundamental interactions in Nature

- All forces can be brought back to these interactions

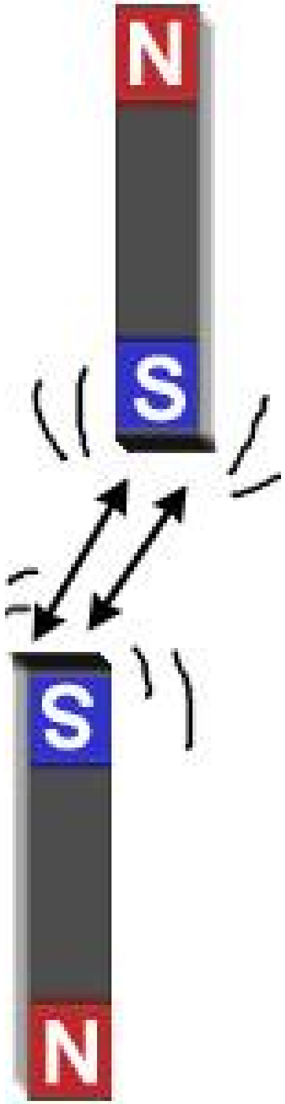
- The gravity is attractive, all other forces can also be repulsive

- The interactions are also responsible of the nucleus decays



How do particles interact?

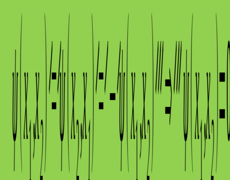
- Objects can interact without being in contact
- How do magnets attract or repulse?
- How does the Sun attract the Earth?
- A force is something which is propagating in between objects



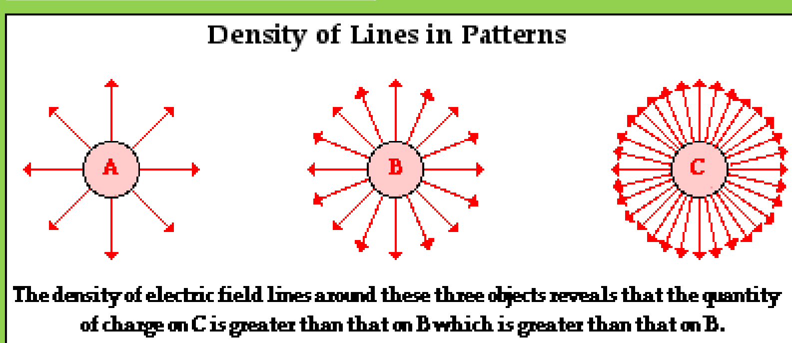
The concept of Force

In Classical Physics :

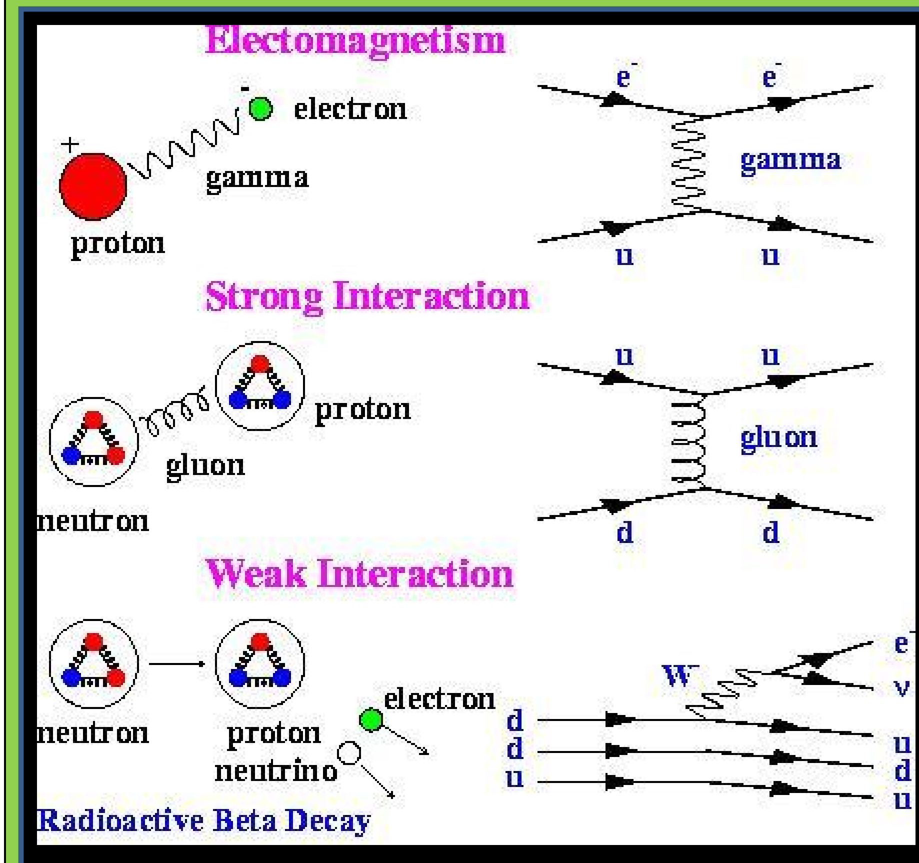
- Instantaneous action at a distance
- Field (Faraday, Maxwell)



Inverse square law

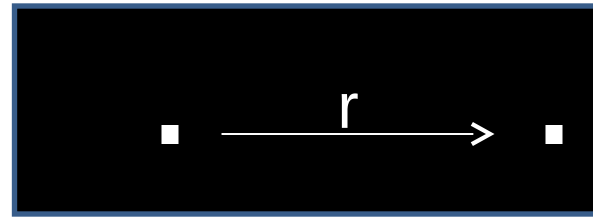


In Quantum Physics :



Classical and Quantum concepts of Force

Let us consider two particles at a distance r



If a source particle emits a quantum that reaches the other particle, the change in momentum will be:

$$r \ \Delta p \approx \hbar$$

And since: $c \ \Delta t \simeq r$ $\Longrightarrow$ $\dfrac{\Delta p}{\Delta t} \approx \dfrac{\hbar}{r}\dfrac{c}{r}$

We have: $$F = \frac{\Delta p}{\Delta t} \approx \frac{k}{r^2}$$

Range of interactions

The range of the interaction is related to the mass of the exchange particle M.

An amount of energy $\Delta E = Mc^2$ is 'borrowed' for a time Δt governed by the Uncertainty Principle $\Delta E \, \Delta t \sim \hbar$ i.e. $\Delta t = \hbar / \Delta E$.

The maximum distance the exchange particle can travel in this time is

$$\Delta x = c \, \Delta t$$

(c is the maximum velocity it can have)

$$\therefore \Delta x = c \, \hbar / \Delta E = c \, \hbar / Mc^2$$

$$\boxed{\Delta x = \hbar c / Mc^2}$$

$\hbar c$ in funny units (see later)

The photon has zero mass → infinite range

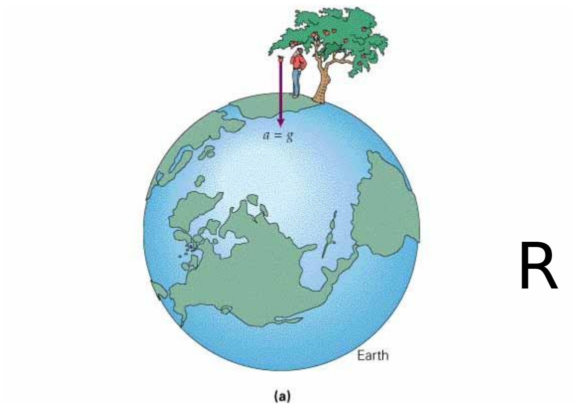
Converts GeV to MeV

The W has a mass of ~ 80 GeV/c^2 → 197 MeV fm / 80×10^3 → $\underline{2 \times 10^{-3}\text{fm}}$

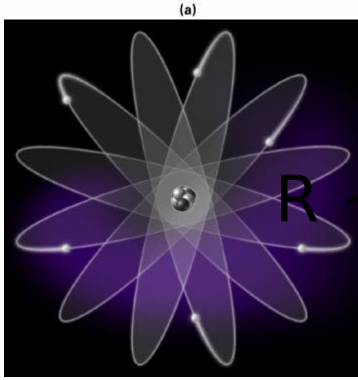
Forces in Nature

Force	Intensity	Carriers	Happens in
Strong Nuclear	~ 1	Gluons (massless)	Atomic nuclea
Elettro-magnetic	$\sim 10^{-3}$	Photons (massless)	Atomic levels
Weak Nuclear	$\sim 10^{-5}$	W^+, W^-, Z^0 (heavy)	Beta radioactive decay
Gravitation	$\sim 10^{-38}$	Gravitons (?)	Heavy bodies

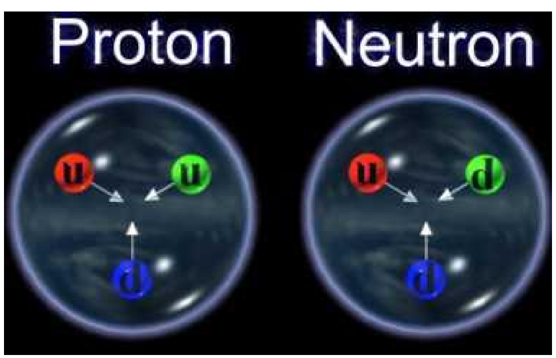
Forces and distances



R > 10^6 m (gravitational force)



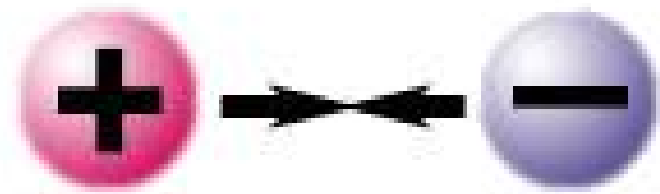
R ~ 10^{-10} m (forza elettromagnetica)



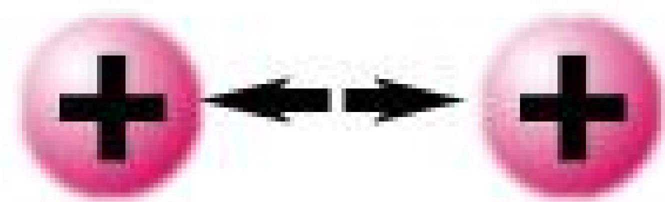
R ~ 10^{-15} m (forza forte)

Electromagnetism

- The electromagnetic forces are such that opposite charges attract and equal charges repulse



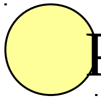
- The force carrier is the photon (γ)
-
- The photon is massless and move at the speed of light



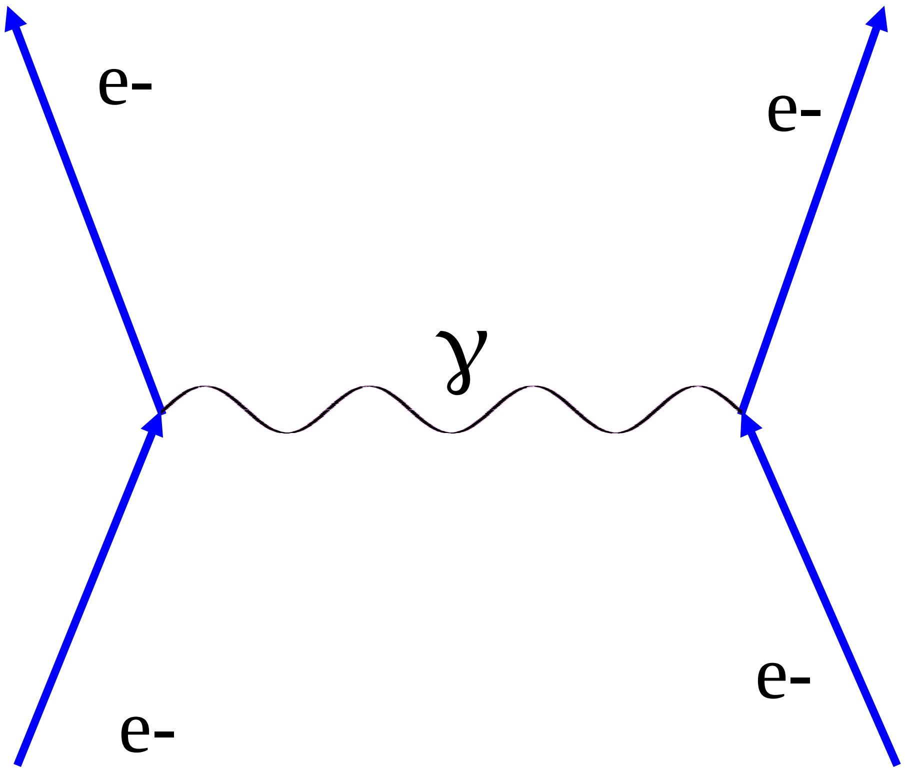
Electromagnetic force

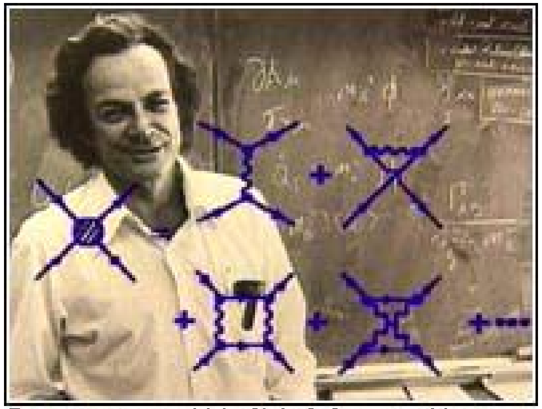
The repulsive force that two approaching electrons “feel”

Photon is the particle
associated to the electromagnetic force
“smallest bundle” of force


Photon

Photon exchange Feynman Diagram





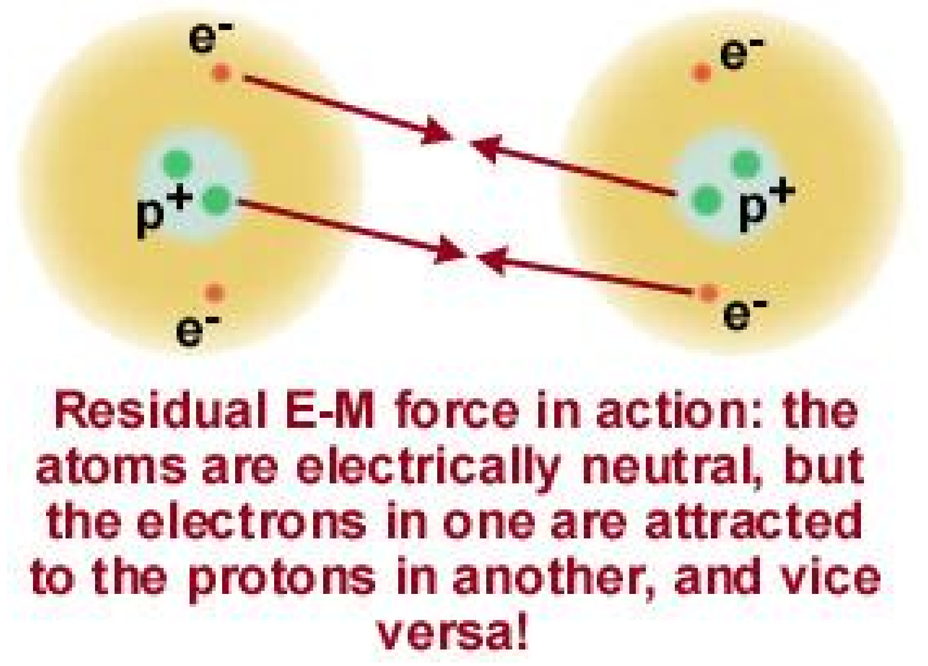
Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)

Electromagnetic residual force

- Normally the atoms are neutral having the same number of protons and neutrons

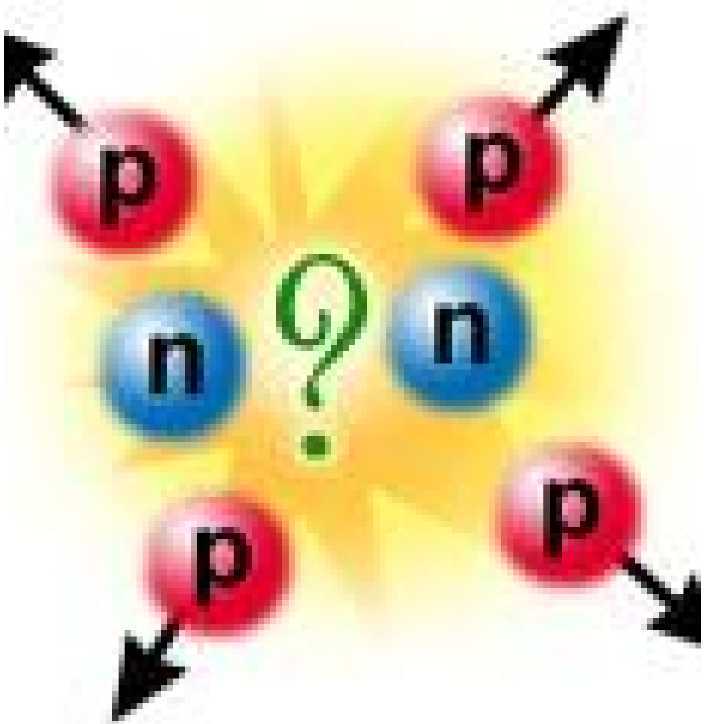
- The charged part of an atom can attract the charged part of another atom

- The atoms can link themselves to form molecules



Why nuclea do not explode?

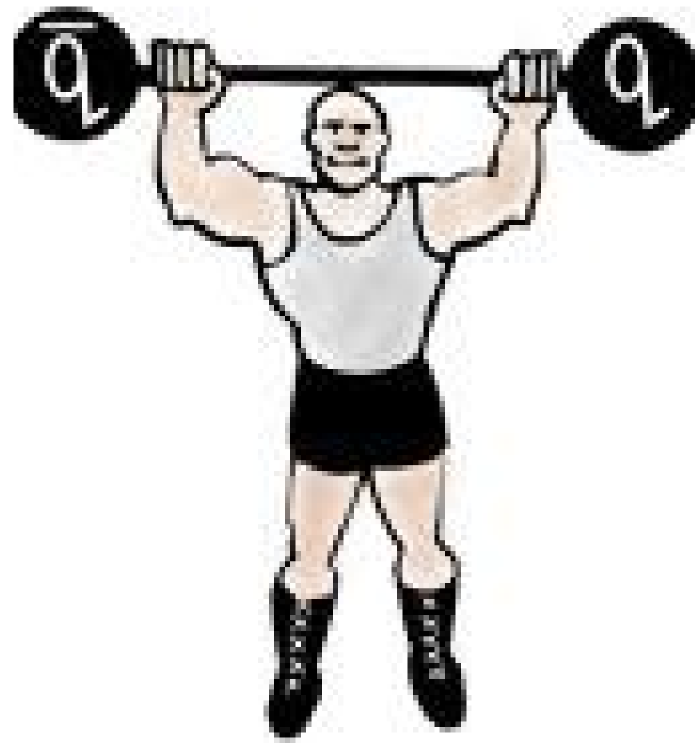
- A heavy nucleus contains many protons, all with positive charges
- These protons repulse each others
- Why the nucleus does not explode?



Strong force

- In aggiunta alla carica elettrica, i quarks portano anche un nuovo tipo di carica, detta “carica di colore”

- La forza tra le particelle che hanno carica di colore e’ detta forza forte



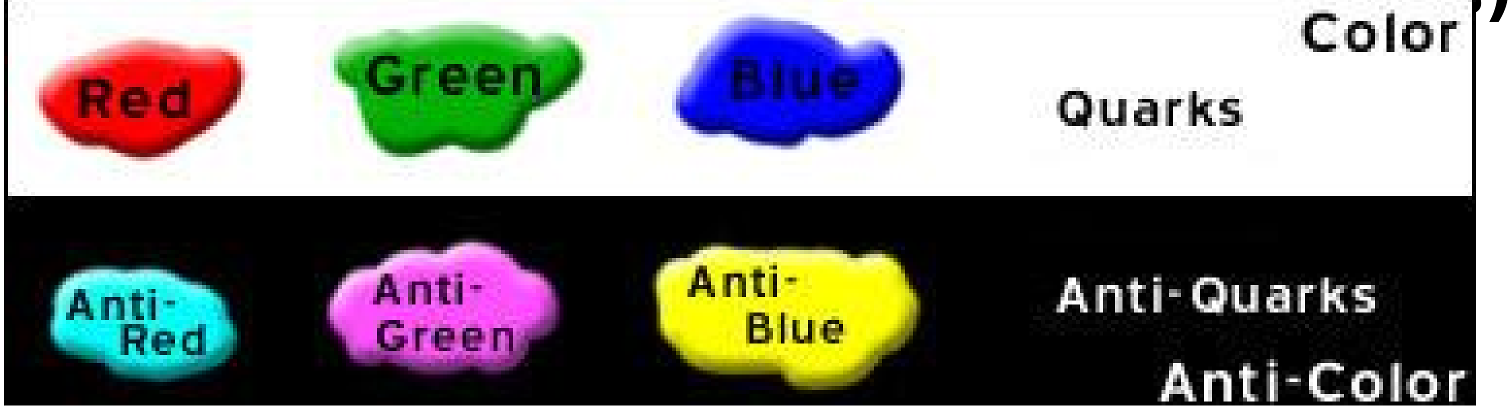
The gluon

- The strong force keeps the quark together, to form the hadrons.
- The force carriers are the gluons: there are 8 different gluons
- The strong force acts only on short distances

Colour and anti-colour

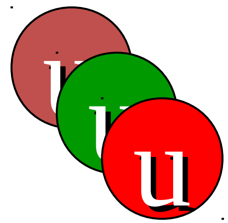
- There are 3 colour charges and 3 anti-colour charges

- **Note that these colours are not at all related with the standard colour and with the visible light. It is just a way to describe the physics (quantum numbers)**

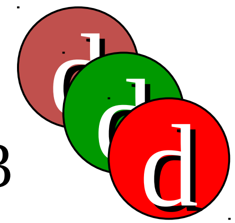


Quarks and colour

All quark flavours come in 3 versions, called “colours”



up
+2/3

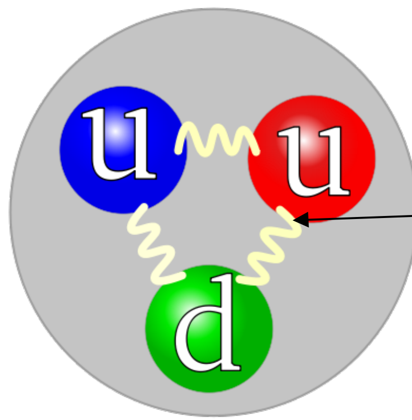


down
-1/3

Quarks combine together to form colourless particles

-***Baryons*** (three quarks: red+ green + blue = white)

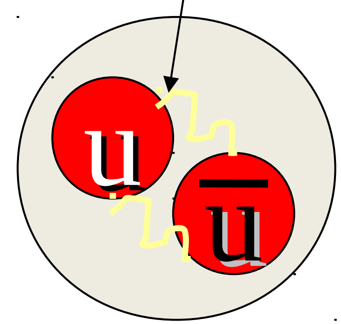
proton
p



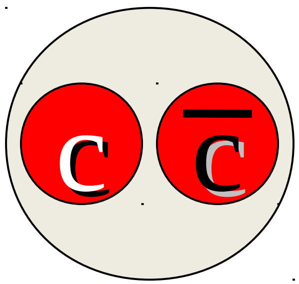
Strong forces “glue” quarks together in bound states

-***Mesons*** (quark-antiquark pair)
such as red+anti-red u-ubar state

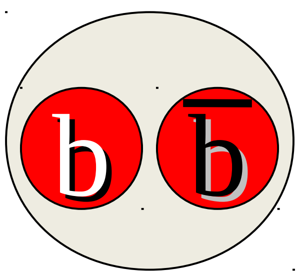
pion
π



Building more particles

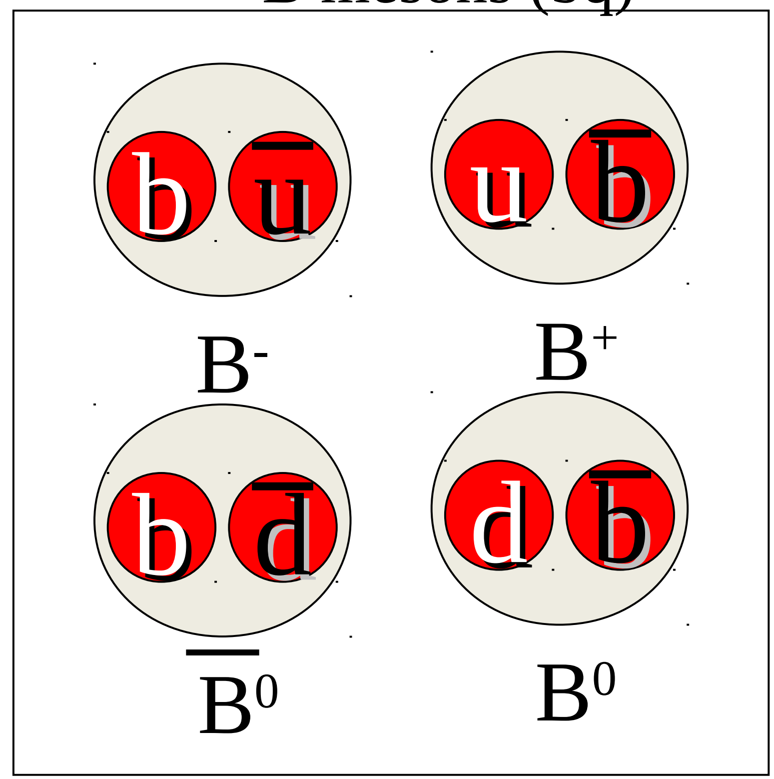


J/ψ



Υ

B mesons ($b\bar{q}$)



Many more mesons and baryons…

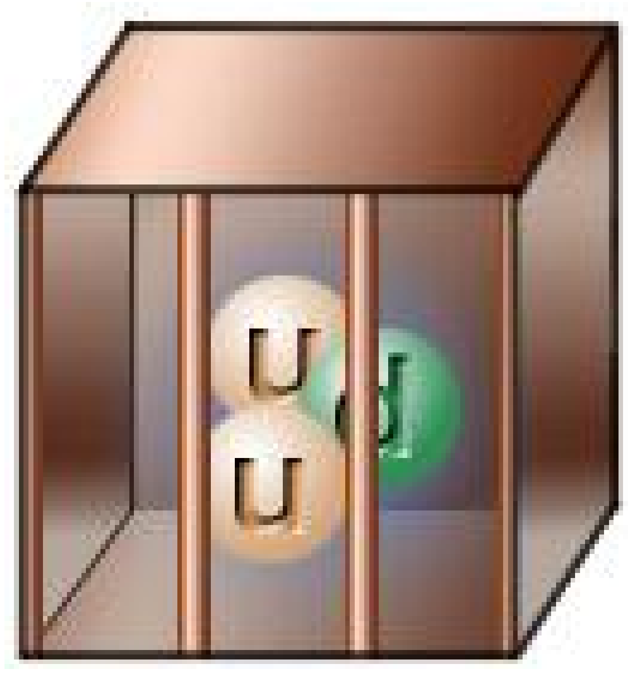
Coloured quarks and gluons

- Every quark has one of the three colour charges and every antiquark has one of the three anticolour charges

- Barions and mesons are neutral in colour

Quarks confinement

- The colour force increase with the distance
- Partciles with colour charge cannot exist as isolated particles
- Quarks are confined with other quarks to form hadrons
- Hadrons are neutral in colour

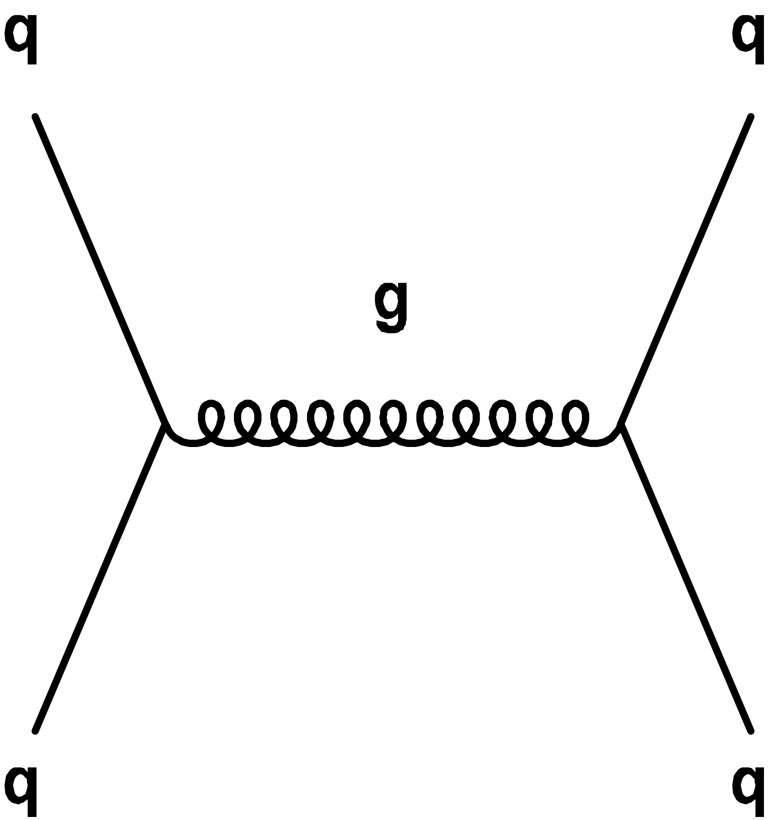


Quarks emit gluons

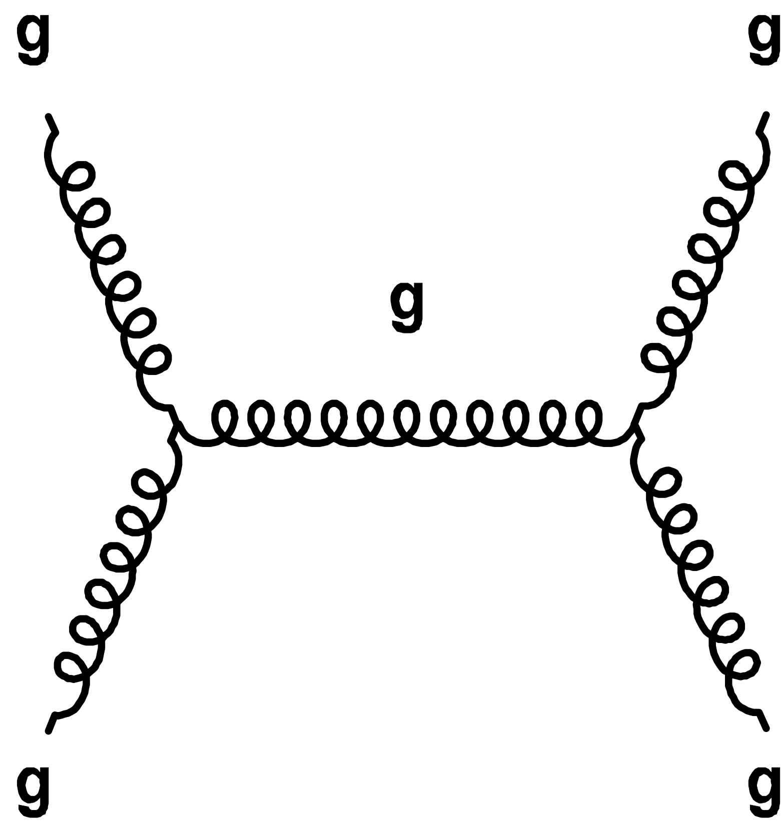
- When a quark emits or absorbs a gluon, the colour of the quark changes, in order to save the colour charge

- A red quark emits a red/anti-blue gluon, and becomes blu

Strong force: gluons



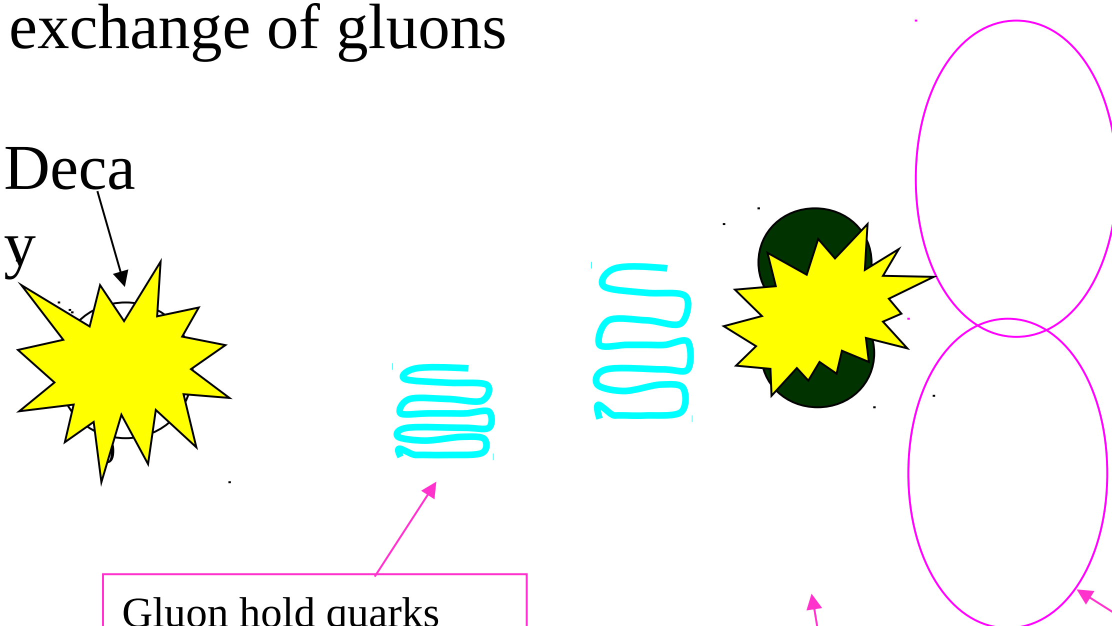
Gluons interact with quarks



Gluons interact with other gluons

Quark confinement

- There are no free quarks, quarks and antiquarks are “confined” in colourless doublet (mesons) or triplets (baryons) by the exchange of gluons



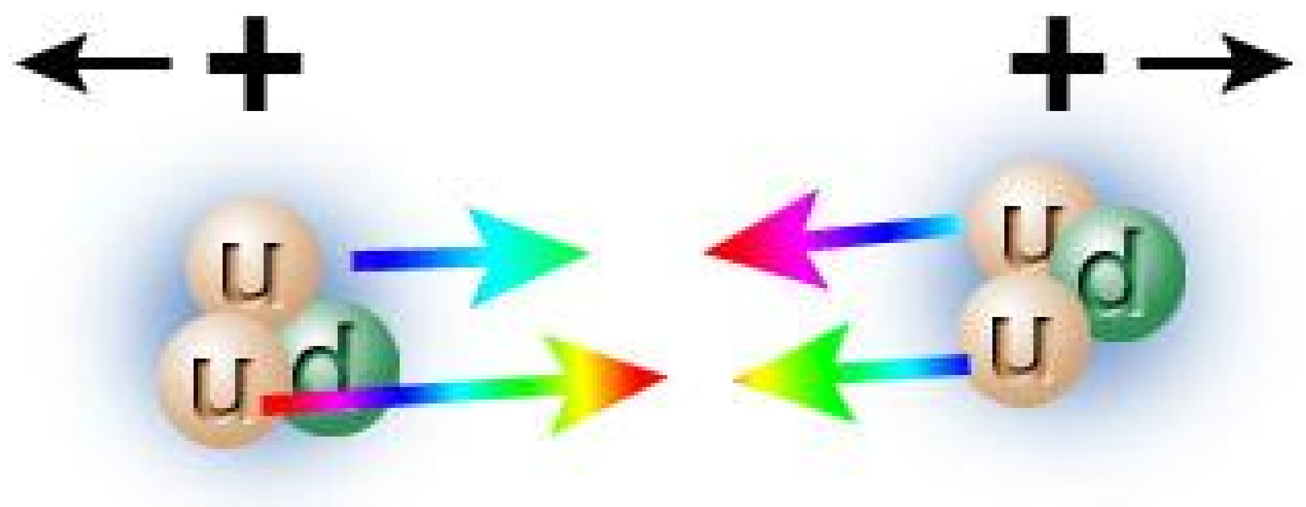
Gluon hold quarks together as they move further apart

until the gluon connection snaps, and other quark-antiquark pairs are created out of the energy released

The new quarks bound to the old quarks and form new mesons

Residual strong force

- The strong force between the quarks of a proton and the quarks of another proton is strong enough to win on the repulsive electromagnetic force



Weak force

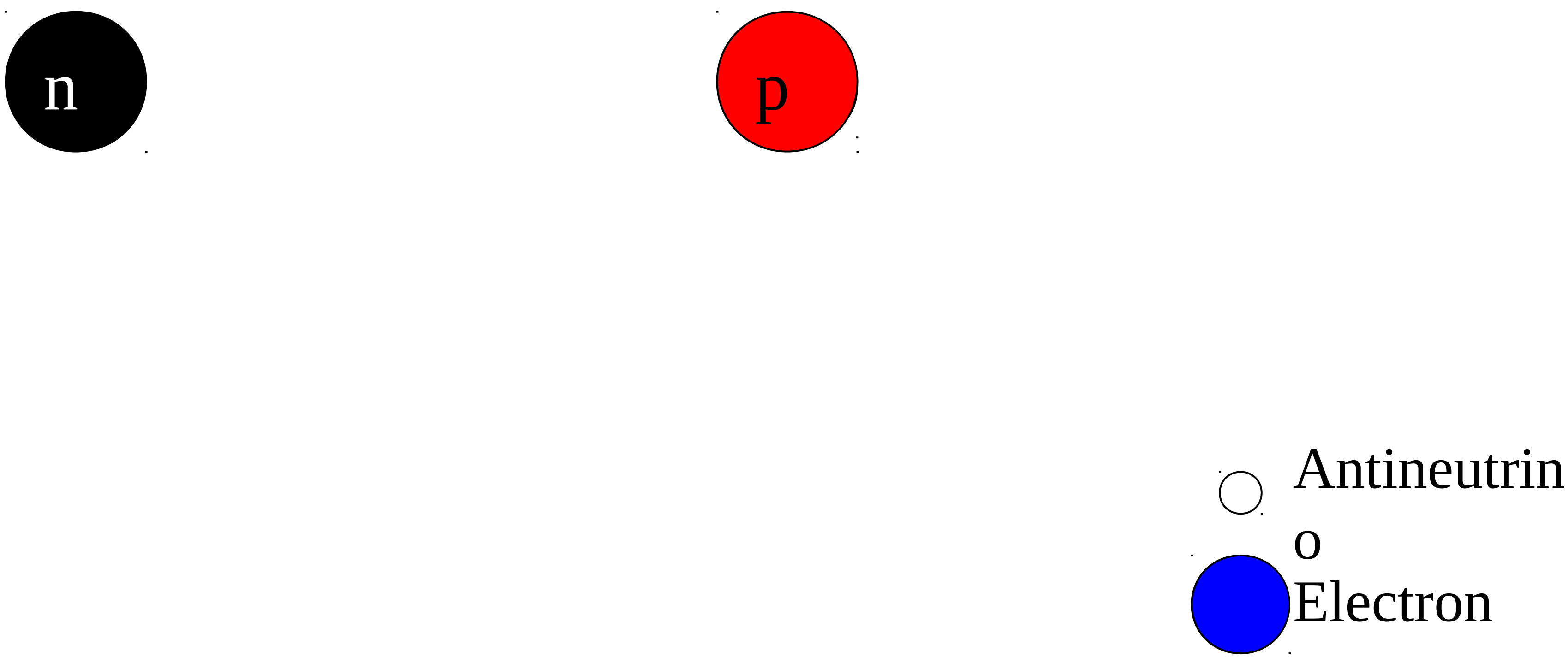
- Weak interactions are responsible for the decays of heavy quarks and leptons

- Example: the neutron decays in a proton + electrons + neutrino

- This explains why all matter is composed by the lighter leptons and quarks

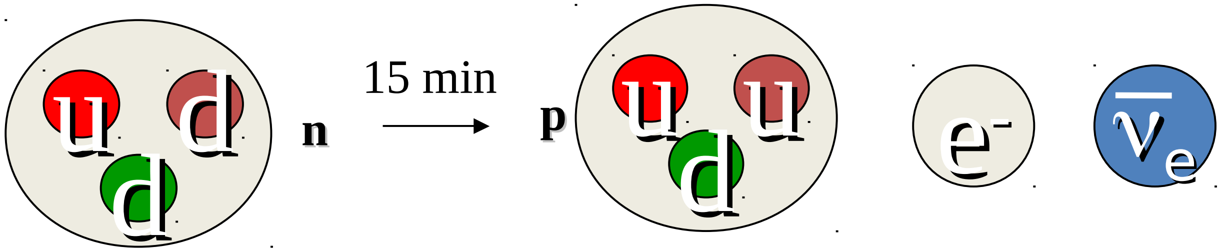
THE WEAK FORCE

Beta Decay



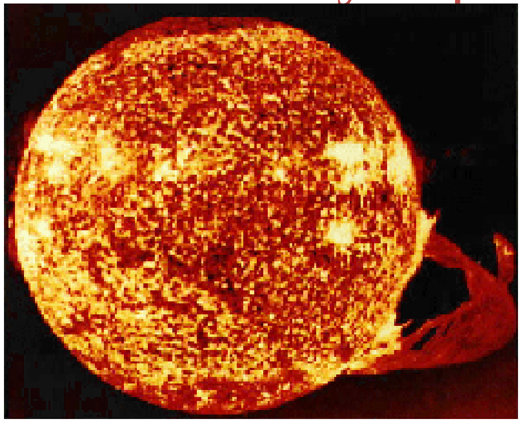
Neutron β-decay

At quark level: $d \rightarrow u\, e^- \,\overline{\nu}_e$



A (free) neutron decays after 15 min

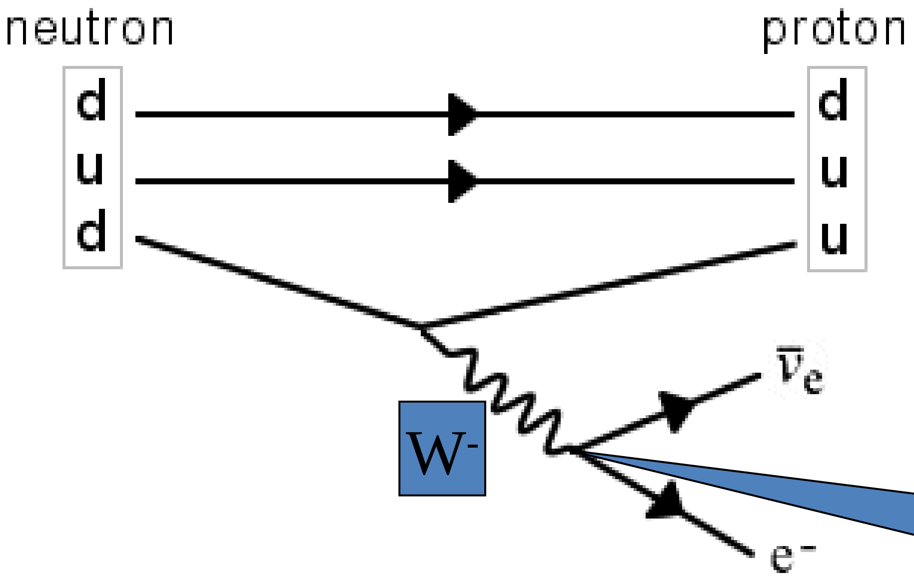
Long life time (15min is an eternity in particle physics!) ⇒ "weak "



Electroweak force

- In the SM the electromagnetic and weak forces have been unified in a single electro-weak force
- At very short distances (~10^{-18} meters), the weak and electromagnetic interactions have the same intensities
- The carriers are photons, W and Zs.

Weak force: W^-,W^+,Z^0



Beta radioactive decay via the weak interaction

β-decay

$n \rightarrow p e \bar{\nu}_e$

Electric charge conserved at each vertex

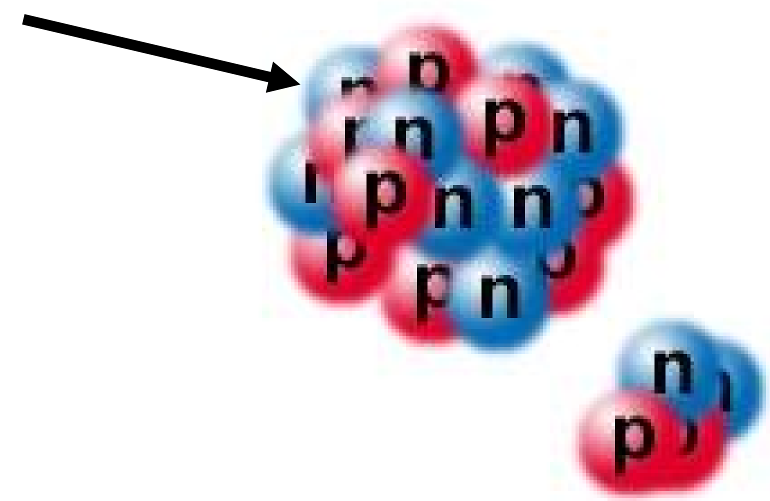
And the gravity?

- Gravity is very weak
- Is important at macroscopic distances
- The force carriers (gravitons) is predicted by theory but not yet observed

The unstable nucleus

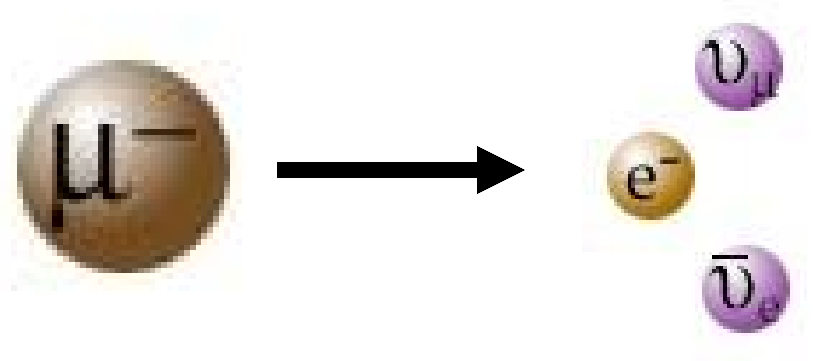
- We saw that strong forces keep the nucleus together, against the repulsive force between protons.
- However, not all nuclea are stable
- Some of them decay

- The nucleus can split in smaller nuclea
- This happens for example in a nuclear reactor



Muon decay

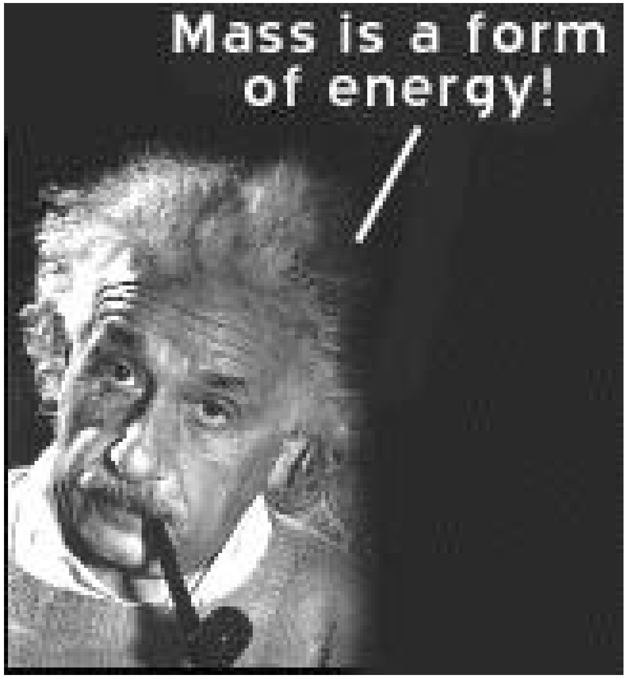
- Example of a particle deca
- Here the produced particle are not pieces of the initia particle, but are complete new ones.



Missing mass

- In most of the decays, the particles and the nucleus which are left have a total mass smaller than that of the initial particle or of the originating nucleus

- The missing mass it is transformed in kinetic energy of the decay products



How does a particle decay?

- When a particle decay, it is transformed in a lighter particle and in a particle which is one of the carriers of the weak force (the W boson)

- A particle decays if its total mass is higher than the sum of the masses of the decay products and if there is a force which mediates the decay

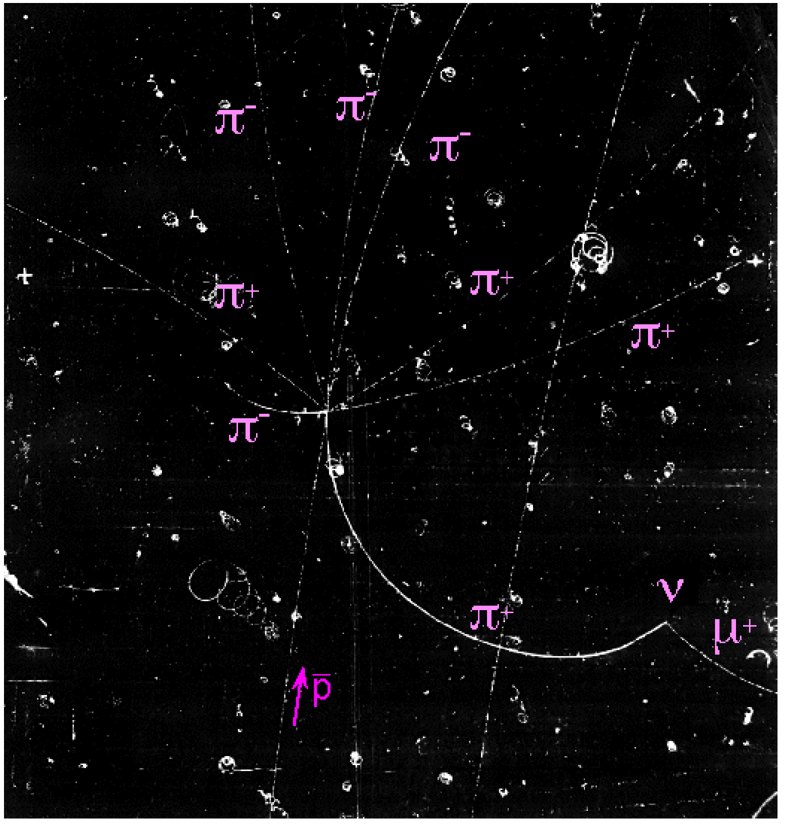
Virtual Particles

- Particles decay via particles which are force-carriers
- In some cases, a particle may decay via a force-carrier that is more massive than the initial particle
- The force-carrier particle is immediately transformed into lower-mass particles
- The short-lived massive particle appears to violate the law of energy conservation

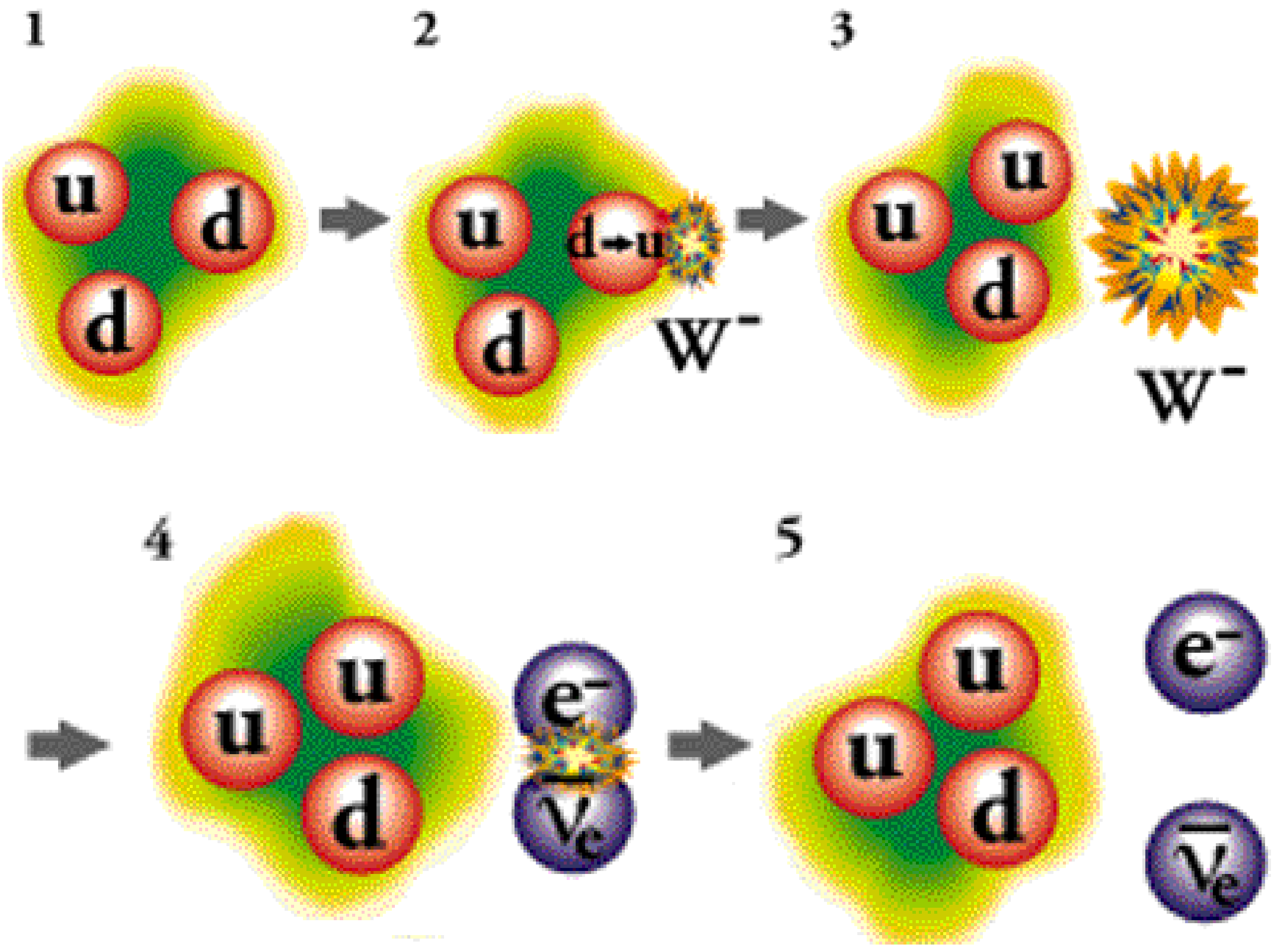
Annihilation

- Annihilations are not decays but, in the same way, they take place thanks to virtual particles
- The annihilation of light quarks at high energies can bring to the production of heavy quarks in the laboratory

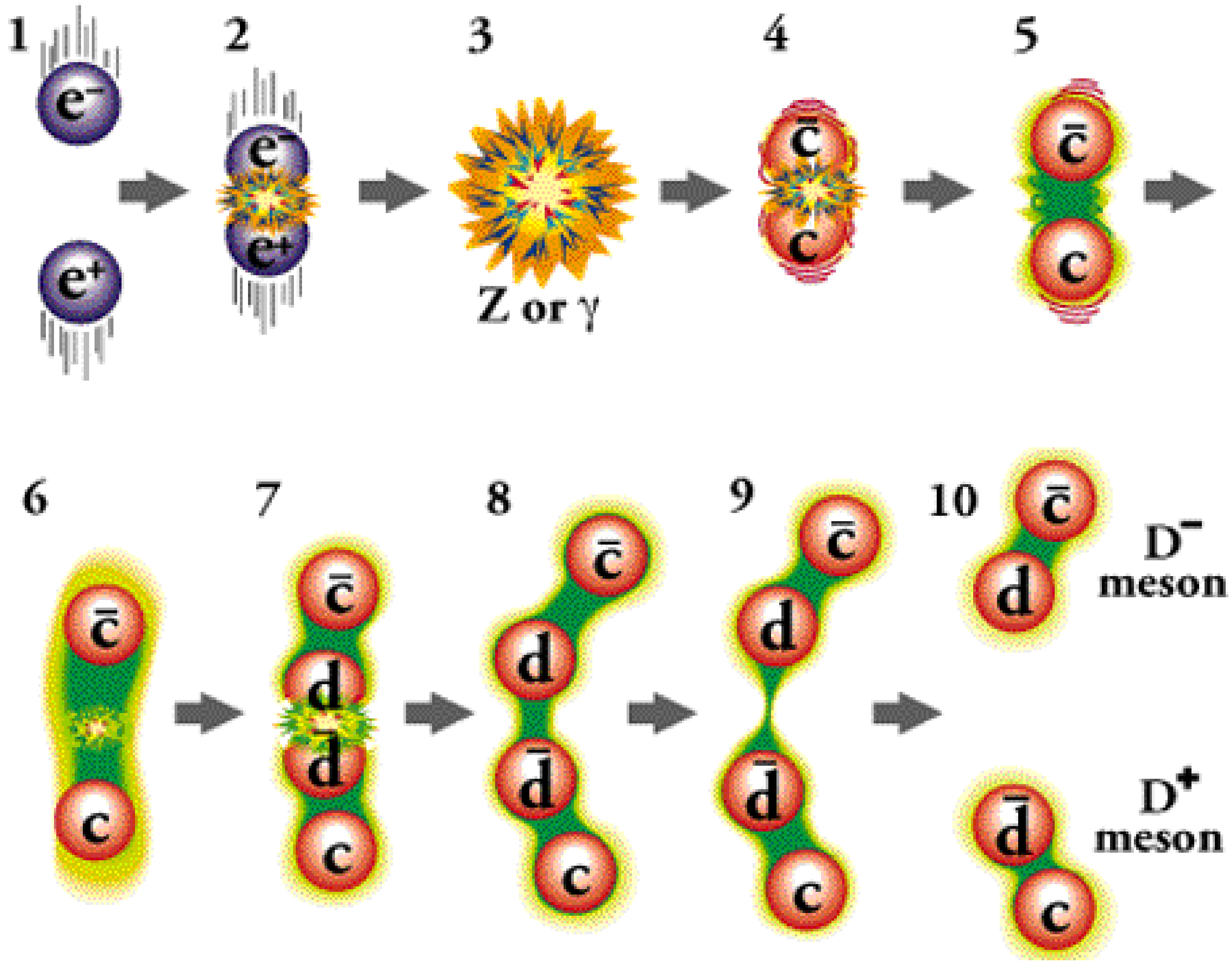
- This bubble chamber shows an anti-proton which hits against a proton, annihilates and produces 8 pions. One of the pion then decays in a muon and a neutrino (neutrino does not leave any trace)



Neutron beta decay



Electron-Positron annihilation

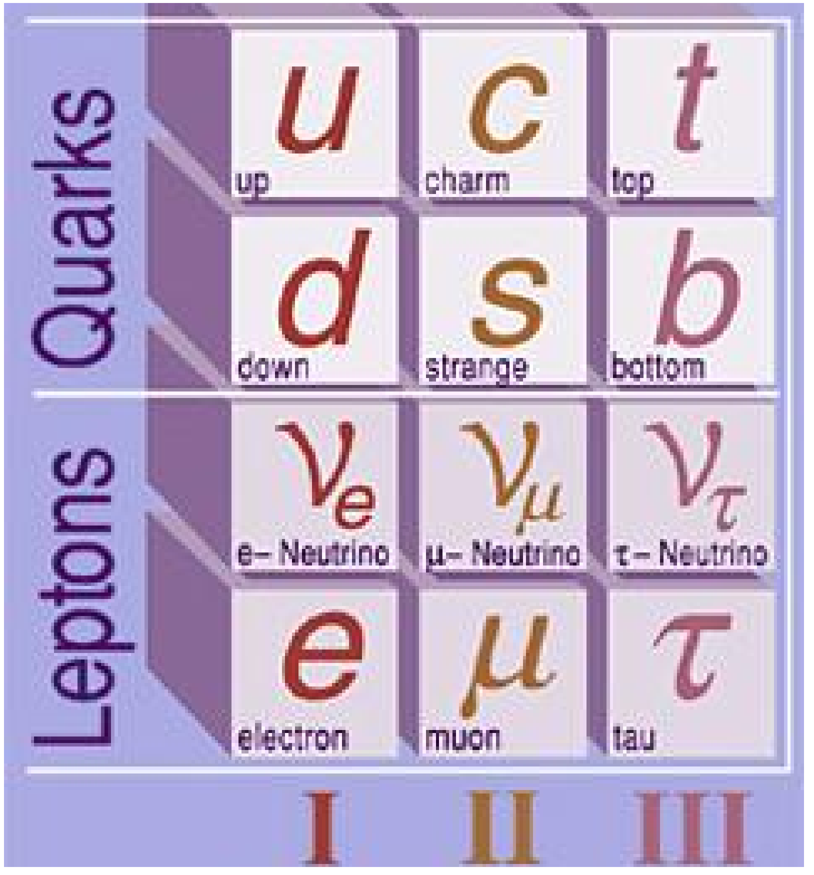


Mysteries and failures

- The SM is a theory of the Universe
- It gives a good description of the phenomena which we observe experimentally
- Under many respects is not complete: why there are 3 generations? What is the dark matter?
- As Enstein has extended the laws of mechanics of Newton with the Relativity theory, we now have to go beyond the SM
- We have to do it to explain masses, gravity etc..

Three families

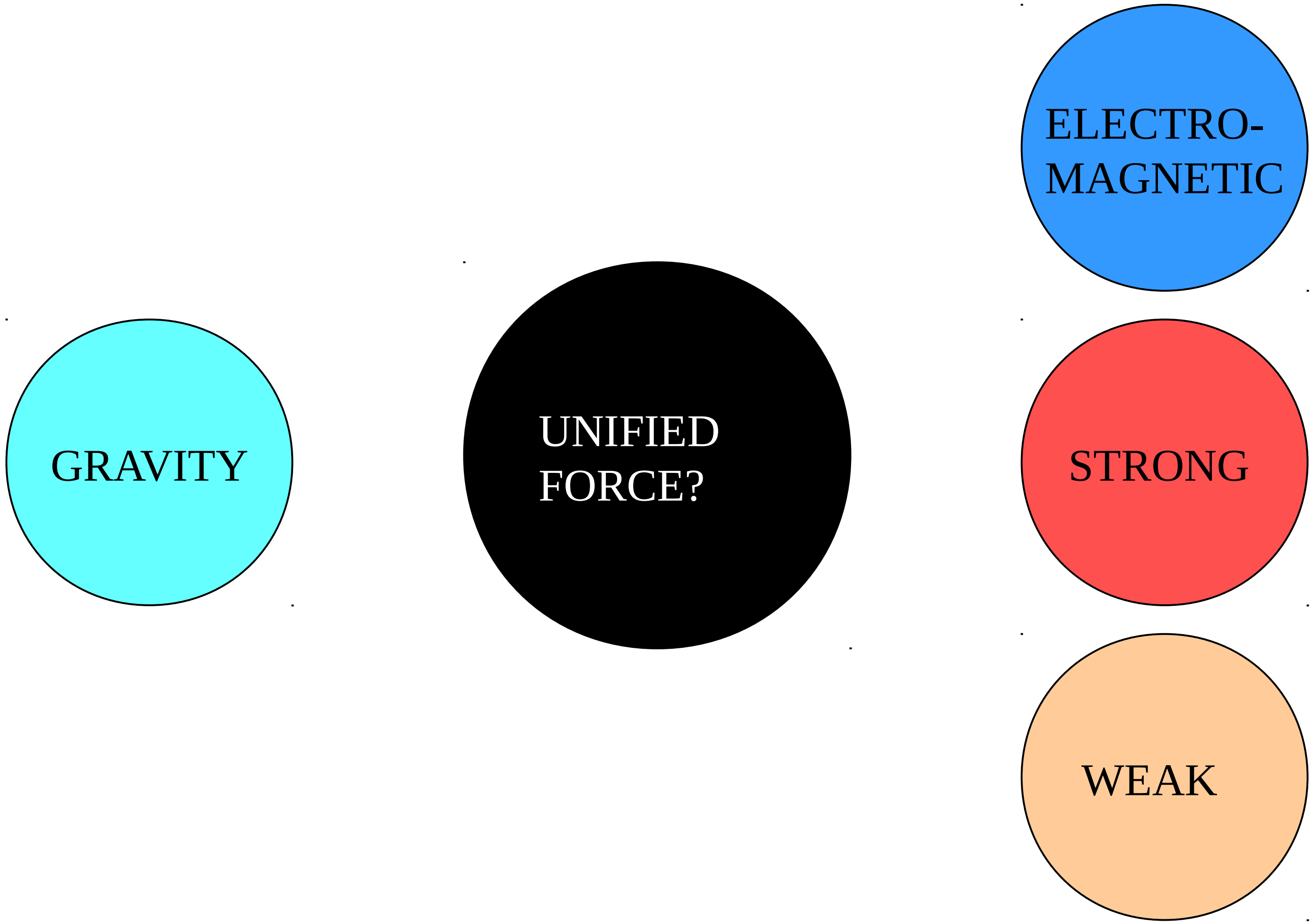
- There are 3 families of fundamental particles
- Why only 3?
- And why we just see one of them in the real world?



What can we say about mass?

- The SM cannot explain why a given particle is characterized by its mass.
- Physicists “invented” a new field, called **Higgs field**, which interacts with all the other particles to give their masses.

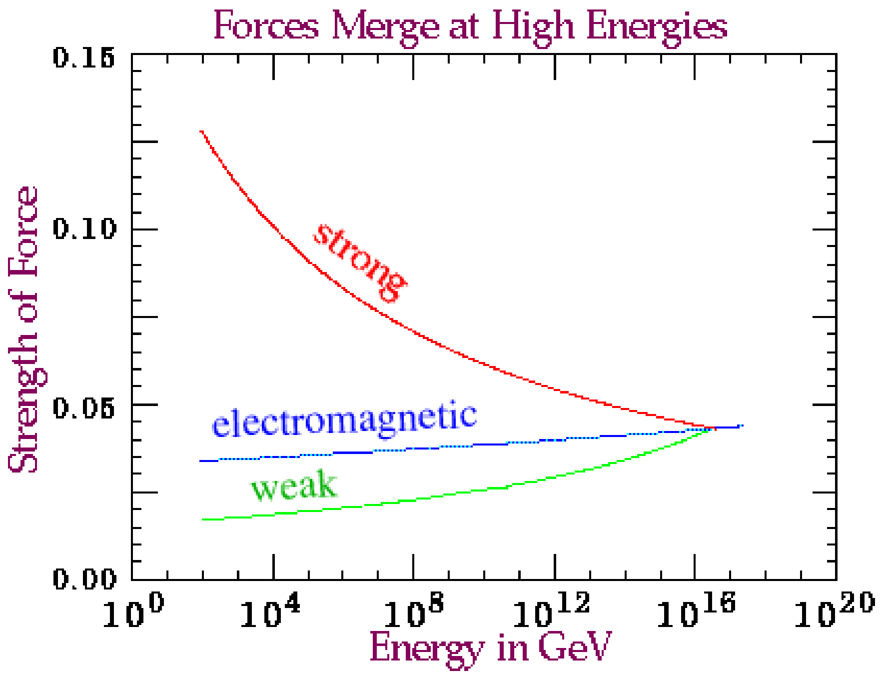
Beyond the Standard Model:Unification of forces



Looking for a simple elegant unified theory

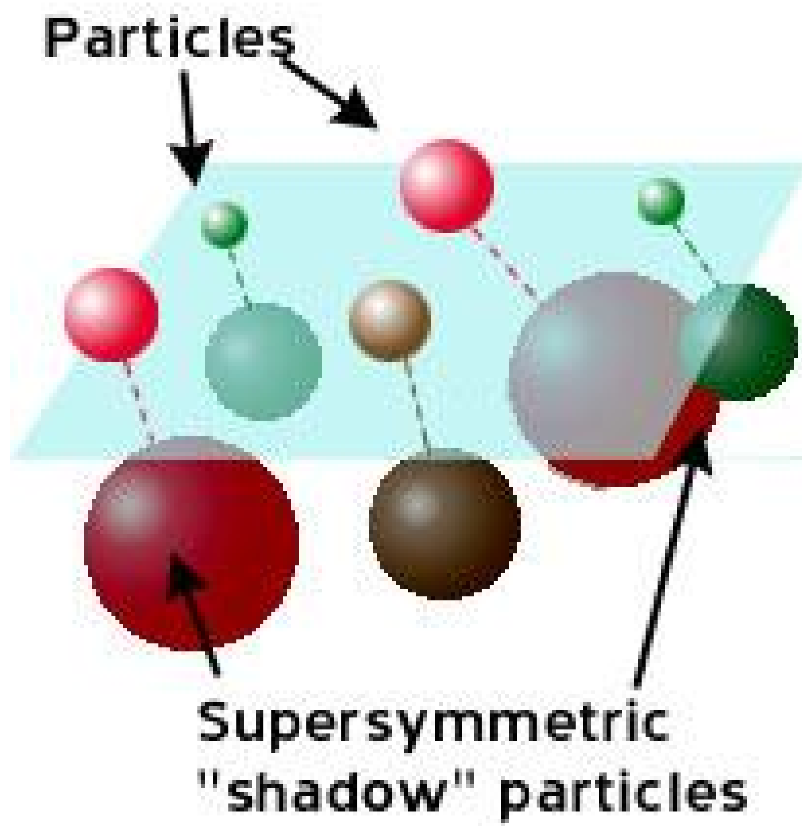
Theory of Grand Unification

- It is believed that a GUT will unify the strong, weak, and electromagnetic forces.
- These 3 forces will then be visible as different manifestations – at low energy – of a unique force
- The 3 forces will unify at a very high energy



Supersymmetry

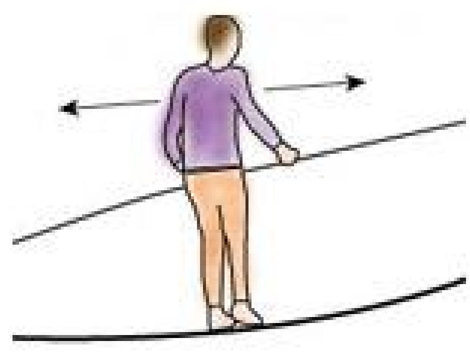
- Some physicists, in the attempt to unify gravity with the other fundamental forces, have suggested that every fundamental particle should have a shadow particle. It is more than 20 years that we are looking for these supersymmetric particles!



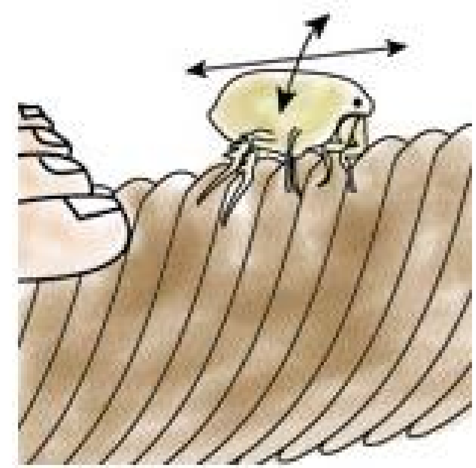
- Today, physics has a theory for quantum mechanic, for relativity and for gravity, but these 3 theories are not unified. .
- If we would live in a world with more than 3 spatial dimensions, maybe this problem could be overpassed.
- The string theory suggests that in a world where there are the 3 standard dimensions and some additional (but smaller) dimensions, the particles would be like strings.

Extra Dimensions

- The String theory requires more than just 3 dimensions
- These extra-dimensions can be so small that we cannot see them
- Experiments now look for evidence of these extra-dimensions



An acrobat can only move in one dimension along a rope..

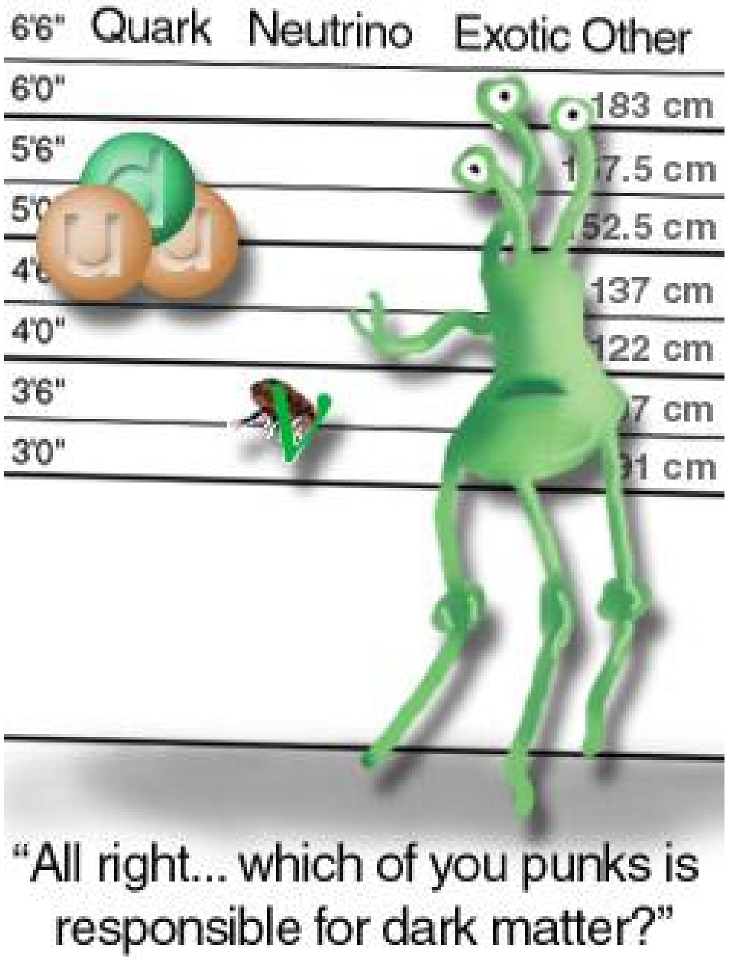


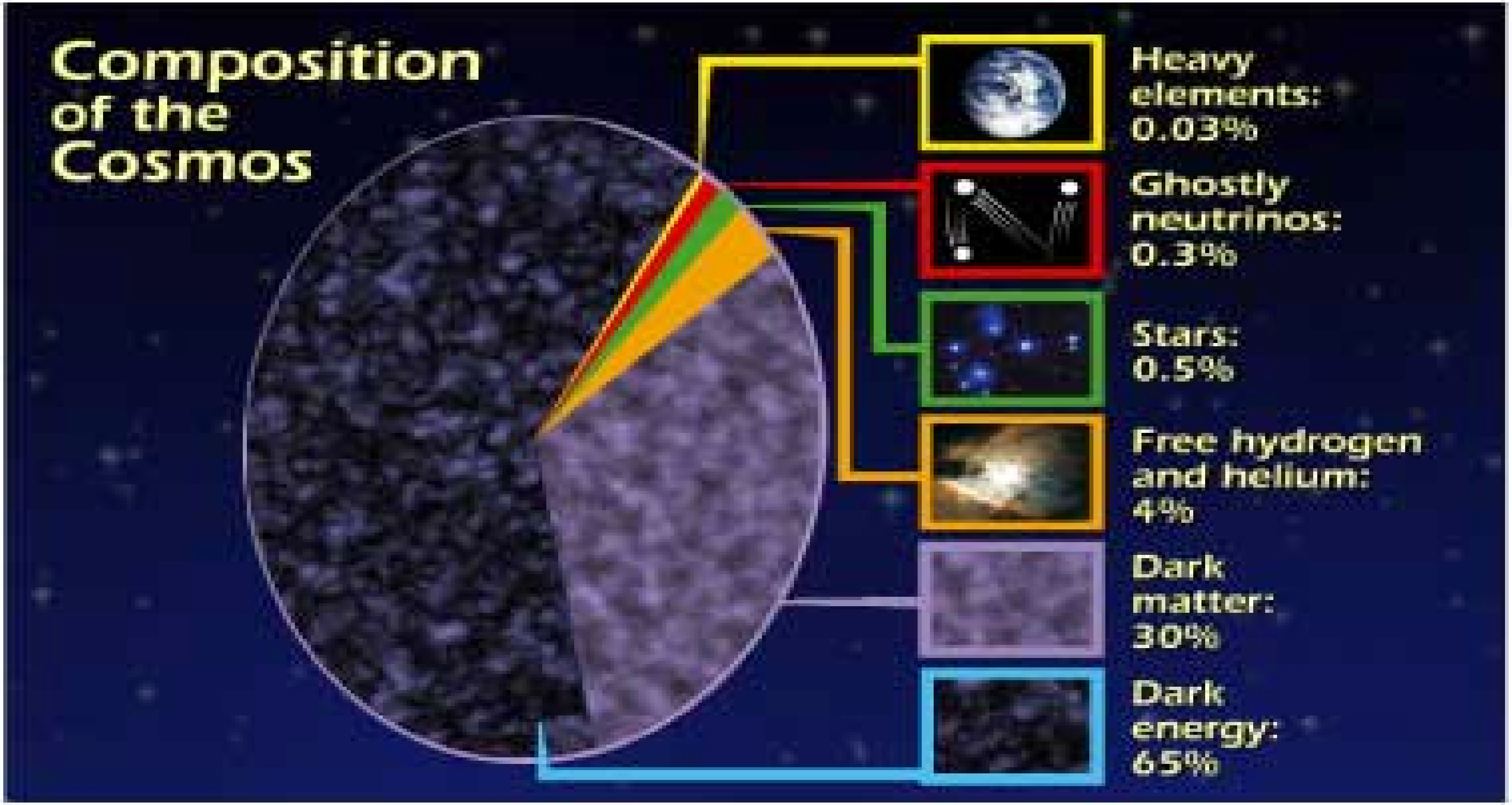
...but a flea can move in two dimensions.

Dark Matter

- It seems that the Universe is made by a different matter than our Sun and stars

- The dark matter attracts normal matter, but it has not been identified yet




Composition of the Cosmos
Heavy elements: 0.03%
Ghostly neutrinos: 0.3%
Stars: 0.5%
Free hydrogen and helium: 4%
Dark matter: 30%
Dark energy: 65%