Origin of Mass
Lect. 1: Motivation

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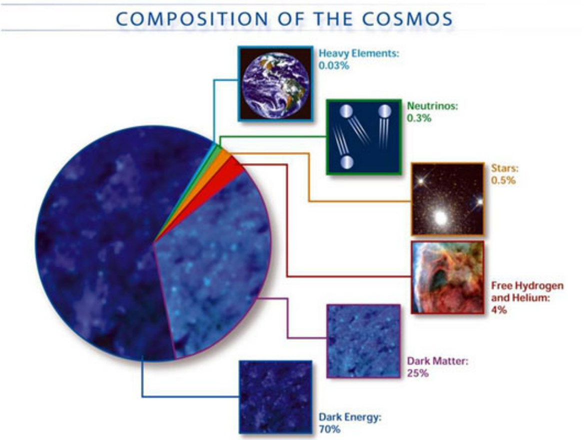
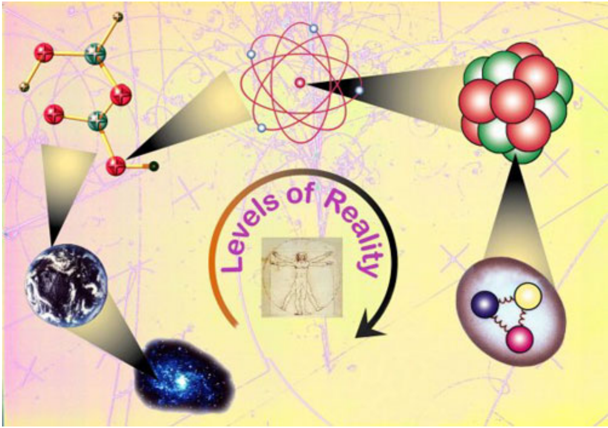


Our place in the Universe



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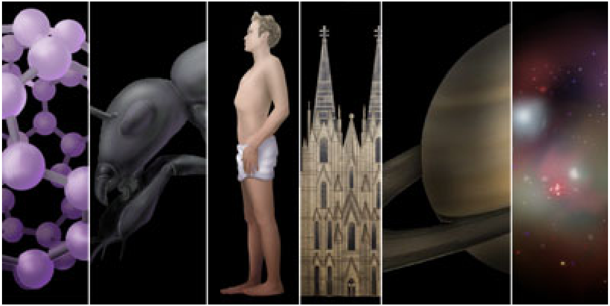

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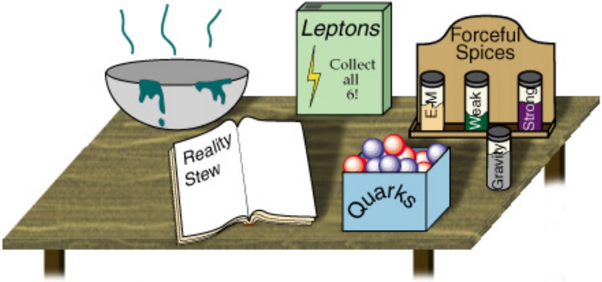

Is the mass a fundamental property of matter?

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- "Mass is the quantity of matter arising from its density and bulk conjointly"

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- Newton's 2nd Law: $a = \frac{F}{m}$

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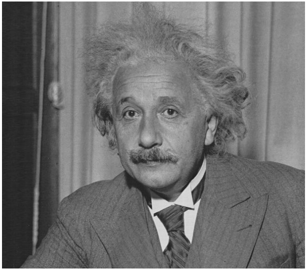
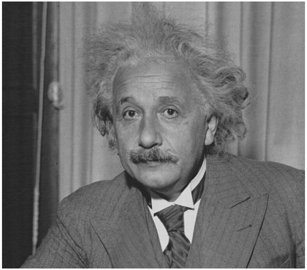
- Lavoisier: Mass is conserved

Is the mass a fundamental property of matter?



- Modern conception: “Mass of a body is a measure of its energy content”

Is the mass a fundamental property of matter?



- Modern conception: "Mass of a body is a measure of its energy content"
- $m = \frac{E_0}{c^2}$, $E_0 \longrightarrow$ body's rest energy

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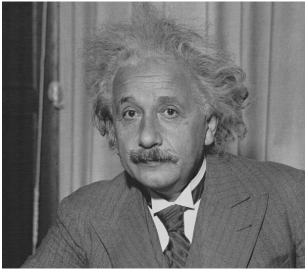

- Modern conception: "Mass of a body is a measure of its energy content"
- $m = \frac{E_0}{c^2}$, $E_0 \longrightarrow$ body's rest energy
- This is realized in particle accelerators

Is mass Newtonian or Einsteinian?

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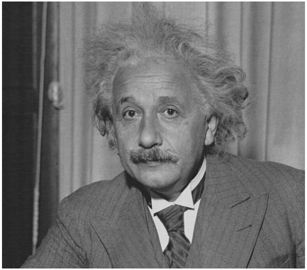
- Mass of an object is the mass of its parts

Is mass Newtonian or Einsteinian?



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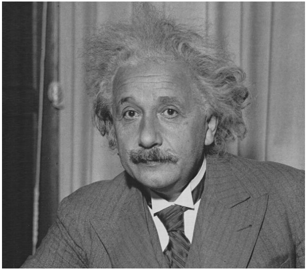

- Mass of an object is the mass of its parts
- Mass of an object is its rest energy

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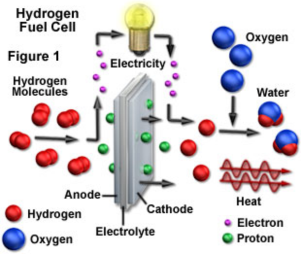
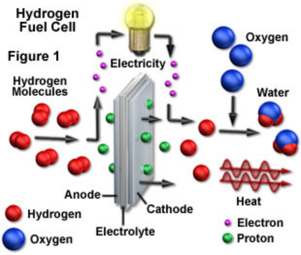


Molecules

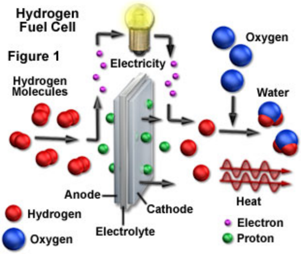
Is mass Newtonian or Einsteinian?



- Reaction
$$2H_2 + O_2 \rightarrow 2H_20$$

Molecules

Is mass Newtonian or Einsteinian?



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  $2H_2 + O_2 \rightarrow 2H_20$
- If 1 m^3 of H is burned, some 13 MJ are liberated

Molecules

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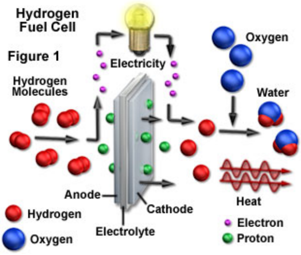
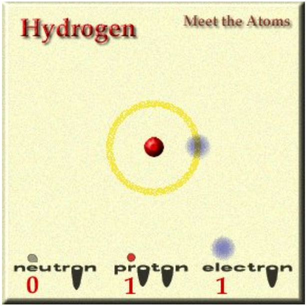


Molecules

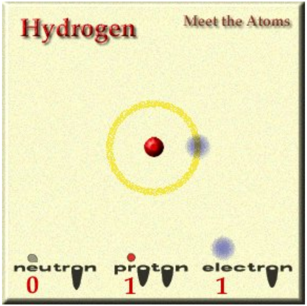
- Reaction
  $2H_2 + O_2 \to 2H_20$
- If 1 m^3 of H is burned, some 13 MJ are liberated
- Mass difference of reactants and products: $\mathcal{O}(10^{-11})$

Is mass Newtonian or Einsteinian?



Atoms

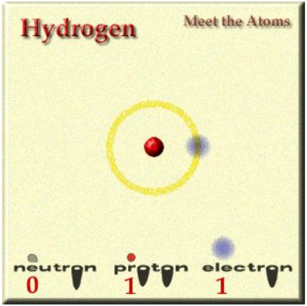
Is mass Newtonian or Einsteinian?



- Mass of the H atom: M_p

Atoms

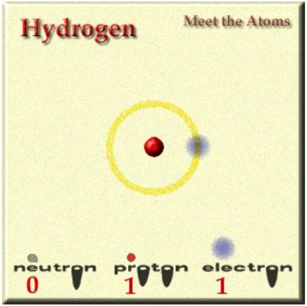
Is mass Newtonian or Einsteinian?



- Mass of the H atom: M_p
- Binding energy $13{,}6 eV$

Atoms

Is mass Newtonian or Einsteinian?



- Mass of the H atom: M_p
- Binding energy 13,6eV
- Mass difference: $\mathcal{O}(10^{-8})$

Atoms

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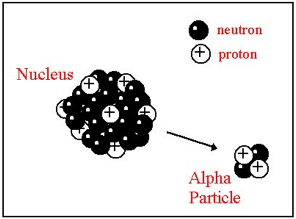
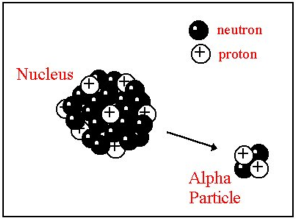


Nuclei

Is mass Newtonian or Einsteinian?



- Mass of nuclei comes from mass of protons and neutrons

Nuclei

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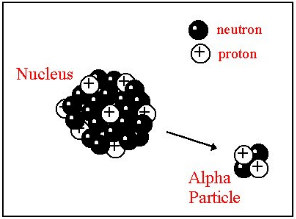

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- α-particle $\Rightarrow$ deep bound of 2 p and 2 n

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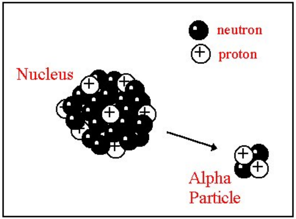
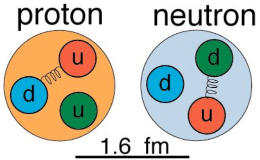


Nuclei

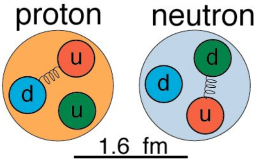
- Mass of nuclei comes from mass of protons and neutrons
- α-particle $\Rightarrow$ deep bound of 2 p and 2 n
- Mass difference: 0.75 %

Is mass Newtonian or Einsteinian?



Nucleons

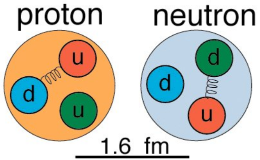
Is mass Newtonian or Einsteinian?



Nucleons

- Mass of 3 light quarks $\sim$ 10MeV

Is mass Newtonian or Einsteinian?



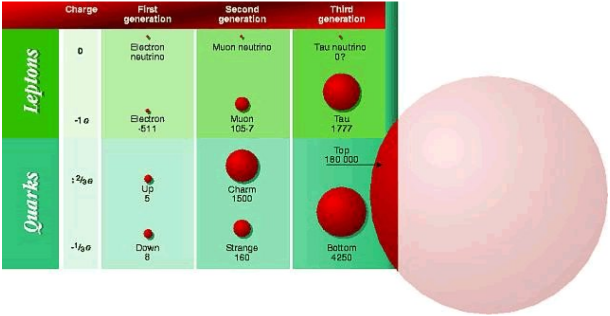
Nucleons

- Mass of 3 light quarks $\sim$ 10MeV
- Mass difference: 98 % missing!

Particles

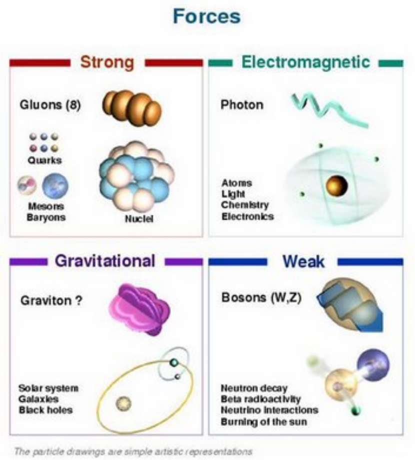
1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	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	89 Ac	104 Unq	105 Unp	106 Unh	107 Uns	108 Uno	109 Une	110 Unn								
			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	
			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	

Particles

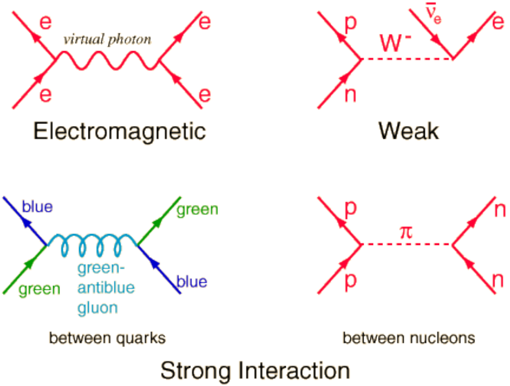


Charge
First generation
Second generation
Third generation
Leptons
Quarks
0
-1 e
+2/3 e
-1/3 e
Electron neutrino
Muon neutrino
Tau neutrino 0?
Electron .511
Muon 105.7
Tau 1777
Top 180 000
Up 5
Charm 1500
Down 8
Strange 160
Bottom 4250

Forces

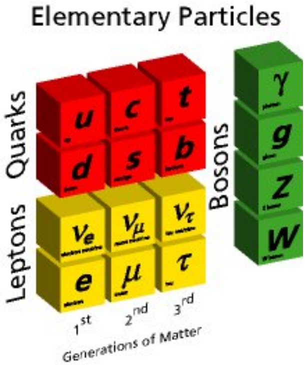

Forces
Strong
Gluons (8)
Quarks
Mesons
Baryons
Nuclei
Electromagnetic
Photon
Atoms
Light
Chemistry
Electronics
Gravitational
Graviton ?
Solar system
Galaxies
Black holes
Weak
Bosons (W,Z)
Neutron decay
Beta radioactivity
Neutrino Interactions
Burning of the sun
The particle drawings are simple artistic representations

Forces



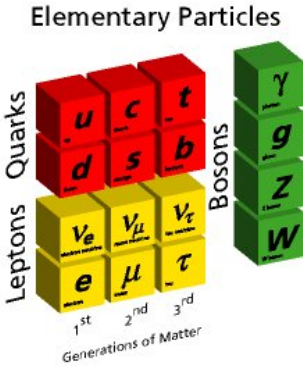
e
virtual photon
e
e
e
Electromagnetic
p
W⁻
$\bar{\nu}_e$
e
n
Weak
blue
green
green-
antiblue
gluon
green
blue
between quarks
p
π
n
p
n
between nucleons
Strong Interaction

Standard Model



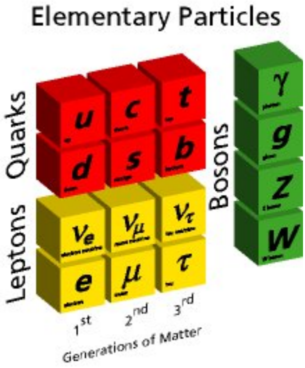
- Interactions are described by gauge theories

Standard Model



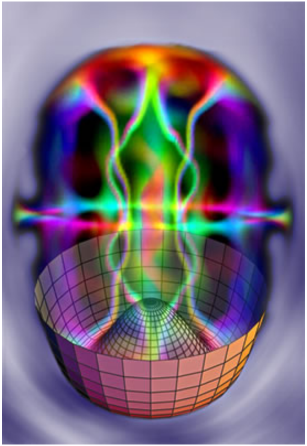
- Interactions are described by gauge theories
- The gauge group of the EWSM is $SU(2)_L \times U(1)_Y$

Standard Model



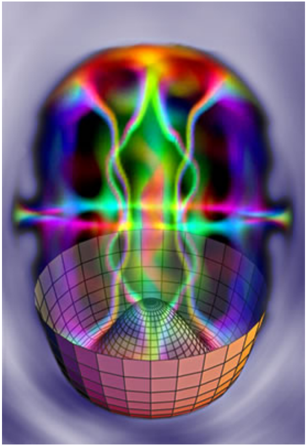
- Interactions are described by gauge theories
- The gauge group of the EWSM is $SU(2)_L \times U(1)_Y$
- Gauge symmetry forbids mass terms for the gauge bosons

Spontaneous Symmetry Breaking



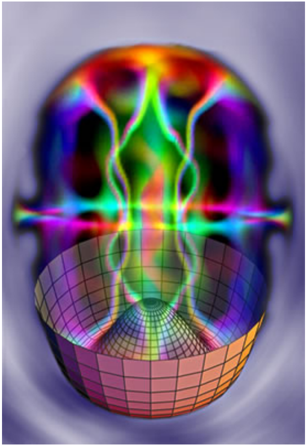
- The Higgs field ϕ spontaneously condensates

Spontaneous Symmetry Breaking



- The Higgs field ϕ spontaneously condensates
- Gives mass to the weak bosons $W^{\pm}$ and Z^{0}

Spontaneous Symmetry Breaking



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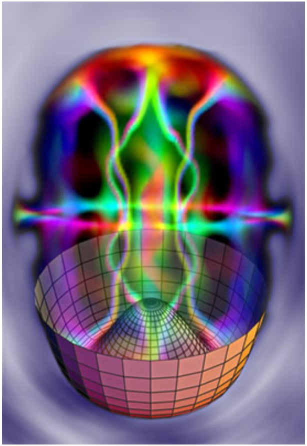
Spontaneous Symmetry Breaking



- The Higgs field ϕ spontaneously condensates
- Gives mass to the weak bosons $W^{\pm}$ and Z^0
- Leaves the photon massless
- Through Yukawa couplings, gives mass to leptons and quarks

Higgs Condensate

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Facts of the Higgs boson

- Accounts for the masses of weak gauge bosons

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- Gives EW masses to quarks and leptons

Facts of the Higgs boson

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- Could explain why atoms exist

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- Gives EW masses to quarks and leptons
- Could explain why atoms exist
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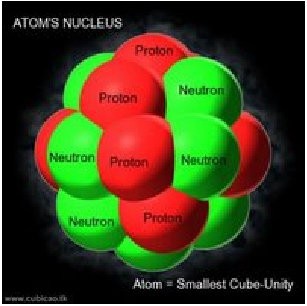
- Could explain why there are stable atomic structures
- Is NOT the source of all mass of the Universe

Facts of the Higgs boson

- Accounts for the masses of weak gauge bosons
- Gives EW masses to quarks and leptons
- Could explain why atoms exist
- Could explain why atoms can form chemical bonds
- Could explain why there are stable atomic structures
- Is NOT the source of all mass of the Universe; not even of visible matter

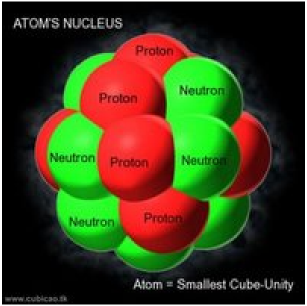
Facts of the Higgs boson

What holds the nuclei together?



- Protons in a nucleus should electrically repel

What holds the nuclei together?



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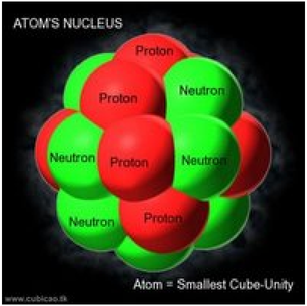
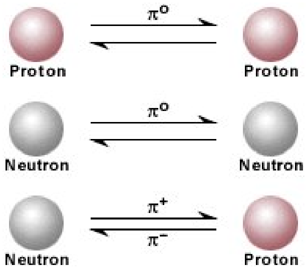


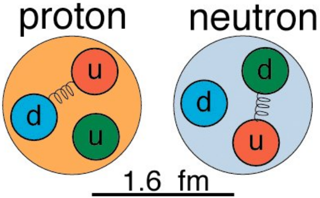
- Protons in a nucleus should electrically repel
- There must be a stronger force that cancels the electrostatic repulsion and holds the nuclei together
- Such a force can only be perceptible at the nuclear level

Strong Nuclear Force



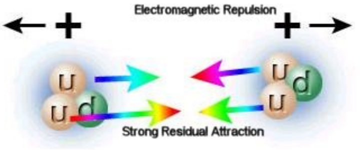
- Yukawa proposed the pion to be the nuclear force mediator

Strong Nuclear Force



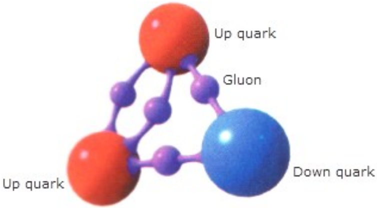
- But nucleons are not fundamental themselves

Strong Nuclear Force



- So strong nuclear force is realized at the level of nucleon constituents

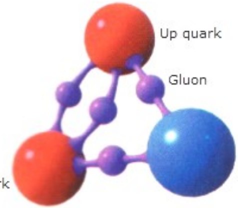
Color Interaction



Gluons holding quarks together to form a proton
(diagram from *Scientific American*)

- At the fundamental level, strong interaction is mediated by gluons, which come with 8 different charges (colors)

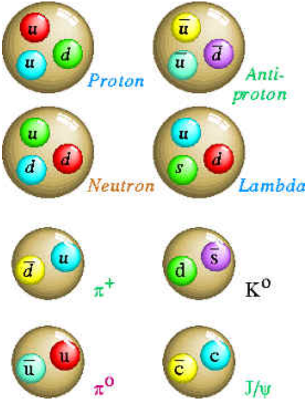
Color Interaction



Gluons holding quarks together to form a proton
(diagram from *Scientific American*)

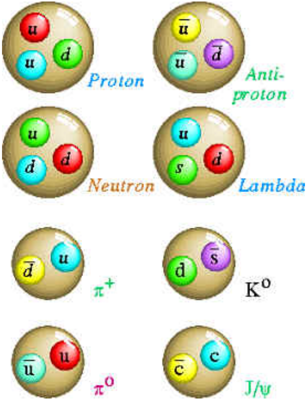
- At the fundamental level, strong interaction is mediated by gluons, which come with 8 different charges (colors)
- Quarks come in 3 different colors

Color Interaction



- Gluons hold together colorless structures of quarks, called hadrons

Color Interaction



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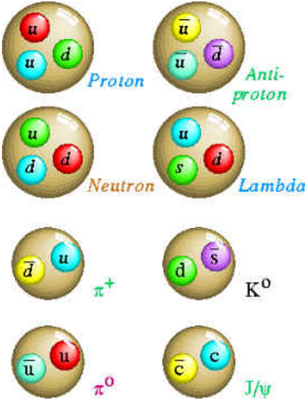
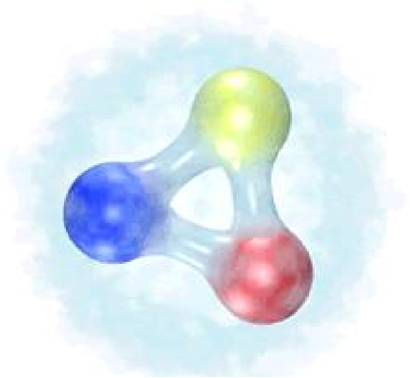


- Gluons hold together colorless structures of quarks, called hadrons
- When 3 quarks are combined, they form a baryon
- When a quark and an antiquark combine, they form a meson

Confinement



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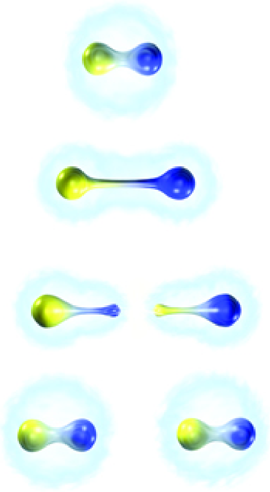
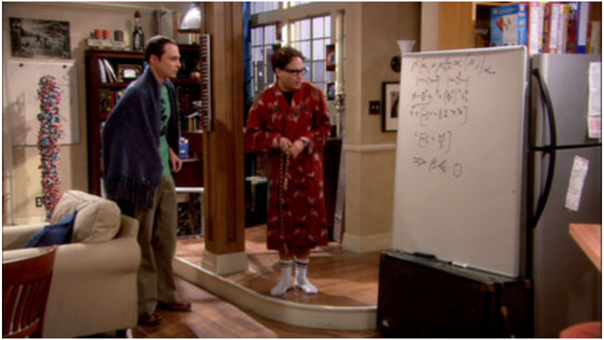


QCD: The strange theory of quarks

QED	**QCD**
$U(1)$	$SU(3)$
Electric charge	Color Charge
γ (neutral)	gluons (colored)
No Confinement	Confinement

QCD: The strange theory of quarks



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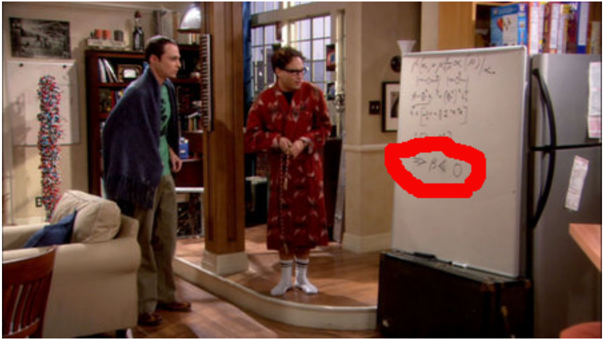
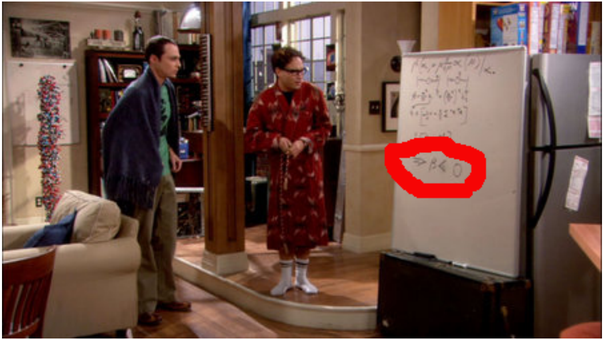


QCD: The strange theory of quarks



$$\beta(\alpha_s) = -\left(11 - \frac{2N_f}{3}\right)\frac{\alpha_s^2}{2\pi}$$

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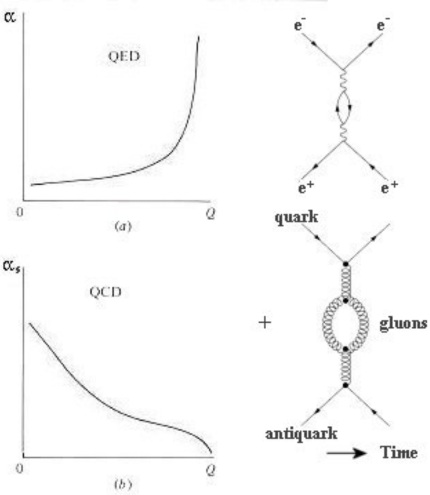
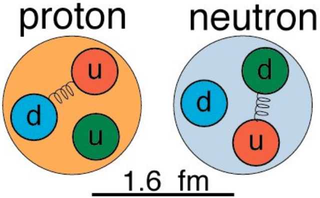


Masses out of the blue



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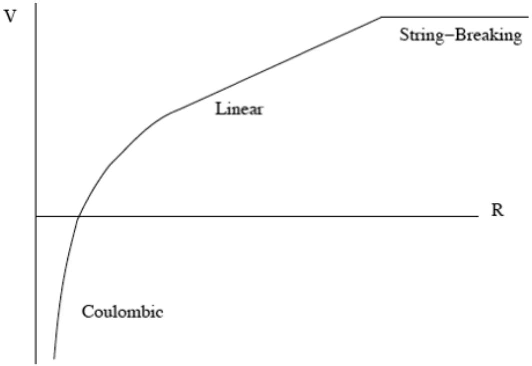

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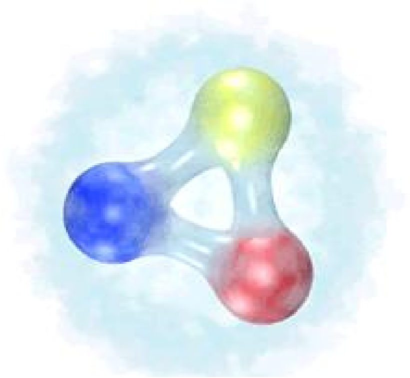

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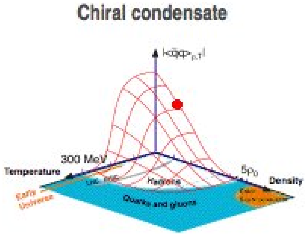

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