

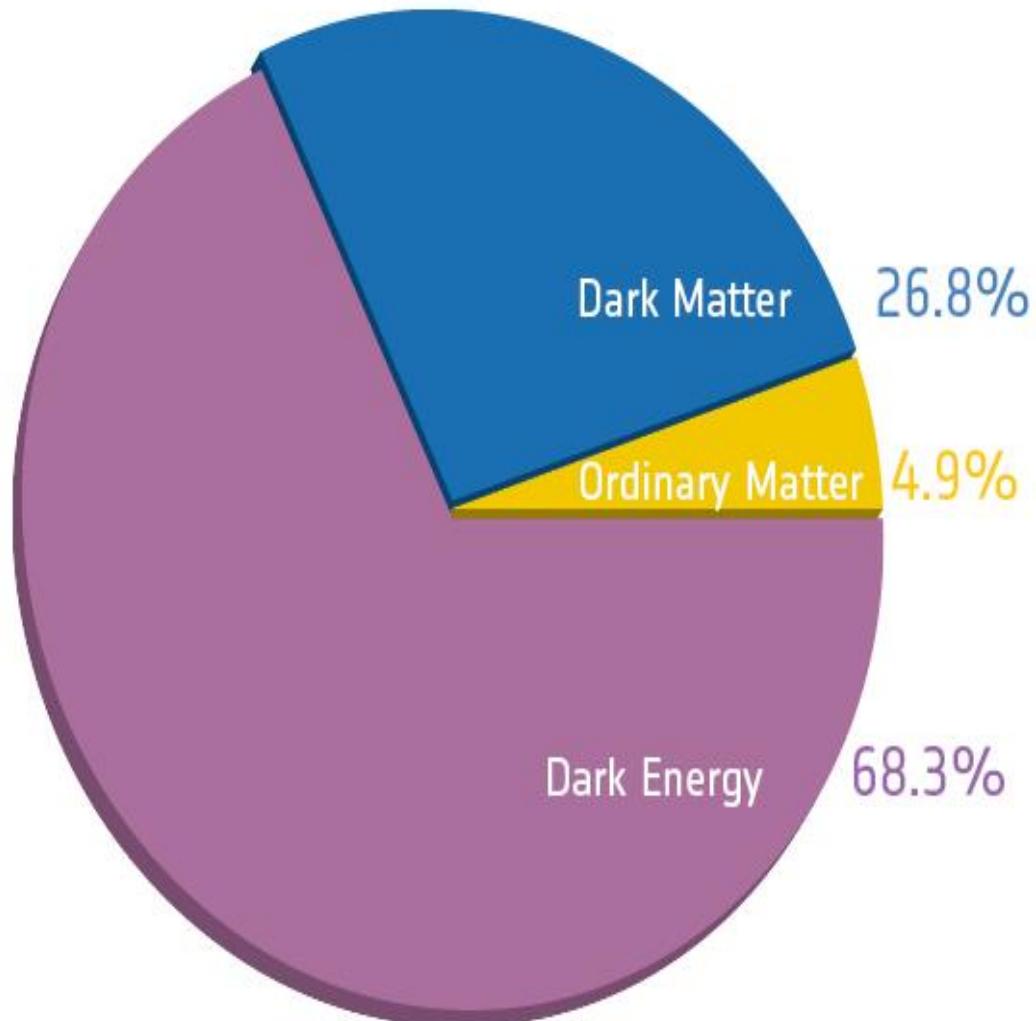
# Nuclear and Particle Physics

Εισαγωγή

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Μάθημα Πυρηνικής Φυσικής

# Η σύσταση του σύμπαντος

(σύμφωνα με τα δεδομένα του Planck mission-2013)



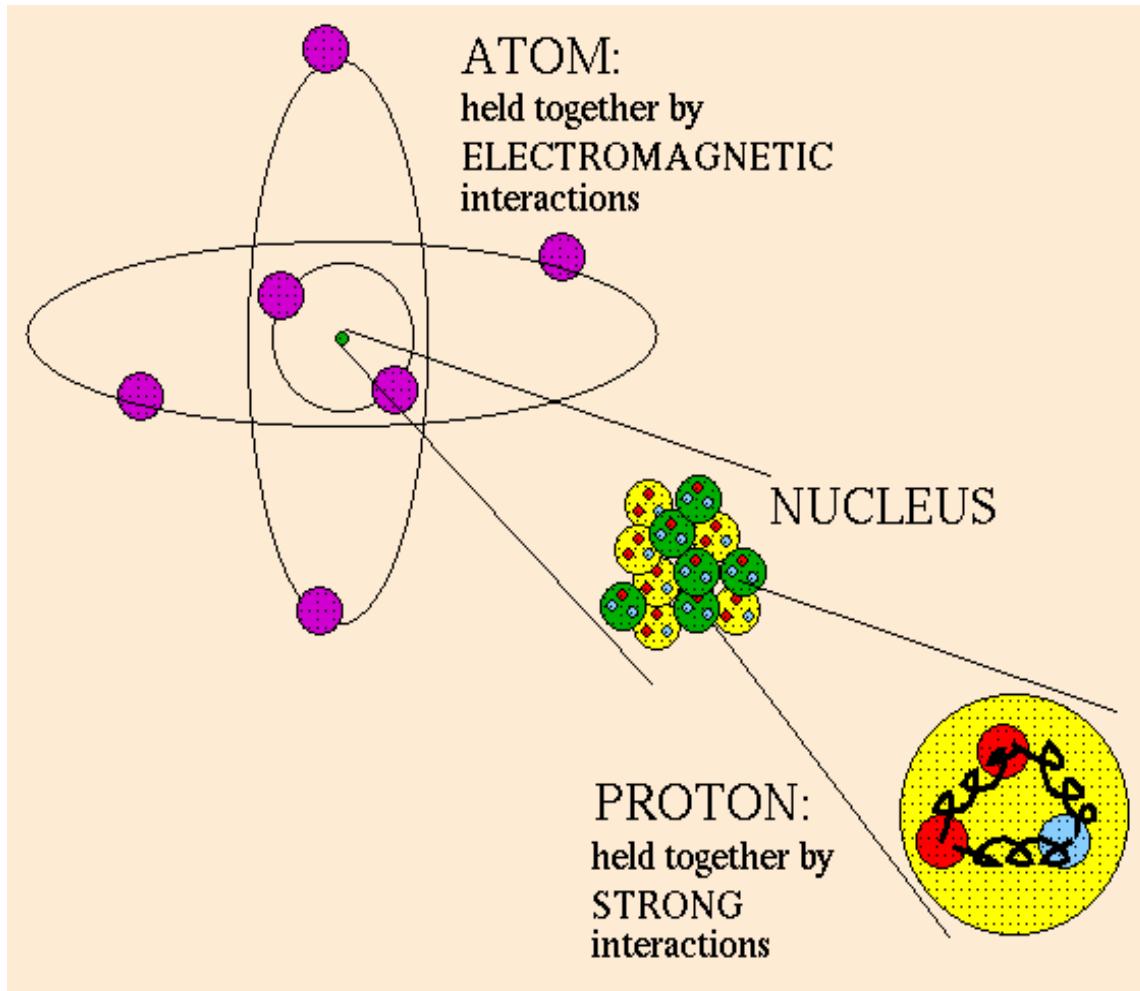
A yellow arrow points from the pie chart to the periodic table, indicating the relationship between the elements and the matter in the universe.

Group	Period	Element	Symbol	Atomic Mass
1	1	Hydrogen	H	1.008
2	1	Lithium	Li	6.941
3	1	Helium	He	4.003
4	1	Li	Li	6.941
5	1	Be	Be	9.012
6	1	Boron	B	10.81
7	1	Carbon	C	12.01
8	1	Nitrogen	N	14.01
9	1	Oxygen	O	15.999
10	1	Fluorine	F	18.998
11	1	Neon	Ne	20.18
12	1	Hydrogen	H	1.008
13	2	Li	Li	6.941
14	2	Be	Be	9.012
15	2	Boron	B	10.81
16	2	Carbon	C	12.01
17	2	Nitrogen	N	14.01
18	2	Oxygen	O	15.999
19	2	Fluorine	F	18.998
20	2	Neon	Ne	20.18
21	3	Hydrogen	H	1.008
22	3	Li	Li	6.941
23	3	Be	Be	9.012
24	3	Boron	B	10.81
25	3	Carbon	C	12.01
26	3	Nitrogen	N	14.01
27	3	Oxygen	O	15.999
28	3	Fluorine	F	18.998
29	3	Neon	Ne	20.18
30	4	Hydrogen	H	1.008
31	4	Li	Li	6.941
32	4	Be	Be	9.012
33	4	Boron	B	10.81
34	4	Carbon	C	12.01
35	4	Nitrogen	N	14.01
36	4	Oxygen	O	15.999
37	4	Fluorine	F	18.998
38	4	Neon	Ne	20.18
39	5	Hydrogen	H	1.008
40	5	Li	Li	6.941
41	5	Be	Be	9.012
42	5	Boron	B	10.81
43	5	Carbon	C	12.01
44	5	Nitrogen	N	14.01
45	5	Oxygen	O	15.999
46	5	Fluorine	F	18.998
47	5	Neon	Ne	20.18
48	6	Hydrogen	H	1.008
49	6	Li	Li	6.941
50	6	Be	Be	9.012
51	6	Boron	B	10.81
52	6	Carbon	C	12.01
53	6	Nitrogen	N	14.01
54	6	Oxygen	O	15.999
55	6	Fluorine	F	18.998
56	6	Neon	Ne	20.18
57	7	Hydrogen	H	1.008
58	7	Li	Li	6.941
59	7	Be	Be	9.012
60	7	Boron	B	10.81
61	7	Carbon	C	12.01
62	7	Nitrogen	N	14.01
63	7	Oxygen	O	15.999
64	7	Fluorine	F	18.998
65	7	Neon	Ne	20.18
66	8	Hydrogen	H	1.008
67	8	Li	Li	6.941
68	8	Be	Be	9.012
69	8	Boron	B	10.81
70	8	Carbon	C	12.01
71	8	Nitrogen	N	14.01
72	8	Oxygen	O	15.999
73	8	Fluorine	F	18.998
74	8	Neon	Ne	20.18
75	9	Hydrogen	H	1.008
76	9	Li	Li	6.941
77	9	Be	Be	9.012
78	9	Boron	B	10.81
79	9	Carbon	C	12.01
80	9	Nitrogen	N	14.01
81	9	Oxygen	O	15.999
82	9	Fluorine	F	18.998
83	9	Neon	Ne	20.18
84	10	Hydrogen	H	1.008
85	10	Li	Li	6.941
86	10	Be	Be	9.012
87	10	Boron	B	10.81
88	10	Carbon	C	12.01
89	10	Nitrogen	N	14.01
90	10	Oxygen	O	15.999
91	10	Fluorine	F	18.998
92	10	Neon	Ne	20.18
93	11	Hydrogen	H	1.008
94	11	Li	Li	6.941
95	11	Be	Be	9.012
96	11	Boron	B	10.81
97	11	Carbon	C	12.01
98	11	Nitrogen	N	14.01
99	11	Oxygen	O	15.999
100	11	Fluorine	F	18.998
101	11	Neon	Ne	20.18
102	12	Hydrogen	H	1.008
103	12	Li	Li	6.941
104	12	Be	Be	9.012
105	12	Boron	B	10.81
106	12	Carbon	C	12.01
107	12	Nitrogen	N	14.01
108	12	Oxygen	O	15.999
109	12	Fluorine	F	18.998
110	12	Neon	Ne	20.18
111	13	Hydrogen	H	1.008
112	13	Li	Li	6.941
113	13	Be	Be	9.012
114	13	Boron	B	10.81
115	13	Carbon	C	12.01
116	13	Nitrogen	N	14.01
117	13	Oxygen	O	15.999
118	13	Fluorine	F	18.998
119	13	Neon	Ne	20.18
120	14	Hydrogen	H	1.008
121	14	Li	Li	6.941
122	14	Be	Be	9.012
123	14	Boron	B	10.81
124	14	Carbon	C	12.01
125	14	Nitrogen	N	14.01
126	14	Oxygen	O	15.999
127	14	Fluorine	F	18.998
128	14	Neon	Ne	20.18
129	15	Hydrogen	H	1.008
130	15	Li	Li	6.941
131	15	Be	Be	9.012
132	15	Boron	B	10.81
133	15	Carbon	C	12.01
134	15	Nitrogen	N	14.01
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136	15	Fluorine	F	18.998
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140	16	Be	Be	9.012
141	16	Boron	B	10.81
142	16	Carbon	C	12.01
143	16	Nitrogen	N	14.01
144	16	Oxygen	O	15.999
145	16	Fluorine	F	18.998
146	16	Neon	Ne	20.18
147	17	Hydrogen	H	1.008
148	17	Li	Li	6.941
149	17	Be	Be	9.012
150	17	Boron	B	10.81
151	17	Carbon	C	12.01
152	17	Nitrogen	N	14.01
153	17	Oxygen	O	15.999
154	17	Fluorine	F	18.998
155	17	Neon	Ne	20.18
156	18	Hydrogen	H	1.008
157	18	Li	Li	6.941
158	18	Be	Be	9.012
159	18	Boron	B	10.81
160	18	Carbon	C	12.01
161	18	Nitrogen	N	14.01
162	18	Oxygen	O	15.999
163	18	Fluorine	F	18.998
164	18	Neon	Ne	20.18
165	19	Hydrogen	H	1.008
166	19	Li	Li	6.941
167	19	Be	Be	9.012
168	19	Boron	B	10.81
169	19	Carbon	C	12.01
170	19	Nitrogen	N	14.01
171	19	Oxygen	O	15.999
172	19	Fluorine	F	18.998
173	19	Neon	Ne	20.18
174	20	Hydrogen	H	1.008
175	20	Li	Li	6.941
176	20	Be	Be	9.012
177	20	Boron	B	10.81
178	20	Carbon	C	12.01
179	20	Nitrogen	N	14.01
180	20	Oxygen	O	15.999
181	20	Fluorine	F	18.998
182	20	Neon	Ne	20.18
183	21	Hydrogen	H	1.008
184	21	Li	Li	6.941
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186	21	Boron	B	10.81
187	21	Carbon	C	12.01
188	21	Nitrogen	N	14.01
189	21	Oxygen	O	15.999
190	21	Fluorine	F	18.998
191	21	Neon	Ne	20.18
192	22	Hydrogen	H	1.008
193	22	Li	Li	6.941
194	22	Be	Be	9.012
195	22	Boron	B	10.81
196	22	Carbon	C	12.01
197	22	Nitrogen	N	14.01
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208	23	Fluorine	F	18.998
209	23	Neon	Ne	20.18
210	24	Hydrogen	H	1.008
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212	24	Be	Be	9.012
213	24	Boron	B	10.81
214	24	Carbon	C	12.01
215	24	Nitrogen	N	14.01
216	24	Oxygen	O	15.999
217	24	Fluorine	F	18.998
218	24	Neon	Ne	20.18
219	25	Hydrogen	H	1.008
220	25	Li	Li	6.941
221	25	Be	Be	9.012
222	25	Boron	B	10.81
223	25	Carbon	C	12.01
224	25	Nitrogen	N	14.01
225	25	Oxygen	O	15.999
226	25	Fluorine	F	18.998
227	25	Neon	Ne	20.18
228	26	Hydrogen	H	1.008
229	26	Li	Li	6.941
230	26	Be	Be	9.012
231	26	Boron	B	10.81
232	26	Carbon	C	12.01
233	26	Nitrogen	N	14.01
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255	29	Hydrogen	H	1.008
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282	32	Hydrogen	H	1.008
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286	32	Carbon	C	12.01
287	32	Nitrogen	N	14.01
288	32	Oxygen	O	15.999
289	32			

# Τα δομικά στοιχεία της συνήθους ύλης (σε ατομικό επίπεδο - χημικά στοιχεία)

s-block		s-block																																	
1 New Designation		18																																	
IA Original Designation		VIIIA																																	
1 H 1.0094		2 He 4.00260		2																															
1 IIA		Non-Metals																																	
1	2	Atomic #																																	
s-block		Symbol																																	
1	2	Atomic Mass																																	
3 Li 6.941	4 Be 9.0122	p-block																																	
2	3	13 IIA 14 IVA 15 VA 16 VIA 17 VIIA																																	
11 Na 22.990	12 Mg 24.305	d-block																																	
19 K 39.098	20 Ca 40.08	3 21 Sc 44.956	4 22 Ti 47.88	5 23 V 50.942	6 24 Cr 51.996	7 25 Mn 54.938	8 26 Fe 55.847	9 27 Co 58.933	10 28 Ni 58.69	11 29 Cu 63.546	12 30 Zn 65.39	13 31 Al 26.982	14 32 Si 28.086	15 33 P 30.974	16 34 S 32.06	17 35 Cl 35.453	18 36 Ar 39.948	Transition Metals																	
37 Rb 85.468	38 Sr 87.62	39 39 Y 88.906	40 40 Zr 91.224	41 41 Nb 92.906	42 42 Mo 95.94	43 43 Tc (98)	44 44 Ru 101.07	45 45 Rh 102.91	46 46 Pd 106.42	47 47 Ag 107.87	48 48 Cd 112.41	49 49 In 114.82	50 50 Sn 118.71	51 51 Sb 121.75	52 52 Te 127.60	53 53 I 126.91	54 54 Xe 131.29	IB																	
55 Cs 132.91	56 Ba 137.33	57 57 to 71 Hf 178.49	72 Ta 180.95	73 W 183.85	74 Re 186.21	75 Os 190.2	76 Ir 192.22	77 Pt 195.08	78 Au 196.97	79 Hg 200.59	80 81 204.38	82 82 Tl 207.2	83 83 Pb 208.98	84 84 Po (209)	85 85 At (210)	86 86 Rn (222)	VIIIB																		
87 Fr 223	88 Ra 226.03	89 89 103 Unq (261)	104 Unp (262)	105 Unh (263)	106 Uns (262)	107 Uno (265)	108 Une (266)	109 Uun (267)	(Mass Numbers in Parentheses are from the most stable of common isotopes.)										Phases																
Rare Earth Elements		Solid																																	
Lanthanide Series		Liquid																																	
Actinide Series		Gas																																	
d-block		f-block																																	
57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97	Rare Earth Elements																				
89 Ac 227.03	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)	Lanthanide Series																				

# Ατομική και υπο-ατομική δόμηση της ύλης



Πώς τα ξέρουμε αυτά; Ακολουθεί λίγη ιστορία...

# 20<sup>th</sup> Century Elementary Particle Physics Timeline

## Theoretical Breakthroughs

## Discoveries of Building Blocks

1900 Black body radiation spectrum (Planck)

1905 Light quanta (Einstein)  
1905 Theory of special relativity (Einstein)

1913 Bohr's model of atom, momentum quantum (Bohr)

1925 Hypothesis of "no two fermions in identical states" (Pauli)

1925-26 Quantum Mechanics (Heisenberg, Schrodinger)

1928 Electron relativistic QM equation; antimatter (Dirac)

1930 Neutrino hypothesis (Pauli)

1934 Weak Force (Fermi)

1935 Nuclear Force and Yukawa particles (Yukawa)

1897-1899 Discovery of electron (Thompson)

1911 Discovery of nucleus (Rutherford)

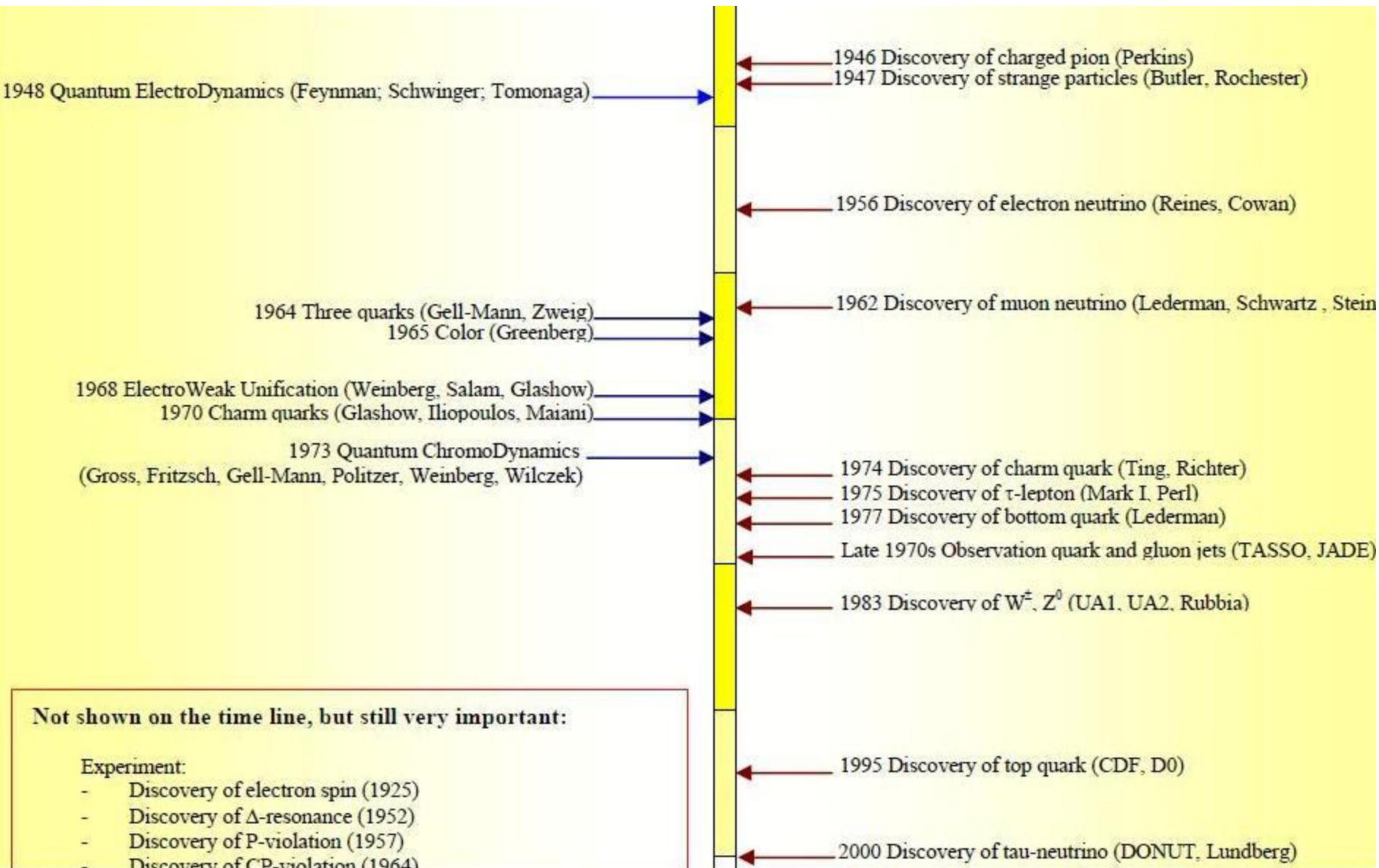
1919 Discovery of proton (Rutherford)

1923 "Discovery" of photon (Compton)

1932 Discovery of neutron (Chadwick)

1933 Discovery of antimatter, positron (Anderson)

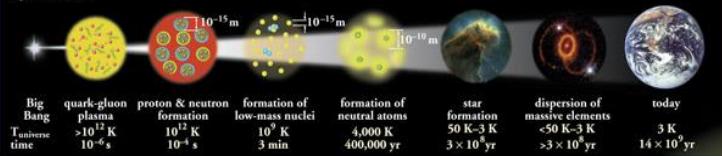
1937 Discovery of muon (Anderson, Neddermeyer)



# Nuclear Science

## Expansion of the Universe

After the Big Bang, the universe expanded and cooled. At about  $10^{-6}$  second, the universe consisted of a soup of quarks, gluons, electrons, and neutrinos. When the temperature of the Universe,  $T_{universe}$ , cooled to about  $10^9$  K, this soup coalesced into protons, neutrons, and electrons. As time progressed, some of the protons and neutrons formed deuterium, helium, and lithium nuclei. Still later, electrons combined with protons and these low-mass nuclei to form neutral atoms. Due to gravity, clouds of atoms contracted into stars, where hydrogen and helium fused into more massive chemical elements. Exploding stars (supernovae) form the most massive elements and disperse them into space. Our earth was formed from supernova debris.

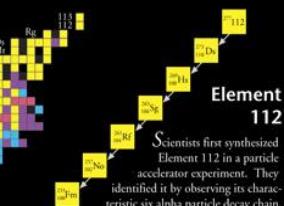


**Nuclear Science** is the study of the structure, properties, and interactions of the atomic nuclei. Nuclear scientists calculate and measure the masses, shapes, sizes, and decays of nuclei at rest and in collisions. They ask questions, such as: Why do nucleons stay in the nucleus? What combinations of protons and neutrons are possible? What happens when nuclei are compressed or rapidly rotated? What is the origin of the nuclei found on Earth?

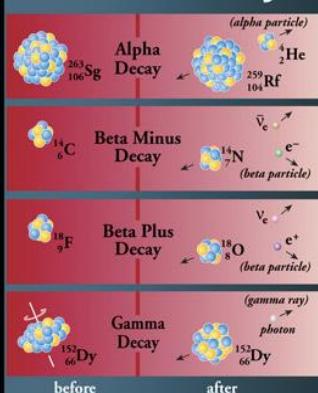
Legend	electron ( $e^-$ )	quark	$A_{mass}$
proton	positron ( $e^+$ )	gluon field	$Z_{atomic}$
neutron	neutrino ( $\nu$ )	gluon	$Z_{number}$
	antineutrino ( $\bar{\nu}$ )	photon ( $\gamma$ )	$N_{number} = A - Z$

## Unstable Nuclei

Stable nuclides form a narrow white band on the Chart of the Nuclides. Scientists produce unstable nuclides far from this band and study their decays, thereby learning about the extremes of nuclear conditions. In its present form, this chart contains about 2500 different nuclides. Nuclear theory predicts that there are at least 4000 more to be discovered with  $Z \leq 115$ .



## Radioactivity



Radioactive decay transforms a nucleus by emitting different particles. In **alpha decay**, the nucleus releases a  $^4_2\text{He}$  nucleus—an alpha particle. In **beta decay**, the nucleus either emits an electron and antineutrino (or a positron and neutrino) or captures an atomic electron and emits a neutrino. A positron is the name for the antiparticle of the electron. Antimatter is composed of anti-particles. Both alpha and beta decays change the original nucleus into a nucleus of a different chemical element. In **gamma decay**, the nucleus lowers its internal energy by emitting a photon—a gamma ray. This decay does not modify the chemical properties of the atom.

## Chart of the Nuclides

The Chart of the Nuclides presents in graphic form all known nuclei with atomic number,  $Z$ , and neutron number,  $N$ .

Each nucleus is represented by a colored rectangle according to its predominant decay mode.

**Magic numbers** ( $N$  or  $Z = 2, 8, 20, 28, 50, 82$  and 126) are indicated by a

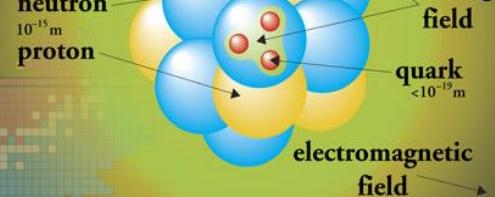
rectangle on the chart. They correspond to major closed shells and show regions of greater nuclear binding energy.



[www.CPEPweb.org](http://www.CPEPweb.org)

## The Nucleus

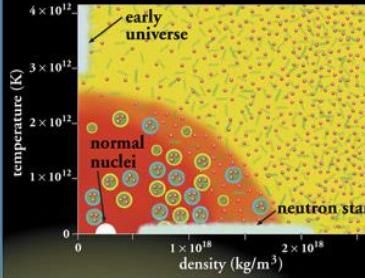
At the center of the atom is a nucleus formed from nucleons—protons and neutrons. Each nucleon is made from three quarks held together by their strong interactions, which are mediated by gluons. In turn, the nucleus is held together by the strong interactions between the gluon and quark constituents of neighboring nucleons. Nuclear physicists often use the exchange of meson-particles which consist of a quark and an antiquark, such as the pion to describe interactions among the nucleons.



In an atom, electrons range around the nucleus at distances typically up to 10,000 times the nuclear diameter. If the electron cloud were shown to scale, this chart would cover a small town.

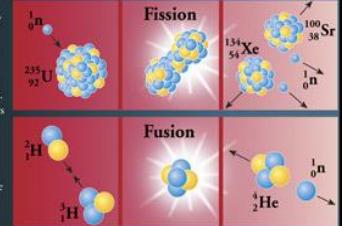
## Phases of Nuclear Matter

Nuclear matter can exist in several phases. When collisions excite nuclei, individual protons and neutrons may evaporate from the nuclear fluid. At sufficiently high temperature or density, a gas of nucleons (red background) forms. At even more extreme conditions, individual nucleons may cease to have meaningful identities, merging into the quark-gluon plasma (yellow background). Current data provide hints that physicists have glimpsed the quark-gluon plasma.



126 Nuclear reactions release energy when the total mass of the products is less than the sum of the masses of the initial nuclei. The "lost mass" appears as kinetic energy of the products ( $E = mc^2$ ). In fission, a massive nucleus splits into two major fragments that usually eject one or more neutrons. In fusion, low mass nuclei combine to form a more massive nucleus plus one or more ejected particles—neutrons, protons, photons, or alpha particles.

## Nuclear Energy



In the early stages of stellar evolution of our sun and other stars, hydrogen fuses to form helium, releasing energy in the form of photons (light) and neutrinos. During the later stages of stellar evolution, more massive nuclei up to and beyond uranium are synthesized by fusion. By measuring the number of neutrinos that come from the Sun, scientists recently have demonstrated that neutrinos must have a mass greater than zero.

## Applications



### Radioactive Dating

Naturally occurring radioactive isotopes such as  $^{14}\text{C}$  are used to date objects that were once part of living organisms. For example, from a study of artifacts found at the site, scientists determined that Stonehenge was built nearly 4,000 years ago.



### Smoke Detectors

Many smoke detectors use a small amount of the alpha emitter  $^{241}\text{Am}$  to ionize the air. Smoke entering the detector reduces the current and sets off the alarm.



### Space Exploration

Spirouette used alpha particles to identify chemical elements present in meteor rocks. On Earth, nuclear reactions are used in many areas from criminal investigations to art authentication.



### Nuclear Reactors

Nuclear reactors use the fission of  $^{235}\text{U}$  or  $^{94}\text{Pu}$  nuclei to produce energy. Reactors and most other nuclear applications generate radioactive waste. Disposal of this waste is a subject of current research.



### Nuclear Medicine

Radioactive isotopes, such as  $^{99m}\text{Tc}$ ,  $^{67}\text{Ga}$ ,  $^{113}\text{In}$ ,  $^{131}\text{I}$ , and  $^{153}\text{Sm}$  are commonly used in the diagnosis and treatment of disease. Positron emitters such as  $^{11}\text{C}$  are used in Positron Emission Tomography (PET) to generate images of brain activity.

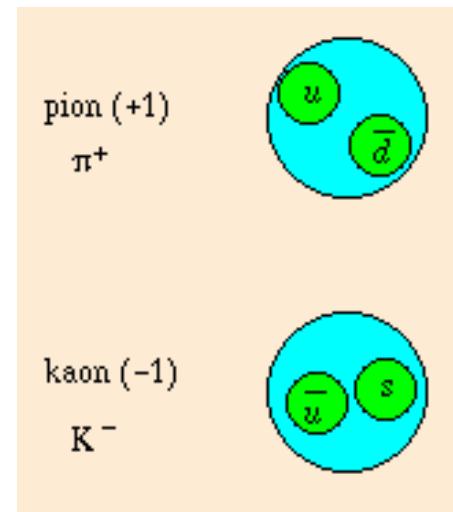
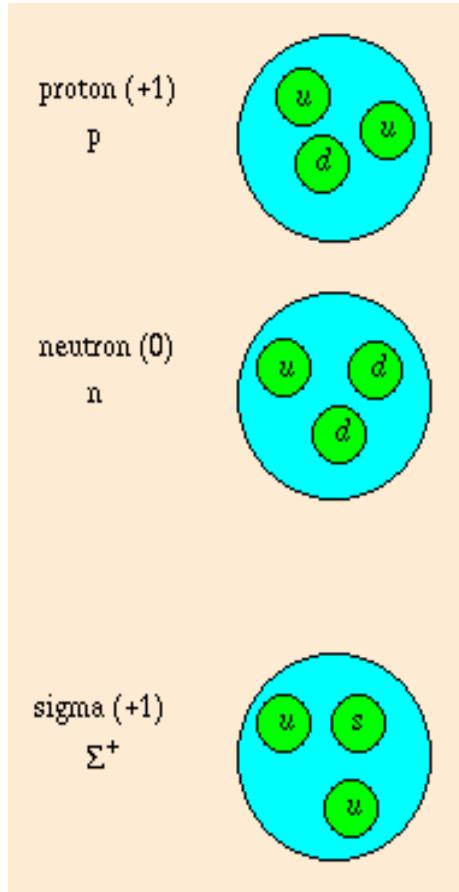


### Magnetic Resonance Imaging

Magnetic Resonance Imaging (MRI) makes use of atomic transitions involving the magnetic field of a nucleus to study the local chemical environment. This technique accurately maps the density of hydrogen to produce three-dimensional images of the human body.

Astrophysical pictures courtesy NASA/JPL/Caltech and AURA/STScI.

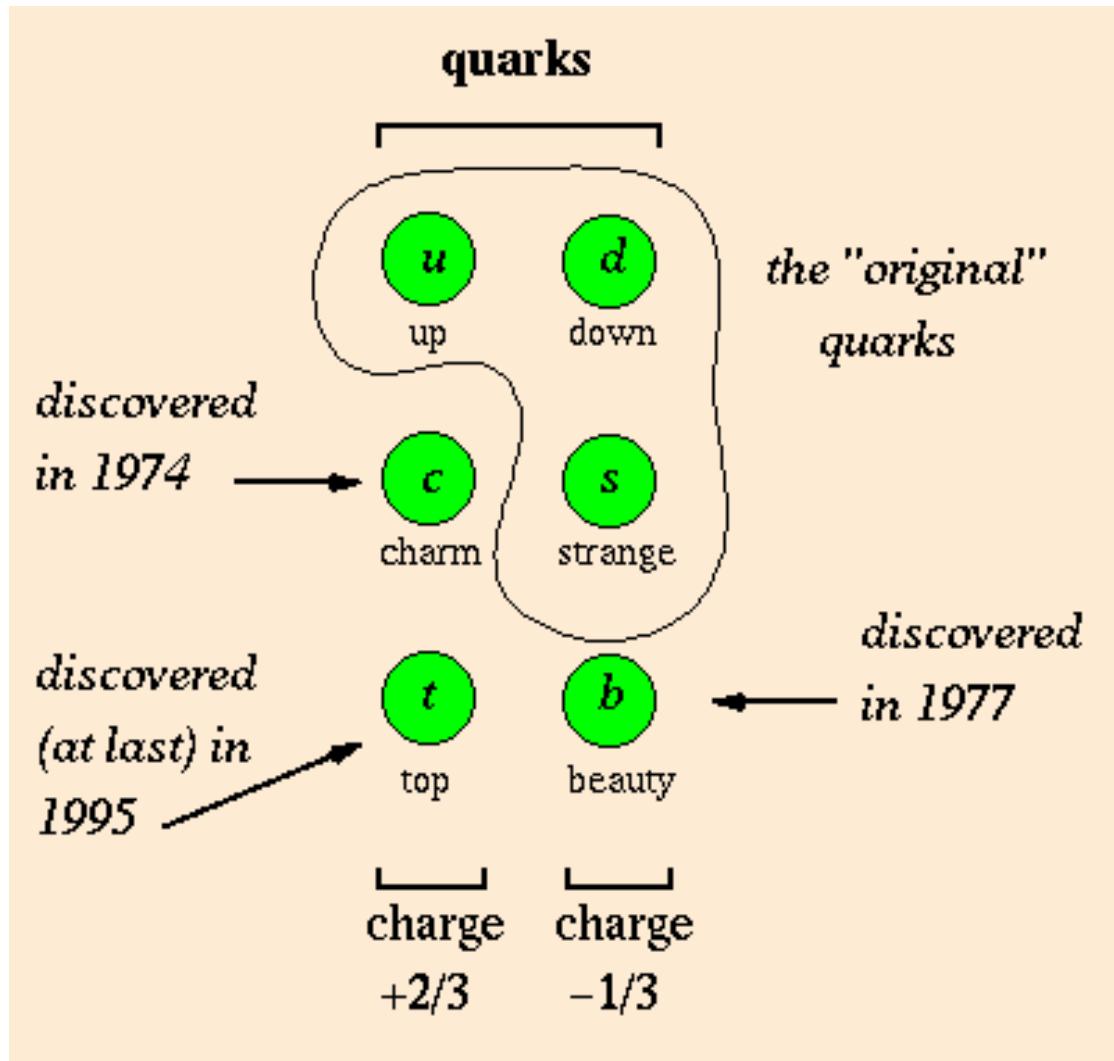
# Στοιχειώδη σωματίδια με εσωτερική δομή – αδρόνια (strong interactions)



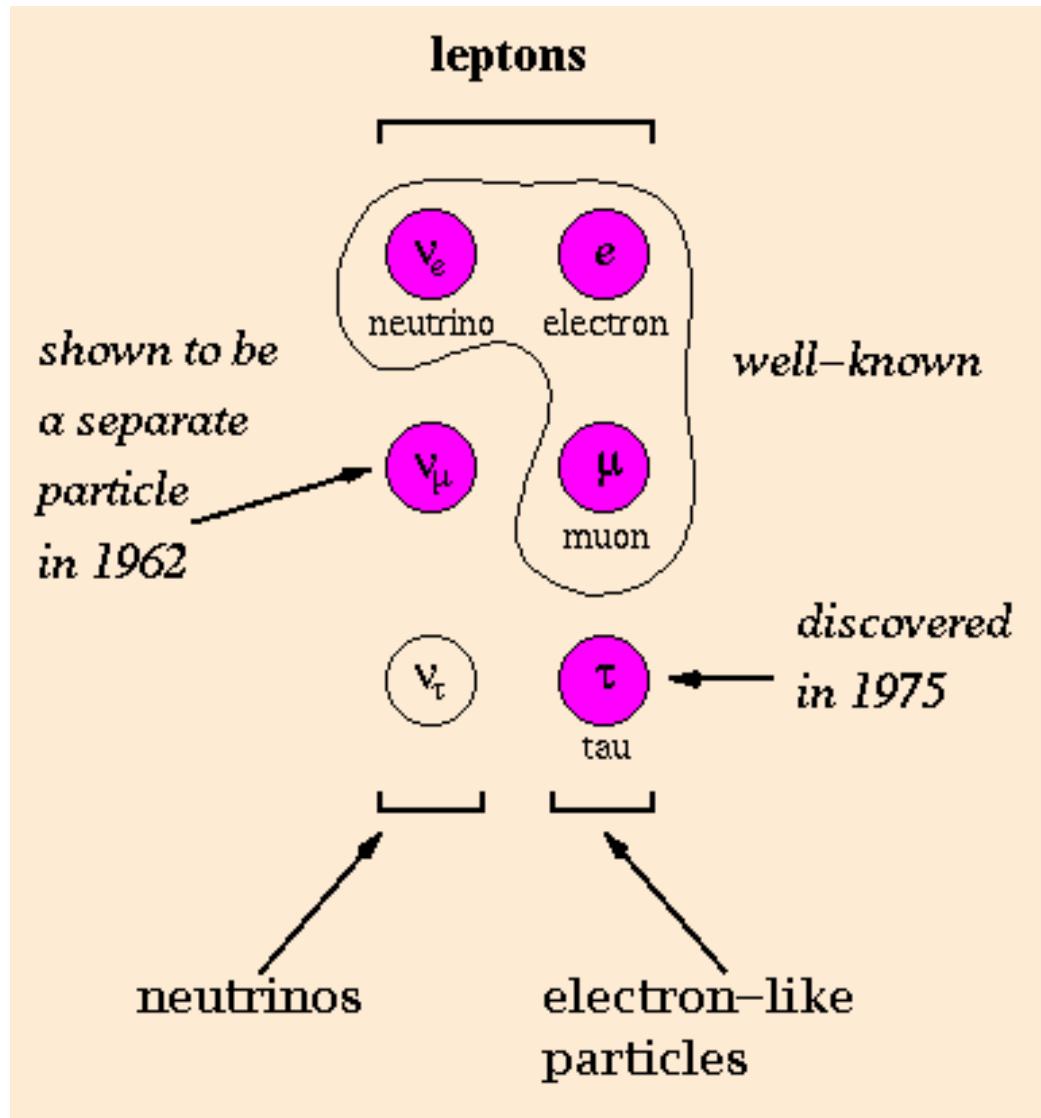
**Μεσόνια:**  
αδρόνια με 1 quark και 1 antiquark

**Βαρυόνια:**  
αδρόνια με 3 quarks ή 3 antiquarks

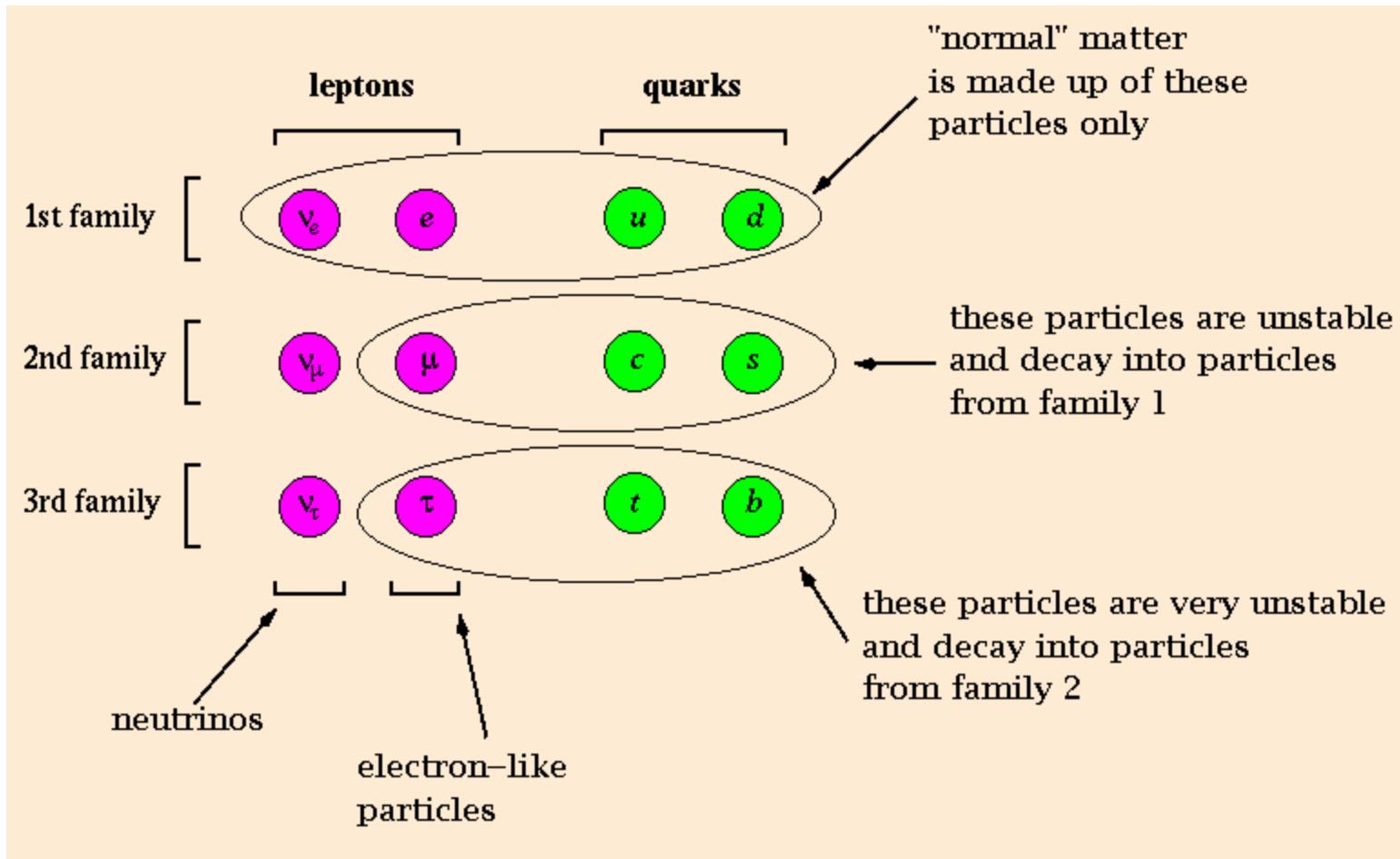
# The 6 quarks



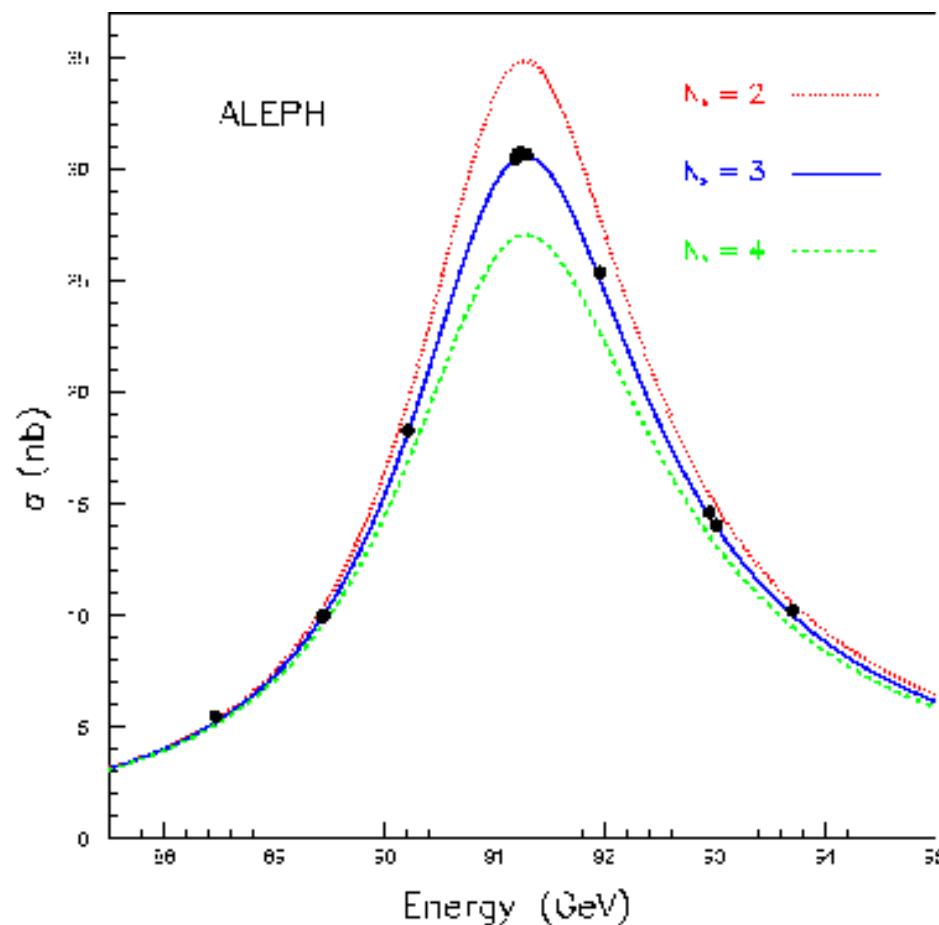
# The 6 leptons



# λεπτόνια και quark σε 3 οικογένειες

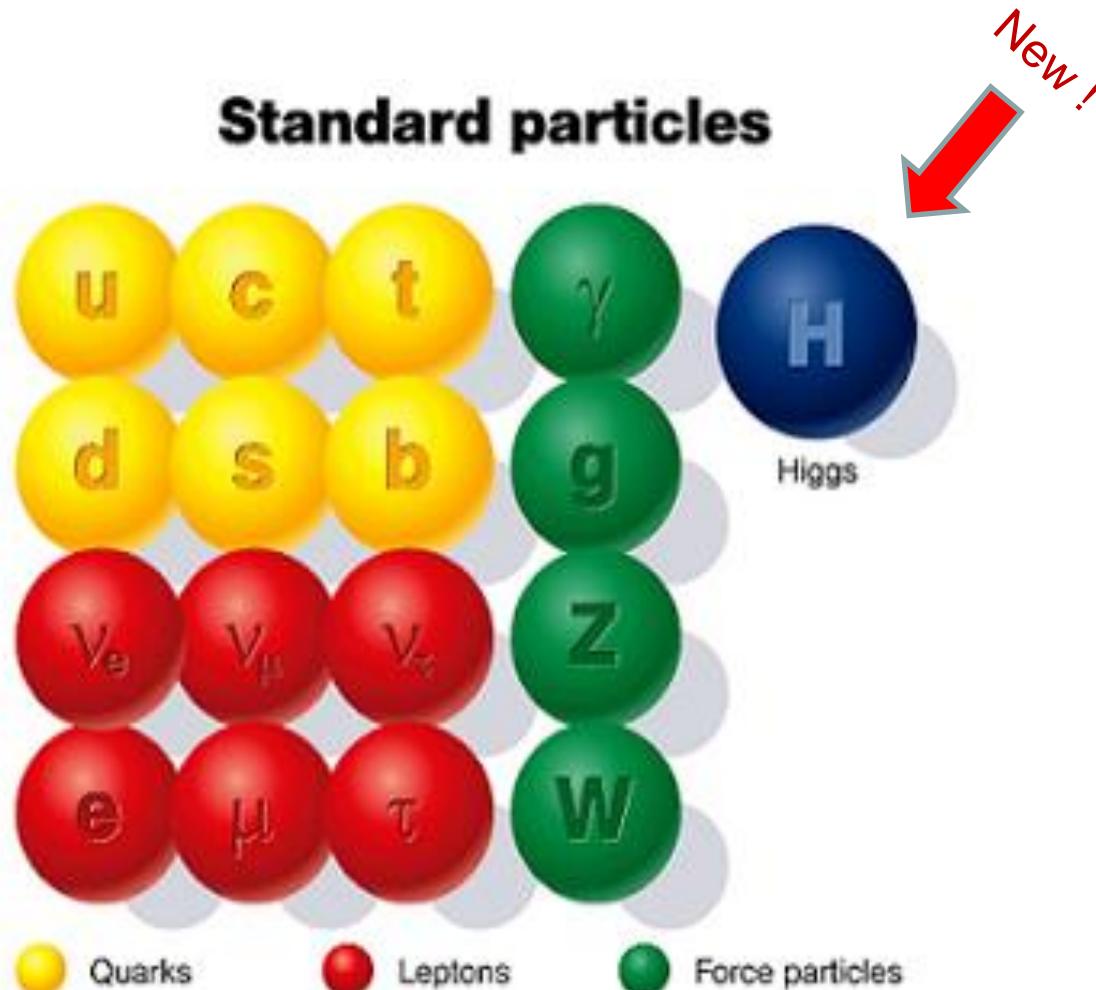


Measurement of  $Z$  hadronic decays, versus energy,  
with predicted rates if there were 1, 2 or 3 types of neutrino  
(ALEPH collaboration)



# Τα δομικά στοιχεία της ύλης

(σε υποατομικό - υποπυρηνικό επίπεδο)



# Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

## FERMIIONS

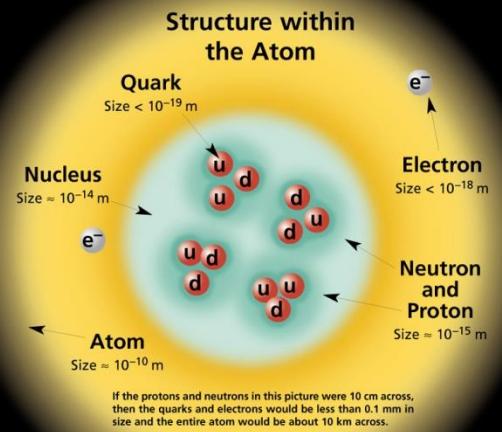
matter constituents  
spin = 1/2, 3/2, 5/2, ...

Leptons			spin = 1/2	Quarks			spin = 1/2
Flavor	Mass GeV/c <sup>2</sup>	Electric charge		Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge	
$\nu_e$ electron neutrino	$<1 \times 10^{-8}$	0		$u$ up	0.003	2/3	
e electron	0.000511	-1		$d$ down	0.006	-1/3	
$\nu_\mu$ muon neutrino	$<0.0002$	0		c charm	1.3	2/3	
$\mu$ muon	0.106	-1		s strange	0.1	-1/3	
$\nu_\tau$ tau neutrino	$<0.02$	0		t top	175	2/3	
$\tau$ tau	1.7771	-1		b bottom	4.3	-1/3	

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is  $1.60 \times 10^{-19}$  coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c<sup>2</sup> (remember  $E = mc^2$ ), where 1 GeV =  $10^9$  eV =  $1.60 \times 10^{-10}$  joule. The mass of the proton is 0.938 GeV/c<sup>2</sup> =  $1.67 \times 10^{-27}$  kg.



## BOSONS

force carriers  
spin = 0, 1, 2, ...

Unified Electroweak			spin = 1
Name	Mass GeV/c <sup>2</sup>	Electric charge	
$\gamma$ photon	0	0	
$W^-$	80.4	-1	
$W^+$	80.4	+1	
$Z^0$	91.187	0	

### Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and  $W$  and  $Z$  bosons have no strong interactions and hence no color charge.

### Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons**  $q\bar{q}$  and **baryons**  $qqq$ .

### Residual Strong Interaction

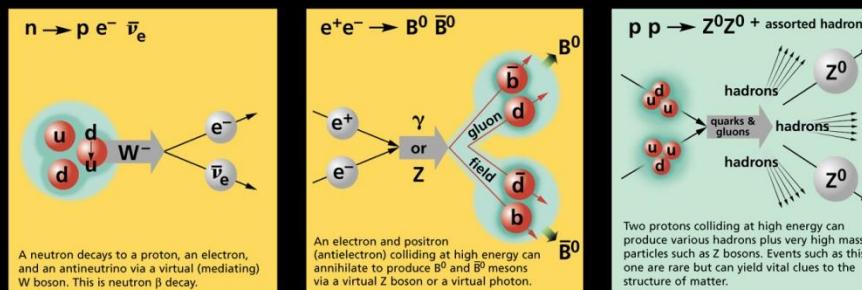
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

## PROPERTIES OF THE INTERACTIONS

Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Baryons are fermionic hadrons. There are about 120 types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{d}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
$\Lambda$	lambda	uds	0	1.116	1/2
$\Omega^-$	omega	sss	-1	1.672	3/2

Property	Interaction		Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
	Acts on:	Mass – Energy				Fundamental	Residual
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons	
Particles mediating:		Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$	$\gamma$	Gluons	Mesons	
Strength relative to electromag for two u quarks at: for two protons in nucleus	$10^{-18}$ m $3 \times 10^{-17}$ m	$10^{-41}$ $10^{-41}$ $10^{-36}$	0.8 10 <sup>-4</sup> 10 <sup>-7</sup>	1 1 1	25 60 Not applicable to hadrons	Not applicable to quarks 20	

Mesons $q\bar{q}$					
Mesons are bosonic hadrons. There are about 140 types of mesons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c <sup>2</sup>	Spin
$\pi^+$	pion	u $\bar{d}$	+1	0.140	0
K <sup>-</sup>	kaon	s $\bar{u}$	-1	0.494	0
$\rho^+$	rho	u $\bar{d}$	+1	0.770	1
$B^0$	B-zero	d $\bar{u}$	0	5.279	0
$\eta_c$	eta-c	c $\bar{c}$	0	2.980	0



**The Particle Adventure**  
Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:  
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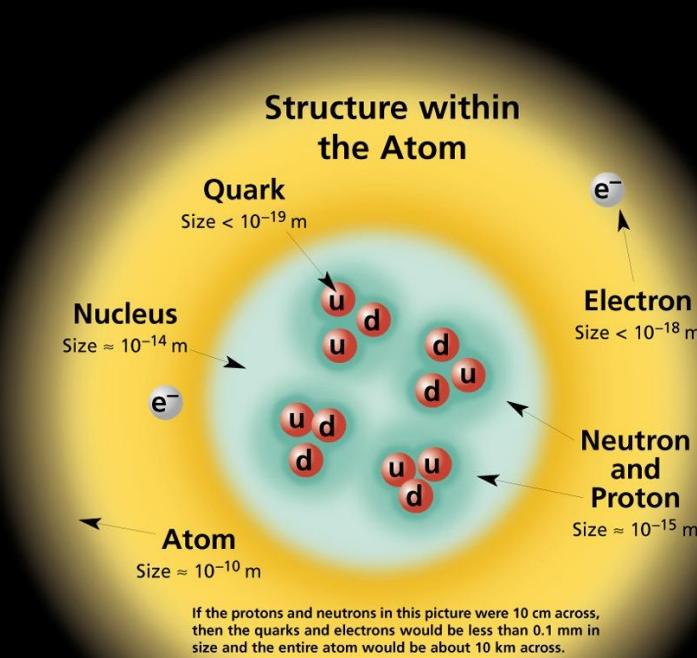
### Figures

These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

# *The Standard Model of Particles and Fields*

Main postulates of SM:

- 1) Basic constituents of matter are *quarks* and *leptons* (fermions i.e. spin 1/2).
- 2) They interact by means of gauge bosons (spin 1).
- 3) Quarks and leptons are subdivided into 3 *generations*.



# FERMIIONS

matter constituents  
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Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c <sup>2</sup>	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
b bottom	4.3	-1/3

Standard Model does not explain neither appearance of the mass nor the reason for existence of 3 generations

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of  $\hbar$ , which is the quantum unit of angular momentum, where  $\hbar = h/2\pi = 6.58 \times 10^{-25}$  GeV s =  $1.05 \times 10^{-34}$  J s.

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# Forces of Nature

Forces are being carried by specific particles, called *gauge ['gejdz] bosons*.

Property	Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong	
					Fundamental	Residual
Acts on:	Mass – Energy	Flavor		Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons		Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	$W^+$ $W^-$ $Z^0$		$\gamma$	Gluons	Mesons
Strength relative to electromag for two u quarks at: 3 $\times 10^{-17}$ m	$10^{-41}$ $10^{-41}$ $10^{-36}$	0.8 $10^{-4}$ $10^{-7}$		1 1 1	25 60 Not applicable to hadrons	Not applicable to quarks 20

- ➡ Electromagnetic and weak forces can be described by a single theory ⇒ the “*Electroweak Theory*” was developed in 1960s (Glashow, Weinberg, Salam).
- ➡ Theory of strong interactions appeared in 1970s: “*Quantum Chromodynamics*” (QCD).
- ➡ The “*Standard Model*” (SM) combines both.

# BOSONS

force carriers  
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$W^+$	80.4	+1
$Z^0$	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c <sup>2</sup>	Electric charge
g gluon	0	0

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## Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown).

Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g.,  $Z^0$ ,  $\gamma$ , and  $\eta_c = c\bar{c}$ , but not  $K^0 = d\bar{s}$ ) are their own antiparticles.

### Baryons $qqq$ and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

There are about 120 types of baryons.

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