

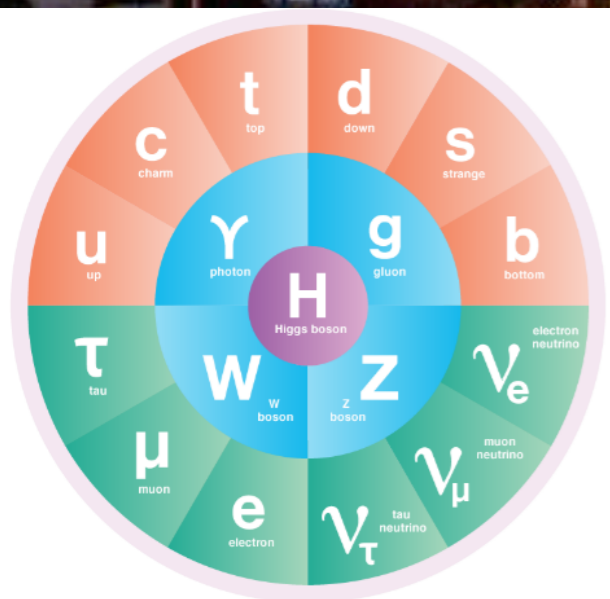
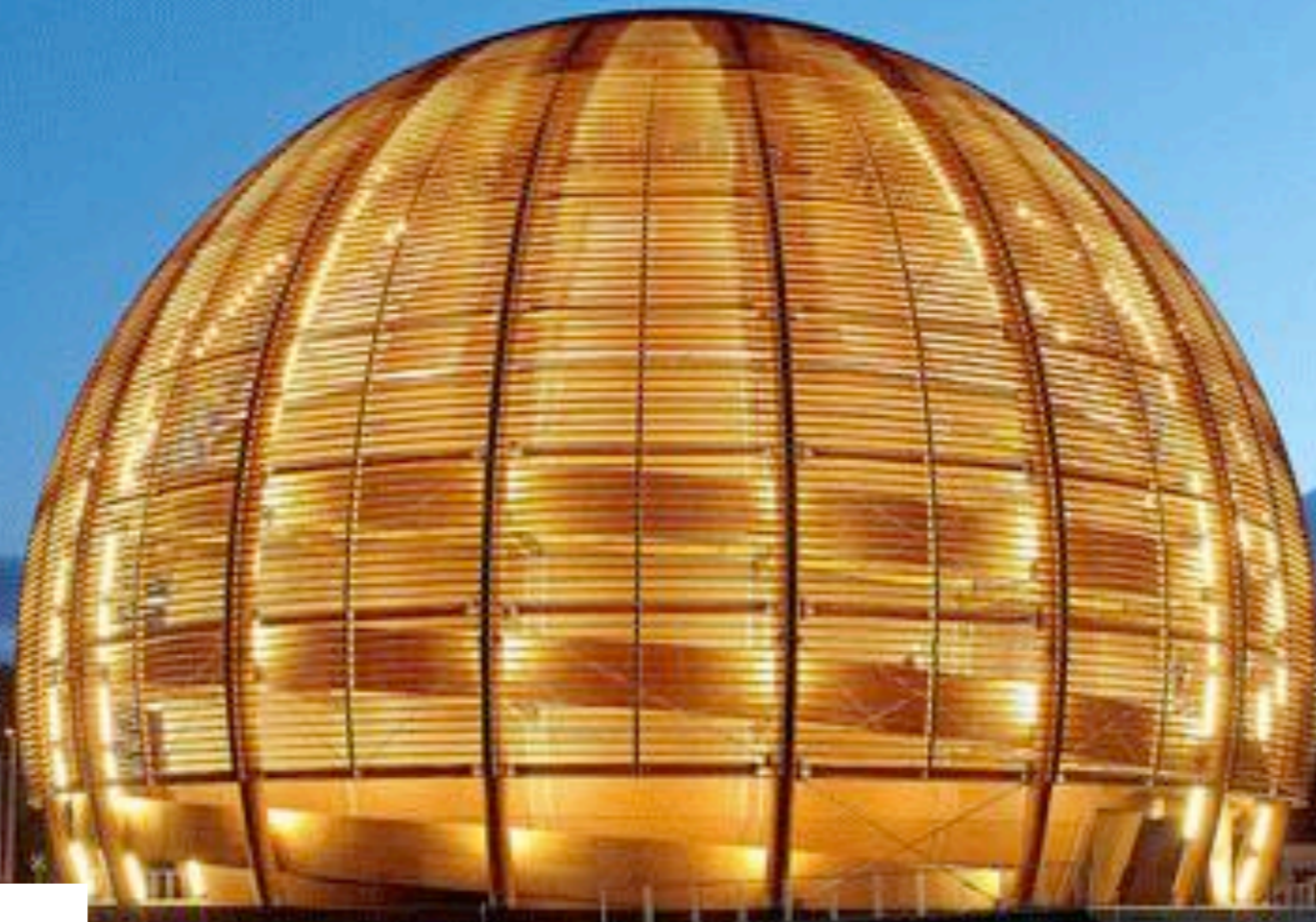
VA QuarkNet Center  
October 28, 2023



There are more hydrogen atoms in a single molecule of water than there are stars in the entire Solar System.



# The Standard Model of Particle Physics



*Josh Erlich*  
*QuarkNet workshop*  
*October 28, 2023*



# The Periodic Table of Elements

Reihen	Gruppo I. — R'O	Gruppo II. — RO	Gruppo III. — R'O <sup>3</sup>	Gruppo IV. RH <sup>4</sup> RO <sup>2</sup>	Gruppo V. RH <sup>5</sup> R'O <sup>5</sup>	Gruppo VI. RH <sup>6</sup> RO <sup>3</sup>	Gruppo VII. RH R'O <sup>7</sup>	Gruppo VIII. — RO <sup>4</sup>
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,8	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	So=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —



Mendeleev (1871)



# The Periodic Table of Elements

## The Periodic Table of Elements

IA	IIA	IIIB	IVB	VB	VIB	VII B	VIII B			IB	II B	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.01 ∞ +1																	2 He Helium 4.00 0
3 Li Lithium 6.94 +1	4 Be Beryllium 9.01 +2									5 B Boron 10.81 +3	6 C Carbon 12.01 +/-4	7 N Nitrogen 14.01 -3	8 O Oxygen 16.00 -2	9 F Fluorine 19.00 -1	10 Ne Neon 20.18 0		
11 Na Sodium 22.99 +1	12 Mg Magnesium 24.31 +2									13 Al Aluminum 26.98 +3	14 Si Silicon 28.09 +4	15 P Phosphorus 30.97 -3	16 S Sulfur 32.07 -2	17 Cl Chlorine 35.45 -1	18 Ar Argon 39.95 0		
19 K Potassium 39.10 +1	20 Ca Calcium 40.08 +2	21 Sc Scandium 44.96 +3	22 Ti Titanium 47.87 +3	23 V Vanadium 50.94 +5,3,2	24 Cr Chromium 52.00 +6,3,2	25 Mn Manganese 54.94 +7,6,4,2,3	26 Fe Iron 55.85 +2,3,6	27 Co Cobalt 58.93 +2,3	28 Ni Nickel 58.69 +2,3	29 Cu Copper 63.55 +2,1	30 Zn Zinc 65.39 +2	31 Ga Gallium 69.72 +3	32 Ge Germanium 72.61 +4	33 As Arsenic 74.92 -3	34 Se Selenium 78.96 -2	35 Br Bromine 79.90 -1	36 Kr Krypton 83.80 0
37 Rb Rubidium 85.47 +1	38 Sr Strontium 87.62 +2	39 Y Yttrium 88.91 +3	40 Zr Zirconium 91.22 +4	41 Nb Niobium 92.91 +5,3	42 Mo Molybdenum 95.94 +6,2,3,4,5	43 Tc Technetium (98) +7	44 Ru Ruthenium 101.07 +2,3,4,6,8	45 Rh Rhodium 102.91 +2,3,4	46 Pd Palladium 106.42 +2,4	47 Ag Silver 107.87 +1	48 Cd Cadmium 112.41 +2	49 In Indium 114.82 +3	50 Sn Tin 118.71 +4,2	51 Sb Antimony 121.76 +/-3,5	52 Te Tellurium 127.60 -2	53 I Iodine 126.90 -1	54 Xe Xenon 131.29 0
55 Cs Cesium 132.91 +1	56 Ba Barium 137.33 +2	71 Lu Lutetium 174.97 +3	72 Hf Hafnium 178.49 +4	73 Ta Tantalum 180.95 +5	74 W Tungsten 183.84 +6,2,3,4,5	75 Re Rhenium 186.21 +7,6,4,2	76 Os Osmium 190.23 +2,3,4,6,8	77 Ir Iridium 192.22 +2,3,4,6	78 Pt Platinum 195.08 +2,4	79 Au Gold 196.97 +3,1	80 Hg Mercury 200.59 +2,1	81 Tl Thallium 204.38 +3,1	82 Pb Lead 207.20 +4,2	83 Bi Bismuth 208.98 +3,5	84 Po Polonium (209) +4,2,6	85 At Astatine (210) -1	86 Rn Radon (222) 0
87 Fr Francium (223) +1	88 Ra Radium (226) +2	103 Lr Lawrencium (266) +3	104 Rf Rutherfordium (267) -	105 Db Dubnium (268) -	106 Sg Seaborgium (269) -	107 Bh Bohrium (270) -	108 Hs Hassium (269) -	109 Mt Meitnerium (278) -	110 Ds Darmstadtium (281) -	111 Rg Roentgenium (280) -	112 Cn Copernicium (285) -	113 Nh Nihonium (286) -	114 Fl Flerovium (289) -	115 Mc Moscovium (289) -	116 Lv Livermorium (293) -	117 Ts Tennessine (294) -	118 Og Oganesson (294) -
		Lanthanides* 57 La Lanthanum 138.91 +3 58 Ce Cerium 140.12 +3,4 59 Pr Praseodymium 140.91 +3,4 60 Nd Neodymium 144.24 +3 61 Pm Promethium (145) 62 Sm Samarium 150.36 +3,2 63 Eu Europium 151.97 +3,2 64 Gd Gadolinium 157.25 +3 65 Tb Terbium 158.93 +3,4 66 Dy Dysprosium 162.50 +3 67 Ho Holmium 164.93 +3 68 Er Erbium 167.26 +3 69 Tm Thulium 168.93 +3,2 70 Yb Ytterbium 173.05 +3,2															
		Actinides** 89 Ac Actinium (227) +3 90 Th Thorium 232.04 +4 91 Pa Protactinium 231.04 +5,4 92 U Uranium 238.03 +6,5,4,3 93 Np Neptunium (237) +6,5,4,3 94 Pu Plutonium (244) +6,5,4,3 95 Am Americium (243) +6,5,4,3 96 Cm Curium (247) +3 97 Bk Berkelium (247) +4,3 98 Cf Californium (251) +3 99 Es Einsteinium (252) +3 100 Fm Fermium (257) +3 101 Md Mendelevium (258) +3 102 No Nobelium (259) +2,3															

**Key**

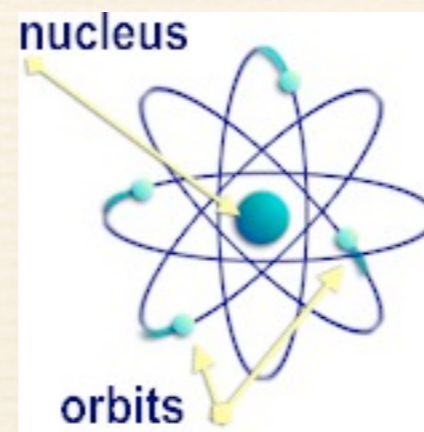
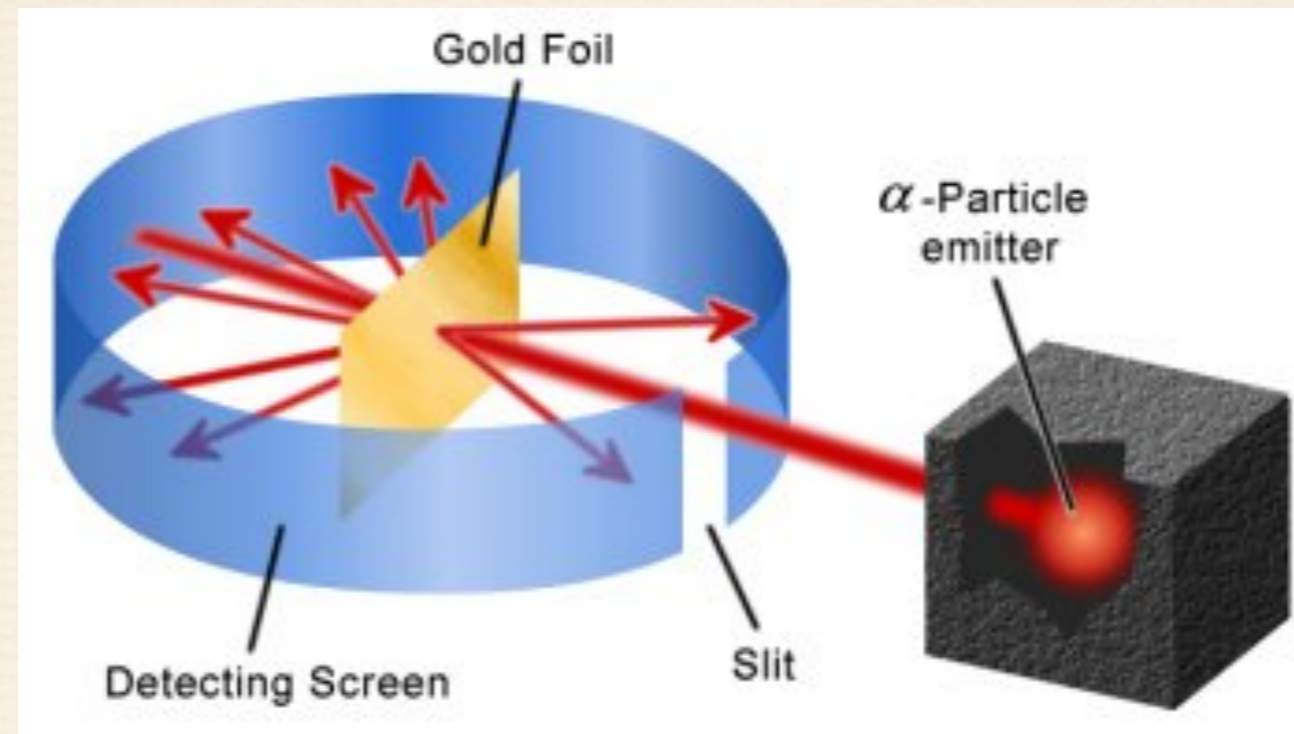
Solid: □  
Liquid: ▽  
Gas: ○  
Synthetic: ✖  
Radioactive: ☛  
Diatomic: ∞

Atomic Number: 19  
Symbol: K  
Name of Element: Potassium  
Atomic Weight: 39.10  
Charge on Ion: +1

□ Metal  
▨ Metalloid  
□ Nonmetal

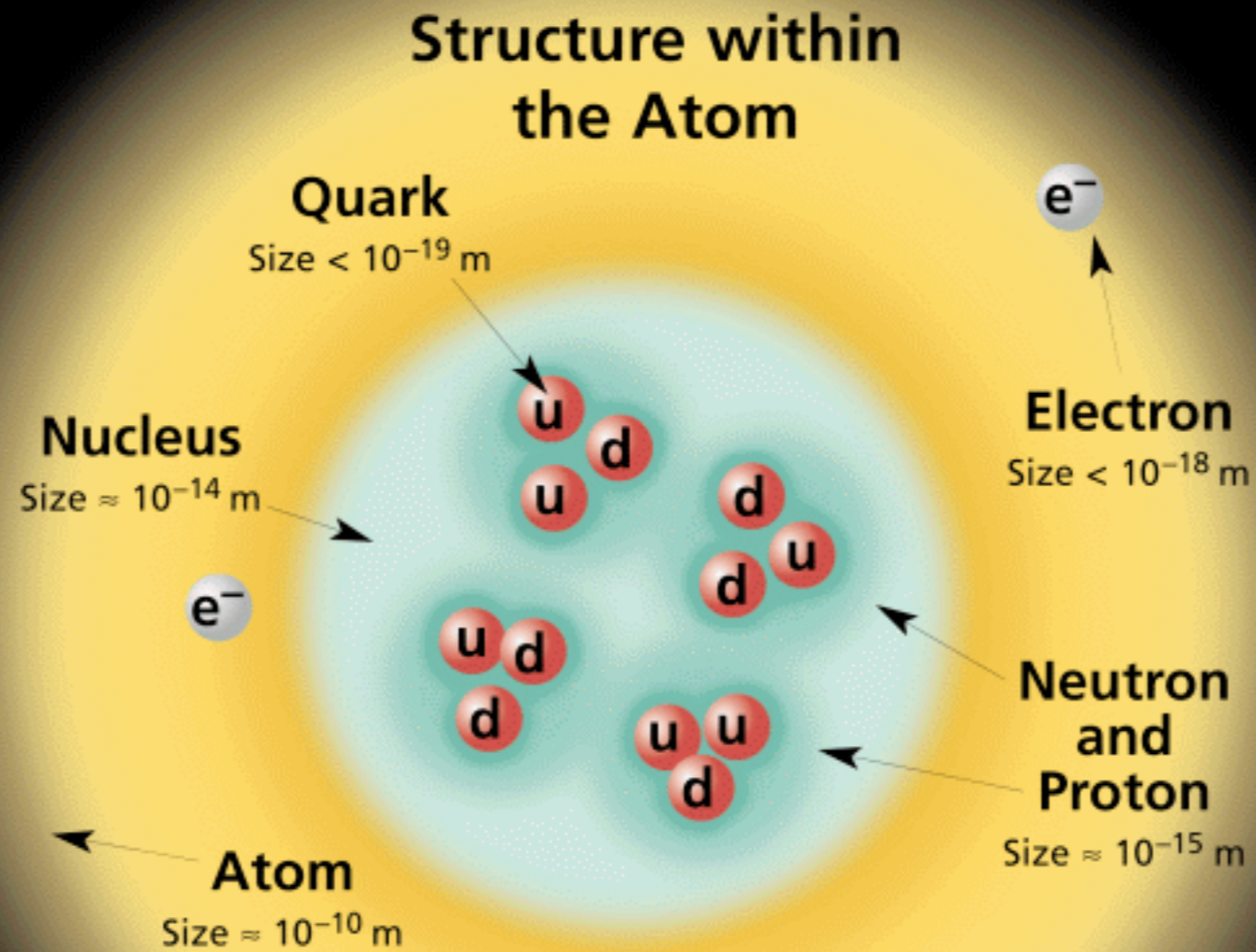


# Ernest Rutherford's Atom (1911)





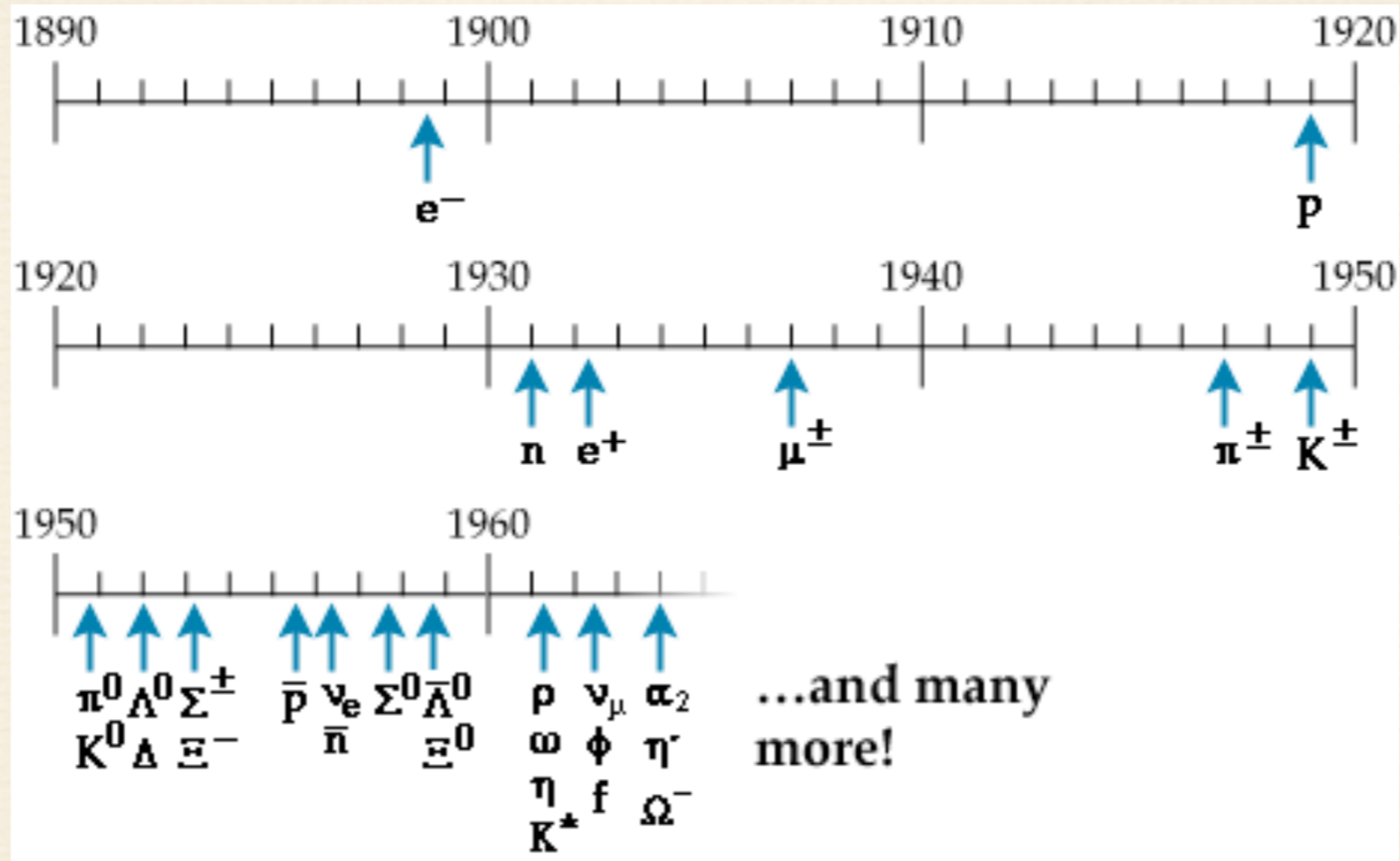
# Inside the atom



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.



# Particle discoveries galore!





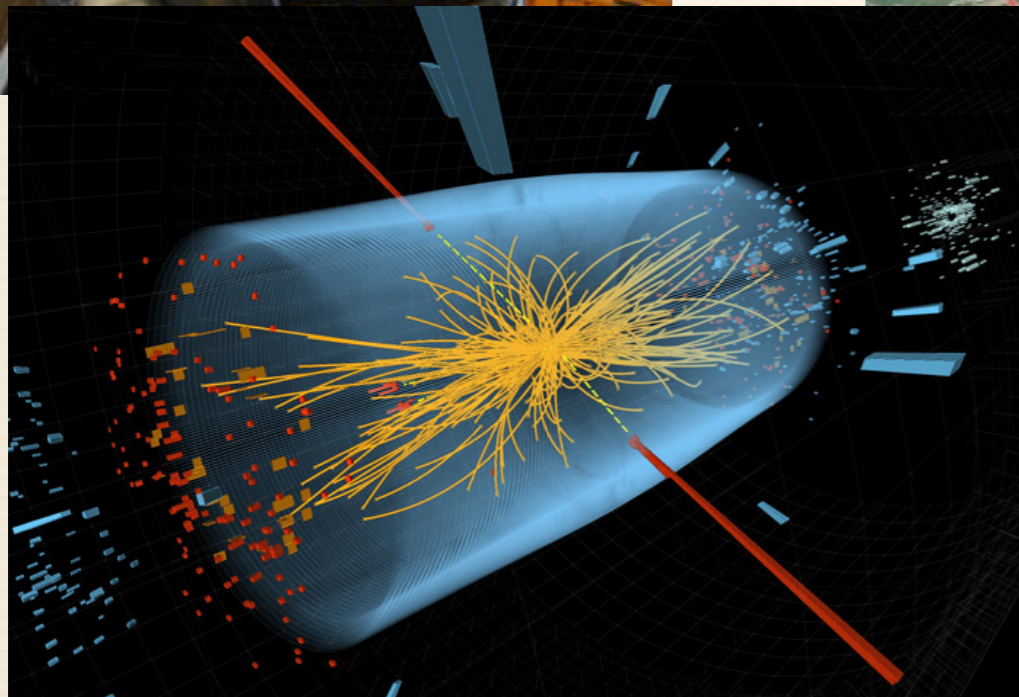
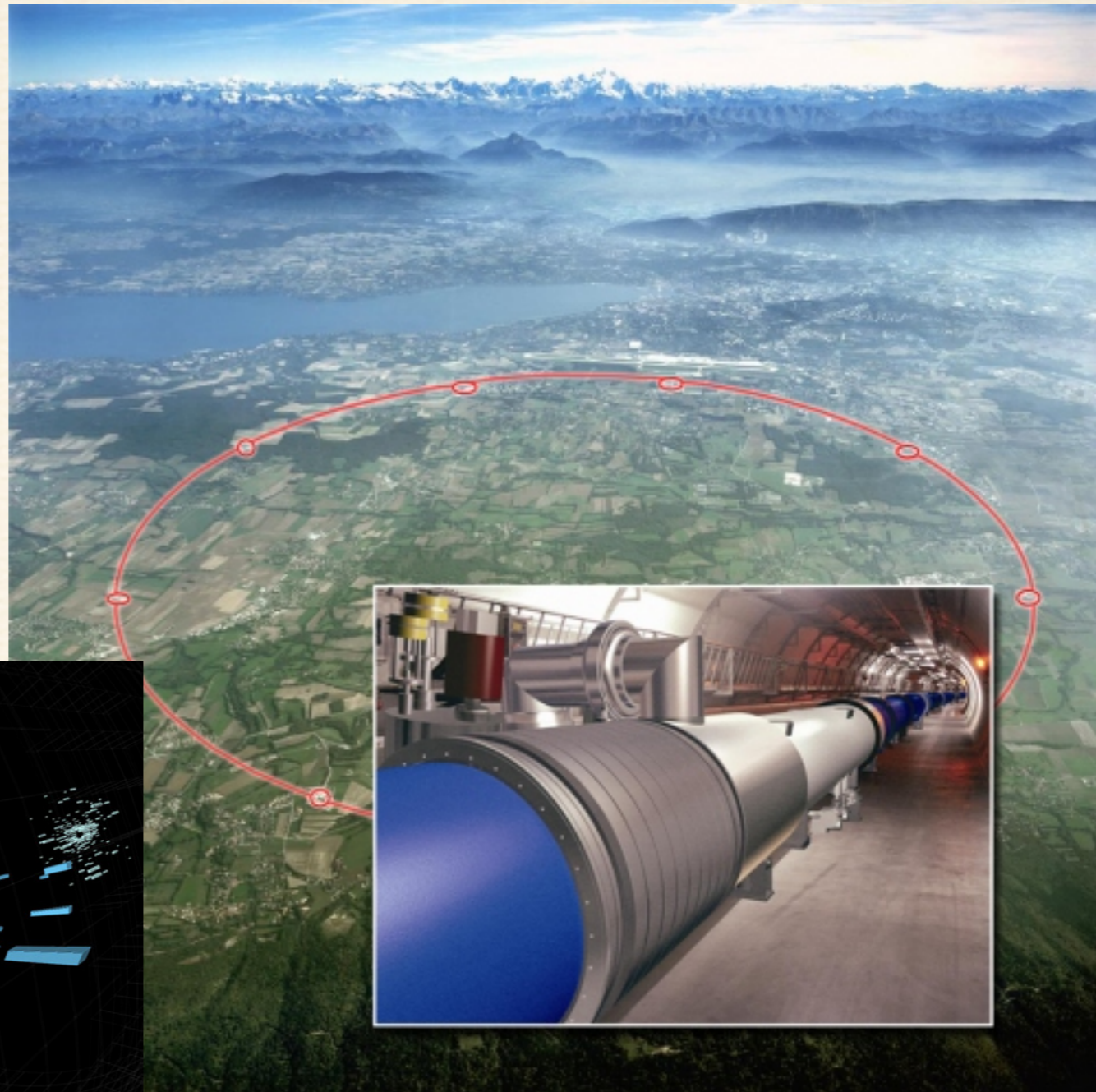
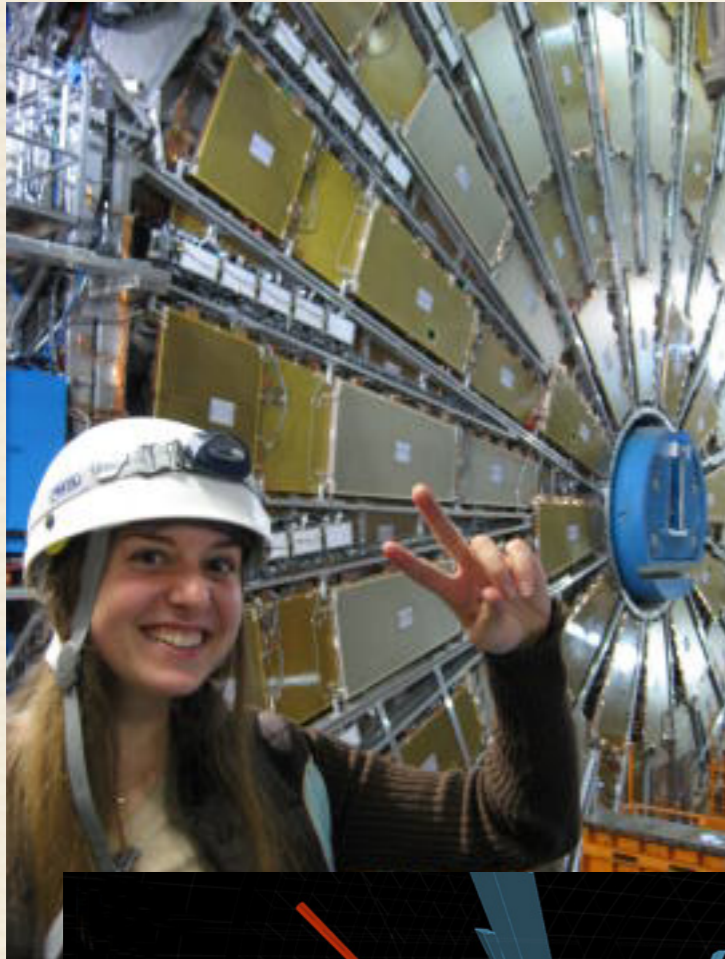
# Modern Day Colliders



Jefferson Lab



# Modern Day Colliders

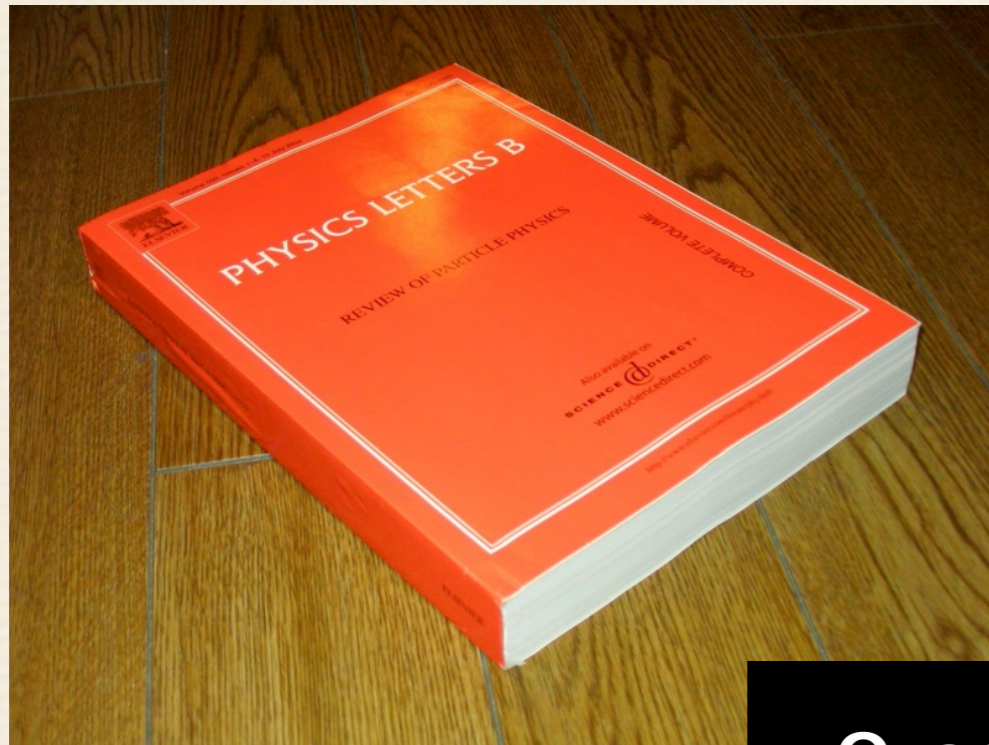


CERN

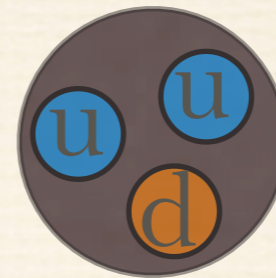
Conseil Européen pour la Recherche Nucléaire



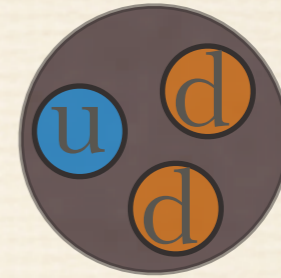
# The Particle Zoo



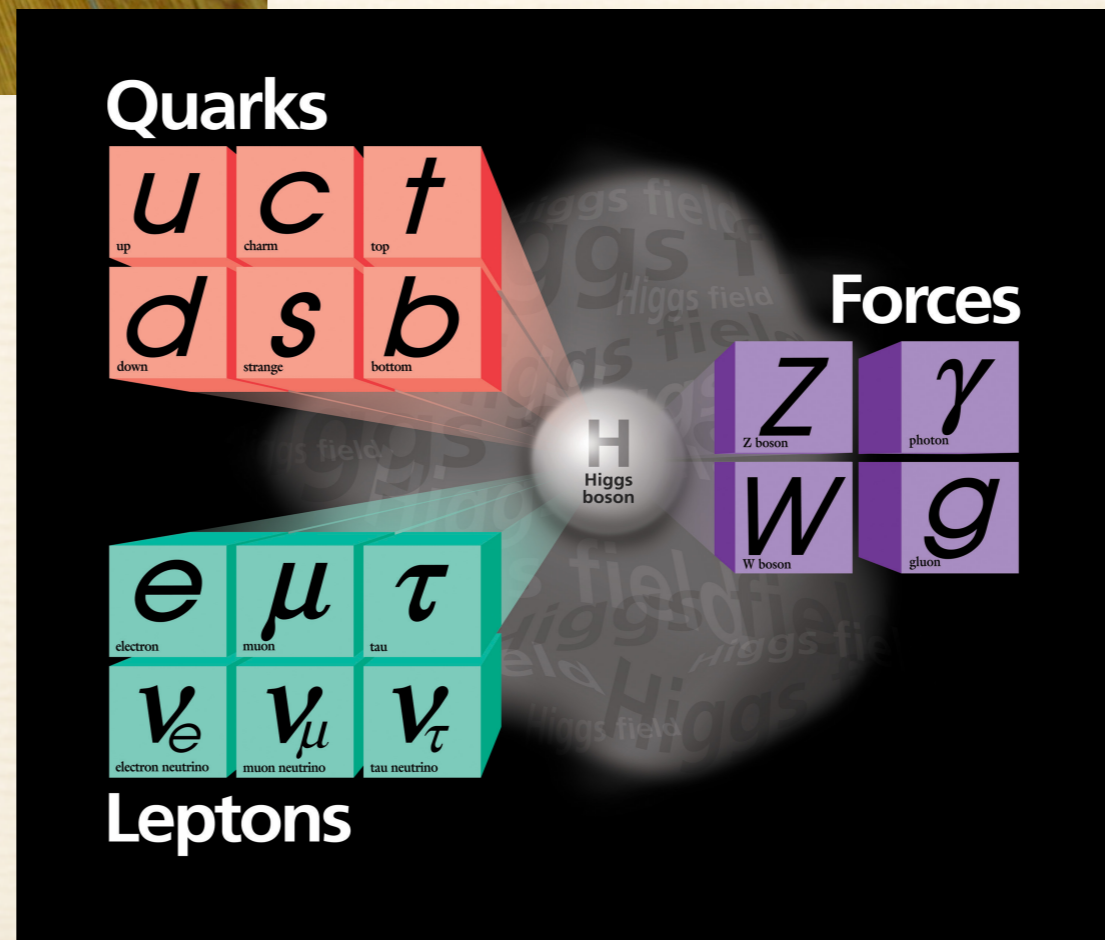
Proton



Neutron









## The Standard Model





# The Periodic Table of Elements

## The Periodic Table of Elements

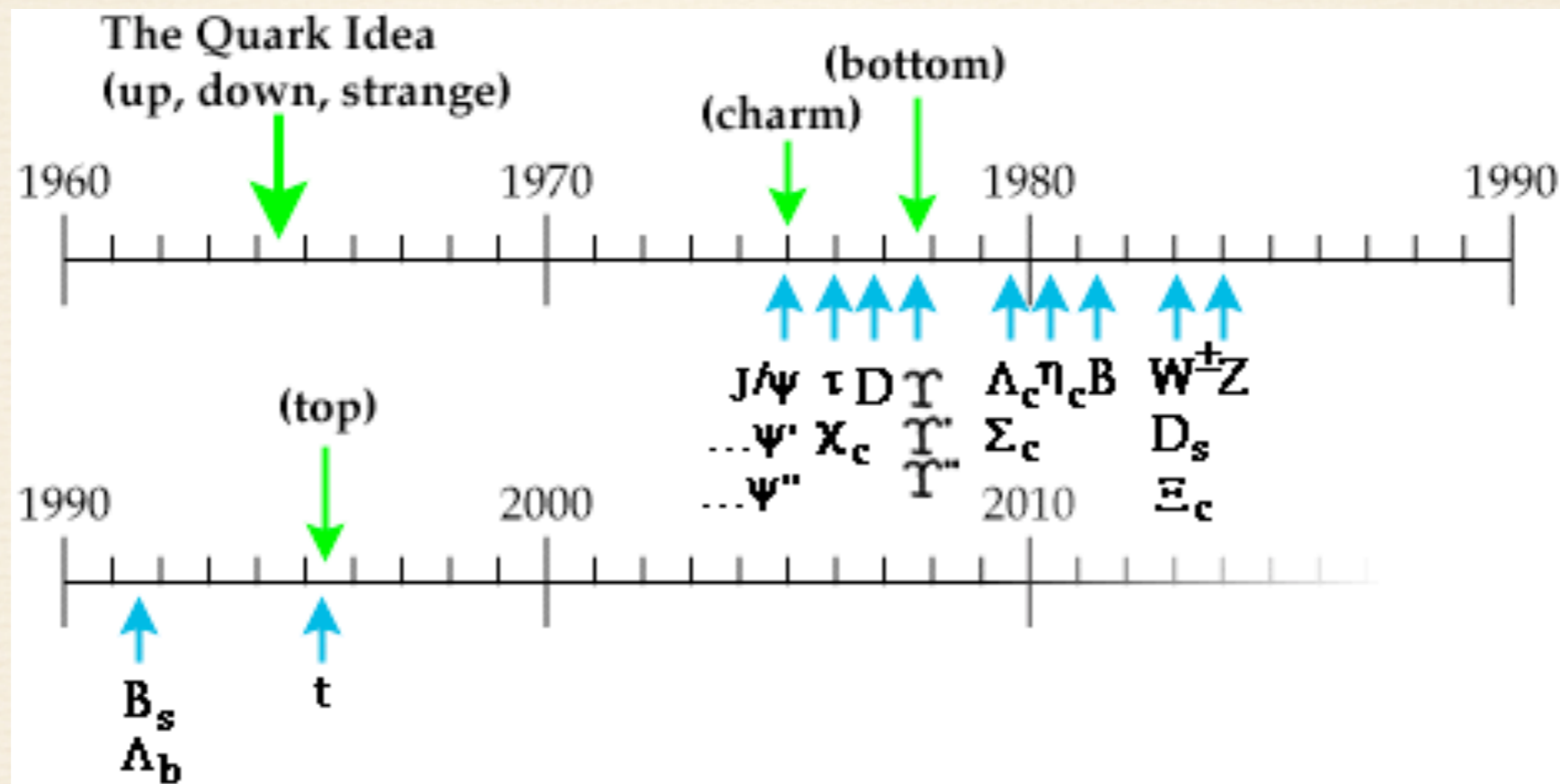
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1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18																												
<p><b>Key</b></p> <p>Atomic Number    Symbol    Name of Element    Atomic Weight</p> <p>Radioactive    Diatomic</p> <p>  Solid   Liquid   Gas   Synthetic   Charge on ion   Diatomic         </p>																																													
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		<table border="1"> <tr> <td>57 La Lanthanum 138.91 +3</td> <td>58 Ce Cerium 140.12 +3,4</td> <td>59 Pr Praseodymium 140.91 +3,4</td> <td>60 Nd Neodymium 144.24 +3</td> <td>61 Pm Promethium (145) +3</td> <td>62 Sm Samarium 150.36 +3,2</td> <td>63 Eu Europium 151.97 +3,2</td> <td>64 Gd Gadolinium 157.25 +3</td> <td>65 Tb Terbium 158.93 +3,4</td> <td>66 Dy Dysprosium 162.50 +3</td> <td>67 Ho Holmium 164.93 +3</td> <td>68 Er Erbium 167.26 +3</td> <td>69 Tm Thulium 168.93 +3,2</td> <td>70 Yb Ytterbium 173.05 +3,2</td> </tr> <tr> <td>89 Ac Actinium (227) +3</td> <td>90 Th Thorium 232.04 +4</td> <td>91 Pa Protactinium 231.04 +5,4</td> <td>92 U Uranium 238.03 +6,5,4,3</td> <td>93 Np Neptunium (237) +6,5,4,3</td> <td>94 Pu Plutonium (244) +6,5,4,3</td> <td>95 Am Americium (243) +6,5,4,3</td> <td>96 Cm Curium (247) +7</td> <td>97 Bk Berkelium (247) +4,3</td> <td>98 Cf Californium (251) +1</td> <td>99 Es Einsteinium (252) +3</td> <td>100 Fm Fermium (257) +3</td> <td>101 Md Mendelevium (258) +3</td> <td>102 No Nobelium (259) +2,3</td> </tr> </table>																57 La Lanthanum 138.91 +3	58 Ce Cerium 140.12 +3,4	59 Pr Praseodymium 140.91 +3,4	60 Nd Neodymium 144.24 +3	61 Pm Promethium (145) +3	62 Sm Samarium 150.36 +3,2	63 Eu Europium 151.97 +3,2	64 Gd Gadolinium 157.25 +3	65 Tb Terbium 158.93 +3,4	66 Dy Dysprosium 162.50 +3	67 Ho Holmium 164.93 +3	68 Er Erbium 167.26 +3	69 Tm Thulium 168.93 +3,2	70 Yb Ytterbium 173.05 +3,2	89 Ac Actinium (227) +3	90 Th Thorium 232.04 +4	91 Pa Protactinium 231.04 +5,4	92 U Uranium 238.03 +6,5,4,3	93 Np Neptunium (237) +6,5,4,3	94 Pu Plutonium (244) +6,5,4,3	95 Am Americium (243) +6,5,4,3	96 Cm Curium (247) +7	97 Bk Berkelium (247) +4,3	98 Cf Californium (251) +1	99 Es Einsteinium (252) +3	100 Fm Fermium (257) +3	101 Md Mendelevium (258) +3	102 No Nobelium (259) +2,3
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	<p>mass → <math>\approx 2.3 \text{ MeV}/c^2</math></p> <p>charge → <math>2/3</math></p> <p>spin → <math>1/2</math></p> <p><b>u</b></p> <p>up</p>	<p>mass → <math>\approx 1.275 \text{ GeV}/c^2</math></p> <p>charge → <math>2/3</math></p> <p>spin → <math>1/2</math></p> <p><b>c</b></p> <p>charm</p>	<p>mass → <math>\approx 173.07 \text{ GeV}/c^2</math></p> <p>charge → <math>2/3</math></p> <p>spin → <math>1/2</math></p> <p><b>t</b></p> <p>top</p>	<p>mass → <math>0</math></p> <p>charge → <math>0</math></p> <p>spin → <math>1</math></p> <p><b>g</b></p> <p>gluon</p>	<p>mass → <math>\approx 126 \text{ GeV}/c^2</math></p> <p>charge → <math>0</math></p> <p>spin → <math>0</math></p> <p><b>H</b></p> <p>Higgs boson</p>
<b>QUARKS</b>	<p>mass → <math>\approx 4.8 \text{ MeV}/c^2</math></p> <p>charge → <math>-1/3</math></p> <p>spin → <math>1/2</math></p> <p><b>d</b></p> <p>down</p>	<p>mass → <math>\approx 95 \text{ MeV}/c^2</math></p> <p>charge → <math>-1/3</math></p> <p>spin → <math>1/2</math></p> <p><b>s</b></p> <p>strange</p>	<p>mass → <math>\approx 4.18 \text{ GeV}/c^2</math></p> <p>charge → <math>-1/3</math></p> <p>spin → <math>1/2</math></p> <p><b>b</b></p> <p>bottom</p>	<p>mass → <math>0</math></p> <p>charge → <math>0</math></p> <p>spin → <math>1</math></p> <p><b><math>\gamma</math></b></p> <p>photon</p>	
	<p>mass → <math>0.511 \text{ MeV}/c^2</math></p> <p>charge → <math>-1</math></p> <p>spin → <math>1/2</math></p> <p><b>e</b></p> <p>electron</p>	<p>mass → <math>105.7 \text{ MeV}/c^2</math></p> <p>charge → <math>-1</math></p> <p>spin → <math>1/2</math></p> <p><b><math>\mu</math></b></p> <p>muon</p>	<p>mass → <math>1.777 \text{ GeV}/c^2</math></p> <p>charge → <math>-1</math></p> <p>spin → <math>1/2</math></p> <p><b><math>\tau</math></b></p> <p>tau</p>	<p>mass → <math>91.2 \text{ GeV}/c^2</math></p> <p>charge → <math>0</math></p> <p>spin → <math>1</math></p> <p><b>Z</b></p> <p>Z boson</p>	<b>GAUGE BOSONS</b>
	<p>mass → <math>&lt; 2.2 \text{ eV}/c^2</math></p> <p>charge → <math>0</math></p> <p>spin → <math>1/2</math></p> <p><b><math>\nu_e</math></b></p> <p>electron neutrino</p>	<p>mass → <math>&lt; 0.17 \text{ MeV}/c^2</math></p> <p>charge → <math>0</math></p> <p>spin → <math>1/2</math></p> <p><b><math>\nu_\mu</math></b></p> <p>muon neutrino</p>	<p>mass → <math>&lt; 15.5 \text{ MeV}/c^2</math></p> <p>charge → <math>0</math></p> <p>spin → <math>1/2</math></p> <p><b><math>\nu_\tau</math></b></p> <p>tau neutrino</p>	<p>mass → <math>80.4 \text{ GeV}/c^2</math></p> <p>charge → <math>\pm 1</math></p> <p>spin → <math>1</math></p> <p><b>W</b></p> <p>W boson</p>	

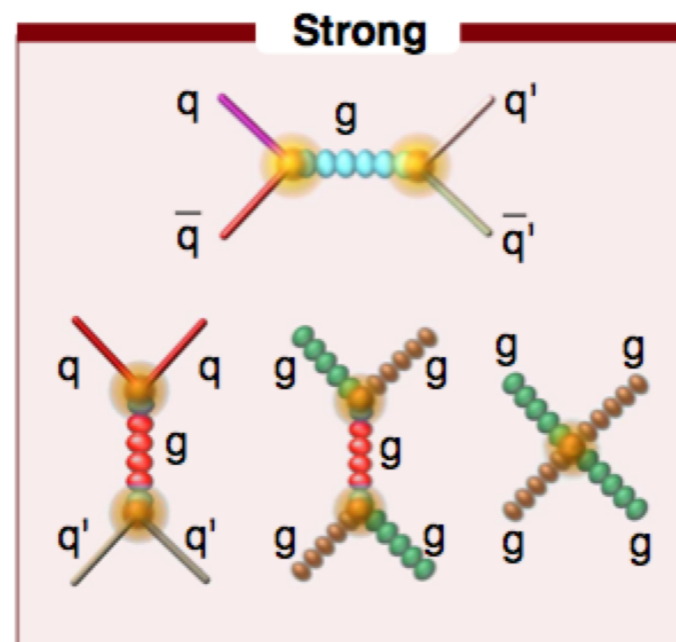
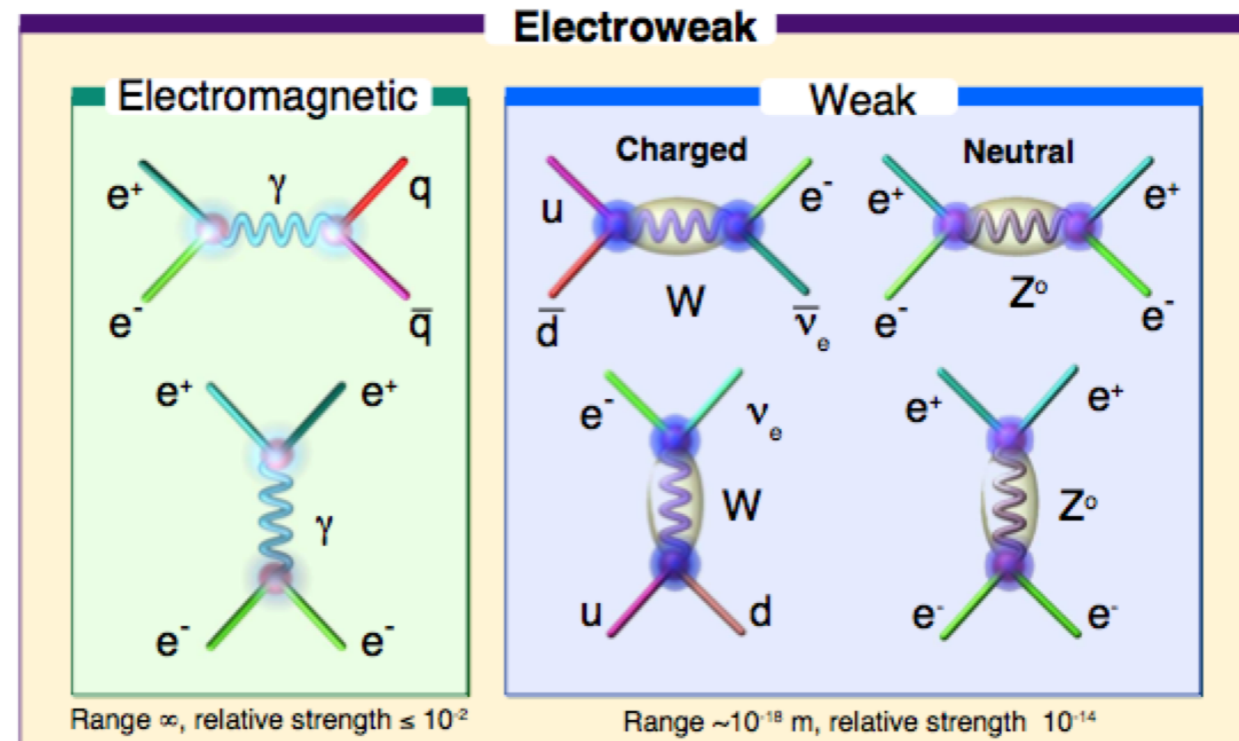


Many particles contain quarks, but some particles are fundamental (as far as we know).





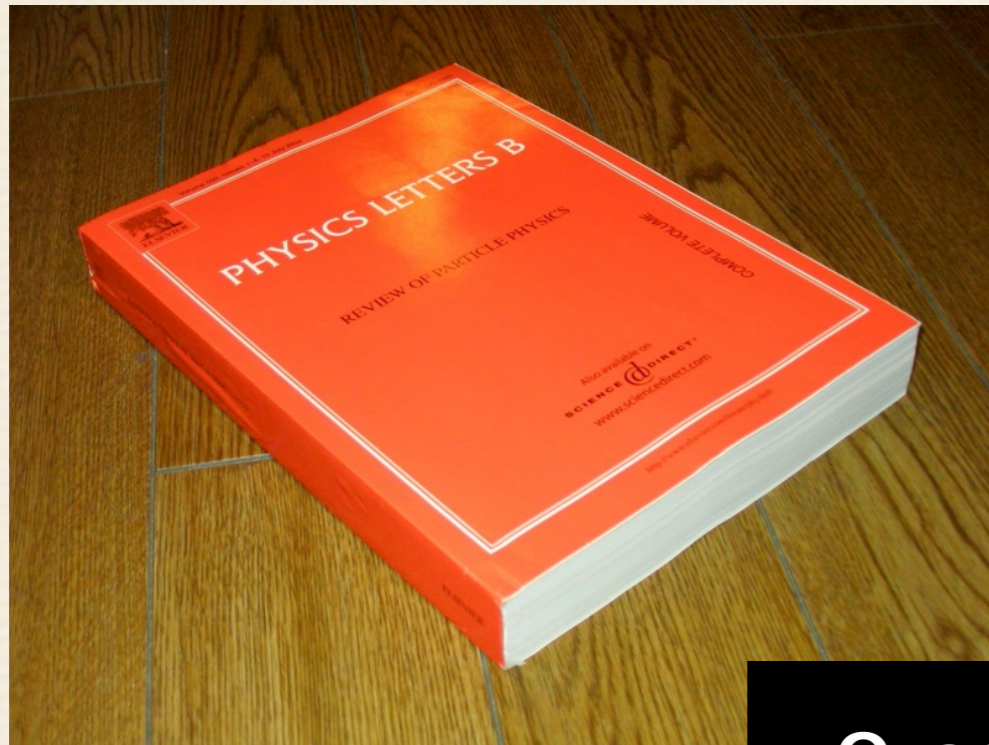
# Particle Interactions



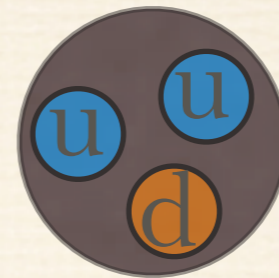
Range  $\sim 10^{-15}$  m, relative strength = 1



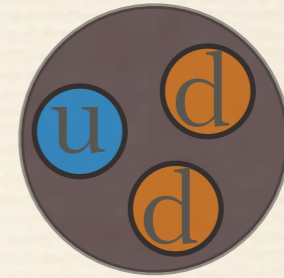
# The Particle Zoo



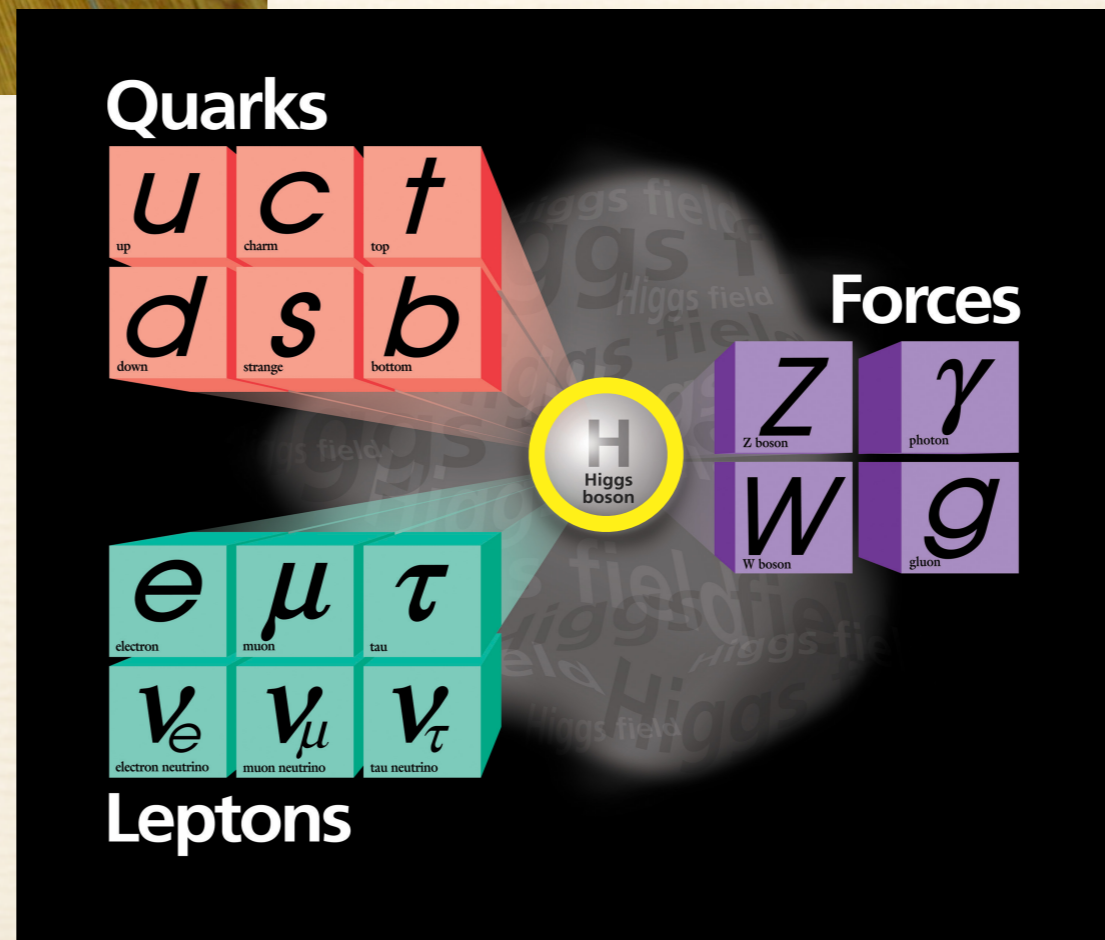
Proton



Neutron



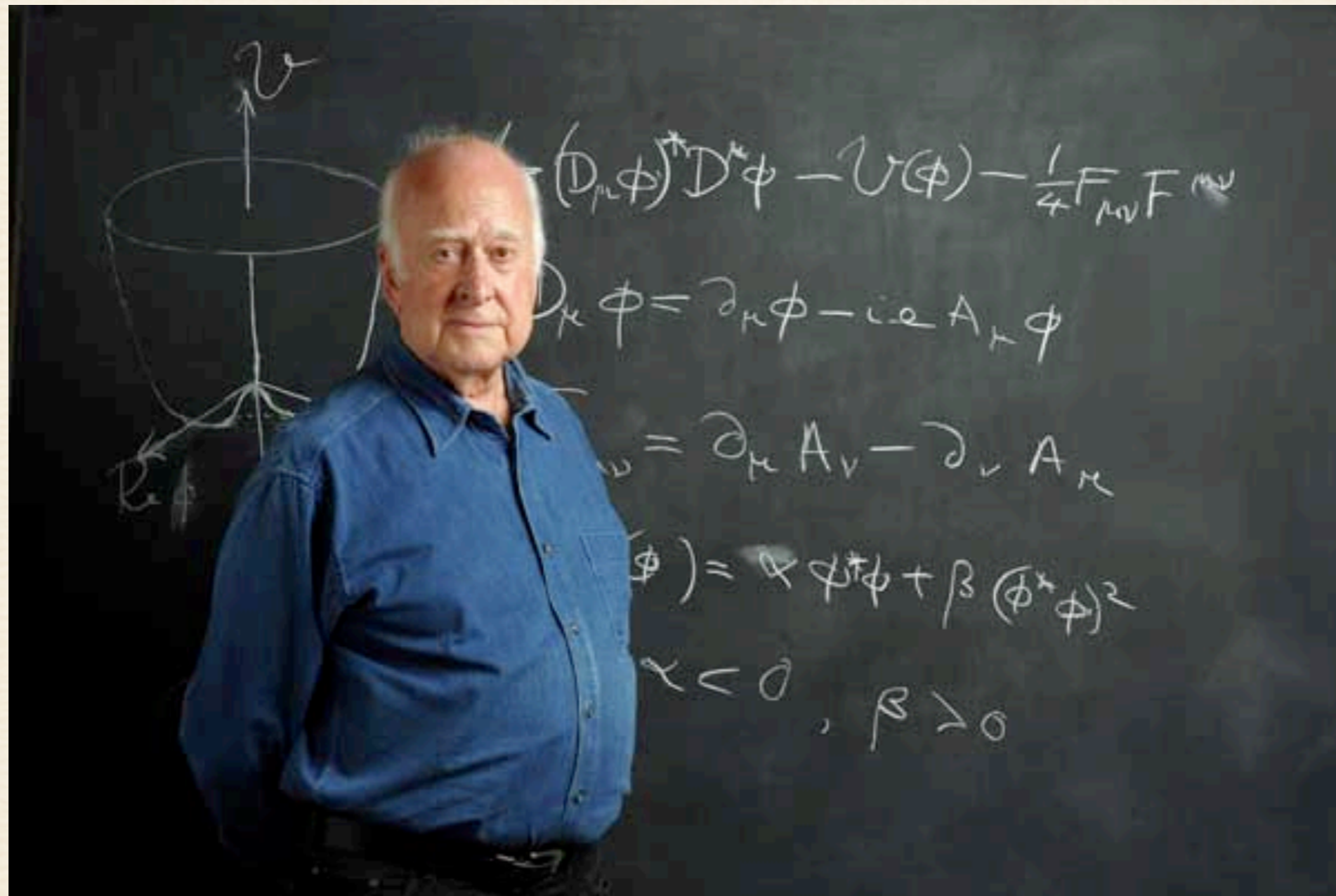
## The Standard Model





# Higgs to the rescue!

(and Brout, Englert, Guralnik, ...)





# The Higgs Field and Mass





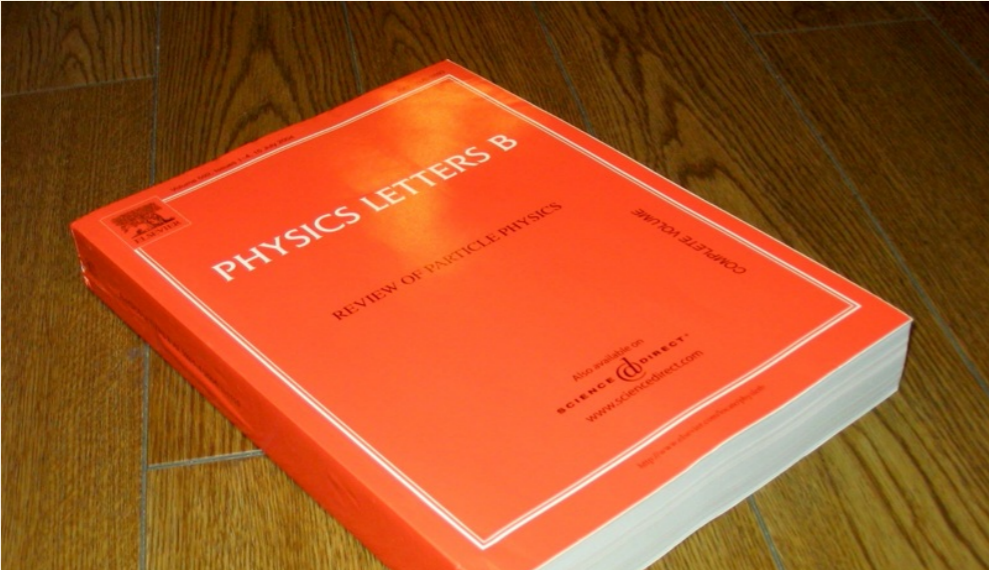
# The Higgs Boson

Just as photons are particles of the electromagnetic field, Higgs bosons are particles of the Higgs field.

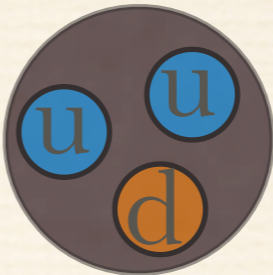




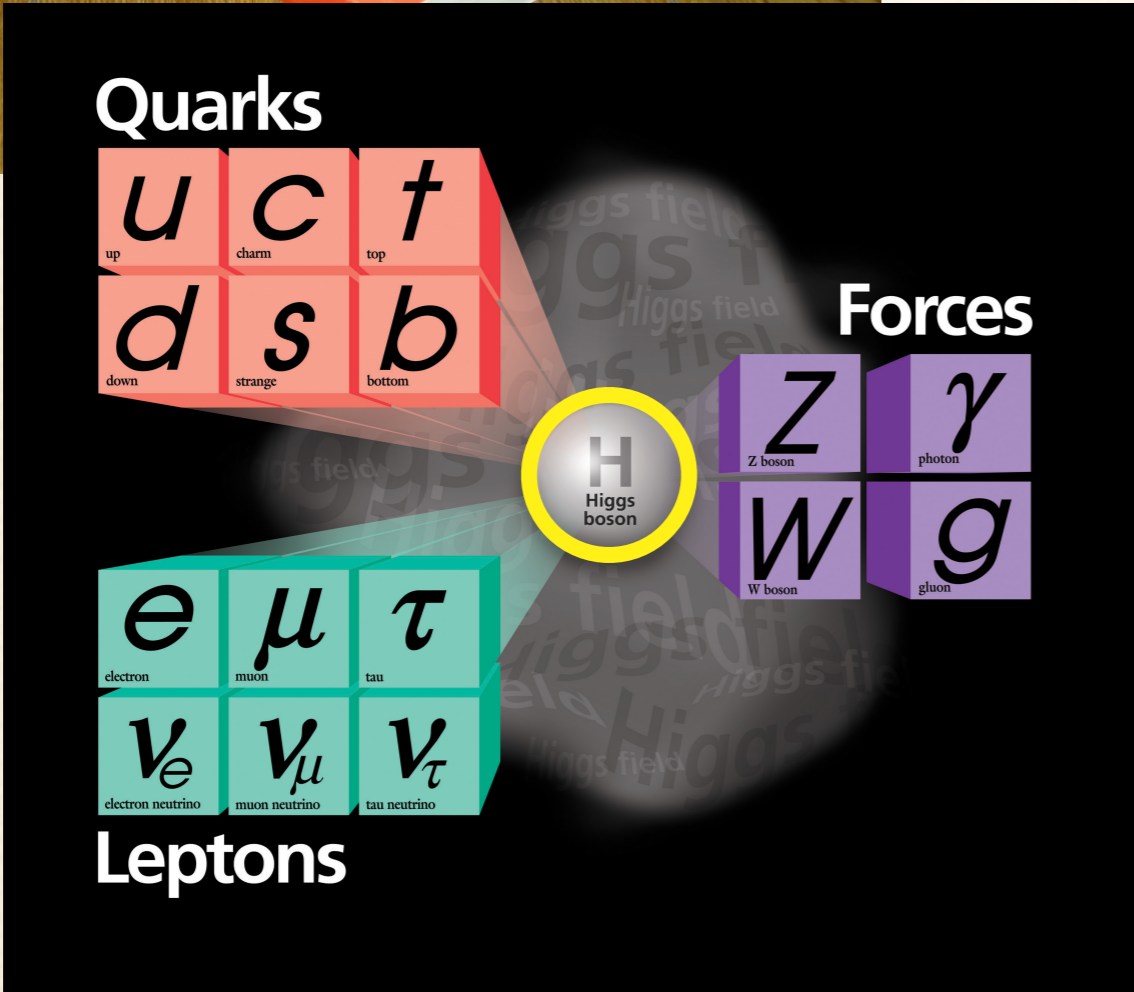
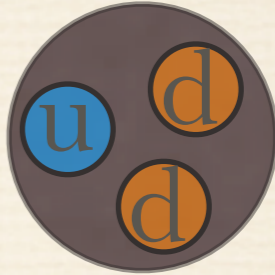
# The Particle Zoo



Proton



Neutron



Everything we understand in the universe is made of these

=

5% of the energy in the universe