

I quark e l'ultimo dei bosoni

*Un'introduzione al Modello Standard delle
particelle elementari e al molto che c'è
ancora da studiare dopo la scoperta
del bosone di Higgs*

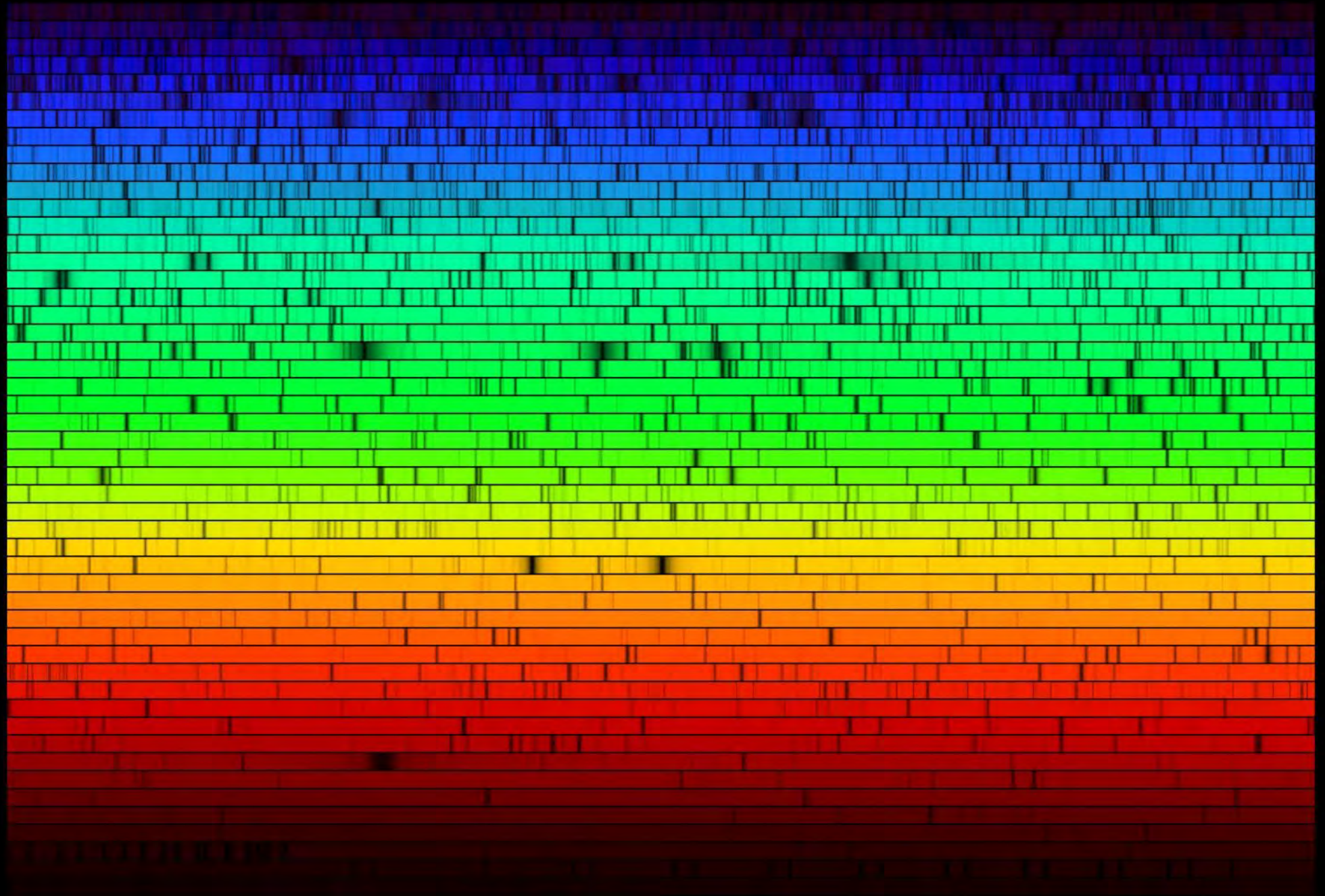


Istituto Nazionale di Fisica Nucleare
LABORATORI NAZIONALI DI FRASCATI

*[Acknowledgements to H. Cliff and
A. Mathad for some contribution]*

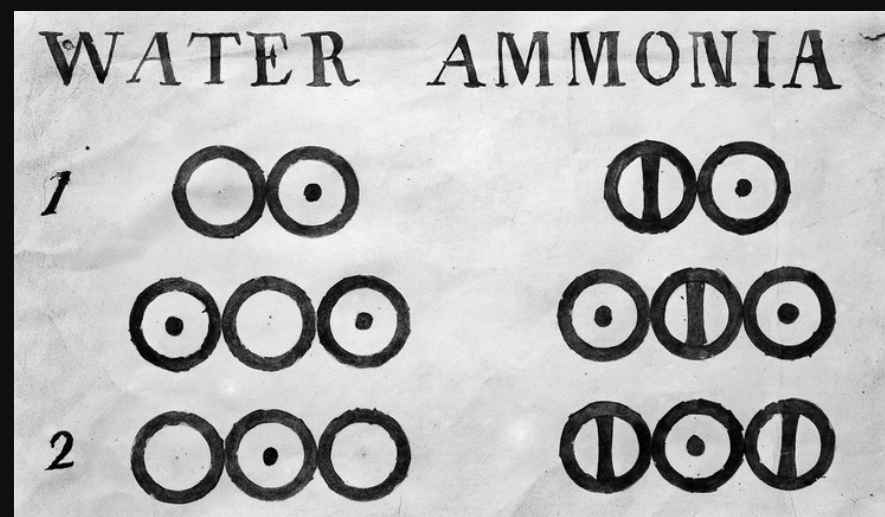
Barbara Sciascia





John Dalton

ELEMENTS.					
	Hydrogen.	1		Strontian	46
	Azote	5		Barytes	68
	Carbon	5		Iron	50
	Oxygen	7		Zinc	56
	Phosphorus.	9		Copper	56
	Sulphur	13		Lead	90
	Magnesia	20		Silver	190
	Lime	24		Gold	190
	Soda	28		Platina	190
	Potash	42		Mercury	167



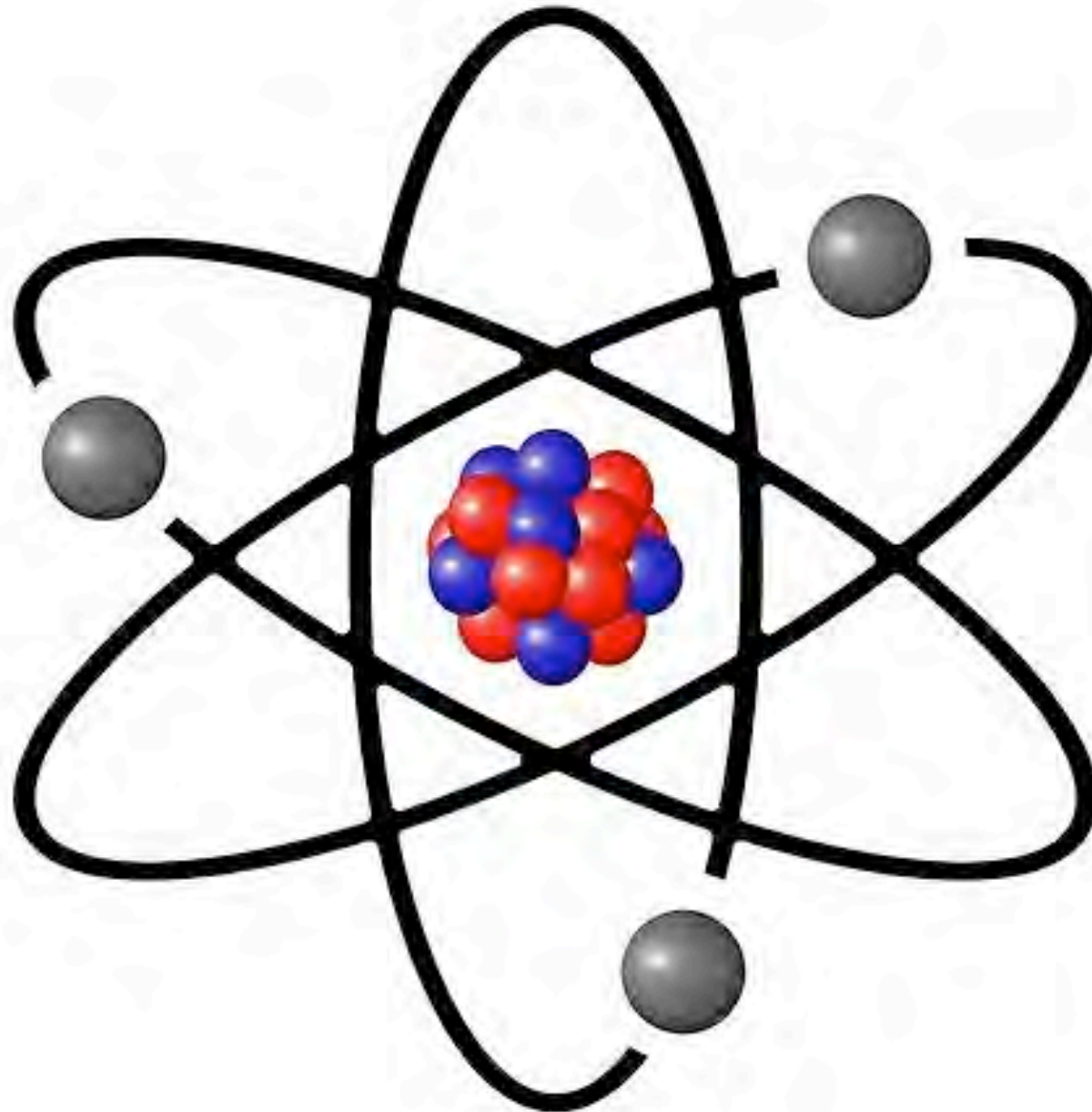
Dimitrij Mendeleev

Periodic Law

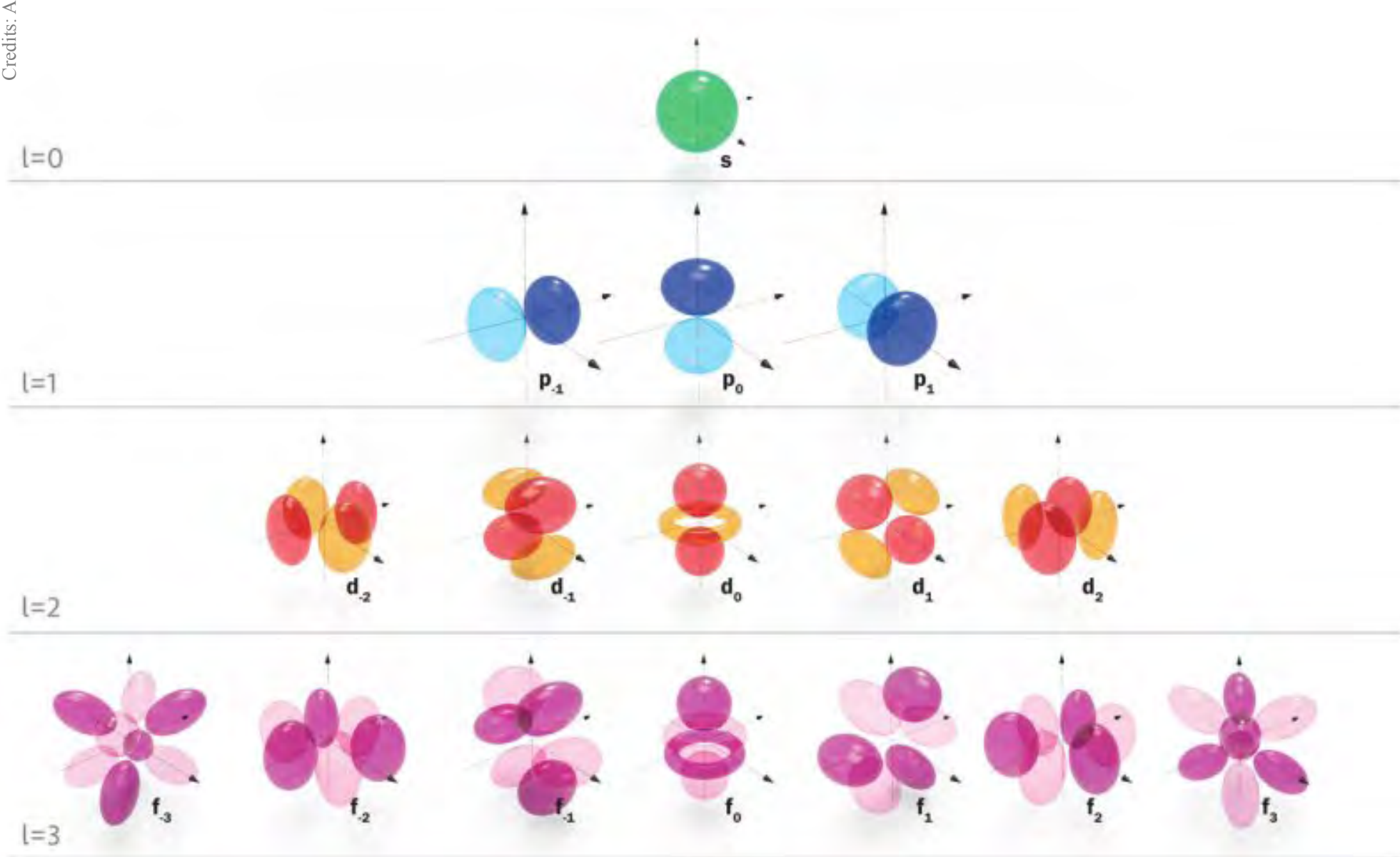
				Ti = 50	Zr = 90	? = 180
				V = 51	Nb = 94	Ta = 182
				Cr = 52	Mo = 96	W = 186
				Mn = 55	Rh = 104,4	Pt = 197,4
				Fe = 56	Ru = 104,4	Ir = 198
			Ni =	Co = 59	Pd = 106,6	Os = 199
				Cu = 63,4	Ag = 108	Hg = 200
				Zn = 65,2	Cd = 112	
				? = 68	Ur = 116	Au = 197?
				? = 70	Sn = 118	
				As = 75	Sb = 122	Bi = 210?
				Sc = 79,4	Te = 128?	
				Br = 80	J = 127	
				Rb = 85,4	Cs = 133	Tl = 204
				Sr = 87,6	Ba = 137	Pb = 207
				? = 45	Ce = 92	
			?Er =	56	La = 94	
			?Yt =	60	Di = 95	
			?In =	75,6	Th = 118?	
H = 1						
	Be = 9,4	Mg = 24				
	B = 11	Al = 27,4				
	C = 12	Si = 28				
	N = 14	P = 31				
	O = 16	S = 32				
	F = 19	Cl = 35,5				
Li = 7	Na = 23	K = 39				
		Ca = 10				
		? = 45				
		?Er = 56				
		?Yt = 60				
		?In = 75,6				

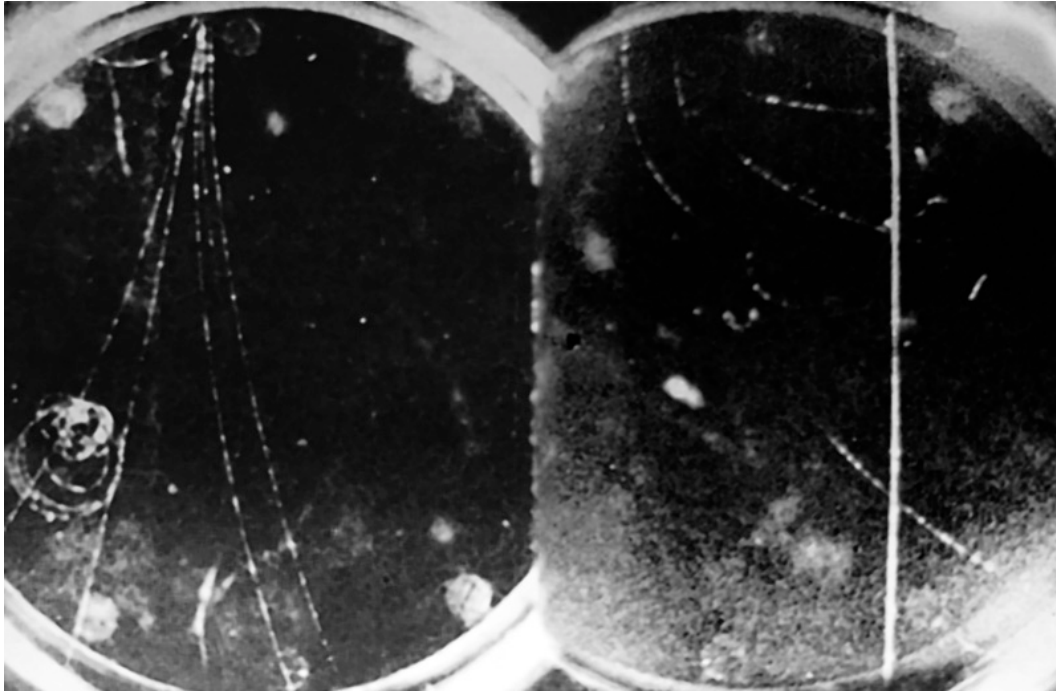
Dimitrij Mendeleev

Group Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	
1	1 H																	2 He	
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne	
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar	
4	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	
5	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
6	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
7	87 Fr	88 Ra	89 Ac	*	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
				*	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	

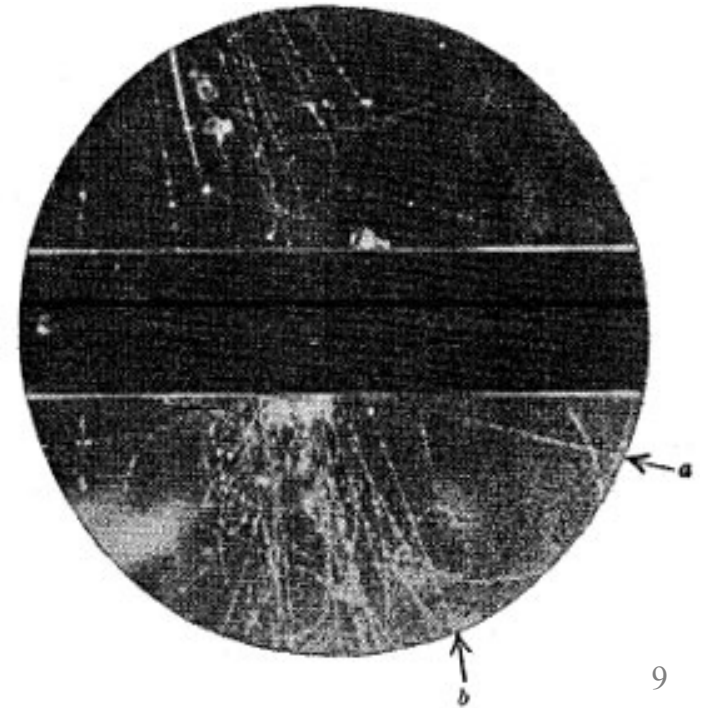
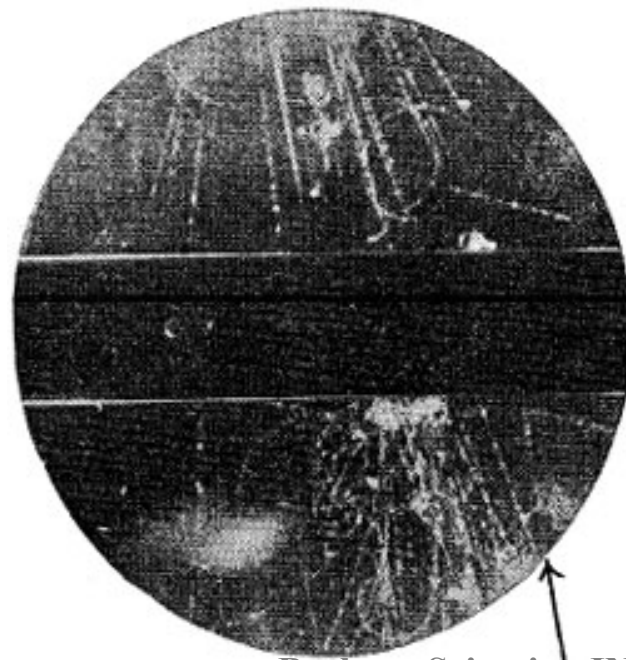


Orbitali atomici





Muons and kaons

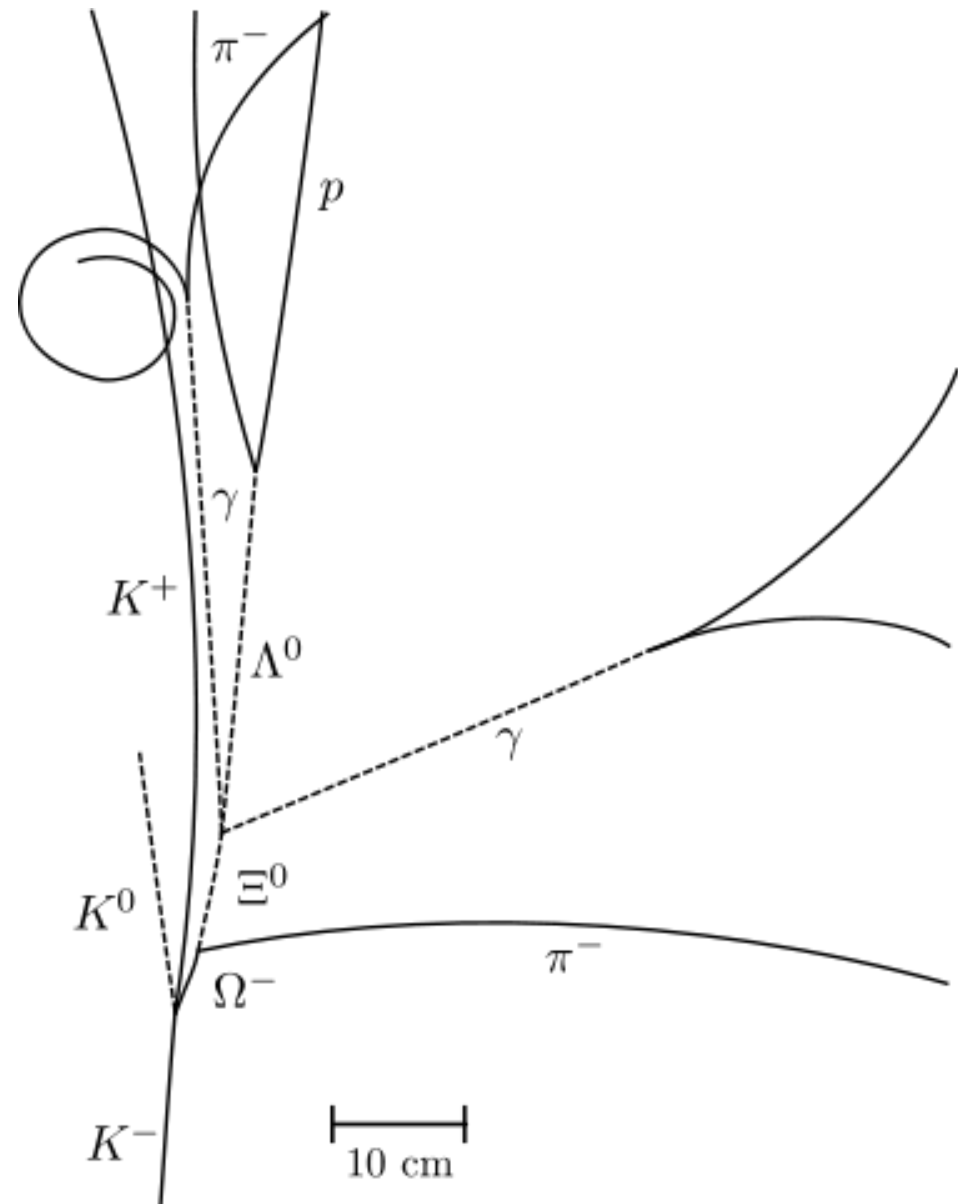
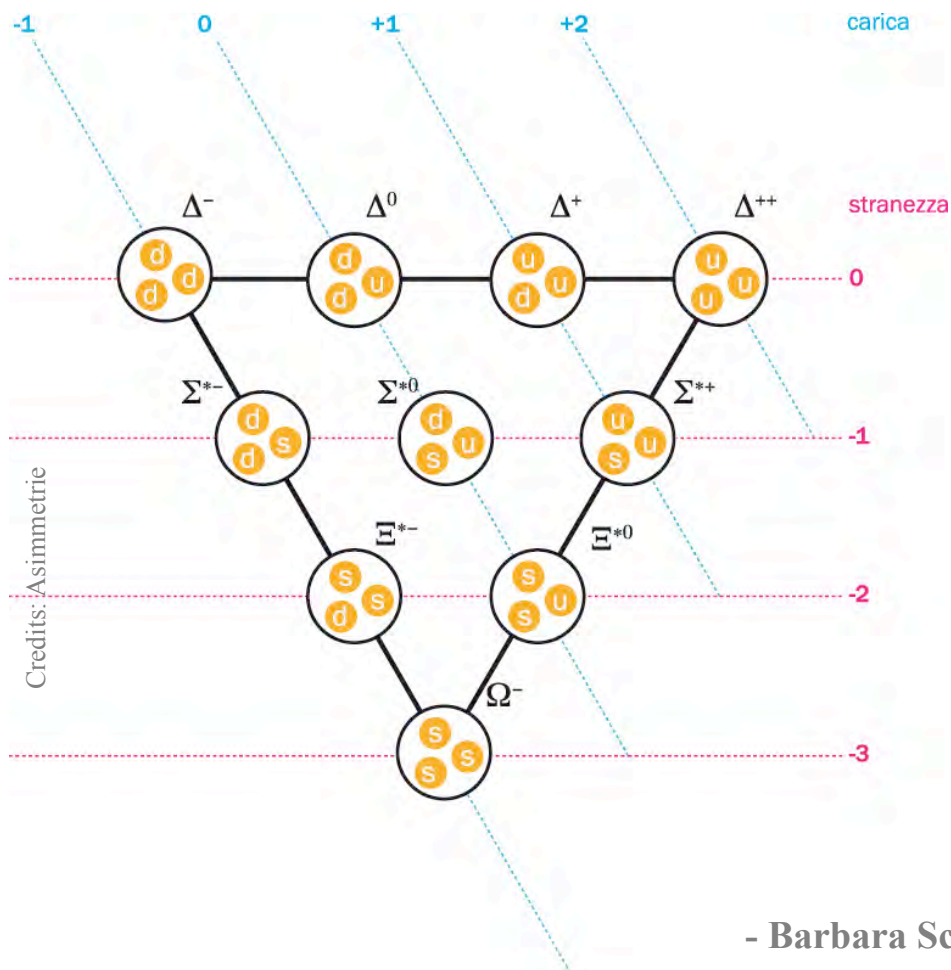


- Barbara Sciascia - INFN/LNF

Particle zoo

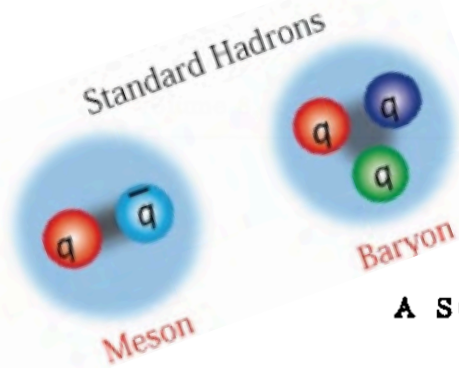
π^+ PION (PI-PLUS) mass: 140 MeV/c ² spin-0 Q = +1 S = 0 discovered: 1947	K^0 KAON (K-ZERO) mass: 498 MeV/c ² spin-0 Q = 0 S = +1 discovered: 1947	K^- KAON (K-MINUS) mass: 494 MeV/c ² spin-0 Q = -1 S = -1 discovered: 1947		
Λ LAMBDA mass: 1116 MeV/c ² spin-1/2 Q = 0 S = -1 discovered: 1951	Ξ^- XI-MINUS mass: 1322 MeV/c ² spin-1/2 Q = -1 S = -2 discovered: 1952	Σ^+ SIGMA-PLUS mass: 1189 MeV/c ² spin-1/2 Q = +1 S = -1 discovered: 1953	Δ^{++} DELTA-DOUBLE PLUS mass: 1231 MeV/c ² spin-3/2 Q = +2 S = 0 discovered: 1954	Σ^0 SIGMA-ZERO mass: 1193 MeV/c ² spin-1/2 Q = 0 S = -1 discovered: 1956
Σ^{*+} SIGMA-STAR-PLUS mass: 1383 MeV/c ² spin-3/2 Q = +1 S = -1 discovered: 1960	η ETA mass: 548 MeV/c ² spin-0 Q = 0 S = 0 discovered: 1961			

“Three quarks for muster mark”

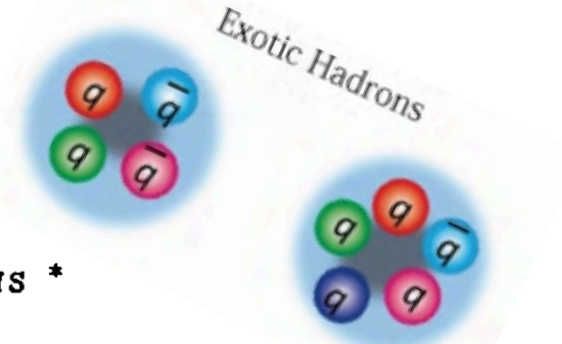


Credits: V. E. Barnes et al. through Wikipedia

Murray Gell-Mann



PHYSICS LETTERS



A SCHEMATIC MODEL OF BARYONS AND MESONS *

M. GELL-MANN

California Institute of Technology, Pasadena, California

Received 4 January 1964

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way" ¹⁻³, we are tempted to look for some fundamental explanation of the situation. A highly promised approach is the purely dynamical "bootstrap" model for all the strongly interacting particles within which one may try to derive isotopic spin and strangeness conservation and broken eightfold symmetry from self-consistency alone ⁴. Of course, with only strong interactions, the orientation of the asymmetry in the unitary space cannot be specified; one hopes that in some way the selection of specific components of the F-spin by electromagnetism and the weak interactions determines the choice of isotopic spin and hypercharge directions.

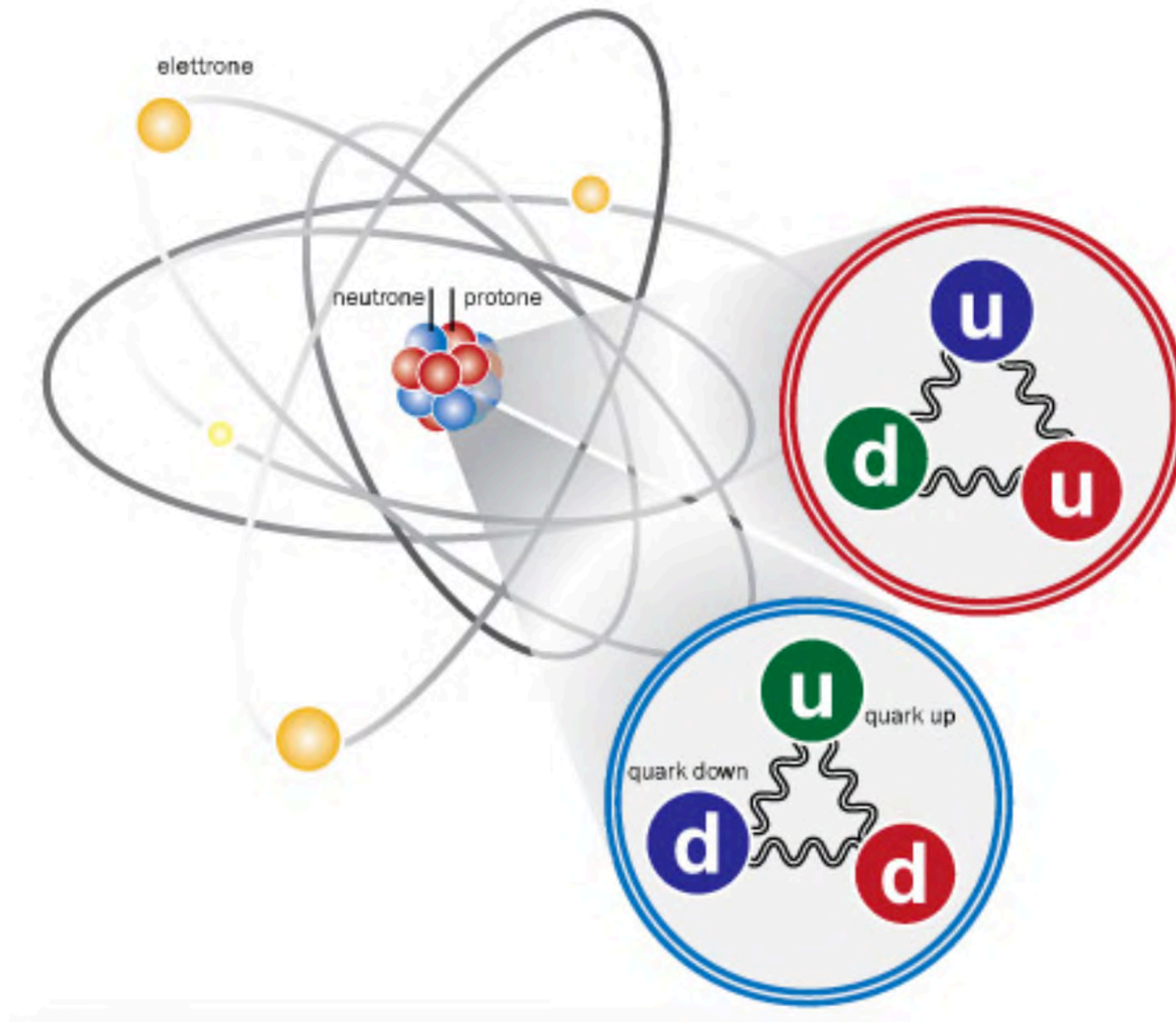
Even if we consider the scattering amplitudes of strongly interacting particles on the mass shell only and treat the matrix elements of the weak, electromagnetic, and gravitational interactions by means

ber $n_t - n_{\bar{t}}$ would be zero for all known baryons and mesons. The most interesting example of such a model is one in which the triplet has spin $\frac{1}{2}$ and $z = -1$, so that the four particles d^- , s^- , u^0 and b^0 exhibit a parallel with the leptons.

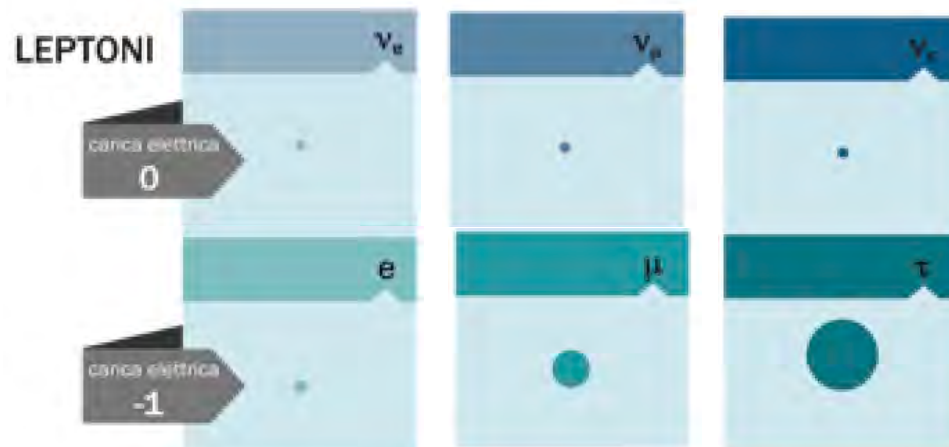
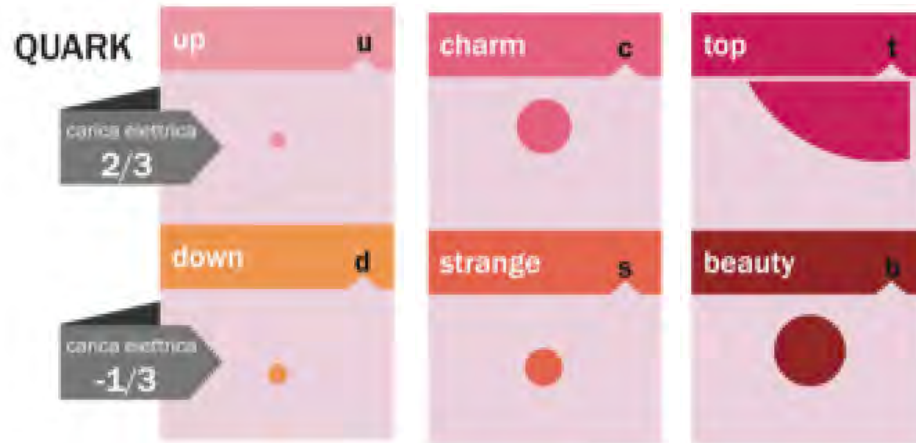
A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$. We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" ⁶ q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq) , $(qqq\bar{q}\bar{q})$, etc., while mesons are made out of $(q\bar{q})$, $(qq\bar{q}\bar{q})$, etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration $(q\bar{q})$ similarly gives just 1 and 8.

Particelle sub-nucleari

Credits: Asimmetrie

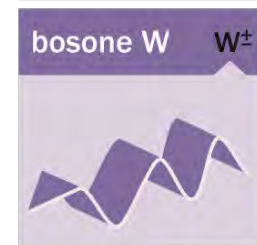
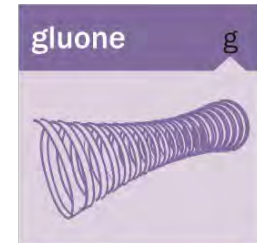


Standard Model



Forze o interazioni

	<i>Intensità relativa</i>	<i>Raggio d'azione</i>	
<i>forte</i>	<i>1</i>	<i>$\sim 10^{-15} \text{ m}$</i>	<i>attrattiva</i>
<i>e.m.</i>	<i>$1/10^2$</i>	<i>infinito</i>	<i>attrattiva o repulsiva</i>
<i>debole</i>	<i>$1/10^5$</i>	<i>$\sim 10^{-18} \text{ m}$</i>	
<i>gravità</i>	<i>$1/10^{40}$</i>	<i>infinito</i>	<i>attrattiva</i>



Credits: Asimmetrie

Standard Model

QUARK	up	u	charm	c	top	t
						
	down	d	strange	s	beauty	b
						

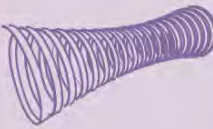
carica elettrica $2/3$

carica elettrica $-1/3$

LEPTONI	ν_e	ν_μ	ν_τ
			
	e	μ	τ
			

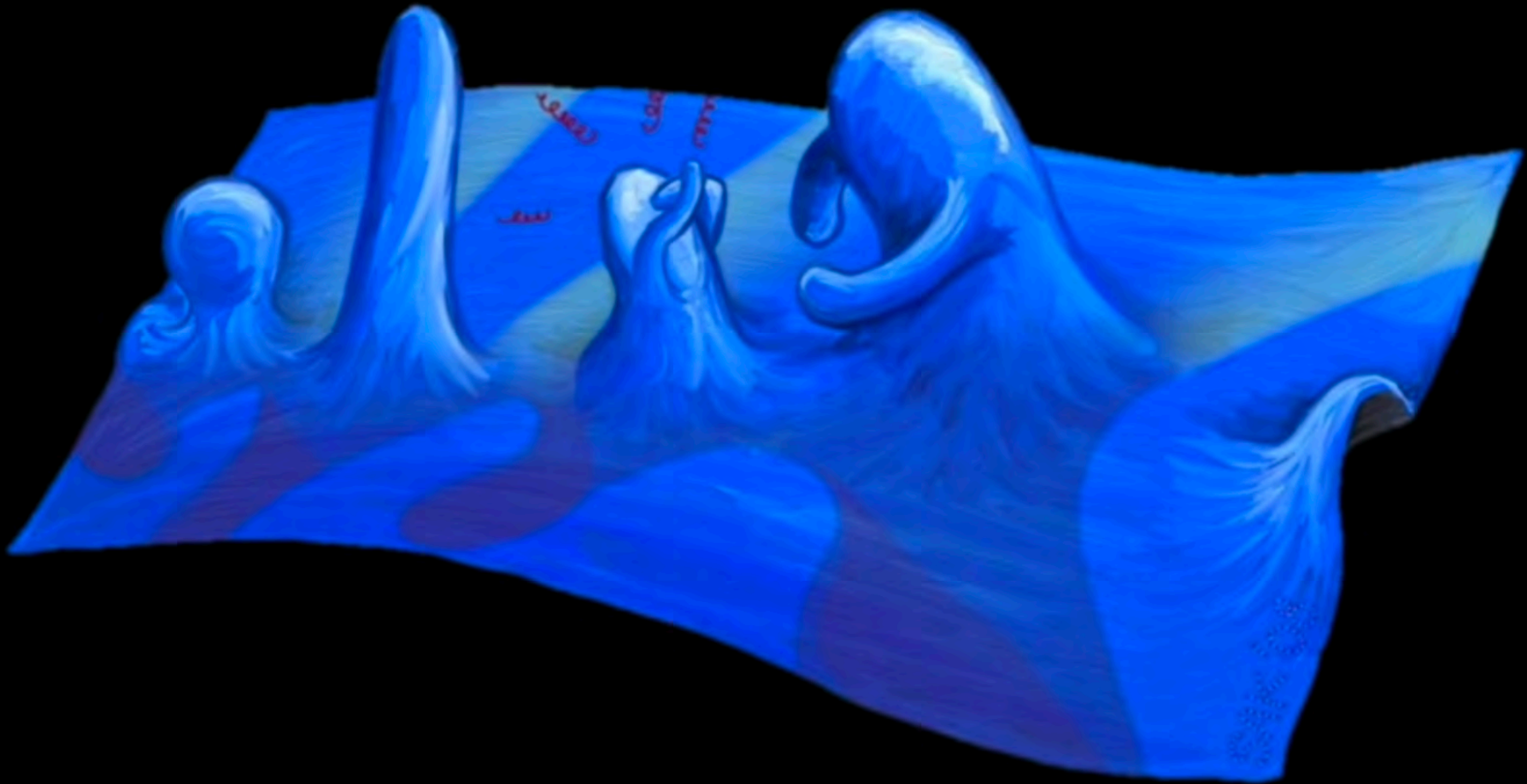
carica elettrica 0

carica elettrica -1

MEDIATORI	gluone	g
		
	fotone	γ
		
	bosone W	$W^\pm$
		
	bosone Z	Z
		



Campi e particelle



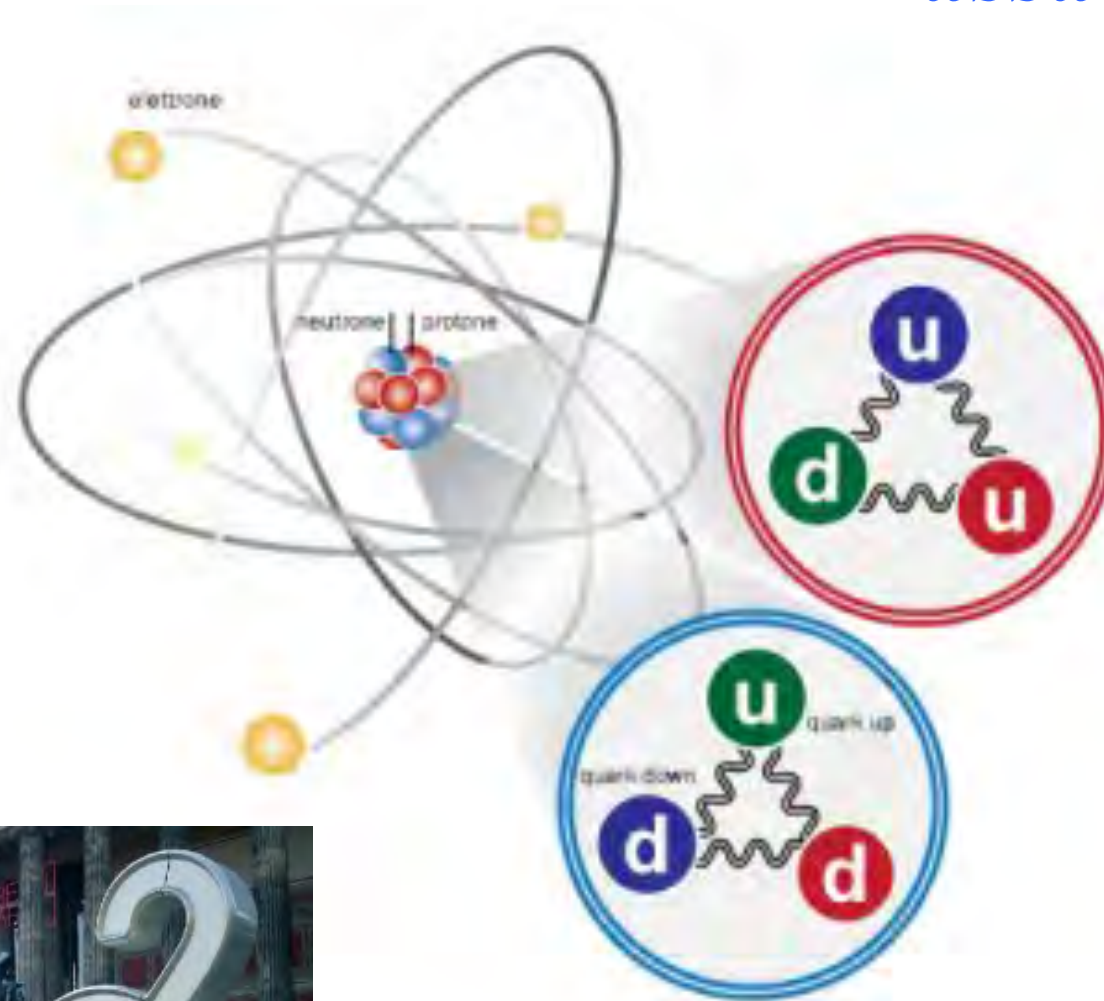
4 luglio 2012

Credits: Reuters



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Massa del protone





The Standard Model of particle physics

Years from concept to discovery

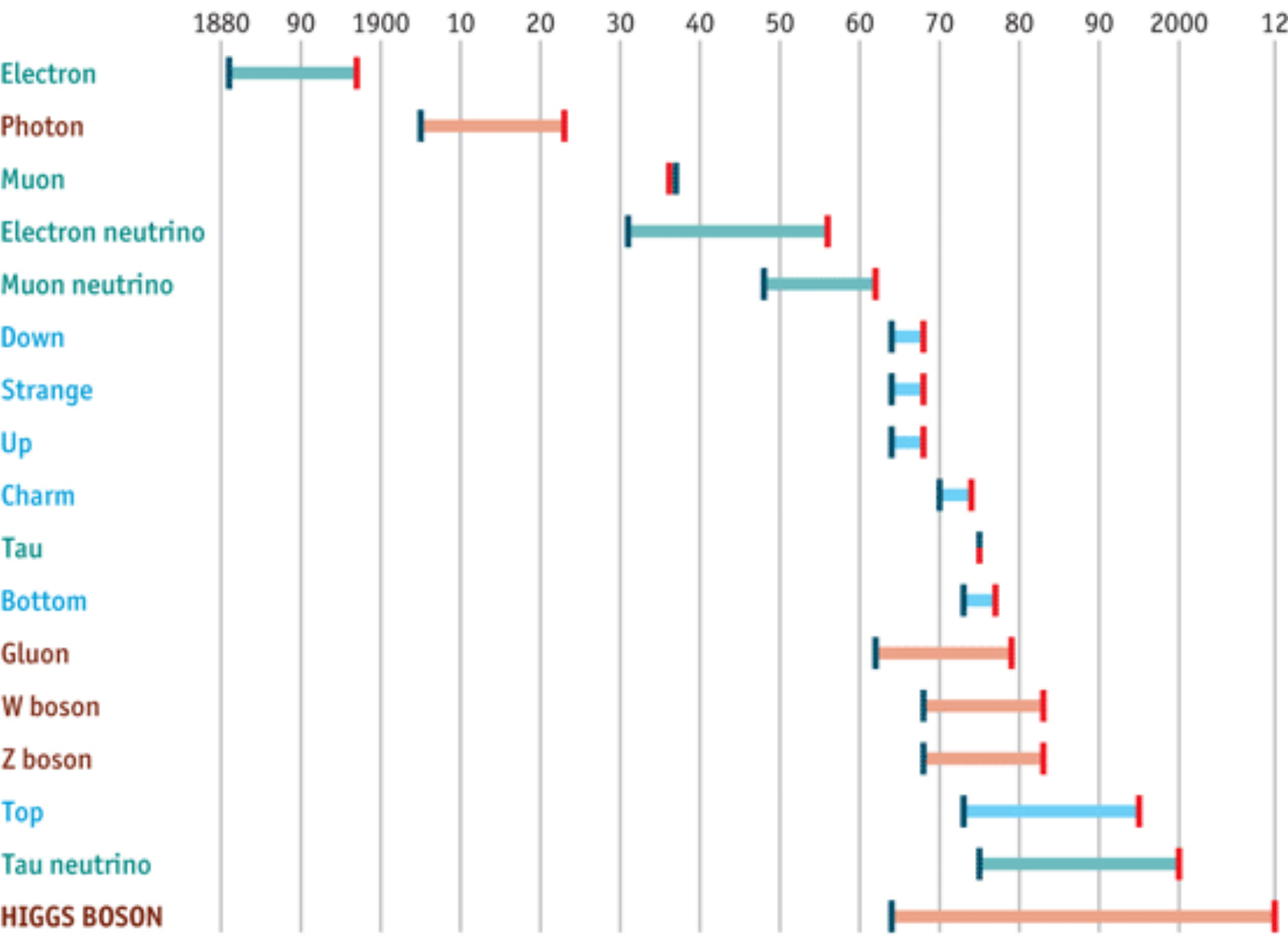
Leptons

Bosons

Quarks

Theorised/explained

Discovered



Source: *The Economist*

Standard Model

QUARK	up	u	charm	c	top	t
						
	down	d	strange	s	beauty	b
						

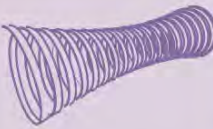
carica elettrica $2/3$

carica elettrica $-1/3$

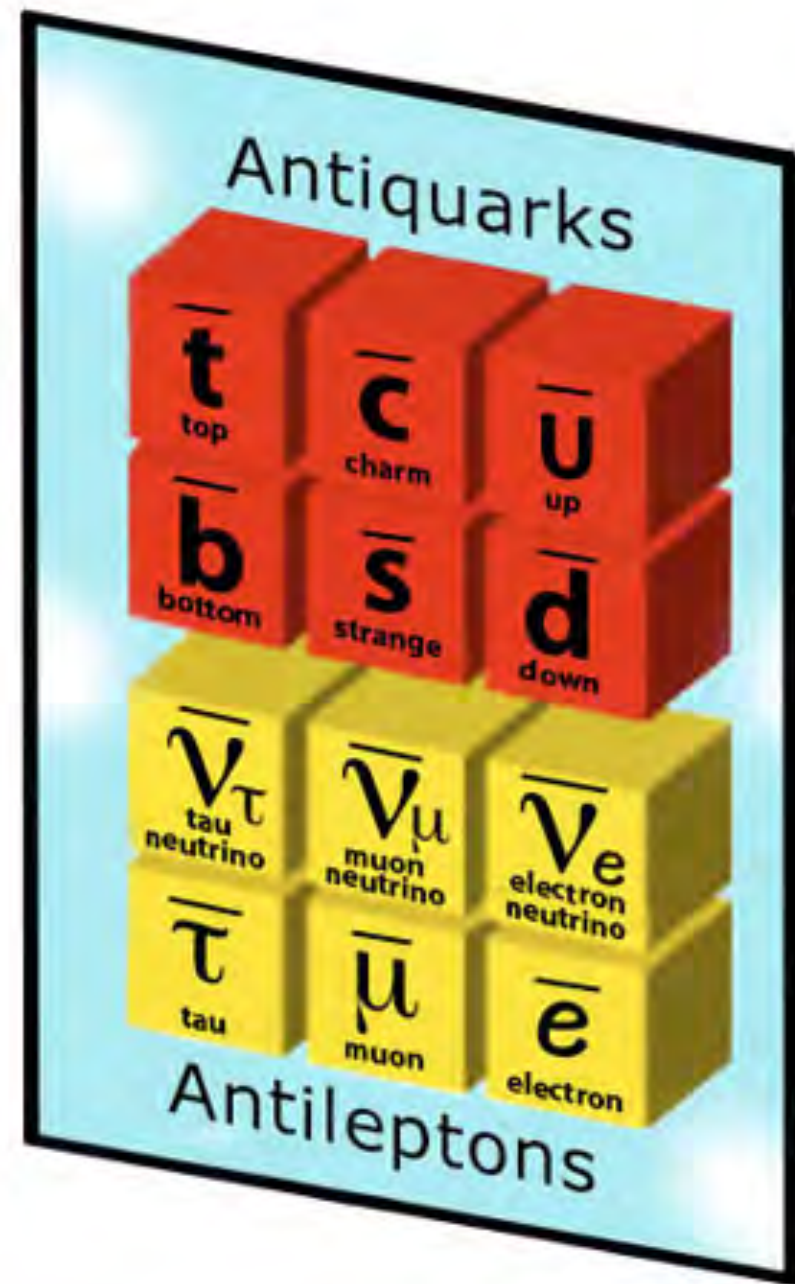
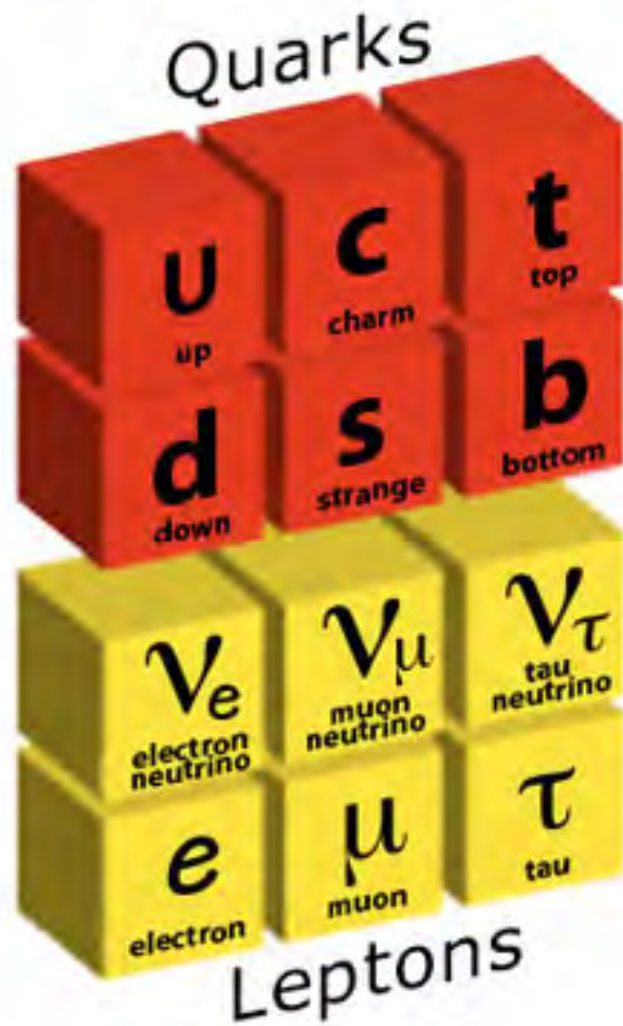
LEPTONI	ν_e	ν_μ	ν_τ
			
	e	μ	τ
			

carica elettrica 0

carica elettrica -1

MEDIATORI	gluone	g
		
	fotone	γ
		
	bosone W	$W^\pm$
		
	bosone Z	Z
		



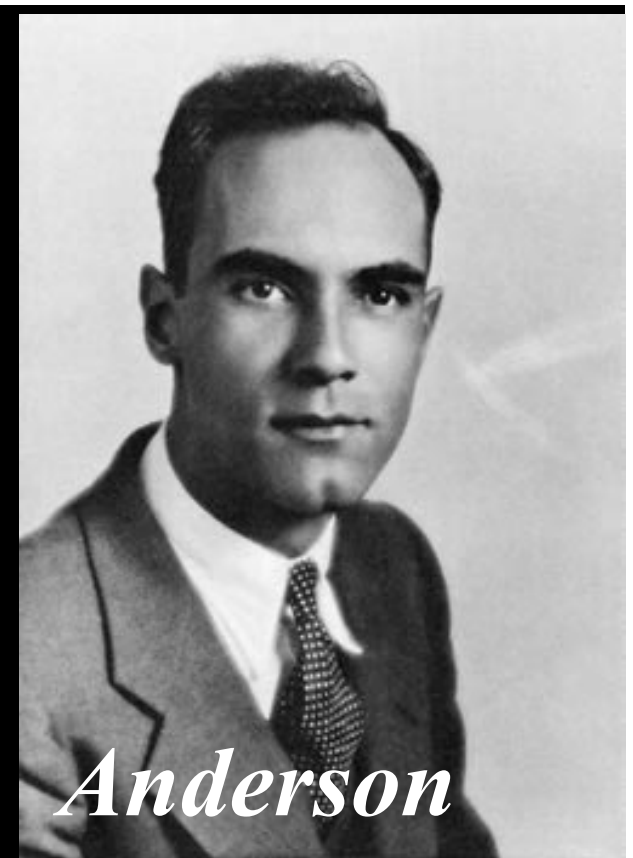




Dirac

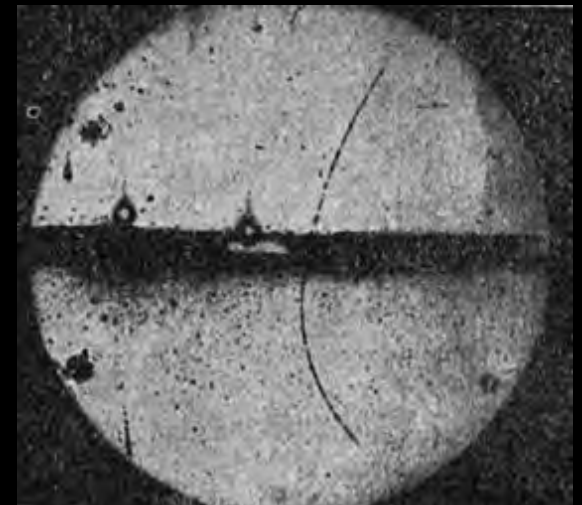
Antimateria

$$x^2 = 4$$

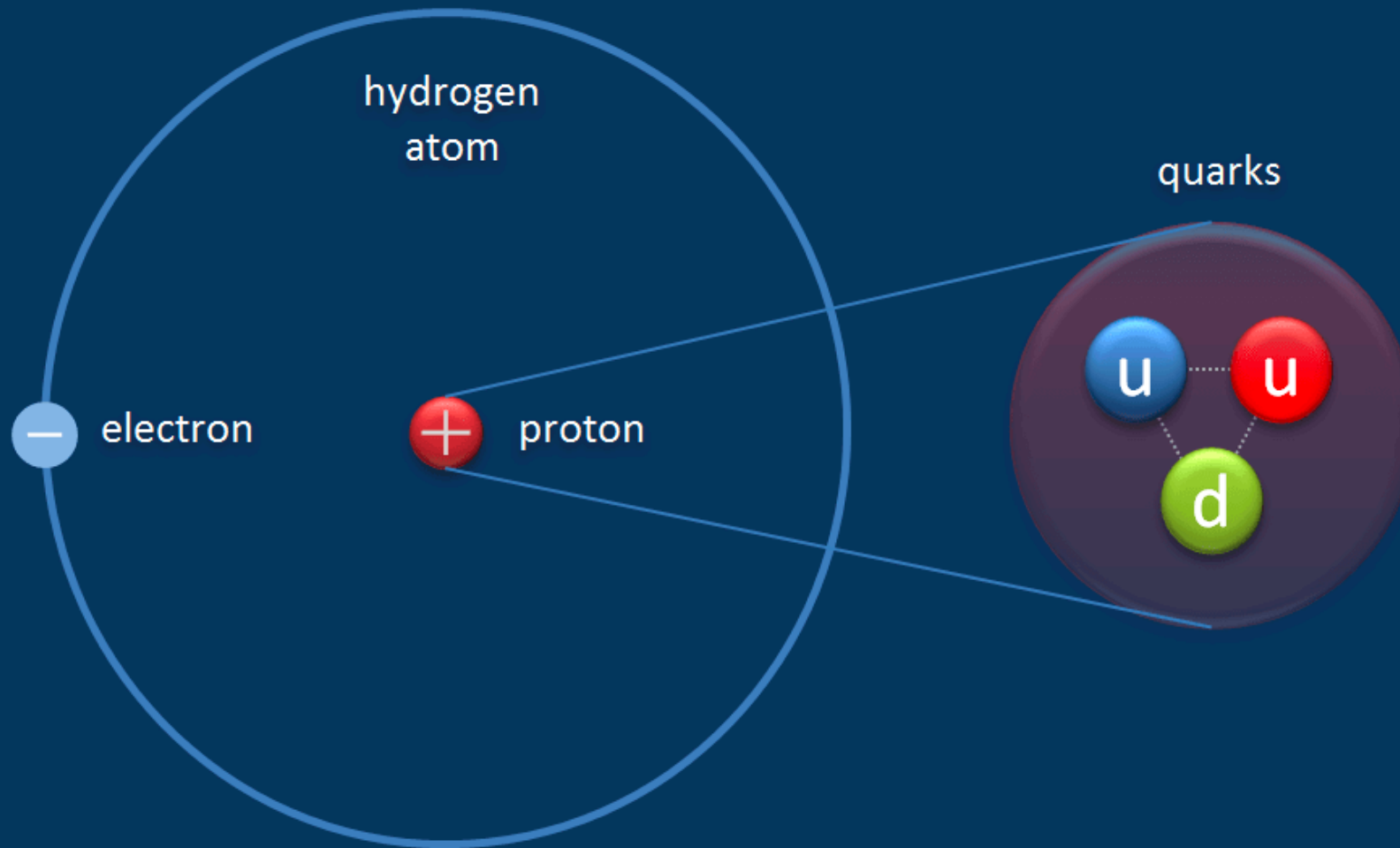


Anderson

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

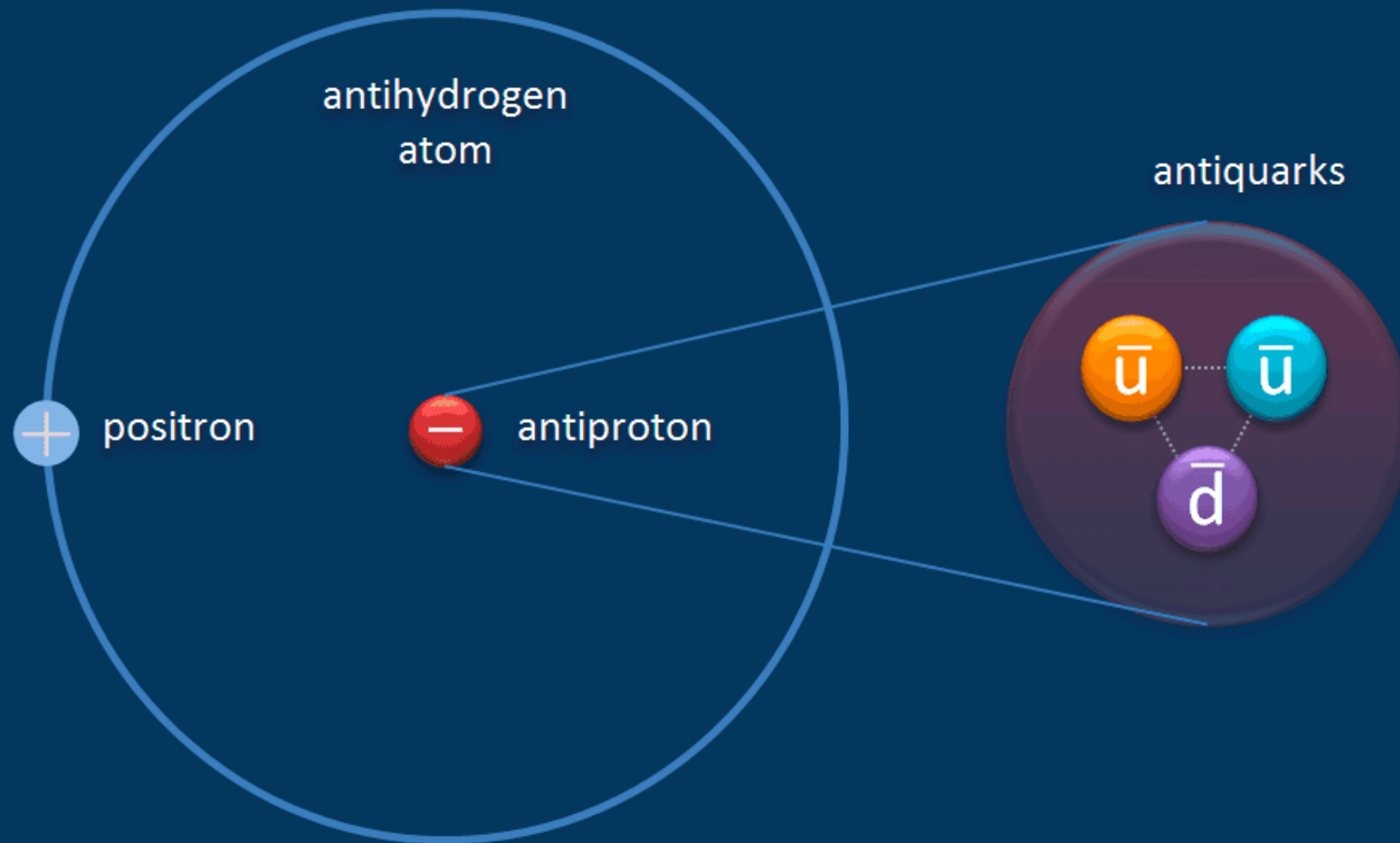


Matter



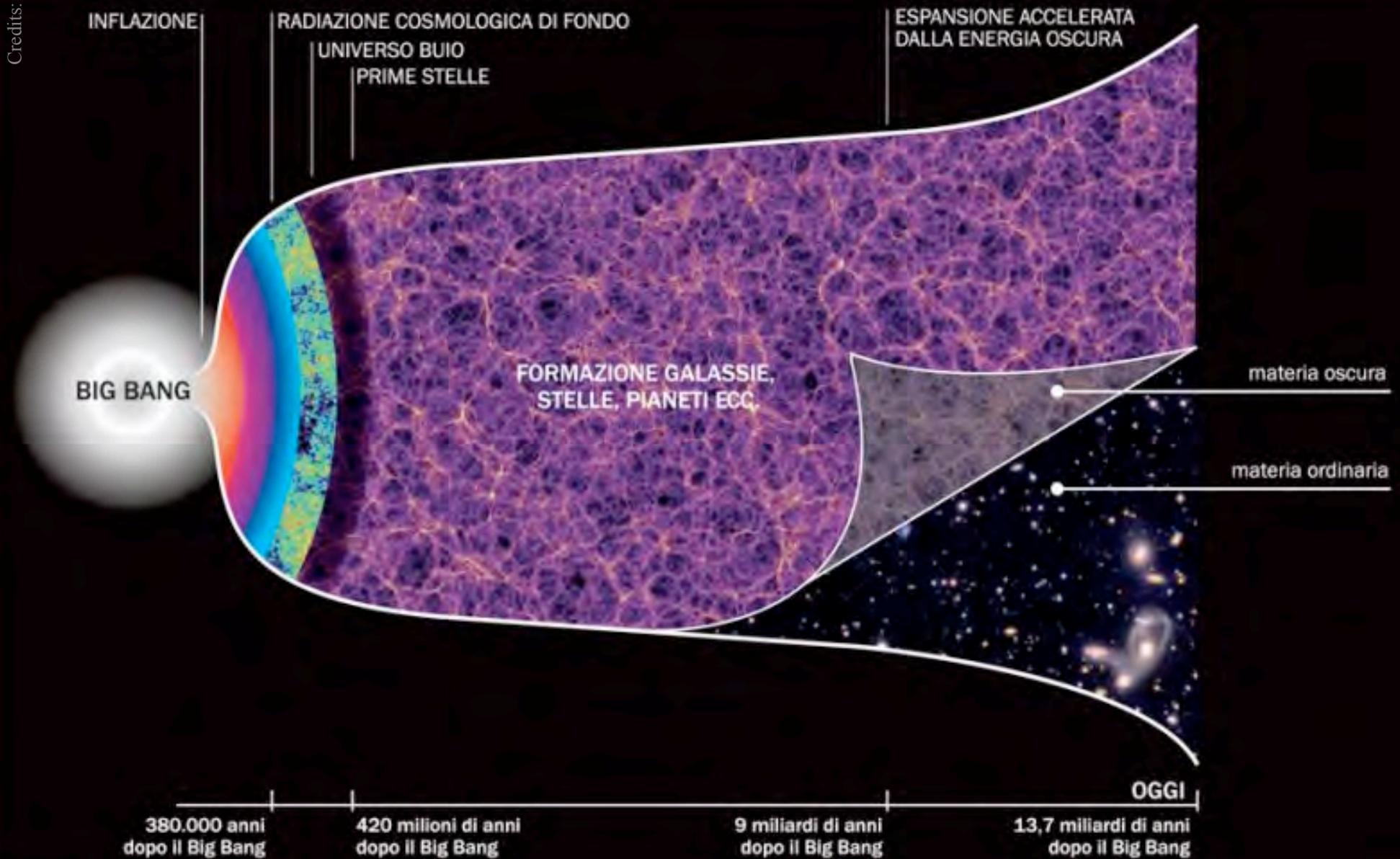
www.nuclear-power.net

Antimatter



www.nuclear-power.net

Modello Standard Cosmologico



Andrei Sakharov

[Christian Hirou/Gamma-Rapho, via Getty Images]



- Barbara Sciascia (INFN/LNF) -

Le condizioni di Sakharov

[proposte nel 1967]



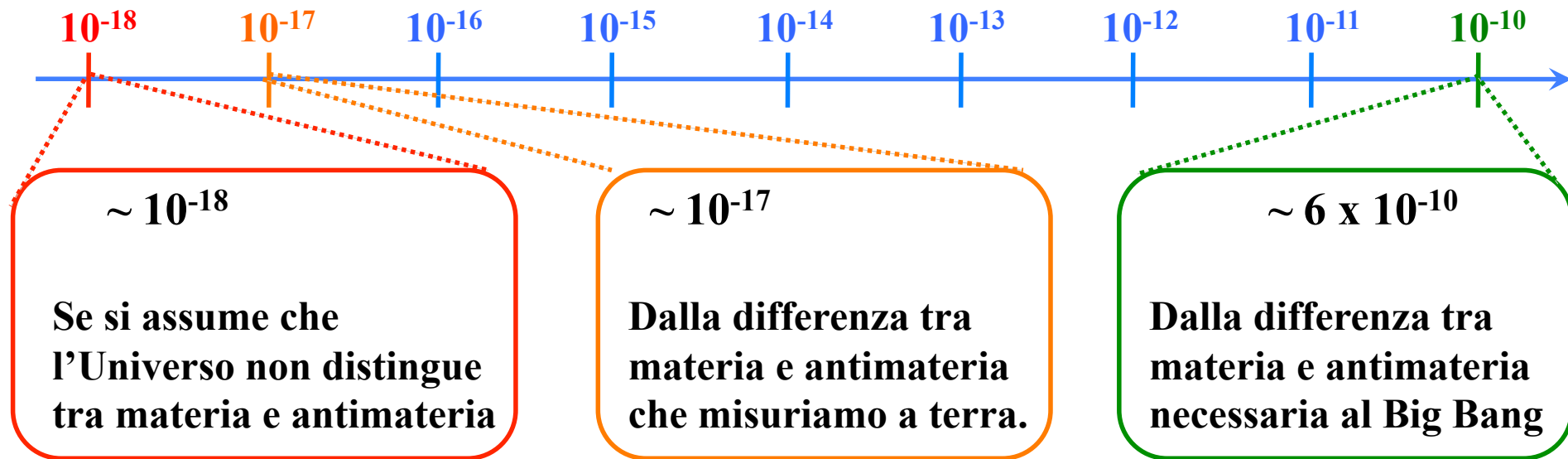
Necessary for evolution of matter-dominated universe, from symmetric state

(1) baryon number violation

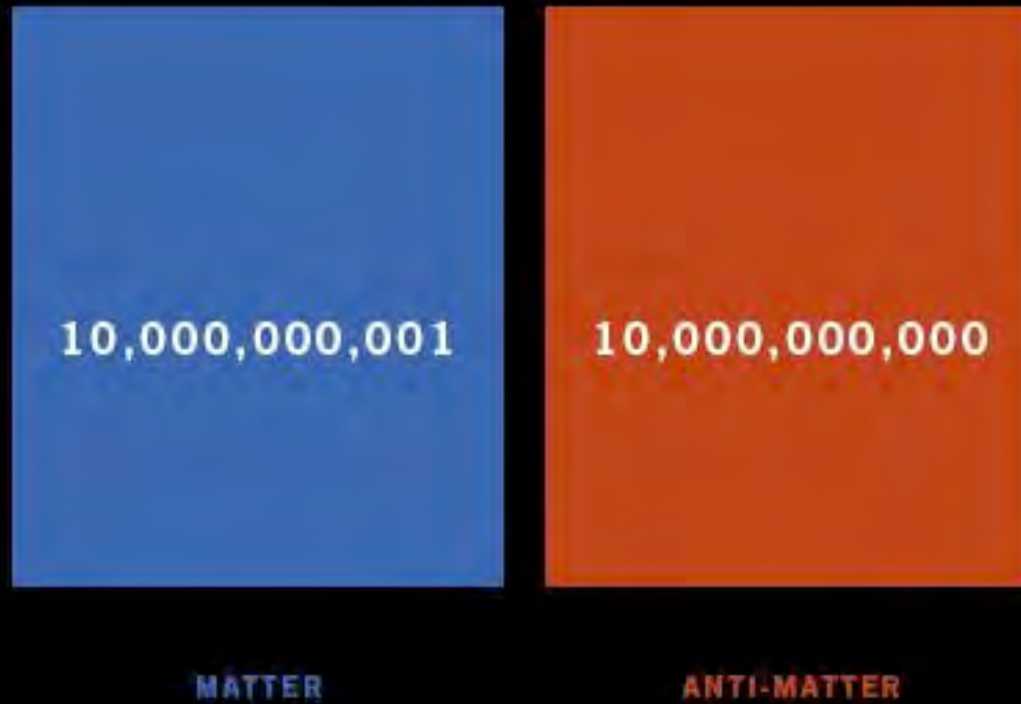
(2) C and CP violation

(3) thermal inequilibrium

“Deve esserci una differenza tra materia e antimateria”



Materia e Antimateria



Credits: Hitoshi Murayama

Materia e Antimateria

US

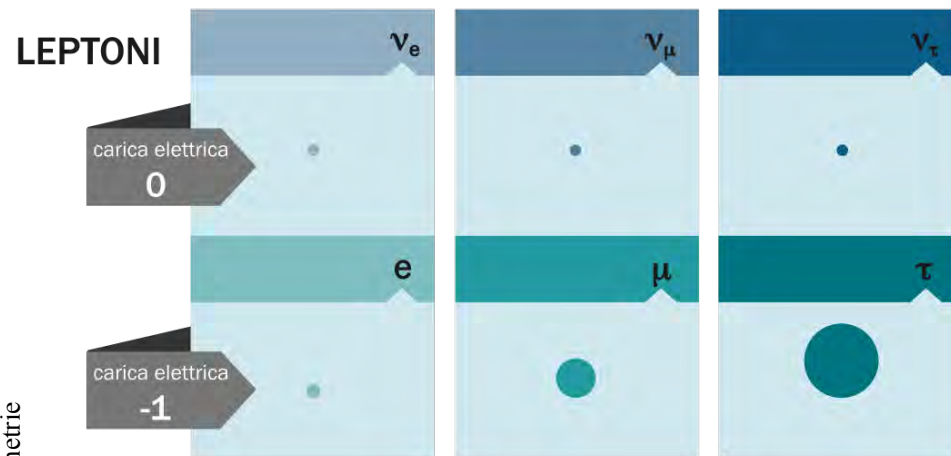
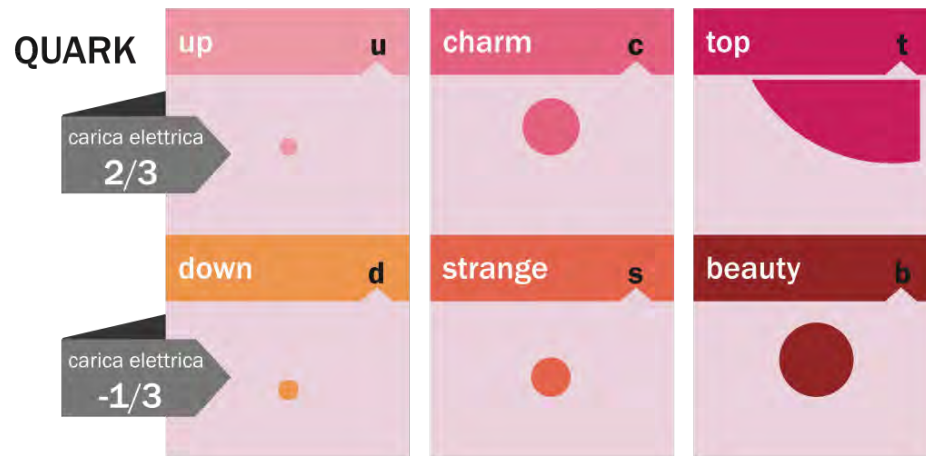
1

MATTER

ANTI-MATTER

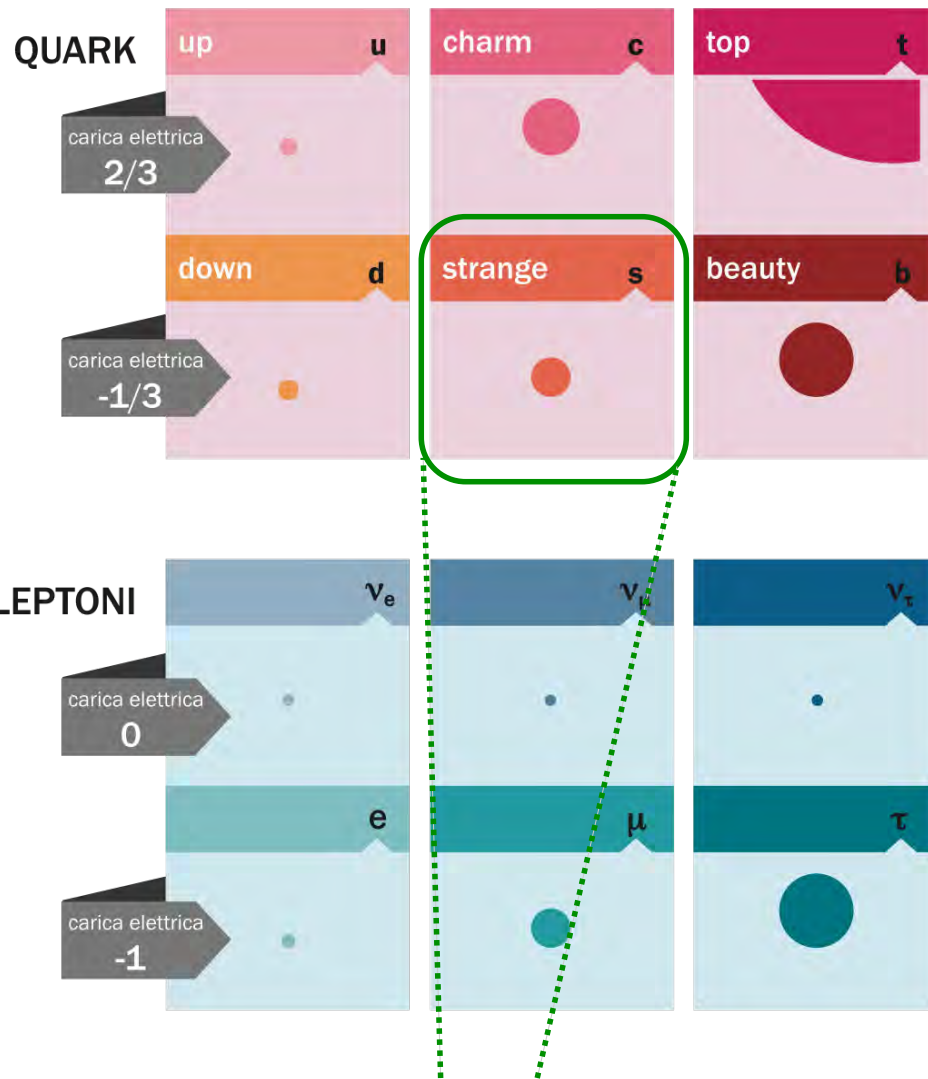
Credits: Hitoshi Murayama

Differenza tra materia e antimateria

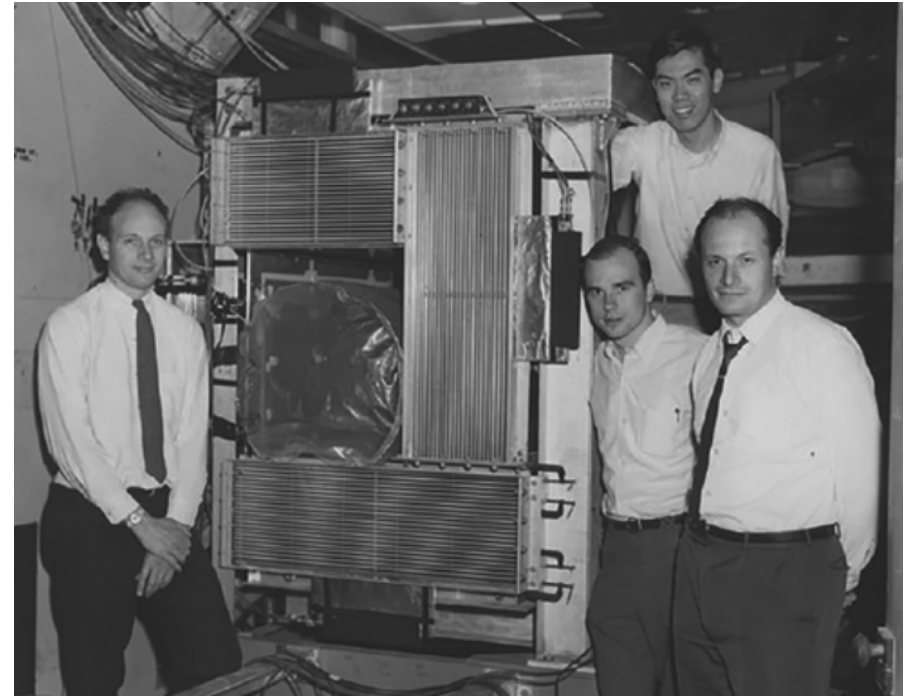


Credits: Asimmetrie

Differenza tra materia e antimateria



1964



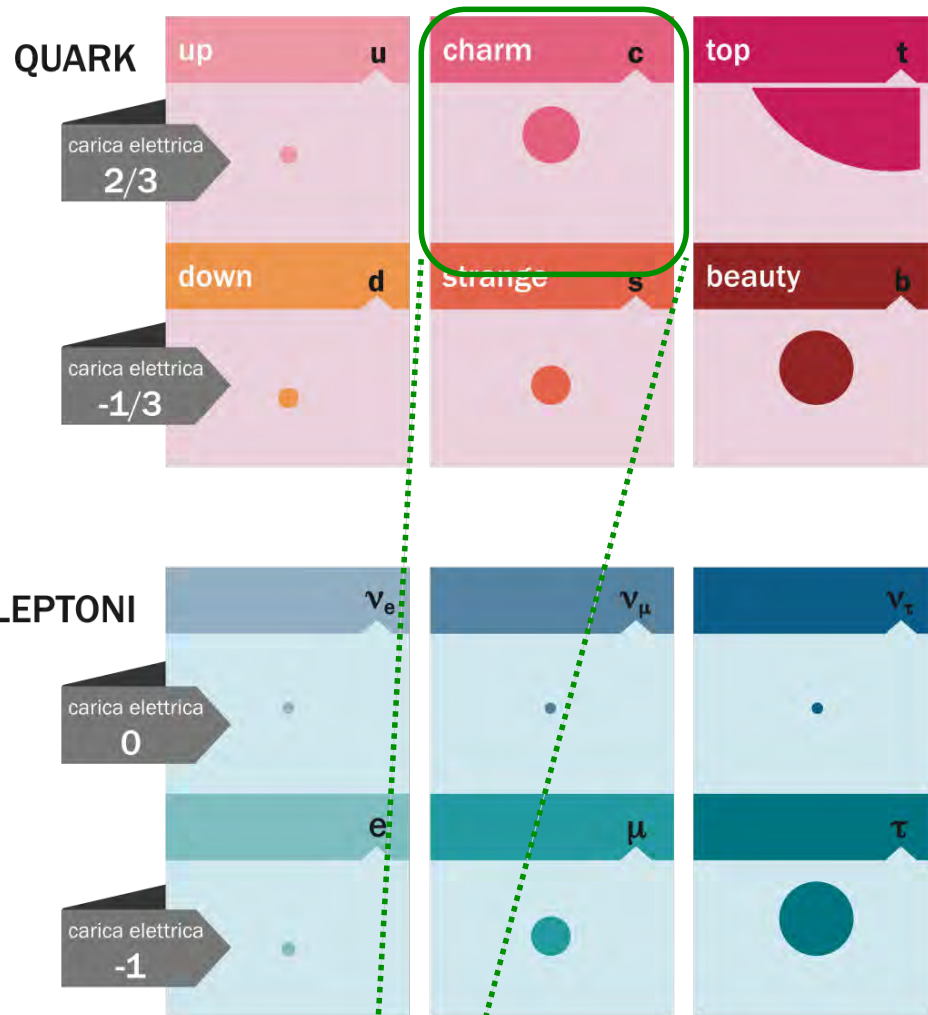
Differenza tra materia e antimateria

QUARK	up u	charm c	top t
	carica elettrica 2/3		
	down d	strange s	beauty b
	carica elettrica -1/3		
LEPTONI	ν_e	ν_μ	ν_τ
	carica elettrica 0		
	e	μ	τ
	carica elettrica -1		



2001

Differenza tra materia e antimateria



[Credits: Maximilien Brice et al./CERN]

2019

Credits: Asimmetrie

Differenza tra materia e antimateria

QUARK

up	u	charm	c	top	t
carica elettrica 2/3					
down	d	strange	s	beauty	b
carica elettrica -1/3					

LEPTONI

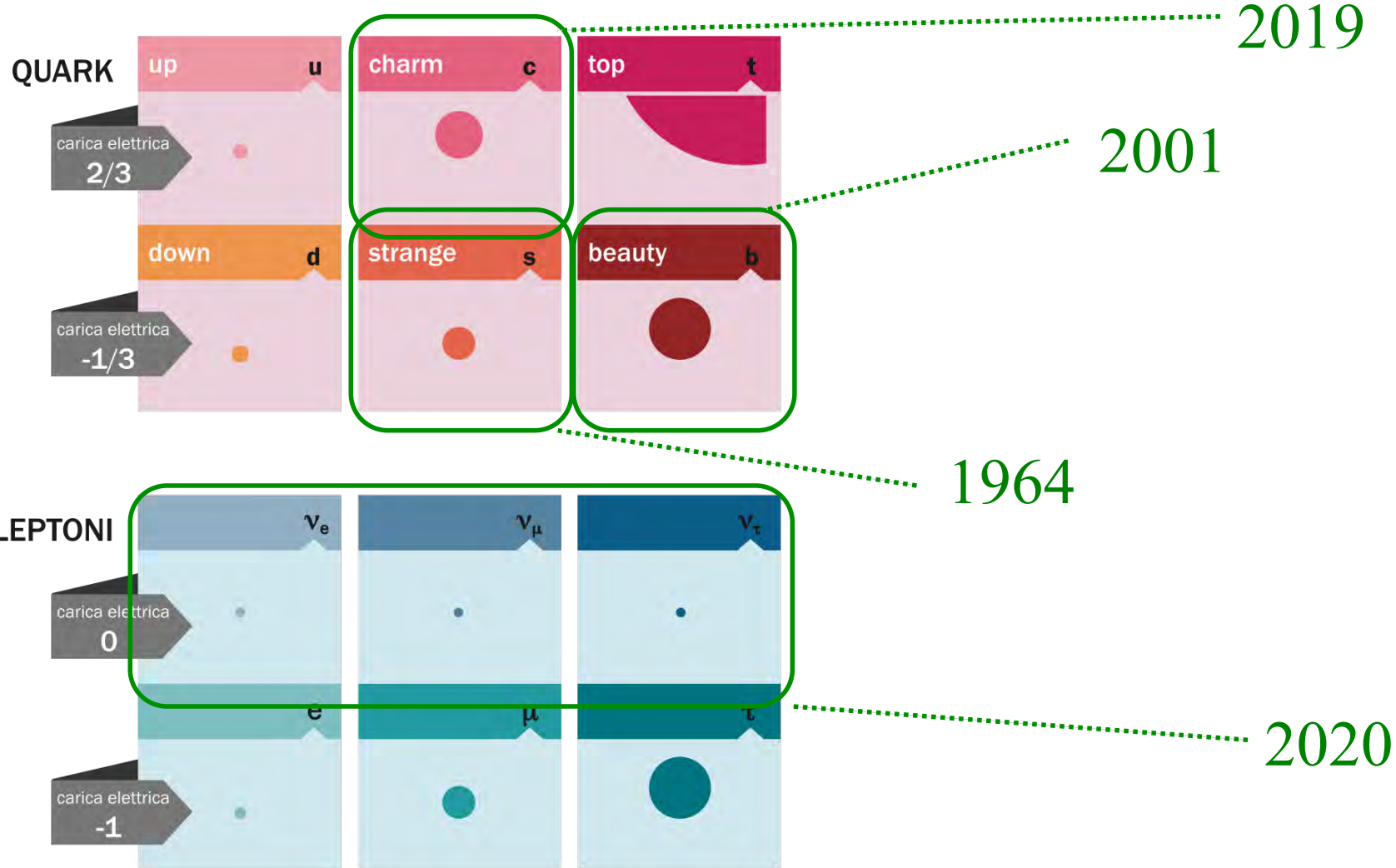
ν_e	ν_μ	ν_τ
carica elettrica 0		
e	μ	τ
carica elettrica -1		



[Enrico Sacchetti/Science Source]

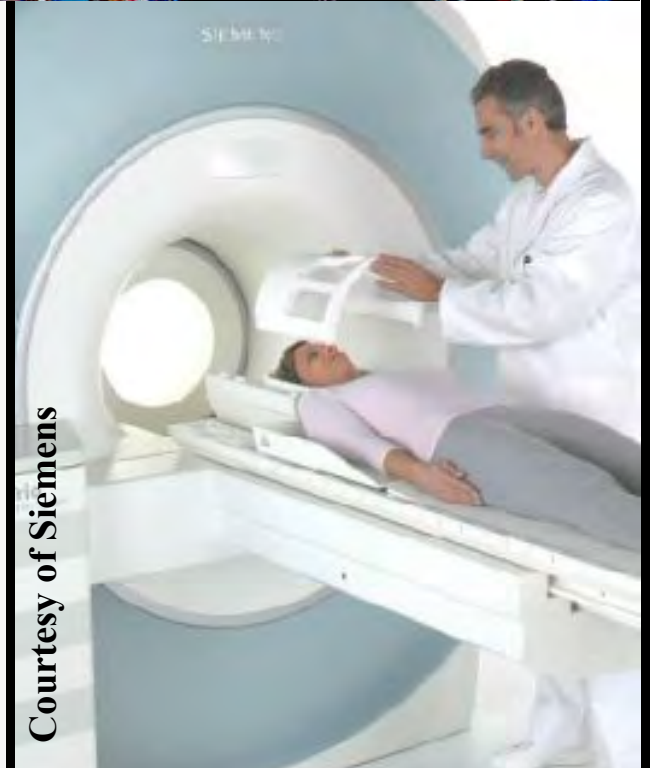
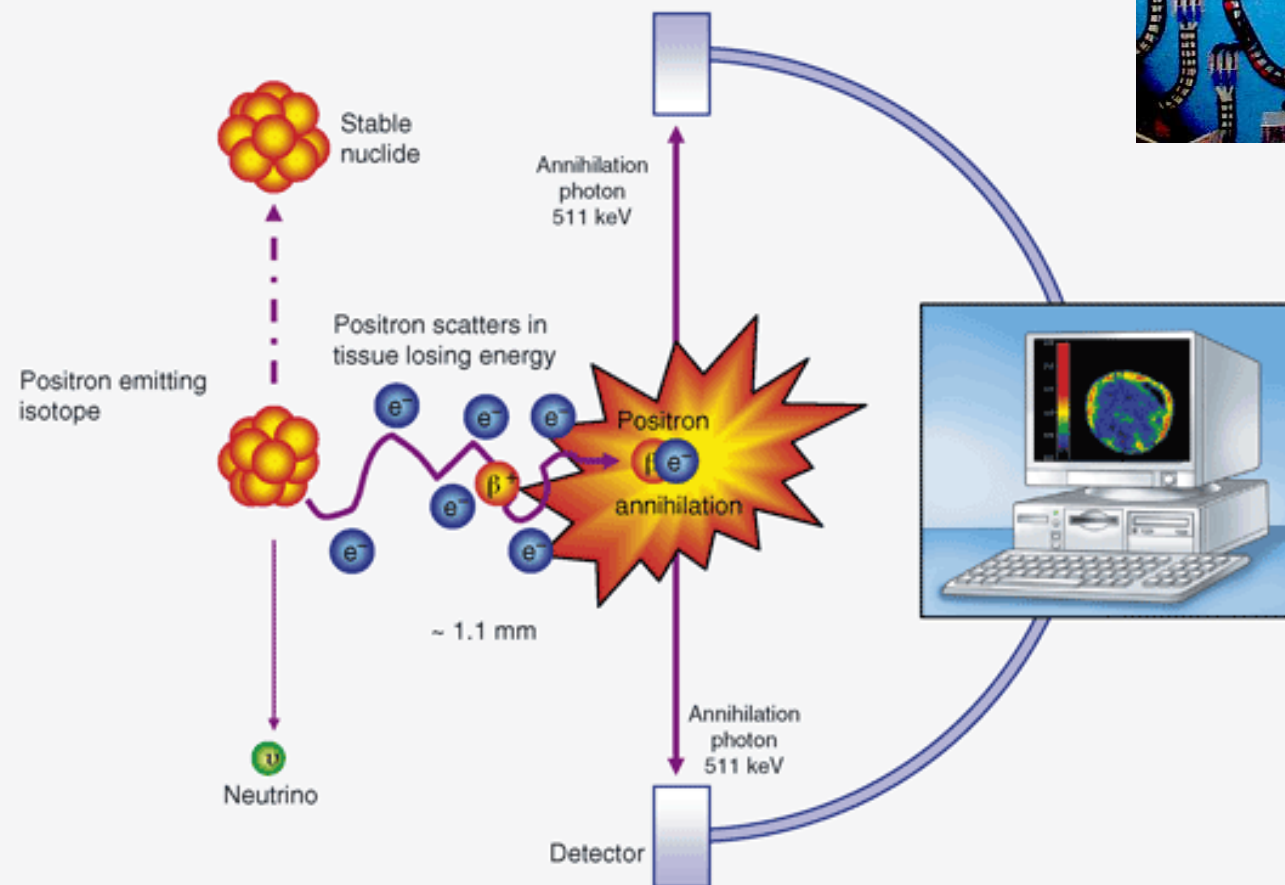
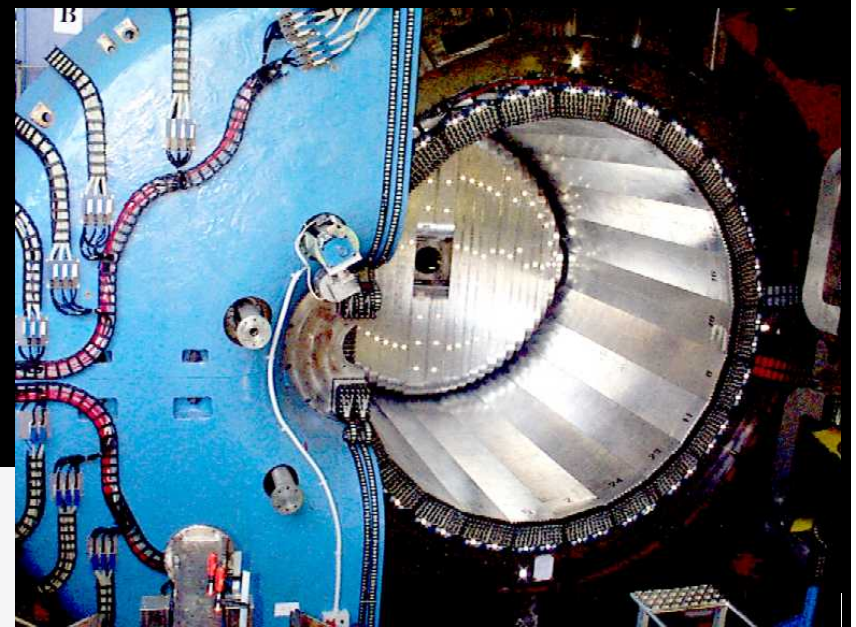
2020

Differenza tra materia e antimateria



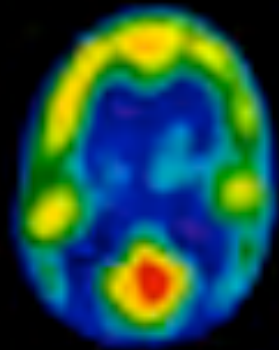
Credits: Asimmetrie

PET

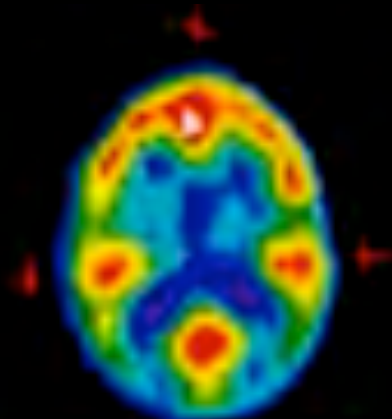


Courtesy of Siemens

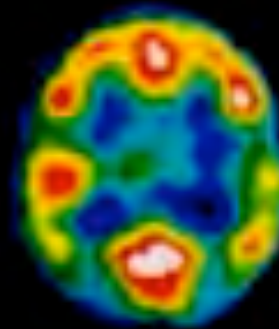
PET



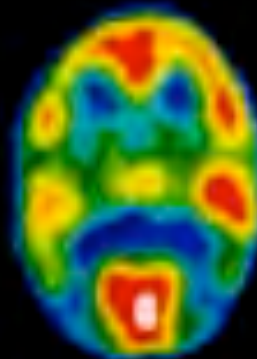
RESTING STATE



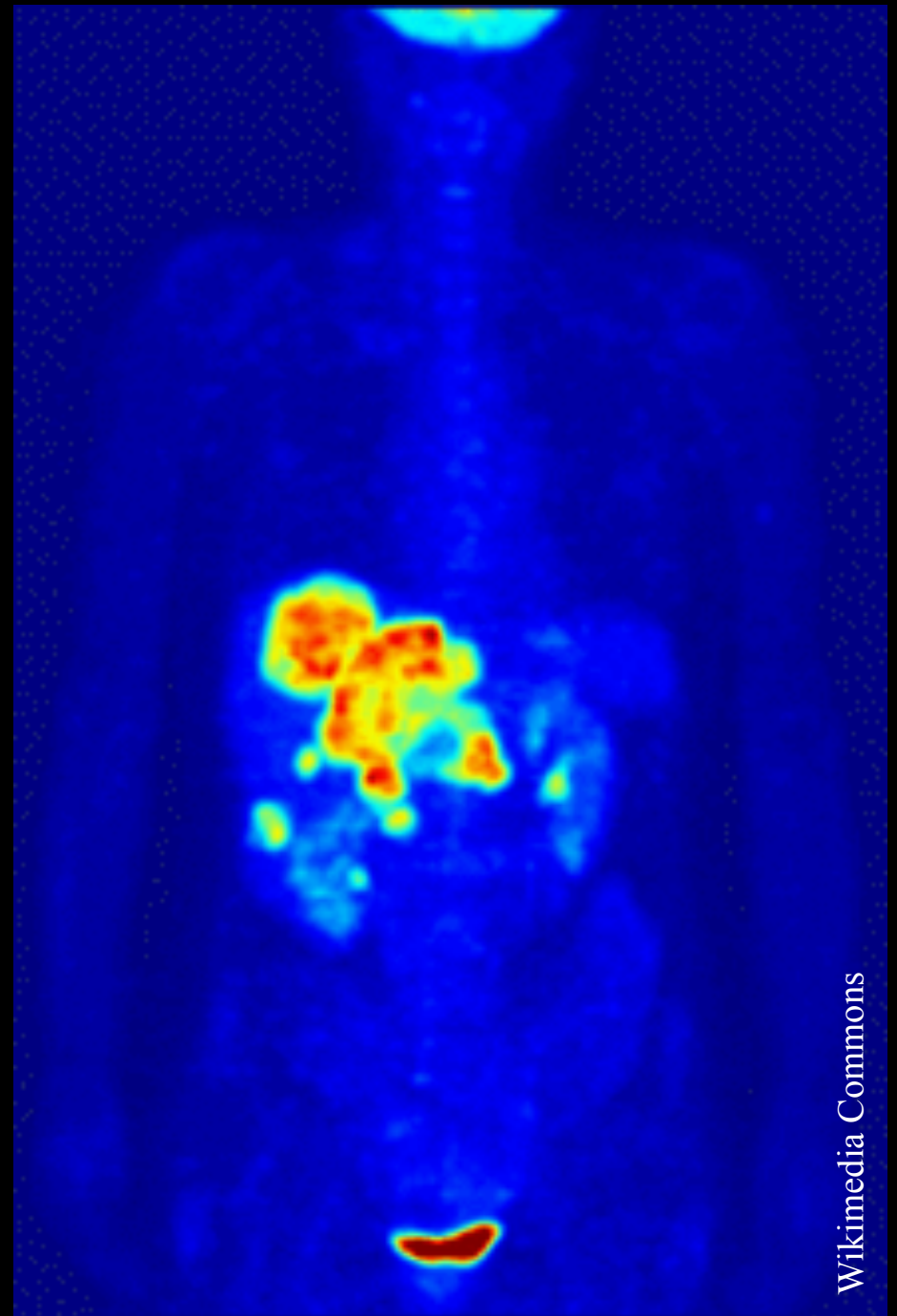
LANGUAGE AND MUSIC



LANGUAGE



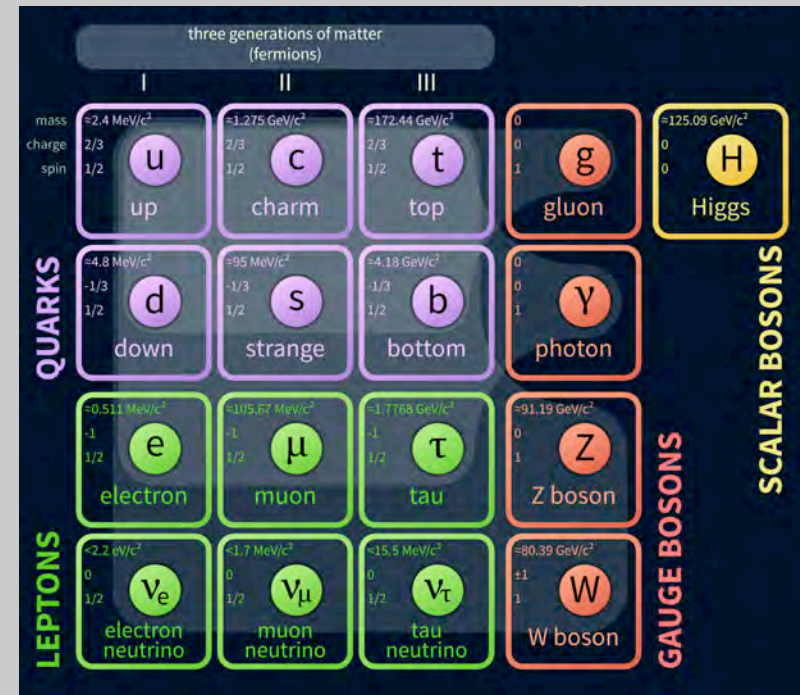
MUSIC



Wikimedia Commons

Open points: SM (and beyond)

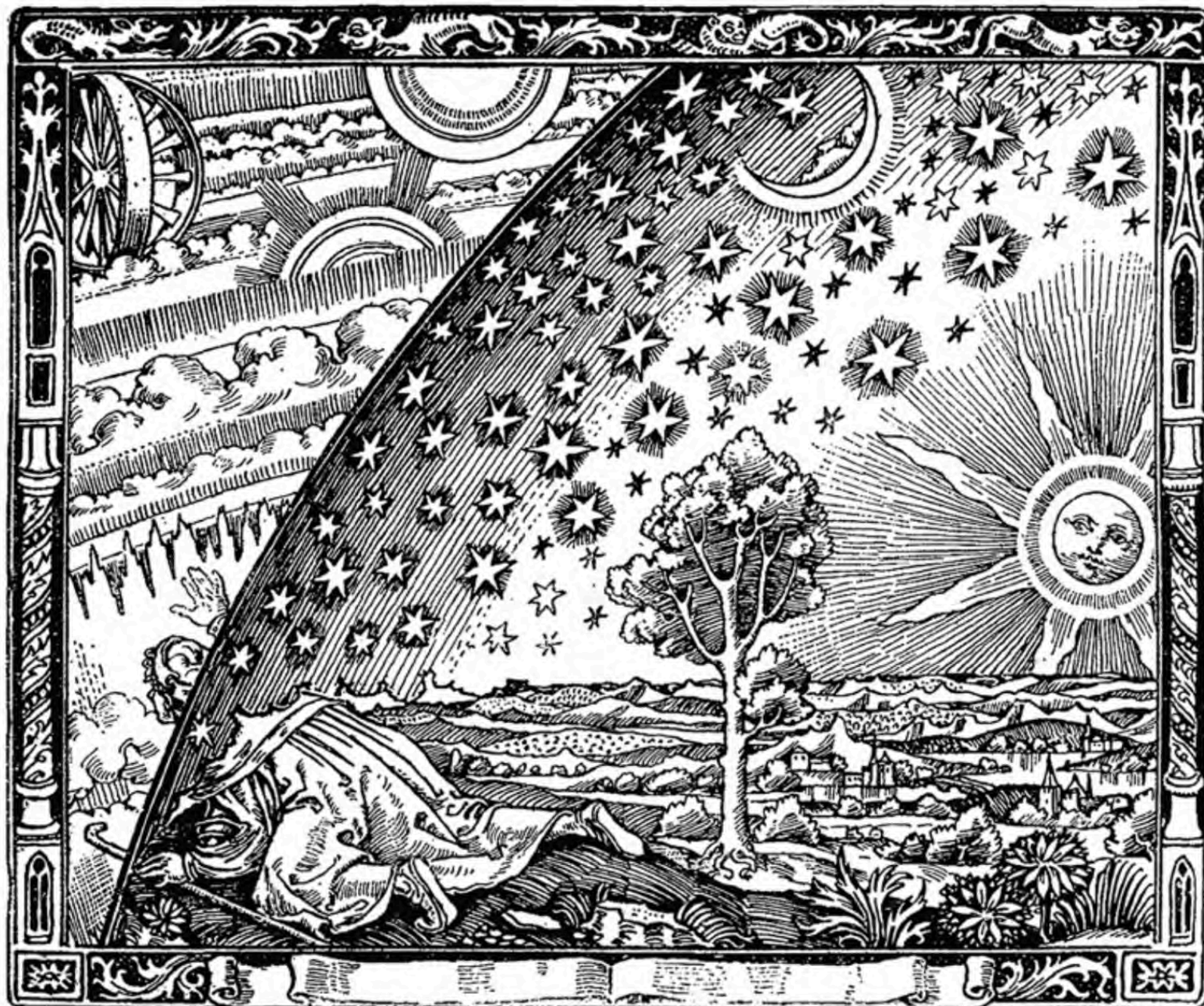
- No explanation for the quark hierarchy
- Why are there 3 families/generations?
- No real explanation for CP violation
- Why it is only found in the weak interaction?
- Mass value of the Higgs boson
- EW and strong unification
- ...



- No explanation for baryogenesis
- Dark matter and dark energy
- Neutrino masses
- Gravity
- ...

By CUSH - Own work - previous version, CC0, <https://commons.wikimedia.org/w/index.php?curid=57404346>

[Urbi et orbi, autore anonimo, xilografia (pubblicato per la prima volta in L'atmosphère: météorologie populaire di Camille Flammarion, Parigi, 1888)]



Approfondimenti

Lezioni e seminari:

- D. Domenici (**Rivelatori di particelle**) e D. Alesini (**Fisica degli acceleratori**)
(<http://edu.lnf.infn.it/ippog-international-masterclass-2019/>)
- Canale YouTube dei LNF
(https://www.youtube.com/channel/UCyi2ABzIOiISreiYPxQ5g_w)

Libri:

- “**L’universo elegante**” di B. Greene, Einaudi
- “**La legge fisica**” di R.P.Feynman, Adelphi
- “**I primi tre minuti**” di S. Weinberg, Mondadori.
- “**Particelle familiari**” di M. Delmastro, Laterza

Asimmetrie, rivista semestrale dell’INFN

(www.asimmetrie.it) in particolare AS6 [acceleratori], AS7 [antimateria], AS8 [bosone di Higgs], AS11 [simmetrie], AS14 [massa], AS16 [1964], AS18 [#NuovaFisica]

Il modello standard:

“**CERN and the rise of the Standard Model**”

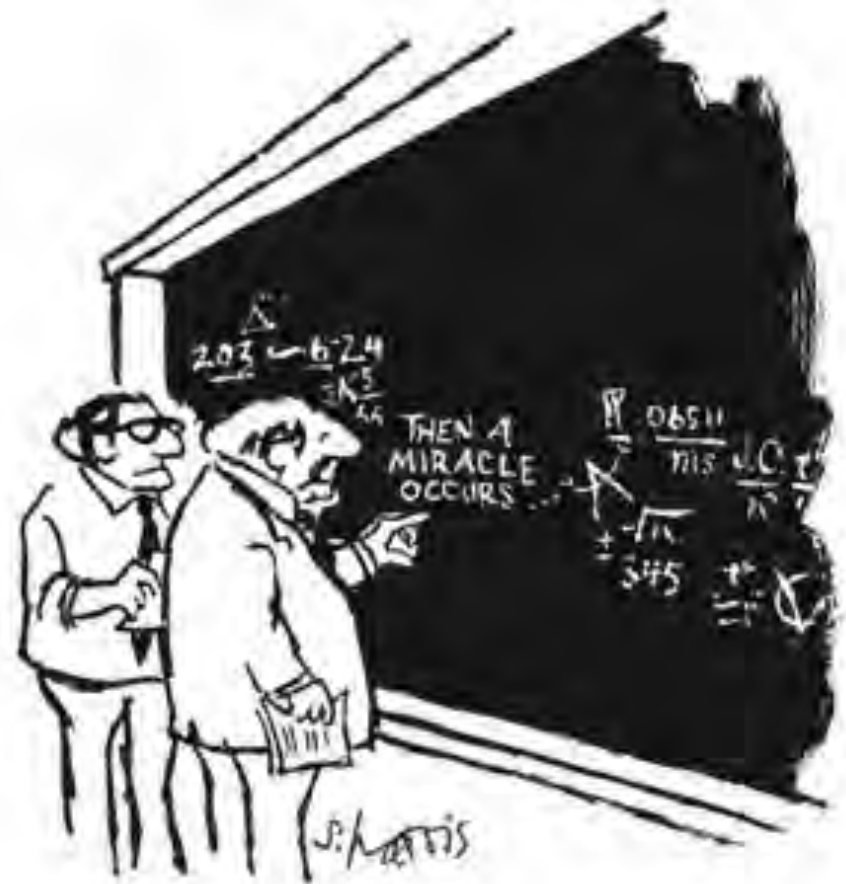
<https://videos.cern.ch/record/1950520>

“**La langrangiana del modello standard**” [didattico, EN]:

https://indico.cern.ch/event/803074/attachments/1832320/3001970/PED_52_034001.pdf

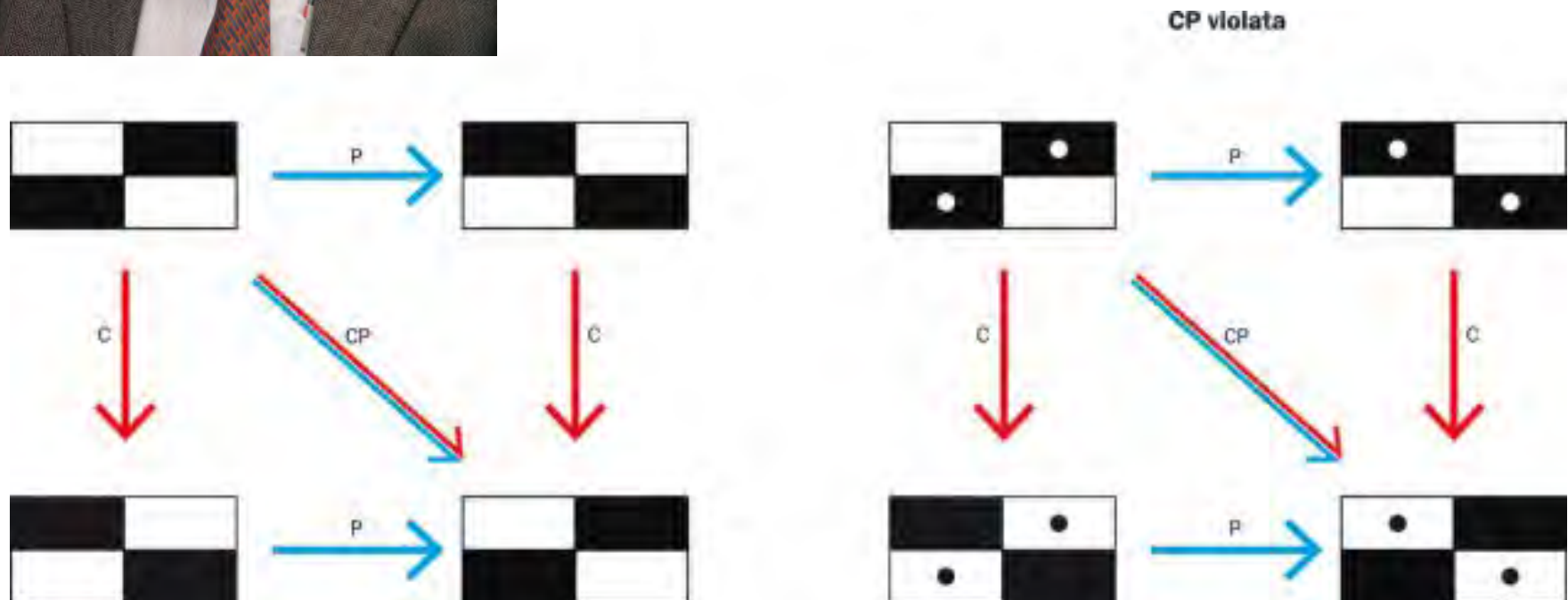


Back up



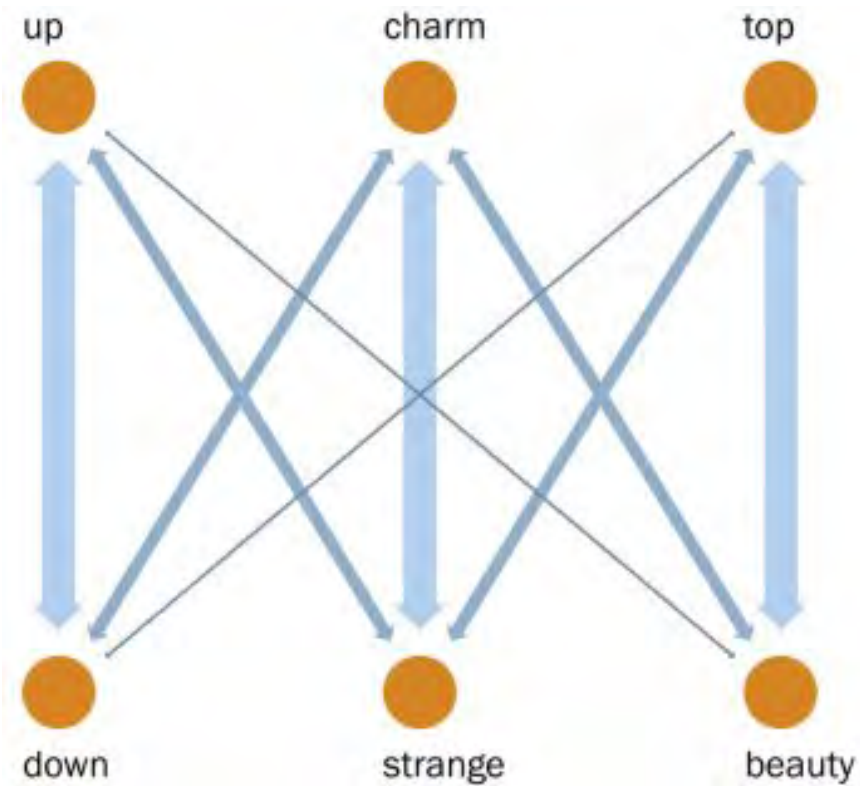
"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Specchi imperfetti



Credits: Asimmetrie

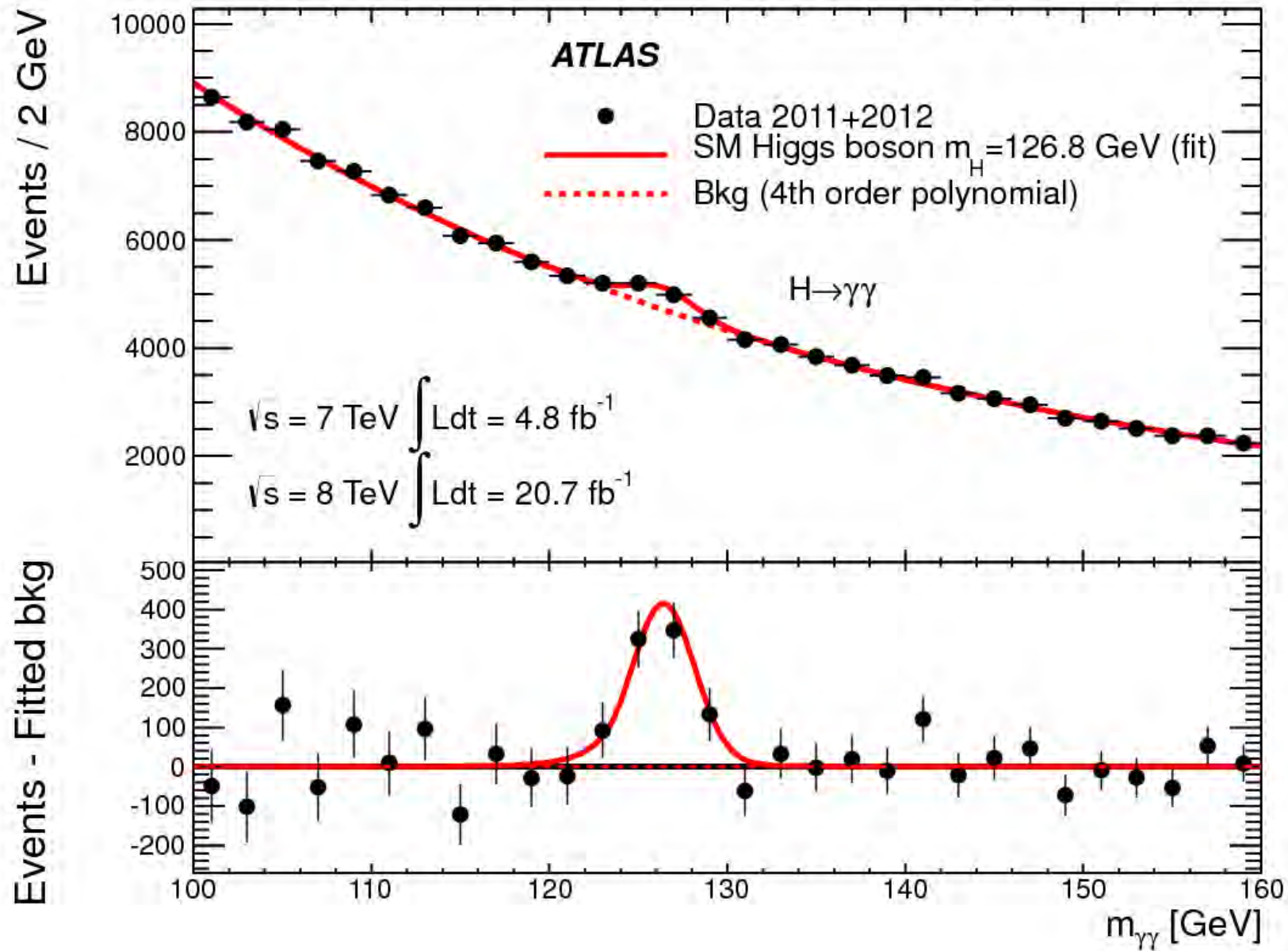
Matrice CKM



$$\begin{pmatrix} d^I \\ s^I \\ b^I \end{pmatrix}_{\text{Weak}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}_{\text{CKM}} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{\text{Mass \& Flavour}}$$



Bosone di Higgs



Lagrangiana

Courtesy of T.D. Gutierrez

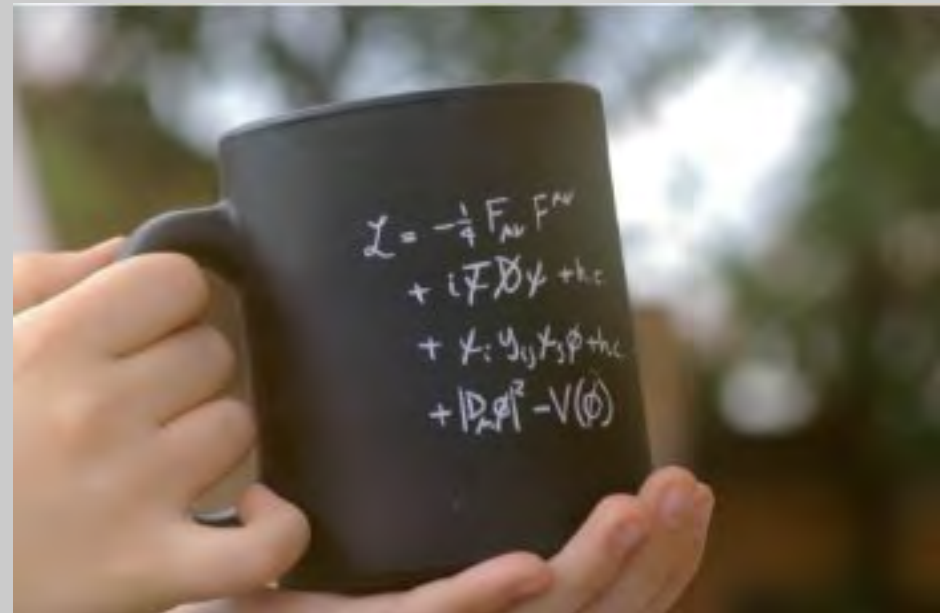
$$\begin{aligned}
 & \frac{1}{2} \partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4} g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e + \\
 & \frac{1}{2} i g_s^2 (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
 & \frac{1}{2} M^2 W_\mu^+ W_\mu^- - \frac{1}{2} \partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2 c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2} \partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2} \partial_\mu H \partial_\mu H - \\
 & \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2} \partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2 c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2 M^2}{g^2} + \right. \\
 & \left. \frac{2 M}{g} H + \frac{1}{2} (H^2 + \phi^0 \phi^0 + 2 \phi^+ \phi^-) \right] + \frac{2 M^4}{g^2} \alpha_h - i g c_w [\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^+ \partial_\nu W_\mu^-) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - \\
 & W_\nu^+ \partial_\mu W_\mu^-) - i g s_w [\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - \\
 & W_\nu^+ \partial_\mu W_\mu^-) + A_\mu (W_\nu^+ \partial_\nu W_\mu^- - W_\nu^+ \partial_\mu W_\mu^-)] - \frac{1}{2} g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \\
 & \frac{1}{2} g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + \\
 & g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w [A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
 & W_\nu^+ W_\mu^-) - 2 A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g \alpha [H^3 + H \phi^0 \phi^0 + 2 H \phi^+ \phi^-] - \\
 & \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4 (\phi^+ \phi^-)^2 + 4 (\phi^0)^2 \phi^+ \phi^- + 4 H^2 \phi^+ \phi^- + 2 (\phi^0)^2 H^2] - \\
 & g M W_\mu^+ W_\mu^- H - \frac{1}{2} g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \frac{1}{2} i g [W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - \\
 & W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W_\mu^- (H \partial_\mu \phi^+ - \\
 & \phi^+ \partial_\mu H)] + \frac{1}{2} g \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \\
 & i g s_w M A_\mu (W_\mu^+ \phi^- - W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + \\
 & i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4} g^2 W_\mu^+ W_\mu^- [H^2 + (\phi^0)^2 + 2 \phi^+ \phi^-] - \\
 & \frac{1}{4} g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 [H^2 + (\phi^0)^2 + 2 (2 s_w^2 - 1) \phi^+ \phi^-] - \frac{1}{2} g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
 & W_\mu^- \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2 c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
 & g^1 s_w^2 A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda (\gamma \partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma \partial \nu^\lambda - \bar{u}_j^\lambda (\gamma \partial + m_u^\lambda) u_j^\lambda - \\
 & \bar{d}_j^\lambda (\gamma \partial + m_d^\lambda) d_j^\lambda + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3} (\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3} (\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \\
 & \frac{i g}{4 c_w} Z_\mu^0 [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4 s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3} s_w^2 - \\
 & 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3} s_w^2 - \gamma^5) d_j^\lambda)] + \frac{i g}{2 \sqrt{2}} W_\mu^+ [(\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) e^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{i g}{2 \sqrt{2}} W_\mu^- [(\bar{e}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger \gamma^\mu (1 + \\
 & \gamma^5) u_j^\lambda)] + \frac{i g}{2 \sqrt{2}} \frac{m_\lambda^2}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \\
 & \frac{g}{2} \frac{m_\lambda^2}{M} [H (\bar{e}^\lambda e^\lambda) + i \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{i g}{2 M \sqrt{2}} \phi^+ [-m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + \\
 & m_\lambda^2 (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa)] + \frac{i g}{2 M \sqrt{2}} \phi^- [m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_\lambda^2 (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \\
 & \gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{i g}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \\
 & \frac{i g}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \\
 & \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \\
 & \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \\
 & \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2} g M [\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \\
 & \frac{1-2c_w^2}{2c_w} i g M [\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{1}{2 c_w} i g M [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \\
 & i g M s_w [\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + \frac{1}{2} i g M [\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]
 \end{aligned}$$

1 - Gluoni [mediatori forza forte]

2 - Bosoni W/Z [forza debole]

3 - Interazioni della materia dovute alla forza debole; interazioni con il bosone di Higgs

4 e 5 - “sistemano” i fantasmi di Higgs



Credits: Asimmetrie