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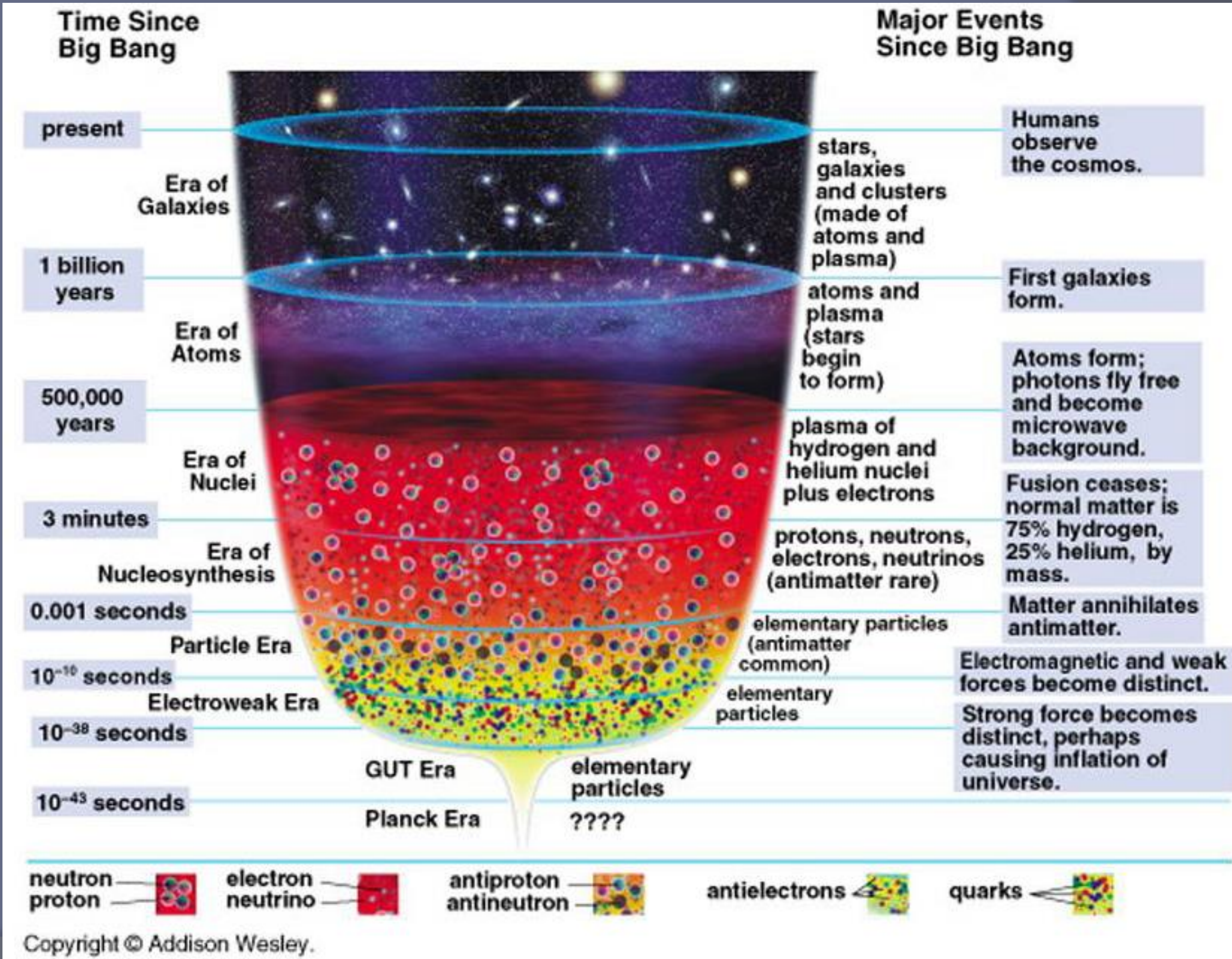
# Introducere în fizica particulelor la energii înalte

**„Romanian High-School Students Internship Programme 2021 "**

8 noiembrie 2021

# Introducere

- Din ce este constituită materia?
- Din ce este compus universul?
- Care este originea universului și cum a evoluat?
- De ce se comportă așa universul?
- Cum va evolua?
- ....


Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
$10^{-10}$ seconds
Electroweak Era
$10^{-38}$ seconds
GUT Era
$10^{-43}$ seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe.
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks
Copyright © Addison Wesley.

# Care sunt elementele din care este constituita materia?


Empedocles 492-432 BC

By convention there is color,
by convention sweetness,
by convention bitterness,
but in reality there are
atoms and space.

Democritus 400 BC

**Periodic Table of the Elements**

| | IA | IIA | IIIB | IVB | VB | VIB | VIIB | VIII | | | IB | IIB | IIIA | IVA | VA | VIA | VIIA | 0 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 Ha | 106 Sg | 107 Ns | 108 Hs | 109 Mt | 110 110 | 111 111 | 112 112 | 113 113 | | | | | |

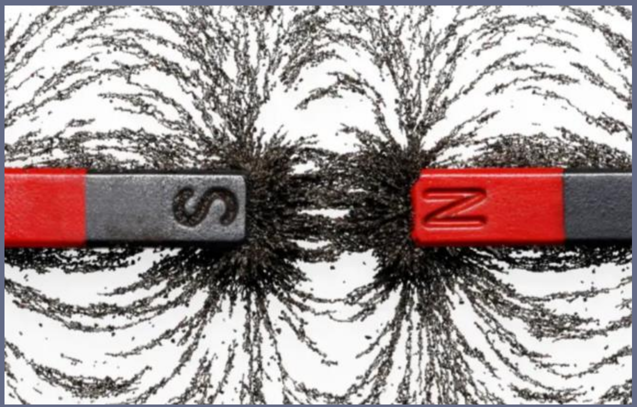
| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| * Lanthanide Series | 58 Ce | 59 Pr | 60 Nd | 61 Pm | 62 Sm | 63 Eu | 64 Gd | 65 Tb | 66 Dy | 67 Ho | 68 Er | 69 Tm | 70 Yb | 71 Lu |
| + Actinide Series | 90 Th | 91 Pa | 92 U | 93 Np | 94 Pu | 95 Am | 96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

Mendeleev, 1869

# Scurt istoric

- **sfârșitul secolului XIX:**
  - **mecanică clasică;**
  - **electromagnetism;**
  - **termodinamică.**

# Electricitate și magnetism




→ electromagnetism

**ecuațiile MAXWELL**

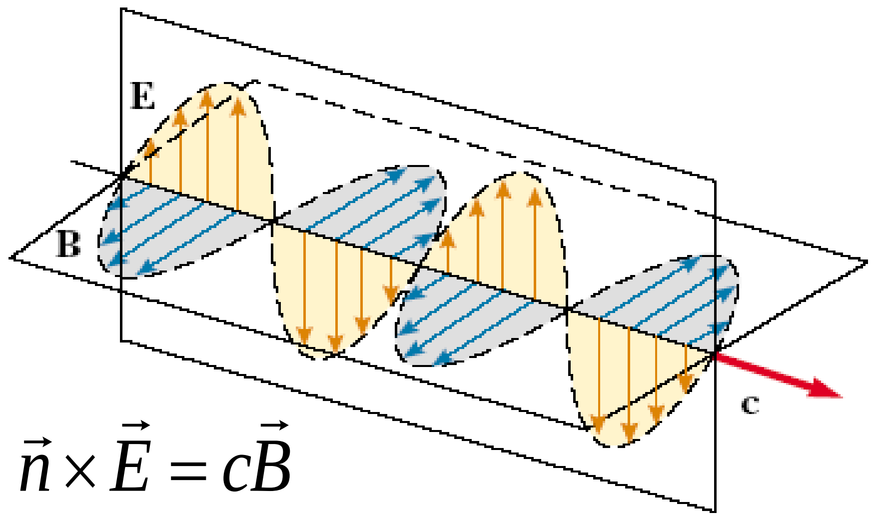
$$div\vec{E} = \frac{\rho}{\varepsilon_0}$$

$$rot\vec{E} = -\frac{\partial\vec{B}}{\partial t}$$

$$div\vec{B} = 0$$

$$rot\vec{B} = \frac{\vec{j}}{\varepsilon_0 c^2} + \frac{1}{c^2}\frac{\partial\vec{E}}{\partial t}$$

# Electromagnetism

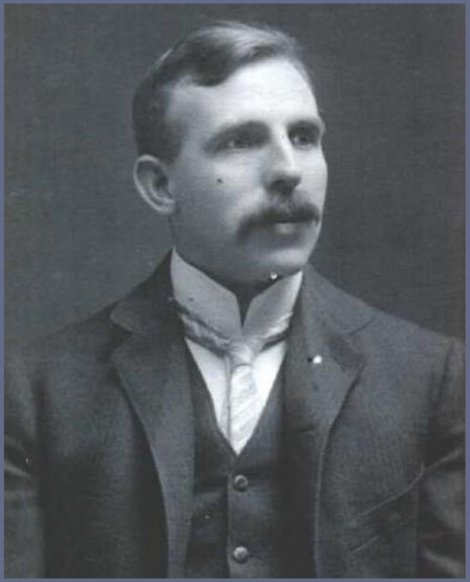


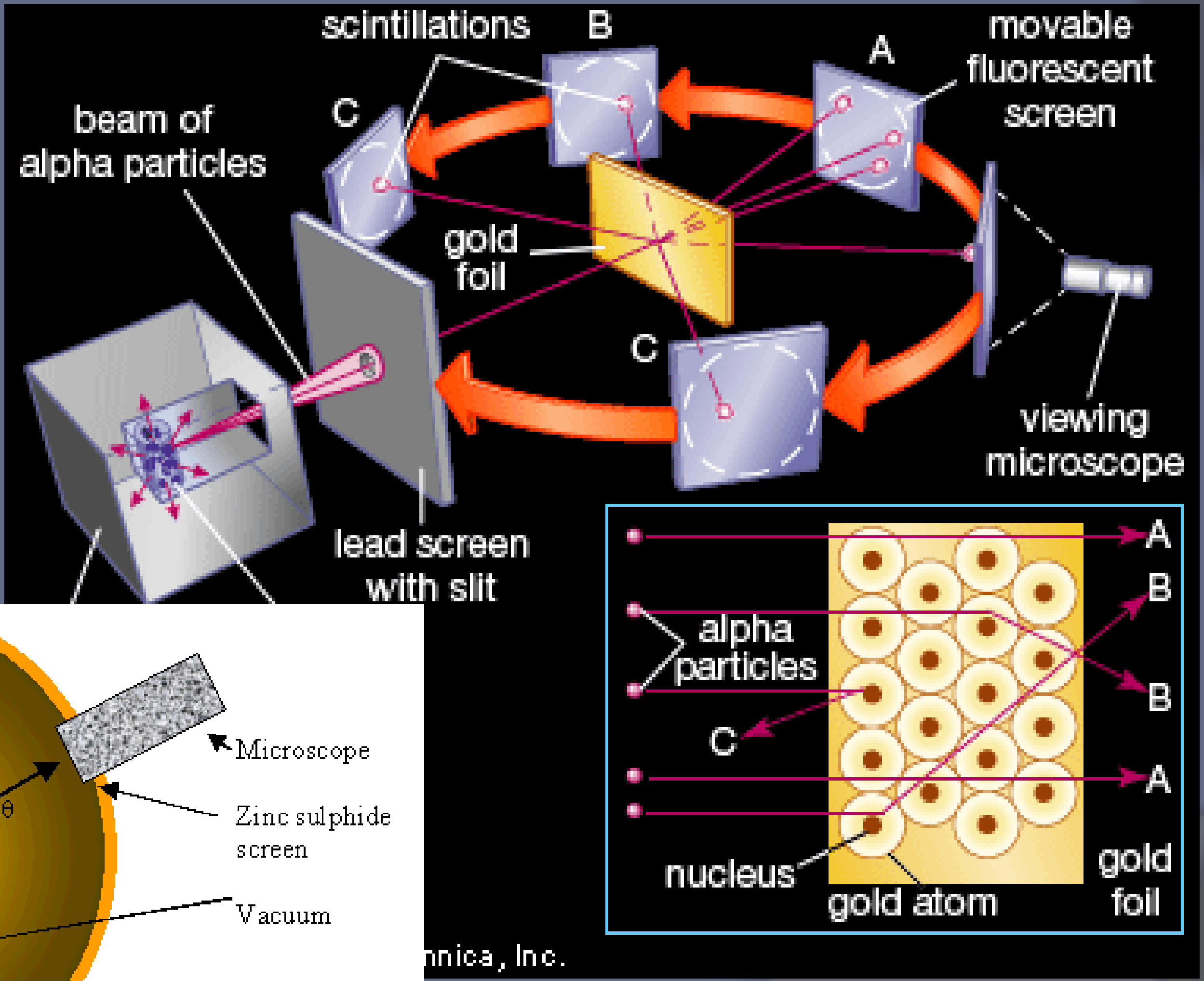

$$\vec{n} \times \vec{E} = c\vec{B}$$

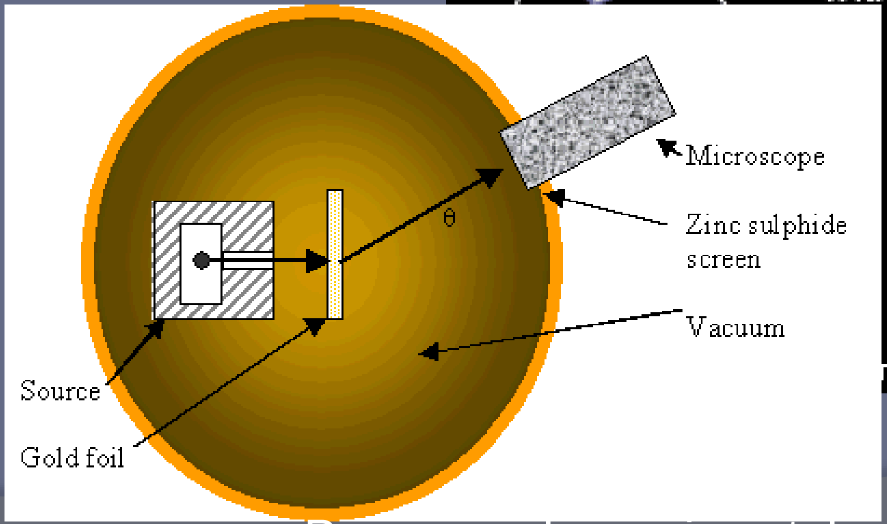
Heinrich Rudolf Hertz

**Confirmare experimentală a existenței undelor electromagnetice (1888)**

# 1911 Rutherford: atomii nu sunt particule elementare!





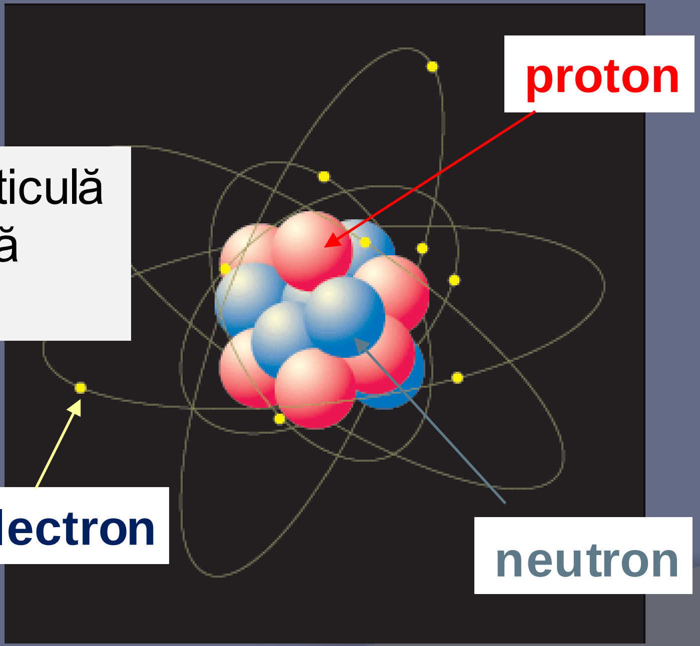




Precursorul experimentelor moderne de împrăștiere.

# Atomii

Atomii:
- protoni și neutroni în nucleu
- electroni

**Electronul -** prima particulă elementară descoperită (J.J. Thomson 1897)




**Sunt protonii și neutronii particule elementare?**

# Provocări

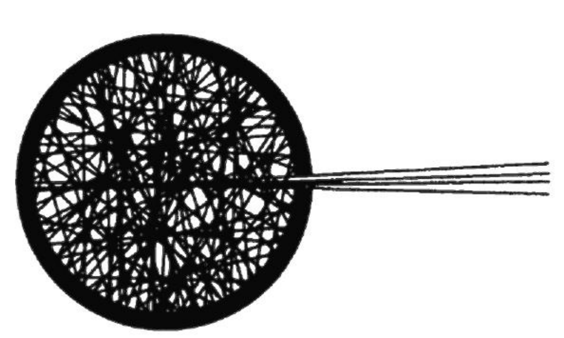
RADIATIA CORPULUI NEGRU

PROBLEMA ABSORBTIEI RADIATIEI

PROBLEMA EMISIEI RADIATIEI SI A STABILITATII SISTEMELOR ATOMICE

# Primele experimente

- **Radiația corpului negru (1895, 1900)**



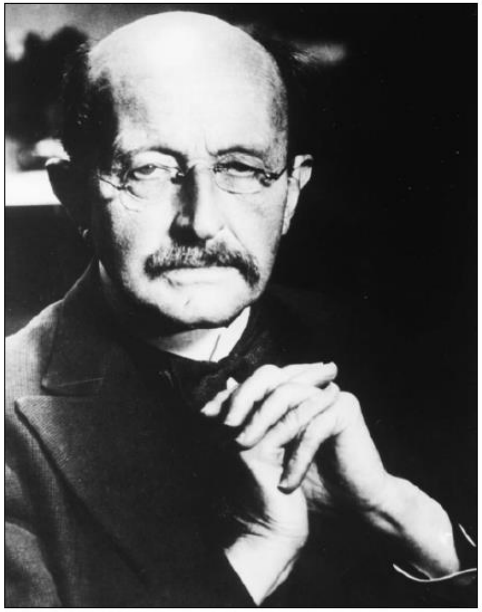
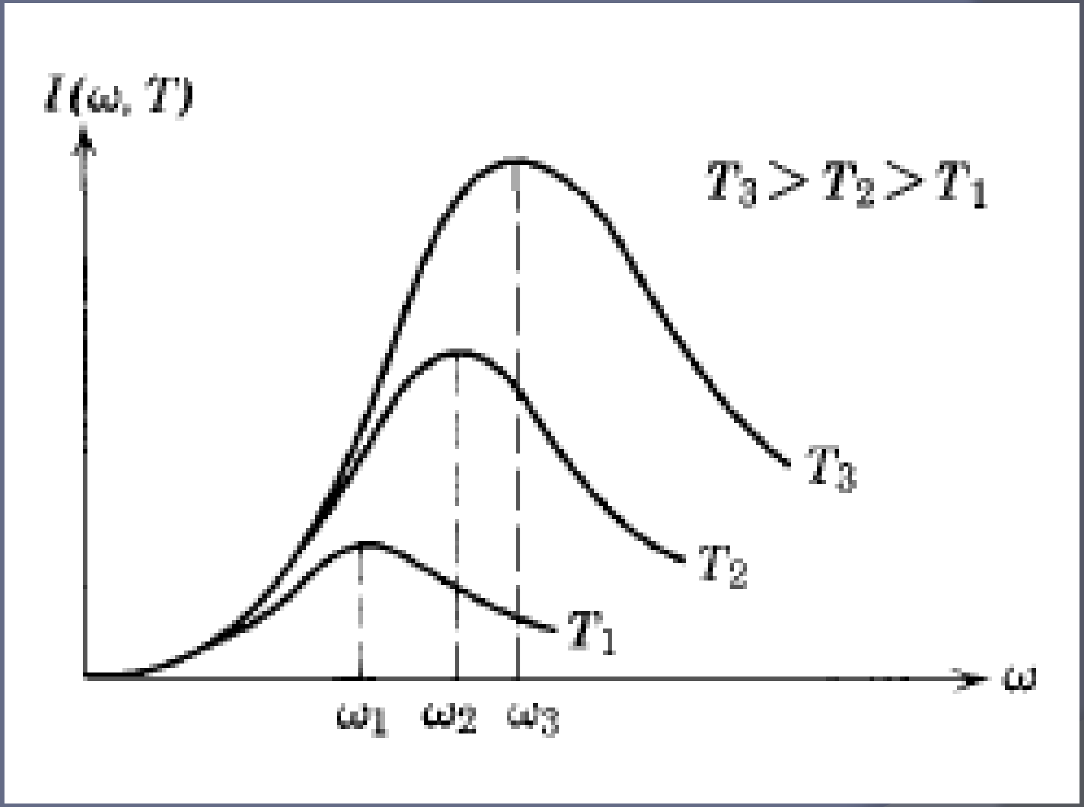


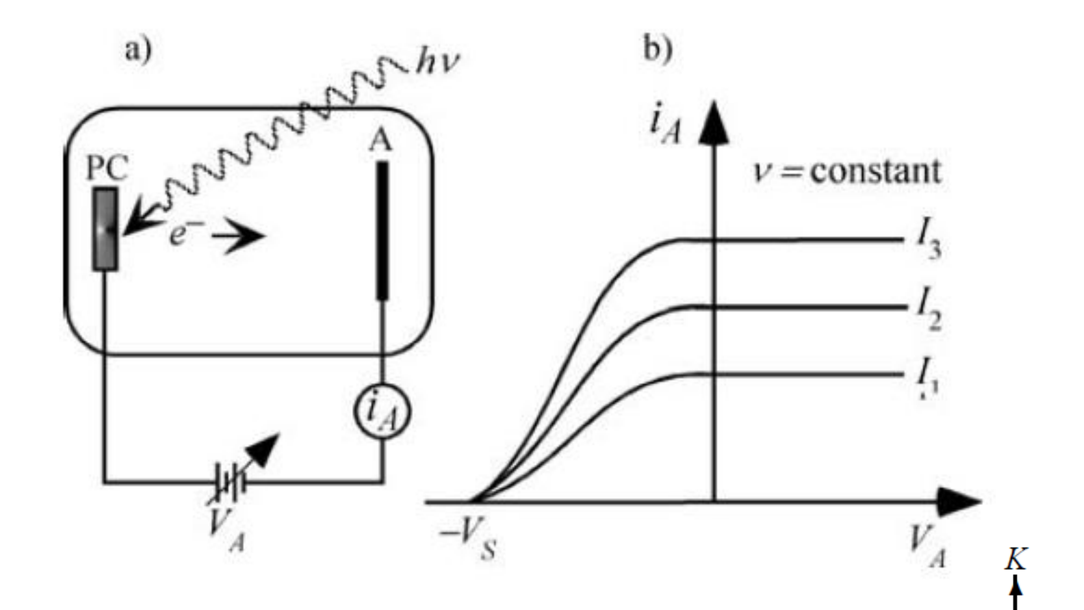
Figure 1.1: Max Planck. AIP Emilio Segre Visual Archives.

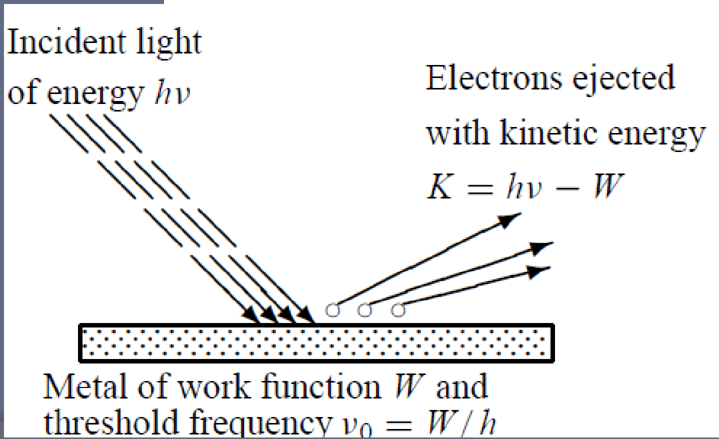


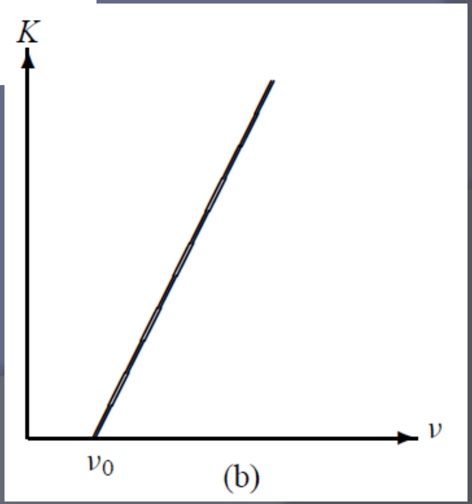

$$\frac{du(\nu,T)}{d\nu} = \frac{8\pi\nu^2}{c^3} h\nu \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

# Primele experimente

- **Efectul fotoelectric (1887,1902,1905)**

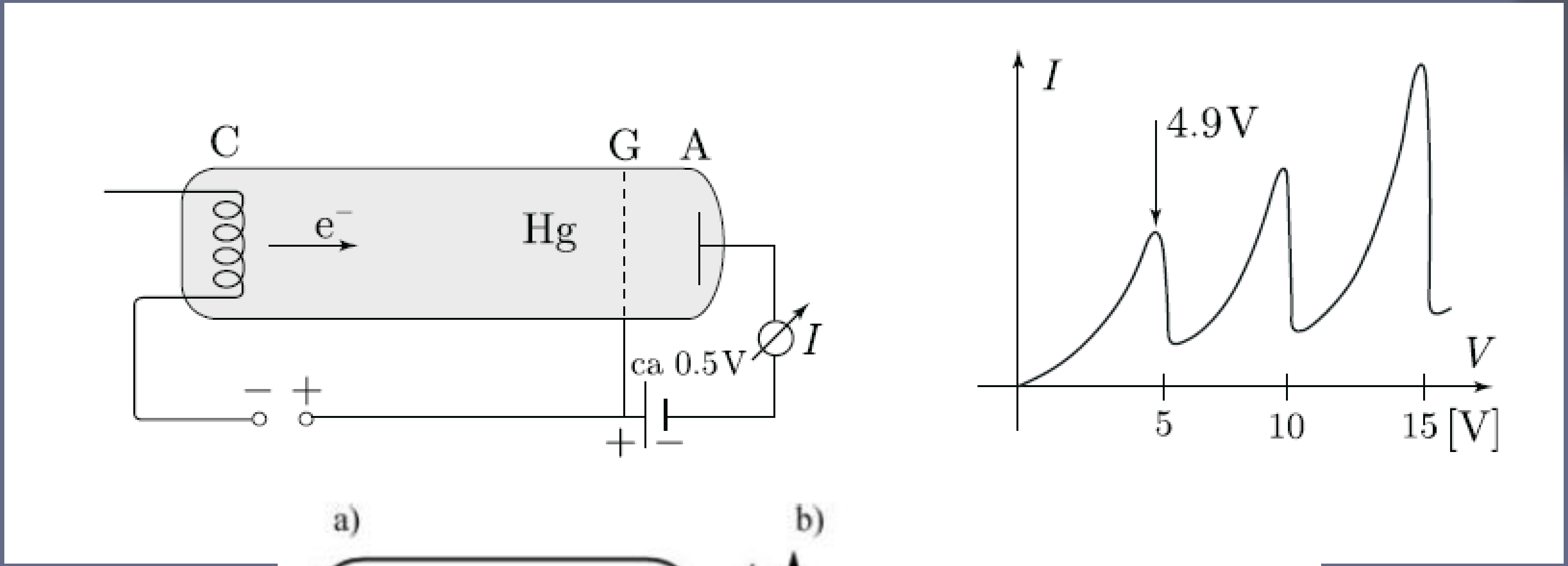


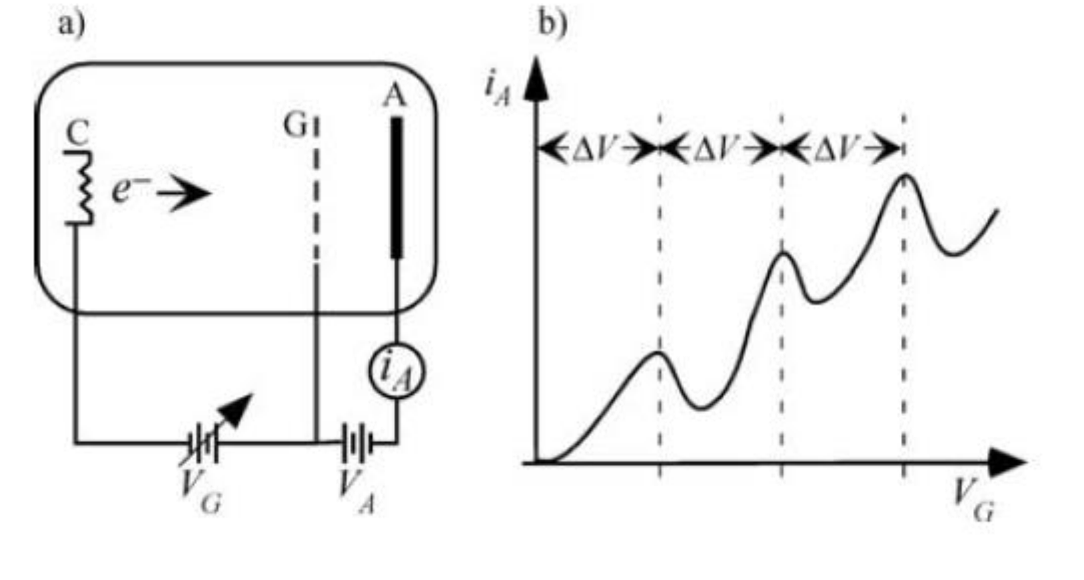



# Primele experimente

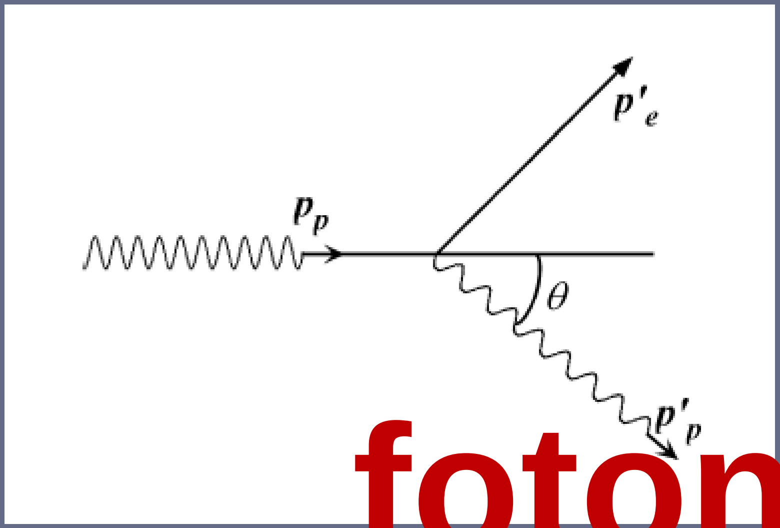
- **Experimentul FRANK-HERTZ (1914)**

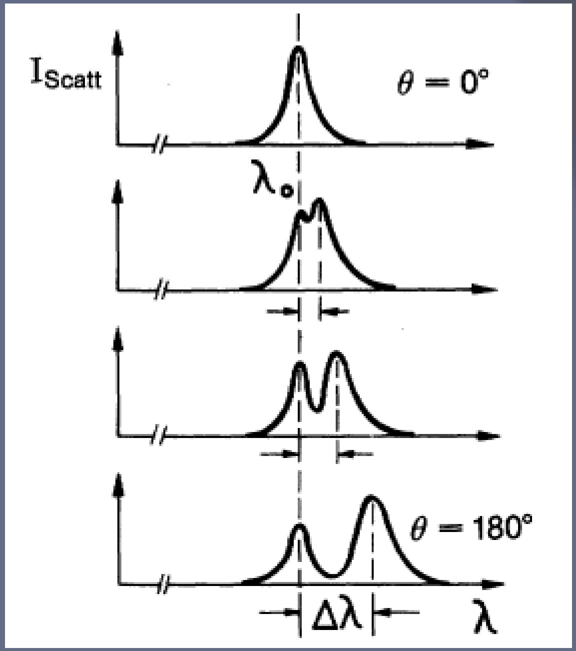


# Primele experimente

- **Efectul Compton (1922)**




**fotonul**

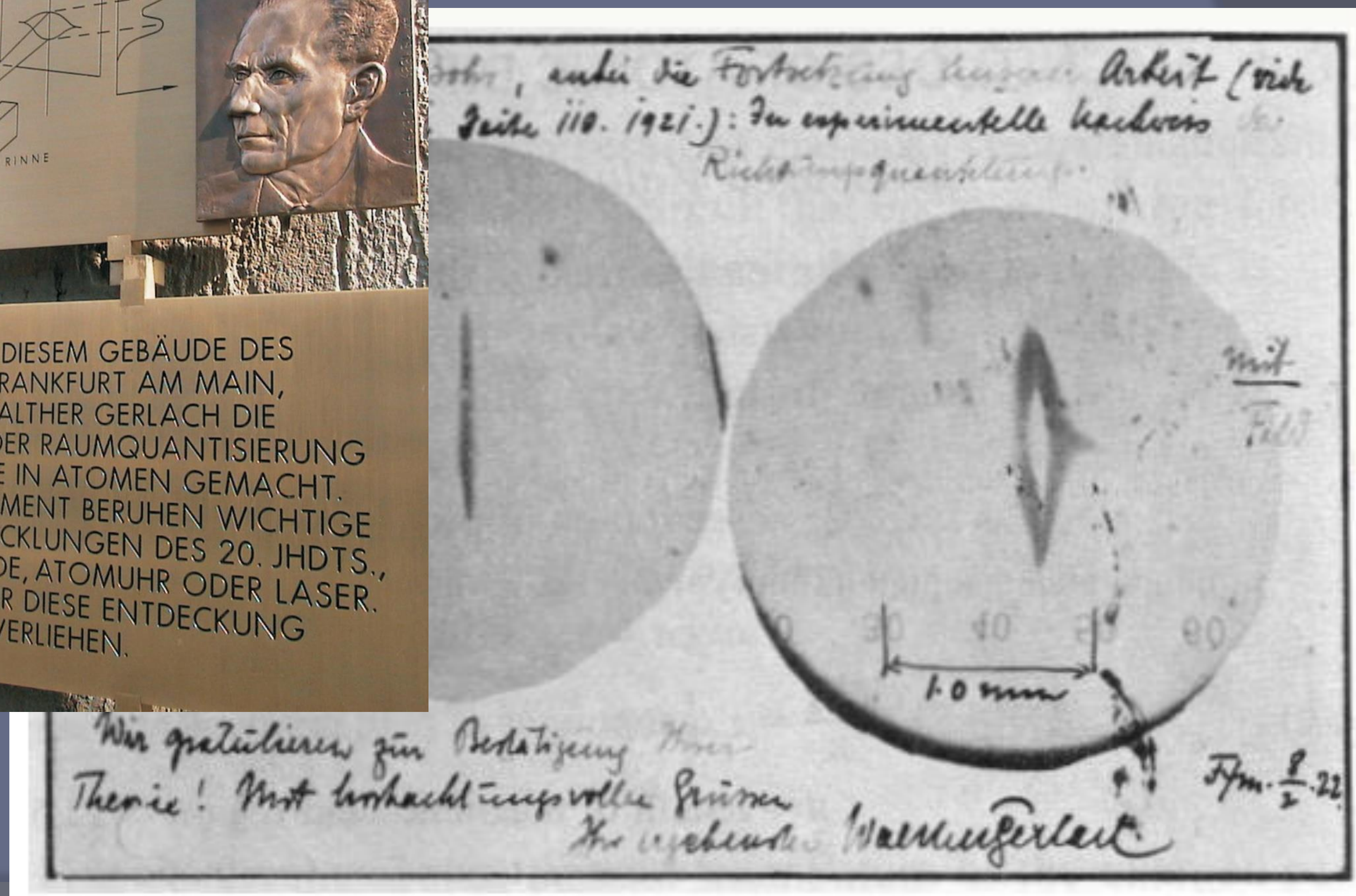
**1926 – G.Lewis**

$$\lambda_c = \frac{h}{m_e c}$$

$$\Delta\lambda = \lambda_c(1 - \cos\theta)$$

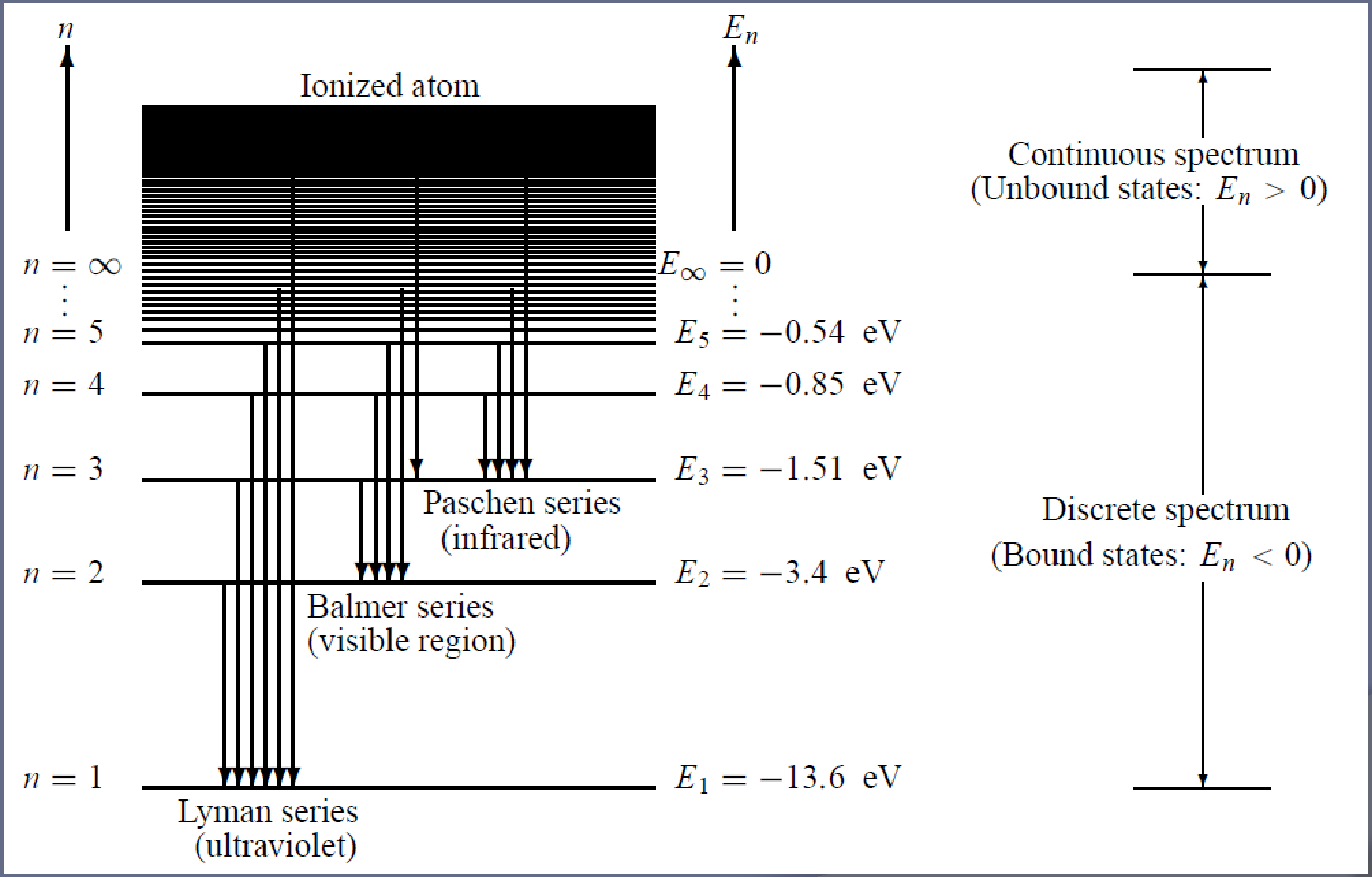
# Primele experimente

- **Experimentul STERN - GERLACH (1922)**

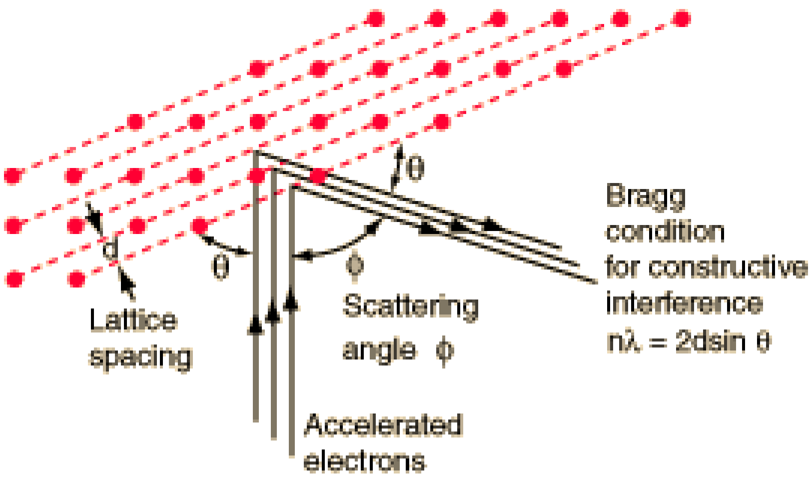
# Primele experimente

- **Spectroscopie atomică**

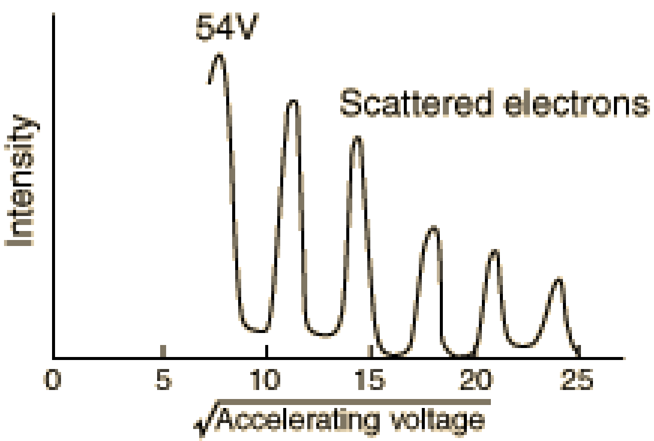


# Primele experimente

- **Experimentele de difracție (1927)**




Davisson and Germer
Phys.Rev. (1927)




$$\frac{1}{\lambda} = \frac{n}{2d\sin\theta} = \frac{p}{h} = \frac{\sqrt{2mE}}{h} = \frac{\sqrt{2meV}}{h}$$

*Electron wavelength* — *Bragg law* — *deBroglie relationship* — *Acceleration through voltage V*

Davisson, C. J., "Are Electrons Waves?," Franklin Institute Journal 205, 597 (1928)

# Scurt istoric

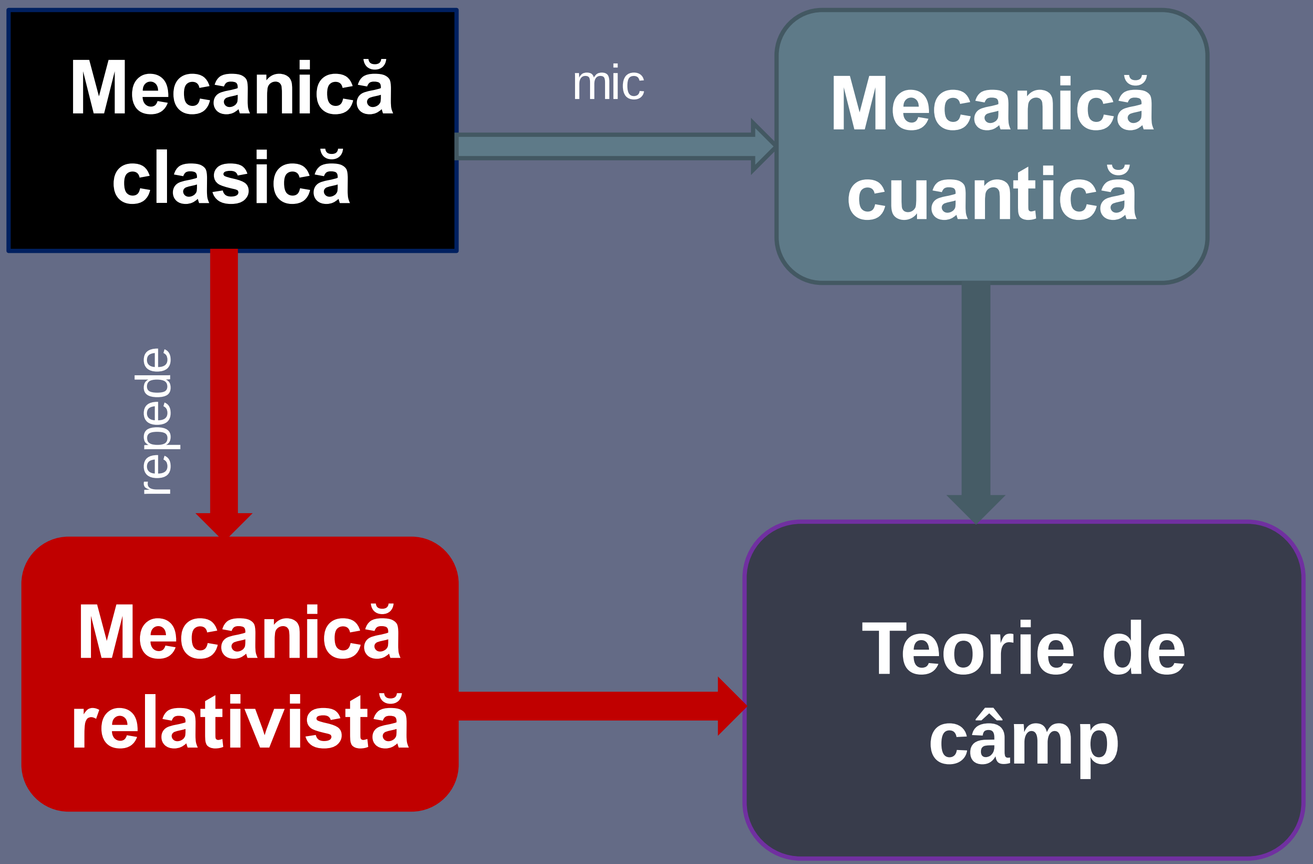
- **sfârșitul secolului XIX:**
  - **mecanică clasică;**
  - **electromagnetism;**
  - **termodinamică.**
- **începutul secolului XX:**
  - **domeniul relativist** **(mecanica Newtoniană nu poate fi folosită la viteze foarte mari)**
  - **domeniul microscopic** **(fizica clasică nu poate fi folosită la nivel microscopic – e.g. pentru descrierea atomilor și moleculelor, a interacției cu câmpul electromagnetic etc.)**

Ce legi folosim?

Ce mecanică folosim?

Legea atracției universale

Legile de mișcare ale lui Newton – mecanica clasică


Mecanică clasică
mic
Mecanică cuantică
repede
Mecanică relativistă
Teorie de câmp

# Câmpul electromagnetic ca sistem fizic

Fenomenele electrostaticii

Fenomenele magnetostaticii

Fenomene legate de curentii electrici

Fenomene electromagnetice cu variatia rapida in timp

Fenomene optice

**Câmpul electromagnetic ca sistem fizic**
**CONCEPTUL DE SARCINA ELECTRICA**

**ELECTRODINAMICA CLASICA**

**QED – Quantum Electrodynamics**

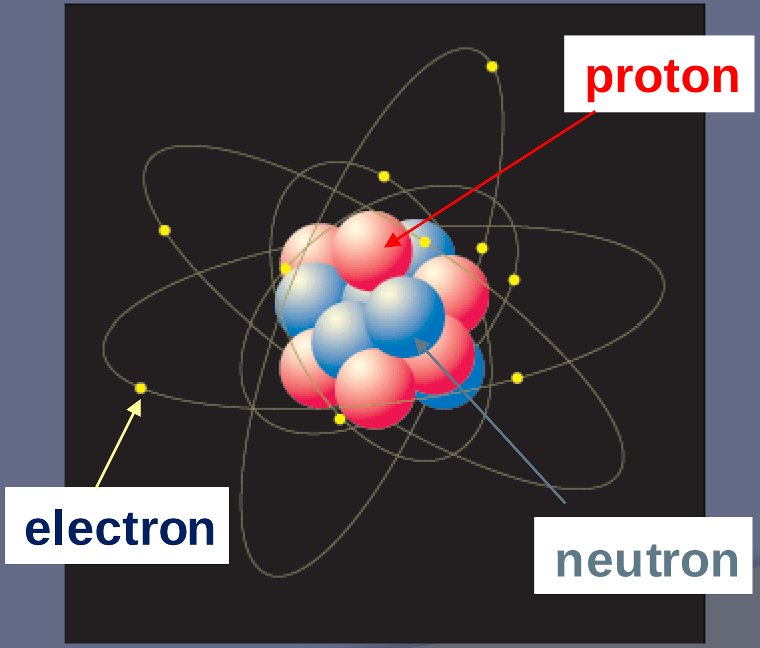
**TEORIA RELATIVITATII RESTRINSE**

**ELECTRODINAMICA CUANTICA**

**TEORII DE ETALONARE (NE)ABELIENE**

# Atomii

Atomii:
- protoni și neutroni în nucleu
- electroni



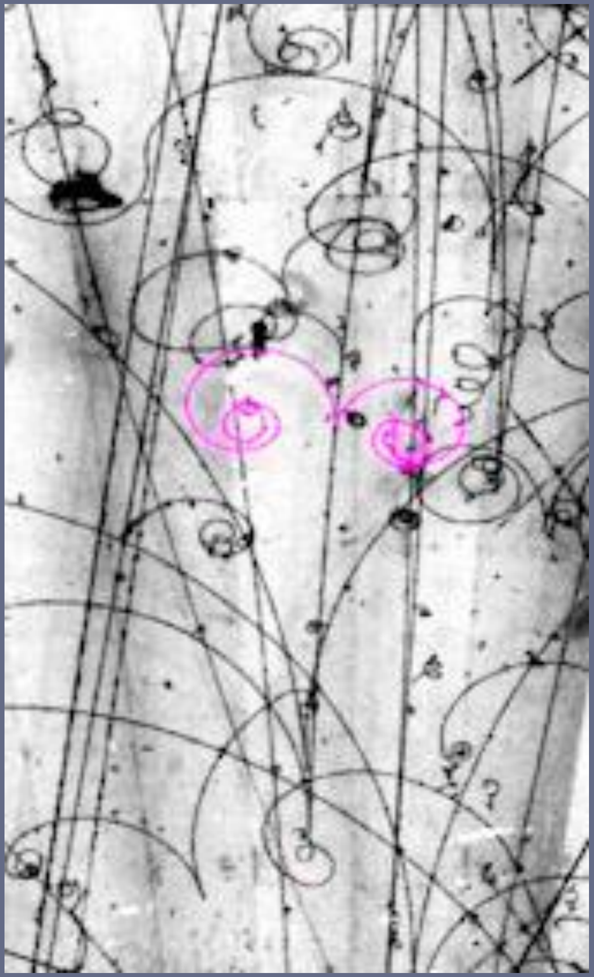

**Sunt protonii și neutronii particule elementare?**

# Fizica particulelor elementare

1. Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, ...)?
2. Cum interacționează?
3. Cum producem particule elementare?
4. Cum detectăm particule elementare?

# Dirac – particulă – antiparticulă

sarcină electrică
de semn opus



• Pereche electron-positron creată din fotoni într-o cameră cu bule.

• Energia fotonului este transformată în materie și anti-materie.

• Energia și impulsul se conservă (dar nu și masa de repaus)

# Yukawa – 1934

- Ce ține protonii și neutronii în nucleul?

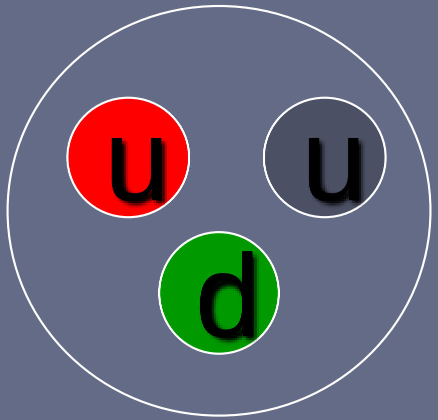
**INTERACȚIA TARE**

- De ce nu o experimentăm în viața de zi cu zi?

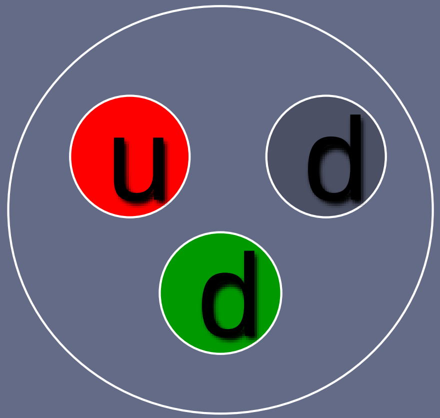
acționează la distanțe scurte

# Protonii și neutronii – modelul cuarcilor (1964)

**proton (sarcină +1)**




**neutron (sarcină 0)**




*Cuarcii au sarcini electrice fracționare*

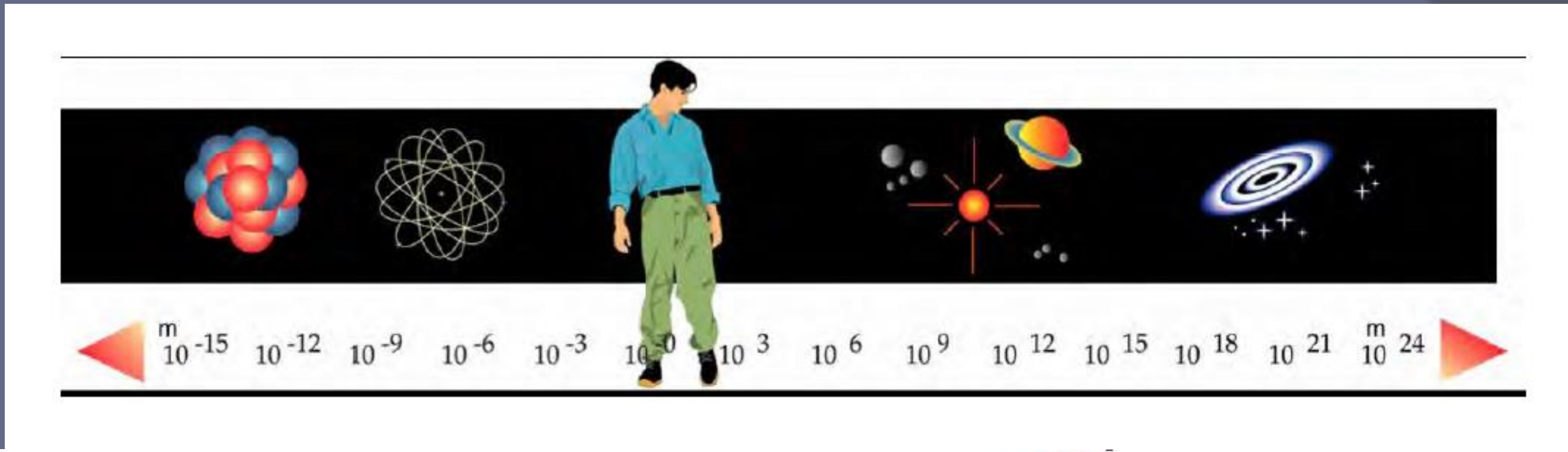
u - cuarcul up – sarcină electrică + 2/3

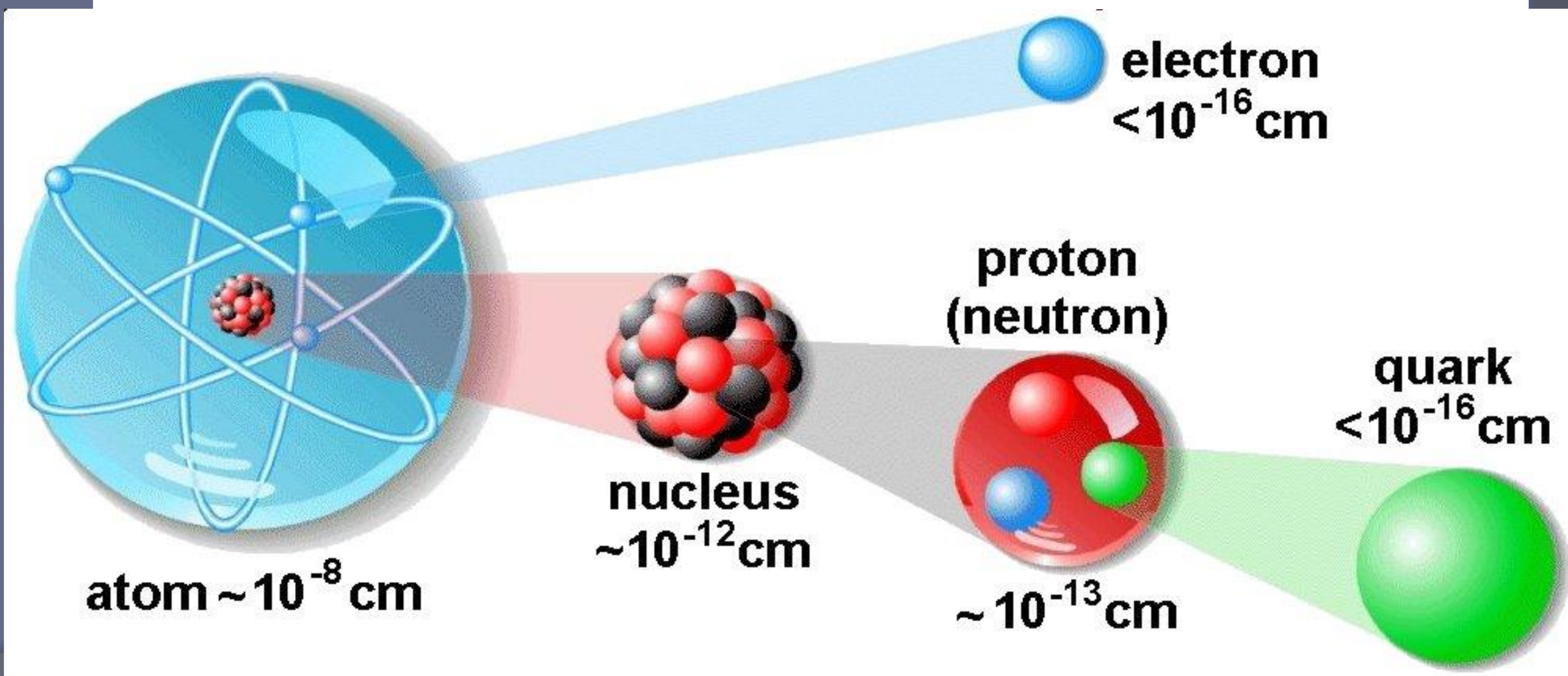
d - cuarcul down – sarcină electrică −1/3

$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

# Structura materiei (astăzi!)



# Cuarcii și culorile

**QCD – Quantum chromodynamics**

Fiecare cuarc poate avea 3 "culori"

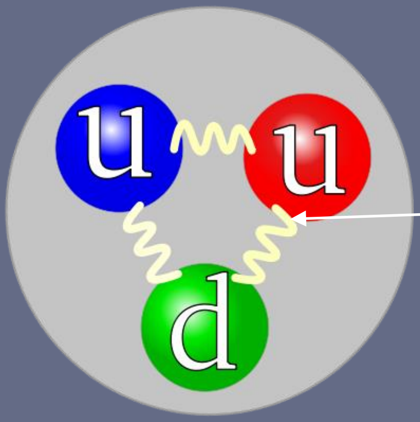

**up** +2/3

**down** -1/3

Cuarcii se combină în așa fel încât să formeze particule „incolore" (confinare).

-***Barioni*** (3 cuarci qqq: roșu + verde + albastru = alb)

**proton**
**p**




interacția tare - "lipește" cuarcii în stări legate -

-***Mezoni*** (cuarc-anticuarc qqbar)

**pion**
**π**

# PDG – Particle Data Group

**STRANGE MESONS**

| | |
|---|---|
| $K_L^0$ | 130 |
| $K_S^0$ | 310 |
| $K^0$ | 311 |
| $K^+$ | 321 |
| $\mathbf{K_0^*(800)^0}$ | **9000311*** |
| $\mathbf{K_0^*(800)^+}$ | **9000321*** |
| $K_0^*(1430)^0$ | 10311 |
| $K_0^*(1430)^+$ | 10321 |
| $K(1460)^0$ | 100311 |
| $K(1460)^+$ | 100321 |
| $\mathbf{K(1830)^0}$ | **9010311*** |
| $\mathbf{K(1830)^+}$ | **9010321*** |
| $K_0^*(1950)^0$ | **9020311*** |
| $K_0^*(1950)^+$ | **9020321*** |
| $K^*(892)^0$ | 313 |
| $K^*(892)^+$ | 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 |
| $\mathbf{K_1(1650)^0}$ | **9000313*** |
| $\mathbf{K_1(1650)^+}$ | **9000323*** |
| $K^*(1680)^0$ | 30313 |

**CHARMED MESONS**

| | |
|---|---|
| $D^+$ | 411 |
| $D^0$ | 421 |
| $\mathbf{D_0^*(2400)^+}$ | 10411 |
| $\mathbf{D_0^*(2400)^0}$ | 10421 |
| $D^*(2010)^+$ | 413 |
| $D^*(2007)^0$ | 423 |
| $D_1(2420)^+$ | 10413 |
| $D_1(2420)^0$ | 10423 |
| $D_1(H)^+$ | 20413 |
| $\mathbf{D_1(2430)^0}$ | 20423 |
| $D_2^*(2460)^+$ | 415 |
| $D_2^*(2460)^0$ | 425 |
| $D_s^+$ | 431 |
| $D_{s0}^*(2317)^+$ | 10431 |
| $D_s^{*+}$ | 433 |
| $D_{s1}(2536)^+$ | 10433 |
| $D_{s1}(2460)^+$ | 20433 |
| $D_{s2}^*(2573)^+$ | 435 |

**BOTTOM MESONS**

| | |
|---|---|
| $B^0$ | 511 |
| $B^+$ | 521 |
| $B_0^{*0}$ | 10511 |
| $B_0^{*+}$ | 10521 |
| $B^{*0}$ | 513 |

**$c\bar{c}$ MESONS**

| | |
|---|---|
| $\eta_c(1S)$ | 441 |
| $\chi_{c0}(1P)$ | 10441 |
| $\eta_c(2S)$ | 100441 |
| $J/\psi(1S)$ | 443 |
| $h_c(1P)$ | 10443 |
| $\chi_{c1}(1P)$ | 20443 |
| $\psi(2S)$ | 100443 |
| $\psi(3770)$ | 30443 |
| $\psi(4040)$ | 9000443 |
| $\psi(4160)$ | 9010443 |
| $\psi(4415)$ | 9020443 |
| $\chi_{c2}(1P)$ | 445 |
| $\mathbf{\chi_{c2}(2P)}$ | **100445*** |

**$b\bar{b}$ MESONS**

| | |
|---|---|
| $\eta_b(1S)$ | 551 |
| $\chi_{b0}(1P)$ | 10551 |
| $\eta_b(2S)$ | 100551 |
| $\chi_{b0}(2P)$ | 110551 |
| $\eta_b(3S)$ | 200551 |
| $\chi_{b0}(3P)$ | 210551 |
| $\Upsilon(1S)$ | 553 |
| $h_b(1P)$ | 10553 |
| $\chi_{b1}(1P)$ | 20553 |
| $\Upsilon_1(1D)$ | 30553 |

**LIGHT BARYONS**

| | |
|---|---|
| $p$ | 2212 |
| $n$ | 2112 |
| $\Delta^{++}$ | 2224 |
| $\Delta^+$ | 2214 |
| $\Delta^0$ | 2114 |
| $\Delta^-$ | 1114 |

**STRANGE BARYONS**

| | |
|---|---|
| $\Lambda$ | 3122 |
| $\Sigma^+$ | 3222 |
| $\Sigma^0$ | 3212 |
| $\Sigma^-$ | 3112 |
| $\Sigma^{*+}$ | $3224^d$ |
| $\Sigma^{*0}$ | $3214^d$ |
| $\Sigma^{*-}$ | $3114^d$ |
| $\Xi^0$ | 3322 |
| $\Xi^-$ | 3312 |
| $\Xi^{*0}$ | $3324^d$ |
| $\Xi^{*-}$ | $3314^d$ |
| $\Omega^-$ | 3334 |

**CHARMED BARYONS**

| | |
|---|---|
| $\Lambda_c^+$ | 4122 |
| $\Sigma_c^{++}$ | 4222 |
| $\Sigma_c^+$ | 4212 |
| $\Sigma_c^0$ | 4112 |
| $\Sigma_c^{*++}$ | 4224 |
| $\Sigma_c^{*+}$ | 4214 |

**BOTTOM BARYONS**

| | |
|---|---|
| $\Lambda_b^0$ | 5122 |
| $\Sigma_b^-$ | 5112 |
| $\Sigma_b^0$ | 5212 |
| $\Sigma_b^+$ | 5222 |
| $\Sigma_b^{*-}$ | 5114 |
| $\Sigma_b^{*0}$ | 5214 |
| $\Sigma_b^{*+}$ | 5224 |
| $\Xi_b^-$ | 5132 |
| $\Xi_b^0$ | 5232 |
| $\Xi_b^{\prime -}$ | 5312 |
| $\Xi_b^{\prime 0}$ | 5322 |
| $\Xi_b^{*-}$ | 5314 |
| $\Xi_b^{*0}$ | 5324 |
| $\Omega_b^-$ | 5332 |
| $\Omega_b^{*-}$ | 5334 |
| $\Xi_{bc}^0$ | 5142 |
| $\Xi_{bc}^+$ | 5242 |
| $\Xi_{bc}^{\prime 0}$ | 5412 |
| $\Xi_{bc}^{\prime +}$ | 5422 |
| $\Xi_{bc}^{*0}$ | 5414 |
| $\Xi_{bc}^{*+}$ | 5424 |
| $\Omega_{bc}^0$ | 5342 |
| $\Omega_{bc}^{\prime 0}$ | 5432 |

# Universul este alcătuit numai din cuarci și electroni?

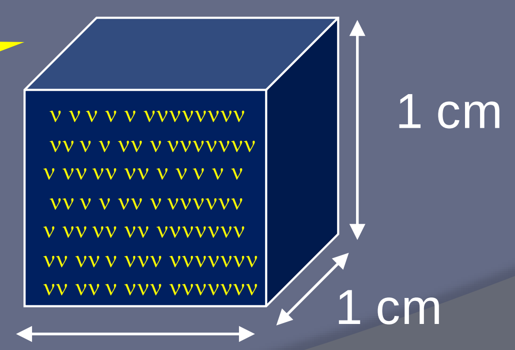
*Există și neutrini!*

ν

Electronul, protonul și neutronul sunt rari!
Pentru fiecare dintre ei, există 1 billion neutrini.

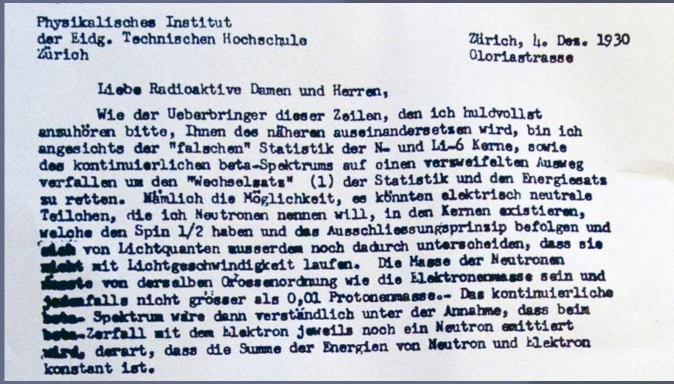
*Neutrinii sunt cele mai abundente particule ale materiei în univers.*

În fiecare $cm^3$ al spațiului sunt ~300 neutrini de la Big Bang




Neutrinii sunt peste tot.

# Dezintegrarea β


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

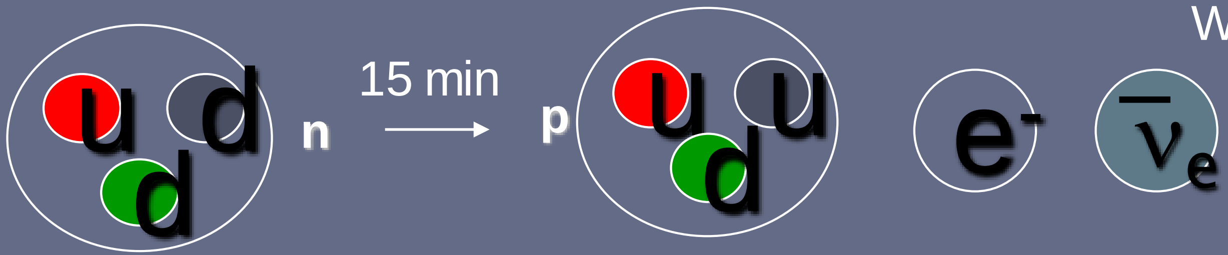
Zürich, 4. Des. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen dürfte von derselben Grossenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.

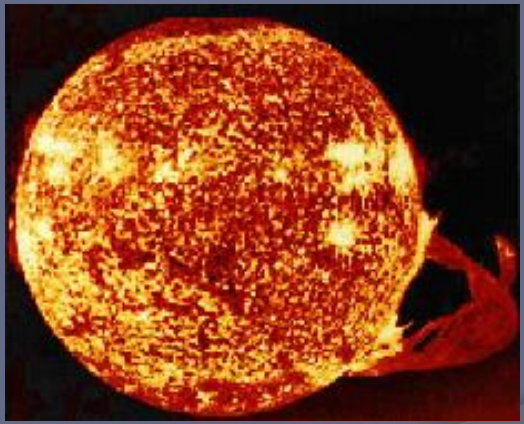
W.Pauli - 1930

La nivelul cuarcilor: $d \rightarrow u\ e^- \ \bar{\nu}_e$




Un neutron se dezintegrează în 15 minute.

**interacție „slabă”!**



**QFD – Quantum flavordynamics**

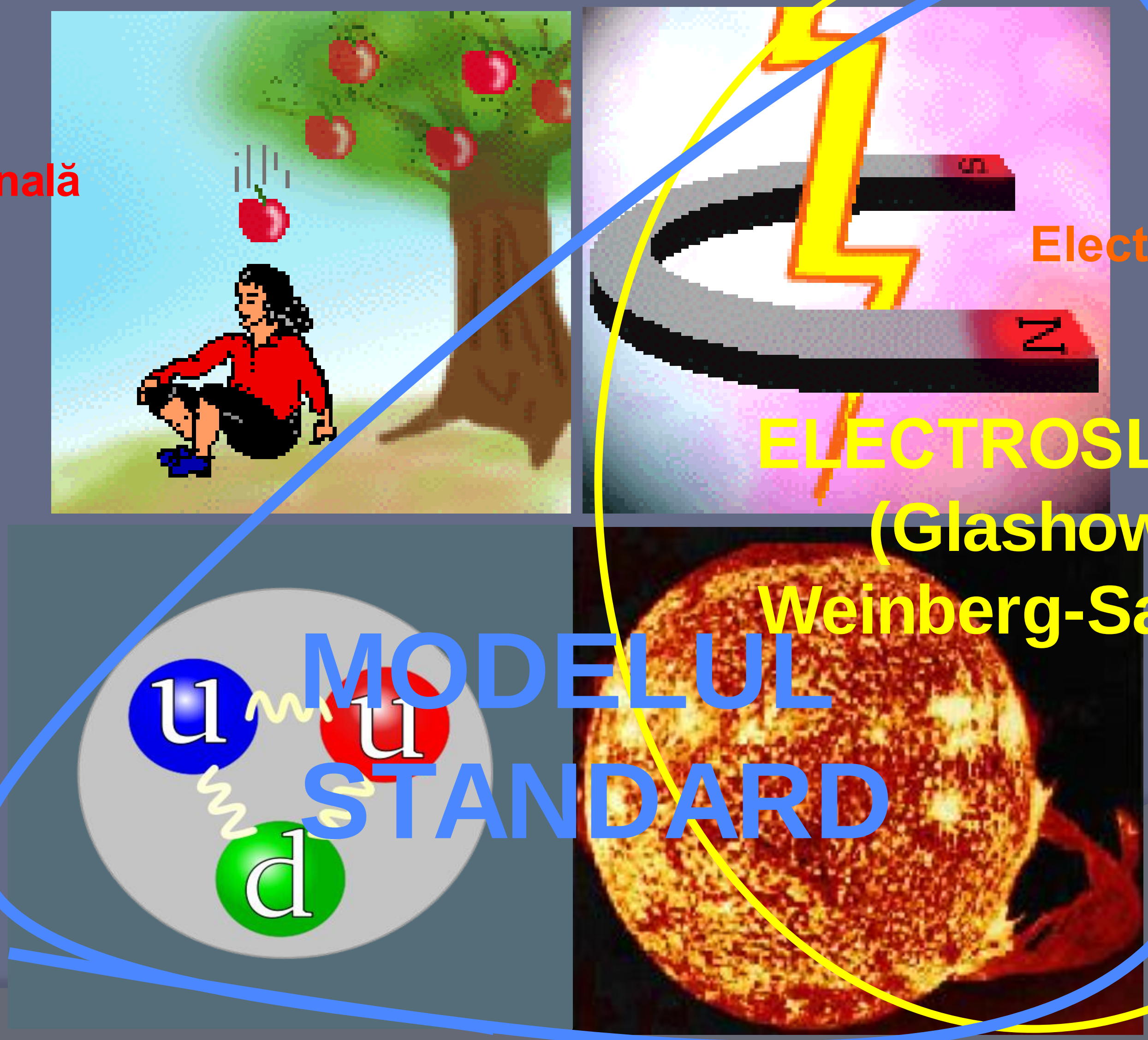
!

# Tipuri de interacție

**Gravitațională**

masa

**Tare**




**Electromagnetică**

**Slabă**

# Cine mediază interacțiile?

**bozonii**

**Gravitațională**

**? graviton ?**

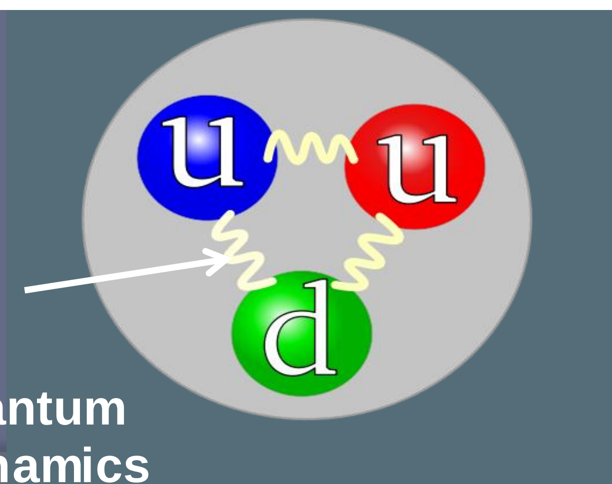
**QED – Quantum Electrodynamics**

**Electromagnetică**

**$\gamma$- fotonul**

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_Q$$

**Tare**




**gluonii**

**QCD – Quantum chromodynamics**

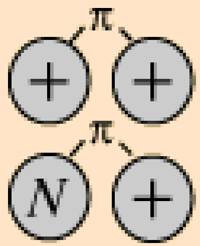
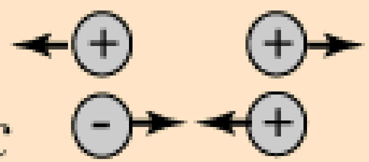
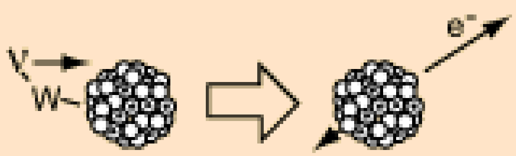
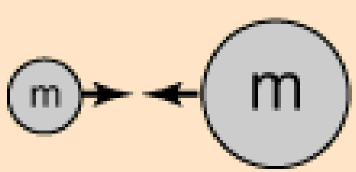
**QFD – Quantum flavordynamics**

**Slabă**

**$W^+$, $W^-$, $Z$**

# Fundamental Forces

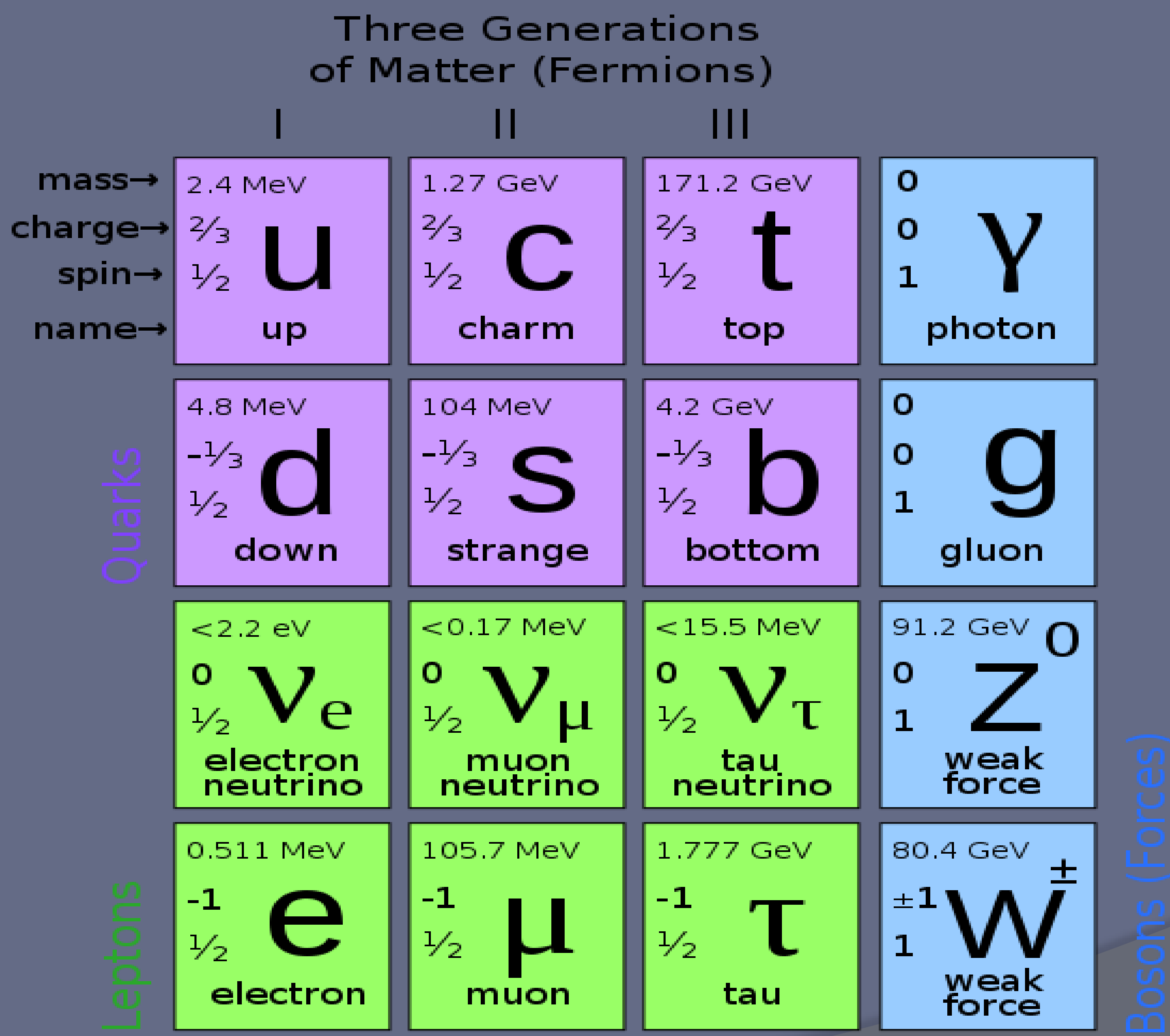
http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/funfor.html

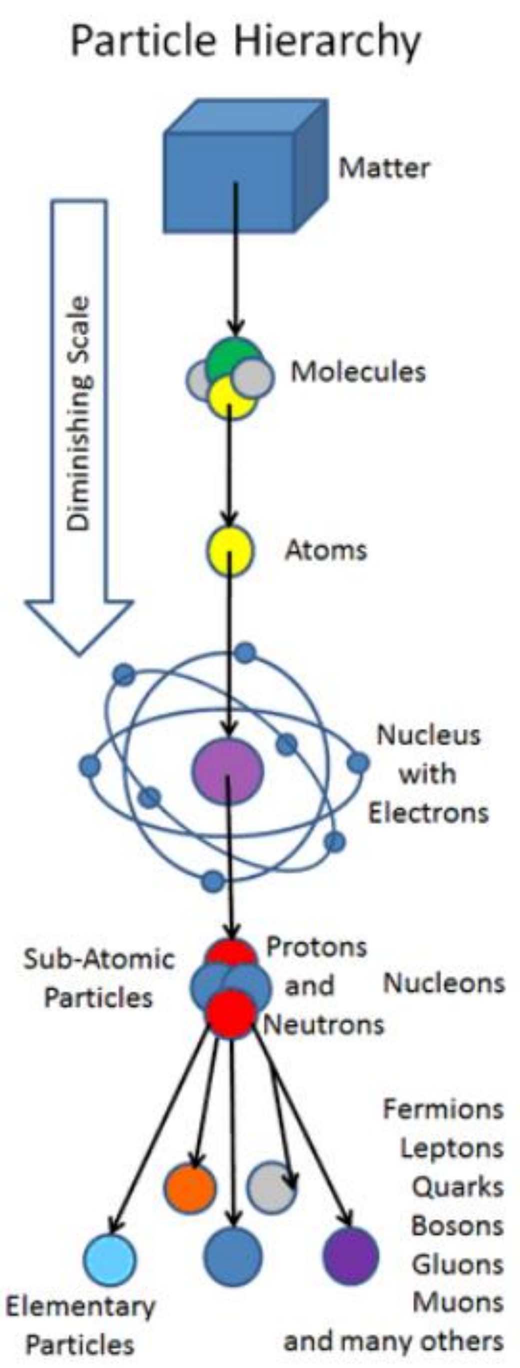
| Force | | Strength | Range (m) | Particle |
|---|---|---|---|---|
| *Strong* |  Force which holds nucleus togeher | 1 | $10^{-15}$ (diameter of a medium sized nucleus) | gluons, π(nucleons) |
| *Electro-magnetic* |  | $\frac{1}{137}$ | Infinite | photon mass = 0 spin = 1 |
| *Weak* |  neutrino interaction induces beta decay | $10^{-6}$ | $10^{-18}$ (0.1% of the diameter of a proton) | Intermediate vector bosons $W^+$, $W^-$, $Z_0$, mass > 80 GeV spin =1 |
| *Gravity* |  | $6 \times 10^{-39}$ | Infinite | graviton ? mass = 0 spin = 2 |

# 3 FAMILII (ASTĂZI!)

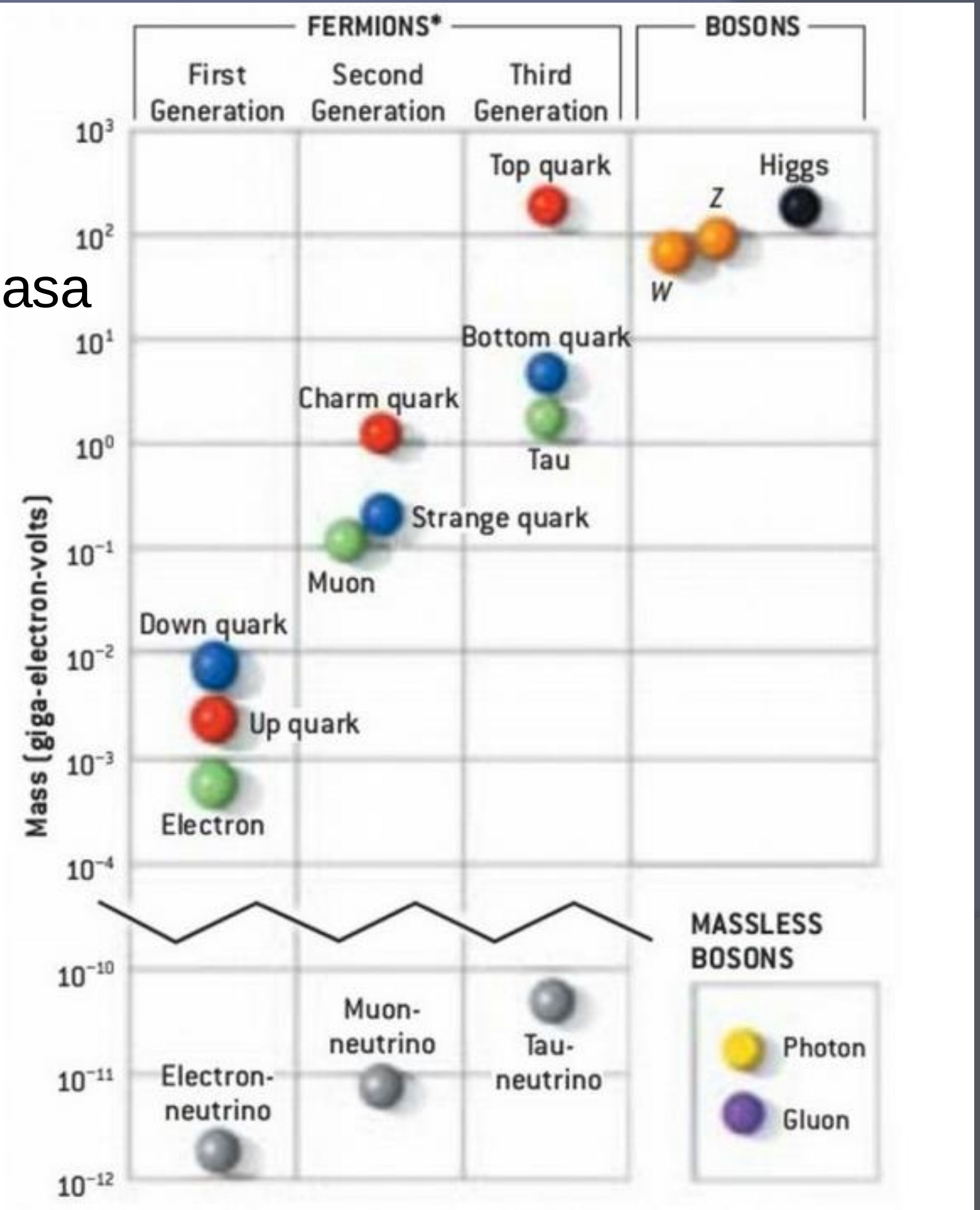
| prima generație | | a doua generație | | a treia generație | |
|---|---|---|---|---|---|
| 0 | +2/3 | 0 | +2/3 | 0 | +2/3 |
| $\nu_e$ | u | $\nu_\mu$ | c | $\nu_\tau$ | t |
| -1 | -1/3 | -1 | -1/3 | -1 | -1/3 |
| $e^-$ | d | $\mu^-$ | s | $\tau^-$ | b |
| materie „obișnuită” | | radiație cosmică | | acceleratori | |

***cele 3 generații diferă prin masă!***


Three Generations
of Matter (Fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV
⅔
½
u
up
1.27 GeV
⅔
½
c
charm
171.2 GeV
⅔
½
t
top
0
0
1
γ
photon
4.8 MeV
-⅓
½
d
down
104 MeV
-⅓
½
s
strange
4.2 GeV
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV
0
½
νe
electron neutrino
<0.17 MeV
0
½
νμ
muon neutrino
<15.5 MeV
0
½
ντ
tau neutrino
91.2 GeV
0
1
Z0
weak force
0.511 MeV
-1
½
e
electron
105.7 MeV
-1
½
μ
muon
1.777 GeV
-1
½
τ
tau
80.4 GeV
±1
1
W±
weak force
Quarks
Leptons
Bosons (Forces)


Particle Hierarchy
Diminishing Scale
Matter
Molecules
Atoms
Nucleus with Electrons
Sub-Atomic Particles
Protons and Neutrons
Nucleons
Fermions
Leptons
Quarks
Bosons
Gluons
Muons
and many others
Elementary Particles

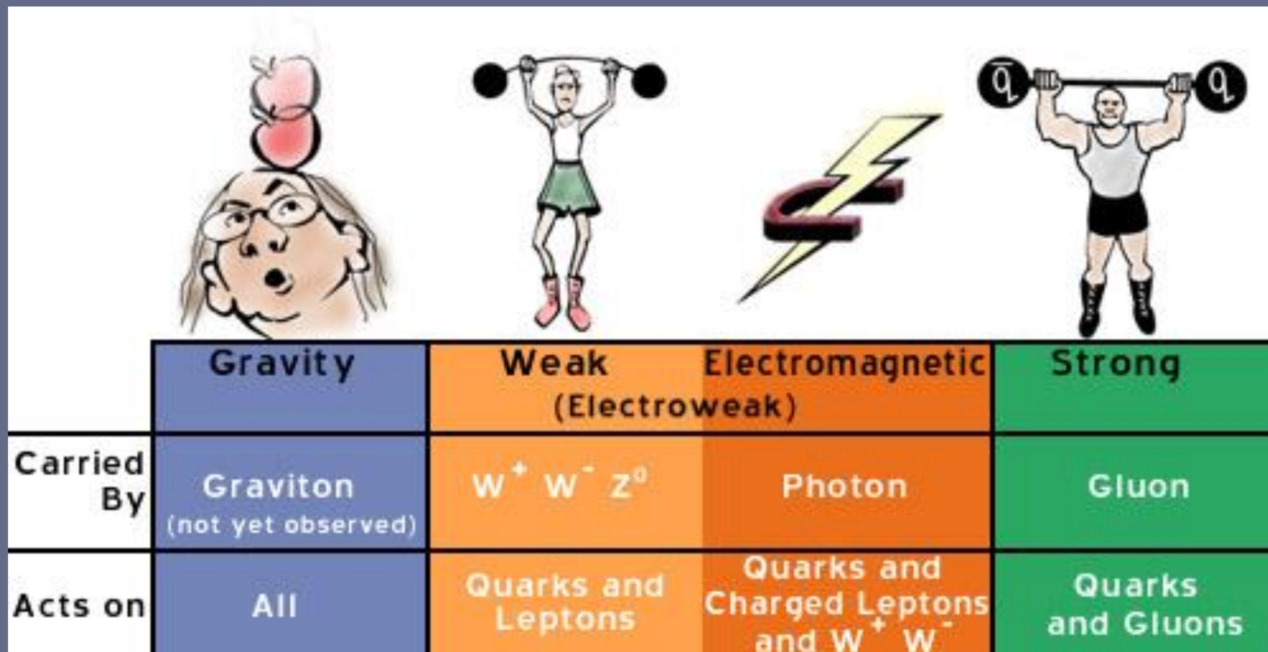
Masa


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
$10^3$
$10^2$
$10^1$
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

**număr asociat sarcinii electrice (Q)**

**număr leptonic L ($L_e$, $L_\mu$, $L_\tau$)**

**număr barionic B**




**interacție slabă**
(cuarcii și leptonii)

**interacție tare** (cuarcii)

**interacție electromagnetică**
(particule cu sarcină electrică:
cuarci, leptoni cu sarcină electrică)

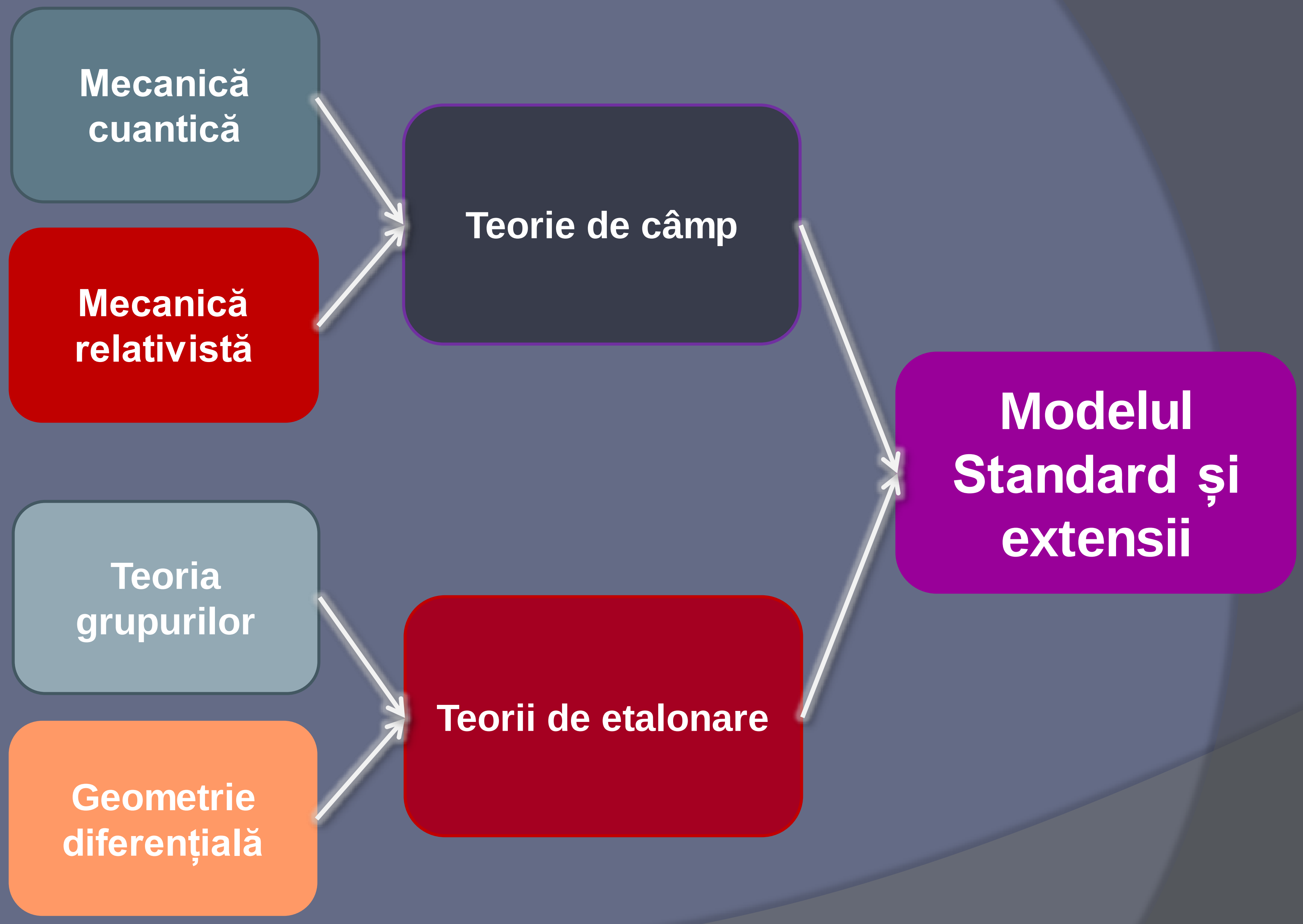
indiscernabilitatea particulelor identice

statistică cuantică

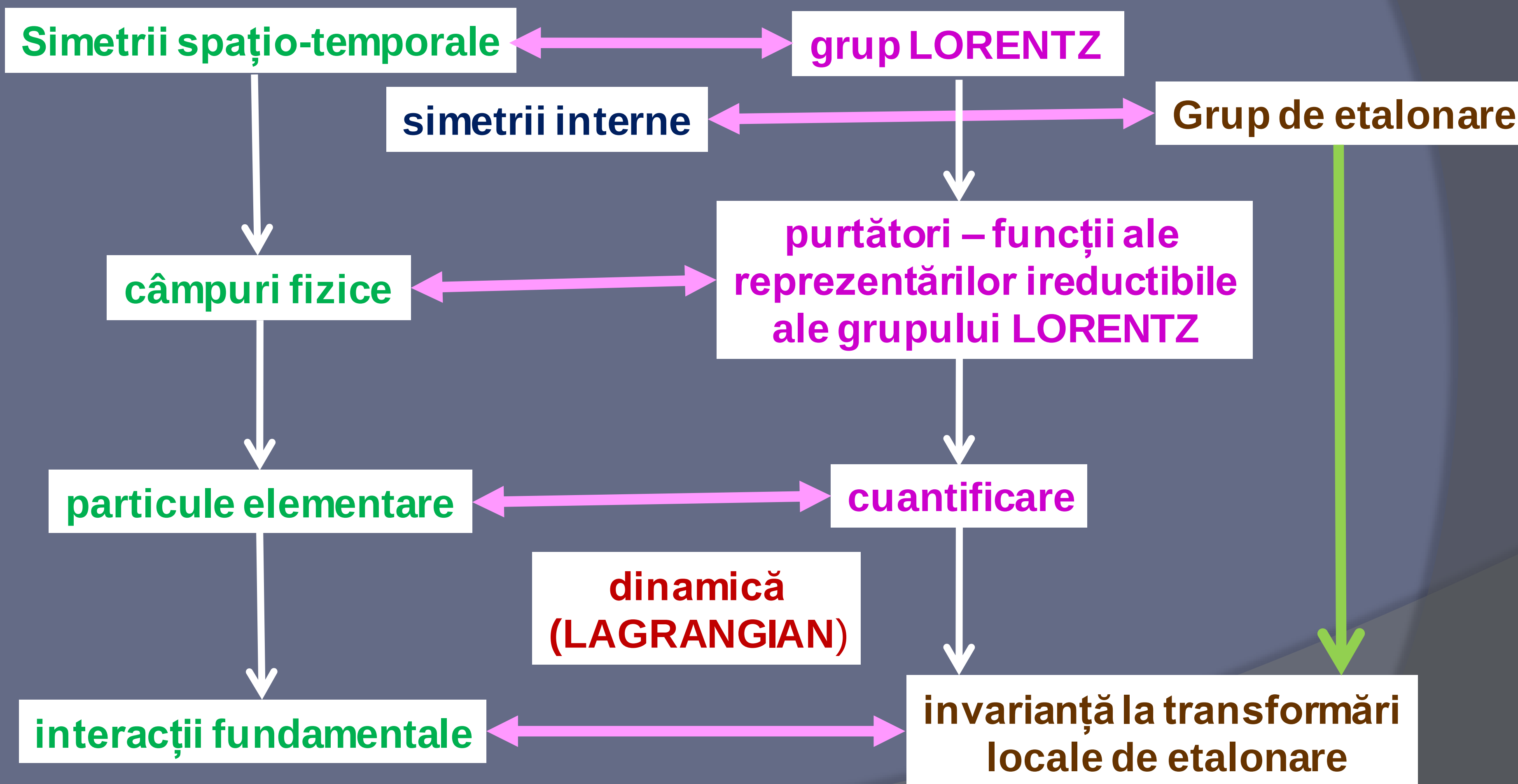
existența antiparticulelor

procese de creare și anihilare a particulelor

interacție cu schimb de particule


Mecanică cuantică
Mecanică relativistă
Teorie de câmp
Teoria grupurilor
Geometrie diferențială
Teorii de etalonare
Modelul Standard și extensii

# Schemă teoretică: de la simetrii spaţio-temporale la particule elementare şi interacţii



Lagrangian – Glashow-Weinberg-Salam (interacție electro-slabă)

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5) \Psi_f Z_\mu +$$

$$-\frac{1}{4}|\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2}|\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

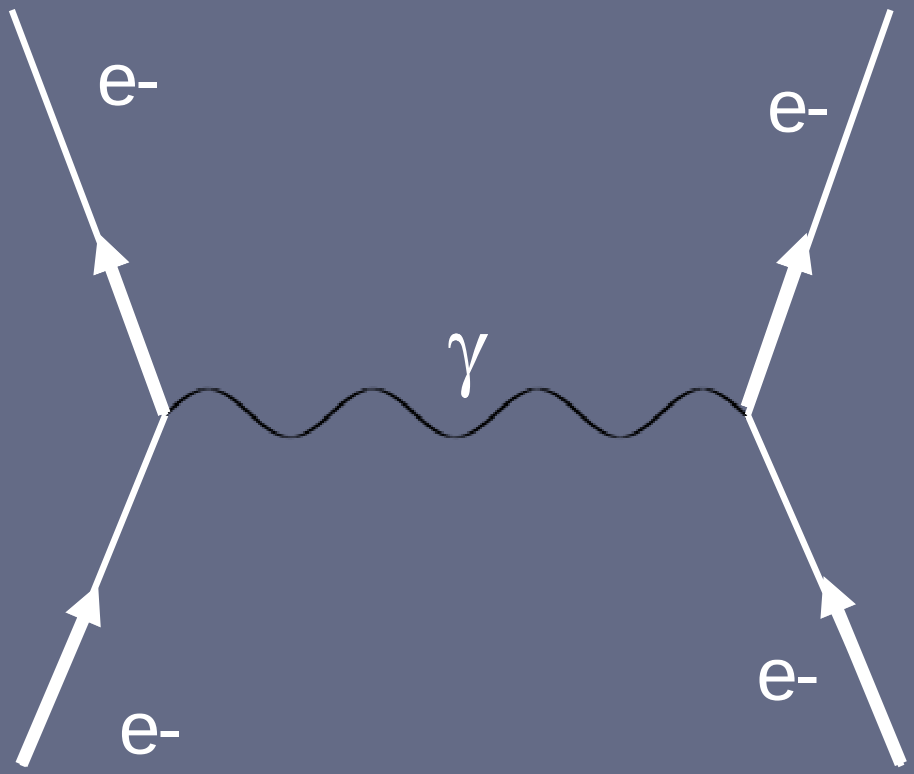
$$-ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

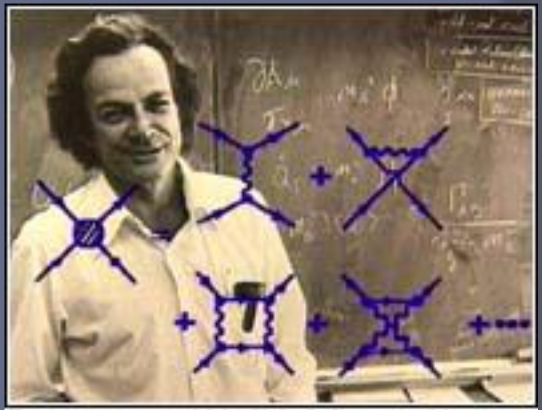
$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$-\frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8 M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 +$$

$$+\frac{1}{2}|\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

# Feynman – diagrame și reguli

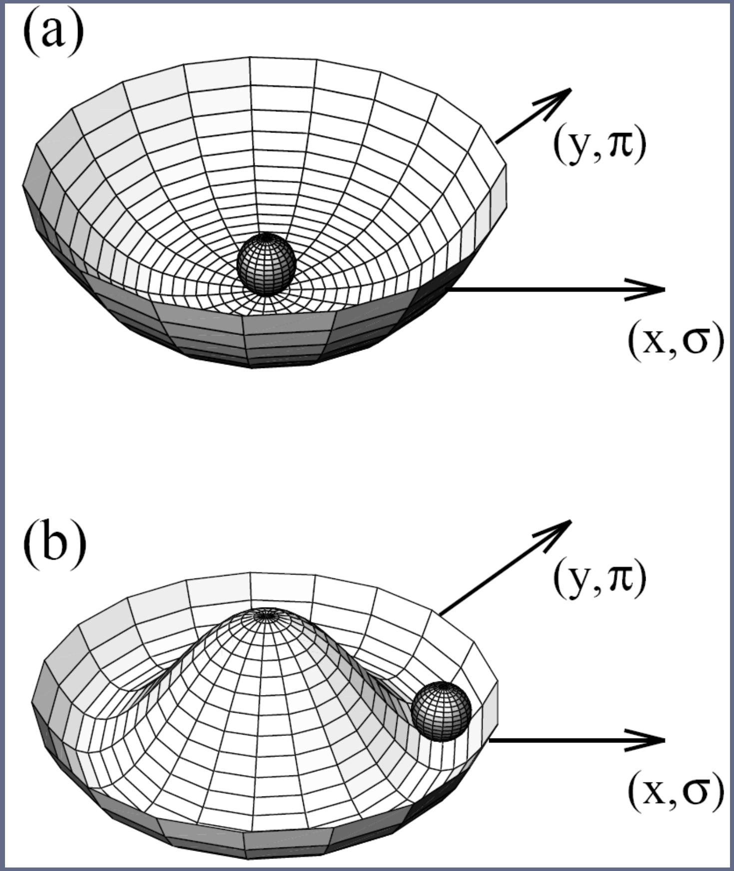


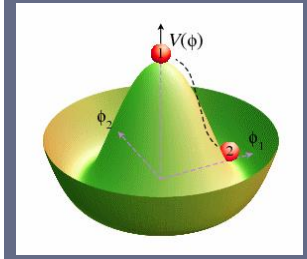



Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)

# De unde apare masa particulelor în teorie?

**$W^{+}$, $W^{-}$, Z – au masă**
**- rezultă bozonul Higgs**




fără rupere spontană de simetrie

rupere spontană de simetrie

the Weinberg-Salam model and beyond

$$\mathcal{L} = -\tfrac{1}{4}\mathbf{W}_{\mu\nu}\cdot\mathbf{W}^{\mu\nu} - \tfrac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

W $^{\pm}$, Z, γ kinetic energies and self-interactions

$$+\bar{L}\gamma^{\mu}\left(i\partial_{\mu} - g\frac{1}{2}\boldsymbol{\tau}\cdot\mathbf{W}_{\mu} - g'\frac{Y}{2}B_{\mu}\right)L$$
$$+\bar{R}\gamma^{\mu}\left(i\partial_{\mu} - g'\frac{Y}{2}B_{\mu}\right)R$$

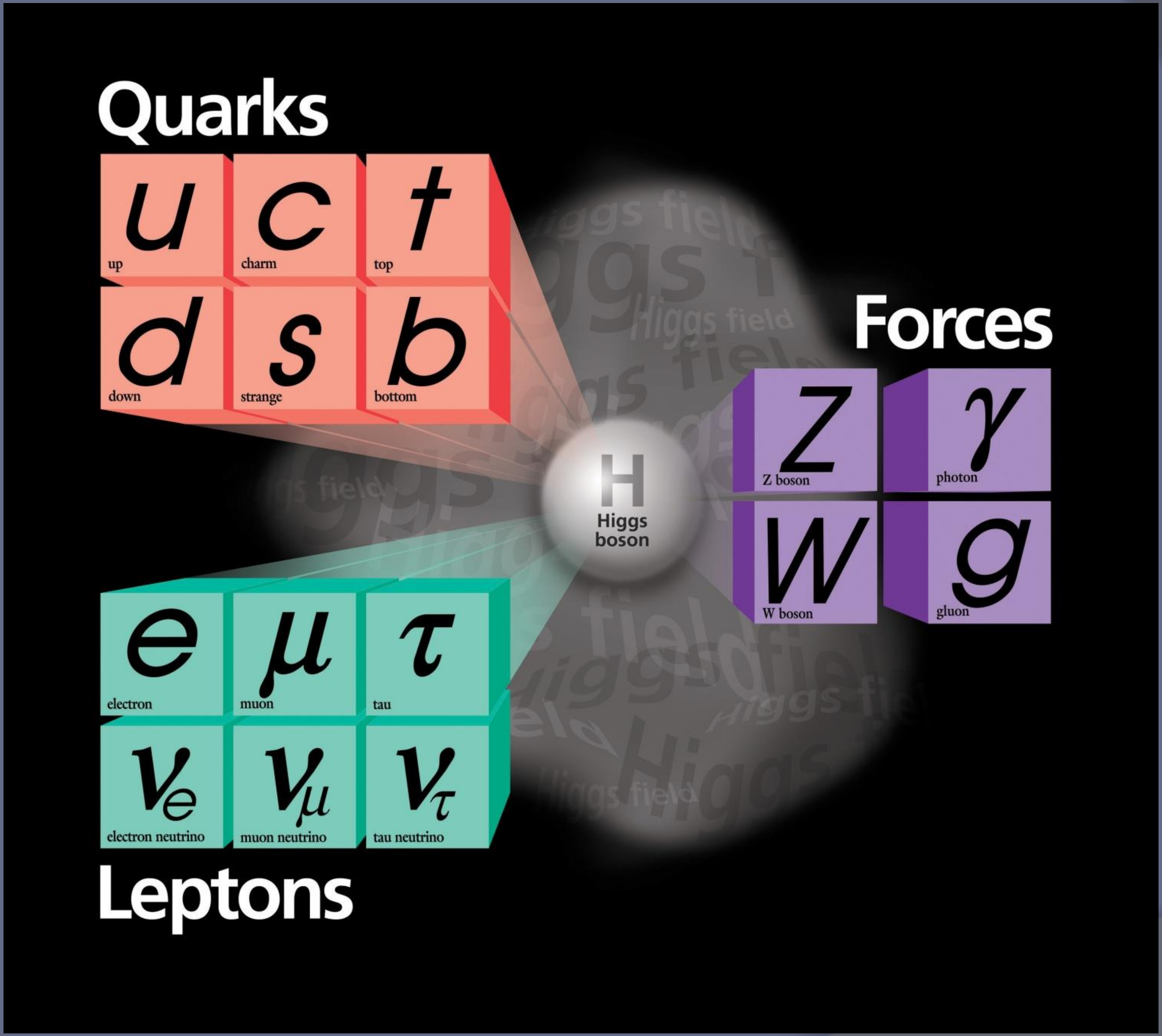
lepton and quark kinetic energies and their interactions with W $^{\pm}$, Z, γ

$$+\left|\left(i\partial_{\mu} - g\frac{1}{2}\boldsymbol{\tau}\cdot\mathbf{W}_{\mu} - g'\frac{Y}{2}B_{\mu}\right)\phi\right|^{2} - V(\phi)$$

W $^{\pm}$, Z, γ, and Higgs masses and couplings

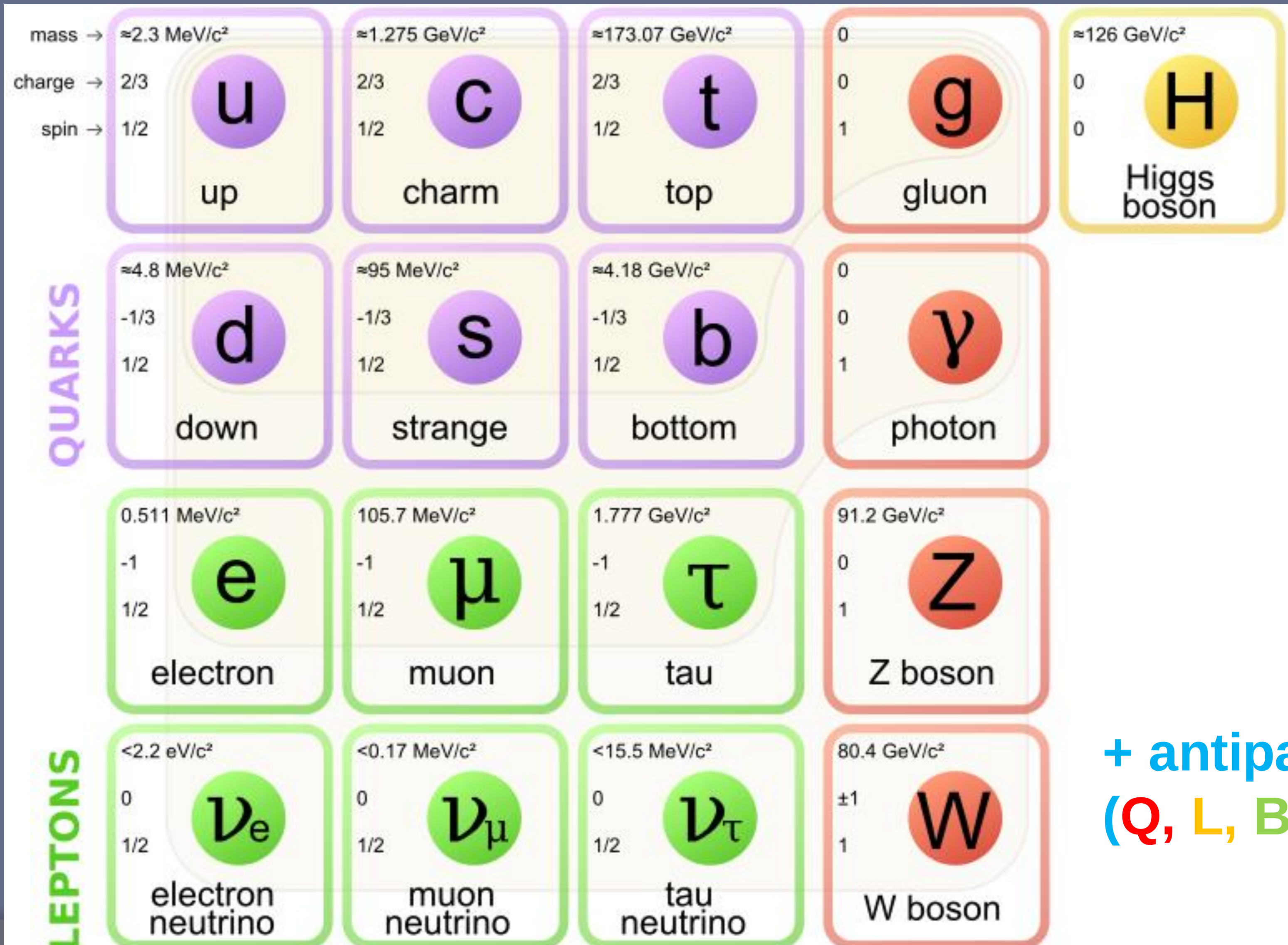
$$-(G_1\bar{L}\phi R + G_2\bar{L}\phi_c R + \text{hermitian conjugate}).$$

lepton and quark masses and coupling to Higgs



Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
Higgs field
e
electron
μ
muon
τ
tau
$\nu_e$
electron neutrino
$\nu_\mu$
muon neutrino
$\nu_\tau$
tau neutrino
Leptons

# Modelul Standard




**+ antiparticule**
**(Q, L, B opus)!**

# Fizica particulelor elementare

1. Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, ...)?
2. Cum interacționează? - De unde obținem informații?
3. Cum producem particule elementare?
4. Cum detectăm particule elementare?

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**2020 Review of Particle Physics.**
P.A. Zyla *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2020**, 083C01 (2020)

## Gauge & Higgs Bosons (reviews)
$\gamma$
gluon
graviton
$W$
$Z$
$H^0$
Neutral Higgs Bosons, Searches for
Charged Higgs Bosons ($H^{\pm}$, $H^{\pm\pm}$)
Heavy Bosons
Axions

## Leptons (reviews)
$e$
$\mu$
$\tau$
Heavy Charged Lepton
Neutrino Properties
Number of Neutrino Types
Double $\beta$-Decay
Neutrino Mixing
Heavy Neutral Leptons

## Quarks (reviews)
Light quarks ($u$, $d$, $s$)
$c$
$b$
$t$
$b'$
$t'$
Free quark

https://pdglive.lbl.gov/

## Mesons (reviews)
Light Unflavored
Further States
Strange
Charmed
Charmed, Strange
Bottom
Bottom, Strange
Bottom, Charmed
$c\bar{c}$ (including possibly non-$q\bar{q}$ states)
$b\bar{b}$ (including possibly non-$q\bar{q}$ states)
Non $q\bar{q}$ Candidates

## Baryons (reviews)
$N$ Baryons
$\Delta$ Baryons
$\Lambda$ Baryons
$\Sigma$ Baryons
$\Xi$ Baryons
$\Omega$ Baryons
Charmed Baryons
Doubly-Charmed
Bottom Baryons
Exotic Baryons

## Other Searches (reviews)
Magnetic Monopole
Supersymmetric Particles
Technicolor
Quark and Lepton Compositeness
Extra Dimensions
WIMPs
Other Particle Searches

## Conservation Laws (reviews)
Discrete Space-Time Symm.
Number Conservation Laws

| Quantity | Symbol, equation | Value | Uncertainty (ppb) |
|---|---|---|---|
| speed of light in vacuum | $c$ | $299\,792\,458$ m s$^{-1}$ | exact |
| Planck constant | $h$ | $6.626\,070\,15\times10^{-34}$ J s (or J/Hz)$^\sharp$ | exact |
| Planck constant, reduced | $\hbar \equiv h/2\pi$ | $1.054\,571\,817\ldots\times10^{-34}$ J s | exact* |
| | | $= 6.582\,119\,569\ldots\times10^{-22}$ MeV s | exact* |
| electron charge magnitude | $e$ | $1.602\,176\,634\times10^{-19}$ C | exact |
| conversion constant | $\hbar c$ | $197.326\,980\,4\ldots$ MeV fm | exact* |
| conversion constant | $(\hbar c)^2$ | $0.389\,379\,372\,1\ldots$ GeV$^2$ mbarn | exact* |
| electron mass | $m_e$ | $0.510\,998\,950\,00(15)$ MeV/$c^2$ $= 9.109\,383\,7015(28)\times10^{-31}$ kg | 0.30 |
| proton mass | $m_p$ | $938.272\,088\,16(29)$ MeV/$c^2$ $= 1.672\,621\,923\,69(51)\times10^{-27}$ kg | 0.31 |
| | | $= 1.007\,276\,466\,621(53)$ u $= 1836.152\,673\,43(11)$ $m_e$ | 0.053, 0.060 |
| neutron mass | $m_n$ | $939.565\,420\,52(54)$ MeV/$c^2$ $= 1.008\,664\,915\,95(49)$ u | 0.57, 0.48 |
| deuteron mass | $m_d$ | $1875.612\,942\,57(57)$ MeV/$c^2$ | 0.30 |
| unified atomic mass unit** | $u = (\text{mass } ^{12}\text{C atom})/12$ | $931.494\,102\,42(28)$ MeV/$c^2$ $= 1.660\,539\,066\,60(50)\times10^{-27}$ kg | 0.30 |
| permittivity of free space | $\epsilon_0 = 1/\mu_0 c^2$ | $8.854\,187\,8128(13)\times10^{-12}$ F m$^{-1}$ | 0.15 |
| permeability of free space | $\mu_0/(4\pi\times10^{-7})$ | $1.000\,000\,000\,55(15)$ N A$^{-2}$ | 0.15 |
| fine-structure constant | $\alpha = e^2/4\pi\epsilon_0\hbar c$ | $7.297\,352\,5693(11)\times10^{-3} = 1/137.035\,999\,084(21)^\dagger$ | 0.15 |
| classical electron radius | $r_e = e^2/4\pi\epsilon_0 m_e c^2$ | $2.817\,940\,3262(13)\times10^{-15}$ m | 0.45 |
| ($e^-$ Compton wavelength)/$2\pi$ | $\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$ | $3.861\,592\,6796(12)\times10^{-13}$ m | 0.30 |
| Bohr radius ($m_{\text{nucleus}} = \infty$) | $a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$ | $0.529\,177\,210\,903(80)\times10^{-10}$ m | 0.15 |
| wavelength of 1 eV/$c$ particle | $hc/(1\text{ eV})$ | $1.239\,841\,984\ldots\times10^{-6}$ m | exact* |
| Rydberg energy | $hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$ | $13.605\,693\,122\,994(26)$ eV | $1.9\times10^{-3}$ |
| Thomson cross section | $\sigma_T = 8\pi r_e^2/3$ | $0.665\,245\,873\,21(60)$ barn | 0.91 |
| Bohr magneton | $\mu_B = e\hbar/2m_e$ | $5.788\,381\,8060(17)\times10^{-11}$ MeV T$^{-1}$ | 0.3 |
| nuclear magneton | $\mu_N = e\hbar/2m_p$ | $3.152\,451\,258\,44(96)\times10^{-14}$ MeV T$^{-1}$ | 0.31 |
| electron cyclotron freq./field | $\omega^e_{\text{cycl}}/B = e/m_e$ | $1.758\,820\,010\,76(53)\times10^{11}$ rad s$^{-1}$ T$^{-1}$ | 0.30 |
| proton cyclotron freq./field | $\omega^p_{\text{cycl}}/B = e/m_p$ | $9.578\,833\,1560(29)\times10^{7}$ rad s$^{-1}$ T$^{-1}$ | 0.31 |

| | | | |
|---|---|---|---|
| gravitational constant‡ | $G_N$ | $6.674\,30(15)\times10^{-11}$ m$^3$ kg$^{-1}$ s$^{-2}$ | $2.2\times10^4$ |
| | | $= 6.708\,83(15)\times10^{-39}\ \hbar c\ (\text{GeV}/c^2)^{-2}$ | $2.2\times10^4$ |
| standard gravitational accel. | $g_N$ | $9.806\,65$ m s$^{-2}$ | exact |
| Avogadro constant | $N_A$ | $6.022\,140\,76\times10^{23}$ mol$^{-1}$ | exact |
| Boltzmann constant | $k$ | $1.380\,649\times10^{-23}$ J K$^{-1}$ | exact |
| | | $= 8.617\,333\,262\ldots\times10^{-5}$ eV K$^{-1}$ | exact* |
| molar volume, ideal gas at STP | $N_A k$ (273.15 K)/(101 325 Pa) | $22.413\,969\,54\ldots\times10^{-3}$ m$^3$ mol$^{-1}$ | exact* |
| Wien displacement law constant | $b=\lambda_{\max}T$ | $2.897\,771\,955\ldots\times10^{-3}$ m K | exact* |
| Stefan-Boltzmann constant | $\sigma=\pi^2k^4/60\hbar^3c^2$ | $5.670\,374\,419\ldots\times10^{-8}$ W m$^{-2}$ K$^{-4}$ | exact* |
| Fermi coupling constant‡‡ | $G_F/(\hbar c)^3$ | $1.166\,378\,7(6)\times10^{-5}$ GeV$^{-2}$ | 510 |
| weak-mixing angle | $\sin^2\widehat{\theta}(M_Z)$ ($\overline{\text{MS}}$) | $0.231\,22(4)^{\dagger\dagger}$ | $1.7\times10^5$ |
| $W^\pm$ boson mass | $m_W$ | $80.379(12)$ GeV/$c^2$ | $1.5\times10^5$ |
| $Z^0$ boson mass | $m_Z$ | $91.1876(21)$ GeV/$c^2$ | $2.3\times10^4$ |
| strong coupling constant | $\alpha_s(m_Z)$ | $0.1179(10)$ | $8.5\times10^6$ |

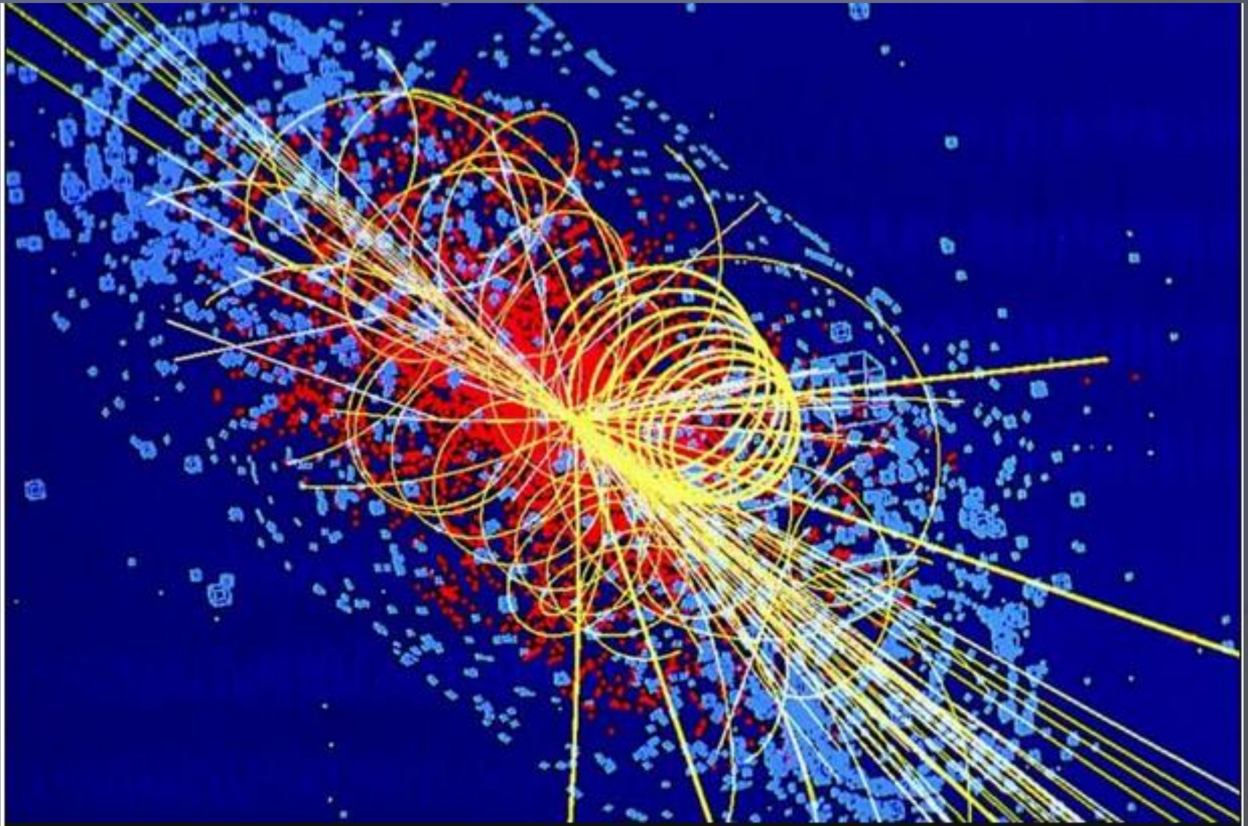
$\pi = 3.141\,592\,653\,589\,793\,238\ldots$ $e = 2.718\,281\,828\,459\,045\,235\ldots$ $\gamma = 0.577\,215\,664\,901\,532\,860\ldots$

| | | | |
|---|---|---|---|
| 1 in ≡ 0.0254 m | 1 G ≡ $10^{-4}$ T | 1 eV = $1.602\ 176\ 634\times10^{-19}$ J (exact) | $kT$ at 300 K = $[38.681\ 740(22)]^{-1}$ eV |
| 1 Å ≡ 0.1 nm | 1 dyne ≡ $10^{-5}$ N | (1 kg)$c^2$ = $5.609\ 588\ 603\ldots\times10^{35}$ eV (exact*) | 0 °C ≡ 273.15 K |
| 1 barn ≡ $10^{-28}$ m$^2$ | 1 erg ≡ $10^{-7}$ J | 1 C = $2.997\ 924\ 58\times10^9$ esu | 1 atmosphere ≡ 760 Torr ≡ 101 325 Pa |

♯ CODATA recommends that the unit be J/Hz to stress that in $h = E/\nu$ the frequency $\nu$ is in cycles/sec (Hz), not radians/sec.
* These are calculated from exact values and are exact to the number of places given (*i.e.* no rounding).
** The molar mass of $^{12}$C is 11.999 999 9958(36) g.
† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is $\sim 1/128$.
‡ Absolute laboratory measurements of $G_N$ have been made only on scales of about 1 cm to 1 m.
‡‡ See the discussion in Sec. 10, "Electroweak model and constraints on new physics."
†† The corresponding $\sin^2\theta$ for the effective angle is 0.23155(4).

# 2. De unde obținem informații despre particule?

- ciocniri
- dezintegrări
- stări legate



Simulation of a particle collision in which a Higgs boson is produced (Image: Lucas Taylor/CMS) particle physics collisions: cross section $\sigma_{fi}$ $= \frac{W_{fi}}{(initial\ flux)}(number\ of\ \ final\ states)$

ciocniri: secțiune eficace de împrăștiere

$$d\sigma = \frac{|M|^2}{F}\,dQ$$

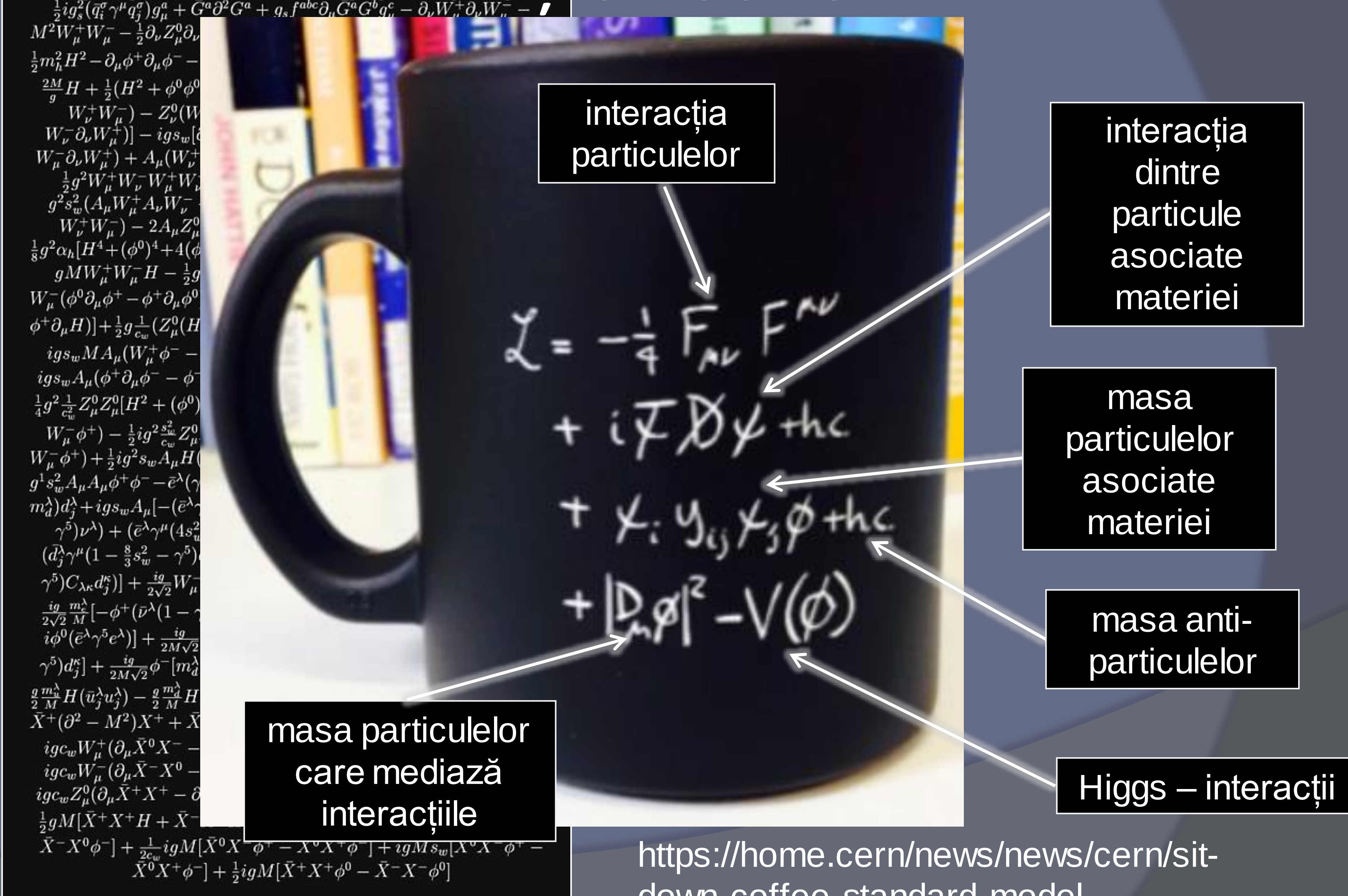
M – amplitudine de tranziție

$$\sigma_{\text{tot}}(\mathrm{a}_1 + \mathrm{a}_2 \to \mathrm{b}'_1 + \cdots + \mathrm{b}'_m) = \frac{1}{2w(s, m_1^2, m_2^2)} \cdot \int \prod_{i=1}^{m} \left( \frac{\mathrm{d}p'_i}{(2\pi)^3} \delta_+(p_i'^2 - m_i'^2) \right) (2\pi)^4 \delta(p'_1 + \cdots + p'_m - p_1 - p_2) \cdot |\langle \mathrm{b}_1(p'_1) \ldots \mathrm{b}_m(p'_m)| \mathbf{T} | \mathrm{a}_1(p_1) \mathrm{a}_2(p_2) \rangle|^2.$$

dezintegrări: rata de dezintegrare

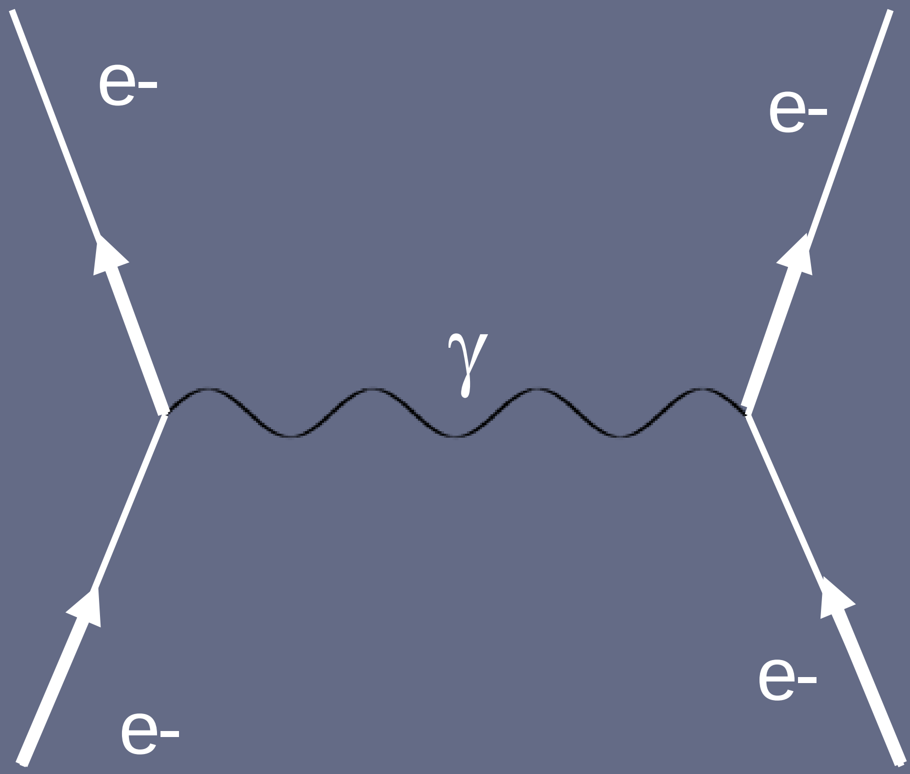
$$\mathrm{d}\Gamma(\mathrm{a}(p) \to \mathrm{b}_1(p'_1) + \cdots + \mathrm{b}_m(p'_m)) = \frac{1}{2m_{\mathrm{a}}}(2\pi)^4 \delta(p'_1 + \cdots + p'_m - p) \cdot \prod_{i=1}^{m} \frac{\mathrm{d}^3 p'_i}{(2\pi)^3 2p_i'^0} |\langle \mathrm{b}_1(p'_1) \ldots \mathrm{b}_m(p'_m)| \mathbf{T} | \mathrm{a}(p) \rangle|^2.$$

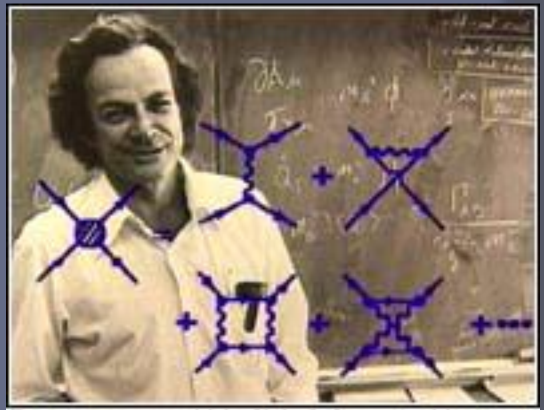
# Cum interacționează?




https://home.cern/news/news/cern/sit-down-coffee-standard-model

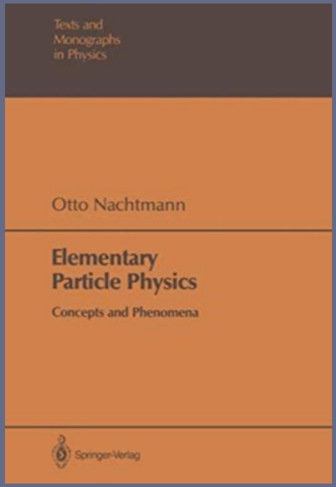
# Feynman – diagrame și reguli



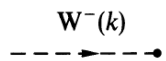
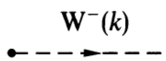
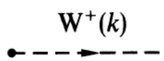
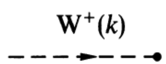
Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)

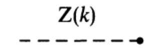
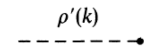
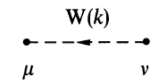
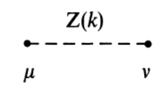
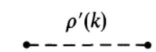
# Feynman – diagrame și reguli
# Electrodinamică cuantică



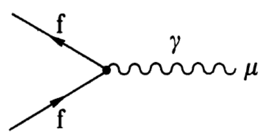
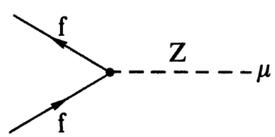
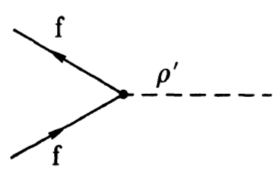
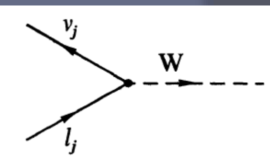
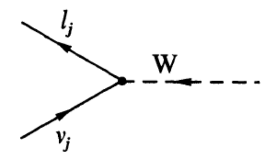
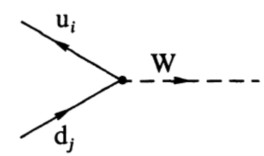
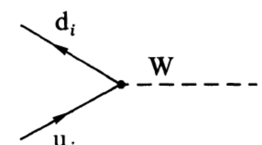

| | | |
|---|---|---|
| electron in initial state $u(p)$ | incoming electron line | $e^-(p)$ |
| electron in final state $\bar{u}(p)$ | outgoing electron line | $e^-(p)$ |
| positron in initial state $\bar{v}(q)$ | outgoing electron line | $e^+(q)$ |
| positron in final state $v(q)$ | incoming electron line | $e^+(q)$ |
| photon in initial state $\varepsilon^\mu$ | incoming photon line | $\gamma(k)$ |
| photon in final state $\varepsilon^{\mu *}$ | outgoing photon line | $\gamma(k)$ |
| virtual photon $\frac{-ig_{\mu\nu}}{k^2 + i\varepsilon}$ | internal photon line | $k$; $\mu$, $\nu$ |
| virtual electron $i\frac{\not{p} + m}{p^2 - m^2 + i\varepsilon}$ | internal electron line | $p$ |
| elementary process $ie\gamma^\mu$ | vertex | |

# Feynman – diagrame și reguli

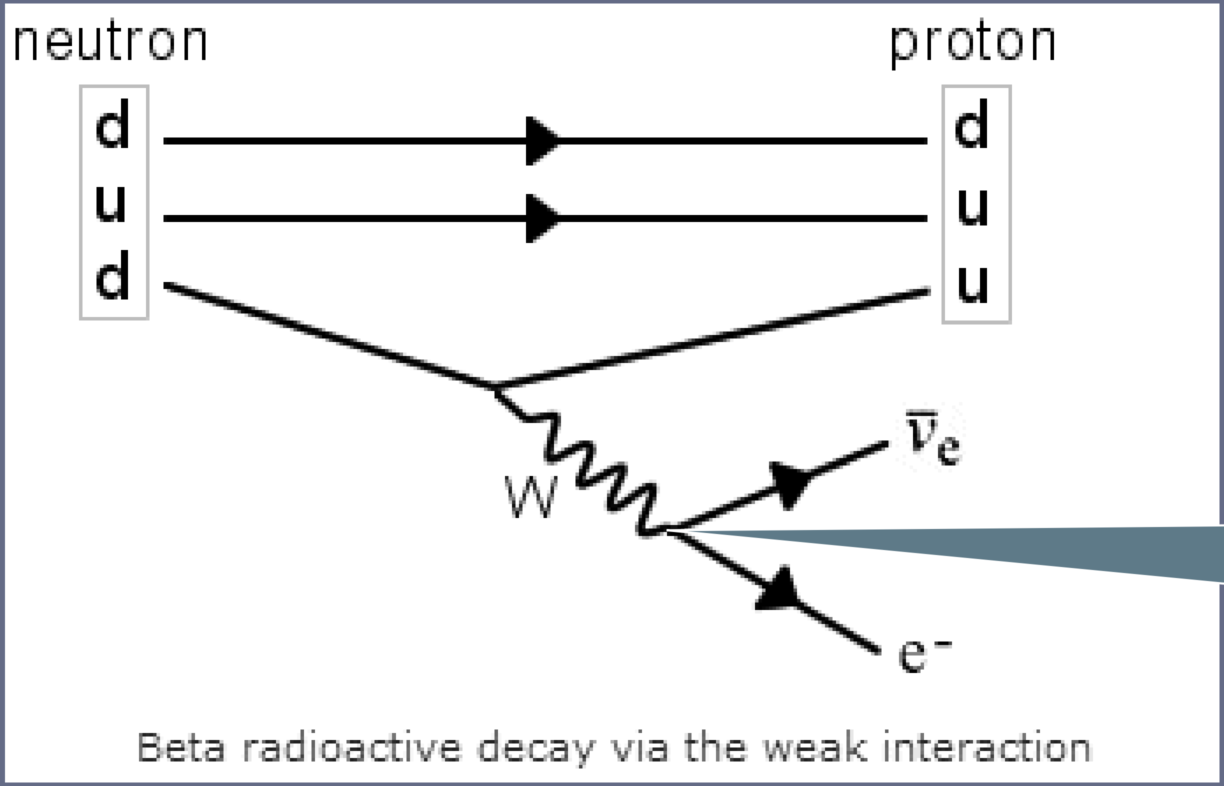
| | | |
|---|---|---|
| $W^-$ initial state | incoming W line | |
| $\varepsilon(k)$ | |  |
| $W^-$ in final state | outgoing W line | |
| $\varepsilon^*(k)$ | |  |
| $W^+$ in initial state | outgoing W line | |
| $\varepsilon(k)$ | |  |
| $W^+$ in final state | incoming W line | |
| $\varepsilon^*(k)$ | |  |

| | | |
|---|---|---|
| Z in initial (final) state | external Z line | |
| $\varepsilon(k)(\varepsilon^*(k))$ | |  |
| Higgs particle in initial (final) state | external $\rho'$ line | |
| 1 | |  |
| virtual W boson | internal W line | |
| $\dfrac{i\left(-g^{\mu\nu}+\dfrac{k^\mu k^\nu}{m_W^2}\right)}{k^2-m_W^2+i\varepsilon}$ | |  |
| virtual Z boson | internal Z line | |
| $\dfrac{i\left(-g^{\mu\nu}+\dfrac{k^\mu k^\nu}{m_Z^2}\right)}{k^2-m_Z^2+i\varepsilon}$ | |  |
| virtual Higgs particle | internal $\rho'$ line | |
| $\dfrac{i}{k^2-m_{\rho'}^2+i\varepsilon}$ | |  |

Fermion–Boson vertices:

| | |
|---|---|
| $-ieQ_f\gamma^\mu$ |  |
| $-i\dfrac{e}{\sin\vartheta_W\cos\vartheta_W}\left\{T_3^f\gamma^\mu\dfrac{1-\gamma_5}{2}-\sin^2\vartheta_W Q_f\gamma^\mu\right\}$ |  |
| $-i\dfrac{m_f}{\rho_0}$ |  |
| $-i\dfrac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\dfrac{1-\gamma_5}{2}$ |  |
| $-i\dfrac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\dfrac{1-\gamma_5}{2}$ |  |
| $-i\dfrac{e}{\sqrt{2}\sin\vartheta_W}V_{ij}\gamma^\mu\dfrac{1-\gamma_5}{2}$ |  |
| $-i\dfrac{e}{\sqrt{2}\sin\vartheta_W}V_{ji}^*\gamma^\mu\dfrac{1-\gamma_5}{2}$ |  |

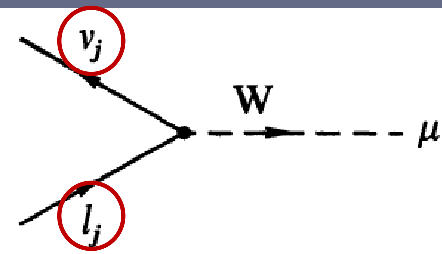
# Feynman – diagrame și reguli



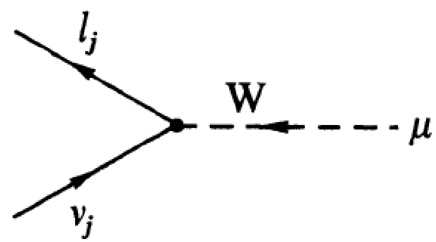

Sarcina electrică se conservă la fiecare vertex

# Feynman – diagrame și reguli

$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$




$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$



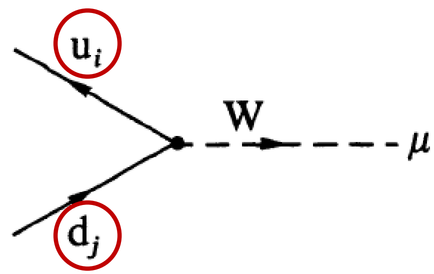

$\nu_1 \equiv \nu_e$, $\nu_2 \equiv \nu_\mu$, $\nu_3 \equiv \nu_\tau$;

$\ell_1 \equiv e$, $\ell_2 \equiv \mu$, $\ell_3 \equiv \tau$;

$u_1 \equiv u$, $u_2 \equiv c$, $u_3 \equiv t$;

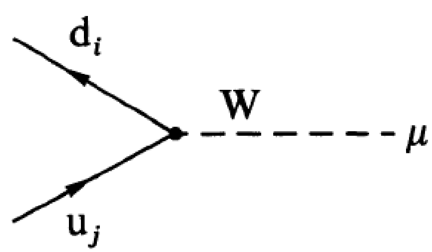
$d_1 \equiv d$, $d_2 \equiv s$, $d_3 \equiv b$.

$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ij}\gamma^\mu\frac{1-\gamma_5}{2}$$

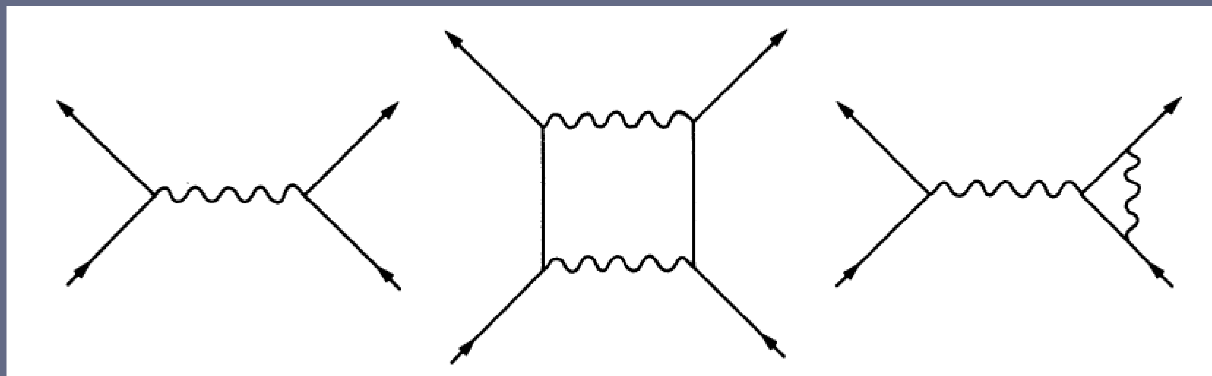


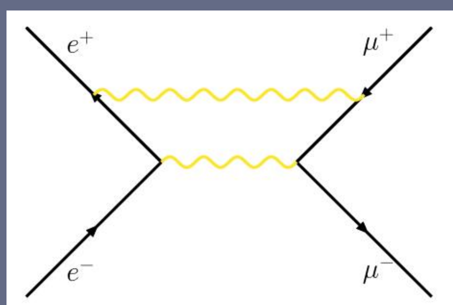

matricea de mixing a cuarcilor
(Cabibbo–Kobayashi–Maskawa)

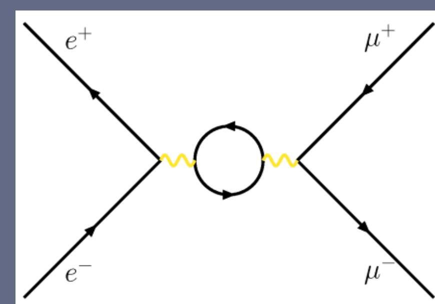
$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ji}^*\gamma^\mu\frac{1-\gamma_5}{2}$$

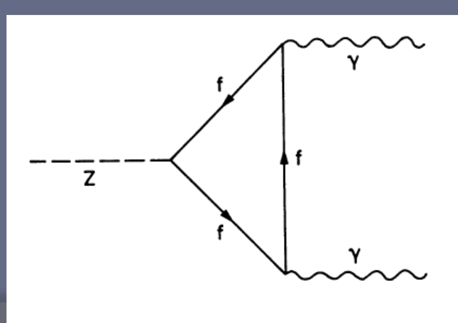


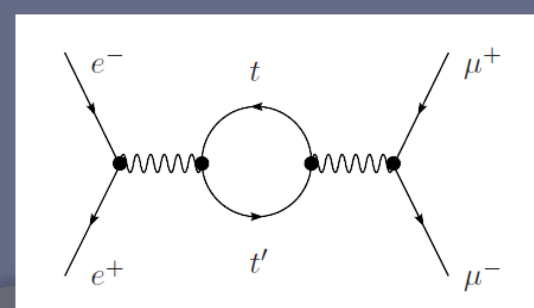
# ...și mai multe!
# Teoria perturbațiilor – corecții

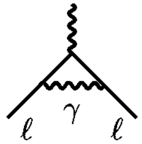




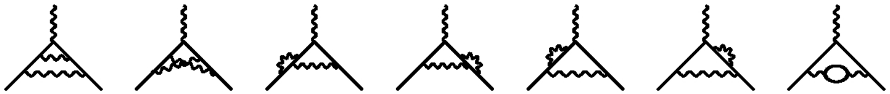



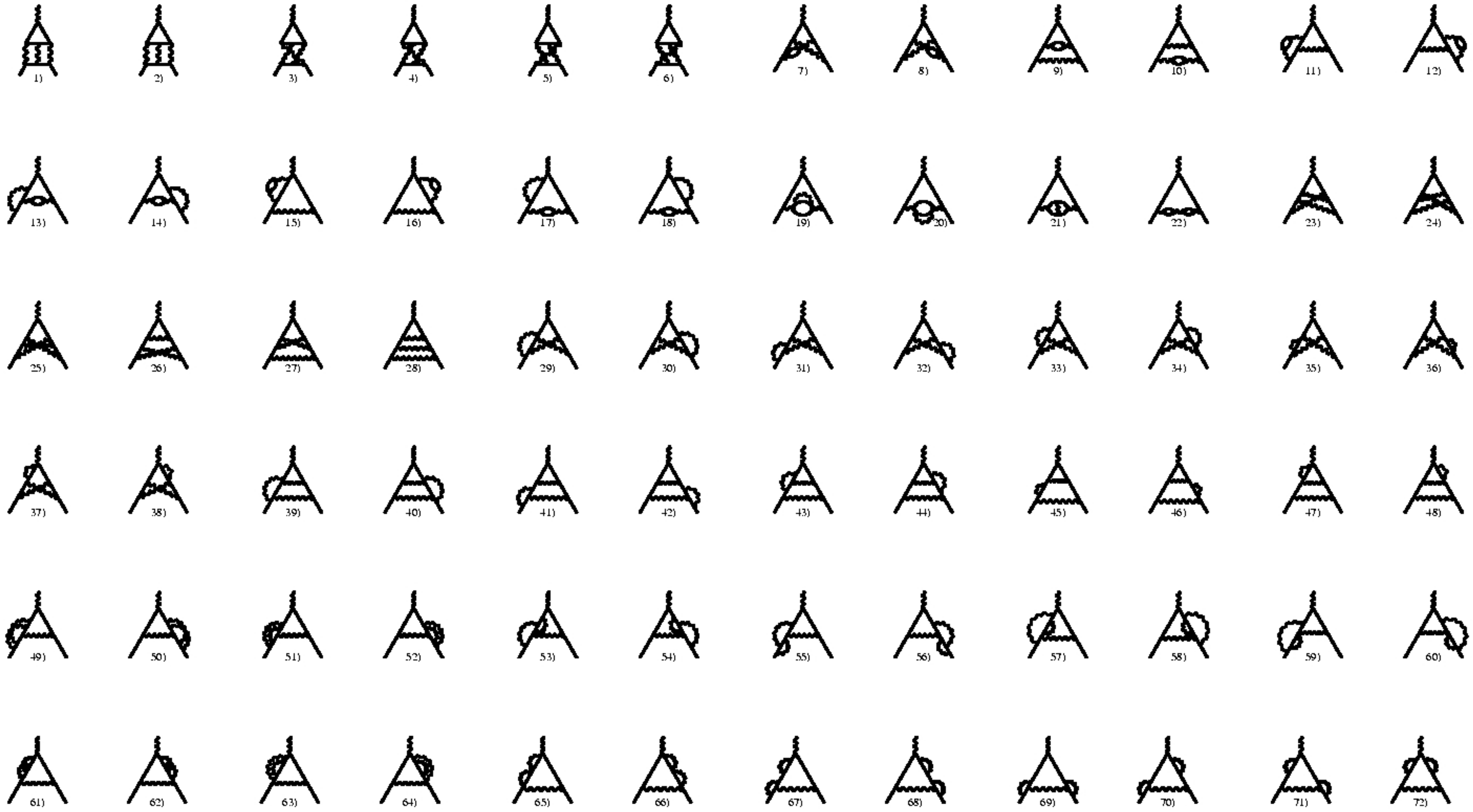






$(g\text{-}2)_\ell$

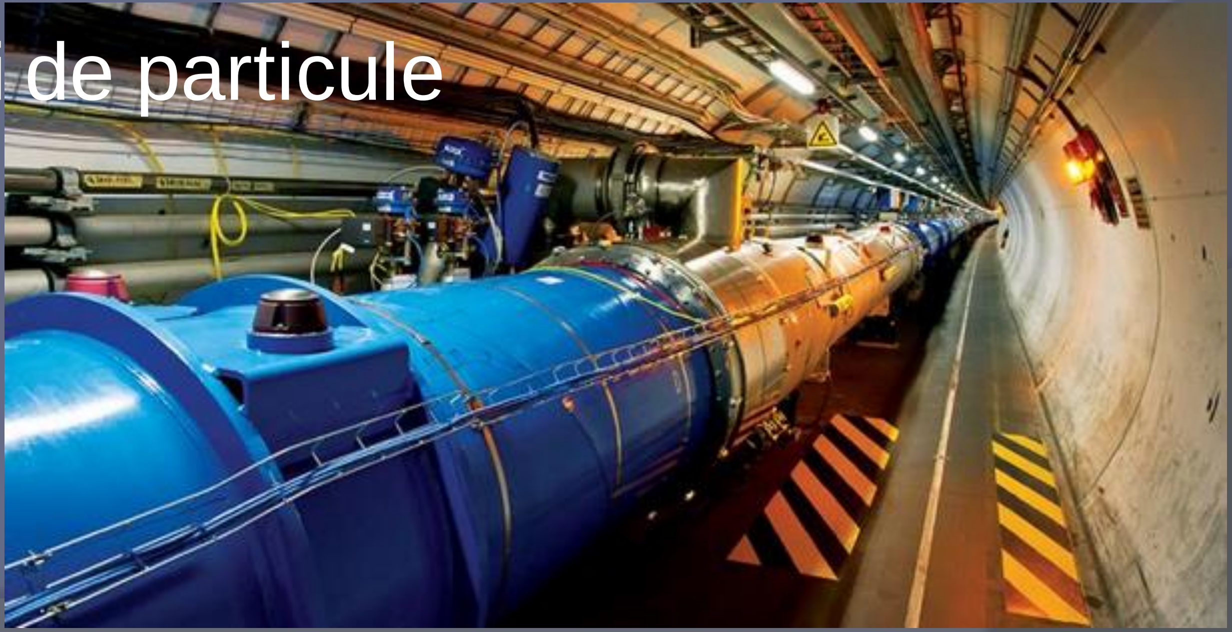
$\ell = e, \mu, \tau$





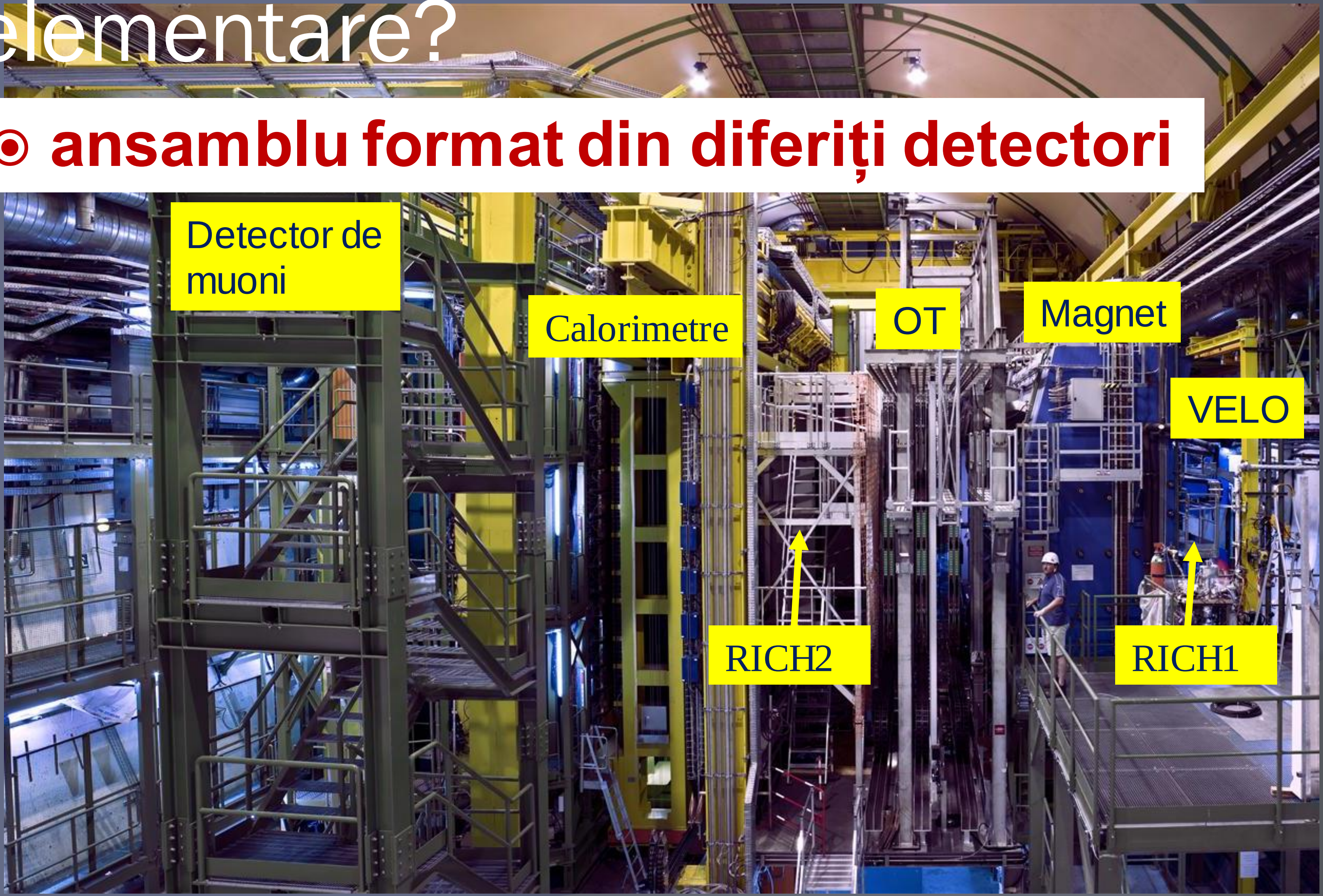
# 3. Cum producem particule elementare?

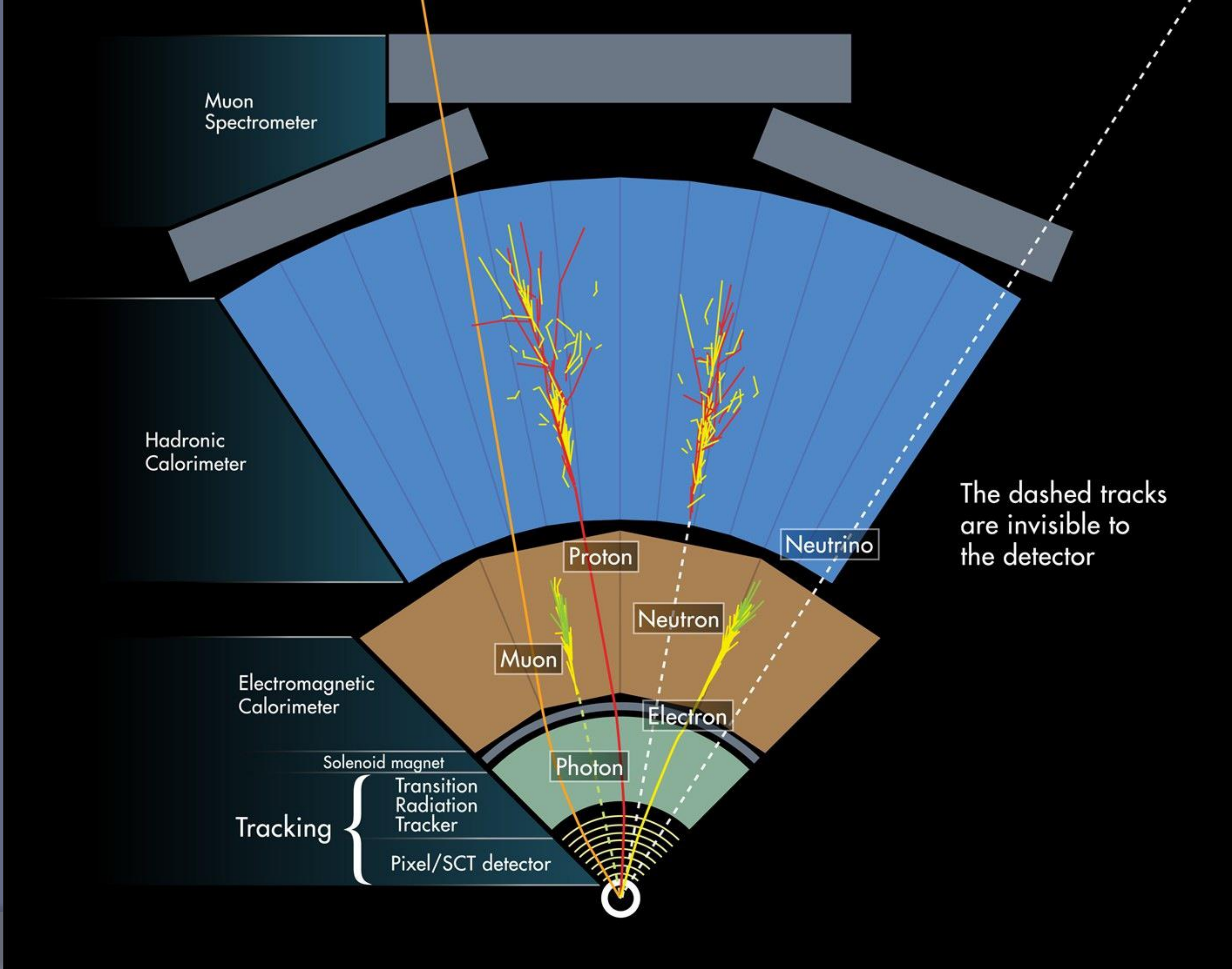
- metode simple pentru electroni, protoni (e.g. ionizări)
- radiații cosmice
- reactori nucleari
- acceleratori de particule



# 4. Cum detectăm particule elementare?

- **ansamblu format din diferiți detectori**




Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
The dashed tracks are invisible to the detector

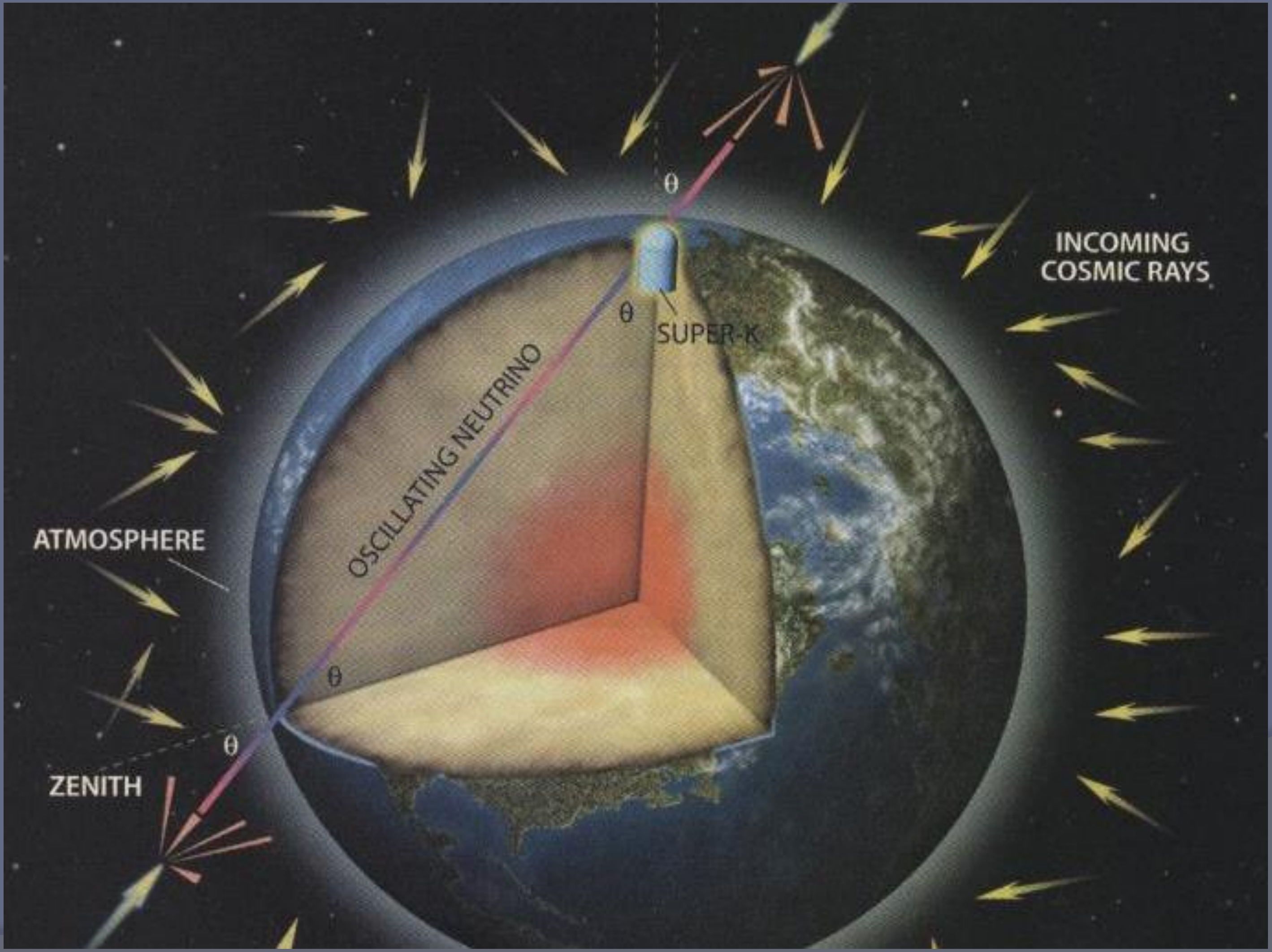
- Din ce este constituită materia?
- Din ce este compus universul?
- Care este originea universului și cum a evoluat?
- De ce se comportă așa universul?
- Cum va evolua?
- ....

Modelul Standard – răspunsul la toate întrebările?

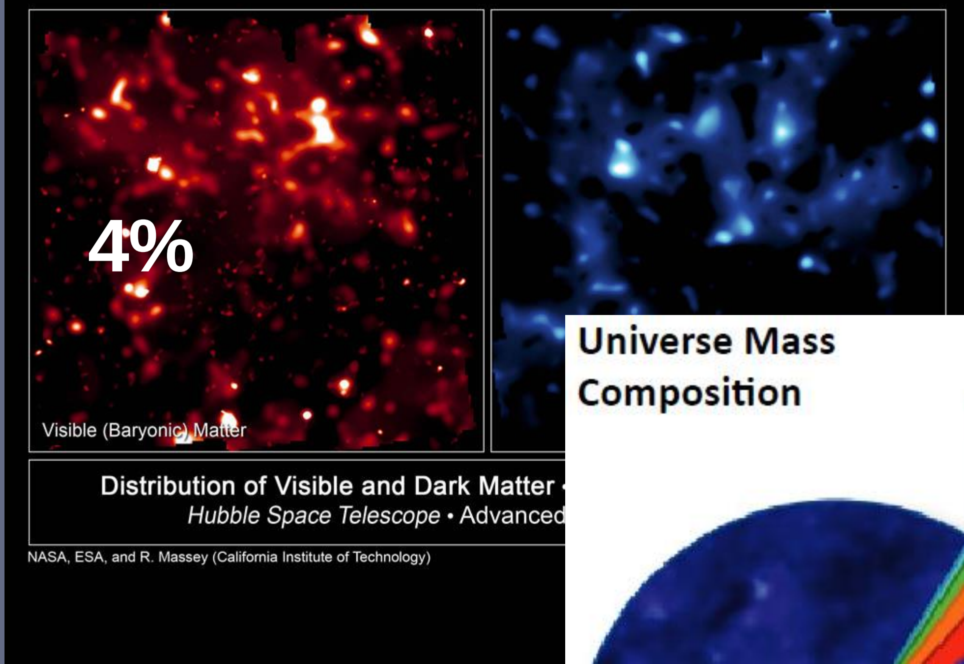
- **NU!**

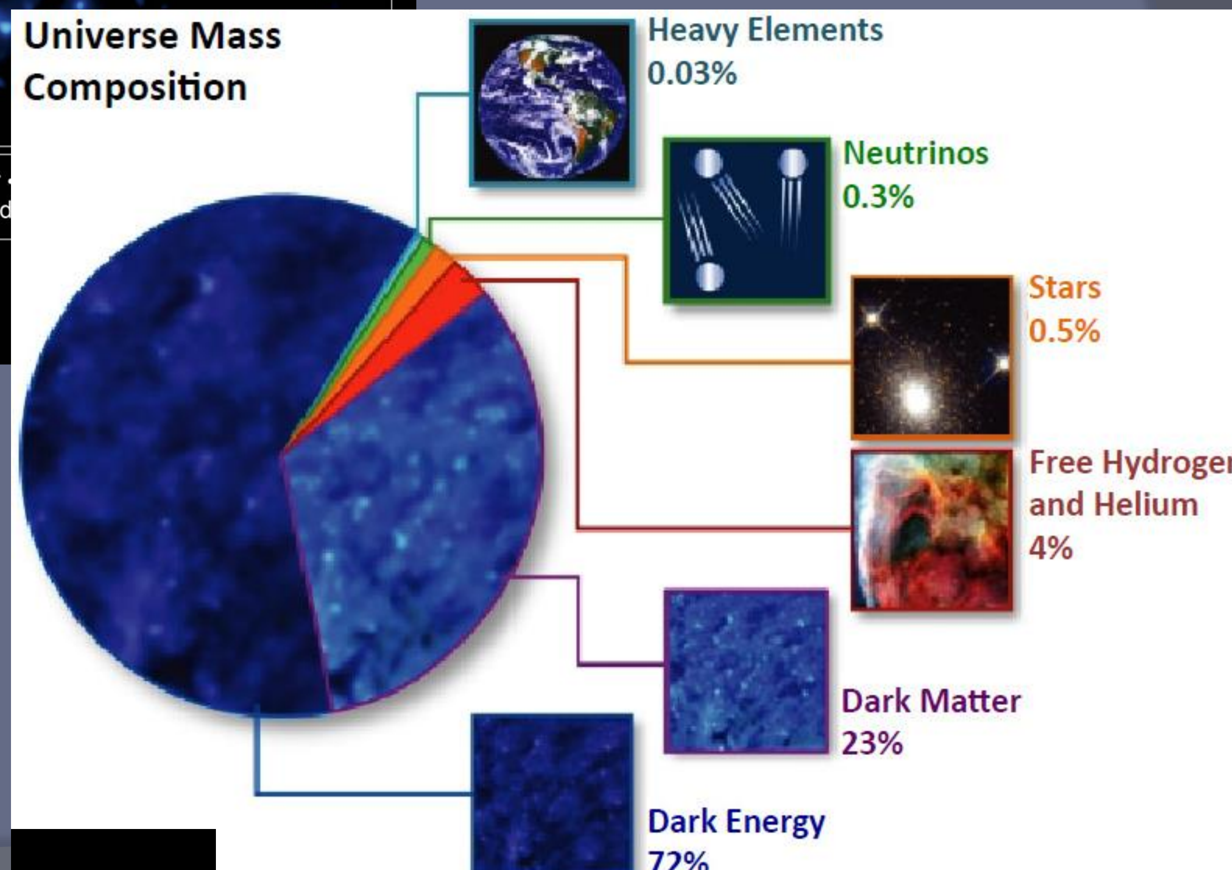
# Cum acomodăm în teorie masa neutrinilor?

matricea de mixing a neutrinilor?



# Ce este „dark matter”?



# De ce în univers există mai multă materie decât antimaterie?

- Există cantități mari de materie, dar nu și dovada unor cantități mari de antimaterie.

**violarea conservării sarcinii și parității**

**CP – charge-parity**

beauty

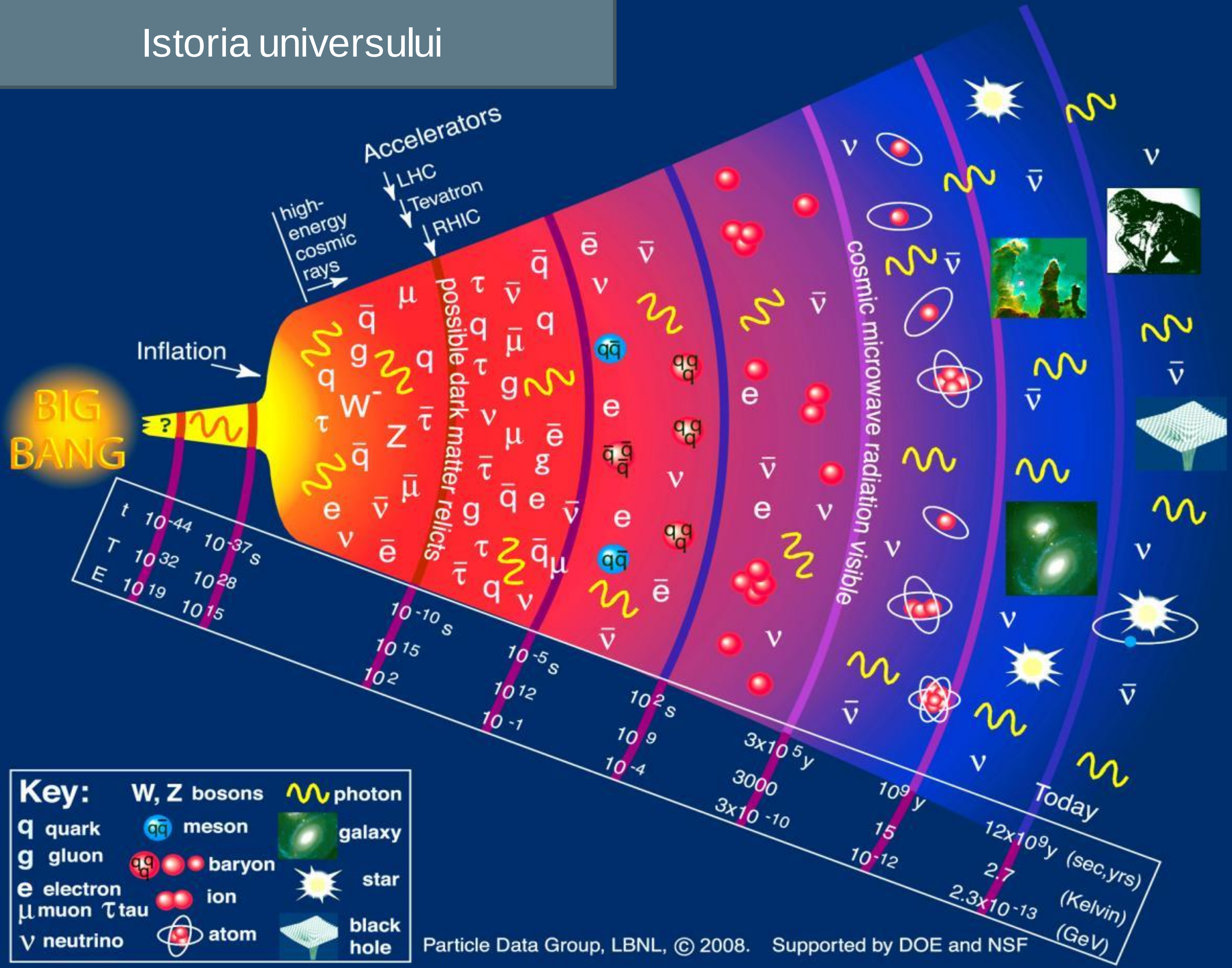
$B^0$

**CP**

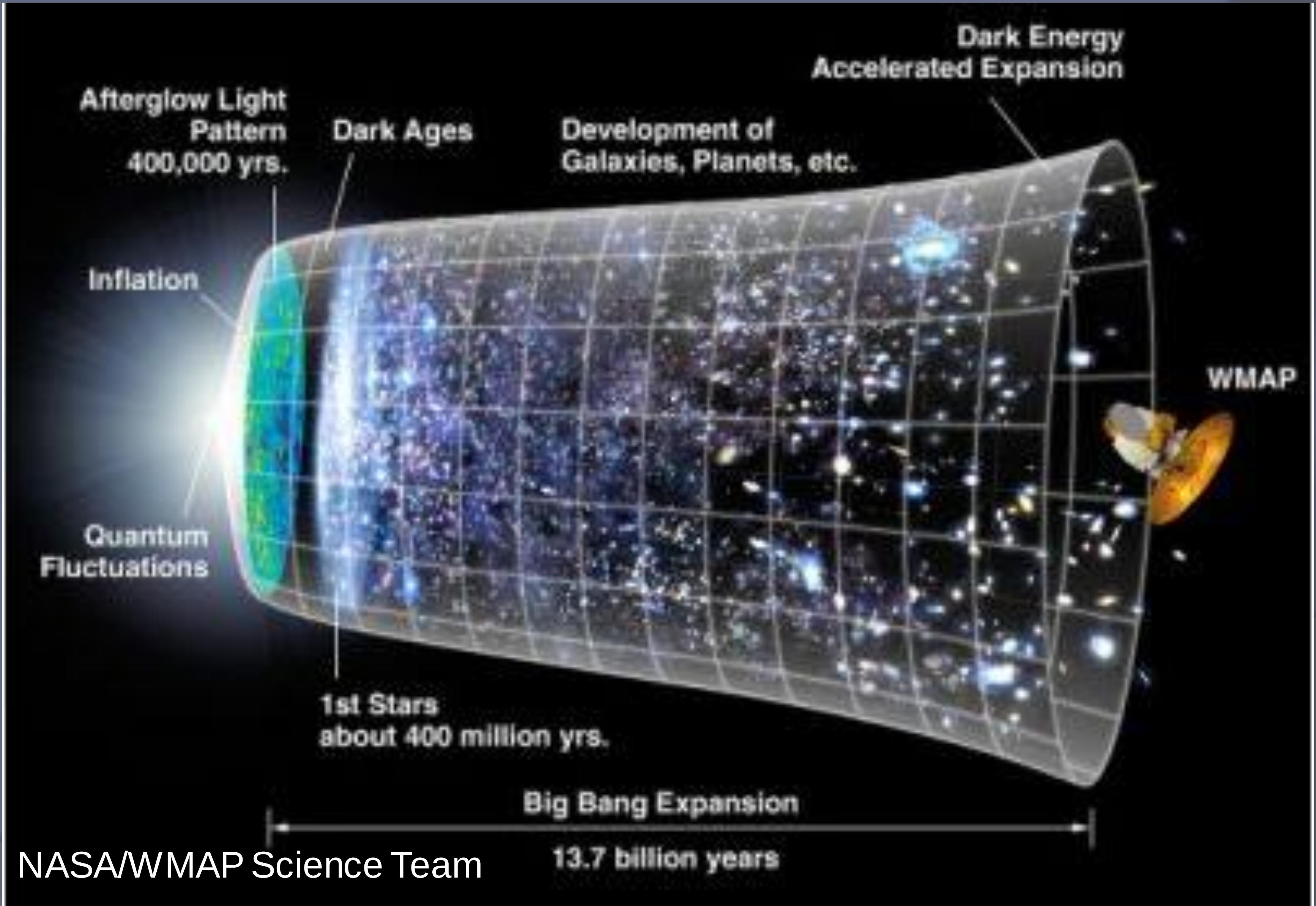
anti-beauty

$\overline{B}^0$

# Istoria universului



# Ce face universul astăzi și cum va evolua?




NASA/WMAP Science Team

# Fizica particulelor

1. Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, ...)?
2. Cum interacționează? - De unde obținem informații?
3. Cum producem particule elementare?
4. Cum detectăm particule elementare?

**Fizică, acceleratori și detectori @CERN**

...va urma!