Le costanti fondamentali del modello standard

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Unità di Misura del SI

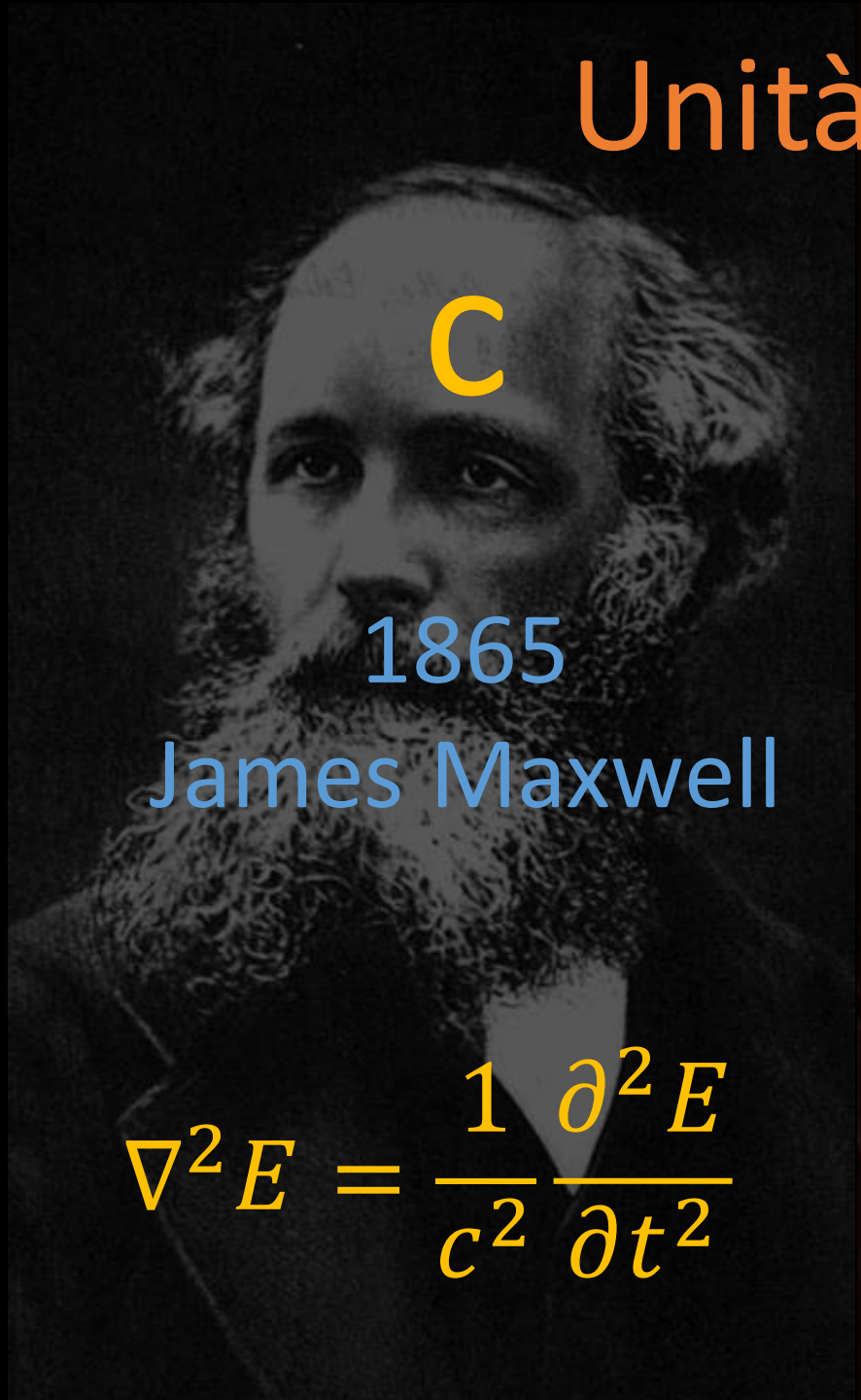
Lunghezza - Massa - tempo

m - kg - s

m	1/10M meridiano terrestre
kg	massa di 1 dm^3 d’acqua
s	frequenza del battito cardiaco

profondamente antropiche

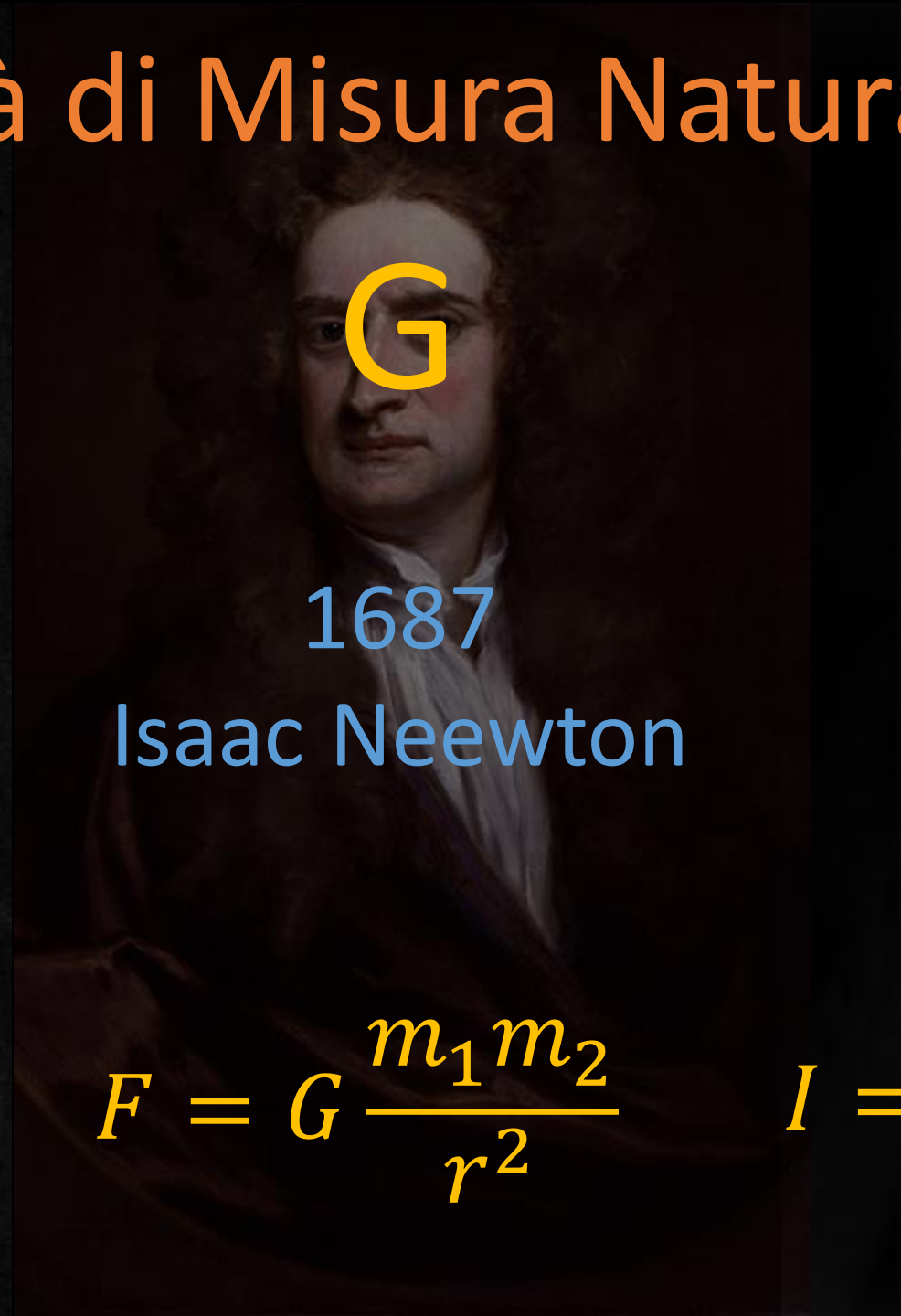
Unità di Misura Naturali



c

1865
James Maxwell

$$\nabla^2 E = \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}$$



G

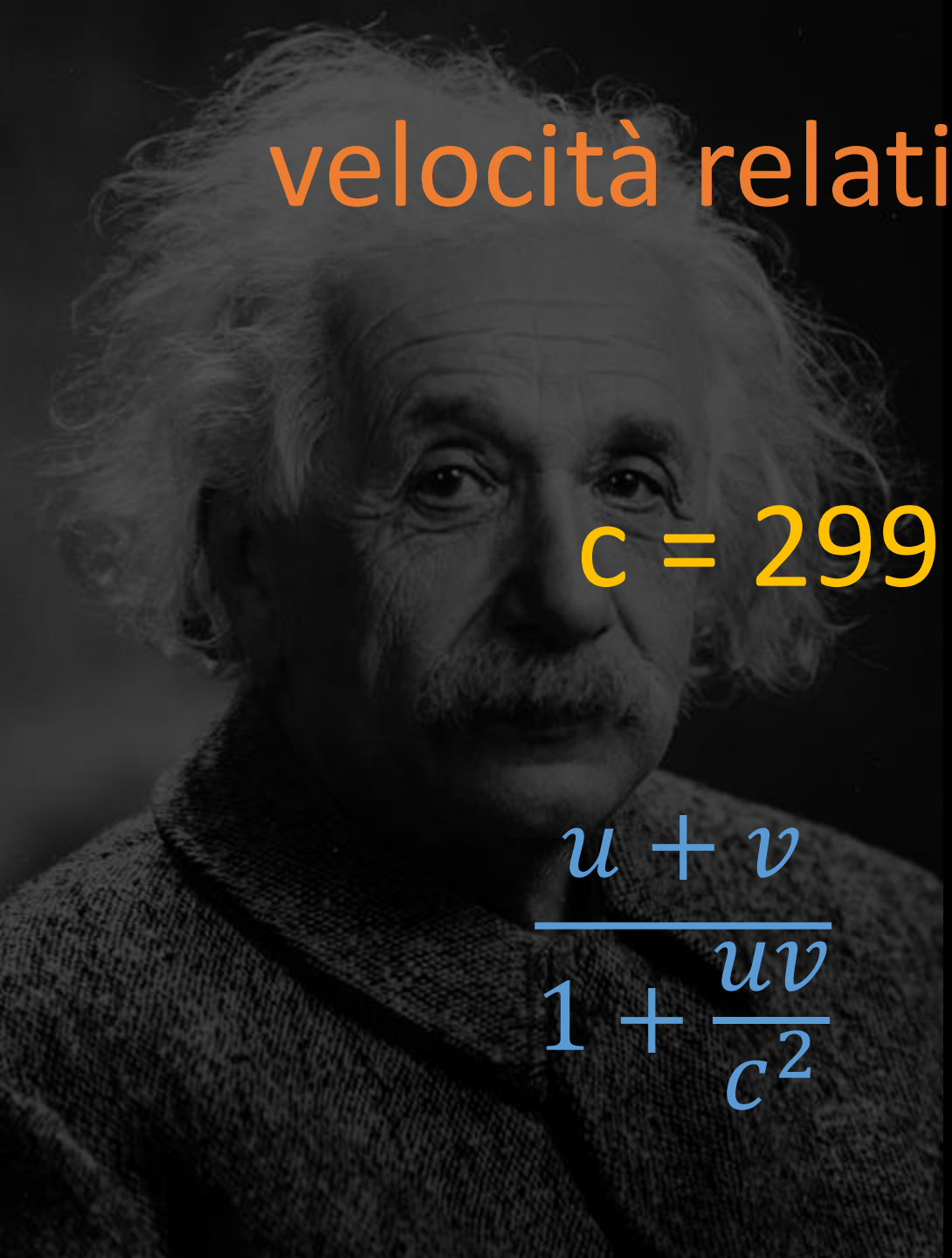
1687
Isaac Neewton

$$F = G\frac{m_1 m_2}{r^2}$$

ℏ

1900
Max Planck

$$I = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

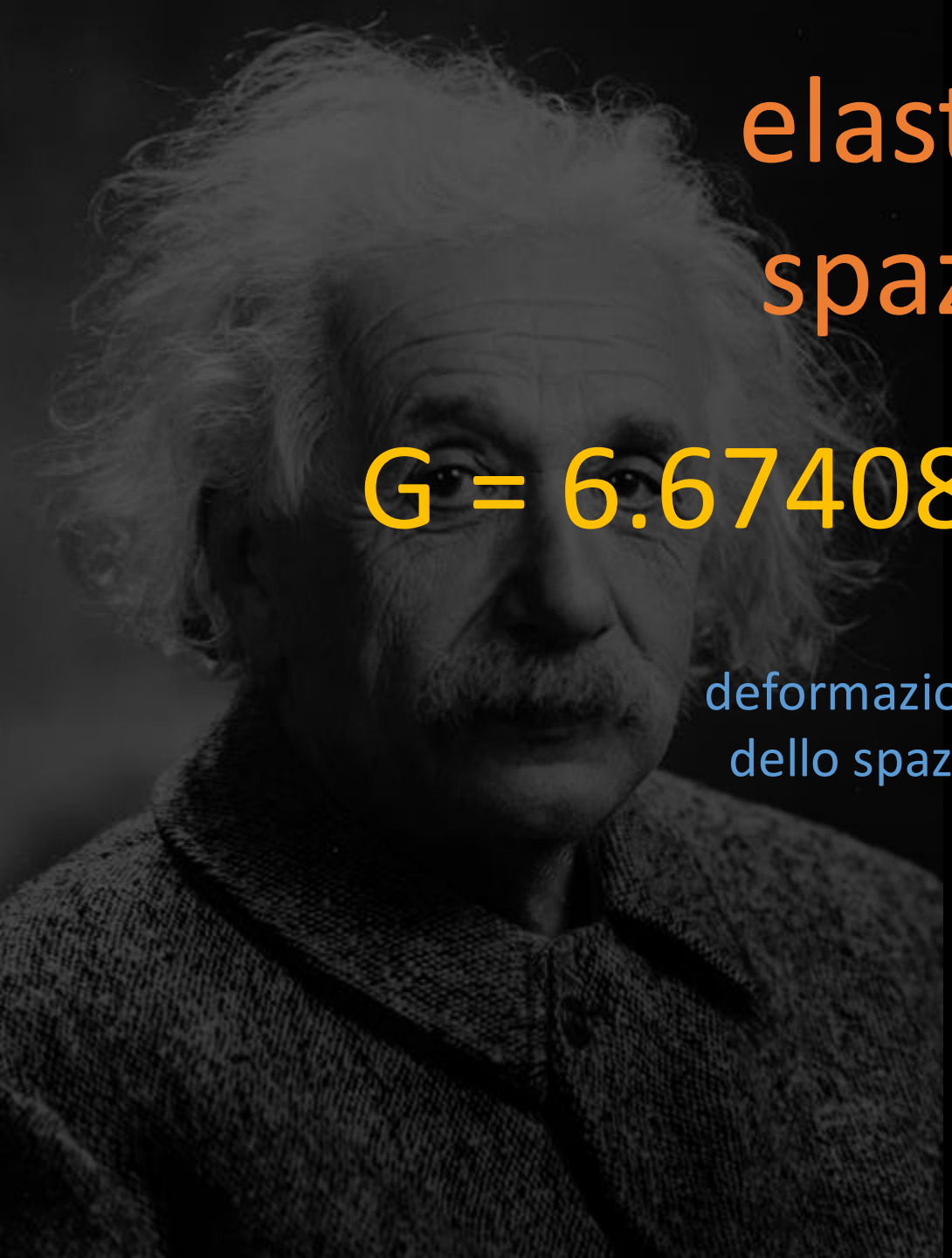


velocità relativa massima tra due corpi

c = 299 792 458 m/s

$$\frac{u+v}{1+\frac{uv}{c^2}}$$

$$\frac{c+c}{1+\frac{cc}{c^2}} = c$$



elasticità dello spazio-tempo

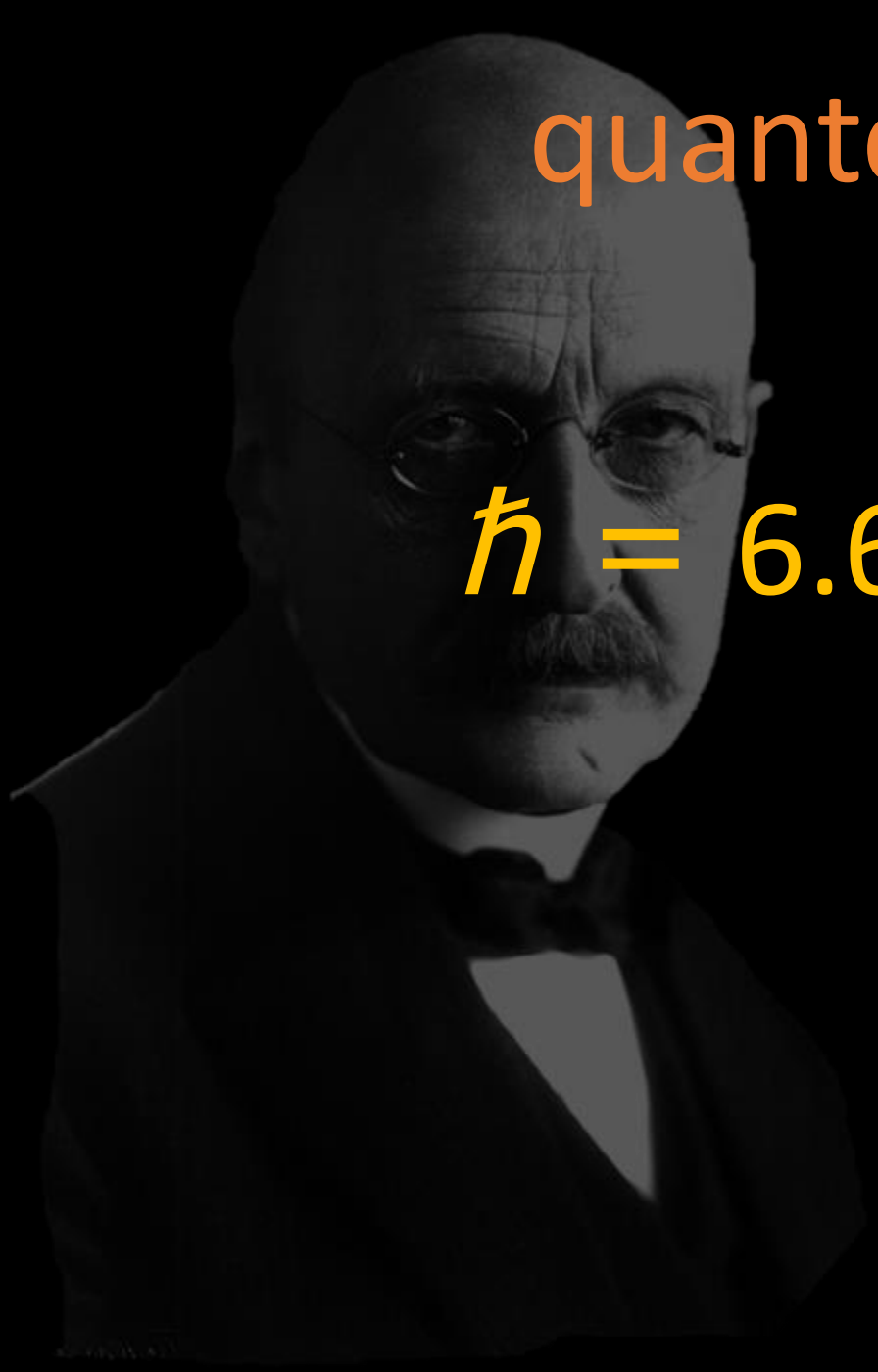
$G = 6.67408 \times 10^{-11}\ \mathrm{N \cdot m^2/kg^2}$

deformazione dello spazio

densità di materia

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$x = -\frac{1}{k} F$$



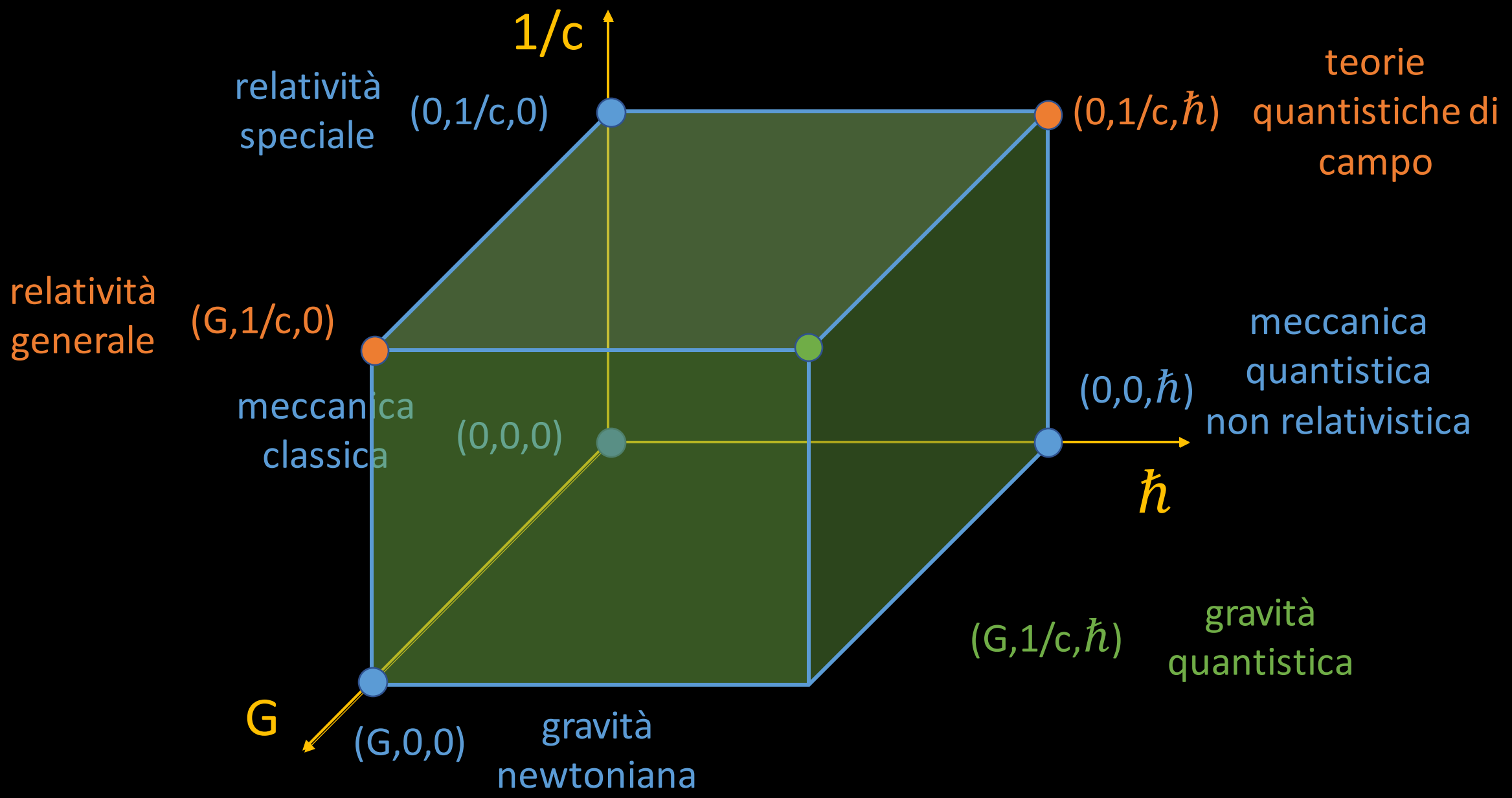
quanto minimo di azione

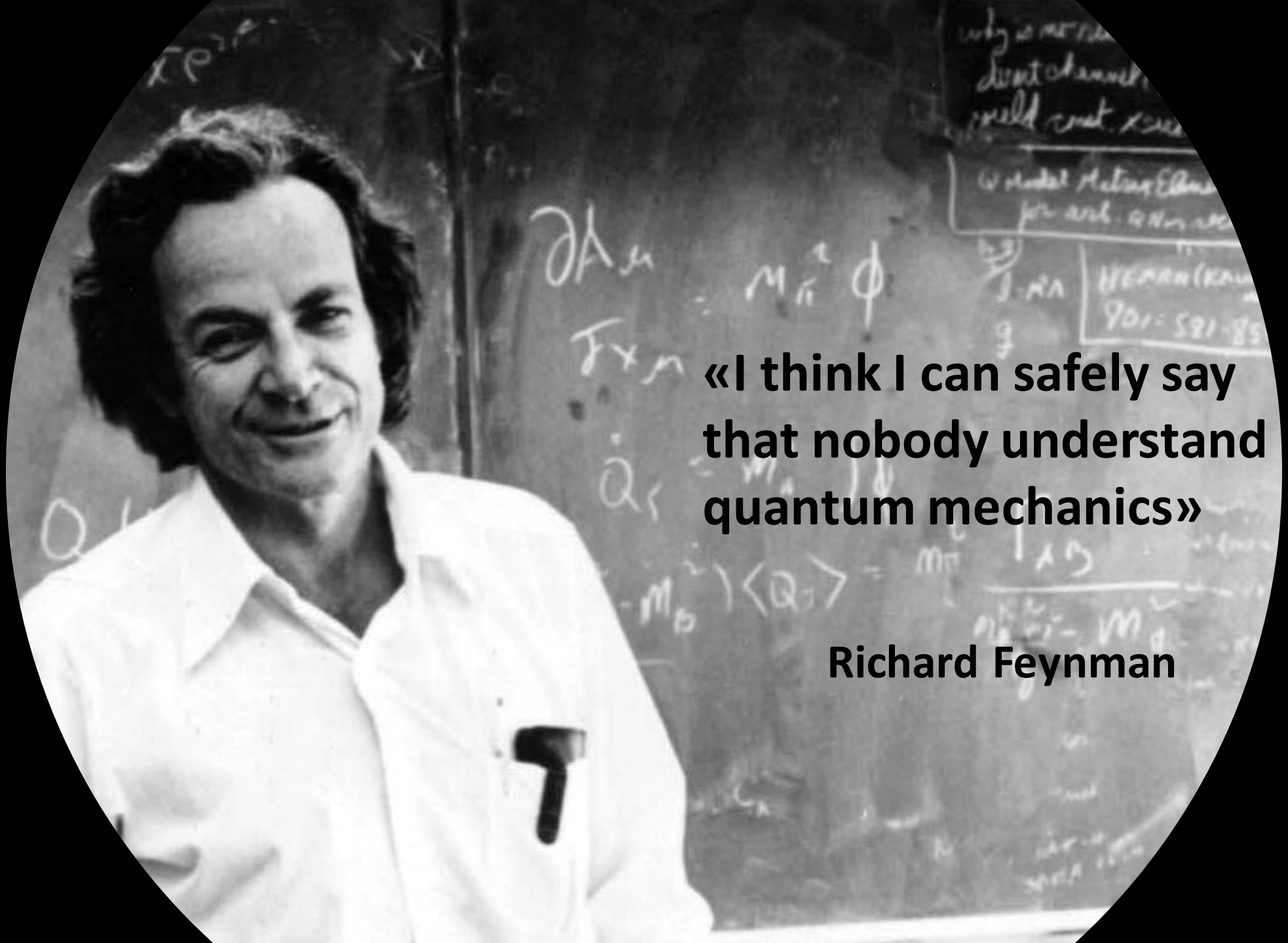
$\hbar = 6.62607004 \times 10^{-34}$ J·s

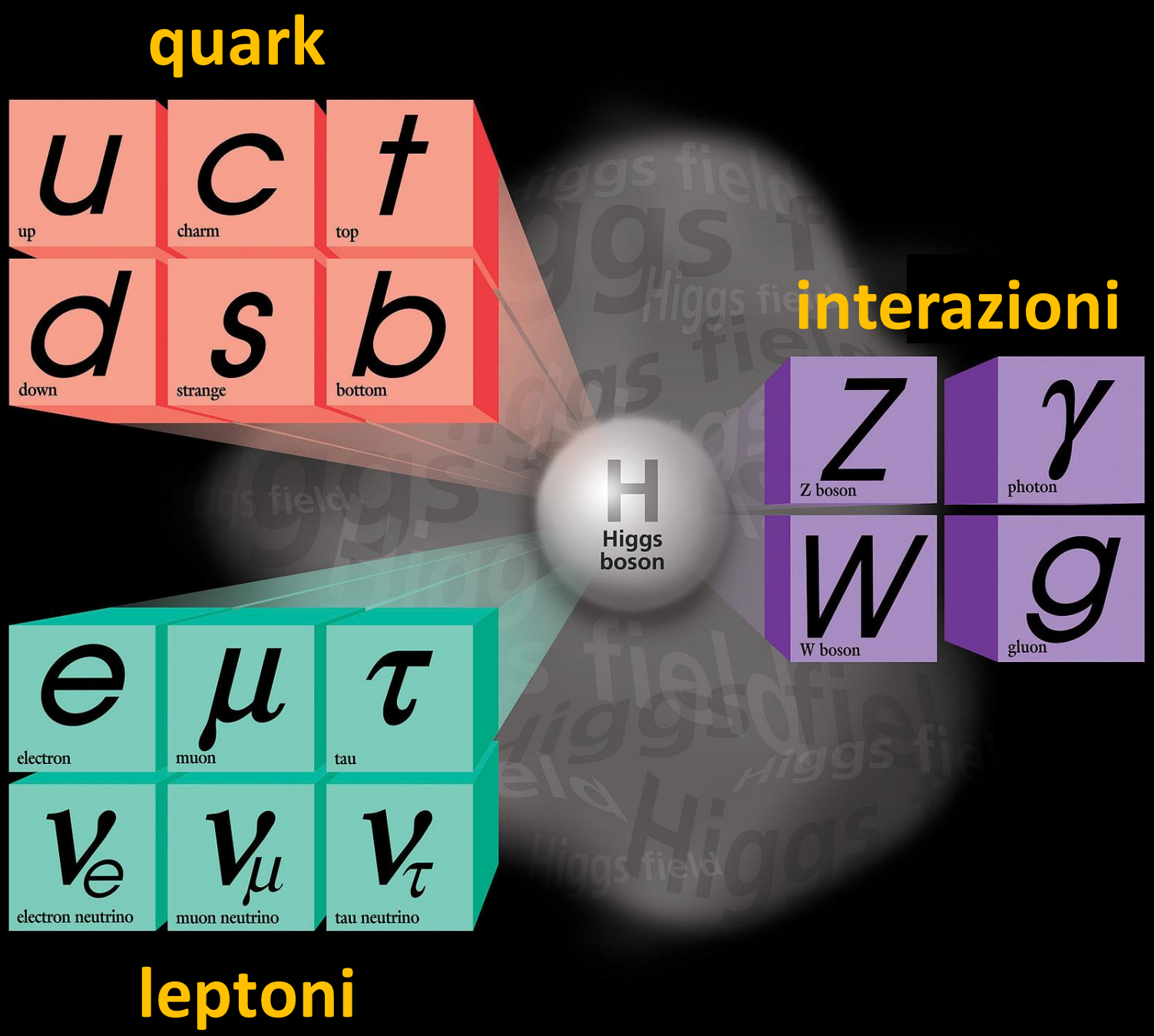
$$S = \int_{t_1}^{t_2} \mathcal{L}\big(x(t), \dot{x}(t)\big)\, dt$$

$$\mathcal{L} = \frac{1}{2} m\dot{x}^2 - V(x)$$

Cubo di Bronštejn




«I think I can safely say
that nobody understand
quantum mechanics»
Richard Feynman

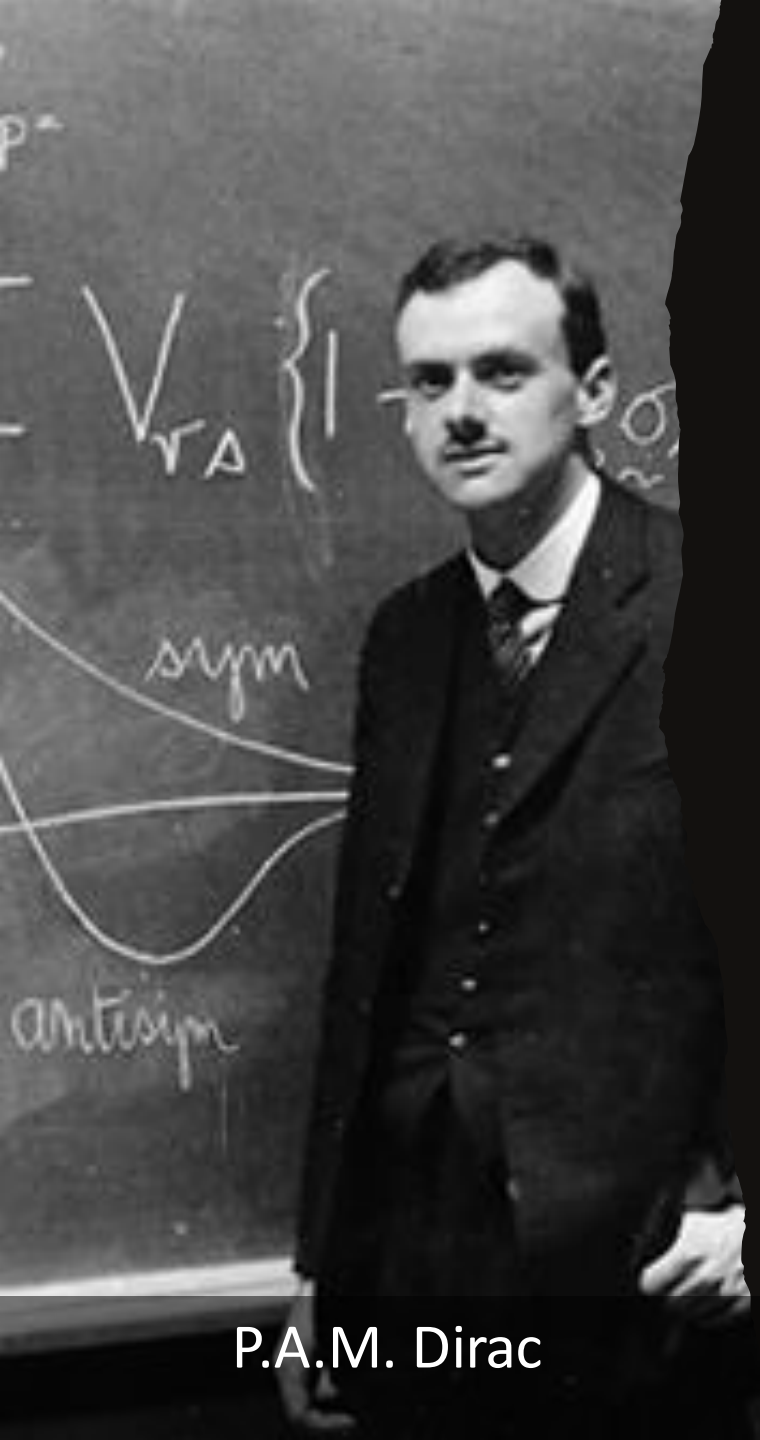


Modello Standard

Modello Standard delle Particelle Elementari e delle Interazioni Fondamentali

$$SU(2)_L \times U(1)_Y \times SU(3)_c$$

insieme di 3 Teorie Quantistiche di Campo che descrivono le 3 interazioni fondamentali



P.A.M. Dirac

1928

teoria dell'elettrone

$$i\gamma^{\mu}\partial_{\mu}\psi = m\psi$$

1947

Dirac ha un problema

shift dei livelli energetici dell'idrogeno non previsto dall'equazione di Dirac

Willis Lamb

Due giovani Fisici risolvono il problema

1948

Elettrodinamica Quantistica

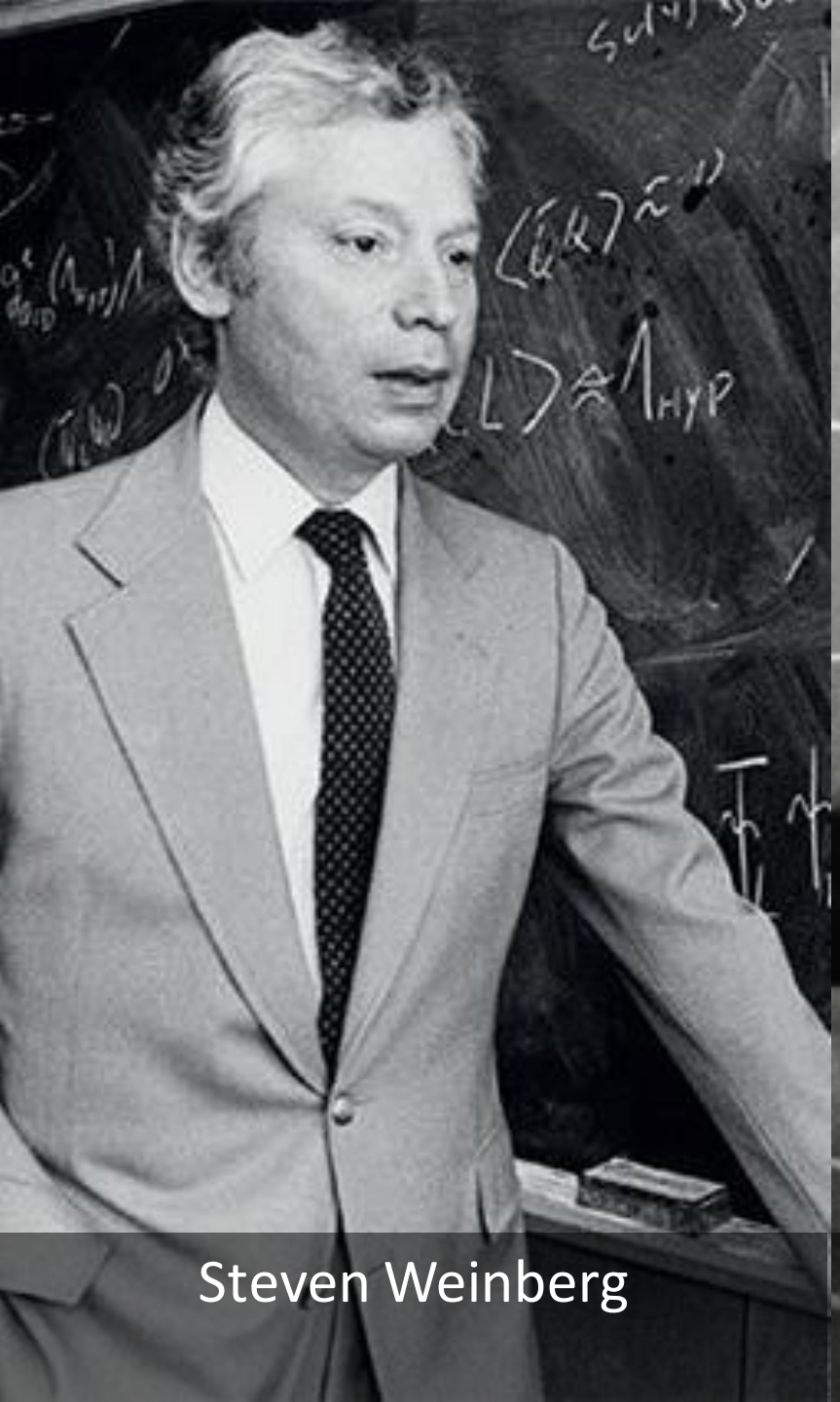
QED

la prima Teoria Quantistica di Campo

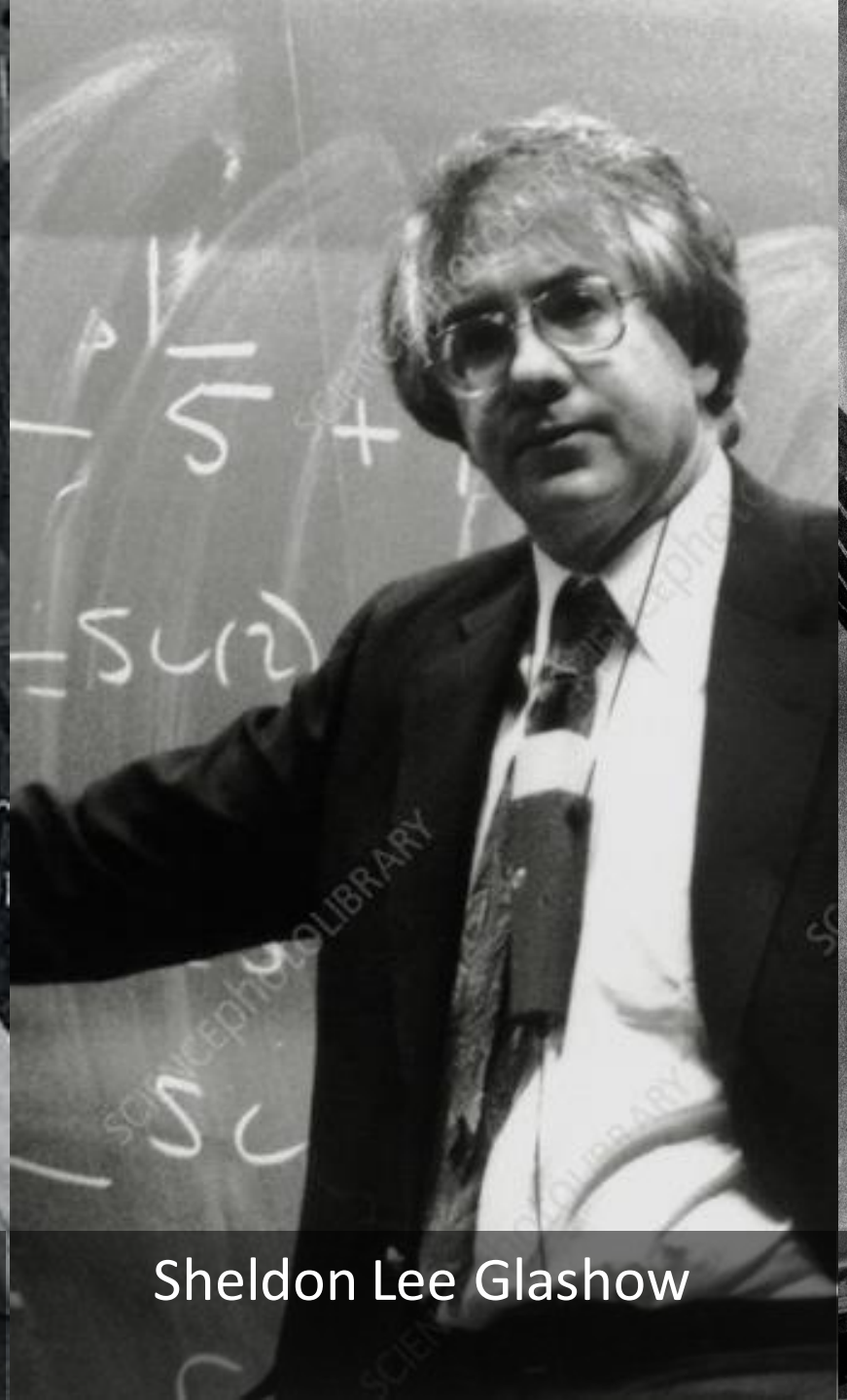
Julian Schwinger

Richard Feynman

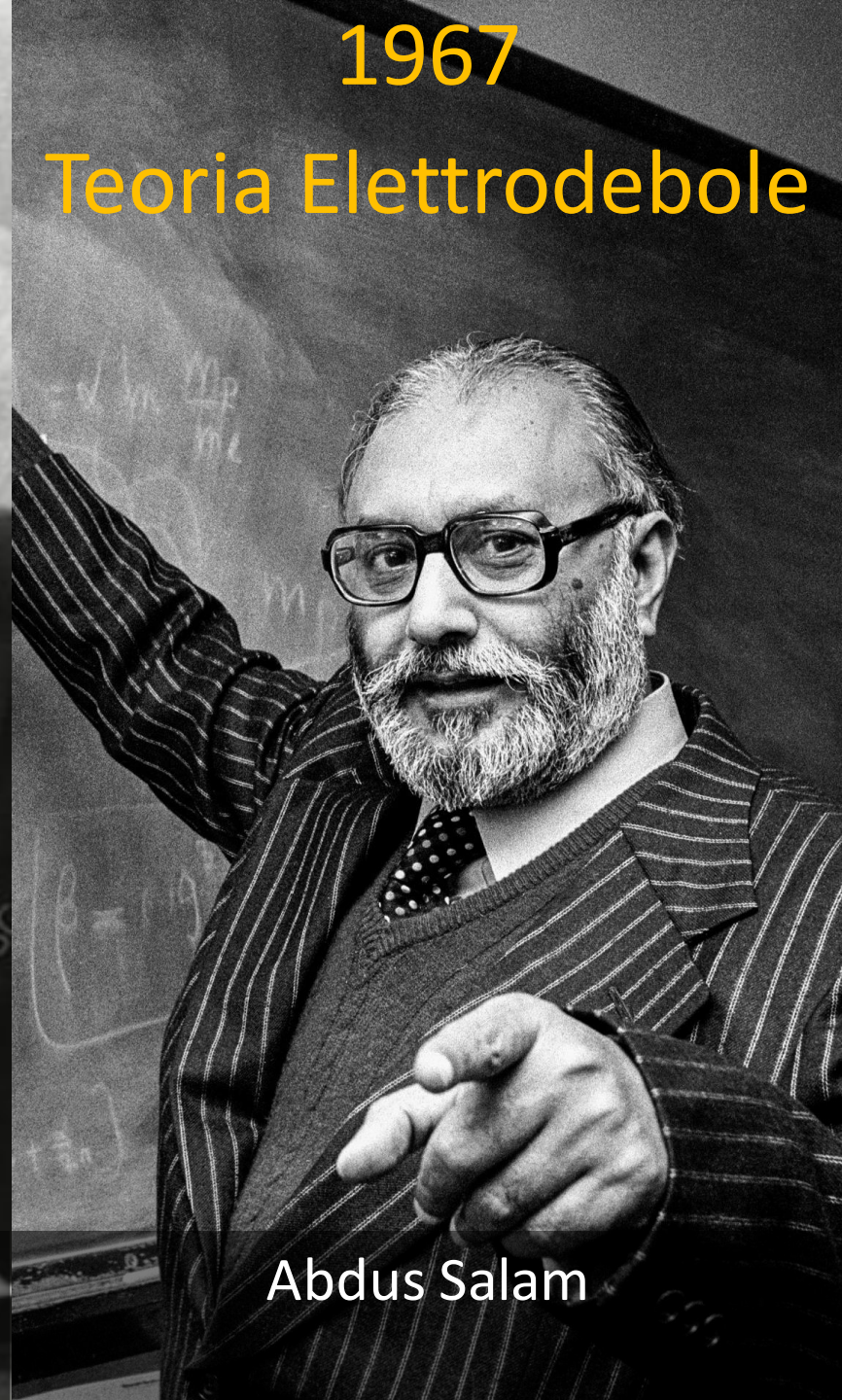
1967
Teoria Elettrodebole



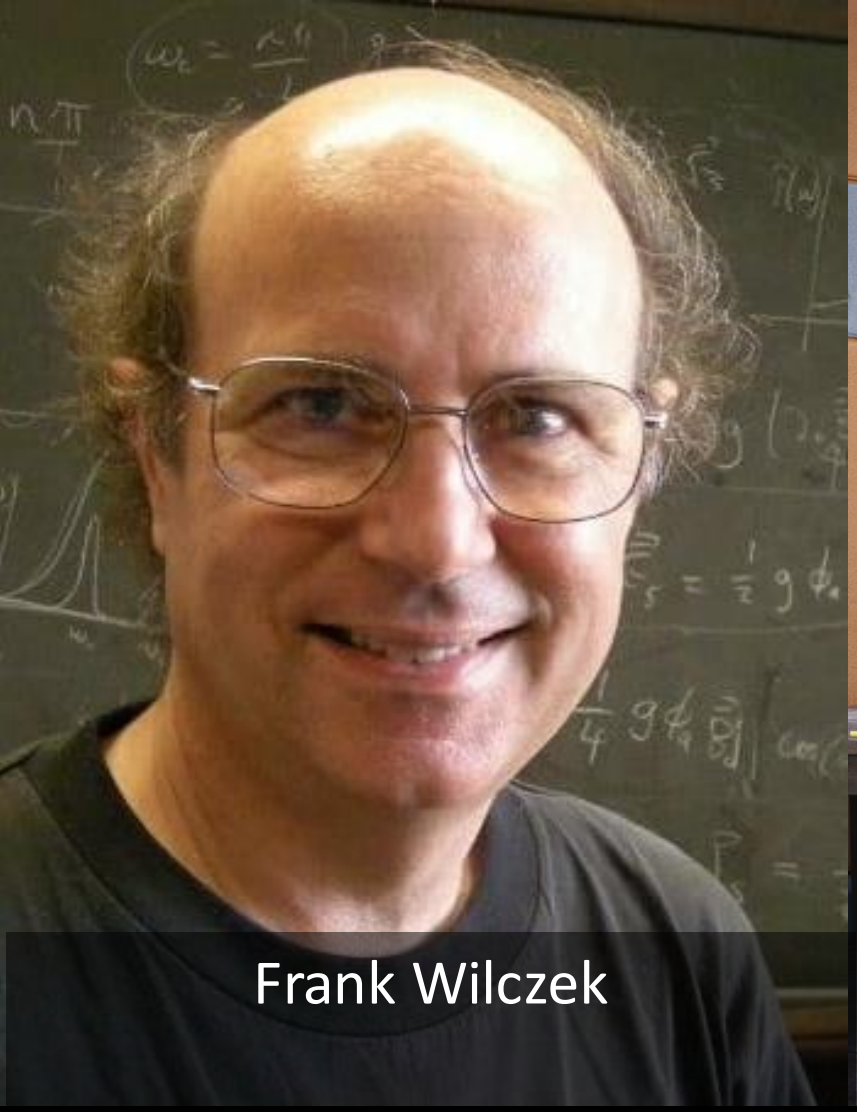
Steven Weinberg



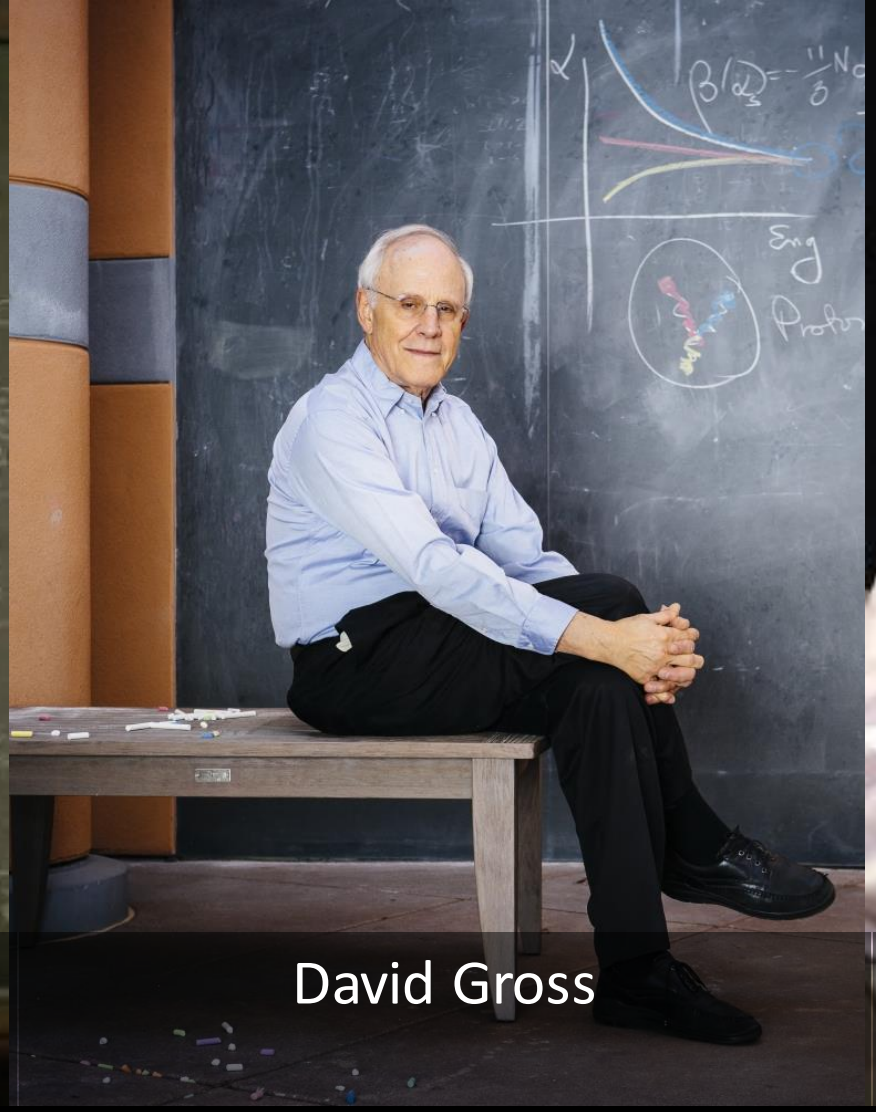
Sheldon Lee Glashow



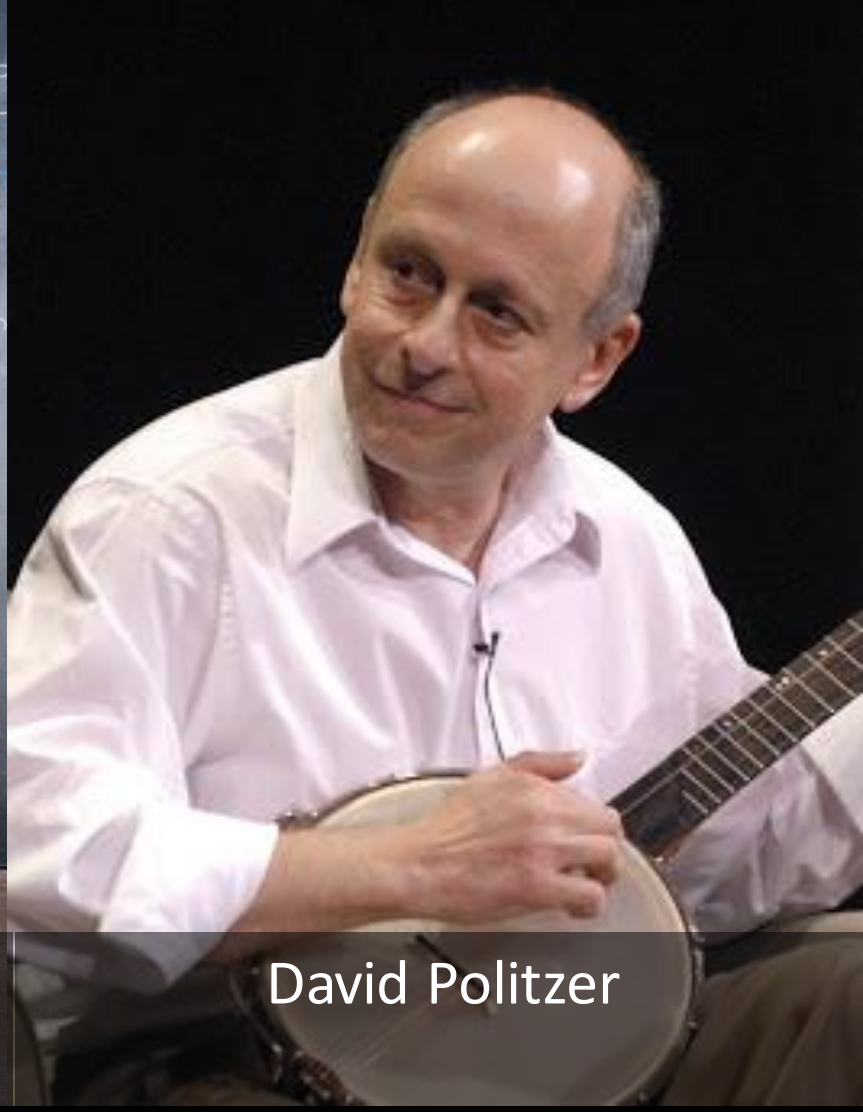
Abdus Salam



Frank Wilczek



David Gross



David Politzer

1973

Cromodinamica Quantistica

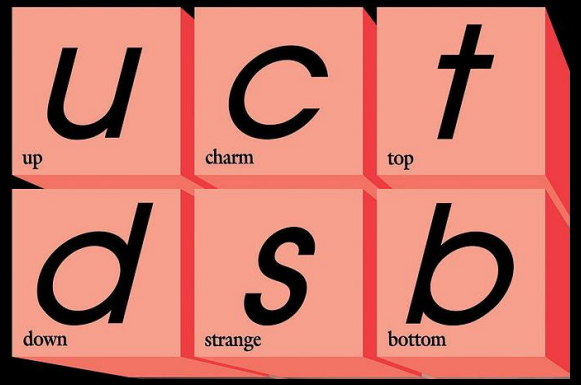
tutto è Campo

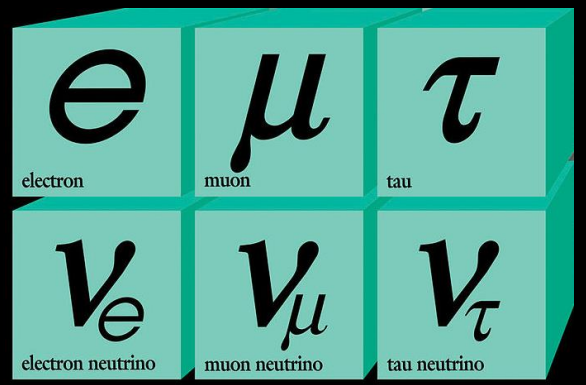
Fermioni e Bosoni

Fermioni

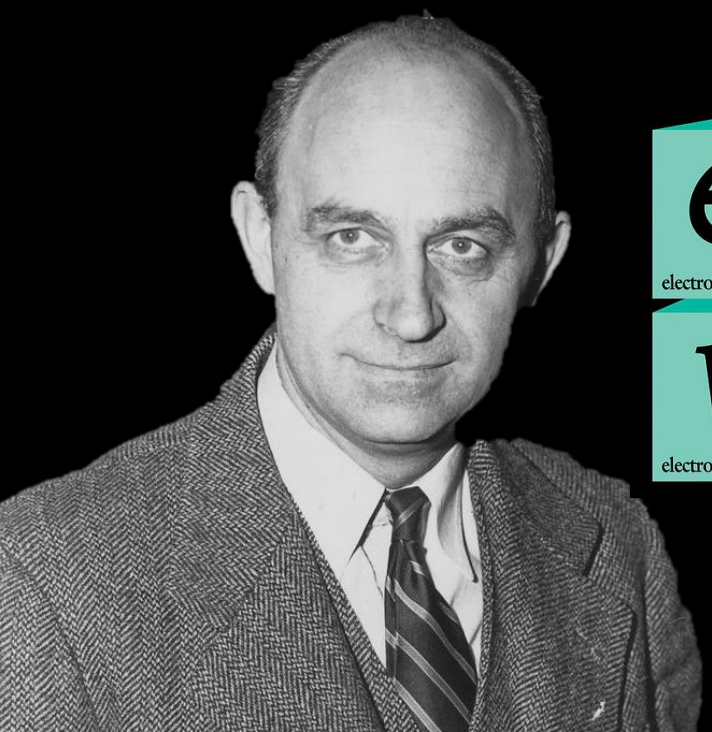
campi che costituiscono la materia

quark



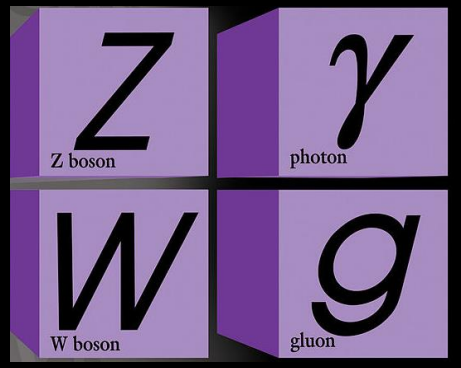


leptoni



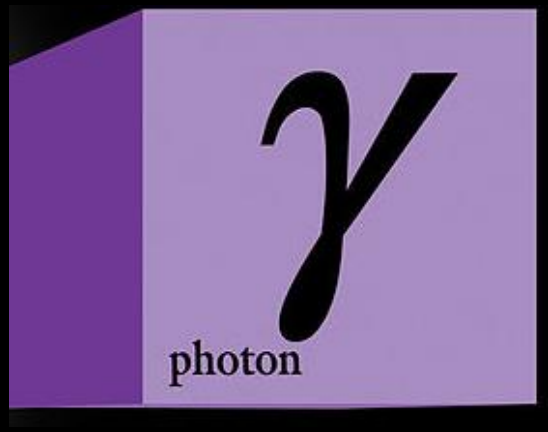
Bosoni

campi che mediano le interazioni

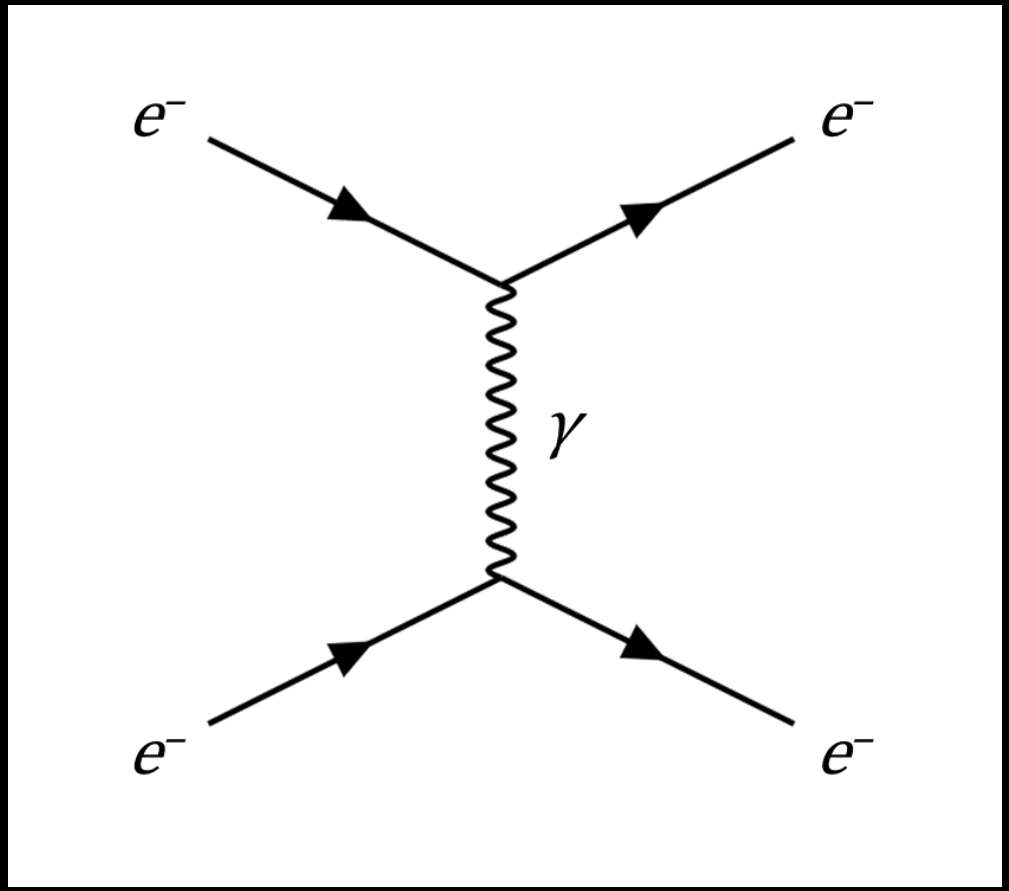


Fotone e Interazione Elettromagnetica

il bosone che trasporta l'interazione elettromagnetica è il fotone



due elettroni interagiscono scambiandosi un fotone

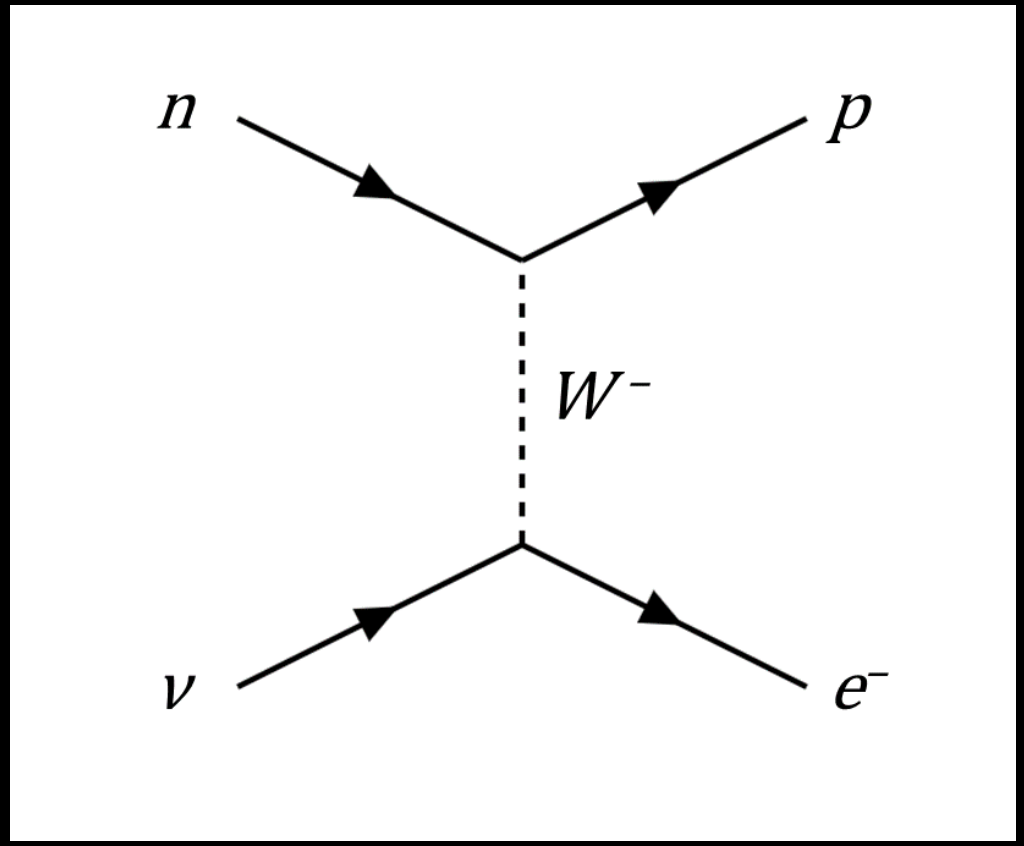


Bosoni Intermedi e Interazione Debole

i bosoni che trasportano l'interazione debole sono i bosoni deboli

W^+	W^-	Z^0
bosone debole	bosone debole	bosone debole

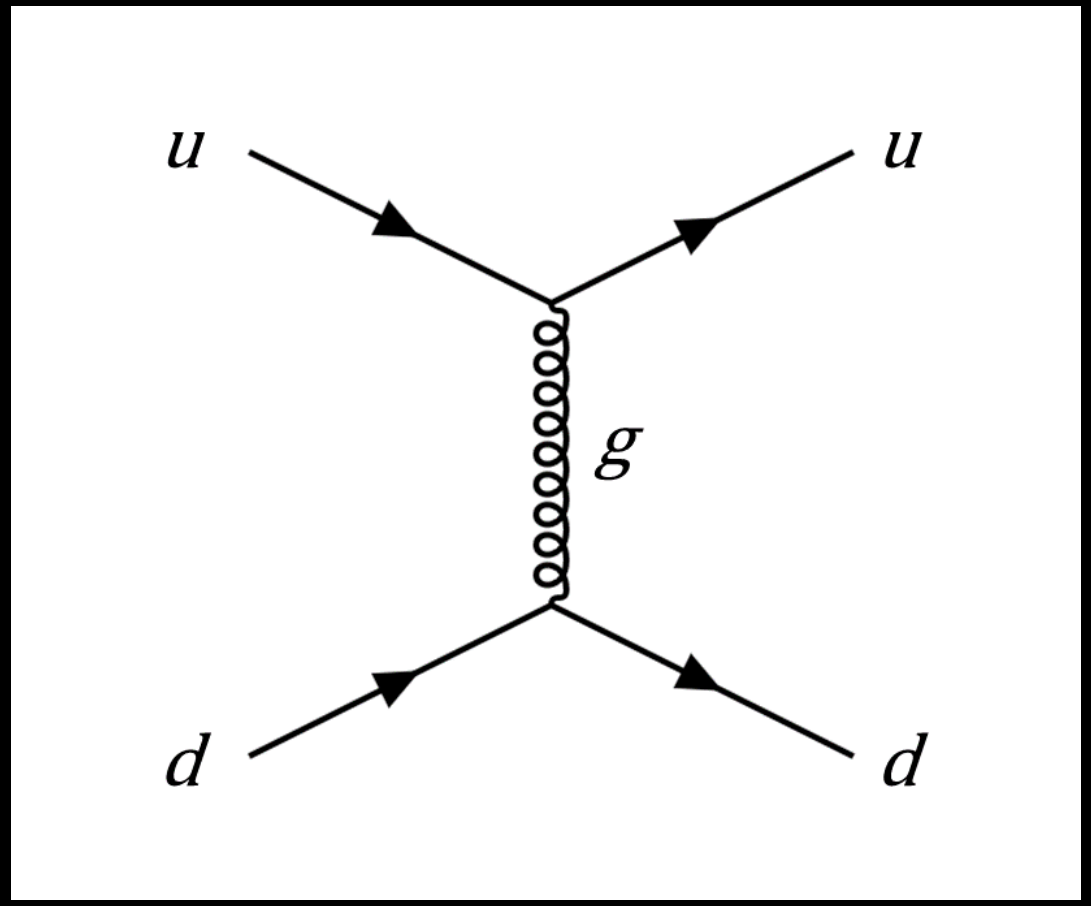
neutroni, protoni, elettroni e neutrini si scambiano bosoni deboli



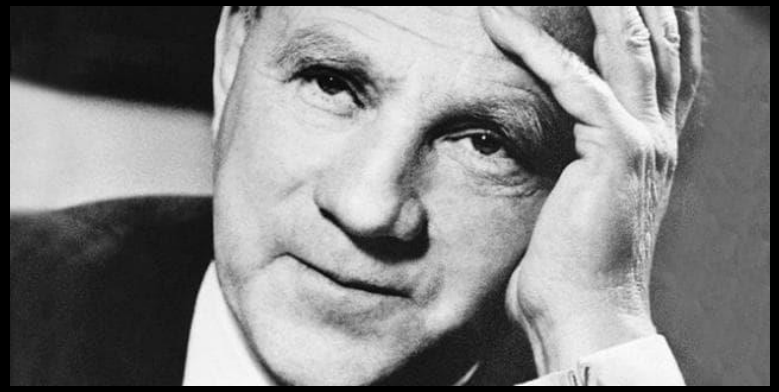
Gluoni e Interazione Forte

i bosoni che trasportano l'interazione forte sono i gluoni

quark interagiscono scambiandosi un gluone

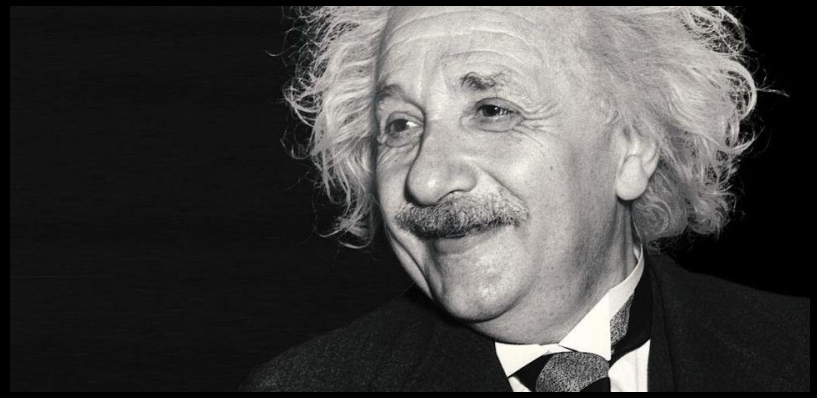


il vuoto non è vuoto



Principio di Indeterminazione

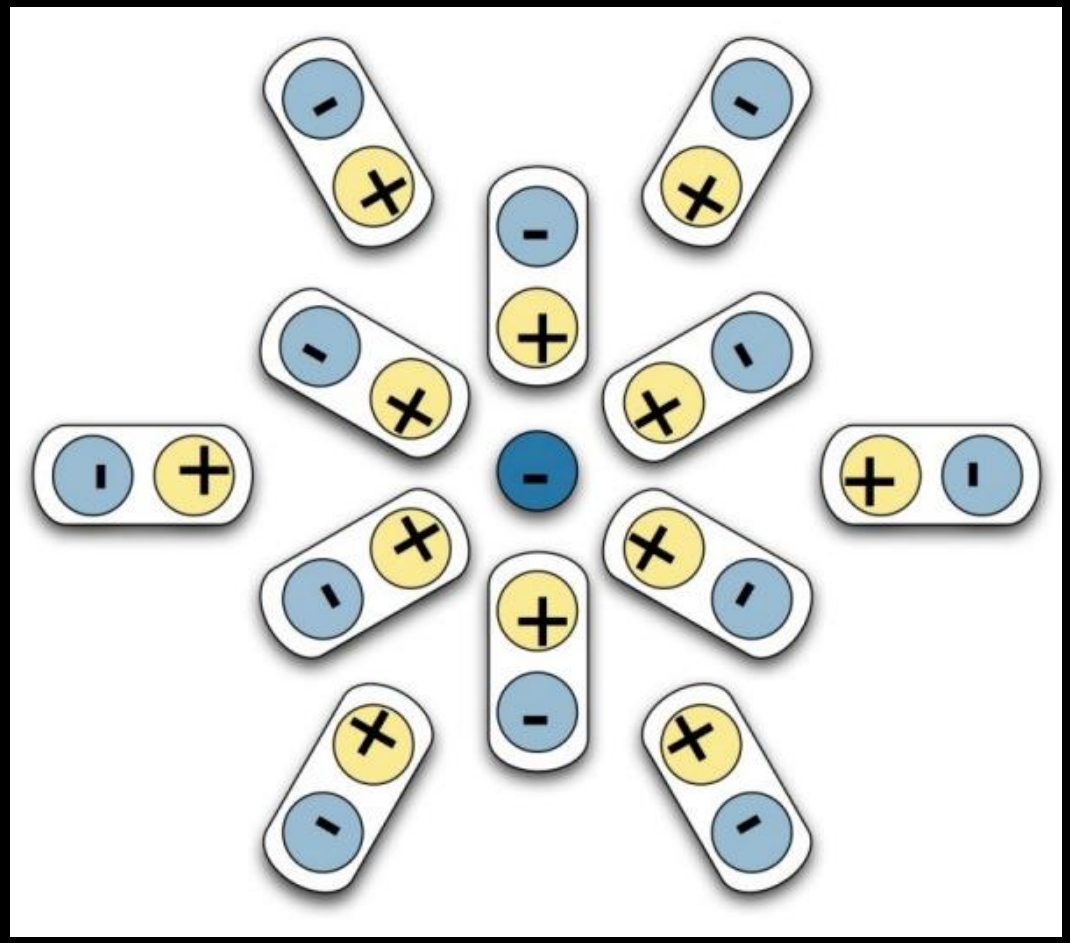
$$\Delta E \cdot \Delta t \geq \hbar$$



Equivalenza Massa Energia

$$E = mc^2$$

Polarizzazione del Vuoto e Rinormalizzazione



la polarizzazione del vuoto scherma la «vera» carica dell'elettrone

avvicinandosi sempre più all'elettrone la sua carica appare aumentare

il valore teorico della carica «vera» è infinito!

si pone il valore «vero» della carica pari a quello sperimentale

definendo un numero limitato di parametri la teoria predice tutti gli altri

le costanti non sono più costanti!

Parametri del Modello Standard

masse dei fermioni

$m_e = 0.511$ MeV
$m_\mu = 105.6$ MeV
$m_\tau = 1777$ MeV

$m_u \approx 3$ MeV
$m_c \approx 1.2$ GeV
$m_t \approx 174$ GeV

$m_d \approx 7$ MeV
$m_s \approx 120$ MeV
$m_b \approx 4.3$ GeV

masse dei bosoni

$m_W = 80.42$ GeV
$m_Z = 91.19$ GeV
$m_H = 125$ GeV

accoppiamenti

$\alpha = 1/137$
$\alpha_s \approx 0.12$

mixing dei quark

$\theta_{12} = 13.1°$
$\theta_{23} = 2.4°$
$\theta_{13} = 0.2°$
$\delta_{CP} = 0.995$

Integrale sui Cammini di Feynman

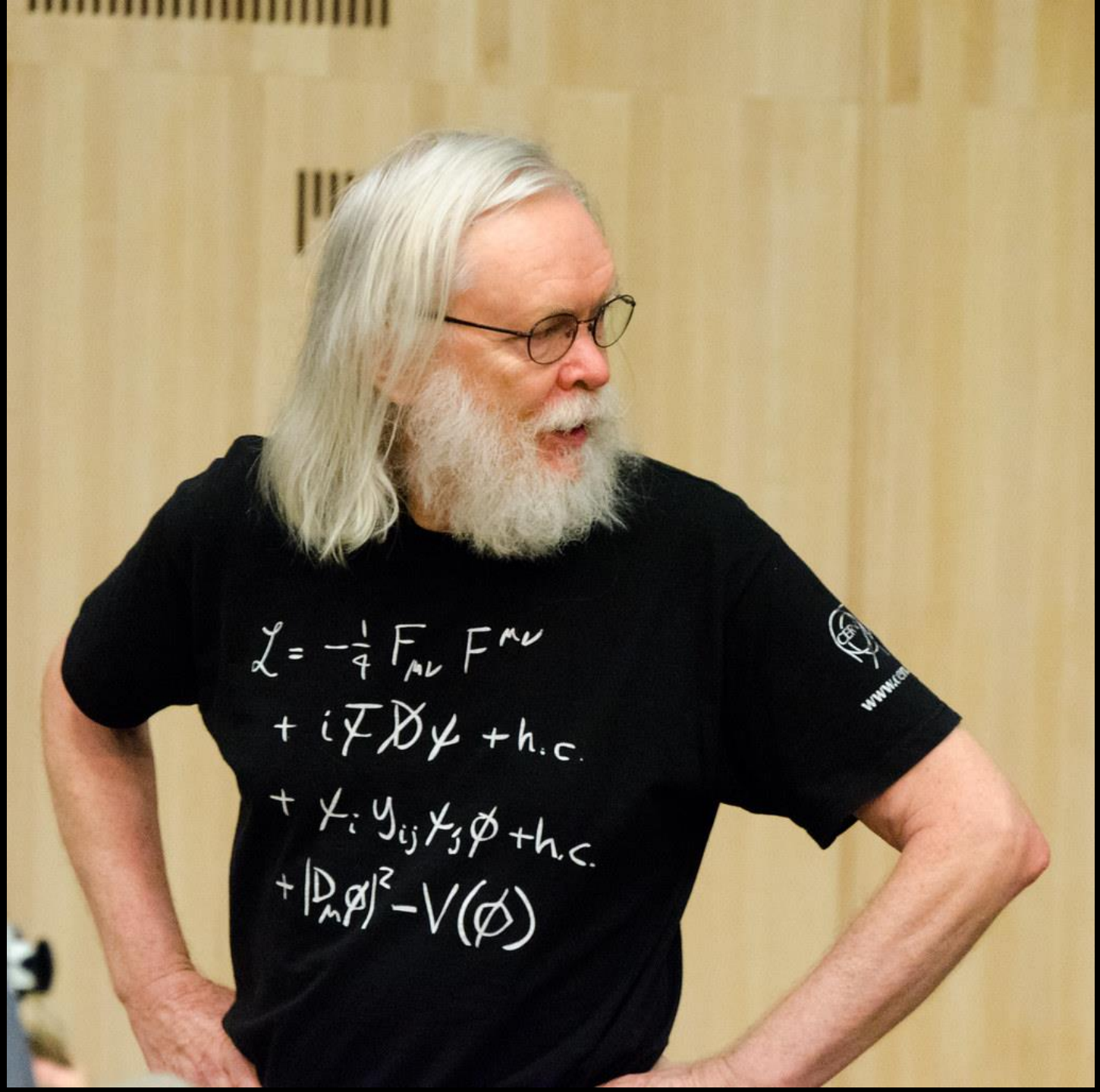
$$S = \int \mathcal{L}(x) d^4x$$

$$\mathcal{P} = \int \exp\left(i\frac{S}{\hbar}\right) Dx$$

in QM un corpo segue TUTTE le traiettorie possibili, ciascuna "pesata" dall'azione in unità $\hbar$

Lagrangiana del Modello Standard

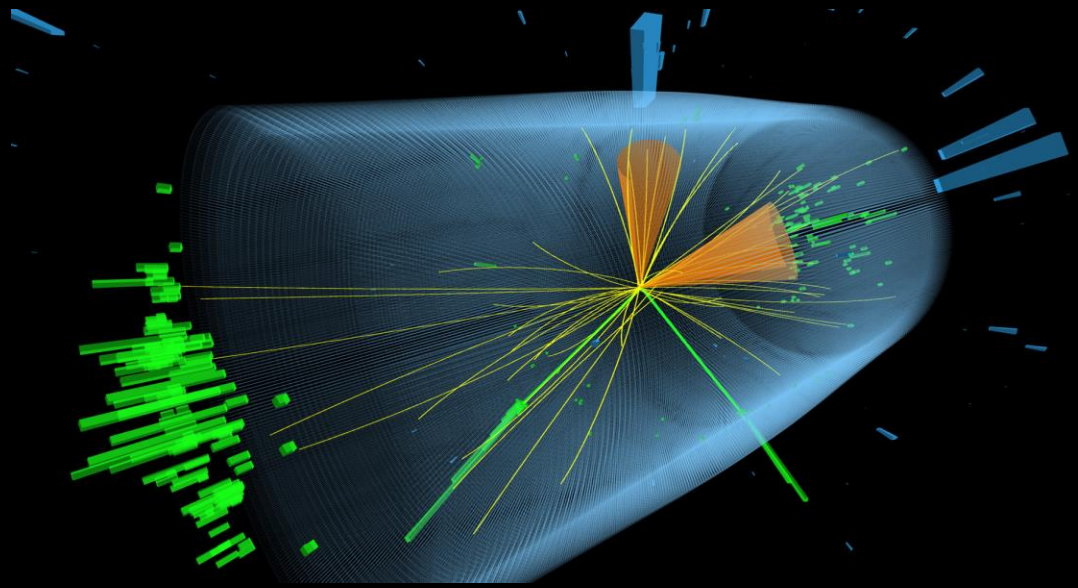
$$\mathcal{L} = \underbrace{\bar{\Psi} i D \Psi}_{\text{campi fermionici}} \underbrace{- \frac{1}{4} F^a_{\mu\nu} F_a^{\mu\nu}}_{\text{campi bosonici}} + \underbrace{\bar{\Psi}_L Y \phi \Psi_R \left| D_\mu \phi \right|^2 - V(\phi)}_{\text{campo di Higgs}}$$


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\chi} \not{D} \chi + h.c.$
$+ \chi_i y_{ij} \chi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

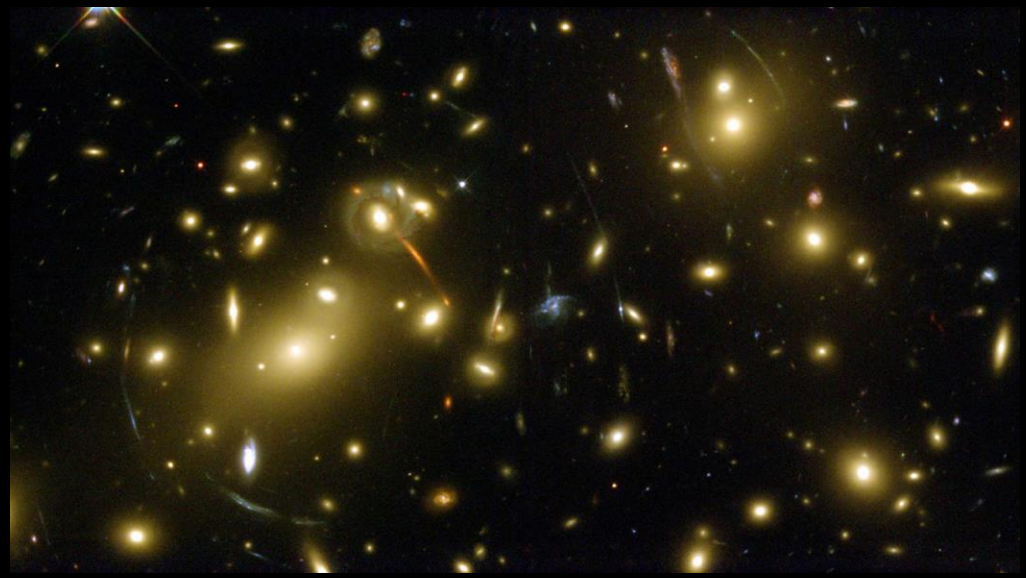
$$\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - g\alpha_h M (H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-) - \tfrac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2) - gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + M\,(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w M A_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu (H^2 + (\phi^0)^2 + 2\phi^+\phi^-) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-) - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\,\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + (\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar{\nu}_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa - \tfrac{1}{4}\,\bar{\nu}_\lambda\, M^R_{\lambda\kappa}\,(1-\gamma_5)\hat{\nu}_\kappa + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j)\right) + \tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+X^+H + \bar{X}^-X^-H + \tfrac{1}{c_w^2}\bar{X}^0X^0H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+X^0\phi^+ - \bar{X}^-X^0\phi^-\right) + \tfrac{1}{2c_w}igM\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + igMs_w\left(\bar{X}^0X^-\phi^+ - \bar{X}^0X^+\phi^-\right) + \tfrac{1}{2}igM\left(\bar{X}^+X^+\phi^0 - \bar{X}^-X^-\phi^0\right).$$

Non descrive la Gravità

una teoria per il mondo subnucleare
Modello Standard



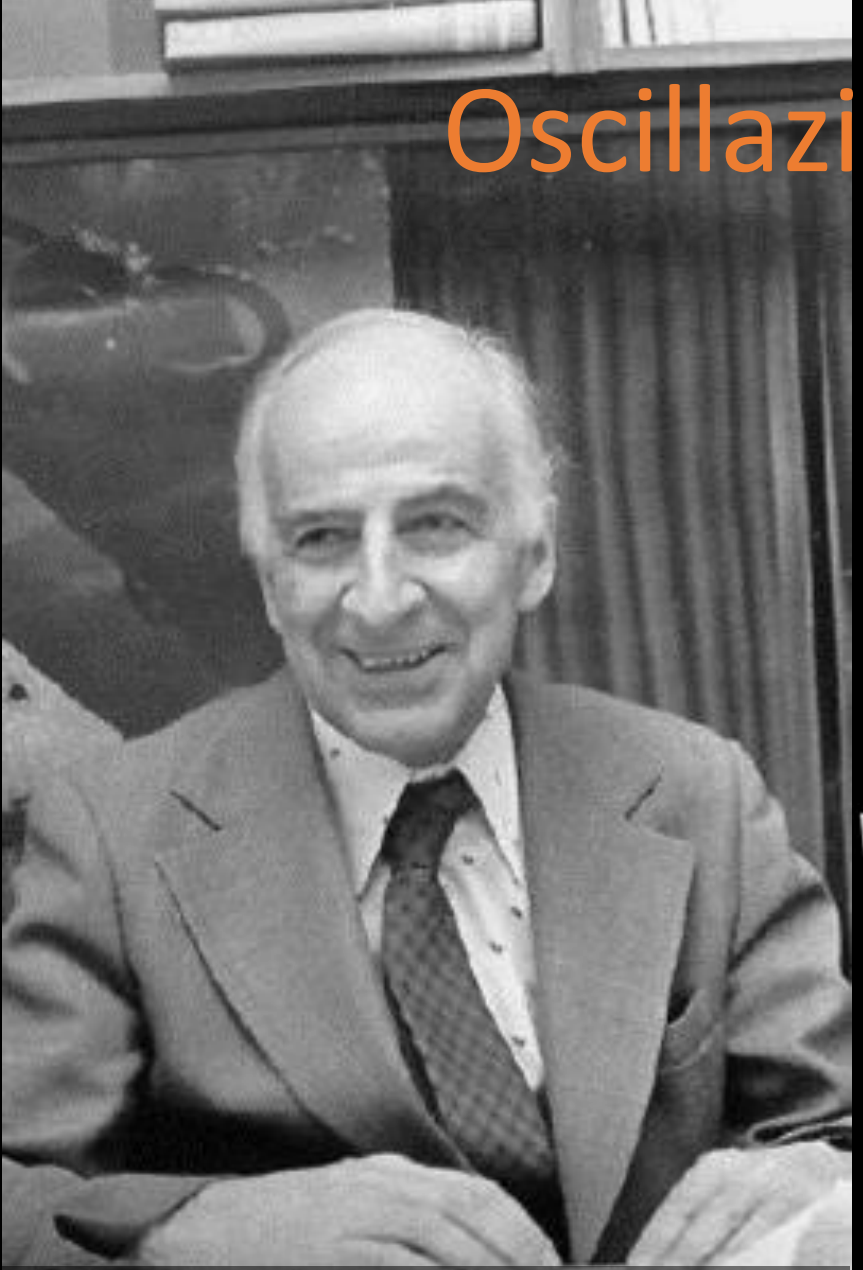
una teoria per il cosmo
Relatività Generale



a una distanza 10^{-35} m (lunghezza di Planck) la gravità non è più trascurabile

Gravità Quantistica

Oscillazioni e Massa dei Neutrini



Bruno Pontecorvo

masse dei neutrini

$m_{\nu e} < 3$ eV

$m_{\nu \mu} < 0.19$ MeV

$m_{\nu \tau} < 18.2$ MeV

mixing dei neutrini

$\theta_{12} \approx 33.4°$

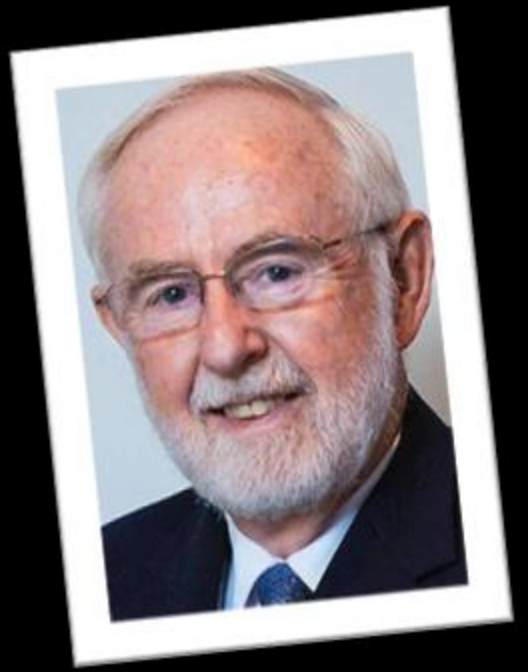
$\theta_{23} \approx 49°$

$\theta_{13} \approx 8.6°$

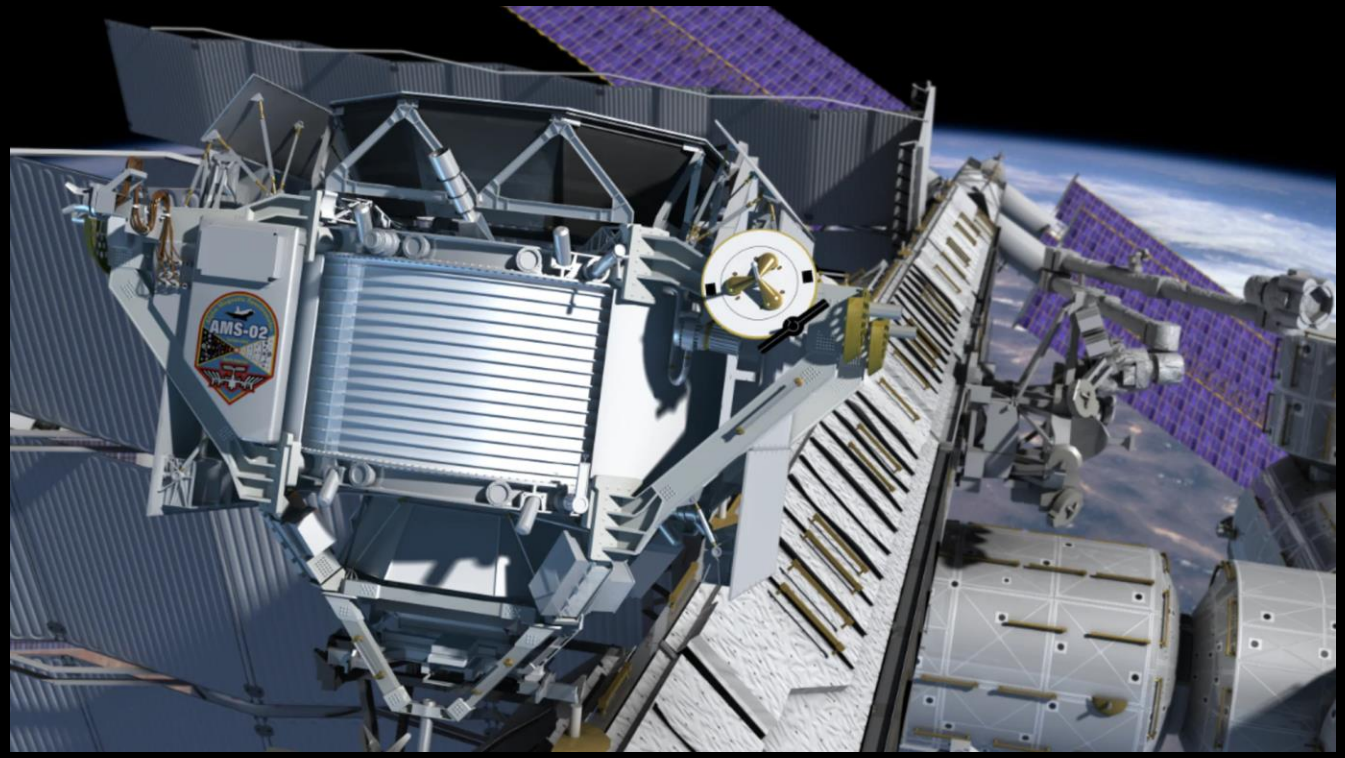
$\delta_{CP} \approx 195°$

Takaaki Kajita

Arthur McDonald



Asimmetria Materia-Antimateria



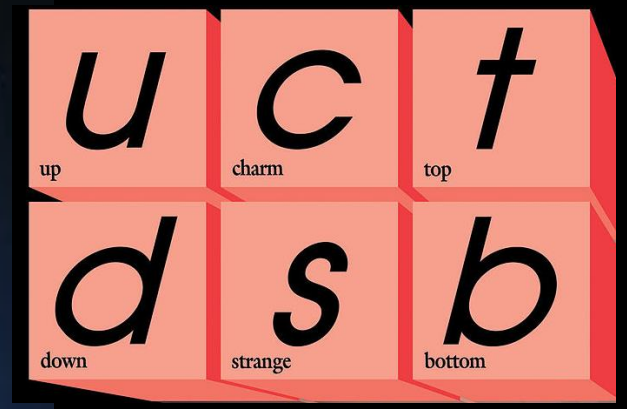
l'antimateria nell'Universo è insignificante: 10^{-10}

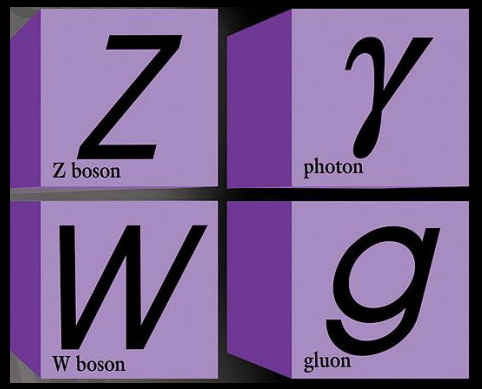
la costante fondamentale del MS che genera asimmetria nei quark δ_{CP} è troppo piccola

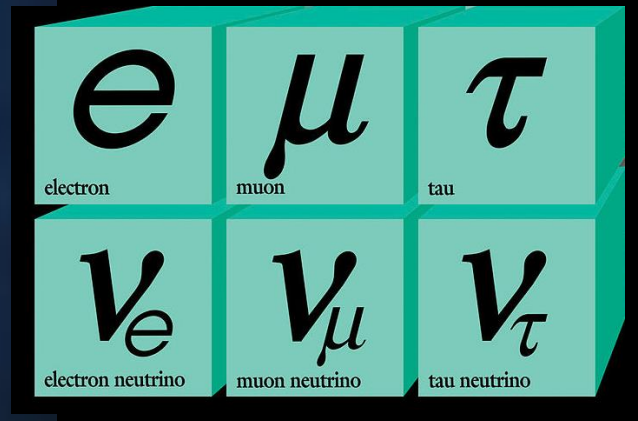
altra sorgente di VCP nei leptoni? serve misurare bene δ_{CP} dei neutrini

Materia Oscura

5 volte più abbondante della materia



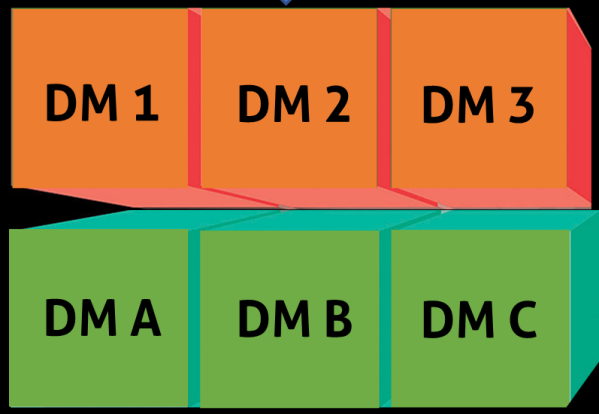




m_{WIMP}

m_U

ε



La cosa più incomprensibile dell'Universo è che esso sia comprensibile

- A. Einstein

spares

Unità di Planck

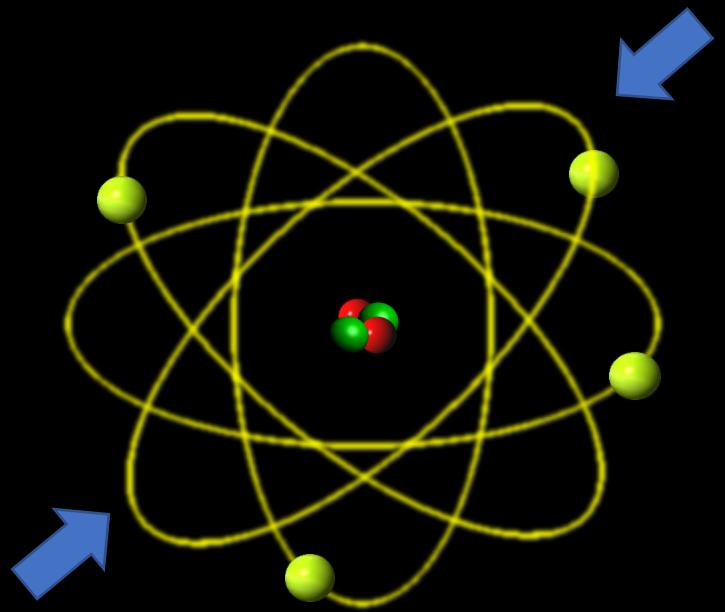
lunghezza di Planck $l_p = \sqrt{\frac{\hbar G}{c^3}} \approx 10^{-35}\ m \approx 10^{-20}\ R_{proton}$

massa di Planck $m_p = \sqrt{\frac{\hbar c}{G}} \approx 10^{-8}\ kg \approx 10^{19}\ M_{proton}$

tempo di Planck $t_p = \sqrt{\frac{\hbar G}{c^5}} \approx 10^{-43}\ s \approx 10^{-21}\ \tau_{Higgs}$

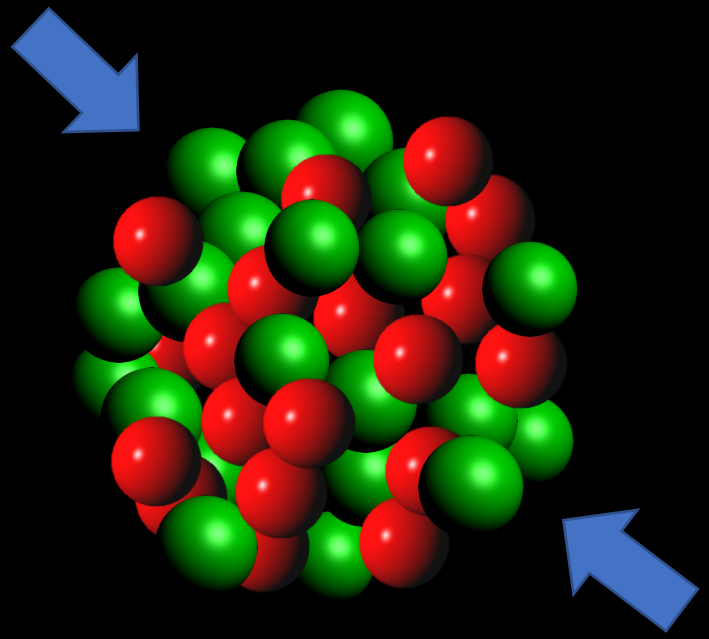
Interazioni Fondamentali

Elettromagnetica



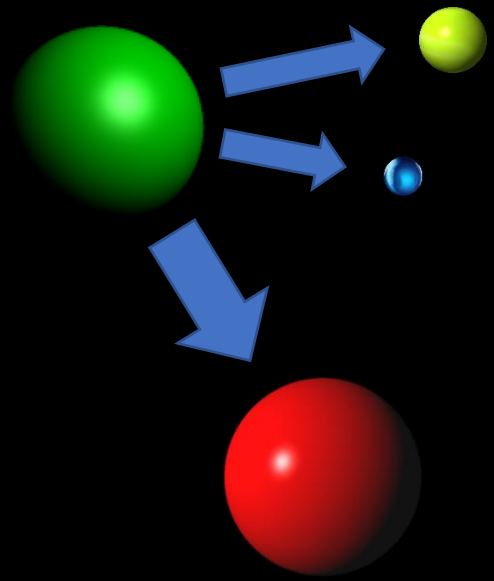
tiene insieme l’atomo

Forte



tiene insieme il nucleo

Debole



trasforma i nuclei

Problema della Naturalezza

se le constanti fondamentali del MS fossero anche poco diverse noi non saremmo qui

disegno intelligente

principio antropico

ignoranza

multiverso