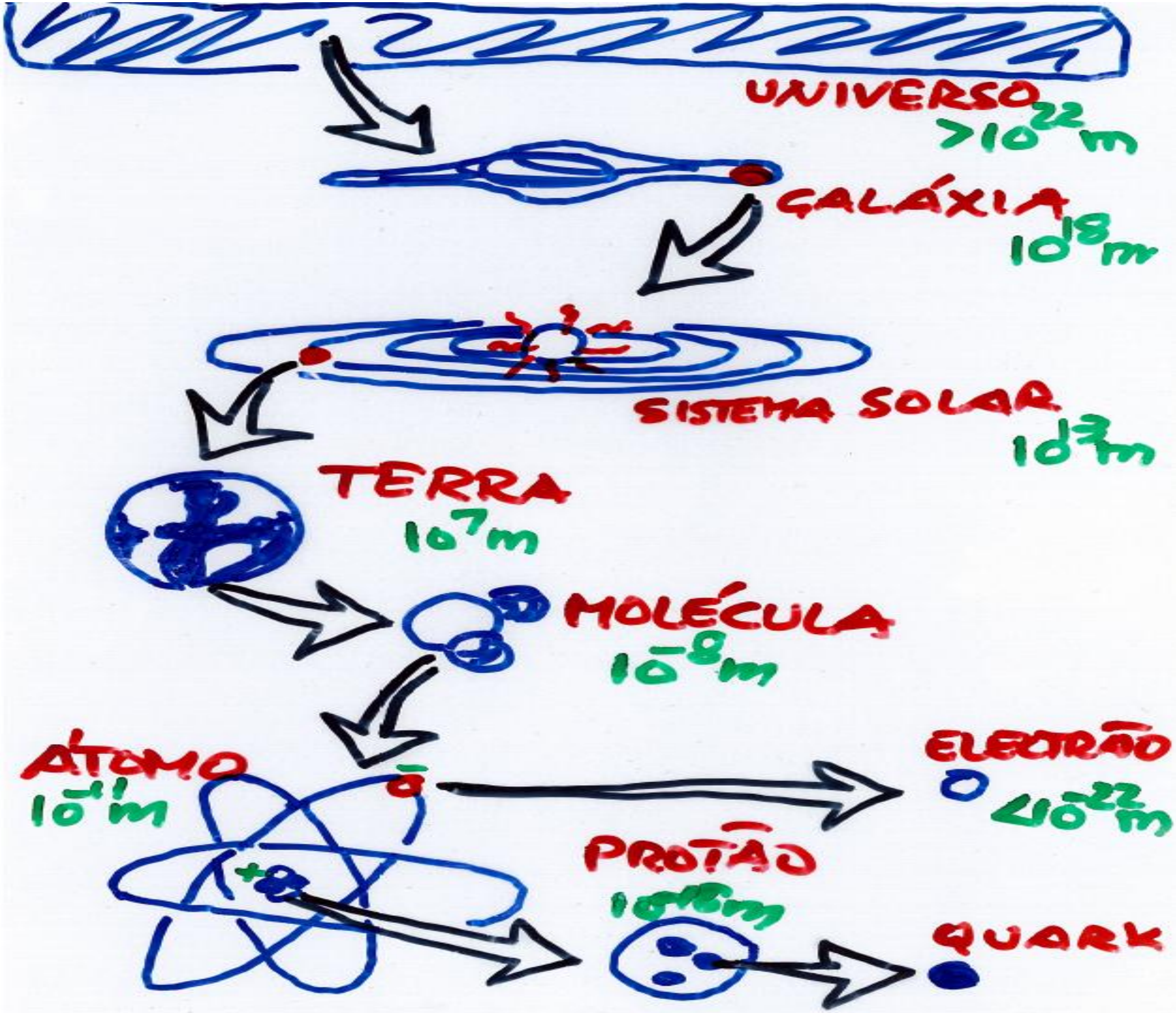
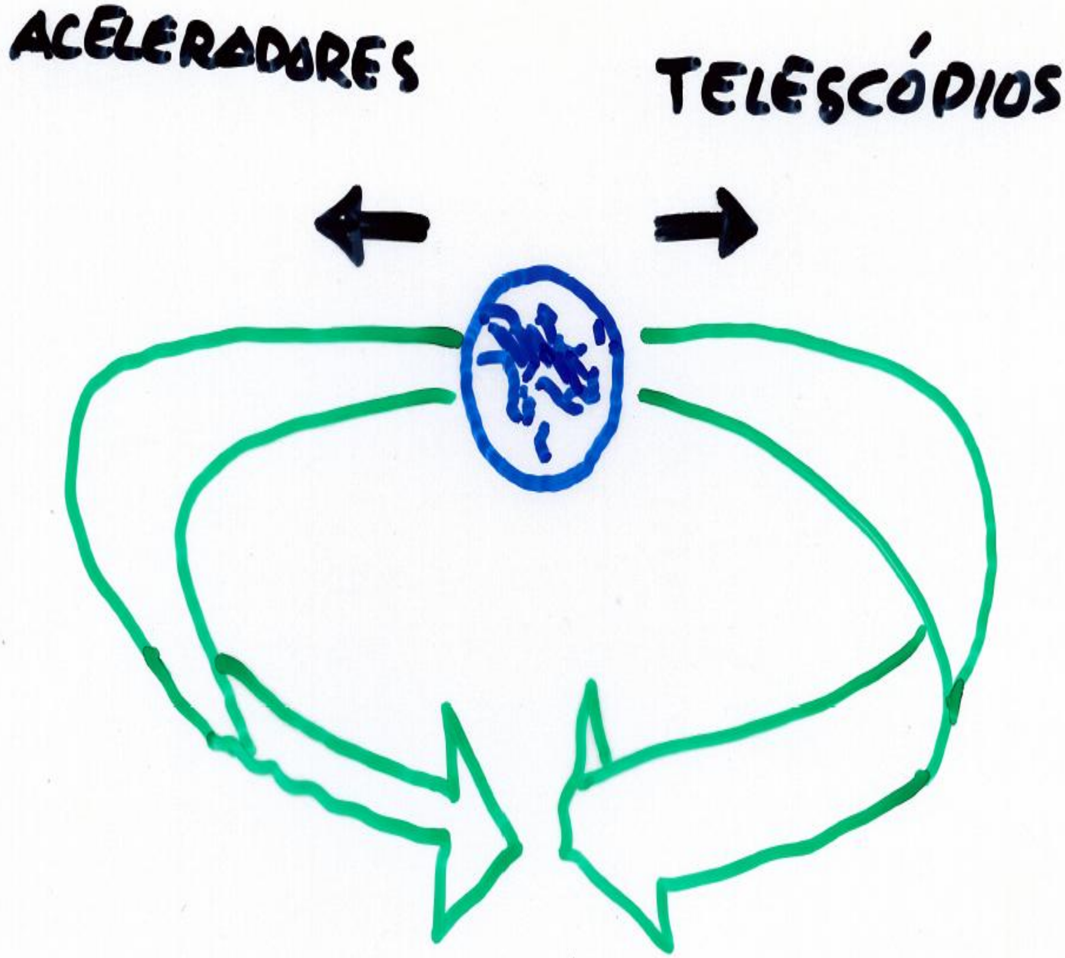
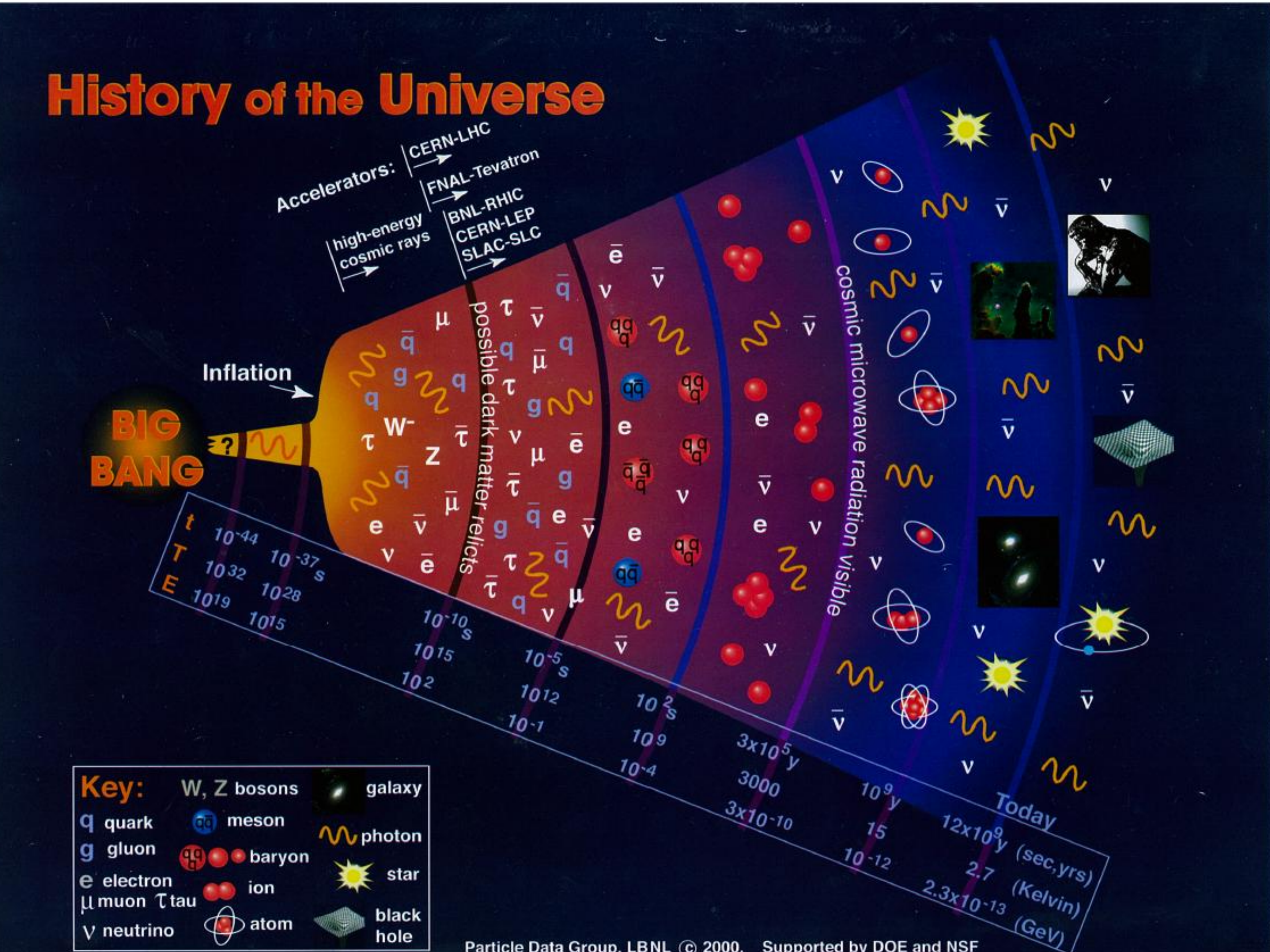
INTERAÇÕES FUNDAMENTAIS NO UNIVERSO

J. DIAS DE DEUS

eag 2012


UNIVERSO
$>10^{22}$ m
GALÁXIA
10^{18} m
SISTEMA SOLAR
10^{13} m
TERRA
10^{7} m
MOLÉCULA
10^{-8} m
ÁTOMO
10^{-11} m
ELECTRÃO
$<10^{-22}$ m
PROTÃO
QUARK


ACELERADORES
TELESCÓPIOS


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t T E
10^-44 10^32 10^19
10^-37 s 10^28 10^15
10^-10 s 10^15 10^2
10^-5 s 10^12 10^-1
10^2 s 10^9 10^-4
3x10^5 y 3000 3x10^-10
10^9 y 15 10^-12
Today 12x10^9 y 2.7 2.3x10^-13
(sec,yrs) (Kelvin) (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
galaxy
photon
star
black hole
Particle Data Group, LBNL © 2000. Supported by DOE and NSF

OBJECTOS & INTERACÇÕES

$$\vec{P} = \overrightarrow{const.} \Rightarrow \frac{d\vec{P}}{dt} = \vec{0}$$

$$\boxed{\begin{aligned} d\vec{p}/dt &= \vec{F} \\ d\vec{L}/dt &= \vec{r} \times \vec{F} \equiv \vec{N} \\ dE/dt &= \vec{F} \cdot \vec{v} \end{aligned}}$$

TRÊS INVARIÂNCIAS:

TRANSLAÇÃO NO ESPAÇO

ROTAÇÃO NO ESPAÇO

TRANSLACÇÃO NO TEMPO

TRÊS LEIS DE CONSERVAÇÃO

$$d\vec{P}/dt = 0$$

Nöther

$$d\vec{L}/dt = 0$$

$$dE/dt = 0$$

EM GERAL :

$$\begin{tikzcd} \vec{r} \arrow[d, "h"'] \arrow[rr, bend left, leftrightarrow, "c"] & \vec{\theta} \arrow[d] & t \arrow[d] \\ \vec{p} & \vec{L} & E \end{tikzcd}$$

← VARIÁVEIS CONJUGADAS

$$(x, y, z; t) \longrightarrow (p_x, p_y, p_z; E)$$

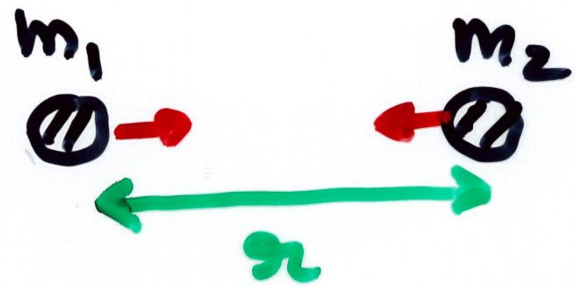
NOTA :

→ LEIS DA FÍSICA

→ MECÂNICA QUÂNTICA

CARGAS & CAMPOS

Newton :



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

$m_1 \longrightarrow Q$ CARGA

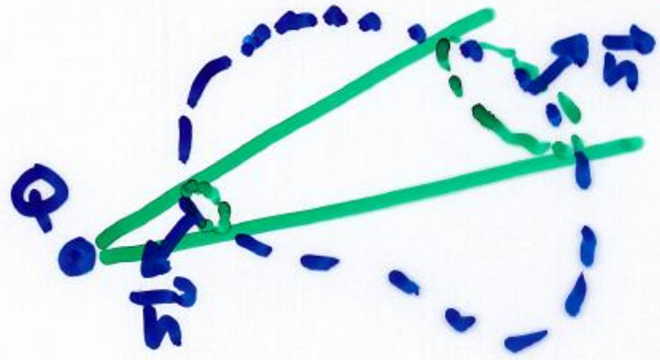
$1 \longrightarrow$ CAMPO $\vec{E}_1 = -G\frac{m_1}{r^2} \longrightarrow -\frac{\alpha Q_1}{r^2}$

$G \longrightarrow \alpha$

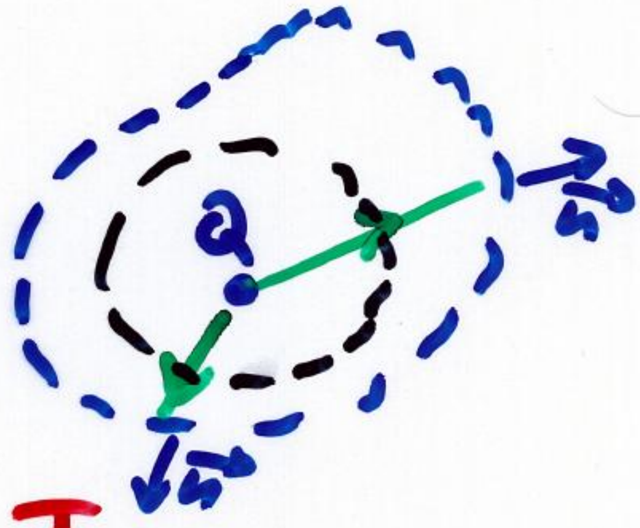
$$F = Q_2 E_1$$

TEOREMA DE GAUSS

$$\Phi = \int_{[\text{Fechada}]} \vec{E} \cdot d\vec{S} = 4\pi\alpha\, Q\Big|_{\text{interior}}$$



$\Phi = 0$



$\Phi > 0$

Newton :
(Coulomb

$$\Phi = \int \frac{\alpha Q}{r^2}\, dS = \frac{\alpha Q}{r^2}\, 4\pi r^2 = 4\pi\alpha Q$$

Em geral:

$$S \longrightarrow r^{D-1}$$

$$r^2 \longrightarrow r^{\tilde{\alpha}}$$

T. Gauss

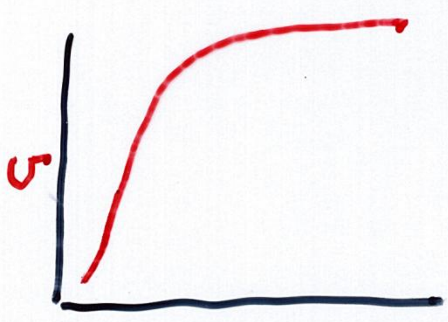
$$\frac{r^{D-1}}{r^{\tilde{\alpha}}} \Longrightarrow \boxed{\tilde{\alpha} = D-1}$$

$D=1$:

O MISTÉRIO DA MATÉRIA ESCURA:

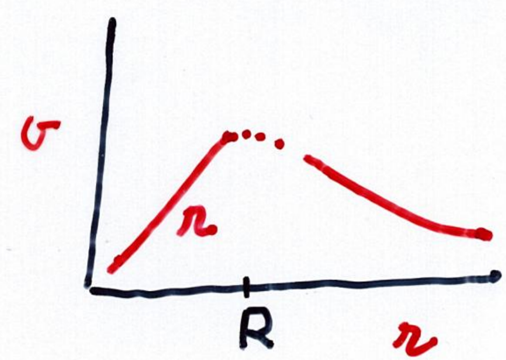
$$G\frac{Mm}{r^2} = \frac{mv^2}{r} \qquad \begin{cases} M \sim r^3, & r \leq R \\ M \sim R^3, & r \geq R \end{cases}$$

$$\begin{cases} v \sim r \\ v \sim 1/r^{1/2} \end{cases}$$



ZWIKI

$\Longleftarrow$ EXP.

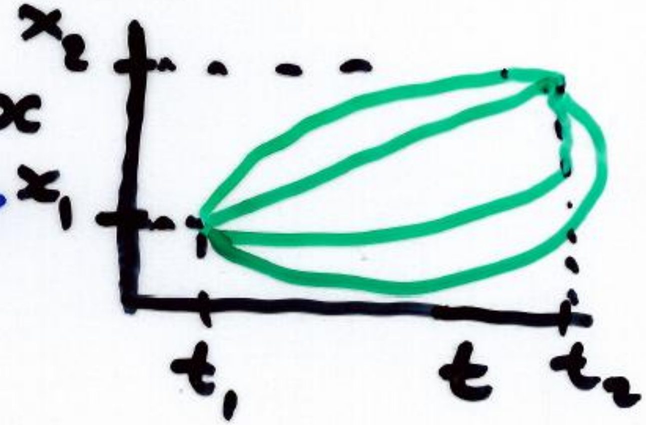


COMO DESCREVER TEORIAS DE CAMPO

LAGRANGEANO $\longrightarrow$ ACÇÃO

CLÁSSICO: $L(x, \dot{x}) = \frac{1}{2} m \dot{x}^2 - U(x)$

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



Hamilton

EQ. Euler-Lagrange

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{x}} - \frac{\partial L}{\partial x} = 0$$

NOTA: SISTEMA ISOLADO

$$\frac{\partial L}{\partial t}=0;\quad \partial L/\partial x=0;\quad \partial L/\partial \theta=0$$

PARTÍCULA $\longrightarrow$ CAMPO

x $(\bullet)$ $\longrightarrow$ $\phi(x)$ (

Ex: $\mathcal{L} \equiv -\frac{1}{2}(\partial_\mu \phi)^2 - \frac{1}{2} m^2 \phi^2 - \lambda \phi^3 - g\phi^4$

$$S[\phi(x)] = \int d^4x \; \mathcal{L}(\phi(x), \partial_\mu \phi(x))$$

$$\partial_\mu \left(\frac{\partial \mathcal{L}}{\partial(\partial_\mu \phi)} \right) - \frac{\partial \mathcal{L}}{\partial \phi} = 0$$

EX: QED

ELECTRÕES $\mathcal{L}_\psi = -\bar{\psi}\,\partial_\mu \psi - m\bar{\psi}\psi$ $[\bar{\psi} \equiv \psi^*]$

INVARIÂNCIAS (PADRÃO)

GLOBAL: $\psi \longrightarrow \psi' = e^{iq\varepsilon}\psi$ ✓

LOCAL: $\psi \longrightarrow \psi' = e^{iq\varepsilon(x)}\psi$?

$$\partial_\mu \psi(x) \to (\partial_\mu \psi(x))' = e^{iq\varepsilon(x)}\left[\partial_\mu \psi + iq\,\partial_\mu \varepsilon(x)\psi\right]$$

NÃO É INVARIANTE

DERIVADA COVARIANTE D_μ:

$$D_\mu \psi(x) \longrightarrow (D_\mu \psi(x))' = e^{iq\varepsilon(x)}(D_\mu \psi)$$

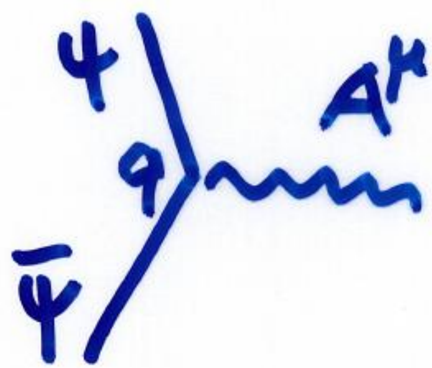
$$\Longrightarrow D_\mu \to \partial_\mu - iqA_\mu(x)$$

$$A_\mu \longrightarrow A'_\mu = A_\mu + \partial_\mu \varepsilon(x)$$ CAMPO PADRÃO (GAUGE)

$$\mathcal{L}_\psi = -\bar{\psi}\partial\psi - m\psi\bar{\psi} + iqA_\mu\bar{\psi}\gamma^\mu\psi$$

$$\mathcal{L}_{A+\psi} = -\frac{1}{4}(\partial_\mu A_\nu - \partial_\nu A_\mu)^2 - \bar{\psi}\partial\psi - m\bar{\psi}\psi + iqA_\mu\bar{\psi}\gamma^\mu\psi$$

[Conservação da corrente]



INVARIÂNCIA PADRÃO GLOBAL

$\uparrow \equiv \phi$

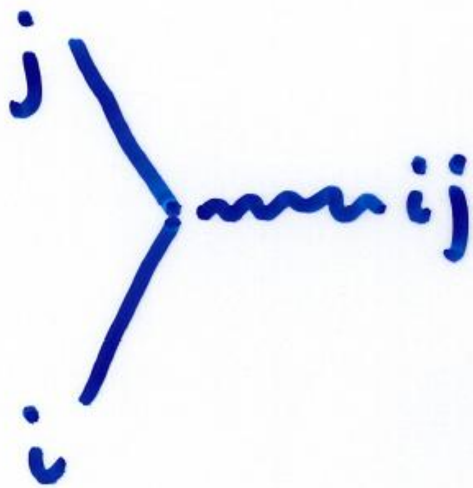
INVARIÃNCIA PADRÃO LOCAL

$\nearrow \equiv A_\mu$

GENERALIZAÇÕES

1) $\psi_i(x) \longrightarrow \psi_i'(x) = U_{ij}\,\psi_j(x)$

$$U^\dagger = U^{-1}$$



$SU(N): \quad N \otimes N = (N^2-1) \oplus 1$

$[N]$: FUNDAMENTAL $\quad s = 1/2$

$[N^2-1]$: GERADORES $\quad s = 1$

[Yang-Mills]

OBSERVAÇÕES:

1) OS FOTÕES NÃO INTERAGEM ENTRE SI !

$1[2,3] - 1[3,2]$

U(1) GR. ABELIANO $[a,b]-[b,a]=0$

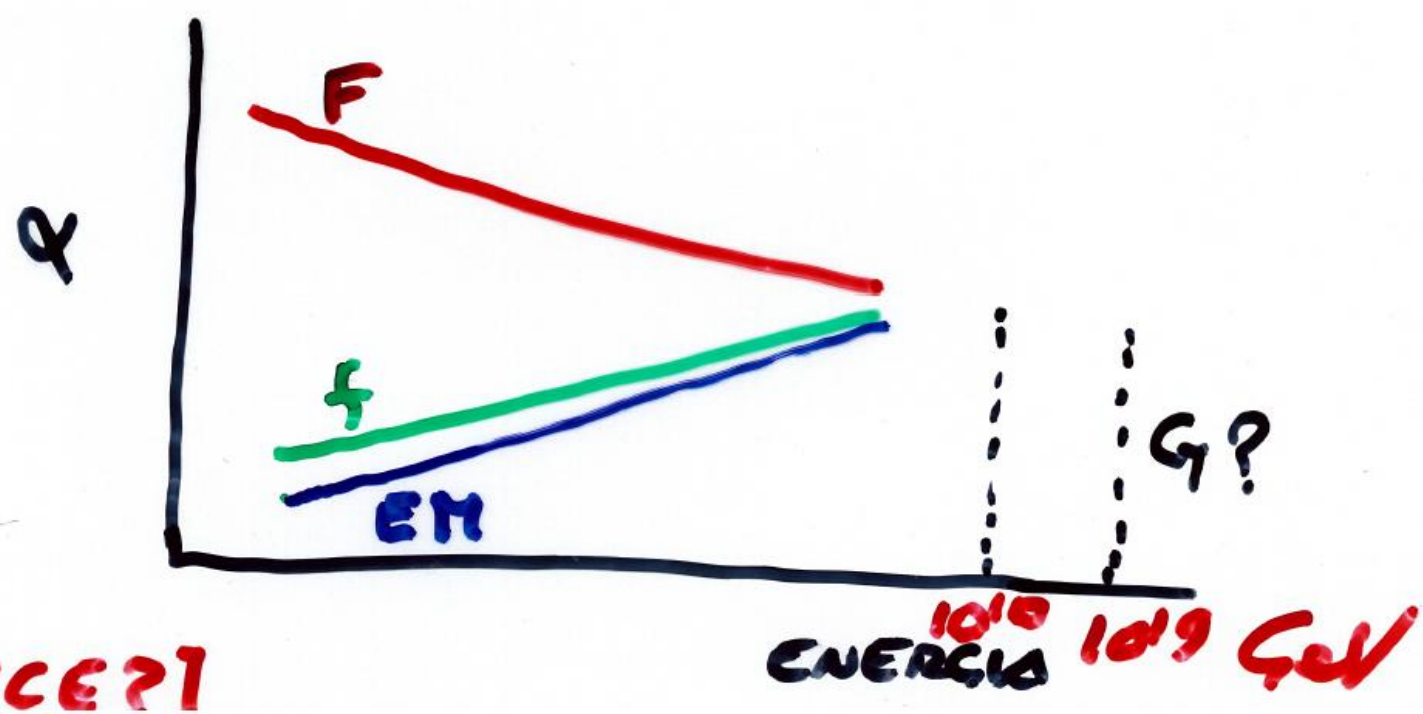
SU(N) GR. NÃO ABELIANO $[a,b]-[b,a]\neq 0$

27 GUTs

EM $\quad \alpha \equiv \frac{1}{4\pi\varepsilon_0}\frac{e^2}{\hbar c}$ sem dimensões

If $\quad g_f$

IF $\quad g_F$

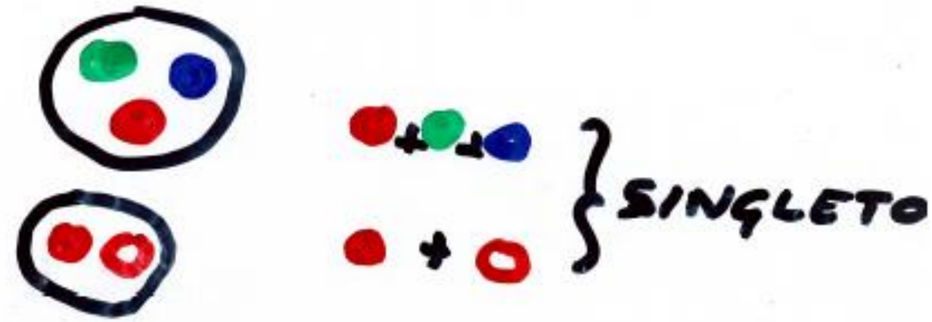


[ALCANCE?]

3) CONFINAMENTO

NUCLEÕES

MESÕES

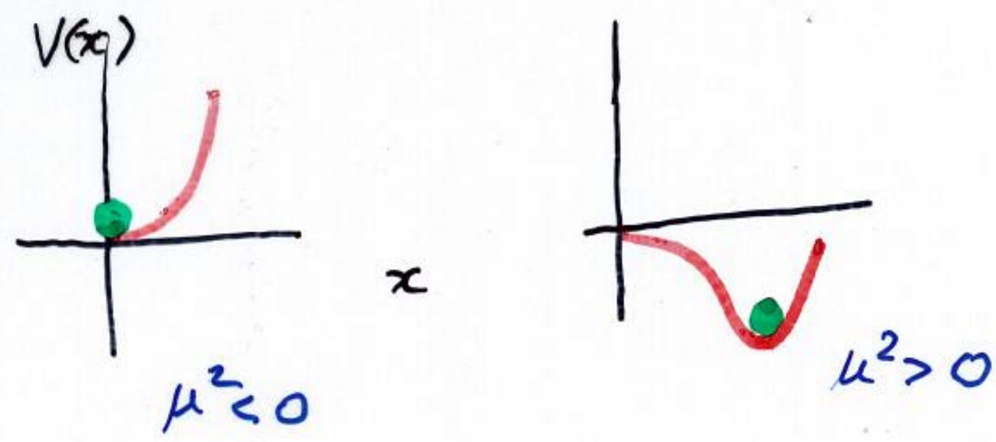


NOTA : PRIMEIROS µ-SEGUNDOS ...

QUEBRA EXPONTÂNEA DE SIMETRIA (LANDAU)

EX: ATOMO DE HIDROGÉNIO
SUPERCONDUTOR
FERROMAGNETO

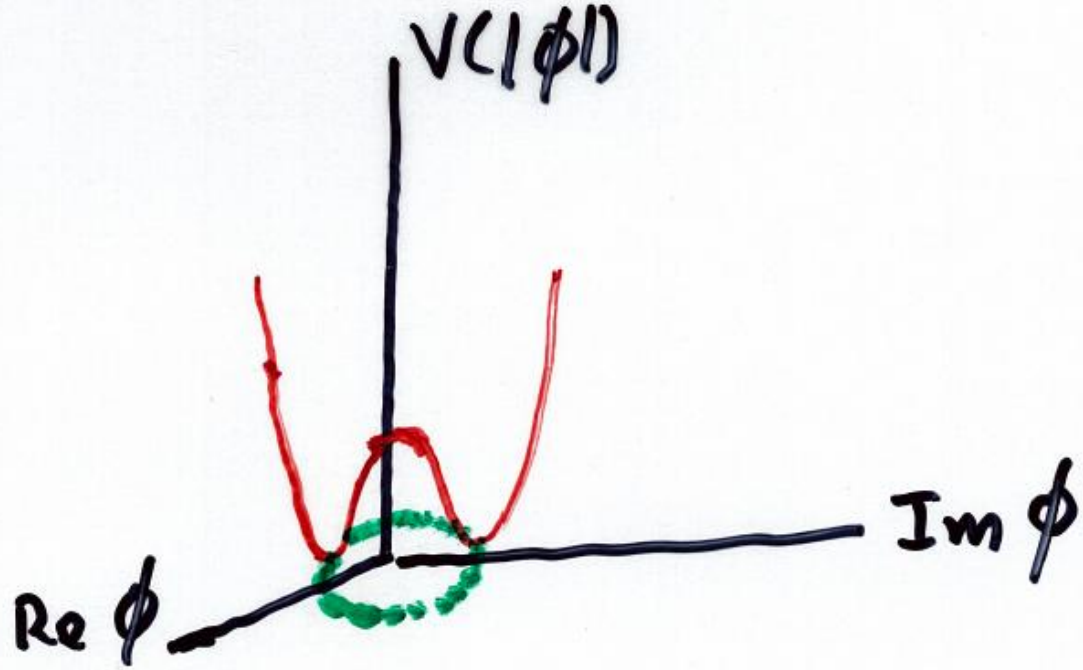
$$V(x) = -\frac{1}{2}\mu^2 x^2 + \frac{1}{4}\lambda x^4 = \left(-\frac{1}{2}\mu^2 + \frac{1}{4}\lambda x^2\right) x^2$$



→ QUEBRA EXPONTÂNEA DE SIMETRIA:

QUANDO A SIMETRIA DA TEORIA NÃO APARECE REFLECTIDA NA SOLUÇÃO

EX: INVARIÂNCIA DE ROTAÇÃO



CAMPO ESCALAR COMPLEXO [Real ϕ, Im ϕ]

LAGRANGEANO:

$$\mathcal{L} = -\partial_\mu |\phi|^2 - V(|\phi|)$$

$$\phi(x) \longrightarrow \phi'(x) = e^{iq\varepsilon} \phi(x)$$ (INV. PADRÃO GLOBAL)

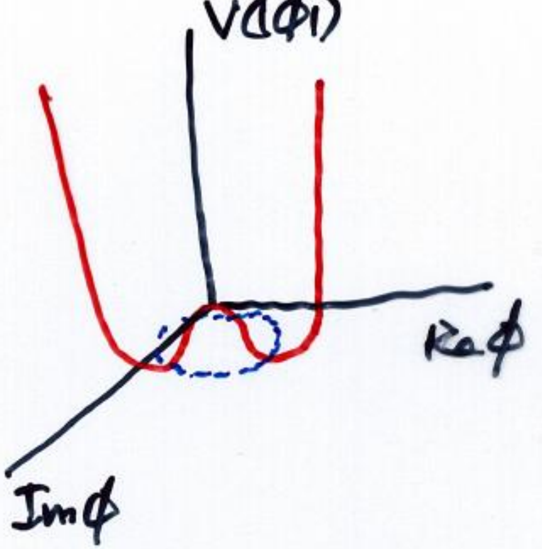
SOLUÇÕES: EM TORNO DO MÍNIMO DE POTENCIAL

CASO "NORMAL": $V(|\phi|) = V(|\phi|)_{MIN.} + \mu^2 |\phi|^2 + \ldots$

$$V(|\phi|)_{MIN} = 0$$

$$\mu^2 \equiv \partial V / \partial |\phi|^2 \equiv \text{massa}$$

CASO "QUEBRA DE SIMETRIA"



$$\phi(x) = \frac{1}{\sqrt{2}}\rho(x)e^{i\theta(x)}$$

$$\partial_\mu\phi = \frac{1}{\sqrt{2}}e^{i\theta(x)}(\partial_\mu\rho + i\rho\,\partial_\mu\theta)$$

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu\rho)^2 - \frac{1}{2}\rho^2(\partial_\mu\theta)^2 - V(\rho/\sqrt{2})$$

EXP. EM TORNO MÍNIMO:

$$\rho: \quad \mu^2 = \frac{\partial^2}{\partial\rho^2}V(\rho/\sqrt{2})\Big|_{\rho_{MIN}}$$

θ: massa zero (GOLDSTONE)

(Brout-Englert-Higgs)

$$\phi(x) \longrightarrow \phi'(x) = e^{iq\varepsilon(x)}\phi(x)$$

$$A_\mu(x) \longrightarrow A'_\mu(x) = A_\mu(x) + \partial_\mu \varepsilon(x)$$

$$\Rightarrow \quad \mathcal{L} = -\frac{1}{4} F^2_{\mu\nu}(A) - |D_\mu \phi|^2 - V(|\phi|)$$

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$D_\mu \phi = \partial_\mu \phi - iqA_\mu \phi$$

POTENCIAL: $\theta(x) \longrightarrow \theta'(x) = \theta(x) + q\varepsilon(x)$

DERIVADA CO-VARIANTE:

$$D_\mu \phi = \frac{1}{\sqrt{2}} e^{i\theta} (\partial_\mu \rho - iq\rho \underbrace{(A_\mu - q^{-1}\partial_\mu \theta)}_{B_\mu}))$$

(insensível à transformação de gauge)

$$D_\mu \phi = \frac{1}{\sqrt{2}} e^{i\theta} (\partial_\mu \rho - iq\rho B_\mu)$$

$$\Rightarrow \quad \mathcal{L} = -\frac{1}{4} F_{\mu\nu}^2(B) - \frac{1}{2}(\partial_\mu \rho)^2 - \frac{1}{2} q^2 \rho^2 B_\mu^2 - V(\rho/\sqrt{2})$$

$$M_B = |q \rho_{MIN}| = |qv|$$

MASSA DE HIGGS

$$V(\rho) = -\frac{1}{2}\mu^2 \rho^2 + \frac{1}{4}\lambda \rho^4$$

$$MIN: \; -\mu^2 + \lambda \rho_{MIN}^2 = 0 \longrightarrow v = \sqrt{\mu^2/\lambda} \qquad M_{HIGGS}^2 = 2\lambda v^2$$