Aulas aluno IC   Fev. 2023

Introdução:

HI

Detetores

Física de Ions pesados ultra relativísticos

Conexão :

Física das Partículas Elementares (Altas Energias) +

Física Nuclear

Ions Pesados : núcleos atomicos pesados

Ultra Relativísticos : energia cinética dos núcleos >> energia de repouso (??

Física das partículas em Altas energias:

partículas (leptons, quarks, hadrons) + suas interações

⇓

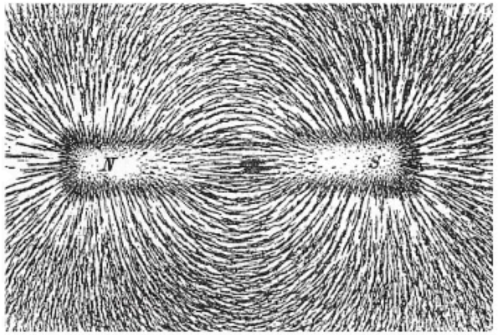
descritas por princípios básicos

≠

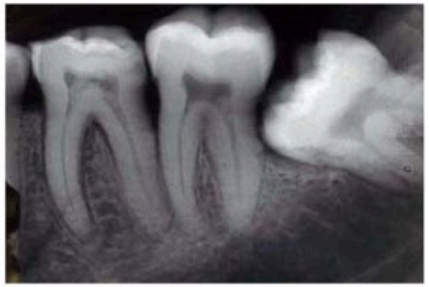
Física nuclear:

núcleos (extensos, objetos complexos) + interações descritas por modelos efetivos

- **Maxwell and electromagnetism: the concept of a field; charges generate fields which (can) permeate all of space… Other "charges" feel this field – and thus they feel a force.**



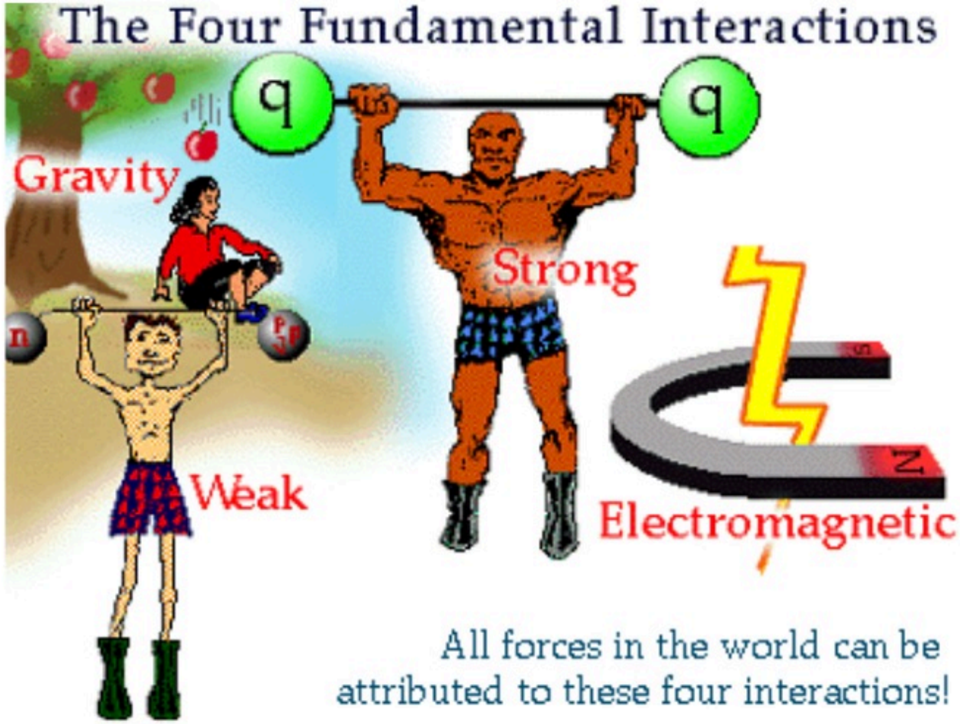
- **The incredible discovery: the E/B fields can exist alone – they propagate in waves in the vacuum! Thus are radio, TV and cell-phones made possible.**



20th century: two more forces at work

- But nuclei are held together – against the electrostatic repulsion. So there is yet another type of force! And it must be very, very strong.
- And nuclei break up! Radioactivity! Neutrons become protons. So there is yet another type of force! And it is very, very weak.

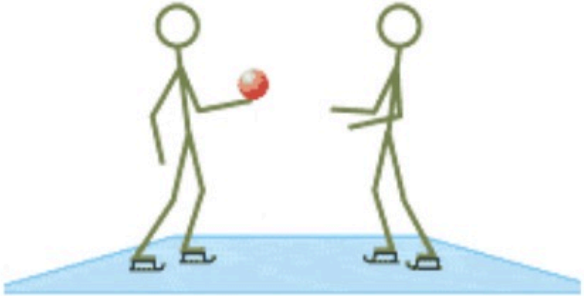
There are, in total FOUR different forces in nature



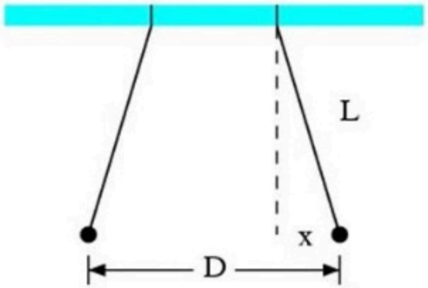
Quantum Field Theory

Relativity Theory + Quantum mechanics: a new picture of what is a "force"

$$L_{\text{int}} = -q\overline{\psi}\gamma^{\mu}A_{\mu}\psi$$



FORCE IS THE EXCHANGE OF PARTICLES!

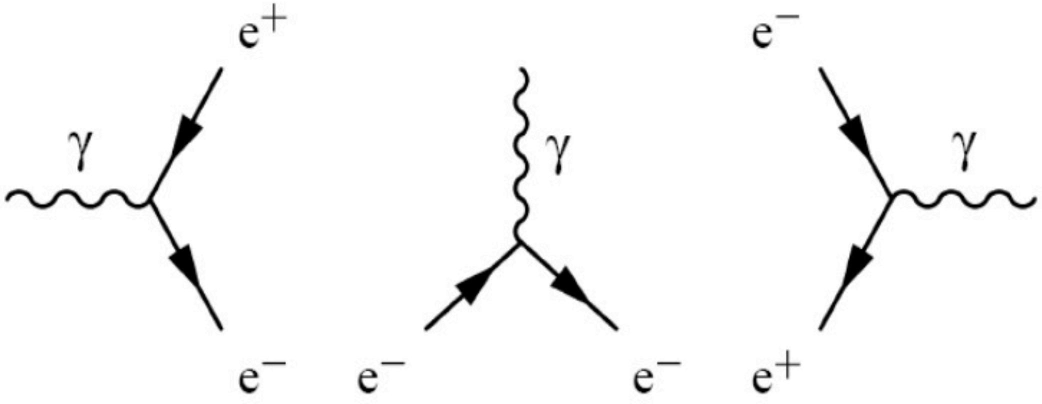


Quantum Electrodynamics (III)

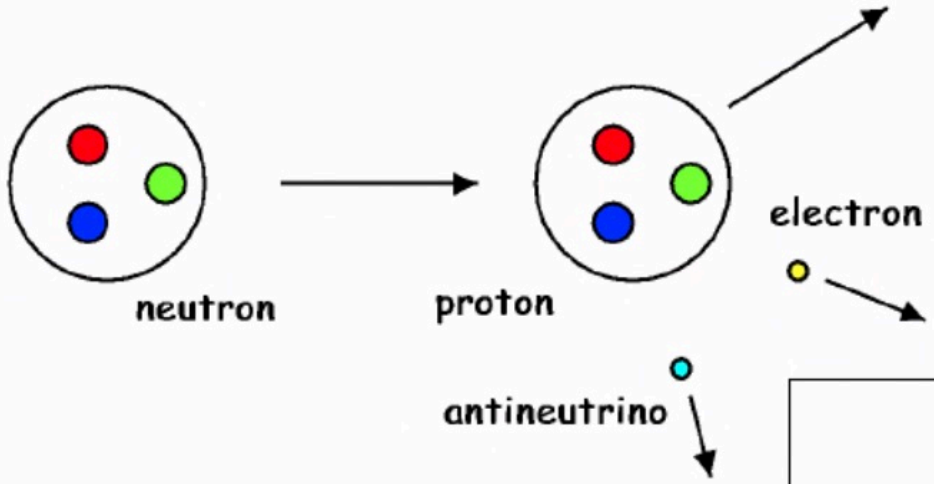
- **The interaction:**

$$L_{\text{int}} = -q\bar{\psi}\gamma^{\mu}A_{\mu}\psi$$

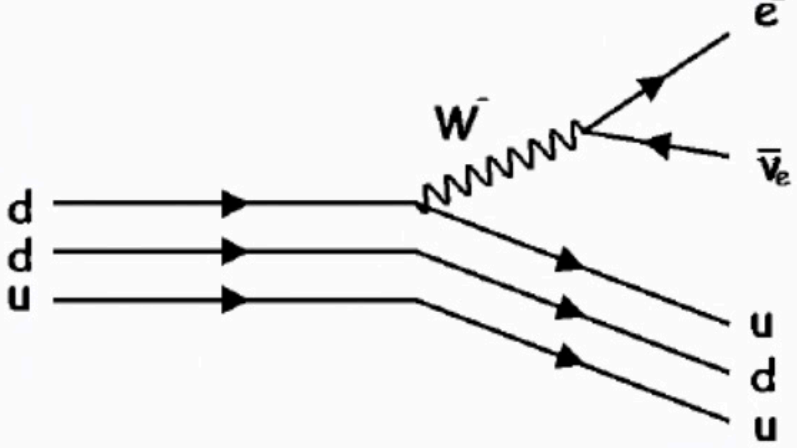
- **And the quantum excitation of the A field will be particles (photons!)**



Weak interaction



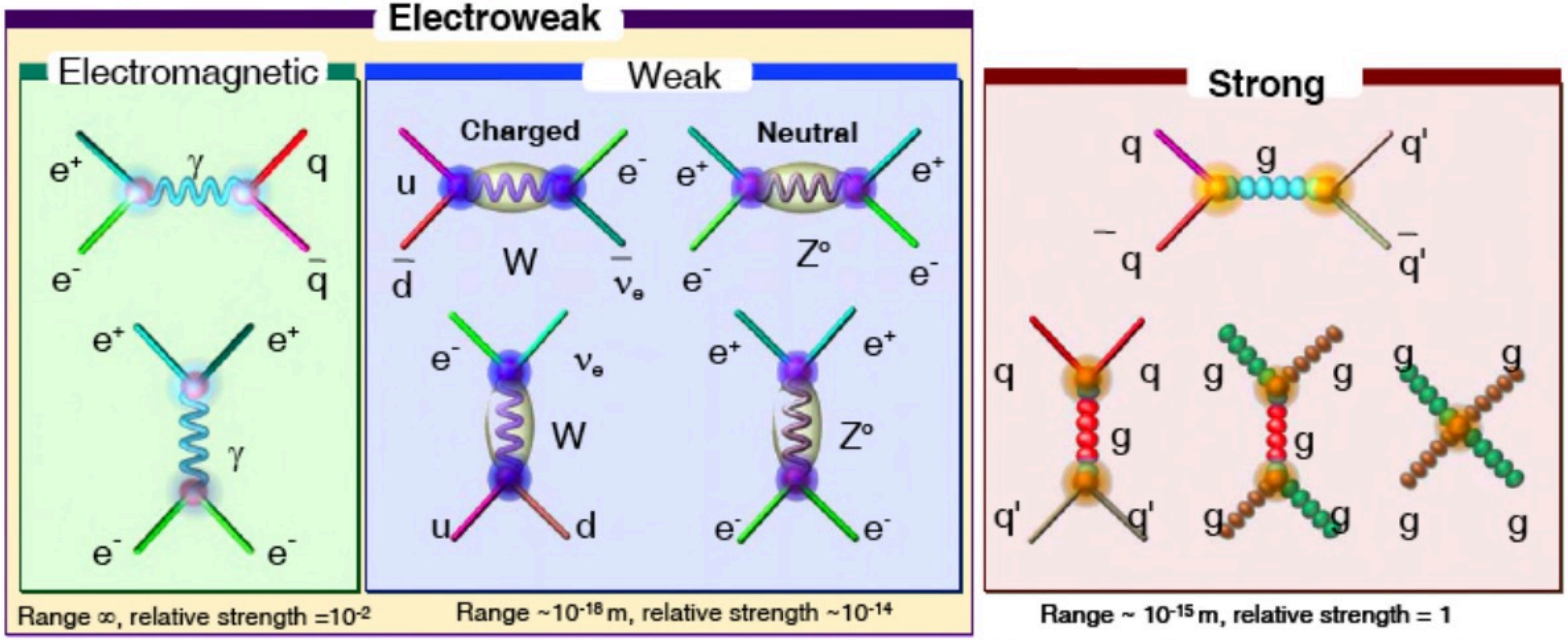
Beta decay $n \rightarrow p + e^{-} + \bar{\nu}_e$



Mediated by charged
W exchange

Standard Model of Particle Physics

- **Quantum Field theory:**
  - **Matter particles (spin-1/2) interact via the exchange of force particles (spin-1)**

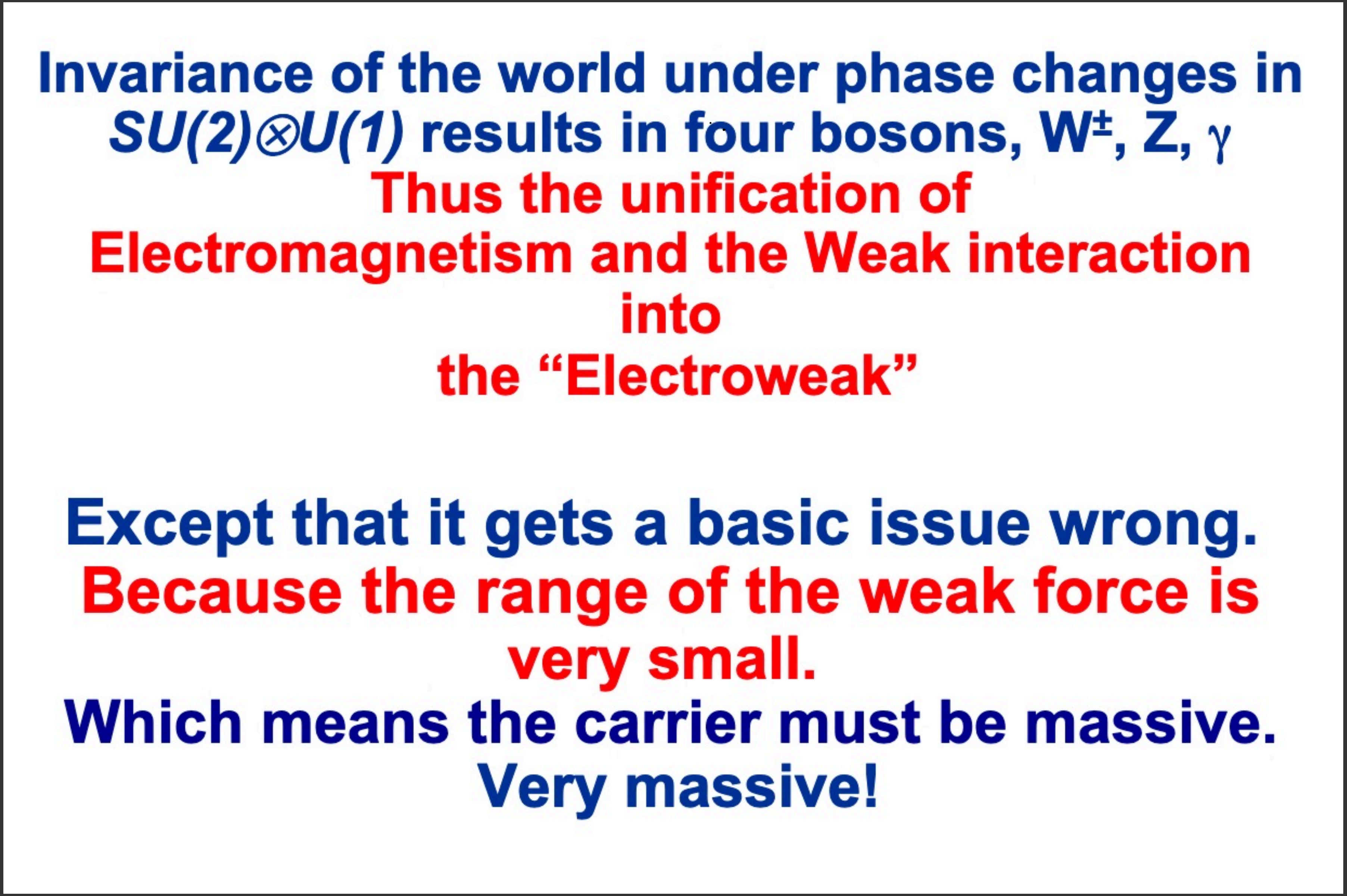


Range ∞, relative strength $=10^{-2}$

Range $\sim 10^{-18}$ m, relative strength $\sim 10^{-14}$

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

  - **Forces: interactions, so need (a) charge(s). Which should be conserved. Which implies some new symmetry…**
  - **Standard Model: internal symmetry (SU(3)xSU(2)xU(1))**



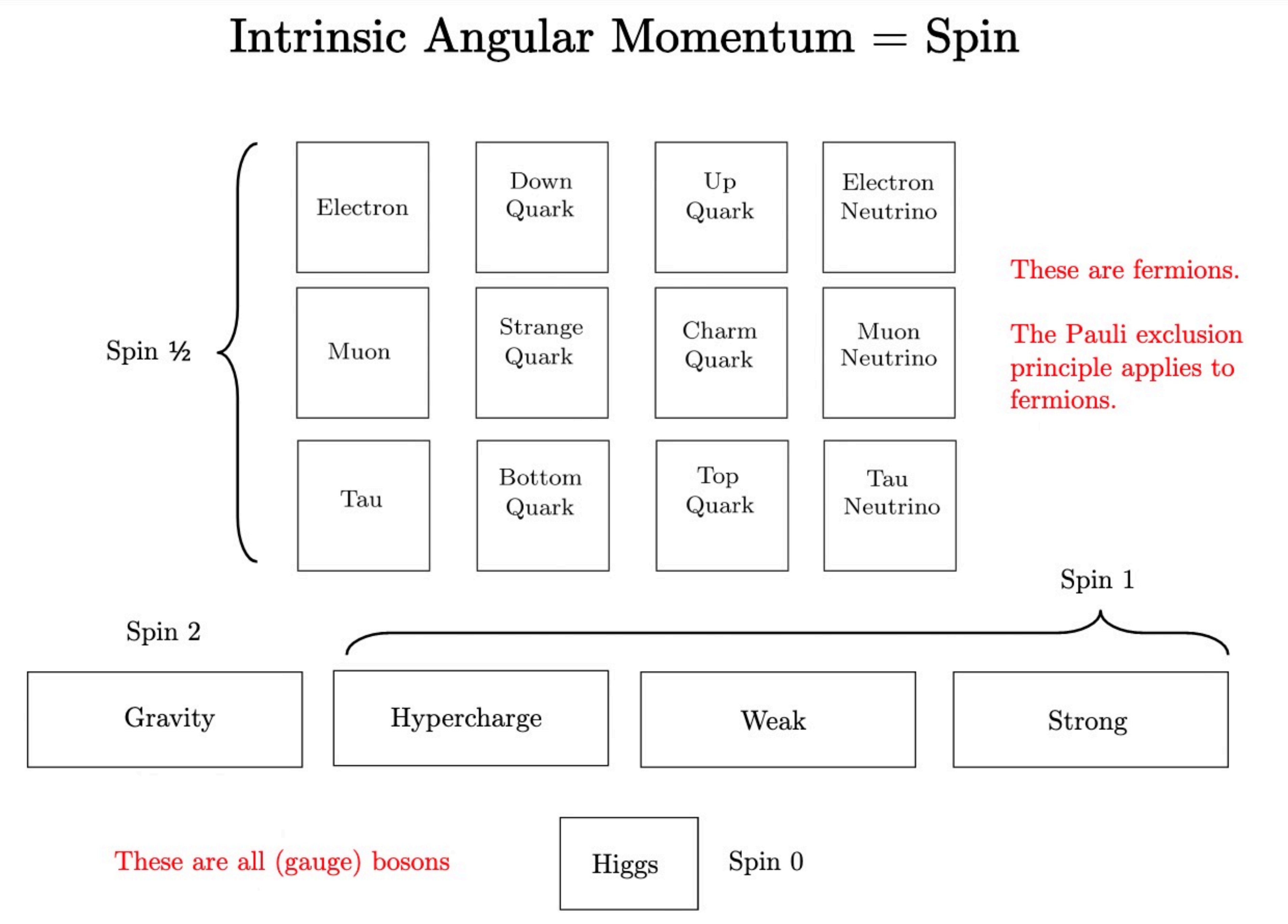
Invariance of the world under phase changes in $SU(2)\otimes U(1)$ results in four bosons, $W^{\pm}$, Z, γ

Thus the unification of
Electromagnetism and the Weak interaction
into
the "Electroweak"

Except that it gets a basic issue wrong.
Because the range of the weak force is very small.
Which means the carrier must be massive.
Very massive!

https://indico.cern.ch/event/1132537/attachments/2446218/4191743/lectures.pdf

Intrinsic Angular Momentum = Spin



Spin ½

Electron	Down Quark	Up Quark	Electron Neutrino
Muon	Strange Quark	Charm Quark	Muon Neutrino
Tau	Bottom Quark	Top Quark	Tau Neutrino

These are fermions.

The Pauli exclusion principle applies to fermions.

Spin 2

Gravity

Spin 1

Hypercharge

Weak

Strong

These are all (gauge) bosons

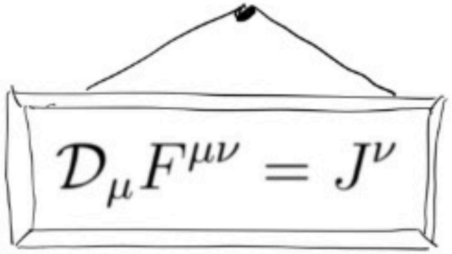
Higgs

Spin 0

- 1 x 1 matrix ⟹ Electromagnetism
- 2 x 2 matrix ⟹ Weak force
- 3 x 3 matrix ⟹ Strong force

or U(1) x SU(2) x SU(3)

These fields are governed by the Yang-Mills equations



$$\mathcal{D}_\mu F^{\mu\nu} = J^\nu$$

The Strong Force (or QCD)

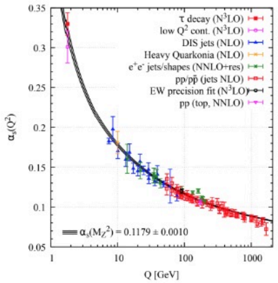
No	Yes	Yes	No
Electron 1	Down Quark 9	Up Quark 4	Electron Neutrino $\sim 10^{-6}$
Muon 207	Strange Quark 186	Charm Quark 2495	Muon Neutrino $\sim 10^{-6}$
Tau 3483	Bottom Quark 8180	Top Quark 340,000	Tau Neutrino $\sim 10^{-6}$

Each quark comes in three *colours*, which we take to be red, green and blue.

(Note: a better counting is that each generation contains 1+3+3+1=8 particles.)

Why is the Strong Force Strong?

strong coupling constant

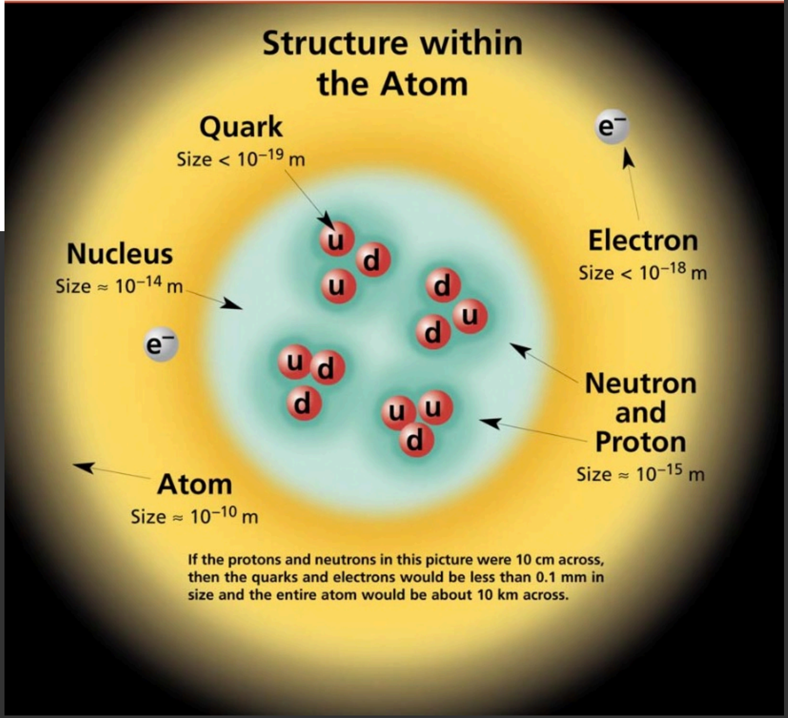


energy = 1/distance

At high energy, say E=100 GeV, we have $\alpha_s \approx 0.1$. But the strong force gets stronger as we go to larger distances. (Asymptotic freedom.)

Taken naively, $\alpha_s \to \infty$ at the energy scale: $\boxed{\Lambda_{\text{QCD}} \approx 200 \text{ MeV}}$

This corresponds to a distance scale $R_{\text{QCD}} = \dfrac{1}{\Lambda_{\text{QCD}}} \approx 5 \times 10^{-15}$ m



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

Confinement

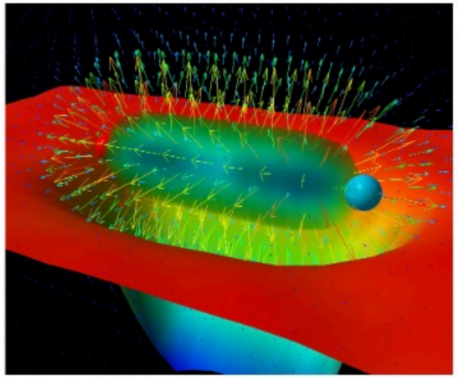
At short distances, $F(r) \sim \frac{\alpha_s}{r^2}$ but at long distances $F(r)$ becomes constant.

In terms of the potential energy, $V(r) \sim -\frac{\alpha_s}{r}$ at short distances, but at long distances

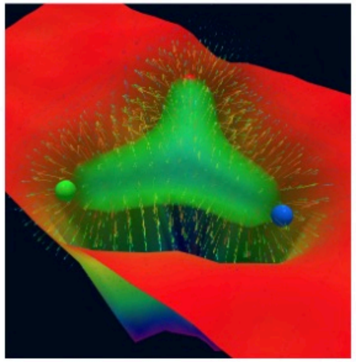
$$\boxed{V(r) \sim \Lambda_{\rm QCD}^2\, r}$$

This is *confinement*. We don't see isolated quarks.

Also, the force carrying field is not massless. The gluons stick together to form glueballs, with mass around $m_{\rm gluon} \approx \Lambda_{\rm QCD}$. This is the "mass gap" problem.



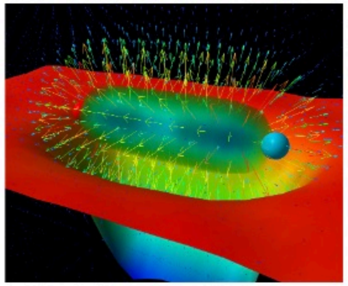
Hadrons (Stuff Made of Quarks)



- Baryons: three quarks. For example

$$\begin{aligned} n\ (ddu) \quad & m_n \approx 939.57 \text{ MeV} \\ p\ (uud) \quad & m_p \approx 938.28 \text{ MeV} \end{aligned}$$

A puzzle: $\mathrm{m}_{\mathrm{down}}$= 5 MeV and m_{up}=2 MeV. Where does the mass come from?



- Mesons: quark-anti-quark pair. For example, pions

$$\begin{aligned} \pi^+\ (\bar{d}u) \qquad & m \approx 139 \text{ MeV} \\ \pi^0\ \tfrac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d) \qquad & m \approx 135 \text{ MeV} \\ \pi^-\ (\bar{u}d) \qquad & m \approx 139 \text{ MeV} \end{aligned}$$

Note: Pions have spin 0 and so should be thought of as “force carrying” particles! So ...

(*) ⇒ analisar propriedades da matéria hadronica / nuclear "quente" em termos das interações fundamentais

⇒ comprovação e testes de novas fases de matéria hadrônica, identificação de transições de fase, reconstrução do diagrama de fase da matéria fortemente interagente em termos de parâmetros de termodinâmica como a temperatura e o potencial químico bariônico

Importante papel do surgimento de novos aceleradores em operação p/ usar íons pesados

desde anos 1970

* Baixas energias ⇒ núcleo intacto ou se desintegra em fragmentos nucleares menores

** Altas energias ⇒ graus de liberdade aumentam ⇒ limites para produção de partículas são alcançados para: pions e kaons (hadrons)

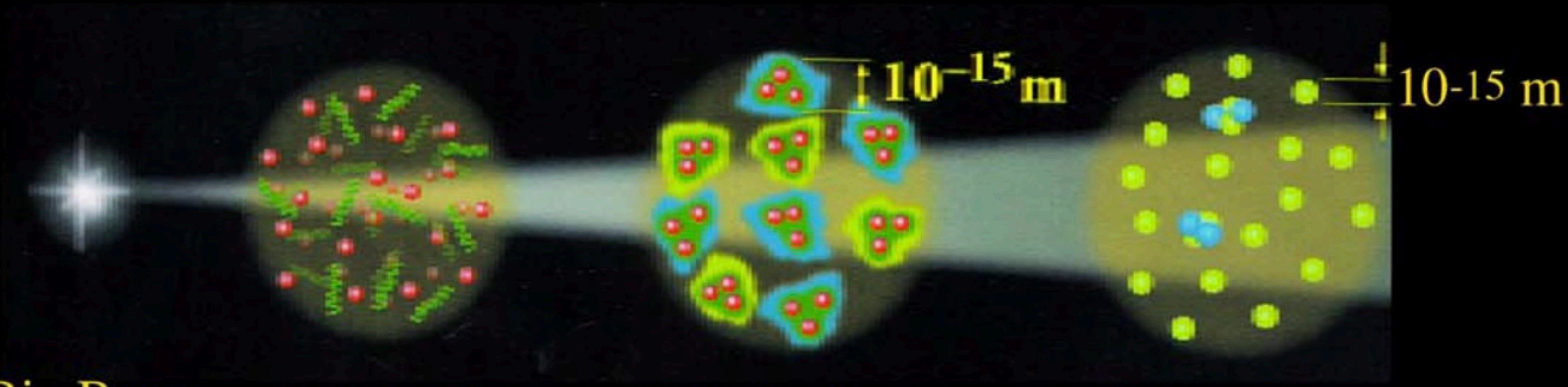
*** Muito altas energias : graus de liberdade passam dos hadrons p/ quarks e gluons ⇒ plasma de quarks e gluons é formado.

Plasma de Quarks e Gluons :

- Matéria que permeou nosso universo nos primeiros 20 μs de sua existência com temperatura $T > 2 \times 10^{12}$ K
- quarks não confinados em objetos (singletos de cor) chamados hadrons

Principal objetivo da pesquisa de íons pesados é entender as propriedades da matéria que interage fortemente (quarks, gluons e hadrons)

History of the Universe

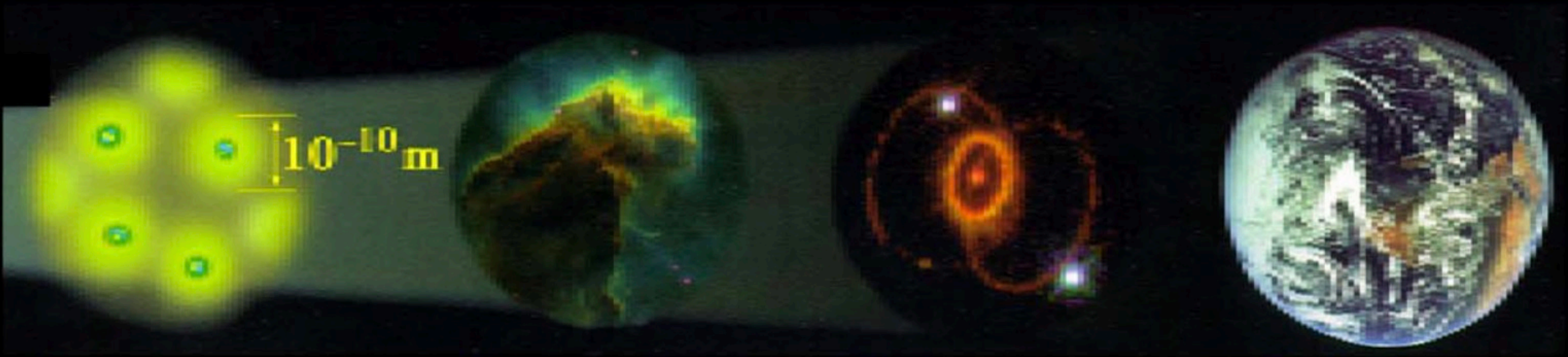


Big Bang

Quark-Gluon
Plasma
10^{13}K, 10^{-6}s

Protons&
Neutrons
10^{12}K, 10^{-4}s

Low-mass
Nuclei
10^{9}K, 3 min



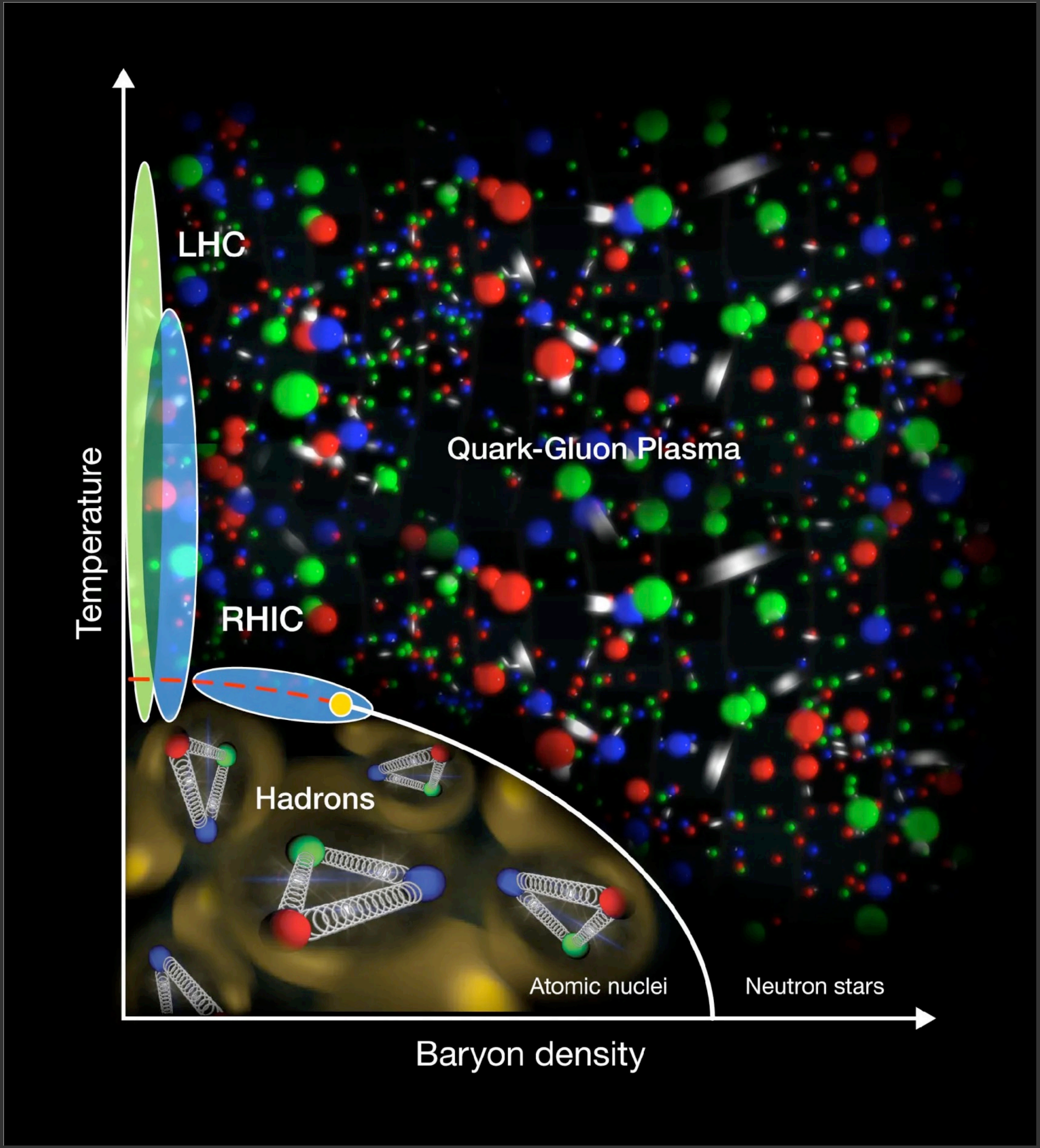
Neutral
Atoms
4000K, 10^{5}y

Star
Formation
10^{9}y

Heavy
Elements
$>10^{9}$y

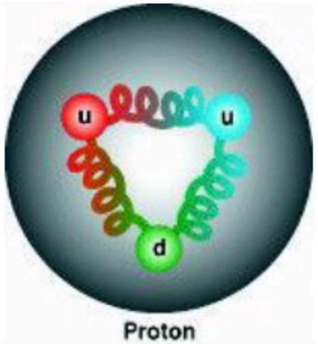
Today

Source: Nuclear Science
Wall Chart


Temperature
LHC
RHIC
Quark-Gluon Plasma
Hadrons
Atomic nuclei
Neutron stars
Baryon density

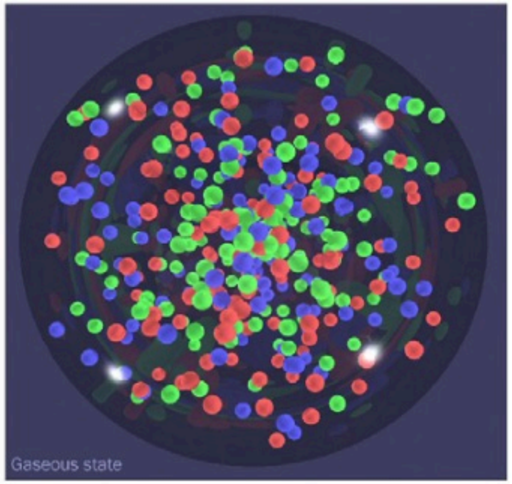
What is Quark-Gluon Plasma?

At room temperature, quarks and gluons are always confined inside colorless objects (hadrons):



protons, neutrons, pions, …..

Very high temperature (asymptotic freedom):

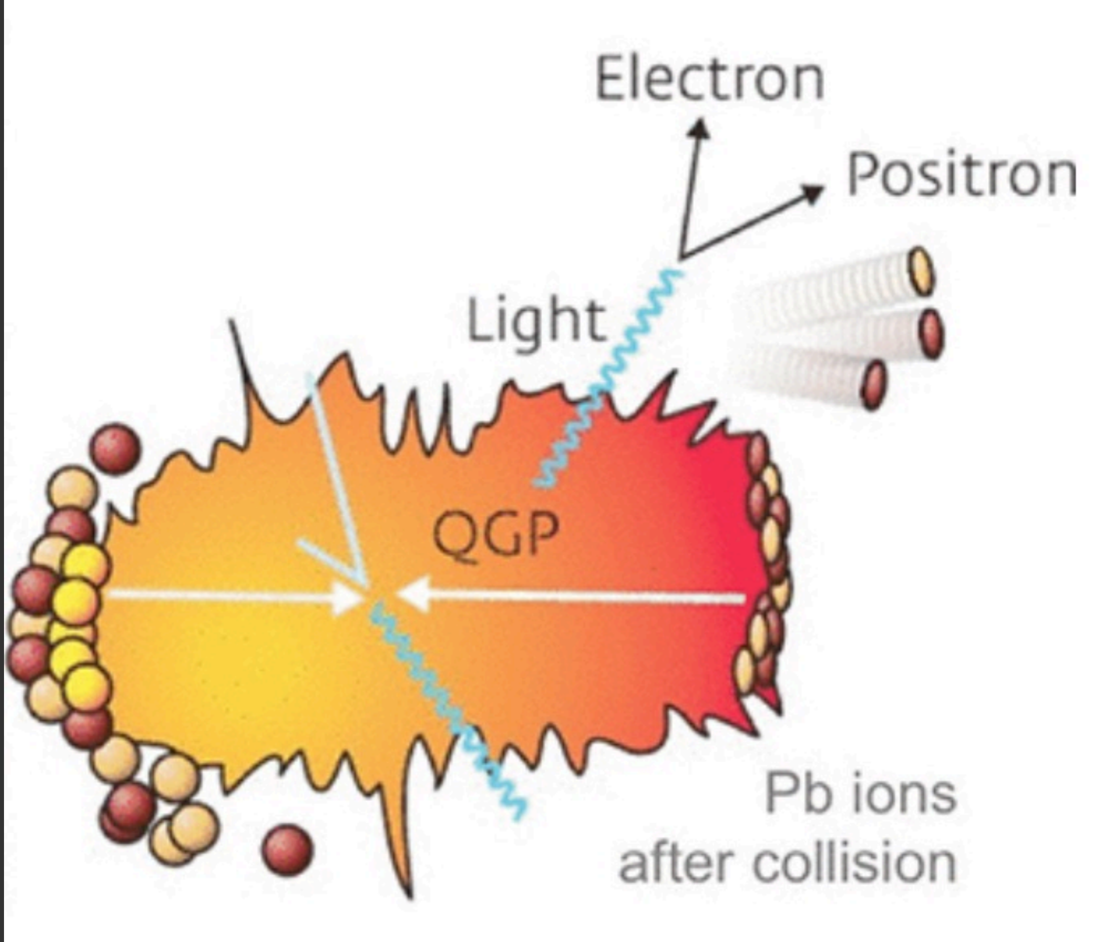


→ Interactions become weak

→ quarks and gluons deconfined

→ Quark-gluon plasma (QGP)

Infinitely high temperature:
QGP may behave like an ideal gas.


Electron
Positron
Light
QGP
Pb ions
after collision

Sobre o programa de verão do CERN p/ estudantes:

- visão geral sobre o que fazemos no CERN
- não restrito à Física de Partículas: tem aulas sobre aceleradores, detetores, aplicações em medicina, feixes, estatística, Física nuclear, ferramentas (Madgraph, ROOT), Eletrônica (DAQ, Trigger etc), Astropartículas, Cosmologia, etc.

Bibliografie :

- Ramone (2007)
- Florkowski (2010)
- Hannah Elfner (2022)