QCD: The color of the force

Inside protons and neutrons

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UAM · CSIC Consejo Superior de Investigaciones Científicas

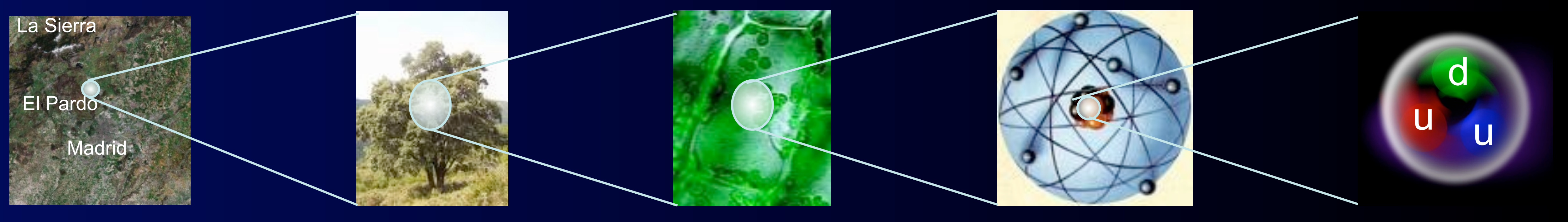
What are we made of?

Everything around us is made up of atoms, which are composed of nuclei (made up of protons and neutrons), around which electrons orbit in a cloud.

Protons and neutrons are themselves made up of smaller particles, quarks. Quarks and electrons are examples of elementary particles, which are not composed of further smaller particles (as far as we have been able to probe experimentally).

There are 6 kinds of quarks (called u, d, c, s, t, b), but quarks u and d are sufficient to form protons (as a uud trio) and neutrons (udd).

With just three particles: electrons, "u" quarks and "d" quarks one can build all atoms in the universe.



10^5 m = 100 Km
Satellite image of the Madrid area, centered on the El Pardo forest

1m
A holm oak tree in the El Pardo forest

10^{-5} m = 10 μm
Plant cell

10^{-10} m = 0.1nm
Carbon atom

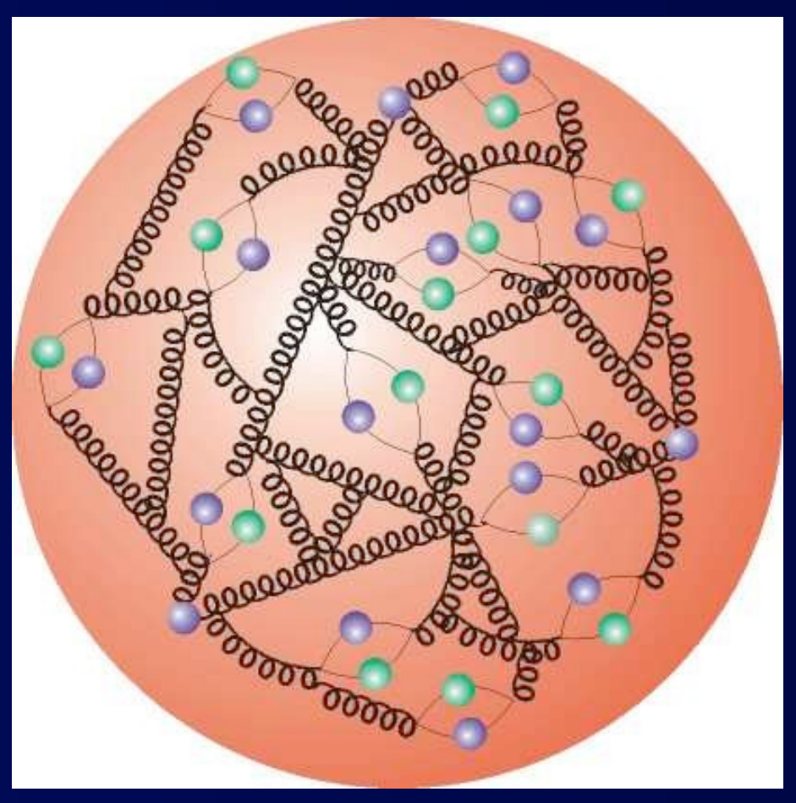
10^{-15} m = 1 fm
Internal structure of the proton

Quantum Chromodynamics (QCD): the color force

What holds quarks together?

Quarks are held together by the strong interaction. The charge associated to this interaction is a new quantum number called "color", and which takes three possible values: "red", "green" and "blue". Needless to say, they have nothing to do with the actual colors perceived in our daily life.

The mediators of the color force are 8 interaction particles, the gluons, which have zero mass and spin 1, just like the photons. However, gluons carry color charge themselves, and are confined by the strong interaction itself, restricting its range to approximately 10^{-15} m, the size of a proton.



The mystery of mass

Essentially almost all the mass of atoms is due to the mass of their nuclei, and the latter comes from that of its constituent protons and neutrons.

However, the u and d quark masses are so small that they are responsible only for about 1% of the mass of a proton or a neutron.

The extra mass is due to the energy of the color force fields present inside protons and neutrons, which keep quarks and gluons confined.

The 8 gluons

Gluons carry a combination of color and anticolor charge. There are 9 possible combinations, but only 8 correspond to actual gluons.

This can be explained by describing gluons as matrices acting on the coordinates of the color space of quarks (red, green, blue):

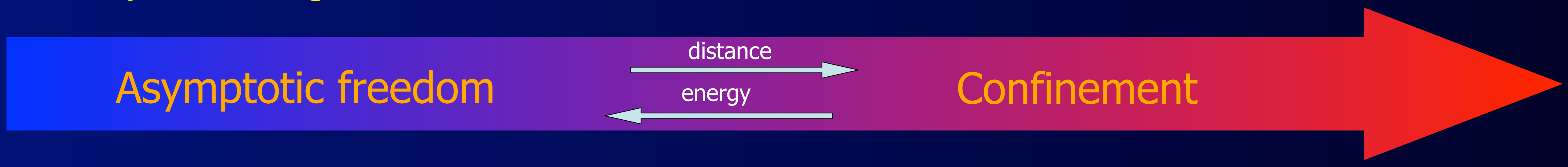
$$\begin{pmatrix} r\bar{r} & r\bar{g} & r\bar{b} \\ g\bar{r} & g\bar{g} & g\bar{b} \\ b\bar{r} & b\bar{g} & b\bar{b} \end{pmatrix}$$

The missing combination is the trace of this matrix

$$r\bar{r} + g\bar{g} + b\bar{b}$$

Intuitively, the non-dynamical nature of this combination is related to the fact that in a space of 3 coordinates (x, y, z) the distance $x^2+y^2+z^2$ to the origin is an invariant of the rotations among coordinates.

Anti-screening: The self-interaction of gluons implies that color charge, and thus the intensity of strong interactions, increases with the distance



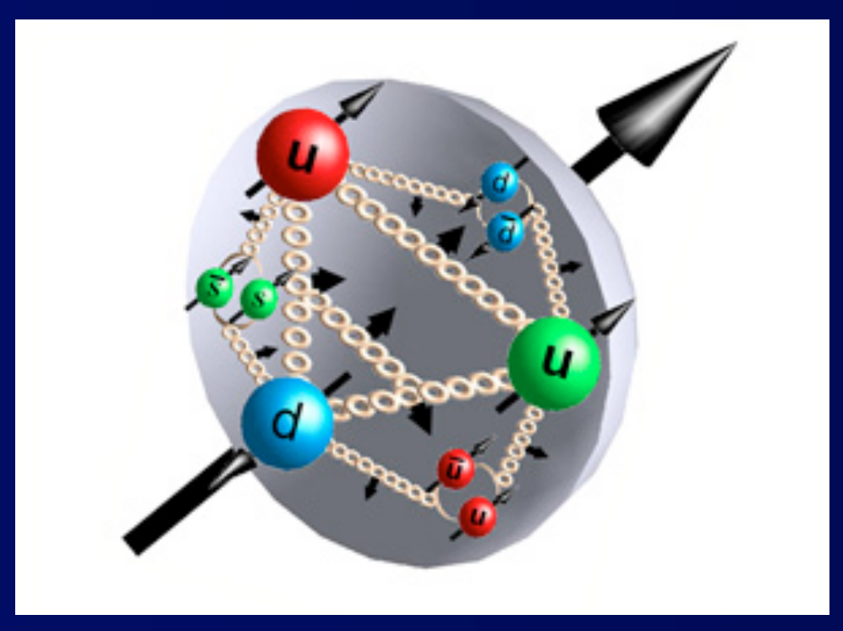
Asymptotic freedom

distance →

← energy

Confinement

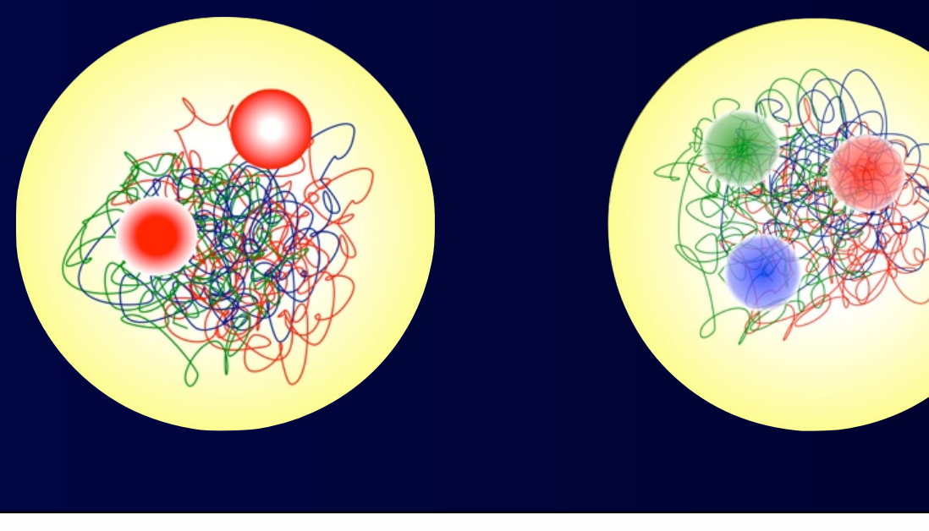
At short distances, or high energies, color interactions are very feeble and quarks behave essentially as free particles. This is in fact how they are observed experimentally in *deep inelastic scattering* experiments, which allows to establish the existence of quarks as physical particles.



At long distances, or low energies, strong interactions are so intense that colored particles cannot be isolated. The only states which can exist in isolated form are color-less composites. These are called hadrons and fall in two classes:

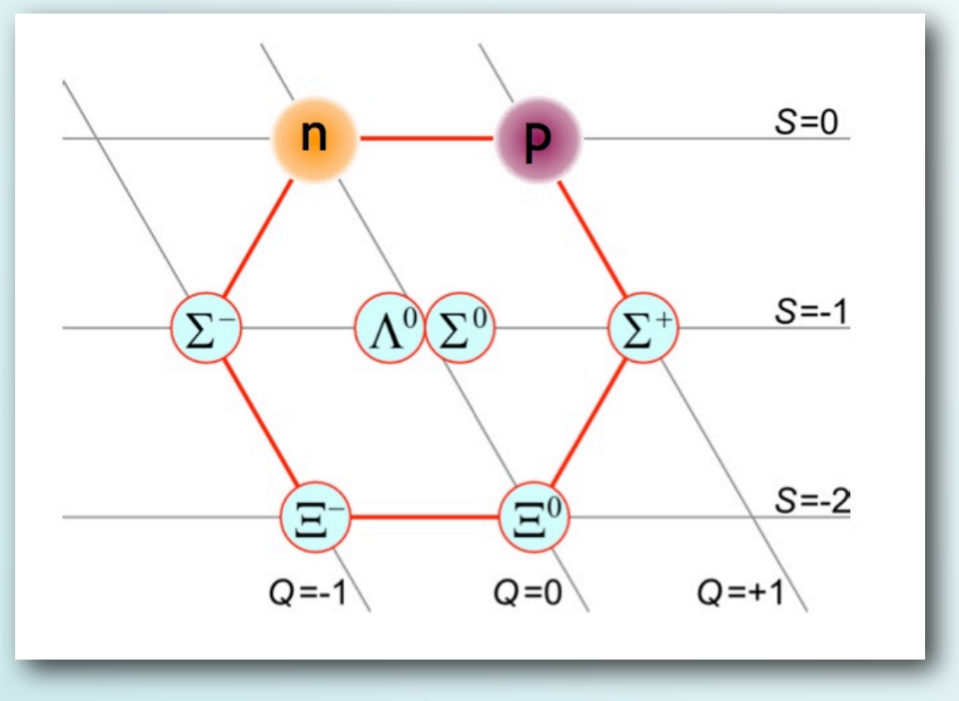
- baryons, made up of three quarks with different color charges (e.g. protons and neutrons).
- mesons, combinations of one quark and one antiquark, with opposite color charges (e.g. pions).

Baryons and mesons are color-less, but they are full of color due to the intense gluon exchanges in their interior.



The "eightfold way"

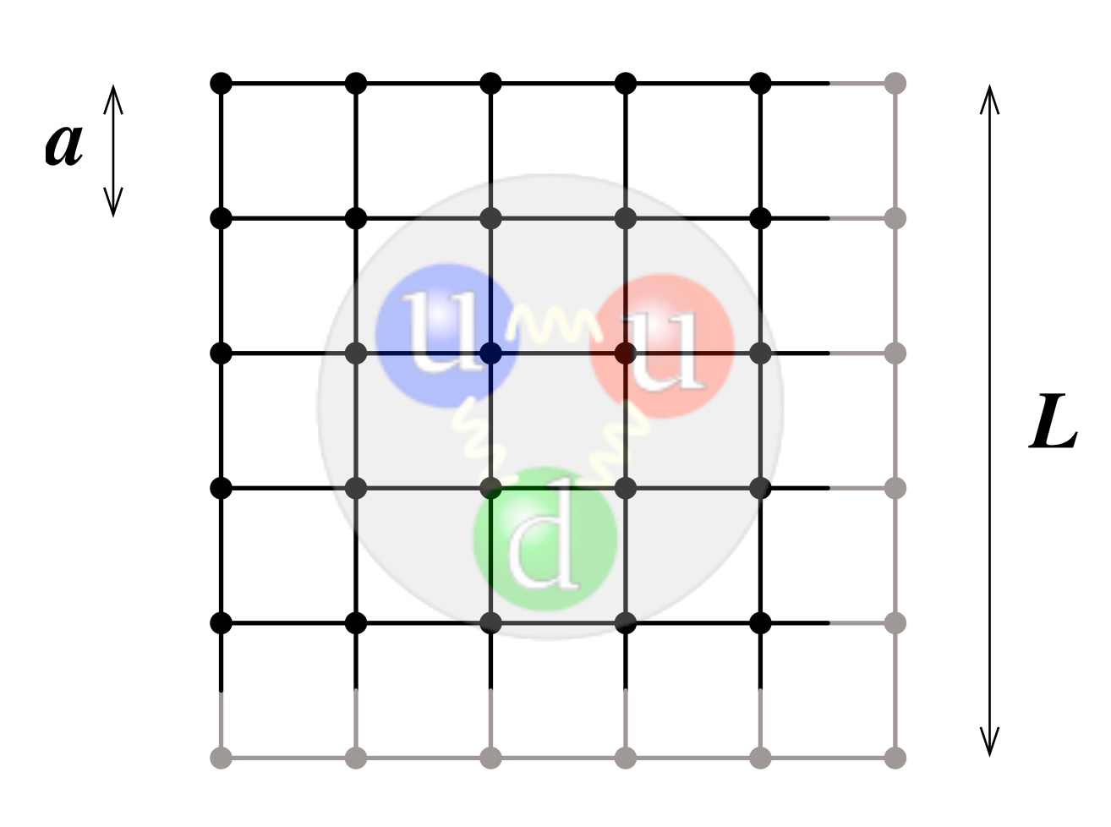
Mesons and baryons built with the different quarks form regular patterns (octets and decuplets for the u, d, s, quarks). Historically, the symmetry underlying these patterns motivated the proposal of the quark model.



Non-perturbative methods: The properties of QCD at low energies cannot be described as a sum over Feynman diagrams.

Quantum Gauge Field Theory in the Lattice

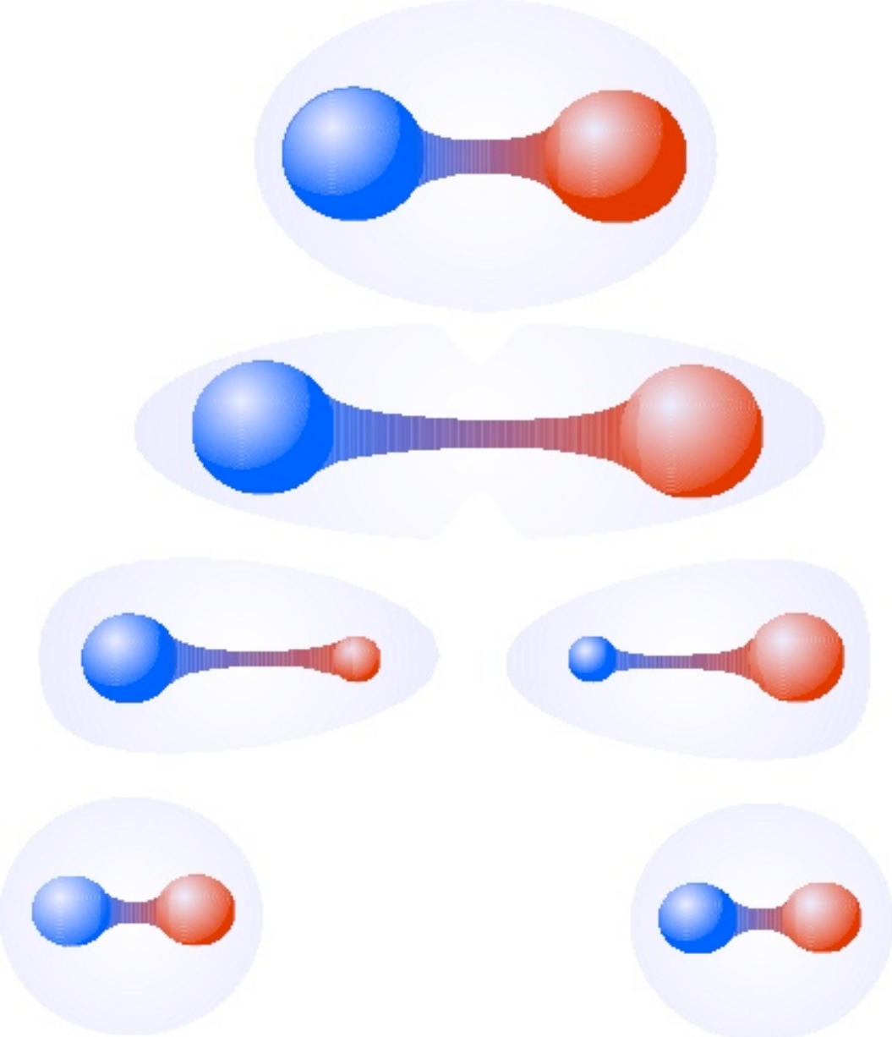
The color interactions among quarks and gluons can be simulated numerically by using models in which space-time is discretized in a lattice. The calculations involved are computationally so heavy that they require the use of supercomputers and long CPU run times, but they allow for precise first principles computations of masses and properties of hadrons.



Hydra Cluster at the IFT UAM-CSIC

The QCD string

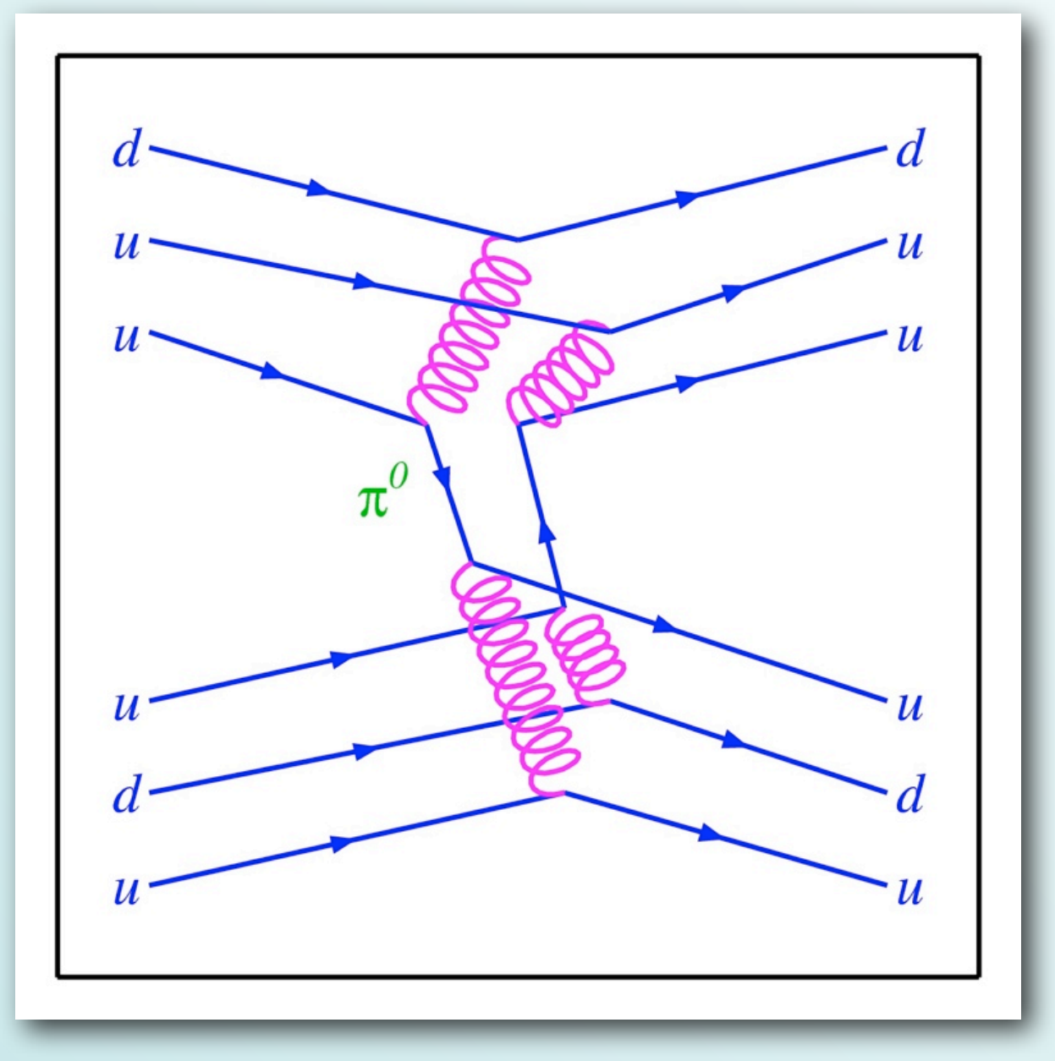
If you try to separate the quark and antiquark inside a meson, there appears a color flux tube stretching between them, like a elastic rope of enormous tension. When the separation distance reaches a critical value, the stored energy is enough to nucleate a new quark and antiquark which snaps the string, and which combine with the original particles to produce two new mesons, preventing the detection of isolated quarks.



The Yukawa model

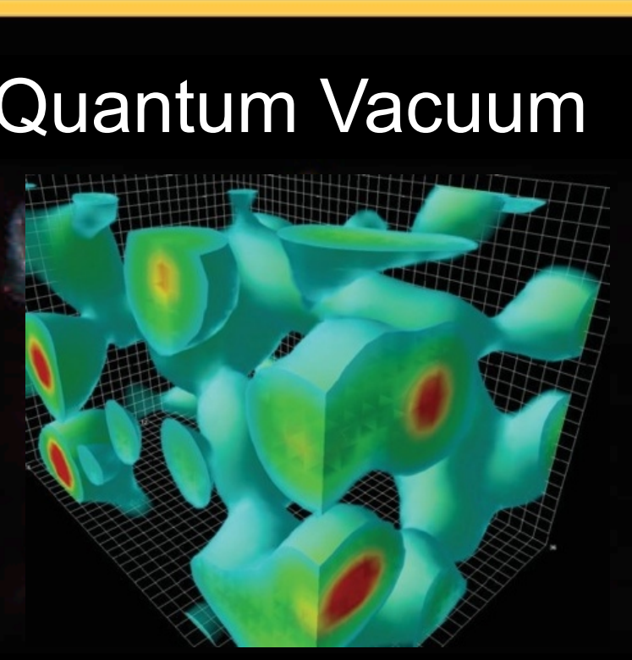
Color interactions among quarks produce a residual interaction among protons and neutrons (similar to how electromagnetic interactions within atoms produce residual Van der Waals forces among molecules).

This residual interaction can be described as the exchange of pions, as described in the Yukawa model of nuclear interactions.



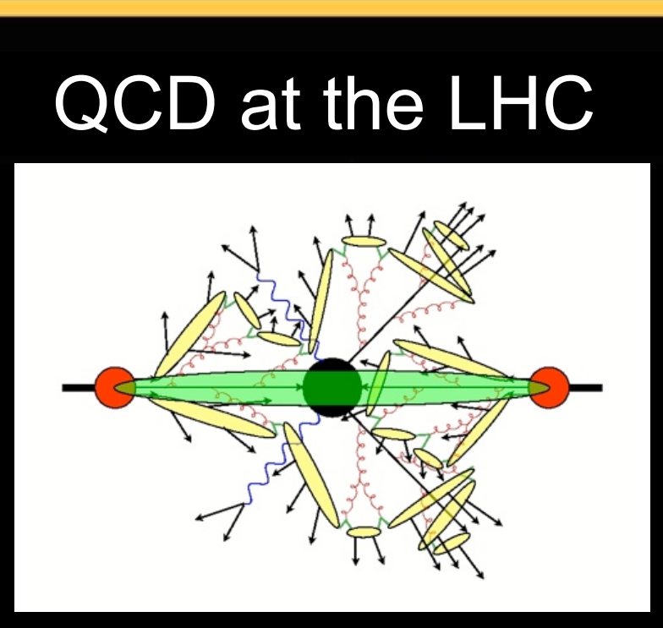
Open puzzles

Quantum Vacuum



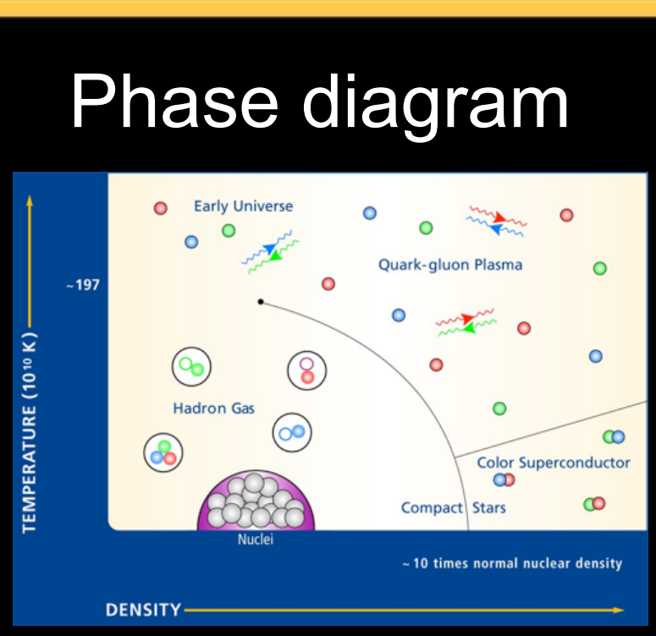
The quantum vacuum of QCD is dominated by non-perturbative dynamics. Although lattice quantum field theory provides numerical computations of its properties, their direct interpretation in terms of non-perturbative phenomena remains open.

QCD at the LHC



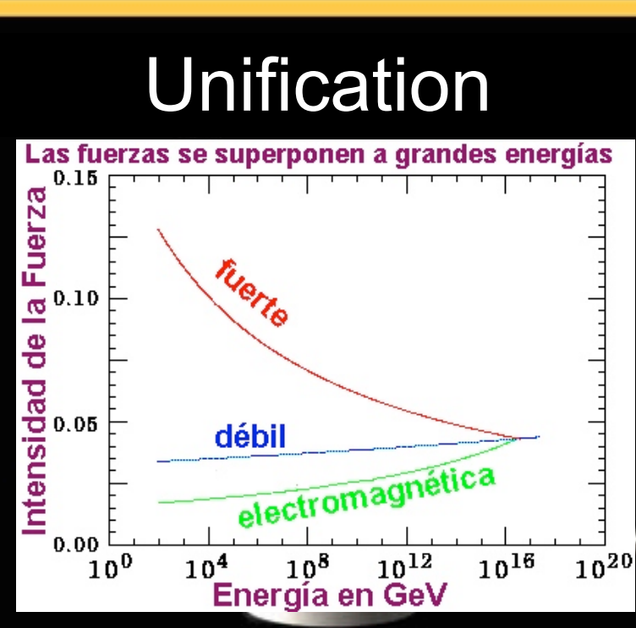
The LHC is a hadron collider, so any collision involves QCD processes at very high energies. Their study reveals new hidden symmetries of the strong interactions in this regime, like integrability or conformal symmetry.

Phase diagram



Quark and gluon states can organize in different physical phases, depending on their density and temperature (e.g. nuclear matter, plasma, neutron stars,...). The QCD phase diagram can reveal the existence of new states of matter.

Unification



The color interaction, extrapolated to very high energies, has an intensity essentially equal to that of electromagnetic and weak interactions. Are all the interactions of the Standard Model part of a unified force, perhaps even including gravity?

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