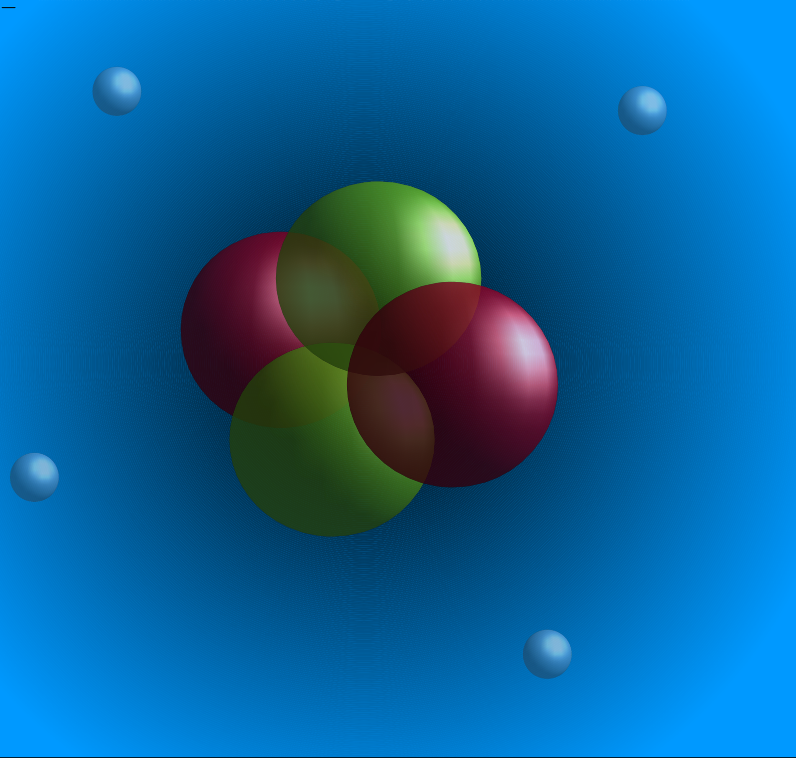

The Strange World of the Strong Force

Understanding why the vacuum isn't so empty

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Four forces of nature

Were all the forces of nature united at the beginning of the universe?

We know at large enough temperatures the weak interaction and electromagnetism are one and the same... ELECTROWEAK FORCE

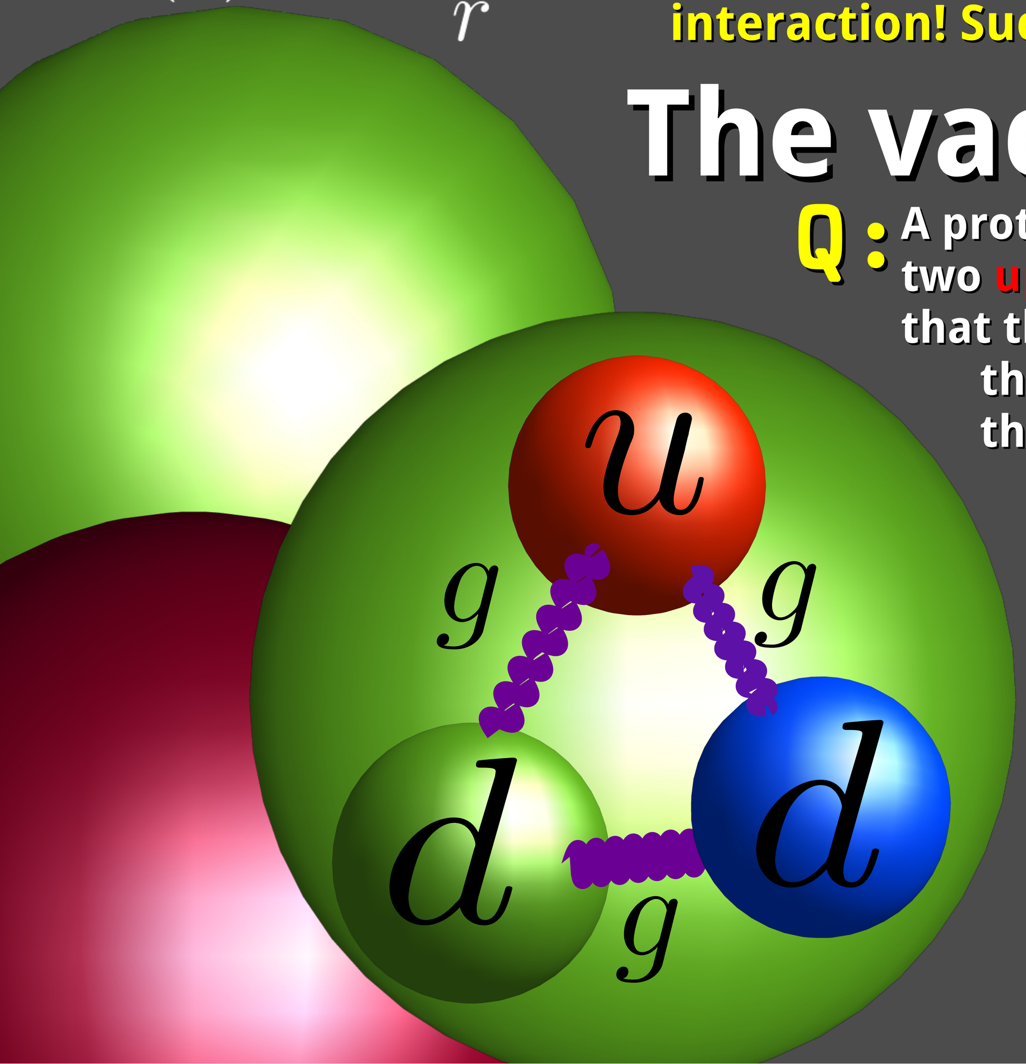
How strong is the strong force?

Consider the electric potential of a point charge. Coulomb's law tells us it goes like $V(r) \sim -\frac{1}{r}$ That is, the further one gets from the source, the weaker the interaction. Now consider a 'strong charge' (called colour charge). The potential for the strong interaction looks very similar at small distances to the Coulombic potential of the electric charge BUT at large distances the potential is dominated by a linear term, akin to the Cornell potential:

$$V(r) \sim -\frac{1}{r} + r$$

This potential tells us that the further the distance, r, between the strongly interaction objects, the GREATER the strength of the strong interaction! Such physics is difficult to model and calculate with.

The vacuum isn't empty

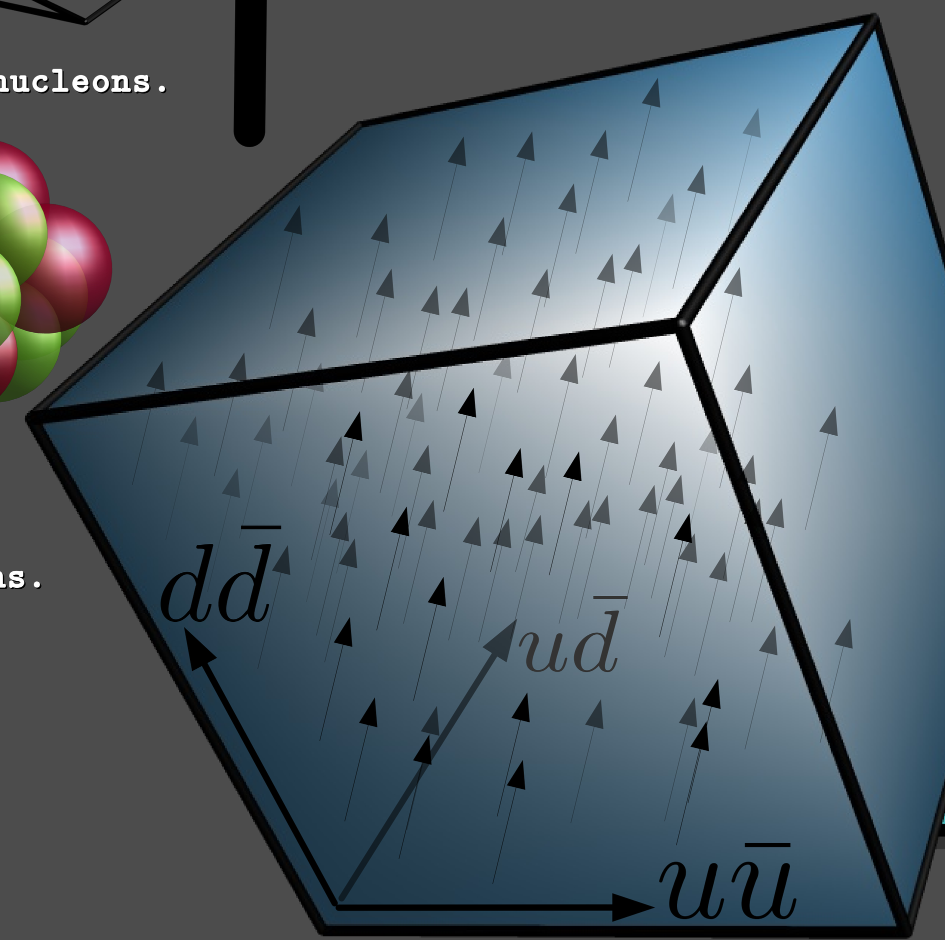


Q: A proton, the nucleus of a hydrogen atom, is comprised of three quarks, two up and one down, which give it its properties. Experiments have shown that the masses of the up and down quarks are about 1000 times lighter than the proton... but how can this be, if the proton is made of three of these quarks?

A: The answer lies with the nature of the vacuum related to the physics of the strong force. Intuition tells us that the vacuum is just empty space. When we say *vacuum*, however, what we really mean is *the lowest energy state of a given system.* Usually, this is the state with nothing in it, i.e. zero energy. But in QCD (the physics of the strong force) the vacuum isn't empty but a bubbling broth of quarks, antiquarks and gluons (particles that, as the name suggests, glue the quarks together inside protons and neutrons). So the majority of the mass of the proton arises from the usual quarks interacting with this rather busy QCD vacuum!

Understanding the QCD vacuum

A good way to try and understand the QCD vacuum is to simplify the situation to a two quark QCD, i.e. the two lightest - up (u) and down (d). Since the vacuum in QCD is a seething realm of quark-anti-quark ($q\bar{q}$) pairs – with only two quarks to choose from (u or d), there are only 4 combinations to pick; $u\bar{u}$ $d\bar{d}$ $u\bar{d}$ $d\bar{u}$



Each of the four possible combinations has a certain probability given by the vacuum, which varies in space. We can represent this on 4-dimensional grid, each axis being a combination. Each location in space is given an arrow which is placed in the 4-D grid, the more the arrow points in the direction of a given combination the more probable it is (see diagram).

In fact the vacuum is a little more constrained. In order to obtain the lowest energy state, i.e. the vacuum, all of the arrows must point in exactly the same way, which is called a condensate. Understanding this condensate is very difficult and its origin is poorly understood.

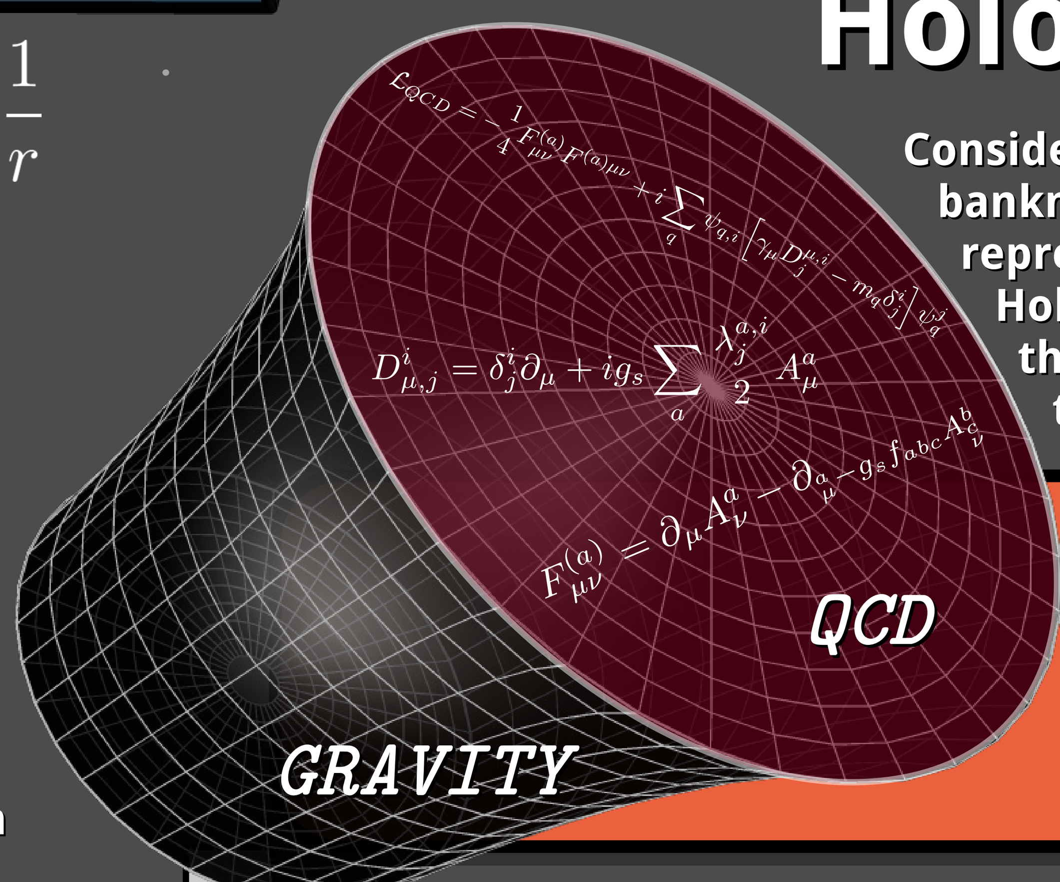
The usual method for analysing interacting systems is *perturbation theory*, but this relies on the strength of the interaction to be small. The strength of the strong force is too large to consider this method.

An alternative approach is to use the concept of HOLOGRAPHY.

Holography

Image: Flickr/FFCU

Consider a hologram (as you might see on a bank card, banknote or DVD). It is a three dimensional image represented on a two dimensional, i.e. flat, plane. Holography (as the name suggests) is based on a similar idea; that certain physics in n-dimensions may be represented by another type of physical system in (n-1)-dimensions.



It turns out that the physics of the strong interaction (QCD) in our usual 4-dimensions (3 space + time) is equivalent to the physics of a system containing some form of gravity of small interaction strength in *five* dimensions.

The holographic principle described above allows us to uncover the elusive properties of the strong interaction by studying a gravitational model.

It turns out that the one extra dimension that we have in on the gravity side, may be representative of an energy scale. So in fact we may come to think of the gravity 'bulk' (the black area on the diagram) as a mathematical loaf of bread, with each slice pertaining to a certain energy.

We therefore can look at the properties of the complex QCD vacuum by looking at its simpler counterpart on the gravity side.

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