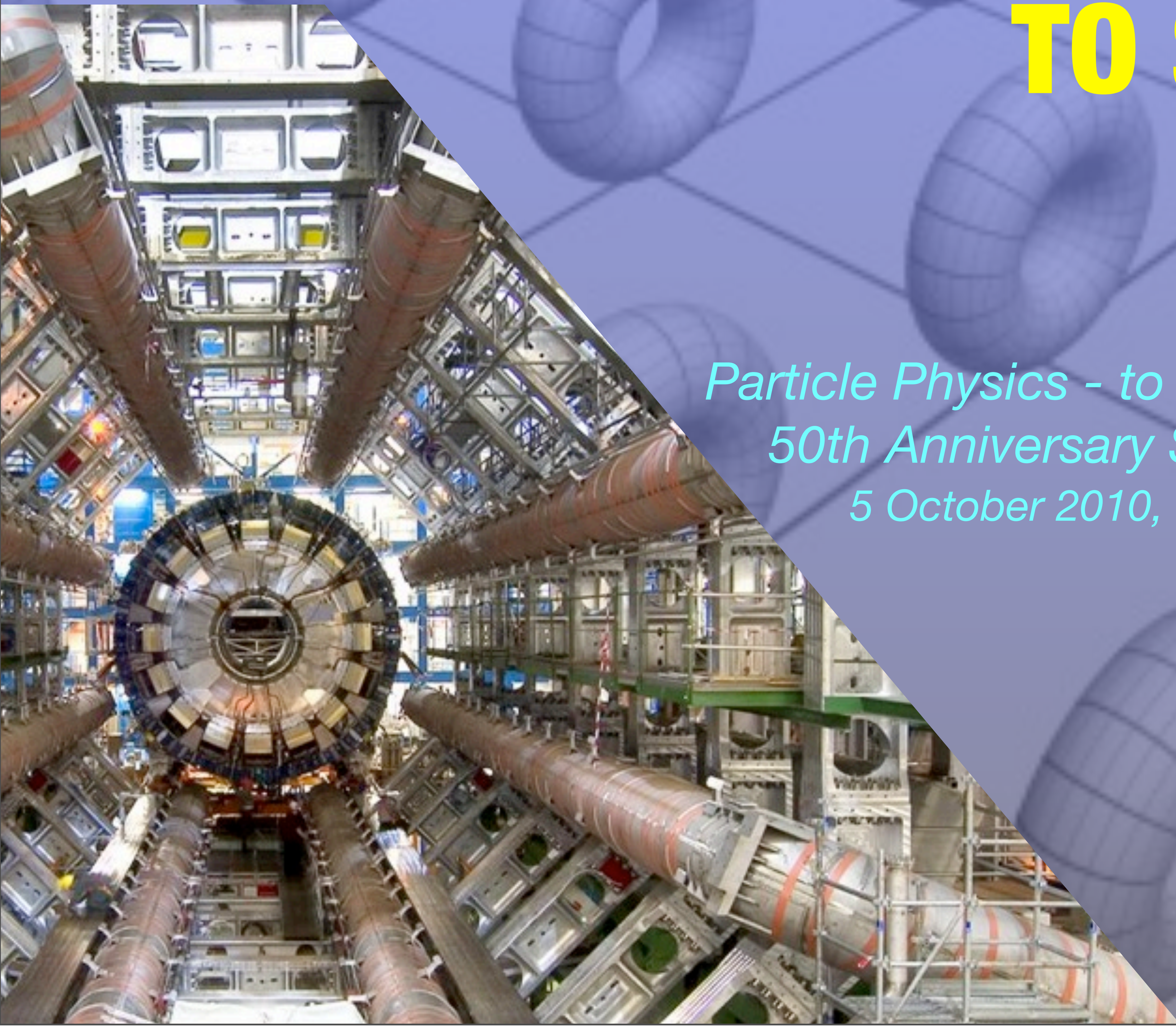
FROM ELEMENTARY PARTICLES TO STRINGS



Particle Physics - to the collision and beyond
50th Anniversary Symposium
5 October 2010, Eindhoven

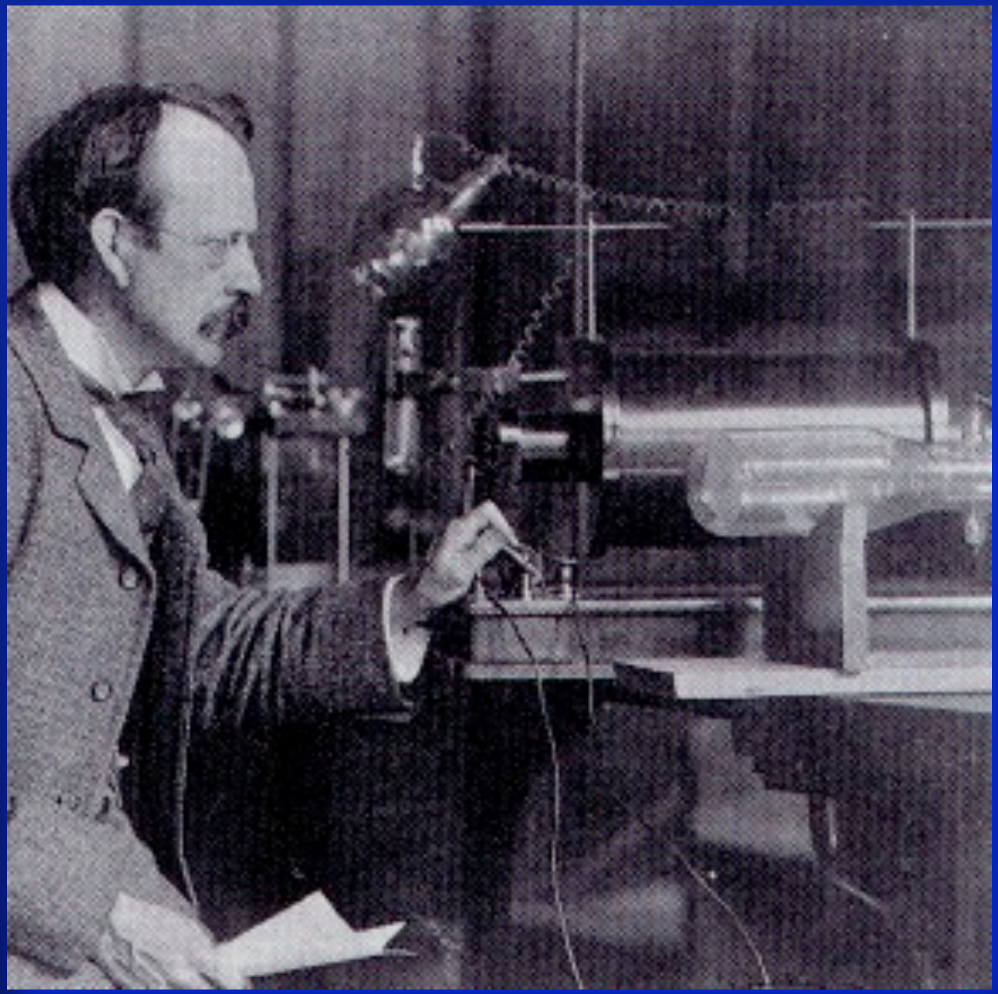
Bernard de Wit

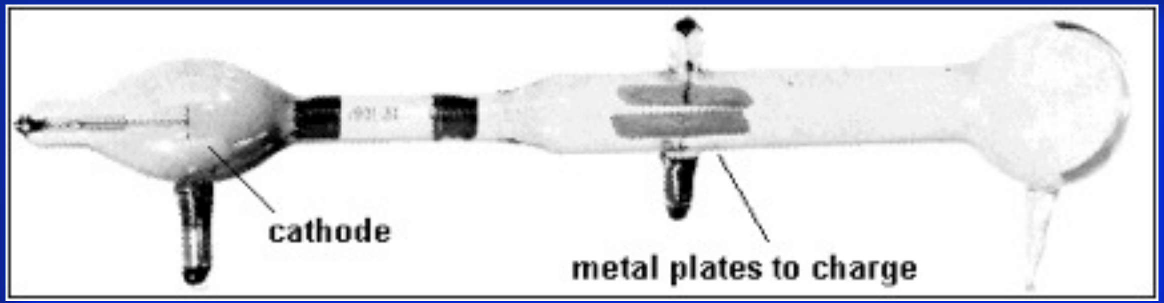
Universiteit Utrecht/Nikhef

1. Particles and fields

The electron

1899: discovery of the electron by Joseph John Thomson:

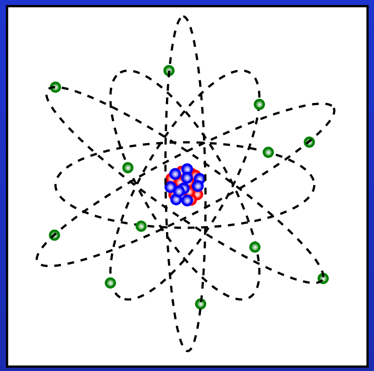




Thomson carried out a number of independent experiments and determined both the mass and the electric charge

Electron: electrically charged particle that is a 1000 times smaller than an atom.

The Bohr atom



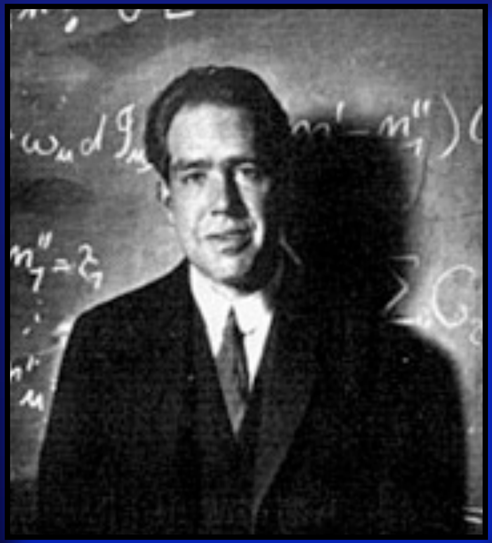
Rutherford's scattering experiment

Geiger and Marsden (1909)

- a positively charged nucleus
- a cloud of electrons

kept together by the electric forcet

Electron clouds are responsible for chemical binding



QUANTUM MECHANICS:
energy levels of the hydrogen atom

Problems.....

I have been thinking a great deal about the relativity problem lately and believe firmly that the solution of the present troubles will not be reached without revision .....

Bohr to Dirac, 1930

The theory is however wrong, since it gives a displacement of the spectral lines from the frequency predicted on the basis of the non-relativistic theory, which is general infinite. This displacement arises from the infinite interaction of the electron with itself......

Oppenheimer, 1930

It is very difficult to describe that state, because it was psychologically so different from the state in 1923 or 1924. In '23 and '24 we knew that there were difficulties and we also had the feeling that we were quite close to the final solution of these difficulties. Just one step and we will be in the new field. It was as if we were just before entering the harbor, while in this later period we were just going out into the sea again, i.e. all kinds of difficulties coming up and really we didn't know where it would lead to. And even if new and good ideas came up, these ideas would work a short way and then again one had new difficulties. It was clearly seen that this was now an entirely new story. So nobody expected quick results at that time.

Heisenberg, interview

The issue....

The issue was not really relativity but the interaction with the quantized radiation field. Because a field theory describes an infinite number of degrees of freedom, the short-distance behaviour of quantum operators will diverge.

The radiation field can be viewed as describing an infinite number of harmonic oscillators. For instance, each one of these oscillators contributes $E_0 = \frac{1}{2}\hbar\omega$ to the vacuum energy. Hence, the total vacuum energy of the radiation field diverges. However, this example represents only a relatively minor problem. The real problems arise once the radiation field interacts with other particles/fields.

Quantum Electrodynamics

Shelter Island
June1947

Shelter Island Conference on Quantum Mechanics (left to right):
I.I. Rabi; L. Pauling; J. Van Vleck; W.E. Lamb; G. Breit; D. MacInnes; K.K. Darrow; G.E. Uhlenbeck; J. Schwinger; E. Teller; B. Rossi; A. Nordsieck; J. von Neumann; J.A. Wheeler; H.A. Bethe; R. Serber; R.E. Marshak; A. Pais; J.R. Oppenheimer; D. Bohm; R.P. Feynman; V.F. Weisskopf; H. Feshbach. Not pictured: H.A. Kramers.

A quantum field theory which enables to make extremely precise predictions!

e.g. the anomalous magnetic dipole moment of the electron:

$$a_e = 1\,159\,652\,180\,85\,(76) \times 10^{-12} \quad \text{(experiment)}$$
$$a_e = 1\,159\,652\,181\,11\,(74) \times 10^{-12} \quad \text{(theory)}$$

General Relativity

Another (classical) field theory (Einstein, 1907 - 15)

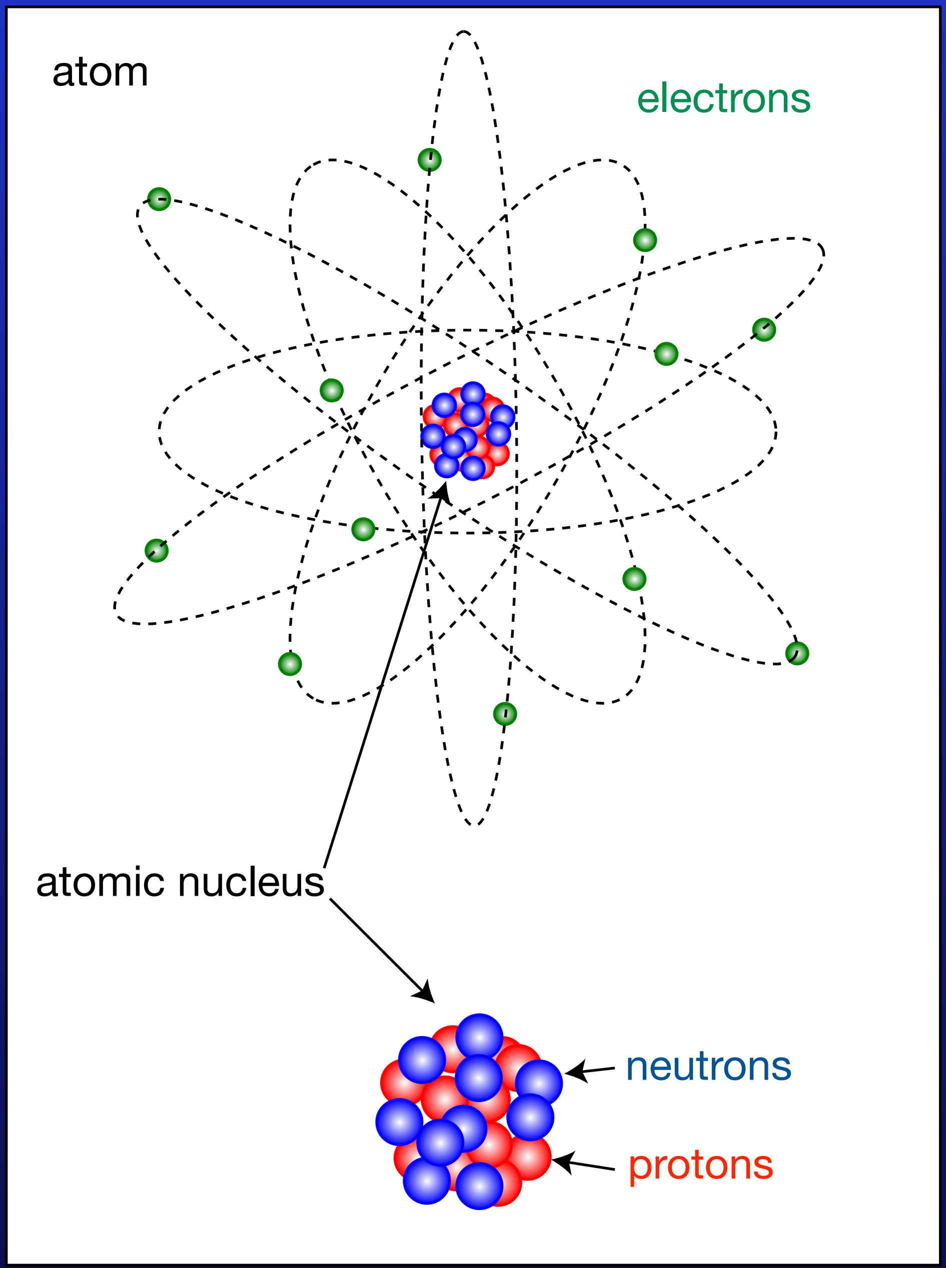
Einstein believed in unification as well as in an extreme form of reductionism.

From the 1930's he worked in vain on a unification of gravity and electromagnetism, assuming that this could be brought about by the non-linear behaviour of the field equations. His hope was that even the probalistic and nondeterministic aspect of quantum mechanics could eventually be explained in this framework.

Debate in later times: "More is different", Anderson, 1972

2. Particles and forces

The atomic nucleus

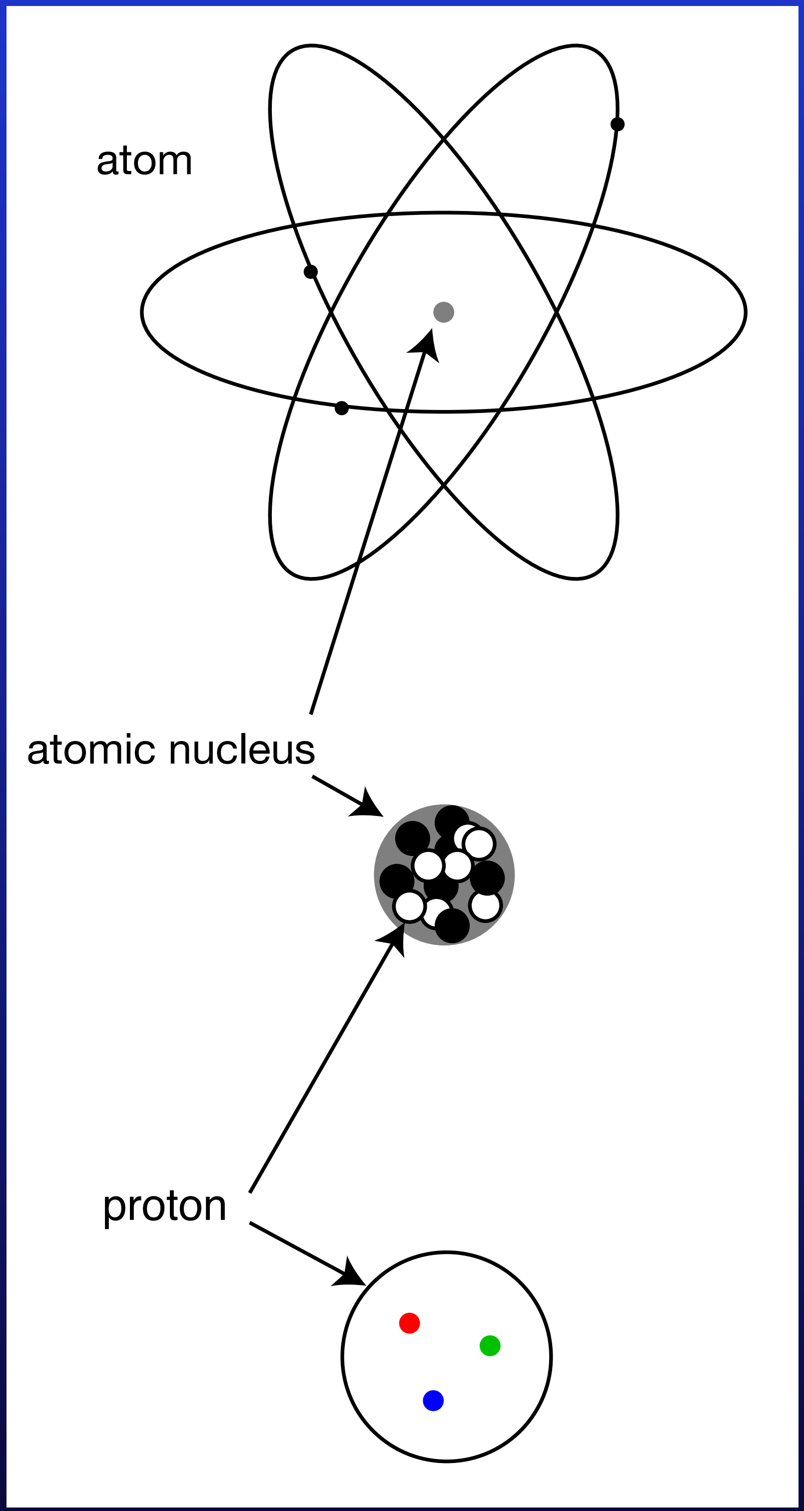


The posively charged nucleus consists of two kinds of particles:

Protons and Neutrons

There exist more than a hundred different nuclei built from protons and neutrons

Quarks and the strong force



Protons en neutrons consist of quarks.

Atomic nucleus, proton and neutron are kept together by the strong force

Quarks discovered by a modern version of the Rutherford experiment (SLAC, Stanford, 1969)

10^{-16} m = 0.000 000 000 000 000 1 m

Particle-wave duality

According to quantum mechanics:

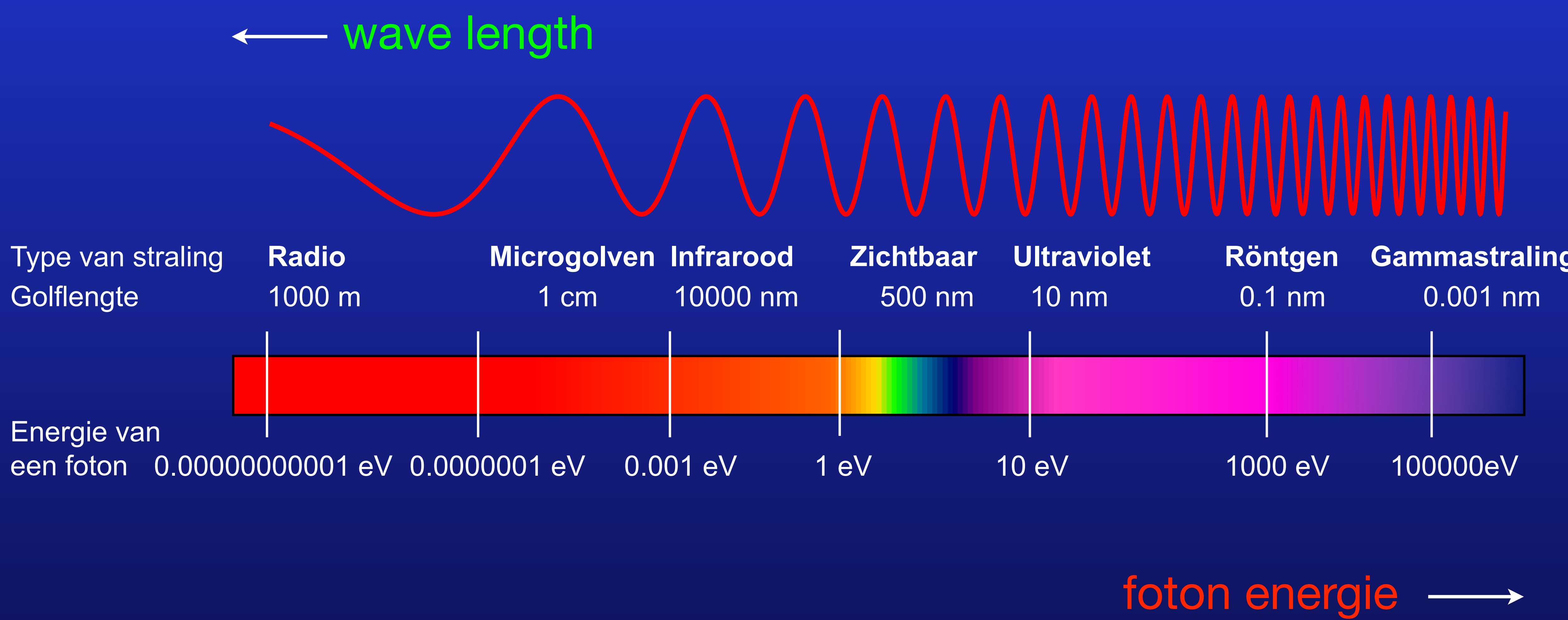
Particles can exhibit wave-like behaviour

Waves (light) can exhibit particle-like behaviour

Electromagnetic waves have a particle character!
The light particle is called photon
The photon moves with the velocity of light

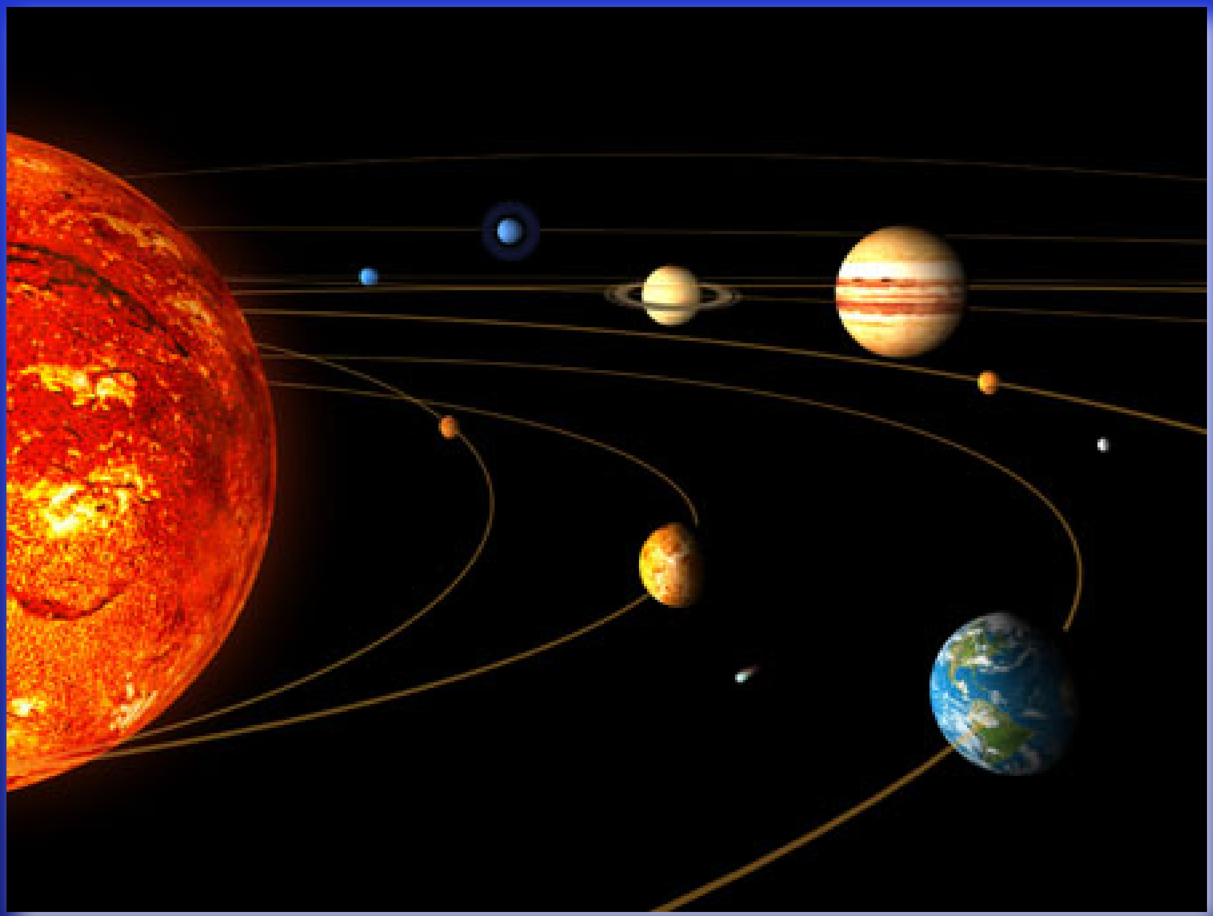
wave ⟵ photon ⟶ force

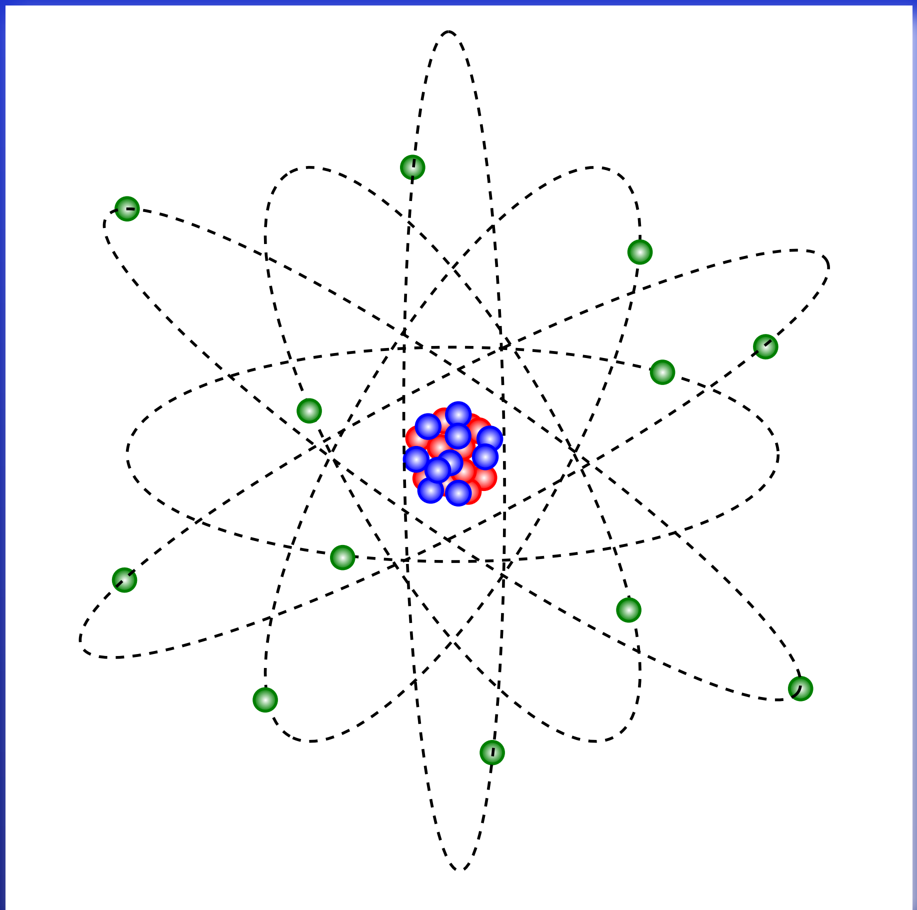
The photon



$$E = \frac{hc}{\lambda}$$

Different forces



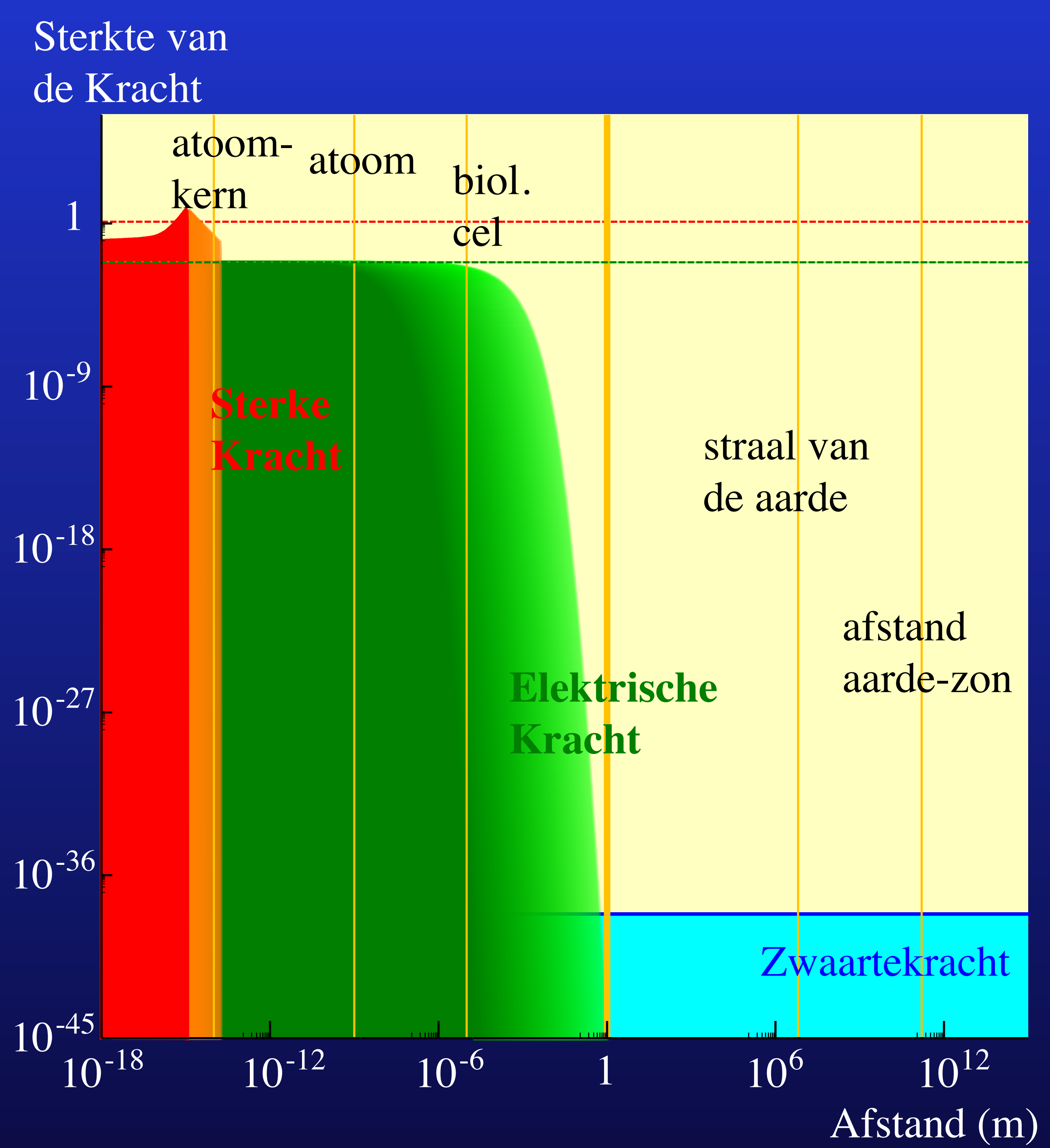


Solar system kept together by the force of gravity

Atom kept together by the electric force

strength: given by the mass/charge
long range: experienced at large distances

Hierarchy of forces



Different forces are important at different distance scales

All forces, except the gravitational one, diminish their strength at larger distances because of neutralization

Fundamental forces

- Electromagnetic force
- Gravity
- Strong force
- Weak force

Fundamental forces

- Electromagnetic force (foton)
- Gravity
- Strong force
- Weak force

Fundamental forces

- Electromagnetic force (foton)
- Gravity (graviton)
- Strong force
- Weak force

Fundamental forces

- Electromagnetic force (foton)
- Gravity (graviton)
- Strong force (gluon)
- Weak force

Fundamental forces

- Electromagnetic force (foton)
- Gravity (graviton)
- Strong force (gluon)
- Weak force (W and Z particles)

Hadrons and Leptons

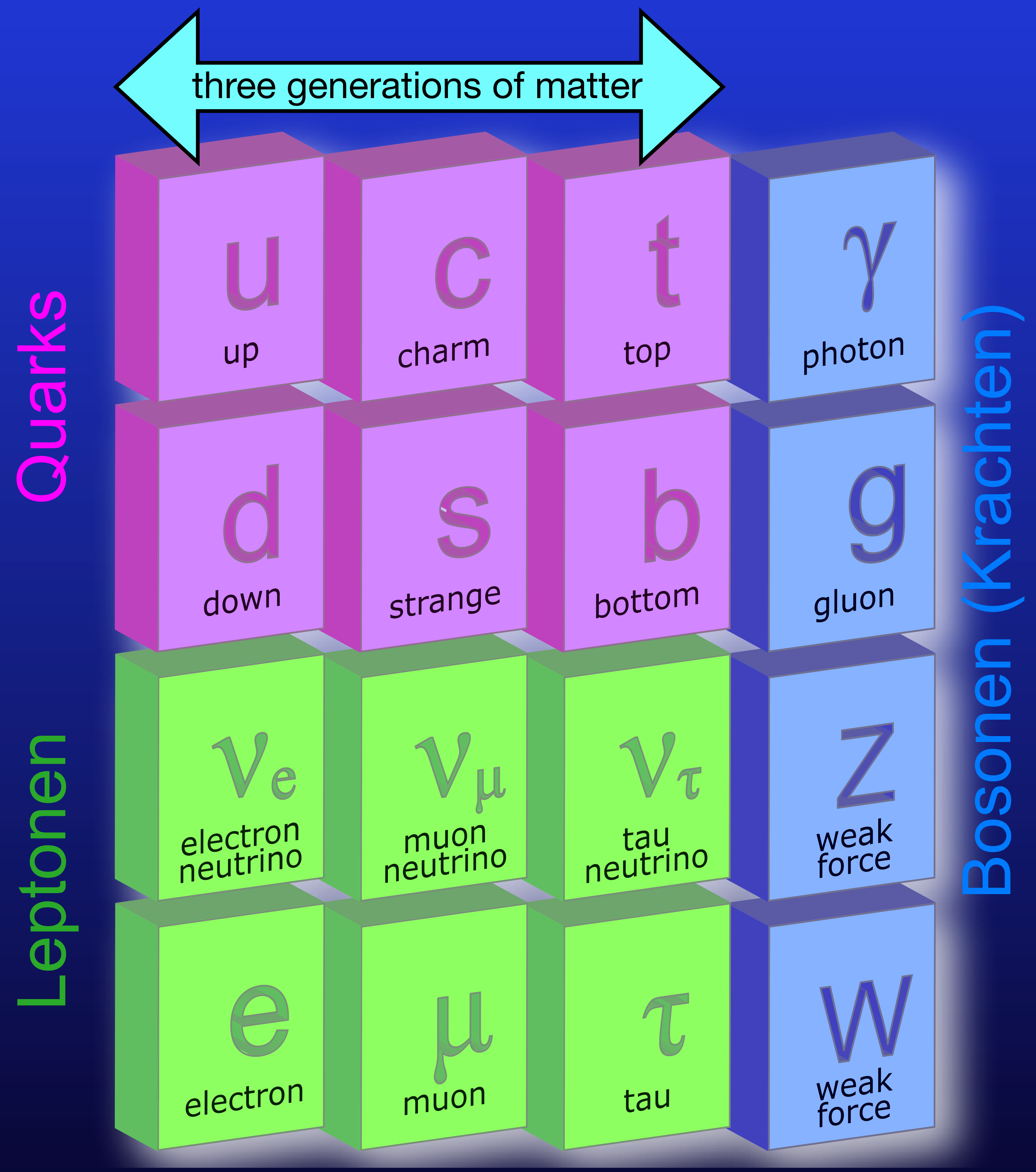
Hadron: quarks and gluons

Leptons: elektrons, ...
neutrinos

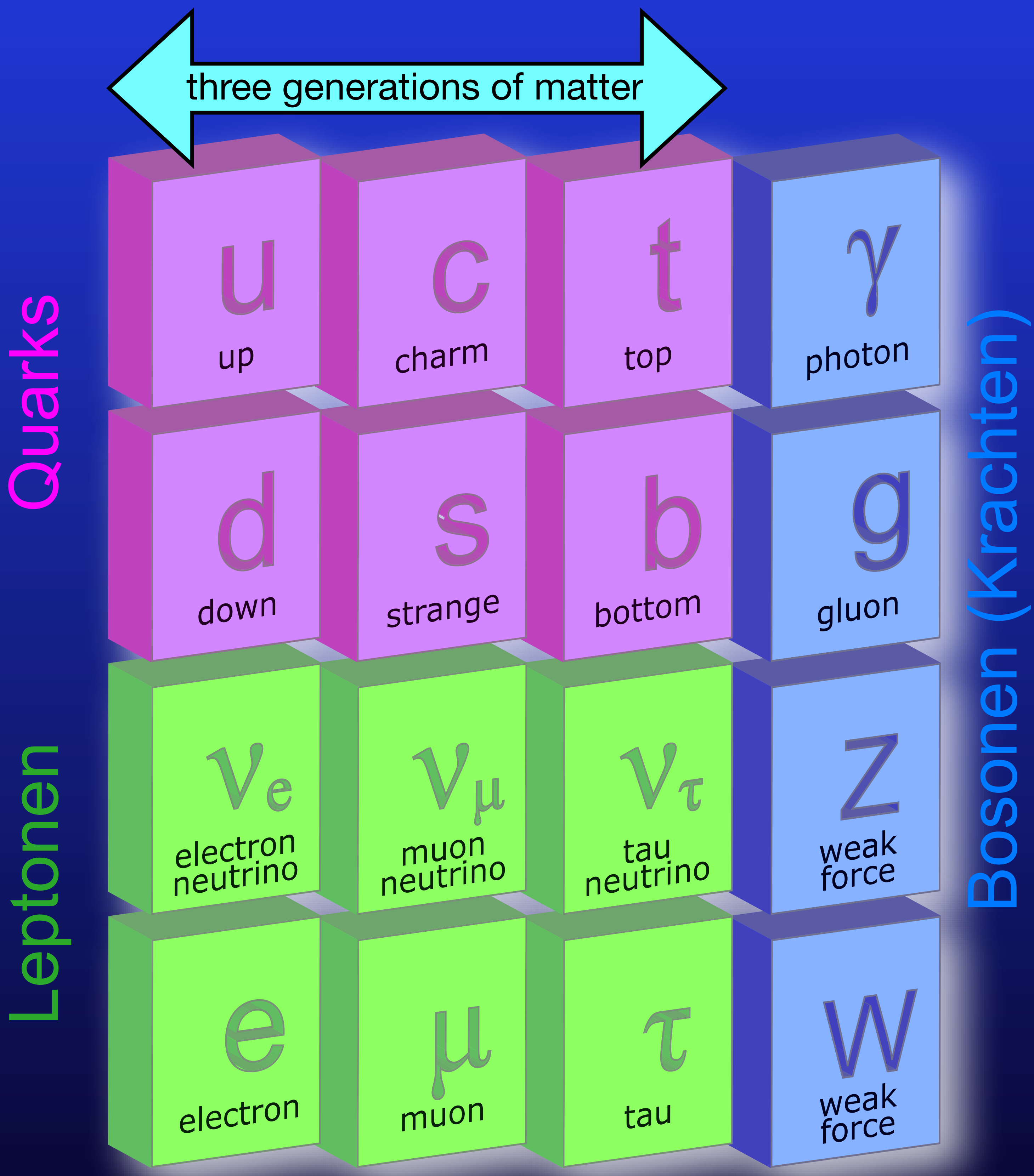
➡ **The Standard Model**

combines quantum mechanics with special relativity

The Standard Model



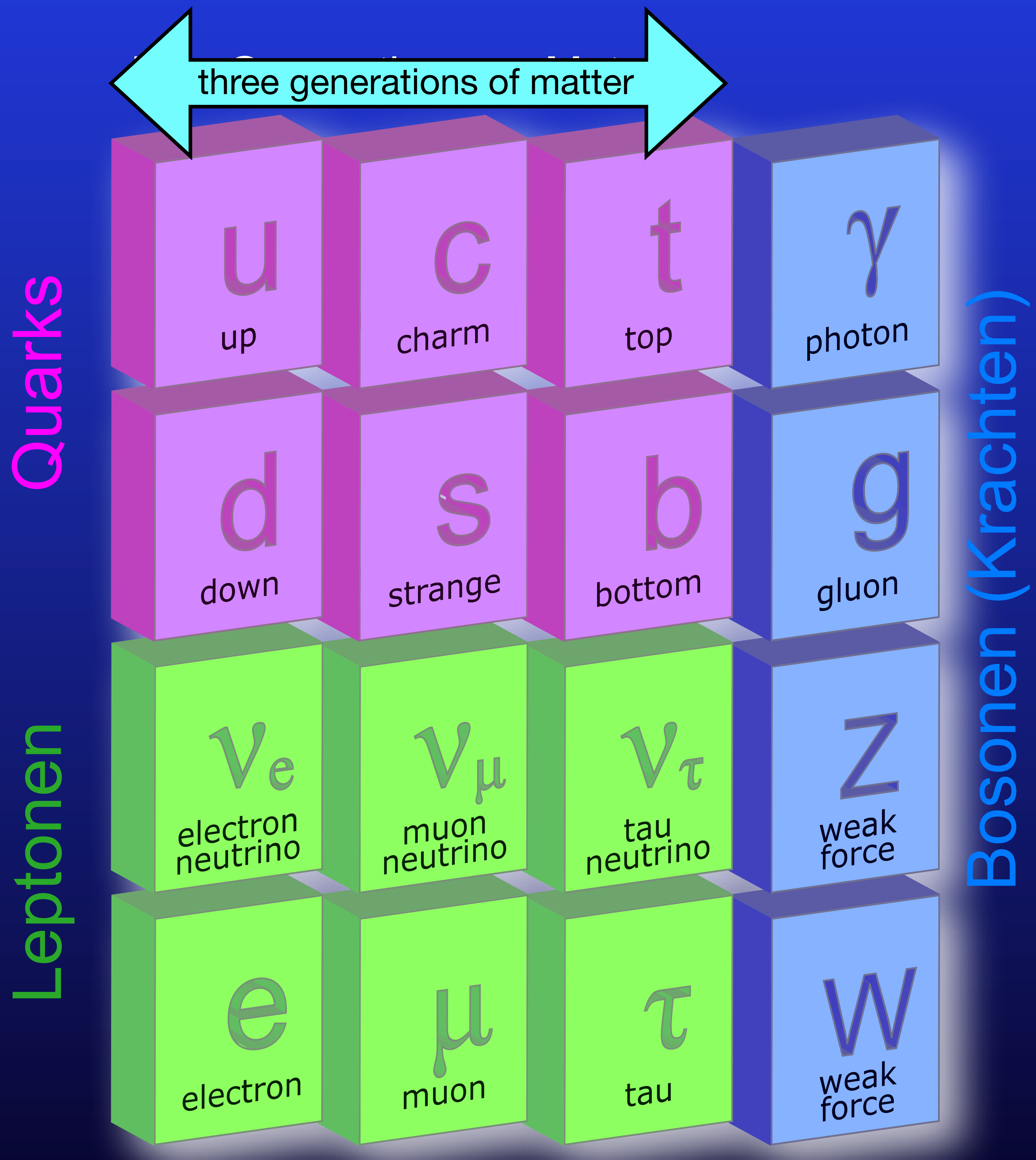
The Standard Model



With the Standard Model we can make many theoretical predictions, also owing to the work of ‘t Hooft and Veltman (almost thirty years after Shelter Island)

The Standard Model

The Standard Model



The Standard Model

Higgs particle

part of the standard model!

electro-weak

The Standard Model

Higgs particle

part of the standard model!

electro-weak

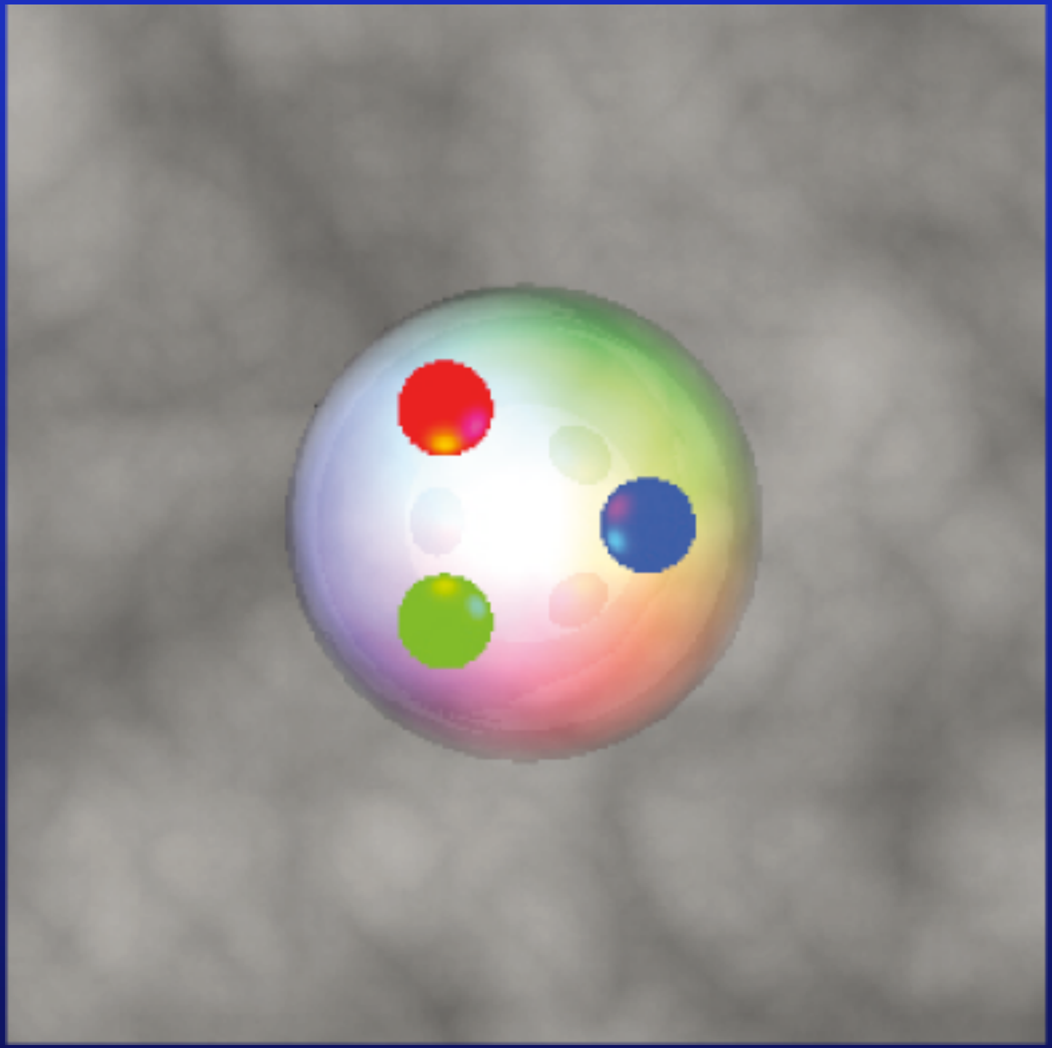
graviton

not part of the standard model!

gravity

3. The strong force

Quarks

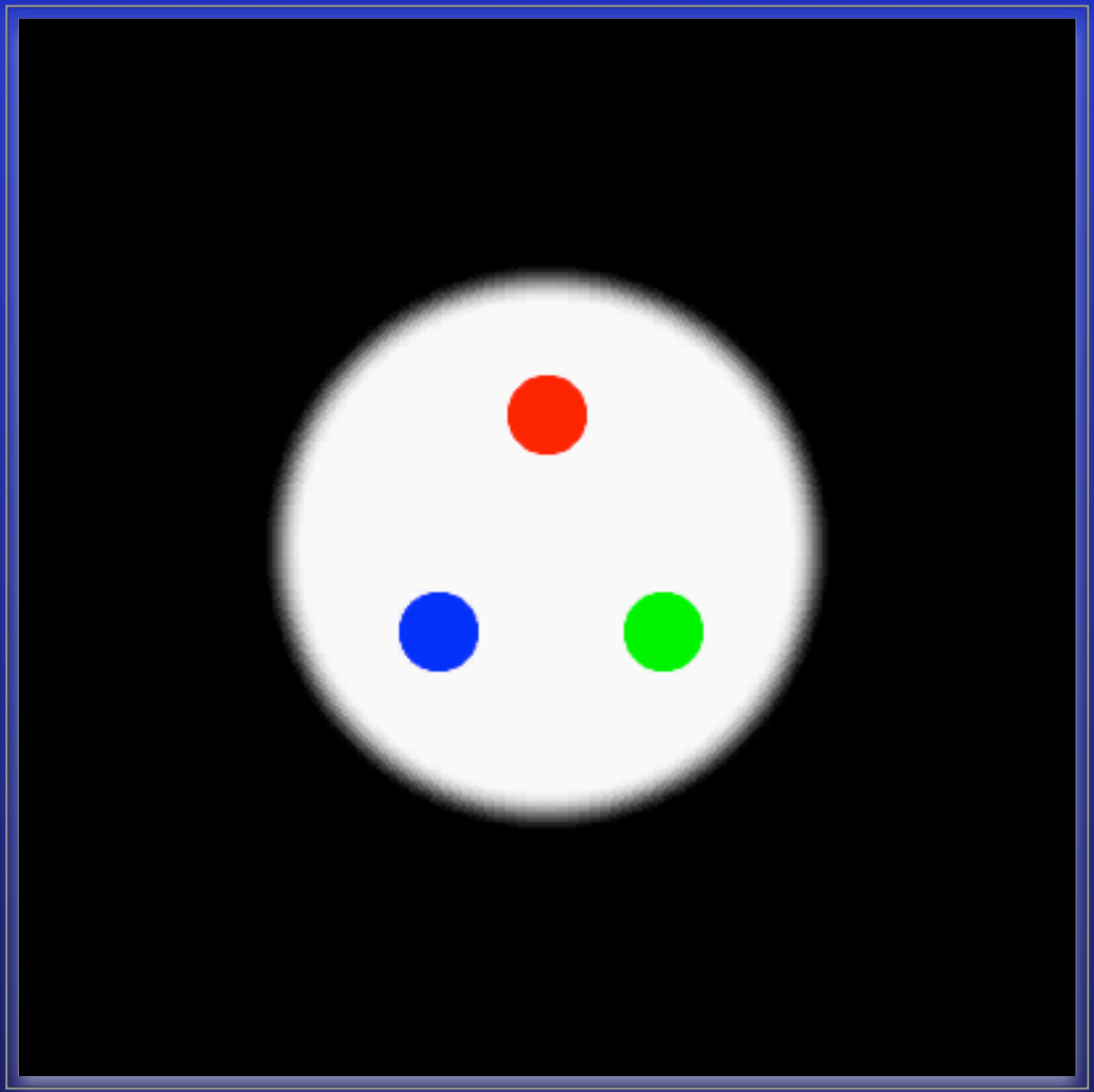


Quarks have strange properties:

‘color’

not (yet) observed as free particles!

Quark confinement

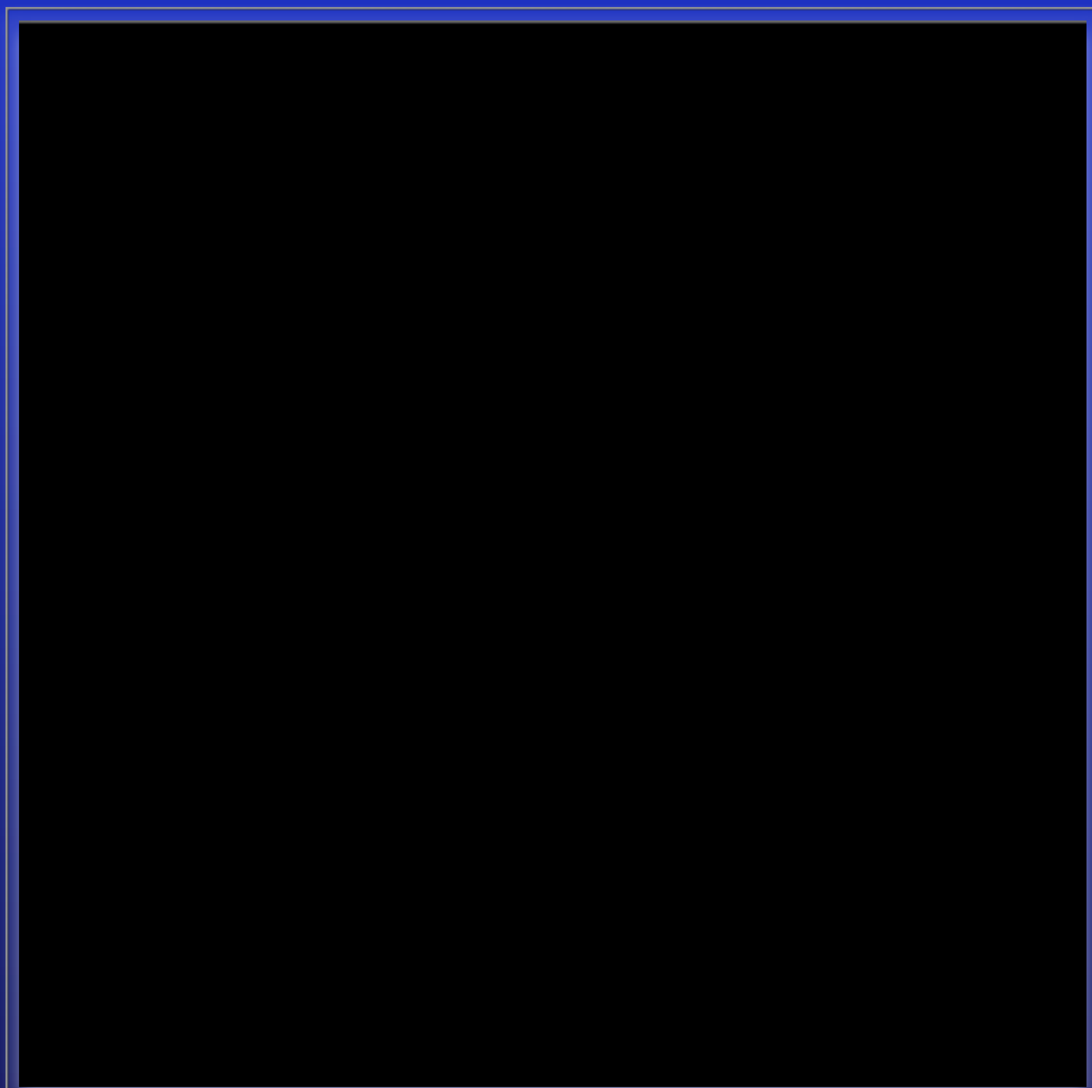


fundamental property of the strong force!

confinement is not fully understood!

The first 10 micro seconds

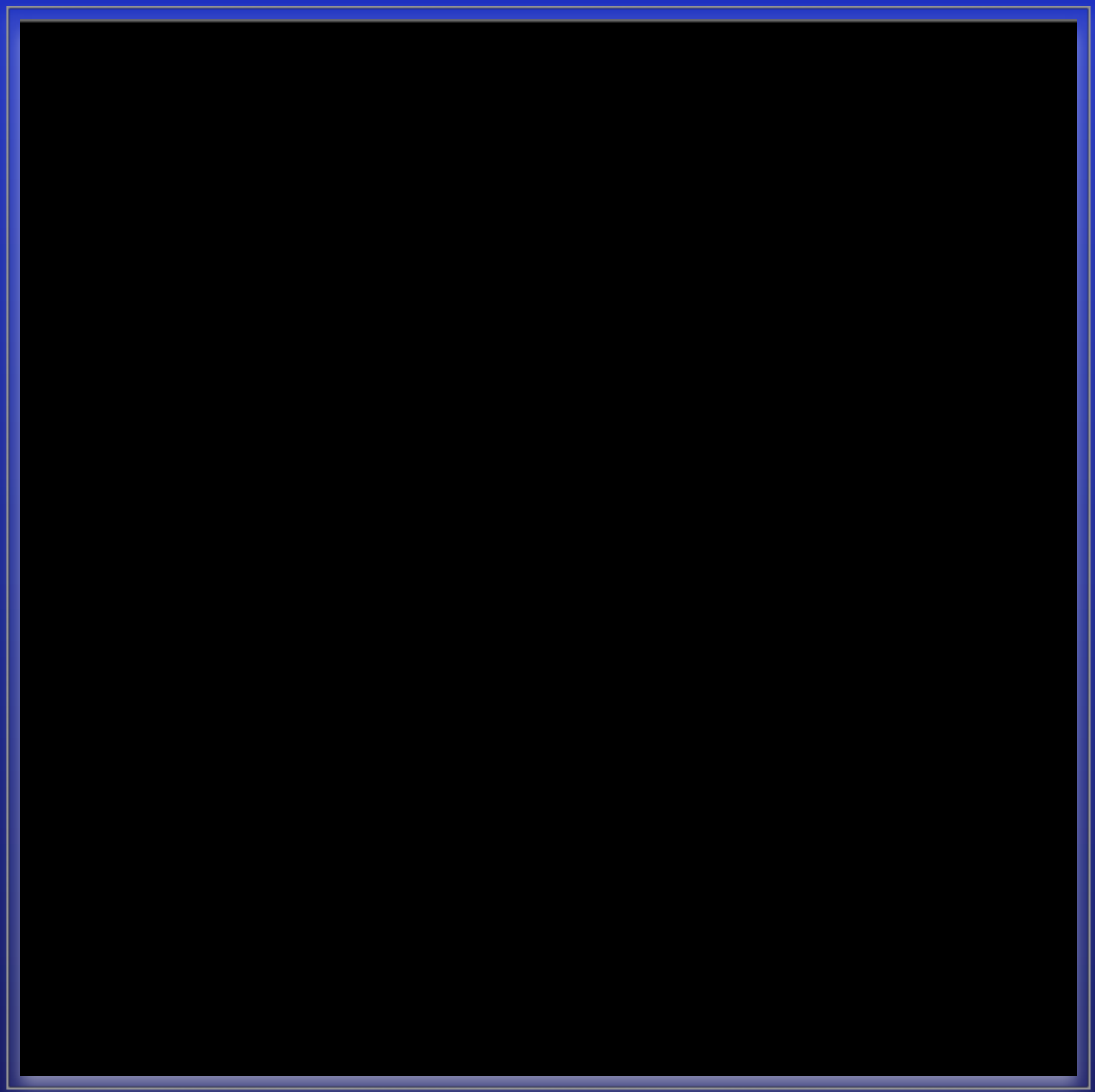
The first 10 micro seconds



In the early universe the quarks behaved as free particles.

- no quark confinement

The first 10 micro seconds



In the early universe the quarks behaved as free particles.

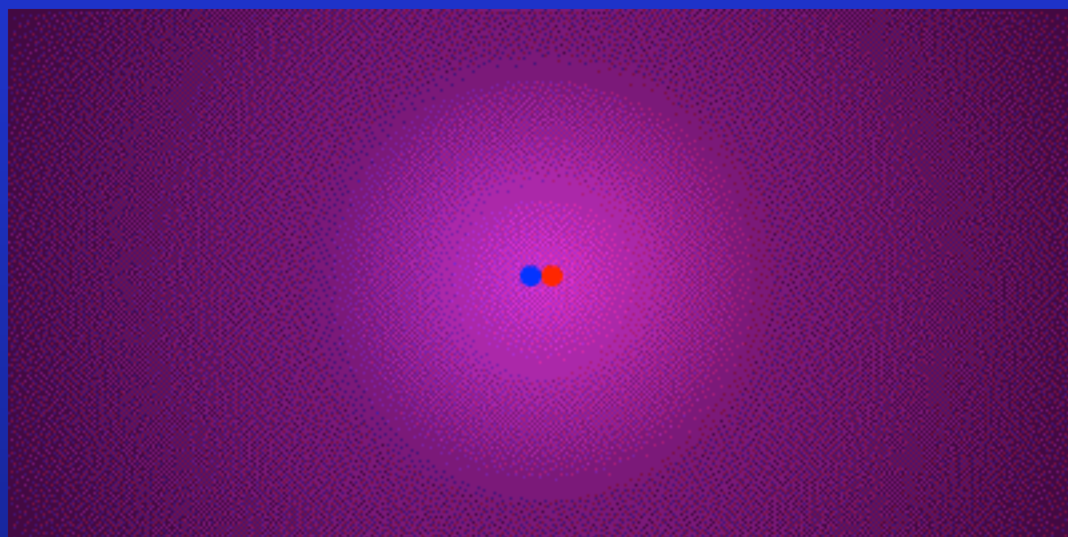
- no quark confinement

Fase transition after ≈10 micro seconds

Quark confinement

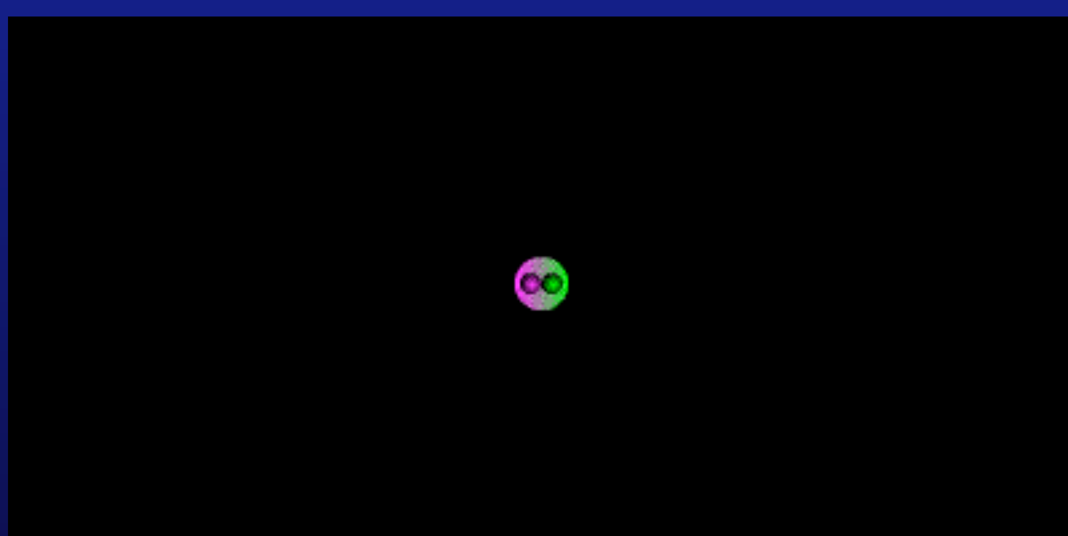
Other considerations about the strong force ......

Quark confinement



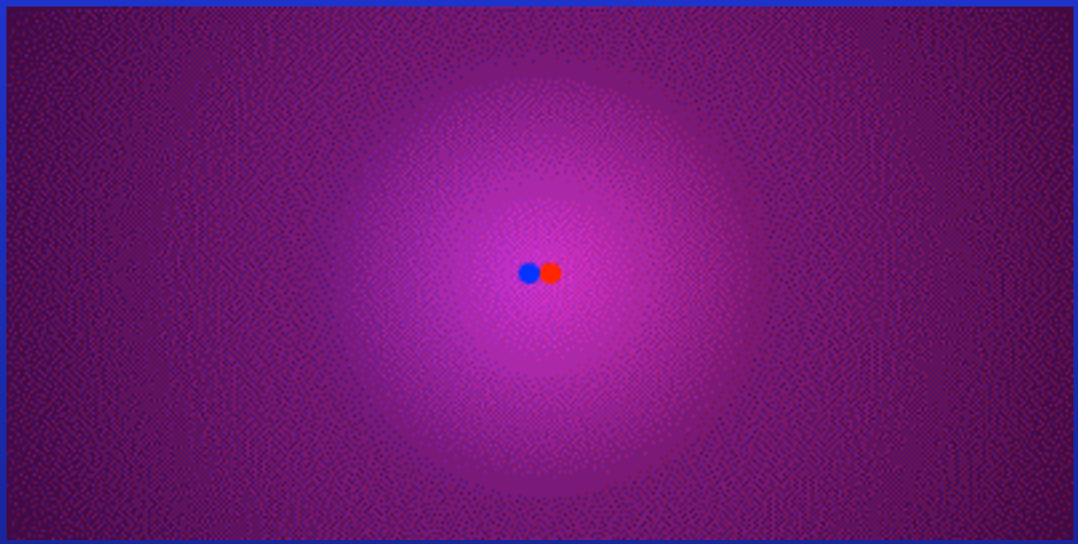
electromagnetic force:

spreads out in space, becomes weaker at larger distances, the charges can be separated



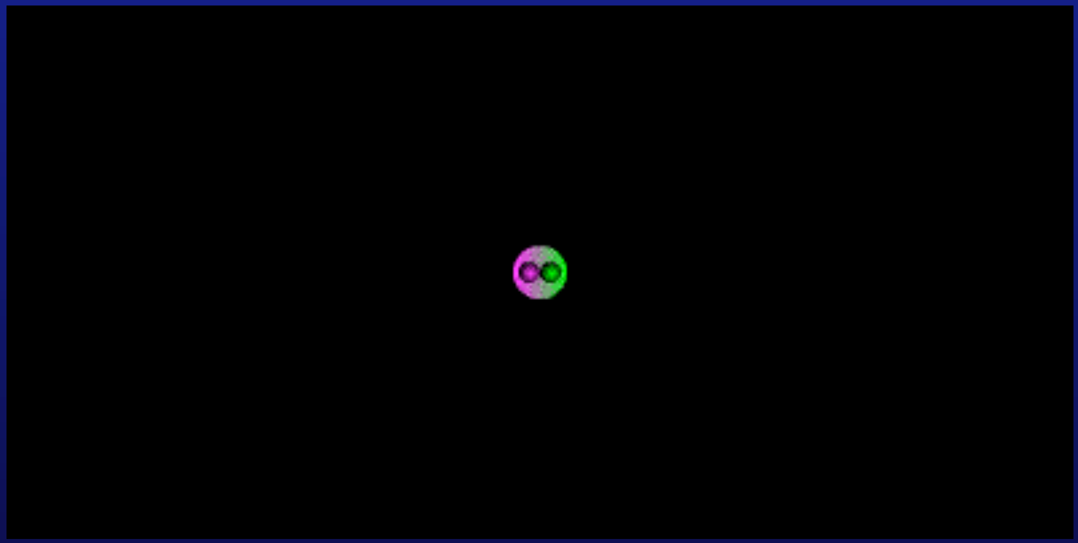
Other considerations about the strong force ......

Quark confinement



electromagnetic force:

spreads out in space, becomes weaker at larger distances, the charges can be separated



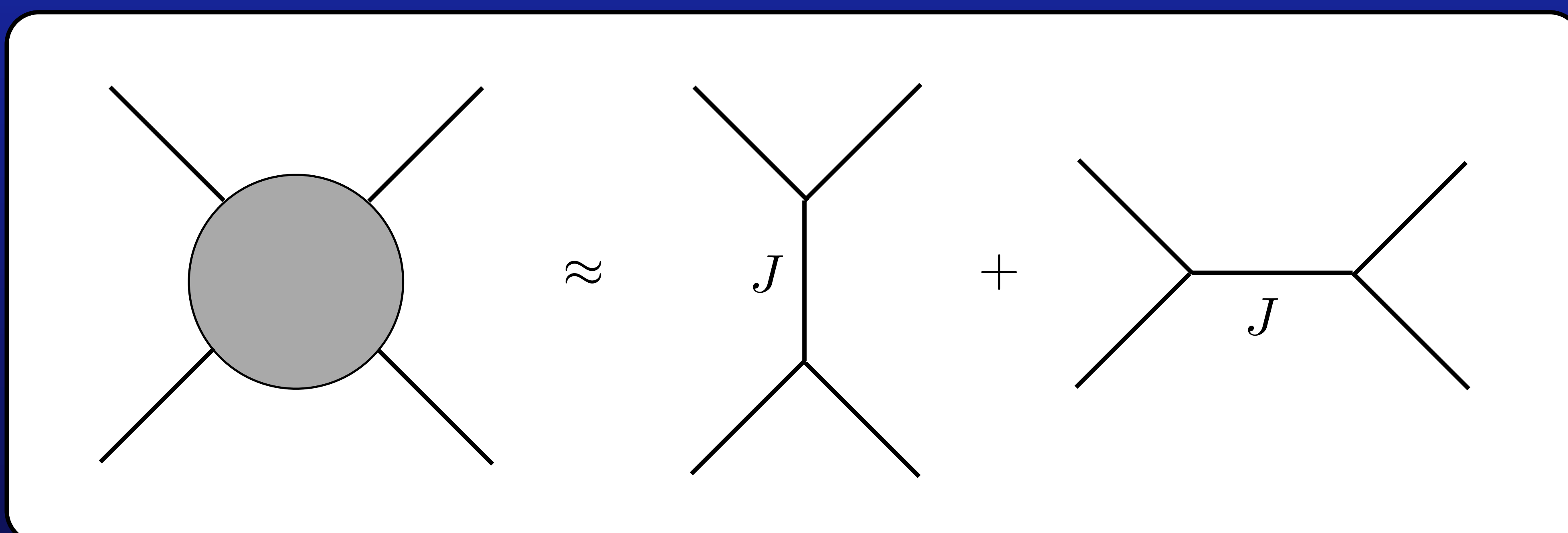
strong force:

confined, together with the quarks, remains strong at larger distances, quarks cannot be liberated

Other considerations about the strong force ......

More and more particles

In the sixties more and more strongly interacting particles (hadrons) were discovered. There was, however, no good theory for them. There were problems concerning the asymptotic behavior of particle-particle scattering at very high energies. Consider, for instance, the simplified Feynman diagrams for such a process:

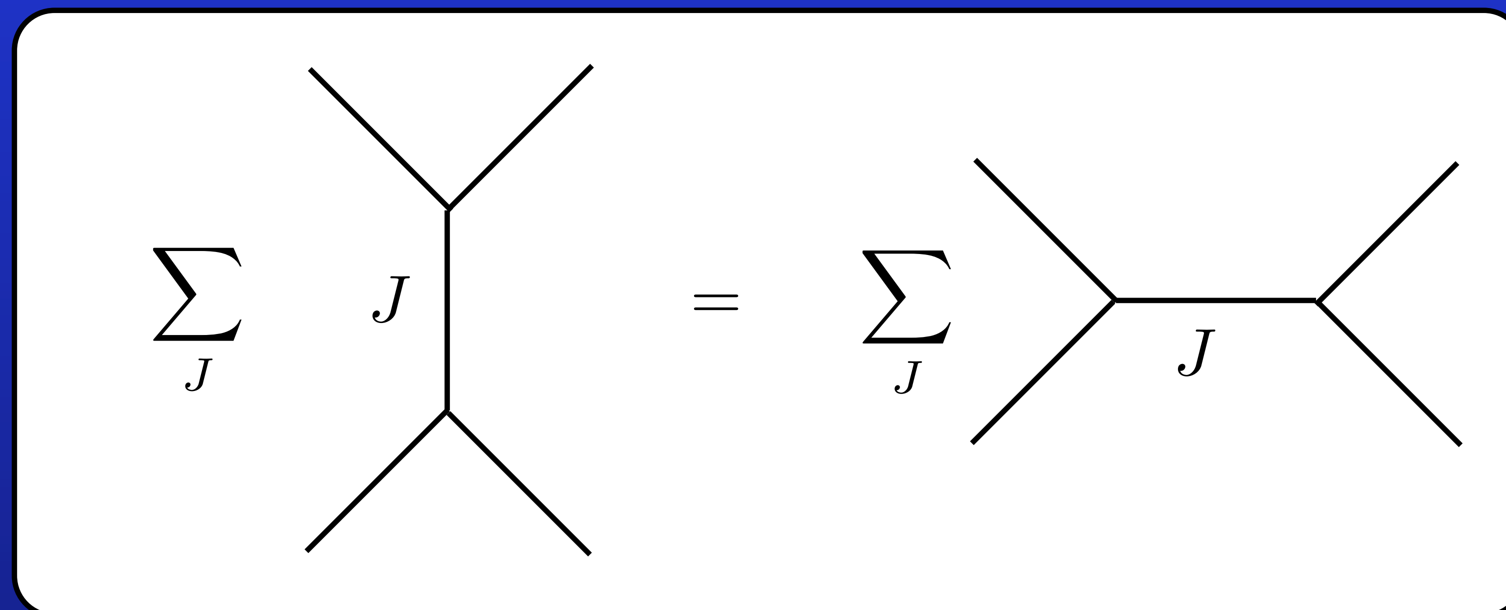


(summed over 'particles' with spin *J*)

These expressions were problematic...

A new formula

DUALITY



This requires an infinite tower of particles with all possible spins *J*

An exact solution: the Veneziano formula (1968):

$$A(s,t) = \frac{\Gamma(-\alpha(s))\,\Gamma(-\alpha(t))}{\Gamma(-\alpha(s)-\alpha(t))}$$

Euler gamma function Γ

$\alpha(s)$: linear ‘Regge trajectory’ with universal slope

Problems.....

The Veneziano amplitude was merely an *ad hoc* way of satisfying a not-so-well motivated hypothesis. Nevertheless its study revealed a rich structure. One was the recognition that the Veneziano model was really a model of a relativistic string!

Nowadays we understand that this model was at best an interesting approximation for the strong interactions. The modern theory of the strong interactions is called Quantum Chromodynamics (QCD). There are, however, definitely string-like features in the strong interactions!

But a relativistic string is interesting in its own right....

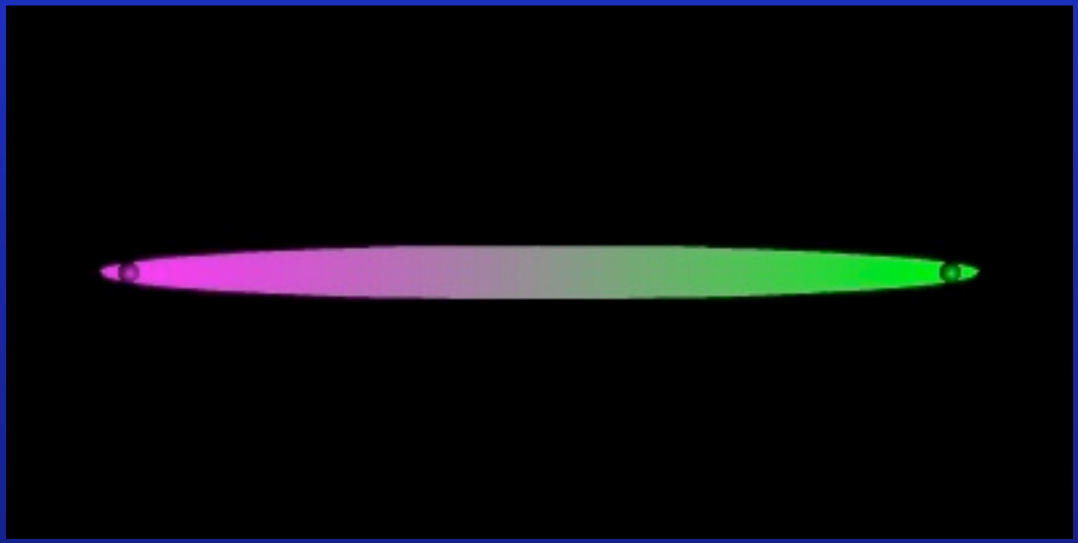
4. String theory

Strings

The squeezed force fields of the strong interaction resembles a little elastic band, or a little string.

The vibrational modes of a string can manifest themselves as elementary particles!

Strings



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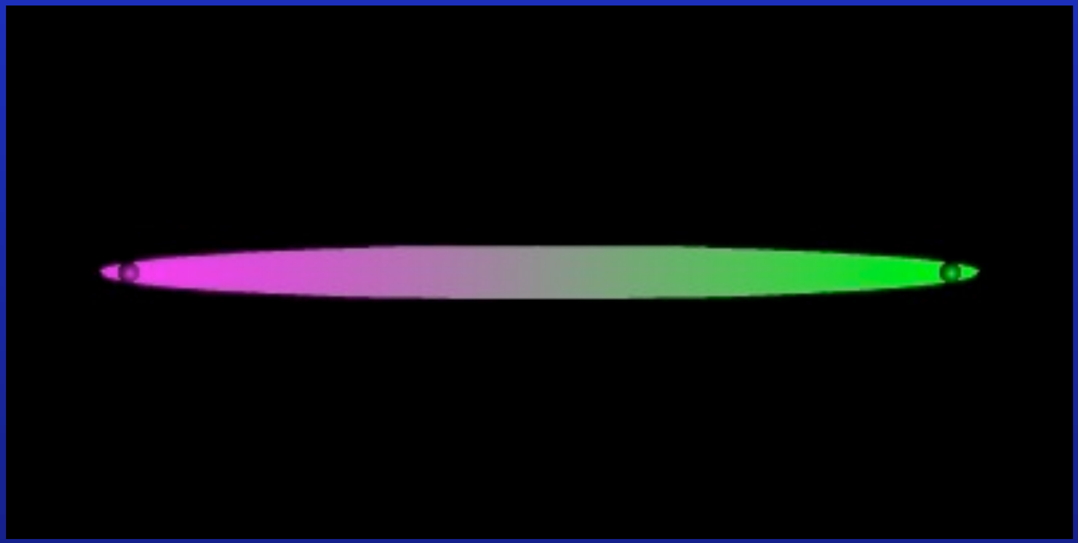

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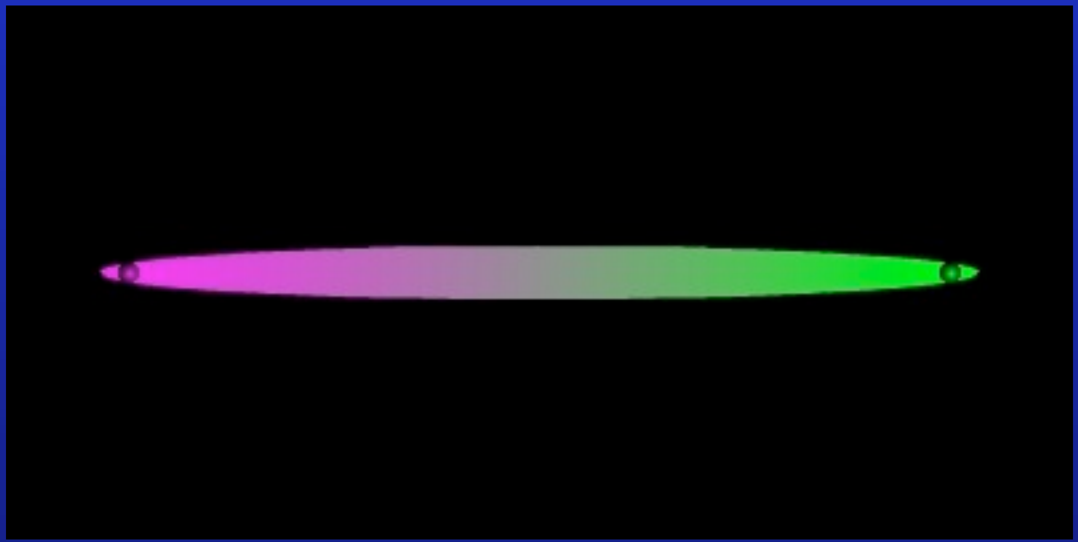
Strings



The squeezed force fields of the strong interaction resembles a little elastic band, or a little string.

The vibrational modes of a string can manifest themselves as elementary particles!

Relativistic quantum string?

Such a string should be in agreement with the theory of relativity and with quantum mechanics

Problematic:

- tachyons: particles faster than light ??
- 22 extra dimensions: 3 → 25 ??

NEW INSIGHTS .....

The graviton!

A closed string has a vibrational mode that has precisely the properties of the graviton !

This is a theory of gravity (and much more)

So string theory is not a theory of strong interactions!

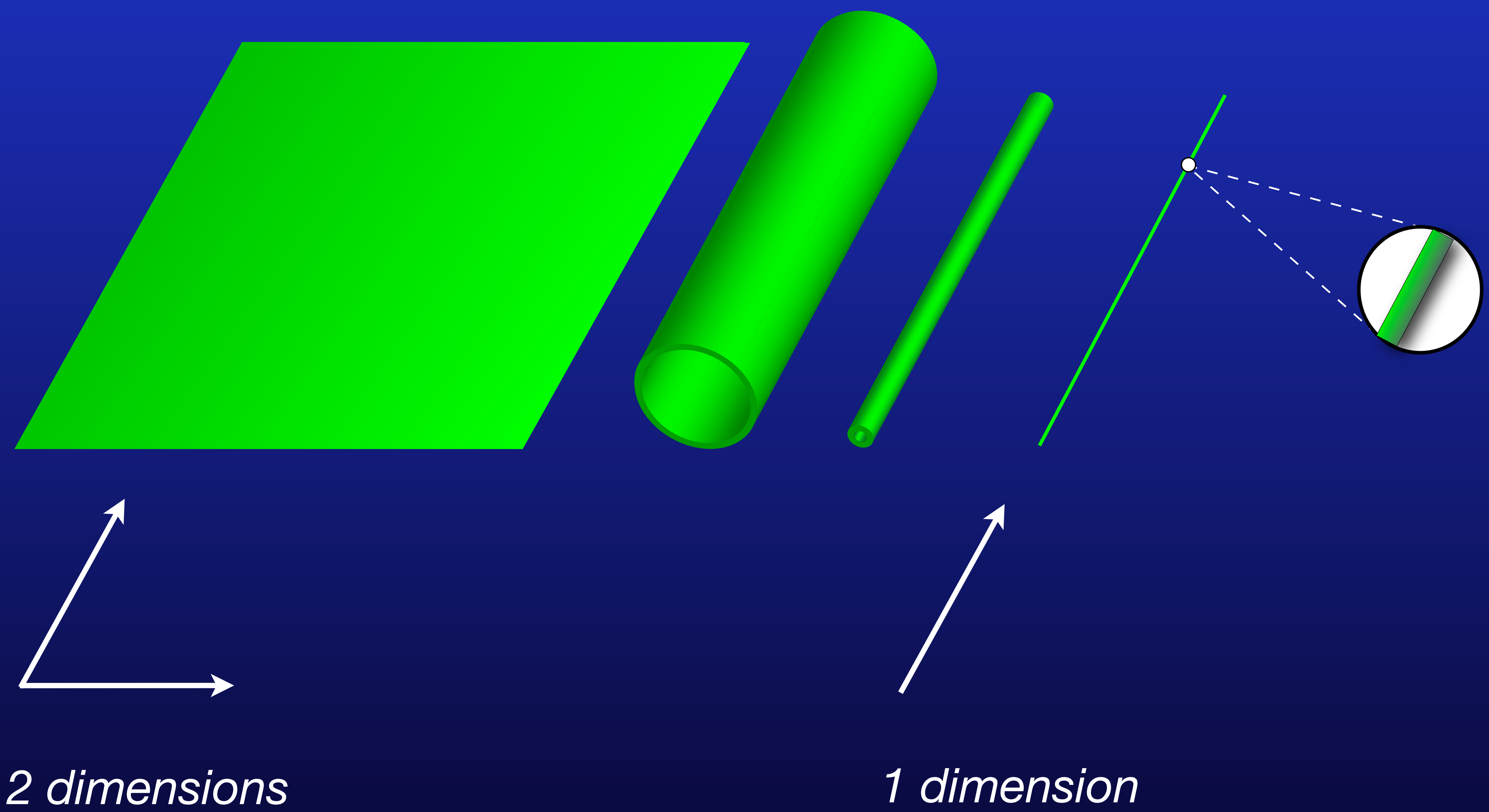
This was a dramatic insight....

Now the string must be much smaller: $\approx 10^{-32}$ meter = 0.000 000 000 000 000 000 000 000 000 000 01 *m* !

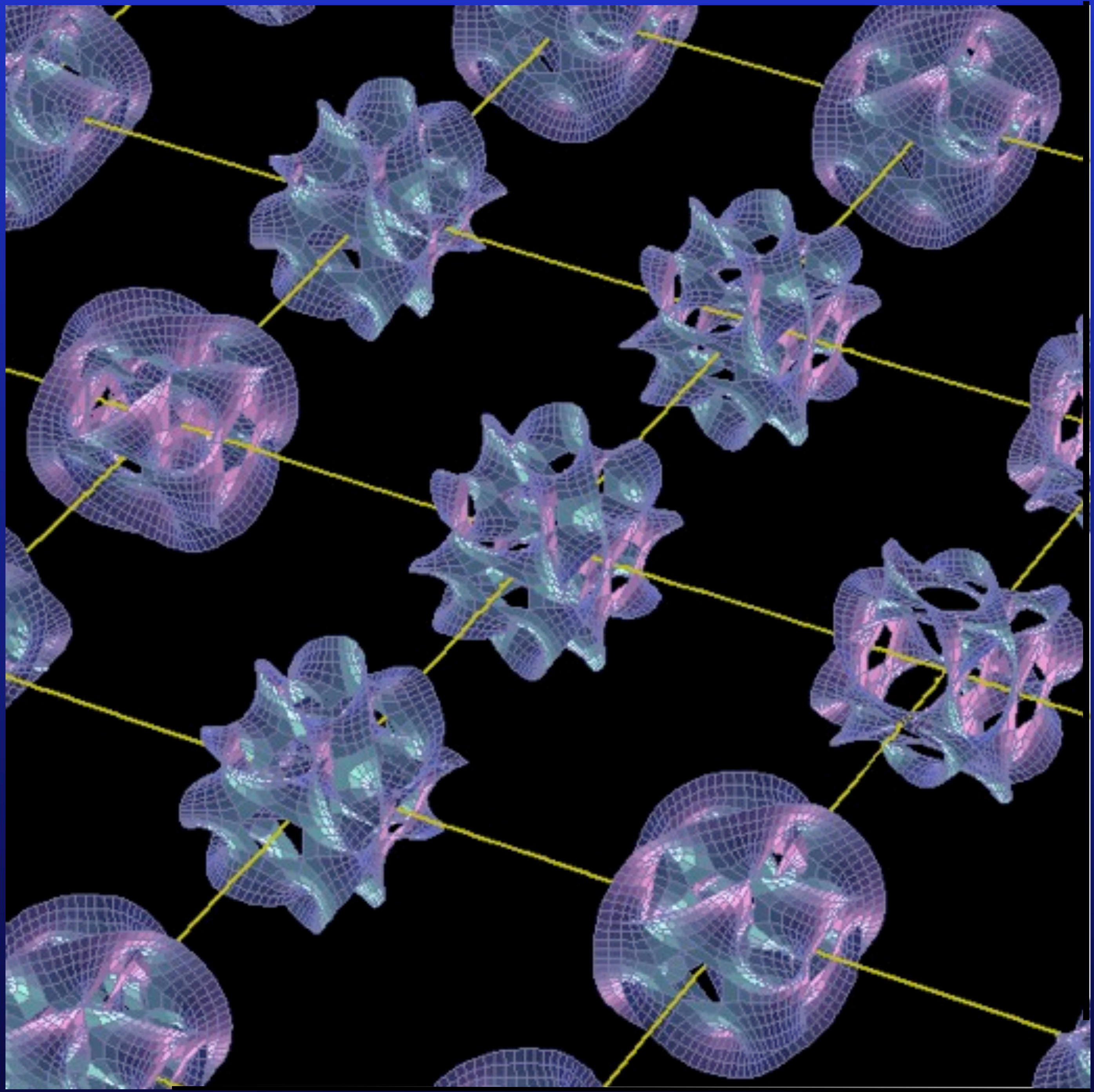
Compare: the size of the string associated with the strong force is approximately ≈ 0.000 000 000 000 000 1 *m* long !

Extra dimensions?

wrapped ....



Compactification

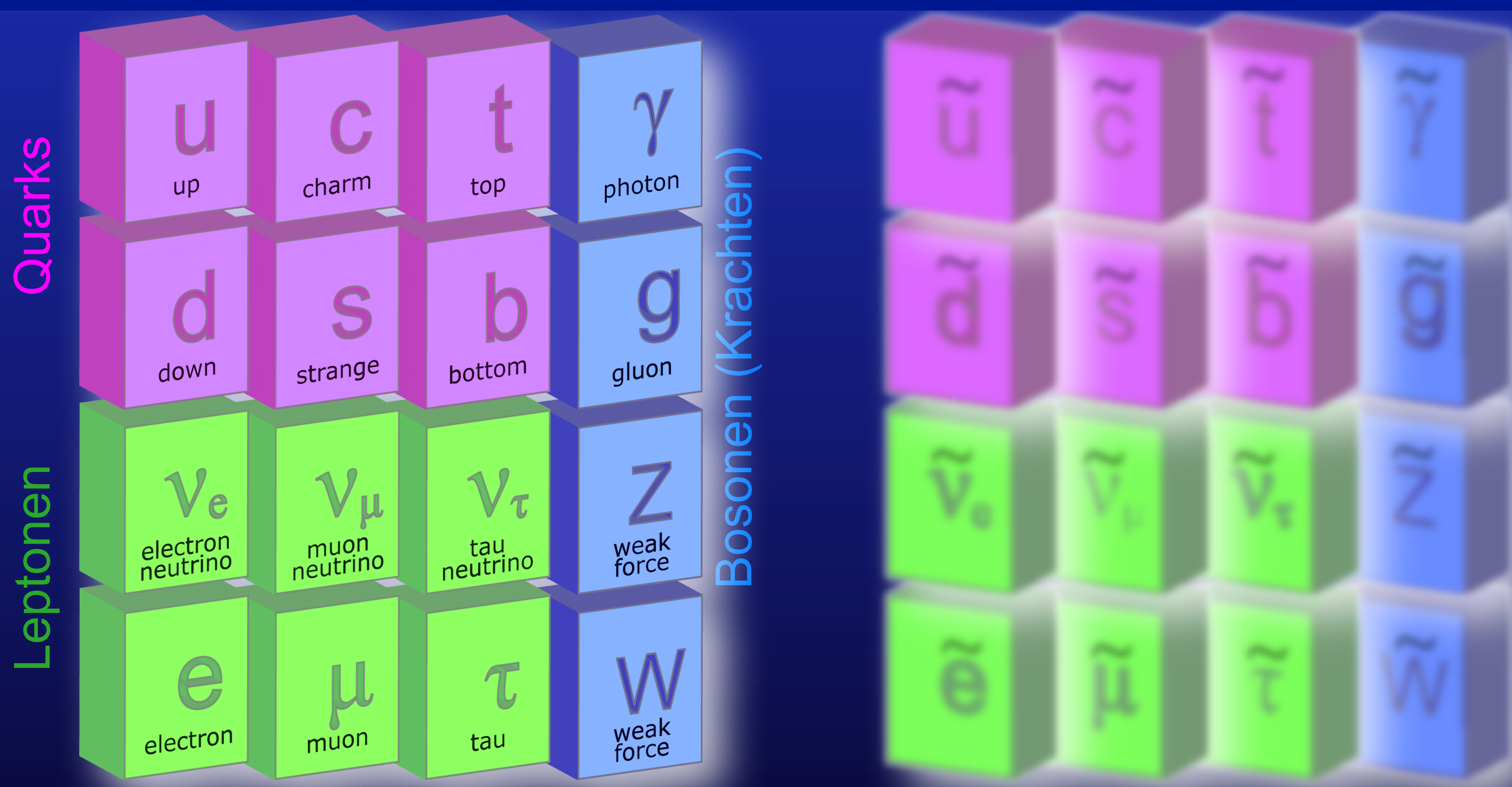


At each point in 3-dimensional space there exists a very small new space, which can be very complicated, but cannot be directly observed

What about tachyons?

The tachyons disappear because of the presence of a new conjectured symmetry:

SUPERSYMMETRY



ordinary matter | superpartners

5. Back to the future...

Why the LHC?

The Higgs particle

Supersymmetry

Dark energy and dark matter

Matter versus antimatter

Secrets of the big bang

Hidden worlds