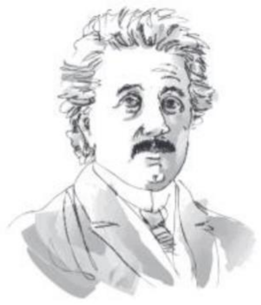
International Particle
Physics Outreach Group

PASSPORT TO THE INFINITE

Quantum Gravity

The effects of quantum mechanics are entirely negligible in the world of the infinitely large. Conversely, in the world of the infinitely small, the masses of objects are so minute that gravitational effects are insignificant. So, how can we link gravity and quantum mechanics?

Albert Einstein (1879-1955)

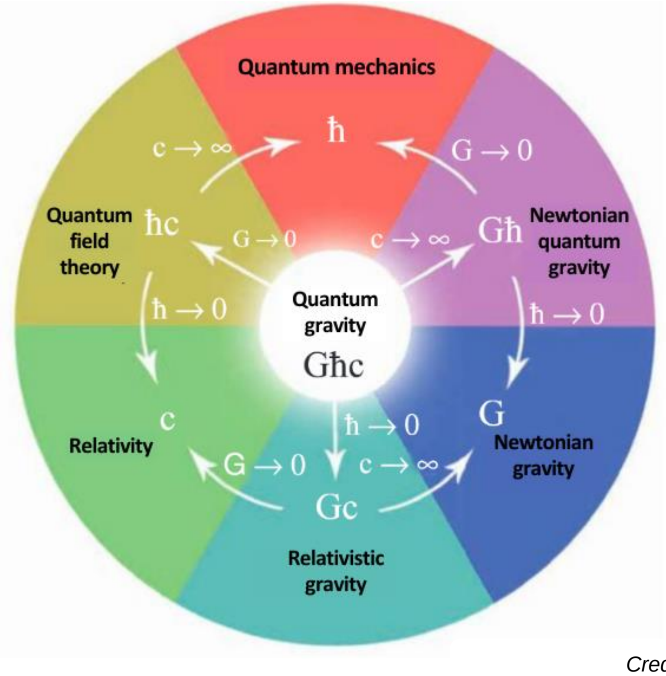


Credit: R. Maraï

The law of universal gravitation posited by Isaac Newton at the end-17th century explained the fall of objects, the movement of stars and galaxies, etc. The formulation of special relativity by Albert Einstein in 1905 made obsolete the notion of instantaneous remote interaction, which was the cornerstone of the Newtonian theory. Ten years later, Einstein proposed general relativity, a gravitation theory that provided a coherent framework for a relativistic description of the Universe as a whole. Gravitation is so weak that its effects can be felt only for colossal masses, such as planets, stars or galaxies; gravitation is predominant in the world of the infinitely large.

On the other hand, quantum mechanics governs the microscopic world of elementary particles. It had to be radically altered to accommodate special relativity. This gave rise to quantum field theory, a mathematical framework for describing both quantum and relativistic effects, such as the creation or annihilation of particles, which are phenomena specific to the world of the infinitely small.

So, how can gravitation operate on these scales? General relativity states that the actual source of the gravitational field – which is responsible for the force of the same name – is not the mass of an object, but rather its energy: this is the equivalence between mass and energy equivalence, as expressed by Einstein's formula $E = mc^2$. More precisely, one has to look at the object's energy density: for intense gravitational effects, a great amount of energy needs to be concentrated in a given volume, or a given energy in a very small volume. We are at the gates of the world of the infinitely small, where nothing escapes the laws of quantum mechanics.



Credit: from universe-review.ca

Well, ‘at the gates’ may be an overstatement! To penetrate the world where the infinitely large and the infinitely small meet, and, with them, gravity and quantum mechanics, we would need to confine the mass energy of a billion galaxies such as ours in the volume of a proton. That is no easy task! Nevertheless, scientists believe that such energy densities might have existed at a very early age in the history of the Universe.

The union of special relativity and the Newtonian gravity theory produced general relativity. The union of the same special relativity with quantum mechanics produced the quantum field theory. But to date, general relativity and quantum field theory remain two close enemies, two seemingly irreconcilable theories. Despite the many developments in this research field over the last few decades, no single theory has been accepted by the scientific community.

Moreover, many unexpected phenomena can occur on the long road that separates us from this ‘two-infinite world’. The scales of energy and distance are so far beyond anything currently known that another fundamental question may be raised: will it ever be possible to subject a quantum gravity theory to the necessary experimental verification?

How can the four interactions be unified?

To unite gravitation and the three other interactions, three parameters are to be considered: Planck’s constant ħ (quantum mechanics), the speed of light c (relativity) and Newton’s constant G (gravitation). At present, satisfactory theories can be drawn that take into account two of the parameters, with the third taking on a specific value, zero or infinity, depending on the case... But a quantum gravity theory still eludes us.

Translated from ‘La gravitation quantique’, **Passeport pour les deux infinis,** *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG*