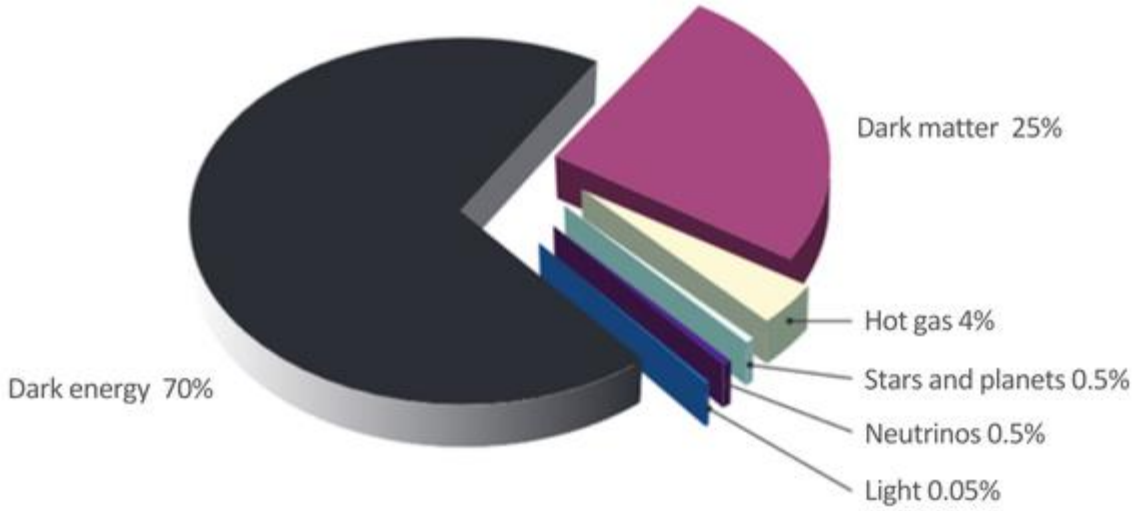
The Forces in the Universe

Of the four fundamental forces, only the electromagnetic force and gravitation are effective over distances as great as can be imagined.

Two electrons separated by a distance comparable to the size of the observable Universe could therefore exert a non-zero, although very weak (inversely proportional to the square of the distance) electromagnetic force on each other. But that's without taking into account the shielding effect: the many charges located between the two electrons, like the protons that make up stars and galaxies, cancel out any electromagnetic effect at very great distances. To explain the acceleration of cosmic rays, we put forth electromagnetic structures that would develop coherently over fairly large scales. However, observation shows that their sizes (one million parsecs) are very small compared with that of the observable Universe (more than ten billion parsecs).

The Universe in its largest dimensions is in fact governed by the force of gravitation, and general relativity is a particularly accomplished theory for describing it. One of Einstein's greatest contributions was to understand that this theory provided a cosmological framework for describing the Universe as a whole, its geometry and its evolution over time. On very large scales, the Universe is considered to be homogeneous and each of its components can be likened to a fluid characterised by pressure and energy density. Light, for example, exerts a non-zero positive pressure that space agencies are planning to use to propel planetary probes by means of solar sails. Ordinary matter, on the other hand, has negligible pressure and its energy is supplied by its own mass, due to the famous relation $E = Mc^2$. Astronomical observations suggest that another form of matter, dark matter, would make up most of the matter in the Universe. It is even postulated that there is a new form of energy, dark energy, whose 'negative pressure' would be accelerating the Universe's expansion.



Credit : A. Bouquet

Energy in the Universe

Distribution of the energy density of the various components of the Universe

However, the phenomena supporting the existence of these new components of the Universe are perhaps first and foremost signs that the laws governing gravitation are altered at the scales of galaxies, galaxy clusters, and even the Universe as a whole. Although general relativity has been remarkably well tested, the force of gravity is indeed the least well known of the four fundamental forces, because it is the weakest. It is therefore essential to verify the laws of gravity at all distance scales, from the most microscopic (gravitation has only very recently been tested at distances under a millimetre) to those of our solar system or galaxy. Perhaps the laws of gravitation will prove to be more complex than is currently imagined.

Translated from 'Les forces dans l'Univers',* Passeport pour les deux infinis, *IN2P3/Dunod, https://pass2i.ijclab.in2p3.fr/ (French); updated with ICHEP2024 conference (https://ichep2024.org) for IPPOG