Black Holes and Holography

Towards a theory of Quantum Gravity

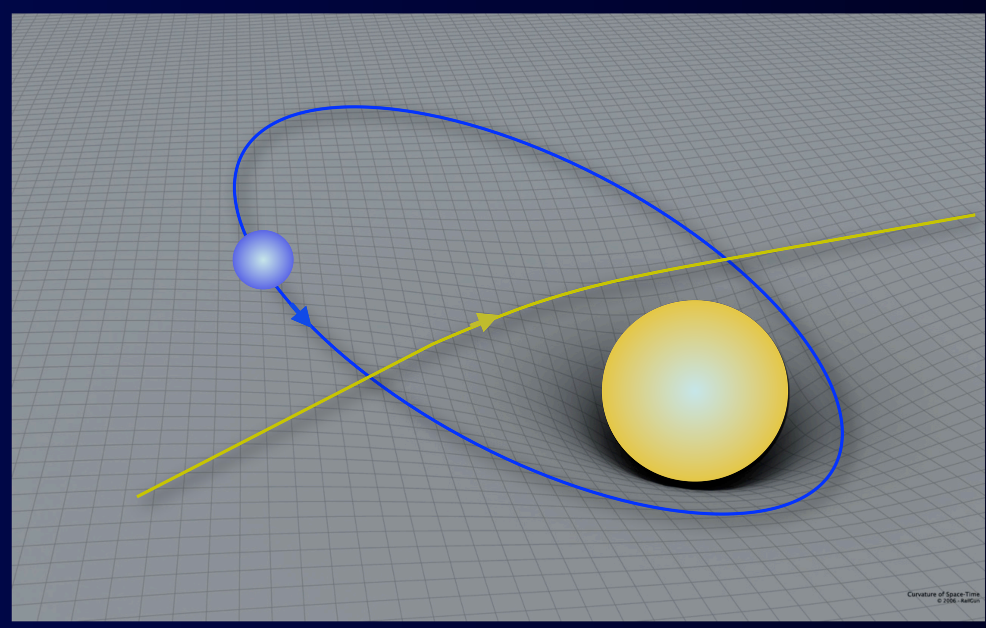
The gravitational force is described by General Relativity

From Newton...

In Newton's theory of gravity, the gravitational force is transmitted instantaneously, as an action at a distance. Hence, it is not compatible with Special Relativity, in which no signal can propagate at a speed faster than light.

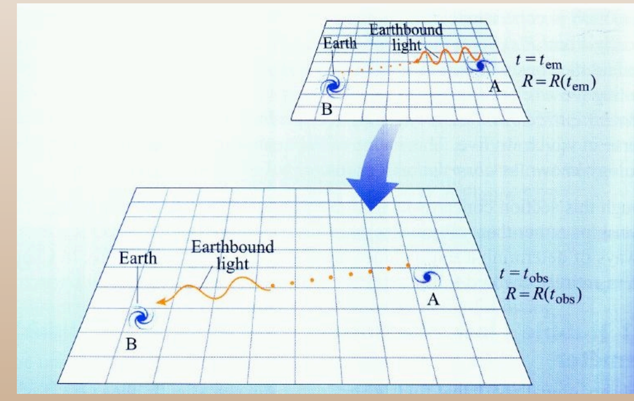
... to Einstein

In his General Theory of Relativity, Einstein realized that a gravitational field should be described as a deformation of space-time. This deformation curves the trajectories of objects, leading to the fall of objects on Earth, to the laws of planetary motion, and the dynamics of stars and galaxies in the universe.

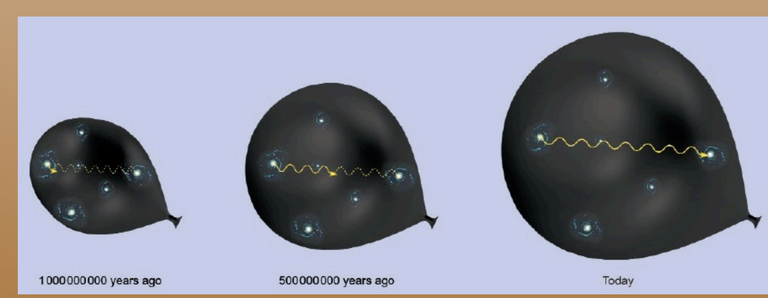


Cosmology

In General Relativity, space-time is dynamical. This allows to describe the expansion of the universe from the Big Bang, as the expansion of empty space among galaxies, such that the farther two galaxies are from each other, the faster their separation speed.



This effect is similar to the separation of dots painted on the surface of an inflating balloon. The bigger the separation, the faster their separation speed.



In the universe, black holes are born in the collapse of very massive stars. There are also supermassive black holes, with millions of solar masses, in the center of galaxies, for example in the Milky Way.

Classical Black Holes

A black hole is a body so massive that not even light can escape from its gravitational pull. The surface on which the escape velocity is that of light is called the horizon. Any signal emitted inside the horizon is unable to escape outside; instead, its trajectory is doomed to a deadly encounter with a singularity, a region formally of infinite curvature.

The Schwarzschild solution of General Relativity describes the space-time geometry of a black hole of mass M and with horizon radius

Schwarzschild radius $$r_s = \frac{2GM}{c^2}$$

Quantum Gravity

Planck scale

Singularities are regions classically of infinitely small size, so their physics requires an still unknown quantum formulation of General Relativity.

The energy at which the quantum features of gravity become manifest is the Planck scale. It is the energy of a particle whose Compton wavelength equals its Schwarzschild radius.

$$M_P = \sqrt{\frac{\hbar c}{G}}$$

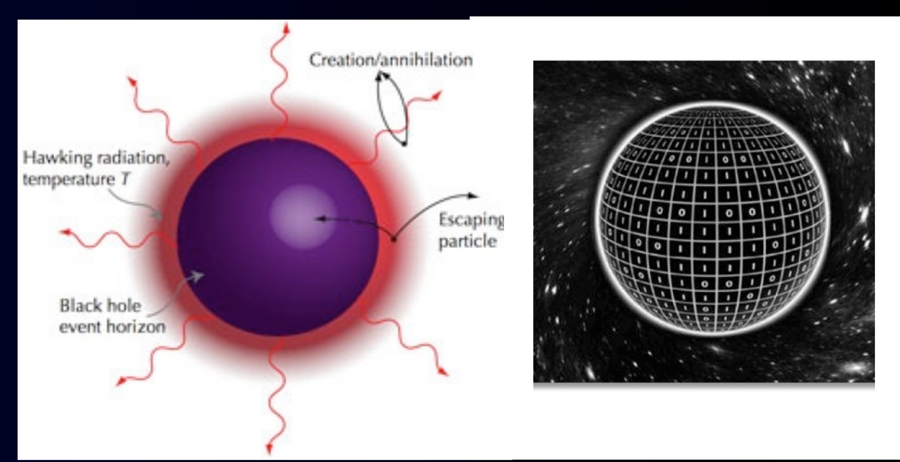
Quantum Black Holes

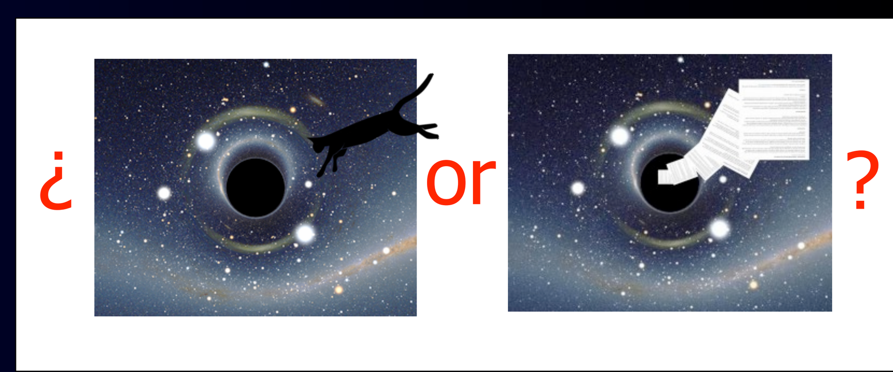
At the quantum level, black holes emit the so called Hawking radiation. Its origin is the quantum appearance of virtual particle-antiparticle pairs near the horizon, when one particle falls inside the horizon while the other escapes to infinity.

Hawking radiation has a black body spectrum with a temperature inversely proportional to the black hole mass. It also has a (Bekenstein-Hawking) entropy proportional to the area of the horizon. These properties form the basis of black hole thermodynamics. The statistical interpretation of entropy suggests the existence of a huge number of quantum microscopic states for each classical black hole solution.

The dependence of entropy with the area of the horizon, rather than the enclosed volume, motivates the formulation of the holographic principle, which proposes that the information about the quantum states of a gravitational system in a region can be encoded in the surface bounding such region.

Hawking radiation leads to the complete evaporation of the black hole. The black hole information problem is to decode how Hawking radiation carries the information of the objects that originally formed the black hole; in particular, of their quantum entanglement, which must be preserved for consistency with the laws of Quantum Mechanics.

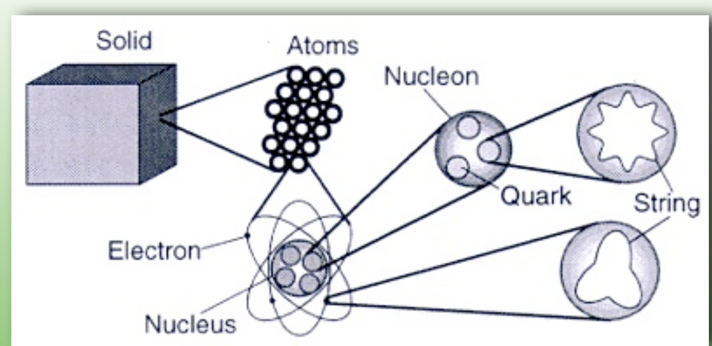




Gravity and black holes in string theory

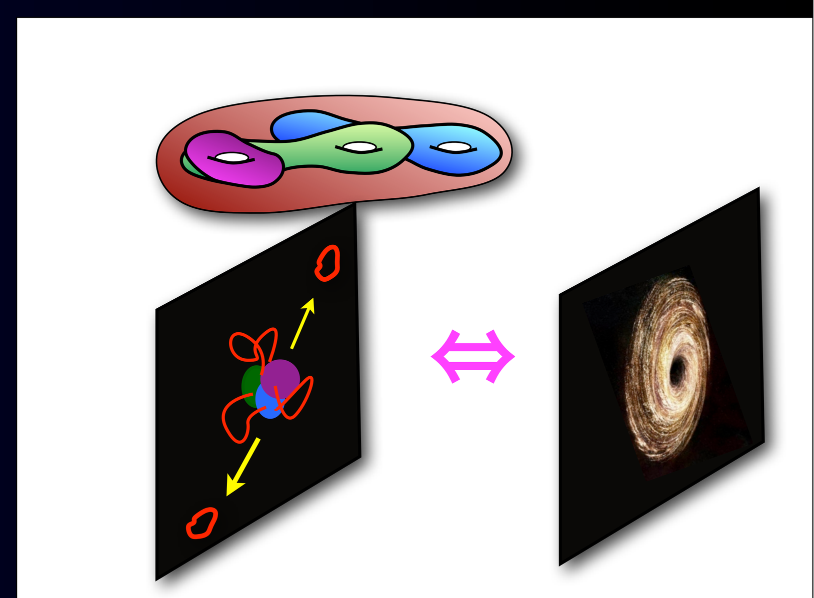
String theory proposes that elementary particles are not point-like, but rather, extended objects, strings in different vibration modes. The theory includes gravitational interactions, since the lightest vibration mode of a closed string is a graviton, the quantum of the gravitational field.

Although it has not been confirmed experimentally, string theory is very interesting, in that it provides a quantum theory which includes General Relativity, as well as other interactions.



String theories contain certain extended objects, D-branes, which can wrap in the extra dimensions to produce very massive objects in four-dimensional space-time. When interactions are intense, these objects turn into classical black holes. When the interactions are feeble, they are described by a sector of open strings with endpoints fixed on the D-branes. The quantum states of these open strings correspond to the quantum microstates of the black holes and allow for an statistical interpretation of the Bekenstein-Hawking entropy.

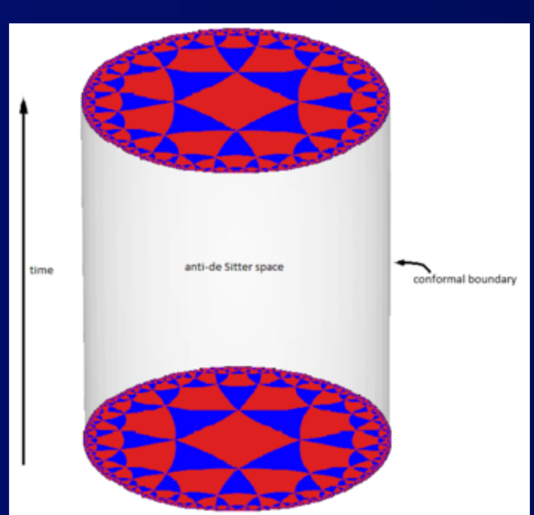
Hawking radiation corresponds to the emission of closed strings in interaction processes of open strings.



AdS/CFT and holography

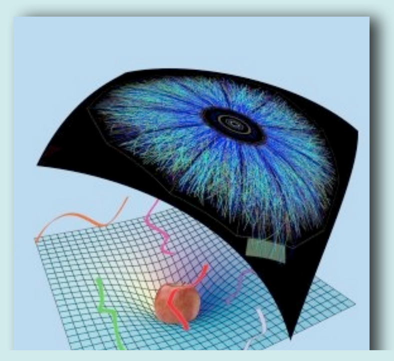
The two-fold description of D-branes in terms of open strings and of gravitational fields allows for a quantitative realization of the holographic principle. Concretely, it implies the AdS/CFT or gauge-gravity duality, a holographic relation between gravity in a 5-dimensional space of anti de Sitter (AdS) kind and a conformal field theory (CFT) on its 4-dimensional boundary.

On top of its conceptual importance, the AdS/CFT duality has led to diverse relevant applications:



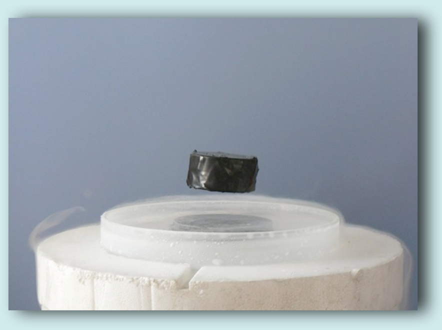
Quark-gluon plasma

The gauge theory at a finite temperature T turns into an interacting plasma at strong coupling. Its gravitational dual describes a black hole in AdS at temperature T. AdS/CFT allows using black hole physics to model the properties of the quark-gluon plasma produced in heavy ion collisions at the experiments RHIC, and ALICE (at the LHC).



Holographic superconductors

A recent development is the construction of gravitational models (charged black holes in AdS spaces) holographically dual to superconducting materials and other exotic systems in condensed matter.

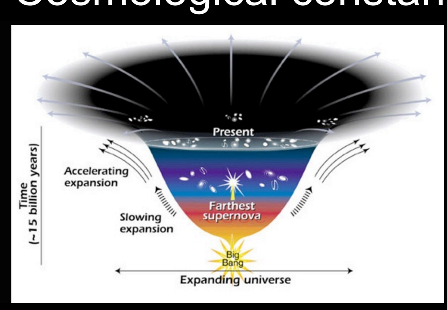


Open puzzles

Big Bang

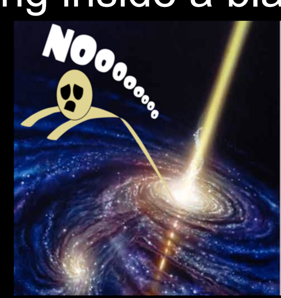
The classical Big Bang corresponds to a singularity in which the distance of any two points in space tends to zero. The mechanisms to eliminate or describe this kind of cosmological singularity remain an open subject under intense research.

Cosmological constant



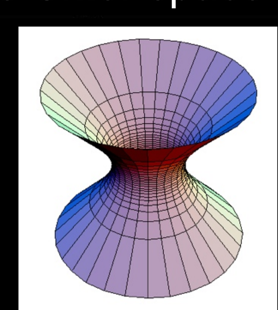
The dark energy of the universe could correspond to a cosmological constant. However, the underlying explanation for the overwhelming cancellations of quantum corrections required the explain its tiny value remains a mystery.

Falling inside a black hole



The existing descriptions for black holes at the quantum level do not yet provide a quantitative answer to the question of what happens really to an observer falling inside their horizon.

De Sitter space-time



Despite its large symmetry, there is still not a quantitative formulation of the holographic principle for space-times of the de Sitter kind (which a universe in exponentially accelerated expansion).

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