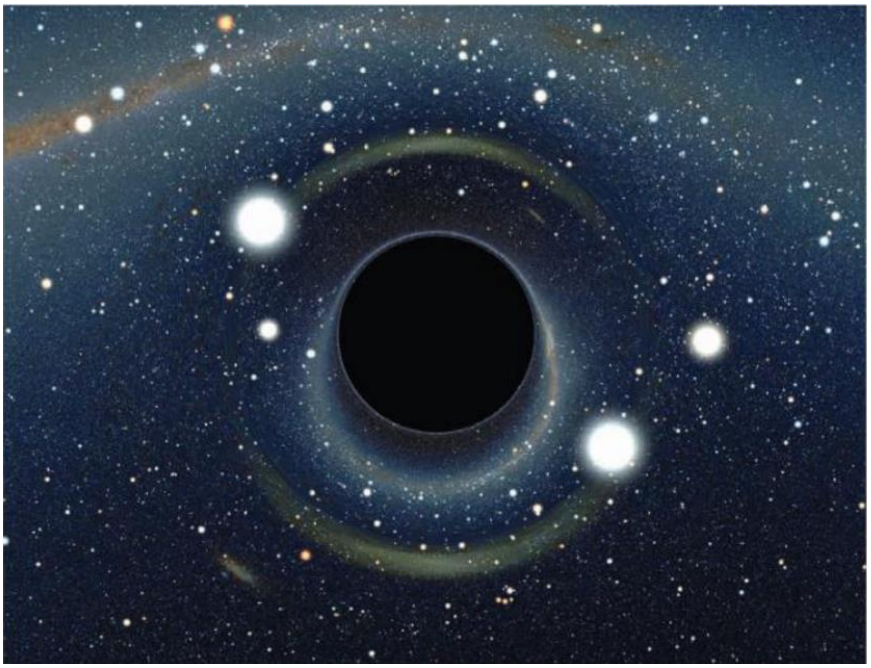
Black Holes

Black holes are regions of the Universe from which nothing can escape, neither matter nor even light.

A black hole

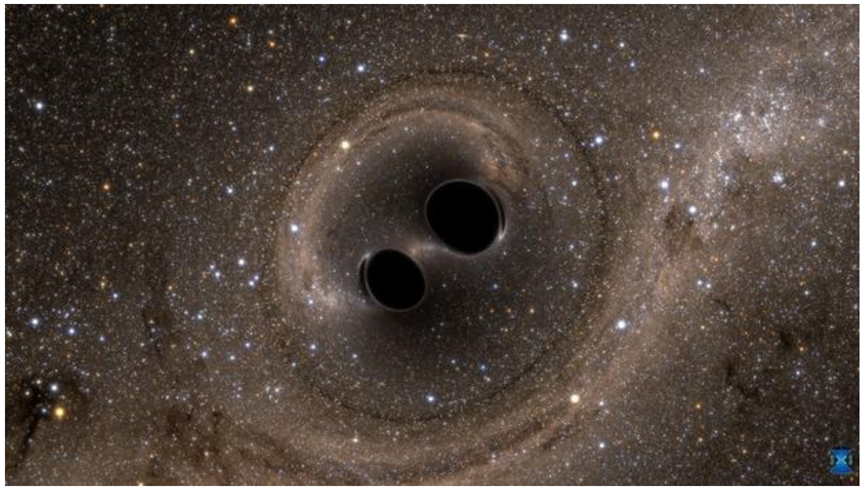


Credit: A. Riazuelo, IAP/UPMC/CNRS

The black hole concept implies that the fabric of the Universe is a four-dimensional continuum, or space-time. It also draws on Einstein's general theory of relativity which states that the presence of matter distorts space-time. For an outsider observer, any object moving freely nearby such matter follows a curved path.

As light follows the curvature of space-time, its path is bent when it passes near a massive object. The stronger gravity, the more pronounced the curvature. Since gravity intensifies when more and more mass is concentrated in an increasingly small volume, it is conceivable that an ultra-dense star could bend space-time so severely that light could no longer escape.

At the end of 1915, Einstein had barely formulated his theory of general relativity when astronomer Karl Schwarzschild already applied it to the case of a massive, supposedly spherical star in order to calculate the space-time curvature it imparts to its environment. The key parameter of its geometry is a critical radius, now known as Schwarzschild radius (R_S), which depends solely on the star's mass. The more compact the star, the closer its radius approaches R_S and the greater the distortion of the surrounding space-time. The immediate consequence of Schwarzschild's work is that an ultra-dense star with a radius equal to R_S would not allow light to escape, hence the term 'black hole' coined by physicist John Weeler in 1967.



Credit: Simulating eXtreme Spacetimes (SXS) project

Merger of two black holes

A computer-generated image of the merger of two black holes, an event observed twice in 2015 – on 14 September and 26 December – by the two LIGO (Laser Interferometer Gravitational-Wave Observatory) detectors, based in the United States.

The boundary sphere of Schwarzschild radius is the black hole's event horizon. Nothing characterises a black hole better than this immaterial surface separating the observable Universe from a region from which it is causally disconnected. What happens below the event horizon can never exert influence beyond it, where only prevails the space-time curvature created by the black hole. The very definition of a black hole – an object confined within a sphere with a radius equal to its Schwarzschild radius – allows astronomers to conceive both micro black holes (mass: 10^{12} kg, R_S: 10^{-11}m, comparable to that of a hydrogen atom) and supermassive black holes (mass: up to 10^9 $M_\odot$, R_S: up to 60 AU).

X-ray and gamma-ray observations have highlighted the existence of black holes (mass: 3–30 $M_\odot$, R_S: 10–100 km) formed from the remnants of massive stars. It is also widely accepted that the Universe contains supermassive black holes residing at the centres of most galaxies. By examining the Milky Way's central region in the near-infrared spectrum, a team of astronomers has uncovered a supermassive black hole (mass: 4×10^6 $M_\odot$) at the very core of our galaxy. The historic detection of gravitational waves on 14 September 2015 provided the first direct evidence of black holes, revealing data from the merger of two black holes.

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