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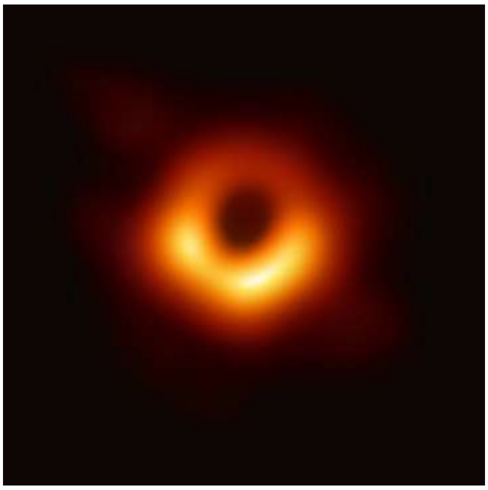
Black hole

A **black hole** is a region of spacetime where gravity is so strong that nothing – no particles or even electromagnetic radiation such as light – can escape from it.[2] The theory of general relativity predicts that a sufficiently compact mass can deform spacetime to form a black hole.[3][4] The boundary of no escape is called the event horizon. Although it has a great effect on the fate and circumstances of an object crossing it, it has no locally detectable features according to general relativity.[5] In many ways, a black hole acts like an ideal black body, as it reflects no light.[6][7] Moreover, quantum field theory in curved spacetime predicts that event horizons emit Hawking radiation, with the same spectrum as a black body of a temperature inversely proportional to its mass. This temperature is of the order of billionths of a kelvin for stellar black holes, making it essentially impossible to observe directly.



Direct image of a supermassive black hole at the core of Messier 87[1]

Objects whose gravitational fields are too strong for light to escape were first considered in the 18th century by John Michell and Pierre-Simon Laplace.[8] In 1916, Karl Schwarzschild found the first modern solution of general relativity that would characterize a black hole. David Finkelstein, in 1958, first published the interpretation of "black hole" as a region of space from which nothing can escape. Black holes were long considered a mathematical curiosity; it was not until the 1960s that theoretical work showed they were a generic prediction of general relativity. The discovery of neutron stars by Jocelyn Bell Burnell in 1967 sparked interest in gravitationally collapsed compact objects as a possible astrophysical reality. The first black hole known was Cygnus X-1, identified by several researchers independently in 1971.[9][10]

Animated simulation of a Schwarzschild black hole with a galaxy passing behind. Around the time of alignment, extreme gravitational lensing of the galaxy is observed.

Black holes of stellar mass form when massive stars collapse at the end of their life cycle. After a black hole has formed, it can grow by absorbing mass from its surroundings. Supermassive black holes of millions of solar masses ($M_{\odot}$) may form by absorbing other stars and merging with other black holes. There is consensus that supermassive black holes exist in the centres of most galaxies.

The presence of a black hole can be inferred through its interaction with other matter and with electromagnetic radiation such as visible light. Any matter that falls onto a black hole can form an external accretion disk heated by friction, forming quasars, some of the brightest objects in the universe. Stars passing too close to a supermassive black hole can be shredded into streamers that shine very brightly before being "swallowed."[11] If other stars are orbiting a black hole, their orbits can determine the black hole's mass and location. Such observations can be used to exclude possible alternatives such as neutron stars. In this way, astronomers have identified numerous stellar black hole candidates in binary systems and established that the radio source known as Sagittarius A*, at the core of the Milky Way galaxy, contains a supermassive black hole of about 4.3 million solar masses.

On 11 February 2016, the LIGO Scientific Collaboration and the Virgo collaboration announced the first direct detection of gravitational waves, representing the first observation of a black hole merger.[12] On 10 April 2019, the first direct image of a black hole and its vicinity was published, following observations made by the Event Horizon Telescope (EHT) in 2017 of the supermassive black hole in Messier 87's galactic centre.[13][14][15] As of 2021, the nearest known body thought to be a black hole is around 1,500 light-years

(460 parsecs) away (see list of nearest black holes). Though only a couple dozen black holes have been found so far in the Milky Way, there are thought to be hundreds of millions, most of which are solitary and do not cause emission of radiation.[16] Therefore, they would only be detectable by gravitational lensing.

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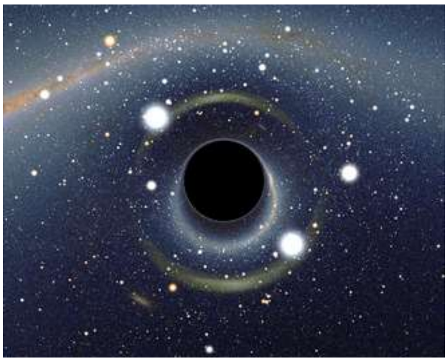
History

The idea of a body so big that even light could not escape was briefly proposed by English astronomical pioneer and clergyman John Michell in a letter published in November 1784. Michell's simplistic calculations assumed such a body might have the same density as the Sun, and concluded that one would form when a star's diameter exceeds the Sun's by a factor of 500, and its surface escape velocity exceeds the usual speed of light. Michell referred to these bodies as dark stars.[18] He correctly noted that such supermassive but non-radiating bodies might be detectable through their gravitational effects on nearby visible bodies.[8][19][20] Scholars of the time were initially excited by the proposal that giant but invisible 'dark stars' might be hiding in plain view, but enthusiasm dampened when the wavelike nature of light became apparent in the early nineteenth century,[21] as if light were a wave rather than a particle, it was unclear what, if any, influence gravity would have on escaping light waves.[8][20]



Simulated view of a black hole in front of the Large Magellanic Cloud. Note the gravitational lensing effect, which produces two enlarged but highly distorted views of the Cloud. Across the top, the Milky Way disk appears distorted into an arc. Published in 2019.[17]

Modern physics discredits Michell's notion of a light ray shooting directly from the surface of a supermassive star, being slowed down by the star's gravity, stopping, and then free-falling back to the star's surface.[22]

General relativity

In 1915, Albert Einstein developed his theory of general relativity, having earlier shown that gravity does influence light's motion. Only a few months later, Karl Schwarzschild found a solution to the Einstein field equations that describes the gravitational field of a point mass and a spherical mass.[23][24] A few months after Schwarzschild, Johannes Droste, a student of Hendrik Lorentz, independently gave the same solution for the point mass and wrote more extensively about its properties.[25][26] This solution had a peculiar behaviour at what is now called the Schwarzschild radius, where it became singular, meaning that some of the terms in the Einstein equations became infinite. The nature of this surface was not quite understood at the time. In 1924, Arthur Eddington showed that the singularity disappeared after a change of coordinates (see Eddington–Finkelstein coordinates), although it took until 1933 for Georges Lemaître to realize that this meant the singularity at the Schwarzschild radius was a non-physical coordinate singularity.[27] Arthur Eddington did however comment on the possibility of a star with mass compressed to the Schwarzschild radius in a 1926 book, noting that Einstein's theory allows us to rule out overly large densities for visible stars like Betelgeuse because "a star of 250 million km radius could not possibly have so high a density as the Sun. Firstly, the force of gravitation would be so great that light would be unable to escape from it, the rays falling back to the star like a stone to the earth. Secondly, the red shift of the spectral lines would be so great that the spectrum would be shifted out of existence. Thirdly, the mass would produce so much curvature of the spacetime metric that space would close up around the star, leaving us outside (i.e., nowhere)."[28][29]

In 1931, Subrahmanyan Chandrasekhar calculated, using special relativity, that a non-rotating body of electron-degenerate matter above a certain limiting mass (now called the Chandrasekhar limit at 1.4 $M_\odot$) has no stable solutions.[30] His arguments were opposed by many of his contemporaries like Eddington and Lev Landau, who argued that some yet unknown mechanism would stop the collapse.[31] They were partly correct: a white dwarf slightly more massive than the Chandrasekhar limit will collapse into a neutron star,[32] which is itself stable. But in 1939, Robert Oppenheimer and others predicted that neutron stars above another limit (the Tolman–Oppenheimer–Volkoff limit) would collapse further for the reasons presented by Chandrasekhar, and concluded that no law of physics was likely to intervene and stop at least some stars from collapsing to black holes.[33] Their original calculations, based on the Pauli exclusion principle, gave it as 0.7 $M_\odot$; subsequent consideration of neutron-neutron repulsion mediated by the strong force raised the estimate to approximately 1.5 $M_\odot$ to 3.0 $M_\odot$.[34] Observations of the neutron star merger GW170817, which is thought to have generated a black hole shortly afterward, have refined the TOV limit estimate to ~2.17 $M_\odot$.[35][36][37][38][39]