Black holes are one of the most fascinating and extreme objects in the universe. They are regions of spacetime where gravity is so intense that nothing—not even light—can escape from them. This extreme condition results from matter being compressed into a very small space, leading to a singularity: a point of infinite density where the laws of physics as we know them cease to function. Black holes were first predicted by Karl Schwarzschild in 1916 as a solution to Einstein's equations of General Relativity. However, they remained a theoretical curiosity for decades. In the 1960s and 70s, observational astronomy and theoretical research revived interest in these cosmic enigmas. There are several types of black holes categorized by mass: stellar-mass black holes (3 to 20 solar masses), intermediate-mass black holes (hundreds to thousands of solar masses), and supermassive black holes (millions to billions of solar masses), which are found at the centers of galaxies. The smallest theoretical type, primordial black holes, may have formed during the Big Bang, but remain hypothetical. Stellar-mass black holes are formed through the gravitational collapse of massive stars—those over roughly 20 times the mass of the Sun. When such a star exhausts its nuclear fuel, it can no longer support itself against gravitational collapse, resulting in a supernova explosion. If the remaining core is massive enough, it collapses into a black hole.

At the heart of a black hole lies the singularity, where density becomes infinite and known physics break down. Surrounding the singularity is the event horizon—the boundary beyond which no information or matter can escape. The event horizon is not a physical surface, but a mathematically defined boundary in spacetime. The Schwarzschild radius defines the size of the event horizon for non-rotating black holes and depends solely on the mass of the black hole. For example, the Schwarzschild radius of a black hole with the mass of the Sun is about 3 kilometers. Rotating black holes, described by the Kerr metric, exhibit even more complex structures. These include an ergosphere, a region outside the event horizon where objects are dragged by the spinning spacetime. Charged black holes (Reissner–Nordström black holes) are also possible in theory, adding further layers of complexity. Black holes can spin and have angular momentum. This rotation can affect nearby matter, accelerating particles and warping spacetime. This spin is often the result of the angular momentum of the original star or the accretion of matter from a surrounding disk. An accretion disk forms when matter spirals toward the black hole, heating up to millions of degrees and emitting radiation, particularly in the X-ray spectrum. Observations of these emissions provide indirect evidence of black holes. In some cases, powerful jets of particles are ejected from the poles of the black hole, traveling at near light-speed. Though black holes are commonly thought of as destructive, they are also essential to galactic evolution. Supermassive black holes influence the formation and behavior of stars in galaxies, regulate growth via feedback mechanisms, and are fundamental to the dynamics of galactic cores.

Because black holes do not emit light, astronomers rely on indirect methods to detect them. X-ray binaries, where a black hole draws material from a companion star, emit high-energy X-rays. These emissions allow astronomers to estimate the mass and location of the black hole. Gravitational lensing, where light from distant stars is bent around a black hole, also offers a method of detection. One of the most groundbreaking confirmations of black holes came in 2015, when the Laser Interferometer Gravitational-Wave Observatory (LIGO) detected gravitational waves from the merger of two stellar-mass black holes. This historic discovery confirmed a key prediction of Einstein's General Relativity and opened a new era of astronomy: gravitational wave astronomy. Another revolutionary idea is Hawking radiation, proposed by physicist Stephen Hawking in 1974. According to quantum theory, particle-antiparticle pairs form spontaneously near the event horizon. One particle falls in, while the other escapes, appearing as radiation. Over immense periods of time, this could cause black holes to lose mass and eventually evaporate. Black holes are not merely cosmic vacuum cleaners—they are key to testing the fundamental laws of physics. They challenge our understanding of gravity, quantum mechanics, and information theory. The so-called "information paradox" arises from the question of whether information that falls into a black hole is destroyed, which would violate the laws of quantum mechanics. This remains one of the most profound unsolved problems in theoretical physics. In 2019, the Event Horizon Telescope collaboration captured the first-ever image of a black hole's shadow in the galaxy M87. This achievement was not only a technical triumph but also a visual confirmation of theoretical models developed over a century. In conclusion, black holes are both mysterious and fundamental. They provide unique insights into the workings of the universe, pushing the boundaries of modern science and continuing to captivate our imagination.