Types and the State-of-art Detections Scenarios for Black Holes

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Abstract. As a matter of fact, the black holes remain a mysterious topic in cosmology and astrophysics. On this basis, plenty of scholars and research aim at detecting the features of black holes and the characteristics of gravitation for black holes in recent years. With this in mind, this study will discuss the state-of-art detection scenarios for black holes. To be specific, this study will first introduce the definition of black hole as well as the types and category for the black holes. Afterwards, the detection principle as well as schemes will be demonstrated. In detail, some of the detection facilities are introduced and demonstrated. Moreover, the state-of-art detection results will be analyzed and the current defects as well as drawbacks will be evaluated. According to the analysis, further suggestions to investigate black holes are put forward. Overall, these results shed light on guiding further exploration of black hole investigations and detections.

Keywords: Black holes, black hole detections, black hole category.

1. Introduction

A black hole is a quasar that is not reflective and has such a strong gravitational pull that all particles and electromagnetic radiation such as light cannot escape. In the 1700s, John Michel and Pierre-Simn Laplace have already considered objects with gravitational fields so strong that light could not escape [1]. The existence of black holes in 1916 was raised by Albert Einstein using his general relativity. After decades, the black hole was only known as a theoretical object because the technology was inadequate to detect it. Cygnus X-1, the first black hole discovered in 1964, is located in the Swan, the Cygnus constellation. Cygnus X-1 is a binary system, the other is a black hole itself, which is an object with a radius of about 30 kilometers and a mass that is around 10 times that of the sun [2].

On September the 14th 2015, a gravitational wave discovery was done by the LIGO detectors. Two black holes sent out the signal, one with masses 36 times the sun and another with 29 times the sun. They collide and form a black hole that has a mass of 62 M⊙, releasing 3 million energy in gravitational waves. These findings show that binary stellar-mass black hole systems occur [3]. It is also the first black hole to be seen merging and the first gravitational wave observation directly, which not only represents a significant discovery in and of itself but also created a brand-new perspective from which to see the cosmos [4].

On April 10, 2019, the "true face" of one black hole in the heart of a galaxy called M87, a massive oval galaxy in the Virgo constellation, 55×10^6 light-years from Earth and having nearly 6.5×10^9 M ⊙, was simultaneously revealed by scientists around the globe. There is a “blank” in the center with a circular arc halo. Until then, when astronomers revealed the first picture of a black hole, no one had actually seen a true black hole [5]. The purpose of this paper is to give a basic introduction to different types of black holes and how to detect and differentiate them.

2. Definition and Category

Black hole, a region in spacetime with such an intense gravitational field, sucks everything, even light toward it [6]. Usually, a large star's death and collapse result in the formation of a black hole. As a star dies, its core becomes unstable and collapses. The falling matter compresses itself into a point that is known as the singularity [7]. Albert Einstein’s general relativity theory calculated the

features of the black hole: a “singularity” with no volume but infinite density pulls in everything that is in the black hole’s event horizon around it. As long as a black hole becomes steady, it will have three physical features to be evaluated: its mass, electric charge, and angular momentum. Based on that, one can distinguish and categorize black holes through these properties. If it has no charge and doesn’t spin, one called it a Schwarzschild black hole. If it has no electric charge but spins, then it is a Kerr black hole. Following this rule, a Kerr-Newman black hole has an electric charge and does spin and Reissner-Nordström black hole has no electric charge but spins. The electric charge and the feature that whether a black hole spins or not is decided by the mass of it, which follows the equation $Q^2+(J/M)^2\leq M^2$. Except for classing them by angular momentum and electric, usually one did that by calculating the mass, which is normally decided by the Schwarzschild Radius. The Schwarzschild Radius is discovered by Karl Schwarzschild, a German scientist. It is a precise solution to a spherically symmetric thing with no charge or angular momentum with a gravitational field, meaning that if this object is completely contained within its Schwarzschild Radius, the singularity will occur, such as a black hole [8]. In other words, Schwarzschild Radius is the event horizon of a Schwarzschild black hole. However, the other three kinds of black holes: Kerr black hole, Reissner-Nordström black hole, and Reissner-Nordström black hole, their solutions are more complicated since they can have 2, 1, or even no layers of event horizon under different conditions.

The Schwarzschild Radius equals to $Rs=2GM/c^2$, where G is the gravitational constant and c is the speed of light. Converting it to the mass of the sun, one has $rs\approx 2.95M/M\odot$. Here, $M\odot$ is the mass of the sun. If rs of a black hole is about only 0.1 mm, one calls it a micro black hole. If it has around 30 kilometers of rs, it is a stellar black hole. If its rs is around 1 thousand kilometers, it is called an intermediate-mass black hole. If a black hole has the rs that is about 0.001 to 400 AU, one calls it a supermassive black hole, and it is kind of special. One knows that if an object is homogeneous, it will have a Schwarzschild radius proportionate to its mass, thus to its volume based on the formula above and $m=\rho V$, where ρ is the density of the object and V is the volume. Contrarily, the object's true radius corresponds to the cube root of its volume because $V = 4\pi r^3/3$

As a result, the body’s Schwarzschild radius will exceed its physical radius one day because the Schwarzschild radius grows faster as the mass of the object incereases, which forms a supermassive black hole. After the calculation, the star which forms these kinds of black holes should have a mass that is around $136M\odot$. The first black hole picture humans took is a supermassive black hole which is in the center of M87 (seen in Fig. 1)

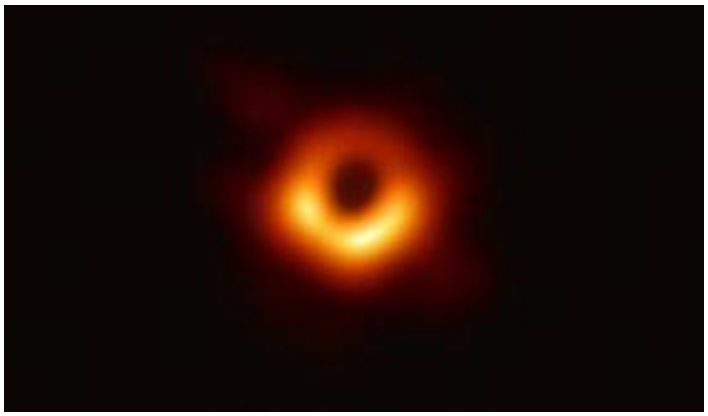


Fig. 1 A photo of supermassive black hole.

3. Principle of Black Hole Detection

As it known to all, telescopes that search for light, x-rays, or other electromagnetic waves cannot see black holes because they are unable to escape from the strong gravitational pull, so one has to find other ways to detect them indirectly. One way to deduce the existence of black holes is by seeing how they affect neighboring matter. A black hole will accrete and capture dust when it goes through

a cloud of interstellar matter or rips apart a star that is attracted by it. The matter accelerates and warms up, which produces an X-ray that can be detected.

Another way is to see their gravity pulling on other things. Because of the black hole's enormous gravitational pull, neighboring stars will be forced to orbit it, allowing us to search for unusual behavior from stars in the vicinity of space. By determining how quickly the orbit moves, one may determine exactly how hefty that black hole must be. Black holes can also be found by observing the alterations in space-time resulting from two of them colliding. It is able to determine the black holes' masses, distances from one another, and collision speeds from that signal [9]. The last way is to use gravitational microlensing. Einstein pointed out that, considering the presence of a small-mass spherically symmetric compact celestial between the distant light source and the observer, the light signal radiated by the distant light source will be deflected by the influence of gravity, and the deflection angle is $\theta = 4GM/c^2rs$. rs is the vertical distance between the extension line of the light signal emitted by a distant light source and the geometric center of a compact object, for example, the black hole, when it is not bent by gravity. This kind of effect that a compact object acts like a convex lens in geometric optics is called a gravitational lens. For the microlensing effect, the luminosity of the distant light source is negative in relation to the angular distance between the place that light comes from and the high-density object. In this way, if the lens object passes through the observer and the light source, scientists can detect a peak on the graph of the luminosity of the light over time [10]. A typical sketch is shown in Fig. 2.

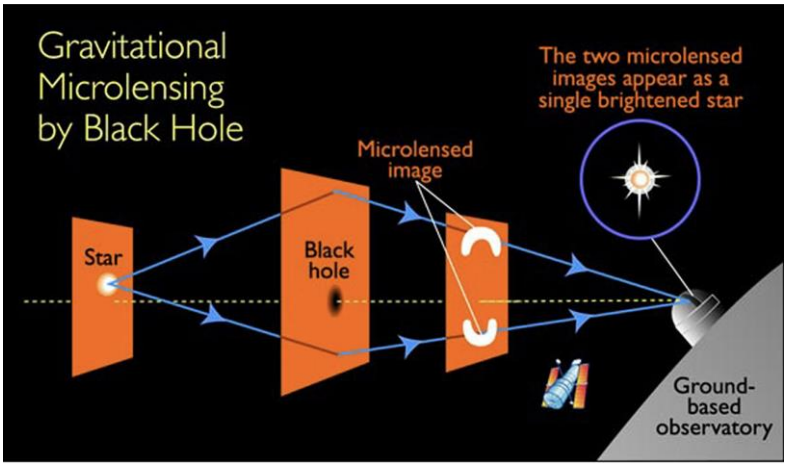


Fig. 2 A sketch of mircolensing for black hole.

4. Detection Result

On the 14th of September, 2015, the first successful direct observation of gravitational waves was published by the LIGO gravitational wave observatory. The gravitational wave was created by merging two black holes, one with a mass of around 36 $M\odot$ and the other with around 29 $M\odot$ [11]. It corresponds to the waveform that is in accordance with general relativity's predictions for the spiraling of two black holes and their union as well as the ringdown of the ensuing black hole [12]. This discovery provides the most compelling evidence of black hole existence to date. The gravitational wave signature, for instance, shows that the two objects were barely 350 km apart when they merged. As a result, they have to be incredibly compact, making black holes the most likely explanation. Additionally, this observation offers the first direct proof of a binary stellar-mass black hole. It is also the first observable proof of stellar-mass black holes with a mass of at least 25 solar masses [13].

On May 12, 2022, Sagittarius A, the supermassive black hole that is in the heart of the Milky Way galaxy, was first captured on camera by the EHT as illustrated in Fig. 3. The image that was published featured the same circular shadow and ring-like shape as the black hole in M87, and it was also detected by the technique used to find the black hole in M87. Lensed rings are ubiquitous

characteristics of black holes, and general relativity may be able to predict this over three different magnitudes in black hole mass [14]. However, due to the changeable circumstance, the imaging procedure for Sgr A is almost less big and one million times smaller than M87. On its way back to the earth, swirling plasma temporarily distorted the picture of Sagittarius A, preventing the image's clarity at wavelengths that are longer.

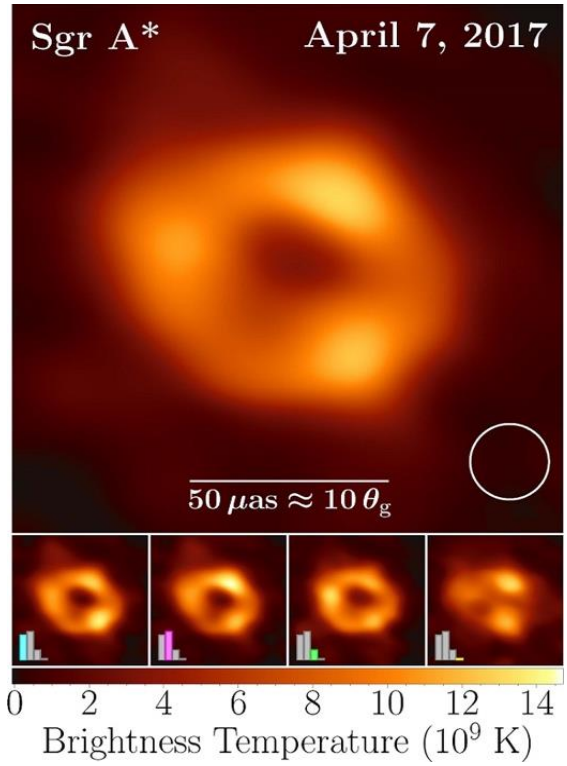


Fig. 3 Measurement results.

5. Meaning and Application

Physics aims to study the world around us, since black holes exist, one needs to clarify and understand it. Black holes have a very important significance for the creation of the universe's structure, the evolution of celestial bodies, and the study of astrophysics. Disc-shaped galaxies have convex central regions called bulges. Scientists discovered a proportionate link between the masses of some massive black holes and the bulge masses of their host galaxies which indicates a strong relationship between the galaxy's creation and the formation of a large black hole. The black hole, together with its galaxy likely develops simultaneously. One explanation is that the accreting black hole's jets and winds may both start and stop star formation by expelling more gas from the galaxy [15]. Black holes are a prediction of Einstein's general relativity. In Newton's law of gravitation, there is no concept of black holes. In 1915, Einstein gave a series of lectures on his theory of general relativity, claiming that space and time are a continuum that can be warped by anything with mass and that the result of the warping is gravity. After months, Karl Schwarzschild discovered the solution to the formula that Einstein used to describe the masses of particles and spheres [16]. However, Schwarzschild's paper contained some radical predictions, and the idea of the bottomless pit in space-time troubled many scientists including Einstein, who himself did not believe that black holes exist. The detections of black holes provide evidence that Einstein's equation and Schwarzschild's thought are particularly correct but Einstein himself is wrong.

As a place where the effects of quantum gravity are significant, black holes are the best platform to test the theory of quantum gravity. Black holes also possess qualities that are common to quantum particles from a study that was published in the Physical Review Letters. The goal of the new study, which relied on digital modeling, was to discover the relationship between the laws governing the

behavior of the smallest subatomic particles and the time-warping physics of supermassive objects [17]. The research team created a mathematical model of a massive simulated black hole, with a fictitious quantum particle outside. According to the simulation, the fictitious black hole demonstrated quantum superposition, as the capacity to simultaneously exist in several states, which meant that it could be both huge and totally the opposite.

6. Difficulties and Outlook

Telescopes cannot be used to directly see black holes by scientists since every form of the electromagnetic wave will be pulled by the strong gravity of black holes. Observers can only obtain information about the black hole by indirect methods such as measuring the moving speed and spectral changes of the material around and measuring its outlook and velocity fields of the galaxies around the black hole. That means the figures gotten from space might not be accurate enough. In addition, because of the observation problem, one can only rely on theoretical models and numerical simulations to explore the mysteries inside black holes. However, without those accurate numbers, the errors in the models and equations can't be found, which will negatively influence the probe of the black hole.

At the same time, the observation and research of black holes need to use some very advanced scientific technology and equipment, such as telescopes and radio telescopes. The limitations of these technologies and equipment also restrict the in-depth research of black holes. Just simply taking a picture of a black hole has already cost nearly $60 million to the U.S. government [18]. Countries with less money can't even afford the basic observation of black holes. In addition, the theoretical study of black holes needs to use the knowledge of multiple disciplines such as physics, astrophysics, relativity, and quantum mechanics, and the interaction and contradiction between these disciplines also make the theoretical study of black holes more difficult.

To understand the black hole better, scientists will conduct a series of experiments. For example, a project called Laser Interferometer Space Antenna (LISA) is under preparation. It is a three-spacecraft gravitational wave detector that is stationed in space and is designed to search for gravitational wave fingerprints resulting from spacetime distortions [19]. Early in the 2030s is when LISA is expected to debut.

7. Conclusion

To sum up, as demonstrated above, the basic types and the detections of black holes are discussed. Humans have made huge progress on the black hole, from assuming its existence, and indirectly observing its surroundings to truly taking a picture of it and categorizing it with different features. Although there are still many difficulties to solve and many setbacks to encounter, the author believes the secrets of the black hole will be unlocked one day. Overall, these results shed light on guiding further exploration of blakc hole investigations.

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