

Principle and State-of-art Observation Scenarios of Black Holes

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Abstract. Tracing back to the 17th century, the concept of black holes emerged as "dark stars," celestial bodies with gravitational pull surpassing the speed of light. Schwarzschild's solution to Einstein's equations in 1916 introduced the concept of a singularity and the Schwarzschild radius, defining black holes as objects compressed within this boundary. Two main classification methods for black holes based on mass and charge/angular momentum are discussed'. The study explores the principles of detection: gravitational waves, generated by events like black hole mergers, and gravitational lensing, where immense mass bends space and time, distorting light from distant objects. Facilities such as LIGO, Virgo, and KAGRA are introduced, showcasing their contributions in detecting gravitational waves. Optical telescopes like the Hubble Space Telescope and the Event Horizon Telescope play a vital role in visualizing black holes. Recent results include numerous successful black hole detections, testing the validity of General Relativity, and providing precise information on black hole masses and locations. While limitations in sensitivity and resolution persist, the future outlook is promising. Advancements in observatory technology, third-generation gravitational wave detectors, and multi-messenger astronomy collaborations will deepen our understanding of black holes and their role in the cosmos, fueling ongoing exploration of these enigmatic cosmic entities.

Keywords: Black holes, detection, facilities, Applications.

1. Introduction

Black holes have been an integral part of humans with the sky for quite some time now. The history of humans with black holes traces back to the 17th century, where the concept of a black hole was initially suggested by John Michell and Pierre-Simon Laplace, who proposed the idea of "dark stars". These are celestial objects that were so massive and dense that their escape velocity exceeded that of light [1]. Then, the Vassi solution, which Karl Schwarzschild discovered in 1916 as an answer to Einstein's field equations for a spherically symmetric, non-rotating electroless system in a vacuum, is really where black holes first appeared in human history [2]. Following the breakthroughs, Einstein proposed in the 20th century that such objects would bend space and time with his general relativity, and extensions were being made throughout that time. The investigations and scientific breakthroughs people are having with black holes are driving our understanding of the universe and fundamental gravity and physics, since black holes are a consequence of general relativity. By finding more about black holes, one also deepens the understanding in cosmological evolutions through knowing more about the giants settled in the center of many galaxies.

The origin of black holes, as mentioned, can trace back to the 17th century, where astrophysicists gave it the definition of a celestial body with a gravitational pull so large that its escape velocity is greater than that of the speed of light, and these bodies were named various names such as "dark stars" [3]. According to Einstein's general relativity, such an object would cause a curve in space and time, as all objects exist in a fabric of space and time, and objects with such a large mass will cause a huge indent in the fabric, leading to the name "black holes", as given by physicist John Wheeler at a conference in 1967 [4]. Before the 1930s, humans only knew how stars, as the hydrogen in their core is used up, collapses and expands, fusing elements in its core during the process, gaining elements of greater and greater mass until the element iron, which by then cannot support the energy of fusing into the next element by burning itself [4]. The stars after the process are either then collapsed into white dwarfs or neutron stars, where the pressure of particles of the star balances with the gravitational

pull of that star. This was the eventual fate of stars about three times as massive as our sun. However, a report in the 1930s by Subrahmanyan Chandrasekhar, Nobel physics prize winner, questioned what would happen if the particles' pressure could not withstand the gravitational pull of the star itself [5], which leads into the modern definition and core parts of a black hole.

The motivation for writing the essay is to explore the state-of-the-art principles of detection for black holes. Black holes are very strong bonding points and seals for the most fundamental yet unreachable mysteries of the universe, and to detect and perhaps study them will unveil many knowledges hidden to human beings about the universe. The essay will analyze the detection and outcomes of doing so to black holes, which will contribute to the refining of the process of detection and thus make investigations around the black hole yield higher accuracy and achieve more with less effort. The essay will follow the logical structure of first giving a brief introduction to black holes and the two main ways to classify them. Then the essay will tread into the principles of detection of black holes, which would be primarily gravitational lensing and gravitational waves, being further elaborated later in the essay. Then this essay will delve into the facility used to detect black holes, and the results of detecting with how they're applied. Finally, this study will give his own opinion on the limitations of state-of-the-art blackhole detection scenarios and the future outlooks of the current technology.

2. Basic Descriptions

The way defined black holes was given by astronomer Karl Schwarzschild, who used Einstein's equations to show that if matter were to be collated into a single point, that point would be called the "singularity", from which extends a region nothing can escape. The boundary of the region is called the "event horizon", or the Schwarzschild Radius, as it is found by Schwarzschild through the following equation [2]:

$$R_s = \frac{2GM}{c^2} \quad (1)$$

Where R_s is the Schwarzschild radius, G is the gravitational constant, M is the mass of the black hole, and c is the speed of light in a vacuum, here acting as the escape velocity (because one is circling a region where the escape velocity is greater than c). Any object that is compressed smaller than its own Schwarzschild radius will form a black hole.

There are two mainstream ways of classifying black holes. The core components of black holes are their mass, charge, and angular momentum. And thus, the two ways people have classified black holes is by their mass, or their charge and angular momentum. The classification by mass splits black holes into micro black holes, stellar black holes, intermediate-mass black holes, and supermassive black holes, ascending in mass [6]. Micro black holes are on the general term black holes that exist on the quantum level. These are thought to be formed during the big bang, according to scientists [6]. Stellar black holes are those that form during stellar collapse, as mentioned in 2.1, these are the most numerous black holes in the universe today. Intermediate-mass black holes are a theoretical class of black holes which cannot be naturally formed by stellar collapse. They are thought to form through stellar black holes engulfing other massive stars, or massive stellar black holes engulfing other stellar black holes. Supermassive black holes have no clear explanation for their formation yet, as if scholars look at the reason of formation for intermediate mass black holes, the universe should not have enough time to form these supermassive black holes. However, they do exist in the center of many galaxies, and can reach hundreds of thousands to billions of solar masses. One can also classify black holes through the charge they carry and their angular momentum. By attaining a cartesian product of charge and angular momentum, one can classify black holes into again, 4 different categories. The Schwarzschild black hole is that of no charge and no rotation. They are also called static black holes for their idleness. The equation of the event horizon is given above.

The second type of black holes are R-N black holes. These are black holes with a charge and no angular momentum. The primary difference between these and static black holes is that there are two

horizons for an R-N black hole, and the distance between these event horizons decrease as the charge of the black hole increases. As the charge becomes big enough, the two horizons might merge and form a single horizon, forming what is so called an extreme R-N black hole.

The third kind are black holes with no charge but an angular momentum, and they are called Kerr black holes. These black holes have no singularity but an odd ring, which is pulled by a large angular momentum. A Kerr black hole also has two horizons, and outside of the external horizon is a static limit, where all matter within it cannot reach rest relative to space and time. The majority of stellar black holes are Kerr black holes, because stars themselves have an angular momentum.

The final kind of black holes are Kerr Newman black holes. These are black holes with a charge and angular momentum, and they have traits of that of Kerr black holes and R-N black holes combined, giving black holes with two horizons and an odd ring in the middle [6].

3. Principles of Detection

There are two mainstream principles of detection for black holes, which are gravitational waves and gravitational lensing.

3.1. Gravitational Waves

Gravitational waves are the fluctuations of space time created when there is dramatic change in material and energy. It is similar to the ripples of water created when a rock is dropped or when a heavy ball is dropped onto a mesh carpet. The shockwave generated by the impacts radiate in all directions, and they work similarly to gravitational waves [7]. To generate gravitational waves, one requires a strong impact in space time, which is often provided by two black holes merging. The strong gravitational waves generated by such events can be detected on earth, such as through the LIGO (Laser interferometer Gravitational-wave Observatory) system. The principle of the LIGO system is that a beam of laser is split into two perpendicular arms, and when gravitational waves pass through, the arms fluctuate a bit, causing the lengthening and shortening of one arm and another. These arms are later reflected and recombined to form a pattern at the beam splitter. When there are no gravitational waves, the light waves will cancel out each other at the beam splitter. However, if there is a difference in the length of arms, light will not destruct perfectly, and there will be light that escapes the beam splitter and hits the photon detector behind [8]. A sketch is shown in Fig. 1. Through the process of detecting for gravitational waves, humans will be able to find black hole merger events and thus the existence of a black hole [7].

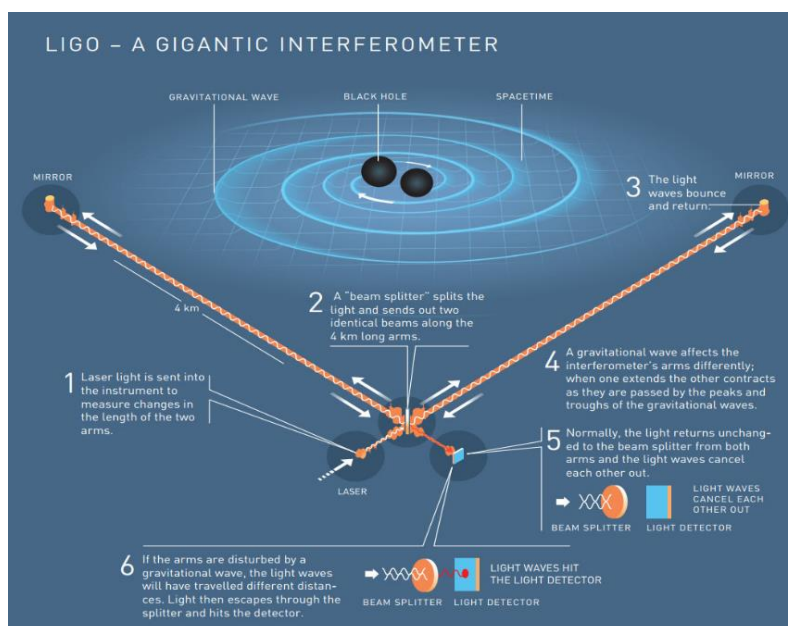


Fig. 1 A diagram and explanation of the LIGO

3.2. Gravitational Lensing

Another way of detecting for black holes is gravitational lensing (shown in Fig. 2). Gravitational lensing is a phenomenon allowed by general relativity, as objects of immense mass can bend space and time around them. The essential way that one can detect black holes is that when the light travels around a black hole, some of the light will be affected by the strong pull of a black hole's gravitational field, thus bending it. The outcome of so can be observed as the magnification, distortion, and even multiple images of the same bodies in a distance because of the interference of the travelling path of light.

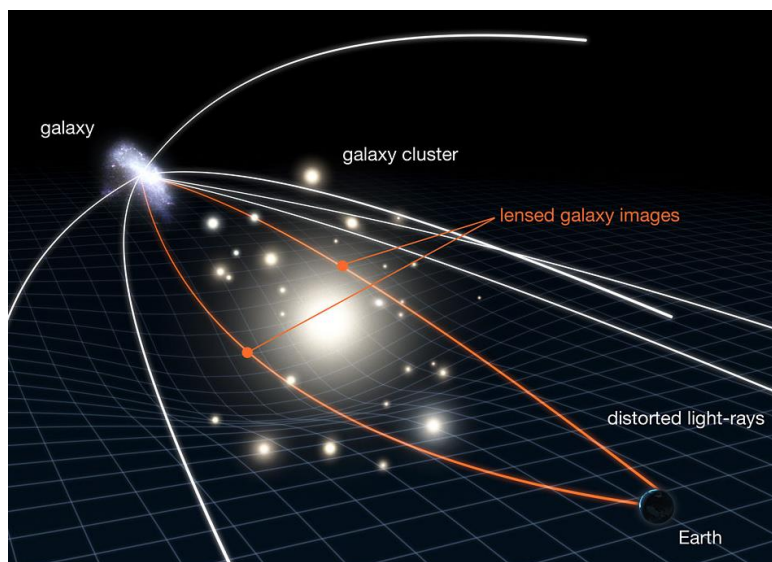


Fig. 2 Diagram of the bending of light

Some of the main ways humans have been able to detect gravitational lensing is by optical, X ray and radio wave observers. Optical methods include using the Hubble space telescope and the Keck observatory to view the optical light form distant galaxies, and to observe the brightness and shape of the light can give an indication of what black holes are doing to the optical light travelling to Earth. Similar goes for radio waves and X rays, as the waves get bent by black holes, human observe distortions of different degrees, such as the doubling of images in certain areas. From these phenomena, scientists have been able to find black holes and even give an indication of what type of black hole one is observing [9].

4. Facilities

LIGO is the facility mentioned above. The laser interferometer allows for the detection of slight fluctuations in gravitational waves, and thus alert scientists that there are huge events such as black holes merging going on in the universe [8]. There are two observatories, one is situated in Livingston, Louisiana, and the other is in Hanford, Washington. The two attained similar results in detecting the first gravitational waves to be found by humans [10]. A similar facility is Virgo, a laser interferometer situated in Cascina, near Pisa, Italy. Virgo works in conjunction with LIGO and provides a strong third pinpoint for determining the source of gravitational wave events [7].

KAGRA is also a laser interferometer located in the Kamioka Observatory, Gifu prefecture, Japan. Being a laser interferometer like the previous two, KAGRA has its unique innovations to up the game for detecting gravitational waves. Firstly, it is the first laser interferometer to operate at cryogenic temperatures, meaning that its core components are cooled to extremely low temperatures (around 20K or -253°C) to reduce thermal noises. The interferometer also uses "detuned" optical cavities, meaning that the arms of the machine have different lengths, suppressing KAGRA's sensitivity to certain types of noises. The machine also has physical renovations such as being built underground and being suspended, which reduces the effect of physical vibrations on the outcomes of the

observatory. Overall, KAGRA has great improvements from the two prior to it, and it serves as great assistance to the detection of gravitational waves by the other two facilities [11]. A sketch is given in Fig. 3

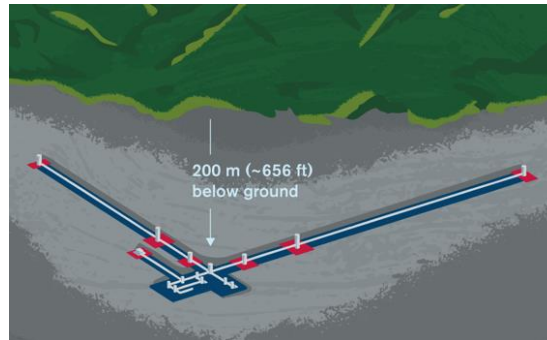


Fig. 3 A diagram of KAGRA

Aside from the observatories that detect gravitational waves, there are also facilities that directly takes in images from space and uses the images to analyze for the existence of black holes. Two typical of such are the JWST and the Hubble space telescope. The Hubble space telescope is useful in it observing the universe through visible, ultraviolet, and near infrared lights. The JWST goes further in that it can detect infrared radiation, which allows it to trace back highly redshifted galaxies, and perhaps unveil secrets further back in time still travelling to get to earth in its highly redshifted state [12]. The EHT (Event Horizon Telescope) is a set of telescopes, and they have been able to work together into functioning as an Earth sized telescope to capture clear images from the universe. The optical facilities are also very important in observing black holes, as they can capture any distortions in space time in distant galaxies reaching earth in visible light form.

5. Results and Applications

In the recent years, LIGO and Virgo have yielded spectacular results. A report in 2020 finds ten candidates [13] and a report in 2021 states that there were 45 candidates for binary black holes [14], and that number has climbed even higher in 2022 and 2023. From these numbers one can see the efficiency in detecting merger events performed by these observatories. In the past 5 years humans have received over 90 signals of such events. The Fig. 4 demonstrates some of the first gravitational waves ever observed by LIGO, through both facilities [15].

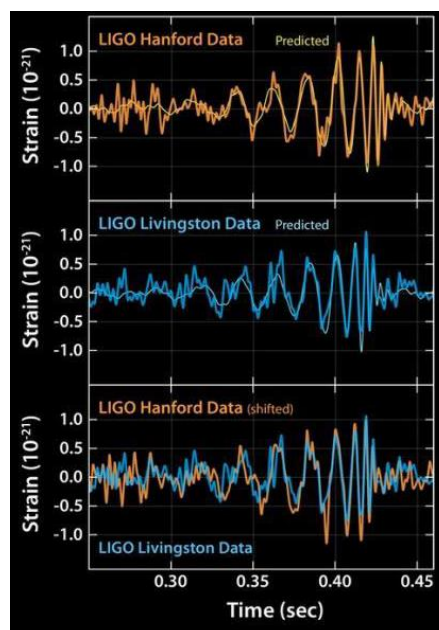


Fig. 4 Some of the first processed data for gravitational waves detected by LIGO. [15]

Some optical telescopes have also had achievements as well. The EHT was the first to capture an image of a black hole and have it displayed to the public as illustrated in Fig. 5. Optical telescopes are very useful in that they can visualize the black hole images for humans to see, which can be used as evidence accordingly to corresponding hypotheses [16].

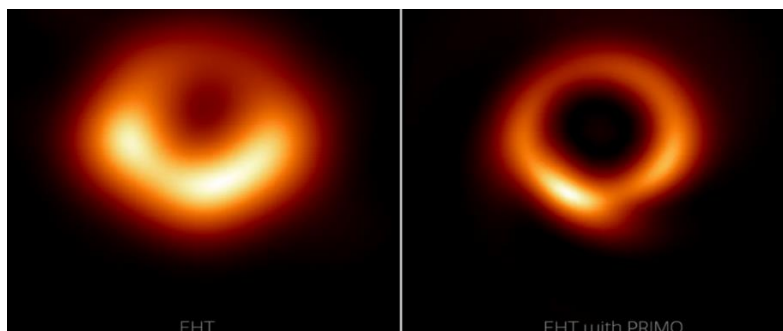


Fig. 5 The first image of a black hole captured by EHT

Being able to detect black holes has yielded scientists great opportunities to explore more about black holes. Through the data provided by the observatories, scientists are able to provide precise masses of some of the black holes involved, meaning giving humans a deeper understanding of black holes. By triangulating the multiple sources received, scientists are also able to pin down some of the location of sources in the sky, giving more exact locations and make further investigations simpler. The validity of the general relativity theories can also be tested through the data obtained. Through using multiple sets of data, researchers can test the consistency of the general relativity theories with the actual data, and the outcome is that the general relativity is accurate [17].

6. Limitations and Prospects

Despite the remarkable capabilities of these observatories, current technology still restricts them with some limitations. LIGO and Virgo have detected some sources of gravitational waves very accurately. However, as their sensitivity declines with distance, it is difficult to find weaker or farther-off gravitational wave sources. The ability to identify more events and deepen our understanding of black hole populations will need future advancements in sensitivity. Although gravitational wave detectors are capable of accurately determining the celestial coordinates of black hole mergers, they do not offer direct insights into the electromagnetic manifestations, like as optical or gamma-ray emissions, that are linked to these occurrences. The establishment of collaborations between gravitational wave and electromagnetic observatories is necessary in order to provide thorough observation and analysis of multi-messenger phenomena. Moreover, the EHT captured the first image of a black hole's event horizon in M87. However, the spatial resolution is still limited, and future observations with more telescopes and longer baselines are needed to achieve higher-resolution imaging of black holes. Currently, the images these telescopes can capture is still limited and cannot allow deep investigations on how the black hole looks like because it only provides a rough outline.

Gravitational wave detectors like LIGO, Virgo, and KAGRA are expected to undergo upgrades to increase their sensitivity and detection capabilities. This will lead to more frequent and precise detections of black hole mergers, enabling population studies and deeper insights into black hole formation and evolution. Plans are underway for third-generation gravitational wave detectors, such as the Einstein Telescope and the Cosmic Explorer. These detectors aim to achieve even higher sensitivities, expanding the volume of the universe that can be probed for gravitational wave sources, including black holes. Collaboration between gravitational wave detectors and electromagnetic observatories will continue to grow, allowing for joint observations of black hole mergers and their electromagnetic counterparts. This multi-messenger approach will offer a more comprehensive understanding of these events. The EHT association is working to include more telescopes and longer baselines in the array to improve the resolution of black hole images. This will lead to higher-resolution images of black hole event horizons and accretion disks.

7. Conclusion

To sum up, this study explores the state-of-the-art black hole observation scenarios. To be specific, this study discusses how the black holes are classified and how they are defined, as by Karl Schwarzschild and his equations on the event horizon. In addition, one sees the two mainstream principles of detection, being gravitational lensing and gravitational waves. The facilities for detecting gravitational waves and optical images are introduced, and their pros and cons are analyzed. Besides, this paper investigates how the facilities are limited in that they have a depth they can investigate and that is the limit, meaning that there are more to the universe human beings cannot reach out to currently. However, as technology advances, detection should become more and more clear, and newer generations of observatories will provide more in-depth investigations and more coverage on the range of waves one can intake and investigate. These results aim to analyze the state-of-the-art observation scenarios, and hopefully bring changes and improvements to our current technology.

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