The Recent progress and state-of-art detection scenarios for black holes and gravitational waves

Jingwen Cao[1, *, †], Shuai Hu[2, †]

[1] Dimensions International College, Guiyang, China

[2] University of Sheffield

* Corresponding Author Email: Vincycao0818@gmail.com

†These authors contributed equally.

Abstract. Gravitational waves, predicted by Einstein within the framework of general relativity, were discovered and confirmed by LIGO in 2015. Based on the detection of gravitational waves, black holes were also confirmed and recorded for the first time. In this article, we provide an overview of the mechanism of gravitational waves generated by black hole mergers, including basic formulae from general relativity, detection principles and approaches, and state-of-the-art equipment and detection results. In addition, we summarise the current limitations of what is known and make predictions for future directions. Gravitational waves are important because they contain information about their origin as well as about fundamental properties of gravity that cannot be detected by looking at the electromagnetic spectrum. These results shed light on guiding future research that focuses on exploring the nature of black holes.

Keywords: Black holes, LIGO, gravitational wave.

1. Introduction

In November 1915, the Swiss-American-Jewish presented description of gravitational waves and stated that they propagate at the speed of light and fill the universe [1]. Gravity is caused by the distortion of space-time by mass. Any accelerated motion of a massive object affects the space-time around it. When space-time expands and compresses, oscillations occur. Gravitational waves are quite weak and the interactions of matter with them are quite weak, so they are quite difficult to detect. Einstein wondered if they could ever be detected, or if their detection would contribute to scientific progress. Blackhole theories developed by Carl Schwarzschild and Roy Kerr, as well as a series of numerical black hole calculations, developed since the 1970s, also played an important role in the probe. It was discovered by LIGO, which was built for the direct detection of gravitational waves, opening the field of gravitational wave astronomy. In the 1970s, Weis' team at THE Massachusetts Institute of Technology, Hans Pilin's team at the Max Planck Institute in Garching and Lana Dreifer's team at the University of Glasgow built prototype gravitational wave interferometers and put them into operation [1]. To make more efficient use of limited resources, Caltech and MIT agreed in 1984 to jointly develop and build the LIGO. The two gravitational wave detectors jointly detected a short gravitational wave signal with a delay of seven milliseconds. In the Southern Hemisphere, near the Large and Small Magellanic Clouds 1.3 billion light years away, a pair of black holes merged and the resulting mass difference was converted into the energy of the gravitational waves detected by LIGO. Gravitational waves contain very different information than electromagnetic waves and will reveal new secrets about the world, including the origins of the universe.

It is not difficult to imagine that if gravitational waves can be detected in space, more frequency bands should be available for gravitational wave signals. Since different frequencies of gravitational waves correspond to different astrophysical processes, the high-frequency (> 10 Hz) gravitational waves observed by ground-based instruments are mainly gravitational radiation corresponding to dense binary stars [2]. Due to the limited distance to space and the influence of the noise of the Earth's gravitational gradient, the ground-based gravitational wave detection instrument cannot detect gravitational waves below 10 Hz, so its research target is relatively limited. Nowadays, the measurement of low- and medium-frequency gravitational waves by laser interferometry in space is the most advanced topic in astronomy and cosmic physics. So far, the use of laser interferometers has been an important way to measure gravitational waves both on the ground and in space. Two years after GW150914, the Virgo spacecraft joined the hunt near Pisa, Italy, recording 10 black hole mergers by August 2017. From 1 April to 26 March 2019, the third series of observations by LIGO and Virgo found 56 new gravitational wave events [3, 4]. As detectors improve, we will have more opportunities to see black holes and neutron star mergers, and possibly even detect neutron star rotations and other astronomical events we do not understand. Our knowledge will not only become more extensive but also more precise.

The importance of this discovery cannot be overstated. Previously, scholars used light waves to study the universe. The discovery of gravitational waves not only helps revolutionise our understanding of the Universe but also allows scholars to gain new insights into phenomena, e.g., black holes, extreme gravity. Gravitational waves have two unique properties that are important to researchers [5]. Gravitational waves offer a completely new way to observe and understand the universe around us. Their discovery is therefore very important.

The rest part of the paper is organized as follows. The Sec. II will describe some basic descriptions. The Sec. III will describe the detection principle and advanced equipment. The Sec. IV will describe the result of detection, and for the last Sec will describe the limitation and future prospects.

Table 1. A simple table of five times that caused gravitational waves

Event	Announced Date	Type	After Combined	Before Combined	Distance/Light years	Maximum frequency Hz
GW150914	11.02.2016	Binary black hole	62.2	35.4+29.8	13	250
GW151226	15.06.2016	Binary black hole	20.8	14.2+7.5	14	450
GW170104	01.06.2017	Binary black hole	48.7	31.2+19.4	29	199
GW170814	27.09.2017	Binary black hole	53.2	30.5+25.3	18	256
GW170817	16.10.2017	Binary neutron star	2.74	1.8+1.2	1.3	200

2. Basic Description

According to the general theory of relativity, when two black holes combine to form one black hole at distance D, the calculation formula of gravitational wave intensity Q is as follows:

$$Q = \frac{2GM}{5Dc^2} \tag{1}$$

where Q refers to the relative scale of the stretching or compression of space-time; G is the gravitational constant; M is the mass of the merged black hole; c is the speed of light in a vacuum. If the mass takes solar mass $M_{\odot}$, and the distance is in units of light years, the formula is

$$Q = 0.62 \times 10^{-13} \frac{M}{D} \tag{2}$$

For example, suppose the mass M of a black hole is 10 M, and the distance D is 1 billion optical years, then $Q = 0.62 \times 10^{-21}$. The relative scale of spacetime stretching or compression Q=10^{-21}. It means that the Earth, with a diameter of 1.3 kilometers would have been stretched or compressed by only 1.3×10^{-14} m, which is only 10 times larger than the diameter of a proton. Measuring such small deformations is the conundrum of gravitational wave research.

QW150914 event occurs when the two detectors detect a brief gravitational wave signal, time interval 7 ms, relative intensity 10^{-21}, frequency 35~250Hz, is identified as the direction of the Barley cloud, the distance is 1.3 billion light-years away, a pair of black holes are generated by the merger, the mass of black holes after the merger is 62 M⊙. According to the above formula $Q = 0.62 \times 10^{-13} M/D = 2.96 \times 10^{-21}$, LIGO arm length is 4km, high vacuum pipe and a series of extremely high precision measurement techniques are used. Therefore, the required expansion of 4 times the arm length is 4.7×10^{-17}, which is about 1/30 of the proton diameter. Table. 1 summarize five times that caused gravitational waves.

We do not discuss the waves from the merger or from the ring-down, as they do not have a significant impact on the distance determination. The in-spiral does not encode the cosmological redshift of a source. Instead, the redshift is interwoven with the evolution of the binary star. For example, masses (m_1, m_2) affect orbital evolution in terms of timescales (Gm_1/c^3; Gm_2/c^3). These time scales result in a redshift, so the measured masses have a redshift. In a reference frame centered on the barycenter of the solar system, the strongest harmonic of the two polarizations of the GW in the spiral has the form

$$h_+ = \frac{2M_z^{\frac{5}{3}}[\pi f(t)]^{\frac{2}{3}}}{D_L}\left[1 + \left(\hat{L} \cdot \hat{n}\right)^2\right]\cos[\Phi(t)]$$
$$h_\times = \frac{2M_z^{\frac{5}{3}}[\pi f(t)]^{\frac{2}{3}}\left(\hat{L} \cdot \hat{n}\right)}{D_L} \cdot\cdot sin[\Phi(t)] \tag{3}$$

The mass parameter Mz $M_z = (1+z)(m_1 m_2)^{\frac{3}{5}}/(m_1+m_2)^{\frac{1}{5}}$ is the redshifted "chirp mass" of the binary star, so called because it largely determines the speed at which the members of the binary star move towards each other and thus determines the "chirp" of the orbital frequency. It depends particularly strongly on M_z. Consequently, phase-coherent measurements of the waves can determine the chirp mass with great accuracy The wave frequency$f(t) = d\Phi/2\pi dt$. The unit vector $\hat{n}$ points from the centre of the barycentre frame to the system, defining its position on the sky; $\hat{L}$ points along the orbital angular momentum of the binary star, defining its orientation. Note that the luminosity distance D_L appears in combination with these two angular factors. Thus, the determination of D_L requires the determination of these angles [6].

3. Detection principles & state of art facilities

Gravitational wave provides a unique method of measuring the properties of black holes. Common-sense gravitational wave detectors can be divided into three categories: resonant mass detectors, laser interferometers and pulsar timing array detectors [7].

Resonant mass detectors are made of piezoelectric crystals which reshapes when an electric voltage is generated. Piezoelectric crystals have specific resonant frequency, at this frequency the crystal provides an oscillating voltage when it repeats expanding and contracting. Gravitational waves can also change the shape of these crystals because they do work and provide energy onto the cylindrical detectors. The sensitivity of resonant mass detectors can be fortified by increasing mass of piezoelectric crystals without changing their resonant frequency to make those large slices of metals more hypersensitive in all directions and polarizations. Precision and accuracy of gravitational wave detection can be improved by diminishing noise sources from the surroundings at experimental detecting conditions, e.g., manipulating seismic noise isolation vehicles and thermal-noise proof coolants during the process of detection.

Laser Interferometers work by converging multiple sources of light to form an interference pattern. The principle of interference is based on classical experiments about the wave-particle duality of light, such as diffraction gratings and the double-slit experiment. Interference can be divided into constructive and destructive interferences. When measuring gravitational waves, the source is firstly divided into two beams of light travelling at two different paths and then combined to create interference and fringes can be observed.

Pulsar timing array detectors (PTA) are constructed using an array of pulsars to determine and analyse for correlated signatures between arrival times of pulses emitted by the millisecond pulsars to detect gravitational waves. The reason why gravitational waves can be detected is that they cause the arrival time of pulses change by a few milliseconds. The universe contains massive astrophysical sources and objects such as super-massive black holes, PTAs are applied as high-precision detectors capturing existences of gravitational waves.

LIGO contains nationwide research facilities including two interferometer detectors and two university research centres. The two detectors are also called LIGO’s twin detectors. Both detectors are hypersensitive to any vibration from the Earth, including tiny seismic waves and disordered acoustic noise, or any other meteorological fluctuations and disturbances. Therefore, the twin detectors are constructed far away from each other in order to distinguish whether the signal is normal noises from the Earth or gravitational waves or other cosmic sources [9].

LIGO also contains sister facilities for data sharing and analysis: three interferometers Virgo, GEO600 and KAGRA. Virgo participated in the current observing runs of LIGO and help localize the source of the first gravitational waves detected from merging neutron stars. GEO600 is prepared to put in use in future detections as it is applied as a test site to develop advanced interferometer and optical suspension systems. KAGRA is a new detector constructed underground, which means it would receive less seismic vibration than surface interferometers. It is also built using cryogenic systems, cooling the optics itself to avoid thermal vibrations and decrease molecular motions to a lowest degree.

The instruments of LIGO are designed to detect a specific range of frequencies of gravitational waves, converting space-time distortion signals into sounds. One of the practical contributions about LIGO detections is to capture the sound of two colliding black holes and binary neutron stars. Unlike optical or radio telescopes, LIGO cannot observe electromagnetic radiation and unable to specifically locate a certain position in space as it does not collect light sources from stars. Fig. 1 presents the gravitational spectrum.

4. Detection results

The first observation of gravitational waves of detected by LIGO interferometers. At the beginning detectors only receive indirect signals produced by different time intervals of pulsars caused by the disturbance of gravitational waves. The variation of frequency of pulsars have verified the existence of gravitational waves, and they are emitted from huge-mass astrophysical objects or high-energy cosmic events such as collision of neutron stars or supermassive black holes. LIGO then observed gravitational waves directly when the arms of the twin interferometers act receiving hypersensitive signals simultaneously and synchronous patterns are displayed onto astrophysical interferometry. The new detections of gravitational waves are unprecedentedly accepted by black holes and other astronomical objects several billions light years far from Earth. For instancing, two black holes merging and smashing together. Humans have detected signals of gravitational waves for about 90 times from the last five years [8].

According to the new detections, scholars have simulated the model of the collisions between neutron stars and variation of shape of black holes enclosing each other. Analysis through detection results also enable scholars to judge the degree and speed of gyration of black holes cosmologically, but according to the physical properties of neutron stars, infinitesimally small and dense objects due to collapsing, humans cannot directly receive weak signals of such stars and some of the detection results remain mysterious. In the future scholars would observe on the gravitational waves of supernovae, when they emit catastrophic amounts of energy during their explosion. From the 35 detections that astronomer newly observed, they simulated the black holes at all shapes and sizes according to frequency and chirp masses of gravitational waves. Fig. 2 illustrates the first gravitational wave detection results.

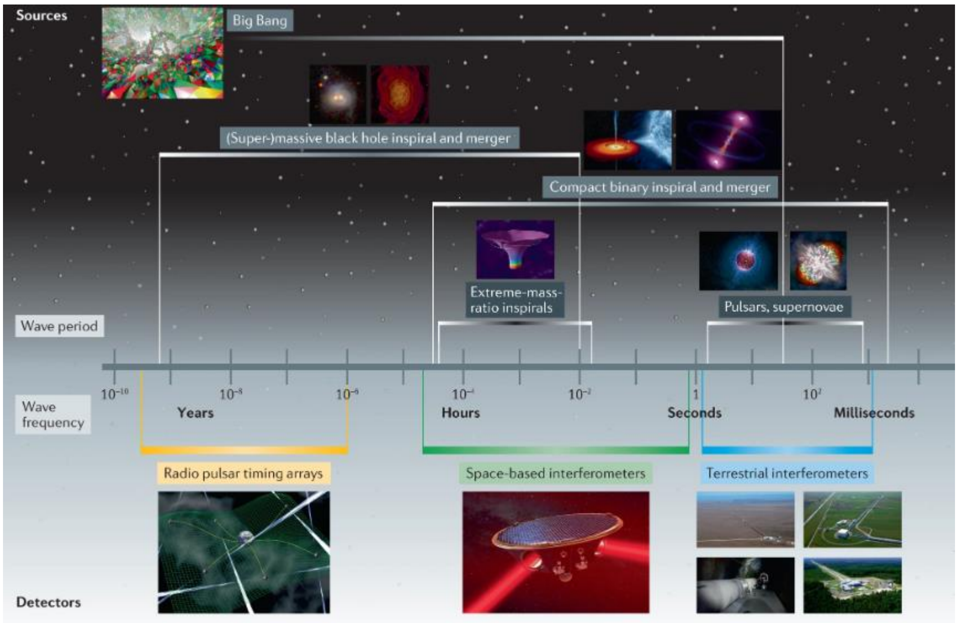

Figure 1 The gravitational-wave spectrum probed by strain-sensitive gravitational-wave detectors, ranging from 10−9 Hz to more than 1,000 Hz [7].

AThe methodology obtaining mathematical detection results is to use deep filtering, inputting a system of two simulating network (deep convolution neutral network, CNN), taking the time-series input of signals into classification (distinguishment of noise signals by generalizing local noises interference) and regression (dealing with data streams arbitrarily comes from gravitational wave detectors). LIGO has distributed the categories of gravitational waves by the detection results of 10 pairs of black holes and two pairs of neutron stars. Gravitational waves can be categorized into continuous waves that are usually the product of a spherical neutron star generating gravitational waves when it rotates, and that is the reason why humans cannot directly detect those weak signals. Compact binary in spiral gravitational waves comes from binary astronomical systems, such as binary neutron stars, black holes, and neutron star-black hole binary (NSBH) system——scholars detected a neutron star that breaks the record of small mass once detecting the gravitational waves in a NSBH system. The binary pair would generate gravitational waves that have specific patterns which is highly distinguishable, the gravitational force of each other in a binary system promotes them to accelerate and enclose each other, losing energy and eventually bind together. The first observation of gravitational waves is due to two merging black holes.

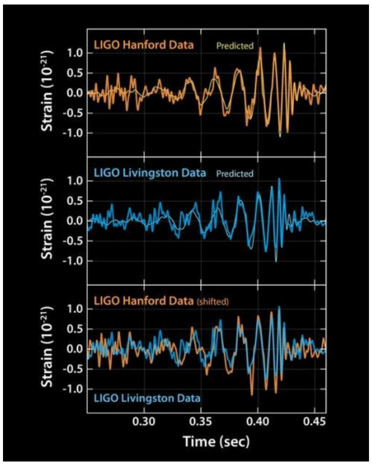

Figure 2 The processed waveform of the first detection of gravitational waves [8].

5. Limitations & Future prospects

When gravitational waves reach us from the distant events that produced them, they distort space-time very little. This distortion is many times smaller than the width of a proton, a particle in the nucleus of an atom. Measuring such a small change in length is almost impossible with most instruments. Since the waveform of the actual gravitational wave signal is affected by the parameters of the wave source and the parameters are unknown, the gravitational wave template library usually has to cover the entire possible parameter space of the wave source. A template library usually contains millions of gravitational wave templates. An inaccurate gravitational wave template does not correspond to the actual waveform of the gravitational wave signal and leads to a loss of the filtered signal-to-noise ratio and thus to a loss of the gravitational wave signal. Therefore, the modelling of the gravitational wave source is very important. From a data analysis point of view, gravitational wave detection is also a typical problem with weak signal and strong noise. Accordingly, it has naturally been thought to use a matched filtering method to improve the detection capability of gravitational waves. To achieve matched filtering, we need to know the shape of the signal in advance, i.e., the waveform. Since gravitational wave detectors are passive receivers of gravitational wave signals, their waveforms cannot be known in advance. The solution to this problem is to construct in theory gravitational wave template banks for different gravitational wave sources. In fact, from the value theory of relativity to the establishment of gravitational waveform template, also traverse lies between the problem of parameter space, only with the precession of the orbit of the circular orbit to describe the black hole template of 15 parameters, if it is with orbital eccentricity or contain a neutron star template requires more parameters to describe, people call the problem of numerical relativity dimension disaster in question. Due to the high computational cost of numerical relativistic waveforms (one waveform requires about 30,000 core hours of computational resources, and a gravitational wave search requires about 10 million waveforms, a total of about 10 to 11 core hours of computational resources), it is difficult to apply it directly to actual data analysis. The semi-analytical model with higher speed and reasonable accuracy has become the first choice for gravitational wave data analysis. In building these models, the relativistic waveforms are compared numerically with the standard waveforms. Currently, work is still underway to gain a deeper understanding of the gravitational waveform of the binary stellar merger system and to attempt to build a complete gravitational wave model and template library of the binary stellar merger system to provide solid theoretical support for future gravitational wave detection in space and the next generation of gravitational wave detection on the ground [9]. Besides binary star systems, other sources of gravitational waves can also be detected. Perhaps general relativity is reaching its limits and we need other sources of gravitational waves and waveforms described by gravitational theory. The history of numerical relativity and waveform modelling will accompany gravitational wave astronomy for a long time to come.

The LIGO and Virgo detectors are expected to begin their fourth scientific operation after June 2022, when the Japanese KAGRA detector officially joins the global observing network and achieves significant sensitivity. In addition, the LIGO-India detector in India will become operational within a few years. These detectors will reach the planned sensitivity around 2025. It is roughly estimated that the sample of gravitational wave events around 2025 will include 500 mergers of binary black holes, 50 mergers of binary neutron stars and 50 mergers of neutron stars and black holes. Between 2025 and 2030, the LIGO detectors will be further upgraded to increase sensitivity by a factor of two to four. In addition to the known compact binary star mergers, ground-based gravitational wave detectors are likely to make new breakthroughs in the next 10 years, detecting new types of gravitational waves, including random gravitational wave backgrounds, continuous gravitational waves, gravitational wave bursts and even previously unknown gravitational wave sources. After 2035, ground-based gravitational wave detection will move into the era of "third-generation" detectors. The planned detectors include the Cosmic Explorer in the US and the Einstein Telescope in Europe, which will achieve extremely high sensitivity and be able to detect almost all black hole mergers and most neutron star mergers in the universe.

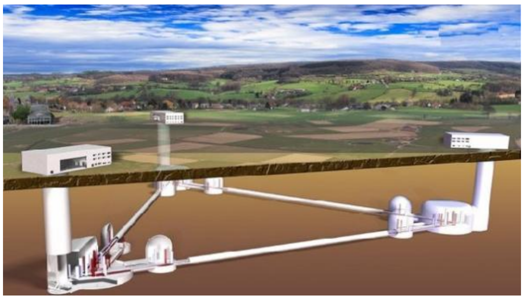

Figure 3 The Einstein Telescope, a10-kilometer-long, triangular probe located underground [10].

Conceptual representation of the planned third-generation ground-based gravitational wave detector. At the other end of the gravitational spectrum, the International Pulsar Timing Array project has collected more than a decade of high-precision data that is expected to open the observational window for nanohertz gravitational waves and detect the merger of supermassive black holes at the center of galaxies in the coming years. At the same time, programs to detect gravitational waves in space at home and abroad are also being progressively advanced, and millihertz gravitational wave astronomy is expected to emerge around 2035. In addition, gravitational waves have been detected for many years based on measurements of cosmic microwave background radiation. Therefore, humanity may soon enter a new era of multi-band gravitational waves and multi-messenger astronomy. A sketch of the Einstein Telescope is presented in Fig. 3.

6. Conclusion

In summary, this article discusses gravitational waves from the perspective of the basic formulae, the techniques of investigation and the discovery of gravitational waves through the merger of black holes. We give an outlook on the future and the present limits. From 1915 to the present day, we never stop exploring the mystery of gravitational waves, hoping to obtain more unknown information about the universe through gravitational waves. Although gravitational waves are relatively small, they are relatively difficult to study, but through the efforts of scholars, future developments in the gravitational field are improving and data is becoming more accurate. Overall, these results provide a guide for better implementation or more efficient surveying in the future.

Authors' Contributions

These authors contributed equally.

References

[1] E. M Cervantes-Cota, J. L. Galindo-Uribarri, S. Smoot. A brief history of gravitational waves. Universe, vol. 2(3), 2016, 22.

[2] A. Cho, Gravitational waves reveal unprecedented collision of heavy and light black holes online information. Science news. DOI: https://www.science.org/content/article/gravitational-waves-reveal-unprecedented-collision-heavy-and-light-black-holes.

[3] LIGO Scientific Collaboration, and Virgo Collaboration. "Tests of general relativity with GW150914." Physical Review Letters, vol. 116.22, 2016, 221101. DOI: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.221101.

[4] B. P. Abbott, et al. Astrophysical implications of the binary black hole merger GW150914. The Astrophysical Journal Letters, 818(2), 2016, L22. DOI: https://iopscience.iop.org/article/10.3847/2041-8205/818/2/L22/meta.

[5] Online information available at: https://futurumcareers.com/why-gravitational-waves-are-of-supermassive-importance

[6] D. E. Holz, S. A. Hughes. Using gravitational-wave standard sirens. The Astrophysical Journal, vol. 629(1), 2005, 15. DOI: https://iopscience.iop.org/article/10.1086/431341/meta.

[7] M. Bailes, et al. Gravitational-wave physics and astronomy in the 2020s and 2030s. Nature Reviews Physics vol. 3.5, 2021, pp. 344-366. DOI: https://www.nature.com/articles/s42254-021-00303-8.

[8] D. Castelvecchi. Astronomers close in on new way to detect gravitational waves. Nature vol. 602.7896, 2022, pp. 194-195. DOI: https://www.nature.com/articles/d41586-022-00170-y.

[9] Online information available at: https://www.nationalgeographic.com/science/article/what-are-gravitational-waves-ligo-astronomy-science

[10] Online information available at: http://www.et-gw.eu/index.php/relevant-et-documents