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Gravitational waves: an update

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Gravitational waves: an update

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1 Introduction

The last six years saw the opening of a new window for exploring the Universe, and after the first detection of a gravitational wave (GW) the field has quickly developed with the detection of many new events and important discoveries. In the meantime the plans to build new and more powerful GW observatories are making significant progress, both for ground based detectors as well for the one in space especially with the LISA mission. Here we give a brief, but not exhaustive, update following some articles which already appeared in the *SPG Mitteilungen* devoted to this topic [1, 2, 3, 4]. (See also the articles on black holes appeared in the *SPG Mitteilungen* [5, 6]).

GW have been predicted by Albert Einstein himself in the framework of his theory of general relativity. He first mentioned them in a paper appeared in 1916 and then in 1918 he wrote a paper with the title: “On gravitational waves” [7, 8]. Einstein, however, concluded that it would be impossible to detect them. Einstein proved to be wrong: GW were detected in 2015 by the two Advanced LIGO (Laser Interferometer Gravitational Wave Observatory) instruments. LIGO consists of two observatories in the US which are 3000 km apart: one near Hanford (in Washington state) and the other in Livingston (state of Louisiana). On 14 September 2015 the two LIGO detectors simultaneously observed a transient GW signal due to the merger of two black holes with masses of about $36 M_{\odot}$ and $29 M_{\odot}$, respectively, some 400 Mega-parsecs (Mpc) away, which formed a new black hole of $62 M_{\odot}$ with the energy equivalent of 3 solar masses emitted as gravitational waves. The announcement of the first detection followed then on 11 February 2016 [9].

After the first detection few other events have been detected during the first - denoted as O1 - and the second O2 runs of the LIGO observatories [10] and [11]. From 1 August 2017 also the VIRGO detector located nearby Pisa started its activity joining the LIGO detectors in the data taking. On 27 September 2017 VIRGO and LIGO announced the first joint observation on 14 August 2017 of a gravitational wave due to the coalescence of two black holes of 30 and 25 solar masses, respectively, located at a distance of about 540 Mpc, and leading to the formation of a black hole of about 53 solar masses [12]. Thanks to the observation with VIRGO as well the position in the sky could be determined much better ¹ and allowed to probe, for the first time, the polarization of the GW, which turned to be in agreement with general relativity ².

¹ From about 1160 deg^2 using only the two LIGO detectors to 60 deg^2 using all three detectors for the area corresponding to the 90 % credible region.

² General relativity predicts that a gravitational wave has two independent states of polarization, called “+” and “x” modes, which are 45 degrees apart, as opposed to 90 degrees for light.

2 Neutron stars coalescence

On 17 August 2017 the three detectors observed for the first time the signal of two coalescing neutron stars, located at the relatively close distance of about 40 Mpc from Earth [13]. From the signal of the GW170817 event the component masses of the binary have been determined to be in the range $0.86 - 2.26 M_{\odot}$, in agreement with masses of neutron stars ³, and a total mass of the coalesced system of about $2.74 M_{\odot}$ ⁴. Based on the GW observations the source could be localized within a sky region of about 28 deg^2 . Only 1.7 seconds after the merger a γ -ray burst (denominated GRB 170817A) was observed by the NASA Fermi Satellite and by the the Spectrometer on board of the ESA INTEGRAL satellite. About 11 hours after the merger the 1-meter Swope Telescope detected the optical transient associated with the GW event in the galaxy NGC 4993 (at $\sim 40 \text{ Mpc}$). This observation was independently confirmed by multiple observational teams within an hour. Early ultraviolet observations revealed a blue transient that faded within 48 hours. Optical and infrared observations showed a red-ward evolution over ~ 10 days. On the other hand X-ray and radio emission were discovered at the transient’s position only ~ 9 and ~ 16 days, respectively, after the merger. Both the X-ray and radio emission likely arise from a physical process that is distinct from the one that generates the UV/optical/near-infrared emission. No ultra-high-energy gamma-rays and no neutrino candidates consistent with the source location were found in the follow-up searches. These observations supported the hypothesis that GW170817 was produced by the merger of two neutron stars in NGC 4993 followed by a short γ -ray burst (GRB 170817A) and a kilonova powered by the radioactive decay of r-process nuclei synthesized ⁵ in the ejecta [14]. Heavy elements such as gold and platinum are produced in the kilonova event. The observation of GW170817 in both gravitational and electromagnetic waves is the first “multi-messenger” astronomical observation. It allowed also to determine in another way the Hubble constant to be about 70 km/s/Mpc , clearly with still large uncertainties but consistent with existing measurement of 67.4 km/s/Mpc [15]. Future observations might improve the accuracy of the Hubble constant determination with this new method. This unprecedented joint gravitational and electromagnetic observation provided insight into various fields of astrophysics, dense matter, gravitation, and cosmology, opening the era of multi-messenger astronomy.

It came then not as a surprise that the 2017 Nobel prize for physics was awarded for the GW discovery to Rainer Weiss, Barry Barish and Kip Thorne [2].

³ Restricting the component spins to the range inferred in binary neutron stars, then the component masses are in the range $1.17 - 1.60 M_{\odot}$.

⁴ The energy radiated away in form of GW is at least $0.025 M_{\odot} c^2$.

⁵ The r-process is one of the processes of nucleosynthesis. It is a neutron capture process which, in contrast to the slow s-process, takes place at high neutron densities and temperatures.

3 Third observational run

The third run, called O3, of observations of the three detectors started in April 2019 and lasted until its early suspension, due to the COVID-19 pandemic, on 27 March 2020, about a month prior to the planned date. The run underwent a month long break during October 2019 for detector work and it is denominated O3a before and O3b after the break, respectively. This third run saw the beginning on 25 February 2020 of the scientific operation of KAGRA, which is a GW observatory located in Kamioka, Japan. However, KAGRA has not yet reached the sensitivity of LIGO or VIRGO. It is the first underground GW observatory with cryogenic mirrors. For GW observations, having multiple detectors operating in different locations on Earth is important since it allows to get much more accurate sky localizations of GW sources, of a few square degrees, enabling the observations in electromagnetic waves in case of emission in the latter one as well. After the suspension of the operation of LIGO end of March 2020, KAGRA and GEO600 continued the observations, making a joint run - O3GK (Observing Run 3 GEO-KAGRA) from 7 to 21 April 2020. GEO600 is a joint British-German GW observatory located near Hannover. Since it has an armlength of only 600 meters it has a much lower sensitivity than LIGO with armlength of 4 km or VIRGO and KAGRA with armlength of 3 km, however GEO600 plays an important role in the development of the technology.

The overall sensitivity of the detectors was increased in the O3 run as compared to the two previous ones. This led to a higher detection rate of more than a GW event per week in average. End of October 2020, the LIGO Scientific Collaboration and the VIRGO Collaboration announced the results for the first half of their third observing run O3a, lasting from 1 April 2019 to 1 October 2019 of their GW searches for events due to coalescing of compact binaries. In total 39 events were reported, which added to the 11 events found

during the O1 and O2 runs [16], brings the total number of observed LIGO/VIRGO GW detections to 50 [17] (see figure 1). Several further events can be expected to be found in the data of the O3b run.

Among the events detected during the O3a run, four are particularly interesting and we shall briefly describe them.

- The GW190425 event, observed as its name suggests on 25 April 2019, lasted around 128 seconds and the form of the gravitational wave indicates that it was produced by a merger of most likely two neutron stars [18]. However, it cannot be ruled out that one or even both of the binary components being black holes. Indeed, the combined mass of the two merging objects was rather high for a neutron star merger, namely about $3.4 M_{\odot}$.
- GW190412 observed on 12 April 2019 was the first event due to the merger of two black holes of notably unequal mass: one of about $30 M_{\odot}$ and the other of about $8 M_{\odot}$ [19]. For asymmetric systems the emitted GW signal contains more contributions from higher multipoles than just the quadrupole. Indeed, strong evidence was found that the gravitational radiation was produced beyond the leading quadrupolar order in the observed signal of GW190412.
- On 14 August 2019 another asymmetric event, GW190814, was observed with the heavier component being a black hole of some $23 M_{\odot}$ and the other lighter companion with a mass in between 2.5 to $3 M_{\odot}$. This latter value makes it either the lightest black hole or the heaviest neutron star ever discovered in a system of two compact objects [20]. Indeed, the value of the maximum mass of a neutron star is still an unresolved issue. Most likely it is between 2.2 and at most $3 M_{\odot}$.
- A spectacular event was detected on 21 May 2019, GW190521, which was produced by the merger of two massive black holes of $85 M_{\odot}$ and $66 M_{\odot}$, respectively, resulting in a $142 M_{\odot}$ black hole after the merging. This makes it the

first clear detection of an intermediate-mass black hole (between stellar-mass and super-massive black holes). A challenge of this discovery is the formation of black holes with masses above about $65 M_{\odot}$ as current stellar evolution models predict that stars in the range $64 - 135 M_{\odot}$ are unstable, due to pair instability, and thus would not lead to compact remnants (black holes) in that mass range. This observation opens thus important issues in the problem of stellar formation and evolution. It has been argued that a candidate electromagnetic counterpart has been observed for this event, which could have been due to a binary black hole merger in the accretion disk of an active galactic nucleus [21].

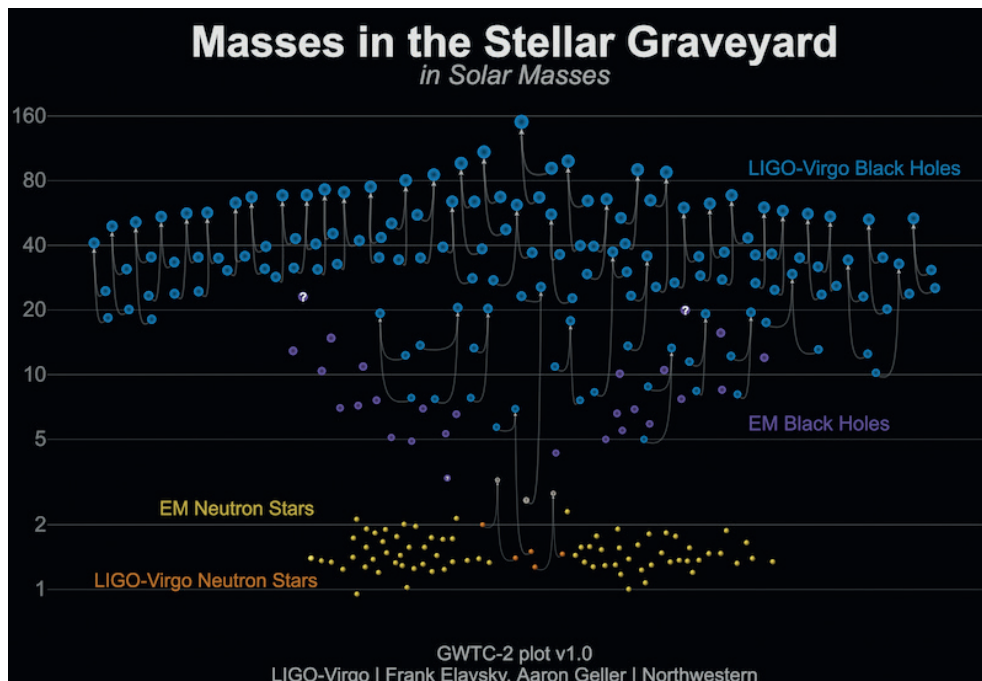


Figure 1: Masses of detected LIGO/VIRGO compact binaries. This plot shows the masses of all compact binaries detected by LIGO/VIRGO, with black holes in blue and neutron stars in orange in the O1, O2 and O3a runs. Also shown are stellar mass black holes (purple) and neutron stars (yellow) discovered with electromagnetic observations. [Image credit: LIGO/VIRGO/Northwestern Univ./Frank Elavsky]

Further events will be analyzed in the data of the O3b run, and shall be published soon. The next run O4 is scheduled to start around mid of 2022 after a further upgrade of

the detectors and last for about a year with an increased sensitivity for all the involved detectors: LIGO, VIRGO and KAGRA. The final maximal sensitivity should be reached in the O5 run, which shall start after 2025.

4 Future ground based detectors

In the meantime there are preliminary plans for building new and more sensitive ground based GW detectors, besides to build a third LIGO detector in India. Indeed, the current-generation GW detectors are sensitive in the frequency range from roughly 20 - 500 Hz and they primarily detect signals emitted during the coalescence of binary neutron stars and binary black holes. Observation of GW signals from binary neutron star coalescences is a powerful way to constrain their equation of state and thus the value of the maximum mass. To achieve this it is important to get information from frequencies above 500 Hz in the final stages of the coalescence.

Cosmic Explorer (CE) is a proposed third-generation GW detector in US, which, with design upgrades and along with the longer arm length of about 40 km, will make CE over 10 times more sensitive than the current detectors (see [22] for more details). The Einstein Telescope (ET) is a planned European third generation GW observatory, designed to observe the whole Universe (thus to very high red-shifts) with gravitational waves [23]. Third-generation (3G) GW detectors, such as ET and CE, will improve the broadband sensitivity of the detectors by a factor of 10 and extend the sensitivity range to lower frequencies. The ET design consists of a single underground infrastructure that hosts three detectors nested in an equilateral triangle with the sides being 10 km long (see figure 2). Each of the three detectors is composed of two interferometers, one being optimized for low-frequency signals, and the other for the high-frequency signals. These detectors together offer broadband sensitivity in the frequency range from a few Hz to about 10 kHz (see figure 3), which will also allow to better follow the coalescence of neutron stars as mentioned above.

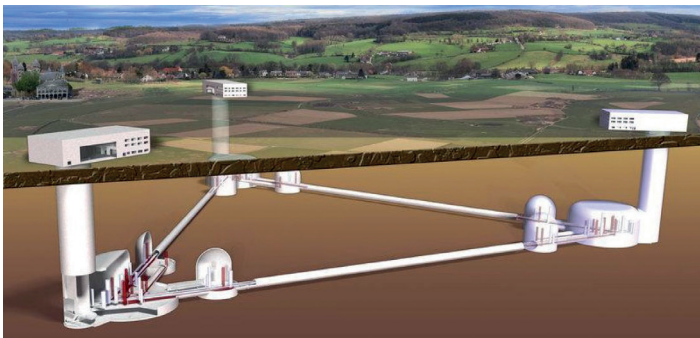


Figure 2: Artists conception of the Einstein Telescope. The proposed underground detector will consist of six V-shaped, interferometers, laid out in an equilateral triangle with sides that are 10 km in length. Source: MPI für Gravitationsphysik / NIKHEF

Last September 2020 the ET consortium has submitted an application such as to add ET to the European roadmap for research infrastructures. If all goes well, it is expected that the first observations will start in the 2030s. Two sites are under consideration to host ET: Sardinia in Italy and the Euregio Meuse-Rhine on the Belgian-Dutch-German border. Both sites are now under more detailed studies, through EU and national funding, with the aim to a better understanding

of their characteristics, such as seismic noise. At present the ET consortium brings together about 40 research institutions and universities in several European countries, including also Switzerland through the University of Geneva.

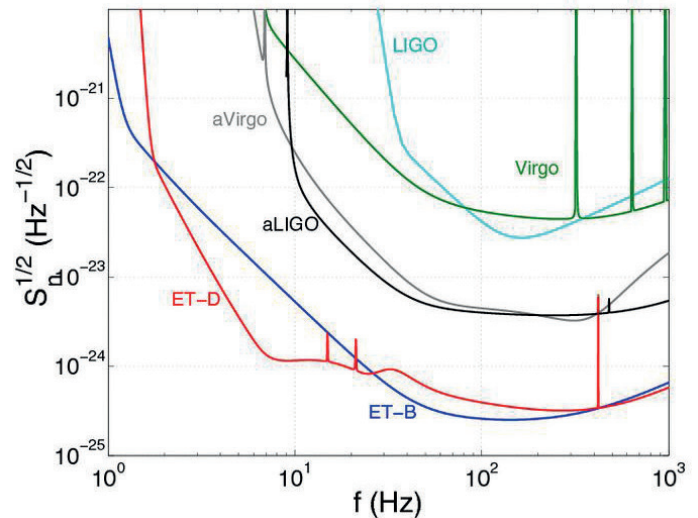


Figure 3: The strain sensitivity of LIGO, VIRGO, Advanced LIGO, Advanced VIRGO and ET (ET-B and ET-D). The sensitivity of Cosmic Explorer is similar to ET (from [23]).

According to the current time line estimates, CE will be observing at the same time as ET and with possibly a facility in Australia, called NEMO (Neutron Star Extreme Matter Observatory) a L shaped interferometer with 4 km armlength [24]. They will form a global network of third-generation GW detectors. This will have far-reaching consequences on our understanding of the universe. The significantly higher sensitivity of 3G GW detectors will allow to detect compact binaries in our local universe with an unprecedented signal-to-noise ratio (from 500 to 5000 or more depending on the source) and localize these events in the sky to within a few tens of square arcminutes. With hundreds of gravitational and electromagnetic observations of compact binaries, kilonovae dynamics could be studied much better. CE and ET observations will help resolving long standing problems on the structure of neutron stars, such as the equation of state. A catalog of almost every stellar-mass black holes merger in the universe would allow to further test general relativity and to better understand the origin of super-massive black holes, which are present in the center of the galaxies. Such observations would undoubtedly bring considerable progress in the fields of astrophysics, cosmology and fundamental physics.

Pulsar timing array (PTA) experiments use the stability of the pulse periods of neutron stars which happen to point their jets in our direction. This causes a lighthouse effect, that can be used as a very precise clock. If a gravitational wave from a distant supermassive black hole binary passes through our galaxy, the pulse gets red or blue-shifted due to the change in the distance between Earth and the pulsar and thus a change in the travel time of the photons. PTA probes much lower frequencies, in the range 10^{-9} to 10^{-6} Hz, than LISA, and thus the expected source is a supermassive black holes in the early stage of inspirals or a merger of an even higher mass supermassive black holes as compared to the ones to which LISA will be sensitive. PTA experiments, which use millisecond pulsars, several tens of which have been detected in our galaxy, have been in operation

over the last decade. So far no detection of gravitational waves has been made but it might well be that in few years interesting results will come [25], due also to new radio telescopes under construction like SKA (the Square Kilometer Array project), with which it will be possible to detect and follow many new pulsars.

5 Future space based detectors

5.1 LISA

LISA (Laser Interferometric Space Antenna) is a planned space based detector which is an ESA mission in collaboration with NASA. On 3 December 2015 the satellite LISA Pathfinder (LPF) of the European Space Agency (ESA) has been launched successfully and reached on 22 January 2016 its final science orbit around the first Sun-Earth Lagrange point L1, 1.5 million km from Earth.

LPF's goal was to place two test masses in a nearly perfect gravitational free-fall, and control and measure their relative motion with unprecedented accuracy at the level required for LISA. This requirement was achieved through innovative technologies comprising inertial sensors, an optical metrology system, a drag-free control system and micro-Newton thruster system. The LPF mission ended very successfully on 18 July 2017, and its performances were far better than expected [26, 27, 1, 2]. In November 2013 ESA selected *The Gravitational Universe* [28] as the science theme to be explored by ESA's Large class mission L3 and on 20 June 2017 ESA confirmed LISA [29] as the realization of the L3 mission. NASA joined the ESA mission, which at present is scheduled to be launched in 2034.

The scope of LISA is to detect and study low-frequency GW from about 0.1 mHz to 1 Hz, and thus to complement ground-based GW observatories. LISA will allow to detect supermassive black holes (typically of $10^6 - 10^7 M_{\odot}$) merging at cosmological distances. Mergers of a supermassive black hole with another compact object (such as another black hole of a few solar masses or a neutron star) produce a very clean GW signal which LISA will be able to measure with high precision. Alternative gravity theories influence the dynamics of such mergers and hence LISA is expected either to directly see the imprints of certain alternative theories or to put severe constraints on them. Another class of objects, which will be observed by LISA, are ultra-compact binaries, in particular of white dwarfs in our Galaxy. They are important sources of gravitational waves in the mHz frequency range. Moreover, it will be possible to detect or put strong constraints on the primordial gravitational wave background, which is just, as the cosmic microwave background, a leftover from the Big Bang. LISA will consist of a constellation of three spacecrafts on solar orbit, each some 2.5 million km apart, such as to form a triangle configuration. This can be achieved since each spacecraft's orbit will lie in a different plane tilted with respect to the ecliptical plane. LISA will detect gravitational waves using laser interferometry (with six links), measuring changes in proper distance between the freely-falling test masses on each spacecraft, similar to the test masses which have been successfully used on LPF. Switzerland, through groups at University of Zürich, ETH and in industry are directly involved in LISA and contributed in an important way to LISA Pathfinder [1, 2].

5.2 Chinese and Japanese programs

China is also developing a space program for the observation of GW. Taiji is a proposed Chinese satellite-based gravitational-wave observatory, which is similar to LISA with three spacecraft orbiting the sun, in a way to form a triangular shape, linked by laser interferometers and about 3 million km apart [30]. The performance of Taiji would thus be similar to LISA. The launch should also be in the mid of the 2030. In the framework of the technology developments for the Taiji mission, the Taiji-1 satellite was launched on 31 August 2019 in order to conduct in-orbit experiments on the needed key technologies.

TianQin is a competing Chinese proposal for a space GW detector in the millihertz frequencies (i.e., 0.1 - 100 mHz), which consists of a constellation of three drag-free spacecrafts orbiting the Earth, forming an equilateral triangle with distance of about 10^5 km between each other [31].

Japan has also developed some very preliminary ideas for a GW satellite in space named DECIGO (Deci-hertz Interferometer Gravitational Wave Observatory), which shall observe in the frequency band of 0.1 Hz to 10 Hz [32]. It aims in particular at the detection of primordial gravitational waves, which could have been produced during the inflationary period right after the Big Bang. DECIGO consists of four clusters of observatories placed in the heliocentric orbit. Each cluster consists of three spacecraft at a distance of 1000 km from each other. Three clusters of DECIGO will be placed far from each other, and the fourth cluster will be placed in the same position as one of the three clusters to obtain the correlation signals for the detection of the primordial GWs. There are also plans to launch B-DECIGO, a scientific pathfinder of DECIGO to demonstrate the required technologies. It is however possible that Japan might, instead of developing these ambitious plans, join the LISA project.

6 Concluding remarks

The discovery of gravitational waves has definitively opened a new window to explore the Universe and has started the multi-messenger era in astronomy. Despite the already many important discoveries done so far with GW, we are just at the beginning of using this new window and the prospects are bright to make important progress and new discoveries. There are many ambitious plans to build and operate new and more powerful observatories both on ground and in space. Perhaps not all these plans, as mentioned above, will be realized, at least within the next decades, but should already some of them be built, this would lead to important advances in astrophysics, cosmology and fundamental physics with most likely many unpredictable discoveries. Undoubtedly, together with the many new planned or in construction instruments: optical telescopes (eg ELT), radiotelescopes (SKA) etc. both on ground and in space astronomy is facing a golden age in the next decades.

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