Joint detection of gravitational waves from binary black hole and binary neutron star mergers by LIGO and Virgo

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Abstract

Advanced Virgo detector joined advanced LIGO twin detectors on 1st August 2017 in the quest to look for the gravitational waves. The global network of three detectors was operational for 25 days until the LIGO shut down on 25th August 2017. Two gravitational wave events were registered during this period. One of them was the binary black hole merger dubbed as GW170814 and other one is binary neutron star merger referred to as GW170817. Electromagnetic counterpart associated with binary neutron star merger was promptly identified which marks the beginning of multi-messenger astronomy. This article describes these events emphasizing on the crucial role played by the Virgo and focusing on some methodological issues.

Keywords

gravitational waves, neutron stars, black holes.

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Introduction

Gravitational waves were predicted by Einstein (1916), one year after he proposed General Relativity, a theory of gravity that superseded Newton's theory. In General Relativity gravity is not a force, but rather it is a manifestation of curvature of space and time. Massive objects warp spacetime around it and a smaller object follows geodesic motion in the curved spacetime. Gravitational waves are the tiny fluctuations in the curvature of spacetime generated by accelerating masses that travel at the speed of light. While Einstein observed that his theory admits wavelike solutions, the amplitude of the gravitational waves produced by objects on Earth was so small, he thought they would never be detected.

Gravitational waves were detected directly for the first time of September 14th 2015 by twin LIGO detectors (Abbott et al., 2016), which is the culmination of relentless effort of thousands of physicists extending over several decades on theoretical and experimental front. Nobel prize in Physics was awarded to Rainer Weiss, Barry Barish and Kip Thorne in the year 2017, barely one year after the announcement of the discovery, for their decisive and pioneering effort towards the LIGO project and the detection. As Kip Thorne says, the detection was made possible primarily because of two things. Firstly the discovery of compact massive objects such as black holes and neutron stars which produce gravitational waves of appreciable strength, when two of them are sufficiently close to one another and spiral in and smash together nearly at speed of light. Secondly due to the technological advancements and inventions such as that of laser which is quite crucial in the construction and working of LIGO detectors.

Gravitational waves appear naturally when we linearise the Einstein's equations around fixed background such as flat spacetime. They are generated by the sources which admit time-varying quadrupole moment. Gravitational waves are extremely weak essentially due to the smallness of the Newton's constant of gravitation G. Gravitational waves are transverse and admit two polarizations which are referred to as Plus and Cross polarizations, which distort the space-time in quadrupolar fashion. To detect the gravitational waves the detectors were built which are L-shaped Michelson interferometers with each arm extending over several kilometers. As the gravitational wave passes by, it increases the length of one arm of the interferometer relative to the other, which results into the shift in the interference pattern in the interferometer signaling the presence of the gravitational waves. Vibrations of the arms of the interferometers due to various sources of noise, despite the best effort to reduce them are larger than the displacement caused by the gravitational waves. Hence advanced statistical techniques were employed to excavate out the tiny signal buried in the noise. This includes the method called *matched filtering* where the expected form of the signal computed theoretically is correlated against the detector output.

The main source of gravitational waves for current ground based detectors is the merger of binary black holes and neutron stars. Black holes contain surface called an event horizon which is a one way membrane that absorbs all infalling matter and radiation and doesn't let anything out. Radius of one solar mass black hole is around 3 km. Neutron stars are the compact objects made up almost entirely of neutrons whose density is of the order of density of atomic nucleus. Their mass ranges typically between one to two solar masses and their size is around 10 km. Two black holes or neutron stars in the binary system, as they go around each other emit gravitational waves, stealing the orbital energy and thus their orbit shrinks. This phase is referred to as inspiral. To predict the gravitational waveform during the inspiral phase the techniques of post-Newtonian expansion is used where Einstein's equations are expanded perturbatively in powers of orbitals velocity of the neutron stars divided by speed of light which is the small parameter and are solved order by order. Black holes and neutron stars eventually merge to form a single remnant black hole. To model merger phase techniques of numerical relativity are used where fully non-linear Einstein's equations are solved on supercomputers to predict the fate of the merger as well as the gravitational waves emitted during this phase.

Virgo joins LIGO

There are three gravitational wave detectors which are operational currently. Two twin LIGO detectors are located in USA at the locations of Livingston in the state of Louisiana and at Hanford in the state of Washington. LIGO stands for Laser Interferometer Gravitational Wave Observatory. Virgo detector is located in Europe in Italy near the town of Pisa. Size of the LIGO detector is 4 km in terms of the arm-length of the interferometer, whereas Virgo is 3km in size. All three detectors were conceived in 1990s, were built around 2000 and operated in their initial configuration for several years up to 2010. They were shutdown by the end of previous decade for upgradation with the aim of improving their sensitivity by the factor of 10. During initial run they did not observe any gravitational waves.

Advanced LIGO began its operation in September 2015. It detected gravitational waves from the merger of two binary black holes merely few days after it started the observational run O1. This landmark event is referred to as GW150914. Two more events were recorded by LIGO during O2 run in December 2015 and January

2017. After the upgrade and commissioning Virgo started the observational run on August 1st 2017. The LIGO-Virgo observatories made joint observation in August 2017 until 25th of August when the twin LIGO detectors were shut down.

Two events of joint detection of gravitational waves were registered by LIGO and Virgo during the joint run. The first event was registered on August 14th (Abbott et al., 2017b, p. 17) and second event was recorded on August 17th (Abbott et al., 2017b, p. 170817). The first gravitational wave signal was due to the merger of two black holes. This event is referred to as GW170814 and it was quite similar to the first detection. The second gravitational wave signal was produced by the merger of two neutron stars and is referred to as GW170817. The second event was quite remarkable since it was accompanied by an optical counterpart, a gamma ray burst or GRB which was recorded by Fermi and INTEGRAL satellites merely 1.7 second after the gravitational wave event. The source was promptly identified and is located in the galaxy NGC 4993. This followed a worldwide campaign of electromagnetic follow-up across entire spectrum by various ground based and space based facilities. This marks the beginning of the era of so called multi-messenger astronomy.

The involvement of Virgo in the quest of detection of gravitational waves is crucial. It allows us to detect the gravitational waves with greater confidence. It reduces the error in the estimation of parameters. Quite importantly it significantly improves the localization of source in the sky making it easier for the partners in the electromagnetic band to hunt down the source. Further it allows us to carry out the additional tests of general relativity which are not possible with two LIGO detectors.

Figure 1: The aerial view of Virgo gravitational wave detector located near Pisa in Italy. The armlength of Michelson interferometer is 3 km. [Image credit: Virgo]

In the near future global network of gravitational wave detectors will widen with the addition of underground cryogenic detector KARGA in Japan and LIGO-India detector to be built in India.

GW170814: Detection of binary black hole merger and role of Virgo

Advanced Virgo joined advanced LIGO in the quest of the detection of the gravitational waves on August 5th 2017. The first joint detection happened almost immediately on August 14th. The gravitational wave signal was produced by the inspiral and merger of two solar mass black holes which were quite similar to the ones involved in the first detection by LIGO in September 2015. The masses of the two black holes were 30 and 25 times the mass of the sun and energy worth 2.7

solar masses was radiated in the gravitational waves. The distance to the source was around 540 Mpc which corresponds to the redshift of z=0.11. This event is dubbed as GW170814. Overall this is the fourth detection of binary black hole merger, but it is the first one involving Virgo.

The event was identified by the low latency pipelines that search for gravitational wave transients using the matched filtering techniques employing data from the two LIGO detectors. The Virgo is not involved in this process since its sensitivity at this stage is not at par with LIGO detectors. The trigger was generated merely 30 seconds after the arrival of gravitational waves. The detailed analysis was carried out later carefully focussing on 6 days of data surrounding the event and significance of this event was calculated, which confirmed that it is indeed a genuine detection with the false alarm rate of one in 27,000 years. False alarm rate indicates the odds against the possibility that the event was generated by the noise in the detector conspiring to generate a fallacy of the presence of the signal.

The gravitational wave signal was seen in Virgo as well. In fact the role of Virgo in the detection is extremely crucial as it allows us to enhance our confidence in the detection significantly. The joint analysis of LIGO and Virgo data was carried out to compare two competing hypothesis in the Baysiean framework, namely the signal is present in all three detectors and the alternative hypothesis that the signal is present in two LIGO detectors and the data in Virgo is sheer noise. The two methods were employed for this purpose, one where the matched filtering technique is used to look for the binary black hole signal and the second method where time frequency methods are used to search for an unmodelled signal in the data with the frequency increasing in time.

The first model where the signal is assumed to be present in all the detectors is preferred over the model where signal is present in the two detectors by the factor of 1600. The signal reconstructed from the unmodelled search matches with the binary black hole signal very well. Further, while the false alarm rate for two LIGO detectors for unmodelled search is one in 300 years, it was quite remarkably reduced down to one in 5700 years with the involvement of Virgo.

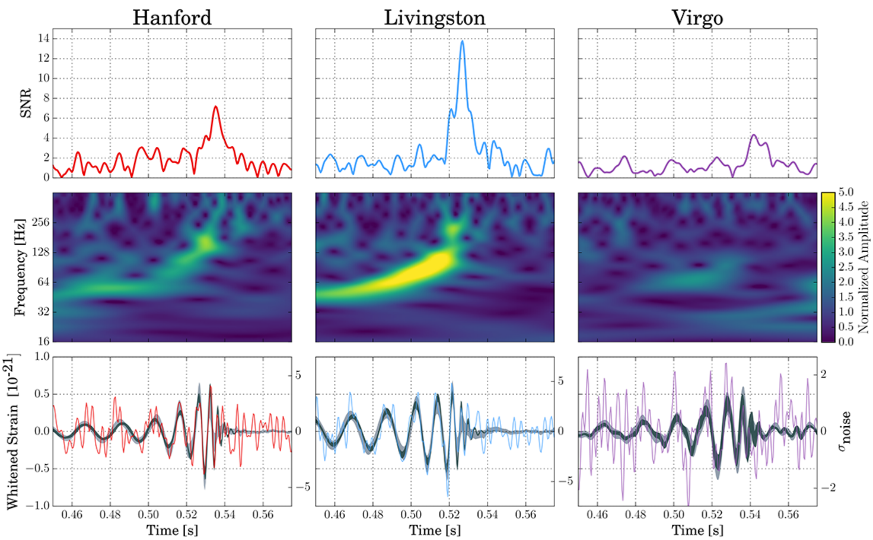

Figure 2: Top panel shows the SNR as a function of time in LIGO and Virgo detectors. The peak indicates the presence of gravitational wave signal. The middle panel shows the time-frequency plot where brightness of a given pixel indicates the strength of the signal at the given frequency at given time. Characteristics of inspiral signal where amplitude and frequency of signal increases with time, can be clearly spotted in the plots. The lower panel shows detector output superimposed with the best fit signal inferred from matched filtering and unmodelled search. [Image credit: LIGO]

Top panel in Fig. 2 shows the signal to noise ratio or SNR computed by correlating expected binary black hole signal with the detector output in a matched filtering search for gravitational wave signal as a function of time for various detectors. Peak present in all three detectors indicates the presence of the signal. The peak occurs in different detectors at different times because gravitational wave travels at finite speed and it arrives at different detectors with appropriate time delay depending on the direction of travel and spatial separation. The signal was seen at LIGO-Livingston initially, 8ms later at LIGO-Hanford and finally at Virgo with further delay of 6ms. The middle panel in Fig. 2 shows the time-frequency representation of the data. The frequency is plotted along y-axis and time is plotted on x-axis. The brightness of a particular pixel in the graph indicates the strength of the signal at that particular frequency at that particular instant of time. The plot indicates the presence of the inspiral signal wherein frequency as well as the amplitude of the signal increase with time as the orbit of the binary system decays with time. Bottom panel in Fig. 2 shows the detector output superimposed with the best-fit signal obtained using matched filtering search as well as the unmodelled search.

Localization of source in the sky is important for the purpose of looking for electromagnetic counterpart associated with gravitational wave event if any. In the event of binary black hole merger it is not expected to find any counterpart. However electromagnetic counterpart is expected in the event of binary neutron star merger. The sky localization is carried out using the information about the time delay of arrival between different detectors and response of detectors in different directions. Information of time delay of arrival between the two detectors allows to draw a circle in sky on which the source is located. Uncertainty in the time delay broadens the circle into annular region.

Now if we have a third detector, we can draw three such annular regions which intersect at two locations. This significantly reduces the region in the sky where source is localized. The information about the relative amplitudes of the signal can also be used to localize the source. The response of a given detector is different for the signal arriving from different directions. For instance detector would not be able to detect the signal which arrives in the plane of two arms along the direction bisecting them, as the two arms respond exactly in the same way rendering difference in the armlengths and hence the shift in the interference pattern zero. This is refers to as the blind spot. The response of the detector is best if the signal arrives from the direction perpendicular to the plane of the detector. Addition of the Virgo detector improves the sky localization by the factor of 10, reducing it to 80 sq degree as compared to 1150 sq degree with only two LIGO detectors for GW170814. The knowledge of luminosity distance from the gravitational wave measurement allows us to localize source in three dimensions, allowing us to identify galaxies from the catalogue of known galaxies and scan them individually to look for the counterpart. As expected no electromagnetic counterpart was found for this event of binary black hole merger.

Various conventional tests of General Relativity were carried out with GW170814 and no statistically significant deviation was found from the hypothesis that General Relativity is true. Due to addition of Virgo to the LIGO detectors additional tests of General Relativity could be carried out. Two LIGO detectors are oriented almost parallel to one another. Since the directional response of two detectors would be almost identical, it allows us to easily slide the detected waveform from one detector to other in time to account for the time delay of travel and directly compare the waveforms to confirm the presence of same signal in both the detectors. The orientation of Virgo detector is however different from that of LIGO detectors. This allows us to test the presence of additional polarizations of gravitational waves. General relativity predicts that the gravitational waves are transverse and admit two polarizations, namely Plus and Cross. This implies that the spacetime is distorted in the direction perpendicular to the propagation of gravitational waves. While space is squeezed in one direction and it is simultaneously squashed in the orthogonal direction. General metric theories of gravity however admit additional polarization states. Apart from the usual plus and cross polarizations it admits additional transverse mode termed as breathing mode. They can also admit three longitudinal modes where spacetime is also distorted along the direction of propagation of gravitational waves. Detectors which are oriented differently would respond differently to various polarization modes. Thus by comparing the waveforms in two such detectors it is possible to infer the presence of additional polarization modes. The first test of polarization of gravitational waves was carried out with GW170814 data from LIGO and Virgo detectors. Bayesian analysis was performed to compare two models, one where only the two transverse polarizations predicted by General Relativity are present and other hypothesis were additional modes were present. Alternative polarization combinations were found to be significantly disfavoured. General Relativity has again passed yet another observational test with flying colours.

GW170817: Multi-messenger observation of binary neutron star merger

Merely three days after the detection of gravitational wave signal from the coalescence of binary black holes, on August 17$^{\text{th}}$ 2017 LIGO-

Virgo network witnessed yet another event, but of a different kind. This time gravitational signal detected was generated by the merger of two neutron stars rather than black holes. This was the loudest event observed so far with the signal to noise ratio of 32. This event is dubbed as GW170817. Interestingly merely 1.7 seconds after the merger NASA's Fermi satellite observed Short Gamma Ray Burst called GRG170817A, an electromagnetic counterpart to the binary neutron star merger. This initiated flurry of activity on the observational front. This is a first ever joint observation of gravitational and electromagnetic signal and marks the dawn of multi-messenger astronomy (Abbott et al., 2016).

We find plenty of neutron stars in our galaxy. Many of them occur in pairs, in the form of a binary system. Careful radio observations of binary neutron star systems such as Hulse-Taylor pulsars have provided the evidence for the decay of the orbit as the time passes by (Taylor and Weisberg, 1982). The rate of decay of orbit is in fact perfectly consistent with the estimate of loss of orbital energy due to the emission of gravitational waves. Observation of Hulse-Taylor binary system provided the indirect evidence of existence of gravitational waves. Hulse and Taylor were awarded Nobel prize for this landmark discovery in 1993. Pulsars in Hulse-Taylor binary systems are expected to spiral in and merge in around 300 million years producing event similar to that of GW170817. Such mergers are expected to occur throughout the universe and hence physicists were expecting and awaiting the gravitational wave signal from binary neutron star merger.

Fig. 3 shows time-frequency spectrograph for LIGO and Virgo detectors. As explained earlier the brightness of a pixel is proportional to the strength of the signal at that time instant at that frequency. The signature of inspiral in clearly visible in the spectrograph of LIGO

Livingston and Hanford. The signal lasted for around 100 seconds unlike binary black hole case where signal lasted for around a second or less for the confirmed detections. The reason being that the masses of neutron stars are around one order of magnitude smaller that the black holes. Thus the signal occurs at higher frequencies, where LIGO is more sensitive. The signal lasts in LIGO band for longer time and larger number of cycles are visible. When the signal appears in LIGO detectors neutron stars are around 100 km apart and orbit around each other around 12 times a second. As they spiral in due to the emission of gravitational waves both the frequency and amplitude of gravitational wave goes on increasing, which is clearly visible in the spectrograph.

Trace in the spectrograph appears as a thin line moving almost horizontally in the beginning, but later it rises upwards and eventually there is a bright vertical upsweep when the stars get close together. The LIGO trigger was generated by the automated software based on the LIGO-Hanford data indicating the presence of gravitational wave signal. Although the signal is clearly visible in LIGO-Livingston data, the trigger was not generated due to the presence of glitch that was coincident with the signal. Glitch is a short loud burst of noise which appears in the detector every few hours. Glitch occurred and lasted for around one second during the final part of the inspiral signal. It was systematically removed while retaining the data for further analysis. Signal is absent in the Virgo detector, because the direction of arrival of signal coincided with the one of the blind spots of the detector, which in turn played an important role in localizing the source in the sky and observation of electromagnetic counterpart.

The strength and shape of the signal which appears in the detector is dependent on many parameters associated with the source such as component masses of two colliding objects, stiffness of the matter they are made up of, luminosity distance and so on. Thus gravitational wave observations allow us to constrain those parameters. The masses of the two objects that merged were determined to be 1.17 and 1.6 solar masses. This is consistent with the masses of the neutron stars observed in our galaxy, while the masses of the black holes observed till date using both electromagnetic and gravitational wave observations are considerably larger. This is the reason it is strongly believed that the signal is produced by merger of two neutron stars. The luminosity distance to the source is merely 40 Mpc which tells that the merger occurred fairly close to us in the nearby universe.

Neutron stars are made up of cold super-dense matter at supernuclear densities. Such conditions cannot be realized in the laboratories on Earth and further it is also difficult to carry out theoretical calculations by means of for instance lattice QCD techniques. Thus neutron stars provide us with laboratories to test physics under such extreme conditions. Behaviour of matter is characterized by so called equation of state which is the relationship between various thermodynamic quantities such an density and pressure. Many nuclear equations of state are proposed theoretically. Observations will allow us to nail down the correct equation of state. During the final stage of inspiral of binary neutron stars, when the two objects are sufficiently close, neutron stars get distorted due to the gravitational pull. Neutron star develops a quadrupole moment which is proportional to the gradient of gravitational field of other neutron star. The proportionality constant is referred to as tidal deformability which depends on the equation of state of the neutron star. The deformation of the neutron stars gets imprinted on the gravitational wave signal at the late stage. Therefore the gravitational wave signal would tell us about the tidal deformibility and allow us to infer the equation of state of super-

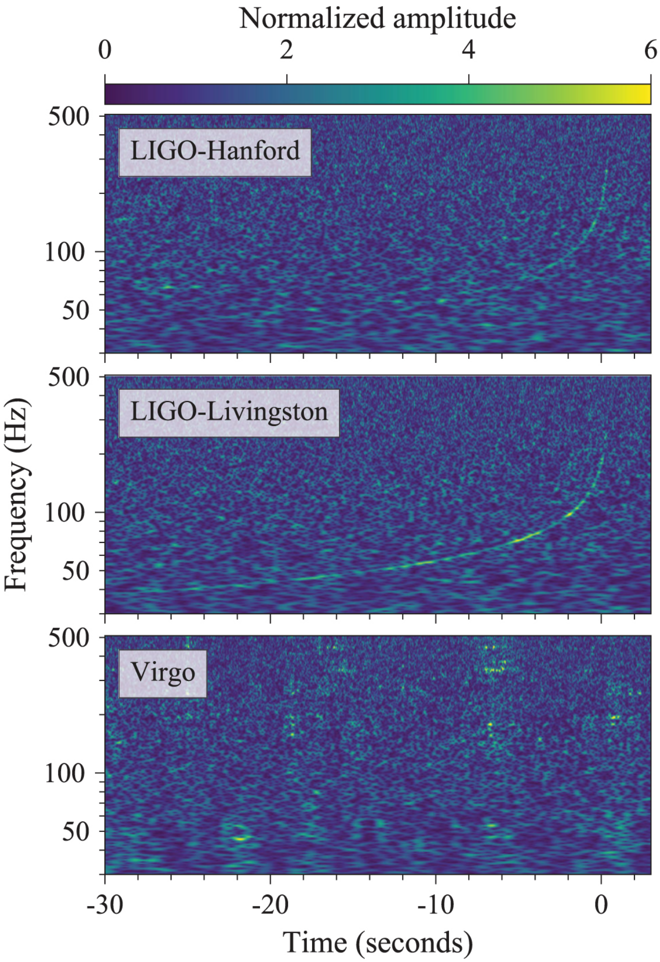

Figure 3: This figure shows the spectrogram, the time-frequency plot where strength of the signal is encoded in the brightness of the spot. The trace of the inspiral and merger, the curve which slowly moves upwards and shoots up vertically as it gains brightness, is clearly visible in LIGO-Hanford and LIGO-Livingston data, but is absent in the Virgo [Credit: LIGO/Virgo/Lovelace, Brown, Macleod, McIver, Nitz].

dense nuclear matter. GW170817 does put interesting constraints on the tidal deformibility, but does not definitively tell us so as to what the nuclear equation of state is.

The result of the merger could either be black hole or stable massive neutron star. Numerical simulations of binary neutron star merger tell us that the hyper-massive neutron star is formed as a result of collision which quickly turns into a black hole. Either the stable neutron star or hyper-massive neutron star would emit gravitational waves at high frequencies, which could be around several thousand kHz. Since the LIGO and Virgo are not sensitive enough at higher frequencies only the inspiral part of the signal was visible. Gravitational waves due to merger and possibly due to the formation of hyper-massive or stable neutron star are not visible in the LIGO band. Thus gravitational wave signal does not provide definitive answer about the remnant. It could either be the most massive neutron star or the lightest black hole known till date.

A short duration Gamma Ray Burst or GRB was seen by two gamma ray observatories orbiting the earth namely Fermi and INTEGRAL merely 1.7 second after the gravitational wave event (see Fig. 2 of Abbott et al., 2017a). GRBs are one of the most energetic events in the Universe releasing energy within matter of seconds that could be comparable to the emission of energy by sun over its entire lifetime. GRBs are divided in two categories, short duration GRBs and long duration GRBs. Short duration GRBs last for less that two seconds and are expected to be produced by the merger of two neutron stars. Whereas long duration GRBs which last for time period which is significantly larger than two seconds, which could even be thousands of seconds, are produced by the core collapse of the massive rotating stars. Now there is an evidence that short duration GRBs are indeed associated with the collision of neutron stars. Fig. 1 of (Abbott et al., 2017c) shows the sky localization of the gravitational wave source by LIGO-Virgo and localization of GRB by Fermi and INTEGRAL. Light green patch shows the localization by LIGO, whereas green patch shows localization with LIGO and Virgo. Virgo did not see the gravitational wave signal indicating that the source must be located in one of its blind spots. The source is localized in the spot of the size 28 sq degrees. Pale blue region shows the localization of the GRB by Fermi and INTEGRAL. Clearly there is an overlap between the two. Probability that the gravitational wave signal and short duration GRB that are otherwise unrelated, coincide in space and time is 1 in 20 million. This provides a confirmation that two are related and short duration GRB is an upshot of a binary neutron star merger that produced gravitational wave signal. Distance to the source was calculated to be around 40 Mpc based on the gravitational wave signal, indicating the GRB occurred in nearby universe, around hundred times closer than the typical GRB. It is however hundred to million times dimmer or sub-luminous. This came as a surprise. The possible reason for the dimness that it is viewed off-axis. GRBs are beamed and are not uniformly bright throughout the whole beam, but their brightness is much lower towards the edge of the beam. It may be viewed along the edge of the beam which accounts for its sub-luminous nature.

In the three dimensional volume mapped out in the universe based localization of source by LIGO-Virgo, Fermi and INTEGRAL and distance estimation using LIGO, one can find around 49 galaxies based on the galaxy catalogue of the local universe. These galaxies were scanned one by one and optical transient dubbed as SSS17a was located in the galaxy NGC 4993 by Swope telescope in Chile 10.9 hours after the merger. The optical counterpart is shown in Fig. 1 of (Abbott et al., 2017c) in the upper panel on right, which is clearly absent in the image taken 20 days before shown in the lower panel. A worldwide campaign was initiated to follow up this event spanning the entire electromagnetic spectrum, in ultraviolet UV, optical, near infrared IR, X-rays and radio, using around 70 ground based and 7 space based telescopes facilities. The radiation in radio and X-ray showed up a bit late. The first X-ray image was taken by NASA's Chandra X-ray observatory 9 days later and first radio image was taken by Jansky Very Large Array 16 days after the merger. Meanwhile observations were made in UV, optical and IR, which also monitored carefully the spectral energy distribution, revealed the exceptional electromagnetic counterpart known as Kilonova, the expanding debris formed by the radioactive decay of the heavy elements synthesized in the neutron star collision.

Hydrogen and helium are synthesised in early universe during big bang nucleosynthesis. Heavy elements up to iron are efficiently synthesized in the cores of massive stars and supernovae by nuclear fusion. But since iron has maximum binding energy per nucleon and consequently it is the most stable nucleus, it is difficult to form elements beyond iron via nuclear fusion. However we know how to synthesise these elements in laboratory. Nuclei are bombarded with high energy nucleons. When they absorb a single neutron their mass number increases by one and when they undergo beta decay their atomic number increases by one. Thus multiple absorption of neutrons followed by beta decays would result in the formation of higher elements beyond iron. Collision of neutron stars provides a site for this process to occur in natural setting and thus are considered to be responsible for the prediction of heavy elements. The observation of electromagnetic spectrum of the optical counterpart indeed provides signature of production of heavy elements such an gold, platinum and uranium. The amount of heavy elements produced during the neutron star merger is estimated to be around sixteen thousand times the mass of the earth, which given a reasonable assumption on rate of mergers could account for the solar heavy element abundance.

The joint gravitational and electromagnetic observation of binary neutron star merger allows us to put constraints on the Hubble constant which is a measure of rate of expansion of universe. Hubble in early part of 20^{th} century discovered that linear relationship between the recession velocity of the nearby galaxies indicated by their redshifts and distance, which is interpreted as the expansion of the Universe. The proportionality constant is referred to as Hubble constant. There are two independent methods employed to measure the Hubble constant. One includes cosmic distance ladder wherein one uses nearby distance indicators to calibrate the astronomical objects which can be then used to measure distances further into the Universe. The other method uses cosmic microwave background radiation CMB, the diffuse light leftover from big bang that fills the space. Two methods yield values of Hubble constant that are not in mutual agreement but differ by around 8%. The binary neutron star merger serves as standard siren. The luminosity distance to the source is measured using the gravitational wave observation. Once the host galaxy is identified one can measure redshift associated with it and thus infer the Hubble constant. The error in the measurement occurs because the distance to the source as measured from gravitational wave signal is degenerate with the inclination angle of the orbital plane of the neutron stars. The value of Hubble constant inferred from GW170817 with relatively large errorbars is consistent both with the standard candle and CMB measurements.

The time delay between the arrival of gravitational wave signal and GRB is 1.7 seconds. This is presumably because it takes some of jet to launch after the merger of neutron stars. But even if the time lag is taken at the face value, the fact that light and gravitational wave both traveled for 130 million years, fell through the gravitational potential of milky way together and arrived only 1.7 seconds apart allows us to put stringent bound on the relative speed of propagation, equivalence principle and on alternative theories of gravity which predict that gravitational waves travel at speed that differs from the speed of light, while both are identical in general relativity.

The exciting era of multi-messenger astronomy has just begun. Future looks bright with improved sensitivity if gravitational wave detectors, more detectors joining the global network and possibility of registering many such events.

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