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Gravitational waves: A review on the future astronomy

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Abstract
Detection of Gravitational waves opened a new path for cosmological study in a new approach. From the detection of gravitational waves signal by advanced LIGO, its research climbed the peak. After the collaboration of LIGO and Virgo, several observations get collected from different sources of binary systems like black holes, binary neutron stars even both binary black hole and neutron star. The rigorous detection of gravitational signals may provide an additional thrust in the study of complex binary systems, dark matter, dark energy, Hubble constant, etc. In this review paper, we went through multiple research manuscripts to analyze gravitational wave signals. Here we have reviewed the history and current situation of gravitational waves detection, and we explained the concept and process of detection. Also, we go through different parts of a detector and their working. Then multiple gravitational wave signals are focused, originated from various sources and then found correlation between them. From this, the contribution of gravitational waves in different fields like complex binary systems (black holes, neutron stars), dark matter, dark energy and Hubble Constant have been discussed in this manuscript.

Keywords: Gravitational waves, black hole, neutron star, dark matter, dark energy, Hubble constant

1. Introduction

Astronomy is the study of astronomical objects like stars and their system, neutron stars, nebulae, galaxy, black- holes, and it is possible because of different spectrums of EM waves. Various telescopes are used to study the different spectrums of light waves coming from deep space, like, gamma-ray, X-ray, UV, optical, IR, microwave, radio wave telescopes (Kembhavi *et al*., 2020) [1]. When we study very distant objects, we face problems like information loss. That happens because of different phenomena of electromagnetic waves like scattering, absorption, reflection, refraction, etc. There are various regions in space where photons cannot completely penetrate, like inside nebulae or the dense dust clouds, at the galactic core, near the black holes, etc. It is difficult to understand there above systems completely by EM wave observation techniques. About 95% of our universe is consists of dark energy and dark matter which are very weakly interactive to observable radiation. These are not directly observable by EM radiation but their gravitational influences on the luminous matter are only observable. That's why we require such a messenger wave that can contribute parallelly with EM astronomy to study these above problems in better resolution and Gravitational Wave can be a suitable candidate for it (Kembhavi *et al*., 2020) [1].

For the first time, GW was detected on 14th September 2015 but officially announced on 15th June 2016 by the LIGO team. Before it, Albert Einstein had predicted the existence of GWs in 1916 in his general theory of relativity. Initially, there were multiple errors in the 1916 paper and later he fixed multiple errors in his 1918 publication. It took about 100 years to detect its presence because of very little interaction and sensitivity (Miller *et al*. 2019) [2]. Laser Interferometer Gravitational-Wave Observatory (LIGO) was able to detect GW signals for the first time. That detection was possible by the collaboration of two LIGO facilities, one is LIGO Hanford at Washington and another is LIGO Livingston at Louisiana.

Both are placed about 3000 km distance from each other. Both the instruments are ground-based interferometers having arm lengths of about 4000 meters (Kalogera *et al*., 2017) [3].

The first observed GWs was originated from the inward merger of binary black hole systems having 36 and 29 solar masses. During the process of merging about 3 solar masses of matter converted into energy that travelled over the space by stretching and squeezing space-time fabric in the form of mater waves and that was GWs. This wave is non-interacting with any matter and any region of space and travels with the velocity of light (Bejger, 2017) [4]. By detecting and understanding this wave, problems like black holes, dark energy, dark matter, etc. can be understood in a better way. Hence, it may help to understand the universe from the beginning of the Big Bang. So, we can say that Gravitational waves will open a new window to understand the universe with a new approach (Kembhavi *et al*., 2020) [1].

2. History of Gravitational waves

In 1916 Albert Einstein had predicted the existence of GWs in his general relativity but there were multiple errors, so later in his 1918 publication, he removed all the errors. But at that time, it was ignored because of very little intensity and the massive energy and mass involvement to produce this type of wave. After that different physicist showed interest to study this wave. In 1974 Russell Hulse and Joseph Taylor observed the orbital motion of binary neutron stars and found that their orbit is reducing over time by radiating energy from the system. It meant that by the orbital motion of both the pulsar, the energy of the system is reducing to GWs (Abbott *et al*., 2017) [5]. In 1968 Joseph Weber came with his concept to detect the wave. He built an experimental setup with the help of a large aluminum cylinder with piezoelectric material to detect the electrical signal produced by the change in the size of the cylinder. But finally, he was unsuccessful to detect it (Cervantes-Cota *et al*., 2016) [6]. About after 100 years of delay finally, the GW was detected by the LIGO observatory. The detected GWs signal was originated 1.3 billion years ago from a binary black hole system. For this achievement in 2017 one half of the Nobel prize was awarded to Rainer Weiss and another half was jointly awarded to Barry C. Barish, and Kip S. Thorne (Weiss, 2019) [7].

3. Gravitational waves

GWs are ripples in space-time fabric produced by the most energetic processes in the universe. In electromagnetism, dipole radiation occurs due to the acceleration of two positive and negative charges, but GWs arise from the dynamics of a quadrupolar distribution of matter. When binary systems of massive bodies like black holes and neutron stars orbit around each other, and before the collision, they emit a gigantic amount of energy to space in the form of GWs. In this process, a large amount of matter converts into energy.

The first GWs signal GW150914 was detected by Laser Interferometer Gravitational-Wave Observatory (LIGO) on 14th September 2015 and later it was confirmed by LIGO on 11th February 2016. That energetic GW signal was originated from a stellar crash of a binary black hole system having 29 and 36 solar masses. GWs having different frequencies are spreading in space all the time, but our instruments were not enough sensitive to detect all of them until very recently. GWs are the transfer of force to space in the form of energy generate from the orbital motion of a massive system. The power produced by a source of gravitational radiation varies as the third time derivative of the source's quadrupole moment squared. The recently detected GW was formed from the energy conversion of about 3 solar masses of matter (Bejger, 2017) [4]. After that, it travels through space with the velocity of light by stretching and squeezing the space-time fabric along with all astronomical objects those were in its contact.

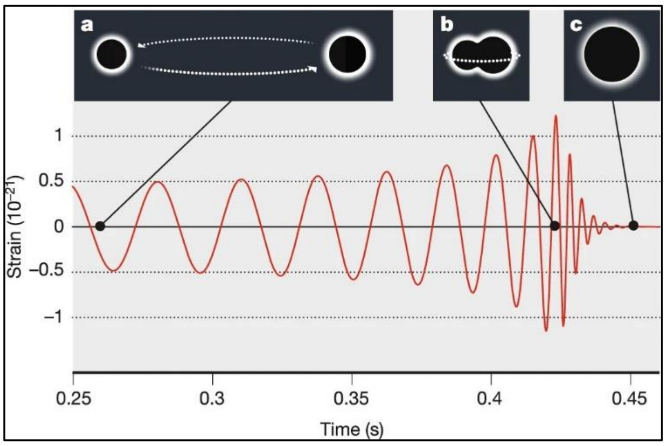

Fig 1: A plot between GWs strain against binary mass separation (Miller *et al*., 2019) [1].

In the above (Fig 1), the merging of two binary objects is shown. With the decrease in radius between them, the amplitude of the GW increase. At a peak time before the merger of two binary objects the amplitude of GWs goes to maximum (Miller *et al*., 2019) [2].

From Einstein's formula of gravitational power (Lipunov, 2016) [8],

$$L = \frac{32}{5}\frac{G^4}{c^5}\frac{M_1^2 M_2^2 (M_1+M_2)}{A^5}$$

Where, G = gravitational constant, M_1 & M_2 are the masses of two astronomical bodies,

A = distance of separation between them,

c = speed of light.

Also, Intensity $F = \frac{c^3}{16G\pi}\left\langle \dot{h}_\times^2 + \dot{h}_+^2 \right\rangle$

The above equation relates that the 'h' is the strain i.e., $\Delta L/L$, is the field quantity.

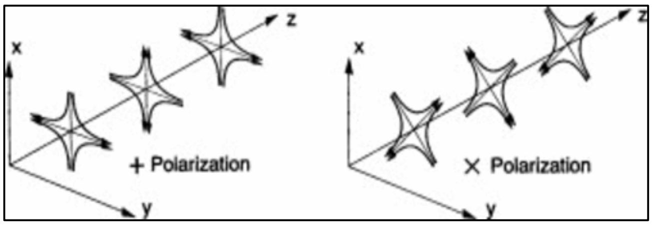

Fig 2 Lines of forces for plane-polarized GW (Centrella *et al*., 2007) [9].

Here lines of forces for sinusoidal GW are shown. Here left side wave is + polarized and the right-side wave is × polarized. GW is purely transverse and acts tidally perpendicular to the direction of propagation. For linearly polarized wave GW consists of two polarization components i.e., h_+ and $h_\times$. In (+ polarization) wave stretches along one axis and squeezes along another axis. Similarly in x polarization waves also stretch and squeeze as well as rotate by 45°. GW wave is the superposition of two states and written as strain h, where $h = h_+ + ih_\times$.

Where, $\frac{c^3}{16\pi G}$ = 7.8 x 1036 erg sec/cm^2 (Ronga, 2006) [10].

Here, $\frac{c3}{16\pi G}$ is a constant large number. It is showing that a tiny bit of strain requires a huge amount of energy. So initially Einstein ignored it because a tremendous amount of energy requires to distort space a little bit. So, it is impossible to make GW in a laboratory. From the above equation, we can see a huge amount of energy of massive binary bodies like a neutron star, black holes require to form GWs. Also, the strain of the wave is very small nearly equal to 10^{-21} m. For the detection, it requires the most advanced and sensitive detectors (Weiss, 2017) [7]. Further, we have to discuss briefly the detection process of GWs signal. Also, have to understand what type of experimental setup is required for the detection of very sensitive less interacting GWs signals. Along with it, the detection result of different gravitational wave signals from different binary objects like BBH, BNS, BHNS to study the relation and concept of DM, DE, and HC.

4. Gravitational wave detectors

Detectors are the major part of GW observation. A group of devices has been designed to detect tiny distortion of space produced by GWs. From the 1960s various kinds of developments and implementations are enhancing GWs detectors. Now today's generation detectors are enough sensitive to detect GWs generated from binary black holes and neutron stars, and this is the primary tool for observation. The journey of GWs detectors was started form 1968 by Joseph Weber.

Now globally mainly four detectors are in the operational stage, among them two are advanced LIGO in the USA, VIRGO in Italy and recently Kagra in Japan became operational on 25th February 2020. Now another ground-based detector is going to build in India i.e., LIGO India and it may be operational in 2025. Einstein Telescope is the third-generation ground-based detector and it is under construction and it may operational in 2030. LISA will be a space base observatory maybe build in the 2030s, which having an arm's length of 2.5 million km. Now for the present time among all operational detectors, advanced LIGO is more sensitive and accurate (Iqbal *et al*., 2014) [11].

4.1 Weber Bar

Weber bar was the first development towards GW detection. In the early 60, Joseph Weber developed a cylindrical antenna bar consist of multiple aluminium cylinders having 2 meters of length and 1 meter of diameter to detect GWs (Fig 3). The concept was similar to a modern cylindrical resonant bar. But there was the only difference in the operating temperature of the detector. Weber bar was working at normal room temperature, but the modern resonant bar work at very low temperatures. In Weber's bar, there was high thermal noise that shown false detection of the gravitational signal (Ronga, 2006) [10]. In 1969 Joseph Weber announced the detection of gravitational signal and that was collected by two-weber bars placed at Washington DC and Chicago. But that was a false signal detected from thermal noise and conversion of mechanical noise into electrical noise (Cervantes-Cota *et al*., 2016; Ronga, 2006) [6, 10]. Maybe he was failed to detect, but his efforts cannot be forgotten towards GW detection.

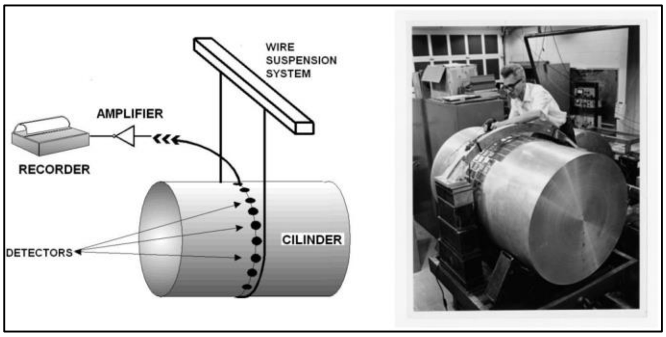

Fig 3: Weber's cylinder bar (Cervantes-Cota *et al*., 2016) [6].

4.2. Laser Interferometer Gravitational Waves Observatory (LIGO)

Laser Interferometer Gravitational Waves Observatory (LIGO) is a ground-based detector place in the USA. Two interferometers jointly working for detecting signals and both are constructed 3000 km away from each other. One is LIGO Hanford is located in Washington (Fig 4) and another LIGO Livingston in Louisiana (Fig 5). LIGO works on the principle of interference. This is a type of large interferometer having the world's most advanced Laser systems, noise cancellation systems and suspended mirror systems, etc. Here the total arm length of both the interferometer is 4 km, and the frequency range of the gravitational waves depends on the arm length of the interferometer (Abbott *et al*., 2009) [12].

Fig 4: LIGO Hanford (Abbott *et al*., 2009) [12]

This is the image of one of the LIGO observatories called LIGO Hanford (Fig 4) located in Eastern Washington. Its construction was completed in 1999 and it is operational since 2002.

Fig 5: LIGO Livingston (Abbott *et al*., 2009) [12]

Another LIGO observatory, LIGO Livingston (Fig 5) located in Louisiana. It is also operational since 2002. Both the detectors are placed 3000 km away from each other. The sensitivity of this instrument is such that, it can detect the change in the arm's length of the dimension 10^{-19} m, which is far smaller than a side of a proton (Kembhavi *et al*., 2020) [1].

5. LIGO instrumental setup

LIGO works on the concept of an interferometer. It consists of multiple thermally stable silica mirrors and beam splitters, a highly stable laser source, most advanced different sensors for detection, noise cancellation, etc. 40 kg of each test masses assembled within a 360 kg quadruple-pendulum and all connected with advanced seismic and thermal isolation system to reduce the unwanted thermal and seismic noises up to the level $2x10^{-13}$m (Fritschel, 2003; Aasi *et al*., 2015) [13, 14].

LIGO has the world's third-largest vacuum chamber, where the atmospheric pressure is one-trillionth as compare to pressure at sea level, to reduce the change in arm length produced from the molecular collision. It also helps to reduce the thermal noise that occurs between LASER and air molecule interaction. LIGO Laser system is perfectly monochromatic and stable, which produces a 200-watt continuous laser beam by multiple amplification processes of wavelength up to 1064nm (Fritschel, 2003; Aasi *et al*., 2015) [13, 14]. 40 kg each test mass is made by purest silica glass which absorbs just one out of 3 million photon incidents on it, which increases the efficiency of LIGO. The high-graded polished mirror measure by atomic-scale which makes reflections about 1120 km of distance before being merge.

High computation systems are used to run LIGO instruments and to process terabytes of data per day. LIGO lab has 35 MSU (million service units) worth of computing cycles/time which equivalent to run a modern pc for 1,000 years. Further, the lab capacity is going up to 400 MSU.

5.1 Internal Seismic Isolation Platform

It is necessary to isolating LIGO and its all instruments from all types of environmental noises. For this LIGO uses mainly two types of vibration isolation systems that are "active damping system" and the "passive damping" system. The active damping system is working as the first line of defence for LIGO. The internal seismic isolation (ISI) system (Fig 6) senses all types of ground moments and vibrations in the minute scale and for eliminating the noise it produces counter moment (Weiss, 2019; Matichard *et al*.,2015) [7, 15].

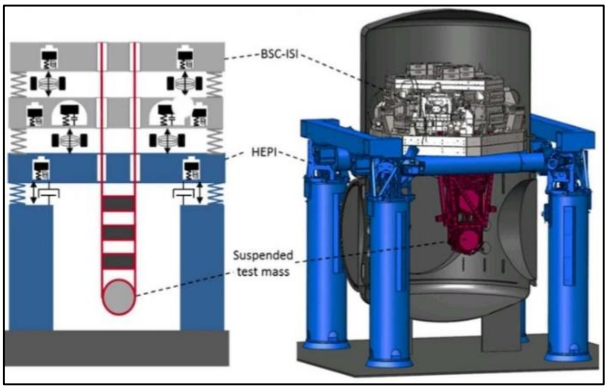

Fig 6 Internal Seismic Isolation platform (Active Vibration Isolation) (Matichard *et al*.,2015) [15].

Here optical equipment of the four-stage pendulum system has connected to the ISI platform. Another type of isolation is the passive vibration isolation system. This isolation system takes care of all the mirrors of the LIGO observatory. It is a four-stage pendulum system called quad (Fig 7). Here all the test masses hanged with the help of 0.4 mm thickness of fused silica glass thread and the main chain is side faces the incoming laser beam. The lower two masses are made of fused silica glass. The lower test mass is the actual mirror, that directly participates in interference of laser beam. The upper masses are called reaction masses; they help to keep the main test mass (mirror) stable.

The upper two masses are made of metal with and multiple sensitive motors to balance the pendulum. This upper test mass produces counter-motion by multiple motors and static electric fields to eliminate unwanted thermal and seismic noises detected with the help of an internal seismic isolation system (Weiss, 2017; Harms *et al*., 2020) [7, 16]. For making this complex process smooth a large computation power is required. For this LIGO has 35 MSU (million service unit) computing systems. The plan is to upgrade up to 400 MSU.

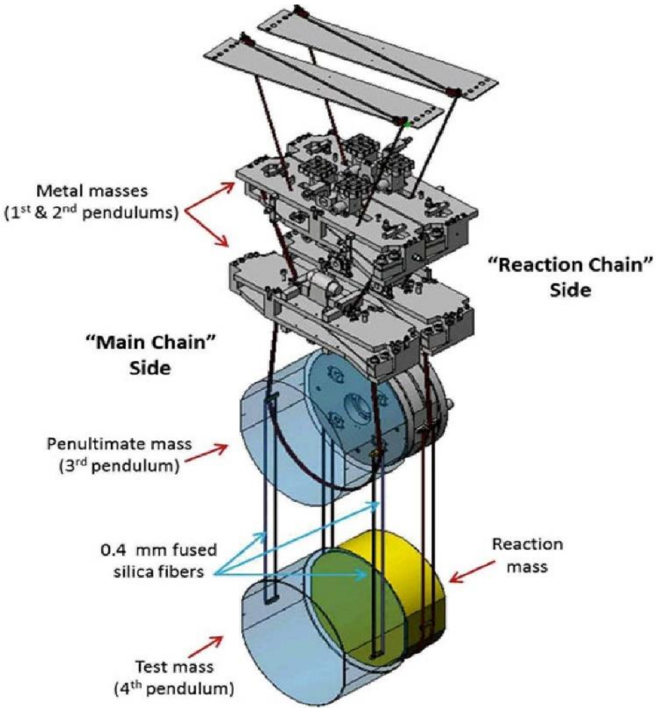

Fig 7: Quadrupole pendulum system (Passive vibration isolation system) (Kembhavi *et al*., 2020) [1].

5.2 Laser System

LASER (Light Amplification by Stimulated Emission of Radiation) system is the heart of the observatory. The laser beam use in LIGO is 800 times more powerful than normal laser pointer use in daily life. Initially, 2 watts and 1064 nm laser beam generate electrically, after that it amplifies by multiple stages to achieve target intensity of 200 w and 1064 nm.

In the first step, the beam passes through Master Oscillator Power Amplifier (MOPA). It consists of 4 thin laser amplifier rods, that boost the power of the laser beam. The material compositions of these rods are neodymium, yttrium, lithium, and fluoride having the size of 3 mm in diameter and 5 cm in length (Nary Man, 20104) [17]. When the seed beam passes through the first rod, the rod molecules energize and emit a 1064 nm photon beam. Again, the first-rod beam enters through the second rod and then second to third and this process repeats up to the fourth rod. In this process, the intensity of the beam increases from 2 watts to 35 watts (Nary Man, 20104; Kwee *et al*., 2012) [17-19]. The path that the beam takes from NPRO by four rods is shown in (Fig 8).

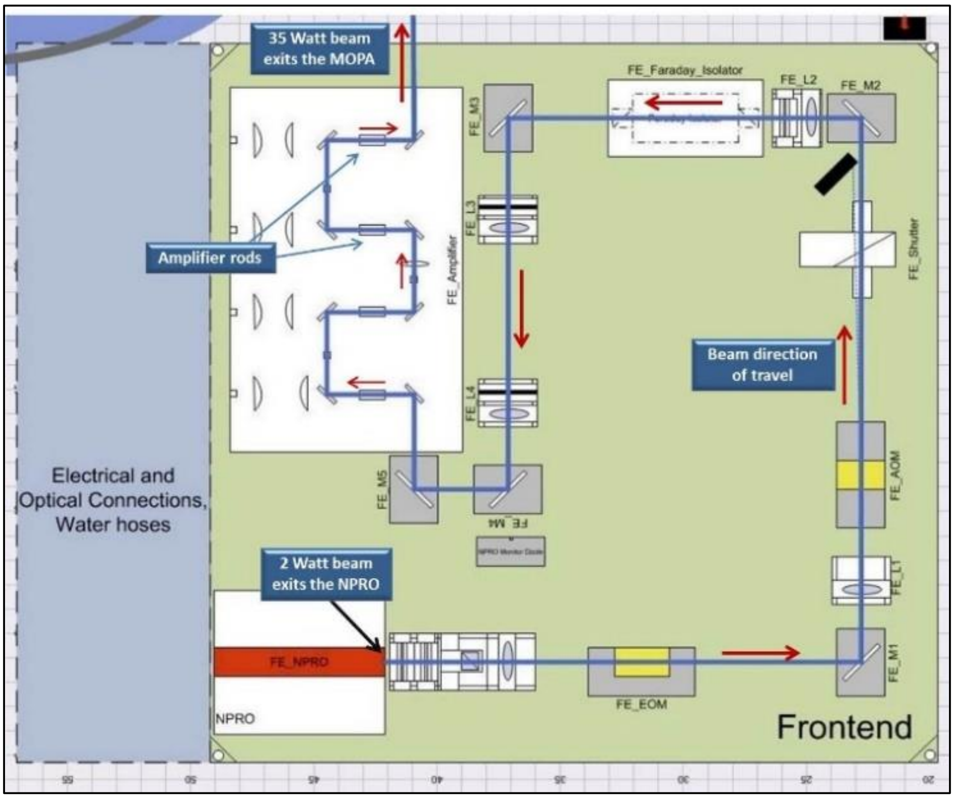

Fig 8: NPRO system to achieve a 35 W laser beam from a 2 W input laser beam (https://www.ligo.caltech.edu/page/laser).

Again, the final stage of amplification achieved by the device (Fig 9) is called HPO (high power oscillators) (Nary Man, 20104) [17], which is the combination of another four rods. Here used four rods are the same in size as MOPA's rod, but having different material compositions. When a beam passes through these rods, an additional power boost takes place like MOPA. In this case, 45 watts of laser power carried by each fiber and each bundle delivers about 315 watts i.e., 7 fibers × 45W, into each HPO rod to emit more and more laser beam.

Finally, by the passage of time, HPO achieves desirable power of 200 W (Fig 9). The frequency and power stability of the LIGO laser are very high about 100 million times, compare to the daily used laser. For achieving this natural frequency and power fluctuations, the laser beams are mechanically reduced by a factor of 100 million. Before use in the interferometer laser beam goes through series of feedback mechanisms. By this feedback control loop, the power fluctuation problem also resolves.

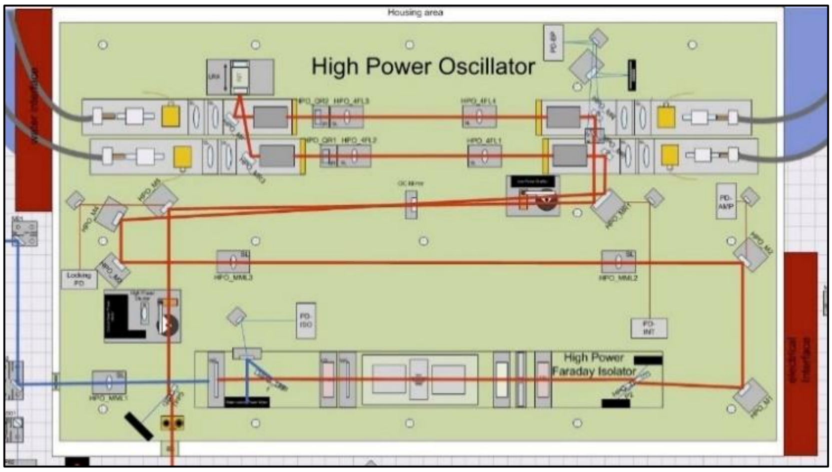

Fig 9: HPO (high power oscillator) system to boost laser signal from 35 W to 200 W (https://www.ligo.caltech.edu/page/laser).

5.3 Ultra-High Vacuum

All the instruments of LIGO are placed inside the vacuum chamber. The vacuum chamber prevents all the instruments from unnecessary environmental sound waves and thermal variations which produce unwanted vibrations on the surface of the mirrors. A vacuum chamber is the most necessary part of the LIGO facility. LIGO has an ultrahigh vacuum tube with having a length of 4 km and a diameter of 1.2 meters. It enhances the detection capability of the detector. The total volume of the vacuum environment is 32,000 m^2 or 10,000 m^3. This is only possible because of specific composite material fabrication. The main parts of the vacuum chamber are the beam splitter chamber, mode cleaner tube, beam tube, LN2 cryopumps, gate valves, etc. There are 2 beam tubes are placed perpendicularly manner having each length 2 km. There are 9 numbers of ports with having a diameter of 250 mm connected to each beam tube. These ports (Fig 10, 11) are used for vacuum pumping to the beam tube (Joshi *et al*., 2014) [20].

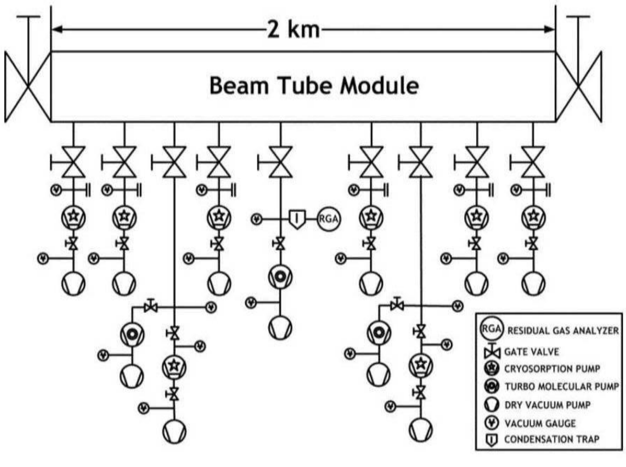

Fig 10: Schematic beam tube arm (Joshi *et al*., 2014) [20]

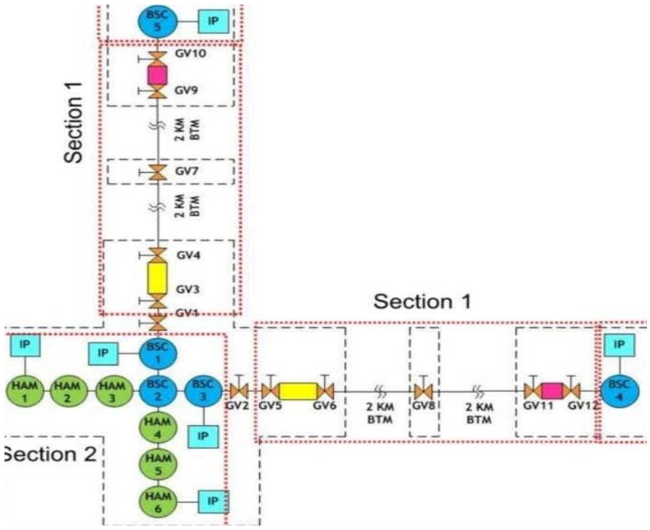

Fig 11: Schematic beam tube (Joshi *et al*., 2014) [20]

In the initial stage dry rough pumping is used to achieve ~10^{-2} Torr of pressure. After that, by the TMP station again 10^{-5} of pressure generate by ~2000 s^{-1} pumping speed in the tube. After reaching 10^{-5} Tor of pressure, cryopumps continuously maintain the pumping process, additional with 1500 C heating process to achieve desired pressure (Kwee, *et al*.,2012) [19]. LIGO 10,000 cubic meters of vacuum environment having air pressure10^{-9} torr take about 1100 hours or 40 days to remove all the air from the chamber. Also, it takes 30 days to remove all moisture and residual gases, by heating the tubes at 150-170 degrees centigrade. At the final state ion pumps and LN2 Cryopumps with non-evaporable getters are used for getting the complete pumping process. Finally, we can say that this process is complex to perform, but it is necessary to getting a noiseless pure gravitational waves signal. Hence, we can say the ultra-high vacuum chamber is the backbone of LIGO depends upon the arm length of the detector (Buikema *et al*., 2020). Advanced LIGO has maximum sensitivity than other ground-based detectors to detect about 10^{-23} m of GW strain in its arm's length.

6. Gravitational Wave detection

The detection and study of GWs are very complicated because of weak signal strength and its property. For this reason, still, now only one successful approach is available to detect this wave. By interferometric technique, it is possible to study GWs. Strain magnitude between the mirror distance gives information about the strength of the GWs. The high-frequency response of the detector directly depends upon the arm length of the detector (Buikema *et al*., 2020) [21]. Advanced LIGO has maximum sensitivity than other ground-based detectors to detect about 10^{-23} m of GW strain in its arm's length.

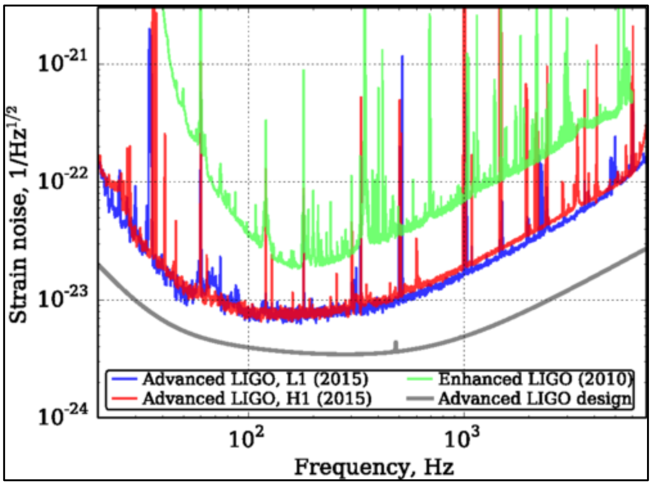

Fig 12 Noise sensitivity of different ground-based detectors (Martynov *et al*., 2016) [22].

In the (Fig 12), the amplitude spectral density of different detectors' noise is shown. Here GWs having amplitude lower than noise floor are very difficult to detect because of very small signal strain. Here advanced LIGO has a maximum range of frequency and strain band, that's why advanced LIGO has the maximum response to low intense signals among all ground-based detectors (Martynov *et al*., 2016) [22]. ST fabric, and those ripples travel over space with the speed of light and i.e., known as GWs (Schmidt, 2020) [23]. The first GWs signal GW150914 (Fig 13) was detected by two LIGO facility and that was the signal of binary black hole system and that was the first evidence of the existence of binary black hole system.

6.1 Binary Black Hole (BBH)

Black holes are highly dense objects in the universe created after the shrinking of massive stars into a small area of size. Their gravity is enough strong to make infinite curvature in the space-time (ST) fabric. Because of this infinite curvature in ST, matter and light near it also get trap. When binary black holes' orbit each other, they make ripples in ST fabric, and those ripples travel over space with the speed of light and i.e., known as GWs (Schmidt, 2020) [23]. The first GWs signal GW150914 (Fig 13) was detected by two LIGO facility and that was the signal of binary black hole system and that was the first evidence of the existence of binary black hole system.

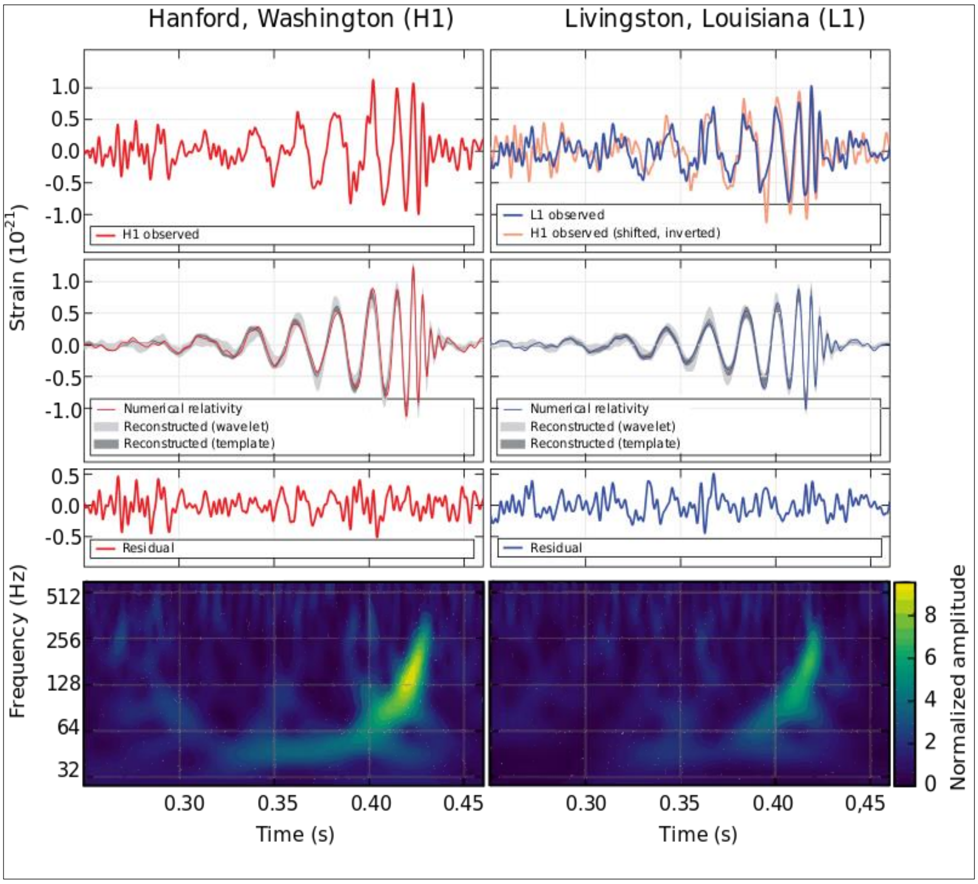

Fig 13: The first detected GWs signal GW150914, by LIGO Hanford (H1) and Livingston (L1) detectors (Bejger, 2017) [4].

In (Fig 13), the top left row is the signal of H1 strain and the top right row is the signal of L1 strain. For the first time, L1 got a signal of GW150914 and $\mathbf{6.9^{+0.5}_{-0.4}}$ ms later H1 got the same signal, that's why in the graph H1 data has shifted. In the second row, the GW strain of 35-350 Hz frequency band is projected on each detector. The third row is the residual noise after filtered by detector time series. The bottom row is the time-frequency representation of the signal showing that the signal frequency is increasing over time (Bejger, 2017) [4].

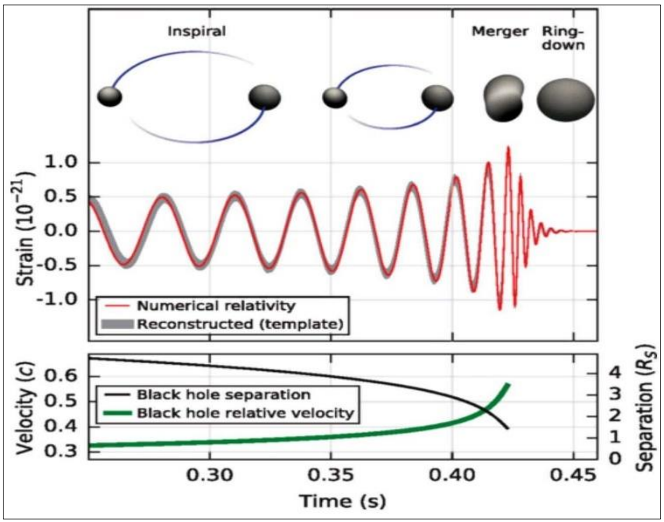

Fig 14: BBH separation and GWs simulated graph (Bejger, 2017; Wynn, 2018) [4, 24].

(a) Top figure represents the GWs strain.
(b) The middle part represents the velocity and binary object separation.
(c) The bottom part of the graph is between time and the BBH velocity, which gives the relations between black hole separation and black hole relative velocity.

The top part (Fig 14) is the amplitude of the GW strain of GW150914 signal detected from H1. This image is the relativity model of the black holes coalesce. The bottom is the Keplerian black hole separation of the unit of Schwarzschild radii Rs = $2GM/c^2$ and the relative velocity is post-Newtonian parameter v/c = $(\text{GM}\pi\text{fGW})^{1/3}/\text{c}$. Where fGW is GW frequency and M is the total mass of the system (Bejger, 2017) [4].

From Einstein's formula of gravitational power (Abbott *et al*., 2009) [12],

$$L = \frac{32}{5}\frac{G^4}{C^5}\frac{M_1^2 M_2^2 (M_1+M_2)}{A^5}$$

Einstein's formula "for the gravitational wave luminosity says that the rate of orbital momentum loss is determined by the distance between components and their masses" (Lipunov, 2016) [8]. The detected GWs signal GW150914 originated from a binary black hole system having each solar mass M1=36 and M2=29 (Fritschel, 2003) [13]. During this process of merging, about 3 solar masses of matter converted into energy, the whole event took 0.2s for the detector sensitivity band above 30 Hz, and near the final merging time, the orbital velocity was 0.5 c (Fig 13). The total energy emitted into GWs by the total lifetime of the system was, E $=3^{+0.5}_{-0.5}\, M\Theta$ c^2 i.e., $3.6^{+0.5}_{-0.4} \times 1049$. That event was the most energetic process in the universe. At that time the total energy of the event exceeded the total EM brightness of all the 1022 stars of the observed universe (Bejger, 2017) [4].

6.2 Binary Neutron Star (BNS)

When a massive star burns its all fuel in the thermonuclear reaction process, its all-surface mass starts to collapse towards its core. Due to the instant collapse, all matters again bounce back from its core by an explosion called a supernova explosion. Supernova explosion of massive stars triggers the formation of neutron stars. The formed neutron star has a mass little above the mass of the sun, but the concentration of mass occupies 25 km in diameter. Because of the highly dense compact atomic core, their magnetic fields are millions of times stronger than the laboratory-created. That makes neutron stars rotate as stable as the atomic clock (Wynn, 2018) [24].

On 17 August 2017, the collaboration of LIGO and Virgo detected a signal GW170817 of the binary neutron star in NGC 4993 in the Hydra constellation. The merger of binary neutron stars was also observed in the different spectrums of EM signal, which gave hints about the location of the signal origin. The gamma-ray from GW170817 BNS was observed after 1.74 s from the merger of BNS confirmed the velocity of GWs (Lasky, 2015) [25]. From the study of PSR B1913+16, it was found that the loss in energy of BNS system and reduction in orbital distance increases the amplitude and luminosity of GWs (Abbott *et al*., 2017) [5], and with that the emission of EM waves increases. By combining the GWs luminosity from the BNS system and EM waves redshift of the host galaxy will make it possible to find the Hubble constant from GW standard siren determination (Ciolfi *et al*., 2020) [26].

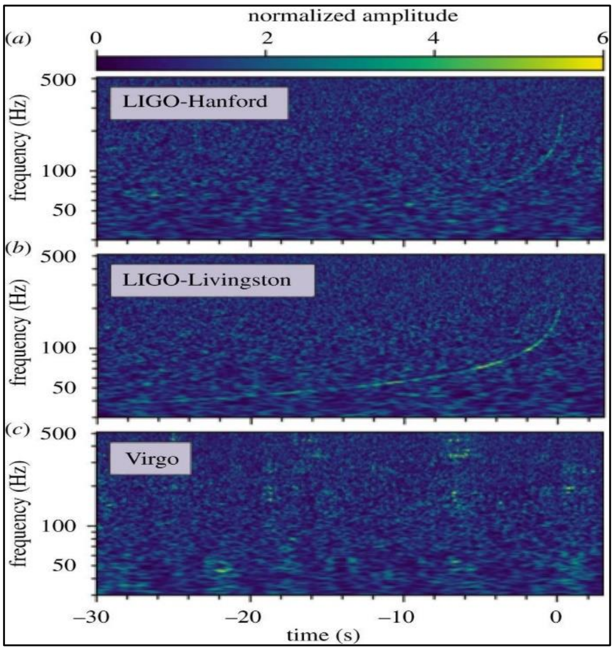

Fig 15: The time and frequency relationship graph for different detectors (Wynn, 2018) [24].

The time-frequency graph was measured by three detectors LIGO-Hanford, LIGO-Livingston, and Virgo (Fig 15). The color scale showing the amplitude of GWs signal originated from the source GW170817 (Wynn, 2018) [24].

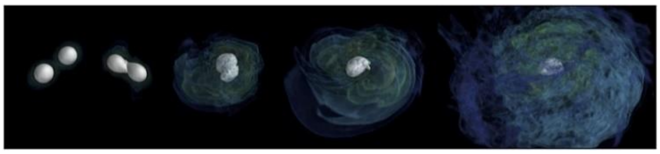

Fig 16: Binary Neutron Star (BNS) merger simulation (Ciolfi *et al*., 2020) [26].

6.3 Black Hole- Neutron Star (BHNS)

Previously more than 50 GW signals were detected from individual pairs of BH and NS systems. But for the first time, researchers confirmed the merging of the BHNS system. Continuous two signals from the BHNS system were detected in 10 days intervals. The first BHNS signal GW200105 was detected on January 5, 2020, and was captured by LIGO Livingston in the USA and Virgo Italy and at that time LIGO Hanford was offline. The second BHNS signal GW200115 was detected on January 15, 2020, by the LIGO and Virgo after 10 days of the first signal detection. At that time both the LIGO detectors LIGO Livingston and LIGO Hanford were in the operational state. In both, the case NS was swallowed by BH (Abbott *et al*., 2021) [27]. Before it already two more signals from the binary merger were found. The first signal was GW190426 detected on April 26, 2019, by LIGO and Virgo (Li Yin-Jie, 2020) [28]. The second signal GW190814 was also detected by LIGO and Virgo on August 14, 2019 (Abbott *et al*., 2020) [29]. In both, the above cases their primary binary masses were not expected as BHNS system, so there is no proper explanation for the BHNS merger. Below we will review both recently confirmed signals GW200105 and GW200115.

In January 2020 two BHNS signals were detected by LIGO and Virgo from two compact binary systems and both the detected signals were fully designated by GW200105_162426 and GW200115_042309. The first signal GW200105 was detected by two detectors LIGO Livingston and Virgo on January 5, 2020, at 16:24:26 UTC, and the second signal GW200115 was detected by three detectors LIGO Hanford, LIGO Livingston, and Vigo on January 15, 2020, at 04:23:10 UTC. During the detection of the GW200105 signal, the LIGO Hanford detector was not in the operational state so Virgo got a small signal-to-noise ratio. For the first signal source, GW200105 component masses were $m1 = 8.9^{+1.2}_{-1.5}$ M⊙ and $m2 = 1.9^{+0.3}_{-0.2}$ M⊙, and for the second signal source, GW200115 component masses were $m1 = 5.7^{+1.8}_{-2.1}$ M⊙ and $m2 = 1.5^{+0.7}_{-0.3}$ M⊙ (Abbott *et al*., 2021) [27].

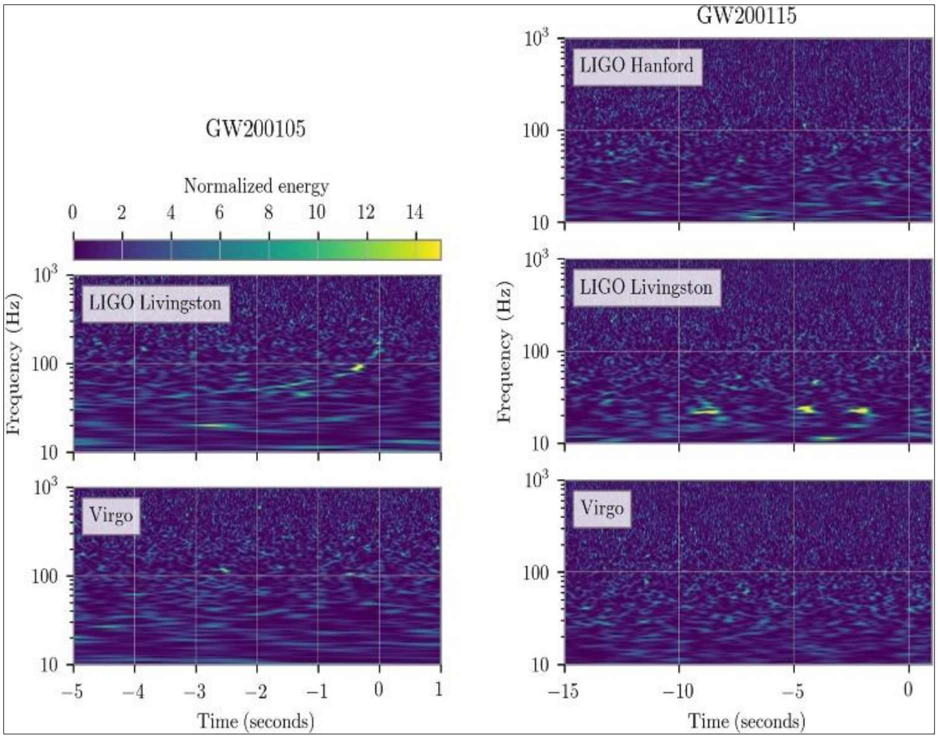

Fig 17: Time-frequency representation for both the signals GW200105 and GW200115 (Abbott *et al.*, 2021) [27].

In the (Fig 17) left side is the time-frequency data containing the signal GW200105 detected by two detectors LIGO Livingston and Virgo. The detection time for this signal was on January 5, 2020, at 16:24:26 UTC, and data for LIGO Livingston was shown after glitch subtraction. The right-side graph explaining the signal GW200115 detected by three detectors, two LIGO detectors, and Virgo. The detection time for this signal was on January 15, 2020, at 04:23:10 UTC. Here below 25 Hz light scattering noise for LIGO Livingston is visible.

The luminosity distance was found to be DL = 280^{+110}_{-110} Mpc and DL = 300^{+150}_{-110} Mpc for the signals GW200105 and GW200115 respectably. For the signal GW200105 the remnant mass and spin were found to be, Mf = $10.4^{+2.7}_{-2.0}$ and spin, χf = $0.43^{+0.04}_{-0.03}$ respectively. And for the signal GW200115 the remnant mass and spin were found to be, Mf = $7.8^{+1.4}_{-1.6}$ and spin, χf = $0.38^{+0.04}_{-0.02}$ respectively (Abbott *et al.*, 2021 The Astronomical Journal Letters) [27].

This type of BHNS system plays an important role in the field of astronomy to understand the formation of heavy elements produced from r-process nucleosynthesis (Foucart, 2020) [30].

7. Dark Matter (DM)

Dark matter (DM) is the most dominant component in the universe. If we see the ratio of matter, DM and Dark energy (DE) is 5%, 27%, and 68% respectively. The properties of its composite particles are still unknown because of their weakly interacting behaviour with EM waves. Some observations like temperature anisotropies of the CMD (Cosmic Microwave Background), gravitational lensing by large galaxy clusters, galactic rotation curves, type Ia supernovae, baryonic acoustic oscillation, etc, indicates the existence of DM (Bertone *et al.*, 2018) [31]. It is 5 times more massive than normal matter and it takes 90 orders of magnitude of mass from ultralight boson to massive hypothetical primordial black hole (PBH). Scientists are assuming GWs could explain the existence of dark matter candidates like PBH and axions (Bertone *et al.*, 2018) [31].

Still, now there is no surety about the particle types of DM, but scientists are thinking PBH may be DM. Like a normal black hole, there are no threshold mass constraints for PBH (Bertone *et al.*, 2020) [32]. By finding the existence of PBH would expand the understanding of DM and the universe. For detecting PBH signals, it requires highly sensitive GWs detectors (Bertone *et al.*, 2018; Bertone *et al.*, 2020; Mohamadnejad, 2020) [31-33].

Axions may be a good candidate for DM. As per scientific analysis, axions may bind together to form axion stars and they may be as compact as neutron stars. It is also possible axions could gather around BH and NS systems in the form of the cloud. That cloud would be visible with GWs when those binary systems merged because of a change in the axion cloud. Even there is a possibility of axion formation from the merger, then it would reflect in the signal (Bertone *et al.*, 2018) [31].

8. Dark Energy (DE)

Dark energy (DE) in the abundance component of the universe has an occupancy of 68%. It is not directly observable like DM, but its effect is observable. The natural accelerated expansion of the universe explains the existence of dark energy. In the end, the universe is going to empty because of the energy density of non-relativistic matter. And now the universe is almost empty having a total matter density of about 25-30% of dark energy density (WEI-TOU, 2010; Marochnik, 2016) [34, 35]. Multi-messenger GWs detection will help to find the rate of cosmological expansion and will give an independent dark energy equation of state. By this, it will help to measure the Hubble parameter (Ezquiaga *et al*., 2018) [36].

Some studies suggest GWs may occur from the dark energy field. This type of GW may produce variations in the periodicity of the earth's orbit. That can be studied by comparing with Ice Ages periodicity. From this we can note GWs having a time period of ~10^5 years, it will make a periodical variation with earth's orbit eccentricity with the time period of ~10^5 years. GWs having a time period T~10^5 and corresponding to its amplitude h0 ~ 10^{-2}, stay at a very low frequency of the order of ~ 10^{-13}. The observation of this gravitational signal is very difficult because of the very low frequency and very high time period. This order of time period of this signal is very large in comparison to the human lifetime. With the help of a more sensitive detector, the study of such sensitive GW signals will be possible, and it may create more understanding about the dark energy concept (Singh, 2020) [37].

9. Hubble Constant (HC)

Hubble constant (HC), H_0 give the current expansion rate of the universe is the function of redshift (z). Previously different methods and approaches have been used to find the value of HC. From Anchor-Cepheid-supernova distance ladder method HC was found to be, $H_0 = 74.2 \pm 1.8$ km s^{-1} Mpc^{-1} (Mortlock *et al*., 2019) [38]. By combining plank CMB data and standard flat cold dark matter (ΛCDM), the result was $H_0 = 67.3 \pm 0.6$ km s^{-1} Mpc^{-1}. Still, there is the uncertainty of finding HC by using different ladder methods. The most relevant approach to finding promising results may be GW signal observation coming from binary BNS and BBH (Mortlock *et al*., 2019; Pozzo, 2014) [38, 39]. On 17 August 2017 by the collaboration of advanced LIGO and Virgo detector, a strong GW signal was observed from the BNS merger. That signal allowed to use GW170817 as a standard siren and for finding Hubble constant and that was,

$H_0 = 69.0^{+16.0}_{-8.0}$ km s^{-1} Mpc^{-1} (Abbott *et al*., 2021 The Astrophysical Journal; Vasylyev *et al*., 2020) [40, 41].

By Hubble constant, the mean expansion rate of the universe can measure.

$vH = H_0$ d,

Where vH called Hubble flow velocity of the source. All cosmological object's distance differs in the order of vH/c, where c is the velocity of light. By combining Hubble flow velocity and optical identification of NGC 4993 galaxy, it provided the most appropriate value of $H_0 = 69.0^{+16.0}_{-8.0}$ km s^{-1} Mpc^{-1} (Abbott *et al*., 2021 The Astrophysical Journal) [40]. That result was the combination of GWs signal BNS GW170817 and EM signal red-shift of host galaxy NGC 4993 along with constraints of galaxy catalogues of BBH event of advanced LIGO and Virgo. Here, in the (Fig 18), Hubble constant H0 (dark blue) of GW was observed from advanced LIGO and Virgo. The orange curve is the signal of GW170817 BNS from host galaxy NGC4993. For the signal GW170814 DES-Y1 galaxy catalogue used and for other remaining signals BBHs, GW170809, GW170104, GW170608, GW151226, GW150914 GLADE catalogue was used (Vasylyev *et al*., 2020) [41]. With the vertical dash line, 68% maximum a-posteriori intervals are represented. All the results on H0 give the interval of 20-140 km s^{-1} Mpc^{-1} that is represented with a dotted blue line. Here the result of H0 is estimated from CMB and supernova observation (Abbott. B *et al*., 2021 The Astrophysical Journal) [40].

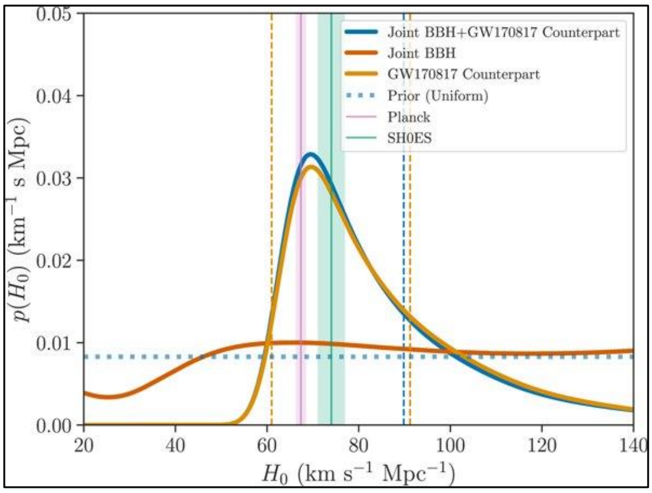

Fig 18: Measurement of Hubble Constant H0 (Abbott B. *et al*., 2021 The Astrophysical Journal) [40].

In the above (Fig 18), the blue line is the measurement of H_0, detected from Advanced LIGO and Virgo's first two observations run.

10. Future of Gravitational Wave detection

Recently many projects of GW detectors are going on, and many of them are ground-based detectors. For ground-based detectors, the main problems are different seismic vibrations produced by environmental disturbances and limitation of the arm length of detectors because of the curvature of the earth's surface.

So, for removing the barrier of gravitational waves detection, Laser Interferometer Space Antenna or (LISA) i.e., a space-based detector project is going on by the collaboration among ESA (European Space Agency), NASA, and an international consortium of scientists. LISA will be a large-scale space mission to detect one of the most elusive phenomena in GWs astronomy. With the success of the LISA project, we will be able to study

GW signals from binary systems in a frequency range of 10^{-4} to 10^{-1} Hz. By this, many problems like galactic structure and their formation, the evolution of stellar objects, state of the early universe, structure of spacetime near the black hole, dark matter, dark energy, primordial objects, etc may be solved (Shaddock, 2008; Pitkin *et al*., 2011) [42, 43].

On the 236th meeting of the American Astronomical Society (AAS), European Space Agency launched the LISA space program for the first time. This mission is a result of collaboration between both ESA and NASA. LISA is the GWs detector is designed for space orbiting missions, in which three satellites are connected with a laser beam by forming the structure of a constellation in a heliocentric orbit.

Here the arm length of this observatory is about 2.5 million km (Pitkin *et al*., 2011) [43]. LISA Pathfinder mission was launched on 3rd December 2015 and was ended in July 2017. This mission aimed to find a suitable location and trajectory for the LISA space crafts. The successful result of this mission shows the pathfinder is working in better precision require than the LISA project. Now existing ground-based detectors can detect GWs having large strength, which is produced from large events in space. By LISA we can detect tiny distortion in space-time fabric precisely having low signal strength. In its success, we can collect all the information about the habitable planet, from smaller binary systems like planets to larger systems like supermassive black holes located at the centre of the galaxy, which is far difficult for electromagnetic wave astronomy (Armano *et al*., 2015; Sesana, 2021; Vetrugno, 2017; Wanner, 2019) [44-47].

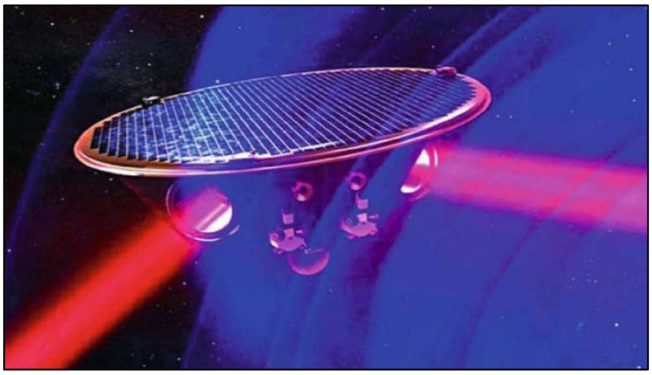

Fig 19: Internal design of LISA spacecraft. (Kembhavi *et al*., 2020) [1]

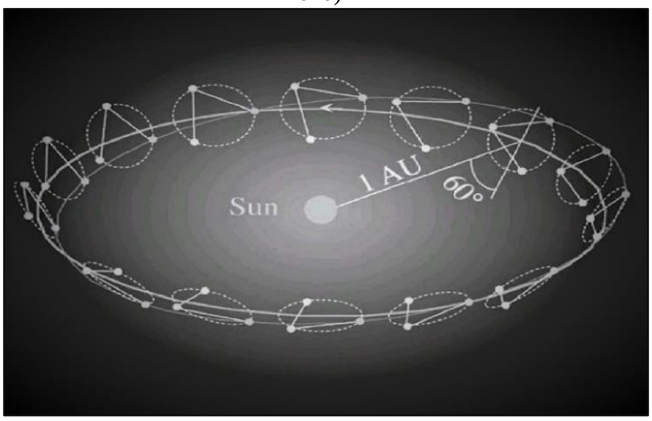

Fig 20: Orbital path designed for LISA (Kembhavi *et al*., 2020 [1]

In the shown picture (Fig 19), single spacecraft assembled with multiple complex instruments for laser beam production, amplification and again detect the interference pattern of GW signals (Shaddock, 2008) [42]. In (Fig. 20), three spacecraft combinedly orbiting in a specific orbit around the sun. It can detect tiny intense gravitational waves by passing through it. It can measure ripples having a time period of few minutes to few hours (Shaddock, 2008) [42]. LISA will be a combination of three spacecraft having Earth-like orbit around the sun. In triangular structure formation, each aircraft will be placed 2.5 million km apart from each other to detect tiny distortion in the space-time fabric. Because of its large arm length, it can detect less intense signals as well as their sources.

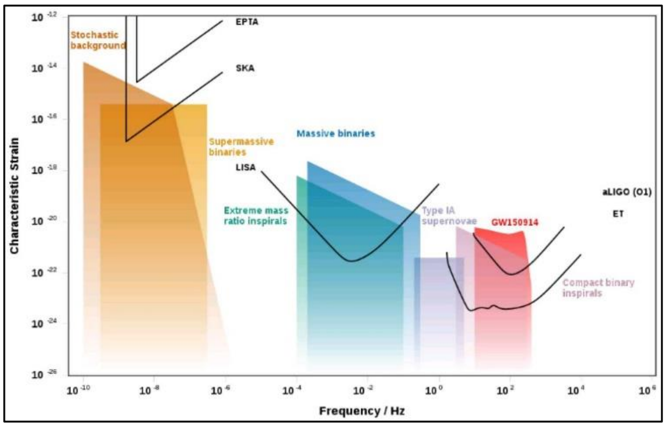

Fig 21: A plot of characteristic strain against frequency for various detectors (Bejger, 2017) [4].

With the help of ground detectors, we can study GWs generated from binary neutron stars and black holes. But LISA (Fig 21), can listen to distance sources like compact supermassive black holes in the galactic core, primordial black holes to low-frequency sensitive signals sources like a binary white dwarf merger, sources from the early universe (Moore *et al*., 2014) [48]. And also, other techniques used for detection of wave (Morozov *et al*., 2021; Mensky *et al*., 2009) [49, 50].

11. Conclusion

In this review paper, we have reviewed the GWs, and how it may open a window to solve many problems like BBH, BNS, DM, DE, HC. Initially, we discussed briefly gravitational waves and their detection. Then we discussed GW detector LIGO and its instrumental setup and how different instruments of an observatory works coordinately to detect GW signal. Then we went through the different sources of origin, and their detection by advanced detectors like LIGO, Virgo, and how different instruments of a detector work simultaneously to detect signals. Then we discussed the first detected BBH (Binary Black Hole) signal GW150914 by advanced LIGO and Virgo. Then we discussed the first BNS (Binary Neutron Star) merger and how it can be helpful to find the Hubble constant (HC). After that, we gathered information, how evolution in GWs detection can open a hand to understand Dark matter (DM) and dark energy (DE) which is the reason for the expansion of the universe. At finally we explained about Hubble constant (HC), which says about the rate of accelerated expansion of the universe. Here we discussed how Hubble constant value was estimated to finding the universe expansion rate and matter density of the universe in the region of space. Then we concluded with the future of gravitational waves detection and how LISA can be an enhanced detector to solve recent problems and mysteries of the universe.

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