Comprehensive review of Physics of Gravitational waves and Functional elements of LIGO

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Comprehensive review of Physics of Gravitational waves and Functional elements of LIGO

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Abstract

The concept of *Gravitational Waves* was first predicted by Albert Einstein in 1916 as a result of his *Theory of General Relativity.* They are disruptions or "ripples" in the space time fabric, caused by the acceleration of massive bodies, such as neutron stars or black holes. These ripples spread out in all directions, stretching and squeezing the space as they pass by, travelling at the speed of light. The review paper explains the theoretical aspects of gravitational waves like linearized theory and experimental setup that provides us with the data that we can use to understand the nature of the sources of these waves and the universe itself. The review is to better understand not only the reasons for their use, but also the very methods in which they are formed and how we can detect them. So, the paper also reviews LIGO, the most prominent Gravitational Wave detector made by mankind and explaining the principle, construction and working, various disturbances affecting LIGO, the different methods used to extract the gravitational wave signals. Before the discovery of gravitational waves, we were limited to looking at the universe only using electromagnetic waves emitted by various celestial objects, but the discovery of GW150914 by LIGO, opened a new window to look into the universe. Lastly we reviewed various observations and Advancements of LIGO.

Keywords— General Relativity, Space time, Tensors, indices, Field equations, Wave equation, Polarization, Energy Flux, Doppler effect, Inverse square law, Inspiral mechanism, Black holes, Neutron stars, Pulsars, Revolving Binary system, LIGO, Interference, Coherency, Laser, CMB, Noise isolation, Signal extraction, Template matching

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1 Introduction

General relativity is an important part of physics which helps us understand our universe in a large scale like black holes, gravitational waves and our expanding universe. It describes gravity as a property of space and time rather than a force as mentioned by Newton. It tells us that the curvature of space time is related to energy and momentum which is present inside matter. Einstein's feild equations also theorizes various phenomena such as the wrapping of space time and gravitational waves. It helps us to understand the region of space having black holes or neutron stars, or a system of dynamical heavy masses which causes great changes in gravity. We know that there are three dimensions of space which we can interact with. But Einstein included time also as the fourth dimension. Thus space time is four dimensional in nature, consisting of three dimensions of space and one dimension of time. When there is no matter, space time is flat, and the shortest distance between any two points will be a straight line. But in the presence of matter, the shape of space time is altered, making the shortest distance between two points a curved line, which is also known as a 'Geodesic'.

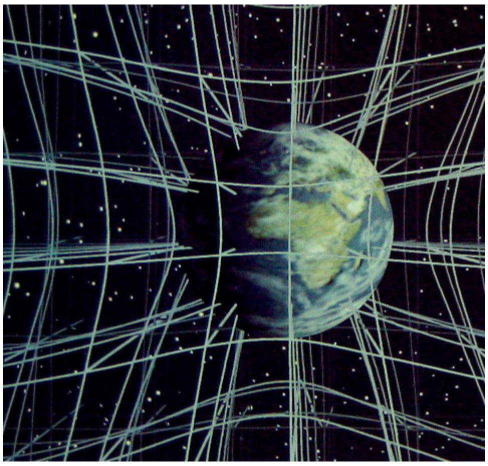


Figure 1: Curved space-time in presence of mass. Source:- Forbes.com

If there are two giant masses orbiting around each other, it results in the formation of ripples in space time which is called as gravitational waves. These ripples move with the speed of light. The farther they move away from their source, the weaker they get. Hence the gravitational waves which are detected are very weak due to various reasons, but are good source of information.

In 1916, Einstein predicted that two bodies orbiting each other would not be in the same orbit all the time, instead they lose energy and in doing so emit gravitational waves. According to his mathematics he showed that two massive accelerating objects such as neutron stars or black holes, while orbiting each other, generate ripples and disrupt the space time causing waves which propagates in every direction away from the source. These ripples carry information about their origin and about gravity as well. The strongest gravitational waves are generated due to colliding black holes or neutron stars. After half a century, the first indirect proof of gravitational waves was given in the year 1974 when astronomers Jocelyn Bell and Antony Hewish discovered a pulsar which produced a gravitational wave. After this they observed how the stars changed their orbit as the time passes. They observed that the stars were getting closer to each other at the rate which was predicted by Einstein in his General Theory of Relativity by producing gravitational waves.

On September 14, 2015, LIGO detected a signal which was due to the collision of two massive black holes which occured 1.3 billion years ago. After analyzing the phenomena, it was observed that the wave was caused due to the objects which are 29 and 36 times more massive than the sun, orbiting with a speed of $58.33\,ms^{-1}$ just before they collided. The gravitational waves which were generated near the source were very large but by the time they were detected here on earth, their strength was so small that their effect on the LIGO was 10000 times smaller than a Proton.

2 Linearized theory of Gravitational waves

Linearized theory of Gravitational waves is a basic understanding of gravitational waves based on an assumption that any perturbation in space time can be approximated to a linear factor whose degree is One. This simplifies the calculations a lot. More over since the sources of gravitational waves are very far away, the effects they produce here on earth will be very small. So we can neglect the higher degree of perturbation and linearize it to the first degree.

Einstein's field equations are a set of ten tensor equations which describe gravity as a curvature in space time. Below equation is one among them:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{1}$$

This is a tensor equation which describes gravity in terms of Einstein's tensor, $G_{\mu\nu}$ which is directly dependent on the geometry of space-time which is altered by the stress-energy tensor $T_{\mu\nu}$. Another field equation that relates the geometry or curvature of space-time to stress-energy tensor is

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{2}$$

where $R_{\mu\nu}$ is the Riemann tensor which describes the curvature of space-time, R is the scalar curvature and $g_{\mu\nu}$ is the gravitational field tensor. Any change in matter distribution will be recorded in in $T_{\mu\nu}$. So if $T_{\mu\nu}$ changes then according to equation 2, gravitational field tensor $g_{\mu\nu}$ also has to change. If $h_{\mu\nu}$ is the perturbation induced in space-time then the new gravitational field tensor $\tilde{g}_{\mu\nu}$ is given by [1]

$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + h_{\mu\nu} \tag{3}$$

To get the new gravitational field, the field equation should be solved for $\tilde{g}_{\mu\nu}$ which gives

$$\tilde{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2}\, \eta_{\mu\nu}\, h^{\alpha}_{\alpha} \tag{4}$$

where $\eta_{\mu\nu}$ is the gravity where space is flat i.e. $\eta_{\mu\nu} = g_{\mu\nu}$ and h^{α}_{α} is summed for all spatial coordinates i.e. α takes values $(1, 2, 3)$ which corresponds to (x, y, z). The admitted solutions for this variations in space time $\tilde{h}_{\mu\nu}$ has solution in the form of

$$\tilde{h}_{\mu\nu} = A^{\mu\nu}\, e^{ik_\alpha x^\alpha} \tag{5}$$

This is a 3D wave equation where $A^{\mu\nu}$ is the Amplitude tensor, $i = \sqrt{-1}$, $k_\alpha = (k_x, k_y, k_z)$ is the wave vector and $x^\alpha = (x^1, x^2, x^2) = (x, y, z)$ is the position vector.

Thus we can say that whenever a body causes disturbances in the curvature of space-time, these disturbances travel through space in the form of waves whose speed is equal to the speed of light.

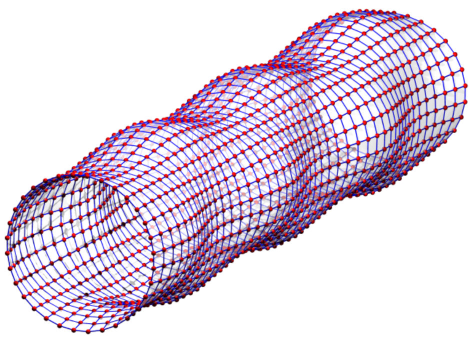


Figure 2: A computer simulated 3D Gravitational wave. Source:- Universetoday.com

3 Properties of Gravitational waves

In this section we shall know about the properties of gravitational waves. Gravitational waves can be characterised by its frequency, amplitude and period. They propagate with the same speed as that of electromagnetic waves. Unlike Electromagnetic waves, the wavelength of GW's can range from a kilometer to the size of the universe itself. Since the wavelength of gravitational waves is larger than the source, they cannot be used for imaging. In contrast to electromagnetic waves which are polarised at 90 degree, i.e orthogonal plane polarized EM waves have their plane 90 degrees apart, where as for polarized gravitational waves the plane of polarization will be 45 degree apart, which will be discussed in the next session. GWs do not interact with matter, but electromagnetic waves do. Electromagnetic waves are known to exhibit a wave-particle duality nature unlike Gravitational waves, the nature of which is still unknown. Although there are quite a few similarities between these two, gravitational waves open a new different window to view the universe. [2]

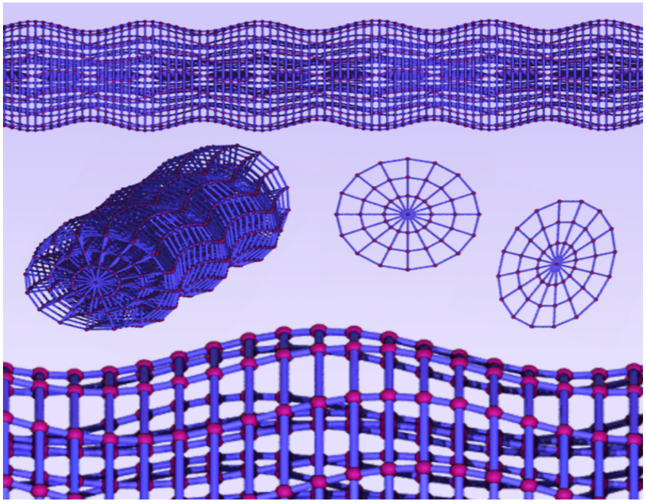


Figure 3: Propagation of GW wave. Source :- Einstein-online.info

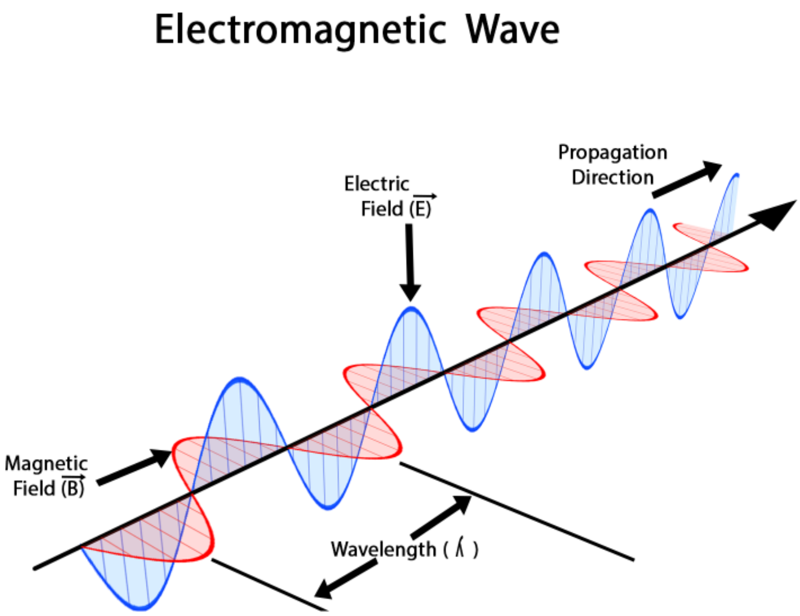


Figure 4: Propagation of EM wave. Source :- Topper.com

3.1 Polarization of Gravitational waves

Gravitational waves can also be polarized. Since they are three dimensional waves their polarization can be restricted to two forms where the the amplitude tensor $A^{\mu\nu}$ has two forms $A_{+}^{\mu\nu}$ and $A_{\times}^{\mu\nu}$ which are orthogonal to each other [3]. They can be represented as

$$A_{+}^{\mu\nu} = h_{+}\,\varepsilon_{+}^{\mu\nu} \tag{6}$$

$$A_{\times}^{\mu\nu} = h_{\times}\,\varepsilon_{\times}^{\mu\nu} \tag{7}$$

where $\varepsilon_{+}^{\mu\nu}$ and $\varepsilon_{\times}^{\mu\nu}$ are unit polarization tensors.

$$\varepsilon_{+}^{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

$$\varepsilon_{\times}^{\mu\nu} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{9}$$

In general relativity any tensor with indices $\mu\nu$ is a rank 2 tensor with 4 rows and 4 columns where each index can take values of space time coordinates which are (t, x, y, z). And position of each element of the tensor is associated with any two of those coordinates. So in such tensors, the positions of elements are associated with space-time as follows:

$$\mu\nu = \begin{bmatrix} tt & tx & ty & tz \\ xt & xx & xy & xz \\ yt & yx & yy & yz \\ zt & zx & zy & zz \end{bmatrix}$$

So when we compare the unit polarization tensors $\varepsilon_{+}^{\mu\nu}$ and $\varepsilon_{\times}^{\mu\nu}$ with the above one, we see that in $\varepsilon_{+}^{\mu\nu}$ the non zero entries are $+1$ in 'xx' direction and -1 in 'yy' direction, hence the $A_{+}^{\mu\nu}$ amplitude is oriented only along X and Y axes. Thus this gravitational wave which oscillates along X and Y axes is called a 'PLUS' polarized wave because the vibration resembles '$+$' symbol. But in $\varepsilon_{\times}^{\mu\nu}$ the non zero entries are $+1$ in 'xy' direction and -1 in 'yx' direction, hence the $A_{\times}^{\mu\nu}$ amplitude is oriented in the 'XY' plane at a an angle of 45° to the axes, thus this gravitational wave which oscillates in the 'XY' plane at a an angle of 45° to the axes is called as 'CROSS' polarized wave because the vibration resembles '$\times$' symbol. So the equation of polarized gravitational waves are:-

$$(+)\text{ wave} \Rightarrow \tilde{h}_{\mu\nu} = h_{+}\,\varepsilon_{+}^{\mu\nu}\,e^{i(\omega t - k_z z)} \quad \text{and} \quad (\times)\text{ wave} \Rightarrow \tilde{h}_{\mu\nu} = h_{\times}\,\varepsilon_{\times}^{\mu\nu}\,e^{i(\omega t - k_z z)}$$

Here the position variable is just 'z', assuming that the wave is travelling along z axis and space-time is oscillating in the X-Y plane, which helps us to visualize polarized GWs easily.

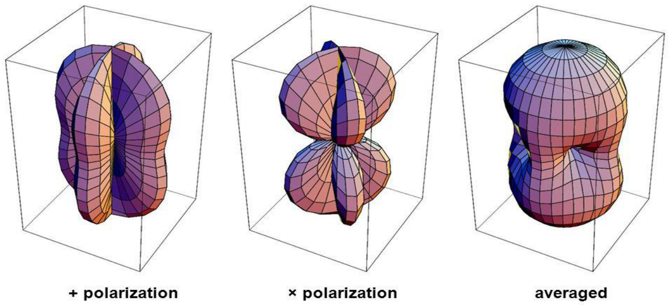


Figure 5: Simulation of Polarized Gravitational waves. Source:- Sudonull.com

3.2 Effect of Gravitational waves on objects

Gravitational waves carry the fluctuations of space along with them. So if they move through an object, since space itself will oscillate, even the object which which is present in that space will oscillate according to the wave. Thus the shape of object will change periodically.

3.2.1 Plus polarized effect

When a plus polarized wave passes through the object, since such gravitational wave makes space-time oscillate in X and Y axes only, so the points in space along the 'X' and 'Y' axes will come very close at a during compression and go very far during stretching. Thus the object itself will be compressed and stretched along the axes, perpendicular to the direction of propagation of wave.

3.2.2 Cross polarized effect

When a cross polarized wave passes through the object, since such gravitational wave makes space-time oscillate along the lines which are at an inclination of 45° with X and Y axes (i.e. along the lines $x = y$ and $x = -y$), so the points in space along those lines will come very close during compression and go very far during stretching. Thus the object itself will be compressed and stretched along those lines, perpendicular to the direction of propagation of wave.

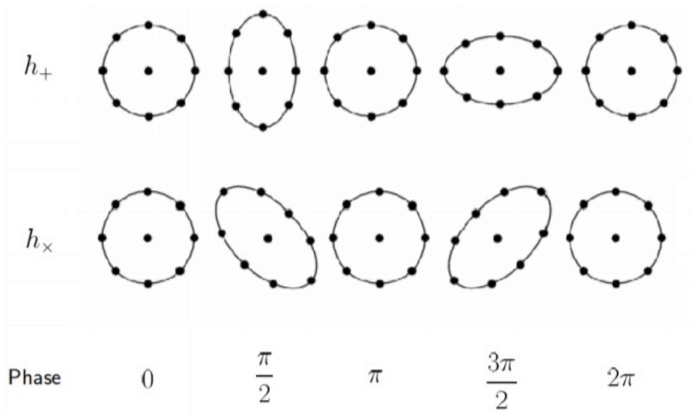


Figure 6: Shape of the object when gravitational wave passes through it when the phase difference of wave changes by $\pi/2$. Source :- Pg. 19 of [4]

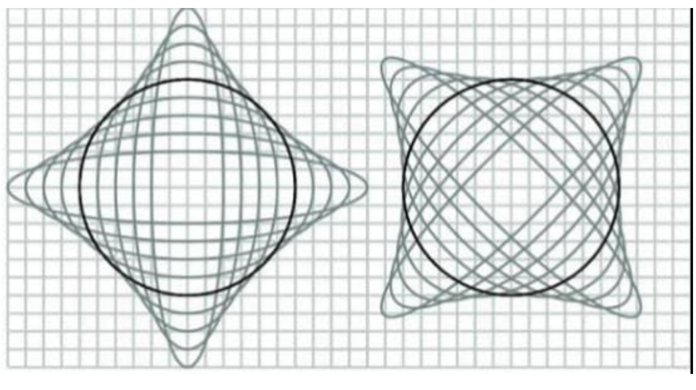


Figure 7: Plus and Cross Polarization of GW. Source :- Pg. 6 of [5]

3.3 Energy transported by gravitational wave

When sources produce gravitational waves, it is their energy which will be transformed to Gravitational waves. And since generally the sources are very massive, energy of gravitational waves fromed by them will be very large. Moreover as the gravitational waves travels at the speed of light, the energy is also transported at that speed. Now, energy flux of gravitational waves is equal to the product of their energy and speed, so the average energy flux 'E' is given by [6]

$$E = \frac{c^3}{16\pi G} \left\langle (h_+)^2 + (h_\times)^2 \right\rangle \tag{10}$$

We see that energy flux is very huge because of the term $\frac{c^3}{16\pi G}$ which is in the order of 10^{33} Joules sec/ metre^2 and it also depends on the average of the square of the plus and cross polarized amplitudes 'h_+' and '$h_\times$'.

Due to such huge energy it carries, the wave can travel unimpeded forever through space and no obstacle can dampen the gravitational wave because the space in which the obstacle lies is itself the medium of the wave. But the Doppler effect and decrease in amplitude due to radiation of energy cause the wave to die out after the wave travels a very long distance according to the relation $Amplitude \propto \frac{1}{r}$.

So the power or intensity of gravitational wave decreases as it moves through space according to this inverse square law i.e. as the wave moves in space through a distance 'r' the energy of the wave will be spread-out in space across a sphere of radius'r' whose surface area is given by $4\pi r^2$. Since the intensity of wave is equal to energy over time, intensity reduces as r^2 [7].

$$E_{flux} = \frac{Energy}{Area} = \frac{E}{4\pi r^2}$$

$$E_{flux} \propto \frac{1}{r^2}$$

But since $E_{flux} \propto Amplitude^2$ we get the relation that $Amplitude \propto \frac{1}{r}$. i.e amplitude decreases as distance from source increases.

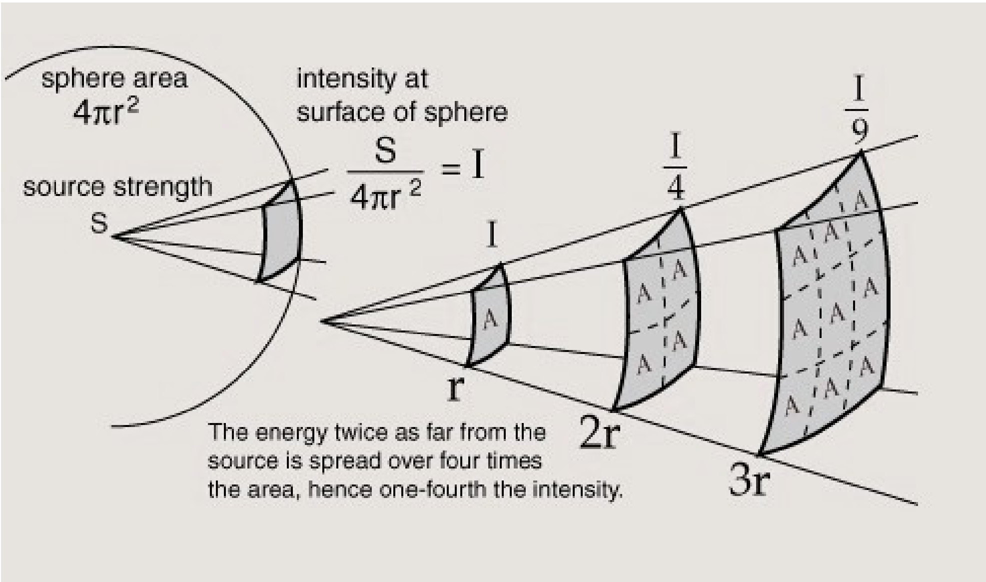


Figure 8: Here we see how the intensity of wave changes as it goes farther from the source according to the inverse square law. Source :- The Mysearch Website

4 Sources of Gravitational waves

The theory of general relativity predicts that gravitational waves can be generated by any dynamically changing system containing moving objects by producing radiation-reaction forces in their source i.e. waves will be generated and carries the exact rate of energy which is extracted from the source. Gravitational waves can be produced by an object which is accelerating or by binary revolving systems like merging black holes, neutron star or by primordial black holes, etc. A common feature in all sources is that they distort space-time curvature, thus radiate gravitational waves.

4.1 Single accelerating object in space

Accelerating objects like pulsars can create gravitational waves [8]. According to general relativity, mass creates stress in space-time and thus can change the geometry of it by bending and changing the curvature. If this object moves, the curvature also moves along with it. But if the object accelerates in space-time in a circular manner, then the object creates ripples in space-time which radiates as gravitational waves. This is similar to creation of water waves when we move our finger in a circular fashion in water. So higher the mass of the object and it's acceleration, stronger the gravitational waves produced. [9].

Any imperfections on the continuously spinning bodies like pulsar produce continuous gravitational waves, where its nature is sinusoidal for a longer period of time. This happens only if the spin rate of this object is constant. Such gravitational waves have same frequency and amplitude but are yet to be discovered.

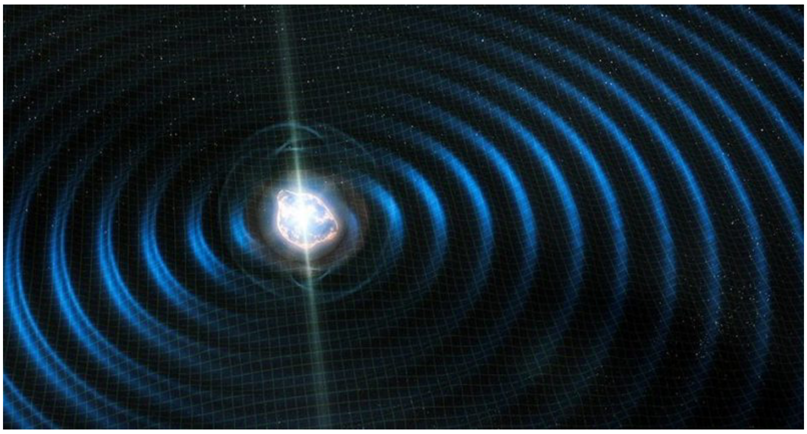


Figure 9: Continuous gravitational wave by a pulsar. Source :- Earthsky.org

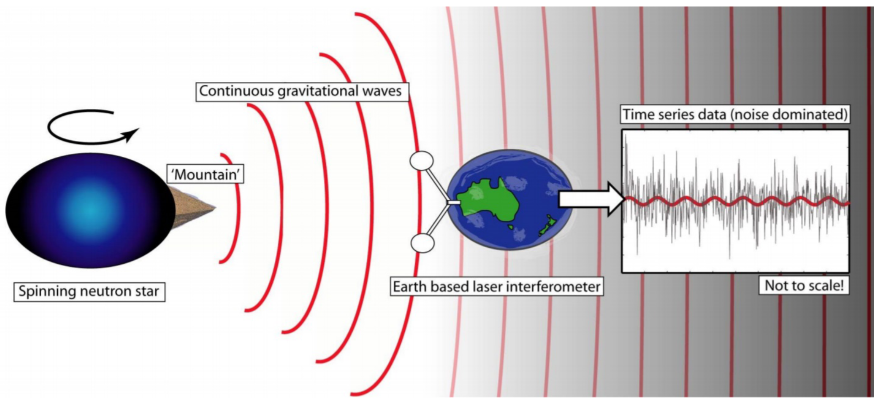


Figure 10: A rotating pulsar. Source :- indico.cern.ch

4.2 Revolving Binary Systems

Revolving binary systems are a very high energy systems which are formed when two massive objects orbit around their common centre of mass called barycenter. They are a very good source for gravitational waves because of their unique nature. Average total mass of such systems are usually greater than 30 solar masses. And average loss of energy per second by such systems will be every high which will be converted to gravitational waves. Thus gravitational waves from such systems will have very high energy which can be detected. Such systems create the gravitational waves by a mechanism called 'Inspiral' [10]. There are four phases in this mechanism :

Interlocking phase :- This is the longest phase where the bodies come closer and get interlocked by their gravity and each start to revolve around their barycentre

Spiral phase :- Here the objects start getting closer as they revolve. Due to the decrease in the distance between them the orbital energy is decreased and is radiated as gravitational waves. But as they come closer and closer, they loose more and more energy, thus the intensity of gravitational wave increases.

Merger phase :- During this phase, the bodies collide by producing immense gravitational waves and merge [11].

Ring-down phase :- Finally, the merged bodies become stable and the gravitational wave intensity decreases exponentially and they stop producing gravitational waves.

Revolving binary systems produce compact binary inspiral gravitational waves. This is because the intensity of gravitational waves increases slowly during interlocking phase, and exponentially during the spiral phase, then it reaches a peak in merger phase, and finally it decreases rapidly to zero during ring-down phase. The detectors are capable of recording the signal only for a small range of frequency, So in this wave form, the frequency comes to the detecting range and rapidly goes out of range. Thus the signal strength suddenly increases and stops. So far most of the detected gravitational waves are of this type.

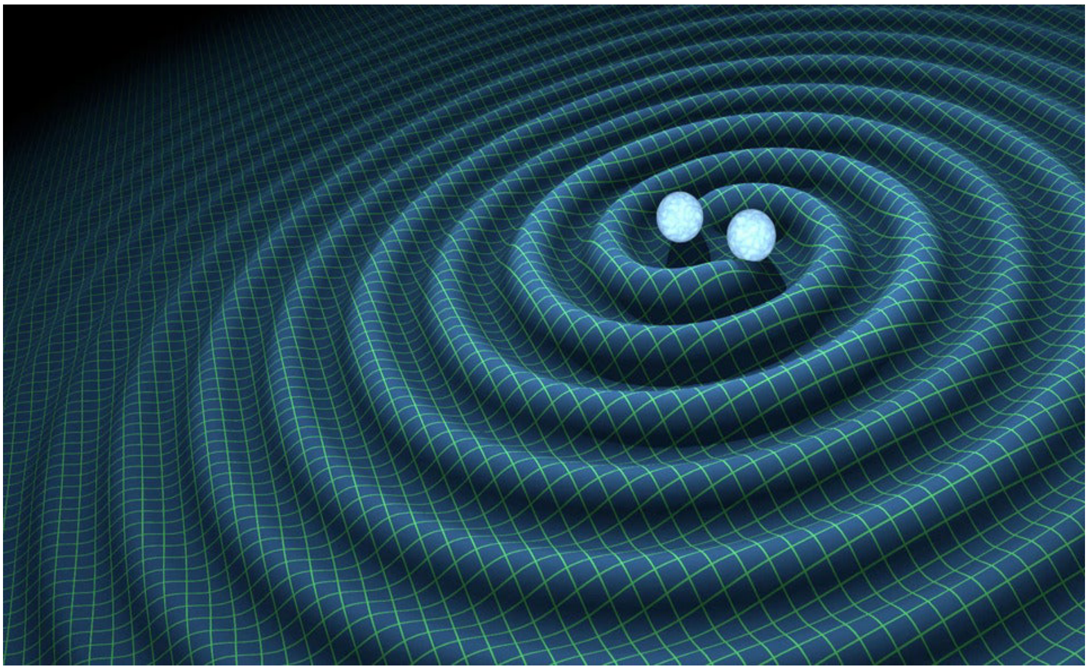


Figure 11: Two massive bodies in inspiral mechanism. Source :- Scientificamerican.com

4.2.1 Binary Black Holes (BBH)

Black holes are massive objects that can warp space-time extensively. If two black holes get closer and start the inspiral mechanism ,they create ripples in space-time and radiate gravitational waves. Such gravitational waves were the first ones to be detected by LIGO in 2015, September 14th. It was estimated that the collision occurred 1.3 billion years ago, thus the merger occurred 1.3 billion light-years away. This merger was named as '**GW150914**' meaning, "Gravitational Wave detected on 15/09/14". This signal lasted for about half a second.

4.2.2 Binary Neutron Stars (BNS)

Neutron stars are dense stars formed by the remnants of a star exploding as a supernova. So, when two neutron stars merge through inspiral mechanism, they can radiate gravitational waves. First BNS merger was detected on 17th August 2017 and this was named as '**GW170817**'. It was analyzed by both electromagnetic waves (Gamma ray) and gravitational waves. The signal lasted for comparatively longer duration for about 100 seconds, thus the mass was estimated to be lesser than black holes and was recognised as a neutron star merger. [12]

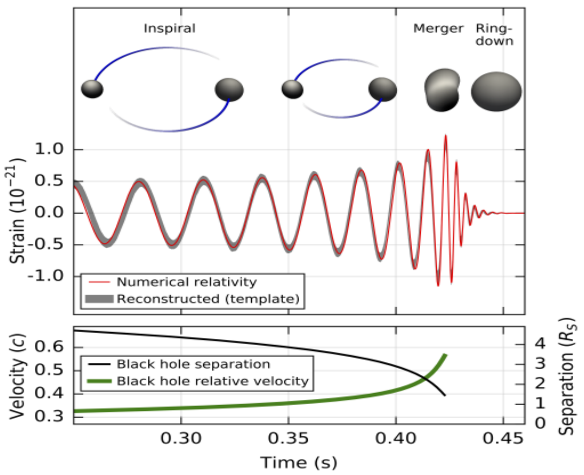


Figure 12: Characteristics of GW150914. Source:- LIGO.org/Publications

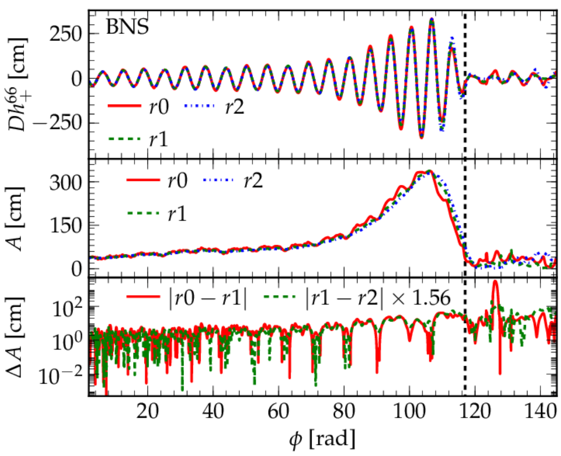


Figure 13: Characteristics of GW170817. Source :- Pg. 24 of [12]

4.3 Gravitational Waves from Collision of Neutron Stars

4.3.1 The First BNS Merger Detection: GW170817

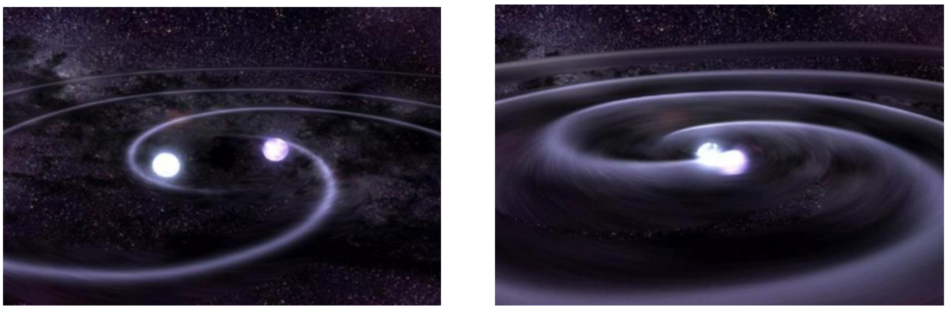
The stage was set, LIGO's second observation run 02 was coming to a close. When one week was left, on 17th august 2017, the LIGO and Virgo observatory came online and detected a Gravitational Wave (GW170817). Two seconds after the LIGO and Virgo GW detection, the fermi satellite detected a burst of gamma ray radiation (GRB170817A). So loud, you can see it by eye (SNR=32.4). This alerted telescopes and satellites all over the world, which gave the beginning to the most studied astronomical event (-1225 days).

4.3.2 The origin of the GW170817

135 million years ago, two neutron stars were spiralling faster and faster towards each other, stretching and squeezing space-time which created distortions in the fabric, i.e., gravitational waves. As soon as they reached the distance between Atlanta and Nash-field, they started merging. When they merged a huge explosion of gamma ray radiation was produced. In the last $\frac{1}{10}^{th}$ of a second, the energy released by these stars were 50 times greater than anything else in the universe. Theses waves reached earth after travelling billions of light years at the speed of light. We interpret the component masses of these stars to be between $0.86M_{\odot}$ and $2.26_{\odot}$, in agreement with masses of neutron stars. It's the closest and most precisely calculated gravitational wave signal yet. This gravitational wave signalises loudest yet observed, with a combined signal to noise ratio of 32.4. After the study conducted, it led to look at an area of 28 $\deg^2$ which led to the discovery of its home NGC 4993. Normally we believe that if neutron stars merge and form heavier neutron stars which spin rapidly and generate a very strong magnetic field. But it lead to the formation of lowest mass black hole ever found.

4.3.3 The dynamics of neutron-star binaries and collision

The initial coordinate separation between the maxima in the rest-mass density is 45 km. The neutron stars inspiral with increasing angular velocity, which deforms each of them tidally. This increases the inspiral rate as it depends on total angular momentum of the system.

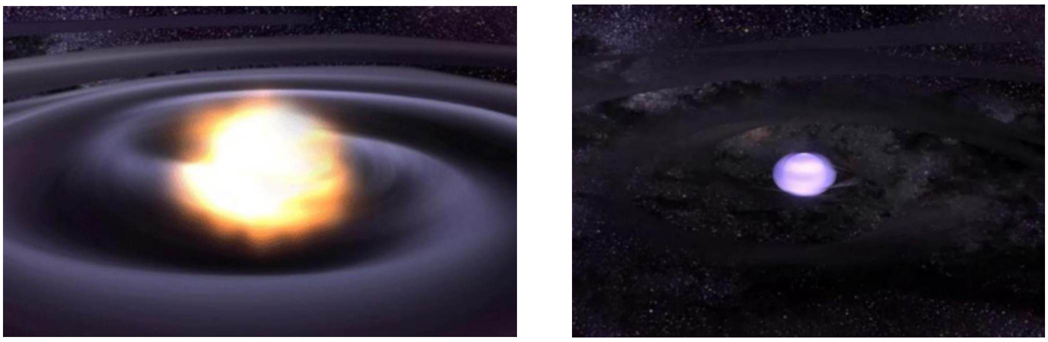


(a) (b)

Figure 14: (a) Neutron stars in inspiral mechanism. (b) Neutron stars in merger phase.

During the merger, when regions of the neutron stars with density less than their maximum density come into contact, the tangential components of the velocity exhibit a discontinuity. This can develop an instability called the Kelvin-Helmholtz instability, which leads to the overall amplification of the magnetic field. Such high magnetic fields are seen in magnetars and short hard gamma-ray bursts, which are the consequences of the neutron star collision.

After the merger, the cores of the two neutron stars combine into one and the central rest-mass density starts increasing. The maximum rest-mass density then increases exponentially, and the object collapses to a rotating black hole. This was seen in the detection of gravitational wave-GW170817.



(a) (b)

Figure 15: (a) Neutron stars after merging. (b) Neutron stars in ring-down phase.

In accordance with the dynamics of the neutron-star binaries, during the inspiral, gravitational wave forms increase in amplitude and in frequency. The wave forms after the merger have more variation and finally they try to become a stable body, thus even the emission of gravitational wave decreases exponentially with time. Hence, in many cases, the wave forms after the merger mostly terminate during the ring down. The ring down signal for black holes formed in binary neutron star mergers is at frequencies of the order of kHz and cannot be detected by the present detectors so easily. The post-merger signal is at lower frequencies than the ring down. Here we have a picture of waveform of gravitational waves emitted from a neutron stars merger where axes represents strain in space vs time in various modes. Initially the strain which signifies the frequency of waves, and its amplitude is small which increases slowly with time, reach a peak in merger phase, then abruptly become zero during ring down phase.

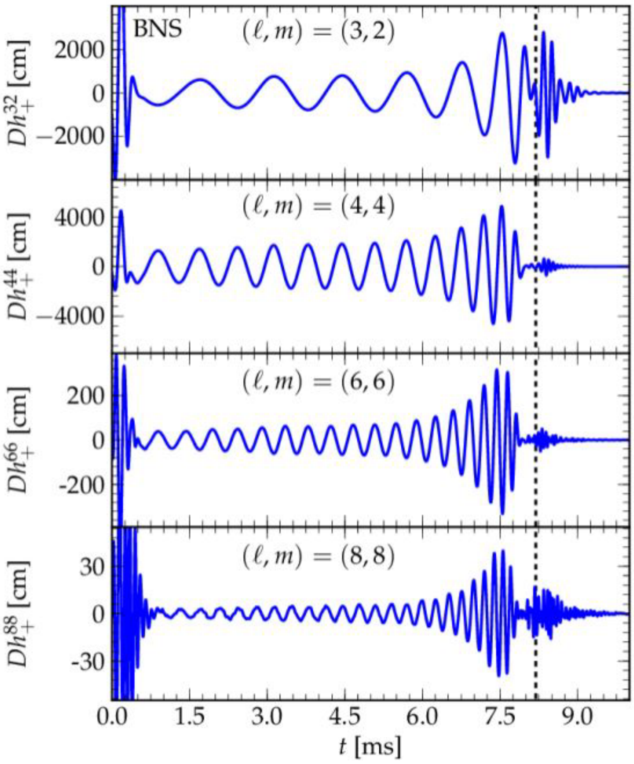


Figure 16: Gravitational Waveform by Neutron star collision. Source :- Pg. 23 of [12]

4.4 Primordial Black Holes

Primordial Black Holes (PBH) are hypothetical black holes thought to have formed in the early universe due to the gravitational collapse of highly dense regions. Since these black holes don't have the usual star as a progenitor, their masses can be lower than the actual mass required for forming a normal black hole. They were first theorized by Yakov Barisovich Zel'dovich and Igor Dmitriyevich Novikov in 1966, and theories of their origin were studied by Stephen Hawking in 1971. [13]

4.4.1 PBH and Stochastic Gravitational Waves

In the early universe, quantum fluctuations made the inflaton field highly unstable and non-uniform. In rare cases, these fluctuations might have spiked high enough to form energetic peaks which then collapse to form PBHs. This phenomenon would also result in the generation of a stochastic GW (discussed in the next section) background. But, to form such a background, a sufficient number of PBHs are required, which is only possible if the amplitude of the fluctuations are high enough at small scales. [14]

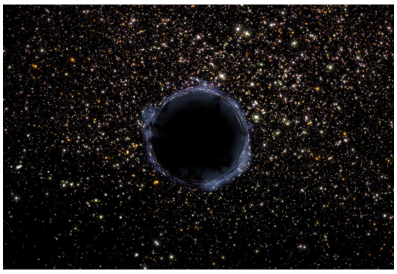


Figure 17: Computerized image of a primordial black hole.
Source:- Astronomy.com

Related with PBH and stochastic GW is the concept of cosmic horizon reentry. As the universe expands, represented by the scale factor a, comoving length scales[1] between two objects grow along with it. During inflation, a grows exponentially, $a(t) \sim e^{Ht}$, where H is the Hubble constant. But, the horizon stays nearly constant during inflation. Now, the quantity $aH = \dot{a}$ tells us, through its variations in time, whether the comoving length scales grow at a greater or lesser rate than the horizon. During inflation, $a\dot{H} = \ddot{a} > 0$, so the comoving scales grow larger than the Hubble horizon, and after inflation, $a\dot{H} = \ddot{a} < 0$, so the horizon overtakes the comoving lengths, thus an object which was moved outside the horizon during inflation is back inside the horizon. This phenomenon is called Cosmic Horizon Reentry.

The survival of oscillation modes of the inflaton field depend on this phenomenon. The modes which leave the horizon and reenter it undergo a 'classical-to-quantum' transition, which transform them into curvature perturbations. These are the perturbations which have the chance to get highly energetic and yield PBH and the stochastic GW. The modes which never leave the horizon don't undergo the transition, so they don't have a major impact on the inflaton field. [15]

4.4.2 PBH and Gravitational Wave Bursts

If in a small region, numerous curvature perturbations collapse, then a cluster of PBH could form. They dynamics of such PBH is completely different from that of binary PBH systems. Instead of ending up in traditional bound systems and spiral in, majority of PBHs in a cluster would produce a single scattering event via a hyperbolic encounter, only if their relative velocity or relative distance is high enough to escape getting captured into bound systems. Such events would produce bursts of GWs, which can be detected up to several Gpc.

In hyperbolic encounters, majority of the energy is released near the closest approach. This has a characteristic peak frequency, which mainly depends on the impact parameter b, the eccentricity e and the total mass of the system M. These encounters has a duration of the order of a few milliseconds to several hours. GWs from such encounters have very different properties and signature when compared to those from traditional binaries, so detecting them would strengthen the possibility of the existence of PBH. [16]

[1]Comoving length scales/distances are the measure of distances between fundamental observers, i.e, observers that are moving with the expansion of the universe (Hubble Flow), and doesn't change with time.

5 Types of Gravitational Waves

Gravitational waves are produced by each and every body which is accelerating, for e.g. moving cars, air planes, humans, etc. However, they are too small to be noticed and detected with our current technology. In order to study gravitational waves, we need to look at objects which are massive and much more bigger than our own solar system like black holes, neutron stars, or huge stars at the end of their lives like gamma ray bursts, pulsars, orbiting black holes, rapidly spinning neutron stars, etc. In fact our universe is filled with many such objects which produce gravitational waves with a significant amplitude and energy.

Gravitational wave sources have been divided into the following categories:-

1. **Short duration sources :-** Compact binary coalescence, supernovae, gamma ray burst.
2. **Continuous sources :-** Pulsars, magnetars, rapidly spinning neutron stars, low mass X Ray binaries, super massive black hole binaries.
3. **Stochastic sources :-** Metric fluctuations generated in the very early universe.

To understand gravitational waves better, LIGO scientists have divided the waves in four categories. The division of the gravitational waves is based on their sources and their characteristic vibration as detected by the interferometers. They are divided into Continuous, Compact Binary Inspiral, Stochastic and Burst Gravitational waves. This section was referred by [9], [17], [18], [19]

1. **Continuous Gravitational Waves**

   Such gravitational Waves are produced by objects that have constant frequencies and amplitude like a single spinning neutron star. Neutron stars are basically a result of the supernova explosion of a massive star, combined with gravitational collapse, that compresses the core so much that the star density becomes same as that of atomic nuclei. Radius of neutron stars are in the order of 10 kilometers, and mass is around 1.4 Solar masses. So density will be around $10^{17}\,\mathrm{Kgm}^{-3}$. The properties of the gravitational waves depend on the spin rate of the star. Therefore, If the spin rate is constant, the properties of gravitational waves (frequency and amplitude) will also remain constant i.e. *continuous*. Spinning neutron stars that possess asymmetric deformations or imperfections in their space produce gravitational waves as it swiftly rotates about its axis. The reasons or effects which can produce asymmetry could be Accretion (large mountain), Magnetic deformations or Pulsar glitches.

2. **Compact Binary Inspiral Gravitational Waves**

   Most of the waves detected so far by LIGO are part of this category. Compact Binary In spiral Gravitational Waves are formed by orbiting pairs of massive objects like neutron stars or black holes. There are three kinds of systems in this category of gravitational wave generators where each one has different characteristics. They are Binary Black Hole system (BBH), Binary Neutron Star system (BNS) and Black Hole-Neutron Star binary system (BHNS). The main phases involved in such systems are spiral, merger and ring-down.

   Let us start by considering two black holes orbiting each other. Initially they are widely separated, spiral occurs over millennia and with each revolution, they emit very weak gravitational waves. Slowly as the energy is lost from the system in the form of gravitational waves, the binary is thus pushed into an orbit with smaller radius and higher orbital frequency. Thus the distance between them decreases and their speeds increase. This causes the frequency of the gravitational waves to increase. Now comes the Merger stage where the black holes come very close and are about to collide to form a single black hole and the black hole thus formed has large distortions in its shape. The strongest gravitational waves are emitted during this process. The distortions thus formed are radiated away as more gravitational waves during the ring-down phase and an undistorted but rotating black hole is left behind. Due to the increase in frequency, the pitch also increases and as a result these gravitational waves would produce a chirp sound. Current results indicate that compact binary objects may well be the most promising sources of gravitational waves rather than supernova collapse.

3. **Stochastic Gravitational Waves**

   These types of waves are generated from random sources, typically arising from a large number of unresolved and uncorrelated events and thus they are the most difficult gravitational waves to detect. Stochastic Gravitational Waves are believed to be the result of processes that took place shortly after the big bang. Just like the Cosmic Micro-wave Background (CMB), these gravitational waves arise from a large number of independent, random events merging to create a cosmic gravitational wave background. Due to their random motion, these waves are the most smallest, that's why the final signal has stochastic nature and the difficult to detect with our current technology. These waves may be analyzed statistically but they cannot be predicted precisely. Detecting these gravitational waves from the Big Bang could allow us to see back in the history of the Universe.

4. **Burst Gravitational Waves**

   Of all the types of gravitational waves, these waves come from the sources which are yet to be known and thus the form of waves which will be produced is also unexpected. Burst gravitational waves come from short-duration unknown sources. Since we are unfamiliar with these sources, thus its modelling is a big challenge since these will not have well defined properties which are known earlier to us like those of compact binary inspiral waves. Some believe that these waves are produced from systems like supernovae. They are believed to have a 'pop' and 'crack' sound. However, it is difficult to say anything as of now due to the lack of knowledge about their origin. But if we discover an efficient way to detect such GW, revolutionary information about the universe could be revealed.

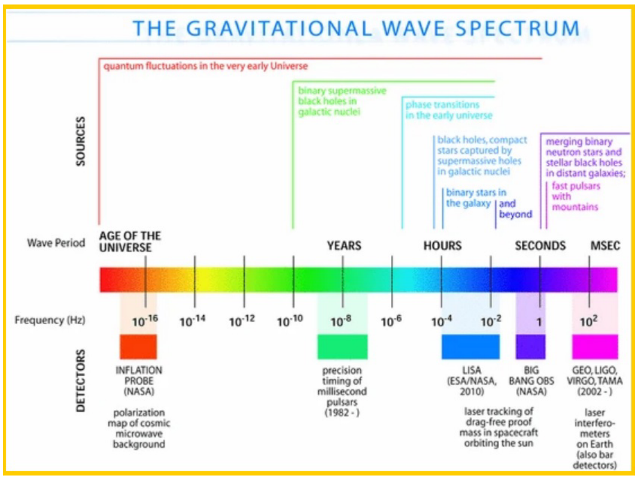


Figure 18: Gravitational Wave Spectrum. Source :- Pg. 9 of [20]

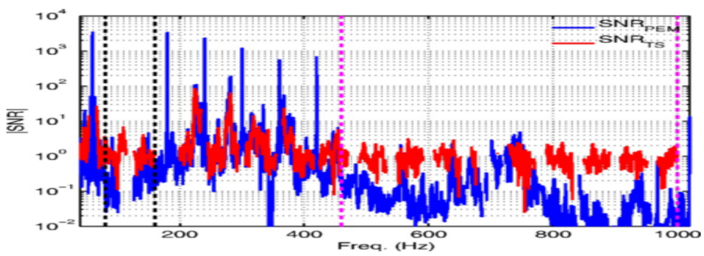


Figure 19: Stochastic gravitational wave form. Source :- Pg. 10 of [21]

6 Why study Gravitational Waves

Gravitational waves are already used as an important member of multi-messenger astronomy and can be used to study in depth many objects or phenomena such as:

- Cataclysmic variables
- Binary Neutron Stars
- Young Neutron Stars (the r-mode instability)
- Low-mass X-ray binaries
- CMB and Galaxy formation

Gravitational waves are emitted by the masses and sent as ripples across spacetime which is completely different from the mechanism of production and transmission of EM waves. Therefore, it could give us more information on the subject matter at hand.

Gravitational waves provide further information about black holes that would otherwise be invisible. Gravitational waves also weakly interact with matter (apart from lensing), thereby reducing energy lost or scattered before reaching the detector. This implies better understanding of inconspicuous regions of space, like the interior of a supernova or the Big Bang.

Uses of their Detection

Gravitational Waves are also used in Astronomy because it allows us to observe the universe in a different way, providing us information about matter such as:

1. Information about the big bang

   Gravitational waves have travelled almost unimpeded through the universe since they were generated (which happened 10^{-24}s after the Big Bang, far earlier than the CMB radiation). Possibilities of non-inflation mechanisms that produce gravitational waves are high. One such possibility could be cosmic strings, which ought to be detectable using gravitational waves. Observations of inspiral compact binaries made by the LIGO/VIRGO experiments can give us a lot more information about the system than just the binary masses and spins.

2. Test the theory of General Relativity

   They can be used for high-precision tests of general relativity. Radiation reaction to some scalar waves in scalar-tensor theories has a signature that can be found with high precision in LIGO/VIRGO.

3. Detection of the Hubble constant

   They can be used to measure the Universe's Hubble constant, deceleration parameter, and cosmological constant.Gravitational waves bring a new window to validate the general theory of relativity and cosmological constant as the perfect/correct theory of gravity and the expanding universe(cosmic acceleration). Hubble's Constant shows the expansion of the Universe by showing how distant galaxies are moving away from us and is given by:

   $$v = H_0 \times d \tag{11}$$

   where, v is the Velocity of a galaxy, in kms^{-1}

   H_0 is the Hubble Constant, measured in $kms^{-1}Mpc^{-1}$

   d is the distance of the galaxy from the earth in megaparsecs(Mpc)

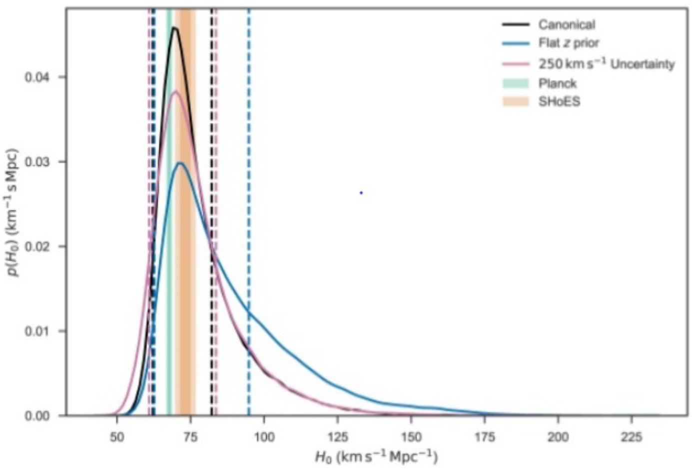


Figure 20: Hubble's Constant using Gravitational waves. Source :- Pg. 3 of [22]

4. Polarization of Gravitational waves

   Gravitational waves carry 2 independent polarizations. A wave will usually have a combination of both. Some sources (rotating) will emit both polarizations with some lag between them. Studying this would give the nature of the source and its rotation.

5. Centrifuge of Binary Stars

   A more careful calculation shows that, for unequal masses, the quadrupole amplitude and the rate of shrinking depend on the masses only through the combination:

$$M = \mu^{3/5} \times M^{2/5} \tag{12}$$

   This is called the chirp mass, where, μ is the reduced mass and M the total mass. The chirp mass can be easily determined if the shrinking time is observed in gravitational radiation. After measuring the amplitude, the only quantity that would not be known to us is the radial distance r from here to the source. By observing the gravitational waves that are produced by shrinking orbits due to loss in energy via gravitational radiation, we can thus obtain the distance to the source. This is another example how gravitational wave observations provide information that is hard to find using electromagnetic waves.

6. Spiralling of Black Holes and Neutron Stars

   For a neutron star or black hole spiralling inwards, the inward spiral has a sort of "map" of it that are emitted in the form of gravitational waves. Analysis of these waves could give information of the body, help determine the type of body(black hole or any other exotic object like a naked singularity) and can be studied better by LISA for low masses and high frequencies as opposed to LIGO/VIRGO that can capture large masses and low frequencies.

Conclusively, we can say gravitational waves provide a new tool for astronomy as well as cosmology and will be ever evolving in terms of types of observations possibly ranging from new ways to test for dark matter and the validity of general relativity with high precision and observations that simply would not be possible with just electromagnetic waves.This also provides an alternate method to validate the cosmological constant, Hubble's constant, and various other uses. This section was referred from these papers [23],[24].

7 Indirect Evidences of Gravitational Waves

Neutron stars are highly compacted cores of dead stars, left behind as remnants of supernova explosion. Pulsars are a unique type of neutron stars that emits beams of electromagnetic radiation out their magnetic poles. The radiation can be detected from earth as blinking of a star through radio telescopes. The radiation is emitted in a periodic pattern so it appears as a pulsed emission of radiation. The discovery of pulsars was made by Jocelyin Bell, a graduate student at Cambridge University in England in the year 1967 who was working under Antony Hewish [25]. She found out a peculiar pattern in the data in the form of regular pulses. This data was different from the radio signals of the celestial bodies that they had detected earlier. At first, they thought that the signal is from some alien civilization so they named them as Little Green Men (LGM) but after few weeks they observed that there were three more objects in other parts of the sky pulsing with different periods, hence they dropped the name Little Green Men and renamed them as Pulsar.

Pulsars are among the strangest objects within the universe. Astronomers and scientists use pulsars as an instrument to detect gravitational waves. Pulsars are still observed by using large radio telescopes. The largest radio telescope in the world is located at Arecibo in Puerto Rico. A telescope scans the entire sky and scientists look for objects that appear in and out. When a pulsar rotates, it produces detectable pattern of radio emission which is very precise and repeats periodically. Its maximum intensity rises and falls every 23 hours 56 minutes. Pulsars spin because the stars from which they are formed also rotated. The slowest pulsar ever detected spins on the order of one rotation per second and the fastest pulsars can spin hundreds of times per second. From earth, pulsars often look like flickering stars - on and off, on and off and they seem to blink with a regular rhythm. But the light waves from pulsars don't actually flicker or pulse. It radiates two steady, narrow beams of light in opposite direction. The light from the beam is steady and pulsars appear to flicker because they also spin at the same time. [25]

Pulsars are considered to be a great tool in determining the existence of gravitational waves.In 1974 the first evidence of gravitational waves was deduced through the motion of the double neutron star system PSRB1913+16 [9]. In this system one of the star is a pulsar which emits electromagnetic pulses at radio frequencies precisely at regular intervals as it rotates. Russell Hulse and Joseph Taylor who discovered this binary pulsars also noticed that the frequency of pulses shortened and the stars were gradually spiraling towards each other with an energy loss which is closely equal to the energy predicted to be radiated by gravitational waves. For this discovery, Hulse and Taylor were awarded the Nobel Prize in Physics 1993 [26]. Further observations of the binary pulsar and other multiple systems also agree with the General theory of Relativity to high precision. This evidence of gravitational waves is considered as the first indirect evidence of gravitational waves.

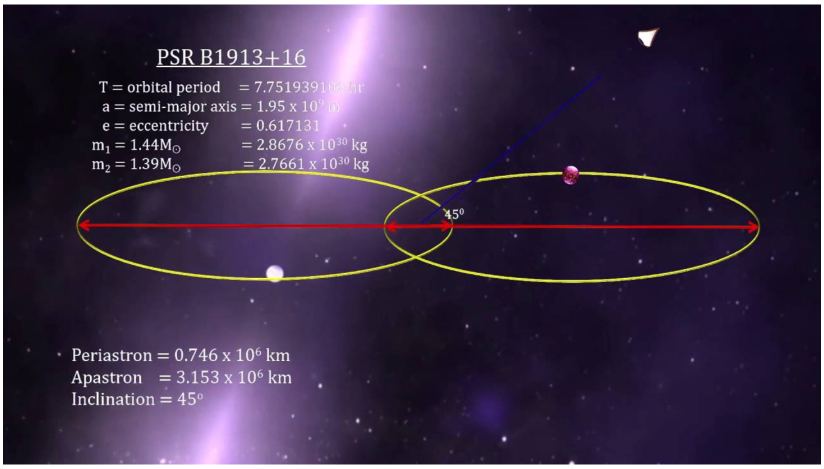


Figure 21: Binary pulsar PSR B1913+16. Source :- Astroblogs.nl

8 Direct search for Gravitational waves

A successful attempt to detect gravitational waves was made by LIGO which stands for Laser Interferometer Gravitational wave Observatory, and was founded by Reiner Weiss (MIT) , Barry Barish (Caltech) and Kip Thorne (Caltech). A joint - initiative to establish LIGO was taken by MIT and Caltech, and was funded by the National Science Foundation(NSF). The construction of the two detection sites at remote locations of Hanford and Livingston, commenced in 1994 and ended in 1999.

Two sites were built instead of one, in order to avoid detection of an anomaly caused by external events at the particular location. In addition to the detection sites, LIGO also includes two primary university research centers; MIT and Caltech. The Initial LIGO project, which used the very first interferometers built for observations, was conducted from 2002 to 2010. During this period, not a single detection was made. Later on, an upgraded version of the same, The Advanced LIGO project was installed over the span of four years, between 2010 to 2014. Within days of initiating observations with newly installed equipment, LIGO made the first successful detection of gravitational waves on September 14, 2015. The gravitational waves which were detected, were known to have originated from the collision of two black holes in a binary system, 1.3 billion light years away. Seeing its success over years, the co-founders were awarded a Nobel Prize in the year 2017.

Currently, LIGO employs around 40 people at each construction site. They are engineers, technicians and scientists who operate and overlook the functioning of the instruments and systems. On the other hand, LIGO engineers at Caltech and MIT work on improving LIGO's stability and sensitivity, and LIGO physicists and astrophysicists interpret the nature of the detected gravitational waves. LIGO's mission is to open a window for a new area of scientific research on gravitational-wave astrophysics. It also conducts public outreach programs in order to provide opportunities for the scientific community to contribute to the enhancement of detectors, observation and data analysis.

8.1 Principle of LIGO

When the gravitational wave reach us, without a doubt, they are only very weak perturbations on our local flat space. Be that as it may, they will provide information about the strong-field regions where they began. They will additionally permit us to decide the wave properties of the gravitational radiation—for ex-sufficient, their spread speed and polarization states [27]. The essential construction of LIGO's interferometers differs a little from the interferometer that Michelson planned more than 125 years prior, however for certain additional highlights. The visible pattern occurring where the coherent waves intersect is simply an "interference" pattern.[28]

8.1.1 Interference Pattern

In nature, the peaks and troughs of one wave cannot absolutely meet the peaks or troughs of another wave. Regardless of how in-sync they are once they merge, the peak of the wave coming out from the interference always equals the sum of the heights of the merging waves on every point wherever they are physically interacting. What dictates how well-aligned the beams are once they merge is the path length they travel before merging. So the core principle of LIGO is interference of light. When the path difference between two light waves is equal to integral multiple of wavelength, then constructive interference occurs where the resultant light will have maximum brightness. And if the path difference is equal to half-integral multiple of wavelength, then destructive interference occurs and resultant light will have minimum brightness.

If the beams travel precisely the same distance, their light waves will be absolutely aligned such that they lead to total destructive interference (LIGO is designed to get total destructive interference if no gravitational waves are detected). But if the lasers don't travel identical distances, their light waves are no longer in synchrony as they merge, which implies no light, a bit light, or a light as bright before the original laser beam reaches the photodetector. And if the arms are changing length over time, a flicker appears as the beams suffer a variety of interference. This time difference is manifested within the interference pattern once the two laser beams superimpose on the path to the photodetector, which can quantify stage movements to ten-billionths of an interference fringe.[27]

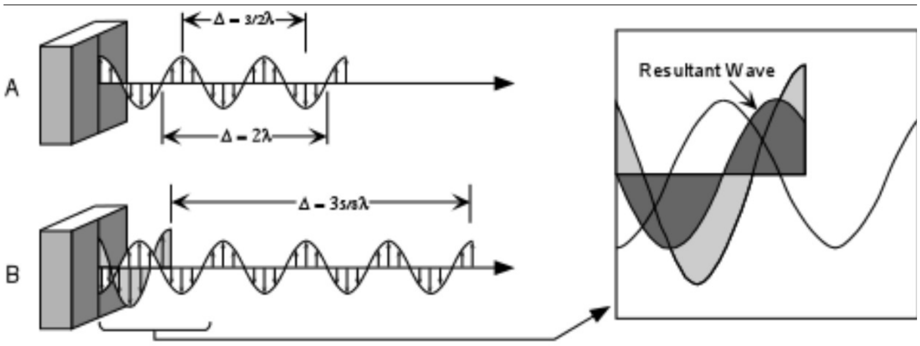


Figure 22: Interference. Source :- Interference Phenomena by Prof. Stephen A. Nelson

8.1.2 Differential mode of vibration

The gravitational waves result in the space to stretch in a direction, at the same time, compress in a direction perpendicular to it. In LIGO, this results in one arm getting longer whereas the opposite gets shorter, then the other way around, back and forth as long as the wave is passing. The technical term for this motion is “Differential Arm” motion, or differential displacement where the arms are differing in lengths at the same time in opposing ways deferentially. Since the lengths of the arms differ, the total path traveled by each laser beam will also differ.

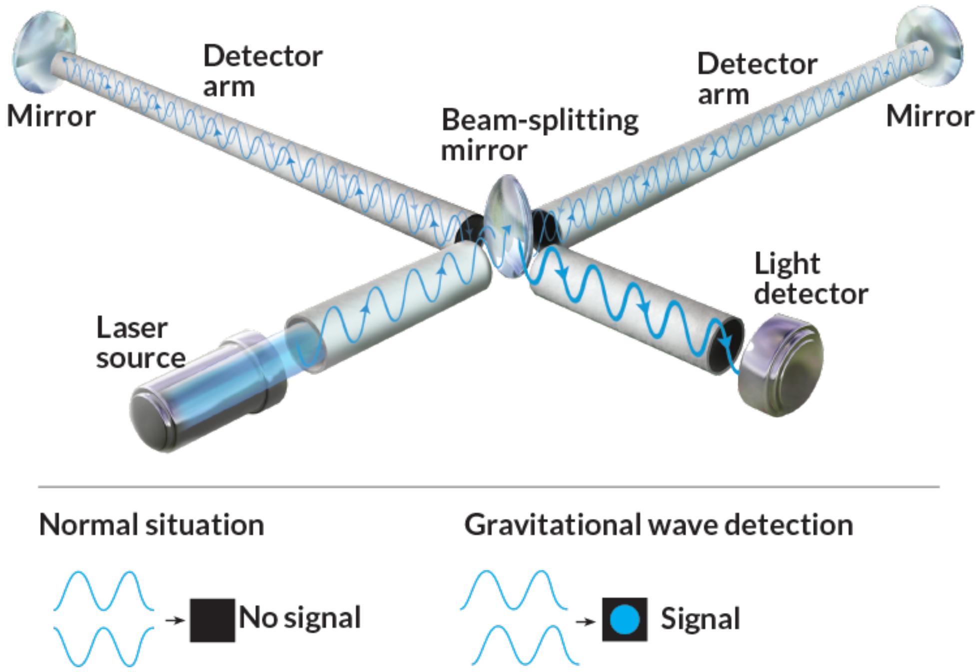


Figure 23: Michelson interferometer. Source :- Sciencenews.org

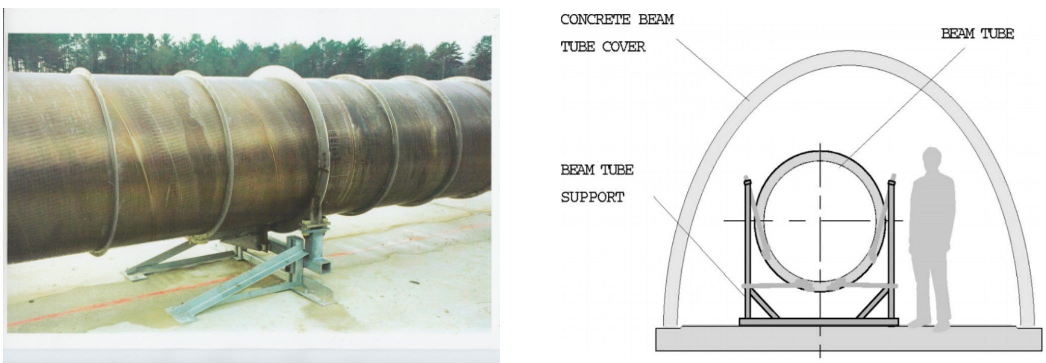
As the lengths of the arms change, so too does the space traveled by each beam. A beam travelling in the shorter arm will return to the beam splitter before the beam which is ravelling in the extended arm, then things switch because the arms oscillate between being longer and shorter. Arriving at different times, the laser beams do not align perfectly when recombined at the beam splitter. Instead, they shift in and out of alignment or "phase" as they merge. One thinf to notice is unlike other telescopes, LIGO doesn’t detect electromagnetic waves. It doesn’t need to because gravitational waves aren’t a part of the EM spectrum. In fact, EM waves are inessential to LIGO that it is completely isolated and sheltered from the surface world.

8.2 Construction

The idea of a laser interferometer to detect LIGO started in the 1960s, where American scientist Joseph Weber and Soviet scientists Mikhail Gertsenshtein and Vladislav Pustovoit, merged their ideas of a basic interferometer based on Michelson's interferometer. In 1967, Rainer Weiss affiliated to Massachusetts Institute of Technology (MIT) published his paper on the analysis of usage of interferometer and with the help of military funding he initiated the construction of interferometer prototype, but it couldn't be completed. In 1968, Kip S. Thorne did extensive research on gravitational waves and their sources at Caltech, he was convinced that interferometers could successfully detect gravitational wave. Thus finally construction of LIGO began in Hanford, Washington in 1994 and Livingston, Louisiana in 1995. The construction was completed by 1997, under the leadership of Barry C. Barish. After successful detection of GW150914, in 2017, Rainer Weiss, Kip Thorne and Barry C. Barish who were the frontiers of LIGO won the Nobel Prize in Physics.
LIGO is constructed in such a way that it can even feel the changes in the weakest fundamental force. Some important parts of this gigantic detector are:-

8.2.1 LIGO arms

LIGO's arms are placed orthogonal to each other which extends for $4\,km$ in two perpendicular directions. The arms of LIGO are made of cylindrical tubes each of $20\,m$ in length and $1.2\,m$ in diameter welded together. The tube is made of 304L-steel with a thickness of $3\,mm$ [29]. This particular material has extremely low carbon content making it relatively resistant to corrosion when compared to other materials. The tubes are evacuated to a pressure of 10^{-10} to $10^{-8}\,torr$. This is to prevent the scattering of laser and also to not allow sound to interfere (as sound can't travel in vacuum). The arm is constantly evacuated by the Ion pumps to maintain the vacuum inside the arms. Initially when LIGO was set-up it took approximately 40 days to fully evacuate the beam tubes, and it was heated to 150°C to remove residual gases. [30]

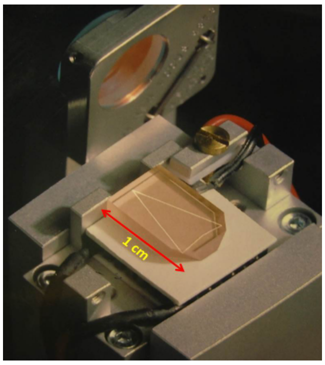


(a) (b)

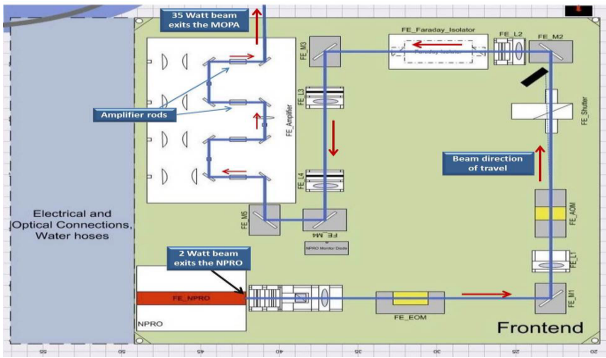
Figure 24: (a) LIGO Beam tube. Source :- [30] (b) C.S view of beam tube. Source:- [31]

8.2.2 Laser system

The laser used in LIGO has Nd-YAG (Neodymium-Yttrium Aluminium Garnet) as its active material and diode as the pump. Initially the laser output is $4\,W$ and wavelength of lasing light is $808\,nm$ wheich is in near infrared range. This light travels through Non-Planar Ring Oscillator (NPRO), from which a $2\,W$, $1064\,nm$ light called seed beam is generated. This is the laser which will be amplified and begins it's journey in the interferometer. The seed beam is then passed through a Master-Oscillator Power Amplifier (MOPA), which consists of four thin rods of $3\,mm$ thick and $5\,cm$ long which is made similar to glass, using Nd, Y, Li and F^{-}. The laser power increases in each of these four rods and finally a 35W laser with the constant wavelength of 1064nm is obtained. It is now further amplified in a High-Power Oscillator (HPO) which is similar to MOPA. This results in an immensely powerful light of 200W. [32]



(a)

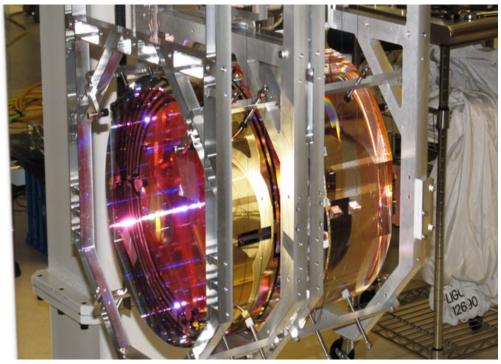


(b)

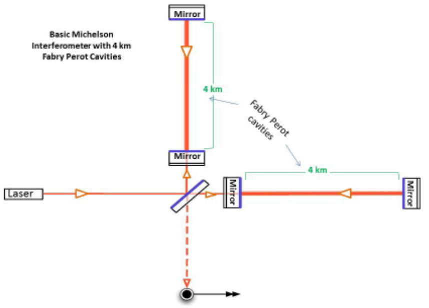
Figure 25: (a) NPRO crystal. (b) schematic representation of laser amplification. [32]

8.2.3 Beam Splitter and Mirrors

Each arm carries two fully reflecting mirrors at its ends and a partially reflecting mirror called as Beam splitter is present at the common vertex of the arms. The space between the mirrors forms a Fabry-Perot cavity. The light travels $4km$ from one end to other, but this cavity makes the laser light to reflect approximately 300 times, so apparently the laser travels a total of $1200\,km$, which increases the laser power to $750\,kW$. The mirrors are coated extensively to nanometer smoothness (i.e the imperfections on the surface of mirror is in the order of nanometers). This is required to make the system very precise to detect even feeble gravitational waves. [33]



(a)



(b)

Figure 26: (a) Fully reflecting mirror[33] (b) Fabry-Perot cavity. Source:- LIGO.caltech.edu

8.2.4 Test mass and Photo-detector

The fully reflecting mirrors are $40\,kg$ each with thickness of $20\,cm$ and width of $34\,cm$ which act as test masses. This test mass is one among three such test masses which are hung to a quadruple suspension system aided by silica fibers. They reduce the effect of noise vibration by 100 million times by the time it reaches the mirrors [33]. The last component is the photo detector. When light falls on the photo detector, the bond between atoms breaks and creates electron-hole pairs, where electrons go towards cathode and holes go towards anode, this movement of electrons and holes conduct electric signal. Since the wavelength of operational laser is $1064\,nm$, which lies in infrared spectrum, the photo detector should work in the infrared region. LIGO uses Broad Band Photo Detector (BBPD) which is built around a low capacitive, series resistant silicon photo-diode "FFD-100", and coupled to a $50\,\Omega$ Radio frequency amplifier called Teledyne Cougar AP389. [34]

8.3 Working

8.3.1 Working of laser system

To operate LIGO at its fullest potential, we need an immensely powerful laser. In order to obtain such a laser beam, it must undergo multiple stages of amplification. Initially Nd-YAG laser produces a beam in the near-infrared region of the electromagnetic spectrum at 1064 nm. Then the beam passes through Non-Planar Ring Oscillator (NPRO), Master-Oscillator Power Amplifier (MOPA) which consists of four thin rods and finally through High-Power Oscillator (HPO). Thus a powerful laser of power $200\,W$, with wavelength $1064\,nm$ is obtained.

8.3.2 Working of Fabry-Perot cavity and Beam splitter

The powerful collimated light beam incidents on a power recycling mirror followed by a beam splitter. The partially reflecting beam splitter splits the light into the $4\,km$ long ultra-high vacuum chambers which are present orthogonal to each other. The laser beam is spread to a diameter of 6cm when it reaches each mirror reducing the thermal effects of heating the mirror surface. The Fabry-Perot cavities make the light to reflect ≈ 300 times which increases the laser power to $100\,kW$. Thus as the laser accumulates power gradually, after a certain value the beam splitter allows the laser beam to pass through it towards the photo-detector. The interferometer is designed such that these two coherent light beams from the perpendicular arms recombine at the beam splitter almost exactly out of phase thereby mostly cancelling the output signal when the two arms are of the same length, and the photo detector shouldn't receive any light if no disturbances are present. However, this is not the scenario if a gravitational wave passes nearby. [35]

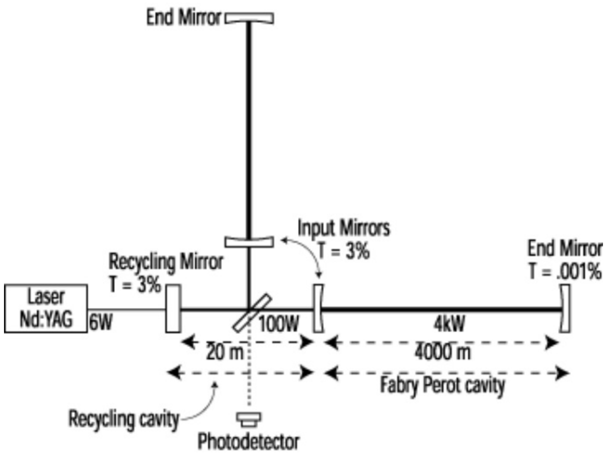


Figure 27: Working of Fabry-Perot cavity. Source :- spie.org

8.3.3 Working of Interferometer when gravitational wave passes

As we've seen the effect of gravitational waves, which stretch space in one direction and compress it in the perpendicular direction. Hence, when the gravitational wave passes through the arms of LIGO, they will be subjected to compressing and stretching strain, so if the length of one arm increases, simultaneously length of other arm decreases. Even the laser light gets compressed and stretched which alters the phase difference between the perpendicular light beams, causing a variation in the effective length travelled by the laser beam. Hence when the light beams recombine neither destructively nor constructively, where the resultant amplitude decides the intensity (I) of light that will be detected finally according to the relation

$$I \propto (A_1)^2 + (A_2)^2 + 2(A_1)(A_2)\cos(\Delta\phi) \tag{13}$$

where A_1 and A_2 are the amplitudes of each laser beam and $\Delta\phi$ is the phase difference between the interfering light beams.

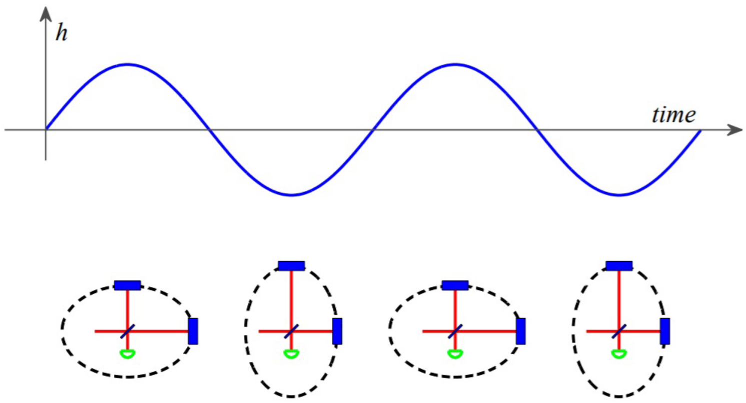
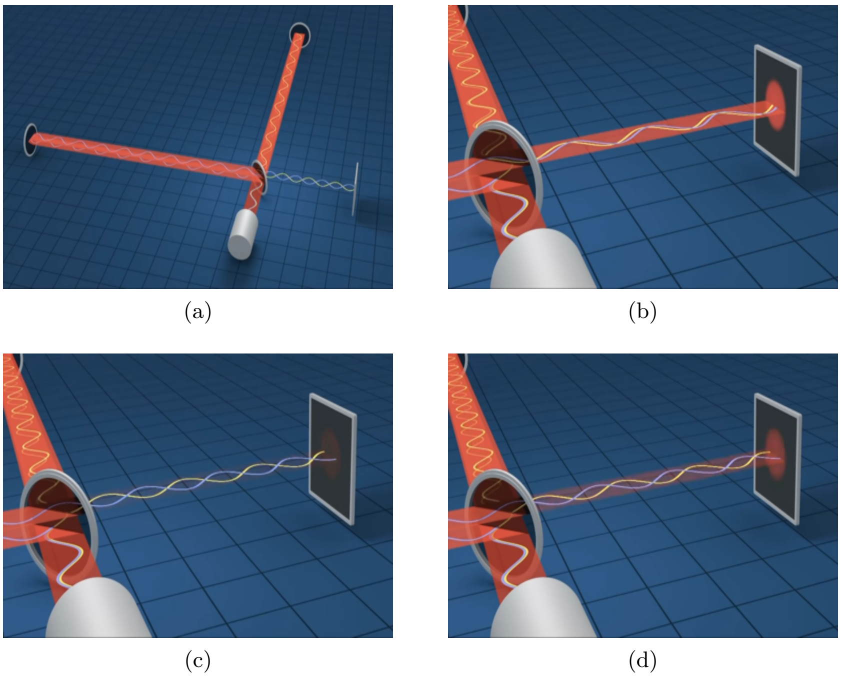


Figure 28: Gravitational wave effect on LIGO arms. Source :- Semanticscholar.org [36]

If there is no disturbance, then the arms will be intact, thus the light interfere destructively and the intensity of light detected by the photo detector will be zero, thus no signal is recorded. But if a gravitational wave passes, due to change in length of LIGO arms, a phase difference will be created such that the light will interfere partially, thus the intensity of light will fluctuate. The frequency of fluctuation of intensity will be a function of time which will be calculated by the photo detector and that can be converted to the strain caused on the arms which in turn will be a function of frequency. This will be calculated by the computers which is generally shown as the wave form of the detected gravitational wave.



(a) (b) (c) (d)

Figure 29: (a) Initial Condition (b) Constructive interference.
(c) Destructive interference (d) Partial interference

But apart from gravitational waves, there are other unwanted disturbances like earthquakes which can also influence the interference pattern. To avoid this, the whole system is evacuated. Other measures are also taken to dampen these vibrations which are described in the next session.

8.4 Noise and its Cancellation

Any disturbance in the surrounding could potentially act as noise for LIGO which tends to interfere with the detector and could produce its own signal instead of a gravitational wave. So changes in environment like vibrations in earth's crust, movement of vehicles, tides, winds, volcanic eruption, mining, etc. Even intensive changes like temperature and even the limitations of systems can add its own noise to the signal. Broadly noise can be classified into:

- Seismic Noise
- Thermal Noise
- Optical Noise

8.4.1 Seismic Noise

A gravitational wave is measured by monitoring the relative distance between two test mass surfaces. Any force affecting the centre of mass would then result in an ambiguous and faulty measurement. A ground-based interferometer is mechanically coupled to the earth where the masses are prone to seismically driven vibrations. The dominant part of the seismic power spectrum is at low frequencies. A moderately quiet site will have a spectrum of roughly,

$$x(f) = \frac{1}{f^2} \times 10^{-8} m(Hz)^{3/2} \tag{14}$$

where $x(f)$ is Band-width of the noise as a function of frequency(f).

Passive technique of seismic noise reduction

It utilizes the inertial response of a mass on a spring. Passive isolation takes advantage of the fact that above the resonant frequency, f_0, of the mass-spring system, the response of the mass to driving forces decreases by $(\frac{f_0}{f})^2$. Systems with lower resonant frequencies give higher isolation at a given frequency. These passive systems can also be staged by suspending one isolation system from the isolated stage of a previous system. The total isolation then is the product of each mass-spring system, $(\frac{f_0}{f})^{2n}$, where 'n' is the number of stages (assuming the same resonant frequency).

Active technique of seismic noise reduction

Active isolation techniques employ a bootstrapping method. A proof mass is placed on the platform being isolated. The proof mass is more inertial than the platform it sits on. Monitoring the relative displacement, velocity, or acceleration between the platform and the proof mass generates an error signal when the platform has suffered a disturbance to its state. Feedback control systems are used to correct the error signal, locking the position of the platform to the inertial reference of the proof mass. The level of isolation is proportional to the closed-loop gain of the system when the sensor noise is low enough. The limits to the closed-loop gain, the isolation are the sensor's bandwidth and noise. An advantage to arranging the isolation system in stages is that loop gain in each stage can be more modest, which is sometimes forced by the available bandwidths and mechanical resonances of the structure.

LIGO I uses a simple, multi-layer passive isolation system which places a "wall" in the seismic noise spectrum at roughly 40 Hz. The proposed LIGO II seismic isolation is largely active [37]. A quiet hydraulic system is used externally to the vacuum chambers which house the test masses. This external system has large dynamic range, and is used primarily to take out long-time scale drifts and disturbances. A two-stage active isolation system inside the test mass chambers is supported by the external system through bellows. The active system isolates an optical table in all six degrees of freedom, from which the test mass is hung as the lower mass of a quadruple pendulum. This design is expected to move the seismic wall to $\sim 10Hz$

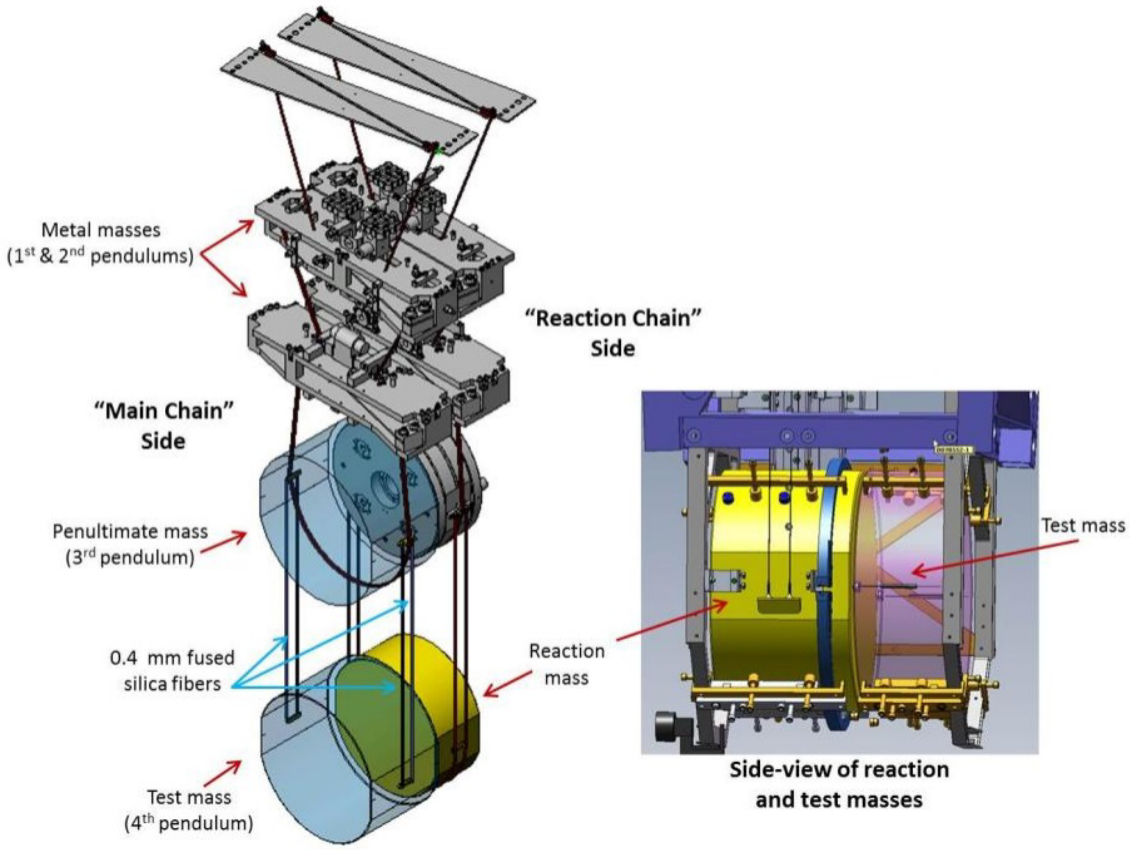


Figure 30: Mechanism to isolate seismic noise. Source :- LIGO.caltech.edu

8.4.2 Thermal Noise

Another noise source is due to the fact that the masses are at finite non-zero temperature. Non-zero temperature dictates that the atoms which comprise the masses, as well as the wires which suspend the masses, vibrate, according to entropy. Vibrations of the test mass atoms cause the surfaces of the mirrors to vibrate, which generates a signal. Thermal noise affecting the surface of the test mass directly is called internal thermal noise while the thermal noise from the suspension wires is called pendulum thermal noise. Fibers having low thermal noise and minimum coupling to test mass displacement have been developed. The suspension for LIGO II has been developed using specifically improved fibre and crystalline coating materials like Al-Ga-As. Fused silica ribbons, which are silicate bonded to the test masses are included in this proposal. It is currently predicted that pendulum thermal noise will only contribute to the sensitivity limit in a small region around $10Hz$.

8.4.3 Optical noise

The last of the fundamental noise sources is a limitation of the measurement process itself. The measurement process involves the interaction of light with the test masses, and the subsequent counting of the signal photons by a photo-detector. This has traditionally been thought of in terms of two uncorrelated sources - the Poissonian statistics of the counting of photons, otherwise known as shot noise, and the Poissonian statistics of the force on the test masses from photons, known as radiation pressure noise. [38] , [39]. Shot and radiation pressure noise are manifestations of the two quadrature of the vacuum. The square-law photo-diode measures the product of the amplitudes of the vacuum and the coherent light from the laser. Increasing the laser power increases the shot noise sensitivity while the radiation pressure noise sensitivity decreases. In LIGO I, 6 watts of light are incident on the interferometer, and radiation pressure noise is negligible. In LIGO II, however, 120 watts of power are planned, making radiation pressure an important factor. The shot noise spectral density is flat, while the radiation pressure amplitude spectral density has a 1/f shape. At a given frequency, the quadrature sum of the shot and radiation pressure noise can be minimized by using the right amount of power. This defines the standard quantum limit. [40]

$$h_{SQL}(f) = \sqrt{\frac{8\hbar}{(2\pi f)^2 m L^2}} \tag{15}$$

where the minimum level of quantum noise is defined as a function of frequency '$h_{SQL}(f)$', 'm' is the mass of the test mass, 'L' is the length of the interferometer arms, '$\hbar$' is the reduced plank's constant. This is actually a locus of the optimum strain spectral density at frequency 'f' assuming the optimized input power for that frequency,

$$P_{SQL} = \frac{mL^2(2\pi f)^4}{4\omega_0} \tag{16}$$

where ω_0 is the angular frequency of the light. This limit makes the assumption that the shot noise and the radiation pressure noise are uncorrelated. Recent work has discovered that there are correlations in the radiation pressure noise in signal tuned interferometers. [41],[42]. Dozens of layers of optical coatings are used, and the test mass is polished to nanometer smoothness. This precision is required to make sure that a near perfect reflective surface is available. Furthermore, laser power and mirror weight are increased to reduce the amount of optical noise present.

8.5 Signal Extraction

Once the excess noise has been diminished, the gravitational wave signal needs to be identified and pulled. Excess power and Template matching are some of the more frequently used methods to identify and extract the signals.

Excess power method

The "excess power" method is much enhanced when several detectors are employed. With it, the data streams from each observatory are searched for signals that are not easily accounted for by the noise characteristics of that particular instrument. When such interesting signals are found, corresponding signals, using an appropriate time window, are searched for in the data from the other observatories. Essentially, the signals from the different detectors are cross-correlated with each other. Since the noise in each experiment is uncorrelated with that of the others, a real signal should give a large spike in the correlation statistic. Complicating the analysis is the sensitivity of the detectors to the direction to the source, which can weaken the signal in one observatory relative to the others. But this effect can be taken into account and poses no serious problem.

Template matching

Another method to find gravitational waves is to look for signals that coincide with events that are visible using other means, and that should also emit gravitational waves. The first step in computing a template signal is computing the gravitational wave signature of different astrophysical sources. While template matching is a powerful way to extract a gravitational wave signal from the noise, it only works for sources that can be easily modelled.

The models compared to the LIGO data are called phenomenological models, and they are fit to numerical simulations of systems created by solving the Einstein equations on supercomputers. A smaller number of simulations are computed, and then an analytic model is created that links one simulation to another. A set of freely adjustable parameters is used with these models that allow them to match all of the available numerical simulations and to interpolate between them. There are several models that are used for this. Each uses a slightly different method, and so they produce slightly different wave forms. The implied properties of the modelled systems also differ as a result, but only in small ways. However, template matching alone would result in a lot of spurious matches and random data fluctuations.

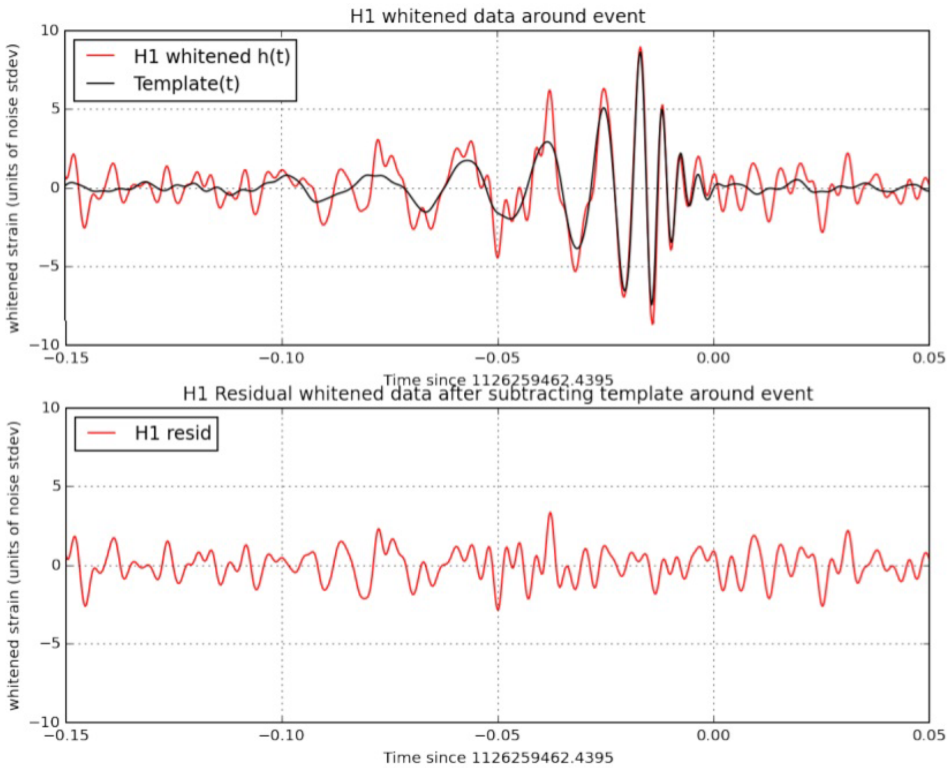


Figure 31: Matching the received signal using Gravitational waveform as a template.
Source :- Introduction to Data Analysis of Gravitational Wave Signals by Stanislav Babak

Therefore, we need to apply a "SNR" filter13, taking only the samples above some threshold value of the signal-to-noise ratio. In the LIGO data, it turns out that if one sample has a high SNR, then it is usually surrounded by neighbors that also have high SNR. Most of these are false positives and LIGO performs yet another cut, keeping only the single highest SNR candidate in each such cluster. This further reduces the size of the data set. After that, the software looks for coincidence between the two LIGO antennas. From the reduced data set, a statistic called the log likelihood ratio, or LLR is computed . The larger the LLR for a candidate, the more likely it is to be caused by a signal rather than noise, and vice versa. When a real signal is present in the data, it is generally surrounded by a large number of candidates which are the result of matches by similar-shaped templates to the matching one. This has been determined by many runs in which simulated waveform data have been injected into the data stream to test the software.

This allows candidates to be clustered, similar to the way the SNR threshold peaks were clustered; in this case, if a candidate falls within 4 seconds of another candidate that has a higher LLR, the weaker candidate is discarded. It turns out that there is a high probability of finding a low-ranked candidate next to a high ranked one, and so this method successfully trims many low ranked candidates from the sample. However, for candidates with LLR larger than about 6, this clustering method is not effective because the probability of two such candidates being within 4 seconds of one another is so low: the recent data run produced one candidate like this about every 5 minutes, or 10, 000 of them for the entire run. The total sample in the data set has now been reduced from 500 million per second to only 10,000 total, a small enough sample that it is possible to perform detailed statistical testing on each one of them.

Once the GW signal is extracted, then its frequency will be changed by multiplying it with a conversion ratio, such that the resulting frequency lies in the audible range. On September 14 2015, the first characteristic 'chirp' sound of the GW150914 was decoded using LIGO.

9 Detection of Gravitational waves using LIGO

9.1 Discovery of the the First Gravitational Wave

GW150914 was detected for the first time by the two detectors of LIGO at 09:50:45 UTC on the 14th of September, 2015 [43]. The signal received opened up a gateway with deeper understanding of astronomy and particle physics [44]. The source was discovered to be of a binary black hole coalescence. This detection serves to be groundbreaking in terms of both GW and binary black hole systems. The possibility of detecting gravitational waves were feeble due to the technology available during Einstein's time, although, experiments in search for the signal began in the 1960s with resonant mass detectors. The indirect evidence for the presence of gravitational wave was observed by Hulse and Taylor by the discovery of a binary pulsar system PSR B1913+16.1 where system depicted subsequent loss of energy. [43]

9.1.1 Source of GW150914

The source of GW150914 is a binary black hole merger. On analysis it was found that the source was an undisturbed binary black hole system whose masses were $\sim$ 36 and 29 $M_{\odot}$ successfully collapsing into a single black hole [44]. The mass of the system decreased considerably after the merger, indicating the emission of gravitational waves [45],[46]. From the merger, energy with three times the mass of our sun was converted into gravitational wave energy [46]. This system is located 1.3 billion light years away from our solar system. The coalescence produced tremendous power and energy during the final 20 milliseconds of the merger. The increase in their tangential velocity to 60 percent the speed of light, the short separation of 350km between them, orbital frequency of 75 Hz, half the gravitational frequency of 150 Hz, confirms the signal to be from a merger of two enormous black holes because no other compact objects other than black holes can come that close without merging, not even neutron stars as they wouldn't have the required mass. [43],[46]

9.1.2 Detection of GW150914

The two LIGO detectors at Washington State and Louisiana received the GW150914 signal, however, they were running in engineering mode. Hence, it required a 16 day analysis to confirm the signal to be legitimate and not a test simulation [46]. In order to confirm its validity, the environment detectors were checked to have no disturbances having similar properties as the GW150914 signal. At the time, LIGO was the only observing detector, the Virgo detector was not functional since it was being upgraded while GEO 600 was not sensitive enough to catch the signal [43]. The LIGO detector at Hanford suffered a 7 millisecond delay than Livingston. The signal was processed in only 3 minutes after detection. It lasted for 0.2 seconds during which its frequency increased in 8 cycles from 35 Hz to 150 Hz. By Signal conversion process, it was brought to the audible range which created a noise similar to the chirp of a bird and was termed as the chirp signal [43],[46]. The LIGO detectors detected the gravitational wave signal emitted from a binary black hole system in 2015. It was a successful prediction of the general theory of relativity which served influential in terms of both the gravitational wave and as well as existence of binary black hole mergers. [43].

Figure 32: Black Hole merger which created GW150914. Source :- ligo.caltech.edu

9.2 Some Detections of LIGO

9.2.1 GW190814

Two advanced-LIGO detectors (Hanford, Washington and Livingston, Louisiana, USA) and the advanced-Virgo detector (Cascina, Italy), have detected gravitational waves from the inspiral and merger of a stellar-mass black hole and another compact object on 14th August, 2019 at 21:10:39 UTC. It has been named as GW190814 as the date suggests.

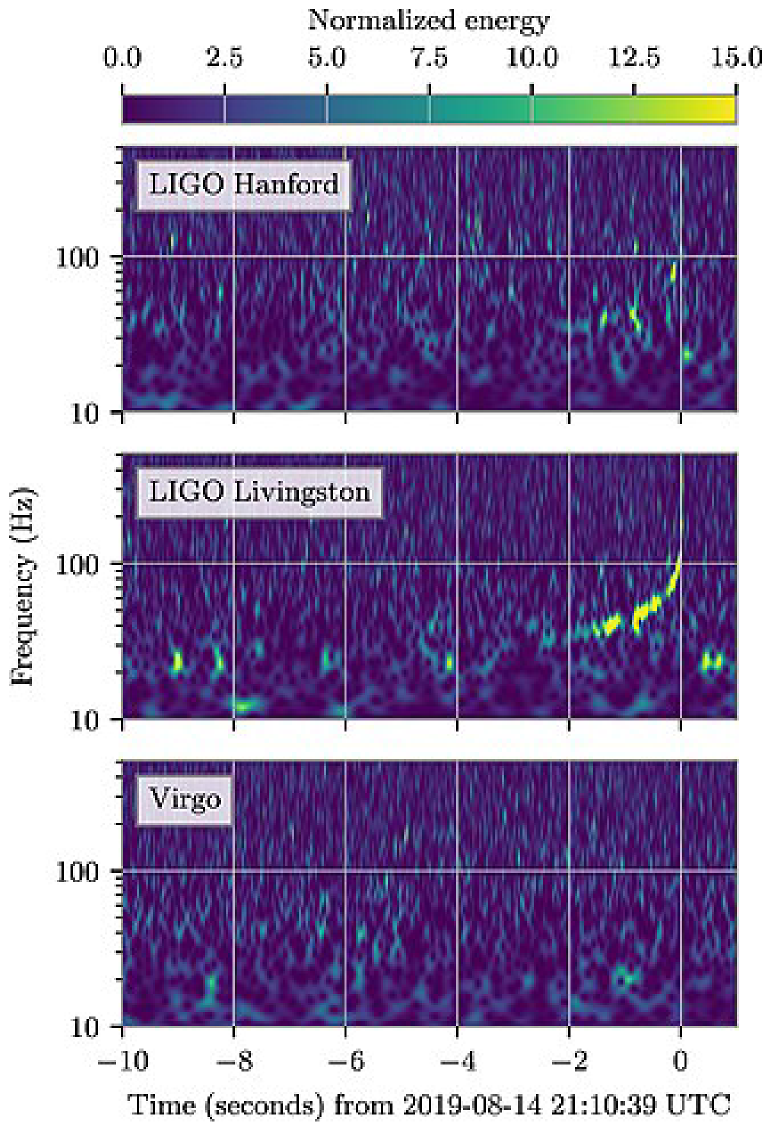


Figure 33: Frequency Vs Time data of GW190814 in three observatories. Source:- Wikipedia

While the mass of one component of this binary could range from 22.2 to 24.3 $M_\odot$ black hole, the other component which was of 2.6 solar mass could be either a low-mass black hole or a heavy neutron star. The masses of the objects before merging differed by a factor of 9. This makes it the most extreme mass ratio known for some gravitational wave event. The source of this gravitational wave was in a small patch of sky of around 20 square degrees. Even after doing so much research, the counterpart of the black hole which was in the inspiral mechanism wasn't observed. It can be that, either black hole consumed the neutron star completely or both were black holes. Had we observe an electromagnetic counterpart, which may not have happened due to a number of reasons, we could say the smaller object is mostly neutron star.

9.2.2 GW170817

On 17th August, 2017, LIGO and Virgo detectors observed a gravitational wave named as GW170817. It is known to be produced by two neutron stars merging into each other while spiralling closer and closer. The aftermath of this gravitational wave was observed by around 70 observatories on 7 continents as well as through space, across the electromagnetic spectrum, marking a significant breakthrough for multi-messenger astronomy. The discovery and subsequent observations of GW170817 got Breakthrough of the Year award for 2017 by the journal Science.

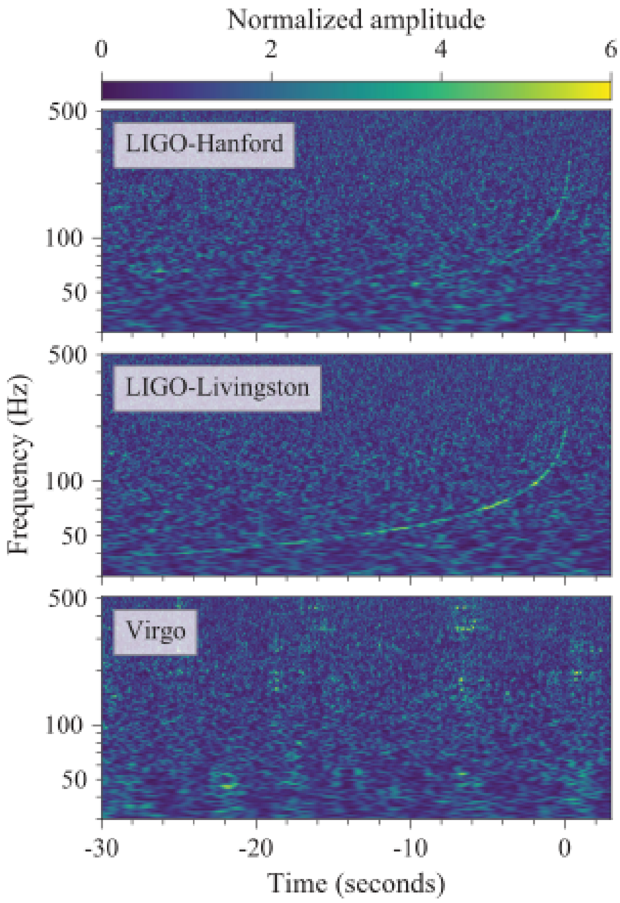


Figure 34: Frequency Vs Time data of GW170817 in three observatories. Source:- Wikipedia

The component masses of the binary are inferred to be between 1.17 and 1.60 $M_{\odot}$. After merging it makes the mass of about 2.74 $M_{\odot}$. The gravitational wave signal lasted for about 100 seconds. It started with a frequency of 24 Hz. It inspiralled for around 3,000 cycles. The amplitude and frequency increased to a few hundred hertz as both the objects came nearer in the typical inspiral chirp pattern. Lastly, it ended with the collision at 12:41:04.4 UTC which was received as a signal in the interferometer. At first, it arrived at the Virgo detector in Italy. After 22 milliseconds, detectors at the LIGO-Livingston detector in Louisiana, United States got the signals. After another 3 milliseconds, the waves reached at the LIGO-Hanford detector in the state of Washington, United States. It was then compared with a prediction from the general theory of relativity given by Einstein to analyse it further. The source was localised within a sky region of 28°square which has a probability of 90%.

A gamma-ray burst, GRB 170817A was detected. It lasted for $\approx$ 2 seconds. It was detected by Fermi and INTEGRAL spacecrafts. This bursts began at 1.7 seconds after the signal received denoting the merge of the objects. It's a hypothesis that neutron star mergers cause gamma-ray bursts which gets confirmed with this merger.

9.2.3 GW190521

LIGO-VIRGO detectors detected a short signal from a binary black hole merger on May 21,2019 at 03:02:29 UTC. The event occurred at a luminosity distance $5.3^{+2.4}_{-2.6}\,Gpc$ with a red shift of $0.82^{+0.28}_{-0.34}$. The signal lasted for about 0.1 seconds long and had a peak frequency of about $60\,Hz$. Since the time period and frequency is inversely proportional to the binary's total mass, and since the signal was so short, this could imply that in this event the most massive black holes could have collided when compared to the collisions detected so far with a total mass of $150^{+29}_{-17}\,M_{\odot}$. The two black holes weighed upto $85^{+21}_{-14}\,M_{\odot}$ and $66^{+17}_{-18}\,M_{\odot}$ giving rise to a $142^{+28}_{-16}\,M_{\odot}$ remnant black hole. [47]

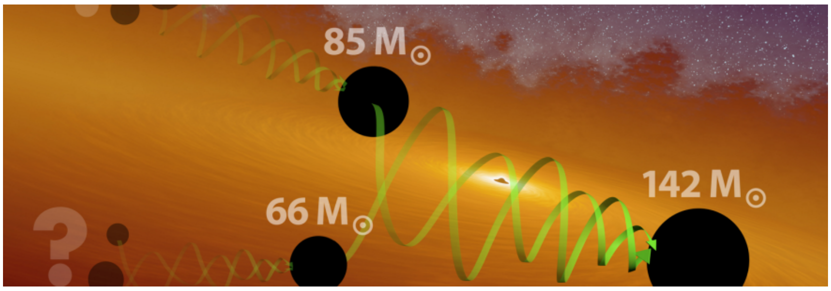


Figure 35: Pictorial representation of GW190521 merger. Source :- en.uw.edu.pl

The mass of the remnant black hole is between 100 and 1000 $M_{\odot}$, making it the first intermediate mass black hole to be detected. Not only is the remnant black hole bizarre, but the two mergers had masses which are impossible to be directly formed by collapsing stars. This led to the theory that these kinds of black holes may be formed by merging of smaller black holes or stars can form black holes with higher masses. Regions like the galactic centre or star clusters might favour the existence of such black holes [48]. An electromagnetic counterpart was also detected but its association with the event GW190521 is uncertain. This is the first time an electromagnetic counterpart has ever been detected from the merging of black holes. The one unsolved problem here is why an electromagnetic counterpart observed as the black hole mergers do not emit light. It is approximated that the two black holes orbited a super massive black hole. After the formation of the intermediate mass black hole, it must have crossed the gaseous disk, that caused it to light up. The first largest merger and the unexplained electromagnetic counterpart are some of the most notable features.

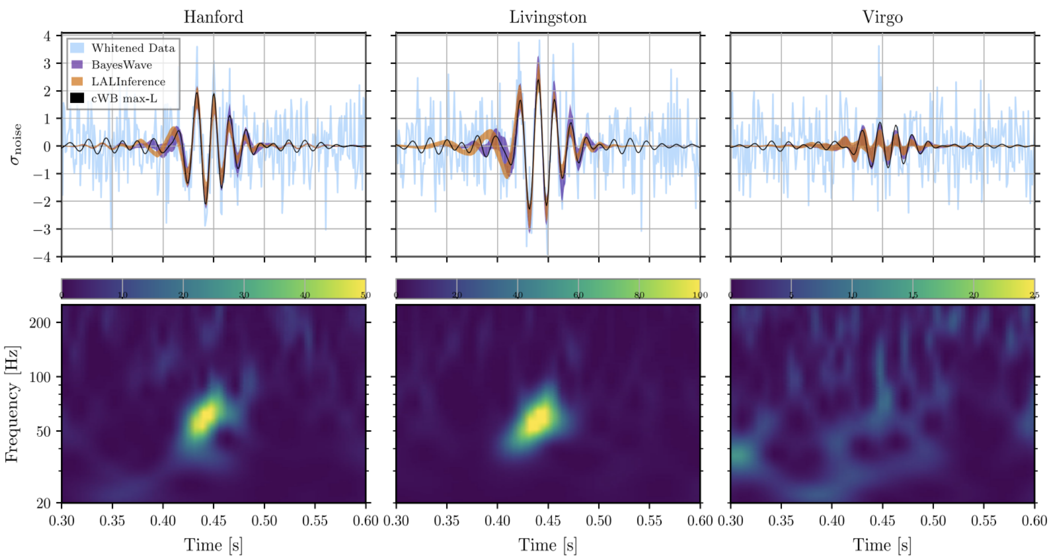


Figure 36: Wave form of GW190521 signal. Source :- pg. 2 of [49]

9.2.4 GW190425

The signal was detected by LIGO-Livingston and VIRGO detector during the third observational run on 25 April,2019 at 08:18:05 UTC where the LIGO-Hanford was temporarily offline. The signal originated from a region of the sky which was not in plain sight for VIRGO, it lied just above the detection threshold for LIGO-Livingston. Luminosity distance of the event was 159^{+69}_{-71} Mpc. [50]

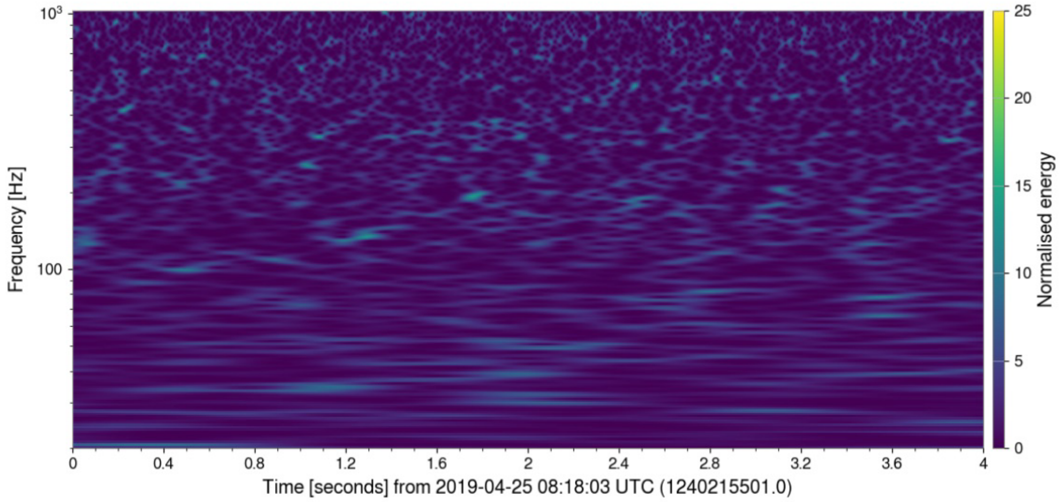


Figure 37: Signal detected by L1. Source :- gw-openscience.org

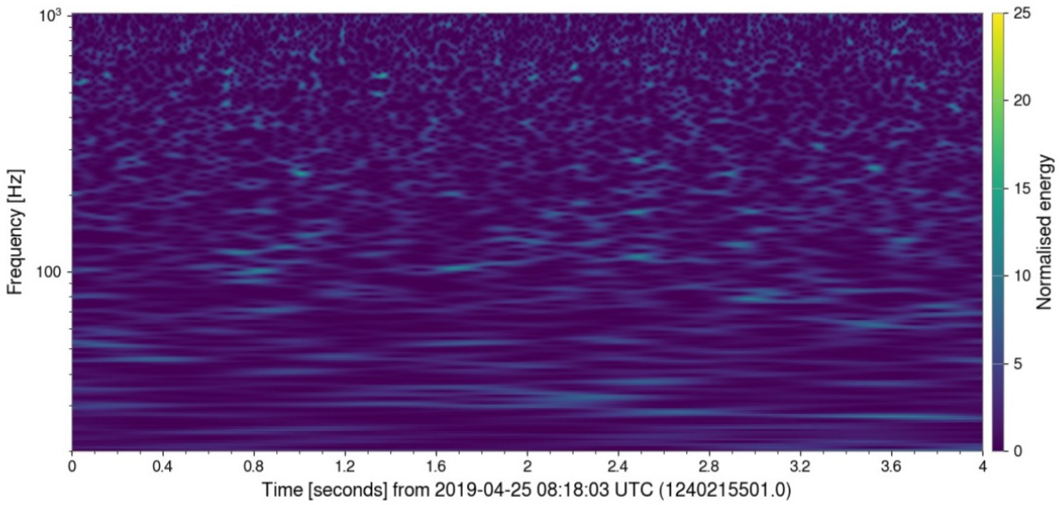


Figure 38: Signal detected by V1. Source :- gw-openscience.org

The mass of the mergers was estimated to be $1.61 - 2.52\, M_\odot$ and $1.12 - 1.68\, M_\odot$.The total mass of the compact binary was $3.4^{+0.3}_{-0.1}\, M_\odot$, greater than any known binary neutron stars. This suggests that the formation of GW190425 was different than the known binary neutron stars. One possible explanation for this is that the source consisted of a neutron star and a $4.5\, M_\odot$ helium star which evolved to form an eccentric double neutron star [51]. Unlike the other neutron star mergers that produced electromagnetic counterparts, no such counterparts were observed for GW190425 [50].

9.2.5 GW190412

On 12th April, 2019 05:3:44 UTC, the Advanced Virgo detector and both of the Advanced LIGO detectors, detected a gravitational wave which was named GW190412. The signal was recorded with a network signal-to-noise (SNR) ratio of 19. In this event, a $\sim 30\,M_\odot$ black hole coalesced with a $\sim 8\,M_\odot$ black hole. This merger was significant because a combined signal-to-noise ratio (SNR) of 19 was found in across all three gravitational wave detectors, in addition to the BBH (Binary Black Hole) system being the first to be observed with an asymmetric component mass ratio. [52]

While the inferred individual masses of the coalescing black holes (BHs) are each within the range of masses that have been observed before, previously detected binaries all had mass ratios $q = \frac{m_2}{m_1}$ (with $m_1 \geq m_2$) that were according to unity. GW190412, is the first observation of Gravitational waves by LIGO from a coalescing binary with indubitably unequal masses. GWs from this event carry faint but clearly measurable evidence of radiation that oscillates at frequencies with subdominant contributions for the first time as a result of the mass asymmetry of the BBH system.

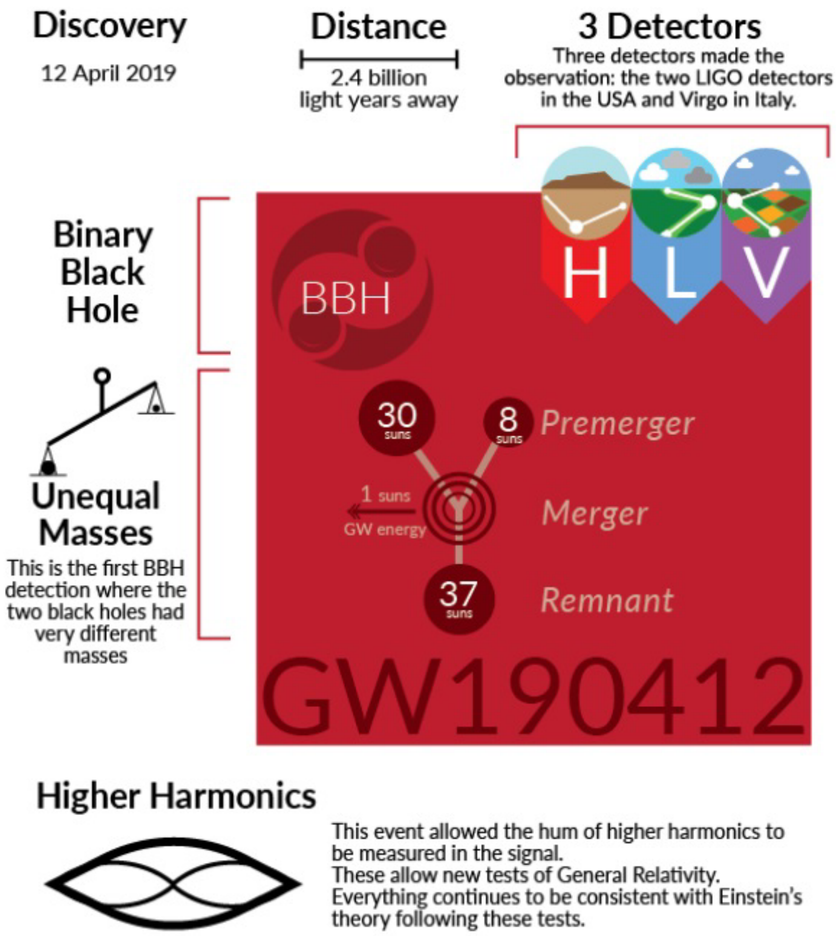


Figure 39: Characteristics of GW190412. Source :- LIGO-India.in

Einstein's Theory of General Relativity predicts that although gravitational radiation from compact binaries is dominated by a quadrupolar structure, it also contains weaker contributions from subdominant multi poles. In particular, gravitational radiation from systems with significantly asymmetric component masses consist of stronger contributions from higher multi poles. GW190412 presents strong evidence for contribution to gravitational radiation beyond the leading quadrupolar order in asymmetric systems.

9.2.6 GW170104

GW170104, a gravitational-wave signal produced by the coalescence of a pair of stellar-mass black holes, was measured on 4th of January 2017 at 10:11:58.6 UTC by the Hanford and Livingston advanced detectors of the Laser Interferometer Gravitational-Wave Observatory with a network signal-to-noise ratio of 13 and a false alarm rate less than 1 in 70 000 years. The inferred component black hole masses are $31.2^{+8.4}_{-6.0}\,M\odot$ and $19.4^{+5.3}_{-5.9}\,M\odot$ (with 90% credibility). The gravitational wave frequency at peak GW strain was 160 to 199 Hz. [53]

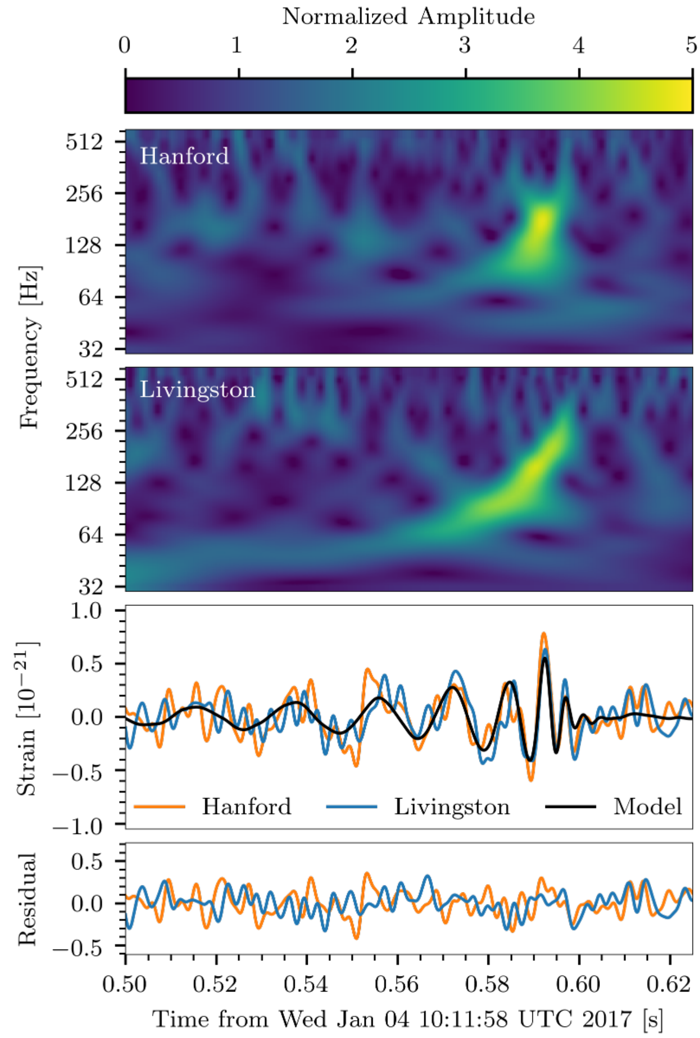


Figure 40: Signal of GW170104 merger. Source :- LIGO.org

Analyzing GW170104 signal yielded a new upper bound on the mass of gravitons assuming they are dispersed in vacuum like massive particles. This upper bound is equal to $7.7 \times 10^{-23}\,eV/c^2$. The spin axes of the black holes were unlikely to be aligned with the axis of the binary orbit. This hints that the binary black hole system was formed dynamically in a dense star cluster as an outcome of gravitational interaction between stars and binary stars, where randomly aligned spin axes are expected. The alternative scenario suggests that the system was formed out of a binary star system consisting of two main sequence stars. Although not entirely ruled out, this scenario is not favoured because black holes formed in such a binary are more likely to have positively aligned spins.

10 Advanced LIGO and other Gravitational Wave Detectors

10.1 Advancements in LIGO

With the aim to detect the smallest of gravitational waves from the farthest of places in the universe, the LIGO team strived harder to perfect the LIGO setup. They made a myriad of changes to LIGO, and a few are discussed in this section.

10.1.1 Enhanced LIGO

After the end of the Science Run 5 in 2007, a few changes and upgrades were made to the initial LIGO, which enhanced its performance dramatically and was, hence, dubbed Enhanced LIGO. Some of the upgrades include:

- Increased laser power
- Homodyne detection[2]
- Output-mode cleaner
- In-vacuum readout hardware

At the most sensitive frequencies, the strain sensitivity was improved by approximately 30%, which helped the instrument's root-mean-square strain noise reach an unprecedented level of 2×10^{-22} in a 100 Hz band.[55]
After the changes, Science Run 6 began in 2009 and concluded in 2010. Even though no gravitational waves were detected during this run, there were some interesting astrophysical results obtained, including gaining some insight on the upper limit on stochastic GW background of cosmological origin. [56]

10.1.2 Advanced LIGO

After Science Run 6 ended in 2010, LIGO went offline for quite a few years for a major upgrade, installing new second-generation detectors in both the infrastructures. To increase the interaction time with a gravitational wave, just like in Initial LIGO, Fabry-Pérot cavities were used in the arms, and to increase the effective laser power, power recycling was used. With the help of signal recycling, the frequency response of Advanced LIGO was improved, increasing the design strain sensitivity in the most sensitive frequency region (around 100 Hz) to a factor of 10 in comparison to Initial LIGO. Since the gravitationally probed volume of the universe is directly proportional to the cube of the strain sensitivity, an increase by a factor of 10 means that there is an enormous increase in the number of potential astrophysical sources waiting to be detected by these instruments.

By replacing every interferometer components with improved technologies, and by employing much better seismic isolation and test mass suspension, the low frequency end of the sensitivity band was moved from 40 Hz to 10 Hz. At mid and high frequencies, higher laser power, larger test masses and improved mirror coatings helped improve the sensitivity. [55]

These and other changes helped Advanced LIGO operate at a sensitivity roughly 3 times more than initial LIGO. This project attracted a lot of participants, including the Australian National University and University of Adelaide who made significant contribution to the project. By the time it was ready to start its first operation in September 2015, the LIGO team was composed of more than 900 scientists worldwide. [56]

Advanced LIGO has the exciting potential to detect hyperbolic encounters of primordial black holes (PBH). Such encounters will have shapes similar to "tear drop glitch" shapes, and will look like bursts with characteristic frequency at peak strain amplitude. Advanced LIGO has reported such events, and even though accidental noise in the detectors were given credit for that, those events

[2]Homodyne detection is a method of extracting information encoded as modulation of the phase of an oscillating signal, by comparing with a signal of standard oscillation that would be the same as the signal, if it carried null information. [54]

being PBH hyperbolic encounters is a possibility worth exploring. And if these events are PBH encounters,then they can be used to obtain valuable information about PBH velocity,mass and their spatial distribution. [16]

10.2 Gravitational Wave Interferometers around the World

Other than LIGO and Advanced LIGO, there are and were other GW Interferometers around the world. These interferometers are grouped into generations based on the technology they used. The first generation interferometers were deployed in the 1990s and the 2000s and were the ones to lay down the foundations of the important technologies. The second generation of detectors improved upon the previous ones and ran in the 2010s. They introduced new technologies cryogenic mirrors and injection of squeezed vacuum, with the help of which the GW event GW150914 was detected. The third generation of detectors are still in the planning phase, and aim to improve the technologies of the previous generation detectors. [57]

10.2.1 First Generation

- **TAMA 300** - This GW detector is located at the Mitaka campus of the National Astronomical Observatory of Japan. It is a project of the GW studies group at the Institute of Cosmic Ray Research (ICRR) of the University of Tokyo. The project's construction start in 1995, and data was collected from 1999 to 2004. [58]
- **Virgo** - A scientific collaboration of six different countries, Virgo Interferometer is located in Santo Stefano a Macerata, near the city of Pisa, Italy. Its arms are a kilometer shorter than LIGO's arms. The construction was completed in 2003, and initial data was taken from 2007 to 2011 during four science runs. [59]

10.2.2 Second Generation

- **Advanced Virgo** - Not being able to detect any GWs, the initial Virgo was decommissioned in 2011 and replaced by Advanced Virgo, which is 10 times more sensitive than initial LIGO, had larger mirrors, and improved optical performances. It started commissioning in 2016, and in August 2017, along with Advanced LIGO, detected a GW signal GW170814. [59]
- **LIGO-India** - This is a planned advanced GW interferometer, which will be identical to the advanced LIGO interferometers in USA. Spearheaded by a consortium of Indian gravitational-wave physicists (IndiGO), the inception of the planning phase of the project occurred way back in 2009. A site near Aundha Nagnath in the Hingoli District, Maharashtra has been selected. The aim of this project is to join a network of detectors throughout the world, which will help in increasing the number of sources of GWs detected. [60]

10.2.3 Third Generation

Einstein Telescope (ET) - Currently under study by a few institutions in the European Union, the ET aims to test Einstein's General Theory of Relativity in strong field conditions and increase the precision of gravitational wave astronomy. The current second generation detectors lack the technologies to realize precision gravitational wave astronomy, especially with the likes of massive stellar bodies and highly asymmetric (in mass) binary systems. To increase precision and circumvent any technological problem posed by the second generation detectors, new infrastructure will have to be implemented: ET will be an underground detector to reduce seismic noise and cryogenic facilities will be used to cool down the mirrors. [61]

10.2.4 Space based Observatories

Laser Interferometer Space Antenna (LISA) - A joint effort between NASA and the ESA, the LISA will constitute a constellation of three spacecrafts arranged in an equilateral triangle with sides of about 2.5 million kms long, flying along a heliocentric orbit. The entire arrangement will be ten times larger than the orbit of the moon and will be placed at the same distance from the Sun as the Earth, but 20 degrees behind Earth. [62]

Conclusion

In this research paper we came to know that gravitational perturbation in space-time travels in the form of waves. When gravitational waves pass through an object it gets stretched and compressed. But as the source of the wave is farther from us, the effect it produces becomes lesser according to the inverse square law. Accelerating objects, revolving binaries and PBH's are some of the important sources of gravitational waves.

LIGO is one of the promising detectors of gravitational waves, which is based on the principle of interference of light. The operational wavelength of laser light is 1064 nm. There are noise sources which could interfere with working of LIGO like seismic, thermal and optical noise sources. So LIGO uses Active and Passive technique of noise cancellation to help focus on the desired signal. Signal extraction is also done mainly using template matching technique. Finally the first gravitational wave was detected on 14th September, 2015. And from then on a plethora of gravitational waves were and are being detected by LIGO. At the end we also understood the advancements used in LIGO to get better results.

Analysing gravitational waves could reveal to us more about its origin which usually is a huge-scale astronomical event, such as collision of black holes and neutron stars, and probably the birth of the universe itself.This was a groundbreaking proposition for all of astronomy, astrophysics, cosmology and so much more.

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