DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

CERTIFICATE

This is to certify that this report titled **Gravitational Waves** is a bona fide record of the seminar work presented by **Namburi GNVV Satya Sai Srinath, B150843EC**, in partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology in Electronics and Communication Engineering from the National Institute of Technology Calicut.

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26/02/2019

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Abstract

Albert Einstein, in his general theory of relativity predicted about existence of "Gravitational waves" in 1916. Approximately, a century later on September 14, 2015, mankind has ever witnessed the first wave of this kind at an experimental setup named Laser Interferometer Gravitational Observatory (LIGO). Though it is known as an observatory, it stands apart from the usual observatories in many aspects. This wave was named as GW150914, following the nomenclature as GW(Gravitational Wave), the year of discovery, the month followed by the date of discovery.

Subsequent discoveries of gravitational waves has been achieved in the next couple of years. But the GW170817 wave i.e 17 August, 2017's discovery has another peculiarity of identifying electromagnetic waves along with gravitational waves which fetched the 2017 Nobel Prize award in Physics amongst many breakthroughs in areas of astronomy and astrophysics.

The first question that strikes a common man when this discovery was made is "How it is going to effect mankind?" Apart from that, there are many questions including "How it has been detected?", "Why it has taken 100 years to detect these waves though it has been predicted by several scientists beforehand?"

1 Introduction

According to the present day science, there are four elemental forces in nature. They are

1. Electromagnetic forces
2. Gravitation forces
3. Weak interaction
4. Strong interaction

While the other three forces are much more experienced in the subatomic world, "Gravitational force" is experienced by all the particles having mass and is the weakest of all the forces. The relative strengths is as follows

Gravitational<Weak nuclear<Electromagnetic <Strong nuclear.

While gravitational and electromagnetic forces have infinite range, the other two have short range and are significant in subatomic world.

1.1 Newtons postulates

Undoubtedly, Newton is considered as one of the best scientist and mathematician in the world for his contributions in areas of Calculus, Optics and Mechanics. His famous theory about Gravitation[1] - "action-at-a-distance" theory where he proposes that objects varying from an apple to the giant planets interact with each other with this "invisible attraction" without any medium with information transmitting at infinite speed i.e the force acts instantaneously. He describes gravity as a "force". When asked proper explanation about the working of this force, how exactly the transmission occurs etc; he said "Hypotheses non fingo" which roughly translates to "I haven't the faintest idea but the equation works". As this is the first theory explaining a natural phenomenon, it received both applauses and critics from all over the world. Newton himself was very doubtful about this force, its working principles. While his maths fits with reality, he doesn't have an explanation for that which created an interesting problem in the scientific community.

After two centuries, James Maxwell proposed a theory[2] which regards electricity and magnetism as fields and are interrelated. He also proposed that the resultant wave which he named as "Electromagnetic waves" travel with the speed of light. Equivalently stating, light propagates as a field of electric and magnetic waves. This theory posed a question as "Whether gravity can also be thought as propagation of a field?"

Though many scientists have worked and proposed that gravity propagates as a field with finite velocity, it is Einstein who clearly explained the working of this field.

1.2 Einstein's postulates

1.2.1 Special Theory of Relativity[3]

He proposed this theory in 1905 which basically states

1. The laws of physics are same for all inertial/ constant speed frames
2. Speed of light is same for all observers irrespective of their velocity

These two postulates helped in explaining many problems associated in astronomy. One such is time dilation. Time dilation is a difference in the elapsed time between two observers who has a relative velocity or influenced by different gravitational fields. This theory has been verified with various experiments the famous one being "Hafele-Keating experiment" where four cesium atomic clocks were put in commercial flights and are made to travel around the globe twice. When compared, the clocks in flights are ticking slow to that of the ground clock thus validating Einstein's theory. Currently it is used in satellites to synchronise time with respect to earth using the following equation

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - \frac{v^2}{c^2}}} \tag{1}$$

where $\Delta t'$ corresponds to time observed in moving object and Δt corresponds to time of a clock at rest.

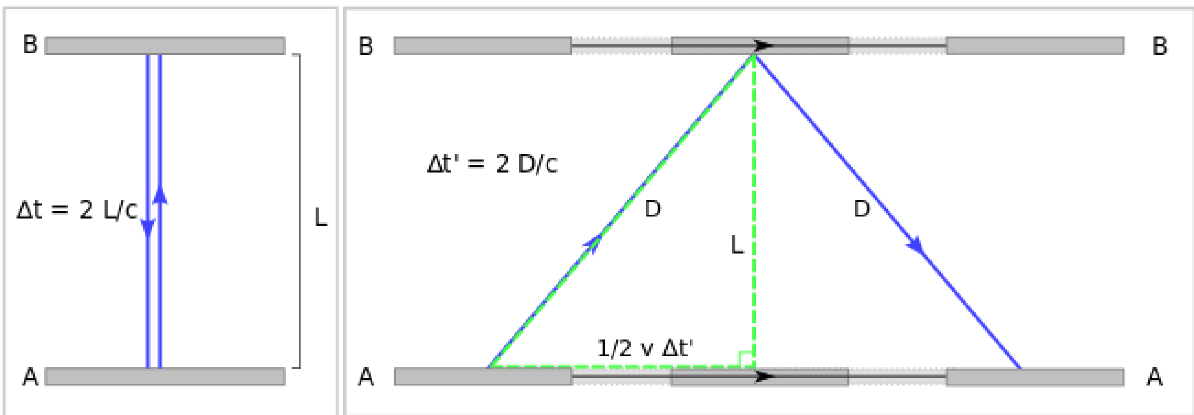

Figure 1: Time dilation explained. Source: Wikipedia

It follows from these postulates that nothing can travel faster than light which contradicts Newton's assumption about gravity(where he assumes gravity transmits information instantaneously). What Einstein proposed through his famous equation $E = mc^2$ is that as an object approaches the speed of light(c), its mass reduces till it become massless, just as photon travelling with speed of light. Assuming the speed is further increased it becomes negative mass, an abstract concept which doesn't exist in reality. Thus Newton's assumption on gravity is has to be modified.

1.2.2 Principle of equivalence[4]

Einstein could not incorporate gravity in special theory of relativity because of principle of equivalence: All the masses irrespective of their nature and composition fall at the same rate in gravitational field i.e a person in an elevator can not distinguish whether the elevator is still on earth(thus experiencing 9.8m/s^2 due to earth's gravitation) or falling with 9.8m/s^2 in outer space. In other words, special theory of relativity holds good only for constant velocity frames while gravity is something analogous to acceleration and the frames can't be considered as inertial. Thus he developed General theory of relativity to include gravity.

1.2.3 General Theory of relativity[5][6]

Einstein proposed this theory around 1915 and in a nutshell, he describes that all the objects has something called as "Space-time curvature" i.e everything is wrapped in a sheet covering entire space and which changes with time thus space-time. Massive objects tend to warp more space-time around them creating smaller objects to come inwards. But as the smaller objects do warp a bit of this space-time, instead of directly falling normally towards the larger mass, it starts revolving as a resultant of tangential and normal fields.

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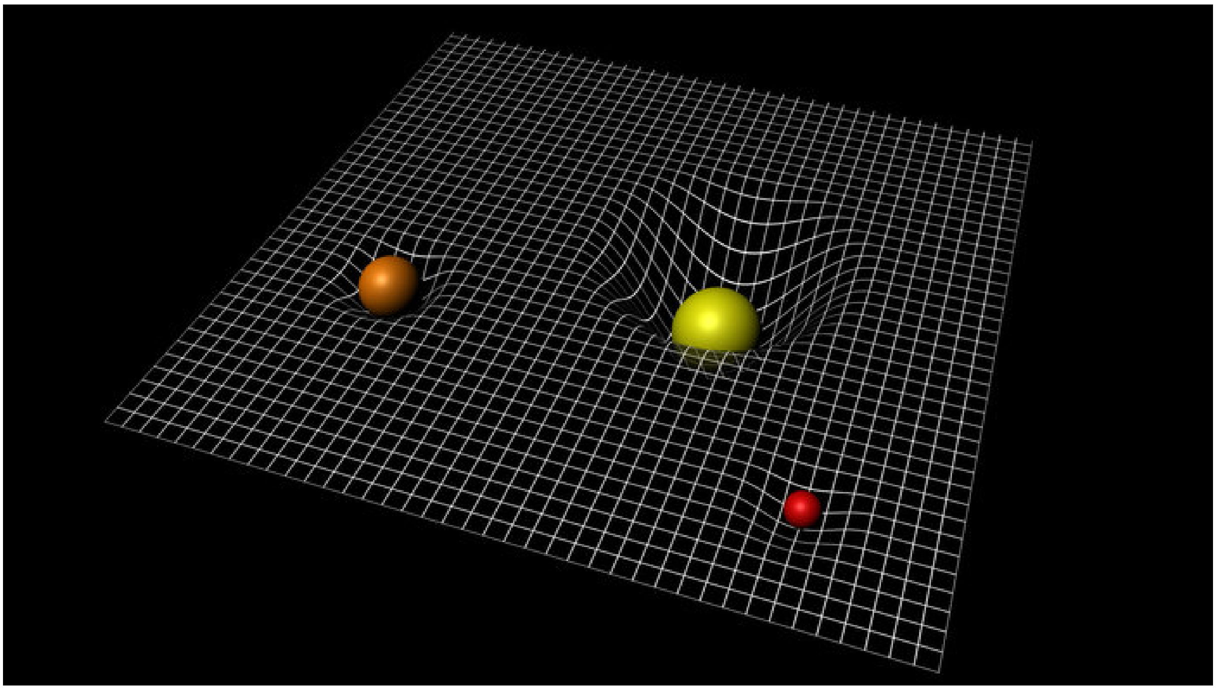

Figure 2: Example illustration of space-time curvature. Source: Wikipedia

It can be easily visualised as a thick blanket tightly held along its corners and a large mass placed at its center, smaller mass at some point on blanket. The larger mass protrudes into the blanket more than the smaller mass making the smaller mass to move inwards. But as the smaller mass also protrudes a bit, this combined effect makes it to revolve around larger mass till at a point where the larger mass space-time has a dominant effect that the smaller mass starts falling inwards completely and thus colliding. The movement of one object in this sheet produces a wave which effects other objects which are in this sheet. It can be compared as the waves produced in a pond by throwing a stone. This wave is what described by Einstein as Gravitational waves and its movement in space is responsible for all the forces(attraction between moon and earth etc) in the universe. Simply, he states that gravity is the ripples caused in this space-time curvature due to the masses which is responsible for all the motions in the universe.

1.3 Effects explained

1.3.1 Gravitational Lensing[7]

Dense mass bends light due to its gravitational field. It is similar to a lens bending light. So, light deviates from its original straight line path.

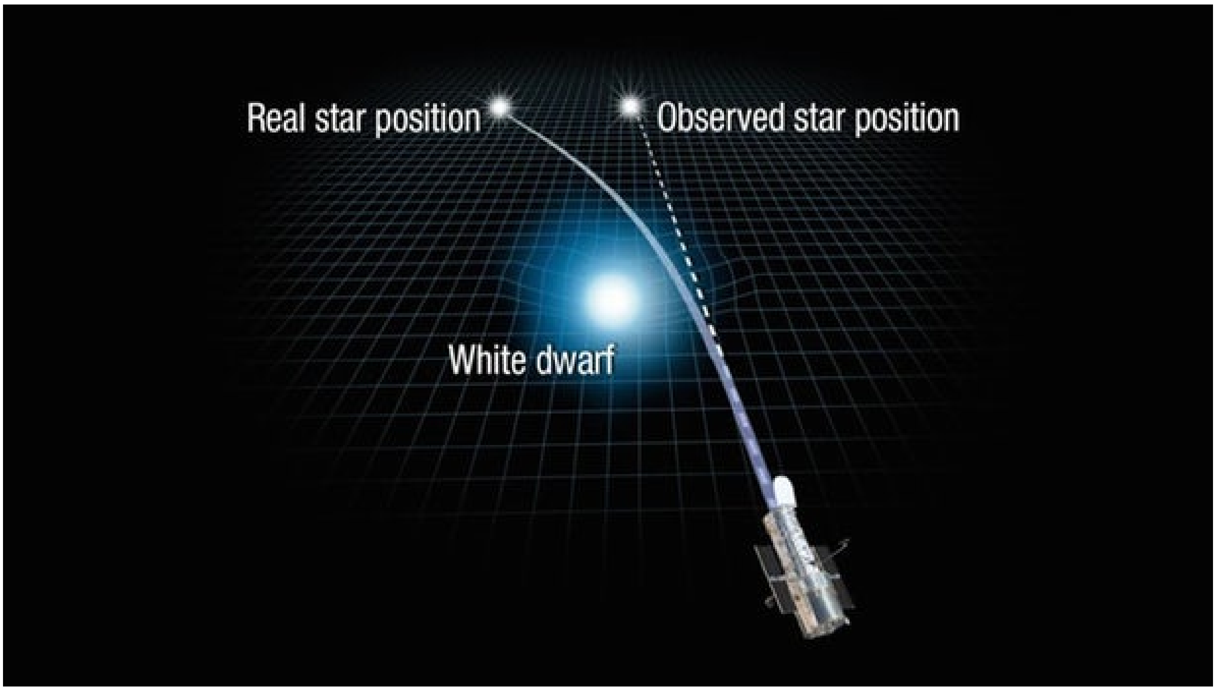

Figure 3: Due to warping of space by mass, light has deviated from its path which may mislead its position. Source: Wikipedia

1.3.2 Gravitational redshift[8]

It is the phenomenon that clocks present in a gravitational field tick slower when observed by a distant observer. The light source appears to be more red near the massive object causing a shift in wavelength. Photons must gain energy as they fall toward a gravitating body and lose energy as they climb away from it.

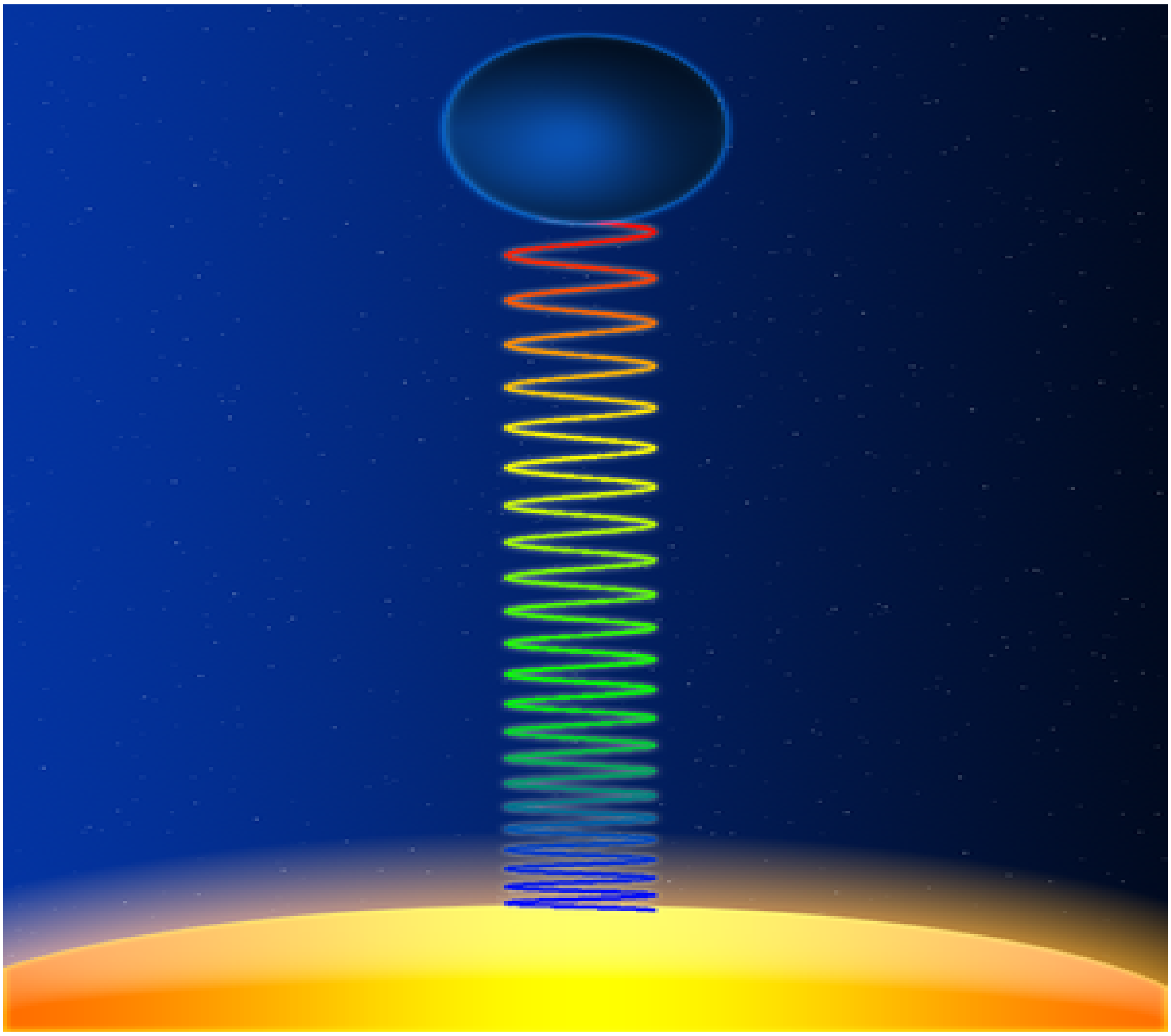

Figure 4: Light near the massive is blue while shifts to red at the less massive place. Source: Wikipedia

As wavelength$_{red}$>$wavelength_{blue}$ and speed of light is constant, the frequency$_{red}$ < frequency$_{blue}$. In other words, time ticks slower near massive bodies thus being consistent with previous effects.

2 Laser Interferometer Gravitational Observatory(LIGO)

2.1 Challenges in discovery

While his time dilation, gravitational lensing effects were tested successfully by various experiments around 1970's, it took nearly a century to discover the first gravitational wave after it's proposal. Why did it take so long to discover?

First reason which impeded its discovery is Einstein himself because he is uncertain about this particular field after few years of its proposal. Scientists are also not clear about this as the notion is entirely new at that time and contradicting the popular beliefs.

But the main and important reason for the delay in its discovery is the lack of proper equipment which can measure the strength of this wave because the most strongest gravitational wave makes a displacement of order of diameter of a proton. So, it took a lot of time to develop an apparatus to measure with that level of accuracy as there is a high probability of confusing some external/internal noise or artefacts for this wave.

2.2 Details of LIGO

One such facility was established in America known as the Laser Interferometer Gravitational Observatory(LIGO) which uses lasers to detect the gravitational waves. In contrast to the usual observatories which has a dome, this observatory is in 'L' shape as it doesn't require any light to observe celestial bodies. It's initial construction was completed around 2002 and was turned on for 8 years but there is no detection of any gravitational wave. Scientists formulated the precision required, understood the feeble nature of the gravitational wave and started upgrading the observatory which took around four years. When they turned on in 2015, they detected the first gravitational wave just within few days. Precision, accuracy are very important factors for this observatory to detect these waves and it took these many years to attain this level thus often named as the "Most sensitive device made by mankind".

Figure 5: LIGO observatory located at Livingston, US. Source:LIGO/Caltech/MIT

The arms stretch apart for 4km and can detect a change in distance of ten-thousandth the diameter of proton which is equivalent to say that the distance between Earth and Proxima Centauri(next nearest star after sun) can be measured with an accuracy smaller than width of human hair. To avoid local disturbances, it has been put in vibration isolation chambers. Its arms has been evacuated from all gases to avoid vibrations from sound, light excitations. As artifacts can creep because of this level of sensitivity, a second detector was build near Hanford, US which is 3000km from the present detector. So, if a wave passes a detector, assuming that the wave travels with speed of light, it will take 10ms to reach other detector thus distinguishing vibration caused by gravitational waves to that of a local artifact or internal disturbances. A third detector VIRGO was placed in Europe thus giving more authenticity to the existing detectors.

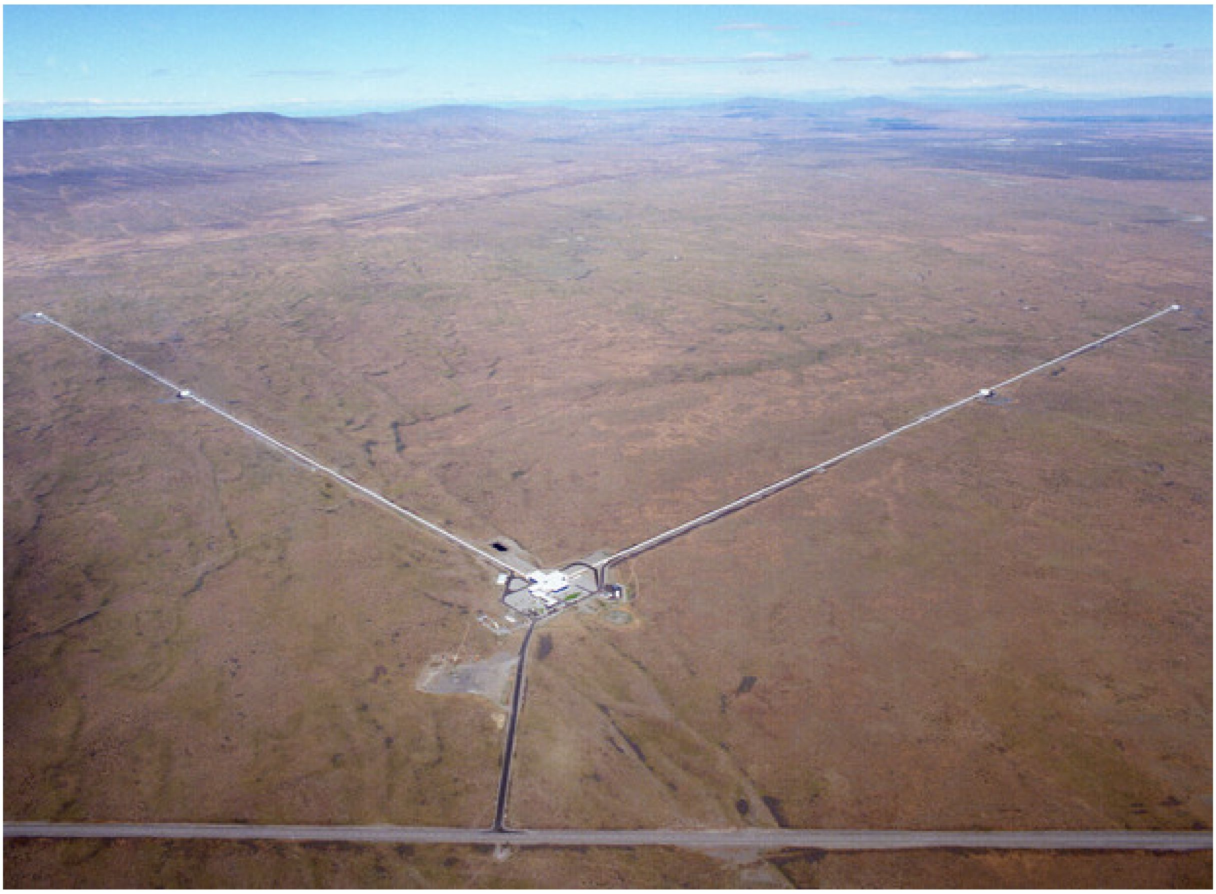

Figure 6: LIGO observatory located at Hanford, US. Source: LIGO/Caltech/MIT

One property of gravitational wave is when it passes through an object, it expands and contracts the object in perpendicular directions and vice versa till the wave passes the object. This property inspired scientists to come up with this 'L' structure. They believed when such a wave passes the earth, it contract one support of 'L' while expanding the other support. The mirrors placed in the L are perfectly reflective and distance is precisely calculated. It works as follows

Figure 7: A third detector VIRGO in Italy, Europe collaborated with LIGO to improve authenticity of collected data. Source:VIRGO

- Laser light is sent into the instrument to measure the changes in length of arms
- Arms are perfectly constructed such that if there is no gravitational wave, the laser from the two arms cancel each other at source after their round trip by "Destructive Interference" thus ensuring its stability, ground state i.e no change in length of arms
- If a gravitational wave passes, the arms oscillate back and forth, one getting longer while the other shorter, then vice versa, and so on, for as long as the gravitational wave passes. This makes unequal length in arms which makes different travelling time for laser thus not getting cancelled out after their round trip. This confirms the passage of gravitational waves through the detector thus confirming its existence
- Properties of these waves such as the time taken to pass the object, the frequency of oscillations, its origin can be understood by studying the properties of laser signals collected at the source

2.3 Experimental setup

2.3.1 Mirrors

Two arms are exactly 4km length and at the end hang "Test-mass" i.e highly polished mirrors made of fused silica which absorbs one in 3.3million photons thus making it nearly one-hundred percent reflective. Each test-mass weighs exactly 40kg. At the source beam spliters are present which splits the IR laser produced at source.

Figure 8: Test masses used in arms. These will be hanging at the end of the arms. Source: LIGO/Caltech/MIT

2.3.2 Laser

2.3.2.1 Basic principle:

The basic principle behind the working of laser are

1. **Absorption:**
   Electrons absorb photons focused on them

2. **Spontaneous Emission:**
   Electrons which are in excited state for more than 10^{-8}sec return to their ground state by releasing photon of equivalent energy

3. **Stimulated Emission:**
   Photons of particular wavelength and frequency when projected makes the electrons fall to ground state thus emitting yet another photon

By placing in an apparatus and using stimulated emission, laser of desired frequency, wavelength and energy can be produced

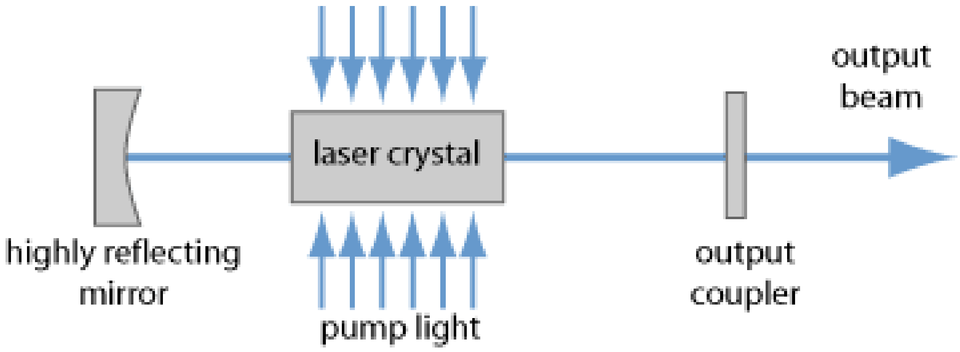

Figure 9: Working of a laser. Source: Wikipedia

2.3.2.2 Laser room in LIGO: The 200W beam with 1064nm wavelength which is about to make its journey in arms will be produced in laser room which has

1. **Non planar ring oscillator(NPRO):**
   The journey of laser starts here. It produces 2W, 808nm wave

2. **Master oscillator power amplifier(MOPA):**
   It has 4 rods made of neodymium, yttrium, lithium, and fluoride and are size of graphite in a pencil. Its final output will be a 1064nm and 35W wave

3. **High power Oscillator(HPO):**
   Similar to MOPA but made of different materials. Output will be of 200W and 1064nm

4. **Feedback systems:**
   The obtained laser is passed through a million feedback systems to make the most stable laser to be passed in the arm

2.3.3 Damping systems

To avoid artifacts due to external sources, LIGO implements varying damping systems mainly classified as

2.3.3.1 Active Damping system

The test mass is placed inside ISI(Internal Seismic Isolation) system which detects the physical vibrations associated with external world and produces counter-waves thus cancelling its effects.

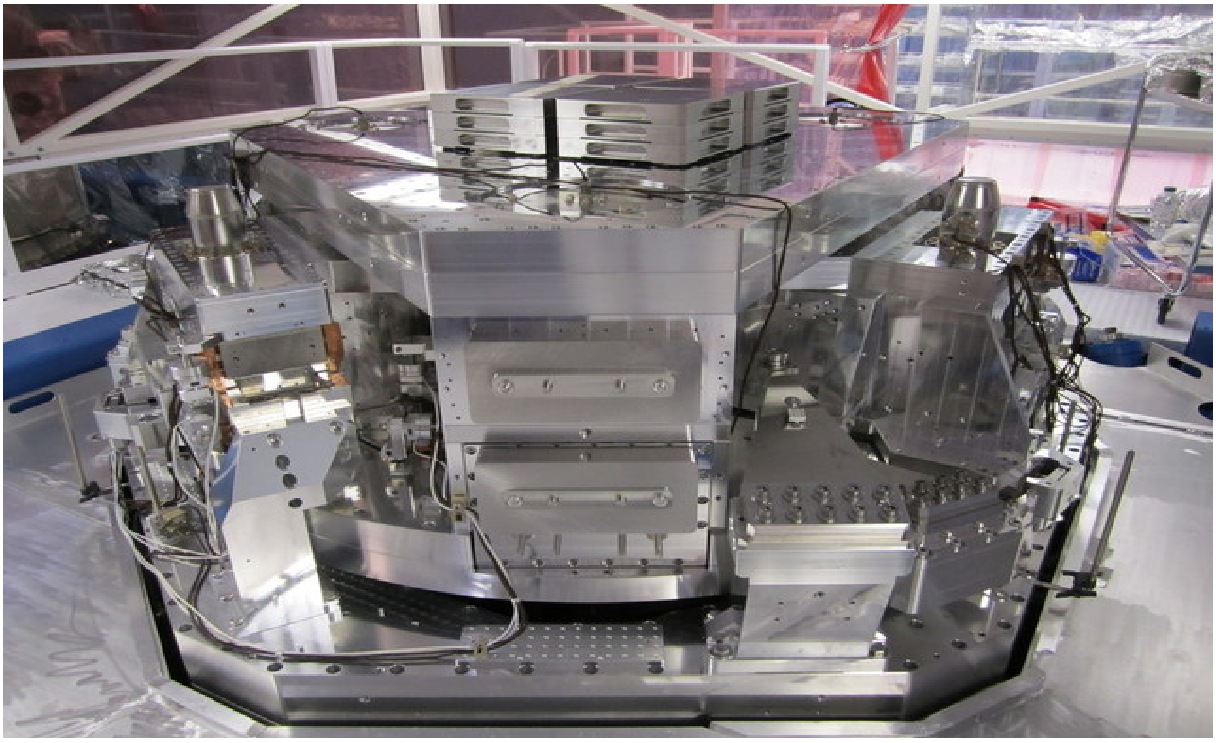

Figure 10: ISI system. LIGO's test-mass suspension systems hang below these 'active' isolation platforms. Source: LIGO/MIT/Caltech

2.3.3.2 Passive Damping system

It holds the mirror system perfectly still by "quad". Main chain side faces the laser and the Reactive chain side cancels any waves that haven't cancelled by the ISI

2.3.4 Data collection

LIGO collects data equivalent to terrabytes per day. These are to be transferred to super computers and further processing is to be done. LIGO's archive has data equivalent to 1-million DVD and adds around 178-thousand DVD to its archive each year. Caltech archive already stores 4.5Petabyte data.

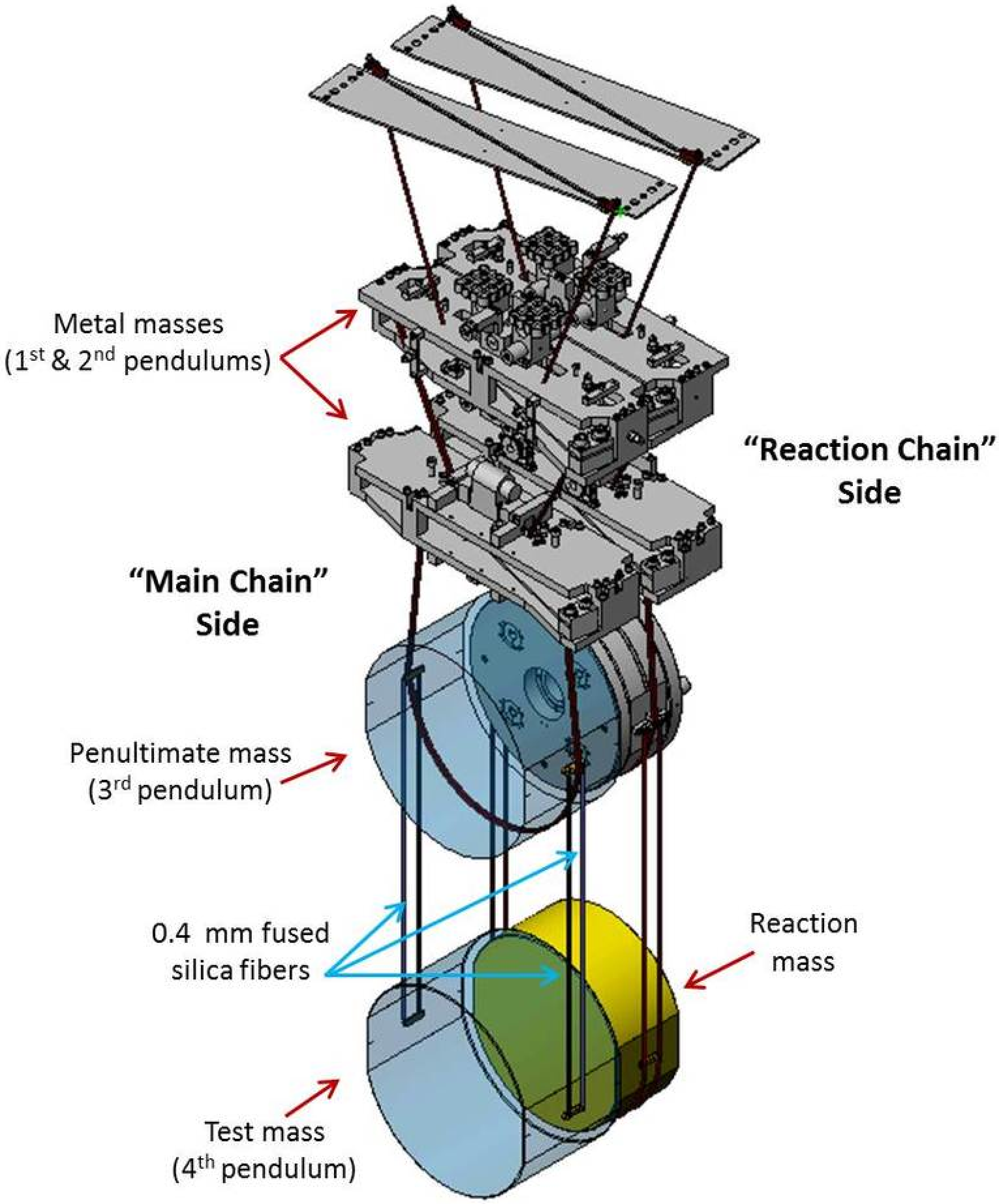

Figure 11: Quad system which hangs and holds the 2test masses perfectly still. Source: IGR, University of Glasgow

3 Discoveries made by LIGO

To understand about the discoveries made by LIGO, some terms must be familiarised

3.1 Nomenclature

Just as any other branch of science has its own nomenclature for its new discoveries which can be understood across the globe, LIGO made some set of rules to name its waves. It is made as a pair of characters (like AABBCCDD) where

- The first one(AA) indicates the nature of wave
- Second pair(BB) describe the year
- Third pair(CC) tells about the month
- Fourth pair(DD) tells about the date of discovery

3.2 Supernovae

It is an event that occurs as a death of certain types of stars. After this, the star may convert to a black hole or a neutron star depending on its mass. If it is heavier, it converts to a black hole. Else to a white dwarf or neutron star.

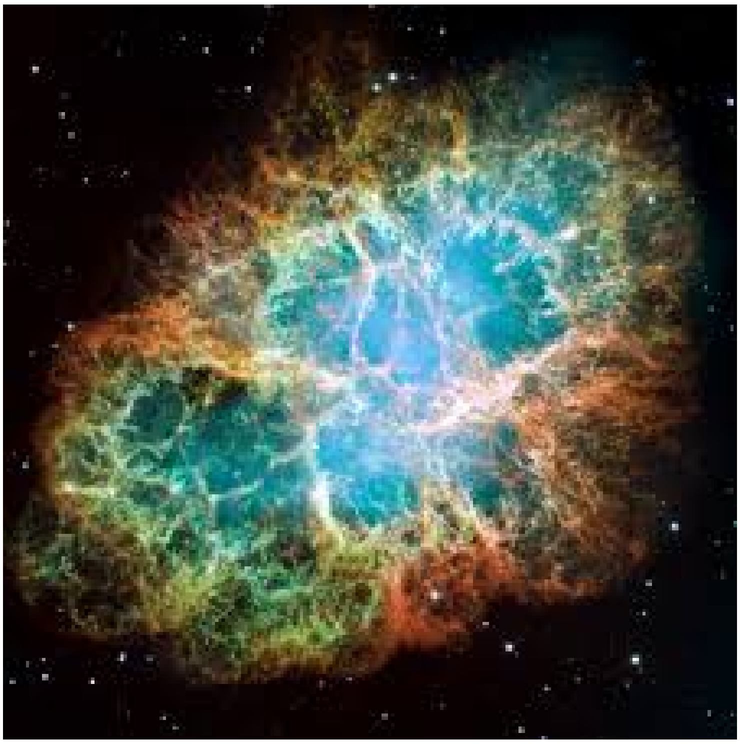

Figure 12: An artist depiction of Supernovae. Source: Wikipedia

3.3 White Dwarf

A star of about the mass of sun and the radius of earth can be termed as white dwarf. Upon reaching Chandrasekhar's limit i.e M = 1.4*M_s, where M is the mass of the celestial body and M_s is the mass of Sun which is also known as "solar mass", it collapses and turns out to be a neutron star.

3.4 Neutron Star

A celestial object of very small radius (typically 30 km) and very high density, composed predominantly of closely packed neutrons. Neutron stars are thought to form by the gravitational collapse of the remnant of a massive star after a supernova explosion, provided that the star is insufficiently massive to produce a black hole.

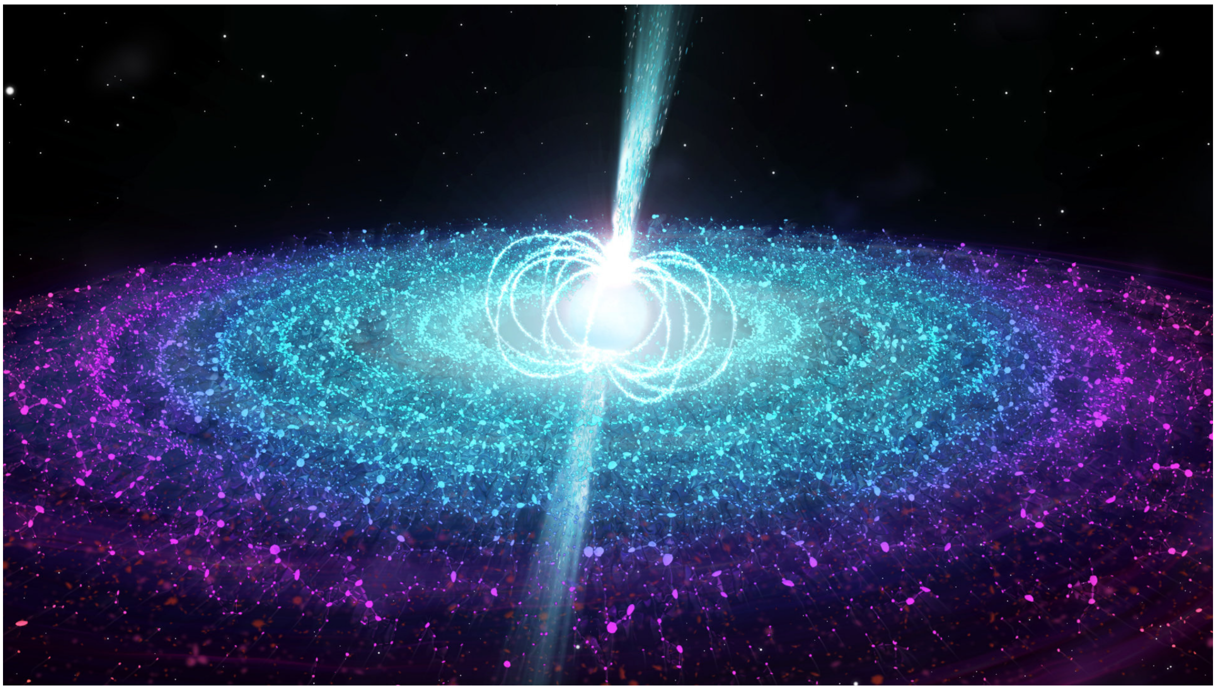

Figure 13: An artist depiction of Neutron star. Source: Wikipedia

3.5 Binary Star

A binary star is a star system consisting of two stars orbiting around their common center of mass.
Eg: Mizar and Alcor of Ursa Major constellation

3.6 Black hole

A black hole is a region of space-time exhibiting such strong gravitational effects that nothing—not even particles and electromagnetic radiation such as light can escape from inside it. More technically, its escape velocity is far greater than the speed of light and its radius of influence is known as "Event Horizon".

If the earth is squeezed to 1cm radius or sun squeezed to 3km radius, it would result in a black hole from the following relation

$$R = \frac{2MG}{c^2} \tag{2}$$

where R is the radius of the body, M is the mass of the body, G is the gravitational constant and c being speed of light

3.7 Binary black hole

A binary black hole (BBH) is a system consisting of two black holes orbiting each other.

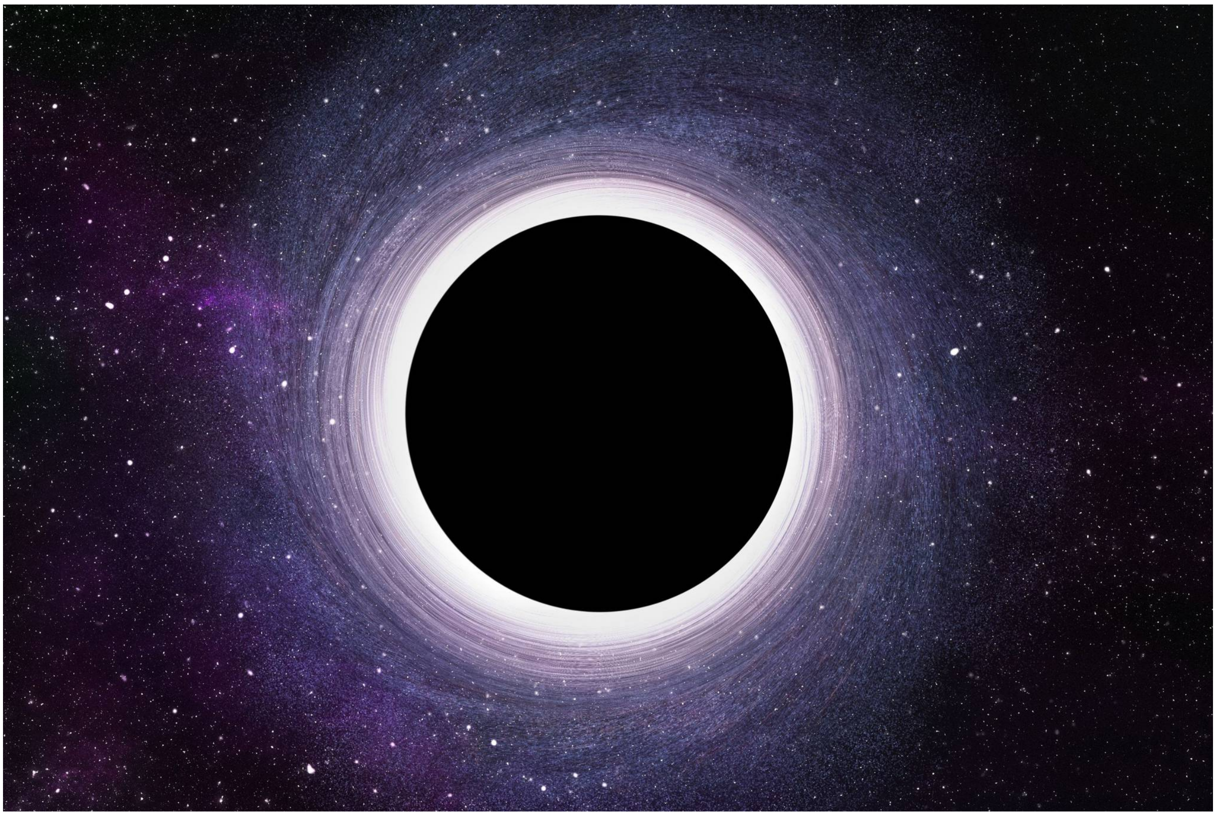

Figure 14: An artist depiction of Black hole. Source: Wikipedia

3.8 Notable detections

GW150914[9], which was detected on 14 September 2015 just after few days of turning on the detector is the first one to be detected by the observatory. It was caused by the binary black hole merger, one black hole having 36 solar masses and the other one having 29 solar masses releasing energy which is greater than the combined power of all light radiated by all the stars in the observable universe.

The next notable discovery is GW170817[10][11], 17 August, 2017 which is special due to the nature of the wave and the source. It was produced by neutron star merger which was also confirmed by EM physicists thus confirming the presence of neutron stars as well.

Kip Thorne, Rainer Weiss and Barry C.Barish were awarded the Nobel Prize for Physics towards their contributions in formulating, developing the techniques used by LIGO. Kip Thorne worked on strength detection of these feeble waves. Rainer Weiss contributed towards the laser technique and Barry C.Barish towards formulation of the nature of waves, signal spectrum formed by mergers.

3.9 Waveforms

From the waveforms obtained at the observatory, the source has been interpreted by the scientists as follows

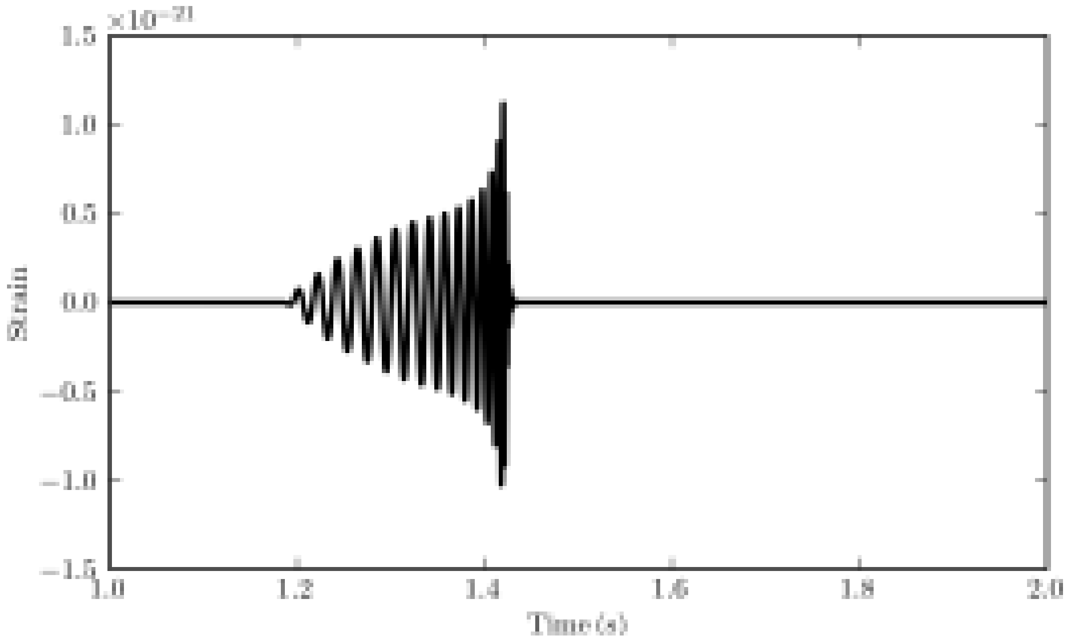

Figure 15: Waveform interpreted due to merge of binary black hole. The strain increases with time and reaches its peak during merger. Source: LIGO/MIT

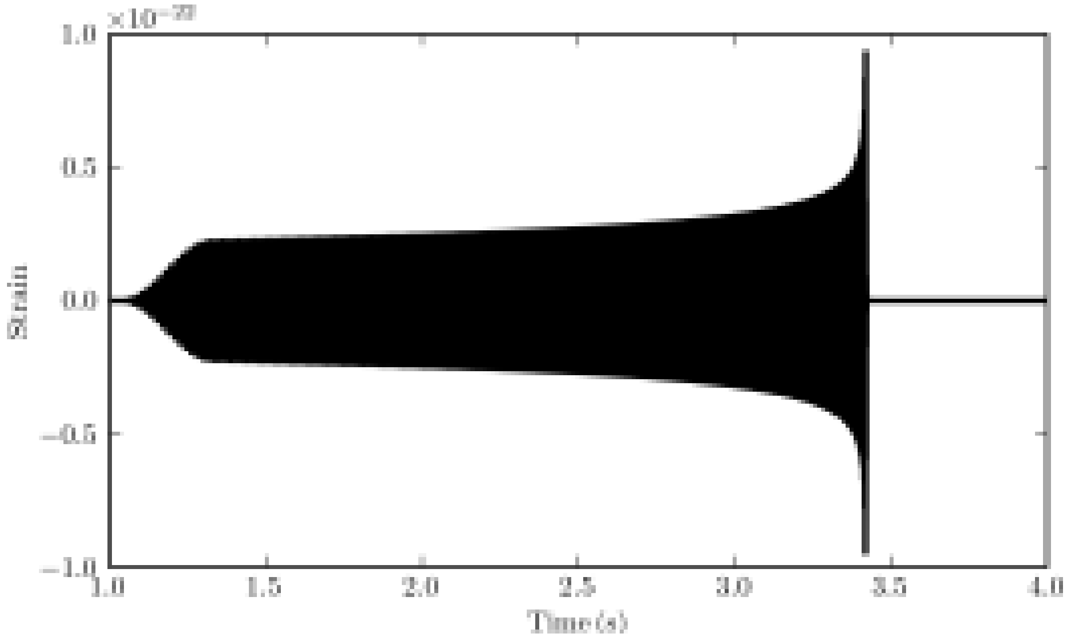

Figure 16: Waveform interpreted due to merge of neutron star. Strain maintains a constant value post merger and suddenly reaches maximum. Source: LIGO/MIT

3.10 Gravity waves

Gravity Waves are physical perturbations driven by the restoring force of gravity in a planetary environment. In other words, gravity waves are specific to planetary atmospheres and bodies of water. This should not be confused with Gravitational waves.

4 Uses

One may question “If these waves are too feeble, why to detect them? They won’t harm us right.” or “Can we make any technology from them?”

While it is true that even the strongest gravitational wave passed through all of us and we are safe, in theory we have been elongated and contracted for that duration. It may not be useful for the study of the inner space but it is useful to study the outer space in new way where light can’t escape such as black holes. It can also be used to observe celestial bodies which can’t be observable by large telescope maybe because of the interference of Earth’s atmosphere, light constraints. As the concept of gravitational lensing demystified and now can be more clearly understood, using along with optics principles, one can estimate the location of galaxies from where light comes, location of black holes, neutron stars which acts as lens and are responsible for bending.

Doppler shift and its techniques are currently used in determining the mass, radius, orbital period, velocity and other information regarding the binary stars given its absorption spectrum which lies in electromagnetic region. Now this technique can be further extended and modified to gravitational waves and further analysis maybe carried in future.

The core of the star which is responsible for gravitational pulling of the matter and finally exploding cannot be observed because it is opaque and too hot for electromagnetic waves that they will distort. But new techniques can be developed by observing the gravitational waves emitted by them and interpreting them.

Coming to technology side, all the present day technology has derived from the previous science. So, yes we can make some sort of technology from this but it is very challenging and time taking because its detection itself has taken a century with such a sophisticated apparatus.

4.1 India's contribution

LIGO's detection can be divided as three parts

1. Experimental setup and development of detectors
2. Formulation of shape of waves that are likely to observe
3. Data Analytics

Indians have contributed a lot in the second and third parts. Recently it was announced that Indian LIGO(INLIGO) will be completed by 2024 and the required funds will be assured by Government thus having our own observatory in Maharashtra, India which strengthens our research in the areas of astrophysics and its related branches.

There are some upcoming LIGO detectors across Germany, Japan to improve the accuracy, reduce the artifacts and to apply triangulation technique to know the distance of the mergers etc;

Figure 17: KAGRA in Japan, sister of LIGO. Going to be the first underground detector and using cryogenics to control molecular vibrations. Source: Wikipedia

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