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Recent Advances

The Era of Multi Messenger Astronomy

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Abstract. Theoretical and technological developments in the last century paved the way for probing the universe using multiple cosmic messengers. The recent opening up of the previously inaccessible domains of messengers is providing us with a plethora of information that would revolutionize our fundamental understanding of the universe. In this article we explore two new messengers of the universe : Gravitational waves and Neutrinos, their cosmological origins and the methods of detection. Moreover, we explain the current and future observational facilities intended for exploring these aspects.
Keywords: Gravitational Waves, Neutrino Physics, Astronomy

1. Introduction

The universe has a lot of stories to tell us and we have been listening to this by deciphering the spectrum of information that reach us through the various messengers, travelling even billions of light years. Almost everything that we know about the Universe are a result of the information carried to us by the messenger, namely electromagnetic waves or photons. Over the last century, we have progressed from developing optical telescopes to telescopes across nearly every wavelength of the electromagnetic spectrum. However, the current understanding of cosmology suggests that all the information accessible through electromagnetic waves cover only around $4-5\%$ of the Universe. This is only a tiny fraction of the total content of the Universe. Also, at the highest energies and largest distances the Universe becomes opaque to photons. So physicists wanted to transcend beyond electromagnetic waves and unravel the unknown aspects of our Universe. Fortunately with the efforts of a large community, we have reached a point to detect and study previously inaccessible domains of cosmic messengers such as gravitational waves and neutrinos.

On the 17th August 2017, a gravitational wave signal corresponding to the merger of two binary neutron stars was detected by the LIGO and Virgo detectors. The signal was named GW170817. 1.7 seconds after the merger has been registered, a gamma ray signal was observed by FERMI and INTEGRAL spacecrafts. This Gamma Ray Burst(GRB) motivated astronomers to look out for signals in other parts of the EM spectrum and eventually signals were registered in all bands from x-ray to radio waves. Similarly on 22^{nd} September 2017, a highly energetic neutrino event was registered by the Ice-Cube observatory in Antartica, which immediately alerted other observatories around the globe eventually resulting in the detection of a gamma ray signal by Fermi-LAT collaboration, consistent with the neutrino

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event. *These observations marked the beginning of a new branch of astronomy called the multi-messenger astronomy*.

Multi-messenger astronomy is the observation of events based on the combined study of all cosmic messengers like EM waves, gravitational waves, neutrino and cosmic rays. The exploration of our Universe with multiple cosmic messengers is very promising and can reveal valuable information about our Universe. The aim of the article is to introduce the reader to the two new realms that will play a crucial role in the multi-messenger era: *gravitational waves* and *neutrinos*.

The emission of electromagnetic waves by accelerating charges are a fundamental source of our information. EM waves emitted by the astrophysical sources travel several light years and reach our telescopes, from which we gather data and analyse them to understand the underlying physical processes. These sources include different constituents in a galaxy such as stars at various stages of their life cycle, Inter Stellar Medium(ISM) and much more. This could also include stars that met with their end such as neutron stars and white dwarf or even the signals those were created in the initial stages of the Big Bang. In short, EM waves are our main source of information. But are we sure that EM waves are the only cosmic messenger that we can detect?. Exploration in this direction during the last century resulted in the initiation of the neutrino and gravitational wave telescopes capable of observing inaccessible domains of our vast universe.

This article is organised as follows in section [2] we briefly introduce the GW astronomy: the history, different instruments used to detect GWs and the possibilities that they open up. The same pattern is followed for *neutrino physics* in section [3].

2. Gravitational Waves

The propagation of electromagnetic waves can be expressed as a solution to Maxwell's equations. We have been using the various parts of the electromagnetic spectrum for observing the Universe in various wavelengths. This has resulted in the coinage of the term 'multi-wavelength astronomy'. Apart from observing the Universe, electromagnetivc waves finds applications in telecommunication, navigation, cooking food and countless other applications. Similar to the maxwell's equations in EM waves the fundamental equation in General Relativity known as the Einstein Field Equation(EFE) predicts such a wave like phenomenon, which was identified by Albert Einstein immediately after the conception of his theory in 1916. However, since the concept of gravitational wave and its physical existence was skeptical over many decades, the historical developments that led to the current state of gravitational wave research is worth discussing.

Few years after predicting the formula for gravitational waves in 1918, Einstein along with his new student *Nathan Rosen* expressed concerns regarding the validity of such a wave like solutions for his non-linear theory of gravity. However this research paper concluding that *gravitational waves cannot exist* authored by *Einstein & Rosen* in 1936 was refused to publish in the journal *Physical Review* by the referee H.P.Robertson, who was a famous physicist. Einstein who was not happy with this decision decided to withdraw the paper and to submit it to another journal *Journal of the Franklin Institute*, which was eventually accepted for publication. while Nathan Rosen was on a research visit to Russia, Einstein appointed a new assistant Leopold Infeld, who happened to meet Robertson, just arrived from Pasadena. Eventually they discussed about the paper which *Einstein & Rosen* had submitted, which led to Robertson pointing out to the error in Einstein's calculations. *Infeld* then went to Einstein and discussed what Robertson had told him. By then, Einstein being aware of his mistakes, corrected the paper which was accepted for publication. The paper predicted cylindrical gravitational waves instead of plane waves. This is now known as *Einstein-Rosen waves*.

The controversies continued even after 1940's, until the ideas started to take a turn around in a conference in Bern, Switzerland in 1955, convened to celebrate the 50^{th} anniversary of special relativity. It was in this conference that Felix Pirani has shown how to describe the tidal forces experienced by the particles mathematically, through *geodesic deviation equation*. This is one of the major ideas wherein the equation tells us how a ring of test particles move when a GW passes through it. Simultaneously, Hermann Bondi took up the study of energy radiated by gravitating systems. In 1957 another famous conference was held in Chapel Hill, North Carolina and was attended by Hermann Bondi, Richard Feynman and many other experts. Bondi's talk on the energy carried by GWs has motivated several discussions during the conference. When people were skeptical about whether GW's carry energy or not, Feynman came up with his own explanation of the problem, which is now famously known as the *sticky bead argument*.

"I think it is easy to see that if gravitational waves can be created, they can carry energy and do work. Suppose we have a transverse-transverse wave generated by impinging on two masses close together. Let one mass A carry a stick which runs past touching the other B. I think I can show that the second in accelerating up and down will rub the stick, and therefore by friction make heat. "

The important point is that the energy for heating the rod due to friction is given by the passing gravitational waves. This convinced the theoretical community that gravitational waves can carry energy. However its detection remained as an important problem, since gravitational force is much weaker compared to electromagnetic forces. The developments in radio astronomy during the second half of the last century helped astronomers to detect several new sources. In 1974 Russel Hulse and Joseph Taylor discovered the first binary pulsar PSR B1913+16 and noted that the systematic variations and periodic patterns in their pulses were possible only if it is in a binary orbit. Moreover in the next seven years of observations they noted an orbital decay and found that the orbital period decreases $76.5\mu s$ per year, which agrees well with the energy loss via gravitational waves predicted by general relativity. This further motivated the gravitational wave community. It took a century for the first direct detection of gravitational waves, of which the last four decades were to develop the Laser-interferometric-Gravitational Wave Observatory(LIGO) and achieve the present sensitivity. On 14^{th} September 2015 LIGO detected the first gravitational wave emitted as a result of a merger of two binary black holes of masses 36 $M_{\odot}$ and 29 $M_{\odot}$, marking the beginning of a new branch of astronomy called gravitational wave astronomy. This signal was named as GW150914. These extremely heavy masses undergoing merger created ripples in space-time, that travel many light years to reach the GW detectors.

Readers who are interested in knowing more about the history of the developments that led to the advent of gravitational wave astronomy, are encouraged to read the papers,[1].[2]

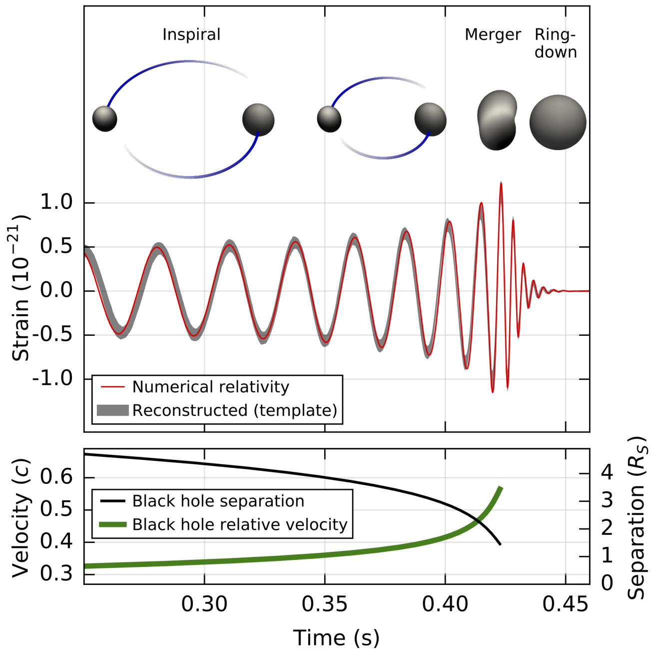

Fig. 1. The figure illustrates inspiral, merge and the ringdown stages as well as their corresponding waveforms. In the bottom part of the figure we observe that their separation decrease and the velocity increases as time elapses. The end product is a BH of larger mass[3] .

2.1. Sources of gravitational waves—The main sources of gravitational waves that are sensitive to existing detectors are compact binary objects such as Black Holes(BHs), Neutron Stars(NSs) and White Dwarfs (WDs). When two NS's or BH's orbit, their orbital period and separation decreases due to the emission of gravitational waves. When they are close to collision (merger), their amplitude and frequency increases and hence they become observable to current generation detectors. Three important phases of such a merger event are shown in the fig.1. lThe end product of such a merger is usually a compact object of the same type (but not always). Based on the nature of the waveform astrophysical sources of gravitational waves are classified into three types : *burst*, *periodic* and *stochastic*. The merger of stellar mass BHs or NSs which we discussed above is a burst signal. The best example of a periodic source is an isolated rotating neutron star with a mountain on top of it. The stochastic sources of gravitational waves consists of weak and unresolved signals. They collectively form a stochastic background of gravitational waves which include gravitational waves from the early universe resulting from inflation, phase transitions and other unresolved binary star systems.

2.2. How do we detect them ?—In the last century we have mastered in producing and detecting electromagnetic signals of different frequencies. A conducting material could act as an antenna to detect such waves and there is literally no one who has not seen a TV dish antenna receiving electromagnetic signals. However gravitational waves falls under a different category. If oscillating Electric ($\vec{\mathbf{E}}$) and Magnetic ($\vec{\mathbf{B}}$) fields are responsible for EM Waves , the space itself is oscillating when a gravitational wave passes. Moreover, gravitational waves are much weaker than electromagnetic waves. Therefore

Fig. 2. Joseph Weber with his resonant mass detector[4]

detecting such a phenomenon requires an entirely different type of instrument. In total it is an engineering challenge and it was far ahead for the technological capabilities that we had in the last century. In this section we see the type of instruments that physicists have built, currently being used and ones proposed for the future to detect gravitational wave spectrum of our universe

2.2.1. Bar detectors—One of the first constructed gravitational wave antennae is a bar detector. It was built by Joseph Weber of Maryland University and hence it is also known as Weber bar as shown in Fig. 2. He used an aluminum cylinder of 2 m in length and 1m in diameter which has a resonant frequency close to 1660 Hz . Therefore an incoming gravitational wave close to this frequency sets the cylinder in deformation. As this works based on the phenomenon of resonance, the detector was also called as resonant mass detector. To measure the deformation caused by gravitational waves, Weber used sensitive piezoelectric sensors, which under mechanical deformation can generate electric voltages. These sensors are attached around the bar. One of the demerits of this detector is that they are sensitive only to astrophysical events that can generate gravitational waves close to the resonant frequency (around 1 KHz). Weber also placed a similar detector 1000km apart so that he can find coincidences. Soon after the bar detectors became operational in 1965 Weber claimed detection of gravitational wave events. This news paved way for excitement in the community and many groups all around the world began to set up resonant mass detectors similar to what Weber built. But unfortunately none of the groups were able to reproduce Weber's results. However Weber's pioneering work gave a kick start to gravitational wave research.

2.2.2. Ground based detectors—The idea to use Michelson interferometers to detect gravitational waves came in the 1960's. They are the best instruments to make small measurements and it works by superimposing two beams of light from the same source sent along two different paths which leads to the formation of interference patterns whenever there is a difference in path length. The Laser Interferometric Gravitational wave Observatory $(LIGO)$ is an L-shaped observatory with two arms each of 4 km in length. Pure fused silica mirrors of 40 kg are located at the ends of the arms which will act as a test

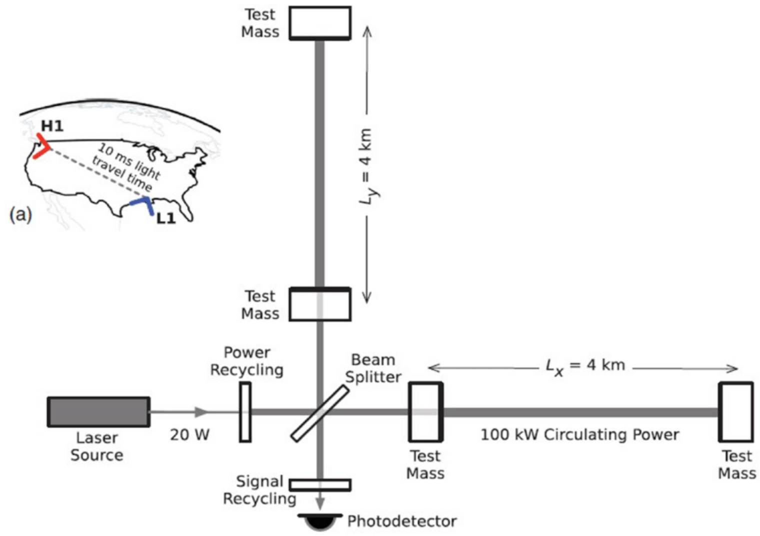

Fig. 3. Laser Interferometer - a schematic diagram[5]

mass. A laser beam in the infrared wavelength is directed to the mirrors and the resulting interference pattern can reveal information about the passage of a gravitational wave signal. The region between the mirrors are evacuated maintaining a high quality vacuum which is crucial, otherwise laser beams will be absorbed and deflected by the particles in air, creating noise in the system. Maintaining such a high quality vacuum is a 40 day long process and involve several stages. For more details regarding the LIGO interferometer and its working we encourage the reader to refer to.[5] A schematic representation of LIGO interferometer is given in fig: 3. Interferometric detector currently in operation are two LIGO's in US (Louisiana and Hanford), Virgo in Italy and KAGRA in Japan. There are mini detectors like GEO600 in Germany mainly used for research purpose.

As mentioned previously, gravitational waves are ripples in space. When one such wave passes through an interferometer one of the arm is stretched to a minuscule while the other one is compressed. The length of the arm oscillates while a gravitational wave passes, causing the laser beam in one arm to arrive earlier than the other. This causes an interference pattern and the photo-detector measures it marking the presence of a gravitational wave. But in reality the situation is not so simple, the wave that reach us has an amplitude several times smaller than the size of a proton. LIGO is capable of detecting such tiny changes in distance, making it the most sophisticated instrument to measure the smallest distances in the world. However this increased sensitivity makes it sensitive to other sources which can cause the mirrors to move, these are noises to us. Extracting the signal from this sea of noise require efficient statistical methods.Interested readers are encouraged to refer the following[6,7,8] for more details regarding the statistical techniques involved in the extraction of source parameters from the signal.

The ground based detectors that are currently existing and making detection are known as second generation(2G) detectors, more sensitive detectors of much larger length are currently being planned. They are called as third generation (3G) gravitational wave detectors. These next generation gravitational wave detectors that are currently in the early stages of development are European based Einstein Telescope(ET) and the American counterpart Cosmic Explorer(CE). They can detect GW sources much before they merge.

ET is a combination of three LIGO like interferometers joined to form a triangle with sides of 10 KM while CE is an L-shaped interferometer similar to LIGO with an arm length of 40 km. They are expected to detect GWs from isolated pulsars and supernovae besides understanding the black hole and neutron star properties in detail. Moreover, answers to several open questions in fundamental physics and cosmology such as the nature of dark matter, dark energy and the presence of exotic compact objects are included in the science goals[8] of ET. GW signals from binary neutron star mergers detected by ET will be available for a longer duration and this will help us to understand the equation of state of matter at such denser conditions and during phase transitions.

A natural question arises to every beginner: why do we build so many different observatories, if all of them measure the same gravitational wave?.
The answer is that not all astrophysical sources emit gravitational waves in the frequency band of LIGO. They can detect only a small spectrum of sources(10Hz - 10,000 Hz) whereas for the merger of small BH's orbiting around big supermassive BHs like the one at the center of a galaxy we need space-based detectors like Laser Interferometric Space Antenna (LISA).

A network of GW detectors is more advantageous than a single detector making it more sensitive to signals from all parts of the sky and also compensating for any downtime. Moreover it can increase the accuracy in estimating the source information such as the masses, location in the sky, their distance from us and much more. This justifies the involvement of many nations around the globe in investing in such facilities. An Indian version of LIGO called LIGO India is being built in Maharashtra. With more than 100 detections the gravitational wave network is growing strong. In the forthcoming decade of space based detectors like LISA, DECIGO (DECi-hertz Interferometer Gravitational wave Observatory) and the third generation ground based detectors we will have an opportunity to understand the GW universe in a wide range of frequencies. Each type of detector records GW events in different frequency window thereby studying different astrophysical sources.

2.2.3. Space detectors—The ground based gravitational wave observatories have several limitations like the noise arising from various sources, limitations in maximum arm-length etc. As mentioned earlier the sensitivity of a detector can be improved by increasing the length of the arms. Although there is a limitation in increasing the length of an arm beyond a certain limit in Earth, such a limitation does not exist in space. These factors motivated physicists to consider building space based GW observatories. Some of the proposed experiments include the ESA led Laser Interferometric Space Antenna(LISA), the Japanase counterpart DECi-hertz Interferometer Gravitational wave Observatory(DECIGO) and B-DECIGO. LISA also works by laser interferometry and has a constellation of three spacecrafts arranged in an equilateral triangle in an heliocentric orbit in space. The sides of the triangle is 2.5 million KM's long.[9] At present the mission is planned to be launched in the year 2037. The frequency range in which LISA is most sensitive is $10^{-4}Hz - 1Hz$.Similarly, DECIGO consists of three drag-free satellites separated by 1000 km in length and works by the same laser interferometry. The operating frequency of DECIGO is 0.1-10 Hz and observing gravitational waves from the beginning of the universe is one of its primary objectives. On the other hand B-DECIGO is a mini version of DECIGO

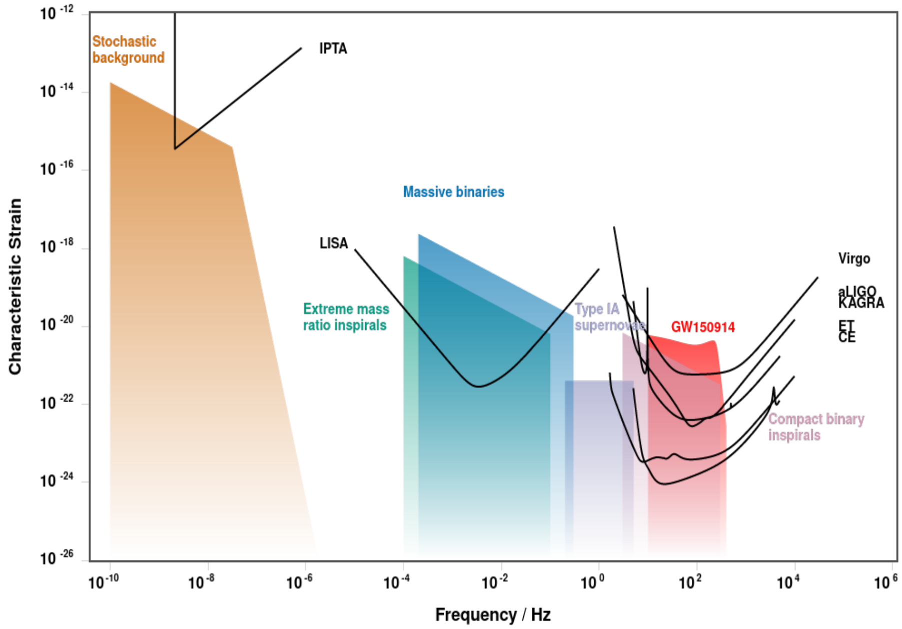

Fig. 4. Sensitivity curves for different Gravitational Wave Detectors and Sources. credits : http://gwplotter.com/

with a shorter arm length(100km). It is expected to be launched in 2030's and its main objective it to develop scientific technologies necessary for DECIGO.[10]

2.2.4. International Pulsar Timing Array—The International Pulsar Timing Array(IPTA) is a venture to sample signals from rotating pulsars, which are nothing but neutron stars emitting beams. This pulsar network can work as a gravitational wave detector. The position of a pulsar with respect to another pulsar will change when gravitational wave arrives. This change in position will be recorded as a Doppler shift in the recorded pulse from the pulsar. Hence pulsar timing array is a good detector of gravitational wave. but it works for detecting signals from low frequency GW sources. The advantages of using millisecond pulsars are that they are stable clocks and sensitive to very low frequency($10^{-9}Hz - 10^{-6}Hz$) gravitational waves.

3. Neutrinos

Neutrinos are fundamental particles proposed by Wolfgang Pauli in 1930 to explain β-decay and after 25 years, its existence was proven experimentally by Clyde L. Cowan and Frederick Reines. According to the standard model of particle physics, neutrinos are electrically neutral, massless and spin-1/2 particles(fermions), they come in three flavours each associated with a charged lepton. By three flavours we mean there are three types of neutrinos; electron neutrino(ν_e) associated with electron(e), muon neutrino(ν_μ) associated with muon(μ) and tau neutrino(ν_τ) associated with tau(τ). Each type of neutrino also has an antimatter component, called an antineutrino which has the same spin and does not carry any charge. However, anti-neutrinos are distinguished from neutrinos by having opposite-signed lepton number, weak isospin and right-handed chirality instead of left-handed chirality.

Developments in neutrino-physics and facilities to detect and study them are already

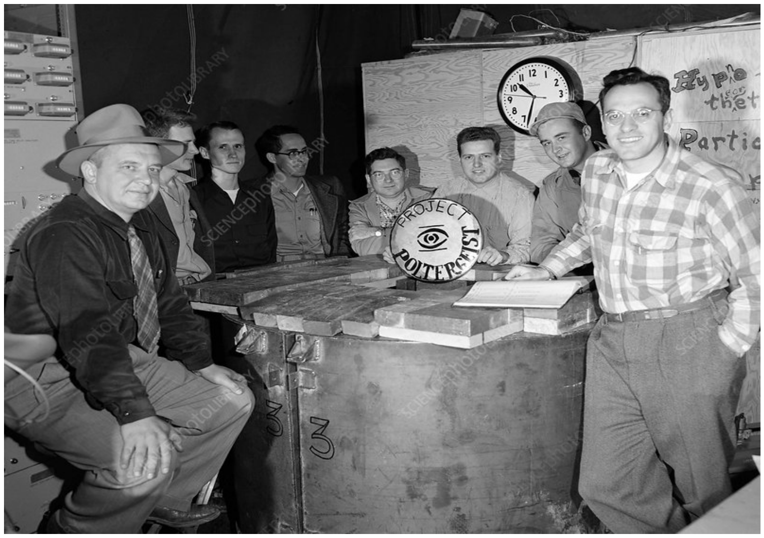

Fig. 5. Cowan–Reines Neutrino Experiment Team[11]

underway across the globe which include experiments like T2K,[12] Super-K, NOvA, Ice-Cube, JUNO, KamLAND, BOREXINO etc. Neutrinos are very weakly interacting particles with negligible mass and hence they travel close to the speed of light(*ultra-relativistic particles*). As they are weakly interacting they almost travel in straight lines from their source. Different experiments play different role in understanding various features of this elusive particle. An interesting feature about neutrinos are that they come in three flavours(types) : electron neutrino, muon neutrino and tau neutrino; and they can change or oscillate between them which is a consequence of their mass. However,the mass of individual neutrinos are still unknown. *KArlsruhe TRItium Neutrino* (KATRIN)[13] experiment in Germany is dedicated to detecting their absolute mass.

3.1. Solar Neutrinos—Solar neutrinos are the neutrinos produced in the sun during the nuclear fusion. Sun is a major source of most of the neutrinos that are passing through Earth. During the nuclear fusion in sun, the protons fuse together to form Helium releasing energy and electron-neutrinos in large number. When scientists started to look for this electron neutrinos from the sun,they observed an interesting fact that the detected neutrinos are only about one third to one half of the predicted number of neutrinos. This deficit in electron neutrinos from the sun was known as *solar neutrino problem*, and it took nearly four decades to find an explanation for this phenomena. A history of solar neutrino can be found here.[14]

An astrophysicist John N. Bahcall had predicted the amount of neutrinos that should arrive from the sun using a solar model developed by him. Once the theoretical calculation was done, they waited for the experimental confirmation. The *Homestake experiment* used 100,000 liters of perchloroethylene to search for solar neutrinos. The experiments operated several years and the solar neutrinos detected by the experiment was 20% less than the theoretical predictions. It was not sure either it was a problem with the solar model or with the neutrino models and our understanding.

Many physicists reviewed and redid Bahcall's calculations and Raymond Davis even repeated his experiment. But there were no difference in the observation: there are still missing neutrinos. The *Gallium Experiment* (GALLEX) in Italy and *Soviet–American*

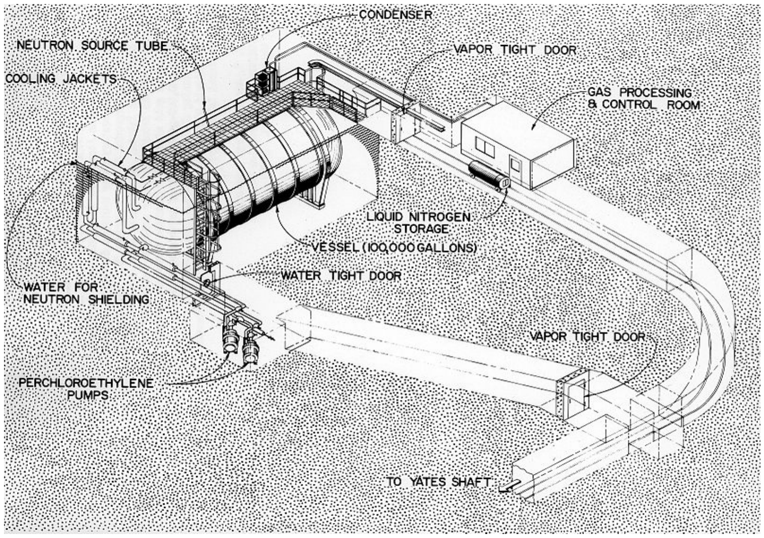

Fig. 6. Homestake Experiment Setup[15]

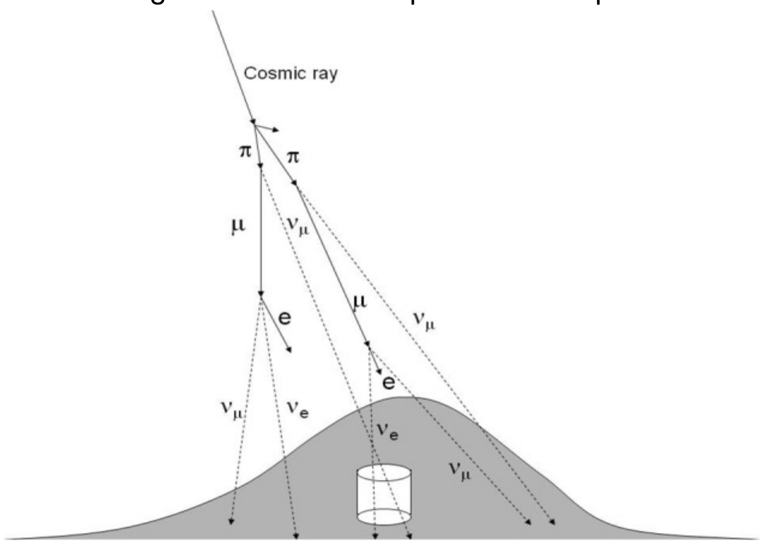

Fig. 7. Cosmic rays producing neutrinos[16]

Gallium Experiment (SAGE) in Russia also had the similar observations on their search for solar neutrinos. Hence the question about all those missing neutrinos remained.

3.2. Atmospheric Neutrinos—Atmospheric neutrinos are produced due to collisions of cosmic rays with nuclei in the atmosphere, around 15 kilo meter above the earth's surface. The collision of the primary cosmic rays, with atmospheric nuclei produce pions. These pions are unstable particles, and hence they decay into muons and muon antineutrino. Also, the muons are unstable, and it usually decay into an electron, electron neutrino and a muon neutrino. Calculations showed that two third of atmospheric neutrinos are muon neutrinos and one-third is electron neutrinos.

At the end of the 1980s, the first results of the Cherenkov detector *Kamiokande* and *Irvine-Michigan-Brookhaven* (IMB) detector showed a small deficit of muon-neutrinos. This discrepancy between the observed and expected ratio, 2:1 of muon neutrinos to electron neutrinos from cosmic rays was known as *atmospheric neutrino anomaly*. Only 61% of the expected muon neutrinos was found in the observatories. It was this anomaly which provided evidence for the existance of neutrino oscillations. Readers who are interested in reading further on anomaolous atmospheric neutrinos could refer this paper.[17]

3.3. Neutrino Oscillation—Neutrino oscillation is a well established phenomenon explained by quantum field theory (QFT), proposed by Bruno Pontecorvo, in 1957. In late 1960s his idea explained the solar neutrinos as: the electron neutrinos that are coming from the sun are changing its form and were no longer electron neutrinos when they reach the Earth. This oscillations are generated by the interference of different mass eigen states of neutrinos. Which implies that, neutrinos can oscillate only if they have mass. But in the standard model(SM) description, neutrinos are massless and are very weakly interacting particles. Experimental verification of neutrino oscillation proved that the neutrino has a non-zero mass and, indicates an incompleteness in the Standard Model and opens a window for physics beyond SM.

A practical method for investigating neutrino oscillation was first suggested by Bruno Pontencorvo using an analogy with Kaon oscillations; over subsequent 10 years he developed the mathematical formalism. The experimental discovery of neutrino oscillation and thus neutrino mass, by the Super-Kamiokande Observatory,[18] an improved version of the Kamiokande experiment and the Sudbury Neutrino Observatories[19] was recognized with the award of the 2015 Nobel prize for Physics. The data from these experiments shows that, two-thirds of the electron neutrinos coming from the sun were changing their flavor as they traveled, and arriving as muon or tau neutrinos. Evidence that neutrinos changed type also proved that they have mass, which is not predicted by the Standard Model.

3.4. Cosmic Neutrinos—Cosmic neutrinos are the highly energetic neutrinos, which are not from earth. They carry more energy than any other kind of neutrinos we have observed and they are coming from outside our solar system. The exact sources of cosmic neutrinos are still mystery. They can be from the remnants of supernovae, black holes, pulsars, explosions called gamma ray bursts, active galactic nuclei etc. It could also be something entirely new that physicists haven't observed yet. Cosmic neutrino travel from places that are opaque and carry information on the events happening in the dense places in our universe. Also the reluctance of neutrinos to interact with matter they are unperturbed on their journey. This makes them a great messengers for phenomena happening far beyond our own galaxy. They can point back to their sources and provide clues to the extremely energetic processes that caused them. Cosmic neutrinos are classified into 3 categories according to their origin and energy.

3.4.1. Big Bang Neutrinos—All of us are familiar with the Big Bang theory which describe how the Universe expanded from a singular point of high temperature and density. Physicists are always interested in understanding the early epochs of the Universe. The most common method to do so is to map the relic radiation from the early universe called, Cosmic Microwave background (CMB). It is the oldest electromagnetic radiation existing in the Universe, from around 400,000 years after the Big Bang.

Similar to Cosmic Microwave Background(CMB), a particle radiation background from early universe, called Cosmic Neutrino Background (CνB) also exist. This particle radiation background is composed of neutrinos and these neutrinos are known as relic neutrinos. As neutrinos interact so rarely, they should have been able to free themselves from the matter within one second of the Big Bang. Theoretical calculations have estimated that

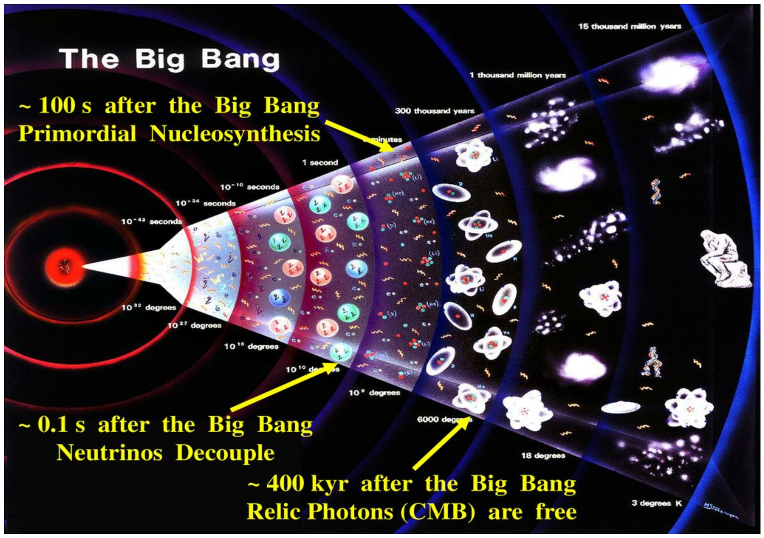

Fig. 8. Neutrino and Big Bang[20]

the cosmic neutrino background has a temperature of 1.95K, even colder than the cosmic microwave background.

These relic neutrinos still exists everywhere in the Universe. Also the big bang cosmology have predictions about CνB and there are indirect strong evidences from big bang nucleosynthesis. However, it is very difficult to detect these relic neutrinos as they have a very low energy, around 10^4 to 10^6 eV. Precise observations by the Wilkinson Microwave Anisotropy Probe revealed the presence of the cosmic neutrino background through its effects on the cosmic microwave background.

We need a confirmation for the existence of these relic neutrinos which is only possible if we could detect them using experiments on earth. Using tritium is the proposed method for the detection of CνB. The relic neutrinos of CνB with tritium will lead to the production of electrons;

$$\nu + {}^3H \rightarrow {}^3He + e^- \tag{1}$$

and the main background comes from electrons produced via natural beta decay

$${}^3H \rightarrow {}^3He + e^- + \bar{\nu} \tag{2}$$

These electrons produced should be detected with instruments, to measure the size of CνB. The background electrons are numerous and their maximum energy is smaller than the average energy of the CνB - electrons, by twice the average mass of neutrino. As the neutrino mass is tiny a detector must have an excellent energy resolution in order to separate the signals from the background. A proposed experiment is Princeton University's PTOLEMY, which will be made up of 100 g of tritium target.

3.4.2. Stellar Neutrinos—All stars are shining because of the nuclear fusion reaction in its core and necessary product of this reaction is electron neutrinos. As neutrinos are weakly interacting, these electron neutrinos escape from the star. A supernova is a violent explosion of a dying star. These explosion generate more energy in a few seconds than the sun. Supernova are seen in other galaxies, but they are difficult to observe in our own galaxy, the Milky Way, as the dust particles always blocks the view.

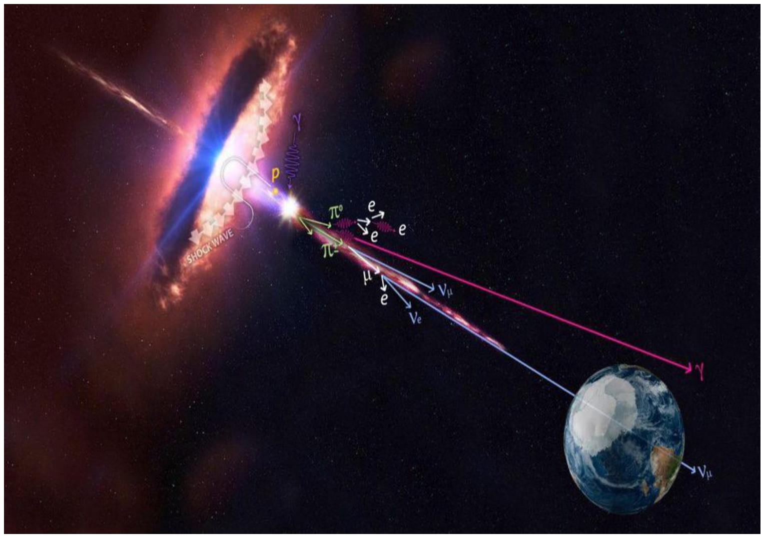

Fig. 9. Ultra High Energy Neutrinos[21]

A supernova explosion release enormous amount of energy and 99% of this energy is carried by the neutrinos. As the core of a collapsing star is more dense and as neutrinos interact weakly, it is the neutrinos which escape from the center more quickly than the light. The *KamiokaNDE-II observatory* in Japan captured 25 neutrino events from the supernova SN 1987A, which was observed in the Large Magellanic Cloud in 1987. This event marked the beginning of neutrino astronomy. Davis and Koshiba were jointly awarded the 2002 Nobel Prize in Physics, for the detection of supernova neutrinos.

It's expected that a supernova will occur in a galaxy like the Milky Way once every 10 to 50 years. Neutrino observatories will be the first place on the earth to see a supernova and it can be used to get direction of arrival of supernova light, with the help of optical telescopes. Researchers hope to get significantly more data, when a supernova goes off next time, as we have a large number of neutrino observatories now and more planned for the future. It's predicted that a supernova in our galaxy could result in 5,000 to 8,000 neutrino events in a single detector. Many neutrino detectors are connected through the Supernova Early Warning System (*SNEWS*), which will trigger experiments to record and save additional data if a sudden influx of neutrinos, which indicates the arrival of a supernova.

3.4.3. Cosmogentic Neutrinos—Cosmogentic neutrinos are neutrinos from the propagation of extragalactic cosmic rays in the Universe. These extremely high energy cosmic neutrinos are produced by the collisions between Ultra High Energy Cosmic Rays(UHECR) and CMB photons. This was first proposed in 1969 by Berezinsky $\&$ Zatsepin and in 1973 independently by Stecker. But it is often called or known as Greisen-Zatsepin-Kuzmin(GZK) neutrinos. The presence of UHECR with energy 10^{20} and CMB on the earth indicates that GZK neutrinos must exist. However, these neutrinos have not been observed yet.

Ultra-High Energy (UHE) neutrino astronomy is aiming for higher energy ($> 10^{15}$eV) neutrinos which have travelled cosmologically interesting distances, as they are excellent cosmic messengers to advance the understanding of extreme astrophysical objects, in addition to probe all possible new physics. Cosmic rays in this energy range have impact on the earth at a rate of 1 per century per km^2. This very low rate in addition to the fact that neutrino interact only weakly, make the detection of UHE neutrinos very challenging.

A solution for this is to have many detectors in a large region or else we need a highly sensitive detector that can detect over a large region.

IceCube observatory in Amundsen-Scott South Pole Station in Antartica have captured high energy neutrinos, which must have originated outside our solar system. It was the highest energy neutrino—the first cosmogenic neutrino–-ever detected! They found two cosmogenic neutrino candidates. The first one deposited energy of 2.6 PeV and scientists estimated that the actual energy was around 9 PeV. The second one was recorded in December 2016 with an estimated energy of around 6 PeV. Interestingly, both of them were found to be compatible with the measured astrophysical neutrino flux. This detection confirmed cosmic neutrinos as the key messengers to reveal an uninterrupted view of the universe. This ushered neutrinos into the age of multi-messenger astronomy. To search for GZK neutrinos, several international projects like balloon-borne *ANITA observatory* and the ground based *Askaryan Radio Array (ARA) Observatory* have been launched.

4. Conclusion

The field of gravitational wave physics and neutrino physics offers some promising future. They travel almost un-interrupted from their source to their point of detection. With several new detectors and technological advancement we are likely to observe more and more events. Therefore together they offer us an opportunity to unlock the secrets of our universe like never before.

Readers who are interested in learning more about General Relativity are recommended to read the following books. If you are beginner the best book to start with is either *Gravity* by James.B.Hartle[22] or *A first course in general relativity* by Bernard.F.Schutz.[23] The above books develops the mathematics sufficient to understand general relativity and slowly introduces the reader to the subject. If you are looking for a rigours book dedicated to tensor algebra, my personal favourite is the book by *Lovelock & Rund*.[24] Apart from these,there are many books suitable for advanced reading[25],[26],[27].[28]

In comparison to the books on general relativity, there are not many which describe gravitational waves. However one book which deserves its mention is *Gravitational waves: Theory and experiments Volume 1 & 2* by M.Maggiore.[8] It covers all important topics in gravitational waves including the detection part. There are few books dedicated to gravitational wave data analysis, one of my favourite is.[7]Readers who are interested in Neutrino are recommended to refer the book *Fundamentals of neutrino and astrophysics* by Carlo Giunti and Chung W. Kim.[29]

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