Introduction To Multi-Messenger Astronomy

Learners' Space Astronomy

Contents

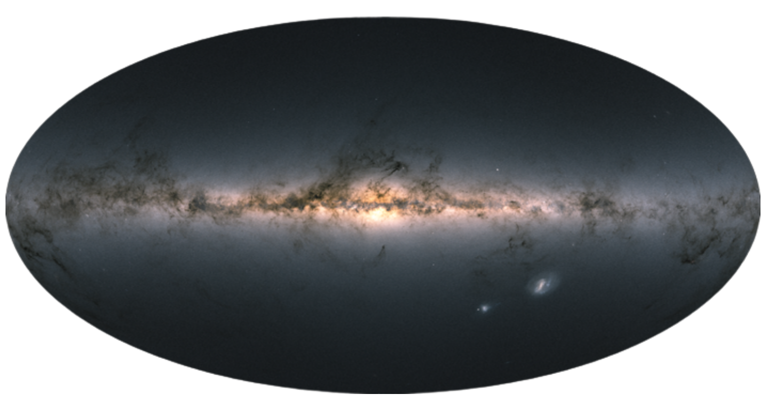
Introduction

Our knowledge of the Universe around us was acquired throughout centuries via the detection of electromagnetic signals from different types of astronomical sources. This changed in 2013 with the discovery of new astronomical messengers transmitting signals from distant sources outside the Solar system: the high-energy neutrinos. Further breakthroughs were achieved in 2015 with addition of one more "messenger": gravitational waves. In this way the new field of "multi-messenger" astronomy has been born.

1.1 Visual Astronomy

Originally, astronomy was confined to a very narrow regime: the only signals we were capable of receiving were in the form of visible light. Since that is what our eyes had adapted to see, those were the tools we had at our disposal to examine the Universe. For countless millennia, human eyes viewed the Sun, Moon, planets, stars, and the fuzzy, distant nebulae we now know to be galaxies as they slowly but surely migrated across the sky.

Even after the invention of the telescope, astronomy was still confined to what we could perceive in visible light. All the telescope did was enhance our light-gathering power by using mirrors and/or lenses to increase the light-collecting area far beyond the limits of even the most thoroughly dilated pupil. Instead of thousands of stars, these telescopes revealed hundreds of thousands, millions, and eventually billions of stars.



Nevertheless, our knowledge of the universe was based solely on the information collected through the visible light photons. The energy of photons of wavelength λ is given by $E = hc/\lambda$ where c is the speed of light and h is the Plancks constant . For visible wavelengths, E comes out to be $\approx 4eV$. Such photons are typically produced by stars obeying the blackbody radiation law, with surface temperature approximately given by Wein's Law $\lambda T = 2898\mu mK \implies T \approx 5500K$, just like our sun.

Modern visible band astronomy builds upon Galileo's invention and uses larger aperture telescopes and CCD(Charged Couple detectors) to detect fainter objects with higher angular resolutions.
The energy of the visible light photons is comparable to the energy gap width in the CCDs semiconductor, and that is the main principle behind how CCDs detect visible photons.

1.2 Multi-Wavelength Astronomy

Look at the first figure given below. This is the famous M1 Crab Nebula, a supernova remnant in the constellation of Taurus. But what are the 2nd and 3rd images?

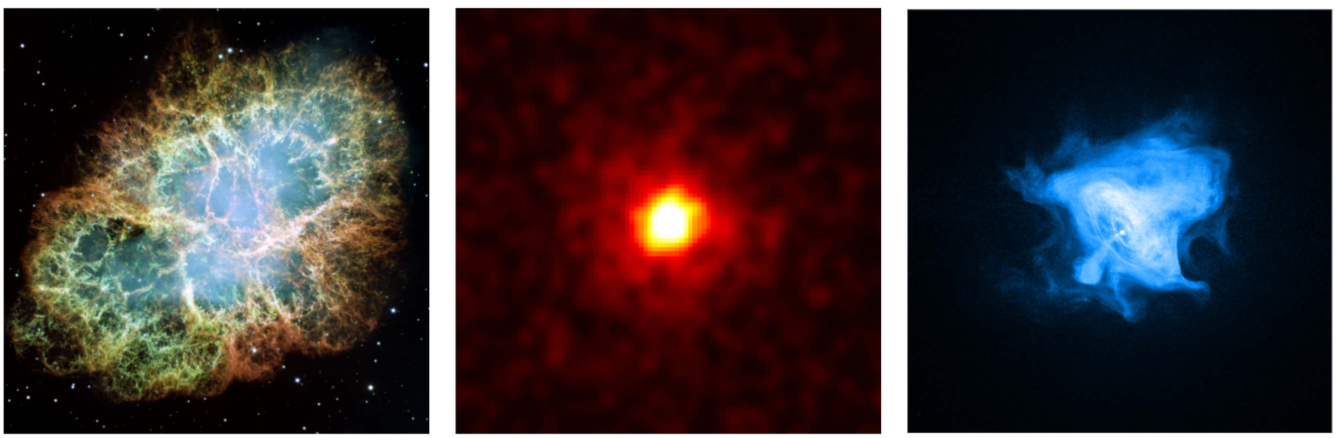


Figure 1.1: Crab Nebula : Through different wavelengths

They are images of the crab nebula as well, just observed through different wavelengths of light!

The first image is taken through the visible band, showing the envelope of the supernova explosion and its various gases. The second image is taken through Gamma Rays, which are electromagnetic waves with extremely small wavelengths and having energies from hundreds of keV up to Tera eVs. This reveals a massive gamma-ray source in the center of the Crab Nebula, the Crab Pulsar. A pulsar is a quickly spinning, highly magnetized neutron star formed when a massive star ran out of its nuclear fuel and collapsed. The combination of rapid rotation and a strong magnetic field in the Crab generates an intense electromagnetic field that creates jets of matter and anti-matter moving away from both the north and south poles of the pulsar and an intense wind flowing out in the equatorial direction, which is evident in the 3rd image, taken through X-rays.
Thus, observing the same target through different wavelengths reveals new things and increases

our understanding of the Universe.

Today, we take advantage of all the different forms of light that there are to study the objects present in the Universe.

- **Gamma-rays and X-rays** reveal high-energy objects like pulsars, black holes, and transient "burst" events,
- **Ultraviolet, Visible, and Near-infrared light** reveal stars and star-forming material,
- **Mid-infrared and Far-infrared light** shows the presence of cooler gas and dust,
- **Microwave and Radio light** reveals jets of particles, diffuse background emissions, and details in individual protoplanetary disks.

Whenever we look at an object in a different wavelength of light, we have the potential to reveal an entirely new class of information about it.

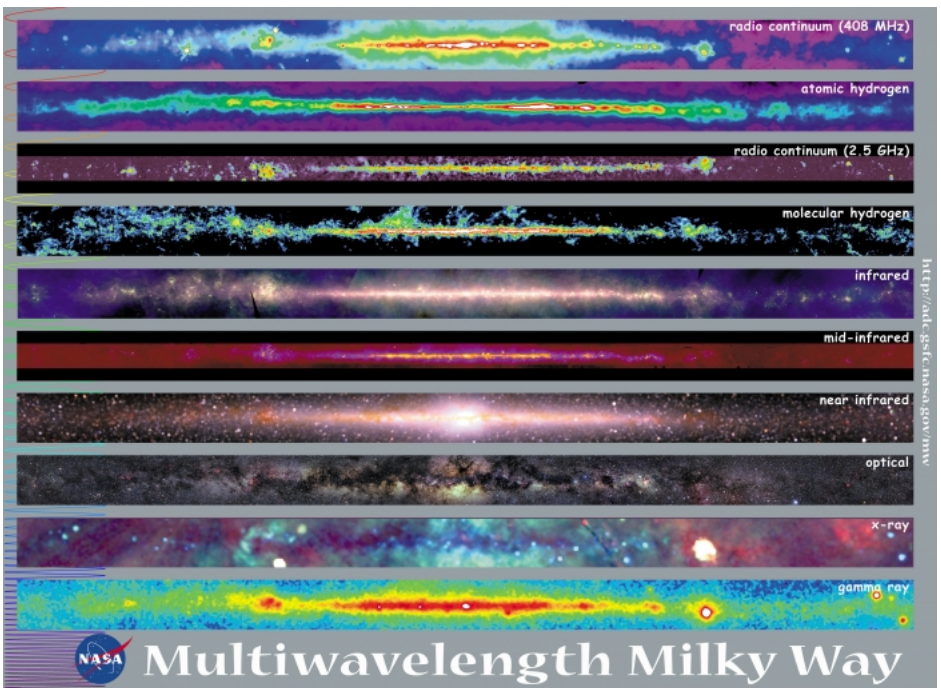


Figure 1.2: Milky Way as observed through different wavelengths

Even though we have different names for these various types of astronomical observing — some of what we observe are rays (gamma-rays and X-rays), some are light (ultraviolet and visible), some are radiation (infrared) and some are waves (radio) — they're all still light. From a physics point of view, we're collecting the same thing: photons, or quanta of light. We're just looking at light with different properties when we're doing any of these types of astronomy.

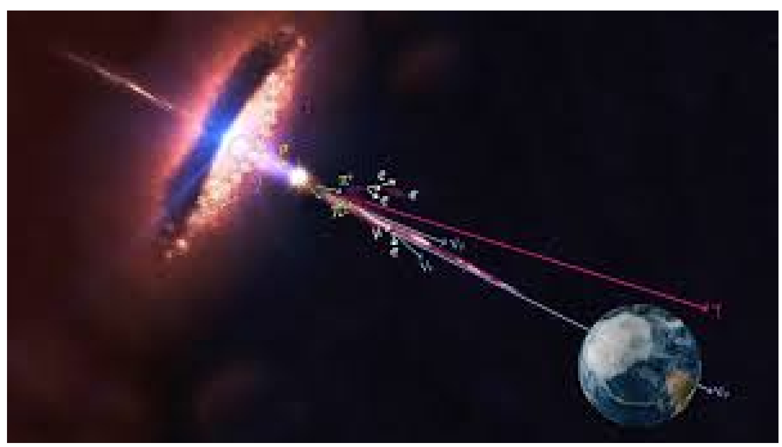
In other words, doing astronomy by collecting light of any type always involves the same type of messenger: the same type of information-carrier. However, there are other forms of astronomy, too, because the objects in the Universe doesn't just emit light. As they undergo all the various astrophysical processes that the Universe allows, they can emit a wide variety of classes of signal, including signals from fundamentally different messengers.

Neutrino Astronomy

2.1 What are Neutrinos?

Neutrino is a fundamental subatomic particle, a fermion belonging to the lepton family with half-integral spin and very little mass, and which only interacts through weak force and gravity. What does this mean? Just that neutrons are really tiny particles which travel at near the speed of light and do not interact with matter for the most part due to their extremely low mass and low-range of weak force. Due to this nature of neutrons, they are often called "ghost particles" as well. They are the most abundant particles that have mass in the universe, yet are very difficult to detect.

(a) Centaurus A



(b) Neutrinos from AGN entering Earth

Neutrons could be produced during the "electron-capture" reaction $p + e^- \to n + \nu$ On the left is the image of Centaurus A, taken in multiple wavelengths. The blue jets shown is taken in X-ray and represents charged particles interacting with the magnetic fields. Now as super-massive blackhole in the centre of the galaxy gobble up the gases around it, it heats up the gas and ionizes it, thus splitting them into e^- and p. Protons gets shot out in these jets of magnetic fields with very high speed, and they slam into more gases basically undergoing a particle accelerator reaction and producing all sorts of electrons, muons and neutrinos. The electrons and muons produced are all charged particle, and interact with the magnetic field and get deflected. The neutrinos however do no interact, just keep on travelling straight and point exactly towards the AGN(see the figure on the right.)

2.2 IceCube Neutrino Observatory

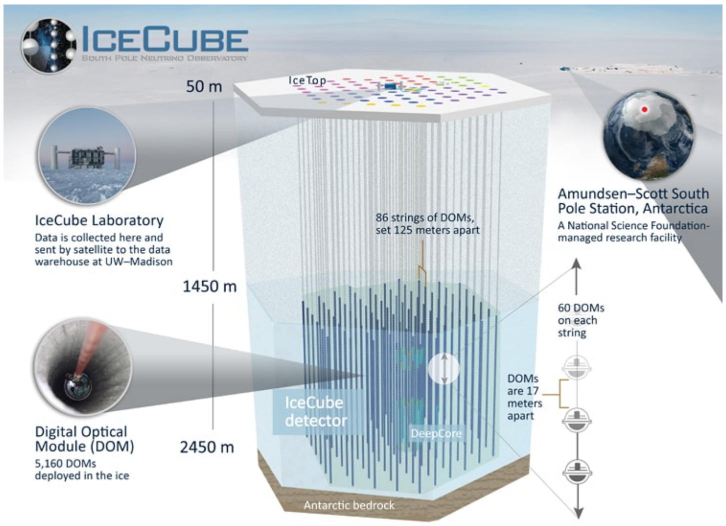
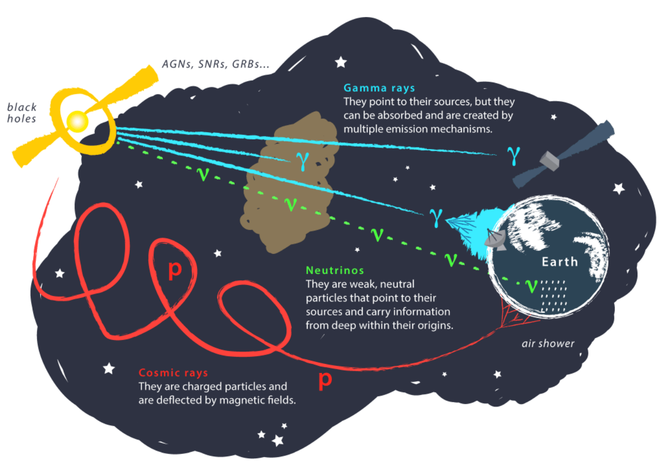


Figure 2.2: IceCube Neutrino Observatory

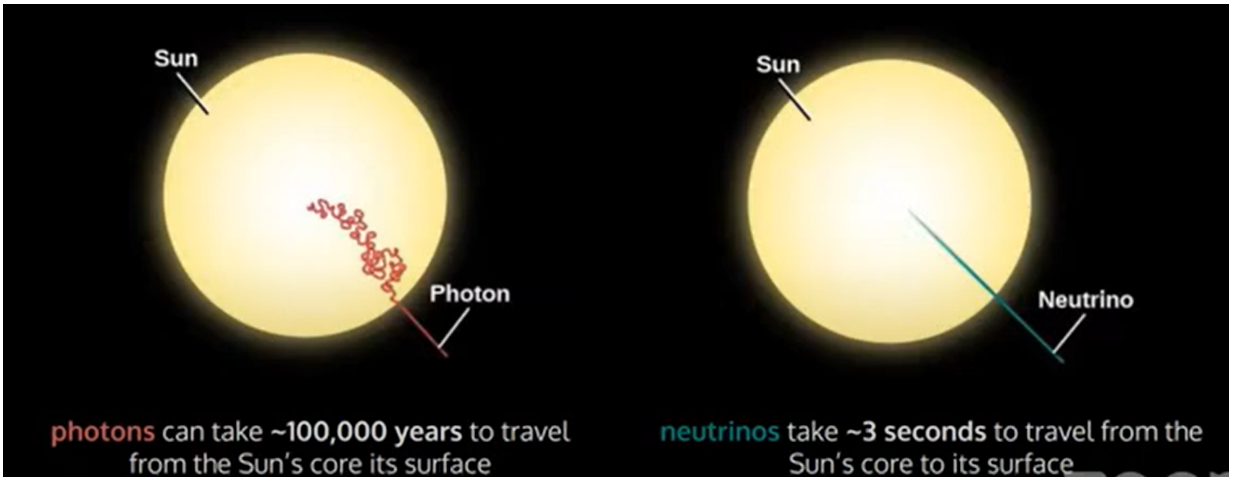
The IceCube Neutrino Observatory located in Antarctica is an underground facility with multiple strings equipped with photo-multiplier tubes(PMTs) to detect photons. The PMTs are under more than a kilometer of ice. A neutrino coming from an extra-galactic source reacts with one of the water molecules(although neutrinos chances of interacting are rather weak, with so many water molecules, it has significant chance of reacting) and produces a charged particle- electron or muon.
This charged particle can now react with light, it moves across the ice and emits Cherenkov Radiation, which is basically a bluish light which can be detected by the PMTs.
Tracking this cherenkov radiation gives us the trajectory of the neutrino, and that is precisely the location of our neutrino source! Neutrino reaches IceCube



All the facilities like IceCube need to be built deep underground so as to isolate the detector from cosmic rays and other background radiation. If these detectors were placed on the surface of earth, muons created by cosmic rays coming from various galaxies and the Cosmic Wave Background Radiation would interfere with the muons created by neutrinos. It would be like searching for a dim star during the day.

2.3 Solar Neutrinos

Our sun in the process of undergoing p-p chain nucleur fusion produces neutrinos, as a result 1.7 trillion neutrinos pass through our palm every second. And what's interesting about these neutrinos are that they are coming directly from the core of the sun. This is unlike photons produced in the core, which get reabsorbed and reemitted in the different layers while travelling, and essentially undergo a random walk before arriving at the surface. Thus the photons contain information about the surface, while the neutrinos contain information about the core.



2.4 Neutrino imaging

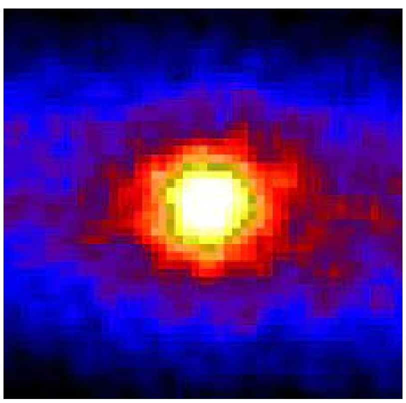


Figure 2.3: Image of core of the sun under "neutrino-light"

These solar neutrinos can be detected using very large tanks of water and many photo-sensors to detect the Cherenkov Radiation of the produced-charged particles. Using this one can image the core of the sun and find out about its size.

What else does neutrino astronomy has to offer? What if like the map of the Cosmic MicroWave Background Radiation, we are able to map the Cosmic Neutrino Background radiation. Since the neutrinos interact only through weak forces, they would have stopped interacting with matter after about $\approx 1s$ of Big-Bang, when the characterstic length-scale exceeded the range of weak forces. Thus it would provide us information about the early stages of the Big-Bang and the origins of the universe

Gravitational Wave Astronomy

3.1 Introduction

What is a Gravitational Wave? Gravitational waves are 'ripples' in space-time caused by some of the most violent and energetic processes in the Universe.

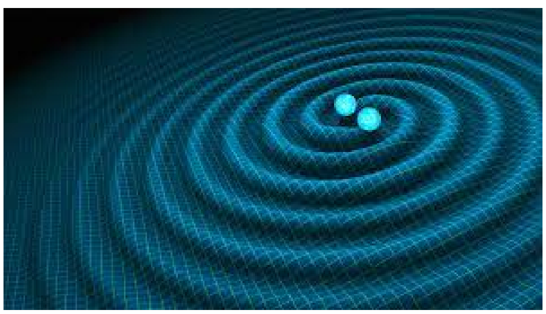


Figure 3.1: Representation of 'Ripples" in space-time by Gravitational Waves of two neutron-star orbiting close to each other

Albert Einstein predicted the existence of gravitational waves in 1916 in his general theory of relativity. Einstein's mathematics showed that massive accelerating objects (things like neutron stars or black holes orbiting each other) would disrupt space-time in such a way that 'waves' of undulating space-time would propagate in all directions away from the source. These cosmic ripples would travel at the speed of light, carrying with them information about their origins, as well as clues to the nature of gravity itself.

How are these generated? Well that seems like a complex GR problem but we can think of gravitational waves being generated in a manner analogous to electromagnetic waves.

Classically, changing electric or magnetic fields can generate electromagnetic waves, a radio antenna being a good example. That's all an electromagnetic waves is, just changing electric and magnetic fields, transporting energy. In a similar way, Gravitational waves are expected in cases of "changing gravitational fields".

In general terms, gravitational waves are radiated by objects whose motion involves acceleration and its change, provided that the motion is not perfectly spherically symmetric (like an expanding or contracting sphere) or rotationally symmetric (like a spinning disk or sphere). A simple example of this principle is a spinning dumbbell. If the dumbbell spins around its axis of symmetry, it will not radiate gravitational waves; if it tumbles end over end, as in the case of two planets orbiting each other, it will radiate gravitational waves. The heavier the dumbbell, and the faster it tumbles, the greater is the gravitational radiation it will give off. In an extreme case, such as when the two

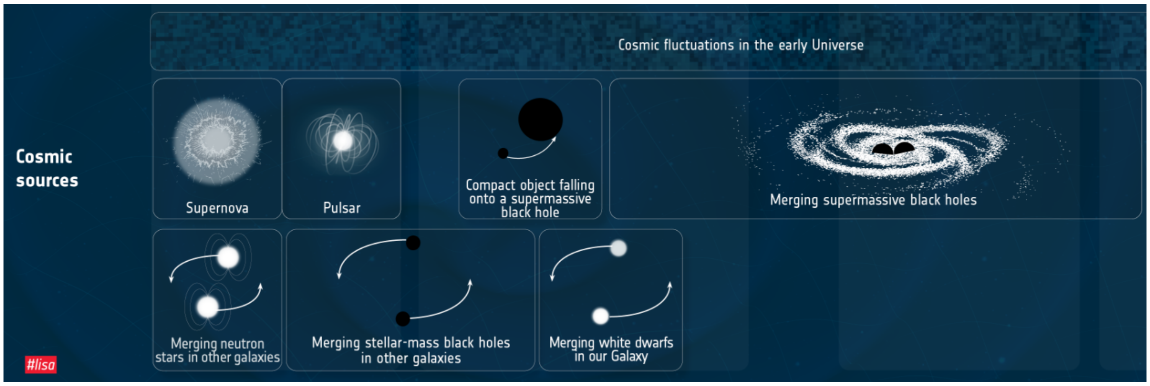


Figure 3.2: Various sources of Gravitational Waves

weights of the dumbbell are massive stars like neutron stars or black holes, orbiting each other quickly, then significant amounts of gravitational radiation would be given off.

3.2 First evidence of Gravitational waves

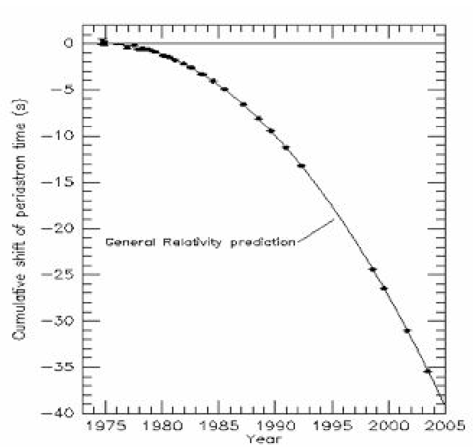


Figure 3.3: Weisberg and Taylor, 2004

The **first indirect evidence of gravitational waves** was discovered in 1974 when Russell Alan Hulse and Joseph Hooton Taylor, Jr. discovered the first binary pulsar, which earned them the 1993 Nobel Prize in Physics. Pulsar timing observations over the next decade showed a gradual decay of the orbital period of the Hulse–Taylor pulsar that matched the loss of energy and angular momentum in gravitational radiation predicted by general relativity.

The figure shows the cumulative shift of periastron time. This shows the decrease of the orbital period as the two stars spiral together. Although the measured shift is only 40 seconds over 30 years, it has been very accurately measured and agrees precisely with the predictions from Einstein's theory of General Relativity.

3.3 LIGO: Direct detection of GW!

A major breakthrough in the field of Gravitational wave astronomy was the first direct observation of gravitational waves was made in 2015, when a signal generated by the merger of two black holes was received by the LIGO gravitational wave detectors in Livingston, Louisiana, and in Hanford, Washington. How exactly did we detect the waves?

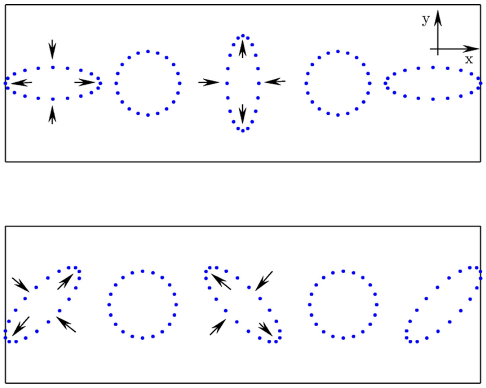
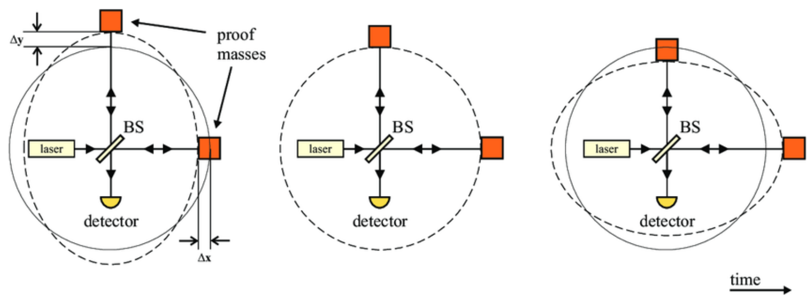


Figure 3.4: + and × Polarization modes

The effects of a passing gravitational wave, in an extremely exaggerated form, can be visualized by imagining a perfectly flat region of spacetime with a group of motionless test particles lying in a plane, e.g., the surface of a computer screen. As a gravitational wave passes through the particles along a line perpendicular to the plane of the particles, i.e., following the observer's line of vision into the screen, the particles will follow the distortion in spacetime, oscillating in a "cruciform" manner. The area enclosed by the test particles does not change and there is no motion along the direction of propagation. In the figure, the top and bottom panels show the effect of the 'plus' and 'cross' polarisation modes respectively, of a gravitational wave going into the plane of the paper.

Now LIGO (Laser Interferometer Gravitational-Wave Observatory) makes use of this "squishing and stretching matter" nature of Gravitational waves to detect them. It consists of two perpendicular arms that are a whopping 4km in length! A powerful laser beam is made incident on a Beam Splitter and the light splits into two perpendicular paths, travelling down the entire length of the arm, gets reflected at the end and then comes all the way back onto the detector and interferes with the light from the other arm.

(a) Ligo Hanford Observatory



(b) Effect of GW on LIGO Arms leading to interference

The beams returning from two arms are kept out of phase so that when the arms are both in coherence and interference (as when there is no gravitational wave passing through), their light waves subtract, and no light should arrive at the photodiode. When a gravitational wave passes through the interferometer, the distances along the arms of the interferometer are shortened and lengthened, causing the beams to become slightly less out of phase. This results in the beams coming in phase, creating a resonance, hence some light arrives at the photodiode and indicates a signal. Youtube : Working of LIGO interferometer

The orthogonal arms actually make use of partially reflecting mirrors, creating Fabry–Pérot cavities that increase the effective path length of laser light in the arm from 4 km to approximately 1,200 km by making the light complete multiple round trips(around 280) before allowing them to interfere. A great youtube video explaining Fabry-Perot and Michelson interferometer in LIGO, using basic wave equations and Linear Algebra can be found here. Do watch it, it has some excellent animations like the ones shown below and explains the topic quite well.

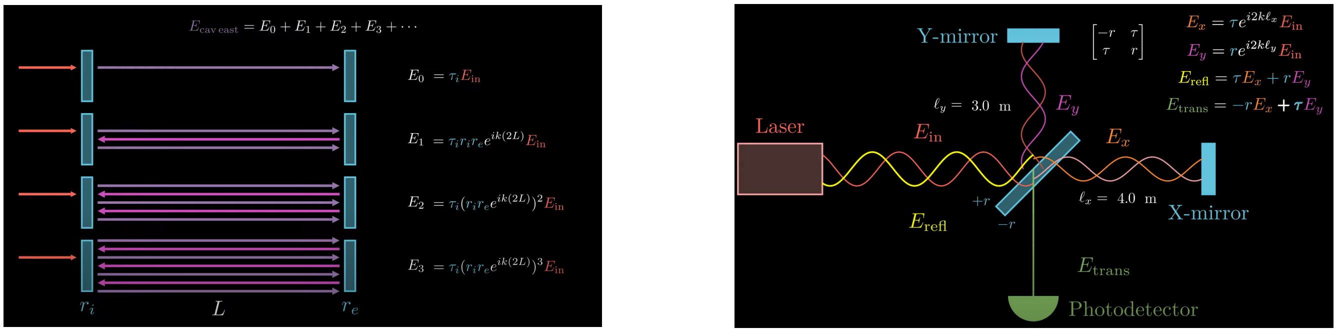


Figure 3.6: YouTube: How does LIGO detect Gravitational Waves?

On 11 February 2016, the LIGO collaboration announced the first observation of gravitational waves, from a signal detected at 09:50:45 GMT on 14 September 2015[35] of two black holes with masses of 29 and 36 solar masses merging into a 62 solar mass black holeabout 1.3 billion light-years away. During the final fraction of a second of the merger, it released more than 50 times the power of all the stars in the observable universe combined.

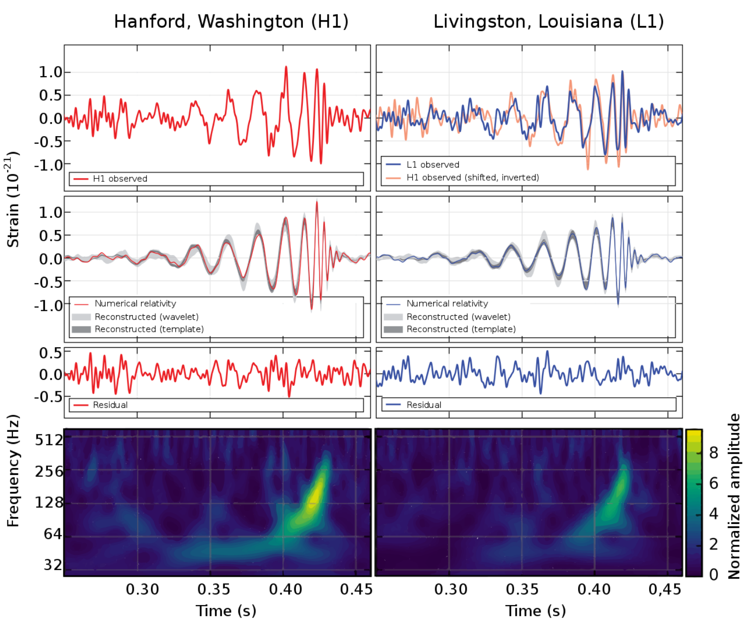


Figure 3.7: LIGO measurement of the gravitational waves at the Hanford (left) and Livingston (right) detectors, compared to the theoretical predicted values.

The signal increased in frequency from 35 to 250 Hz over 10 cycles (5 orbits) as it rose in strength for a period of 0.2 second. The signal is in the audible range and has been described as resembling the **"chirp" of a bird**; Link: The Sound of Two Black Holes colliding (The frequency increases because each orbit is noticeably faster than the one before during the final moments before merging.)
Energy equivalent to three solar masses was emitted as gravitational waves.
The signal was seen by both LIGO detectors in Livingston and Hanford, with a time difference of 7 milliseconds due to the angle between the two detectors and the source. This delay in the the arrival of the signal can be used to find the position of the source in the sky. With just two observatories, the position of the source was restricted to an arc in the sky, however observations from more Gravitational Wave Observatories(like LIGO India! Check sec.4.2) can be used to triangulate the exact position of the source in the sky.

Here's a Video simulation showing the warping of space-time and gravitational waves produced, during the final inspiral, merge, and ringdown of black hole binary system GW150914.

3.4 Chirp Mass

For a two body system with component masses m_1 and m_2, using General Relativity the phase evolution of their binary orbit is calculated which is a peturbative expansion in powers of v/c. The frequency f of this evolution, is the gravitational wave frequency and is given by

$$\frac{df}{dt} = \frac{96}{5}\pi^{\frac{8}{3}}\left(\frac{G\mathcal{M}}{c^3}\right)^{\frac{5}{3}} f^{\frac{11}{3}}$$

where G is the Gravitational Constant, c is the speed of light and $\mathcal{M}$ is called the chirp-mass, named after the chirp like sound obtained on merging, and is defined as-

$$\mathcal{M} = \frac{(m_1 \cdot m_2)^{\frac{3}{5}}}{(m_1 + m_2)^{\frac{1}{5}}}$$

If one is able to measure both the frequency f and frequency derivative $\dot{f}$ of a gravitational wave signal, the chirp mass can be determined using -

$$\mathcal{M} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{\frac{-8}{3}} f^{\frac{-11}{3}} \dot{f}\right)^{\frac{3}{5}}$$

and can be used to gain information about the masses of the merging objets.

3.5 Approx timescale of merger :

Like previously discussed, Gravitational waves are produced by accelerating masses just like electromagnetic waves are generated by accelerating charges, provided that the motion is not spherically symmetric.
According to General Relativity, the gravitational radiation is mostly due to changing mass quadrupoles. Just like electric dipoles are two point charges of opposite nature seperated by a distance, an electric quadrupole consists of alternating positive and negative charges, arranged on the corners of a square. Mass quadrupoles are defined similarly, just using mass distribution instead of +ve and -ve charges.

The Gravitational Waves produced due to such changing mass quadupoles has a luminosity given by

$$L_{GW} = \frac{1}{5}\frac{G}{c^5} < \dddot{I}_{jk}\dddot{I}_{jk} >$$

proportional to the third time derivative of the quadrupole moment of the mass distribution.(ref.)

For a binary system with companion object masses $m_1 \approx M$ and $m_2 \approx M$ and binary separation r, I is given as $\sim Mr^2$ and its third time derivative is proportional to the orbital angular frequency $\Omega = \sqrt{\frac{GM}{r^3}}$ in the third power:

$$I \sim \Omega^3 M r^2$$

This gives

$$L_{GW} \approx \frac{G\Omega^6 M^2 r^4}{c^5} \approx \frac{G^4 M^5}{c^5 r^5}$$

At the same time, total gravitational energy which could be released by a merger of companions is a fraction η of the total rest energy of the two bodies:

$$E_{grav} = \eta \frac{GM^2}{r}$$

The final stage of the merger occurred when the binary separation was about the gravitational radius of the black holes, $r \sim \frac{2GM}{c^2}$ (ref.). The characteristic time scale of this final stage is

$$t \sim \frac{E_{grav}}{L_{GW}}$$

Substituting in $M \approx 30M_\odot$ and $\eta \approx 0.1$(because about $3M_\odot$ of energy was lost as Gravitational Waves) we get that

$$t \approx \frac{\eta c^5 r^4}{G^3 M^3} \approx 1ms$$

Although we have used some crude approximations, the above analysis leads to some key insights into Gravitational waves and mergers.

- First of all, $t \propto r^4$. A close binary composed of two stellar mass black holes with separation just about 10-100 times the size of the black hole horizon would loose all its energy onto gravitational radiation on an hour time scale. A binary with the orbital separation 10^3 times larger looses energy via gravitational radiation on the time scale comparable to the age of the Universe.

- Secondly, as the two bodies inspiral towards each other, their seperation r decreases and that leads to increasing frequency as they come closer as

$$f = \frac{1}{t} \propto \frac{1}{r^4}$$

.

- Thirdly, during the final stages of inspiral, the frequency of Gravitational waves produced is $f_{GW} = \frac{1}{t} \approx 1000Hz$. This lies in the audible range and that is exactly why we could "hear" what two black holes colliding sounded like.

  See the video The Sound of Two Black Holes colliding again. One can see that the frequency is increasing as the black holes come closer to each other and finally terminates at about $500Hz$, which is very close to our crude estimates ;)

  Further note that the intensity of Gravitational Waves is quite low when they are apart, almost indistinguishable from the noise. However as they come closer, r decreases $\implies L_{GW}$ increases $\implies$ We hear the signal over the noise.

Notice the time scale too. The total duration that the merger lasts is pretty small, about 0.1 second which is a small multiple of our timescale. Thus the two bodies rapidly inspiral towards each other and only make a small number of revolutions around each other before finally merging. This can be seen in all simulations online like this one by LIGO themselves: Youtube: Simulation by LIGO showing two black holes merge into one

- Fourth, The masses of the objects involved dictate how long they emit detectable gravitational waves. Heavy objects, like black holes, move through their final inspiral phase much more rapidly than 'lighter' objects, like neutron stars. This means that black-hole merger signals are much shorter in duration than neutron star merger signals, and the differences are quite striking.

On 17 August 2017, the LIGO/Virgo collaboration detected a pulse of gravitational waves, named GW170817, which was the first observation by LIGO of a merger of a binary neutron star system.

Now the mass of a Neutron Star is given by the Chandrashekhar Limit $\approx 1.4M_\odot$ as you must have seen in the Stellar Evolution Module. The mass of the black holes in the 2016 merger was approximately $30M_\odot$. Thus the characterstic timescale of Neutron Star merger is given by

$$t \propto \frac{1}{M^3} \approx \left(\frac{M_{BH}}{M_{NS}}\right)^3 t_{BH} \approx 10s$$

Checkout the video Chirp of the binary neutron star merger(GW170817). Though the entire signal was detectable in LIGO for over 100 seconds, only the last 32 seconds of the signal are included in the video.

Notice both the similarities and the differences with the Black hole chirp. Although the general shape of the curve is quite similar, the timescale is VASTLY different, due to Neutron Stars being much lighter than blackholes. For comparison, the blackhole merger signal lasted for only 0.2 seconds.

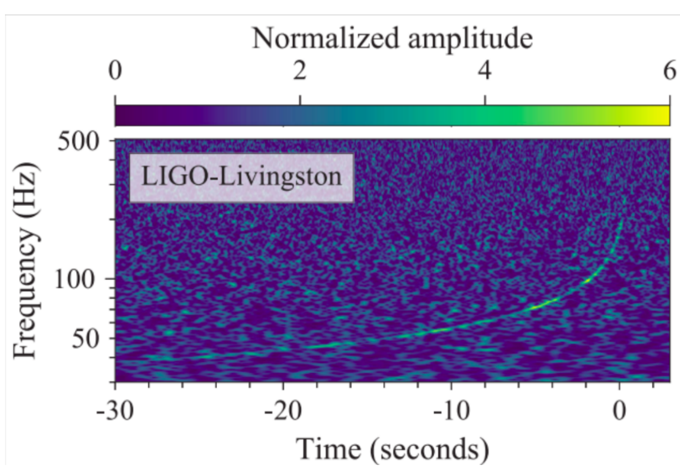


Figure 3.8: GW170817: First observation of binary neutron star merger

3.6 More to Gravitational Waves than just LIGO?

Till now we have only being discussing Gravitational Waves produced by inspiral of compact binaries, because that's what we could detect using LIGO. Gravitational Waves, just like electromagnetic waves have a frequency like we discussed, and thus a spectrum! And what we can "see" of Gravitational Waves using LIGO is just a part of this spectrum!

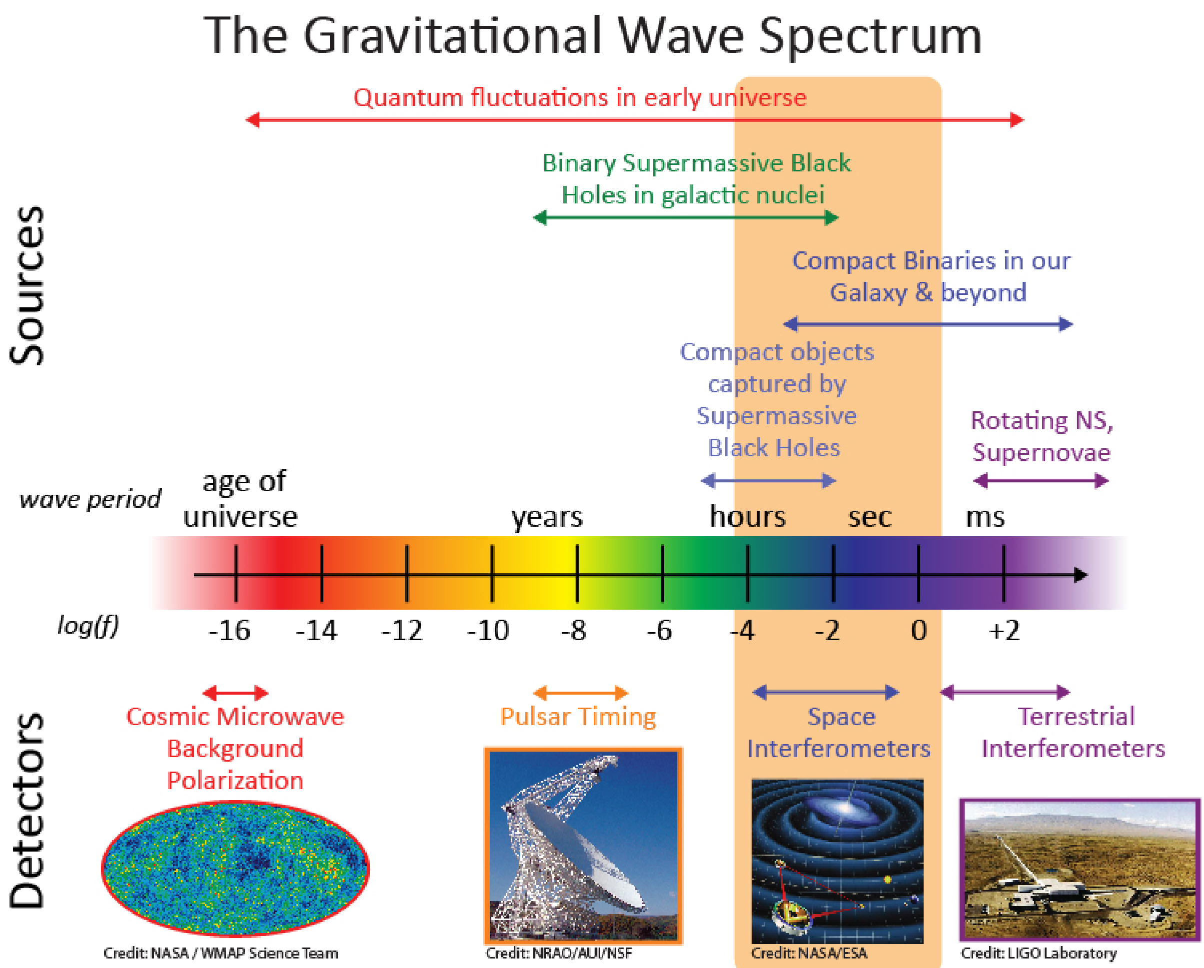


Figure 3.9: Gravitational Waves Spectrum

The above image contains a LOT of info, so just spend a couple of minutes looking at it thoroughly.

Up until now, we have only discussed GWs produced by "Compact Binaries in our Galaxy and beyond" which have a wave period in "seconds and milliseconds" and can be detected by "Terrestrial Interferometers" . But that's just the beginning.

What's next for Multi-Messenger

4.1 LISA: Our Next-Gen Space Based GW detector

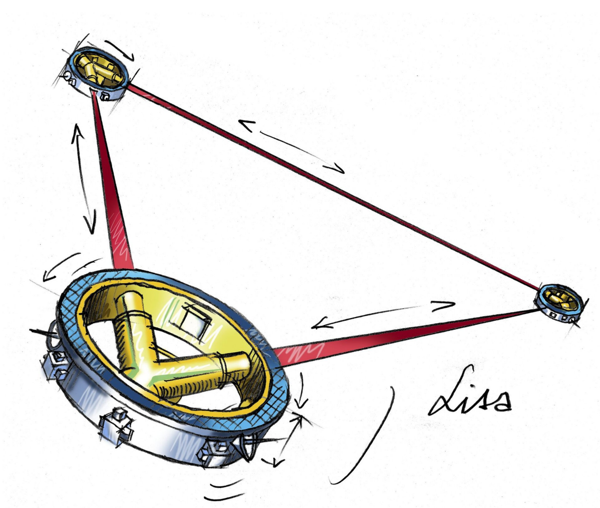


Figure 4.1: LISA

The Laser Interferometer Space Antenna (LISA) is a proposed space probe and consists of three spacecraft that are separated by millions of miles and trailing tens of millions of miles, more than one hundred times the distance to the Moon, behind the Earth as we orbit the Sun. These three spacecraft relay laser beams back and forth between the different spacecraft and the signals are combined to search for gravitational wave signatures that come from distortions of spacetime.
We need a giant detector bigger than the size of Earth to catch gravitational waves from orbiting black holes millions of times more massive than our sun.

But Why do we need to go to Space? The gravitational wave spectrum covers a broad span of frequencies. LISA operates in the low frequency range, between 0.1 mHz and 1 Hz (compared to LIGO's frequency of 10 Hz to 1000 Hz). The difference means that the waves LISA is looking for have a much longer wavelength, corresponding to objects in much wider orbits and potentially much heavier than those that LIGO is searching for, opening up the detection realm to a wider range of gravitational wave sources.

LISA has three spacecraft that form an equilateral triangle in space where the sides of the triangle, also called LISA's "arms", extend about a million miles. Therefore, from space, LISA can avoid the noise from Earth and access regions of the spectrum that are inaccessible from Earth due to these extremely long arms. The gravitational wave sources that LISA would discover include ultra-compact binaries in our Galaxy, supermassive black hole mergers, and extreme mass ratio inspirals, among other exotic possibilities.

4.2 LIGO-India

The United States and India have jointly unveiled plans to construct a Laser Interferometer Gravitational-Wave Observatory (LIGO) in India, a major scientific alliance aimed at unravelling the mysteries of the universe. The LIGO observatory in India will be built in Maharashtra's Hingoli district, and is expected to be operational by the year 2030. This will be the third LIGO site in the world besides Hanford and Livingston.

While two detectors in a network that sense the same polarization of gravitational-waves are the minimum needed to ensure confidence that a signal is a gravitational-wave and not some terrestrial or instrumental artifact, two such detectors cannot effectively localize the source of the waves on the sky nor can they reveal a wave's actual polarization.

A network of three detectors can improve the polarization information extracted from the wave and the source location. But even a three-observatory network only provides a sharp sky location for about half of all possible locations on the sky which is our ultimate aim.

This would be improved once LIGO-India becomes operational. It would be scientifically managed and operated in collaboration with the US LIGO detectors, VIRGO detector in Italy and the Kagra detector in Japan to optimize the scientific returns.

4.3 IceCube releases image of MilkyWay as seen through Neutrinos

Remember the image of MilkyWay in multiple wavelengths shown earlier? 1.2

On 29th June 2023 (yes, this recent!) the IceCube Neutrino Observatory announced the production of an image of the Milky Way using neutrinos, and evidence of high-energy neutrino emmision from our own galaxy.

The search focused on the southern sky, where the bulk of neutrino emission from the galactic plane is expected near the center of our galaxy. However, the background of muons and neutrinos produced by cosmic-ray interactions with the Earth's atmosphere posed significant challenges.

To overcome them, IceCube developed analyses that select for "cascade" events, or neutrino interactions in the ice that result in roughly spherical showers of light.

However, the final breakthrough came from the implementation of machine learning methods that improve the identification of cascades produced by neutrinos as well as their direction and energy reconstruction. The observation of neutrinos from the Milky Way is a hallmark of the emerging critical value that machine learning provides in data analysis and event reconstruction in IceCube.

Checkout the following links to learn more

Announcement on the Official IceCube Website

Youtube: Official Conference by IceCube on the announcement

4.4 Gravitational Wave Background using PTAs

On the same day as the announcement by IceCube, the International Pulsar Timing Collaboration announced the successful observation of a Gravitational Wave Background radiation after collecting over 15years worth of data for 68 pulsars.

Many small gravitational waves are passing by from all over the Universe all the time, and that they are mixed together at random. These small waves from every direction make up what is called a "Stochastic Signal", coming from all over the cosmos and is detected as a Gravitational Wave background, just like the Cosmic Microwave Background Radiation(CMBR).

These backgrounds GWs are thought to be produced by Binary Supermassive Blackholes in galactic nuclei. They are extremely faint and have a wave period in years, making it impossible to detect them using LIGO or other interferometers.

So how do we detect them? That's where Pulsar timing comes in. Checkout the following links to know more about Pulsar Timing and how it was used to detect these Gravitational Waves

The Nanohertz Gravitational-Wave Detection Explained

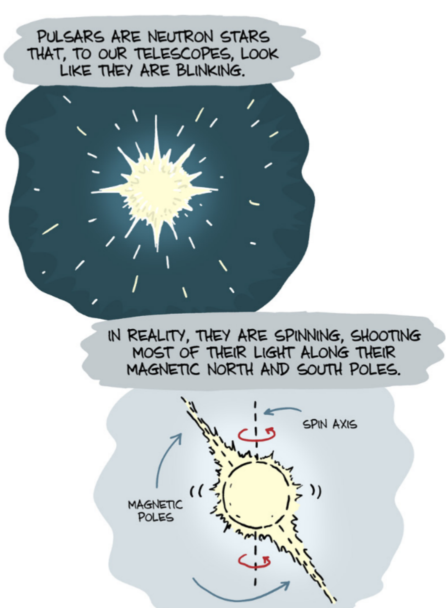
Instagram: Post explaining how Pulsar Timing is used to detect Gravitational waves

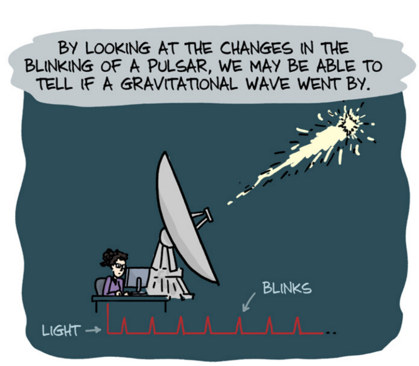
Some FAQs regarding the discovery

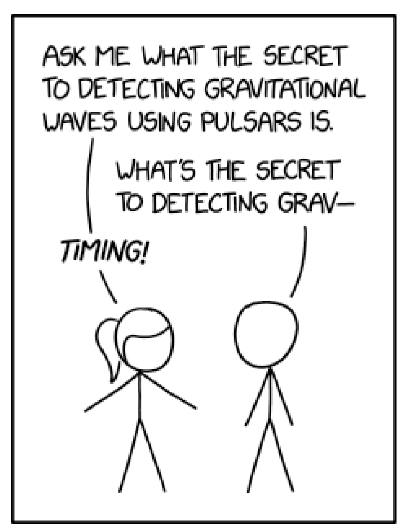
Official 15 Year Data Release info by NANOgrav

Youtube: Official announcement and Q&A by NANOgrav

You can also read the official paper cited here [1]







4.5 Cases studied with atleast 2 messengers

Three observations, each involving at least two messengers, can be given as examples for multi-messenger discoveries.

The first one was the supernova SN 1987A observed in electromagnetic waves and low-energy neutrinos (in MeV energy range) in 1987 (Arnett et al. 1989 [2]).

The second was the observation of the binary neutron star merger, GW170817, which was discovered with gravitational waves and gamma-rays (Abbott et al. 2017a [3]). Later it was tracked in all of the electromagnetic spectrum.

Finally, the last one was a flaring blazar observed in gamma-rays and high-energy neutrinos with 3σ significance (Aartsen et al. 2018 [4]).

Tidal Disruption Events(TDEs) are rare transients that occur when stars pass close enough to SMBHs and get destroyed by tidal forces. The result of this destruction is a luminous electromagnetic flare with a timescale of $\sim$ months. Theoretical studies have suggested that TDEs might be sources of high-energy neutrinos and ultrahigh-energy cosmic rays.

AT2019fdr, a candidate TDE in a Narrow-Line Seyfert 1 (NLSy1) active galaxy. AT2019fdr was identified as a likely neutrino source by the neutrino follow-up program of the Zwicky Transient Facility (ZTF) AT2019fdr lies within the reported 90% localization region of the IceCube high-energy neutrino IC200530A. The following paper [5] discusses how the location of AT2019fdr, which was a very long-lived transient, one of the most luminous ever detected coincided with a High-energy neutrino observed in IceCube. Do check it out if you are interested.

4.6 Trifecta of observation

The three types of signals we know how to collect from the Universe—light, particles, and gravitational waves - all deliver fundamentally different types of information right to our front door. By combining the most precise observations we can take with each of these, we can learn more about our cosmic history than any one of these signal types, or "messengers," can provide in isolation.

And we may very well have already observed some candidates producing such 'trifecta' signals!

Just a generation ago, multi-messenger astronomy was nothing but a dream. But today, we have stepped into this new Era of Multi-messenger astronomy, allowing us to see a deeper and fuller picture of the universe, and revealing the secrets behind some of it's most mysterious and fascinating phenomena.

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