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Invited review

THE PAST, PRESENT AND FUTURE OF GRAVITATIONAL WAVE ASTRONOMY

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SUMMARY: Gravitational Waves (GWs) have become a major source of insight in Multi Messenger Astronomy since their first direct detection in 2015 (Abbott et al. 2016) where the Nobel prize in Physics was awarded in 2017 to LIGO founders Barry C. Barish, Kip S. Thorne, and Rainer Weiss. They complement electromagnetic and particle measurements by providing cosmic scale evidence which cannot be detected in any other way. Their rise to prominence has not been straightforward since the founder of general relativity, Albert Einstein, who predicted GWs, was nevertheless skeptical of their existence and detectability. This skepticism put a damper on Gravitational Wave (GW) research that was not overcome until the 1950's, the decade of Einstein's death. Since then, ever more sensitive GW detectors have been designed for construction on earth and in space. Each of these detector approaches was designed to expand the types of cosmic events that could be detected.

Key words. Gravitational waves – History and philosophy of astronomy

1. INTRODUCTION

Isaac Newton was the first to describe gravitation mathematically as a force. Its behaviour, as a force at a distance, was fundamentally no different than the force of two bodies in contact (Cohen and Whitman 1999). The question to Newton of how force at a distance could be explained was answered with *"Hypotheses non fingo"*, basically he had no idea of how it worked (Newton 1758, Cohen and Whitman 1999). The nature of gravity described in this way suggested that action at a distance was instantaneous so that changes in gravitational force operated instantaneously, at infinite speed.

Perhaps the earliest conception of GWs is to be found in Maxwell (1865) who mused about the possibility of gravity being a field similar to electromagnetism since they each were described by the inverse square law. Heaviside (1893)[1] examined this idea as a "Gravitational Analogy", re-casting electromagnetic theory in terms of mass, inertia, and gravitational force as described by Newton's law. He also showed that gravitational force propagates at a single finite speed providing for the possibility, at least mathematically, that GWs could exist. Heaviside also considered the changes in a gravitational field when masses are moving. He found that changes in the gravitational field would produce small perturbations in objects orbiting the sun depending on the propagation speed of the field. The lack of these perturbations set the upper speed limit of gravitational propagation to that of the speed of light.

With the publication of the special theory of relativity, Einstein (1905) completed the merger between electricity and magnetism which began with Maxwell. The propagation of gravity could not be faster than

[1]Oliver Heaviside (1850–1925) was an English self-taught electrical engineer, mathematician, and physicist.

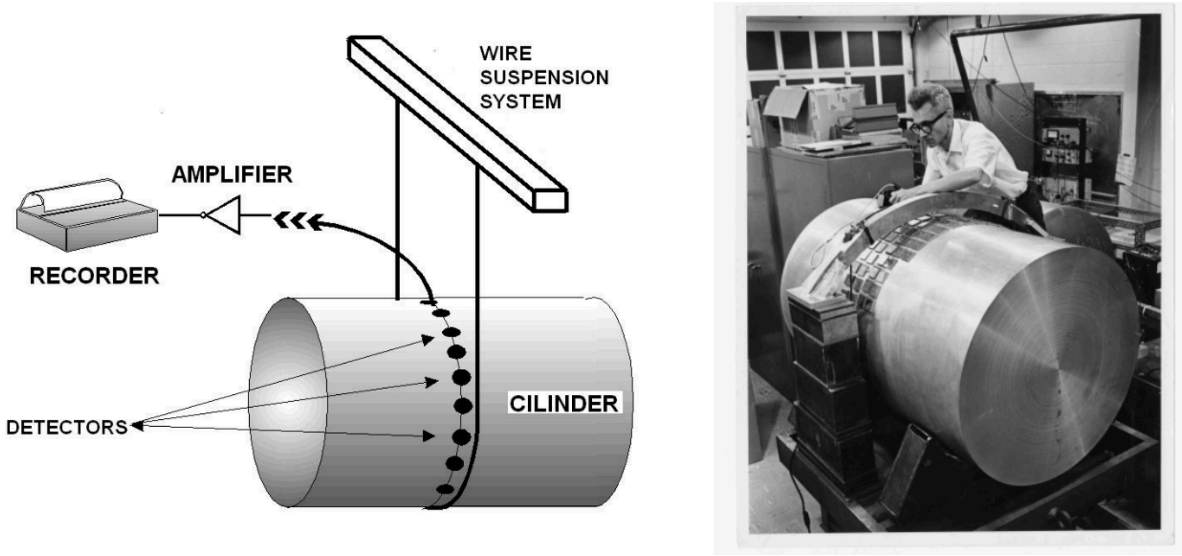

Fig. 1: Left: The Bar antenna sketch. Right: The Bar antenna picture with J. Weber. From Cervantes-Cota et al. (2016).

the speed of light and was equal, in fact, to the speed of light. Nearly contemporaneous with Einstein's paper was one by Poincaré (1905)[2] which presented very similar results but lacked important features of Einstein's theory. Poincaré showed that, since gravitational force propagates at the speed of light, there will be a time lag between a change in gravity and its effect. This delay due to the finite propagation velocity of gravity could be the source of GWs.

Founded upon Einstein's theory of relativity, GWs, the youngest branch of Multi-Messenger Astronomy (Filipović and Tothill 2021a,b) might revolutionise our understanding of the Universe. It is widely accepted that GWs were predicted by Einstein in 1916 as a specific consequence of his general theory of relativity. However, they quickly became a common feature of all modern theories of gravity that obey special relativity (Schutz 1984).

After 1916, there was a long debate on whether GWs were actually physical or were artefacts of coordinate freedom in general relativity. Einstein's skepticism regarding the reality of gravitational radiation impeded research into GWs until his death in 1955, particularly the question of whether or not they could be detected. A consensus on the detectability of GWs was not resolved until the late 1950s, opening the way to serious GW research.

2. THE EARLY STUDY OF GRAVITY

The field of gravity research was re-invigorated in the 1950s by Agnew Bahnson[3]. He sponsored an essay contest through the Gravity Research Foundation (GRF) on the possibility of insulators, reflectors, or absorbers of gravity. In 1953, Bryce DeWitt entered an essay contest conducted by the GRF with a submission that dismissed the entire anti-gravity concept (DeWitt et al. 1995)[4]. He won the contest and a prize of $1000. DeWitt, supported by several senior physicists including Oppenheimer, Dyson, Teller, Feynman, and Wheeler, then helped to establish something akin to an "Institute for Advanced Study" for gravity research with real scientific goals, distancing the new institute from the GRF. As a group, they were very concerned that gravity research had been neglected for many years. The details are fascinating and may be found in DeWitt and Rickles (2011, Report from the 1957 Chapel Hill Conference). Any mention of anti-gravity was scrupulously avoided in order to maintain the legitimacy of the organisation and in order not to discourage sponsors and scientists.

The 1957 Chapel Hill conference had 40 speakers from 11 countries and met for six days. A critical discussion in that conference concerned the effect of a gravitational pulse on a particle and whether or not

[2] Jules Henri Poincaré (1854–1912) was a French mathematician, theoretical physicist, engineer, and philosopher of science.

[3] Agnew Bahnson was a wealthy North Carolinian industrialist who had a passion for gravitational physics, especially anti-gravity.

[4] `http://www.aip.org/history-programs/niels-bohr-library/oral-histories/23199`

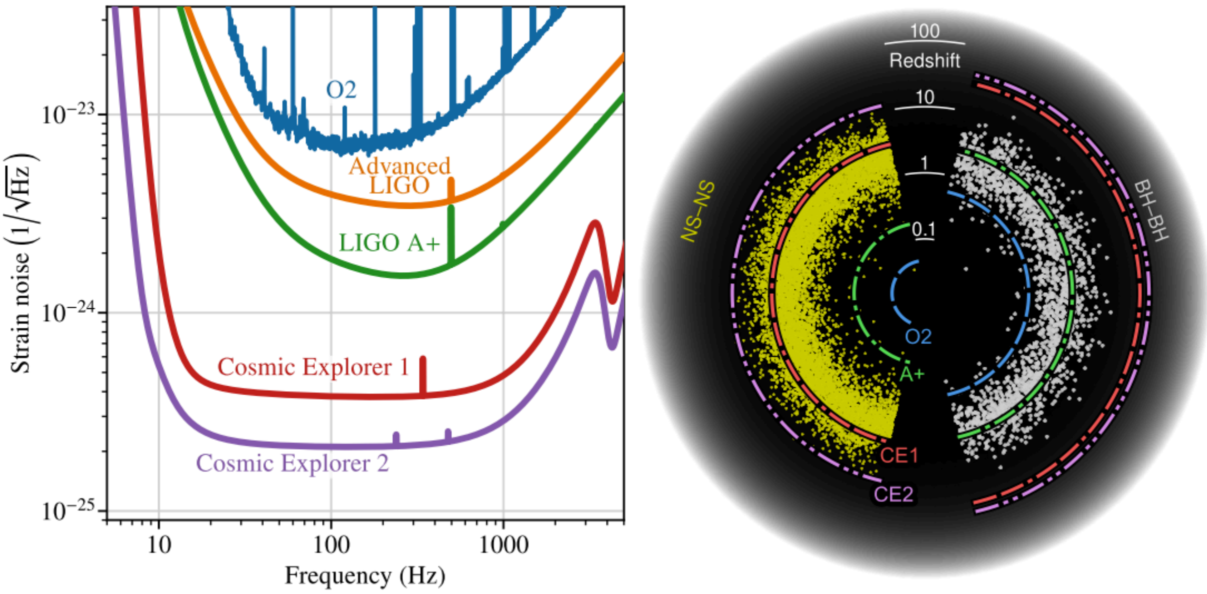

Fig. 2: Left: LIGO and CE strain noise for different versions of each. CE1 is scheduled for the 2030's and CE2 for the 2040's. Right: Response distance for LIGO implementations and CE designs superimposed on a population of 1.4–1.4 $M_\odot$ neutron star mergers (yellow) and 30–30 $M_\odot$ black hole mergers (grey). Figure from Reitze et al. (2019).

the wave would transmit energy to the particle. Feynman reasoned, through a thought experiment now referred to as the "sticky bead argument", that heating would occur and energy would be deposited in the system, giving rise to the expectation that GWs could be detected, at least theoretically. This idea was bolstered by the paper by Bondi (1957, who attended the Chapel Hill conference) which demonstrated that GWs exist, that they carry energy, and that the passage of a GW through matter can deposit energy in that matter.

GWs are now described as the result of the strain response (distortions) in space-time due to the stress of GWs propagating through space-time. The distortions are perpendicular to the direction of propagation with an amplitude of $\Delta L/L \sim 10^{-20}$. The strain response produces changes in the distance between masses which can be measured. Accelerated masses create the space-time stresses that propagate outward from the accelerated masses as GWs.

3. WEBER'S EXPERIMENT TO DETECT GRAVITATIONAL WAVES

Among the attendees of the 1957 Chapel Hill meeting was Joseph Weber, an engineer at the University of Maryland. He published an approach to GW detection using a mechanical system employing piezoelectric crystals attached to the antenna mass as detectors (Weber 1960). He modeled antenna mass as a linear quadrupole harmonic oscillator driven by GWs with frequency components at the mass's resonant frequency. The Q[5] of the antenna, due to radiation damping, was calculated to be $Q_R \sim 10^{34}$ providing for extremely low energy loss. However, a practical antenna was calculated to have a $Q \sim 10^6$ suggesting that the material used in a resonant antenna would greatly affect its sensitivity. He proposed using the amplified electrical output from piezolectric crystals on two bar antennas routed through a cross correlator to reveal the GWs.

Weber (1966) describes the GW antenna and its sensitivity. The bar antenna was a 1360 kg cylinder $\sim$ 150 cm long with a diameter of $\sim$ 61 cm with its lowest compressional resonant mode at $\sim$ 1657 Hz (see Fig. 1). The bar antenna, suspended in a vacuum chamber, is isolated from external mechanical vibrations using acoustic filters. Thermal measurements implied a sensitivity of $\sim 2 \times 10^{-14}$ cm from a strain of $\frac{\Delta l}{l} \sim 10^{-16}$.

Weber (1969) reported GW detection from an experiment with two large, resonant, metal cylinder bar GW antennas which detected coincidence in the detectors with $\sim$ 1000 km separation between them. The detection frequency of $\sim$ 1660 Hz was chosen because it was a frequency that was expected to be present in a Supernova (SN) collapse and the dimensions of the antennas suggested that it could be done with reasonable resources and effort. The bandwidth for the detector was 1.6×10^{-2} Hz. These high-Q bar

[5] $Q = \omega \times (\mathrm{stored}-\mathrm{energy})/(\mathrm{power}-\mathrm{dissipated})$

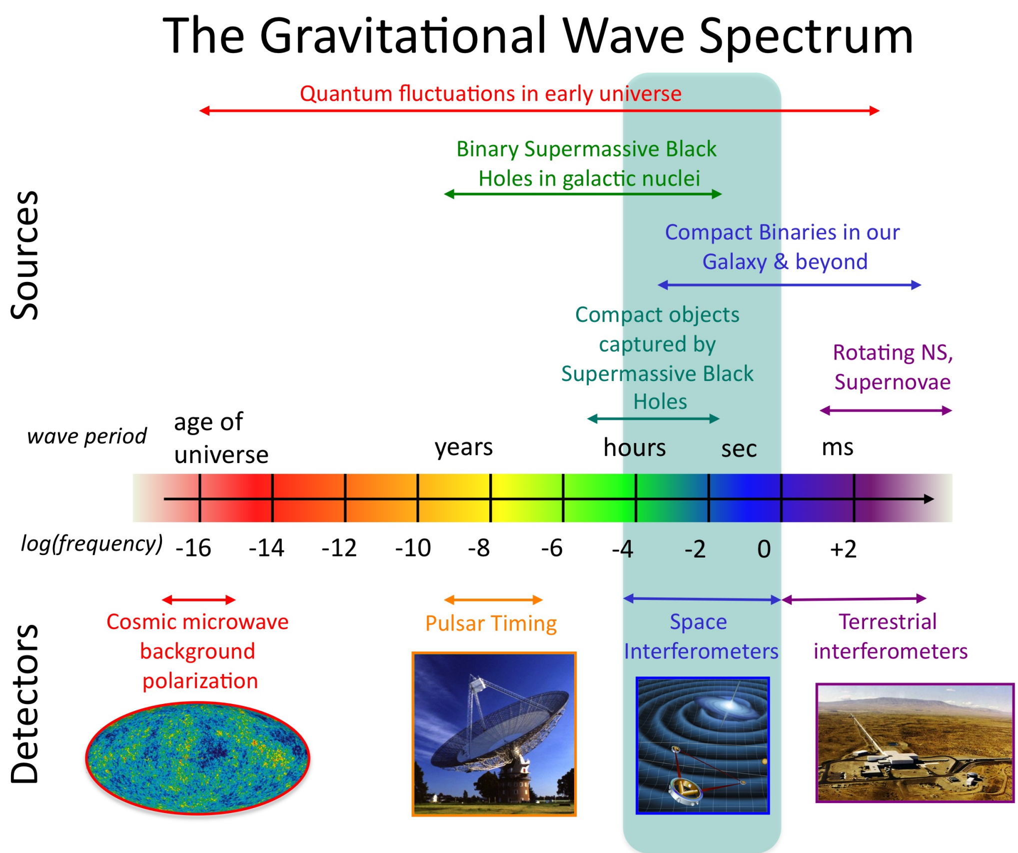

Fig. 3: GW spectrum, detectors, and sources of those frequencies (Image From NASA Goddard). Similar to the necessity for different instruments to detect electromagnetic waves at specific frequencies, distinct device designs are required to detect GWs from diverse sources which emit a wide range of frequencies. Current terrestrial interferometers can detect relatively high frequency GW sources, space-based detectors will be able to detect lower frequencies from other more massive GW sources, and the IPTAP will be able to detect the lowest frequencies from very large mass accelerations (`http://ipta4gw.org/`).

antenna mechanical systems began to oscillate as soon as they were excited and decayed within a predetermined time. Two additional detectors were in operation during this experiment and events were recorded for two, three, and four way coincidences. In an 81 day period, 17 two way, 5 three way, and 3 four way coincidence events were recorded. The evidence for GW detection was several coincidence events recorded that occurred much more frequently than one would predict from random noise.

Weber (1970) explored GW source anisotropy by using the directional characteristics of the bar antennas. A total of 311 coincidences are included in histograms plotting detection count vs. sidereal time and local daylight-saving time for a span of 24 hours. The data is plotted with a time base of 24 hours and then 12 hours with 0-12 and 12-24 hour data added. The result shows the expected 12 hour sidereal symmetry of the antennas and a strong peak in the direction of the Galactic centre. The event count vs. daylight-saving time histogram shows little deviation from the mean coincidence rate over the entire time displayed. The sidereal plot shows that there is no significant GW attenuation through the earth and that the source of the GWs observed is the $\sim 10^{10}$ solar masses in the Galactic centre. Weber wrote a popular article describing his work to this point which is found in (Weber 1971, Scientific American).

An interesting essay (Kafka 1972, "Are Weber's Pulses Illegal?") examines the mass loss of the galaxy needed to create the GWs detected in Weber's experiments and suggests that the predicted mass loss rate could not be sustained. A GW Astronomy review was presented by Press and Thorne (1972) which included a consideration of the Weber GW experimental results. Some issues were discussed including that each of the coincidences have the energy of a strong supernova or stellar collapse, but this is 1000 times

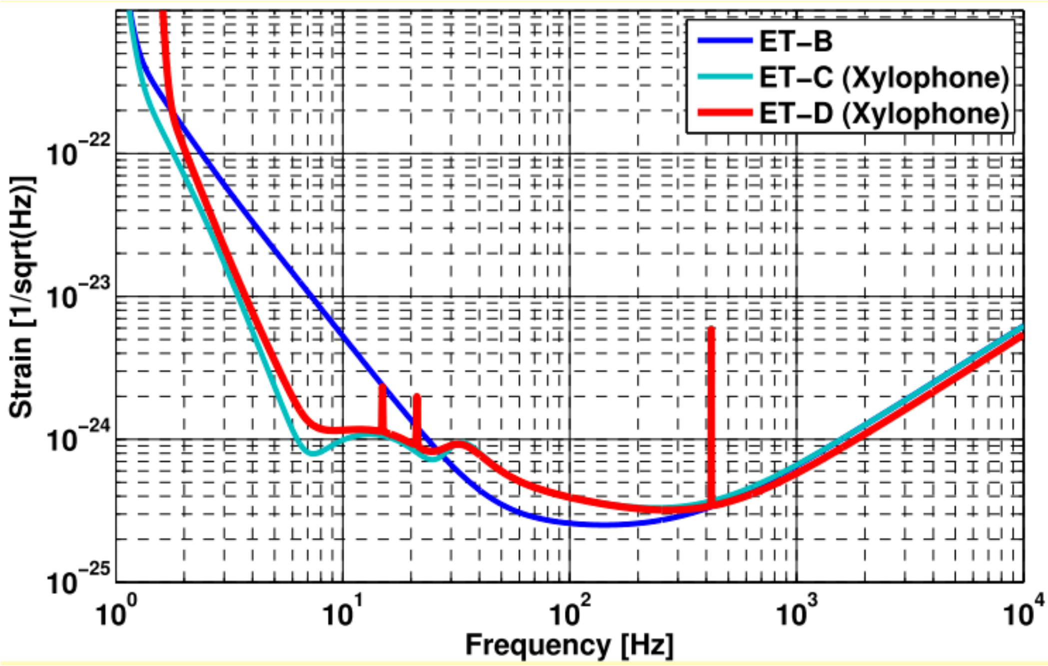

Fig. 4: Sensitivity of the Einstein Telescope. Figure from European Commission (2011). ET-B is the sensitivity when each detector is a single interferometer. ET-C is an enhanced version when each interferometer is split into two co-located interferometers: one with optimisation at high frequencies and the other at low frequencies. ET-C is the best sensitivity that is expected when all of the noise terms are included in the predicted sensitivity.

the number of such events predicted in the Galaxy. The energy loss by the Galaxy measured by Weber's experiment is $\sim 10^6$ $M_\odot$/ year compared to the total luminosity of the Galaxy from electromagnetic radiation of $\sim 10^{-2}$ $M_\odot$/ year.

Tyson and Giffard (1978) reported that Weber's positive results published through 1974 were not observed by any other workers even with detectors that had much higher sensitivity than Weber's instruments. Clearly, Weber was the driving force that gave birth to the GW detector field and had been the prototype of virtually all GW detection experiments up to 1978. The conclusion by 1978 was that the GWs seen by Weber would have been detected by several more sensitive experiments so it was not likely that Weber detected GWs.

4. INTERFEROMETER BASED GRAVITATIONAL WAVE DETECTION APPROACH

Interferometric detection of GWs was first considered in the 1960s (Forward 1978). The basic design was a folded Michelson interferometer with environmental isolation including vibration isolation from the ground and with all optical components mounted in a vacuum. From the 1960's through the 1980's, several GW experiments were conducted which included the construction of instruments with sizes of 3 m to 30 m (Cervantes-Cota et al. 2016) and with unrealised design proposals for up to 3 km. Much was learned and techniques were developed as progress was made towards a viable instrument which included noise suppression methods later used in the Laser Interferometer Gravitational-Wave Observatory (LIGO) project (de Sabbata and Weber 1977).

Indirect observational evidence for the existence of GWs was first obtained in the late 1980s, from monitoring the Hulse-Taylor binary pulsar (discovered in 1974). The pulsar's orbit was found to evolve exactly as would be expected for GW emission (Hulse and Taylor 1975). In 1993 Hulse and Taylor were awarded the Nobel Prize in Physics for this discovery.

In the 1990s, major advances were made with a 600 m interferometer designed in Germany. The GEO 600 interferometer construction began in 1995. This instrument has been in operation since 2002 with an extended LIGO-GEO science run in 2005.

The LIGO organisation was created by a 1984 agreement between Caltech and MIT (LIGO 2020). The plan was to build and operate a pair of "Initial Interferometers" based on existing technology followed by "Advanced Interferometers" (also referred to as second generation GW (2G) detectors) which would utilise the newest technology developed for the experiment. In 1997 the LIGO Scientific Collaboration (LSC) was established. It has the responsibility for operations, advanced interferometer research and development, and the expansion of technical and scientific cooperation beyond Caltech and MIT.

By 2016 approximately 1000 scientists at 75 institutions in 15 nations were participating. The first GW search using the initial interferometers was performed in 2002–2005. In 2007 coordination was established with the European interferometric GW experiment VIRGO, named for the Virgo galactic cluster.

On September 4, 2015, during the commissioning and testing of the advanced LIGO detectors, GWs were detected directly for the first time (Abbott et al. 2016). In recognition of this monumental triumph, the 2017 Nobel Prize in Physics was awarded to the project leaders for the LIGO experiment: Barry C. Barish, Kip S. Thorne, and Rainer Weiss.

Since then, further improvements have been made in sensitivity. Additionally, the number of interferometers in use has increased. As more interferometric detectors become available, sensitivity and source position accuracy will be greatly improved. Wide geographic distribution of the interferometers enables improved localisation of the sources detected. As of 2020 two detectors are operating in the United States (US): Hanford in Washington state and Livingstone in Louisiana state. Three interferometers also operating on other continents are the VIRGO interferometer near Pisa, Italy; GEO 600 near Hannover, Germany; and KAGRA located underground in Japan. Planned for operation as early as 2025 is LIGO-India.

The number of GW detections continues to grow. The web site in LIGO-Detections (2020) should be consulted for the current list.

The current GW telescopes are terrestrial interferometers and have specific frequencies at which they have useful sensitivities (see Fig. 2). These telescopes can detect only the highest frequency GWs.

5. GRAVITATIONAL WAVE SOURCE CATEGORIES

The sources of gravitational waves include every massive object in the Universe which experiences acceleration. The frequencies of GWs span at least 16 orders of magnitude. Detectable gravitational waves require a large mass and a large acceleration. The combination of the mass and acceleration can be used to predict the frequencies that will be produced. The span of frequencies is so great that different types of GW detectors must be used to detect the different frequencies (see Fig. 3).

An example of a detectable event is a “Compact Binary Inspiral Gravitational Wave” event which is produced by massive, very dense, objects spiraling in together. Most of the currently identified LIGO detections are in this class of events. Variations of this class include “Binary-Neutron Star” events (NS-NS), “Binary-Black Hole” events (BH-BH), and “Neutron Star-Black Hole” events (NS-BH). “Continuous GWs” are predicted to be produced by massive spinning objects, like neutron stars, due to imperfections in their mass distribution. An additional category predicted is that of “Stochastic GWs” which are the result of the random coincidence of GWs from different parts of the Universe coming together to produce a detectable signal. Finally, unexpected signals from unknown sources or from unknown mechanisms are categorised as “Burst Gravitational Signals”.

6. GRAVITATIONAL WAVE ASTRONOMY IN THE FUTURE

With the initial detection of GWs now a *fait accompli*, the capability is an established astronomical tool and part of the Multi Messenger approach to astronomy. Work to improve the sensitivity and frequency response of this new window into the Universe is well underway.

For a telescope to be included in the third generation GW (3G) detector category it needs to have an increased sensitivity by a factor of at least 10 over 2G detectors such as LIGO. The new 3G detectors being designed include the Cosmic Explorer (CE)[6], the Einstein Telescope (ET)[7] and Laser Interferometer Space Antenna (LISA)[8].

6.1. Gravitational wave detection parameters

There are significant differences between GW and “traditional” electromagnetic astrophysics and cosmology (Chen et al. 2021). Familiar quantities such as magnitude limit, B-band luminosity, sky brightness, Vega magnitudes, and other usual measurements are not applicable to the GW realm.

Even the concept of distance is different in cosmology. At large distances, redshift is the observable quantity, not radial distance. The measured redshift consists of the cosmological redshift, due to the expansion of the Universe or Hubble flow, and the peculiar velocity of the source relative to the Hubble flow. For small redshifts, the relation of distance to redshift is linear, $d \approx zD_H$, where D_H is the Hubble distance (Peebles 1993, Hogg 1999). Many galaxy redshift surveys have used the non-relativistic velocity approximation of $v = cz$.

Distances to distant objects calculated from redshifts measured in electromagnetic astronomy are dependent on cosmological parameters such as the Hubble constant which is now in a state of uncertainty. GW detections of BH-BH mergers, on the other hand,

[6] https://cosmicexplorer.org/

[7] http://www.et-gw.eu/index.php

[8] https://www.elisascience.org/

can provide absolute distance measurements at large redshifts (Hogan et al. 2009). Electromagnetic measurements of the redshift of the galaxy containing the GW event could provide an independent method to calculate the Hubble constant. Note that there are four different distance scales used in cosmology: luminosity distance, angular diameter distance, comoving distance, and light travel time distance (Chen et al. 2021) and the values are dependent on the Hubbble constant and the cosmological model being used.

GW telescopes are sensitive to sources over the entire sky all of the time. In order to determine the direction to a detected GW event, more than one detector, preferable several widely spaced across the earth or beyond, are required. The number of detectors and their position will determine the accuracy of the determined location of the source. Details of error estimates in distance for GW observations are discussed in Hogg (1999) and Chassande-Mottin et al. (2019).

A GW detector's ability to detect a source depends on the sensitivity curve of the detector, the position of the source, and on the source characteristics (Reitze et al. 2019). Important GW telescope parameters include:

- Horizon Distance: furthest luminosity distance detectable at maximum sensitivity.
- Redshifted Volume: the space-time volume in which detection is possible in Mpc^3.
- Range Distance: the Euclidean equivalent spherical radius that would contain the Redshifted Volume.
- Response Distance: the luminosity distance corresponding to a specific percentage of isotropic sources detected at exactly that distance, each with a random inclination/orientation to the detector.
- Reach Distance: the luminosity distance within which a specific percentage of total detections take place with 100% corresponding to the Horizon Distance.

Advanced LIGO detectors with 2G sensitivity for binary coalescence events with masses of 1.4–1.4 $M_\odot$ have a median luminosity distance of 202 Mpc, and with masses of 30–30 $M_\odot$ a median luminosity distance of 2440 Mpc. The 3G detectors have a luminosity distance for these events of 12 Gpc and 30 Gpc respectively (Chen et al. 2021). The 3G detectors will be sensitive to a 10–10 $M_\odot$ to 30–30 $M_\odot$ binary coalescence anywhere in the Universe.

6.2. The 3G cosmic explorer telescope

The US contribution to the next generation of GW telescopes beyond LIGO will be the 3G CE1 (Reitze et al. 2019). The 40 km CE1 will employ 2G advanced LIGO technology with 10x the size and sensitivity. The 10× 2G sensitivity boost for CE1 is due to the 10x size increase.

The second generation CE, the CE2, will have cryogenic mirrors and other enhancements to give it a sensitivity of $\sim 2\times$ for a factor of $8\times$ that of the advanced LIGO (Fig. 2). The arm-lengths will move the lower frequency to 5 Hz from the LIGO minimum of 10 Hz. The CE2 bandwidth of 5–4000 Hz will allow detection of a vast number of sources.

Some key goals for the CE2 (Reitze et al. 2019) and for 3G in general are:

- Characterising the nature of neutron stars by observation of mergers and post-merger remnants possibly revealing new physics from matter at ultra-high densities.
- Observing binary systems including neutron star mergers in conjunction with electromagnetic telescope observations.
- Observing black hole mergers throughout cosmic time.
- Detecting stellar mass black hole mergers out to $z \sim 20$. (This includes the epoch during which the first stars were forming.)
- Uncovering the evolution of the Universe using GWs independently from electromagnetic measurements.
- Comparing luminosity distances measured with GWs to electromagnetic source redshift measurements.
- Measuring GWs to inform cosmological measurements (independent of electromagnetic observations) of the Hubble constant, dark matter density, and dark energy density.
- Observing the nature of gravity and compact objects in regions of strong gravity and large curvature.
- Observing the evolution of massive stars including formation and the detailed examination of supernovae and pulsars.

The CE1 telescope, in conjunction with the European 3G ET, will add to the global GW network and provide more precise localisation of detected GW sources.

6.3. The 3G Einstein telescope

This European 3G telescope is applying new design ideas to produce an optimal telescope design. It is an underground, planar, triangular configuration with three co-located arms, each 10 km long with an angle of 60° between (see Fig. 5). This provides

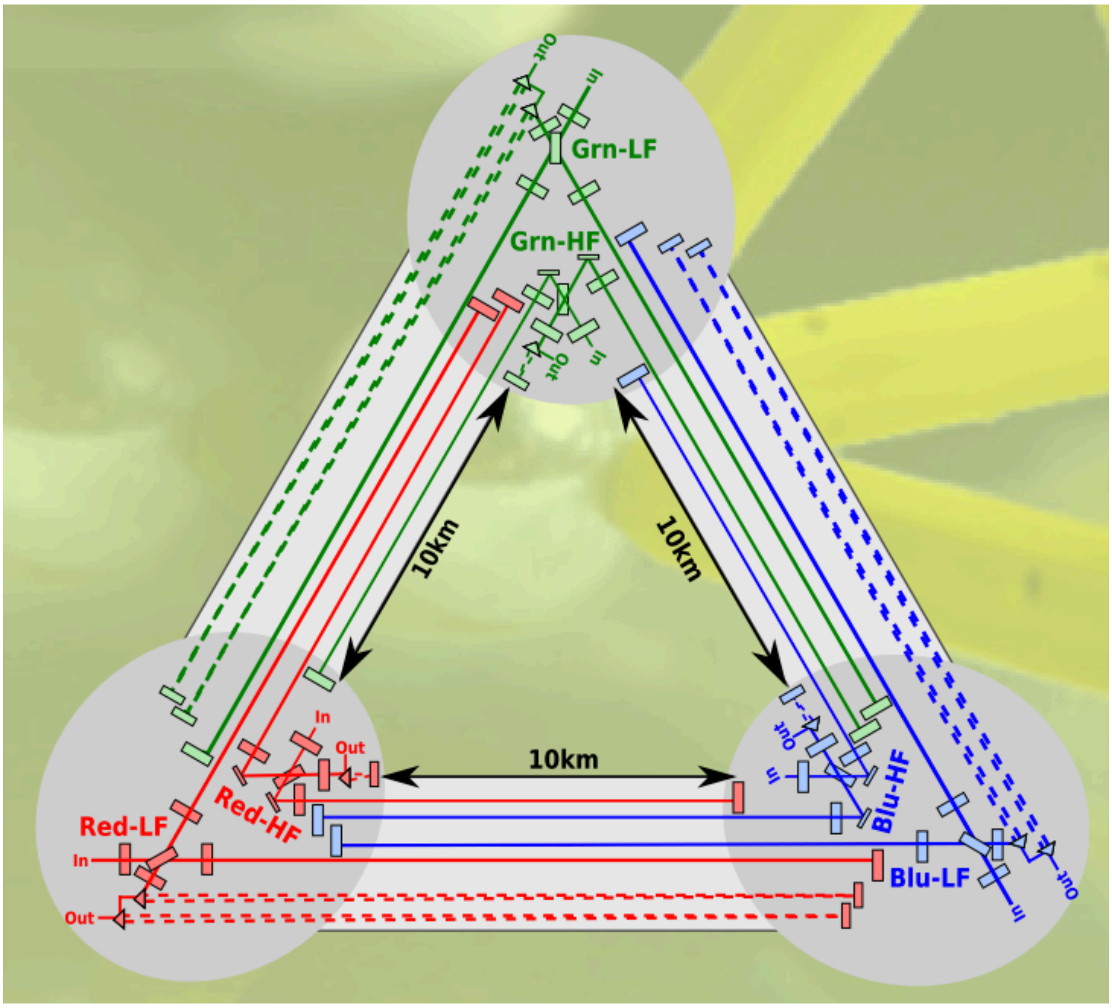

Fig. 5: Conceptional layout of the Einstein Telescope, Figure from European Commission (2011). The instrument has 3 pairs of km sized interferometers in a triangular shape. Each pair consists of a low frequency optimised detector and a high frequency optimised detector. This graphic is not to scale.

three nested detectors (Freise et al. 2009, European Commission 2011, 2020).

The goals for the telescope included expanding the detection frequency down to a few Hz and up to 10 kHz in two bands, $10-10^4$ Hz and $1-250$ Hz (Fig. 4). Each detector is comprised of two interferometers: one designed for low frequency and the other for high frequency GWs. The configuration is referred to as a "Xylophone".

The ET is designed to measure many previously inaccessible quantities in astrophysics as well as in fundamental physics and cosmology (Maggiore et al. 2020). It is well suited to be used in conjunction with other GW telescopes like the 3G CE telescope (see Fig. 6).

For equal coalescing mass non-spinning binaries, the CE and the ET telescopes have similar detection ranges. The ET telescope has better detection with the highest mass coalescing events and the CE is able to detect lower mass coalescing events to larger redshift values. Generally, ET will be able to detect heavier systems while the CE will be able to detect lighter systems like NS-NS mergers at larger distances.

The 3G telescopes will be able to measure systems with masses of 20–100 $M_{\odot}$, typical of BH–BH or BH–NS binaries from the dark era of the Universe preceding the birth of the first stars. For NS-NS binaries, with a smaller total masses of ~ 3 $M_{\odot}$, the reach will be limited to $z \sim 2-3$. Detection rates for BH-BH coalescences is expected to be $\sim 10^5 - 10^6$ per year and NS-NS coalescences, $\sim 7 \times 10^4$ coalescences per year. The large number of NS-NS mergers detected will provide information about the fundamental structure of neutron stars.

The detection of continuous GWs from neutron stars is also possible depending on 1) the neutron star's internal equation of state, 2) its composition,

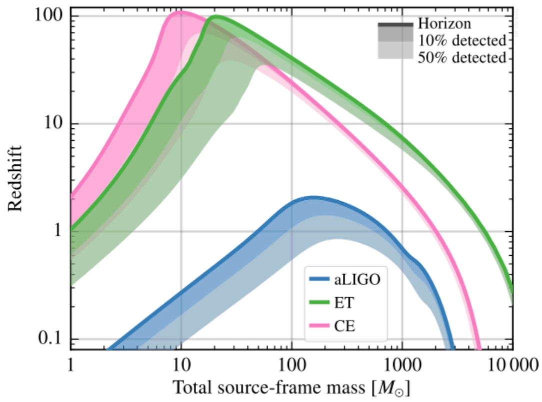

Fig. 6: Astrophysical reach comparison between advanced LIGO, CE, and ET for equal mass non-spinning binaries (Maggiore et al. 2020).

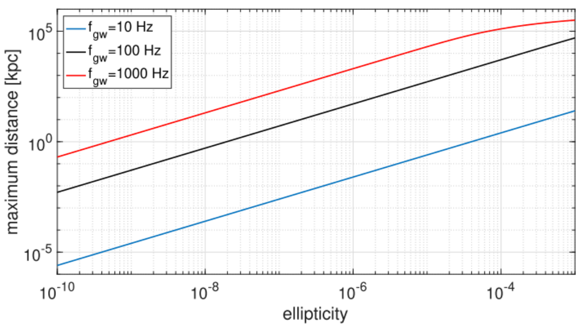

Fig. 7: Maximum distance a continuous wave source could be detected as a function of ellipticity with a coherent search for 5 years using the ET-B configuration (Maggiore et al. 2020).

and 3) its deformation (which is quantified as ellipticity). For a neutron star, described by the current standard equation of state, the maximum ellipticity is $\epsilon \sim 10^{-6}$. Exotic objects, composed of hyperons or quark matter, may also be detectable because they may be able to sustain much higher ellipticities, $\epsilon \sim 10^{-4} - 10^{-3}$, making them much easier to detect (see Fig. 7).

6.4. The laser interferometer space antenna

LISA is the first instrument with the aim to study the entire Universe with GWs (Danzmann 2017). LISA is an all-sky observatory recording the dynamic cosmos in GWs with exceptional sensitivity at the low frequencies that characterise so much of the dynamics of the Universe with a bandwidth greater than the most relevant astronomical frequencies of $10^{-4} - 10^{-1}$ Hz (see Fig. 9).

The frequency range of $f \sim 0.1$ mHz to 100 mHz is predicted to be populated by many strong sources of GWs. This includes binary sources with frequencies of twice the Keplerian orbital frequency, or $(M/a^3)^{1/2}$ with M the total mass and a the semi-major axis. Close binaries of stellar-mass objects have periods of several minutes down to just a few minutes. This important frequency range is not observable by ground-based instrumentation. Low frequency GWs may reveal the first black holes at redshifts of $z \geq 20$.

The low frequency sensitivity of LISA (see Fig. 9) enables several scientific objectives (Amaro-Seoane et al. (2013) and Danzmann (2017)) which include:

- Detect, resolve, and characterise $\sim$ 25,000 Galactic binary stars:
  - Survey the period distribution of the binaries.
  - Measure the masses, distances, and locations of the stars.
  - Study the near Galaxy environment of massive black holes.
  - Determine the Universe's expansion rate using GW sirens at high redshifts in order to measure the Hubble constant using GWs only.
  - Search for new, unique sources of GWs.
- Study massive black hole origins by measuring accretion events and repeated coalescences.
- Observe the electromagnetic counterparts of merging events.
- Search for intermediate mass black hole binaries.
- Study Extreme Mass Ratio Inspirals.

An interesting GW observation proposed by Naoz et al. (2020) suggests that since most galaxies appear to be the result of galaxy mergers, there should be at least a binary black hole at the centre of many galaxies soon after the merger. This leads to the suggestion that LISA be applied to a search for a black hole companion to the Galaxy's super massive black hole Sgr A*. Fig. 8 shows the feasibility of such a detection.

The LISA experiment consists of three identical laser interferometer satellites (see Fig. 10) in an earth-trailing heliocentric orbit. The satellites will form a constellation orbiting a point $\sim$ 20 deg behind the earth. Each satellite is separated by 2.5×10^6 km from each other with the constellation $50 - 65 \times 10^6$ km trailing the Earth. The satellite design is based on the successful LISA pathfinder demonstration vehicle (Hechenblaikner and Flatscher 2013).

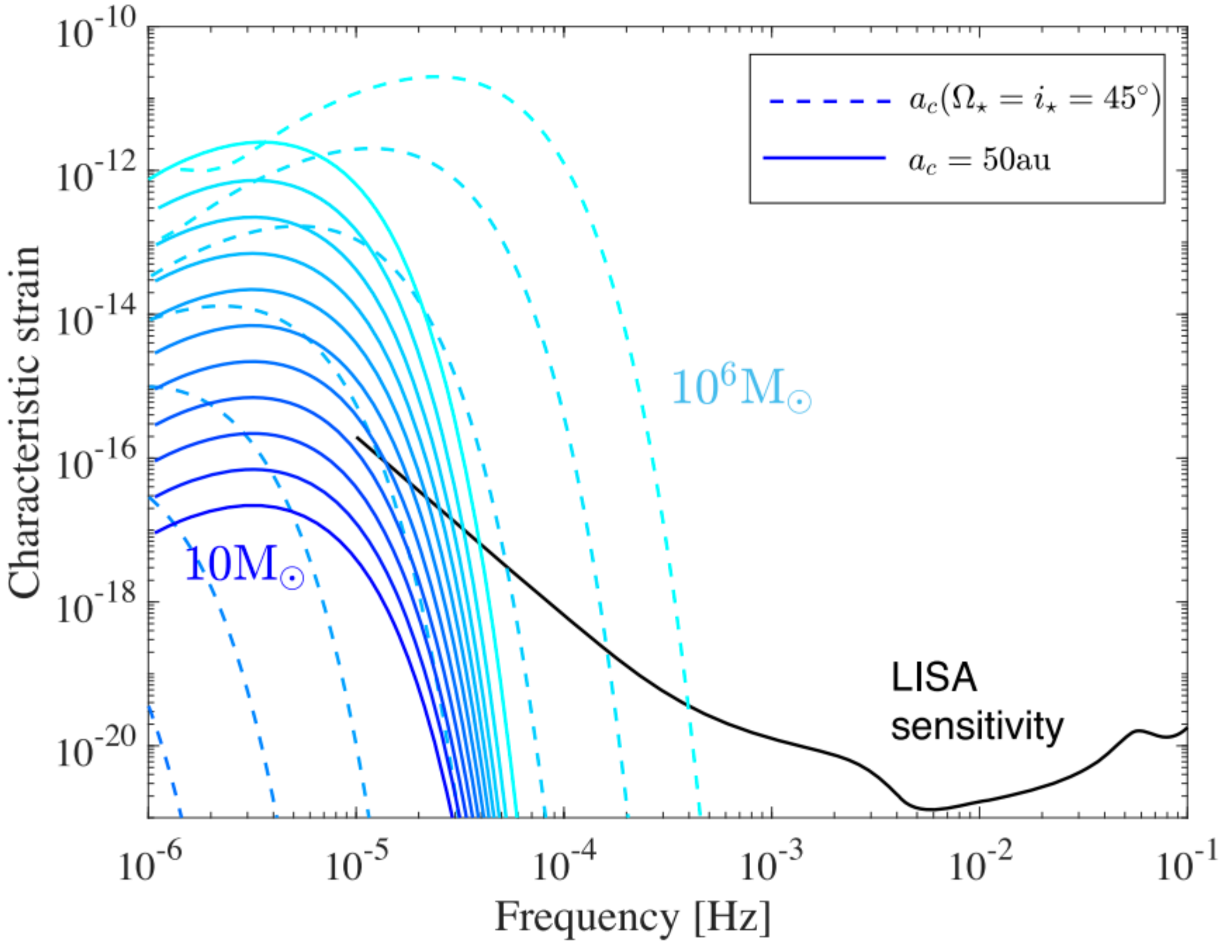

Fig. 8: Naoz et al. (2020) shows the characteristic strain function in frequency for an observation of 4 yr. This shows the detectability of a black hole "Friend" of Sgr A* with a range of masses from 10 $M_\odot$ to 10^6 $M_\odot$. Strain measurements above the LISA sensitivity line are predicted to be detectable. The frequency is the inverse period of the "Friend" around Sgr A* with an eccentricity of 0.9.

6.5. The pulsar timing array gravitational wave detection

Pulsars were discovered by Hewish et al. (1968) with a radio telescope which was designed to detect interplanetary scintillation. The detection of pulsars has led to measurements of many phenomena by using the extreme predictability of millisecond (ms) pulsar timing (Lommen 2015). The use of a PTA for GW research was proposed in Detweiler (1979) for GW frequencies of $10^{-9} - 10^{-7}$ Hz with dimensionless amplitudes of $\sim 10^{-11}$. This frequency range is dictated by observational constraints, specifically: 1) telescope scheduling which limits the highest frequency detectable (observations may be limited to only one measurement every few weeks), and 2) the arm-length which limits the low frequency.

The key to understanding the PTA is to note that the distance from the earth to the pulsar is essentially the measurement arm whose length is being modulated by GWs (see Fig. 11). This dwarfs even the LISA arm-length of 2.5×10^6 km. Fundamentally, the arrival time of the pulses from a pulsar is modulated by the change in the distance to the pulsar by the strain imposed on the space-time continuum. In order to determine the sky coordinates of the GW source, a combination of multiple pulsars must be measured. The set of pulsars used for a measurement is referred to as a pulsar "array".

The GW detection is performed by measuring the arrival time of pulses from millisecond pulsars over an extended period of time (Dahal 2020). This data can be applied to several different experimental measurements including GW detection. Millisecond pulsars are selected because of their very small long-term timing irregularities. The expected Time of Arrival (TOA) from a pulsar is modelled to include all known influences, e.g., planetary movement and pulsar energy loss. The measured TOA from a pulsar, after removing known effects of other physical proce-

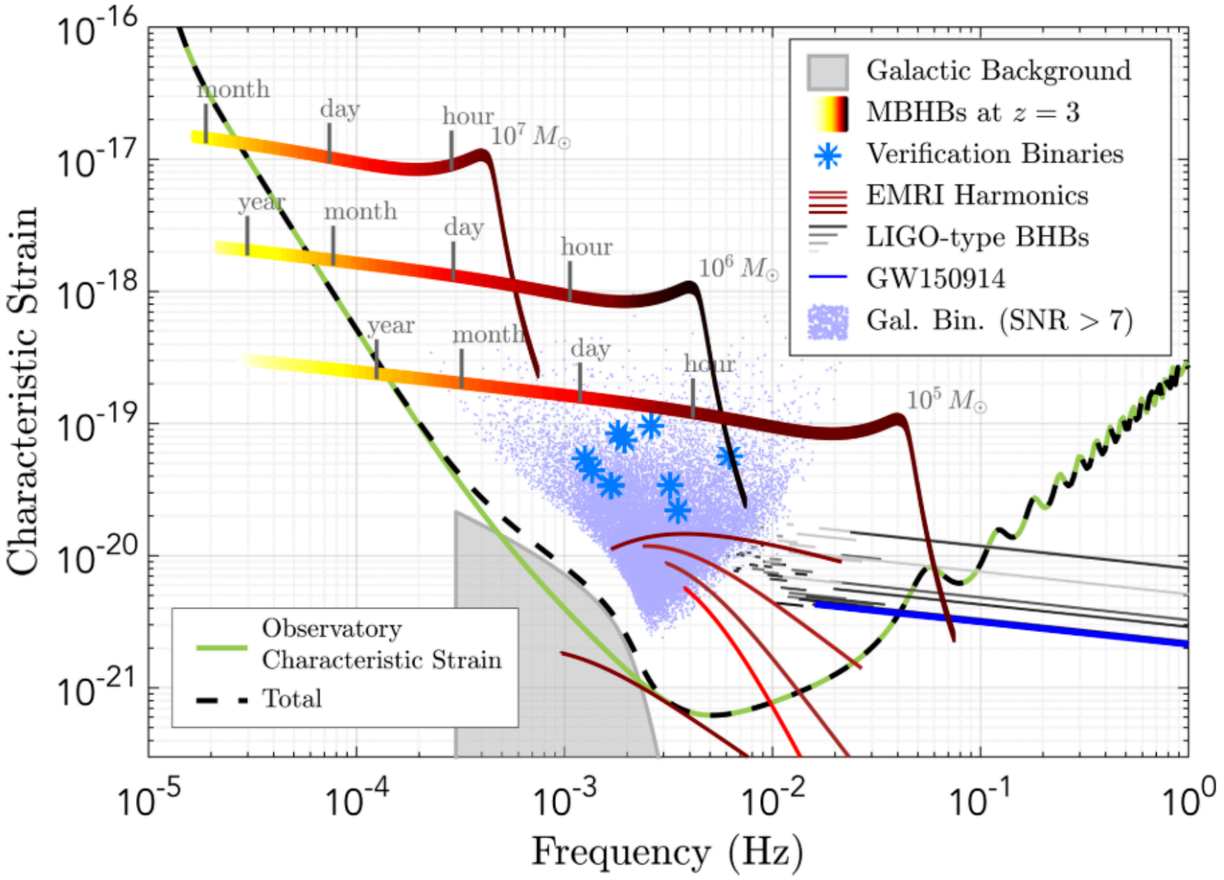

Fig. 9: GW sources detected by LISA as a function of frequency, from Danzmann (2017). This shows the basic sensitivity (green line) with various sources with their emission characteristics. Background "noise" is represented by the grey area which slightly reduces the telescope sensitivity resulting in the black-dashed line. The Strain-Frequency tracks for 3 equal mass black hole binaries are shown at z=3. The masses are $10^5, 10^6$ and 10^7 $M_\odot$. The time tics on those tracks indicate the time before the coalescence plunge.

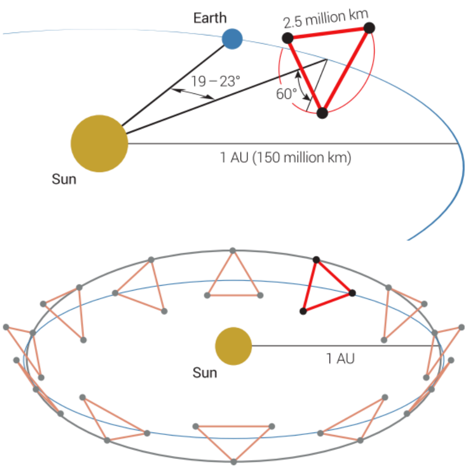

Fig. 10: LISA orbit diagram (Danzmann 2017).

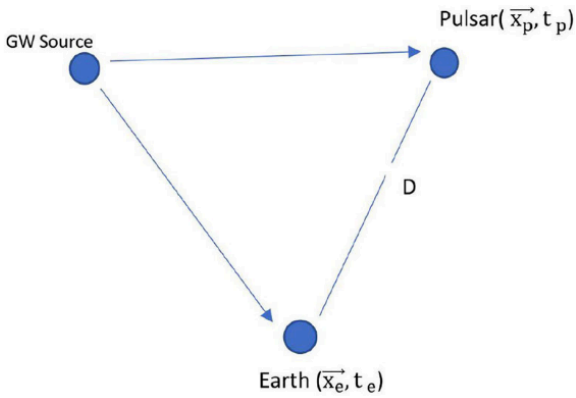

Fig. 11: The relation between the radio telescope on Earth, one detection arm to the pulsar with a length of "D", and the GW source (Dahal 2020). Many pulsars at different distances and directions will be used to reconstruct the GW.

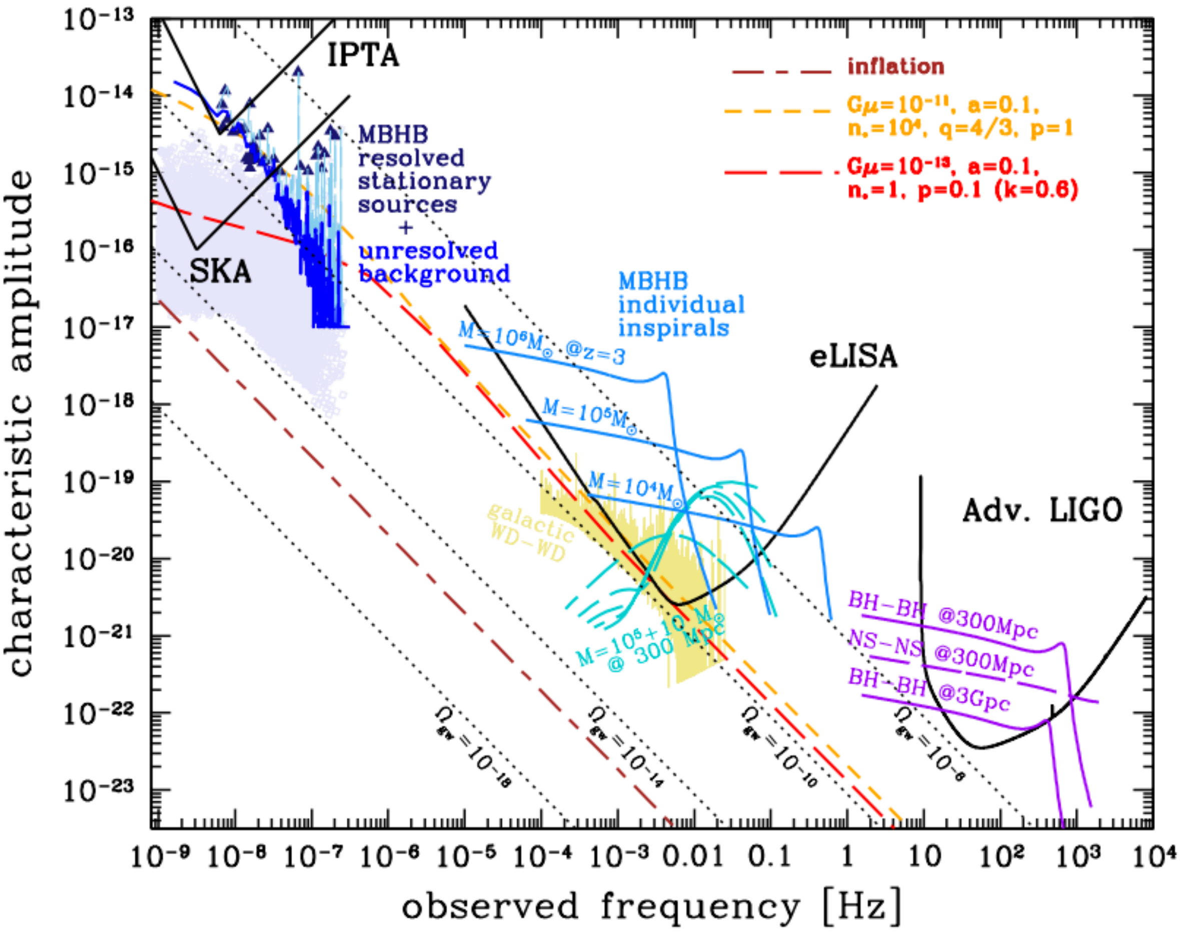

Fig. 12: Figure by Alberta Sesana from Lommen (2015). This graph shows many features with the black lines delimiting the sensitivity of advanced LIGO, LISA, and IPTAP. The relative sensitivity of the SKA results when used for PTA purposes is also shown with ~ 2 orders of magnitude increase in sensitivity over the current planned IPTAP.

sses by modelling, is the TOA residual due to GW signals causing movement of the pulsar or the earth. Various errors can affect the measurement of the TOA so that many pulsars must be measured and correlations examined to extract the GW measurements reducing errors. Measurements of the TOA residuals from an array of pulsars can be used to reconstruct the location, strength, and other parameters of a GW that caused the TOA residuals observed from the PTA. Sources producing such low frequency GWs are massive objects, $> 10^8$ $M_\odot$ (Lommen 2015, Hobbs and Dai 2017, Dahal 2020).

The construction of a PTA was discussed in Foster and Backer (1990). They reported experimental results using the National Radio Astronomy Observatory (NRAO) 43-m telescope from a 3 pulsar PTA experiment which operated for 2 years starting in 1987. In 2004 a much larger project, the Parkes Pulsar Timing Array (PPTA), began an observation program monitoring 25 pulsars which continues to this day. The first release of data from this project is described in Manchester et al. (2013). The timing model computer program for data analysis, TEMPO2, was specifically designed to detect GWs directly (Hobbs et al. 2009) and the latest version can be found in Dai & Filipović (in prep.).

Also in 2004, a collaboration in North America among universities, colleges, national laboratories, and observatories called the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) was established. The data from the 300-m Arecibo Observatory (AO) and the 100-m Green Bank Telescope (GBT) were specifically collected to detect GWs (McLaughlin 2013). The latest available data sets include data from 12.5 years of observation. Forty-five pulsars are currently being monitored.

In 2006, plans were being made for the European Pulsar Timing Array (EPTA) (Stappers et al. 2006). It consists of four European telescopes: the Lovell

Jodrell Bank (76-m), the Westerbork Synthesis array (93-m), the Effelsberg (100-m), and the Sardinia Radio Telescope (64-m).

Finally, the IPTAP has been established as a consortium of the three consortia described above. The IPTAP will combine the data from all sources to create the best possible data set, including all available data, and will provide it to researchers in different common formats. The data releases will include the popular TEMPO2 (Hobbs et al. 2010) analysis program formatted files. Two major releases of data have been produced and are available from the IPTAP or http://ipta4gw.org//data-release/.

7. SUMMARY

The development of GW detectors, started in the 1960's (Weber 1960), has recently been successful as reported in Abbott et al. (2016). This is the first of the terrestrial-based detectors with interferometer arm-lengths of 4 km. This arm-length limits the lowest frequencies which can be detected to ~ 1 Hz. This limitation is overcome by LISA, a space-based interferometer which reduces the minimum frequency detectable to $\sim 10^{-5}$ Hz by creating an interferometer with 2.5 million killometres arm-lengths (Figs. 3, 12). It is useful to note that the frequency of GWs is inversely related to the mass which is being accelerated to produce the GWs. The lowest frequency GWs are produced by objects like super massive black holes with periods of hundreds of years. PTAs are capable of detecting such GWs.

With conventional electromagnetic spectrum observations and neutrino observations (Aiello et al. 2019, Ageron et al. 2020, Aiello et al. 2021, KM3NeT Collaboration et al. 2021, Acharyya et al. 2021), GWs may provide additional information which may reveal many previously-hidden processes which govern the behaviour of the Universe. We may be able to seriously address such questions as: What is dark matter? What is dark energy?

GWs herald a new era in astronomy. The history of astronomy is almost entirely a record of what we could discover using electromagnetic energy detection. Electromagnetic energy (visible light, radio waves, X-rays, etc.) is easily modified by matter between the emission source and the detector. This can transform the electromagnetic energy into a very different form, changing its information content from that of the source of the emission into a representation of the intervening medium.

GWs will change astronomy because the Universe is essentially transparent to them. Intervening matter and gravitational fields do not absorb or deflect GWs to any significant degree. GWs will help answer some of the great questions in physics: Does general relativity correctly describe gravity and GWs? How do black holes form? How does matter behave under extreme temperature and pressure in neutron stars, during supernovae, and in the Big Bang?

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ПРОШЛОСТ, САДАШЊОСТ И БУДУЋНОСТ АСТРОНОМИЈЕ ГРАВИТАЦИОНИХ ТАЛАСА

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Прегледни рад по позиву

Од њихове детекције 2015. године и Нобелове награде за физику 2017. (ЛИГО оснивачи Бери Бериш, Кип Торн и Рајнер Вајс), гравитациони таласи постају један од главних стубова развоја модерне астрономије – астрономије више носилаца информација. Они су један од есенцијалних додатака електромагнетним и честичним посматрањима космоса и тако додатно омогућују боље изучавање небеских тела. Њихов успон и детекција нису били нимало лаки и једноставни још од времена утемељивача опште теорије релативности — Алберта Ајнштајна — који их је лично предвидео али и био скептичан када је у питању њихово постојање. Овај скептицизам је трајао до 1950-их, декаде коју је на овом пољу обележила Ајнштајнова смрт. Од тада до данас конструисани су или осмишљени осетљиви земаљски и свемирски детектори гравитационих таласа. Сваки од ових детектора је пажљиво дазајниран да би омогућио детекцију различитих космичких догађаја.