ABSTRACT

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What is gravitation? Why do we think it is propagated in waves? Where and how are these waves produced? How would we go about observing them? Gravity has been a difficult concept for millennia. From quintessence and aether to Newton's mathematics describing instantaneous action at a distance, pre-Einsteinian physics was a slow process that eventually lead to the realisation that spacetime is a fabric and supports waves that carry energy away from cataclysmic events in the distant universe. Poincaré first suggested waves, then Lorentzian and Minkowski mathematics anticipated the relativity revolution and that gravitation travelled at the speed of light. Astronomical observation and theory leapfrogged each other until the mid twentieth century when bar detectors failed to see the miniscule waves from massive stellar mergers. It took another 50 years, and a change to laser interferometry, before a positive detection was recorded in 2015. We now have a handful of detections of gravitational waves and an open door to extraordinary science. Black hole mergers have corroborated theory about themselves and spacetime. Neutron star mergers produce gravitational waves as well as broad spectrum electromagnetic emissions, paving the way for multi-messenger astronomy. Ground and space-based observatories offer a panoply of avenues to understanding the current and past universe. This essay highlights the chronology of thought, technology and discovery that recently culminated in the first detection of a gravitational wave. Outshining the entire universe by an order of magnitude, these split-second, distant events reach us as a hugely diluted wave just a few percent the size of a proton. Their detection is the result of global collaborations between thousands of scientists working at hundreds of institutions.

1. Scope

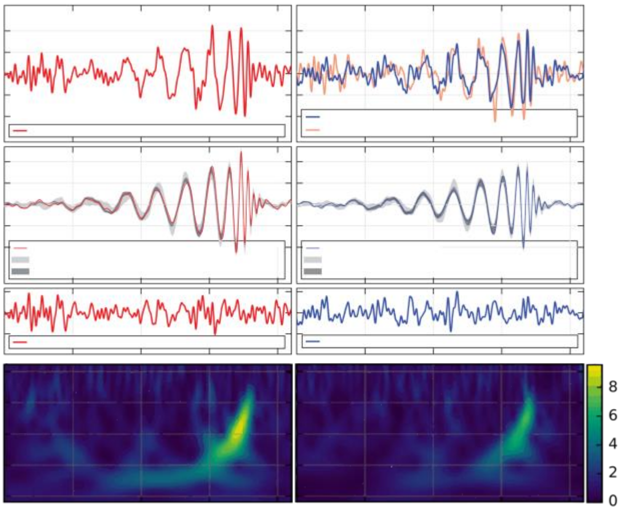


Fig. 1 Chirps recorded from an in-spiral merger of two BHs as detected by LIGO detectors in the USA in 2015. (Credit: LIGO Collaboration)

On 14th September, 2015 Fig. 1 changed astrophysics for ever. The detection (Abbott et al 2016) of gravitational waves (GW) was a triumph of theory and technology spanning more than a century. These 'chirps' put us in direct contact with the fabric of the cosmos, offering tantalizing insights and potential. But, exactly what are GWs? Where do they come from, how do we detect them, and why do they matter?

The aim of this essay is to provide an overview of the theory of GWs, their nature, detection and implications. It will answer the when, what, where and how of associated science and technologies, as well as future science directions. I have included towards the end, a case study of the first detection mentioned above, where I revisit Fig. 1.

Research was entirely internet based, analysis took a 'discover and report' approach, and the reader is assumed to be tertiary educated in science, technology, engineering and mathematics (STEM).

2. Background

In the beginning …. well, around 10^{-43} seconds after the Big Bang, Standard Big Bang Theory posits that the temperature had dropped to 10^{32} K and gravity froze out of the primordial timeline before the remaining three universal forces came into being (see Gibson 2001). As yet, there is no Grand Unifying Theory that connects gravity to the other three: electromagnetism, weak nuclear, and strong nuclear forces. Before getting to the concept of gravity, however, it's important to understand the evolution of thought around the nature of movement and its cause.

Today, 'quintessence' refers to a dynamic vacuum energy (Chiba 1999), a cosmically evolving 'empty space' density that can be shown to exist as it pushes apart two very close, parallel plates in a Casimir experiment (Sola 2014). It has been offered up by some as an explanation of the so-called Dark Energy that prevents the universe from collapsing (Ratra & Peebles 1988) but it had a somewhat different meaning in the past and it influenced the development of Newtonian gravity, from which we have now, also graduated.

In one of Plato's dialogues, "Timaeus", the universe is described as having four elements (earth, air, fire and water) each with their associated, infinitesimally small shapes, providing a particular type of energy that explained different phenomena in the observed world - the four causes of change where 'change' implies motion. Plato's student, Aristotle added an all-encompassing fifth element which became known as quintessence. It was said to provide a superstructure for the other natural 'forces', have a foundation of dodecahedra, and be an expression of the breath of God (Plato 430 BC).

The idea stuck for many centuries in western culture. Arabic philosophers critically analysed ancient Greek ideas during the scientific Dark Ages (variously the 13th - 16th centuries), but came to similar conclusions as Newton did in the 17th century (see StAndrewsweb). By 120 BC

Chinese cosmology had a name for all of space (yu) and all of time (chou) and used the phrase yuchou (spacetime) when referring to the universe. Additionally, by the 6th century Chinese astronomers of the Kai Thien school, pre-empted later thought with teachings of condensed vapour (stars) freely floating in a single, airless void rather than the solid, fixed, crystalline spheres of Ptolemy (Needham & Wang 1959).

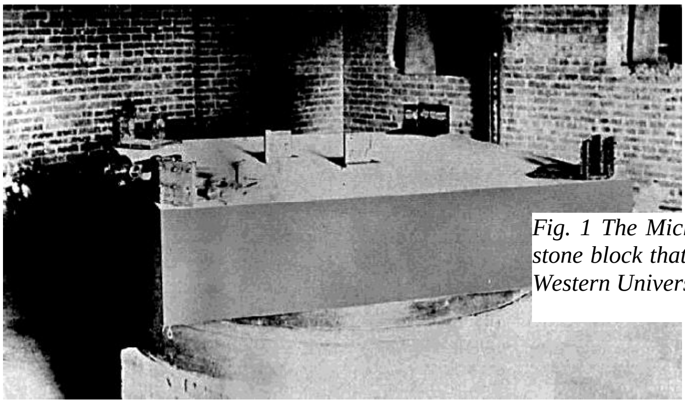


Fig. 1 The Michelson-Morley interferometer was fastened to a huge stone block that floated on a circular moat of mercury. (Credit: Case Western University)

By the 15th century, quintessence had gained strong and widespread support as an actual substance that could be distilled from alcohol and used by alchemists, medical practitioners and others as an all-purpose elixir (Unknown c1460). It gained somewhat more respect in the 17th century when Descartes espoused the tongue-in-cheek view (again via the theologically safe instrument of a ‘dialogue’) that when God commanded a universe full of movement, it was the movement of massive bodies within the vortices of a swirling fabric (Heilbron 2015).

Quintessence was required in Aristotle’s theory because the four Earth-based elements were believed to act only towards, or away from the ground, and the postulated crystal celestial spheres must therefore move, in perfect circles, within their own medium (Heilbron 2015). Today, the four pillars of the Standard Theory of particle physics are baryons, leptons, photons and Dark Matter with quintessence as the new descriptor of the aforementioned vacuum energy (Steinhardt 2003).

This ancient ‘quintessence’, AKA aether, played a central role in Newton’s earlier explanations of a mechanism for gravity, although these ideas were not expressed in his crowning publication, Principia (Cajori 1962, p633). In that famous 1687 document, Newton combined the Galilean notions of equally-accelerating, falling bodies; the Cartesian concept of inertia; and Kepler’s work on eclipses, to formulate relatively simple geometric relationships that describe gravity. He ignored the obvious problem of instantaneous influence at a distance (Heilbron 2015), and did not consider relativistic motion.

Newton developed the familiar proportional relationship between the masses of two bodies, the square of their separation, and the assumed ‘force’ of gravity experienced between them. Newtonian physics was very successful and exactly two hundred years later, an ingenious experiment (Fig. 2) to detect the aether produced a negative result (Michelson & Morley 1887) as did subsequent, more precise experiments, down to a sensitivity of one part in 10^{17} (Eisele et al. 2009). These results for detection of an aether have been regarded as a watershed moment in scientific thinking (Hoover 1977) and the methodology will re-surface later.

The great mathematician Poincaré, required “*une onde gravifique*” in his equations - a wave to transmit gravity (Poincaré 1905). He was guided and swayed by Lorentz who added an important constraint to Newton’s laws - Lorentz’s reference frame transformations implied that gravity must be transmitted at a finite rate. Subsequently, on July 5, 1905, the Comptes Rendus of the French Academy of Sciences published Poincaré’s article on relativity, containing the prediction of GWs (Cervantes-Cota et al. 2016).

Poincaré understood the reliance on Lorentz transformations to move between relativistic reference frames (Adlam 2011) and it was he who reckoned that gravity's finite transmission rate was in fact, the speed of light (Poincaré 1905). However, it was Einstein who grasped the importance of relativity and of not, as Poincaré did, relying on a fixed observer (Adlam 2011).

Fig. 3 Joseph Weber tending his GW bar antenna at the University of Maryland in College Park. (Credit: Volker Steger Science Photo Library)

3. Einstein

A decade before the 1915 paradigm shift that was the Theory of General Relativity (GR), Einstein took a fresh look at relativity and transformations between moving reference frames. He developed two basic postulates:

i. the laws of physics remain the same everywhere but particularly when transformed to another reference frame, and
ii. the speed of light in a vacuum is the same no matter the speed of the emitting body.

In terms of gravitation theory, the main consequence of these Special Relativity (SR) postulates is that there is no absolute reference frame - everything is relative and there is no background aether against which to measure movement (Einstein 1905) and no instant causality at a distance (qv Newton's law). Modifications to Newtonian gravity that allowed for gravitational interactions at the speed of light were close, but not close enough to satisfy Einstein. This set the scene for further development of a universal theory of how gravity works. If inertial mass and gravitational mass are (observed to be) equal in magnitude, then a constantly accelerating body initiates a homogeneous gravitational field around it. This is known as the Equivalence Principle. Acceleration is indistinguishable from gravitation.

Other properties of SR include the bending of light and the slowing of time by gravity, but the GR punch line came after some very talented, German mathematicians (eg Hilbert) inspired one of Einstein's teachers, Minkowski to describe these outcomes by combining the usual three dimensions of Cartesian space with time, thus creating Minkowski spacetime.

An apparent consequence of Minkowski spacetime is the existence of gravitational waves, but Einstein vacillated over the idea because unlike electromagnetic (EM) waves, gravity has no dipole - no positive/negative 'ends' to vibrate (Cervantes-Cota et al. 2016). Minkowski spacetime relates to a Euclidean, flat universe, and Einstein couldn't get the equations to resolve until he swapped to spherical coordinate mathematics which subsequently revealed to him that spacetime is actually curved near mass, energy and momentum. This encouraged in him, the Poincaré idea that spacetime itself could potentially carry gravitational waves at the speed of light (Ryden 2006).

4. Theory and Early Detectors

This new zeitgeist for the physics of motion and mass was paralleled by developments in stellar physics theory. A body so massive that even light could not escape from its gravity well had been postulated in the 18th century (Mitchell 1784) but this was an outlier idea that had to wait for Einstein's contemporaries to discover and develop the constituents of the atomic model. Bohr combined Planck's quantum theory with Rutherford's interrogation of the atom, to derive a complete picture of the structure of the hydrogen atom (Bohr 1913). A decade later, and not until after the neutron had been discovered, neutron stars (NS) were predicted (Baade & Zwicky 1934). These details will coalesce soon.

Einstein's anguish over his theories of relativity is understandable given the lack of stellar physics of the day. Observations that support a Minkowski spacetime and GR consumed much astrophysical research in the following century but solid confirmations came in three well known observations:

i. the slightly erroneous precession of Mercury's orbit (see Le Verrier 1859) was accounted for by GR (Einstein 1916),
ii. the 18th century idea that light could be bent around massive objects (see Soldner 1804) was observed by Eddington's famous expeditions (Dyson et al. 1920), and
iii. the GR-predicted redshift loss of energy as photons climb out of a strong gravity well, was eventually confirmed by observations of the Sirius's white dwarf partner (Adams 1925 in Holberg 2010).

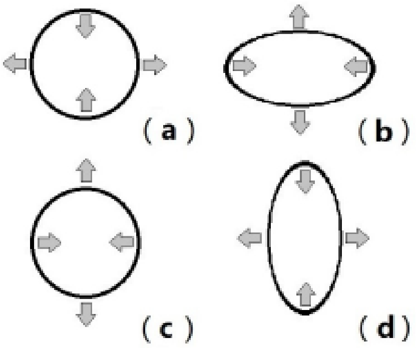


Fig. 4 A GW travelling perpendicular to this page will distort a ring of test particles (a) such that the ring bulges along one transverse axis, returns to circularity, then bulges along the orthogonal axis and again returns to circularity (b)-(d). This vibration is repeated as the GW passes through the test object, creating a linear polarized, quadrupole output. (Credit: Cervantes-Cota)

So, by the mid 1930s, astronomers had an observationally verified theory that predicted very massive stellar bodies perturbing spacetime sufficiently to produce gravitational waves, carrying information about their location and magnitude, travelling no faster than the speed of light (LIGOweb).

The next logical questions to address are an intertwined doublet:

i. how would a GW detector work?
ii. what real-world situation could produce a GW?

Pirani (1956) provided the mathematical structure from which the physical effects of GWs could be determined, making it clear that a GW passing through a detector would cause a vibration transverse to the propagation direction of the wave as subsequently illustrated by one of Einstein's student collaborators, Bergmann (1968). Fig. 4 is copied from Cervantes-Cota et al (2016) and shows how Bergmann represented the effect of GWs on a hypothetical ring of detector particles.

Since time is an integral part of a Minkowski space, and GWs are a phenomenon of the entire 4-dimensional frame, the question of conservation of energy is raised when a GW distorts a test target. Would a passing GW impart any energy to the recording antenna, and if so, is this not a violation of conservation of momentum? Feynmann's famous 'sticky beads' thought experiment illustrated to a 1957 conference that, given a locally flat universe, energy could indeed transfer into the body of a detector collecting an incident GW (DeWitte 1957). Feynmann demonstrated how the flexion of a cylindrical antenna situated transversely to an incident GW, should produce measurable distortion in the antenna.

This ushered in a generation of mechanical GW detectors, the first of which was built by Weber, who claimed a sensitivity of "*a few parts in 10^{16}*". The devise was a 1.5 ton, aluminium cylinder (Fig. 3) approximately 150 cm long and 61 cm diameter (Weber 1966). Comments in that paper show the thinking at that time about GW generators, by referring to two unpublished articles: “*It is currently believed that the collapse of a supernova core or a double neutron star (Dyson & Forward 1962) might result in emission of large amounts of gravitational radiation with increasing frequency as the collapse proceeds. Calculations indicate that the sensitivity reported here might under favorable conditions result in detection of such events within our galaxy (Sachs undated).*”

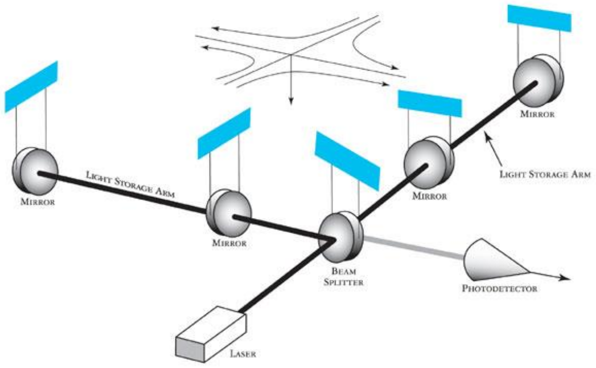


Fig. 5 The basic setup of a MFPI showing laser source, splitter, paired test mirrors and photodetector. The quadrupole, transverse GW is shown approaching from above the apparatus indicating that it will alternately stretch and squeeze each arm. (Credit:LIGO)

So, three decades after the aforementioned prediction of NSs, astronomers were searching for GWs without *really* knowing their sources. Today, we expect GWs to be produced by a merging binary of NSs or BHs or by an asymmetric NS (Abbott et al. 2017) but the first detection of a NS was still decades away (Taylor et al. 1976).

Weber’s results were shown to be erroneous and although several similar antennae were built and refined by other teams during the 1970s, they produced no detections of GWs (Cervantes-Cota et al 2016). It was timely then, that NS binaries had by then, been observed and that astronomers were considering other ways to measure the tiny, tiny gravitational waves - a big one is just 0.01 times the diameter of a proton (some 10^{-18} m) and only rarely produced by very distant events (LIGOweb).

Hulse and Taylor were awarded a 1993 Nobel Prize for their determination of a 3 mm reduction per orbit for their aforementioned binary NS - the orbital energy carried away by gravitational waves (NPweb). More on the next generation of detectors below, but first a slight detour to understand what GWs actually are and how they look when detected.

Supernovae (SN) have been observed for millennia but not effectively understood until recent times. A ‘core collapse’ SN occurs after a ~ 10^{+} solar mass star has completed its fusion conversion reactions and the core has become pure iron. At this point, the star can no longer support its massive layers of nucleosynthetic products which, within seconds, fall to the core, rebound off it and are driven outwards by neutrino pressure, through the debris, making heavier elements.

The resultant sphere at the centre may have been crushed under such pressure and temperature as to produce a degenerate fluid of neutrons - electrons and protons fused into neutrons (Brown et al. 1982), resulting in a NS of around 1.38 solar masses (Rotondo et al. 2011). Alternatively, depending on the initial mass, a black hole (BH) may be the result. These are literally shocking events on a hugely energetic scale, and they can generate GWs in spacetime (LIGOweb).

The common phrase used here is “ripples in spacetime”. What are they, exactly? Taking a ‘spherical chicken’ approach (EOweb) whereby some much simplified initial conditions are assumed (Gowdyweb), it is time for some generic mathematics. A massive ‘body’ (for instance, a pair of merging BHs or a lumpy NS) can have the uneven distribution of its mass described by a gravitational moment found within a series of mass distribution expressions. The idealised, spherical moment looks like this:

$$J_n \equiv \frac{1}{MR^n}\int_0^R \int_{-1}^{1} r^n P_n(\mu)\rho(r,\mu)2\pi r^2\, d\mu\, dr,$$
… Eq. 1 (Credit: Wolframweb)

where M is the mass, R is the radius, P_n is a polynomial expression, ρ is density and $\mu = \cos\theta$

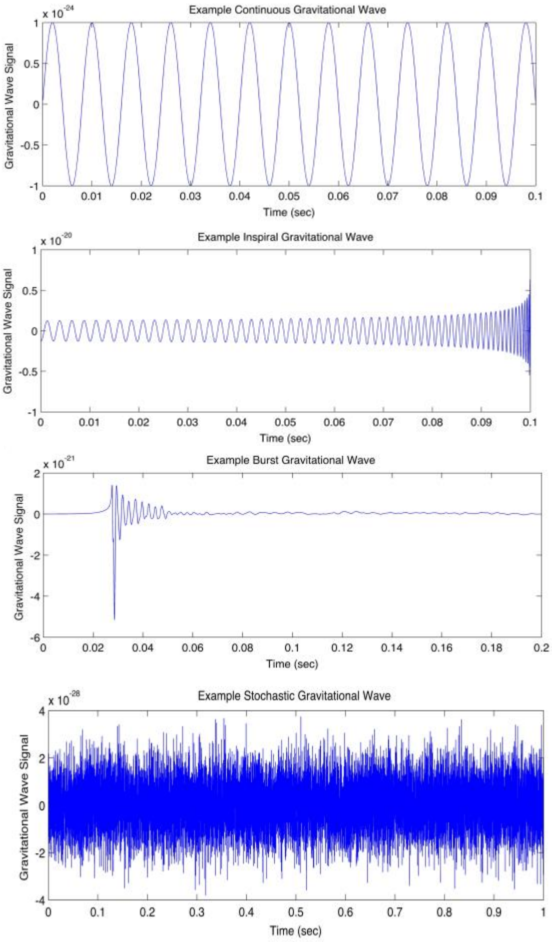


Fig. 6 GWs are expected to take four forms: continuous (from an uneven NS), in-spiral (from merging massive stars), burst(from high energy explosions) and stochastic (from all of the above as well as primordial echos from the inflationary period of the Big Bang. (Credit: LIGO)

In Eq. 1, the fourth moment is the third term of this series and reflects the nature of the gravitational harmonic. The larger the number of terms in the series, the more the outcome is determined by 'surface' effects, and even numbered terms are linked to the rotation. Thus, the quadrupole effectively determines the properties of an emitted gravitational wave (Wolframweb).

GWs are polarized in two dimensions - circularly as they rise 'upwards' from the orbital plane of the merging stars, and linearly in the orbital plane. As they approach (Earth) they alternately stretch and squeeze spacetime orthogonally, so this also gives us a tool to determine the inclination of the merger (Thorne 2016). Theoretically, the frequency of GWs can range from very high to very low (Thorne 2016), but around 10^2 - 10^3 Hz is typical for NS/BH mergers.

Polarized, cylindrical outcomes also exist (at least in a Gowdy spacetime - a simplified metric characterised by a universe full of variable gravitational wave patterns). That the amount of energy output from a binary system is strongly proportional to their masses and extremely sensitive to their separation, R, is evident from Eq. 2 below where E is energy, t is time, G is the gravitational constant, R is the separation, c is the speed of light and $m_{1/2}$ are the masses. Notice the fifth power of radius in the denominator, ensuring that the power quickly reduces with separation.

But consider that the curvature of spacetime is 43 orders of magnitude smaller than the mass energy of an object (GWweb) and that even Einstein said they were vanishingly small and probably not effectively real (Einstein 1916b).

$$dE/dt = -\frac{32G^4}{5c^5R^5}(m_1m_2)^2(m_1+m_2)$$
…. Eq 2 (Credit: COSMOSweb)

GWs can be generated in four different environments, each producing a recognizable signal. Binary systems that develop slowly and have a consistent orbital period, will output a weak, monotonous signal that looks much like a regular, sinusoidal wave. This type of wave (top, Fig. 6) can be produced by a single NS that happens to have an irregularity on its surface, or possibly from such environments as Bose-Einstein axion regions associated with BHs (Riles 2017).

This looks like a sound wave, and so it is. After a fashion. The frequencies are in the same part of the spectrum as sound waves, though of course, they're not the usual longitudinal, compression/rarefaction waves that constitute sound. To appreciate them, astronomers can produce a sound-analogue of gravitational waves and the reader is recommended to search the internet to hear some examples.

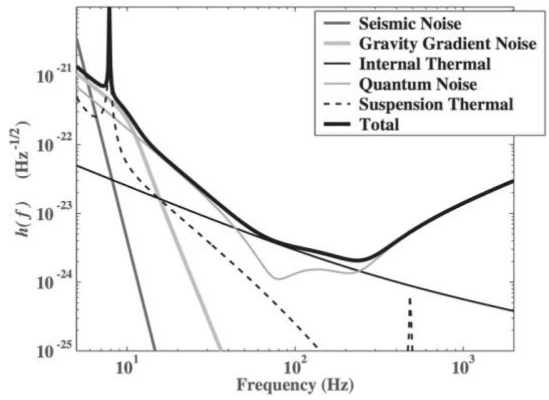


Fig. 7 Projected noise at the LIGO MFPI. Note the large contributions from internal thermal over wide frequency range and also the huge interference from seismic and suspension thermals at low frequencies. At the expected strains of around 10^{-21}, approximate frequency range is still 10-1,000 Hz. (Credit: LIGO Collaboration)

A second type, in-spiral GWs are as the name suggests, a result of the death throes of a binary pair of massive stars (NS or BH or one of each) whose orbits have decayed such that they merge in a huge disruption of spacetime. Imagine the continuous situation described above to have evolved to the extent that the stars have finally spiralled into each other (Fig. 6) (LIGOweb).

Burst signals, like continuous ones, are theorized. They are predicted to come from short-lived, cataclysmic events such as gamma ray bursts or perhaps the population III era of stellar evolution. Their signals may look like the third from top in Fig. 6 (LIGOweb.

At a time very shortly after the freeze-out of primordial gravity mentioned at the start of this essay, quantum fluctuations in gravity may have resulted in a background noise of GW signals that could be observed coming from all directions in today's sky. Much akin to the cosmic microwave background, these signals would be mixed with the three types of signals mentioned above and look/sound like irregular static. These are named stochastic (= random) GWs and described by a graph similar to the bottom plot in Fig. 6 (LIGOweb).

5. Some Perspective on the Side

In the Einsteinian interpretation of gravity, GWs are produced by the extremely high accelerations associated with SN and mergers of NSs and/or BHs. Another interpretation of gravity is described by a tensor metric (expression of the directional 'pressures' on each point in a curved space) which contains a non-invariant gravitational parameter in place of the Einsteinian cosmological constant. This scalar field parameter conforms with the observed equivalence principle and other aspects of Einsteinian physics (see Brans & Dicke 1961) and predicted GWs, although there was discussion in the 60s about pulsating NSs actually producing scalar fields that annihilate GWs (Morganstern & Chiu 1967).

Events causing GWs were thought to be relatively rare. SN frequency estimates have ranged from a handful/year/galaxy (Tsvetkov 1983) to 40/year/galaxy (Katgert & Oort 1967) and into the hundreds (Kalogera et al 2004), but these may not all be the core-collapse variety that can generate GWs. Estimates of NS and BH merger frequency are also low, but the large number of BHs suggests a (LIGO) detection could be in the order of one every few years (Voss & Tauris 2003). Controversially, Kalogera (2004) suggested the frequency of detections may be as good as hundreds per annum.

The amount of energy dissipated from a BH/BH merger is in the order of 50 times the luminosity of the entire universe! This occurs in a fraction of a second at the moment of merging, and by virtue of the Einstein's mass/energy equivalence ($E=mc^2$) carries away mass from the BHs in the form of GWs. A NS/NS merger produces GWs as well as the full range of EM radiation, giving us many opportunities to see the event – more on this below.

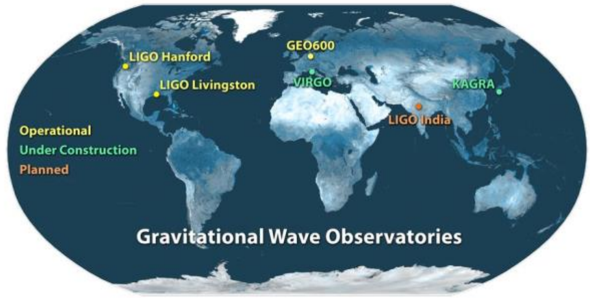


Fig. 8 The LIGO Scientific Collaboration is a global network of scientists, institutions and facilities dedicated to further opening the door to gravitational astronomy. Installations cost hundreds of millions of dollars to build and are frequently off-line for maintenance and upgrading. (Credit: LSC)

Such cataclysmic events occur at huge distances with the resultant radiations taking billions of years to reach Earth. They are very small by the time they get here! The infrequency (perhaps!) and distance to GW-generating events, along with their tiny amplitudes and variable frequency, puts their detection at the coal face of technological innovation.

Detecting GWs is therefore, all about signal/noise improvement. Fig. 7 is a chart showing how different contributions to noise behave at different frequencies. It is the go-to chart for building Michelson-Fabry-Pérot-Interferometers (MFPI) - more on them below.

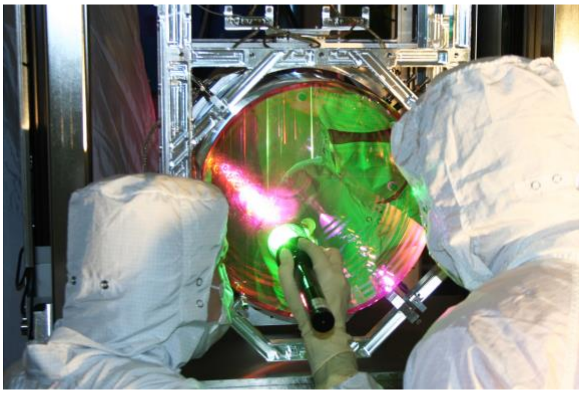
6. Laser Interferometry

The Weber-type resonant bar antennas described above were refined in the 1970s, 80s and 90s but are generally considered not to be sensitive enough to pick up an average sized GW. Bucking that trend, the AURIGA bar project in Italy is cryogenically cooled and fitted with superconducting quantum interference devices (SQUID) that can detect extraordinarily small variations in magnetic fields (see Marin et al 2013). Today, there exists a collaboration with the Laser Interferometer Gravitational Wave Observatory (LIGO) and AURIGA to marry the science from these two dissimilar detectors (Baggio et al 2008). In fact, SQUIDS were used in the reaction wheels of the recent Gravity B space probe.

Emergent laser technology was recommended for use in interferometry in the early 60s for a 10^{10} increase in sensitivity over Weber-type bars (Gertsenshtein & Pustovoit 1962), and has been developing for GW detection ever since (LIGOweb). Fig. 5 shows the basic set up of an interferometer used for GW detection - precisely the architecture of the Michelson-Morley experiment from the 19th century.

Modern observatories use long baseline laser interferometry to search for a GW which would alternately stretch then contract the length of one arm as it contracts then stretches the other arm. This is due to the quadrupole nature of the incident GW as described above and illustrated in Figs. 4 and 5. For context, a binary NS 100 Mpc away, with an oscillation of 100 Hz will produce a fractional strain ($\Delta L/L$) around 1 in 10^{-21} in the length of a detector on Earth (Thorne 2016). Modern facilities therefore try to maximise the base length of the detector and minimise the noise (see again Fig. 7), so that a statistically significant mechanical strain can be measured.

By splitting a laser beam shone through this system, an interference fringe pattern can be expected at the output detector if the relative length of the arms has been altered. If the tubes have not been impacted by a GW while the light beam was in transit, then the lengths of the arms will not have changed and light waves arriving at the photodetector will destructively interfere, producing no light. A successful interference pattern contains information about the nature of the GW and its source. (It is assumed here that the reader is familiar with constructive and destructive wave interference.)



To improve the sensitivity of a long baseline interferometer, a Fabry-Pérot tube is used such that multiple folding light paths store the photons longer within the evacuated tube, before they exit, recombining at the photodetector. This effectively lengthens the detector baseline. To minimize the disturbance of internal atmosphere that would refract the laser, the tubes are typically taken down to a vacuum around one trillionth of an atmosphere and constantly subject to cryopump removal of stray water molecules and other outgassing species. It goes without saying, that the structural facility to house this extremely clean, cold, evacuated experiment is 'high tech'.

Fig. 9 One of the test mirrors at LIGO undergoing inspection by technicians in extreme, low dust protective clothing. (Credit: LIGO)

Australian International Gravitational Observatory (AIGO)

Under the auspices of the University of Western Australia, AIGO is located on sandy coastal plains an hour north of Perth, WA. Since 1990, AIGO has strengthened international connections, especially with China, and has onsite, the largest public astronomy facility in the southern hemisphere, reaching 20,000 customers per year (Li 2010).

In 2010, LIGO (see below) contributed $140M as 50% of the re-branded LIGO-Australia consortium. Tens of millions of dollars more were input from Chinese and Indian interests, and after international recognition was attained for the need of an Australian location, research onsite has had important results. AIGO plans to construct 4 km-long detector arms and is developing unique vibration mitigation technologies (UWAweb).

Outcomes from such observatories are not always obvious, but often evolve from the technological advancements that must take place during the development of such new and exciting facilities. Spin-off technologies from LIGO-Australia research include a new type of quantum measurement device, the Opto-acoustic Parametric Amplifier that can measure subatomic movement (see Torres et al 2010) near the Heisenberg limit of measurement (Munch et al 2010); a data analysis algorithm, called Summed Parallel Infinite Impulse Response filter for GW detection (see Hooper et al 2012); curriculum improvements in Australian schools with the addition of Einsteinian physics, and many more. In fact a 2010 report lists 38 outcomes from fundamental research (Li 2010).

Laser Interferometer Gravitational Wave Observatory (LIGO)

The current global group known as the LIGO Scientific Collaboration (LSC) formed from its member facilities (Fig. 8). LIGO itself, is collaboration between CalTech and MIT, and is actually two installations separated by around 3,000 km in the USA. These identical MFPIs each have two, 4 km-long arms at right angles and operate in conjunction with each other and with others around the globe, to 'subtract out' local noise vibrations and to triangulate the direction of the source from signal arrival delays (LIGOweb).

LIGO’s MFPIs each have a main mirror at the ends of each arm made from extremely high quality fused silica coated with Titanium/Tantalum/Silicon oxides. They lose less than 10 ppm to scattering because they are fabricated to a smoothness less than the diameter of an atom (Pinard et al 2011). They also absorb very low ppm photons so as to minimize thermal deformation of the mirrors. The currently installed mirrors (Fig. 9) are about 35 cm diameter, 20 cm thick and weigh 40 kg each (Pinard et al 2017).

LIGO mirrors are kept extremely stable against the tidal pull of the Sun and Moon by placing small magnets on them and monitoring their shadows. An EM feedback system constantly tweaks their position (LIGOweb). The input optics supplying the 1 micron laser at LIGO is also damped (actively and passively) with six degrees of freedom addressed (Ciani et al 2016).

LIGO is currently undergoing upgrades and will be known as Advanced LIGO, and in fact the facility in the northwest USA has two MFPIs, one of which will become resident at the proposed Indian detector described below (IndIGOweb).

Virgo, GEO, KARGA, IndIGO and Global Collaboration

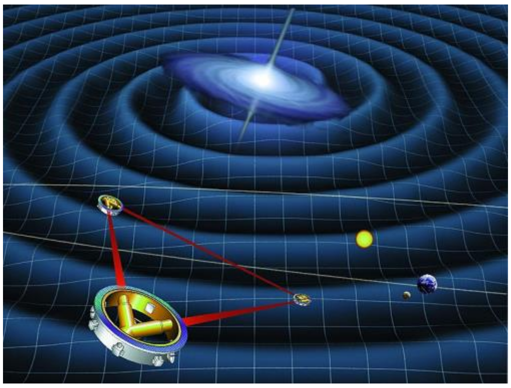


Fig. 10 LISA will be an equilateral triangle of three base space probes, each with lasers and photodetectors. They will each be 2.5 million Km long and the whole system will be in heliocentric orbit, trailing Earth by 50 million km. (Credit: LISA)

The Italian/French/Dutch Virgo facility at the European Gravitational Observatory in Cascina, Italy, has 3 Km long MFPI arms that are effectively 100 Km long due to the internal reflections of the Fabry-Pérot design. In 2017, Virgo joined with LIGO’s growing global network, the LSC (LSCweb). The LSC funding comes from many sources including the United States National Science Foundation, and it now includes over 1200 scientists, in more than 100 institutions from 18 countries.

Construction began on the GEO600 facility in Ruthe, outside Hanover, Germany in 1995. It is managed by a German/British agreement within the Albert Einstein Institute and funds mainly come from the German and British governments and the Volkswagon Foundation (GEOweb). As with the LIGO MFPIs, GEO600 mirrors are suspended by fused silica threads to drastically reduce their contributions to noise, and GEO600 has pioneered the use of quantum entangled photons (‘squeezed light”) to improve the sensitivity of their laser system (Caves 1981), and also re-inserting output signals into the MFPI tubes to amplify any detections (GEOweb).

A unique and long-running program of GEO600 is its Einstein@home program, a citizen science project that uses idle processor time of contributors’ home computers to analyse data. This outreach effort is complimented by several online games, and the Einstein-Online encyclopedia for the public. GEO600 also holds Open Days (next one is in June, 2018) and other events to capture the interest and support of the general public.

Commencing construction just five years ago, KAGRA is a University of Tokyo managed MFPI and is located in a disused mine of the Kamioka Mining and Smelting Co. at Hida in Gifu Prefecture, central Japan. It has 3 km long arms operating at a temperature of just 20 K, and sapphire mirrors for extremely high optical and thermal performance (KAGRAweb). KAGRA will cost in the vicinity of US$200M and be the first to use cryogenic temperatures for the arms and also the first GW detector built underground for seismic stability. The first full test of the MFPI will be in the 2020s (KAGRA 2017).

IndIGO will use one of the Advanced LIGO, 4 km-arm MFPIs and be located in Aundh, Hingoli district, central India. It is anticipated to be functional by the middle of the 2020s in the full knowledge that mirrors already fabricated and stored for over a decade at LIGO, will still perform within manufacturers specifications (Kinley-Hanlon et al 2016). IndIGO will be a key facility enabling accurate sky location of events and corroboration of the global detection network (see Iyer, 2015).

8. Futures

Advanced LIGO, Advanced Virgo and KAGRA anticipate major improvements in outcomes for the next ten years (Abbott et al 2018). Currently, with detection data from two MFPIs of high sensitivity, the best that can be done to locate a source on the sky is several thousand square degrees. This should improve 1000-fold by the time LIGO, Virgo, KAGRA and IndIGO are working at full sensitivity. Target distances for detection of NS/NS mergers range up to 190 Mpc and for BH/BH mergers, up to 1,640 Mpc (Abbott et al 2018).

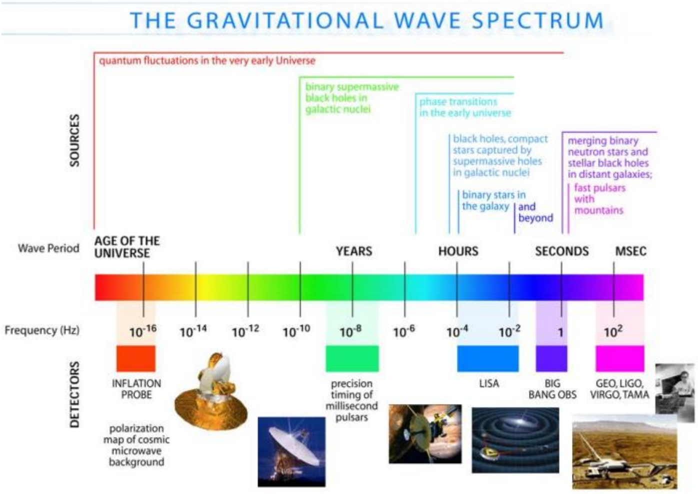


Fig. 11 GWs span the full spectrum of wavelengths from extremely long at the birth of the universe, to very short waves produced in massive merging events. Different detectors, facilities and spacecraft are suited to specific observing windows as shown. (Credit: LIGO)

When designing upgrades for MFPIs, an entire re-fit is usually the case and the next generation at LIGO may be fully reflective optics, cryogenic arms, a 20-fold increase in laser power and better electronics and computing to deal with the quantum measurement challenges (ALIGOweb). For example, LIGO was first designed with 25 cm, 11 kg mirrors but now has the larger mirrors mentioned above, to help damp out vibration noise.

Suggested some decades ago, the regular observation of an array of millisecond pulsars (PTA) can be used to detect passing GWs (Foster & Backer 1990). Today there are at least three major projects trying to do just that (Hobbs & Dai 2017). One is at Parkes in Australia and observes 25 pulsars (see Manchester *et al*. 2013), another in North America, NANOGrav, looks at 36 (see McLaughlin 2013), and the European Pulsar Timing Array observes 42 pulsars (see Kramer & Champion 2013).

By recording the progressive distortion that a passing ultra-low frequency GW causes in these exquisitely precise signals, astronomers will be able to explore a whole new field (green band in Fig. 11). Future telescope like the FAST (see Li *et al*. 2013) and QTT (see Xu & Wang 2016) in China, the MeerKAT (see Foley et al. 2016) in South Africa, and the SKA in Australia (see Janssen *et al*. 2015) will contribute greatly to the PTA efforts.

Probing the Primordial

If Inflation Theory is correct, the immediate, post-Big Bang gravitational tensor mentioned at the very top of this essay would leave a faint, polarized signature in the Cosmic Microwave Background (CMB), the fingerprint of the very first quantum fluctuations that lead to all subsequent objects in the universe (Ryden 2006). Polarimetry experiments like the Background Imaging of Cosmic Extragalactic Polarization (BICEP) are designed to detect this miniscule signal (BICEPweb).

Astrophysicists and cosmologists are excited at the prospect of detecting GWs in the CMB. A ‘false positive’ reported by the BICEP2 project in the Antarctic a few years ago (Ade et al 2014) was subsequently attributed to dust (Adam et al 2016), but plans are underway for BICEP3.

LISA in the Sky with DecIGO

The European Space Agency (ESA) has initiated a 1 billion € collaboration of institutions to fly a space-based GW detector. The Laser Interferometer Space Antenna (LISA) has already flown a pathfinder mission with great success and intends to launch a triangular formation of spacecraft, each of which form a corner of a MFPI with 2.5 million km arms.

The detector will reside in a heliocentric orbit, trailing some 50 million km behind Earth and will be able to detect the much longer wavelengths of supermassive BH (SMBH) mergers (blue band in Fig. 11), compared to the solar mass BH mergers possible to detect from Earth (pink band in Fig. 11) (LISAweb). Set to launch in 2034, LISA has eight key science projects including detection of stochastic GWs and informing us about the birth, life and death of SMBHs at the core of galaxies (Holley-Bockelmann 2018, Danzmann 2017).

A smaller, 1,000 km arm space MFPI called DECi-hertz Gravitational wave Observatory (DECIGO) has been proposed by the Japanese Aerospace Exploration Agency (JAXA) for launch in the 2030s. It is being designed to detect in the 0.1 Hz range and look for GWs from cosmic inflation and from in-spiral mergers (Musha et al 2017).

8. Conclusion

The background for this essay on GWs covered conceptualization from Plato to the Dark Ages, Arabic, Chinese and Newtonian physics, and up to Poincaré’s 1905 discovery that a waveform can describe gravity. With significant input from German mathematicians, Einstein took over and wrestled with curved spacetime and relativity.

Cataclysmic events like SN, NS and BH mergers were considered likely generators of GWs, and as astrophysics strengthened theory and made observations, bar detectors were built but failed. Lasers were the solution from the 1960s and, borrowing from an 1887 test design for an all-pervasive aether, Michelson-Fabry-Pérot-Interferometry was assumed as the technology of choice.

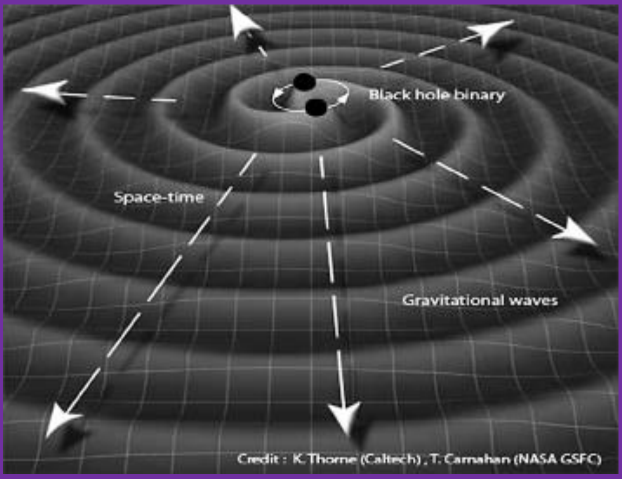
Theory and detection were self-fulfilled when the LIGO/Virgo collaboration announced the first positive detection - from two merging BHs. This corroborated all manner of theory. Black holes exist, they merge, they distort spacetime, they convert mass into energy in the form of GWs whose waveforms are now known, as is their polarization.

The several subsequent detections not mentioned in this essay have shed much light on our theories of cosmology and astrophysics. For example, NS mergers produce EMR across the spectrum as well as GWs, allowing an enormous opportunity to study the universe as it is and as it was soon after coming into existence. Multi-messenger astronomy is in its infancy.

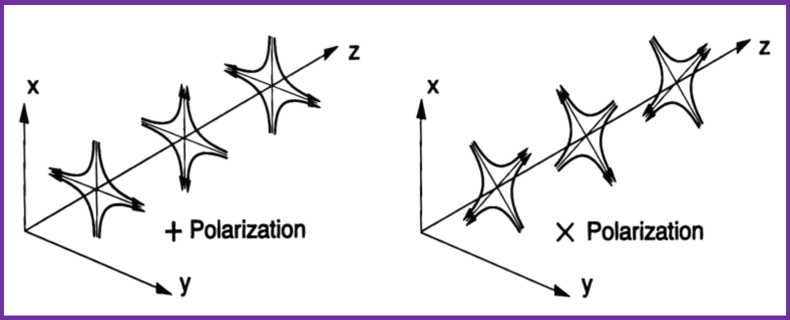
The future of astronomy is extremely exciting. Larger and more sensitive facilities on Earth and in space will leverage the new bandwidth that is gravitational waves.

First Detection of a Gravitational Wave GW150914

09:51 GMT on 14th September, 2015

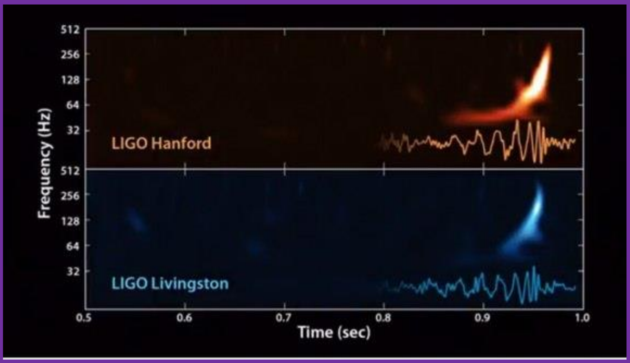


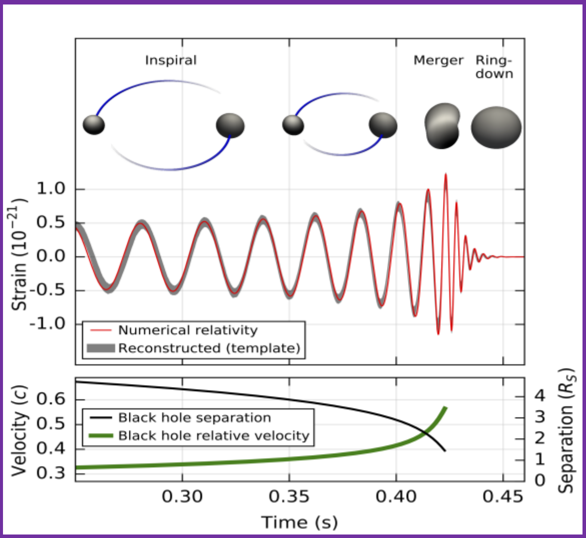
Credit : K.Thorne (Caltech), T. Carnahan (NASA GSFC)

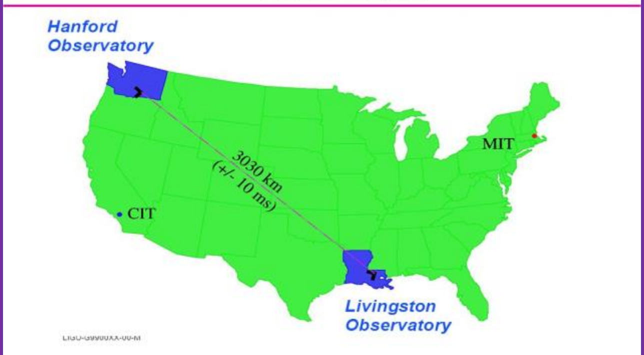


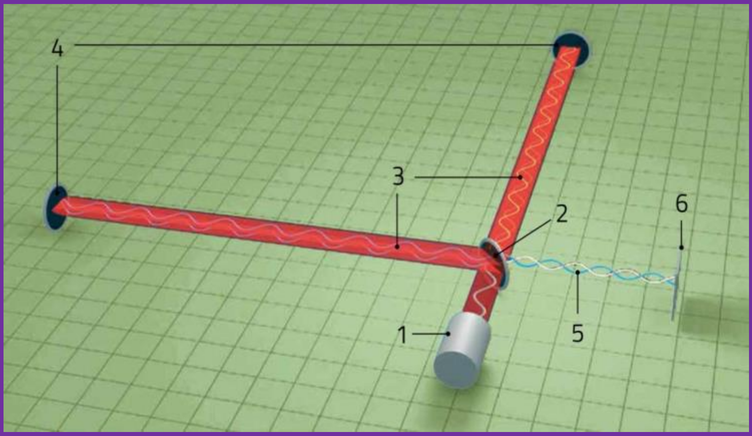
Clockwise from top-left:

- Over a billion light years away, a 30 solar mass BH and a 35 solar mass BH in a close binary system, finally merged into a single 63 solar mass BH. The deficit mass energy was dissipated as gravitation waves in spacetime;
- These waves stretch and squeeze spacetime in two polarized directions perpendicular to the transmission axis;
- Two MFPI detectors separated by over 3,000 km were waiting for just such an event;
- The MFPIs have two, orthogonal, 4 km long vacuum tubes in which a laser beam is reflected between pairs of high precision mirrors after being split in two;
- Exquisitely precise construction and monitoring is required to detect the alternating strain in these tubes as a passing GW causes the re-united split beam (5) to display an out-of-phase interference pattern at the photodetector (6);
- The in-spiralling BHs orbit faster and faster (bottom plot) until they merge in a spike of frequency and amplitude;
- Matching chirps are recorded a few microseconds apart at the two MFPIs in the USA and also at Virgo in Italy. The GW came from the southern hemisphere, ‘up’ through the Earth before passing through the detectors. (Images: LIGO)









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