KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

3 OCTOBER 2017

Scientific Background on the Nobel Prize in Physics 2017

THE LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY
AND
THE FIRST DIRECT OBSERVATION OF GRAVITATIONAL WAVES

The Nobel Committee for Physics

THE ROYAL SWEDISH ACADEMY OF SCIENCES has as its aim to promote the sciences and strengthen their influence in society.

BOX 50005 (LILLA FRESCATIVÄGEN 4 A), SE-104 05 STOCKHOLM, SWEDEN
TEL +46 8 673 95 00, KVA@KVA.SE ⋆ WWW.KVA.SE

KUNGL.
VETENSKAPS-
AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

The Laser Interferometer Gravitational-Wave Observatory
and
the first direct observation of gravitational waves

Introduction

Our knowledge and understanding of the Universe is based on millennia of observations of the quanta of electromagnetic radiation – photons – in a wide range of wavelengths. These studies have taught us a lot – not only about planets, stars and galaxies but also about the origins of structure, the evolution and possibly the fate of the Universe. It turns out, however, that highly energetic photons do not reach us from the furthest recesses of the cosmos. So, during the past few decades, new kinds of telescopes have been developed, leading to unexpected breakthroughs. These detectors exploit other forms of radiation: cosmic rays, neutrinos and gravitational waves.

The existence of gravitational radiation is linked to the general theory of relativity and was predicted by Einstein a century ago [1, 2]. Gravitational waves are travelling ripples in space-time. They arise when heavy objects accelerate and hence generate disturbances in the gravitational fields. These distortions, described as waves, move outward from the source at the speed of light and give rise to effects that, in principle, are measurable when they reach Earth given sufficiently sensitive detectors. The effects are minuscule, even in the case of black holes spiralling ever closer to each other or exploding stars.

Einstein himself was of the opinion that gravitational radiation never would be detected, the interaction between a passing gravitational wave and matter would be too weak to measure directly. Indirect effects, however, have been demonstrated, with the pioneering discovery in 1974 of the binary pulsar PSR 1913+16 for which measurements of the decay of the orbital period with time are consistent with the energy losses expected for gravitational-wave emission (R. A. Hulse and J.H. Taylor, Jr., Nobel Prize 1993) [3-5].

The first experimental attempts to directly detect the passage of gravitational waves date back to the early 1960's. Although the possibility had been discussed earlier, theoretical arguments raged over the likelihood of gravitational radiation actually carrying energy and hence of the waves being able to cause the motion of objects at some distance from the source. The breakthrough is attributed to an article by Hermann Bondi [6] and to Richard Feynman who in 1957, at a conference in Chapel Hill, North Carolina, described a thought experiment in which a gravitational wave caused motion of beads on a rod, heating it by friction [7]. This convinced many experts of the detectability of the waves given a sufficiently sensitive "antenna" – a fascinating suggestion triggering one of the conference participants, Joseph Weber from University of Maryland, to construct the first detector for gravitational waves [8].

A passing gravitational wave is expected to distort space-time through the effects of strain in a very specific way, predicted by the general theory of relativity. Distances in space increase and decrease with a steady cadence in two directions at 90 degrees to each other, orthogonal to the direction of motion of the wave. Weber's antenna was a solid aluminium bar weighing about 1.5 tonnes, with a belt of piezoelectric crystals mounted on the surface, about midway between the ends of the cylinder. The bar was suspended from a frame and enclosed in a vacuum tank to isolate it from potential outside vibrations. A passing gravitational wave would produce spatial strains, expected to make the bar vibrate at a resonant frequency of 1657 Hz. The crystals would convert the mechanical strains to voltages which were recorded. The detector started operation in 1965 and the first events were reported soon after, in 1966 [9]. In 1969 Weber claimed coincidences between two of his bars that were situated 1000 km apart, with an incredibly small probability for accidental occurrence, and published an article entitled "Evidence for discovery of gravitational radiation" [10].

Weber’s pioneering efforts and his claimed results created great excitement and stimulated the development and construction of other resonant-mass bar detectors, both in the USA and in Europe. Unfortunately, the new results were negative and by mid-1970’s most scientists agreed that Weber’s claims could not be confirmed.

Speculations flourished, but the field had gained impetus and new technologies for detection of gravitational waves were being developed across the world: cryogenic resonant detectors, cooled to a working temperature close to the absolute zero to improve their sensitivity – and interferometers. As opposed to resonant bars, only sensitive in a narrow frequency range close to the resonance, interferometers have a large bandwidth. This makes them potentially useful for astronomical observations since the full waveform can be registered, allowing extraction of the masses and distances of the sources.

The Laser Interferometer Gravitational-Wave Observatory (LIGO) [11] is the largest and most sensitive interferometer facility ever built. It has been taking data since 2002, periodically undergoing upgrades to increase its sensitivity. The most recent upgrade, Advanced LIGO, came online by the end of summer 2015 and within mere weeks, on September 14 that year, LIGO registered for the first time the passage of a gravitational wave, with a significance far above the expected background noise levels [12]. The event, named GW150914, was interpreted as the result of a merger of two black holes at a distance of about 400 Mpc from Earth. This extraordinary discovery confirmed predictions of the general theory of relativity and pointed to a means to study the astrophysics of black holes in ways that were previously inaccessible. Two additional, significant detections, GW151226 and GW170104, were reported later [13, 14].

The basic theory of gravitational waves

Following the work of Einstein from 1916 [1], wave-like solutions can be obtained by solving the vacuum field equations of general relativity. Neglecting the cosmological constant these equations are given by

$$\mathcal{R}_{\mu\nu} - \frac{1}{2}\mathcal{R} g_{\mu\nu} = 0,$$

where $\mathcal{R}_{\mu\nu}$ is the Ricci-tensor and $\mathcal{R}$ is its trace, the Ricci-scalar. The Ricci-tensor measures the curvature of the metric $g_{\mu\nu}$, which, in turn, is used to calculate distances in space-time. With an ansatz of the form

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu},$$

where the perturbation $h_{\mu\nu}$ around the flat metric $\eta_{\mu\nu}$ is assumed to be small, one obtains a wave equation for $h_{\mu\nu}$ given by

$$\Box\, h_{\mu\nu} = 0,$$

where $\Box$ is the d’Alembert operator $\eta^{\mu\nu}\partial_\mu\partial_\nu$. Einstein also calculated the energy contained in the waves, and showed that a tensor of inertia varying in time acts like a source for gravitational waves. Unfortunately, the paper from 1916 contained “*einen bedauerlichen Rechenfehler*” (“a regrettable error”), in the form of a missing factor 2. This was corrected in 1918 [2].

It is easy to reproduce these results qualitatively without detailed calculations using the full power of general relativity. To do this, one first needs to establish which kinds of waves are possible. In the case of electromagnetic radiation, monopole radiation is forbidden due to charge conservation, and the lowest multipole is dipole radiation. Similarly, in the case of gravitational radiation, energy conservation forbids monopole radiation, and momentum conservation forbids dipole radiation, leaving the quadrupole as the lowest multipole. This can be realized by two masses in orbit around each other, and for such a system it is easy to estimate the magnitude of the waves up to a numerical factor.

In electromagnetism the strength of dipole radiation emitted by a charge Q, oscillating with amplitude R and angular frequency ω, is set by $QR\omega$. In case of quadrupole radiation, the corresponding expression is $QR^2\omega^2$. In both cases the strength decreases with distance as $1/r$. If one wants to borrow this expression and use it in the case of gravitational waves, one needs to replace charge by mass and make sure the expression is dimensionless. In this way one finds

$$h \sim \frac{GmR^2\omega^2}{rc^4},$$

where, for simplicity, the space-time indices of the metric perturbation have been suppressed. The expression assumes two equal bodies with masses m in an orbit with radius R, and angular frequency ω around their common center of mass. The distance from the observer to the system is r. As expected, the estimate involves the time-varying moment of inertia of the source, mR^2. A simple Newtonian analysis of the orbit gives $\omega^2 = \frac{Gm}{4R^3}$, from which one concludes that the amplitude of the wave is given by

$$h \sim \frac{G^2m^2}{Rrc^4} \sim \frac{R_s^2}{Rr},$$

where $R_s = \frac{2Gm}{c^2}$ is the Schwarzschild radius. A particularly interesting case is the maximum amplitude that is reached in the case of two black holes when their orbit has shrunk so that their horizons are just touching each other. With $R = R_s$, one finds

$$h \sim \frac{R_s}{r}.$$

This extremely simple result can be obtained using no more than dimensional analysis and the fact that the amplitude must decrease as $1/r$. With typical values, such as $R_s \sim 100$ km and $r \sim 10^9$ light years, we find $h \sim 10^{-20}$. (The exact result is somewhat smaller than this.)

Finally, the energy flux is easily estimated as $\sim \omega^2 h^2$, leading to an energy loss from the system $\frac{dE}{dt} \sim -\omega^6 m^2 R^4$. The peak power, reached when the two black holes touch, becomes $\frac{c^5}{G} \sim 10^{52}$W, independent of the masses of the black holes. In reality, the radiated power is a few orders of magnitude lower, but still much higher than that of the combined light of all stars in the visible Universe.

While these rough estimates are easy to obtain, the numerical coefficients require a more careful analysis, briefly sketched here. With an appropriate choice of coordinates, one can use the transverse-traceless gauge in which $h_{\mu\nu}$ only has spatial components, is traceless, and transverse to the direction of the wave. This leaves only two independent components that, according to the linearized Einstein equations, are given by

$$h_{ij}^{TT} = \frac{2G}{rc^4}\frac{\partial^2 I_{ij}^{TT}}{\partial t^2}.$$

Here, I_{ij}^{TT} is the transverse and traceless piece of the tensor of inertia for the source relative to the direction in which the wave travels. To calculate the energy carried by the wave, one needs to keep track of some subtle factors. The tensor of inertia is symmetric and involves six different components, but when the trace is removed only five remain that can contribute to the radiation. Taking the appropriate average, keeping in mind that the radiation only has two independent components, introduces a factor 2/5. Putting all factors together one obtains

$$\frac{dE}{dt} = -\frac{128}{5}\omega^6 m^2 R^4.$$

Since there are two objects in orbit around each other, the angular frequency of the waves is actually 2ω.

For practical purposes, it is convenient to express the frequency f of the waves and its time derivative, $\dot{f}$, determined by the energy loss, in terms of the "chirp mass":

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} = \frac{c^3}{G}\left(\frac{5}{96}\pi^{-8/3} f^{-11/3}\dot{f}\right)^{3/5}.$$

Except for the numerical coefficient argued for above, the dependence on all parameters can be derived using a Newtonian analysis with Keplerian orbits for two masses m_1 and m_2 revolving around a common center of mass. The total wave amplitude is calculated as a sum of two contributions

$$h \sim \frac{G\left(m_1 {R_1}^2 + m_2 {R_2}^2\right)\omega^2}{rc^4},$$

where $m_1 R_1 = m_2 R_2$. Using $E \sim \frac{G m_1 m_2}{R_1 + R_2}$ it is then straightforward to obtain the expression for the chirp mass. The chirp mass is an extremely useful quantity because it can be directly read-off from data such as the ones in figure 4, without considering the detailed waveform.

Beyond the lowest order

The simplified analysis presented above may give the impression that the theoretical understanding of gravitational waves has a rather straightforward history. This is far from true. It took many years after Einstein first proposed the waves before even their theoretical existence was firmly established.

There are two main problems that need to be confronted. First, due to the coordinate covariance of general relativity, one runs the risk that the solution studied is nothing else than flat space viewed in an unusual coordinate system. Second, one must make sure that the solutions at the linear level still hold at the non-linear level. Einstein had serious doubts himself about the reality of the waves, and in 1936 he attempted to publish a paper in *Physical Review* together with his assistant Nathan Rosen, claiming that the waves did not exist. The anonymous referee, later disclosed to be the renowned cosmologist Howard P. Robertson, spotted some serious errors in the manuscript, and as a consequence it was rejected. Einstein was furious but eventually became convinced that he had made a mistake. The corrected paper was later published in *Journal of the Franklin Institute* [15]. It was not until the late 1950's that it was rigorously proven that the waves actually exist as solutions to the full non-linear equations, and that they carry energy [16-18]. Similarly, the understanding of possible sources of gravitational radiation also has a long and difficult history. It was not until the 1960's that black holes became accepted even among theorists.

Considering the collision of two black holes a bit more carefully, there are roughly three stages to understand: the "inspiral", when the two black holes approach each other, the "merger", when they form a single black hole, and the "ringdown", when the final black hole settles down.

The results that were discussed above describe with good accuracy the early inspiral, but need to be improved as the speed increases and the distance decreases. This can be done using a post-Newtonian expansion, pioneered by Einstein, Leopold Infeld and Banesh Hoffmann in 1938 [19], which leads to a corrected waveform [20]. The merger is much more complicated to handle than the inspiral while the final ringdown can be treated using fairly straightforward, analytical techniques. The key ingredients are the "quasi-normal modes", which correspond to gravitational waves oscillating in an effective potential constraining the waves to a region close to the horizon of the final black hole [21]. As time goes by, the waves are either caught by the black hole or they leak out.

The post-Newtonian analysis can be improved by various resummation techniques within the framework of the Effective-One-Body (EOB) method [22]. These waveforms can be matched to the ringdown to produce realistic waveforms for the whole process. While these waveforms provide a reasonable match, further important improvements are obtained using numerical methods that are very computationally intensive [23]. The analytical methods are crucial to producing the big library of template waveforms used by LIGO.

While the waveforms produced in this way are necessary for determining the detailed properties of the objects involved, as well as identifying weak signals, they were not essential for the very first detection of GW150914. This was a model-independent detection of a gravitational-wave transient. An analysis of the physics of the binary black hole merger GW150914 can be found in [24].

Sources of gravitational waves

In general terms, gravitational waves are emitted by accelerated objects whose motion is not spherically symmetric. A classic example would be a dumbbell rotating around an axis orthogonal to its axis of symmetry – although the expected gravitational-wave amplitude in this case would be incredibly tiny for any reasonable configurations of masses and distances, in human terms. On the other hand, the Universe harbours many astrophysical processes that produce gravitational waves in frequency ranges that may prove accessible to ground-based or space-based observatories, see figure 1.

Following Riles [25] the sources can be divided into four categories:

– Short-lived and fairly well-modelled sources:

This class includes compact objects in tight orbits such as a pair of neutrons stars, a pair of black holes or a black hole and a neutron star. The sequence of inspiral and merger, leading to a single massive body, gives rise to a characteristic signal that first increases in both amplitude and frequency with time and subsequently dies out as the final object "rings down". The inspiral stage can be fairly well described theoretically, depending on parameters such as the masses, spins, separation, ellipticity and orbital inclination of the binary. This makes it possible to develop templates that facilitate detection of such mergers and extraction of the properties of the detected coalescing system. A study of the features of the damping "ringdown" phase can be used to extract the mass and spin of the final black hole. The merger phase is challenging and requires numerical relativity calculations to permit comparison between observation and theory. LIGO's sensitivity range is well-matched to the frequency band for the inspiral of neutron binaries. For coalescing black holes, not only the inspiral but also the merger and damping phases fall within LIGO's sensitivity.

– Short-lived and poorly known sources:

Bursts of gravitational radiation are expected from sources such as supernovae, provided the core collapse process entails some asymmetry. The fact that many pulsars move with substantially greater speeds than their progenitors, has been claimed to be a possible indication of an asymmetry in the motion of the rapidly rotating, exploding star. Such asymmetries could result from magneto-hydrodynamical instabilities at the pre-supernova stage. Due to the uncertain initial conditions and the unclear dynamics of the explosion, these sources are not well-modelled. Similar reasoning applies to the long duration gamma-ray bursts (GRB) that are believed to be associated with supernovae or hypernovae. Short GRBs appear to originate from the merger of binary neutron stars and therefore belong to the well-modelled category above.

Another example of a potential "burst" source is the sudden release of energy from a magnetar, a neutron star with an extremely powerful surface magnetic field, 100 to 1000 times stronger than that of an ordinary neutron star. Sporadic release of magnetic field tension is thought to power the observed electromagnetic emission in X-rays or gamma rays. If the underlying processes release energy into the surface layers of the neutron star, crustal vibrations might result in gravitational waves which can be searched for but which are difficult to model.

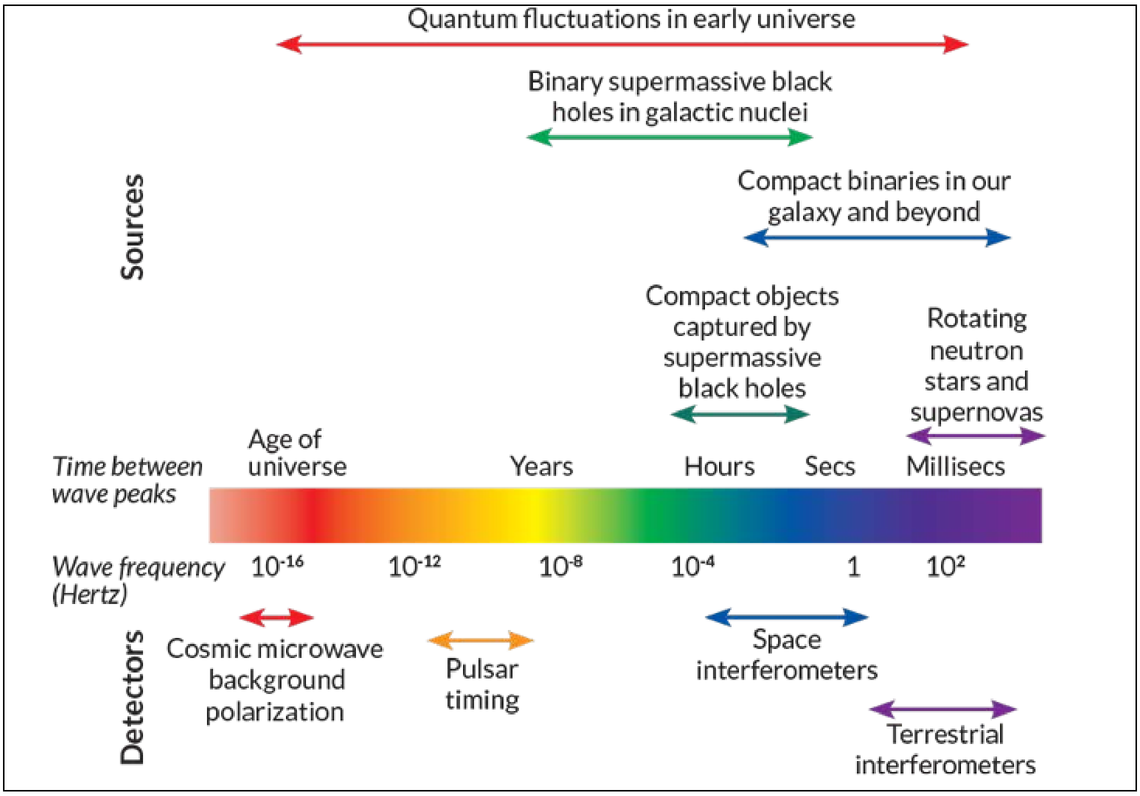

Figure 1: Gravitational-wave spectrum (*credit*: *NASA*)

– Long-lived and well-modelled sources:

Rapidly spinning non-axisymmetric neutron stars produce gravitational waves that are periodic and nearly monochromatic at a frequency that is twice the rotation frequency. The asymmetry might be due to a deformation of the crust or to non-isotropic accretion from a companion star. The potential sources for observatories such as LIGO are within our galaxy and include relatively young pulsars, such as the Crab. The searches, both over the full sky and for targeted sources are facilitated by the fact that the waves can be observed over many cycles.

– Long-lived, diffuse sources:

This category includes the primordial background of gravitational waves, predicted by most cosmological theories, although the associated power spectral density varies widely. The relic gravitational waves carry an imprint of the very early history of the Universe, much earlier than the ubiquitous cosmic microwave background radiation. A hypothesized source of stochastic radiation would be snapping "cosmic strings", leftover defects from an early phase transition in the Universe. More mundanely, a large number of binary coalescence events involving neutron stars or black holes too far way to be resolved individually would add up to an unresolvable – or diffuse – background of gravitational waves. Potentially, these very-low-frequency signals could be detected through correlations in the background noise data from two or more detectors.

A brief history of LIGO

The basic concept of a Michelson-like interferometric detector for gravitational waves was first sketched in an article by the Soviet physicists M.E. Gertsenshtein and V.I. Pustovoit, in the early 1960's [26]. The idea was resurrected a few years later by Weber and his former graduate student Robert L. Forward who constructed the first prototype gravitational-wave laser interferometer at Hughes Aircraft Research Laboratories, Malibu, California, where he and his colleagues had started research and development of gravitational-wave detectors [27]. In parallel, Rainer Weiss at the Massachusetts Institute of Technology (MIT), inspired by Pirani [28], developed similar ideas which, in 1967, enabled him to demonstrate a laser interferometer with sensitivity limited only by photon shot noise.

Decades of ambitious efforts building on Weiss' designs resulted in the realisation of the Advanced Laser Interferometer Gravitational-Wave Observatory (aLIGO for short). Weiss' report from 1972 [29] constitutes an early exploratory study of an interferometric gravitational-wave antenna targeting detection of pulsar signals, notably from the Crab, and describes and evaluates the fundamental sources of background noise that critically limit the antenna performance. These include seismic noise, gravitational field gradients, noise due to thermal gradients in the vacuum chamber, thermal noise associated with the test masses (mirrors) and their suspensions, amplitude variations in the laser output power, laser frequency instabilities, pressure recoil effects on the mirrors and shot noise in the photocurrent at the output. Potential effects from geomagnetic storms and cosmic-ray showers are also considered. At the end of the document Weiss points out that a meaningful pulsar search requires a kilometre-sized interferometer.

For several years, Weiss' research and development efforts were financed by MIT, partly in the form of graduate projects. The funds were insufficient, however, and in 1974, Weiss submitted a proposal to the US National Science Foundation (NSF) to enlarge his meter-long prototype to 9-m arms. This first step was meant to eventually lead to an instrument on a much larger scale for astrophysical observations.

At the time, more powerful argon-ion lasers were becoming available and the interferometer idea spread across the Atlantic: at the Max Planck Institute for Astrophysics in Garching, Germany, a group led by Heinz Billing developed a 3-m prototype followed by a 30-m instrument [30]. At the University of Glasgow, Ronald Drever, James Hough and others constructed a 1-m instrument and later a 10-m interferometer using Fabry-Pérot cavities in the arms [31].

The German and the Scottish groups eventually decided to collaborate, in order to secure sufficient funds for a planned large-scale facility, and succeeded in financing an interferometer with 600-m arm-length. This is the current GEO600 observatory south of Hannover in Germany. The construction of GEO600 started in 1995 and design sensitivity was reached in 2006. Since

2002, GEO600 has occasionally participated in joint observation runs with LIGO. Scientists from GEO600 are members of the LIGO Scientific Collaboration and have developed a number of advanced technologies that have been adopted by LIGO.

A few years after the developments at MIT, another interferometer prototype saw first light at the California Institute of Technology (Caltech) under the auspices of theorist Kip Thorne. During the 1970's, Thorne and his research group worked with great enthusiasm on the theory of gravitational waves and their astrophysical sources. Their predictions of the expected signals from various astrophysical events played a decisive role for the design and funding of LIGO – and for the first steps to prepare the online and offline analytical tools enabling LIGO's breakthrough discovery of GW150914. In the late 1970's, Thorne succeeded in convincing the Caltech leadership to create an experimental gravitational-wave group led by Drever, recruited from Glasgow in 1979, and Caltech's Stanley Whitcomb.

In the early1980's, NSF financed the construction of prototype interferometers both at MIT and at Caltech, and funded a study proposed by Weiss to work out the design and the costing for a several-kilometre-long device. The results were presented in October 1983, in a report known as "the Blue Book" [32]. The study demonstrated the scientific case and the technical feasibility of the project and recommended a long-baseline facility consisting of two 5-km-long interferometers separated by a distance of several thousand kilometres. Based on this report and the promising results from the prototypes at MIT and Caltech – as well as those from the Max Planck Institute and the University of Glasgow – NSF decided to endorse the project, provided the groups at MIT and Caltech joined forces. This was the beginning of LIGO, initiated in 1984 as a joint project led by Weiss, Drever and Thorne and with headquarters at Caltech.

The planning and prototype development for LIGO continued through the 1980's. Following a strong recommendation from the NSF, a new leadership structure was implemented under a single director Rochus Vogt from Caltech. Finally, in 1990, the National Science Board, a body that oversees NSF's new major programs and awards, approved the construction of LIGO with an expected cost close to 300 million US dollars. The LIGO interferometers, downscaled to 4-km, would be constructed at sites on opposite sides of the American continent – in Hanford, near Richland in Washington State, and in Livingston, Louisiana – at a distance of about 3000 km. To ensure the successful transition from a prototype activity to a realistic "big science" venture, Caltech, in consultation with NSF, appointed Barry Barish, who had leadership experience from large particle physics projects, as LIGO director starting 1994.

Barish transformed LIGO from a limited MIT/Caltech endeavour to a major international, gravitational-wave project. Barish's aim was to construct LIGO in steps, with the first stage (Initial LIGO or iLIGO) providing a verification of the technology and, in the best case, offering a possibility to detect gravitational waves. The second stage (Advanced LIGO or aLIGO) would be based on more advanced technology and reach a sensitivity that would make detection of gravitational waves probable. The construction of the facilities at Hanford and Livingston proceeded under Barish' leadership from 1994 to 1998. He then oversaw the installation and commissioning of LIGO's initial interferometers from 1999 to 2002, and the first data-taking runs, 2002 to 2005. In 2005, Barish accepted the leadership of the Global Design Effort for the International Linear Collider, remaining meanwhile a member of the LIGO Scientific Collaboration (LSC), which he created in 1997. The Collaboration is responsible for organizing LIGO's technical and scientific research and data analysis, while the operations and advanced LIGO research and development are led by the LIGO laboratories at Caltech and MIT, and the laboratories at the sites Hanford and Livingston. LSC includes scientists from all over the world, at the time of writing approximately a thousand researchers from close to a hundred institutions on five continents. Weiss was LSC's first spokesperson (1997 – 2003), and Barish remained as LIGO director until 2005. At the time of the breakthrough discovery, in September 2015, the LSC was led by Gabriela González (Louisiana State University), and David Reitze (Caltech) was director of LIGO.

The late 1980's also saw the beginnings of a French-Italian effort that eventually resulted in the VIRGO detector at Cascina near Pisa in Italy [33]. The detector has an arm-length of 3 km and is designed for superior low-frequency performance, down to 10 Hz. The construction started in 1996 and the observatory was inaugurated in 2003. A formal collaborative agreement between VIRGO and LIGO has existed since 2007, and the two detectors have occasionally taken data in parallel. An advanced version of VIRGO with higher sensitivity, came on line in August 2017 and joined the ongoing LIGO observation run during several weeks. On August 14, a gravitational-wave signal was detected jointly by the twin LIGO interferometers and the Advanced VIRGO detector. The information registered by the three instruments allowed, for the first time, to substantially narrow down the region of the sky where the source is located. The VIRGO interferometer is operated by the European Gravitational Observatory (EGO).

For completeness, it should be mentioned that the gravitational-wave detector TAMA300 with 300-m-long arms ran at the National Astronomical Observatory in Japan, collecting data from 1999 to 2004. This detector has now been decommissioned [34]. It is considered a prototype for the planned advanced Japanese interferometer KAGRA [45].

Advanced LIGO

Interferometric gravitational-wave detection relies on the precise measurement of the optical phase difference between two light beams from a common source travelling back and forth in the two interferometer arms whose lengths are distorted by the passage of the wave. The detectable signal is proportional to the gravitational strain amplitude and to the length of the interferometer arms. The challenge is the extreme smallness of the predicted strain amplitudes at Earth from astrophysical events, of the order 10^{-22} or lower [35, 36]. As a consequence, to make the signal as large as possible, the arm length of a gravitational-wave interferometer should be large, optimally close to a quarter of the wavelength of the gravitational wave i.e. about 750 km at 100 Hz. Operationally, that requires creating an optical path within each arm which is much longer than its physical length.

This is the principle governing the design of the LIGO detectors at the two sites, Hanford and Livingston. The two instruments are identically designed, enhanced Michelson interferometers, each enclosed in an L-shaped ultra-high vacuum system with pressure typically below 1 μPa (see figure 2). The detectors are separated by 3002 kilometres, which at the speed of light implies a time difference of close to 10 milliseconds.

Optically, each interferometer arm consists of two massive (40 kg) fused silica mirrors, called test masses, with specially developed multilayered optical coating to achieve the required high reflectivity while minimizing coating thermal noise. Each mirror is suspended by a quadruple pendulum system, mounted on an actively controlled seismic isolation platform. This suppresses vibrations from tidal motion of Earth's crust and microseismic activity. Considerable care is taken to avoid thermally driven motion of the mirrors by choosing fused silica fibre suspensions for the last stage of the pendulum. The test masses are separated by a distance of 4 km.

The light beam in each arm originates from a pre-stabilized Nd:YAG laser with a wavelength of 1064 nm. The laser injects 20 W into the interferometer where the power is increased by a power-recycling cavity before the beam-splitter to 700 W. At the beam-splitter, the light splits into two paths one along each of the two arms of the L. To improve sensitivity, each arm of the basic Michelson interferometer contains a Fabry-Pérot cavity that stores the photons while the light bounces back and forth between the test mass mirrors, thus increasing the duration of the gravitational wave's interaction with the light. The effect on the light phase is a factor 300, an effective increase of the arm length to over 1000 km.

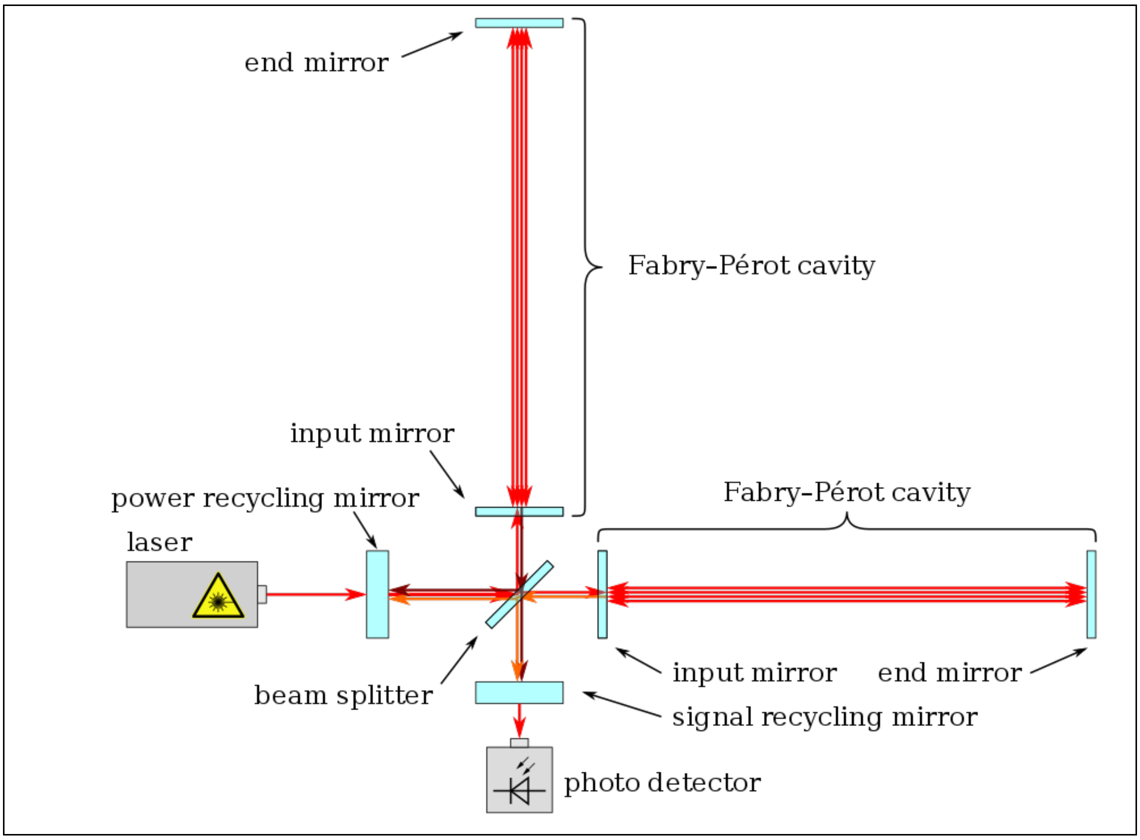

Figure 2: Simplified layout of a LIGO interferometer (credit: Menner [CC0], via Wikimedia Commons)

The light travelling in the two arms, returns to the beam-splitter and is channelled to the output port where the interference pattern between the two light beams is registered by means of a photodetector. A signal-recycling mirror at the output increases the sensitivity of the device. Changes in the phase difference between the two returning light beams and the resulting shifts in the interference pattern reflect a departure from perfectly matching arm lengths, as the space-time is locally strained by a passing gravitational wave. The detected laser-light power at the output is converted to a measure of the mirror displacement relying on a calibration method that applies a known force to a test mass [37].

The Advanced LIGO detectors that started operation in September 2015 provide a considerable increase in sensitivity over the previous LIGO versions, over a wide frequency range and especially at low frequencies (see figure 3).

The sensitivity of the LIGO interferometers is limited by noise: at high frequencies, mainly photon shot noise and at low frequencies, radiation pressure recoil effects on the mirrors, and thermal noise in the mirror suspensions. Plans exist to increase the circulating laser power in the detector arms from about 100 kW to 750 kW, to improve LIGO's high frequency response.

High sensitivity to gravitational strain requires not only the minimization of all the many known detector noise sources, but also the monitoring of potential environmental disturbances and their impact on the detectors. To this end the observatory is equipped with thousands of sensors – accelerometers, seismometers, microphones, magnetometers and many others, as described by

Effler et *al.* [38]. The fact that LIGO operates two detector systems at far-apart sites is extremely important as coincident detection allows rejection of transient local environmental disturbances. In addition, the long baseline of the observatory provides some directional sensitivity, further improved when additional observatories like VIRGO can be included to allow triangulation.

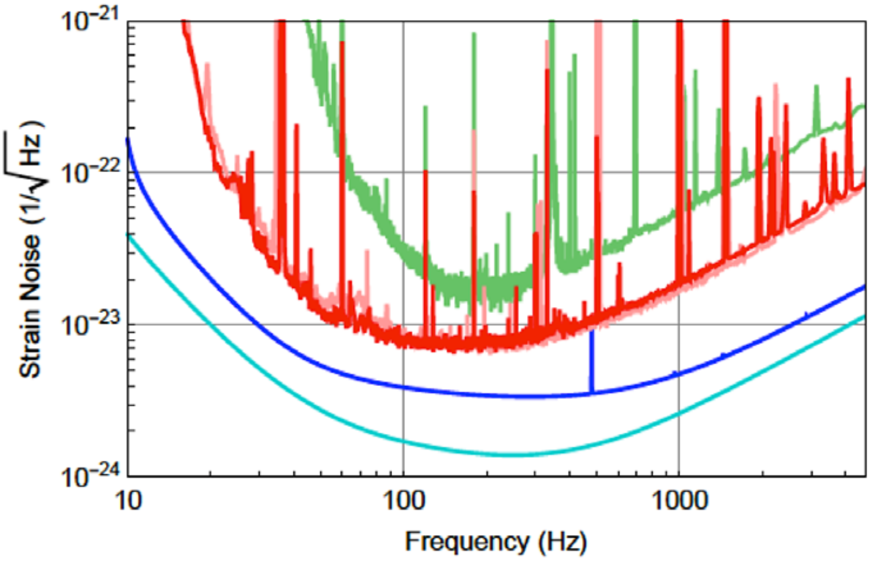

Figure 3: The strain sensitivity of the Advanced LIGO detectors during the first observation run in 2015 (red) and the last science run of the Initial LIGO detectors (green). The improvement in sensitivity is a factor of 3-4 in the most sensitive frequency band 100-300 Hz, and nearly a factor 100 at 50 Hz. The Advanced LIGO design sensitivity, which has not been reached yet, is shown in dark blue, and a possible future upgrade – in light blue. The narrow features include calibration lines, vibrational modes of suspension fibres and 60-Hz power grid harmonics (figure from [37]).

First direct observation of a gravitational-wave event

Advanced LIGO commenced operations in September 2015 and the conditions were stable at the time of the detection of a strong signal on September 14 that could be interpreted as the signature of a passing gravitational wave [12]. Livingston registered the wave 6.9 milliseconds before Hanford – as expected from a source in the southern hemisphere.

The event was first reported by a low-latency online search for gravitational-wave bursts from short-lived transient sources, creating an alert 3 minutes after the detection. The rapid analysis provided a first estimate of the location on the sky and event parameters for the LIGO/Virgo electromagnetic follow-up partners [39]. The procedure is described in B.P. Abbott *et al.* [40]. It requires no *a priori* knowledge of signal waveforms but is based on conversion of strain data from both detectors to the time-frequency domain, followed by a search for clusters well above the detector noise floor in the combined time-frequency power map. A second online low-latency burst search, designed to produce results within 30 minutes of detection, confirmed the discovery. Sometime later, the discovery was reconfirmed once more – by an offline matched-filter search targeting coalescing compact binaries. This search relies on close to 250000 template waveforms to map out the parameter space in terms of masses and spins. It provides approximate values for the source parameters, which are then refined using numerical simulations of binary black hole mergers.

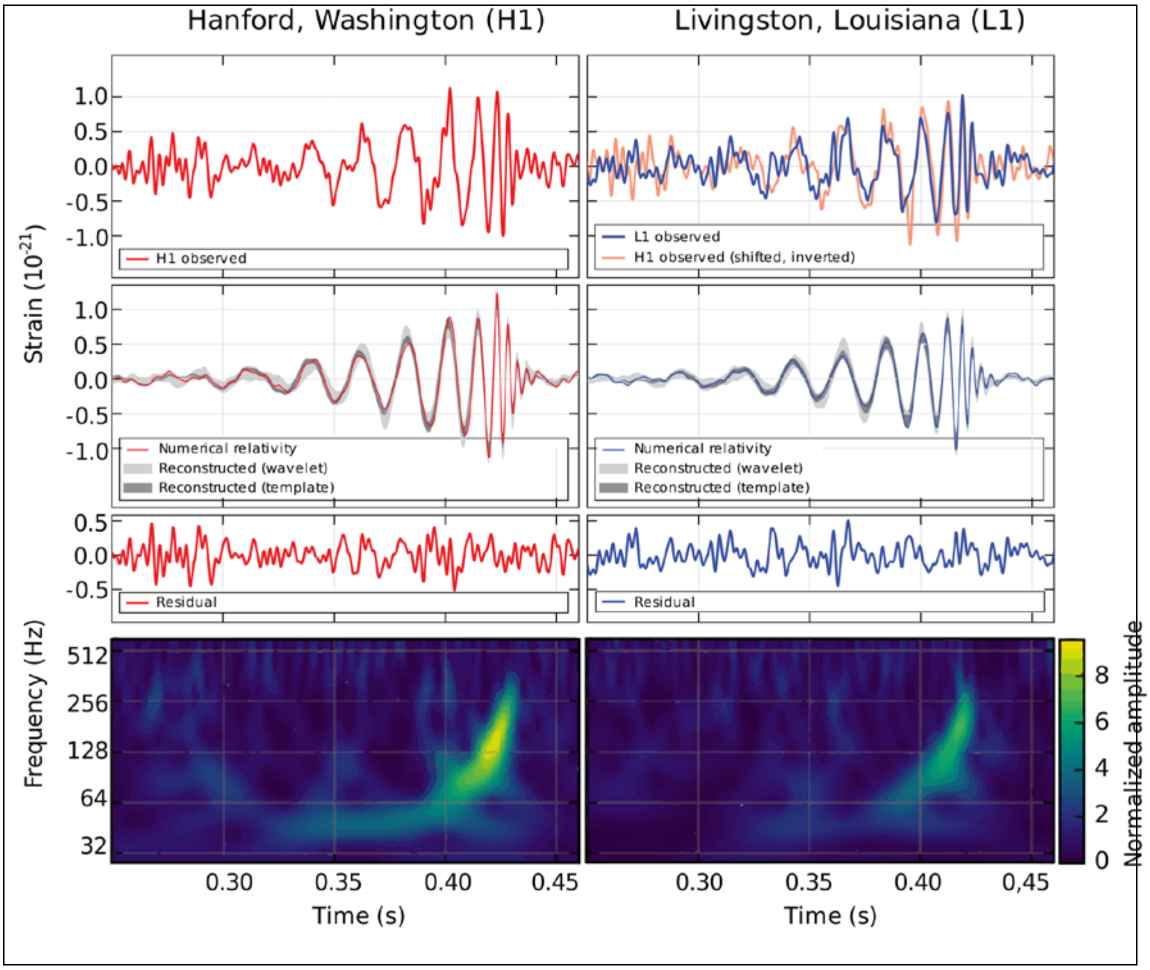

Figure 4: The gravitational-wave event GW150914. Left column: LIGO Hanford (H1) time series, filtered (top panel); theoretical waveform for a system with parameters consistent with those for GW150914 and the residual remaining after subtraction of the theoretical waveform from the observed, filtered time series (middle panels); time-frequency representation of the strain data (bottom panel). Right column: corresponding information for the LIGO Livingston (L1) observation. For a visual comparison, the top right panel shows as an overlay the H1 data, corrected for the difference in the detectors' relative orientation and shifted by the difference in arrival times of $6.9^{+0.5}_{-0.4}$ *ms. All times are relative to the trigger time, September 14, 2015 at 9:50:45 UTC (figure from [12]).*

Figure 4 [12] summarizes the observations: The signal increases in frequency and amplitude over 200 ms, reaching a maximum amplitude at about 150 Hz. The most likely interpretation for this evolution is the inspiral of two orbiting massive bodies, while emitting gravitational radiation. Estimating the frequency and its time derivative from the data shown in figure 4, the formula for chirp mass indicates that the lower limit for the sum of the masses of the two objects is about 70 M⊙. The large total mass and the fact that the objects reach a relatively high frequency before merging points to inspiraling black holes.

Further analysis, using general-relativity-based waveform models, shows that GW150914 is consistent with the coalescence of a binary black hole system, with the initial black holes massing $36^{+5}_{-4}\ M_\odot$ and $29^{+4}_{-4}\ M_\odot$ merging into a final black hole at $62^{+4}_{-4}\ M_\odot$. The final object is more massive than any other previously known stellar black hole. Its luminosity distance is estimated to 410^{+160}_{-180} Mpc. Energy corresponding to $3.0 \pm 0.5\ M_\odot$ was released in the event in the form of gravitational radiation. The analysis leading to these parameters and an investigation of the effects of waveform model systematics are described in B.P. Abbott *et al.* [41]. A direct comparison with numerical simulations in general relativity is shown in B.P. Abbott *et al.* [42].

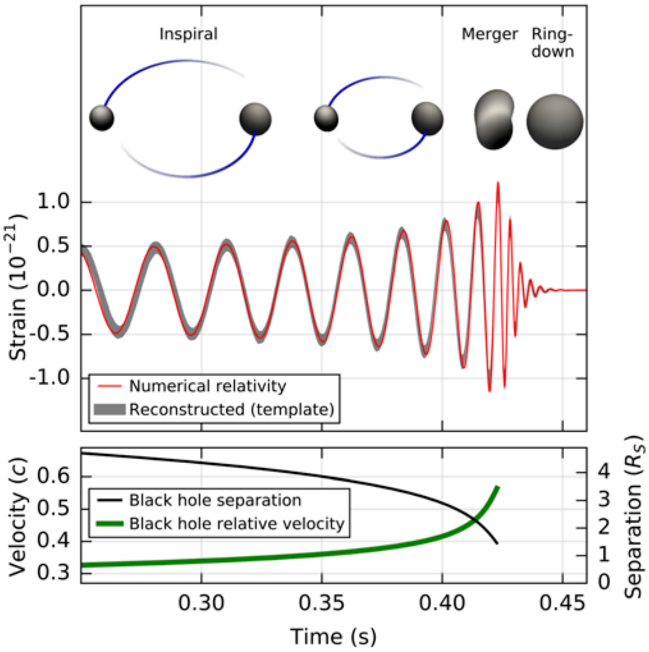

Figure 5: Top: The calculated gravitational-wave amplitude. Bottom: The Keplerian effective black hole separation, in units of the Schwarzschild radius, and relative velocity, in units of the speed of light (figure from [12]).

The probability of the event occurring by chance, due to coincident background noise in the two detectors was estimated to be less than 2×10^{-7}. The corresponding false alarm rate is one event in 203000 years. Searches for long-range correlations between the two sites showed no evidence for significant temporally correlated disturbances [12] (see also [43]).

Figure 5 shows the numerical-relativity based waveform for GW150914 using the estimated black hole parameters.

Gravitational-wave detectors have very poor spatial resolution. Given the coincident observation at the two LIGO sites, the source of GW150914 could only be mapped out as an arc on the sky located mainly in the southern hemisphere. This region was studied in many follow-up campaigns looking for coincident electromagnetic signals in radio, optical, infrared, X-ray and gamma-ray, and for coincident neutrinos. No significant coincidences were reported.

Two additional significant detections of passing gravitational waves, GW151226 and GW170104 [13, 14], have been reported. GW170104 was again a loud event, first identified by inspection of low-latency triggers from the Livingston detector. GW151226 was found using a matched-filter procedure. In both cases, the observations could be interpreted in terms of the merging of black holes.

Outlook

The first direct observation of gravitational waves is a milestone, showing a new way to explore the distant non-thermal Universe and providing a means to investigate general relativity in a previously inaccessible regime. This is illustrated by the hundreds of publications following in the wake of the first detection. The LIGO instruments will presently be further upgraded through injection of squeezed light [44] as a means of reducing the quantum noise of the detectors and improving the sensitivity in the shot-noise-limited region at high frequencies, independently of the circulating light power. A new observation run is expected to start in autumn 2018.

Several new detectors are under way: The Kamioka Gravitational Wave Detector (KAGRA), a laser interferometer with 3-km-long arms, developed at the University of Tokyo will hopefully start operations in 2018 [45]. The prototype TAMA300 demonstrated the feasibility of the project. LIGO-India [46] is a planned advanced gravitational-wave observatory envisaged as a collaboration between several Indian institutions, the LIGO laboratories in the US and LIGO's international partners in Australia, Germany and the UK. The project will relocate a third LIGO interferometer, identical in design to the other two and originally planned for installation at Hanford. Both KAGRA and LIGO-India will operate as part of a gravitational detector network together with LIGO and VIRGO, contributing to superior source localisation. A next-generation ground- based observatory, the Einstein Telescope, which aims to probe a thousand times larger volume than LIGO, is currently under study within European Framework Programme FP7.

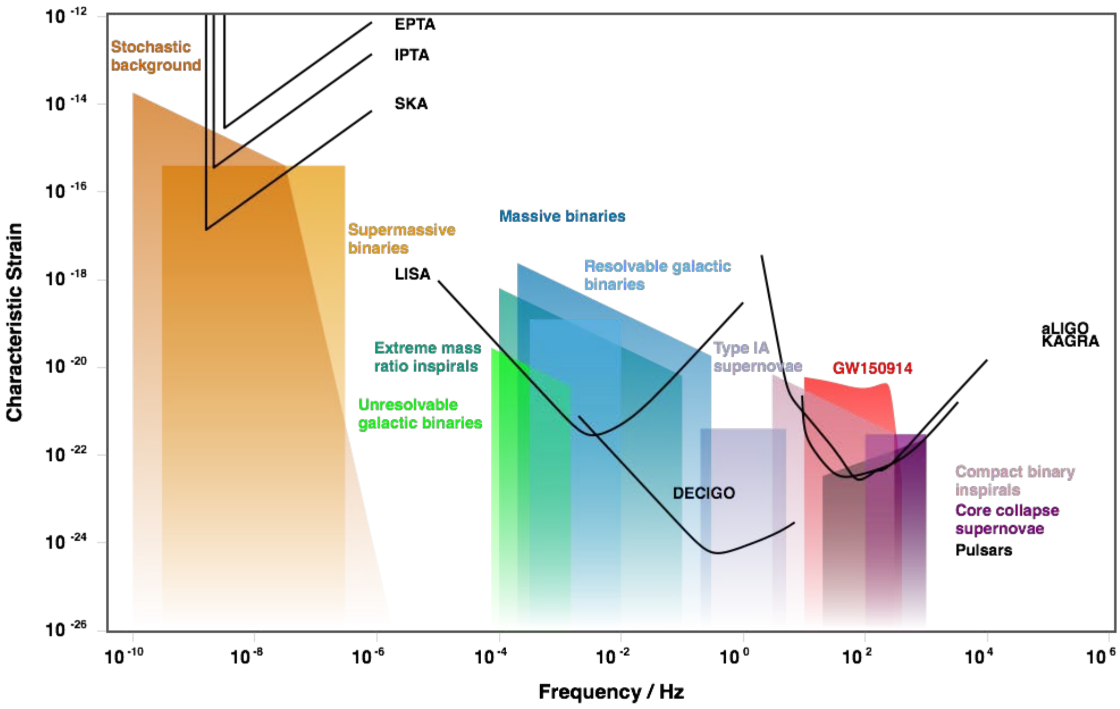

Figure 6: The expected performance of future detectors in terms of strain and frequency [35].

A planned gravitational-wave observatory in space is the Laser Interferometer Space Antenna (LISA) [47], consisting of three spacecraft arranged in an equilateral triangle with 2.5-million-km-long sides. The three craft will maintain their formation while following a circumsolar orbit, at the same distance from the Sun as the Earth. Each LISA craft contains two test masses and two test lasers pointing at the other two craft, hence forming a system of Michelson-like interferometers. The orbital motion of the triangle will allow LISA to measure not only the amplitude of the gravitational waves but also the direction to the source. Compared to LIGO, LISA will be mainly sensitive in a lower frequency range, accessing galactic sources of gravitational waves and extreme mass-ratio inspirals. In June 2017, the European Space Agency (ESA) successfully completed the LISA Pathfinder mission demonstrating the feasibility of the project. Similar to LISA but sensitive in a frequency band between LIGO and LISA, the Deci-hertz Interferometer Gravitational-wave Observatory (DECIGO) [48] is a proposed Japanese space-based project.

At the lowest frequencies, 10^{-9}–10^{-6} Hz, pulsar timing arrays use millisecond pulsars to search for gravitational waves by looking for disturbances in the correlations between arrival times of pulses emitted by objects at different angular separations. Gravitational waves at such low frequencies are expected from galaxy collisions causing mergers of the supermassive black holes at their centres. Three pulsar timing arrays are currently active: the Parkes Pulsar Timing Array, the European Pulsar Timing Array (EPTA) and the North American Nanohertz Observatory for Gravitational Waves. They collaborate within the International Pulsar Timing Array (IPTA) [49] consortium. The Square Kilometer Array (SKA) [50] will contribute significantly to these efforts by detecting many more millisecond pulsars than is currently possible, timing them to a very high precision.

Figure 6 shows the complementarity of the proposed detectors over a wide frequency range.

The multitude of projects aiming to detect gravitational waves over a wide range of frequencies heralds the flourishing of gravitational-wave astronomy within the next few decades. Gravitational waves travel unhindered through the Universe carrying information on its most violent processes, even those occurring in previously unexplored regions, opaque to photons. In addition, the direct gravitational-wave observations open a path and test the extreme limits of the general theory of relativity, possibly pointing out a way to unite it with quantum mechanics.

References

[1] A. Einstein, *Näherungsweise Integration der Feldgleichungen der Gravitation*, Sitzungber. Preuss. Akad. Wiss. Berlin, part 1, 688 (1916)

[2] A. Einstein, *Über Gravitationswellen*, Sitzungber. Preuss. Akad. Wiss. Berlin, part 1, 154 (1918)

[3] R.A. Hulse and J.H. Taylor, *A high-sensitivity pulsar survey*, Astrophys. J. 191, L59 (1974)

[4] R.A. Hulse and J.H. Taylor, *Discovery of a pulsar in a binary system*, Astrophys. J. 195, L51 (1975)

[5] J.H. Taylor, L.A. Fowler and J.M. Weisberg, *Measurements of general relativistic effects in the binary pulsar PSR1913+16*, Nature 277, 437 (1979)

[6] H. Bondi, *Plane gravitational waves in the general relativity*, Nature 179, 1072 (1957)

[7] R.P. Feynman in *Proc. conf. on the role of gravitation in physics*, Chapel Hill, North Carolina, Jan 18-23, 1957, Cecile M. DeWitt and Dean Rickles (eds.), *www.edition-open-sources.org /sources/5/*

[8] J. Weber, *Detection and generation of gravitational waves*, Phys. Rev. 117, 306 (1960)

[9] J. Weber, *Observation of the thermal fluctuations of a gravitational-wave detector*, Phys. Rev. Lett. 17, 1228 (1966)

[10] J. Weber, *Evidence for discovery of gravitational radiation*, Phys. Rev. Lett. 22, 1320 (1969)

[11] J. Aasi et al. (LIGO Scientific Collaboration), *Advanced LIGO*, Class. Quantum Grav. 32, 074001 (2015)

[12] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Observation of gravitational waves from a binary black hole merger*, Phys. Rev. Lett. 116, 061102 (2016)

[13] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *GW151226: Observation of gravitational waves from a 22-solar-mass binary black hole coalescence,* Phys. Rev. Lett. 116, 241103 (2016)

[14] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), GW170104: *Observation of 50-solar mass binary black hole coalescence at redshift 0.2*, Phys. Rev. Lett. 118, 221101 (2017)

[15] A. Einstein and N. Rosen, *On gravitational waves*, J. Franklin Inst. 223, 43 (1937)

[16] H. Bondi, F.A.E. Pirani and I. Robinson, *Gravitational waves in general relativity III. Exact plane waves*, Proc. Roy. Soc. Lond. A251, 519 (1959)

[17] F.A.E. Pirani, *Invariant formulation of gravitational radiation theory*, Phys. Rev. 105, 1089 (1957)

[18] I. Robinson and A. Trautman, *Spherical gravitational waves*, Phys. Rev. Lett. 4, 431 (1960); I. Robinson and A. Trautman, *Some spherical gravitational waves in general relativity*, Proc. Roy. Soc. Lond. A265, 463 (1962); A. Trautman, *Boundary conditions at infinity for physical theories*, Bull. Acad. Polon. Sci. 6, 403 (1958); A. Trautman, *Radiation and boundary conditions in the theory of gravitation*, Bull. Acad. Polon. *Sci.* 6, 407 (1958)

[19] A. Einstein, L. Infeld, and B. Hoffmann, *The Gravitational equations and the problem of motion*, Ann. Math. 39, 65 (1938)

[20] L. Blanchet, *Gravitational radiation from post-Newtonian sources and inspiralling compact binaries*, Living Rev. Relativity 17, 2 (2014); an earlier version in Living Rev. Relativity 5, 3 (2002)

[21] S.A. Teukolsky, *Perturbations of a rotating black hole. 1. Fundamental equations for gravitational, electromagnetic, and neutrino-field perturbations*, Astrophys. J. 185, 635 (1973); S.L. Detweiler, *Klein-Gordon equation and rotating black holes*, Astrophys. J. 239, 292 (1980)

[22] A. Buonanno and T. Damour, *Effective one-body approach to general relativistic two-body dynamics*, Phys. Rev. D 59, 084006 (1999); A. Buonanno and T. Damour, *Transition from inspiral to plunge in binary black hole coalescences*, Phys. Rev. D62, 064015 (2000); T. Damour, P. Jaranowski and G. Schafer, *Effective one body approach to the dynamics of two spinning black holes with next-to-leading order spin-orbit coupling*, Phys. Rev. D78, 024009 (2008); T. Damour and A. Nagar, *An improved analytical description of inspiraling and coalescing black-hole binaries*, Phys. Rev. D79, 081503 (2009); E. Barausse and A. Buonanno, *An improved effective-one-body Hamiltonian for spinning black-hole binaries*, Phys. Rev. D81, 084024 (2010)

[23] F. Pretorius, *Evolution of binary black hole spacetimes*, Phys. Rev. Lett. 95, 121101 (2005); M. Campanelli, C.O. Lousto, P. Marronetti and Y. Zlochower, *Accurate evolutions of orbiting black-hole binaries without excision*, Phys. Rev. Lett. 96, 111101 (2006); J.G. Baker, J. Centrella, D.-I. Choi, M. Koppitz and J. van Meter, *Gravitational wave extraction from an inspiraling configuration of merging black holes,* Phys. Rev. Lett. 96, 111102 (2006)

[24] B.P. Abbott et al. (LIGO Scientific Collaboration and VIRGO Collaboration), Ann. Phys. 529, 1600209 (2017)

[25] K. Riles, *Gravitational waves: Sources, detectors and searches*, Prog. Part. Nucl. Phys. 68, 1-54 (2013)

[26] M.E. Gertsenshtein and V.I. Pustovoit, *On the detection of low frequency gravitational waves*, Sov. Phys. JETP 16, 433 (1963) (Original in Russian – ZhETF 43, 605 (1962)

[27] R.L. Forward, *Multidirectional, multipolarization antennas for scalar and tensor gravitational radiation*, Gen. Rel. and Grav. 2(2) 149, 1971; G.E. Moss, L.R. Miller and R.L. Forward, *Photon –noise-limited laser transducer for gravitational antenna*, Appl. Opt. 31(10), 1641 (1971); R.L. Forward, *Wideband, laser interferometer gravitational radiation experiment*, Phys. Rev. D17, 379 (1978)

[28] F.A.E. Pirani, *On the physical significance of the Riemann tensor*, Acta Phys. Polon. 15, 389 (1956)

[29] R. Weiss, *Quarterly progress report,* MIT Research Lab of Electronics 105, 54 (1972)

[30] H. Billing *et al.*, *An argon laser interferometer for the detection of gravitational radiation*, J. Phys. E: Sci. Instrum. 12, 1043 (1979); D. Shoemaker *et al.*, *Noise behaviour of the Garching 30-meter prototype gravitational-wave detector*, Phys. Rev. D 38, 423 (1988)

[31] R.W.P. Drever *et al.*, *Gravitational wave detectors*, Proc. Roy. Soc. Lond. A368, 11 (1979); H. Ward *et al.*, *Laser interferometric sensing techniques for very small displacements with applications to gravitational radiation*, IEEE Trans. Instrum. Measur. 34, 261 (1985); J. Hough *et al.*, *Gravitation, geometry and relativistic physics*, Lecture Notes in Physics vol. 212, 204 (1984), Springer Verlag

[32] R. Weiss, P.R. Saulson, P. Linsay and S. Whitcomb,
dcc.ligo.org/public/0028/T830001/000/NSF_bluebook_1983.pdf

[33] F. Acernese(VIRGO Collaboration), *Status of VIRGO*, Class. Quantum Grav. 21, S385 (2004)

[34] R. Takahashi (TAMA Collaboration), *Status of TAMA300*, Class. Quantum Grav. 21, S403 (2004)

[35] C.J. Moore, R.H. Cole and C.P.L. Berry, *Gravitational wave sensitivity curves,* Class. Quantum Grav. 32, 015014 (2015)

[36] *J. Abadie et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors*, Class. Quantum Grav. 27, 173001 (2010)

[37] B.P. Abbott et al. (LIGO Scientific Collaboration and VIRGO Collaboration), *GW150914: The Advanced LIGO detectors in the era of first discoveries*, Phys. Rev. Lett. 116, 131103 (2016)

[38] A. Effler *et al.*, *Environmental influences on the LIGO gravitational wave detectors during the 6th science run*, Class. Quantum Grav. 32, 035017 (2015)

[39] B.P. Abbott et al. (LIGO Scientific Collaboration and VIRGO Collaboration), *Localization and broadband follow-up of the gravitational-wave transient GW150914*, Astrophys. J. Lett. 826, L13 (2016)

[40] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Observing gravitational-wave transient GW150914 with minimal assumptions*, Phys. Rev. D93, 122004 (2016)

[41] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Properties of the binary black hole merger GW150914*, Phys. Rev. Lett. 116, 241102 (2016); B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Effects of waveform model systematics on the interpretation of GW150914*, Class. Quantum. Grav. 34, 104002 (2017)

[42] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Directly comparing GW150914 with numerical solutions of Einstein's equations for binary black hole coalescence*, Phys. Rev D94, 064035 (2016)

[43] B.P. Abbott *et al.* (LIGO Scientific Collaboration and VIRGO Collaboration), *Tests of general relativity with GW150914*, Phys. Rev. Lett. 116, 221101 (2016)

[44] J. Abadie *et al.* (LIGO Scientific Collaboration), *A gravitational wave observatory operating beyond the quantum shot-noise limit*, Nat. Phys. 7, 962 (2007); J. Aasi *et al.* (LIGO Scientific Collaboration), *Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light*, Nat. Phot. 7, 613 (2013); H. Grote *et al.*, *First long-term application of squeezed states of light in a gravitational-wave observatory*, Phys. Rev. Lett. 110, 181101 (2013)

[45] K Somiya (KAGRA Collaboration), *Detector configuration of KAGRA – the Japanese cryogenic gravitational-wave detector*, Class. Quantum Grav. 29, 124007 (2012)

[46] C.S. Unnikrishnan, *IndIGO and LIGO-India: Scope and plans for gravitational wave research and precision metrology in India*, Int. J. Mod. Phys. D22, 1341010 (2013), updated in arXiv:1510.06059

[47] P. Amaro-Seoane *et al.*, *Laser Interferometer Space Antenna*, arXiv:1702.00786

[48] S. Kawamura et al., The Japanese space gravitational-wave antenna: DECIGO, Class. Quantum Grav. 28, 094011 (2011)

[49] R.N. Manchester (IPTA), *The International Pulsar Timing Array*, Class. Quantum Grav. 30, 224010 (2013)

[50] C.L. Carili and S. Rawlings, *Science with the Square Kilometre Array*, New Astron. Rev. 48, 979 (2004); J. Lazio, *The Square Kilometre Array*, arXiv:0910.0632