Gravitational Wave Detection

Marie-Anne Bizouard, Paris-Saclay University, Orsay, France
Nelson Christensen, Carleton College, Northfield, MN, United States and University of Côte d'Azur, Nice, France

Introduction

In the later part of the 19th century, Albert Michelson performed extraordinary experiments that shook the foundations of the physics world. Michelson's precise determination of the speed of light was an accomplishment that takes great skill to reproduce today. Edward Morley teamed up with Michelson to measure the velocity of Earth with respect to the aether. The interferometer that they constructed was exquisite, and through amazing experimental techniques the existence of the aether was disproved. The results of Michelson and Morley led to a revolution in physics, and provided evidence that helped Albert Einstein to develop the general theory of relativity. Now the Michelson interferometer has provided dramatic confirmation of Einstein's theory of general relativity through the direct detection by the Laser Interferometer Gravitational-Wave Observatory (LIGO) of gravitational waves, and the observation of black holes (Abbott *et al.*, 2016a,b).

An accelerating electric charge produces electromagnetic radiation – light. It should come as no surprise that an accelerating mass produces gravitational light, namely, gravitational radiation (or gravitational waves). In 1888 Heinrich Hertz had the luxury to produce and detect electromagnetic radiation in his laboratory. There will be no such luck with gravitational waves because gravity is an extremely weak force.

Albert Einstein postulated the existence of gravitational waves in 1916, and Taylor and Weisberg (1989) indirectly confirmed their existence through observations of the orbital decay of the binary pulsar $1913+16$ system. The direct detection of gravitational waves has been difficult, and has literally taken decades of tedious experimental work to accomplish. The only possibility for producing detectable gravitational waves comes from extremely massive objects accelerating up to relativistic velocities. The gravitational waves that have been detected so far have come from the coalescence of binary black hole systems. For example, GW150914 was produced by the merger of a 29 $M_\odot$ black hole and a 36 $M_\odot$ black hole some 1.3×10^9 light-years away. The total energy radiated in gravitational waves was equivalent to 3 $M_\odot$ c^2, with a peak luminosity of 3.6×10^{56} ergs/s.

Other possibly detectable gravitational wave sources are also astrophysical: supernovae, pulsars, neutron star binary systems, newly formed black holes, or even the Big Bang. The observation of these types of events would be extremely significant for contributing to knowledge in astrophysics and cosmology. Gravitational waves from the Big Bang would provide unique information of the universe at its earliest moments. Observations of core-collapse supernovae will yield a gravitational snapshot of these extreme cataclysmic events. Pulsars are neutron stars that can spin on their axes at frequencies up to hundreds of Hertz, and the signals from these objects will help to decipher their characteristics. Gravitational waves from the final stages of coalescing binary neutron stars could help to accurately determine the size of these objects and the equation of state of nuclear matter; they would also help to explain the mechanism that produces short gamma ray bursts. The observation of black hole formation from these binary systems, and the ringdown of the newly formed black hole as it approaches a perfectly spherical shape, would be the *coup de grâce* for the debate on black hole existence, and the ultimate triumph for general relativity.

Advanced LIGO (Aasi *et al.*, 2015) and Advanced Virgo (Acernese *et al.*, 2015) are second generation interferometric gravitational wave detectors. Initial LIGO and Virgo conducted observations from 2002 through 2010. Advanced LIGO and Advanced Virgo will ultimately have better sensitivities, by a factor of 10, over their initial designs. They will search for gravitational waves from 10 Hz up to a few kilohertz. Their target sensitivities will allow them to observe signals from the coalescence of binary neutron star systems (1.4 $M_\odot$ – 1.4 $M_\odot$) out to distances of 200 Mpc for Advanced LIGO and 150 Mpc for Advanced Virgo. The mergers of more massive binary black holes systems will extend much farther.

Electromagnetic radiation has an electric field transverse to the direction of propagation, and a charged particle interacting with the radiation will experience a force. Similarly, gravitational waves will produce a transverse force on massive objects, a tidal force. Explained via general relativity it is more accurate to say that gravitational waves will deform the fabric of spacetime. Just like electromagnetic radiation there are two polarizations for gravitational waves. Let us imagine a linearly polarized gravitational wave propagating in the *z*-direction, $h(z,t) = h_{0+}e^{i(kz-\omega t)}$. The fabric of space is stretched due to the strain created by the gravitational wave. Consider a length L_0 of space along the *x*-axis. In the presence of the gravitational wave the length oscillates like

$$L(t) = L_0 + \frac{h_{0+}L_0}{2}\cos(\omega t)$$

Hence, there is a change in its length of

$$\Delta L_x = \frac{h_{0+}L_0}{2}\cos(\omega t)$$

A similar length L_0 of the *y*-axis oscillates, like

$$\Delta L_y = -\frac{h_{0+}L_0}{2}\cos(\omega t)$$

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One axis stretches, while the perpendicular one contracts, and then vice versa, as the wave propagates through. Consider the relative change of the lengths of the two axes (at $t=0$),

$$\Delta L = \Delta L_x - \Delta L_y = h_{0+} L_0$$

or

$$h_{0+} = \frac{\Delta L}{L_0}$$

So the amplitude of a gravitational wave is the amount of strain that it produces on spacetime. The other gravitational wave polarization (h_{0x}) produces a strain on axes 45 degree from (x, y). Imagine some astrophysical event produces a gravitational wave that has amplitude h_{0+} on Earth; in order to detect a small distance displacement ΔL one should have a detector that spans a large length L_0. The first gravitational wave observed by LIGO had an amplitude of $h \sim 10^{-21}$ with a frequency at peak gravitational wave strain of 150 Hz (Abbott *et al.*, 2016a). The magnitude of a gravitational wave falls off as $1/r$, so it will be impossible to observe events that are too far away. However, when the detectors' sensitivity is improved by a factor of n, the rate of signals should grow as n^3 (the increase of the observable volume of the universe). This is because the gravitational wave detectors to be discussed below measure signals from all directions; they cannot be pointed, but reside in a fixed position on the surface of the Earth.

A Michelson interferometer, with arms aligned along the x and y axes, can measure small phase differences between the light in the two arms. Therefore this type of interferometer can turn the length variations of the arms produced by a gravitational wave into changes in the interference pattern of the light exiting the system. This was the basis of the idea from which modern laser interferometric gravitational wave detectors have evolved. Imagine a gravitational wave of amplitude h is incident on an interferometer. The change in the arm length will be $\Delta L \sim h\, L_0$, so in order to optimize the sensitivity it is advantageous to make the interferometer arm length L_0 as large as possible. The Advanced LIGO and Advanced Virgo detectors will measure distance displacements that are of order $\Delta L \sim 10^{-18}$ m or smaller, much smaller than an atomic nucleus. The recent observation of gravitational waves has been one of the most spectacular accomplishments in experimental physics, and has been greeted with much excitement across the globe.

The history of the attempt to measure gravitational waves has been long. The realization that gravitational waves might be detectable crystalized as a result of the Conference on the Role of Gravitation in Physics, Chapel Hill, NC in 1957 (De Witt, 1957). Pirani (2009) had recently published a paper, and then gave presentation at the conference. He showed that the relative acceleration of particle pairs can be associated with the Riemann tensor. The interpretation of the Chapel Hill attendees was that nonzero components of the Riemann tensor were due to gravitational waves. Pirani, Richard Feynmann, and Hermann Bondi came up with the *sticky bead* argument (Bondi, 1957), essentially showing that gravitational waves exist and can be detected. Joe Weber, of the University of Maryland, was also at the Chapel Hill Conference, and from this inspiration he started to think about gravitational wave detection.

A few years after, in the early 1960s, Weber initiated the first experimental attempts to detect gravitational waves. Weber used a 1400 kg aluminum cylinder; a gravitational wave would excite the fundamental mechanical oscillation mode of the bar (Cho, 2016). The idea of using a Michelson interferometer to detect gravitational waves is almost as old as Weber's bar detector. In 1962 two Soviet physicists, Pustovoit and Gertsenshtein, noted that the use of a Michelson interferometer would be a possible means to detect gravitational waves over a frequency range that was broader than the Weber bars. In addition, the authors noted that the interferometers would have a sensitivity that would potentially be better than the Weber bars (Pustovoit and Gertsenshtein, 1963).

Also in the early 1960s, Weber and his student, Robert Forward, also considered using a Michelson interferometer to detect gravitational waves. After completing his PhD with Weber, Forward worked with Hughes Research Laboratories. It was at Hughes that Forward first constructed a Michelson interferometer to be used as a gravitational wave detector. Forward used earphones to listen to the motion of the interference signal (Forward, 1978). The engineering of signal extraction for modern interferometers is obviously far more complex.

At the time Forward was implementing an interferometric gravitational wave detector, Rainer Weiss at MIT produced a thorough investigation into not only how a Michelson interferometer could be used to detect gravitational waves, but also a systematic and comprehensive investigation into the noise sources that would constrain such a measurement (Weiss, 1972). However, as opposed to Forward's design where the laser beam traveled down the arms of the interferometer once, Weiss proposed a system where the laser beam would bounce back and forth multiple times in the interferometer, thereby increasing the effective arm length (and increasing the strain sensitivity of the detector). This is known as a Herriott optical delay line system. In what could be considered as the most important part of Weiss's (1972) presentation, he systematically listed and quantified the most important noise sources in an interferometric gravitational wave detector. These noise sources included amplitude noise on the laser source (including shot noise), frequency noise of the laser source, thermal noise in the masses and their suspension systems, radiation pressure noise from the laser light, seismic noise, noise due to residual gas in the vacuum system housing the interferometric detector, cosmic ray noise, gravitational-gradient noise, and residual electric and magnetic field noise. This comprehensive description of a realistic broadband interferometric gravitational wave detector initiated the experimental effort that has led to the present day LIGO and Virgo detectors.

Subsequently there was rapid activity on the construction of prototype laser interferometric gravitational wave detectors. The goal was to make prototypes that demonstrated the technology needed to construct kilometer-length interferometers. In the late 1970s, the Max Planck group in Garching, near Munich, Germany, created a 3 m arm length detector (Billing *et al.*, 1979), and a 30 m detector in the early 1980s (Shoemaker *et al.*, 1988); this instrument was the first which showed a correspondence between noise models and performance in the spirit of Weiss's (1972) paper. Also, in the early 1980s Weiss and his team at MIT built laser interferometric gravitational wave detector with a Herriott optical delay line system and 1.5 m length arms. The Munich interferometers were also Herriott delay lines. The early 1980s also saw the construction of a 10 m prototype in Glasgow, Scotland (Ward *et al.*, 1985). The uniqueness of this system was that instead of the Herriott delay lines in the arms it used resonant optical cavities (Drever *et al.*, 1981, 1983), an idea by Ron Drever (then at Glasgow, before moving to Caltech). These Fabry–Perot cavities, to be discussed below, also have the light bounce back and forth a number of times, but in a resonant fashion within an optical cavity. A similar interferometer, albeit with 40 m arms, was then constructed at Caltech in the late 1980s (Spero, 1986). Fabry-–Perot cavities were eventually incorporated into the design of LIGO and Virgo. The work on all of these prototypes were absolutely critical in establishing the technology needed for LIGO (Abramovici *et al.*, 1992). Similarly in the 1980s, the work on lasers, laser stabilization and interferometer optics in Orsay, France, plus the research on vibration isolation systems in Pisa, Italy, helped to create Virgo (Bradaschia *et al.*, 1990).

Numerous collaborations are building and operating second generation interferometers in order to detect gravitational waves. Advanced LIGO in the United States consists of two 4 km interferometers located in Livingston, Louisiana, and Hanford, Washington (Aasi *et al.*, 2015). Advanced LIGO started observations in 2015, and will be working over the coming years to achieve its design sensitivity, with the goal to reach it by 2019. The European Advanced Virgo is a 3 km interferometer near Pisa, Italy (Acernese *et al.*, 2015), and will start acquiring data in 2017, and will also be aiming for its target sensitivity in the coming years. GEO-600, a German-British collaboration, is a 600 m detector near Hanover, Germany (Affeldt *et al.*, 2014), and is currently operational. KAGRA is the Japanese 3 km interferometer that is presently under construction, and should commence observations in 2019 (Somiya, 2012). There will be a third 4 km LIGO interferometer, LIGO-India (Unnikrishnan, 2013), located in India, with the goal to be operational by 2024. All of the kilometer-length detectors will be attempting to detect gravitational waves with frequencies from 10 Hz up to a few kilohertz.

As will be described below, there are a number of terrestrial noise sources that will inhibit the performance of the interferometric detectors. The sensitivity of detection increases linearly with interferometer arm length, which implies that there could be advantages to constructing a gravitational wave detector in space. This is the goal of the laser interferometer space antenna (LISA) consortium. The plan is to deploy three satellites in a heliocentric orbit with a separation of about 2.5×10^6 km. LISA is a European Space Agency project, with a target launch date of 2034. LISA will observe gravitational waves in a frequency band from below 10^{-4} Hz to above 10^{-1} Hz. Due to the extremely long baseline, LISA is not strictly an interferometer, as most light will be lost as the laser beams expand, while traveling such a great distance. Instead, the phase of the received light will be detected and used to lock the phase of the light that is reemitted by another laser. Much of the technology needed for LISA to succeed was recently demonstrated with the LISA Pathfinder mission; in this mission the relative acceleration between two test masses was measured to be $5.2 \pm 0.1\,\mathrm{fm/s^2/\sqrt{Hz}}$ for frequencies between 0.7 and 20 mHz (Armano *et al.*, 2016).

Interferometer Configurations

The Michelson interferometer is the tool to be used to detect a gravitational wave. **Fig. 1** shows a basic optical setup. The beamsplitter and the end mirrors would be suspended by wires, and effectively free to move in the plane of the interferometer. The arms have lengths L_1 and L_2 that are roughly equal on a kilometer scale. With a laser power P and wavelength λ incident on the beamsplitter, the light exiting the dark port of the interferometer is

$$P_{\mathrm{out}} = P \sin^2\left[\frac{2\pi}{\lambda}(L_1 - L_2)\right]$$

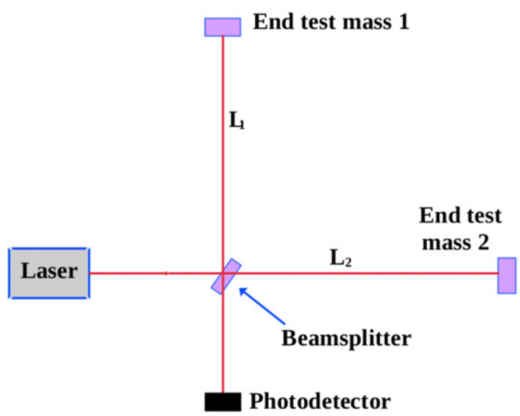

Fig. 1 A basic Michelson interferometer. The photodetector receives light exiting the dark port of the interferometer and hence the signal.

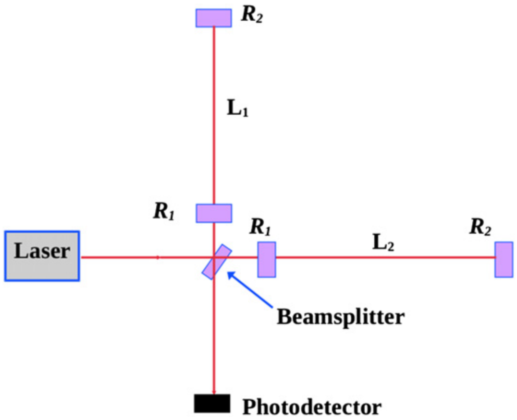

Fig. 2 A Michelson interferometer with Fabry–Perot cavities in each arm. The front cavity mirrors have reflectivity R_1, while the end mirrors have $R_2 \sim 1$. By using Fabry–Perot cavities Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) will increase the effective arm length by a factor of 140.

The interferometer operates with the condition that in the absence of excitation the light exiting the dark port is zero. This would be the case for a simple and basic interferometer. If E_0 is the amplitude of the electric field from the laser, and assuming the use of a 50–50 beamsplitter, the electric field (neglecting unimportant common phase shifts) for the light incident on the photodetector would be

$$E_{\text{out}} = E(e^{i\delta\phi_1} - e^{i\delta\phi_2}) \approx i\frac{E_0}{2}(\delta\phi_1 - \delta\phi_2) = iE_0\frac{2\pi}{\lambda}(L_1 - L_2)$$

A gravitational wave of optimal polarization normally incident upon the interferometer plane will cause one arm to decrease in length, while the other increases. The Michelson interferometer acts as a gravitational wave transducer; the stretching and squeezing of the spacetime between the mirrors results in more light exiting the interferometer dark port. The mirrors in the interferometer are suspended via fibers so that they are free to move under the influence of the gravitational wave, acting like relativistic freely falling masses.

An interferometer's sensitivity to gravitational waves increases with arm length, but geographical, physical, and financial constraints will limit the size of the arms. If there could be some way to bounce the light back and forth to increase the effective arm length it would increase the detector performance. Fabry–Perot cavities do just that. When they are on resonance they have a storage time for the light of

$$\tau_s = \frac{2L(R_1R_2)^{1/4}}{\left[c\left(1 - \sqrt{R_1R_2}\right)\right]}$$

where (R_1 and R_2 are power reflection coefficients). **Fig. 2** shows the system of a Michelson interferometer with Fabry–Perot cavities. This gravitational wave interferometer design was proposed in the late 1970s by Ron Drever, and subequently tested by his research group in the early 1980s (Drever *et al.*, 1981, 1983). The far mirror R_2 has a very high reflectivity ($R_2 \sim 1$) in order to ultimately direct the light back toward the beamsplitter. The front mirror reflectivity R_1 is such that LIGO's effective arm length increases from $L = 4$ km to $L \sim 560$ km. The optical properties of the mirrors of the Fabry–Perot cavities must be exquisite in order to achieve success. The mirror substrates are made via a combination of super-polishing for small scale smoothness, and then ion-beam milling for large scale uniformity. The coatings (doped tantala) for the mirrors are ion-beam sputtered, multilayer dielectrics. The mirrors for Advanced LIGO (and Advanced Virgo) were coated by Laboratoire des Matériaux Avancés (LMA, Lyon, France). Advanced LIGO's mirrors were tested, and the surface errors are between 0.08 and 0.23 nm, with absorption between 0.2 (parts per million) and 0.4 ppm. In terms of both absorbtion and scattering, the Advanced LIGO arm round-trip loss goal is less than 75 ppm. The radius of curvature for the input mirrors (R_1) is 1934 m, while for the end mirrors (R_2) it is 2245 m, with a radius of curvature spread between -1.5 and 1.0 m (Aasi *et al.*, 2015). A LIGO test mass (and therefore a Fabry–Perot mirror) can be seen in **Fig. 3**. The mirrors for Advanced Virgo have similar exquisite properties (Acernese *et al.*, 2015).

In 1888 Michelson and Morley, with their interferometer, had a sensitivity that allowed the measurement of 0.02 of a fringe, or about 0.126 rad. The Advanced LIGO interferometers during the first observing run O1 have already demonstrated a phase noise spectral density of

$$\phi(f) = 5 \times 10^{-11} \text{radian}/\sqrt{\text{Hz}}$$

for frequencies around 150 Hz. Assuming a 150 Hz signal with a 150 Hz bandwidth this implies a phase sensitivity of $\Delta\phi = 6.1 \times 10^{-10}$ rad. There has been quite an evolution in interferometry since Michelson's time.

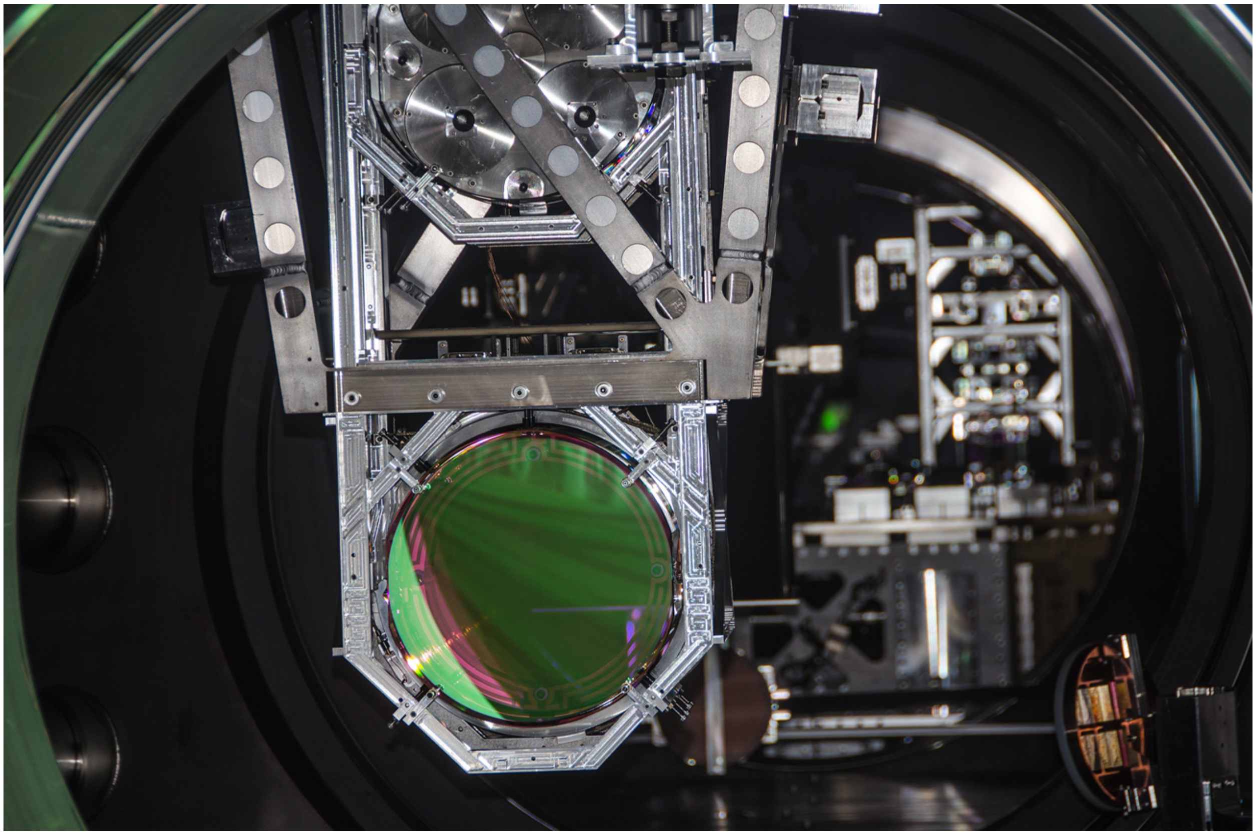

Fig. 3 A picture of the input test mass (mirror R_1) for Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) within its vibration isolation suspension system. The fused silica component is 40 kg, 34 cm in diameter, and 20 cm thick. Photograph courtesy of LIGO/Caltech/MIT.

The noise sources that inhibit the interferometer performance are discussed below. However, let us consider one's ability to measure the relative phase between the light in the two arms. The Heisenberg uncertainty relation for light with phase ϕ and photon number N is $\Delta\phi\Delta N \sim 1$. For a measurement lasting time τ using laser power P and frequency f, the photon number is $N = P\lambda\tau/hc$ (here h is Planck's constant), and with Poisson statistics describing the light $\Delta N = \sqrt{N} = \sqrt{P\lambda\tau/hc}$. Therefore

$$\Delta\phi\ \Delta N = \frac{2\pi}{\lambda}\Delta L\sqrt{P\lambda\tau/hc} = 1$$

implies that

$$\Delta L = \frac{1}{2\pi}\sqrt{hc\lambda/P\tau}$$

With more light power the interferometer can measure smaller distance displacements and achieve better sensitivity. Advanced LIGO and Advanced Virgo will use about 200 W of laser light. However, there is a nice trick one can use to produce more light circulating in the interferometer, namely power recycling (Meers, 1988). **Fig. 4** displays the power recycling interferometer design. The interferometer operates such that virtually none of the light exits the interferometer dark port, and the bulk of the light returns toward the laser. An additional mirror, R_r, in **Fig. 4**, recycles the light. The Advanced LIGO goals are to have 125 W actually impinging on the recycling mirror R_r, creating 5.2 kW upon the beamsplitter, and 750 kW within the Fabry–Perot cavities in each of the interferometer's arms. For Advanced LIGO, recycling will increase the effective light power by another factor of 42. Advanced Virgo has a similar design. The higher circulating light power therefore improves the sensitivity of these interferometric detectors. It is also interesting to note that the GEO-600 detector has been operating for years using squeezed light, namely quantum states of light, as a way to reduce the noise below the shot noise limit (Affeldt *et al.*, 2014).

There is one additional modification to the interferometer system that can further improve sensitivity, but only at a particular frequency. A further Fabry–Perot system can be made by installing what is called a signal recycling mirror (SRM); this would be mirror R_s in **Fig. 5** (Meers, 1988). Imagine the light in arm 1 of the interferometer, and that it acquires phase as the arm expands due to a gravitational wave. The traveling gravitational wave's oscillation will subsequently cause arm 1 to contract, while arm 2 expands. If the light that was in arm 1 could be sent to arm 2, while it is expanding, then the beam would acquire additional phase. This process could be repeated over and over. Mirror R_s serves this purpose, with its reflectivity defining the storage time for light in each interferometer arm. The storage time defined by the cavity formed by the SRM, R_s, and the mirror at the front of the interferometer arm cavity, R_1, determines the resonance frequency. Signal recycling will give a substantial boost to interferometer

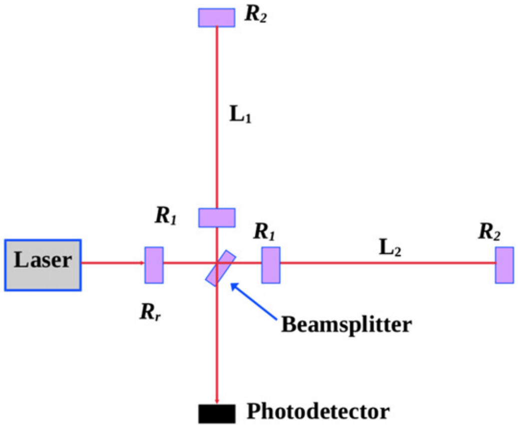

Fig. 4 A power recycled Michelson interferometer with Fabry–Perot cavities in each arm. Normally light would exit the interferometer through the light port and head back to the laser. Installation of the recycling mirror with reflectivity R_r sends the light back into the system. A Fabry–Perot cavity is formed between the recycling mirror and the first mirror (R_1) of the arms. For Advanced LIGO this strategy will increase the power circulating in the interferometer by a factor of 42.

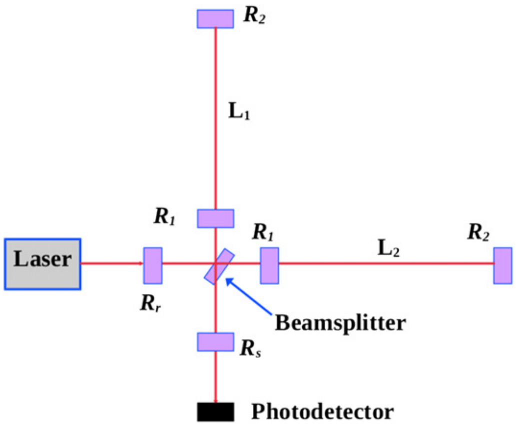

Fig. 5 A signal recycled and power recycled Michelson interferometer with Fabry–Perot cavities in each arm. Normally light containing the gravitational wave signal would exit the interferometer via the dark port and head to the photodetector. Installation of the SRM with reflectivity R_s sends the light back into the system. The phase of the light acquired from the gravitational wave will build up at a particular frequency determined by the reflectivity R_s.

sensitivity at a particular frequency, and will eventually be implemented in all the main ground-based interferometric detectors. The Advanced LIGO and Advanced Virgo interferometers are infinitely more complex than the relatively simple systems displayed in the figures of this paper.

Fig. 6(a) presents an aerial view of the LIGO site at Hanford, Washington. The magnitude of the 4 km system is apparent. Fig. 6 (b) displays the Virgo detector with its 3 km, located near Pisa, Italy.

Noise Sources and Interferometer Sensitivity

If the interferometers are to detect distance displacements less than 10^{-18} m then they must be isolated from a host of deleterious noise sources. Seismic disturbances should not shake the interferometers. Thermal excitation of components will affect the sensitivity of the detector and should be minimized. The entire interferometer must be in an adequate vacuum in order to avoid fluctuations in gas density that would cause changes in the index of refraction and hence a modification of the optical path length. The laser intensity and frequency noise must be minimized. The counting statistics of photons influences accuracy. If ever there was a detector that must avoid Murphy's law this is it; little things going wrong cannot be permitted if such small distance displacements are to be detected. The target noise sensitivity for the Advanced LIGO interferometers is displayed in Fig. 7.

In the best of all worlds the interferometer sensitivity will be limited by the counting statistics of the photons. A proper functioning laser will have its photon number described by Poisson statistics, or shot noise; if the mean number of photons arriving per unit time is N then the uncertainty is $\Delta N = \sqrt{N}$, which as noted above implies an interferometer displacement

(a)

(b)

Fig. 6 (a) Aerial view of the Laser Interferometer Gravitational-Wave Observatory (LIGO) Hanford, Washington site. The vacuum enclosure at Hanford contains the 4 km interferometer. Photograph courtesy of LIGO/Caltech/MIT. (b) Aerial view of the Virgo detector, with 3 km arms, located near Pisa, Italy. Photograph courtesy of the European Gravitational Observatory.

sensitivity of

$$\Delta L = \frac{1}{2\pi}\sqrt{\frac{hc\lambda}{P\tau}}$$

(where P is the light power impinging on the beamsplitter) or a spectral density of

$$\Delta L(f) = \frac{1}{2\pi}\sqrt{\frac{hc\lambda}{P}}$$

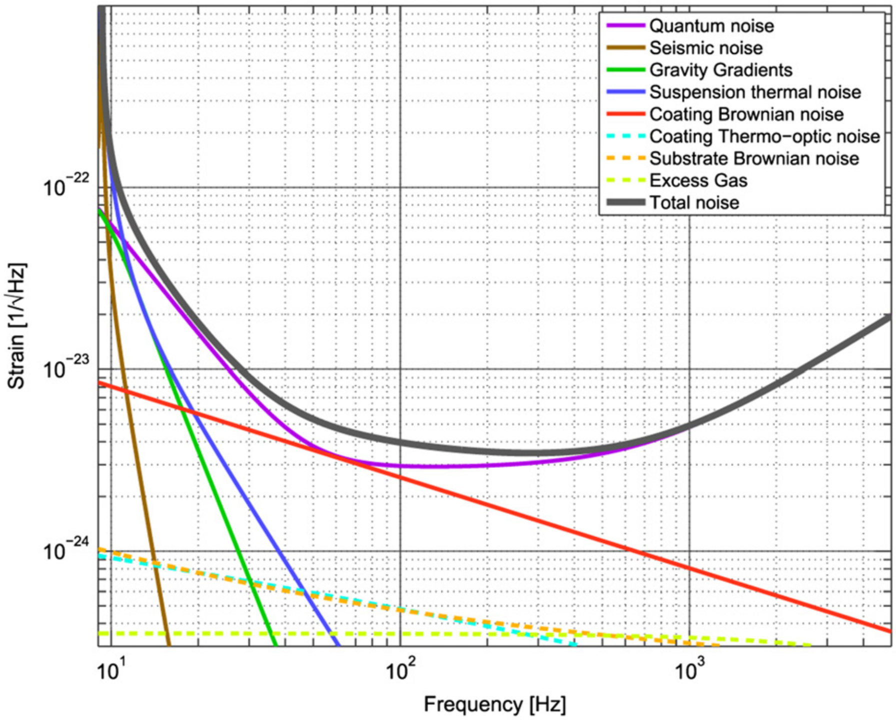

Fig. 7 The target spectral density of the noise for the Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) system. Advanced LIGO will be limited by seismic noise at low frequencies (∼10 Hz), thermal noise (from the suspension system and the coatings of the mirrors) in the intermediate regime (∼100 Hz). Radiation pressure will also be a dominating noise source from ∼10 to ∼100 Hz, while photon shot noise will be the limiting noise thereafter. Together the radiation pressure noise and the shot noise are referred to as quantum noise. Other sources of noise are also noted in the figure. This figure is from Aasi, J., Abadie, J., Abbott, B., *et al.*, 2015. Classical and Quantum Gravity 32. Available at: http://stacks.iop.org/0264-9381/32/i=7/a=074001.s; which should be consulted for a more expansive description of the limiting noise sources for Advanced LIGO.

in units of $\mathrm{m}/\sqrt{\mathrm{Hz}}$. Note also that the sensitivity increases as the light power increases. The reason for this derives from the statistics of repeated measurements. The relative lengths of the interferometer arms could be measured, once, by a photon. However, the relative positions are measured repeatedly with every photon from the laser, and the variance of the mean decreases as $\sqrt{N}$ where N is the number of measurements (or photons) involved. The uncertainty in the difference of the interferometer arm lengths is therefore inversely proportional to photon number, and hence the laser's power. In terms of strain sensitivity this would imply

$$h(f) = \frac{1}{2\pi L}\sqrt{\frac{hc\lambda}{P}}$$

This assumes the light just travels down the arm and back once. With Fabry–Perot cavities the light is stored, and the typical photon takes many trips back and forth before exiting the system. In order to maximize light power the end mirrors ($R_2 \sim 1$) and the strain sensitivity is improved to

$$h(f) = \frac{1}{4\pi\tau_s}\sqrt{\frac{\pi\hbar\lambda}{Pc}}$$

where the Fabry–Perot cavity storage time τ_s was defined above.

As the frequency of gravitational waves increases the detection sensitivity will decrease. If the gravitational wave causes the interferometer arm length to increase, then decrease, while the photons are still in the arm cavity, then the phase acquired from the gravitational wave will be washed away. This is the reason why interferometer sensitivity decreases as frequency increases, and explains the high frequency behavior seen in **Fig. 7**. Taking this into account, the strain sensitivity is

$$h(f) = \frac{1}{4\pi\tau_s}\sqrt{\frac{\pi\hbar\lambda}{Pc}}\left(1 + (4\pi f\tau_s)^2\right)^{1/2}$$

and f is the frequency of the gravitational wave.

If the gravitational wave is to change the interferometer arm length then the mirrors that define the arm must be free to move like freely falling masses. In systems like Advanced LIGO and Advanced Virgo, wires suspend the mirrors; each mirror is like a pendulum. The mirrors and the wires that suspend them are a monolithic-fused silica assembly, with the wires annealed and welded to the sides of the mirrors. The pendulum itself is the first component of an elaborate vibration isolation system. Seismic noise will be troublesome for the detector at low frequencies. The spectral density of the seismic noise is about $x(f) = \left(10^{-9}\ m/\sqrt{\mathrm{Hz}}\right)(10\ \mathrm{Hz}/f)^2$ for $f > 10$ Hz (the low frequency observational limit for Advanced LIGO and Advanced Virgo) (Saulson, 1994). A simple pendulum, by itself, acts as a motion filtering device. Above its resonance frequency a pendulum filters motion with a transfer function like $T(f) \propto (f_0/f)^2$, where f_0 is the resonant frequency for the pendulum. The mirrors for Advanced LIGO will actually be suspended by a four-stage pendulum system. The various gravitational wave detector collaborations have different vibration isolation designs. The mirrors in these interferometers are suspended in elaborate vibration isolation systems, which may include multiple pendulums, isolation stacks, and isolated optical tables. For example, for many years super-attenuators have made Virgo the most sensitive gravitational wave detector in the low frequency regime (below ~ 40 Hz) (Acernese *et al.*, 2015). Active feedback is used on some parts of the isolation system to control seismic noise below ~ 10 Hz. Seismic noise will be the limiting factor for interferometers seeking to detect gravitational waves in the vicinity of ~ 10 Hz, as can be seen in the sensitivity curve presented in **Fig. 7**.

Due to the extremely small distance displacements that these systems are trying to detect it should come as no surprise that thermal noise is a problem. This noise enters through a number of components in the system. The two most serious thermal noise sources are the wires suspending the mirrors in the pendulum, and the mirrors themselves, especially the optical coatings on the mirror surfaces. Consider the wires; there are a number of notes at which they can oscillate (i.e., violin modes). At temperature T each mode will have energy of $k_B T$, but distributed over a band of frequencies determined by the quality factor (or Q) of the material. Low-loss (or high-Q) materials work best; for the violin modes of the wires there will be much noise at particular frequencies (in the hundreds of hertz). For the Advanced LIGO mirrors the first violin mode is at 510 Hz, while the vertical stretching mode of the wires is at ~ 9 Hz.

The best sensitivity for Advanced LIGO and Advanced Virgo occurs around ~ 100 Hz. The limiting source of noise in this region (along with quantum noise) is due to Brownian noise in the optical coatings on the mirror surfaces. There is a tremendous amount of on-going research to try and reduce the mechanical dissipation in the optical coatings. The Japanese detector KAGRA, which is currently under construction, will have its mirrors and the bottom parts of its suspension system cooled to 20K (Somiya, 2012) in order to reduce thermal noise.

The frequency noise of the laser can couple into the system to produce length displacement noise in the interferometer. With arm lengths of ~ 4 km, it will be impossible to hold the length of the two arms absolutely equal. The slightly differing arm spans will mean that the light sent back from each of the two Fabry–Perot cavities will have slightly differing phases. As a consequence, great effort is made to stabilize the frequency of the light entering the interferometer. The Advanced LIGO laser can be seen in **Fig. 8**. The primary laser is a nonplanar ring-oscillator (NPRO). This beam is then amplified to 35 W with a medium power oscillator, and then up to 220 W with a high power oscillator; see Aasi *et al.* (2015) for more details. For Advanced LIGO, the laser is locked and held to a specific frequency by use of signals from a reference cavity, a mode cleaner cavity, and the interferometer.

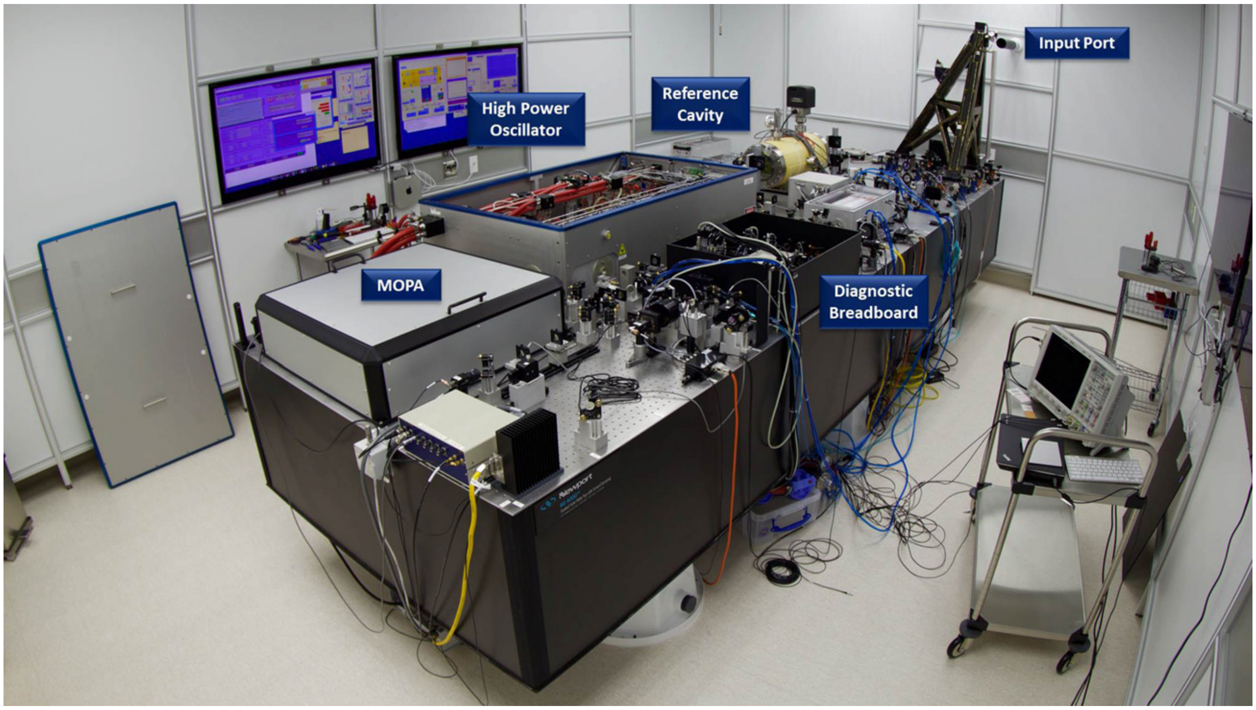

Fig. 8 The Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) laser system. This is a multistage Nd:YAG system that can deliver 200 W. Photograph courtesy of LIGO/Caltech/MIT.

For low frequency stabilization the temperature of the NPRO is adjusted. At intermediate frequencies adjustment is made by signals to a piezoelectric transducer within the NPRO cavity. At high frequencies the noise is reduced with the use of an electro-optic crystal. The Advanced LIGO lasers currently have a frequency noise of $1 \times 10^{-6}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz; this requirement is needed by Advanced Virgo too.

It is also important to worry about the stability of the laser power for the interferometric detectors. The goal is to be quantum noise limited at frequencies within the observational frequency band. The Nd:YAG power amplifiers used are pumped with an array of laser diodes, so the light power is controlled through feedback to the laser diodes. The Advanced LIGO requirements for the fluctuations on the power P are $\Delta P/P < 2 \times 10^{-9}/\sqrt{\mathrm{Hz}}$ at 10 Hz; Advanced Virgo's requirements are similar. In these laser interferometric gravitational wave detectors, the spatial quality of the light is ensured through the use of an input mode cleaning cavity. Advanced LIGO uses an isosceles triangular array of mirrors with the two base mirrors separated by 0.465 m and the third mirror displaced by 16.24 m. The length of the input mode cleaner for Advanced Virgo is 143.424 m. The optical system for Advanced LIGO is displayed in **Fig. 9**. Aside from the laser and the phase modulator, the entire optical system is an ultra-high vacuum. Note that at the output of the interferometer there is a SRM. Given the reflectivity of the mirror, and the phase of the light when arriving at there, it is possible to enhance the gravitational wave signal at a particular frequency by feeding it back into the interferometer for enhancement. The output mode cleaner is used to improve the spatial quality of the output beam, and remove modulation frequency sidebands, before the photodetection.

The target light powers for Advanced LIGO are displayed in **Fig. 9**. When Advanced LIGO attains its target sensitivity there will be 750 kW within the Fabry–Perot cavities. Advanced Virgo's light powers will be similar. With such a large amount of power the

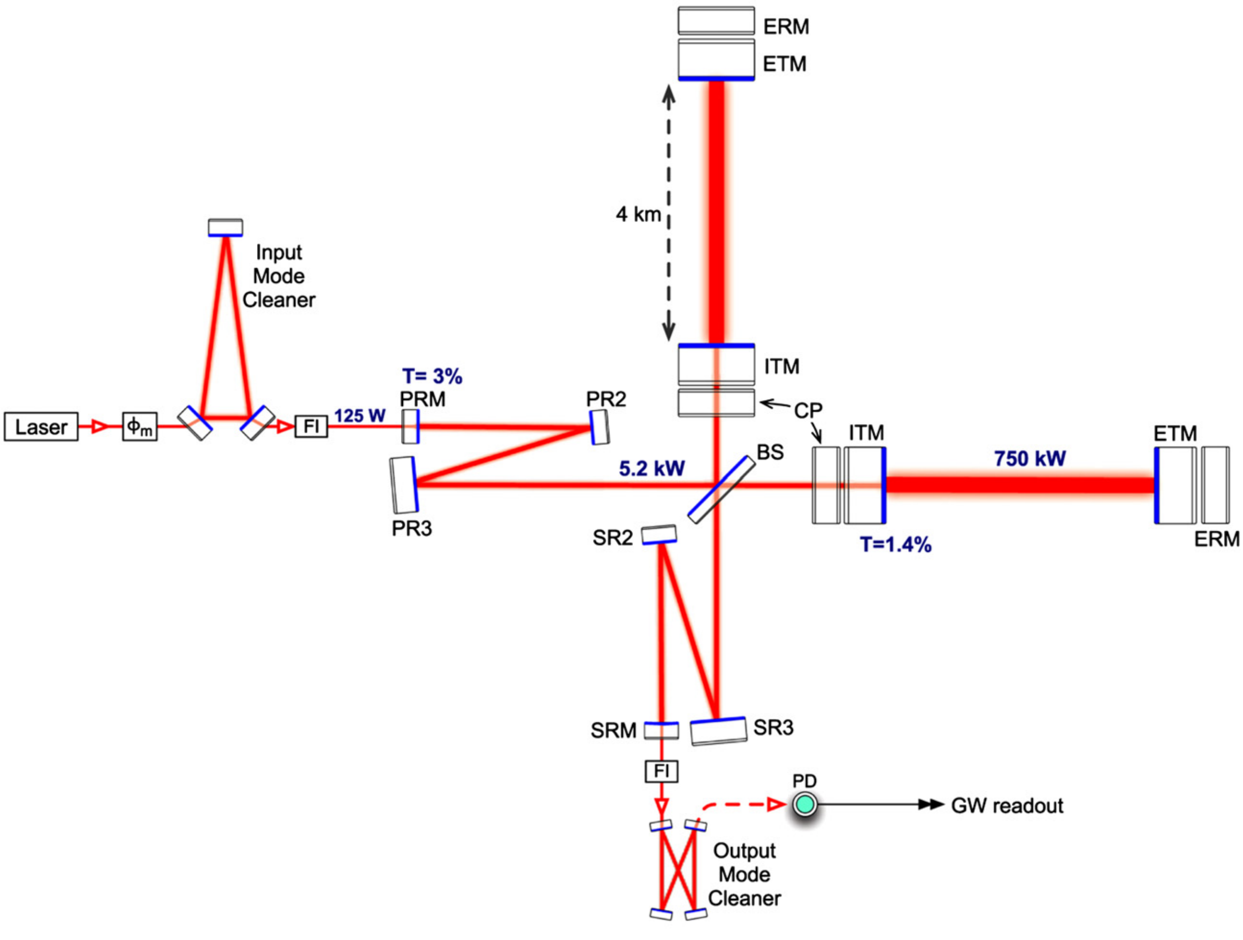

Fig. 9 The Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) optical system. The laser ($\sim$200 W) light propagates from the stabilized laser through a phase modulator (ϕ_m) to the input mode cleaner, then through a Faraday isolator (FI) to the power recycling mirror (PRM). The folding mirrors, PR2 and PR3, direct the light to the beamsplitter (BS) input of the interferometer. Note that approximately 125 W of light impinges upon the power recycling mirror, resulting in 5.2 kW at the input port to the beamsplitter. The Fabry–Perot cavities are formed with the input test mass (ITM), which is coupled to a compensation plate (CP), and the end test mass (ETM) which is coupled to a end reaction mass (ERM). The Fabry–Perot cavities will contain 750 kW of light power. Note too that the output signal from the interferometer can itself be recycled and amplified at specific frequencies, dependent on the reflectivity of the SRM; SR2 and SR3 are folding mirrors. The output beam also has its spatial features cleaned with the output mode cleaner before the light falls upon a photodetector (PD). The figure is from Aasi, J., Abadie, J., Abbott, B., *et al.*, 2015. Classical and Quantum Gravity 32. Available at: http://stacks.iop.org/0264-9381/32/i=7/a=074001.s.

mirrors will actually get heated and lightly change their shape. Ring heaters encircle the input test masses and the end test masses, and are used to correct the shape of the masses. A CO_2 laser beam is also sent onto the surface of the compensation plate to provide further corrections to the thermal lens of the input test mass. The compensation plate serves as a reaction mass for the input test mass in its isolation suspension system; the same is true for the end reaction mass with respect to the end test mass.

Parametric instabilities are another consequence of high power operation for Advanced LIGO and Advanced Virgo. This is an interaction between a mechanical oscillation mode of the mirror and higher order optical modes via light scattering. This can be a nonlinear process and can prevent the interferometers from operating at higher powers. Advanced LIGO has observed parametric instabilities (Evans *et al.*, 2015). To eliminate the excited modes one can heat the mirror to slightly change its shape, thereby changing the mechanical oscillation mode with respect to an excited optical mode. Advanced LIGO uses electrostatic actuators to move the masses; the actuators can also be used to damp excited mechanical modes.

The immense number of photons, coupled with the fact that the photon arrival times are random (Poisson statistics) means that radiation reaction noise will be important. This can be seen in the low frequency component of the quantum noise in **Fig. 7**. The low frequency radiation reaction noise, plus the high frequency shot noise, combine to create the total quantum noise in the interferometer. At high frequencies the shot noise decreases with laser power, while at low frequencies radiation reaction noise and the basic interferometer's quantum noise is a tradeoff between these two effects. While this quantum noise seems to be an unavoidable noise source, quantum states of light (namely squeezed states of light) can reduce this noise. This reduction of noise was demonstrated by initial LIGO (Aasi *et al.*, 2013) where squeezed light reduced the noise below the shot noise level for frequencies above 150 Hz; for higher frequencies a 2.15 dB (28%) reduction in the shot noise was observed. The GEO-600 gravitational wave detector now uses squeezed light continuously, and has achieved an impressive 3.7 dB reduction in the shot noise level (Affeldt *et al.*, 2014). The use of quantum states of light is one of the ways that Virgo and LIGO hope to reduce their noise in the years to come.

Gravitational Wave Detection GW150914

On September 14, 2015, at 09:50:45 UTC a gravitational wave was detected directly for the first time. The gravitational wave was first observed at the LIGO Livingston Observatory (Louisiana), and then 7 ms later at the LIGO Hanford Observations (Washington). An on-line signal search algorithm identified the signal in 3 min. An off-line examination of the data using a template-based search for compact binary coalescence signals identified the gravitational wave with a signal-to-noise ratio of 24

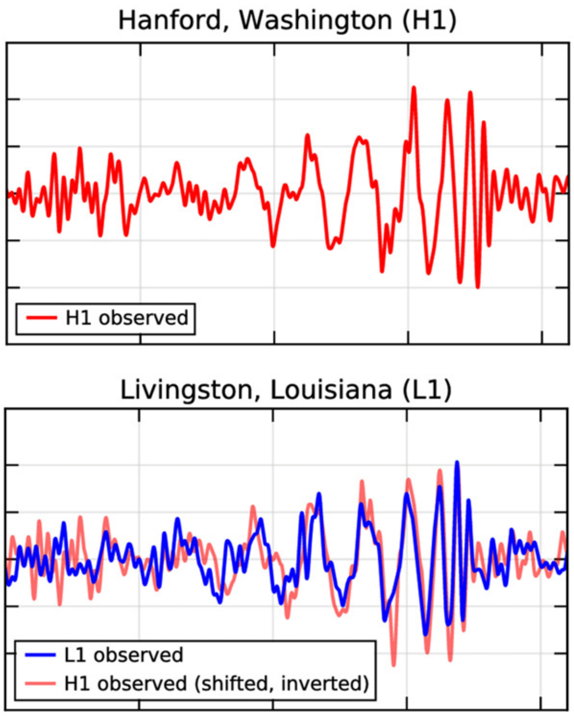

Fig. 10 The measured gravitational wave signal GW150914 as observed at the two Advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) interferometric detectors. The data has been bandpass filtered (35–350 Hz), and the gravitational wave signal is clearly observable by eye. Top: the signal as observed from the LIGO Hanford detector. Bottom: the signal as observed from the LIGO Livingston detector (blue). In addition, the Hanford signal (red) is superimposed after it has been displaced by 7 ms and inverted (due to the relative orientation of the two detectors). The similarity of the two measured signals is clearly visible. Figures courtesy of the LIGO Open Science Center (losc.ligo.org).

(Abbott *et al.*, 2016a). Parameter estimation routines were used to determine that the gravitational wave signal was emitted from the merger of two black holes with masses of 36 $M_\odot$ and 29 $M_\odot$. The newly created black hole had a mass of 62 $M_\odot$, meaning that the total energy of gravitational wave emitted was equivalent to 3 $M_\odot c^2$. The system was 1.3 billions light-years away from us when it merged.

The measured gravitational wave signal, GW150914, from the two LIGO detectors is displayed in **Fig. 10** (Abbott *et al.*, 2016a). The peak amplitude of GW150914 is $h \sim 10^{-21}$ which corresponds to a displacement of the interferometers' arms of $\Delta L \sim 2 \times 10^{-18}$ m. The exquisite sensitivity of these interferometers can be seen from these numbers. In addition to GW150914, during Advanced LIGO's first observing run two other gravitational wave events were observed (also stellar mass binary black hole mergers) (Abbott *et al.*, 2016b,c).

Conclusions

The observation of gravitational waves using Michelson interferometers testifies to the utility of these devices, and to the scientists that have made them work so well. More than a hundred years ago Michelson succeeded in carrying off experiments of amazing difficulty as he measured the speed of light and disproved the existence of the aether. Gravitational wave detection is an experiment worthy of Michelson. In addition, the detection of gravitational waves a century after their prediction by Albert Einstein, and his observation that they will never be observed, testifies to the tremendous progress that has been made in technology, notably here in optics. A new window into the universe has been created, gravitational wave astronomy.

LIGO, Virgo, GEO, and KAGRA are creating a new type of telescope to peer into the heavens. With every new means of looking at the sky there has come unexpected discoveries. This has started with the unexpected observation of gravitational waves produced by binary black hole systems with tens of solar masses. Physicists do know that there will be other signals that they can predict: binary systems containing neutron stars, for example. It is suspected that short gamma ray bursts come from the coalescence of binary neutron stars, or neutron star – black hole binary systems. A core-collapse supernova will produce a burst of gravitational waves that will hopefully rise above the noise. Pulsars, or neutron stars spinning about their axes at rates sometimes exceeding hundreds of revolutions per second, will produce continuous sinusoidal signals that can be seen by integrating for sufficient lengths of time. Gravitational waves produced by the Big Bang will produce a background stochastic noise that can possibly be extracted by correlating the outputs from two or more detectors. These are exciting physics results that will come through tremendous experimental effort. The exciting initial observations of gravitational waves have been made, but it is just the beginning of a new astronomy.

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