Chapter 2
Gravitational Waves and the Quest for Their Direct Detection

Abstract This chapter introduces gravitational waves and reviews the optical-interferometric experiments for their direct detection. This is intended as an overview of the field—for further detail, a recommended source is Pitkin et al. (Living Rev Relativ 14(5):75 pp, 2011, [1]). Section 2.1 presents the basics of gravitational waves and potential sources of such waves in our Universe. Section 2.2 presents an introduction to current, second generation and future ground-based interferometric detectors. Section 2.3 provides an overview of noise sources currently affecting ground based measurements.

2.1 The Nature of Gravitational Waves

As presented in Einstein's theory of General Relativity [2], the gravitational force exists due to the curvature of space-time. This curvature implies that space-time is a flexible medium, and allows the existence of propagating waves of space-time known as *gravitational waves*. Gravitational waves are oscillations of space-time itself. This is intrinsically different to the more familiar electromagnetic waves, which propagate through space-time [3].

Some of the predicted astrophysical sources of gravitational waves include:

- **Inspiral/Coalescing Binary Systems** [4, 5]—Binary systems of compact objects, such as neutron stars and black holes, emit gravitational waves as they orbit. As angular momentum and energy are lost via gravitational waves, the orbital distance decays. Asymptoting to coalescence, the emitted gravitational waves increase in both strength and frequency, resulting in a chirp signal.
- **Spinning Massive Objects** [4]—Spinning massive objects will lose angular energy via emission of periodic gravitational waves, whose signal strength increases as the degree of axial-asymmetry increases. Possible candidates include non-symmetric pulsars and neutron stars.

S.S.Y. Chua, *Quantum Enhancement of a 4 km Laser Interferometer Gravitational-Wave Detector*, Springer Theses,
DOI 10.1007/978-3-319-17686-4_2

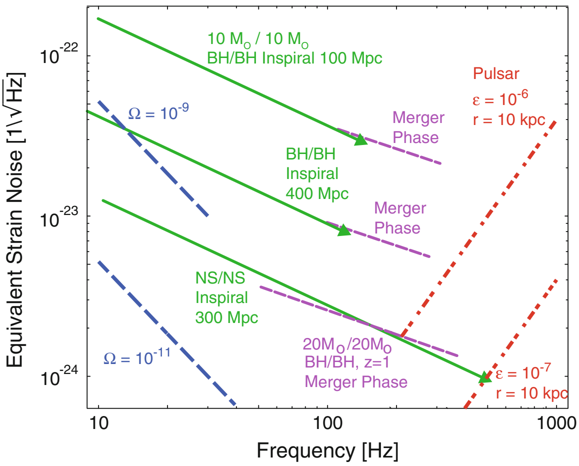

Fig. 2.1 Predicted sources of gravitational waves—adapted from [4]. Symbol meanings: M_O solar mass, ε ellipticity, Ω stochastic background energy density

- **Stochastic Background** [4, 6]—A stochastic background of gravitational waves, similar to the cosmic microwave background, is expected to be a remnant from the early Universe. Predictions of signal strength for inspiral systems, spinning massive objects and Stochastic background are shown in Fig. 2.1.
- **Supernovae** [7, 8]—The non-symmetric dynamics of these stellar explosions are predicted to emit gravitational waves. Detecting these emissions will be a potential source of direct information about these events that are currently not well understood.

Propagating at the speed of light, gravitational waves interact very weakly with matter. This characteristic means that detecting gravitational waves may offer a relatively unhindered view of the Universe, a view that is inaccessible to electromagnetic radiation-based astronomy. For example, it allows the possibility of gaining insights from the formation of the Universe from 10^{-36} s after the Big Bang, or approximately 300,000 years earlier than electromagnetic-based astronomy is capable of [6], as well as dynamics of Supernovae core collapses [8] (above). Furthermore, gravitational waves are generated from these phenomena directly, thus carry direct information about the characteristics of these objects/events [9].

The lowest mode of gravitational-wave oscillation is the quadrapole, and can be best described by their effect on a region of space-time [10]. Figure 2.2 shows the effect of the two basic polarisations (h_+ and $h_\times$) of a passing gravitational wave on two rings of free-falling test particles. The rings are truncated and elongated in orthogonal directions.

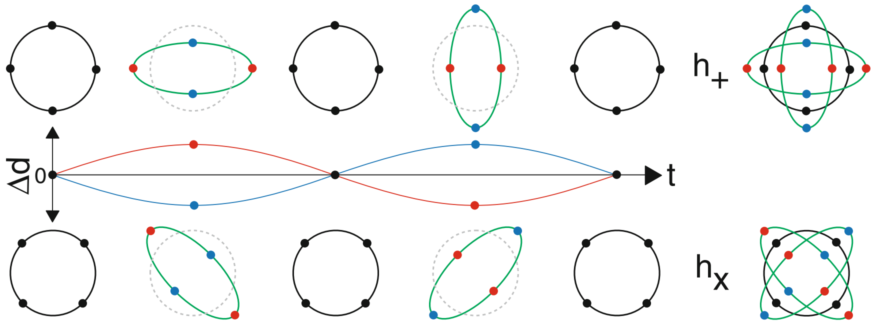

Fig. 2.2 The effect of the two basic gravitational wave polarisations (h_+ and $h_\times$) passing into the page on free-falling test particles, where Δd represents the displacement of the particles from their neutral position over a full cycle. The strain is an exaggerated $h = 0.4$ to clearly demonstrate the effect

The strength of the gravitational wave is measured by the *strain*, h, or the fractional length change it induces, given by:

$$h = \frac{\delta L}{L} \tag{2.1}$$

where δL is the change in length and L is the original length that the change is measured over. The largest astrophysical sources/events are expected to have extraordinarily small strains, of order $h \approx 10^{-21}$ and lower [10].

Observations by Hulse and Taylor [11, 12] on a binary neutron star-pulsar system, PSR B1913+16, provided the indirect evidence of the existence of gravitational waves. They found that the changing orbital period of the binary system was consistent with the predicted loss of energy from system via the emission of gravitational waves [13].

2.2 Ground-Based Gravitational-Wave Interferometric Detectors

This section presents an overview of current and future ground-based interferometric gravitational-wave detector projects around the world. Other direct detection efforts and methods are being developed, such as space-based detectors [14, 15], resonant mass detectors [16–19], as well as pulsar timing arrays [20–24]. These efforts and methods are acknowledged but are not discussed.

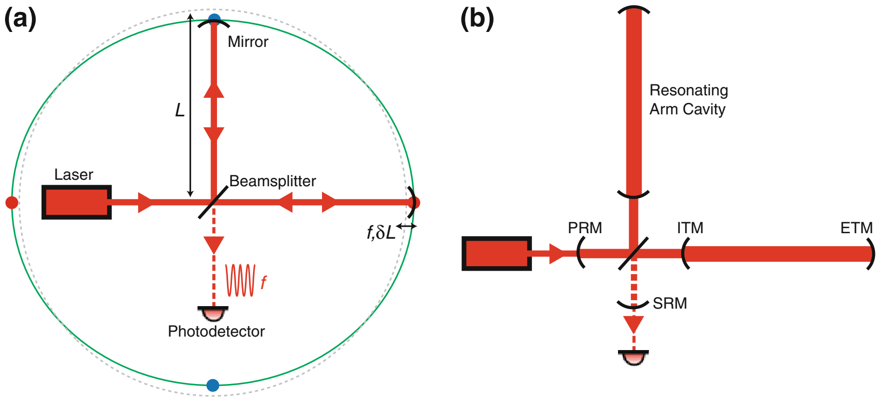

Fig. 2.3 **a** A basic Michelson interferometer, showing the effect of a gravitational wave passing into the plane of the page. Details found in Sect. 2.2.1, **b** A Michelson interferometer with resonating arm cavities, power recycling and signal recycling mirrors. *PRM* Power Recycling Mirror, *ITM* Input Test Mass, *ETM* End Test Mass, *SRM* Signal Recycling Mirror, f gravitational-wave frequency, δL change in Michelson arm length

2.2.1 Interferometers for Direct Detection

Ground-based interferometric gravitational-wave detectors are based on a Michelson Interferometer topology. For the remainder of this thesis, references to "gravitational-wave detectors" will specifically refer to such devices. A basic Michelson Interferometer is shown in Fig. 2.3a. Continuous-wave light from a laser is split into two beams with a beamsplitter. The two beams then travel in the orthogonal *arms* of the Michelson (length L). Both beams are reflected back towards and interfered on the beamsplitter via the *test mass* mirrors, resulting in an interference signal that encodes information about the relative optical path difference between the two arms, detectable by the photodetector. Any change in the relative optical path difference (δL) of the two arms will change the interference signal at the beamsplitter. A gravitational wave of a particular Fourier frequency f reveals itself in an interferometer as a modulation signal on the light at the same frequency.

Gravitational-wave detectors use additional techniques to further increase the sensitivity. These include resonating optical cavities for the Michelson arms, optical recycling mirrors, as shown in Fig. 2.3b. The first generation gravitational-wave detectors included LIGO [25], Virgo [26], GEO600 [27] and TAMA300 [28] interferometers. All first generation detectors broadly reached their design sensitivities by 2006.

2.2.2 The "Generation 1.5" Detectors

The "Generation 1.5" interferometers formed intermediate upgrade stages for LIGO and Virgo instruments, working towards their respective second generation devices.

- **Enhanced LIGO** [31]—The Enhanced Laser Interferometer Gravitational-wave Observatory (also known as eLIGO) were two Michelson interferometers, operated by the US-led LIGO Scientific Collaboration. Situated at two sites in the United States (Hanford, Washington State and Livingston, Louisiana), they are purposely separated by approximately 3000 km to allow for triangulation of gravitational-wave sources in the sky. Each site had an interferometer with 4 km arm cavities and power recycling.
- **Virgo+** [32]—The Virgo+ Interferometer was also a power-recycled Michelson interferometer, but with 3 km resonating arm cavities. Situated near Pisa in Italy and operated by the French-Italian Virgo Collaboration, Virgo+ had smaller peak-strain sensitivity due to shorter arm lengths, but deployed more advanced seismic isolation systems resulting in better sensitivity at lower detection frequencies.

A joint scientific measurement run between Enhanced LIGO and Virgo+ [33] was concluded in October 2010. The start of the second-generation upgrade/installation programs for Enhanced LIGO and Virgo+ then immediately followed. The estimated development timelines from Generation 1.5 to second generation detectors are shown in Fig. 2.5. The work presented in the later chapters of this thesis were undertaken on the Enhanced LIGO interferometer at Hanford, thus greater detail about the Enhanced LIGO interferometer will be covered in Chap. 8.

2.2.3 Second Generation Detectors

The locations of the gravitational-wave detectors comprising the second generation network described below, are shown in Fig. 2.4a.

- **Advanced LIGO** [34]—The Advanced LIGO interferometer network will consist of three 4 km interferometers, one interferometer located in each of the two USA sites and the third interferometer located in India (LIGO India with the IndIGO consortium [35]). These interferometers will have arm cavities and use *dual recycling*, that is both power recycling and signal recycling. With improved seismic isolation, test mass mirrors, mirror coatings and mirror suspension technologies, and an increase in operating laser power, the target sensitivity improvement is an order of 10 in magnitude over (initial) LIGO. This translates to an increased observational reach of 1000 in volume space compared to LIGO, pictorially shown in Fig. 2.4b.
- **Advanced Virgo** [36]—The Advanced Virgo interferometer will be a 3 km dual-recycled interferometer with arm cavities, with increased operating laser power and improved mirrors and mirror coatings to augment their advanced seismic isolation

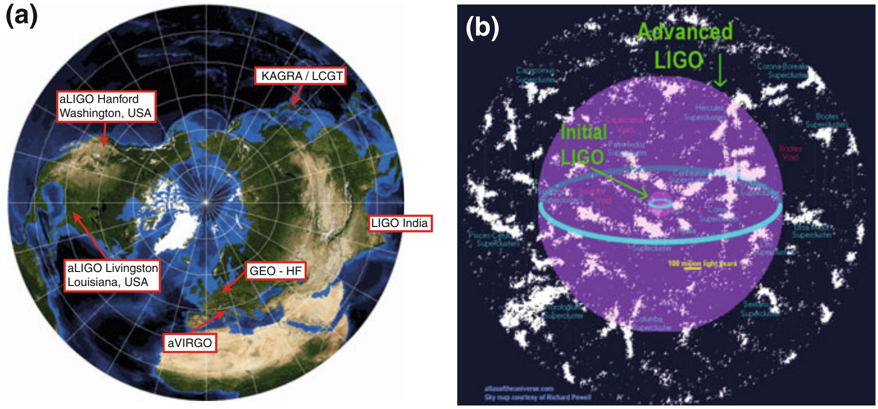

Fig. 2.4 **a** Second-generation gravitational-wave interferometric detector sites around the world; **b** Observational reach of Advanced LIGO, one thousand times larger volume space compared to Initial LIGO [29]. Sky map courtesy of Richard Powell [30]

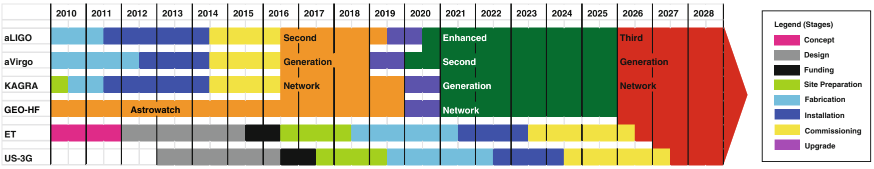

Fig. 2.5 Development timelines for ground-based gravitational-wave detectors—adapted from [40]

system. The target sensitivity improvement is also an order of 10 in magnitude relative to first generation Virgo.

- **KAGRA (LCGT)** [37]—Located underground at Kamioka, Gifu Prefecture, Japan, construction of KAGRA Large-scale Cryogenic Gravitational-wave Telescope (LCGT) began in January 2012. KAGRA will be a 3 km power-recycled interferometer with arm cavities, and will be the first underground kilometre-scale interferometer and the first to employ cryogenics as part of its baseline technology.
- **GEO-HF/GEO600** [38]—Operated by the British-German GEO collaboration, GEO-HF is the second generation upgrade of GEO600 [27] interferometer, whose main upgrade took place during the S6/VSR2-3 Science Run. The sole interferometer in operation during the second generation detector upgrade/installation phase (labelled 'Astrowatch' in Fig. 2.5), it is in dual-recycled configuration with 600 m folded arms and no arm cavities. It is the first interferometer to employ squeezed states [39] as part of its baseline operation.

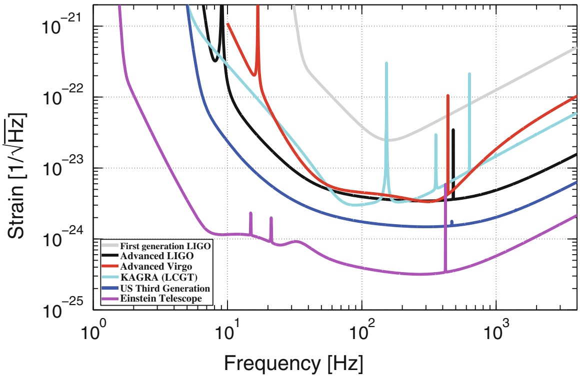

Fig. 2.6 Design strain-sensitivities for selected second generation and future laser-interferometric gravitational wave detectors. The achieved design sensitivity for first generation LIGO [25], is also plotted

2.2.4 Third Generation Detectors

- **Einstein Telescope** [41, 42]—Design studies for a third generation European detector called the Einstein Telescope have been undertaken. This interferometer looks to combine dual-recycled Michelsons with arm cavities, squeezed states and cryogenics, along with being housed within a deep-underground facility.
- **Third Generation LIGO** [43]—The early stages of planning/discussion for the third generation LIGO instruments started in early 2012. Various designs with different technologies and optical topologies are being studied, including different materials for test masses and different cooling/cryogenic strategies. However, one common technology included in all third generation LIGO designs being discussed is the use of squeezed states.

2.2.5 Strain Sensitivities and Development Timelines

For the second generation and third generation detectors, their estimated development timelines are shown in Fig. 2.5, and their respective design/predicted sensitivities have been graphically presented in Fig. 2.6.

2.3 Noise Sources Affecting Ground-Based Interferometers

For the second generation interferometers, the target strain sensitivity is of order $h = 10^{-23}/\sqrt{\text{Hz}}$, as shown in Fig. 2.6. This presents a great challenge within the audio frequency detection band of interest (10 Hz–10kHz). A multitude of noise sources can limit the strain sensitivity, some of which are introduced below. Their contributions to the Advanced LIGO sensitivity, as an example, are shown in Fig. 2.7.

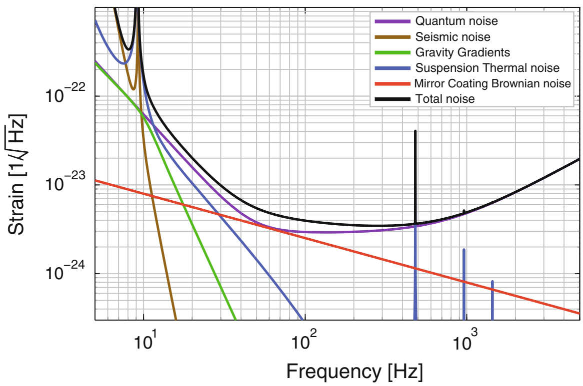

Fig. 2.7 The predicted noise budget of Advanced LIGO, showing the contributions of the various limiting noise sources. Plot made using GWINC v3 [44]

2.3.1 Quantum Noise

Quantum noise in interferometric detectors arise due to the quantum mechanical fluctuations of the electromagnetic field used to sense the displacement of the test masses. This noise source manifests through both measurement photon arrival time at the photodetector and photon momentum transfer onto the test masses, and is related to the operating optical laser power. Quantum noise is expected to be the main sensitivity-limiting noise source in second generation gravitational-wave detectors across the audio frequency detection band.

The primary focus of the work in this thesis is the generation and application of squeezed states to surpass quantum noise to enhance interferometric detector measurements. Quantum noise will be in detail in subsequent chapters.

2.3.2 Thermal Noise

The term 'thermal noise' covers the displacement noise of the test masses that arise from the thermal fluctuations of the atoms that make up the components. This includes the thermal noise from mirror coatings [45], surface vibration modes of the test mass mirrors [46], internal modes of the test mass mirrors [47], thermal noise from the suspension wires, and thermo-refractive noise [48] through input-test-mass transmission.

The current approach for mitigating thermal noise is to use low mechanical loss materials for test masses, optics and suspensions [10]. However, the choice of such materials is limited, complicated by key requirements such as their light absorption properties. Other approaches being considered include cryogenic test masses [49, 50] and exotic test mass surface structures that reduce the need for mirror coatings [51].

2.3.3 Seismic Noise

To reach the required sensitivity, the test masses must be isolated from seismic ground motion. The displacement spectral density of ground motion at the LIGO sites are of the order $10^{-8}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 1 Hz, decreasing gradually with increasing Fourier frequency [52]. A combination of active and passive isolation is typically deployed, however, it remains a limiting floor at lower frequencies of the audio detection band. The underground location of the KAGRA detector was chosen to minimise the impact of seismic noise.

2.3.4 Gravity Gradient Noise

Fluctuations in the gravitational field of the local environment cause uncorrelated displacement noise on to the test masses. This noise, called gravity gradient noise, is caused by moving mass bodies (e.g. trains, cars, people), and changes in environmental-media densities (e.g. atmospheric pressure, subterranean sediment settlement) [53, 54]. The Einstein Telescope looks toward deep-underground facilities to mitigate the effect of this noise source. This noise source represents the fundamental low frequency (to a few Hz) limit of ground-based interferometers.

2.3.5 Other Noise Sources

Other noise sources affecting the sensitivity of gravitational-wave detectors include feedback control noise, electronic component noise, photothermal noise [55], residual gas [10, 56] and stray light [57–59]. These noise sources are not expected to limit detection-sensitivity.

2.4 Summary

An overview of gravitational waves and the quest for their direct detection has been presented. The nature of gravitational waves, and astrophysical sources predicted to emit gravitational waves were reviewed. Generation 1.5 and second generation ground-based interferometric detectors were then introduced. The sensitivity-limiting noise sources affecting gravitational-wave detector measurement were covered. Quantum noise of the electromagnetic field broadly limits the detection sensitivity across the audio gravitational-wave detection band.

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Quantum Enhancement of a 4 km Laser Interferometer Gravitational-Wave Detector
Chua, S.S.Y.
2015, XX, 220 p. 100 illus., 59 illus. in color., Hardcover
ISBN: 978-3-319-17685-7