# Gravitational Wave Detectors: a new window to the Universe

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**Summary.** The LIGO gravitational wave detectors have achieved their designed sensitivity, and are currently in operation. We describe the technology of the detectors, as well as results from the analysis of some of the data collected so far.
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## 1 Introduction

The existence of gravitational waves is a beautiful, if straightforward, prediction of Einstein's theory of relativity, arising from the deep relationship between space and time: dynamic changes in matter distribution will distort the space time, and the space-time "ripples" will travel outwards from the source, carrying energy and precious information about the astrophysics of the source. Many black holes scenarios would not emit electromagnetic waves and thus be invisible to instruments detecting different wavelengths of light; they would, however, produce gravitational waves traveling at the speed of light. Many other astrophysical sources (supernovae, collisions of neutron stars,...) would produce both electromagnetic and gravitational waves, but they would carry very different information: gravitational waves would tell us about the macroscopic structure of the mass of the source and the effects on the space time produced by the large relativistic fields. Gravitational waves interact very weakly with matter: most of the universe is essentially transparent to the traveling waves; the information encoded in them is pristine.

Gravitational waves distort space-time, changing distances between freely falling objects (acting as coordinate markers) by an amount proportional to the gravitational wave strength, and the distance between the objects: $\Delta L = hL$. Gravitational waves have a transverse and quadrupolar nature: a plane wave would change distances in the plane perpendicular to the direction of propagation, and it would make distances shorter in one direction, and longer in the perpendicular direction, as shown in Figure 1. There are two polarizations of a plane wave, called "x" and "+" corresponding to maximum distortions along two directions $45^o$ apart.

Gravitational waves are produced by accelerated mass quadrupoles $Q_{ij}$, and the strength of the wave is proportional to the second derivative of the mass quadrupole, and inversely proportional to the distance $r$ to the source: $h \approx 2G\ddot{Q}/c^4 r$. The rate

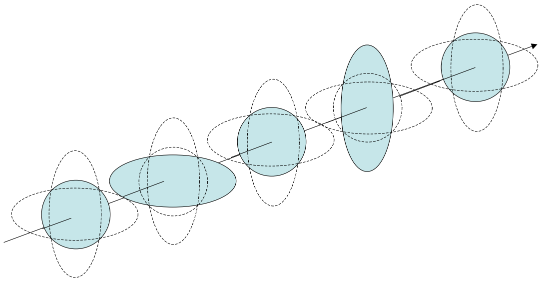

**Fig. 1.** Spatial distances changed by a propagating gravitational wave with a "+" polarization.

of energy radiated away from the source is $P = (G/5c^5)(d^3Q/dt^3)^2$: the source will be changed due to the loss of radiated energy. An orbiting system of the most compact of stars, neutron stars, is known to exist from pulsar observations, and forms a radiating quadrupole, thus emitting gravitational waves. The energy of the system decreases due to the emission of gravitational waves: the orbit shrinks, and the orbiting frequency of the system increases (from Newton's law $\omega^2 = GM/r^3$). The agreement of the predicted change in orbit parameters has been beautifully demonstrated with observations of the first pulsar binary system PSR 1913+16, discovered by Hulse and Taylor in 1974 [1].

Since gravitational waves do exist, as proven by the Hulse Taylor system, it is the nature of human curiosity to try to directly detect them. However, the effect of gravitational waves is very small: a binary system of neutron stars, about 10 diameters or 200 km away from each other, at a distance $r$ from Earth, would emit gravitational waves of about 300 Hz with an amplitude of $h \sim 10^{-22}(20\mathrm{MPc}/r)$. The changes in distance produced by a source in the Virgo Cluster is an atom diameter for a distance of several million kilometers! This shows the incredible challenge to measuring such small effects, even from large astrophysical systems. However, we will show that present detectors can achieve measurements of sub-nuclear distances, over distance of kilometer scale, making the direct observation of gravitational waves a plausible, and very exciting, enterprise.

## 2 Interferometric gravitational wave detectors

The quadrupolar nature of gravitational waves seems naturally appropriate to be measured by some of the oldest precision measurement instruments, Michelson interferometers. Such a detector measures differences in length between perpendicular arms, so it can be naturally adapted to measure the effect of a passing gravitational wave that changes the length of its arms. However, even for a 4km long interferometer (as they now exist!), a gravitational wave with strength $h \sim 10^{-22}$ produces a difference in arm length of $\Delta L = hL \leq\ 10^{-18}$m, or a thousandth of a nucleon diameter. The measurement of such a small quantity, with an instrument with km scale, seems to defy quantum mechanics, not just common sense. Are gravitational waves detectable? The answer is yes, if the question is well defined, and the instrument sensitive enough. First, even though we talk about sub-nuclear length scales, the question does not enter the realm of quantum uncertainty, because we are not measuring the position of any one nucleon, or atom, but instead we are measuring changes in distances defined by macroscopic objects, whose position is well defined, well beyond nuclear distances: in other words, we are measuring the average position of many atoms, which is better defined than the position of any one of the atoms forming the system. The quantum nature of the world does limit the sensitivity of the measuring instruments, but the limitations depend on the instrumental set up.

Techonology has also been available to measure such small distances, in more than one way. Resonant bar detectors, pioneered by Joseph Weber in the '70s and still in use in the US and Italy, have achieved sub-nuclear displacement sensitivities, even if not reaching their quantum limit (most are limited by the noise in their transducers). These detectors consist of a large resonant masses of meter scale in length, and 1-2 tons in mass, placed in vacuum, at low temperatures, with very sensitive transducers to measure the differential displacement of the ends of the mass. The measurements are most sensitive near the resonance frequency bars, about a kHz.

The LIGO interferometric detectors, through very different measurement techniques than resonant bars, achieve similar precision for displacement sensitivity, but over longer length scales (kilometers!), which then makes for more sensitive detectors to *strain*, the natural measure of gravitational wave strength. Interferometers are also most sensitive at lower frequencies ($\sim$ 100 Hz), and have a broader response, which makes for a better chance of measuring signals from several other astrophysical sources, other than collisions or explosions of stars.

## 2.1 The LIGO detectors

The LIGO detectors [2] use interferometric techniques: they are essentially Michelson interferometers that use coherent light and an optical readout to deduce, from the interference of the beams returning from each arm, the difference in arm length. In the famous Michelson-Morley experiment, such interference would be caused by the different light speed in each arm, presumably affected by ether. In a gravitational wave detector, the difference in arm length would ideally be caused by the distance between the beamsplitter and the mirrors at the ends of the arms being affected differentially by a gravitational wave. In the LIGO detectors, a coherent laser source is used (a NdYAF laser with $\lambda$ =1064nm wavelength), and the signal detected at the antisymmetric port is the power on a photodiode, measuring the phase difference between beams that travel in the different arms of the detector. The antisymmetric port is kept "dark" with feedback controls, which push on the mirrors to make the interference between the returning beams to be destructive. In this case, the beams returning to the laser source have constructive interference, making the whole detector behave like a mirror. In order to enhance the signal, the light in each arm is stored in a Fabry-Perot optical resonant cavity, using partially transmissive input mirrors; two more feedback loops are needed to keep these cavities resonant. The circulating power in the detector is increased by making another optical resonant cavity between the light reflected by the detector, and a partially transmissive mirror at the input, or a ”recycling” mirror. A schematic drawing of the optical topology used in the LIGO detectors is shown in Fig. 2.

In order to allow an approximation of free masses for the mirrors (and to improve seismic isolation), the mirrors are suspended as pendulums by single looping wires. The mirrors are cylindrical, made of fused silica, 25 cm in diameter, 10cm thick, and 10 kg heavy. To avoid spurious phase differences due to varying index of refraction, the light travels in vacuum beam tubes: this is the largest volume high vacuum system in the world!

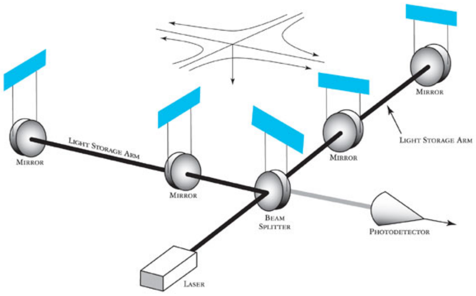

**Fig. 2.** Optical topology used by the current LIGO detectors

Of course, even in the absence of a gravitational wave, the signal at the output is not identically zero: there is a certain amount of “noise” that will then limit the magnitude of detected gravitational waves. The noise detected will be the sum of several different noise sources: some sources of noise make the actual distance between mirrors change (like seismic noise and brownian motion of the mirrors), and some sources of noise affect the readout (like shot noise of the laser light). The different noise sources have each their own spectral features, with different power at different frequencies: seismic noise is largest at low frequencies, brownian motion is largest at the resonances of the pendulum systems and the mirror masses, shot noise is largest at frequencies above the optical cavity pole frequency ($\sim$ 100 Hz). The resulting sum of all the noise sources makes the detectors most sensitive at frequencies near 100-200 Hz, but have a broad sensitive band between $\sim$ 50 Hz and a few kHz, as shown in Figure 3.

There are two 4km long LIGO detectors in the United States, one in the LIGO Livingston Observatory, in the state of Louisiana, and another in the LIGO Hanford Observatory, in the state of Washington; they are about 3000 km away. This will allow increased confidence in an eventual detection, since the false alarm rate is greatly reduced by requiring coincidence between the detectors, within the maximum 10ms of light travel distance. In the LIGO Hanford Observatory there is also an independent 2km long detector, which again reduces the false alarm rate, and allows for a consistency check on amplitude of a possible detection: since the gravitational wave produces a change in distance proportional to distance, for a true signal, the measured change in length in the 2km detector should be half as large as in the 4km detector.

The LIGO detectors have improved their sensitivity since they were first turned on, as noise sources were identified and reduced or eliminated one by one. Since 2002, the detectors reached significantly better sensitivity than any previous gravitational wave detector in its frequency band, and work in the detectors was stopped four times to allow for data taking. These "Science Runs" were called S1, S2, S3 and S4, and happened for 17, 61, 70, and 30 days respectively, starting in Aug 23 2002, Feb 14 2003, Oct 31 2003 and Feb 22 2005, also respectively. Not only the sensitivity, but also the duty cycle improved in S4 with respect to previous runs, since an improved, active seismic isolation system was installed in the LIGO Livingston Observatory to allow daytime operations (the LIGO Hanford Observatory is more isolated from human noise sources). In fall of 2005, the detectors achieved their designed sensitivity, and starting taking data in continuous mode since November 2005 for an extended period of time, which will end when a year of coincident data is obtained.

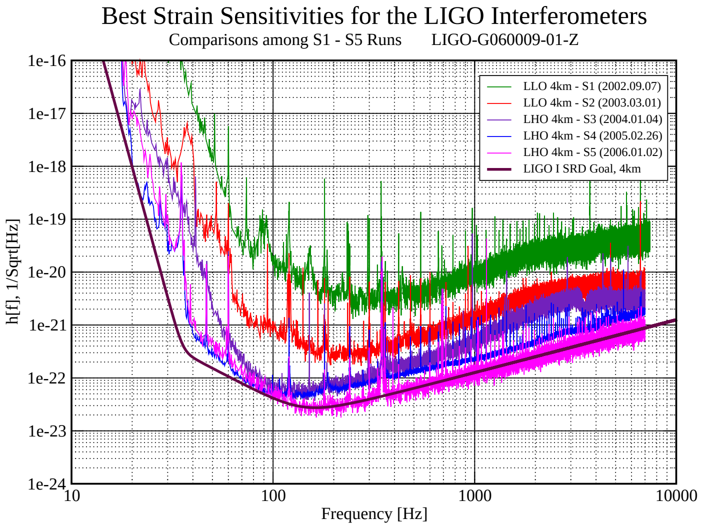

**Fig. 3.** Improvement of sensitivity of the LIGO detectors in the different Science Runs S1-5. The solid line represents the goal for the detectors' sensitivity, taking into account fundamental noise sources like seismic noise, brownian motion of the suspended mirrors, and shot noise in the detected light.

## 3 Astrophysical Sources of gravitational waves

There are several different astrophysical sources of gravitational waves that may produce signals in the LIGO detectors' sensitive frequency band. According to their spectral content, we classify them in four groups: continuous signals from rotating stars; signals from binary systems; stochastic signals from a cosmological background; and burst signals from collisions and explosions of stars.

Rotating stars will produce gravitational waves if they are not perfectly spherical, and have a mass quadrupole. The signal produced at the source is monochromatic, with the frequency of the gravitational wave being twice the rotation frequency of the star. There are many neutron stars in our Galaxy that are pulsars, emitting radio waves that can be detected on Earth by radio telescopes. From the detected radio signals, we know their position in the sky and their rotational frequency. Some of these sources are also known to be slowing down: they are "spinning" down. If we attribute the loss of energy to the emission of gravitational waves, we obtain from the known spin derivative an upper limit on the magnitude of the gravitational waves. With the LIGO detectors, we can obtain a direct observational limit for the known pulsars, since the predicted gravitational waves are in the detectors' band. The data is searched for a periodic signal with the appropriate Doppler shift for the star's position in the sky and Earth's rotation; in the absence of a signal, an upper limit can be deduced on the strength of the gravitational waves emitted by the source. This upper limit can also be translated into an upper limit for the ellipticity of the star. With S2 LIGO data, 28 isolated radio pulsars were studied, and limits were set in strain as low as few times $10^{-24}$ and in ellipticity of $10^{-5}$ [3]. The search for rotating stars at all positions in the whole sky is computationally more challenging, and must be tackled by different techniques [4], or using shared resources. The American Physics Society sponsored an exciting project, "Einstein@Home", which uses people's idle computers to search for gravitational waves from rotating stars in LIGO data.

The emission of gravitational waves from binary star systems is well understood as long as the objects are far enough away from each other for Post-Newtionina approximations to apply: the signal emitted will have a frequency equal to twice the orbital frequency, and will increase in frequency and amplitude as the system loses energy. Binary neutron star and small black holes systems ($< 20M_\odot$) will emit waves in the LIGO detectors' band. We can in fact translate a sensitivity curve into a distance at which we would detect a binary neutron star system with average position in the sky and average orientation, with a signal to noise larger than 8. The curves shown in Figure3 correspond to a range of 80 kpc (S1), 1Mpc (S2) , 6.5 Mpc (S3), 8.4 Mpc (S4) and 12 Mpc (S5). With optimal orientation and position in the sky, systems from distances up to 2.2 times farther away could be detected: in S5, we are observing a fraction of the systems in the Virgo Cluster of galaxies. The search in S2 data for neutron stars and black holes smaller than $1M_\odot$ resulted in no detections, and the first direct upper limits on galactic and extra-galactic systems[5],[6].

Looking for signals from violent events such as collisions of stars (the final stage of a binary system) or supernova explosions does not have models to use in the search, so they rely on techniques looking for excess power in the data, as measured by Fourier transforms, wavelet transforms, or other appropriate methods. Searches for "bursts" in S2 data with frequency content in the 100-1100 Hz data yielded no candidates. The sensitivity of this search, measured in *root-sum-square* of the strain of possible waveforms, lies in the range of $h \sim 10^{-20} - 10^{-19}/\sqrt{\mathrm{Hz}}$.

Sources of Gamma Ray Bursts are known to be supernova explosions, at least for a large fraction of the "'long" bursts (more than two seconds long): depending on the asymmetry of the mass distribution of the star and the explosion, these sources can also originate gravitational waves in the LIGO detectors' frequency band. During one of the brightest Gamma Ray bursts, GRB030329, the LIGO Hanford detectors were in operation, taking data for the Second Science Run, and a dedicated search of the data at the time of the Gamma Ray Burst yielded no detection, and an upper limit on the emitted strain by an optimally polarized source of $h_{rss} \sim 10^{-20}$[8].

The superposition of many unresolved burst signals results in a continuous random signal, or a "stochastic background". These signals can be generated by astrophysical sources such as the ones considered earlier, or to cosmological processes, similar to the cosmic microwave background. Although the signal in a single detector would be undistinguishable from other random noise sources, the signal in a *network* of independent detectors can be detected by finding correlated noise. The correlation will get weaker and eventually vanish for signals with wavelengths shorter than the distance between the detectors. A stochastic background can be characterized by a dimensionless function of frequency $\Omega_{gw}(f)$, the gravitational wave energy density per unit logarithmic frequency, divided by the critical energy density to close the universe; if the spectrum is flat, the quantity $\Omega_{gw}$ is a constant $\Omega_0$ independent of frequency. The analysis of LIGO S3 data resulted in an upper limit $\Omega_0 < 8.4 \times 10^{-4}$ in the frequency band between 60 Hz and 156 Hz[9].

## 4 Present and future of gravitational wave astrophysics

Although there has not been any direct observation of gravitational waves yet, the data being taken now with the LIGO detectors in the Fifth Science Run that started in November 2005 shows enormous promise: even if no signal is found, the observational upper limits on the strength of different sources of gravitational waves will be orders of magnitude better than previous published results. The prediction for the rate of observation of signals from binary neutron systems, extrapolated from the few known pulsar binary systems known in the galaxy, is low enough so that no signal is expected in a year of operation [10] (barring serendipity, necver out of the question). However, extrapolations from recent observations of short gamma ray burst implying an association with the coalescence of compact binary systems[11], suggest that the rates, especially for black holes, may be high enough to either expect direct observations in a year of data, or, in the absence of signals, to begin ruling out some possible evolutionary astrophysical scenarios. A detector in Europe built by the VIRGO French-Italian collaboration[12], with topology and sensitivity similar to the LIGO detectors, may also begin operations in the near future; the existence of a network with four detector will not only lower the frequency of possible false alarms, but also, in the case of detections, help identify physical parameters of the source, such as polarization and location in the sky.

The most exciting prospect, however, is that now that we know that the basic technologies work in detectors of kilometer scale (a non trivial task!), new and better technologies can be used to improve the sensitivity of the LIGO detectors by about an order of magnitude. Since the reach in distance is proportional to the sensitivity, the volume surveyed increases with the cube of the sensitivity, and the rate of sources could be as much as 1,000 times higher than in the present LIGO detectors. The predicted rate for such Advanced LIGO detectors from binary neutron star systems extrapolated from galactic systems [10] is a detection every few days! The Advanced LIGO detectors could be operating at the beginning of the next decade. Even a few months of observations will result in a significant advance in our knowledge of the Universe: a new window will be opened, and we cannot expect less than a few surprises...

## References

1. Hulse, R. A. and Taylor, J. H. 1974, ApJ, 191, L59.
2. B. Barish, R. Weiss, Phys. Today, 52, 44-50 (1999)
3. B. Abbott et al. (LIGO Scientific Collaboration), Phys. Rev. Lett. 94, 181103 (2005)
4. B. Abbott et al. (LSC), Phys. Rev. D 72, 102004 (2005)
5. B. Abbott et al. (LSC), Phys. Rev. D. 72, 082001 (2005)
6. B. Abbott et al. (LSC), Phys. Rev. D. 72, 082002 ( 2005)
7. B. Abbott et al. (LSC), Phys. Rev. D 72, 062001 (2005)
8. B. Abbott et al. (LSC), Phys. Rev. D 72, 042002 (2005)
9. B. Abbott et al. (LSC), Phys. Rev. Lett. 95, 221101 (2005)
10. V. Kalogera et al., Astrophys.J. 601 (2004) L179-L182; Erratum-ibid. 614 (2004) L137
11. E. Nakar, A. Gal-Yam, D. Fox, preprint astro-ph/0511254, (2005)
12. F. Acernese et al., Class. Quantum Grav. 22 No 18 (21 September 2005) S869-S880

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