

Searching for gravitational waves with LIGO

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Abstract. The Laser Interferometer Gravitational-wave Observatory (LIGO) detectors have reached their design sensitivity, and searches for gravitational waves are ongoing. We highlight current attempts to detect various classes of signals. These include unmodelled sub-second bursts of gravitational radiation, such as from core-collapse supernovae and gamma-ray burst engines. Gravitational waves from isolated neutron stars and from the inspiral/merger of compact binary systems carry information about the bulk properties of black holes and neutron stars. A stochastic background of gravitational waves of cosmological origin would provide a unique view of conditions in the very early universe. We discuss current attempts to detect gravitational waves from these sources and comment on future prospects for these searches.

1. Introduction

The direct detection of gravitational waves will usher in a new era of astronomy. For example, gravitational waves (GWs) will allow us to study strong-field gravity around black holes and in the early universe, and provide probes of the neutron star equation of state. Routine astronomical observations of GWs will help us to understand compact binary populations, core-collapse supernova mechanisms, and gamma-ray burst engines.

The Laser Interferometer Gravitational wave Observatory (LIGO) [1] is one of several projects dedicated to opening the GW sky. LIGO consists of three long-baseline interferometers: a 4 km instrument “L1” in Livingston, USA, and 4 km “H1” and 2 km “H2” instruments in Hanford, USA. These detectors are Michelson interferometers with Fabry-Perot arm cavities. A passing GW changes the relative lengths of the arms, which is sensed as a change in the output light intensity. Supporting research in all aspects of LIGO science is carried out by the LIGO Scientific Collaboration (LSC), a worldwide network of institutions that also includes the British-German GEO-600 detector in Hannover, Germany [2]. Other large-scale interferometers in operation are the French-Italian Virgo detector [3] and the Japanese TAMA 300 detector [4].

LIGO performed its first science run, S1, in 2002. At the time of writing, LIGO is completing its fifth science run, S5 (Nov 2005 - Oct 2007), having acquired one full year of data in coincident operation at the design sensitivity. Figure 1 shows the sensitivity of the LIGO detectors in mid-2007. Two major upgrades are planned: Enhanced LIGO (c. 2009, 2-4 times more sensitive), and Advanced LIGO (c. 2014, 10-15 times more sensitive than the current detectors).

Searches for GWs with LIGO are divided into four broad categories, based on the nature of the signal: compact binary inspirals, unmodelled bursts, continuous quasi-monochromatic emission, and a stochastic background. We now briefly review highlights from the most recently published search results: the third and fourth science runs, S3 (Dec 2003 - Jan 2004) and S4 (Feb - Mar 2005).

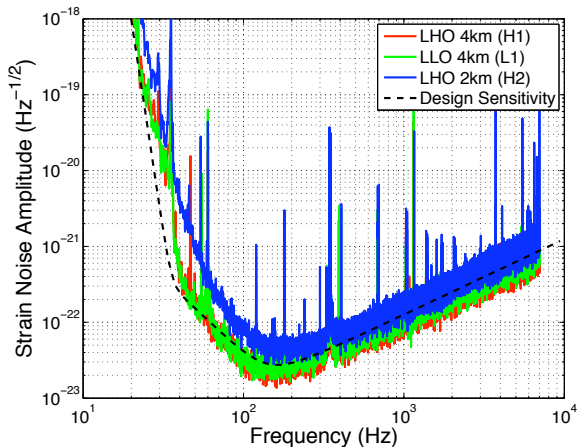


Figure 1. Strain-equivalent noise amplitude spectral density of the LIGO detectors. The dotted curve indicates the design sensitivity.

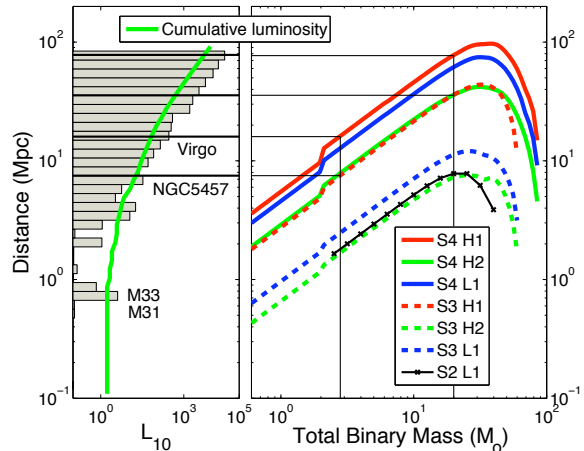


Figure 2. Cumulative luminosity and maximum distance for detecting inspirals vs. binary mass in the S3 and S4 runs.

2. Inspiralling compact binaries

The orbits of sufficiently tight binaries of neutron stars (NSs) or black holes (BHs) will decay due to GW emission, producing a characteristic “chirp” GW signal preceding the binary merger. The precise waveform depends on the masses and spins of the binary components, and is well-modeled for systems up to approximately $80 M_{\odot}$. These signals can therefore be detected by matched filtering of the data for the known waveforms.

The rate of NS-NS mergers has been inferred, albeit with large uncertainties, from known binary systems [5]: $R_{NS-NS} \simeq 10 - 170 \times 10^{-6} \text{yr}^{-1} L_{10}^{-1}$, where $L_{10} \equiv 10^{10}$ times the solar blue-light luminosity. BH-NS and BH-BH merger rates are estimated to be $R_{BH-NS} \simeq 0.15 - 10 \times 10^{-6} \text{yr}^{-1} L_{10}^{-1}$ and $R_{BH-BH} \simeq 0.1 - 15 \times 10^{-6} \text{yr}^{-1} L_{10}^{-1}$. Searches therefore need to encompass least $O(10^4)$ galaxies to provide a reasonable chance of making detections.

Figure 2 shows the distance to which inspirals could be detected by LIGO as a function of mass in the S3 and S4 searches [6]. For example, the 4 km interferometers were sensitive to NS-NS inspirals (total mass $2.8 M_{\odot}$) to a maximum distance of approximately 15 Mpc. Figure 2 also shows the cumulative luminosity in L_{10} (essentially a count of galaxies) as a function of distance. No inspirals were detected. Based on the instrument sensitivity, the expected detection rate was $< 0.01 \text{yr}^{-1}$ (NS-NS), and $< 0.1 \text{yr}^{-1}$ (BH-BH). The extrapolated NS-NS detection rate for Enhanced LIGO is $< 0.3 \text{yr}^{-1}$, while for Advanced LIGO it is $\simeq 7 - 400 \text{yr}^{-1}$.

3. GW bursts

GW bursts are defined loosely as any transient signal for which there is no good theoretical model. Sources include core-collapse supernovae, and gamma-ray burst engines. Searches for GW bursts typically focus on detecting generic waveforms with durations in the range 1-100 ms.

There are two main types of burst searches in the LSC. “Untriggered” searches scan all available data (subject to cuts on data quality). They look for simultaneous jumps in all detectors of the energy in some time-frequency region, with consistent measures of amplitude or correlation between the detectors. “Triggered” searches scan a small amount of data around the time of an astronomical event (e.g., a GRB), by cross-correlating data from pairs of detectors. Triggered searches exploit knowledge of the time of and direction to the astronomical event to improve the sensitivity of the search. The most recent such search looked for GWs associated with 39 GRBs using data from science runs 2, 3, and 4 [7].

One measure of the sensitivity of burst searches is the amount of energy that a source at a given distance would need to emit in GWs in order to be detected with 50% efficiency. For isotropic emission at LIGO’s most sensitive frequency (about 150 Hz), the S4 untriggered burst search could detect approximately $8 \times 10^{-8} M_{\odot} \simeq 10^{47} \text{erg}$ at 10 kpc (a typical galactic distance), or $0.2 M_{\odot} \simeq 4 \times 10^{53} \text{erg}$ at 16 Mpc (the distance to the Virgo cluster) [8]. A targeted search for GWs associated with the Dec 2004 giant flare of SGR 1806-20 looked for evidence of GWs corresponding to quasi-periodic oscillations observed in the electromagnetic emission [9]. The upper limit for the 92.5 Hz mode was $4.3 \times 10^{-8} M_{\odot} = 7.7 \times 10^{46} \text{erg}$, comparable to the electromagnetic energy emitted in the flare.

4. Pulsars and continuous waves

Spinning neutron stars will emit gravitational waves if they are non-axisymmetric. While the expected signal will be weak, the radiation will be continuous and quasi-monochromatic, so that it can in principle be detected by, e.g., heterodyning the data to follow the pulsar phase and integrating over a sufficiently long observation time.

The “known pulsar” search uses catalogs of pulsars to search for GWs in this manner. Figure 3 shows the upper limits from the most recent search for GWs from 78 known pulsars [10]. Astrophysically interesting sensitivities are being reached for some pulsars. For example, the equatorial ellipticity of PSR J2124–3358 is constrained to be less than 10^{-6} . Furthermore, the upper limit for the Crab pulsar will drop below the fiducial spin-down limit in the S5 search.

All-sky or “blind” searches for previously unknown pulsars are computationally very expensive, as the phase of the GW signal depends sensitively on the pulsar parameters (sky position, frequency, spin down rate, *etc.*). These searches rely on hierarchical methods; see [11] for the S4 search results. Einstein@Home [12] is another innovative approach that harnesses idle time of volunteers’ computers to perform pulsar searches.

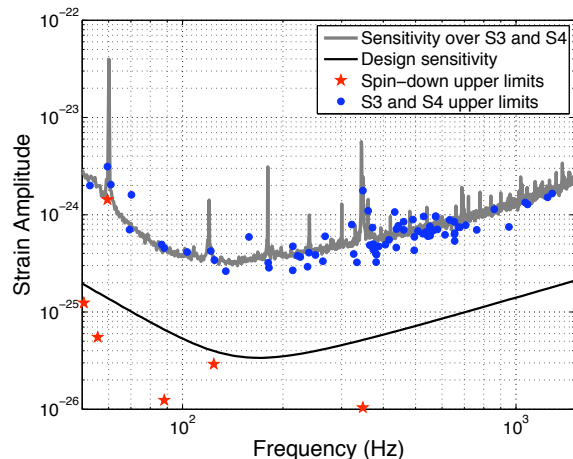


Figure 3. Upper limits (circles) from the S3 and S4 data on GW emission by 78 known pulsars. The spin-down limits (stars) are the expected signal amplitudes if the observed spin down was due entirely to gravitational-wave emission. Also shown are the expected sensitivities based on the S3 and S4 data and for one year of data at design sensitivity.

5. Stochastic background

Stochastic searches target a possible cosmological GW background from the big bang, and astrophysical backgrounds due to unresolved individual sources such as BH mergers. The searches are based on cross-correlating data streams from pairs of detectors at different sites, specifically H1-L1 and H2-L1. (Separate sites are used to minimize the potential for environmental noise to produce a spurious correlated signal.) Two types of search are performed.

The “isotropic” search places an upper limit on the GW background, expressed as the fractional energy density per log frequency interval relative to the critical energy density for

closure of the universe. The most recent result, from S4, is $\Omega_{90\%} = 6.5 \times 10^{-5}$ [13]. This is comparable to the limit implied by big-bang nucleosynthesis, $\Omega_{BBN} < O(10^{-5})$. The expected limit from the S5 run (1 year of data at design sensitivity) is approximately 4×10^{-6} , while that from one year of Advanced LIGO observations should be $O(10^{-9})$. This is sufficient to detect or place interesting limits on a stochastic background from, e.g., cosmic string networks [14].

The “radiometer” search places upper limits on stochastic emission by point sources. A recent search targeted Sco-X1, an LMXB in which accretion onto the neutron star could be powering GW emission. The radiometer analysis yielded an upper limit on the RMS GW amplitude of $h_{rms} < 3.4 \times 10^{-24}(f/200Hz)$ in each 0.25 Hz bin above 200 Hz [15]. This is sufficiently low to indicate that Sco-X1 may be detectable with this method with Advanced LIGO.

6. Summary

The LIGO detectors have reached their design sensitivity, and the fifth LIGO science run is about to conclude after gathering 1 year of coincident observational data. Searches are ongoing for GWs from compact binaries, pulsars, GRBs, the early universe, and other sources, and limits from LIGO observations are beginning to reach astrophysically interesting levels. The next decade will see extensive upgrades to both LIGO and its international partners, increasing their sensitivity by up to a factor of 15, and bringing us into the era of gravitational-wave astronomy.

Acknowledgments

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