Searching for the Stochastic Gravitational-Wave Background with Advanced LIGO and Advanced Virgo

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The Advanced LIGO detectors have commenced observations with Advanced Virgo joining in the near future. Gravitational waves from the merger of binary black hole systems have been observed. A major goal for LIGO and Virgo will be to detect or set limits on a stochastic background of gravitational waves. A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved cosmological and/or astrophysical sources. A cosmologically produced background would carry unique signatures from the earliest epochs in the evolution of the Universe. Similarly, an astrophysical background would provide information about the astrophysical sources that generated it. The observation of gravitational waves from binary black holes implies that there will be a stochastic background from these sources that could be observed by Advanced LIGO and Advanced Virgo in the near future. The LIGO and Virgo search for a stochastic background should probe interesting regions of the parameter space for numerous astrophysical and cosmological models. Presented here is an outline of LIGO and Virgo's search strategies for a stochastic background of gravitational waves, including the search for gravitational wave polarizations outside of what is predicted from general relativity. Also discussed is how global electromagnetic noise (from the Schumann resonances) could affect this search; possible strategies to monitor and subtract this potential source of correlated noise in a the global detector network are explained. The results from Advanced LIGO's observing run O1 are presented, along with the implications of the gravitational wave detections. The future goals for Advanced LIGO and Advanced Virgo are explained.

1 Introduction

A consequence of Einstein's general theory of relativity are gravitational waves, perturbations to spacetime that travel away from their source at the speed of light. A stochastic gravitational-wave background (SGWB) signal is formed from the superposition of many events or processes that are too weak and too numerous to be resolved individually, and which combine to produce a SGWB. Cosmological sources, such as inflation, pre-Big Bang models, or cosmic strings, could create a SGWB. Astrophysical sources can also create a SGWB; this background could be produced over the history of the Universe from compact binary coalescences, supernovae, and neutron stars. In fact, the recent observations by Advanced LIGO of gravitational waves from binary black hole mergers [1,2,3] implies that a SGWB will be created from these events happening throughout the history of the universe and it may be detectable by Advanced LIGO [4] and Advanced Virgo [5] in the coming years [6]. As Advanced LIGO and Advanced Virgo conduct their observations a major goal will be to measure the SGWB.

The spectrum of a SGWB is usually described by the dimensionless quantity $\Omega_{gw}(f)$ which is the gravitational-wave energy density per unit logarithmic frequency, divided by the critical energy density ρ_c ($\rho_c = 3c^2H_0^2/8\pi G$, where H_0 is the present value of the Hubble constant) to close the universe,

$$\Omega_{gw}(f) = \frac{f}{\rho_c}\frac{d\rho_{gw}}{df} \ . \tag{1}$$

Theoretical models of the SGWB in the observation band of LIGO and Virgo are characterized by a power-law spectrum which assumes that the fractional energy density in gravitational waves has the form

$$\Omega_{gw}(f) = \Omega_\alpha \left(\frac{f}{f_{ref}}\right)^\alpha \ , \tag{2}$$

where α is the spectral index and f_{ref} is a reference frequency. Cosmologically produced SGWBs are typically approximated by a power law in the LIGO frequency band, $\alpha = 0$, while $\alpha = 3$ is characteristic of many astrophysical models. A SGWB from binary black holes in Advanced LIGO and Advanced Virgo's most sensitive frequency band (10 Hz - 100 Hz) would have $\alpha = 2/3$.

The method by which LIGO and Virgo have attempted to measure the SGWB is, in principle, not difficult; optimally filtered correlations from the output strain data from two detectors are calculated [7,8] Initial LIGO [9] and initial Virgo [10] have used this method on their data to set upper limits on the energy density of the SGWB [11,12,13]. No signal was detected, but the results constrain the energy density of the SGWB to be $\Omega_0 < 5.6 \times 10^{-6}$ at 95% confidence [13] in the 41.5–169.25 Hz band. The advanced detectors will ultimately have about 10-times better strain sensitivity than the initial detectors; the low frequency limit of the sensitive band is also extended from 40 Hz down to 10 Hz. Furthermore, the number of detectors operating in a worldwide network will increase, eventually including sites at LIGO-Hanford, LIGO-Livingston, Virgo, GEO-HF (at high frequencies) [14], KAGRA (Japan) [15], and potentially LIGO-India [16]. The significant strain sensitivity improvements and wider bandwidth will enable real breakthroughs in the searches for the SGWB, with a potential sensitivity of $\Omega_0 < 6 \times 10^{-10}$. The detection of a cosmologically produced SGWB would be a landmark discovery of enormous importance to the larger physics and astronomy community. The detection of an astrophysically produced SGWB would also be of great interest; the loudest contribution to such an SGWB would likely be stellar mass binary black hole systems, due to their large apparent abundance [6].

Gravitational-wave signals that are too weak to be detected individually combine to form a SGWB. The SGWB that LIGO and Virgo hope to observe could be created from two classes of sources. A cosmologically produced SGWB would be created in the earliest moments of the Universe. There are a host of cosmological processes that could contribute to the SGWB, such as the amplification of vacuum fluctuations following inflation [17], phase transitions in the early universe [18,19], cosmic strings [20,21,22,23], and pre-Big Bang models [24,25]. An astrophysically produced SGWB would arise from the ensemble of what would be considered to be standard astrophysical events [26]. In total the astrophysical background would be the result of a broad spectrum of events, including core collapses to neutron stars or black holes [27,28,29,30,6], rotating neutron stars [31,32] including magnetars [33,34,35,36], phase transition [37,38] or initial instabilities in young neutron stars [39,40,41,40], compact binary mergers [42,43,44,45,46,47] and compact objects around super-massive black holes [48,49]. As LIGO and Virgo observe in the advanced detector era, the cosmologically produced SGWB and the astrophysically produced SGWB are both exciting targets for observation.

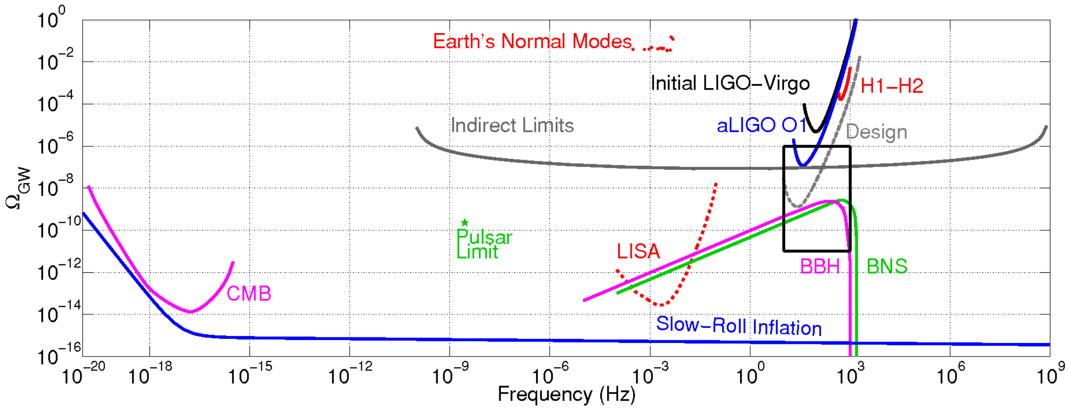

Figure 1 – Constraints on the SGWB, as well as some representative models, across many decades in frequency. Presented are the limits from ground-based interferometers from the final science run of Initial LIGO-Virgo, the co-located detectors at Hanford (H1-H2), Advanced LIGO (aLIGO) O1, and the projected design sensitivity of the advanced detector network assuming two years of coincident data, with constraints from other measurements: CMB measurements at low multipole moments [53], indirect limits from the Cosmic Microwave Background (CMB) and Big-Bang Nucleosynthesis [54,55], pulsar timing [55], and from the ringing of Earth's normal modes [56]. The predicted SGWB from binary black holes (BBH) [6] and binary neutron stars (BNS) [57] are displayed. Also given are the projected limits for the proposed space-based detector LISA [51]. Displayed in Figure 2 is the region in the black box in more detail. Figure from [50].

2 Results from Advanced LIGO Observing Run O1

Advanced LIGO's first observing run went from September 2015 to January 2016. The data from the two Advanced LIGO detectors, LIGO Hanford and LIGO Livingston, were used for the search for a SGWB. Data quality cuts removed problematic times and frequencies from the analysis. In total, 29.85 days of coincident data were analyzed. No SGWB was detected.

2.1 O1 Isotropic Results

Assuming that the frequency dependence of the energy density of the SGWB is flat, namely $\alpha = 0$, the constraint on the energy density is $\Omega(f) < 1.7 \times 10^{-7}$ with 95% confidence within the 20 Hz - 86 Hz frequency band [50]. This is a factor of 33 better than the upper limit set by initial LIGO and initial Virgo [13]. Assuming a spectral index of $\alpha = 2/3$ the constraint on the energy density is $\Omega(f) < 1.3 \times 10^{-7}$ with 95% confidence within the 20 Hz - 98 Hz frequency band, while for $\alpha = 3$ it is $\Omega(f) < 1.7 \times 10^{-8}$ in the 20 Hz - 300 Hz band [50] (the reference frequency is $f_{ref} = 25$ Hz when $\alpha \neq 0$). Figure 1 provides the O1 SGWB results, as well as constraints from from previous analyses, theoretical predictions, the expected sensitivity at design sensitivity for Advanced LIGO and Advanced Virgo, and the projected sensitivity of the proposed Laser Interferometer Space Antenna (LISA) [51]. The O1 results will be used to limit cosmic string parameters, similar to what was done with initial LIGO and initial Virgo [11,52].

The dramatic improvement in the upper limit on the SGWB energy density was important, but not the most important SGWB outcome of observing run O1. The observation of the gravitational waves from stellar mass binary black hole mergers [1,2,3] implies that these events are far more numerous in the universe than previously expected. In fact, it is likely that the SGWB produced from these type of events will be at the level of $\Omega_{GW} \sim 10^{-9}$ in the observing band of Advanced LIGO and Advanced Virgo [6]. See Figure 2.

2.2 Anisotropic O1 Results

Within the LIGO-Virgo observational band it is expected that the SGWB will be essentially isotropic. However, LIGO and Virgo have decided to look for a SGWB that would be anisotropic.

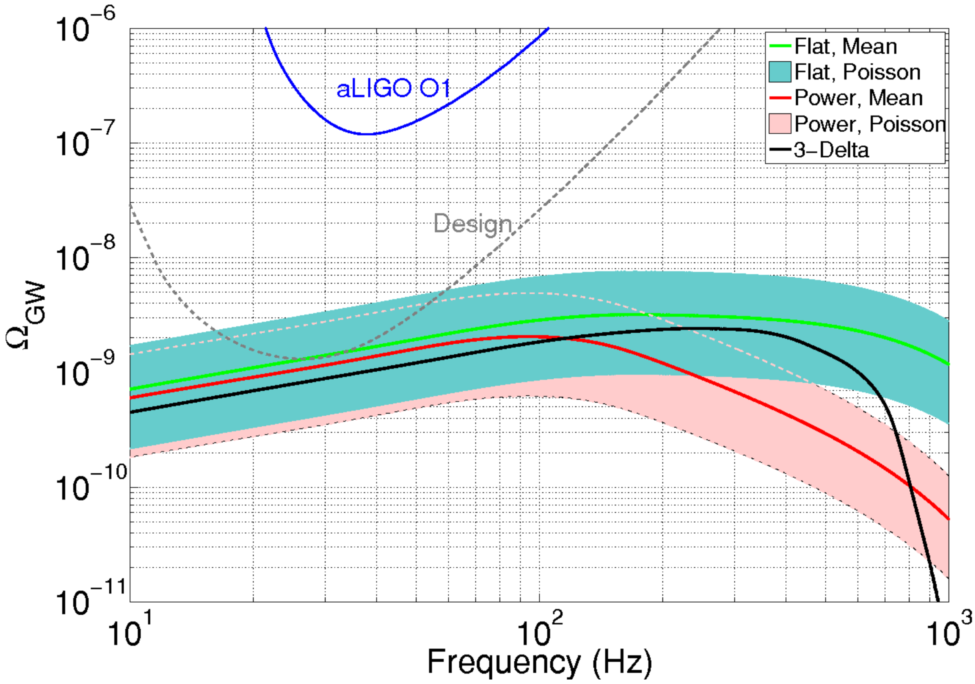

Figure 2 – The range of potential spectra for a BBH background assuming the flat-log, power-law, and three-delta mass distribution models described in [58,3], and the local rate derived from the O1 detections [3]. Also displayed is the O1 sensitivity and the projected ultimate design sensitivity for Advanced LIGO and Advanced Virgo. Figure from [50].

Such an anisotropic background could provide even more information about the early universe, or the astrophysical environment in our region of the universe. Using the recent O1 data there have been three different types of searches for an anisotropic background [59]. To look for extended sources, LIGO and Virgo use what is known as the spherical harmonic decomposition [60]. In order to search for point sources, a broadband radiometer analysis is used [61,62]. Finally, LIGO and Virgo employed a narrowband radiometer search to look for gravitational waves in the direction of interesting objects in the sky, such as the galactic center, Scorpius X-1 and SN 1987A.

An anisotropic SGWB was not observed with the Advanced LIGO O1 data, but important upper limits were set [59]. For broadband point sources, the gravitational wave energy flux per unit frequency was constrained to be $F_{\alpha,\Theta} < (0.1 - 56) \times 10^{-8}$ erg cm^{-2} s^{-1} Hz$^{-1}(f/25 \text{ Hz})^{\alpha-1}$ depending on the sky location Θ and the spectral power index α. For extended sources, the upper limits on the fractional gravitational wave energy density required to close the Universe are $\Omega(f,\Theta) < (0.39 - 7.6) \times 10^{-8}$ sr$^{-1}(f/25 \text{ Hz})^{\alpha}$, again depending on Θ and α. The directed searches for narrowband gravitational waves from Scorpius X-1, Supernova 1987 A, and the Galactic Center had median frequency-dependent limits on strain amplitude of $h_0 < (6.7, 5.5,$ and $7.0) \times 10^{-25}$ respectively, for the most sensitive detector frequencies 130 - 175 Hz. See [59] for further details.

2.3 Tests of General Relativity with the Stochastic Gravitational-Wave Background

LIGO and Virgo have used the recent observation of gravitational waves from binary black hole coalescences to test general relativity [63,3]. The LIGO-Virgo SGWB search will also be extended in order to test general relativity. There is not necessarily a reason to expect extra polarizations of gravitational waves, nor extra polarizations in the SGWB; however, LIGO and Virgo have the ability to search for these modes, and will do so. With general relativity there are only two possible polarizations for gravitational waves, namely the two tensor modes. Alternative theories of gravity can also generate gravitational waves with scalar or vector polarizations [64].

Since there are six possible polarization modes, Advanced LIGO (with only two detectors, that are essentially co-aligned with respect to each other) cannot identify the polarization of short duration gravitational wave signals [3,65,64], such as those that have been recently observed [1,2,3]. A minimum of six detectors would be necessary to resolve the polarization content (scalar, vector and tensor) of a short duration gravitational wave [64]. A search for long duration gravitational waves, such as those from rotating neutron stars or the SGWB by the two Advanced LIGO detectors, can directly measure the polarizations of the gravitational waves [65,66,67,68]. A detection of a SGWB by Advanced LIGO and Advanced Virgo would allow for a verification of general relativity that is not possible with short duration gravitational wave searches.

The LIGO-Virgo search for a SGWB will now be expanded to a search for 6 polarizations: two tensor modes, two vector modes, and two scalar modes [68]. This will soon be applied to Advanced LIGO Observing Run O1 data. The addition of Advanced Virgo to the network does not improve detection prospects (because of its longer distance displacement from the LIGO detectors), however it will improve the ability to estimate the parameters of a SGWB of mixed polarizations. The eventual inclusion of KAGRA [15] and LIGO-India [16] will further expand the ability to resolve different polarizations of the SGWB, and further test general relativity. Bayesian parameter estimation techniques have been developed in order to search for tensor, vector and scalar polarizations in the LIGO-Virgo data [68].

3 Correlated magnetic noise in global networks of gravitational-wave detectors

A search for the SGWB uses a cross-correlation between the data from two detectors. Inherent in such an analysis is the assumption that the noise in one detector is statistically independent from the noise in the other detector. Correlated noise would introduce an inherent bias in the analysis. It is for this reason that the data from two separated detectors is used. At one time initial LIGO had two co-located detectors at the LIGO Hanford site. An attempt was made to measure the SGWB with these two detectors, but correlated noise at low frequencies contaminated the measurement, and a clean analysis could only be made for frequencies above 460 Hz [12].

The LIGO and Virgo detectors' sites are thousands of kilometers from one another, and the simple assumption is that the noise in the detectors at these sites is independent from one another. However, this assumption has been demonstrated to be false for magnetic noise. The Earth's surface and the ionosphere act like mirrors and form a spherical cavity for extremely low frequency electromagnetic waves. The Schumann resonances are a result of this spherical cavity, and resonances are observed at 8, 14, 20, 26, ... Hz [69]. Most of these frequencies fall in the important SGWB detection band (10 Hz to 100 Hz) for Advanced LIGO and Advanced Virgo. The resonances are driven by the 100 or so lightning strikes per second around the world. The resonances result in magnetic fields of order 0.5 - 1.0 pT $\mathrm{Hz}^{1/2}$ on the Earth's surface [69]. In the time domain, 10 pT bursts appear above a 1 pT background at a rate of ≈ 0.5 Hz [70].

This magnetic field noise correlation has been observed between magnetometers at the LIGO and Virgo sites [71]. Magnetic fields can couple into the gravitational wave detectors and create noise in the detectors' output strain channel. It has been determined that the correlated magnetic field noise did not affect the SGWB upper limits measured by initial LIGO and Virgo, but it is possible that they could contaminate the future results of Advanced LIGO and Advanced Virgo [72]. If that is the case, then methods must be taken to try and monitor the magnetic fields and subtract their effects. This could be done, for example, via Wiener filtering [72,73]. Low noise magnetometers are now installed at the LIGO and Virgo sites in order to monitor this correlated magnetic noise, and to be used if Wiener filtering is necessary for the SGWB searches. In addition to long term magnetic noise correlations, short duration magnetic transients, produced from lightning strikes around the world, are seen to be coincidently visible at the detector sites and could affect the search for short duration gravitational wave events [74].

4 Future Observing Runs for LIGO and Virgo

Advanced LIGO has completed its first observing run, and the results of the search for a SGWB have been published [50,59]. At the time of this writing Advanced LIGO is in the middle of its second observing run, with Advanced Virgo to join soon. Over the next few years further observing runs will happen as Advanced LIGO and Advanced Virgo approach their target sensitivities [75]. At their target sensitivities LIGO and Virgo should be able to constrain the energy density of the SGWB to approximately $\Omega_{gw} \sim 1 \times 10^{-9}$ (in the 10 Hz to 100 Hz band) with a year of coincident data, while 3 years of data will give a limit of $\Omega_{gw} \sim 6 \times 10^{-10}$. At this point it is likely that LIGO and Virgo could observe a binary black hole produced SGWB [50,6]. Various cosmological models [18,19,24,25], or cosmic strings [20,21,22,23] might produce a detectable SGWB at this level as well. Similar sensitivity advances will also be made with the directional searches as Advanced LIGO and Advanced Virgo reach their target sensitivities. In fact, the addition of Advanced Virgo to the network, with its long distance displacement from the LIGO sites, will make a further important contribution to the directional searches and their ability to map the sky [59]. One can expect to see many important results pertaining to the search for a SGWB from LIGO and Virgo in the coming years.

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