Laser Interferometers, Gravitational Waves and Echos from the Universe

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Abstract. The Laser Interferometer Gravitational-wave Observatory (LIGO) and its sister project Virgo aim for the first direct detections of gravitational waves. Such detections will provide not only a test of general relativity, but also a fundamental, new probe into the Universe. To achieve this goal, LIGO and Virgo use laser interferometers to monitor changes in the relative separation of mirrors at the ends of each of two perpendicular arms of km-scale length, in response to the space-time distortions induced by the passage of gravitational waves. This paper gives an overview of the status and the science of LIGO and Virgo, with selected results from the initial detector phase and predictions for the enhanced and advanced detector configurations.

1. Gravitational Waves and How to Listen
The theory of general relativity predicts that, when large masses accelerate, their gravitational field changes. Such changes propagate as gravitational waves, tiny ripples in the fabric of space-time which carry information from the most catastrophic events in the Universe: the death of a star, the collision of black holes, the Big Bang. Gravitational waves are generated by coherent relativistic motions of large masses; they travel through opaque matter and can reveal the dynamics of strongly curved space-time. As such, they will provide information that is complementary to the multi-wavelength electromagnetic spectrum of traditional astronomy and to the neutrinos and cosmic rays of particle astrophysics, with an impact on the understanding of our Universe comparable to the transition from visible to radio, infrared and X-ray astronomy.

The existence of gravitational waves was indirectly proven by measurements of the orbital period of binary pulsar P1913+16 (Hulse-Taylor, 1974), which over two decades diminished due to emanation of gravitational radiation, as predicted by general relativity [1]. However, due to their small amplitude when they reach earth, gravitational waves have never been directly measured.

The Laser Interferometer Gravitational-wave Observatory (LIGO) [3] aims to detect gravitational waves using laser interferometers: two in Hanford, WA with 4 and 2 km long arms (H1 and H2, respectively) and one in Livingston, LA with 4 km arms (L1). The interferometers monitor changes in the relative separation of mirrors at the ends of each of two perpendicular arms, in response to the space-time distortions induced by gravitational waves. The goal for the initial phase of LIGO is to measure differences in length to one part in $10^{-18}$, which is one thousand times smaller than a typical nuclear diameter. LIGO achieved its design sensitivity in 2005 [2] and carried out a long observing run, S5, which produced one year of
Figure 1. Schematics of the LIGO interferometer, from reference [2]. The laser beam is split in two components that travel along the perpendicular arms, are reflected by mirrors (ITM and ETM) and recombine at the beam splitter (BS). When a gravitational wave modifies the length of the arms, the two beams accumulate phase differences and the photodetector measures a different interference pattern. The inset photo shows a test mass mirror in its pendulum suspension.

Integrated Livingston-Hanford coincident data from November 2005 to September 2007, with strain sensitivity $h = \Delta L/L \sim 10^{-21}$ in a 100 Hz band around 150 Hz and broadband coverage between 60 Hz and a few kHz. Previous science runs (S1 through S4) had durations of only one or two months and lower sensitivity. According to the current plans, the S6 LIGO run (Enhanced LIGO) is scheduled to end in late 2010, when the interferometers will undergo invasive hardware upgrades for a ten-fold improvement in sensitivity. Advanced LIGO was approved by NSF in 2008, and design and fabrication of new components are well under way; installation of new hardware will begin in late 2010, for a scheduled start of science data in 2014.

The Virgo interferometer [4], installed in Cascina, Italy, has a 3 km arm length, and it reached comparable sensitivity to that of LIGO in 2007, when it began its first science run, VSR1, in overlap with the S5 LIGO run, beginning May 18, 2007. The two projects now have an agreement for data sharing; all data is analyzed and results are reviewed and published together by the LIGO Scientific Collaboration and the Virgo collaborations. Current and future data runs and instrumental development are coordinated between the two projects: a joint run plan committee is coordinating the ongoing science runs S6 (LIGO) and VSR2 (Virgo). Virgo also has plans for a second generation phase: Advanced Virgo, approved Fall 2009, should achieve comparable sensitivity to Advanced LIGO, on a similar time scale. Figure 2 shows the measured noise spectra for the initial phases of LIGO and Virgo, as well as a projected noise curve for the advanced phases. As the figure shows, the advanced configuration will yield a factor 10 improvement across the frequency spectrum, and even better at low frequencies.

In the remainder of this paper, we will highlight recent results from LIGO and Virgo, based on data from S5 and VSR1, the first long-term operation of a worldwide network of interferometers of similar performance at three different locations.
Figure 2. Measured noise amplitude spectra for initial LIGO and initial Virgo, compared to the expected spectra in the advanced configuration [5; 6]. On the vertical axis is the square root of the noise power spectral density, in units of $Hz^{-1/2}$. From reference [7].

2. Recent Results
2.1. Gravitational wave transients
Gravitational wave transients are any short signal, with duration ranging from a few milliseconds to several seconds or minutes. Two approaches have been developed in the search for transient signatures. (1) Templated searches are based on knowledge of the signal being sought, using matched filtering to a class of templates to extract a known, weak signal from noise. These searches have been used by LIGO and Virgo to target the coalescence of compact binary systems, isolated ring-downs and cosmic (super)string cusps, which will be discussed in section 2.5. (2) Un-modeled searches, instead, are designed to be sensitive to gravitational wave signatures with a less accurate model, and serendipitous sources as well. They only make minimal assumptions on the signal morphology and rely on the coherence properties of gravitational waves.

The gravitational wave signature of stellar mass compact binary coalescences is considered the most promising for ground based interferometer, both because of waveform knowledge and predicted rate. LIGO and Virgo data has been match-filtered to a bank of inspiral templates to look for binary neutron stars with total mass $M_T=2–35 M_\odot$ [8; 9]. The inspiral waveforms generated by these systems can be reliably predicted using post-Newtonian (PN) perturbation theory, until the last fraction of a second prior to merger. We used waveforms from non-spinning compact binaries calculated in the frequency domain using the stationary-phase approximation (SPA) [10–12]. The waveforms are calculated to Newtonian order in amplitude and second PN order in phase, and extend until the Schwarzschild innermost stable circular orbit (ISCO). The analysis of data from the first 18 months of S5 yielded no gravitational-wave coalescence candidates, so we set upper limits on their rate. The resulting 90% C.L. upper limits on neutron star (1.35 $M_\odot$) and black hole (5.0 $M_\odot$) binary coalescences are [8; 9]:

\[ \text{upper limit} = \ldots \]
neutron star – neutron star rate $< 1.4 \times 10^{-2}/L_{10}/\text{year}$

black hole – black hole rate $< 7.3 \times 10^{-4}/L_{10}/\text{year}$

black hole – neutron star rate $< 3.6 \times 10^{-3}/L_{10}/\text{year}$

where $L_{10} = 10^{10}$ times the blue solar luminosity; the luminosity of the Milky Way is $1.7L_{10}$; these units are used because the rate of binary coalescences in a galaxy follows approximately the star formation rate, or blue light luminosity. These results are still 1 to 2 orders of magnitude above optimistic astrophysical predictions and $\sim 3$ orders of magnitude above best estimates [7], but we are preparing for better targets in Advanced LIGO/Virgo.

A matched-filter search with ringdown templates is also performed for higher mass systems [13–15]. A perturbed black hole, such as a coalescence remnant, is expected to settle to a stationary configuration through emission of gravitational radiation. The waveform is a superposition of quasi-normal modes, or ringdowns, with fundamental mode $l = m = 2$, a well known waveform that can be used in matched filtering. Using data from the S4 run, we placed a 90% C.L. upper limit on the rate of ringdowns from black holes with mass between 85 $M_{\odot}$ and 390 $M_{\odot}$ in the local Universe, assuming a uniform source distribution, of $3.2 \times 10^{-5}/\text{yr}/Mpc^3 = 1.6 \times 10^{-3}/\text{yr}/L_{10}$.

The matched filter technique [16] is now being extended to intermediate mass black holes up to 100 $M_{\odot}$, in a regime where only few cycles are in the LIGO band and most of the signal-to-noise ratio comes from the merger and ringdown phase of the coalescence [17; 18], using EOBNR analytical templates (Effective One Body waveforms, tuned to match Numerical Relativity simulations) that follow the full coalescence [19]. At this moment, these templates only describe non-spinning systems, but an intense effort is in progress to extend them to a broad parameter space, including spinning and precessing systems.

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**Figure 3.** Average inspiral horizon distance during 4.5 months of S5/VSR1, as a function of the total mass of the binary system for each interferometer. The error bars indicate variations over this period. From reference [20].

**Figure 4.** Expected horizon distance in the ringdown matched-filter search for the initial LIGO reference noise (SRD), for a black hole with spin parameter $a = 0.9$ and $\varepsilon = 0.01$, as a function of the black hole mass. For more details, see [15].

The physical reach of templated searches can be quoted as the horizon, or the distance at which an optimally oriented source can be detected with signal-to-noise ratio $\text{SNR}=8$. Figure 3 shows the horizon for the detection of compact binary coalescences with SPA matched filtering at the three LIGO detectors and Virgo during the S5 run, function of the system total mass.
and assuming non-spinning sources. As the mass increases, the inspiral phase of the systems goes out of band and matched filtering to SPA templates becomes less sensitive, while other techniques, such as matched filtering to EOBNR IMR templates and template-less searches, become more effective. Similarly, figure 4 shows the horizon for black hole ringdowns with spin parameter $a = Jc/GM^2 = 0.9$, assuming a fraction $\epsilon = 0.01$ of the black hole’s mass is radiated in gravitational waves.

A complementary approach to the detection of gravitational wave transients is to make no assumptions on the signal morphology, but only rely on the properties of gravitational waves. This is the approach followed by LIGO and Virgo burst searches, which look for coherent excess power in multiple detector and effectively match detectors to each other rather than to a template bank. A burst trigger is characterized by a time, duration, frequency, bandwidth and root-square-sum amplitude $h_{rss}$, in units of strain/$\sqrt{\text{Hz}}$:

$$h_{rss} = \sqrt{\int_{-\infty}^{\infty} \left|h(t)\right|^2 dt} = \sqrt{\int_{-\infty}^{\infty} \left|\hat{h}(f)\right|^2 df},$$

where $h(t)$ is the time dependent waveform, in units of strain, and $\hat{h}(t)$ its Fourier transform. The challenge is to make sure we control the false alarm rate due to noise transients (to $\sim 1$ false alarm per century) so these searches are particularly sensitive to data quality and to coherent coincidence criteria.

The burst all-sky search of S5/VSR1 [21–23] is a network analysis that combines times when all four detectors (Virgo and the three LIGO) were functioning, times with only the three LIGO detectors and times where only the two colocated Hanford detectors were online; other network configurations were not included, since they had minor contribution to the livetime. The analysis covers a frequency band of 50–6000 Hz.

This analysis yielded no plausible gravitational wave candidate, so we set upper limits on rates of gravitational wave bursts of 2.0 events per year at 90% CL in the 64–2048 Hz band, and 2.2 events per year for higher-frequency bursts up to 6 kHz. The IGEC network of resonant bar detectors set a tighter rate limit, 1.5 events per year at 95% confidence level [24; 25]. However, the IGEC detectors were sensitive only around their resonant frequencies, near 900 Hz, and achieved that rate limit only for signal amplitudes one to two orders of magnitude louder than the LIGO-Virgo burst search is sensitive to. Figure 5, from reference [23], shows exclusion curves for the rate of gravitational wave bursts of different frequencies, as a function of the burst $h_{rss}$ amplitude, marginalized over the orientation and inclination of the source. Exclusion curves for previous runs (S1, S2, S4) are also shown. Figure 6 shows the rate upper limit per unit volume at 90% CL for a linearly polarized, sine-Gaussian standard candle with $E_{GW} = M_{\odot}c^2$ [23].

The astrophysical sensitivity of the S5y2/VSR1 search is quoted as the amount of mass converted into gravitational wave burst energy at a given distance $r_0$, that would be sufficient to be detected by the search with 50% probability ($M_{GW}$). A rough estimate for a standard-candle isotropic emission is [23]:

$$M_{GW} \approx \frac{\pi^2 c}{G} r_0^2 f_0^2 h_{rss}^2.$$

For instance, for a sine-Gaussian signal with $f_0 = 153$ Hz and $Q = 9$ (oscillations under the Gaussian envelope) in the four-detector network, the root-sum-square amplitude with 50% detection probability is $h_{50\%} = 6.0 \times 10^{-22}$ Hz$^{-1/2}$. Assuming a typical Galactic distance of 10 kpc, that $h_{rss}$ corresponds to $M_{GW} = 1.8 \times 10^{-8} M_{\odot}$. For a source in the Virgo galaxy cluster, approximately 16 Mpc away, the same $h_{rss}$ would be produced by a mass conversion of $\sim 0.05 M_{\odot}$.

For a model-dependent interpretation of the burst result, we quote a detection range for gravitational wave signals from core-collapse supernovae and from neutron star collapse to a
black hole. Such signals are expected to be produced at a high frequency, up to a few kHz, and with a relatively small gravitational wave energy output \(10^{-9} - 10^{-5} M_\odot c^2\). For a possible supernova scenario, we consider a numerical simulation of core collapse by Ott et al. [26]. For the model s25WW, which undergoes an acoustically driven explosion, as much as \(8 \times 10^{-5} M_\odot\) may be converted to gravitational waves, with dominant frequency content at \(\sim 940\) Hz and the duration of order one second. We estimate such signal could be detected out to a distance of around 30 kpc [23]. The axisymmetric neutron star collapse signals D1 and D4 of Baiotti et al. [27] have detection ranges (at 50% confidence) of only about 25 pc and 150 pc, due mainly to their lower energy \(M_{GW} < 10^{-8} M_\odot\) and also to emitting most of that energy at 2–6 kHz, where the detector noise is greater.

### Figure 5
90% confidence rate limit function of signal amplitude \(h_{rss}\) for Q=9 sine-Gaussian pulses and various frequencies. The most recent S5/VSR1 result is compared to the limits from previous LIGO runs [23].

### Figure 6
90% CL rate limit per unit volume for a linearly polarized, sine-Gaussian standard candle with \(E_{GW} = M_\odot c^2\) [23].

2.2. Multi-messenger searches for gravitational wave transients

One of the most exciting prospects of gravitational wave transient searches is the potential for multi-messenger astrophysics, where the information on gravitational wave signatures is combined to that of electromagnetic observations. Of particular interest, in this context, are Gamma Ray Bursts (GRBs), intense flashes of \(^\gamma\)-rays which occur approximately once per day and are isotropically distributed over the sky [28]. The variability of the bursts on time scales as short as a millisecond indicates that their progenitors are compact, while the identification of host galaxies and redshift measurements have shown they are extra-galactic. GRBs are grouped into two broad classes by their characteristic duration and spectral hardness [29; 30]. The progenitors of most short GRBs (\(\leq 2\) s, with hard spectra) are widely thought to be mergers of neutron star binaries or neutron star-black hole binaries [31]; a small fraction (up to 15%) of short-duration GRBs are also thought to be due to giant flares from a local distribution of soft-gamma repeaters (SGRs) [32–34]. Long GRBs (\(\geq 2\) s, with soft spectra), on the other hand, are associated with core-collapse supernovae [35–38]. Both the merger and supernova scenarios result in the formation of a stellar-mass black hole with accretion disk [39; 40], and the emission of gravitational radiation is expected in this process.

GRB 070201 was a short, hard gamma-ray burst detected during the S5 run. Its error box was consistent with being located in M31, at a distance of 770 kpc. At that time, only the two Hanford detectors were operating. We searched for gravitational wave signatures in a time window of 180 s around the event, both with the inspiral matched filter and with the unmodeled
burst approach, but no plausible candidate was found [41]. Figure 7 shows exclusion regions, at difference confidence levels, for the distance of a compact binary progenitor of GRB 070201, with masses in the range $1 \text{M}_\odot < m_1 < 3 \text{M}_\odot$ and $1 \text{M}_\odot < m_2 < 40 \text{M}_\odot$. If GRB 070201 were caused by a binary neutron star merger, we find that a location in M31 is excluded at more than 99% confidence, while $D < 3.5$ Mpc is excluded at 90% confidence, assuming random inclination. The analysis also implies that an unmodeled gravitational wave burst from GRB 070201 emitted less than $4.4 \times 10^{-4} \text{M}_\odot c^2$ ($7.9 \times 10^{50} \text{ergs}$) in any 100 ms long period within the signal region, if the source was in M31 and radiated isotropically at the same frequency as LIGO’s peak sensitivity ($f \sim 150$ Hz). This upper limit does not exclude current models of SGRs at the M31 distance. This result prompted a review of the properties of this GRB, leading to the conclusion that it was not a binary merger in M31, but possibly an SGR giant flare instead [42; 43].

![Figure 7](image)

**Figure 7.** The shaded regions represent 90%, 75%, 50%, and 25% exclusion regions, from darkest to lightest, respectively. The distance to M31 is indicated by the horizontal line at $D=0.77$ Mpc. Both the amplitude calibration uncertainty and Monte Carlo statistics are included in this result; apparent fluctuations as a function of mass are due to Monte Carlo uncertainty. [41]

In a recent paper [44], we published the analysis of 137 GRBs that were detected by satellite-based gamma-ray experiments during the S5/VSR1 run, mostly by the *Swift* satellite, searching for gravitational wave bursts from both short and long duration GRBs. Since the precise nature of the radiation depends on the progenitor model, we looked for unmodelled burst signals with duration $< 1$ s in LIGO/Virgo band, 60–2000 Hz.

The search implemented a coherent network analysis method that accounts for the different locations and orientations of the interferometers at the three LIGO-Virgo sites. We found no evidence for gravitational-wave burst signals associated with this sample of GRBs; using simulated short-duration ($< 1$ s) waveforms, we set upper limits on the amplitude of gravitational waves associated with each GRB. We also placed lower bounds on the distance to each GRB under the assumption of a isotropic gravitational wave energy emission $E_{GW}^{\text{iso}} = 0.01 \text{M}_\odot c^2$, at frequencies around 150 Hz, where the LIGO-Virgo detector network has best sensitivity, and found typical limits of $D \sim 15$ Mpc, as shown in figure 8. $E_{GW}^{\text{iso}} = 0.01 \text{M}_\odot c^2$ is a reasonable expectation for emission in the LIGO-Virgo band by various progenitor models, such as mergers of neutron star binaries or neutron star – black hole systems. For other values of $E_{GW}^{\text{iso}}$, the distance limit scales as $D \propto (E_{GW}^{\text{iso}})^{1/2}$.

We also performed a search with matched filtering to templates for compact binary coalescences [44], in temporal and directional coincidence with 22 GRBs during S5/VSR1. This analysis was motivated by progenitor scenarios for short gamma-ray bursts (short GRBs) that include coalescences of two neutron stars or a neutron star and black hole. We found no statistically significant gravitational wave candidates within a $[-5, +1]$ s window around the time of any GRB. We constrained the distance to each GRB assuming it was caused by a compact binary coalescence with a neutron star with $1 < m_1 < 3 \text{M}_\odot$ and a companion of mass $1 < m_2 < 3 \text{M}_\odot$ (neutron star–neutron star system, or NS–NS) or $7 < m_2 < 10 \text{M}_\odot$ (neutron star–black hole system, or NS-BH); the median exclusion distance for a NS–NS system is 3.3
Mpc and for a NS–BH system is 6.7 Mpc, assuming no beaming. Lower limits on the distance of individual GRBs are shown in figure 9.

Figure 8. Distribution of lower limits on the distance to each of the 137 GRBs studied, assuming the GRB progenitors emit $0.01M_\odot c^2 = 1.8 \times 10^{52}$ erg of energy in circularly polarized gravitational waves at 150Hz. [44]

Figure 9. Lower limits on distances at 90% CL to NS–NS and NS–BH progenitor systems for 22 GRBs during the S5/VSR1 run [45].

2.3. Continuous sources: gravitational waves from known pulsars

Continuous waves represent a different class of signatures searched for in LIGO–Virgo data. Millisecond and young pulsars are some of the best galactic targets for gravitational wave searches in the 40–2000 Hz frequency band of current interferometric detectors; there are currently over 200 known pulsars with spin frequencies greater than 20 Hz. A search was conducted [46] for 116 known millisecond and young pulsars using LIGO S5 data, using for each pulsar ephemerides from radio and X-ray observations. Knowing the position and spin evolution of a pulsar allows a fully coherent analysis of long time spans, and dig deeply into the detector noise to search for evidence of gravitational wave emission by the pulsar.

This search assumes that the pulsars are triaxial stars emitting gravitational waves at twice their observed spin frequencies, i.e. the emission mechanism is an $l = m = 2$ quadrupole, and that gravitational waves are phase-locked with the electromagnetic signal. For each pulsar, the target sensitivity is the spin-down limit on strain tensor amplitude $h_{0}^{sd}$, which can be calculated by assuming that the observed spin-down rate of a pulsar is entirely due to energy loss through gravitational radiation from an $l = m = 2$ quadrupole, as:

$$h_{0}^{sd} = 8.06 \times 10^{-19} \frac{I_{28}}{r_{kpc}} \sqrt{\frac{|\nu|}{\nu}}$$

where $I_{28}$ is the pulsars principal moment of inertia $I_{zz}$ in units of $10^{38}$ kg m; $r_{kpc}$ is the pulsar distance in kpc, $\nu$ is the spin-frequency in Hz, and $\dot{\nu}$ is the spin-down rate in Hz s$^{-1}$.

We did not detect signals from any of the targets; therefore we interpret our results as upper limits on the gravitational wave signal strength, as shown in figure 10.
Our best upper limit on gravitational wave amplitude is $2.3 \times 10^{-26}$ for pulsar J1603-7202 and our best limit on the inferred pulsar ellipticity is $7.0 \times 10^{-8}$ for pulsar J2124-3358. Of the recycled millisecond pulsars several of the measured upper limits are only about an order of magnitude above their spin-down limits. For the young pulsars J1913+1011 and J1952+3252 we are only a factor of a few above the spin-down limit, and for the X-ray pulsar J0537-6910 we reach the spin-down limit under the assumption that any gravitational wave signal from it stays phase locked to the X-ray pulses over timing glitches.

Of particular interest are the limits on gravitational radiation from the Crab pulsar [47]. The Crab pulsar has a high spin-down rate, $\dot{\nu} \approx -3.7 \times 10^{-10} \text{ Hz/s}$, corresponding to a kinetic energy loss rate of $\dot{E} \approx 4.4 \times 10^{31} \text{ W}$. This loss is due to a variety of mechanisms, including magnetic dipole radiation and particle acceleration in the magnetosphere, but a significant fraction of this energy could be shed in the form of gravitational radiation. We searched for signal in first 9 months of LIGO S5 data and found no evidence for gravitational radiation. The measured upper limit for gravitational emission from the Crab pulsar is now a factor of seven below the spin-down limit. Assuming the gravitational signal is locked to electromagnetic pulses, this null search result implies that no more than $\sim 2\%$ of the available spin-down power is radiated in the form of gravitational waves.

![Figure 10](image1.png)

**Figure 10.** Upper limits for gravitational wave amplitude from known pulsars, superimposed to the estimated sensitivity of the search (grey band). The results of the S3/S4 search are also shown, for comparison [46].

![Figure 11](image2.png)

**Figure 11.** Results for the Crab pulsar, J0537–6910 and J1952+3252 analyses, compared to the spin-down limits, in the moment of inertia–ellipticity plane. Areas to the right of the diagonal lines are excluded. The shaded regions are outside the theoretically predicted range of moments of inertia $I_{38} = 1 - 3$. [46]

### 2.4. Stochastic Background

A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved gravitational wave sources of astrophysical and cosmological origin. Such signal is expected to carry unique signatures from the earliest epochs in the evolution of the Universe, inaccessible to standard astrophysical observations. Direct measurements of the amplitude of this background would provide unaltered information on the physical processes that generated it, and understanding of the evolution of the Universe in its first minute of life.
We quantify the stochastic gravitational wave background by its spectrum:

$$\Omega_{GW}(f) = \frac{f}{\rho_c} \frac{d \rho_{GW}}{df}$$  \hspace{1cm} (4)$$

where $d \rho_{GW}$ is the energy density of gravitational radiation contained in the frequency range $f$ to $f + df$ and $\rho_c$ is the critical energy density of the Universe. To measure $\Omega_{GW}$, we rely on cross correlation of data from pairs of interferometers. The cross correlation is computed in frequency domain and multiplied by a filter factor that is inversely proportional to the noise in each detector, and also depends on the frequency-dependent overlap in the antenna patterns of the two interferometers.

We analyzed data from the LIGO S5 run, and constrained the energy density of the stochastic gravitational-wave background normalized by the critical energy density of the Universe, in the 41.5–169.25 Hz frequency band, to be $< 6.9 \times 10^{-6}$ at 95% confidence. This result improves on the indirect limits from Big Bang Nucleosynthesis (BBN) and Cosmic Microwave Background (CMB) at 100 Hz [48].

![Figure 12](image_url)

**Figure 12.** The landscape of stochastic gravitational wave background upper limits (see text for explanation). From reference [48].

Figure 12 compares the upper limit on gravitational wave stochastic background set by LIGO to previous measurements, other experiments and models [48]. The 95% upper limit $\Omega_0 < 6.9 \times 10^{-6}$, in the 41.5–169.25 Hz band, is compared to the previous LIGO S4 result and to the projected Advanced LIGO sensitivity, using the two co-located instruments at the Hanford site. The corresponding 95% upper bound on the total gravitational-wave energy density in this band, assuming frequency independent spectrum, is $9.7 \times 10^{-6}$. The indirect bound due to BBN acts on $\Omega_{BBN} = \int \Omega_{GW} d(\ln f)$, rather than on the density $\Omega_{GW}$, over the $10^{-13} – 10^{10}$Hz band. A similar integral bound over $10^{-15} – 10^{10}$Hz can be placed using CMB and matter power spectra.
The pulsar limit is based on the fluctuations in the pulse arrival times of millisecond pulsars, at \( \sim 10^{-8} \) Hz frequencies. Measurements of the CMB at large angular scales constrain the possible redshift of CMB photons due to the stochastic gravitational wave background, and therefore limit the amplitude of the stochastic gravitational wave background at largest wavelengths. In addition, the figure shows projected sensitivities of the Planck and LISA experiments, as well as examples of inflationary cosmic strings and pre-Big-Bang models.

Although the evolution of the Universe following the BBN is well understood, there is little observational data probing the evolution before BBN, when the Universe was less than one minute old. The gravitational wave spectrum \( \Omega_{GW} \) is related to the parameters that regulate the evolution of the Universe. As such the upper limit on \( \Omega_{GW} \) allows to constrain parameter space, and to rule out models of early Universe evolution with relatively large equation of state parameter; we refer to reference [48] for details.

2.5. Cosmic Strings and SuperStrings

 Cosmic strings were originally proposed as topological defects formed during phase transitions in the early Universe. More recently, it was realized that fundamental strings may also be expanded to cosmological scales. Hence, searching for cosmic strings may provide a unique and powerful window into string theory and into particle physics at the highest energy scales.

The network of cosmic strings is parametrized by the string tension \( \mu \) (multiplied by the Newton constant \( G \)), and reconnection probability \( p \). The CMB observations limit \( G\mu \) to \( 10^{-6} \), while the size of cosmic string loops, parametrized by \( \varepsilon \), is essentially unconstrained. The mechanism for production of gravitational waves relies on cosmic string cusps: regions of string that move at speeds close to the speed of light. If the cusp motion points towards Earth, a detectable burst of gravitational radiation may be produced. The superposition of gravitational waves from all string cusps in the cosmic string network would produce a stochastic gravitational wave background, thus the limits described in section 2.4 also rule out cosmic (super)string models with relatively small string tension, favoured in some string theory models.

Figure 13 shows how different experiments probe the \( \varepsilon - G\mu \) plane for a typical value of the reconnection probability \( p = 10^{-3} \). The region to the right of this curve is expected to produce at least one cosmic string burst event detectable by LIGO during the S5 run. Note that this search is complementary to the search for the stochastic background, as it probes a different part of the parameter space. Also shown is the region that will be probed by the Planck satellite measurements of the CMB. The entire plane shown here will be accessible to the stochastic gravitational background search of Advanced LIGO.

We also performed a matched filter search for bursts from cosmic string cusps performed on 14.9 days of LIGO S4 data, using times when all three LIGO detectors were operating [49]. No gravitational waves were detected in 14.9 days of data from. This non-detection can be interpreted in terms of a frequentist upper limit on the rate of gravitational wave bursts and use the limits on the rate to constrain the parameter space (string tension, reconnection probability, and loop sizes) of cosmic string models. The sensitivity of the LIGO instruments during the S4 run does not allow us to place constraints as tight as the indirect bounds from Big Bang Nucleosynthesis. In the future, however we expect our sensitivity to surpass these limits for large areas of cosmic string model parameter space.

3. Conclusion

This paper presented a survey of recent results from the analysis of LIGO and Virgo data from the S5/VSR1 run. No gravitational wave detection is reported, but these null results are triggering the interest of the astrophysics community, as they constrain source populations, with limits on the rate of compact binary systems close to coalescence or transient signatures.
Figure 13. Exclusion regions in the $\varepsilon - G\mu$ plane for reconnection probability $p = 10^{-3}$ from the LIGO S5 stochastic gravitational wave background search, compared to the previous limits from the LIGO S4 analysis and limits from the BBN and CMB. Also shown are the region that will be probed by the Planck satellite and the expected limits from a search of LIGO data for cosmic string cusps with gravitational wave transient techniques. The region to the right of these curves is expected to produce at least one cosmnic string burst event detectable by LIGO during the S5 run. For details, see [48] and references therein. For results of a cosmic string cusp search in S4, with different values of the reconnection probability, see [49].

from nearby galaxies, as well as specific source models (e.g. the nature of GRB070201, Crab spindown, stochastic gravitational background spectrum and cosmic string parameters).

At the time of this writing, the S6/VSR2 science run is in progress, part of an enhanced program, where some of the advanced technology is being tested on existing interferometers. By 2011, LIGO will halt data acquisition and begin installation of Advanced LIGO, a tunable, quantum-noise-limited interferometer, with a predicted ten-fold sensitivity improvement down to 10 Hz, due to new fused silica multi-stage suspension, higher laser power, active seismic isolation, signal recycling a careful quantum engineering to balance radiation pressure and shot noise [5]. In parallel, Advanced Virgo will install new monolithic suspensions and better mirrors for lower thermal noise, and higher laser power and signal recycling for an improved sensitivity at intermediate and high frequencies [6].

Within the next few years, Advanced LIGO and Advanced Virgo will probe $\sim$1000 more galaxies, and the science from the first three hours will be comparable to a whole year of Initial LIGO, and the numerical relativity, astrophysics and data analysis communities are now preparing for the predicted first detections, and the inauguration of a new gravitational wave astronomy.
Acknowledgments
The authors gratefully acknowledge the support of the United States National Science Foundation for the construction and operation of the LIGO Laboratory, the Science and Technology Facilities Council of the United Kingdom, the Max-Planck-Society and the State of Niedersachsen/Germany for support of the construction and operation of the GEO600 detector, and the Italian Istituto Nazionale di Fisica Nucleare and the French Centre National de la Recherche Scientifique for the construction and operation of the Virgo detector. The authors also gratefully acknowledge the support of the research by these agencies and by the Australian Research Council, the Council of Scientific and Industrial Research of India, the Istituto Nazionale di Fisica Nucleare of Italy, the Spanish Ministerio de Educación y Ciencia, the Conselleria d’Economia Hisenda i Innovació of the Govern de les Illes Balears, the Foundation for Fundamental Research on Matter supported by the Netherlands Organisation for Scientific Research, the Polish Ministry of Science and Higher Education, the FOCUS Programme of Foundation for Polish Science, the Royal Society, the Scottish Funding Council, the Scottish Universities Physics Alliance, the National Aeronautics and Space Administration, the Carnegie Trust, the Leverhulme Trust, the David and Lucile Packard Foundation, the Research Corporation, and the Alfred P. Sloan Foundation.

This paper was assigned LIGO Document Control Number LIGO-P1000016.

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