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## Improved Upper Limits on the Stochastic Gravitational-Wave Background from 2009–2010 LIGO and Virgo Data

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Gravitational waves from a variety of sources are predicted to superpose to create a stochastic background. This background is expected to contain unique information from throughout the history of the Universe that is unavailable through standard electromagnetic observations, making its study of fundamental importance to understanding the evolution of the Universe. We carry out a search for the stochastic background with the latest data from the LIGO and Virgo detectors. Consistent with predictions from most stochastic gravitational-wave background models, the data display no evidence of a stochastic gravitational-wave signal. Assuming a gravitational-wave spectrum of  $\Omega_{\text{GW}}(f) = \Omega_{\alpha}(f/f_{\text{ref}})^{\alpha}$ , we place 95% confidence level upper limits on the energy density of the background in each of four frequency bands spanning 41.5–1726 Hz. In the frequency band of 41.5–169.25 Hz for a spectral index of  $\alpha = 0$ , we constrain the energy density of the stochastic background to be  $\Omega_{\text{GW}}(f) < 5.6 \times 10^{-6}$ . For the 600–1000 Hz band,  $\Omega_{\text{GW}}(f) < 0.14(f/900 \text{ Hz})^3$ , a factor of 2.5 lower than the best previously reported upper limits. We find  $\Omega_{\text{GW}}(f) < 1.8 \times 10^{-4}$  using a spectral index of zero for 170–600 Hz and  $\Omega_{\text{GW}}(f) < 1.0(f/1300 \text{ Hz})^3$  for 1000–1726 Hz, bands in which no previous direct limits have been placed. The limits in these four bands are the lowest direct measurements to date on the stochastic background. We discuss the implications of these results in light of the recent claim by the BICEP2 experiment of the possible evidence for inflationary gravitational waves.

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*Introduction.*—The stochastic gravitational-wave background (SGWB) has great potential to be a rich area of study since it is expected to include contributions from a superposition of astrophysical and/or cosmological sources. Astrophysical contributions to the background might very well dominate in the LIGO and Virgo frequency band. These contributions may include compact binary coalescences [1–5], rotating neutron stars [6–8], magnetars [9–11], and supernovae [12–15]. Many mechanisms for generating cosmological contributions to the stochastic background have been postulated as well, such as inflationary models [16–23] and cosmic strings [24–27]. The recent observation of *B*-mode polarization in the cosmic microwave background claimed by the BICEP2 experiment [28], when using common dust emission models, suggests the presence of gravitational waves produced by primordial vacuum modes amplified by inflation (although the lack of public dust emission maps means BICEP2 could not

empirically exclude dust emission as being wholly responsible for the excess *B*-mode polarization, and recent analyses reinforce this [29,30]). The energy density of these gravitational waves in the LIGO and Virgo frequency band is several orders of magnitude weaker than typical predictions for astrophysical contributions and 6 orders of magnitude weaker than what Advanced LIGO [31] and Advanced Virgo [32] detectors are expected to achieve. However, nonstandard inflationary models [19,20] might surpass even the predicted astrophysical contributions at the LIGO and Virgo frequencies, thereby facilitating detection with Advanced LIGO and Advanced Virgo to which the BICEP2 measurement is not sensitive. Current alternative theories of inflation, predicting a high-frequency background detectable with Advanced LIGO and Advanced Virgo, remind us that many details of inflation are still unknown, and reality may be more complicated than predicted by simple slow-roll models. Other

cosmological backgrounds, e.g., from cosmic (super) strings, may be detectable as well [27].

The multitude of astrophysical and cosmological sources potentially contributing to a stochastic background offers an opportunity to study many aspects of the Universe that are not accessible through standard electromagnetic astrophysical observations [33]. With the possible observation of a gravitational-wave (GW) imprint on the cosmic microwave background (CMB) [28], we enter an exciting new phase in GW cosmology in which it appears plausible to study the physics of very early times and very high energies.

In this Letter we report on a search for the isotropic stochastic background using data gathered in 2009–2010 by the LIGO and Virgo detectors. For the search, we cross-correlated data streams from different detectors to look for a correlated stochastic signal. Most SGWB models predict backgrounds much lower than these data were capable of detecting. However, this work sets the stage for the Advanced LIGO and Advanced Virgo detectors, which are expected to achieve 4 orders of magnitude improvement in sensitivity to the GW energy density at 100 Hz and be sensitive to frequencies down to 10 Hz. Having found no statistically significant evidence of a stochastic gravitational-wave signal, we present the best constraints to date on the energy density of the SGWB from the LIGO and Virgo detectors.

*Data.*—Previous to this analysis, the best limits on the SGWB from LIGO and Virgo data were obtained using 2005–2007 data [34–36]. For this study, we use data from the LIGO observatories in Hanford, Washington, (H1) and Livingston Parish, Louisiana, (L1) [37] as well as the Virgo observatory in Cascina, Italy (V1) [38]. The H2 observatory in Hanford was decommissioned before these data were collected. LIGO data ran from July 2009 to October 2010. Virgo data spanned July 2009 to January 2010 and July 2010 to October 2010.

*Method.*—The SGWB energy density spectrum is defined as

$$\Omega_{\text{GW}}(f) = \frac{f}{\rho_c} \frac{d\rho_{\text{GW}}}{df}, \quad (1)$$

where  $f$  is frequency,  $\rho_c$  is the critical (closure) energy density of the Universe, and  $d\rho_{\text{GW}}$  is the gravitational radiation energy density contained in the range  $f$  to  $f + df$

[39]. For the LIGO and Virgo frequency bands, most theoretical models are characterized by a power law spectrum, so we assume the gravitational-wave spectrum to be [35,39,40]

$$\Omega_{\text{GW}}(f) = \Omega_\alpha \left( \frac{f}{f_{\text{ref}}} \right)^\alpha. \quad (2)$$

Here,  $f_{\text{ref}}$  is an arbitrary reference frequency (see Table I).  $\Omega_\alpha$  is a constant characterizing the amplitude of the SGWB in a given frequency band. Following the precedent of Refs. [34–36], we consider two spectral index values:  $\alpha = 0$  (cosmologically motivated) and  $\alpha = 3$  (astrophysically motivated).

We employ a cross-correlation method optimized for detecting an isotropic SGWB using pairs of detectors [39]. This method defines a cross-correlation estimator,

$$\hat{Y} = \int_{-\infty}^{\infty} df \int_{-\infty}^{\infty} df' \delta_T(f - f') \tilde{s}_1^*(f) \tilde{s}_2(f') \tilde{Q}(f'), \quad (3)$$

and its variance,

$$\sigma_Y^2 \approx \frac{T}{2} \int_0^\infty df P_1(f) P_2(f) |\tilde{Q}(f)|^2, \quad (4)$$

where  $\delta_T(f - f')$  is the finite-time approximation to the Dirac delta function,  $\tilde{s}_1$  and  $\tilde{s}_2$  are Fourier transforms of time-series strain data from two interferometers,  $T$  is the coincident observation time, and  $P_1$  and  $P_2$  are one-sided strain power spectral densities from the two interferometers. The filter function  $\tilde{Q}$  is given by

$$\tilde{Q}(f) = \lambda \frac{\gamma(f) \Omega_{\text{GW}}(f) H_0^2}{f^3 P_1(f) P_2(f)}, \quad (5)$$

where  $\lambda$  is a normalization constant chosen such that  $\langle \hat{Y} \rangle = \Omega_\alpha$ ,  $\gamma(f)$  is the overlap reduction function arising from the combined antenna patterns of differing detector locations and orientations [42], and  $H_0$  is the present best estimate of the Hubble constant,  $68 \text{ km s}^{-1} \text{ Mpc}^{-1}$  [41].

To combine the measured  $\hat{Y}$  for each of the H1L1, H1V1, and L1V1 detector pairs, we follow Ref. [39] and average results from detector pairs weighted by their variances. The optimal estimator is thus given by

TABLE I. Results of the stochastic analysis of 2009–2010 LIGO and Virgo data. Note that the previous limits are scaled to the current best estimate of  $H_0$  [41].

| Frequency (Hz) | $f_{\text{ref}}$ (Hz) | $\alpha$ | $\Omega_\alpha$                 | 95% C.L. upper limit | Previous limits      |
|----------------|-----------------------|----------|---------------------------------|----------------------|----------------------|
| 41.5–169.25    | ...                   | 0        | $(-1.8 \pm 4.3) \times 10^{-6}$ | $5.6 \times 10^{-6}$ | $7.7 \times 10^{-6}$ |
| 170–600        | ...                   | 0        | $(9.6 \pm 4.3) \times 10^{-5}$  | $1.8 \times 10^{-4}$ | ...                  |
| 600–1000       | 900                   | 3        | $0.026 \pm 0.052$               | 0.14                 | 0.35                 |
| 1000–1726      | 1300                  | 3        | $-0.077 \pm 0.53$               | 1.0                  | ...                  |

$$\hat{Y}_{\text{tot}} = \frac{\sum_l \hat{Y}_l \sigma_l^{-2}}{\sum_l \sigma_l^{-2}}, \quad (6)$$

where  $l$  sums over detector pairs. The total variance  $\sigma_{\text{tot}}^2$  is

$$\sigma_{\text{tot}}^{-2} = \sum_l \sigma_l^{-2}. \quad (7)$$

*Analysis.*—Following Refs. [34–36], we divide the strain time series data, down-sampled to 4096 Hz, into 50% overlapping 60 s segments that are Hann windowed and high-pass filtered with a sixth-order Butterworth filter with knee frequency 32 Hz. The data are coarse grained to obtain a frequency resolution of 0.25 Hz.

We include in the analysis only those times when a detector pair has both detectors in a low noise science mode. Excluded times fall into two different categories. We exclude data (i) from times when detector operation is unstable and (ii) from times associated with hardware injections, where simulated signals are induced by coherent movement of interferometer mirrors. These cuts cause  $< 2\%$  reduction in coincident data for each detector pair. Additionally, we exclude data segments that deviate from the assumption that the power spectra of the detector noise are stationary with time [34]. Depending on the frequency band, this process excludes up to 4.7% of data segments. Combining the above effects, the cuts leave  $\sim 117$  days of live time for the H1L1 detector pair,  $\sim 74$  days for H1V1, and  $\sim 59$  days for L1V1.

Instrumental artifacts can appear in the frequency domain. We identify high coherence bins using the same method as Ref. [34]. Lines of excess coherence are caused, for example, by power line harmonics and 16 Hz harmonics from H1 and L1 data acquisition systems. These frequency bins are excluded from the final analysis.

In order to have an end-to-end test of the detectors and the analysis pipeline, simulations of a stochastic signal are made in both the hardware and the software (by the addition of a stochastic signal to interferometer data). The successful recovery of hardware injections is described in Ref. [43]. We successfully recovered a software injection, which had  $\Omega_0 = 1.2 \times 10^{-4}$  (corresponding to a signal-to-noise ratio of  $\approx 10$ ), in all three detector pairs using about one-third of the data.

Coherence studies have been made comparing data from magnetometers at the LIGO Hanford, LIGO Livingston, and Virgo observatories [44]. These studies report on the observations of correlated magnetic field noise between observatories and its potential coupling to GW detectors. While this may be a concern for future generations of detectors with their improved sensitivity, it does not affect the data used in the analysis presented in this Letter or previous results [34–36].

*Results and discussion.*—Applying the previously described search techniques and data-quality cuts, we

obtain results in each of four frequency bands that together span 41.5–1726 Hz and are summarized in Table I. In Fig. 1 we plot the frequency-dependent contributions to  $\Omega_\alpha$ . We find no evidence for an isotropic gravitational-wave background and set direct upper limits on the energy density of the SGWB.

41.5–169.25 Hz band: We use a spectral index of  $\alpha = 0$ , a value motivated by cosmological models, following the precedent of Ref. [34]. Using the previous LIGO results [34] as a prior and marginalizing over detector calibration uncertainties [45], we determine the 95% confidence level (C.L.) upper limit to be  $\Omega_0 < 5.6 \times 10^{-6}$ . This is the first result using both LIGO and Virgo data in this frequency band and it is the best direct limit on the SGWB energy density at these frequencies. The previous S5 result in this band [34] set an upper limit of  $\Omega_0 < 7.7 \times 10^{-6}$  (when scaled for the current best estimate of  $H_0$  [41]). The limit here is a 38% improvement.

600–1000 Hz band: For this frequency band, we use a reference frequency of 900 Hz and a spectral index of  $\alpha = 3$  (an astrophysically motivated value) following Ref. [35]. After taking detector calibration uncertainties into account and using the previous LIGO and Virgo results as a prior [35], we determine the 95% C.L. upper limit to be  $\Omega_3 < 0.14$ . Previous to this result, the best direct limit in this frequency band was from the combined results of LIGO and Virgo reported in Ref. [35] with  $\Omega_3 < 0.35$  (using the present best estimate of  $H_0$  [41]). Our limit is a factor of 2.5 lower than this result. This improvement comes from enhanced detector sensitivity at frequencies above 300 Hz in S6 and VSR2-3, despite a shorter observation time.

Additional frequency bands: We report additional frequency bands spanning 170–600 and 1000–1726 Hz. For the 170–600 Hz band, we measure the 95% C.L. upper limit to be  $1.8 \times 10^{-4}$ , assuming a flat prior from 0 to 1. We find the 95% C.L. upper limit to be 1.0 for the 1000–1726 Hz band, assuming a flat prior from 0 to 10. These are the first measurements of the SGWB in these bands. For the 170–600 Hz band,  $\Omega_0$  exceeds the single-sigma error bar by a factor of 2.2 which has a 10% chance of happening due to Gaussian noise given that we analyze four independent frequency bands.

*Implications.*—Figure 2 shows the upper limits from our measurement (solid black lines, denoted “LIGO-Virgo”) in comparison with other bounds on the SGWB and several representative SGWB models. We include the indirect bound on the total GW energy density in the  $10^{-10}$ – $10^{10}$  Hz band derived from big bang nucleosynthesis and observations of the abundances of the lightest nuclei [33,46,47] (“BBN,” dashed red line). We also include the similar indirect homogeneous bound from CMB and matter power spectra measurements [48] (dashed blue line). The bound due to millisecond pulsar timing measurements [49] is solid green (“Pulsar Limit”). The projected sensitivity of



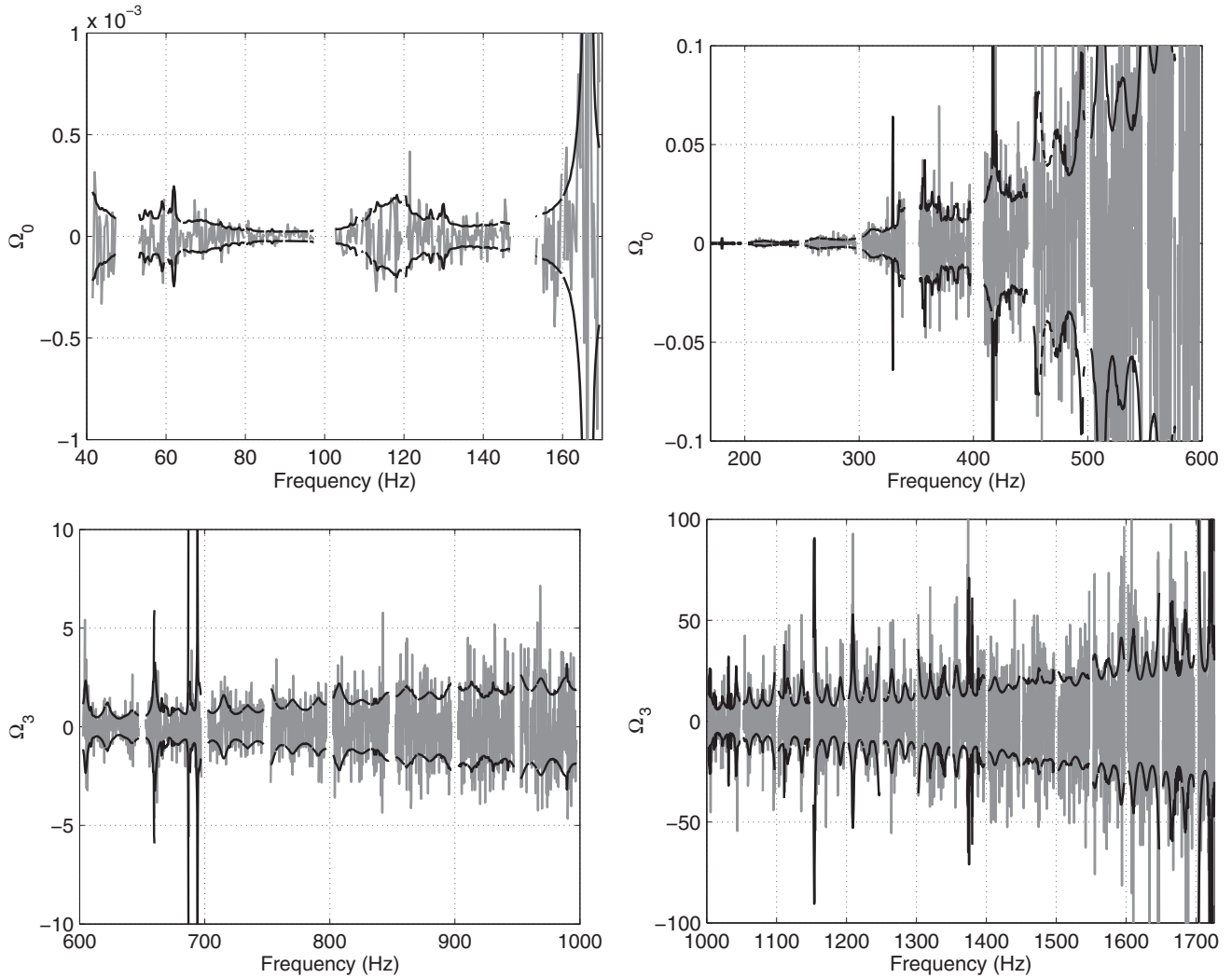


FIG. 1. Integrand of Eq. (3) multiplied by  $df = 0.25$  Hz (gray) and the associated  $1\sigma$  uncertainty (black). Though energy density is a positive quantity, its estimator can be either positive or negative due to noise. Fluctuations of the estimator around zero are consistent with the absence of a signal. The broadband results in Table I are obtained as a weighted average over each observing band following Ref. [39]. Each spectrum includes data from all available detector pairs in 2009–2010. The LIGO and Virgo detectors are most sensitive in the 41.5–169.25 Hz band.

the advanced GW detector network including Advanced LIGO [31], Advanced Virgo [32], and KAGRA [50] is solid blue (“AdvDet”). Recently, the BICEP2 Collaboration claimed observation of  $B$ -mode polarization in the CMB and considered an interpretation where the polarization signal is largely due to tensor modes [28]. A canonical slow-roll inflationary model with tensor-to-scalar ratio  $r = 0.2$  (the BICEP2 best fit) yields the spectrum shown by the solid blue line (“Slow-Roll Inflation”), predicting  $\Omega_{\text{GW}} \sim 5 \times 10^{-16}$  in the frequency band of terrestrial GW detectors [22]. This signal is not within reach of the measurement described here, nor will it be within reach of the advanced detector network. Observation of this signal with GW detectors will require novel technology, possibly satellite based [51] or underground [52].

Future measurements of this inflationary signal by GW detectors, combined with the CMB  $B$ -mode polarization measurements, will constrain the tensor spectral index  $n_t$ , hence constraining inflationary models [53]. GW measurements hold great promise for probing the physics of inflation as well as for probing processes at the energy scales of  $10^3$ – $10^{10}$  GeV [54], well beyond those of the Large Hadron Collider. For example, the late stages of inflation could generate boosts in the GW spectrum at high frequencies, either through a preheating resonant phase [18,23] or via the backreaction of fields generated by the inflaton [19,20]. As shown in Fig. 2, the axion-inflaton model including backreaction (black line, “Axion Infl.”) could produce a GW spectrum sufficiently strong to be observed by the advanced detector network. The evolution

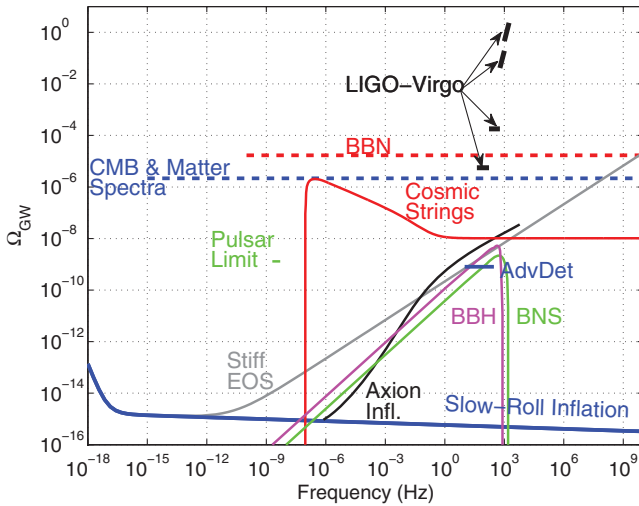


FIG. 2 (color). Normalized GW energy density versus frequency for experimental bounds and for several SGWB models (see text for detail). Note that the different experimental bounds shown in this figure constrain different quantities. The LIGO-Virgo upper limits are on  $\Omega_\alpha$  (for  $\alpha = 0, 3$ , see Table I), which are converted into bounds on  $\Omega_{\text{GW}}(f)$  as defined by Eq. (2). While “BBN” and “CMB & Matter Spectra” constrain the total GW energy density in the frequency bands indicated by their respective lines, “Pulsar Limit” is on  $\Omega_{\text{GW}}(f)$  at the specific frequency of  $f = 2.8$  nHz.

of the Universe after inflation and before big bang nucleosynthesis is not well understood. The presence of a new “stiff” energy component at this time (with equation of state parameter  $w > 1/3$ ) could also result in a significant high-frequency boost to the GW spectrum [55]. Figure 2 shows the example of  $w = 0.6$  (denoted “Stiff EOS” for stiff equation of state), which may also be detectable by the advanced detector network. A cosmological background from cosmic strings (“Cosmic Strings”) is potentially detectable as well [27].

It should also be noted that astrophysical GW foregrounds could mask the inflationary signal. Figure 2 shows the possible GW spectra from the stochastic superposition of all the binary neutron stars (“BNS,” green line) and binary black holes (“BBH,” magenta line) [3], which are too distant to be individually resolved with advanced detectors. Realistic binary rates may lead to a detectable stochastic signal in the advanced detector network. Other astrophysical models (including rotating neutron stars [6–8], magnetars [9–11], and others) may also contribute to the astrophysical foreground. Astrophysical sources are interesting in their own right. However, foreground subtraction may be necessary to reach a slow-roll inflationary signal. Such a subtraction will require detailed understanding of the foregrounds, which in turn may require multiple detectors operating in different frequency bands to disentangle different frequency and spatial contributions [56].

*Conclusions.*—The results presented above include data from both LIGO and Virgo detectors and span the frequency range of 41.5–1726 Hz. The upper limit placed on the low frequency 41.5–169.25 Hz band is 38% lower than previous direct measurements [34]. For the 600–1000 Hz band, the upper limit is a factor of 2.5 lower than previous direct measurements [35]. We also place the first upper limits over the remainder of the LIGO and Virgo frequency range: 170–600 and 1000–1726 Hz. Together, these are the lowest upper limits from direct measurements of the SGWB to date.

With Advanced LIGO and Advanced Virgo detectors on the horizon, the sensitivity of interferometers to the SGWB will improve substantially in the coming years. This will allow us to probe astrophysical sources such as binary black holes and cosmological sources such as axion inflation. We may also detect an unexpected source. To reach the SGWB generated by the standard slow-roll inflationary model, however, more sensitive gravitational wave detectors will be needed, likely deploying novel technologies.

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