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GW150914: Implications for the Stochastic Gravitational-Wave Background from Binary Black Holes

B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration)

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GW150914: Implications for the stochastic gravitational-wave background from binary black holes

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The LIGO detection of the gravitational wave transient GW150914, from the inspiral and merger of two black holes with masses $\gtrsim 30 \, M_\odot$, suggests a population of binary black holes with relatively high mass. This observation implies that the stochastic gravitational-wave background from binary black holes, created from the incoherent superposition of all the merging binaries in the Universe,
could be higher than previously expected. Using the properties of GW150914, we estimate the energy density of such a background from binary black holes. In the most sensitive part of the Advanced LIGO/Virgo band for stochastic backgrounds (near 25 Hz), we predict $\Omega_{GW}(f = 25 \text{Hz}) = 1.1^{+2.7}_{-0.9} \times 10^{-9}$ with 90\% confidence. This prediction is robustly demonstrated for a variety of formation scenarios with different parameters. The differences between models are small compared to the statistical uncertainty arising from the currently poorly constrained local coalescence rate.

We conclude that this background is potentially measurable by the Advanced LIGO/Virgo detectors operating at their projected final sensitivity.

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1 Introduction — On September 14, 2015 the Advanced LIGO [1, 2] Hanford and Livingston detectors observed the gravitational-wave event GW150914 with a significance in excess of 5.1\sigma [3]. The observed signal is consistent with a binary black hole waveform with component masses of $m_1 = 36^{+5}_{-4}$ M$_\odot$ and $m_2 = 29^{+4}_{-3}$ M$_\odot$, as measured in the source frame, and coalescing at a luminosity distance of $410^{+160}_{-180}$ Mpc, corresponding to a redshift of $z = 0.09^{+0.03}_{-0.04}$ [3, 4].

For every event like GW150914 observed by advanced gravitational-wave detectors, there are many more too distant to be resolved. The gravitational waves from these unresolvable events combine to create a stochastic background, which can be detected by comparing the signals from two or more gravitational-wave detectors [5]. While it has long been known that the advanced detectors could observe such a background, the detection of GW150914 suggests that the binary black hole background level is likely to be at the higher end of previous predictions (see, e.g., [6–13]).

Heavy black holes like GW150914 are predicted to form in low-metallicity stellar environments, lower than about half of solar metallicity, and in the presence of relatively weak massive-star winds [14]. These masses are also larger than the masses inferred from reliable dynamical measurements in black-hole X-ray binaries [14]–[44].

More massive binaries emit more energy in gravitational waves. Hence, the measurement of the component masses of GW150914 favors a higher amplitude of the corresponding gravitational-wave background.

In addition, the coalescence rate of binary black holes like GW150914 in the local Universe is estimated to be $16^{+38}_{-13}$ Gpc$^{-3}$ yr$^{-1}$ [15] median with 90\% credible interval.

This rate excludes the lower end of pre-detection rate estimates [14], while being consistent with the higher end. A higher coalescence rate also implies a brighter stochastic background.

There are currently two possible formation channels that are consistent with the GW150914 event [14]. Binary massive stars in galactic fields, or through dynamical interactions in dense stellar environments such as globular clusters [14]. The evolution of the merger rate with redshift depends in part on the assumed formation scenario.

In this paper we discuss the detectability of the stochastic background produced by binary black holes throughout the Universe based on the measured properties of GW150914.

Binary black hole background — The energy density spectrum of gravitational waves is described by the following dimensionless quantity [5]:

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

where $d\rho_{GW}$ is the energy density in the frequency interval $f$ to $f + df$, $\rho_c = 3H_0^2c^2/8\pi G$ is the critical energy density required to close the Universe, and $H_0 = 67.8 \pm 0.9$ km/s/Mpc is the Hubble constant [16].

A population of binary black holes is characterized by the distribution of the intrinsic source parameters $\theta$ (usually the component masses and spin). Since this distribution is unknown at present, following [15] and [17] we divide the distribution into distinct classes corresponding to the observed candidates. If binary black holes in some class $k$, with source parameters $\theta_k$, merge at a rate $R_m(z; \theta_k)$ per unit comoving volume $V_c$ per unit source time, then the total gravitational-wave energy density spectrum from all the sources in this class is given by (see, e.g., [6–13]):

$$\Omega_{GW}(f; \theta_k) = \frac{f}{\rho_c H_0} \int_0^{z_{\text{max}}} \frac{R_m(z; \theta_k) dE_{GW}(f, \theta_k)}{(1 + z) E(\Omega_M, \Omega_L, z)} dz,$$

and the final energy density spectrum is the sum of $\Omega_{GW}(f; \theta_k)$ from each class. In Eq. 2, $dE_{GW}/df_s(\theta_k)$ is the spectral energy density of a source of class $k$ at the frequency $f_s = f(1 + z)$, which depends on the source parameters $\theta_k$; $E(\Omega_M, \Omega_L, z) = \sqrt{\Omega_M(1 + z)^3 + \Omega_L}$ captures the dependence of the comoving volume on redshift for the standard flat cosmology model, with $\Omega_M = 0.31$.

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1 When the distribution of the source parameters is better understood after multiple detections, the discrete sum can be replaced by a continuous integral.
and $\Omega = 1 - \Omega_M$. The $(1 + z)$ factor in the denomi-
ator of Eq. 2 corrects for the cosmic expansion, con-
verting time in the source frame to the detector frame.\textsuperscript{127}

The parameter $z_{\text{max}}$ corresponds to the time of the first\textsuperscript{128}
coevolutions. We set $z_{\text{max}} = 10$, noting, however, that\textsuperscript{129}sources above $z \sim 5$ contribute very little to the total\textsuperscript{130}background (see, e.g., [6–13]).

The merger rate $R_m(z; \theta_k)$ is a convolution of the bi-
ary formation rate $R_f(z; \theta_k)$ with the distribution of the\textsuperscript{131}time delays $P(t_d; \theta_k)$ between binary black hole for-
mation and merger (see e.g., [18])

$$R_m(z; \theta_k) = \int_{t_{\text{min}}}^{t_{\text{max}}} R_f(z_f; \theta_k) P(t_d; \theta_k) dt_d, \quad (3)$$

where $t_d$ is the time delay, $z_f$ is the redshift at the for-
mation time $t_f = t(z) - t_d$, and $t(z)$ is the age of the
Universe at merger.

Inference on GW150914 [4], along with expectations\textsuperscript{132}
that gravitational-wave emission is efficient in circular-
izing the orbit [14], allows us to restrict our models for\textsuperscript{133}the total background is a property of the Universe, the
residual background carries complementarily inferred rate, $16 \text{Gpc}^{-3}\text{yr}^{-1}$[15].

Results — We plot $\Omega_{\text{GW}}(f)$ for the Fiducial model as a solid blue curve in Fig. 1a. The curve is shown against the pink shaded region, which represents the $90\%$ credible interval statistical uncertainty in the local rate. Considering this uncertainty, we predict $\Omega_{\text{GW}}(f = 25\text{Hz}) = 1.1_{-0.9}^{+2.7} \times 10^{-9}$. The spectrum is well approximated by a power law $\Omega_{\text{GW}}(f) \propto f^{2/3}$ at low frequencies where the contribution from the inspiral phase is dominant and the spectral energy density is $dE_{\text{GW}}/df \propto ([G\sigma_T^2/3]M_c^{5/3}f_s^{-1/3}$. This power law remains a good approximation until the spectrum reaches a maximum at $f \sim 100\text{Hz}$. The shape is in agreement with previous predictions (see, e.g., [7–13]), except that the maximum is shifted to lower frequencies, due to the higher mass considered.

This calculation of $\Omega_{\text{GW}}(f)$ captures the total energy density in gravitational waves generated by binary black hole coevolutions. In practice, some of these sources will be individually detected as resolved binaries. We define “the residual background” as the energy density spectrum that excludes potentially resolvable binaries. While the total background is a property of the Universe, the residual background is detector-dependent. As sensitivity improves, the surveyed volume increases, more binaries are resolved and the residual background decreases.

The dashed blue curve in Fig. 1a represents the residual background calculated for the network of the Advanced LIGO [1, 2] and Advanced Virgo [36, 37] detectors at final sensitivity, assuming that a binary black hole signal is detected if it is associated with a single-detector matched filter signal-to-noise ratio of $\rho > 8$ in at least two detectors [38]. The difference between the two curves is about $30\%$ in the sensitive frequency band ($10–50\text{Hz}$), indicating that the residual background carries complementarily inferred rate, $16 \text{Gpc}^{-3}\text{yr}^{-1}$[15].

The sensitive frequency band of the Advanced LIGO-
Virgo network to a gravitational-wave background pro-
duced by binary black holes is $10–50\text{Hz}$, where $\Omega_{\text{GW}} \sim f^{2/3}$. It corresponds to more than $95\%$ of the accumu-
FIG. 1. Expected sensitivity of the network of advanced LIGO and Virgo detectors to the Fiducial field model. Left panel: Energy density spectra are shown in blue (solid for the total background; dashed for the residual background, excluding resolved sources, assuming final advanced LIGO and Virgo [1, 2] sensitivity). The pink shaded region “Poisson” shows the 90% CL statistical uncertainty on the total background, propagated from the local rate measurement. The black power-law integrated curves show the 1σ sensitivity of the network expected for the two first observing runs O1 and O2, and for 2 years at the design sensitivity in O5. (O3 and O4 are not significantly different than O5; see Table I.) If the astrophysical background spectrum intersects a black line, it has expected SNR ≥ 1. In both panels we assume a coincident duty cycle of 33% for O1 (actual) and 50% for all other runs (predicted). Right panel: Predicted SNR as a function of total observing time. The blue lines and pink shaded region have the same interpretation as in the left panel. Each observing run is indicated by an improvement in the LIGO-Virgo network sensitivity [35], which results in a discontinuity in the slope. The thresholds for SNR = 1, 3 (false-alarm probability < 3 × 10−3) and 5 (false-alarm probability < 6 × 10−7) are indicated by horizontal lines.

For a network of detectors $i = 1, 2, \ldots, n$, the sensitivity of the network expected for the two first observing runs O1 and O2, and for 2 years at the design sensitivity in O5 (O3 and O4 are not significantly different than O5; see Table I.) If the astrophysical background spectrum intersects a black line, it has expected SNR ≥ 1. In both panels we assume a coincident duty cycle of 33% for O1 (actual) and 50% for all other runs (predicted). The total background associated with the Fiducial model could be identified with SNR = 3, corresponding to false alarm probability < 3 × 10−3, after approximately 6 years of observing. In the most optimistic scenario given by statistical uncertainties, the total background could be identified after 1.5 years with SNR = 3 and after approximately 2 years with SNR = 5, which is even before design sensitivity is reached. It would take about 2 years of observing to achieve SNR = 3 and about 3.5 years for SNR = 5 for the optimistic residual background.

The most pessimistic case considered here is out of reach of the advanced detector network but is in the scope of third generation detectors, such as the proposed Einstein Telescope [? ? ?]. whose sensitivity would enable to reach $\Omega_{GW} \sim 10^{-12}$ after a year of observation [? ? ?].

**Alternative Models** — We now investigate the impact of
possible variations on the Fiducial model. We consider the following alternatives:

- **AltSFR** differs from the Fiducial model in assuming a different SFR proposed by Tornatore et al. [44], who combined observations and simulations at higher redshift; the formation rate is assumed to be proportional to the SFR, with no metallicity threshold. We also considered the Madau & Dickinson SFR [24], and found that it produces an energy density spectrum that is essentially indistinguishable from the Fiducial model.

- **LongDelay** is identical to the Fiducial model but assumes a significantly longer minimum time delay, $t_{\text{min}} = 5$ Gyr, potentially consistent with binary black hole formation via the chemically homogeneous evolution of rapidly rotating massive stars in very tight binaries [45].

- **LowMetallicity** is the same as Fiducial, but assumes that a significantly lower metallicity is required of $Z_c = Z_\odot/10$ [14].

- **FlatDelay** assumes a flat time delay distribution, with $t_{\text{min}} = 50$ Myr and $t_{\text{max}} = 1$ Gyr. This is inspired by the supposition that dynamical formation of the most massive binaries is likely to happen fairly early in the history of the host environment.

- **ConstRate** follows the assumption of [3] in considering a redshift-independent merger rate, $R_m(z) = 16$ Gpc$^{-3}$yr$^{-1}$. [4, 15], corresponding to the second most significant event (LVT151012) identified in [3, 38] with insufficient significance to decisively claim a detection. We assume here that the metallicity threshold is $Z_c = Z_\odot$.

- **LowMass** is the same as the Fiducial model except we add a second class of lower-mass binary black hole sources corresponding to a smaller range for individual detections during O1. As an example, we assume a chirp mass of half the mass of GW150914, $M_c = 15$ M$_\odot$ and a local merger rate of 61 Gpc$^{-3}$yr$^{-1}$ [4, 15], corresponding to the second most significant event (LVT151012) identified in [3, 38] with insufficient significance to decisively claim a detection. We assume here that the metallicity threshold is $Z_c = Z_\odot$.

Figure 2 shows the impact of alternative models described above. The differences in the spectra of alternative models are not negligible. However, all models considered here fall within the range of statistical uncertainty in the local merger rate estimate relative to the Fiducial model in the sensitive frequency band.

The impact of an alternative star formation rate, as examined through model AltSFR, is particularly small, indicating that the accuracy of SFR models is not a significant source of systematic error in predicting the strength of the gravitational-wave background.

Relative to the Fiducial model, the LongDelay, FlatDelay, and ConstRate models all predict fewer binaries at $z > 0$, even though all of these models are constrained to have the same local merger rate ($z = 0$). These latter three models consequently yield a lower energy density. The LowMetallicity model is characterized by a greater high-redshift merger rate than the Fiducial model, with significant merger rates extending out to $z \sim 5 - 6$. This is because very little of the local Universe has the required low metallicity, so the local mergers come from the long time-delay tail of a large high-redshift population. Consequently, the LowMetallicity model has a higher overall normalization, as well as a different spectral shape at frequencies above 100 Hz due to the redshifting of the dominant high-$z$ contribution to the gravitational-wave background to lower frequencies.

Relative to the Fiducial model, the LowMass model shows a greater energy density at all frequencies, particularly at high frequencies due to the signals from lower-mass binaries. This model indicates that if there is a significant rate of mergers of binaries with smaller masses than GW150914, their contribution to the gravitational-wave energy density spectrum could be significant.
Conclusions and discussion — The detection of gravitational waves from BBH mergers could be a potential noise source for the detection of a cosmological background from the early epochs of the Universe in the frequency band of ground-based detectors. However, this astrophysical background has a different spectral shape and different statistical properties (non-continuous and non-Gaussian) that could be used, in principle, to distinguish it from the primordial background.

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