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Search for Eccentric Black Hole Coalescences during the Third Observing Run of LIGO and Virgo

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Abstract

Despite the growing number of binary black hole coalescences confidently observed through gravitational waves so far, the astrophysical origin of these binaries remains uncertain. Orbital eccentricity is one of the clearest tracers of binary formation channels. Identifying binary eccentricity, however, remains challenging due to the limited availability of gravitational waveforms that include the effects of eccentricity. Here, we present observational results for a waveform-independent search sensitive to eccentric black hole coalescences, covering the third observing run (O3) of the LIGO and Virgo detectors. We identified no new high-significance candidates beyond those that have already been identified with searches focusing on quasi-circular binaries. We determine the sensitivity of our search to high-mass (total source-frame mass $M > 70\ M_\odot$) binaries covering eccentricities up to 0.3 at 15 Hz emitted gravitational-wave frequency, and use this to compare model predictions to search results. Assuming all detections are indeed quasi-circular, for our fiducial population model, we place a conservative upper limit for the merger rate density of high-mass binaries with eccentricities $0 < e \leqslant 0.3$ at 16.9 Gpc^{-3} yr^{-1} at the 90% confidence level.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Eccentricity (441); Astrophysical black holes (98)

1. Introduction

The LIGO (Aasi et al. 2015) and Virgo (Acernese et al. 2015) gravitational-wave observatories have completed three observing runs thus far. During these runs, 90 compact binary merger candidates were identified that had a probability of astrophysical origin of $p_{\rm astro} > 0.5$ (Abbott et al. 2023a, 2024). These discoveries opened previously inaccessible avenues to study the Universe, including the first direct information on binary black holes (Abbott et al. 2016a, 2016b), the multi-messenger observation of a binary neutron star coalescence (Abbott et al. 2017a, 2017; Margutti & Chornock 2021), a new type of constraint on cosmic expansion (Abbott et al. 2017b, 2023), and novel tests of general relativity (Abbott et al. 2016c, 2017c, 2021b).

Despite the growing number of candidates and the insight they have provided, the astrophysical sites and processes that produce the observed merging binaries remain uncertain. Multiple viable scenarios exist. The binary black holes could have formed from an isolated stellar binary (e.g., Bethe & Brown 1998; Dominik et al. 2015; de Mink & Mandel 2016; Marchant et al. 2016; Inayoshi et al. 2017; Gallegos-Garcia et al. 2021), via dynamical interactions in dense stellar clusters (e.g., Portegies Zwart & McMillan 2000; Banerjee et al. 2010; Ziosi et al. 2014; Morscher et al. 2015; Rodriguez et al. 2016a; Mapelli 2016; Askar et al. 2017), or triple systems (e.g., Antonini et al. 2017; Martinez et al. 2020; Vigna-Gómez et al. 2021), or via gas-driven capture in the disks of active galactic nuclei (AGN; e.g., McKernan et al. 2012; Bartos et al. 2017; Fragione et al. 2019; Tagawa et al. 2020). Furthermore, in addition to merging binary black holes formed from stars, there may also be merging binaries of primordial black holes

[304] Deceased, November 2022.
[305] Deceased, March 2022.

(e.g., Bird et al. 2016; Sasaki et al. 2016; Clesse & García-Bellido 2017).

Gravitational waves carry information about the masses and spins of the merging black holes, which can be used to probe the binaries' origin (Abbott et al. 2016b; Mapelli 2021; Zevin et al. 2021a). Different formation channels have diverse predictions for the most common component masses, mass ratios, spin magnitudes, and spin orientations (Belczynski et al. 2002; Dominik et al. 2013; Vitale et al. 2017). For example, isolated stellar binaries are typically expected to produce black holes with spins mostly aligned with the binary's orbital axis with possible misalignments that could stem from recoil velocities imparted during supernova explosion (e.g., Rodriguez et al. 2016b; Gerosa et al. 2018; Wysocki et al. 2019). Dynamically formed binaries, on the other hand, generally have an isotropic spin distribution (e.g., Rodriguez et al. 2016b; Fishbach et al. 2017; Baibhav et al. 2020). However, while masses and spins provide crucial information about the binaries' origin, there is often overlap between their distributions for various formation channels. A catalog of binary black holes must therefore be considered to make statistical inferences about their origins using these properties alone.

Orbital eccentricity e is a unique signature that disfavors isolated binaries and favors triple systems, stellar clusters, or AGN-assisted mergers as the possible formation scenario of the binary. While isolated black hole binaries can be born with an initial eccentricity, gravitational-wave emission will circularize their orbit by the time their orbital frequency reaches the sensitive band of ground-based gravitational-wave observatories (Peters 1964). Dynamical encounters can form binaries closer to merger, leaving insufficient time for orbital circularization. In AGN disks, eccentricity can be enhanced for a significant fraction of mergers, e.g., via binary–single interactions (Tagawa et al. 2021; Samsing et al. 2022). Eccentricity can also be enhanced for field binaries by a nearby third object via the Kozai–Lidov mechanism (Kozai 1962; Lidov 1962; Naoz 2016; Antonini et al. 2017; Randall & Xianyu 2018; Bartos et al. 2023).

Despite the advantages that come with estimating the binary's orbital eccentricity, it has been difficult to probe this parameter through gravitational-wave observations for several reasons. (i) Eccentric orbits have a wider dynamical range than quasi-circular, or $e = 0$ orbits, making them more challenging to model semi-analytically (Huerta et al. 2014; Tanay et al. 2016). (ii) Eccentricity increases the dimension of the binary parameter space, requiring more gravitational waveform templates and substantially increasing the computational cost of both waveform computation (Cornish & Shapiro Key 2010) and running template-based searches (Lenon et al. 2021). (iii) Given these challenges and the lack of expected eccentricity in field binaries, the development of eccentric waveform models began with significant delay compared to circular waveform models (Junker & Schaefer 1992). Nonetheless, eccentric waveform development has been an active area recently, with several promising waveform models that could be useful in the future (e.g., Cao & Han 2017; Hinderer & Babak 2017; Albanesi et al. 2021; Islam et al. 2021; Khalil et al. 2021; Nagar et al. 2021; Setyawati & Ohme 2021; Liu et al. 2022; Ramos-Buades et al. 2022a; Wang et al. 2023).

While no comprehensive eccentric gravitational-wave template bank is currently available, indications of eccentricity may already exist within the catalog of detected gravitational waves. The basis of such results is that standard gravitational-wave search algorithms developed to target circular binaries also have some sensitivity to eccentric binaries. For low masses, $\lesssim 10\,M_\odot$, circular template-based searches show undiminished sensitivity for small residual eccentricities ($e \lesssim 0.05$ at 40 Hz). Here and throughout this work, we refer to eccentricity in the source frame. To detect signals with eccentricities beyond $e \gtrsim 0.1$, we would however require template banks that include eccentric waveforms (Brown & Zimmerman 2010). In contrast, for higher masses and eccentricities, it has been shown that eccentricities can be found without significant loss of signal-to-noise ratio (SNR) using model-agnostic searches (Abbott et al. 2019a).

To identify detected binaries as eccentric, two approaches have been carried out so far that circumvent the need for comprehensive template banks:

1. One approach is to employ Bayesian analyses using existing eccentric waveform models. An eccentric waveform model limited to eccentricities $e < 0.2$ was used to show that the binary merger that produced the signal GW190521 as well as two others are consistent with originating from eccentric binary black holes (eBBHs) and are poorly explained by the zero-eccentricity hypothesis (Romero-Shaw et al. 2020, 2021). Using a different waveform model that includes the full eccentricity range, Gamba et al. (2023) found strong support for the binary coalescence that produced GW190521 being highly eccentric. Both models were limited to waveforms with black hole spins aligned with the binary orbit. Orbital eccentricity and misaligned spins that induce precession of the orbital plane produce similar imprints in the gravitational-wave signal, and both of these effects should preferably be accounted for in order to accurately analyze the event (Calderón Bustillo et al. 2021; Romero-Shaw et al. 2023).
2. A different approach relies on numerical relativity simulations of eBBHs. Due to the computational cost, only a limited number of simulations can be carried out, which can only sparsely cover the parameter space. Gayathri et al. (2022) used such numerical relativity waveforms that discretely cover the full eccentricity space and include waveforms with both aligned and misaligned spin with the binary orbit. Interpolation methods and consistency checks were applied to recover the eccentricity and other parameters of the binary. They found that the signal GW190521 is most consistent with being produced by a highly eccentric ($e \sim 0.7$) binary.

The above approaches are similar as they rely on different approximations to accurate (numerical relativity) waveforms: in the first, waveform models are used to approximate numerical relativity waveforms, while in the second, the analysis results are interpolated. In this paper, we carry out a search focusing on eccentric black hole coalescences over the third observing run (O3) of the LIGO-Virgo network. We use a minimally modeled search algorithm (Klimenko et al. 2005; Tiwari et al. 2016; Salemi et al. 2019) that we optimize for sensitivity for a set of high-mass (total mass $M \geqslant 70\,M_\odot$), eccentric gravitational waveforms (Hinder et al. 2018; Boyle et al. 2019). As methods to estimate the eccentricity of individual events are under development, we instead focus on potential detections that have not already been discovered by other searches, and characterize the sensitivity of our search to eccentric binaries, relying on methods with well-understood performance.

This paper is organized as follows. In Section 2, we introduce our search algorithm and demonstrate its sensitivity to eccentric waveforms. In Section 3, we present our search results. In Section 4, we discuss constraints on astrophysical populations based on our search results. We conclude in Section 5.

Gravitational-wave strain data (Abbott et al. 2021c) and posterior samples (Abbott et al. 2021d) for all events from GWTC-3 are available from the Zenodo platform or the Gravitational Wave Open Science Center (Abbott et al. 2021e, 2023b).

2. Search Algorithm and Sensitivity

2.1. Characterization of Eccentricity

Due to the emission of gravitational waves, binary orbits have a gradually decreasing orbital separation. Eccentric binary orbits also circularize over time due to the emission of gravitational waves (Peters 1964). This makes the definition of eccentricity challenging. Determining eccentricity is particularly difficult at the late stages of the binary evolution when less than a full orbit separates the black holes from merger.

There have been various efforts to define eccentricity for binary compact object systems. These eccentricity definitions involve Keplerian orbit assumptions (Peters & Mathews 1963; Loutrel et al. 2018), angular frequencies at apocenter and pericenter (Mora & Will 2004), calculations using instantaneous radial acceleration (Healy et al. 2018), and using coordinate separations (Buonanno et al. 2011). A detailed list of the different eccentricity definitions that have been developed so far can be found in Loutrel et al. (2018).

For our analysis, we adopt the eccentricity definition following Ramos-Buades et al. (2022b), based on a calculation first developed by Mora & Will (2004) and later used by Lewis et al. (2017), Ramos-Buades et al. (2020a), and Shaikh et al. (2023). To compute eccentricity for each orbit, we used the gravitational-wave frequencies at apocenter (ω_a) and the consecutive pericenter (ω_p). With these, eccentricity for the given orbit is

$$e = \cos(\psi/3) - \sqrt{3}\,\sin(\psi/3) \tag{1}$$

with

$$\psi = \arctan\left(\frac{1 - e_{22}^2}{2e_{22}}\right), \tag{2}$$

where

$$e_{22} = \frac{\sqrt{\omega_p} - \sqrt{\omega_a}}{\sqrt{\omega_p} + \sqrt{\omega_a}}. \tag{3}$$

We used the orbital frequency of the $\ell = 2$, $m = 2$ multipole moments of the gravitational-wave signal.

In order to characterize the eccentricity as a function of time, we associate this eccentricity with a frequency that is an average of the pericenter and apocenter frequencies. This method of computing eccentricity using the waveform itself is advantageous because (i) it enables us to compute the evolution of eccentricity as a function of time (and frequency); (ii) it is gauge independent; and (iii) this definition can be uniformly applied to all waveform models and can be computed during postprocessing.

Ultimately, we want to describe a waveform with a single eccentricity value. For this description, we choose 15 Hz gravitational-wave emission frequency. This selection is motivated by the typical eccentricity definition found in the literature (usually defined at a gravitational-wave emission frequency of ∼10–15 Hz; e.g., Fragione & Bromberg 2019; Zevin et al. 2021b).

2.2. Eccentric Waveforms

There are multiple ongoing efforts to develop a comprehensive set of eccentric binary coalescence waveforms. Multiple waveform families have been generated using the semi-analytical effective-one-body formalism, which is currently restricted to nonprecessing spins (Nagar et al. 2021; Ramos-Buades et al. 2022a). A suite of numerical relativity simulations has also been carried out that cover virtually the full eccentric and spin parameter space (Gayathri et al. 2022; Healy & Lousto 2022).

For our analysis, we adopted 12 state-of-the-art numerical relativity waveforms from the Simulating eXtreme Spacetimes (SXS) Collaboration (Hinder et al. 2018; Boyle et al. 2019), which were the only high-fidelity waveforms available to us at the time of this study. These waveforms cover the eccentricity space up to 0.3 defined at 15 Hz gravitational-wave frequency assuming a source total mass of 90 $M_\odot$, and include a range of mass ratios: $q \equiv m_2/m_1 = \{1, 0.5, 0.33\}$, where m_2 and m_1 are the lighter and heavier masses, respectively. We list the properties of the waveforms in Table 1. In Figure 1, we show the corresponding eccentricity of these waveforms, assuming different source total masses.

As the numerical relativity simulations were carried out for the late stage of the binary coalescence, they cover the gravitational waveform for the full frequency band of the ground-based detectors only for total binary source masses $\gtrsim 70\,M_\odot$. Above this mass limit, any binary mass can be obtained by a simple scaling of the simulated waveforms due to the scale invariance of general relativity (Tiglio & Villanueva 2021). The selected waveforms are nonspinning, which has a limited effect on the sensitivity estimates we compute below. When reconstructing the properties of detected gravitational-wave signals, it is important to include spins, as eccentricity and spin precession can mimic each other (Calderón Bustillo et al. 2021; Romero-Shaw et al. 2023). Since we do not use these waveforms to reconstruct the properties of signals in this analysis, this problem is not relevant here. Figure 2 shows the change in signal morphology as the orbital eccentricity is changed while keeping other source parameters fixed.

We used this set of 12 numerical relativity waveforms to quantify the search sensitivity to high-mass ($\gtrsim 70\,M_\odot$) eccentric black hole mergers. However, with this limited set of waveforms we could not reconstruct the eccentricity of events.

2.3. Search Optimization and Sensitivity Improvement

Current template-based searches (Nitz et al. 2017; Aubin et al. 2021; Cannon et al. 2021; Chu et al. 2022) do not include eccentric gravitational waveforms. As a consequence, their sensitivity is limited for such events, in particular at high eccentricities and low masses (Brown & Zimmerman 2010),

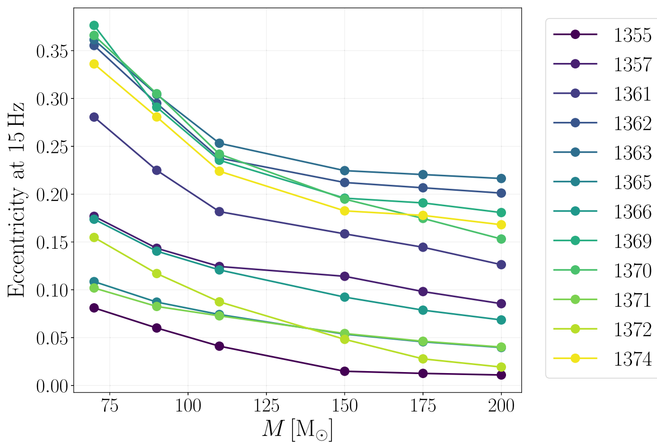

Figure 1. Variation in eccentricity at a fixed source-frame frequency of 15 Hz as a function of total mass for the 12 numerical relativity waveforms analyzed in this study. The identification numbers (IDs) in the legend correspond to the SXS:BBH:ID of each waveform.

Table 1
Parameters of the 12 Numerical Relativity Simulations Adopted from the SXS Binary Black Hole Simulations Catalog (Boyle et al. 2019)

q	e	Waveform ID
0.33	0.08	SXS:BBH:1371
0.33	0.12	SXS:BBH:1372
0.33	0.28	SXS:BBH:1374
0.5	0.09	SXS:BBH:1365
0.5	0.14	SXS:BBH:1366
0.5	0.29	SXS:BBH:1369
0.5	0.30	SXS:BBH:1370
1.0	0.06	SXS:BBH:1355
1.0	0.14	SXS:BBH:1357
1.0	0.22	SXS:BBH:1361
1.0	0.29	SXS:BBH:1362
1.0	0.30	SXS:BBH:1363

Note. Columns show the binary's mass ratio q, and eccentricity e at a reference source-frame frequency of 15 Hz (Section 2.1) for a binary source total mass of 90 $M_\odot$. Spin amplitudes χ_1 and χ_2 are zero for all considered models.

similarly to the effect of neglecting higher-order multipole moments (Capano et al. 2014). Eccentric searches can also be carried out using model-agnostic searches such as the coherent WaveBurst algorithm (cWB; Klimenko et al. 2005; Tiwari et al. 2016; Salemi et al. 2019), which uses minimal assumptions about the signal waveform and hence is expected to be sensitive to eccentric signals. The sensitivity of cWB and template-based searches are comparable for high-mass black hole mergers up to low eccentricities (Chandra et al. 2020; Ramos-Buades et al. 2020b; Abbott et al. 2023a). As the sensitivity of template-based searches drops with eccentricity (Zevin et al. 2021b), we rely on cWB for our search.

The cWB algorithm uses the Wilson–Daubechies–Meyer filter to transform time domain detector data to time-frequency representations (Necula et al. 2012). Excess power regions in the time-frequency representation of strain data that are obtained from the network of detectors are then identified by cWB using clustering algorithms. Selected clusters with excess energy above the expected detector noise are identified as events. The signal waveform, sky coordinates, and waveform polarization of the source are then reconstructed for these events using maximum-likelihood analysis (Klimenko et al. 2016).

Once the search pipeline is run, thresholds are placed by cWB on the coherent statistics that it derives for each candidate event. These are used to better differentiate between astrophysical signals and noise artifacts (Gayathri et al. 2019). We will refer to these thresholds on cWB statistics as vetoes. Vetoes define a part of the parameter space over the coherent statistics that should be excluded from the analysis due to the high rate of non-Gaussian noise artifacts there. To maximize the sensitivity of cWB to eccentric binaries, we carried out an optimization of these vetoes applied by cWB to each event. The first two sets of vetoes that are common to the standard cWB pipeline and the eccentric search pipeline are summarized in the Appendix.

Transient non-Gaussian noise artifacts, also known as *glitches*, can limit the detector's sensitivity to gravitational-wave signals. Targeted vetoes are placed by the standard cWB pipeline to mitigate this problem. These glitch-focused vetoes are derived using cWB summary statistics Q_a and TF. The waveform shape parameter derived by cWB is denoted by Q_a, and is a function of another cWB parameter Qveto ($Q_a = \sqrt{\text{Qveto}}$). This parameter quantifies how well the total energy of the signal is distributed across time (Vedovato 2018; Gayathri et al. 2019; Mishra et al. 2021). The threshold $Q_a > 0.3$ is placed to better distinguish between gravitational waves and a class of low-frequency transient noise artifacts called blip glitches (Cabero et al. 2019; Davis et al. 2021). Signals due to blip glitches, which have most of their energy localized to a small time segment, have low Q_a values as opposed to signals from binary coalescence, which have higher Q_a values as a consequence of signal energy being distributed over a longer duration. The TF parameter is a function of the signal bandwidth, duration, and power, which are additional statistics that cWB estimates for candidate events. A threshold on this parameter is placed to ensure that short-duration glitches that mimic gravitational-wave signals from intermediate-mass binary black hole systems are removed.

We injected simulated gravitational-wave signals from equal-mass, almost head-on systems (Healy & Lousto 2022) into real detector data to find the set of vetoes that do not remove highly eccentric signals while still rejecting most noise artifacts. To perform this optimization, the cWB algorithm was used to detect these injected signals and derive their properties. Vetoes were selected such that they maximized the number of detections at fixed false alarm rates.

We observed that Q_a and TF vetoes were prone to removing a significant fraction of highly eccentric simulated signals. We found that we could mitigate this problem if we removed these two thresholds, and instead introduced a new Q_a–Q_p veto to better distinguish between signals from highly eccentric binaries and short-duration glitches. This veto removes events identified by cWB that do not satisfy the condition $Q_a(Q_p - 0.8) > 0.07$. The summary statistic Q_p quantifies the number of cycles in the reconstructed signal. The Q_a–Q_p veto along with the first two sets of vetoes from the standard search, which are summarized in the Appendix were selected as the set of post-production vetoes for the eBBH search. We will refer to this version of cWB that is optimized for eccentric mergers as cWB-eBBH. While the vetoes were optimized using equal-mass waveforms, we confirmed that the optimized search

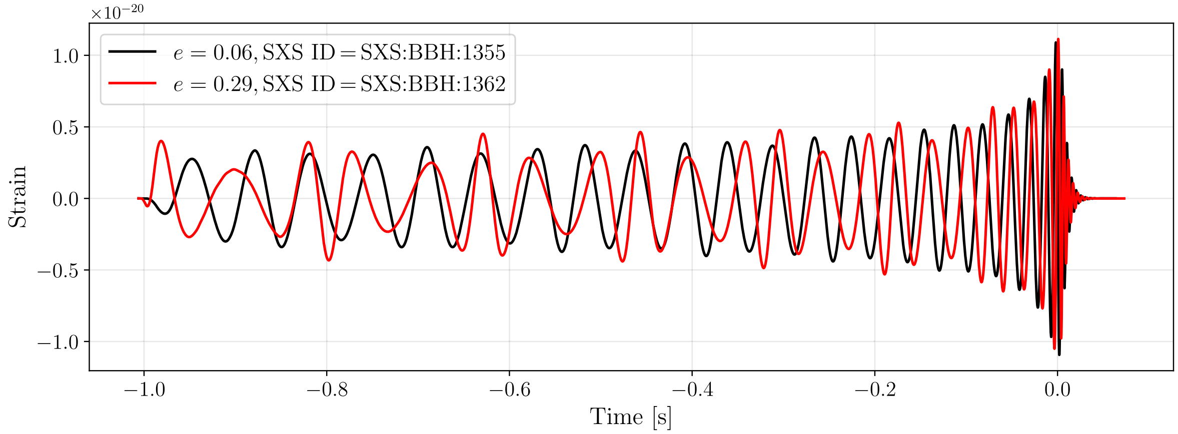

Figure 2. Examples of time domain waveforms with two different eccentricities (indicated in the legend) for equal-mass binary systems with a total source mass of 90 $M_\odot$ at a distance of 100 Mpc. The simulations start at an orbital separation that translates to an orbital frequency $f_{\rm low}$ = 15 Hz. The eccentricity values indicated in the legend are defined at the same $f_{\rm low}$.

improved eccentric event recovery for unequal mass injections as well.

Figure 3 shows an example of the standard cWB Q_a veto and the new cWB-eBBH Q_a–Q_p veto for quasi-circular and highly eccentric systems. We also look at this veto's performance with background events. To generate background events, data from one detector is time shifted relative to the other detector's data by an amount greater than the maximum time for a gravitational-wave signal to travel between the detectors (Abbott et al. 2016d). The standard veto does well in removing background events and recovering the majority of quasi-circular simulation events. However, the distribution of simulation signals in the $Q_a - Q_p$ space changes for highly eccentric systems, and as a consequence, the standard cWB veto removes a significant fraction of simulation events.

We characterize the sensitivity improvement due to the optimization procedure by computing the number of injected gravitational waves detected by cWB-eBBH but not by standard cWB, divided by the total number of detections by standard cWB. Here, we consider a signal detected if it corresponds to an inverse false alarm rate (IFAR) of $\geqslant$1 yr. This IFAR threshold of $\geqslant$1 yr was only used to assess the improvement in sensitivity from the introduction of the cWB-eBBH veto, and not as a general detection threshold.

The fraction of events recovered with IFAR $\geqslant$1 yr by cWB-eBBH that are removed by the standard pipeline with respect to the total number of events recovered by the standard pipeline is ~28% for head-on collision (highly eccentric) equal-mass systems with a source total mass of 150 $M_\odot$. Additionally, we see that this fraction is higher (~34%) for systems with more unequal mass. Therefore, our optimization is the most significant for highly eccentric binaries with unequal masses. The performance of cWB-eBBH for low-eccentricity signals remains comparable (within 5%) to the standard pipeline. We conclude that the cWB-eBBH veto does significantly better than the standard veto to improve sensitivity for highly eccentric systems without degrading sensitivity to less eccentric systems.

3. Results

3.1. Search Sensitivity

We carried out a search for simulated gravitational-wave signals to quantify the sensitivity of the cWB-eBBH search algorithm. We performed injections in offline (high-latency) recalibrated O3 strain data with category 0, 1, 2, and 4 data quality vetoes (Davis et al. 2021; Abbott et al. 2023a). Category 0 vetoes are applied to ensure that the segments of data used in this analysis were collected when the detectors were in observing mode. Category 1 vetoes are used to discard data from periods in which the detectors were running in an improper configuration, data dropout, or on-site maintenance occurred at either detector, or when there are major problems with the operation of an instrument at the detectors. Category 2 vetoes flag data segments that likely contain non-Gaussian noise artifacts. Category 4 vetoes flag data segments that contain hardware injections.

The injected waveforms have source total mass $M \in [70\,M_\odot, 200\,M_\odot]$. We used six choices of total source mass. Waveforms with different masses were obtained by scaling the 12 numerical relativity waveforms listed in Table 1. The simulated signals for each waveform and choice of total mass were uniformly distributed in sky location (θ, ϕ) and inclination ι. They were also distributed uniformly in comoving volume up to a maximum redshift $z_{\rm max}$.

Since each simulated waveform has a fixed initial eccentricity, our six choices of total mass will correspond to different eccentricities at an emitted gravitational-wave frequency of 15 Hz, as this frequency is reached at different points in the waveform. We computed the corresponding eccentricity values at 15 Hz in the source frame for each total mass and each waveform, as explained in Section 2.1. Below, we characterize the sensitive distance as a function of total source mass and eccentricity at 15 Hz.

For each waveform, we separately calculated $z_{\rm max}$ up to which they must be injected so that we do not make unnecessary injections that the search cannot detect. This was calculated with an optimal two-detector-network (Livingston-Hanford) SNR threshold of 5.0. We set the source to be directly overhead with a face-on configuration while calculating the optimal SNR. Since we observe signals with redshifted mass (Krolak & Schutz 1987), it is in principle possible to inject simulations with total source mass <70 $M_\odot$ if we populate them at higher redshifts. This was however not performed in the presented analysis. Injections are spaced uniformly in time, approximately every 100 s in the O3 data set.

We used the fraction of detected and injected waveforms to compute the sensitive distance of the search for the given

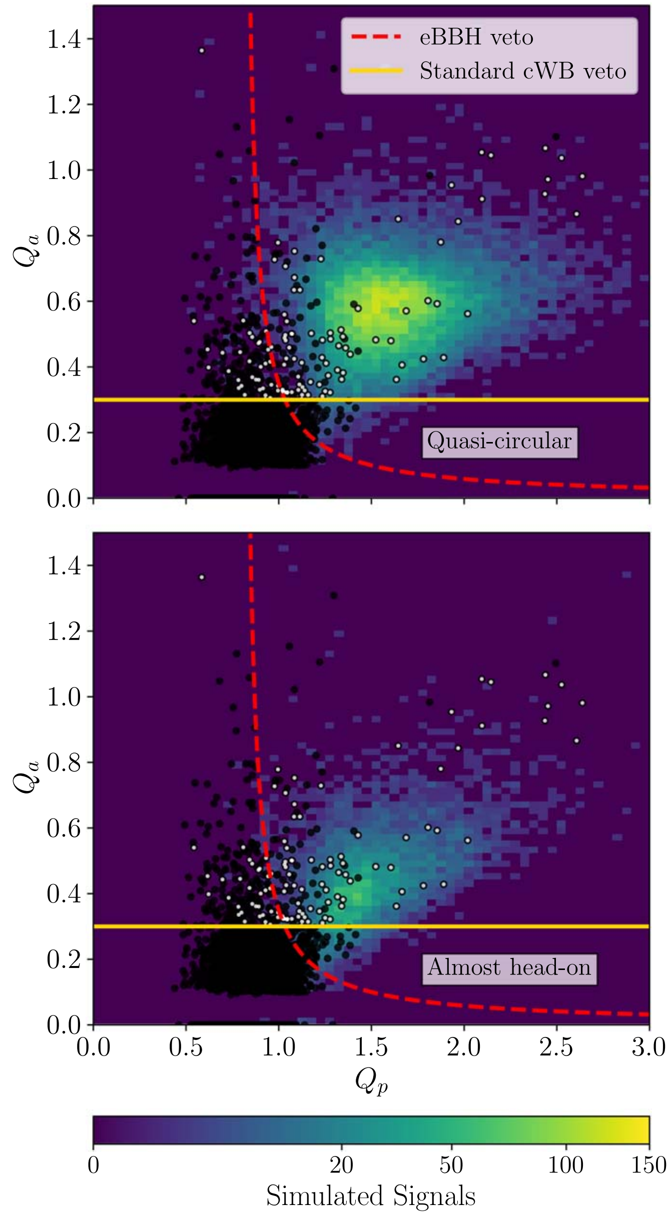

Figure 3. Distribution of Q_a and Q_p for simulated signals (shown as a two-dimensional histogram with a color bar denoting the number of events in each two-dimensional bin) and loud simulated background events (shown as black dots). The cWB statistics Q_a and Q_p describe the morphology of a signal. The yellow line represents the standard cWB Q_a veto and the red-dashed line denotes the eBBH Q_a–Q_p veto. The white dots correspond to loud background events that remain after all standard cWB vetoes (Lopez et al. 2022) are applied. Top: simulated signals correspond to equal mass, source total mass, $M = 150\,M_{\odot}$, quasi-circular orbit systems. Bottom: simulated signals correspond to equal mass, $M = 150 M_{\odot}$, almost head-on (highly eccentric) systems.

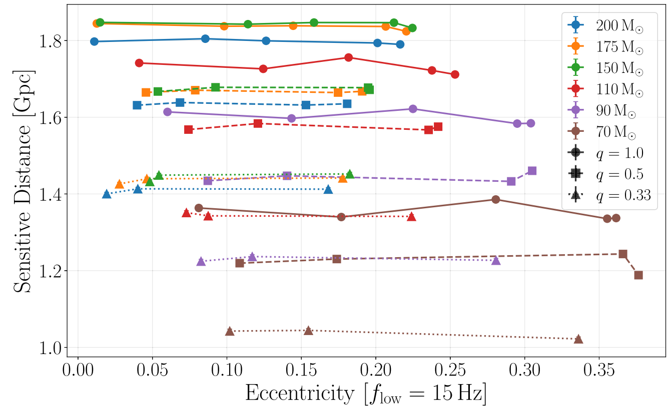

Figure 4. Sensitive distance as a function of orbital eccentricity for different binary total masses and mass ratios. Different marker shapes represent systems with different mass ratios and the different colors represent the various total masses considered here. We used an IFAR threshold of 1.32 yr, which was the loudest new candidate's IFAR. The horizontal axis denotes the eccentricity of the binary at an orbital separation that corresponds to a source-frame frequency of 15 Hz. A given numerical relativity waveform corresponds to different eccentricities for the different total masses as it will reach 15 Hz at different points of its orbital evolution. The statistical error bars on the obtained sensitive distance are smaller than can be presented in this plot.

waveform. Sensitive distance (Abbott et al. 2019b) is defined such that a detector that detects every event within the sensitive distance and no event beyond, it would have the same detection rate as our detector network.

A similar analysis was carried out with data from the first two observing runs of LIGO-Virgo using approximate eccentric waveform models (Abbott et al. 2019a). This analysis spanned the binary mass parameter space from $10\,M_{\odot}$ to $100\,M_{\odot}$ while the analysis described in this paper covers binary mass of $70\,M_{\odot}$ to $200\,M_{\odot}$. The sensitivities reported in this paper are higher than that analysis due to increased sensitivity of the detector during the third observing run, and due to the higher masses considered here. There have also been studies to characterize the effect of eccentricity in the sensitivity of long-duration signals with unmodeled search pipelines using hybrid inspiral–merger–ringdown waveform models (Abbott et al. 2021f). However, these studies were targeted toward low-mass binary black holes and binary neutron stars as opposed to our search, which is targeted toward high-mass eccentric binaries. Therefore, the search sensitivities reported in Abbott et al. (2021f) are lower than what we obtain in this paper.

The obtained sensitive distance is shown in Figure 4, for different source total masses and mass ratios, as a function of binary eccentricity. The statistical error bars for the obtained sensitive distance range between 0.21 and 5.63 Mpc. The sensitivity at the considered high masses is mostly independent of the eccentricity up to our highest eccentricity of 0.3. We observe a sensitivity increase with total mass up to $175\,M_{\odot}$ followed by a decline at $200\,M_{\odot}$. This is because as the total mass of the source increases, the signal shifts toward lower frequencies where the detectors' sensitivity decreases. Additionally, the in-band signals also become shorter in duration as the mass increases, making them more prone to being removed by the glitch-based vetoes. We also see, as expected, that sensitivity is highest for equal-mass binaries, and gradually drops as the difference between the two black hole masses increases.

3.2. Search and Loudest Event

We carried out the cWB-eBBH search over the O3 run of the LIGO and Virgo detectors. For most of the observing run, we used data from only the two LIGO detectors, as search sensitivity was not appreciably affected by the addition of Virgo data. For the 2020 January 4–22 period, we also incorporated Virgo in the search to analyze the candidate 200114_020818, which was found by the intermediate-mass black hole binary search (Abbott et al. 2022) in the three detector network configuration comprising the LIGO and Virgo detectors. Follow-up studies for this event (Abbott et al. 2022,

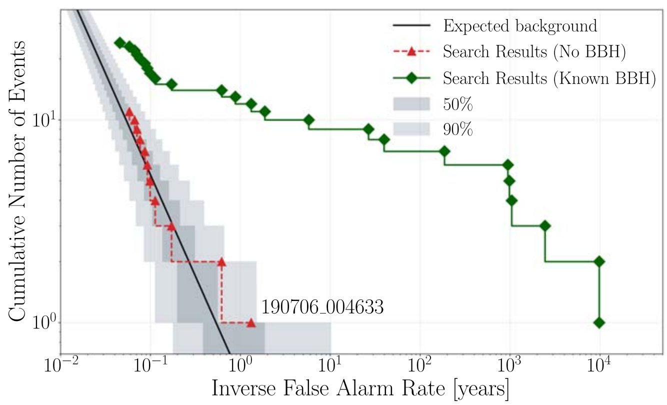

Figure 5. Cumulative number of events as a function of IFAR recovered by the cWB-eBBH search. The solid line represents the expected background for the O3 search, and the gray regions correspond to the 50% and 90% Poisson uncertainty regions. Green-filled squares denote previously reported gravitational-wave candidates (Abbott et al. 2022, 2023a) recovered by our search, and red-filled triangles show events that were not previously reported by other searches.

Appendix B) showed inconsistent results under a quasi-circular binary black hole hypothesis. We investigated if this candidate had higher significance under the eccentric hypothesis. However, this candidate was removed by the cWB-eBBH vetoes. The search and sensitivity results presented below were obtained using data from only the two LIGO detectors.

Our search recovered 28 gravitational-wave candidates with IFAR >1 yr. By choosing this IFAR threshold, we eliminate low-significance candidates that could have been due to noise artifacts in the detector. All but one of these events have been identified previously by other searches as well (Abbott et al. 2022, 2023a).

The results of our search are summarized in Figure 5. The search results excluding previously found candidates are consistent with background noise.

We identified one event candidate with an IFAR >1 yr that was not previously reported. This most significant new candidate, hereafter referred to as 190706_004633, was observed on 2019 July 6. It was recovered with an IFAR of 1.32 yr. It has an SNR of 12.2 and a central frequency of 74 Hz. Figure 6 shows the time–frequency map of this event candidate.

In order to better understand whether 190706_004633 is of astrophysical origin, we carried out a detailed study of the detector's performance and characteristics at the time of the event. This study aims to uncover signs of instrumental or environmental artifacts that could have altered the gravitational-wave data and hence produced the candidate (Davis et al. 2021, Section 3.2.4). No such artifacts were found. However, the Gravity Spy machine learning classifier (Zevin et al. 2017; Soni et al. 2021) classified the excess power in LIGO-Livingston as a Tomte glitch. Tomtes are a common glitch class that are similar in morphology to high-mass binary coalescence signals (Ashton et al. 2022). No glitch or signal was identified in the LIGO-Hanford data by the same classifier. However, as the Gravity Spy machine learning model is not designed to search for astrophysical signals (Glanzer et al. 2023) or to differentiate eBBH merger signals from glitches, we cannot rule out an astrophysical origin.

To further investigate this event we carried out a standard parameter estimation analysis of the data using LALInference (Veitch et al. 2015) with nested sampling assuming a quasi-circular waveform. We investigated the properties of this event using data from the two LIGO detectors as well as the Virgo detector. For this analysis, in lieu of an eccentric waveform that fully covers the necessary parameter space, we adopted the quasi-circular binary approximant IMRPhenomXPHM (Pratten et al. 2021). This estimation found that the estimated source total mass of 190706_004633 is $M \sim 320\, M_{\odot}$, and its estimated redshift is $z \sim 0.3$. Studies have shown that the chirp mass of a binary with low to moderate eccentricity can be reconstructed with a bias of up to 4% using parameter estimation with quasi-circular waveforms (O'Shea & Kumar 2023). However, the reconstructed parameters would be considerably more inaccurate if the signal originated from a highly eccentric binary. Therefore, these results indicate that the signal, if astrophysical, would correspond to a high-mass binary, but should not be used to give precise indications of source properties.

The SNR obtained from the parameter estimation analysis is 14.9, which is higher than the SNR obtained by the search pipeline. We examined the Livingston and Hanford detector responses for the maximum-likelihood sky location that was obtained from parameter estimation. Livingston's detector response was approximately 1.5 times greater than Hanford's. This may explain the observed discrepancy in SNRs, which is highlighted in the caption of Figure 6. The parameter estimation study also yielded a Bayesian coherence ratio (BCR; Veitch & Vecchio 2010), with a corresponding value of $\ln(\mathrm{BCR}) = -3.3$ for the candidate. This ratio characterizes the evidence for a coherent signal origin versus a random coincidence; the obtained value supports an incoherent noise origin over a *circular* binary origin.

Through these investigations, we were unable to conclusively determine if the event was in accordance with an astrophysical origin or an incoherent noise origin. This event was consistent with the expected background for O3 with a confidence level within 50% (Figure 5). In the following section, we therefore compute upper limits to merger rates assuming nondetection of any eccentric event.

4. Eccentric Binary Population Models

In order to understand the astrophysical implications of our results, we computed the expected number of detections for a fiducial source model. For this, we adopt the joint total mass and mass ratio probability density $p(M, q)$ that was inferred using LIGO-Virgo's observations listed in the GWTC-3 (Abbott et al. 2023a, 2023c), assuming the power-law + peak model described in Abbott et al. (2021a). While this population model also incorporated the distribution of black hole spins, we did not include this in the presented analysis. As we have waveforms and simulations that are sparsely sampled in mass and mass ratio, we linearly interpolated the sensitivity of the existing waveforms to points in between the available points in order to obtain a sensitive distance for any source total mass and mass ratio within $70\, M_{\odot} \leqslant M \leqslant 200\, M_{\odot}$ and $0.33 < q < 1.0$. For a more general distribution, we considered a power-law black hole mass distribution of $M^{-2.3}$ (assuming a Salpeter initial mass function; Perna et al. 2019) and a uniform distribution in mass ratio. We further adopted an eccentricity distribution in which the probability density of the binaries' eccentricity is $p(e) \propto 2(1 - e)$. This distribution is chosen to characterize a population that has a larger fraction of low eccentric binaries.

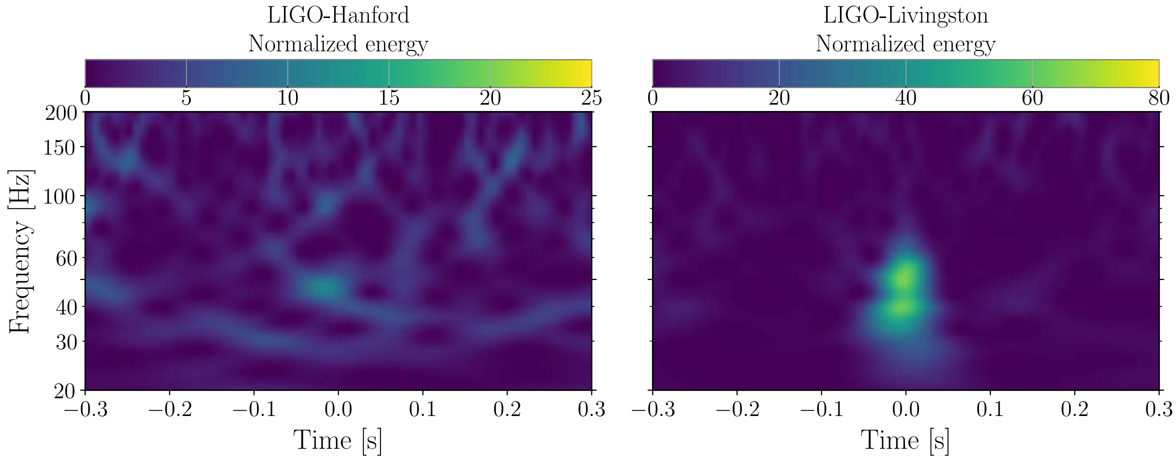

Figure 6. Time–frequency map (spectrogram) of the most significant new candidate identified by the cWB-eBBH search. We show the spectrogram for the LIGO-Hanford (left) and LIGO-Livingston (right) detectors. The individual detector SNRs in the LIGO-Hanford and LIGO-Livingston are 5.6 and 10.9, respectively. Since the energies in the two detectors are very different, we use different scales on the color bar. The Virgo detector was in observing mode during the time of this event. We used data from all three detectors for follow-up studies and observed that the SNR in the Virgo detector for this event was low (∼2).

Having defined the probability density of our fiducial population with respect to the binary parameters, using the sensitive distance obtained over the considered parameter space (see Section 3.1), we computed the total volume–time (VT; Abbott et al. 2019b, the Appendix) covered by our search during O3, assuming an IFAR threshold of 1.32 yr, which is the IFAR of our search's loudest new event. For our fiducial model, we obtained $VT = 6.88$ Gpc^3 yr for eccentric binaries with $0 < e < 0.3$. Adopting a Jeffrey's prior on the merger rate and assuming nondetection of any eccentric event, this would correspond to a constraint of <0.20 Gpc^{-3} yr^{-1} on the merger rate density at 90% confidence level in the $70\,M_\odot \leqslant M \leqslant 200\,M_\odot$ and $0.33 < q < 1.0$ parameter space.

We additionally computed the VT_e of events that are detected by the cWB-eBBH algorithm and are missed by the standard cWB algorithm. We used the same set of simulated signals that we used to compute the full search VT. The sensitive VT is computed using the number of events recovered by the cWB-eBBH pipeline that the standard pipeline misses. The goal of finding VT_e is to gauge the subpopulation of eccentric events that would be *detectable as eccentric* because of being missed by the standard pipeline, which has lower sensitivity to eccentric signals (Figure 3). We computed VT_e for the various distributions considered in Table 2. For our fiducial source population, we obtain $VT_e = 0.08$ Gpc^3 yr. Adopting a Jeffrey's prior on the merger rate and assuming no eccentric events were detected by the cWB-eBBH search, this would correspond to a constraint of <16.9 Gpc^{-3} yr^{-1} on the merger rate density at 90% confidence level in the $70\,M_\odot \leqslant M \leqslant 200\,M_\odot$ and $0.33 < q < 1.0$ parameter space.

With the small number of available eccentric waveforms for this study, we cannot determine if the discovered binaries are eccentric. Therefore, we cannot discount the possibility that previously identified gravitational-wave candidates originate from eccentric binaries. In this case, the number of observed eccentric binaries is greater than zero, and so the merger rate could potentially be higher than our upper limits. Conversely, for some parts of the parameter space, template-based searches have better sensitivities, although we expect them to lose sensitivity at higher eccentricities. Hence, including the VT from these searches (Abbott et al. 2023a, 2024) would tighten our upper limits. For simplicity, we limit our results to those from the cWB-eBBH analysis, assuming all previously identified candidates are from quasi-circular binaries.

Table 2
Total VT Covered by cWB-eBBH Search and VT Probed Exclusively by the cWB-eBBH Search (VT_e) Assuming Various Source Total Mass, Mass Ratio, and Eccentricity Probability Density Functions for the Different Illustrative Models Described in Section 4

$p(M)$	$p(q)$	$p(e)$	VT (Gpc^3 yr)	VT_e (Gpc^3 yr)
GWTC-3	GWTC-3	$2(1-e)$	6.89	0.08
GWTC-3	GWTC-3	Uniform	6.93	0.08
$M^{-2.3}$	Uniform	$2(1-e)$	8.22	0.14
$M^{-2.3}$	Uniform	Uniform	8.27	0.14
AGN	AGN	$2(1-e)$	7.86	0.16
AGN	AGN	Uniform	7.91	0.17
DSC	DSC	DSC	6.69	0.08

Since binary mergers from dynamical formation channels can follow a mass distribution different from the one obtained from GWTC-3, we additionally computed VT, assuming other parameter distributions. We summarize our results in Table 2. Our focus on high-mass, eccentric events can be particularly interesting for astrophysical formation channels that favor the production of both high mass and high eccentricity, such as gas-driven capture in AGN disks. For this scenario, we adopted the AGN model of Gayathri et al. (2021) as an illustrative example. Our search sensitivity for this model is marginally higher than for the GWTC-3 distribution because this model favors higher masses that are more likely to fall in the mass interval that we are most sensitive to in this analysis. Assuming nondetection of any eccentric event, we place a constraint of <8.45 Gpc^{-3} yr^{-1} on the merger rate density at 90% confidence level for AGN-assisted mergers. Taking an estimated ∼70% of mergers being eccentric (Samsing et al. 2022) and ∼4% of mergers having $M > 70\,M_\odot$ (Gayathri et al. 2021), we project the corresponding upper limit on the merger rate density to obtain upper limits on the overall AGN-assisted merger rate density as ~ 8.45 Gpc^{-3} yr$^{-1}/(0.7 \times 0.04) \sim 302$ Gpc^{-3} yr^{-1}. This is consistent with rate estimates in the literature (e.g., Yang et al. 2019; Gayathri et al. 2021).

As a second illustrative model we used the distribution expected in dense star clusters (DSC), adopted from Zevin et al.

(2021b). For this population, we are able to place a constraint of <16.9 Gpc^{-3} yr^{-1} on the merger rate density at 90% confidence level assuming nondetection of any eccentric event. Taking an estimated ∼10% being eccentric and ∼18% of mergers having $M > 70\ M_{\odot}$, we project the corresponding upper limit on the merger rate density to obtain upper limits on the overall DSC-assisted merger rate density as ∼16.9 Gpc^{-3} yr^{-1}/(0.1 × 0.18) ∼ 939 Gpc^{-3} yr^{-1}. This is consistent with rate estimates in the literature (Kremer et al. 2020; Zevin et al. 2021b).

5. Conclusion

We carried out a search that does not rely on template banks, and optimized it to be sensitive to high-mass ($M > 70\ M_{\odot}$) eBBH coalescences. We characterized the sensitivity of this search to understand our findings' implications for possible eccentric astrophysical populations. Our conclusions are:

1. We did not identify any high-significance candidates that had not already been detected by other searches. Our loudest and most significant new event has an IFAR of 1.32 yr. We performed detailed follow-up for this event, and concluded that astrophysical origin could not be ruled out. However, our search results are consistent with the expected background for O3.
2. For our fiducial model, we adopted a mass distribution that assumes a power-law + peak model that was inferred using GWTC-3 observations (Abbott et al. 2023c). We also chose an eccentricity distribution (defined in Section 4) that favors quasi-circular binaries. For this assumed population, our "differential" search sensitivity (that is beyond the sensitivity of the standard cWB search) is such that assuming nondetection of eccentric events, we can place a constraint of <16.9 Gpc^{-3} yr^{-1} on the merger rate density at 90% confidence level. The obtained overall constraint is significantly above that of other searches for circular black hole mergers in a similar mass range (cf. inferred rate of $0.08^{+0.19}_{-0.07}$ Gpc^{-3} yr^{-1} of mergers similar to GW190521; Abbott et al. 2022).
3. As an illustrative example, we found that nondetection of any eccentric event corresponds to a constraint of <302 Gpc^{-3} yr^{-1} on the AGN-assisted merger rate density, consistent with rate estimates in the literature (e.g., Yang et al. 2019; Gayathri et al. 2021).
4. As a second illustrative model, we computed our search sensitivity to mergers in dense star clusters, considering the model of Zevin et al. (2021b). The results are similar to the AGN channel and our expected sensitivity for a generic eccentric model. For this model, we found that nondetection of eccentric events corresponds to a constraint of <939 Gpc^{-3} yr^{-1} on the merger rate density, consistent with rate estimates in the literature (Kremer et al. 2020; Zevin et al. 2021b).

The constraints we place on the rate of eccentric binary coalescences in this work are significantly improved over those computed with data obtained from the first and second observing runs (Abbott et al. 2019a). This improvement can be attributed to increased sensitivity of the detectors, progress in the development of highly accurate eccentric waveforms in the high-mass domain, and an optimized eccentric search. In view of the expected sensitivity of the fourth observing run by LIGO-Virgo-KAGRA (Abbott et al. 2018), we anticipate seeing a significant rise in the number of binary black hole detections. This increases our prospects of detecting gravitational-wave signals from eccentric binary coalescences. Regardless, a nondetection would enable us to further constrain the binary black hole merger rates in astrophysical models favoring eccentric orbits.

Future works will need to expand the study to eccentricities greater than 0.3, and to include masses below 70 $M_{\odot}$ as well as black hole spins.

Acknowledgments

Data quality products and event validation results were computed using the DQR (LIGO Scientific Collaboration & Virgo Collaboration 2018), DMT (Zweizig 2006), gwdetchar (Urban et al. 2021), hveto (Smith et al. 2011), and iDQ (Essick et al. 2020) software packages and contributing software tools. Analyses in this paper relied upon the LALSuite software library (LIGO Scientific Collaboration 2018). The detection of the signals and subsequent significance evaluations in this paper were performed with the cWB (Klimenko et al. 2005, 2016) package. Estimates of the noise spectra and glitch models were obtained using BayesWave (Cornish & Littenberg 2015; Littenberg et al. 2016; Cornish et al. 2021). Source parameter estimation was performed with the LALInference (Veitch et al. 2015) library. PESummary was used to postprocess and collate parameter estimation results (Hoy & Raymond 2021). Plots were prepared with Matplotlib (Hunter 2007) and GWpy (Macleod et al. 2021). NumPy (Harris et al. 2020) and SciPy (Virtanen et al. 2020) were used in the preparation of the manuscript.

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Appendix
Post-production Vetoes

In this appendix, we will describe in detail the post-production vetoes that are applied by the standard cWB pipeline (Gayathri et al. 2019; Lopez et al. 2022) to distinguish between true gravitational-wave signals and non-Gaussian noise artifacts that can mimic gravitational-wave signals.

The first set of vetoes is based on the morphology of the reconstructed signals. These vetoes are applied to the following cWB summary statistics: the energy-weighted central frequency of the signal f_0; the reconstructed chirp mass parameter, $\mathcal{M}^*$, which is obtained by fitting the signal with the characteristic time-frequency evolution for a quasi-circular binary ($f \propto (t - t_c)^{-3/8}$), and Q_a, the waveform shape parameter introduced in Section 2.3. The parameter Q_a is a function of the cWB parameter Qveto (Vedovato 2018; Gayathri et al. 2019; Mishra et al. 2021), which quantifies how well the total energy of the signal is distributed across time. The first set of vetoes removes events that do not satisfy 24 Hz $< f_0 <$ 100 Hz, $|\mathcal{M}^*/M_\odot| > 10$, $|(\mathcal{M}^*/M_\odot)/Q_a^2| > 15$, $\mathcal{M}^*/M_\odot > -100$.

The next set of vetoes is based on cWB reconstruction, and the correlation of the event across the network of detectors. The cWB summary statistics involved in this set are norm, defined as the ratio between the total energy over all wavelet resolution levels used for the analysis and the reconstructed energy of the event; χ^2, a parameter that quantifies the quality of signal reconstruction by computing the residual noise energy that remains once the reconstructed signal is subtracted from data (Gayathri et al. 2019), and finally the $c_c[0]$ and $c_c[2]$ parameters that describe the correlation of the signal across the network of detectors in time domain and frequency domain, respectively (Tiwari et al. 2016). The second set of vetoes removes candidate events that do not satisfy norm > 4, $\log_{10}(\chi^2) < 0.4$, $c_c[0] > 0.8$, $c_c[2] > 0.7$.

The two sets of vetoes described above were optimized with gravitational waveforms for quasi-circular binary black hole coalescences for the standard cWB pipeline. We found that they performed optimally in recovering eBBH signals as well. Therefore, these vetoes along with the new eBBH veto introduced in Section 2.3 were chosen as the final set of vetoes for the cWB-eBBH search pipeline.

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References

Aasi, J., Abbott, B. P., Abbott, R., et al. 2015, CQGra, 32, 074001
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016a, PhRvL, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016b, PhRvL, 116, 241102
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016c, PhRvL, 116, 221101
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2016d, CQGra, 33, 134001
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, ApJL, 848, L12
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017a, ApJL, 848, L13
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017b, Natur, 551, 85
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017c, PhRvL, 118, 221101
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2018, LRR, 21, 3
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019a, ApJ, 883, 149
Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2019b, PhRvD, 100, 064064
Abbott, R., Abbott, T. D., Abraham, S., et al. 2021a, ApJL, 913, L7
Abbott, R., Abe, H., Acernese, F., et al. 2021b, arXiv:2112.06861
Abbott, R., Abe, H., Acernese, F., et al. 2023, ApJ, 949, 76
Abbott, R., Abe, H., Acernese, F., et al. 2023b, ApJS, 267, 29
Abbott, R., Abbott, B. P., Abbott, T. D., et al. 2021c, GWTC-3 Data Release, Gravitational Wave Open Science Center, doi:10.7935/b024-1886
Abbott, R., Abbott, B. P., Abbott, T. D., et al. 2021d, GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run - Parameter estimation Data Release, v1, Zenodo, doi:10.5281/zenodo.5546663
Abbott, R., Abbott, T. D., Abraham, S., et al. 2021e, SoftX, 13, 100658
Abbott, R., Abbott, T. D., Acernese, F., et al. 2021f, PhRvD, 104, 102001
Abbott, R., Abbott, T. D., Acernese, F., et al. 2022, A&A, 659, A84
Abbott, R., Abbott, T. D., Acernese, F., et al. 2023a, PhRvX, 13, 041039
Abbott, R., Abbott, T. D., Acernese, F., et al. 2023c, PhRvX, 13, 011048
Abbott, R., Abbott, T. D., Acernese, F., et al. 2024, PhRvD, 109, 022001
Acernese, F., Agathos, M., Agatsuma, K., et al. 2015, CQGra, 32, 024001
Albanesi, S., Nagar, A., & Bernuzzi, S. 2021, PhRvD, 104, 024067
Antonini, F., Toonen, S., & Hamers, A. S. 2017, ApJ, 841, 77
Ashton, G., Thiele, S., Lecoeuche, Y., McIver, J., & Nuttall, L. K. 2022, CQGra, 39, 175004
Askar, A., Szkudlarek, M., Gondek-Rosińska, D., Giersz, M., & Bulik, T. 2017, MNRAS, 464, L36
Aubin, F., Brighenti, F., Chierici, R., et al. 2021, CQGra, 38, 095004
Baibhav, V., Gerosa, D., Berti, E., et al. 2020, PhRvD, 102, 043002
Banerjee, S., Baumgardt, H., & Kroupa, P. 2010, MNRAS, 402, 371
Bartos, I., Kocsis, B., Haiman, Z., & Márka, S. 2017, ApJ, 835, 165
Bartos, I., Rosswog, S., Gayathri, V., et al. 2023, arXiv:2302.10350
Belczynski, K., Kalogera, V., & Bulik, T. 2002, ApJ, 572, 407
Bethe, H. A., & Brown, G. E. 1998, ApJ, 506, 780
Bird, S., Cholis, I., Muñoz, J. B., et al. 2016, PhRvL, 116, 201301
Boyle, M., Hemberger, D., Iozzo, D. A. B., et al. 2019, CQGra, 36, 195006
Brown, D. A., & Zimmerman, P. J. 2010, PhRvD, 81, 024007
Buonanno, A., Kidder, L. E., Mroué, A. H., Pfeiffer, H. P., & Taracchini, A. 2011, PhRvD, 83, 104034
Cabero, M., Lundgren, A., Nitz, A. H., et al. 2019, CQGra, 36, 155010
Calderón Bustillo, J., Sanchis-Gual, N., Torres-Forné, A., & Font, J. A. 2021, PhRvL, 126, 201101
Cannon, K., Caudill, S., Chan, C., et al. 2021, SoftX, 14, 100680
Cao, Z., & Han, W.-B. 2017, PhRvD, 96, 044028
Capano, C., Pan, Y., & Buonanno, A. 2014, PhRvD, 89, 102003
Chandra, K., Gayathri, V., Bustillo, J. C., & Pai, A. 2020, PhRvD, 102, 044035
Chu, Q., Kovalam, M., Wen, L., et al. 2022, PhRvD, 105, 024023
Clesse, S., & García-Bellido, J. 2017, PDU, 15, 142
Cornish, N. J., & Littenberg, T. B. 2015, CQGra, 32, 135012
Cornish, N. J., Littenberg, T. B., Bécsy, B., et al. 2021, PhRvD, 103, 044006
Cornish, N. J., & Shapiro Key, J. 2010, PhRvD, 82, 044028
Davis, D., Areeda, J. S., Berger, B. K., et al. 2021, CQGra, 38, 135014
de Mink, S. E., & Mandel, I. 2016, MNRAS, 460, 3545
Dominik, M., Belczynski, K., Fryer, C., et al. 2013, ApJ, 779, 72
Dominik, M., Berti, E., O'Shaughnessy, R., et al. 2015, ApJ, 806, 263
Essick, R., Godwin, P., Hanna, C., Blackburn, L., & Katsavounidis, E. 2020, MLS&T, 2, 015004
Fishbach, M., Holz, D. E., & Farr, B. 2017, ApJL, 840, L24
Fragione, G., & Bromberg, O. 2019, MNRAS, 488, 4370
Fragione, G., Grishin, E., Leigh, N. W. C., Perets, H. B., & Perna, R. 2019, MNRAS, 488, 47
Gallegos-Garcia, M., Berry, C. P. L., Marchant, P., & Kalogera, V. 2021, ApJ, 922, 110
Gamba, R., Breschi, M., Carullo, G., et al. 2023, NatAs, 7, 11
Gayathri, V., Bacon, P., Pai, A., et al. 2019, PhRvD, 100, 124022
Gayathri, V., Healy, J., Lange, J., et al. 2022, NatAs, 6, 344
Gayathri, V., Yang, Y., Tagawa, H., Haiman, Z., & Bartos, I. 2021, ApJL, 920, L42
Gerosa, D., Berti, E., O'Shaughnessy, R., et al. 2018, PhRvD, 98, 084036
Glanzer, J., Banagiri, S., Coughlin, S. B., et al. 2023, CQGra, 40, 065004
Harris, C. R., Millman, K. J., van der Walt, S. J., et al. 2020, Natur, 585, 357
Healy, J., Lange, J., O'Shaughnessy, R., et al. 2018, PhRvD, 97, 064027
Healy, J., & Lousto, C. O. 2022, PhRvD, 105, 124010
Hinder, I., Kidder, L. E., & Pfeiffer, H. P. 2018, PhRvD, 98, 044015
Hinderer, T., & Babak, S. 2017, PhRvD, 96, 104048
Hoy, C., & Raymond, V. 2021, SoftX, 15, 100765
Huerta, E. A., Kumar, P., McWilliams, S. T., O'Shaughnessy, R., & Yunes, N. 2014, PhRvD, 90, 084016
Hunter, J. D. 2007, CSE, 9, 90
Inayoshi, K., Hirai, R., Kinugawa, T., & Hotokezaka, K. 2017, MNRAS, 468, 5020
Islam, T., Varma, V., Lodman, J., et al. 2021, PhRvD, 103, 064022
Junker, W., & Schaefer, G. 1992, MNRAS, 254, 146
Khalil, M., Buonanno, A., Steinhoff, J., & Vines, J. 2021, PhRvD, 104, 024046
Klimenko, S., Mohanty, S., Rakhmanov, M., & Mitselmakher, G. 2005, PhRvD, 72, 122002
Klimenko, S., Vedovato, G., Drago, M., et al. 2016, PhRvD, 93, 042004
Kozai, Y. 1962, AJ, 67, 591
Kremer, K., Ye, C. S., Rui, N. Z., et al. 2020, ApJS, 247, 48
Krolak, A., & Schutz, B. F. 1987, GReGr, 19, 1163
Lenon, A. K., Brown, D. A., & Nitz, A. H. 2021, PhRvD, 104, 063011
Lewis, A. G. M., Zimmerman, A., & Pfeiffer, H. P. 2017, CQGra, 34, 124001
Lidov, M. L. 1962, P&SS, 9, 719
LIGO Scientific Collaboration, 2018 LIGO Algorithm Library,
LIGO Scientific CollaborationVirgo Collaboration 2018, Data Quality Report User Documentation, docs.ligo.org/detchar/data-quality-report/
Littenberg, T. B., Kanner, J. B., Cornish, N. J., & Millhouse, M. 2016, PhRvD, 94, 044050
Liu, X., Cao, Z., & Zhu, Z.-H. 2022, CQGra, 39, 035009
Lopez, D., Gayathri, V., Pai, A., et al. 2022, PhRvD, 105, 063024
Loutrel, N., Liebersbach, S., Yunes, N., & Cornish, N. 2018, CQGra, 36, 025004
Macleod, D., Coughlin, S., Southgate, A., et al. 2021, gwpy/gwpy, v3.0.9, Zenodo, doi:10.5281/zenodo.597016
Mapelli, M. 2016, MNRAS, 459, 3432
Mapelli, M. 2021, in Formation Channels of Single and Binary Stellar-Mass Black Holes, ed. C. Bambi, S. Katsanevas, & K. D. Kokkotas (Berlin: Springer)
Marchant, P., Langer, N., Podsiadlowski, P., Tauris, T. M., & Moriya, T. J. 2016, A&A, 588, A50
Margutti, R., & Chornock, R. 2021, ARA&A, 59, 155
Martinez, M. A. S., Fragione, G., Kremer, K., et al. 2020, ApJ, 903, 67
McKernan, B., Ford, K. E. S., Lyra, W., & Perets, H. B. 2012, MNRAS, 425, 460
Mishra, T., O'Brien, B., Gayathri, V., et al. 2021, PhRvD, 104, 023014

Mora, T., & Will, C. M. 2004, PhRvD, 69, 104021
Morscher, M., Pattabiraman, B., Rodriguez, C., Rasio, F. A., & Umbreit, S. 2015, ApJ, 800, 9
Nagar, A., Bonino, A., & Rettegno, P. 2021, PhRvD, 103, 104021
Naoz, S. 2016, ARA&A, 54, 441
Necula, V., Klimenko, S., & Mitselmakher, G. 2012, JPhCS, 363, 012032
Nitz, A. H., Dent, T., Dal Canton, T., Fairhurst, S., & Brown, D. A. 2017, ApJ, 849, 118
O'Shea, E., & Kumar, P. 2023, PhRvD, 108, 104018
Perna, R., Wang, Y.-H., Farr, W. M., Leigh, N., & Cantiello, M. 2019, ApJL, 878, L1
Peters, P. C. 1964, PhRv, 136, B1224
Peters, P. C., & Mathews, J. 1963, PhRv, 131, 435
Portegies Zwart, S. F., & McMillan, S. L. W. 2000, ApJL, 528, L17
Pratten, G., García-Quirós, C., Colleoni, M., et al. 2021, PhRvD, 103, 104056
Ramos-Buades, A., Buonanno, A., Khalil, M., & Ossokine, S. 2022a, PhRvD, 105, 044035
Ramos-Buades, A., Husa, S., Pratten, G., et al. 2020a, PhRvD, 101, 083015
Ramos-Buades, A., Tiwari, S., Haney, M., & Husa, S. 2020b, PhRvD, 102, 043005
Ramos-Buades, A., van de Meent, M., Pfeiffer, H. P., et al. 2022b, PhRvD, 106, 124040
Randall, L., & Xianyu, Z.-Z. 2018, ApJ, 853, 93
Rodriguez, C. L., Chatterjee, S., & Rasio, F. A. 2016a, PhRvD, 93, 084029
Rodriguez, C. L., Zevin, M., Pankow, C., Kalogera, V., & Rasio, F. A. 2016b, ApJL, 832, L2
Romero-Shaw, I., Lasky, P. D., Thrane, E., & Calderón Bustillo, J. 2020, ApJL, 903, L5
Romero-Shaw, I., Lasky, P. D., & Thrane, E. 2021, ApJL, 921, L31
Romero-Shaw, I. M., Gerosa, D., & Loutrel, N. 2023, MNRAS, 519, 5352
Salemi, F., Milotti, E., Prodi, G. A., et al. 2019, PhRvD, 100, 042003
Samsing, J., Bartos, I., D'Orazio, D. J., et al. 2022, Natur, 603, 237
Sasaki, M., Suyama, T., Tanaka, T., & Yokoyama, S. 2016, PhRvL, 117, 061101
Setyawati, Y., & Ohme, F. 2021, PhRvD, 103, 124011
Shaikh, M. A., Varma, V., Pfeiffer, H. P., Ramos-Buades, A., & van de Meent, M. 2023, PhRvD, 108, 104007
Smith, J. R., Abbott, T., Hirose, E., et al. 2011, CQGra, 28, 235005
Soni, S., Berry, C. P. L., Coughlin, S. B., et al. 2021, CQGra, 38, 195016
Tagawa, H., Haiman, Z., Bartos, I., & Kocsis, B. 2020, ApJ, 899, 26
Tagawa, H., Kocsis, B., Haiman, Z., et al. 2021, ApJL, 907, L20
Tanay, S., Haney, M., & Gopakumar, A. 2016, PhRvD, 93, 064031
Tiglio, M., & Villanueva, A. 2021, NatSR, 11, 5832
Tiwari, V., Klimenko, S., Christensen, N., et al. 2016, PhRvD, 93, 043007
Tiwari, V., Klimenko, S., Necula, V., & Mitselmakher, G. 2016, CQGra, 33, 01LT01
Urban, A. L., Macleod, D., Massinger, T., et al. 2021, gwdetchar/gwdetchar, v2.0.4, Zenodo, doi:10.5281/zenodo.4526767
Vedovato, G., 2018 The Qveto algorithm, https://gwburst.gitlab.io/documentation/latest/html/faq.html?highlight=qveto#the-qveto
Veitch, J., Raymond, V., Farr, B., et al. 2015, PhRvD, 91, 042003
Veitch, J., & Vecchio, A. 2010, PhRvD, 81, 062003
Vigna-Gómez, A., Toonen, S., Ramirez-Ruiz, E., et al. 2021, ApJL, 907, L19
Virtanen, P., Gommers, R., Oliphant, T. E., et al. 2020, NatMe, 17, 261
Vitale, S., Lynch, R., Sturani, R., & Graff, P. 2017, CQGra, 34, 03LT01
Wang, H., Zou, Y.-C., & Liu, Y. 2023, PhRvD, 107, 124061
Wysocki, D., Lange, J., & O'Shaughnessy, R. 2019, PhRvD, 100, 043012
Yang, Y., Bartos, I., Haiman, Z., et al. 2019, ApJ, 876, 122
Zevin, M., Bavera, S. S., Berry, C. P. L., et al. 2021a, ApJ, 910, 152
Zevin, M., Romero-Shaw, I. M., Kremer, K., Thrane, E., & Lasky, P. D. 2021b, ApJL, 921, L43
Zevin, M., Coughlin, S., Bahaadini, S., et al. 2017, CQGra, 34, 064003
Ziosi, B. M., Mapelli, M., Branchesi, M., & Tormen, G. 2014, MNRAS, 441, 3703
Zweizig, J., 2006 The Data Monitor Tool Project, labcit.ligo.caltech.edu/~jzweizig/DMT-Project.html