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UPPER LIMITS ON THE RATES OF BINARY NEUTRON STAR AND NEUTRON-STAR–BLACK-HOLE MERGERS FROM ADVANCED LIGO'S FIRST OBSERVING RUN

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ABSTRACT

We report here the non-detection of gravitational waves from the merger of binary neutron star systems and neutron-star–black-hole systems during the first observing run of Advanced LIGO. In particular we searched for gravitational wave signals from binary neutron star systems with component masses $\in [1,3]M_{\odot}$ and component dimensionless spins < 0.05. We also searched for neutron-star–black-hole systems with the same neutron star parameters, black hole mass $\in [2,99]M_{\odot}$ and no restriction on the black hole spin magnitude. We assess the sensitivity of the two LIGO detectors to these systems, and find that they could have detected the merger of binary neutron star systems with component mass distributions of $1.35 \pm 0.13 M_{\odot}$ at a volume-weighted average distance of ~ 70 Mpc, and for neutron-star–black-hole systems with neutron star masses of $1.4M_{\odot}$ and black hole masses of at least $5M_{\odot}$, a volume-weighted average distance of at least ~ 110 Mpc. From this we constrain with 90% confidence the merger rate to be less than 12,600 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ for binary-neutron star systems and less than 3,600 $\mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ for neutron-star–black-hole systems. We discuss the astrophysical implications of these results, which we find to be in tension with only the most optimistic predictions. However, we find that if no detection of neutron-star binary mergers is made in the next two Advanced LIGO and Advanced Virgo observing runs we would place significant constraints on the merger rates. Finally, assuming a rate of $10^{+20}_{-7}\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ short gamma ray bursts beamed towards the Earth and assuming that all short gamma-ray bursts have binary-neutron-star (neutron-star–black-hole) progenitors we can use our 90% confidence rate upper limits to constrain the beaming angle of the gamma-ray burst to be greater than $2.3^{+1.7}_{-1.1}{}^{\circ}$ ($4.3^{+3.1}_{-1.9}{}^{\circ}$).

1. INTRODUCTION

Between September 12, 2015 and January 19, 2016 the two advanced Laser Interferometer Gravitational Wave Observatory (LIGO) detectors conducted their first observing period (O1). During O1, two high-mass binary black-hole (BBH) events were identified with high confidence ($> 5\sigma$): GW150914 (Abbott *et al.* 2016a) and GW151226 (Abbott *et al.* 2016b). A third signal, LVT151012, was also identified with 1.7σ confidence (Abbott *et al.* 2016c,d) In all three cases the component masses are confidently constrained to be above the $3.2M_{\odot}$ upper mass limit of neutron-stars (NSs) set by theoretical considerations (Rhoades and Ruffini 1974; Abbott *et al.* 2016e). The details of these observations, investigations about the properties of the observed BBH mergers, and the astrophysical implications are explored in (Abbott *et al.* 2016e,f,g,h,c,i).

The search methods that successfully observed these BBH mergers also target other types of compact binary coalescences, specifically the inspiral and merger of binary neutron-star (BNS) systems and neutron-star–black-hole (NSBH) systems. Such systems were considered among the most promising candidates for an observation in O1. For example, a simple calculation prior to the start of O1 predicted 0.0005 - 4 detections of BNS signals during O1 (Aasi *et al.* 2016).

In this paper we report on the search for BNS and NSBH mergers in O1. We have searched for BNS systems with component masses $\in [1,3]M_{\odot}$, component dimensionless spins < 0.05 and spin orientations aligned or anti-aligned with the orbital angular momentum. We have searched for NSBH systems with neutron star mass $\in [1,3]M_{\odot}$, black-hole (BH) mass $\in [2,99]M_{\odot}$ neutron star dimensionless spin magnitude < 0.05, BH dimensionless spin magnitude < 0.99 and both spins aligned or anti-aligned with the orbital angular momentum. No observation of either BNS or NSBH mergers was made in O1. We explore the astrophysical implications of this result, placing upper limits on the rates of such merger events in the local Universe that are roughly an order of magnitude smaller than those obtained with data from Initial LIGO and Initial Virgo (Abbott *et al.* 2009; Acernese *et al.* 2008; Abadie *et al.* 2012a). We compare these updated rate limits to current predictions of BNS and NSBH merger rates and explore how the non-detection of BNS and NSBH systems in O1 can be used to explore possible constraints of the opening angle of the radiation cone of short gamma-ray bursts (GRBs), assuming that short GRB progenitors are BNS or NSBH mergers.

The layout of this paper is as follows. In § 2 we describe the motivation for our search parameter space. In § 3 we briefly describe the search methodology, then describe the results of the search in § 4. We then discuss the constraints that can be placed on the rates of BNS and NSBH mergers in § 5 and the astrophysical implications of the rates in § 6. Finally, we conclude in § 7.

2. SOURCE CONSIDERATIONS

There are currently thousands of known NSs, most detected as pulsars (Hobbs *et al.*; Manchester *et al.* 2005). Of these, ∼ 70 are found in binary systems and allow estimates of the NS mass (Ott *et al.*; Lattimer 2012; Ozel and Freire 2016). Published mass estimates range from $1.0 \pm 0.17 M_{\odot}$ (Falanga *et al.* 2015) to $2.74 \pm 0.21 M_{\odot}$ (Freire *et al.* 2008) although there is some uncertainty in some of these measurements. Considering only precise mass measurements from these observations one can set a lower bound on the maximum possible neutron star mass of $2.01 \pm 0.04 M_{\odot}$ (Antoniadis *et al.* 2013) and theoretical considerations set an upper bound on the maximum possible neutron star mass of $2.9–3.2 M_{\odot}$ (Rhoades and Ruffini 1974; Kalogera and Baym 1996). The standard formation scenario of core-collapse supernovae restricts the birth masses of neutron stars to be above $1.1–1.6 M_{\odot}$ (Ozel *et al.* 2012; Lattimer 2012; Kiziltan *et al.* 2013).

Eight candidate BNS systems allow mass measurements for individual components, giving a much narrower mass distribution (Lorimer 2008). Masses are reported between $1.0 M_{\odot}$ and $1.49 M_{\odot}$ (Ott *et al.*; Ozel and Freire 2016), and are consistent with an underlying mass distribution of $(1.35 \pm 0.13) M_{\odot}$ (Kiziltan *et al.* 2010). These observational measurements assume masses are greater than $0.9M_{\odot}$.

The fastest spinning pulsar observed so far rotates with a frequency of 716 Hz (Hessels *et al.* 2006). This corresponds to a dimensionless spin $\chi = c|\mathbf{S}|/Gm^2$ of roughly 0.4, where m is the object's mass and $\mathbf{S}$ is the angular momentum.[1] Such rapid rotation rates likely require the NS to have been spun up through mass-transfer from its companion. The fastest spinning pulsar in a confirmed BNS system has a spin frequency of 44 Hz (Kramer and Wex 2009), implying that dimensionless spins for NS in BNS systems are ≤ 0.04 (Brown *et al.* 2012). However, recycled NS can have larger spins, and the potential BNS pulsar J1807-2500B (Lynch *et al.* 2012) has a spin of 4.19 ms, giving a dimensionless spin of up to ∼ 0.2.[2]

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[1] Assuming a mass of $1.4M_{\odot}$ and a moment of inertia $= J/\Omega$ of $1.5 \times 10^{45}\,\mathrm{g\,cm}^2$; the exact moment of inertia is dependent on the unknown NS equation-of-state (Lattimer 2012).

[2] Calculated with a pulsar mass of $1.37M_{\odot}$ and a high moment of inertia, $2 \times 10^{45}\,\mathrm{g\,cm}^2$.

Given these considerations, we search for BNS systems with both masses $\in [1,3]M_{\odot}$ and component dimensionless spins < 0.05. We have found that BNS systems with spins < 0.4 are generally still recovered well even though they are not explicitly covered by our search space. Increasing the search space to include BNS systems with spins < 0.4 was found to not improve overall search sensitivity (Nitz 2015).

NSBH systems are thought to be efficiently formed in one of two ways: either through the stellar evolution of field binaries or through dynamical capture of a NS by a BH (Grindlay *et al.* 2006; Sadowski *et al.* 2008; Lee *et al.* 2010; Benacquista and Downing 2013). Though no NSBH systems are known to exist, one likely progenitor has been observed, Cyg X-3 (Belczynski *et al.* 2013).

Measurements of galactic stellar mass BHs in X-ray binaries yield BH masses $5 \leq M_{\mathrm{BH}}/M_{\odot} \leq 24$ (Farr *et al.* 2011; Ozel *et al.* 2010; Merloni 2008; Wiktorowicz *et al.* 2013). Extragalactic high-mass X-ray binaries, such as IC10 X-1 and NGC300 X-1 suggest BH masses of $20-30M_{\odot}$. Advanced LIGO has observed two definitive BBH systems and constrained the masses of the 4 component BHs to $36^{+5}_{-4}, 29^{+4}_{-4}, 14^{+8}_{-4}$ and $7.5^{+2.3}_{-2.3}M_{\odot}$, respectively, and the masses of the two resulting BHs to 62^{+4}_{-4} and $21^{+6}_{-2}M_{\odot}$. In addition if one assumes that the candidate BBH merger LVT151012 was of astrophysical origin than its component BHs had masses constrained to 23^{+16}_{-6} and 13^{+4}_{-5} with a resulting BH mass of 35^{+14}_{-4}. There is an apparent gap of BHs in the mass range 3–5$M_{\odot}$, which has been ascribed to the supernova explosion mechanism (Belczynski *et al.* 2012; Fryer *et al.* 2012). However, BHs formed from stellar evolution may exist with masses down to $2M_{\odot}$, especially if they are formed from matter accreted onto neutron stars (O'Shaughnessy *et al.* 2005). Population synthesis models typically allow for stellar-mass BH up to $\sim$ 80–100$M_{\odot}$ (Fryer *et al.* 2012; Belczynski *et al.* 2010; Dominik *et al.* 2012); stellar BHs with mass above $100M_{\odot}$ are also conceivable however (Belczynski *et al.* 2014; de Mink and Belczynski 2015).

X-ray observations of accreting BHs indicate a broad distribution of BH spin (Miller *et al.* 2009; Shafee *et al.* 2006; McClintock *et al.* 2006; Liu *et al.* 2008; Gou *et al.* 2009; Davis *et al.* 2006; Li *et al.* 2005; Miller and Miller 2014). Some BHs observed in X-ray binaries have very large dimensionless spins (e.g Cygnus X-1 at > 0.95 (Fabian *et al.* 2012; Gou *et al.* 2011)), while others could have much lower spins (~ 0.1) (McClintock *et al.* 2011). Measured BH spins in high-mass X-ray binary systems tend to have large values (> 0.85), and these systems are more likely to be progenitors of NSBH binaries (McClintock *et al.* 2014). Isolated BH spins are only constrained by the relativistic Kerr bound $\chi \leq 1$ Misner *et al.* (1973). LIGO's observations of merging binary BH systems yield weak constraints on component spins (Abbott *et al.* 2016e,b,c). The microquasar XTE J1550-564 (Steiner and McClintock 2012) and population synthesis models (Fragos *et al.* 2010) indicate small spin-orbit misalignment in field binaries. Dynamically formed NSBH systems, in contrast, are expected to have no correlation between the spins and the orbit.

We search for NSBH systems with NS mass $\in [1,3]M_{\odot}$, NS dimensionless spins < 0.05, BH mass $\in [2,99]M_{\odot}$ and BH spin magnitude < 0.99. Current search techniques are restricted to waveform models where the spins are (anti-)aligned with the orbit (Messick *et al.* 2016; Usman *et al.* 2015), although methods to extend this to generic spins are being explored (Harry *et al.* 2016). Nevertheless, aligned-spin searches have been shown to have good sensitivity to systems with generic spin orientations in O1 (Dal Canton *et al.* 2015; Harry *et al.* 2016). An additional search for BBH systems with total mass greater than 100 $M_{\odot}$ is also being performed, the results of which will be reported in a future publication.

3. SEARCH DESCRIPTION

To observe compact binary coalescences in data taken from Advanced LIGO we use matched-filtering against models of compact binary merger gravitational wave (GW) signals (Wainstein and Zubakov 1962). Matched-filtering has long been the primary tool for modeled GW searches (Abbott *et al.* 2004; Abadie *et al.* 2012a). As the emitted GW signal varies significantly over the range of masses and spins in the BNS and NSBH parameter space, the matched-filtering process must be repeated over a large set of filter waveforms, or "template bank" (Owen and Sathyaprakash 1999). The ranges of masses considered in the searches are shown in Figure 1. The matched-filter process is conducted independently for each of the two LIGO observatories before searching for any potential GW signals observed at both observatories with the same masses and spins and within the expected light travel time delay. A summary statistic is then assigned to each coincident event based on the estimated rate of false alarms produced by the search background that would be more significant than the event.

BNS and NSBH mergers are prime candidates not only for observation with GW facilities, but also for coincident observation with electromagnetic (EM) observatories (Eichler *et al.* 1989; Hansen and Lyutikov 2001; Narayan *et al.* 1992; Li and Paczynski 1998; Nakar 2007; Metzger and Berger 2012; Nakar and Piran 2011; Berger 2014; Zhang 2014; Fong *et al.* 2015). We have a long history of working with the Fermi, Swift and IPN GRB teams to perform sub-threshold searches of GW data in a narrow window around the time of observed GRBs (Abbott *et al.* 2005, 2008; Abadie *et al.* 2012b,c). Such a search is currently being performed on O1 data and will be reported in a forthcoming publication. In O1 we also aimed to rapidly alert EM partners if a GW observation was made (Abbott *et al.* 2016j). Therefore it was critical for us to run "on-line" searches to identify potential BNS or NSBH mergers within a timescale of minutes after the data is taken, to give EM partners the best chance to perform a coincident observa-

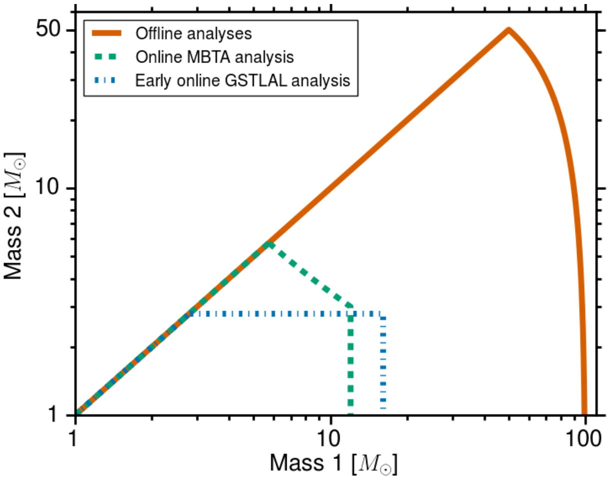

Figure 1. The range of template mass parameters considered for the three different template banks used in the search. The offline analyses and online `GstLAL` after December 23, 2015, used the largest bank up to total masses of $100 M_\odot$. The online `mbta` bank covered primary masses below $12 M_\odot$ and chirp masses[3] below $5 M_\odot$. The early online `GstLAL` bank up to December 23, 2015, covered primary masses up to $16 M_\odot$ and secondary masses up to $2.8 M_\odot$. The spin ranges are not shown here but are discussed in the text.

tion.

Nevertheless, analyses running with minute latency do not have access to full data-characterization studies, which can take weeks to perform, or to data with the most complete knowledge about calibration and associated uncertainties. Additionally, in rare instances, online analyses may fail to analyse stretches of data due to computational failure. Therefore it is also important to have an "offline" search, which performs the most sensitive search possible for BNS and NSBH sources. We give here a brief description of both the offline and online searches, referring to other works to give more details when relevant.

3.1. *Offline Search*

The offline compact binary coalescence (CBC) search of the O1 data set consists of two independently-implemented matched-filter analyses: `GstLAL` (Messick *et al.* 2016) and `PyCBC` (Usman *et al.* 2015). For detailed descriptions of these analyses and associated methods we refer the reader to (Babak *et al.* 2013; Dal Canton *et al.* 2014; Usman *et al.* 2015) for `PyCBC` and (Cannon *et al.* 2012, 2013; Privitera *et al.* 2014; Messick *et al.* 2016) for `GstLAL`. We also refer the reader to (Abbott *et al.* 2016c,d) for a detailed description of the offline search of the O1 dataset, here we give only a brief overview.

In contrast to the online search, the offline search uses data produced with smaller calibration errors (Abbott *et al.* 2016k), uses complete information about the instrumental data quality (Abbott *et al.* 2016l) and ensures that all available data is analysed. The offline search in O1 forms a single search targeting BNS, NSBH, and BBH systems. The waveform filters cover systems with individual component masses ranging from 1 to 99 $M_\odot$, total mass constrained to less than 100 $M_\odot$ (see Figure 1), and component dimensionless spins up to ± 0.05 for components with mass less than 2 $M_\odot$ and ± 0.99 otherwise (Abbott *et al.* 2016c; Capano *et al.* 2016). Waveform filters with total mass less than 4 $M_\odot$ (chirp mass less than $1.73 M_\odot$[3]) for `PyCBC` (`GstLAL`) are modeled with the inspiral-only, post-Newtonian, frequency-domain approximant "TaylorF2" (Arun *et al.* 2009; Bohé *et al.* 2013; Blanchet 2014; Bohé *et al.* 2015; Mishra *et al.* 2016). At larger masses it becomes important to also include the merger and ringdown components of the waveform. There a reduced-order model of the effective-one-body waveform calibrated against numerical relativity is used (Taracchini *et al.* 2014; Pürrer 2016).

3.2. *Online Search*

The online CBC search of the O1 data also consisted of two analyses; an online version of `GstLAL` (Messick *et al.* 2016) and `mbta` (Adams *et al.* 2015). For detailed descriptions of the `mbta` analysis we refer the reader to (Beauville *et al.* 2008; Abadie *et al.* 2012d; Adams *et al.* 2015). The bank of waveform filters used by `GstLAL` up to December 23, 2015—and by `mbta` for the duration of O1—targeted systems that contained at least one NS. Such systems are most likely to have an EM counterpart, which would be powered by the material from a disrupted NS. These sets of waveform filters were constructed using methods described in (Brown *et al.* 2012; Harry *et al.* 2014; Pannarale and Ohme 2014). `GstLAL` chose to cover systems with component masses of $m_1 \in [1,16] M_\odot; m_2 \in [1,2.8] M_\odot$ and `mbta` covered $m_1, m_2 \in [1,12] M_\odot$ with a limit on chirp mass $\mathcal{M} < 5 \mathrm{M}_\odot$ (see Figure 1). In `GstLAL` component spins were limited to $\chi_i < 0.05$ for $m_i < 2.8 \mathrm{M}_\odot$ and $\chi_i < 1$ otherwise, for `mbta` $\chi_i < 0.05$ for $m_i < 2 \mathrm{M}_\odot$ and $\chi_i < 1$ otherwise. `GstLAL` also chose to limit the template bank to include only systems for which it is possible for a NS to have disrupted during the late inspiral using constraints described in (Pannarale and Ohme 2014). For the `mbta` search the waveform filters were modelled using the "TaylorT4" time-domain, post-Newtonian inspiral approximant (Buonanno *et al.* 2009). For `GstLAL` the TaylorF2 frequency-domain, post-Newtonian waveform approximant was used (Arun *et al.* 2009; Bohé *et al.* 2013; Blanchet 2014; Bohé *et al.* 2015; Mishra *et al.* 2016). All waveform models used in this paper are publicly available in the `lalsimulation` repository (Mercer *et al.*).[4]

After December 23, 2015, and triggered by the discovery of

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[3] The "chirp mass" is the combination of the two component masses that LIGO is most sensitive to, given by $\mathcal{M} = (m_1 m_2)^{3/5} (m_1 + m_2)^{-1/5}$, where m_i denotes the two component masses

[4] The internal `lalsimulation` names for the waveforms used as filters described in this work are "TaylorF2" for the frequency-domain post-Newtonian approximant, "SpinTaylorT4" for the time-domain approximant

GW150914, the `GstLAL` analysis was extended to cover the same search space—using the same set of waveform filters—as the offline search (Capano *et al.* 2016; Abbott *et al.* 2016c).

3.3. *Dataset*

Advanced LIGO's first observing run occurred between September 12, 2015 and January 19, 2016 and consists of data from the two LIGO observatories in Hanford, WA and Livingston, LA. The LIGO detectors were running stably with roughly 40% coincident operation, and had been commissioned to roughly a third of the design sensitivity by the time of the start of O1 (Martynov *et al.* 2016). During this observing run the final offline dataset consisted of 76.7 days of analyzable data from the Hanford observatory, and 65.8 days of data from the Livingston observatory. We analyze only times during which *both* observatories took analyzable data, which is 49.0 days. Characterization studies of the analysable data found 0.5 days of coincident data during which time there was some identified instrumental problem—known to introduce excess noise—in at least one of the interferometers (Abbott *et al.* 2016l). These times are removed before assessing the significance of events in the remaining analysis time. Some additional time is not analysed because of restrictions on the minimal length of data segments and because of data lost at the start and end of those segments (Abbott *et al.* 2016d,c). These requirements are slightly different between the two offline analyses and `PyCBC` analysed 46.1 days of data while `GstLAL` analysed 48.3 days of data.

The data available to the online analyses are not exactly the same as that available to the offline analyses. Some data were not available online due to (for example) software failures, and can later be made available for offline analysis. In contrast, some data identified as analysable for the online codes may later be identified as invalid as the result of updated data-characterization studies or because of problems in the calibration of the data. During O1 a total of 52.2 days of coincident data was made available for online analysis. Of this coincident online data `mbta` analysed 50.5 days (96.6 %) and `GstLAL` analysed 49.4 days (94.6 %). A total of 52.0 days (99.5 %) of data was analysed by at least one of the online analyses.

4. SEARCH RESULTS

The offline search, targeting BBH as well as BNS and NSBH mergers, identified two signals with $> 5\sigma$ confidence in the O1 dataset (Abbott *et al.* 2016a,b). A third signal was also identified with 1.7σ confidence (Abbott *et al.* 2016c,d). Subsequent parameter inference on all three of these events has determined that, to very high confidence, they were not produced by a BNS or NSBH merger (Abbott *et al.* 2016e,c). No other events are significant with respect to the noise background in the offline search (Abbott *et al.* 2016c), and we therefore state that no BNS or NSBH mergers were observed.

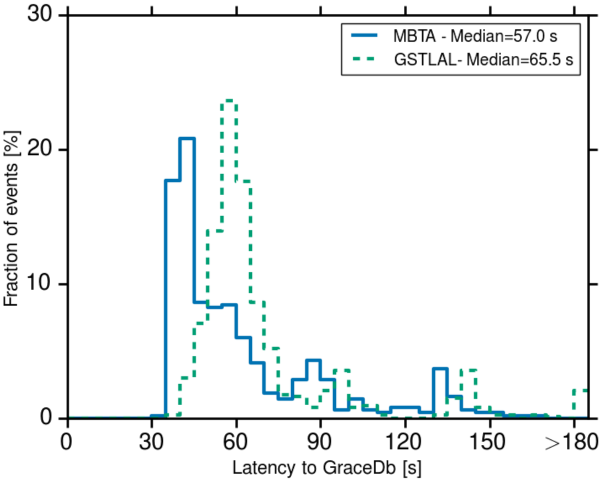

Figure 2. Latency of the online searches during O1. The latency is measured as the time between the event arriving at Earth and time at which the event is uploaded to GraCEDb.

The online search identified a total of 8 unique GW candidate events with a false-alarm rate (FAR) less than $6\,\mathrm{yr}^{-1}$. Events with a FAR less than this are sent to electromagnetic partners if they pass event validation. Six of the events were rejected during the event validation as they were associated with known non-Gaussian behavior in one of the observatories. Of the remaining events, one was the BBH merger GW151226 reported in (Abbott *et al.* 2016b). The second event identified by `GstLAL` was only narrowly below the FAR threshold, with a FAR of $3.1\,\mathrm{yr}^{-1}$. This event was also detected by `mbta` with a higher FAR of $35\,\mathrm{yr}^{-1}$. This is consistent with noise in the online searches and the candidate event was later identified to have a false alarm rate of $190\,\mathrm{yr}^{-1}$ in the offline `GstLAL` analysis. Nevertheless, the event passed all event validation and was released for EM follow-up observations, which showed no significant counterpart. The results of the EM follow-up program are discussed in more detail in (Abbott *et al.* 2016j).

All events identified by the `GstLAL` or `mbta` online analyses with a false alarm rate of less than $3200\,\mathrm{yr}^{-1}$ are uploaded to an internal database known as the gravitational-wave candidate event database (GraCEDb) (Moe *et al.*). In total 486 events were uploaded from `mbta` and 868 from `GstLAL`. We can measure the latency of the online pipelines from the time between the inferred arrival time of each event at the Earth and the time at which the event is uploaded to GraCEDb. This latency is illustrated in Fig. 2, where it can be seen that both online pipelines acheived median latencies on the order of one minute. We note that `GstLAL` uploaded twice as many events as `mbta` because of a difference in how the FAR was defined. The FAR reported by `mbta` was defined relative to the rate

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used by `mbta` and "SEOBNRv2_ROM_DoubleSpin" for the aligned-spin effective one body waveform. In addition, for calculation of rate estimates describe in Section 5, the "SpinTaylorT4" model is used to simulate BNS signals and "SEOBNRv3" is used to simulate NSBH signals.

of coincident data such that an event with a FAR of $1\,\mathrm{yr}^{-1}$ is expected to occur once in a year of coincident data. The FAR reported by `GstLAL` was defined relative to wall-clock time such that an event with a FAR of $1\,\mathrm{yr}^{-1}$ is expected to occur once in a calendar year. In the following section we use the `mbta` definition of FAR when computing rate upper limits.

5. RATES

5.1. *Calculating upper limits*

Given no evidence for BNS or NSBH coalescences during O1, we seek to place an upper limit on the astrophysical rate of such events. The expected number of observed events Λ in a given analysis can be related to the astrophysical rate of coalescences for a given source R by

$$\Lambda = R\langle VT\rangle. \tag{1}$$

Here, $\langle VT\rangle$ is the space-time volume that the detectors are sensitive to—averaged over space, observation time, and the parameters of the source population of interest. The likelihood for finding zero observations in the data s follows the Poisson distribution for zero events $p(s|\Lambda) = e^{-\Lambda}$. Bayes' theorem then gives the posterior for Λ

$$p(\Lambda|s) \propto p(\Lambda)e^{-\Lambda}, \tag{2}$$

where $p(\Lambda)$ is the prior on Λ.

Searches of Initial LIGO and Initial Virgo data used a uniform prior on Λ (Abadie *et al.* 2012a) but included prior information from previous searches. For the O1 BBH search, however, a Jeffreys prior of $p(\Lambda) \propto 1/\sqrt{\Lambda}$ for the Poisson likelihood was used (Farr *et al.* 2015; Abbott *et al.* 2016f,c). A Jeffreys prior has the convenient property that the resulting posterior is invariant under a change in parametrization. However, for consistency with past BNS and NSBH results we will primarily use a uniform prior, and note that a Jeffreys prior generally predicts a rate upper limit that is $\sim 40\%$ smaller. We do not include additional prior information because the sensitive $\langle VT\rangle$ from all previous runs is an order of magnitude smaller than that of O1. We estimate $\langle VT\rangle$ by adding a large number of simulated waveforms sampled from an astrophysical population into the data. These simulated signals are recovered with an estimate of the FAR using the offline analyses. Monte-Carlo integration methods are then utilized to estimate the sensitive volume to which the detectors can recover gravitational-wave signals below a chosen FAR threshold, which in this paper we will choose to be $0.01\mathrm{yr}^{-1}$. This threshold is low enough that only signals that are likely to be true events are counted as found, and we note that varying this threshold in the range 0.0001–1 yr^{-1} only changes the calculated $\langle VT\rangle$ by about ±20%.

Calibration uncertainties lead to a difference between the amplitude of simulated waveforms and the amplitude of real waveforms with the same luminosity distance d_L. During O1, the 1σ uncertainty in the strain amplitude was 6%, resulting in an 18% uncertainty in the measured $\langle VT\rangle$. Results presented here also assume that injected waveforms are accurate representations of astrophysical sources. We use a time-domain, aligned-spin, post-Newtonian point-particle approximant to model BNS injections (Buonanno *et al.* 2009), and a time-domain, effective-one-body waveform calibrated against numerical relativity to model NSBH injections (Pan *et al.* 2014; Taracchini *et al.* 2014). Waveform differences between these models and the offline search templates are therefore including in the calculated $\langle VT\rangle$. The injected NSBH waveform model is not calibrated at high mass ratios ($m_1/m_2 > 8$), so there is some additional modeling uncertainty for large-mass NSBH systems. The true sensitive volume $\langle VT\rangle$ will also be smaller if the effect of tides in BNS or NSBH mergers is extreme. However, for most scenarios the effects of waveform modeling will be smaller than the effects of calibration errors and the choice of prior discussed above.

The posterior on Λ (Eq. 2) can be reexpressed as a joint posterior on the astrophysical rate R and the sensitive volume $\langle VT\rangle$

$$p(R,\langle VT\rangle|s) \propto p(R,\langle VT\rangle)e^{-R\langle VT\rangle}. \tag{3}$$

The new prior can be expanded as $p(R,\langle VT\rangle) = p(R|\langle VT\rangle)p(\langle VT\rangle)$. For $p(R|\langle VT\rangle)$, we will either use a uniform prior on R or a prior proportional to the Jeffreys prior $1/\sqrt{R\langle VT\rangle}$. As with Refs. (Abbott *et al.* 2016f,m,c), we use a log-normal prior on $\langle VT\rangle$

$$p(\langle VT\rangle) = \ln\mathcal{N}(\mu,\sigma^2), \tag{4}$$

where μ is the calculated value of $\ln\langle VT\rangle$ and σ represents the fractional uncertainty in $\langle VT\rangle$. Below, we will use an uncertainty of $\sigma = 18\%$ due mainly to calibration errors.

Finally, a posterior for the rate is obtained by marginalizing over $\langle VT\rangle$

$$p(R|s) = \int d\langle VT\rangle\, p(R,\langle VT\rangle|s). \tag{5}$$

The upper limit R_c on the rate with confidence c is then given by the solution to

$$\int_0^{R_c} dR\, p(R|s) = c. \tag{6}$$

For reference, we note that in the limit of zero uncertainty in $\langle VT\rangle$, the uniform prior for $p(R|\langle VT\rangle)$ gives a rate upper limit of

$$R_c = \frac{-\ln(1-c)}{\langle VT\rangle}, \tag{7}$$

corresponding to $R_{90\%} = 2.303/\langle VT\rangle$ for a 90% confidence upper limit (Biswas *et al.* 2009). For a Jeffreys prior on $p(R|\langle VT\rangle)$, this upper limit is

$$R_c = \frac{[\mathrm{erf}^{-1}(c)]^2}{\langle VT\rangle}, \tag{8}$$

corresponding to $R_{90\%} = 1.353/\langle VT\rangle$ for a 90% confidence upper limit.

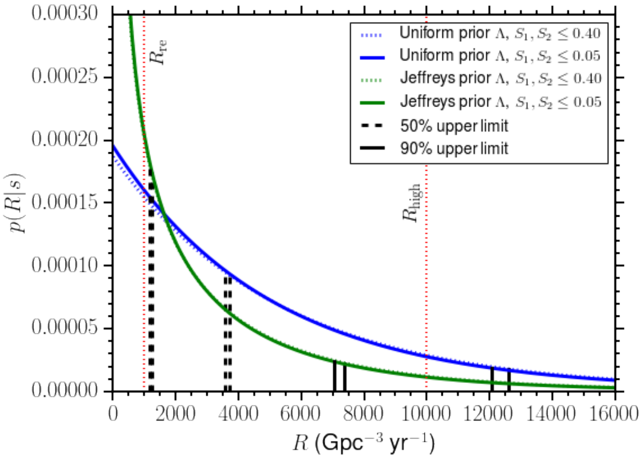

Figure 3. Posterior density on the rate of BNS mergers calculated using the `PyCBC` analysis. Blue curves represent a uniform prior on the Poisson parameter $\Lambda = R\langle VT\rangle$, while green curves represent a Jeffreys prior on Λ. The solid (low spin population) and dotted (high spin population) posteriors almost overlap. The vertical dashed and solid lines represent the 50% and 90% confidence upper limits respectively for each choice of prior on Λ. For each pair of vertical lines, the left line is the upper limit for the low spin population and the right line is the upper limit for the high spin population. Also shown are the realistic $R_{\rm re}$ and high end $R_{\rm high}$ of the expected BNS merger rates identified in Ref. (Abadie *et al.* 2010).

5.2. *BNS rate limits*

Motivated by considerations in Section 2, we begin by considering a population of BNS sources with a narrow range of component masses sampled from the normal distribution $\mathcal{N}(1.35M_\odot, (0.13M_\odot)^2)$ and truncated to remove samples outside the range $[1,3]M_\odot$. We consider both a "low spin" BNS population, where spins are distributed with uniform dimensionless spin magnitude $\in [0, 0.05]$ and isotropic direction, and a "high spin" BNS population with a uniform dimensionless spin magnitude $\in [0, 0.4]$ and isotropic direction. Our population uses an isotropic distribution of sky location and source orientation and chooses distances assuming a uniform distribution in volume. These simulations are modeled using a post-Newtonian waveform model, expanded using the "TaylorT4" formalism (Buonanno *et al.* 2009). From this population we compute the space-time volume that Advanced LIGO was sensitive to during the O1 observing run. Results are shown for the measured $\langle VT\rangle$ in Table 1 using a detection threshold of FAR $= 0.01\,\mathrm{yr}^{-1}$. Because the template bank for the searches use only aligned-spin BNS templates with component spins up to 0.05, the `PyCBC` (`GstLAL`) pipelines are 4% (6%) more sensitive to the low-spin population than to the high-spin population. The difference in $\langle VT\rangle$ between the two analyses is no larger than 5%, which is consistent with the difference in time analyzed in the two analyses. In addition, the calculated $\langle VT\rangle$ has a Monte Carlo integration uncertainty of $\sim 1.5\%$ due to the finite number of injection samples.

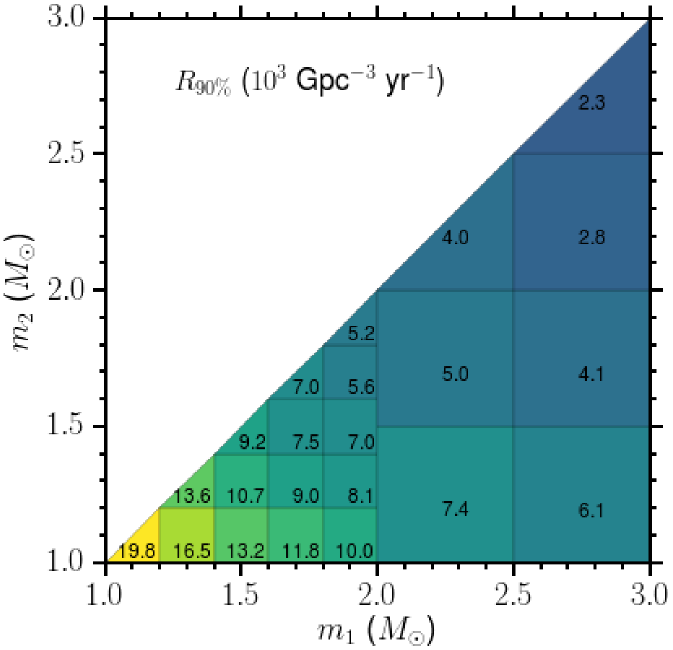

Figure 4. 90% confidence upper limit on the BNS merger rate as a function of the two component masses using the `PyCBC` analysis. Here the upper limit for each bin is obtained assuming a BNS population with masses distributed uniformly within the limits of each bin, considering isotropic spin direction and dimensionless spin magnitudes uniformly distributed in $[0, 0.05]$.

Using the measured $\langle VT\rangle$, the rate posterior and upper limit can be calculated from Eqs. 5 and 6 respectively. The posterior and upper limits are shown in Figure 3 and depend sensitively on the choice of uniform versus Jeffreys prior for $\Lambda = R\langle VT\rangle$. However, they depend only weakly on the spin distribution of the BNS population and on the width σ of the uncertainty in $\langle VT\rangle$. For the conservative uniform prior on Λ and an uncertainty in $\langle VT\rangle$ due to calibration errors of 18%, we find the 90% confidence upper limit on the rate of BNS mergers to be 12,100 Gpc^{-3} yr^{-1} for low spin and 12,600 Gpc^{-3} yr^{-1} for high spin using the values of $\langle VT\rangle$ calculated with `PyCBC`; results for `GstLAL` are also shown in Table 1. These numbers can be compared to the upper limit computed from analysis of Initial LIGO and Initial Virgo data (Abadie *et al.* 2012a). There, the upper limit for 1.35 – $1.35M_\odot$ non-spinning BNS mergers is given as 130,000 Gpc^{-3} yr^{-1}. The O1 upper limit is more than an order of magnitude lower than this previous upper limit.

To allow for uncertainties in the mass distribution of BNS systems we also derive 90% confidence upper limits as a function of the NS component masses. To do this we construct a population of software injections with component masses sampled uniformly in the range $[1,3]M_\odot$, and an isotropic distribution of component spins with magnitudes uniformly dis-

Injection set	Range of spin magnitudes	$\langle VT \rangle$ (Gpc^3 yr)		Range (Mpc)		$R_{90\%}$ (Gpc^{-3} yr^{-1})	
		`PyCBC`	`GstLAL`	`PyCBC`	`GstLAL`	`PyCBC`	`GstLAL`
Isotropic low spin	[0, 0.05]	2.09×10^{-4}	2.20×10^{-4}	73.2	73.4	12,100	11,500
Isotropic high spin	[0, 0.4]	2.00×10^{-4}	2.07×10^{-4}	72.1	72.0	12,600	12,200

Table 1. Sensitive space-time volume $\langle VT \rangle$ and 90% confidence upper limit $R_{90\%}$ for BNS systems. Component masses are sampled from a normal distribution $\mathcal{N}(1.35M_\odot, (0.13M_\odot)^2)$ with samples outside the range $[1,3]M_\odot$ removed. Values are shown for both the `pycbc` and `gstlal` pipelines. $\langle VT \rangle$ is calculated using a FAR threshold of 0.01 yr^{-1}. The rate upper limit is calculated using a uniform prior on $\Lambda = R\langle VT \rangle$ and an 18% uncertainty in $\langle VT \rangle$ from calibration errors.

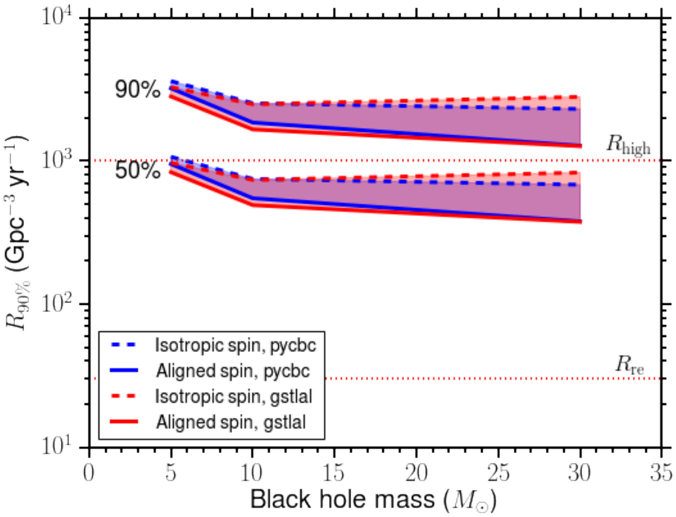

Figure 5. 50% and 90% upper limits on the NSBH merger rate as a function of the BH mass using the more conservative uniform prior for the counts Λ. Blue curves represent the `PyCBC` analysis and red curves represent the `GstLAL` analysis. The NS mass is assumed to be $1.4M_\odot$. The spin magnitudes were sampled uniformly in the range [0, 0.04] for NSs and [0, 1] for BHs. For the aligned spin injection set, the spins of both the NS and BH are aligned (or anti-aligned) with the orbital angular momentum. For the isotropic spin injection set, the orientation for the spins of both the NS and BH are sampled isotropically. The isotropic spin distribution results in a larger upper limit. Also shown are the realistic $R_{\rm re}$ and high end $R_{\rm high}$ of the expected NSBH merger rates identified in Ref. (Abadie *et al.* 2010).

tributed in $[0, 0.05]$. We then bin the BNS injections by mass, and calculate $\langle VT \rangle$ and the associated 90% confidence rate upper limit for each bin. The 90% rate upper limit for the conservative uniform prior on Λ as a function of component masses is shown in Figure 4 for `PyCBC`. The fractional difference between the `PyCBC` and `GstLAL` results range from 1% to 16%.

5.3. *NSBH rate limits*

Given the absence of known NSBH systems and uncertainty in the BH mass, we evaluate the rate upper limit for a range of BH masses. We use three masses that span the likely range of BH masses: $5M_\odot$, $10M_\odot$, and $30M_\odot$. For the NS mass, we use the canonical value of $1.4M_\odot$. We assume a distribution of BH spin magnitudes uniform in $[0, 1]$ and NS spin magnitudes uniform in $[0, 0.04]$. For these three mass pairs, we compute upper limits for an isotropic spin distribution on both bodies, and for a case where both spins are aligned or anti-aligned with the orbital angular momentum (with equal probability of aligned vs anti-aligned). Our NSBH population uses an isotropic distribution of sky location and source orientation and chooses distances assuming a uniform distribution in volume. Waveforms are modeled using the spin-precessing, effective-one-body model calibrated against numerical relativity waveforms described in Ref. (Taracchini *et al.* 2014; Babak *et al.* 2016).

The measured $\langle VT \rangle$ for a FAR threshold of 0.01yr^{-1} is given in Table 2 for `PyCBC` and `GstLAL`. The uncertainty in the Monte Carlo integration of $\langle VT \rangle$ is 1.5%–2%. The corresponding 90% confidence upper limits are also given using the conservative uniform prior on Λ and an 18% uncertainty in $\langle VT \rangle$. Analysis-specific differences in the limits range from 1% to 20%, comparable or less than other uncertainties such as calibration. These results can be compared to the upper limits found for initial LIGO and Virgo for a population of $1.35M_\odot$–$5M_\odot$ NSBH binaries with isotropic spin of 36,000 Gpc^{-3} yr^{-1}at 90% confidence (Abadie *et al.* 2012a). As with the BNS case, this is an improvement in the upper limit of over an order of magnitude.

We also plot the 50% and 90% confidence upper limits from `PyCBC` and `GstLAL` as a function of mass in Figure 5 for the uniform prior. The search is less sensitive to isotropic spins than to (anti-)aligned spins due to two factors. First, the volume-averaged signal power is larger for a population of (anti-)aligned spin systems than for isotropic-spin systems. Second, the search uses a template bank of (anti-)aligned spin systems, and thus loses sensitivity when searching for systems with significantly misaligned spins. As a result, the rate upper limits are less constraining for the isotropic spin distribution than for the (anti-)aligned spin case.

6. ASTROPHYSICAL INTERPRETATION

We can compare our upper limits with rate predictions for compact object mergers involving NSs, shown for BNS in Figure 6 and for NSBH in Figure 7. A wide range of predictions derived from population synthesis and from binary pulsar observations were reviewed in 2010 to produce rate estimates for canonical $1.4M_\odot$ NSs and $10M_\odot$ BHs (Abadie *et al.*

NS mass ($M_\odot$)	BH mass ($M_\odot$)	Spin distribution	$\langle VT\rangle$ (Gpc^3 yr)		Range (Mpc)		$R_{90\%}$ (Gpc^{-3} yr^{-1})	
			`PyCBC`	`GstLAL`	`PyCBC`	`GstLAL`	`PyCBC`	`GstLAL`
1.4	5	Isotropic	7.01×10^{-4}	7.71×10^{-4}	110	112	3,600	3,270
1.4	5	Aligned	7.87×10^{-4}	8.96×10^{-4}	114	117	3,210	2,820
1.4	10	Isotropic	1.00×10^{-3}	1.01×10^{-3}	123	122	2,530	2,490
1.4	10	Aligned	1.36×10^{-3}	1.52×10^{-3}	137	140	1,850	1,660
1.4	30	Isotropic	1.10×10^{-3}	9.02×10^{-4}	127	118	2,300	2,800
1.4	30	Aligned	1.98×10^{-3}	1.99×10^{-3}	155	153	1,280	1,270

Table 2. Sensitive space-time volume $\langle VT\rangle$ and 90% confidence upper limit $R_{90\%}$ for NSBH systems with isotropic and aligned spin distributions. The NS spin magnitudes are in the range $[0, 0.04]$ and the BH spin magnitudes are in the range $[0, 1]$. Values are shown for both the `pycbc` and `gstlal` pipelines. $\langle VT\rangle$ is calculated using a FAR threshold of 0.01 yr^{-1}. The rate upper limit is calculated using a uniform prior on $\Lambda = R\langle VT\rangle$ and an 18% uncertainty in $\langle VT\rangle$ from calibration errors.

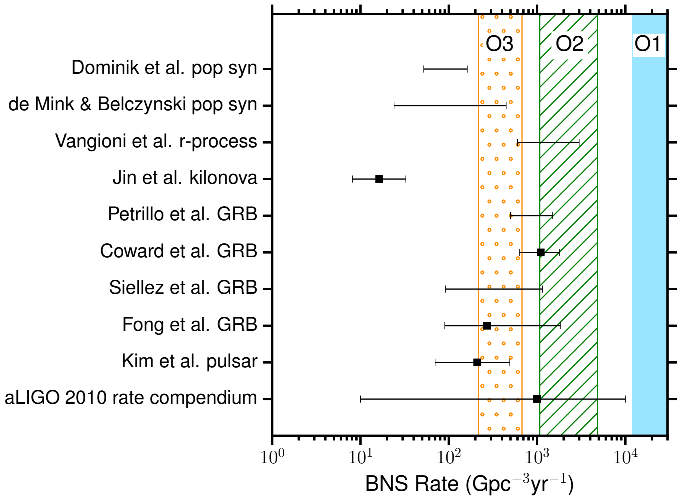

Figure 6. A comparison of the O1 90% upper limit on the BNS merger rate to other rates discussed in the text (Abadie *et al.* 2010; Kim *et al.* 2015; Fong *et al.* 2015; Siellez *et al.* 2014; Coward *et al.* 2012; Petrillo *et al.* 2013; Jin *et al.* 2015; Vangioni *et al.* 2016; de Mink and Belczynski 2015; Dominik *et al.* 2015). The region excluded by the low-spin BNS rate limit is shaded in blue. Continued non-detection in O2 (slash) and O3 (dot) with higher sensitivities and longer operation time would imply stronger upper limits. The O2 and O3 BNS ranges are assumed to be 1-1.9 and 1.9-2.7 times larger than O1. The operation times are assumed to be 6 and 9 months (Aasi *et al.* 2016) with a duty cycle equal to that of O1 ($\sim$ 40%).

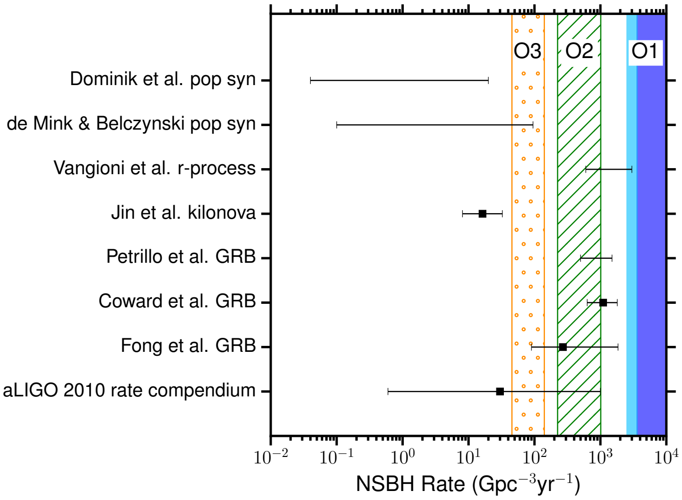

Figure 7. A comparison of the O1 90% upper limit on the NSBH merger rate to other rates discussed in the text (Abadie *et al.* 2010; Fong *et al.* 2015; Coward *et al.* 2012; Petrillo *et al.* 2013; Jin *et al.* 2015; Vangioni *et al.* 2016; de Mink and Belczynski 2015; Dominik *et al.* 2015). The dark blue region assumes a NSBH population with masses 5–1.4 $M_\odot$ and the light blue region assumes a NSBH population with masses 10–1.4 $M_\odot$. Both assume an isotropic spin distribution. Continued non-detection in O2 (slash) and O3 (dot) with higher sensitivities and longer operation time would imply stronger upper limits (shown for 10–1.4 $M_\odot$ NSBH systems). The O2 and O3 ranges are assumed to be 1-1.9 and 1.9-2.7 times larger than O1. The operation times are assumed to be 6 and 9 months (Aasi *et al.* 2016) with a duty cycle equal to that of O1 ($\sim$ 40%).

2010). We additionally include some more recent estimates from population synthesis for both NSBH and BNS (Dominik *et al.* 2015; Belczynski *et al.* 2016; de Mink and Belczynski 2015) and binary pulsar observations for BNS (Kim *et al.* 2015).

We also compare our upper limits for NSBH and BNS systems to beaming-corrected estimates of short GRB rates in the local universe. Short GRBs are considered likely to be produced by the merger of compact binaries that include NSs, i.e. BNS or NSBH systems (Berger 2014). The rate of short GRBs can predict the rate of progenitor mergers (Coward *et al.* 2012; Petrillo *et al.* 2013; Siellez *et al.* 2014; Fong *et al.* 2015). For NSBH, systems with small BH masses are considered more likely to be able to produce short GRBs (e.g. (Duez 2010; Giacomazzo *et al.* 2013; Pannarale *et al.* 2015)), so we compare to our $5M_\odot$–$1.4M_\odot$ NSBH rate constraint. The observation of a kilonova is also considered to be an indicator of a binary merger (Metzger and Berger 2012), and an estimated

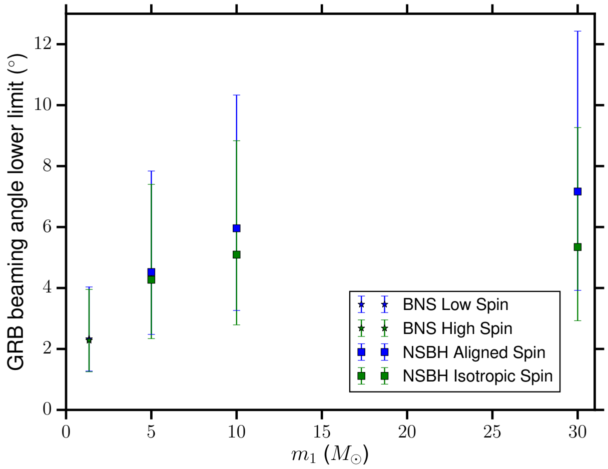

Figure 8. Lower limit on the beaming angle of short GRBs, as a function of the mass of the primary BH or NS, m_1. We take the appropriate 90% rate upper limit from this paper, assume all short GRBs are produced by each case in turn, and assume all have the same beaming angle θ_j. The limit is calculated using an observed short GRB rate of 10^{+20}_{-7}Gpc^{-3} yr^{-1} and the ranges shown on the plot reflect the uncertainty in this observed rate. For BNS, m_2 comes from a Gaussian distribution centered on $1.35M_\odot$, and for NSBH it is fixed to $1.4M_\odot$.

kilonova rate gives an additional lower bound on compact binary mergers (Jin *et al.* 2015).

Finally, some recent work has used the idea that mergers involving NSs are the primary astrophysical source of r-process elements (Lattimer and Schramm 1974; Qian and Wasserburg 2007) to constrain the rate of such mergers from nucleosynthesis (Bauswein *et al.* 2014; Vangioni *et al.* 2016), and we include rates from (Vangioni *et al.* 2016) for comparison.

While limits from O1 are not yet in tension with astrophysical models, scaling our results to current expectations for advanced LIGO's next two observing runs, O2 and O3 (Aasi *et al.* 2016), suggests that significant constraints or observations of BNS or NSBH mergers are possible in the next two years.

Assuming that short GRBs are produced by BNS or NSBH, but without using beaming angle estimates, we can constrain the beaming angle of the jet of gamma rays emitted from these GRBs by comparing the rates of BNS/NSBH mergers and the rates of short GRBs (Chen and Holz 2013). For simplicity, we assume here that all short GRBs are associated with BNS or NSBH mergers; the true fraction will depend on the emission mechanism. The short GRB rate R_{GRB}, the merger rate R_{merger}, and the beaming angle θ_j are then related by

$$\cos\theta_j = 1 - \frac{R_{\rm GRB}}{R_{\rm merger}} \qquad (9)$$

We take $R_{GRB} = 10^{+20}_{-7}$Gpc^{-3} yr^{-1} (Coward *et al.* 2012; Nakar *et al.* 2006). Figure 8 shows the resulting GRB beaming lower limits for the 90% BNS and NSBH rate upper limits. With our assumption that all short GRBs are produced by a single progenitor class, the constraint is tighter for NSBH with larger BH mass. Observed GRB beaming angles are in the range of $3-25°$ (Fox *et al.* 2005; Fong *et al.* 2015; Grupe *et al.* 2006; Soderberg *et al.* 2006; Sakamoto *et al.* 2013; Margutti *et al.* 2012; Nicuesa Guelbenzu *et al.* 2011). Compared to the lower limit derived from our non-detection, these GRB beaming observations start to confine the fraction of GRBs that can be produced by higher-mass NSBH as progenitor systems. Future constraints could also come from GRB and BNS or NSBH joint detections (Dietz 2011; Regimbau *et al.* 2015; Clark *et al.* 2015).

7. CONCLUSION

We report the non-detection of BNS and NSBH mergers in advanced LIGO's first observing run. Given the sensitive volume of Advanced LIGO to such systems we are able to place 90% confidence upper limits on the rates of BNS and NSBH mergers, improving upon limits obtained from Initial LIGO and Initial Virgo by roughly an order of magnitude. Specifically we constrain the merger rate of BNS systems with component masses of $1.35 \pm 0.13M_\odot$ to be less than 12,600 Gpc^{-3} yr^{-1}. We also constrain the rate of NSBH systems with NS masses of $1.4M_\odot$ and BH masses of at least $5M_\odot$ to be less than 3,210 Gpc^{-3} yr^{-1} if one considers a population where the component spins are (anti-)aligned with the orbit, and less than 3,600 Gpc^{-3} yr^{-1} if one considers an isotropic distribution of component spin directions.

We compare these upper limits with existing astrophysical rate models and find that the current upper limits are in conflict with only the most optimistic models of the merger rate. However, we expect that during the next two observing runs, O2 and O3, we will either make observations of BNS and NSBH mergers or start placing significant constraints on current astrophysical rates. Finally, we have explored the implications of this non-detection on the beaming angle of short GRBs. We find that, if one assumes that all GRBs are produced by BNS mergers, then the opening angle of gamma-ray radiation must be larger than $2.3^{+1.7}_{-1.1}{}^\circ$; or larger than $4.3^{+3.1}_{-1.9}{}^\circ$ if one assumes all GRBs are produced by NSBH mergers.

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