Search for Gravitational Waves Associated with Gamma-Ray Bursts Detected by Fermi and Swift during the LIGO–Virgo Run O3a
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We search for gravitational-wave transients associated with gamma-ray bursts (GRBs) detected by the Fermi and Swift satellites during the first part of the third observing run of Advanced LIGO and Advanced Virgo (2019 April 1 15:00 UTC–2019 October 1 15:00 UTC). A total of 105 GRBs were analyzed using a search for generic gravitational-wave transients; 32 GRBs were analyzed with a search that specifically targets neutron star binary mergers as short GRB progenitors. We find no significant evidence for gravitational-wave signals associated with the GRBs that we followed up, nor for a population of unidentified subthreshold signals. We consider several source type and signal morphologies, and report for these lower bounds on the distance to each GRB.

Unified Astronomy Thesaurus concepts: Gravitational waves (678); Gravitational wave astronomy (675); LIGO (920); Gamma-ray bursts (629); Compact binary stars (283); Neutron stars (1108); Black holes (162)

1. Introduction

Gamma-ray bursts (GRBs) are transient flashes of gamma radiation of cosmological origin observed at a rate of $\geq 1$ per day (Nakar 2007). The interaction of matter with a compact central object, e.g., an accreting black hole (BH; Woosley 1993; Popham et al. 1999) or a magnetar (Usov 1992; Zhang & Meszaros 2001), is believed to drive highly relativistic jets which power the prompt emission of these astrophysical events. GRBs are broadly grouped into two classes—long and short GRBs—depending on the duration and spectral hardness of their prompt emission (Mazets et al. 1981; Norris et al. 1984; Kouveliotou et al. 1993).

Long, soft GRBs have durations $\geq 2$ s and are firmly associated by optical observations to the collapse of massive stars (Galama et al. 1998; Hjorth et al. 2003; Stanek et al. 2003; Hjorth & Bloom 2012). Gravitational waves (GWs) will be radiated by the core-collapse process, (e.g., Fryer & New 2011). Several models of this process do not yield radiation that is detectable by the current generation of GW interferometers beyond Galactic distances (Abbott et al. 2020c). However, rotational instabilities and instabilities induced by the additional presence of an accretion disk as part of the GRB engine may enhance the GW emission, making it detectable even for extragalactic sources (van Putten 2001; Davies et al. 2002; Fryer et al. 2002; Kobayashi & Meszaros 2003; Shibata et al. 2003; Piro & Pfeil 2007; Corsi & Meszaros 2009; Romero et al. 2010; Gossan et al. 2016; Abbott et al. 2020c).

The unambiguous association (Abbott et al. 2017a) of neutron star (NS) binary merger GW170817 (Abbott et al. 2017b, 2019d) and short GRB 170817A (Goldstein et al. 2017; Savchenko et al. 2017) has confirmed that compact binary mergers of this kind can...
produce short GRBs. This milestone in multimessenger astronomy corroborated the idea first proposed in the 1980s (Blinnikov et al. 1984; Paczynski 1986; Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992) that the progenitors of short GRBs are compact binaries containing NSs (for a review of proposed progenitors, see Lee & Ramirez-Ruiz 2007; Nakar 2007). Indirect evidence that had previously reinforced this idea was due to the observation of a possible kilonova associated with GRB 130603B (Berger et al. 2013; Tanvir et al. 2013), and to numerous studies of the environments of short GRBs (for reviews see Berger 2011, 2014), starting with the afterglow observation and host-galaxy association of GRB 050509B (Castro-Tirado et al. 2005; Gehrels et al. 2005; Bloom et al. 2006).

In addition to confirming the origin of some short GRBs, combining data from observations of GW170817 and GRB 170817A allowed for the inference of basic properties of short GRB jets. These include the isotropic equivalent luminosity of the jet, determined through a redshift measurement made possible by the gamma-rays observed from GRB 170817A at the edge of the jet and the ejecta mildly relativistic cocoon due to interactions between the material the jet drills through the surrounding merger ejecta it in.

The production mechanism of GRB 170817A is still ongoing (Williams et al. 2018; Farah et al. 2020; Mogushi et al. 2019). The precise mechanism by which the jet is launched is still unknown, although it is typically believed to be either neutrino-driven or magnetically driven (Nakar 2007, but see also Liu et al. 2015 and references therein). Indeed, the scientific debate about the emission profile of the jet and the subsequent gamma-ray production mechanism of GRB 170817A is still ongoing (Hallinan et al. 2017; Kasliwal et al. 2017; Lamb & Kobayashi 2017; Troja et al. 2017; Gottlieb et al. 2018b; Lazzati et al. 2018; Gill & Granot 2018; Mooley et al. 2018; Zhang et al. 2018; Ghirlanda et al. 2019). It is generally believed that there are symmetric polar outflows of highly relativistic material that travel parallel to the total angular momentum of the binary system (Aloy et al. 2005; Kumar & Zhang 2014; Murguia-Berthier et al. 2017). These jets are thought to be collimated and roughly axisymmetric, emitting preferentially in a narrow opening angle due to a combination of outflow geometry and relativistic beaming. The data from extensive multi-wavelength observation campaigns that ran for nearly 20 months following the merger (Fong et al. 2019; Makhathini et al. 2020; Troja et al. 2020) are in agreement with a structured jet model, in which the energy and bulk Lorentz factor gradually decrease with angular distance from the jet symmetry axis (e.g., Dai & Gou 2001; Lipunov et al. 2001; Rossi et al. 2002; Zhang & Mészáros 2002; Ghirlanda et al. 2019; Beniamini et al. 2020). Further, according to one of the models proposed, as the jet drills through the surrounding merger ejecta it inflates a mildly relativistic cocoon due to interactions between the material at the edge of the jet and the ejecta (Lazzati et al. 2017; Gottlieb et al. 2018a). In this case, it is possible that the cocoon alone could produce the gamma-rays observed from GRB 170817A (Gottlieb et al. 2018b). Additional joint detections of GRBs and GWs will significantly aid our understanding of the underlying energetics (Lamb & Kobayashi 2017; Wu & MacFadyen 2018; Burns et al. 2019), jet geometry (Farah et al. 2020; Mogushi et al. 2019; Biscoveanu et al. 2020; Hayes et al. 2020), and jet ignition mechanisms (Veres et al. 2018; Ciolfi et al. 2019; Zhang 2019) of binary neutron star (BNS) coalescences.

A targeted search for GWs in sky and time coincidence with GRBs enhances our potential of achieving such joint detections. In this paper we present our results for the targeted GW follow-up of GRBs reported during the first part of the third observing run of Advanced LIGO and Advanced Virgo (O3a) by the Fermi (Meegan et al. 2009) and Swift (Gehrels et al. 2004; Barthelmy et al. 2005) satellites. As in the first (Abbott et al. 2017c) and second (Abbott et al. 2017a, 2019b) observing runs, two searches with different assumptions about signal morphology are applied to the GW data: we process all GRBs with a search for generic GW transients (X-Pipeline; Sutton et al. 2010; Was et al. 2012, see Section 3.2 for details) and we follow up short GRBs with an additional, modeled search for BNS and neutron star–black hole (NSBH) GW inspiral signals (PyGRB; Harry & Fairhurst 2011; Williamson et al. 2014, see Section 3.1 for details). These searches were able to process 105 and 32 GRBs in O3a, respectively.

The scope of these targeted searches is to enhance our ability to detect GW signals in coincidence with GRBs with respect to all-sky searches for transient GW signals carried out by the LIGO Scientific & Virgo Collaboration (Abbott et al. 2019c, 2021). These may lead to joint GW–GRB detections in the case of loud GW events, as for GW170817 and GRB 170817A, but the targeted searches we report on here aim at uncovering subthreshold GW signals by exploiting the time and localization information of the GRBs themselves. The Fermi Gamma-ray Burst Monitor (GBM) team conducts an analogous effort when searching through GBM data for gamma-ray transients coincident with confirmed events and low-significance candidates reported by LIGO–Virgo offline analyses (Hamburg et al. 2020). Similarly, the Swift/Burst Alert Telescope (BAT) team has developed their own autonomous pipeline to enable subthreshold GRB searches for externally triggered events (Touhuvahvuto et al. 2020).

This first part of the third observing run took place between 2019 April 1 15:00 UTC and 2019 October 1 15:00 UTC. Setting the false-alarm-rate threshold to two per year, 39 compact binary coalescence events were identified in O3a (Abbott et al. 2021). The majority of these have been classified as signals emitted by binary BH mergers; however, three events have the possibility of coming from a binary with at least one NS, that is, a potential short GRB progenitor.

1. GW190425 (Abbott et al. 2020a) was a compact binary coalescence with primary mass $2.0_{-0.3}^{+0.6}$ and secondary mass $1.4_{-0.3}^{+0.5}$ (all measurements quoted at the 90% credible level) and is therefore consistent with being the result of a BNS merger (Abbott et al. 2020a, 2021).
2. GW190426 was the GW candidate event with the highest false-alarm rate in Abbott et al. (2021); assuming it is a real signal, its inferred component masses of $5.7_{-2.3}^{+1.5}$ and $1.5_{-0.5}^{+0.8}$ indicate that it may have originated from an NSBH, or a binary BH merger.
3. GW190814 (Abbott et al. 2020b) could have originated from an NSBH, or a binary BH merger, as it has a primary mass measurement of $23.2_{-10.0}^{+13.2}$ and posterior support for a secondary mass $2.59_{-0.09}^{+0.08}$. This makes the secondary compact object either the lightest BH or the heaviest NS known to be in a compact binary system.

While there is considerable uncertainty in source type for all three of these events, GW190425 is the one for which the prospects of observing an associated GRB were most promising, as it is consistent with a BNS merger, rather than a binary BH merger or an NSBH merger with high or moderately high mass ratio. However, no confirmed electromagnetic or neutrino counterparts were observed in association with this event (Hosseinzadeh et al. 2019; Lundquist et al. 2019; Abbott et al. 2020a; Coughlin et al. 2020, 2020; see also
Pozanenko et al. 2020, 2020) despite extensive searches, which are logged in the Gamma-ray Coordinates Network (GCN) Circular archive.\footnote{204} There are a number of reasons for which an electromagnetic counterpart associated with GW190425 may not have been detected. First, the large area covered by the localization region of GW190425 determined from GW data (> 8000 deg$^2$) posed a considerable challenge for electromagnetic follow-up. 45.4% of this localization region was occulted by the Earth for the Fermi satellite so, if gamma-rays were emitted from the source, it is possible they were not detectable. Other gamma-ray observatories with lower sensitivities to short GRBs, such as INTEGRAL and KONUS-Wind, were covering relevant fractions of the localization region, however (Martin-Carrillo et al. 2019; Svinin et al. 2019). Second, GRB jets are expected to be aligned with the total angular momentum of the binary system, and thus more easily detectable at small viewing angles. The binary inclination angle of GW190425 was poorly constrained, so it is possible that a jet from this system was formed but was oriented away from our line of sight. Additionally, the luminosity distance inferred for GW190425 (~160 Mpc) was significantly larger than that for GW170817 (~40 Mpc). GRB 170817A, which followed GW170817, was such an exceptionally faint short GRB (Abbott et al. 2017a) that its prompt emission photon flux would have dipped below the detection threshold for Fermi-GBM, had the source been farther than ~75 Mpc (Abbott et al. 2017a; Goldstein et al. 2017), and by ~100 Mpc it would become undetectable by Swift/BAT (Tohuvavohu et al. 2020). Thus, if emission from the system that produced GW190425 was similarly faint, it would not have been detectable by Swift/BAT or Fermi-GBM. Therefore, we do not necessarily expect a GRB detection to be associated with GW190425 due to its almost unconstrained inclination angle, large localization region, and distance, even if gamma-rays were emitted from this system. Scenarios like this one further motivate the need for GW follow-up analyses of GRB events which, by definition, constrain the sky localization and inclination angle of the progenitor.

In Section 2 we discuss the set of GRBs analyzed in this paper. In Section 3, we summarize the two targeted search methods used to follow up GRBs. Section 4 presents the results obtained with these two methods. We also consider each of the two sets of results collectively and quantify its consistency with the no-signal hypothesis. Finally, in Section 5 we provide our concluding remarks.

2. GRB Sample

The sample of GRBs analyzed in this paper includes events circulated by the GCN,\footnote{205} complemented with information from the Swift/BAT catalog (Lien et al. 2016),\footnote{206} the online Swift GRB Archive,\footnote{207} and the Fermi-GBM Catalog.\footnote{208} (Gruber et al. 2014; von Kienlin et al. 2014; Narayana Bhat et al. 2016) Once an alert detailing an event has been received via the GCN, the dedicated Vetting Automation and Literature Informed Database (Coyne 2015) is applied to find the latest

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\footnote{204} All GCN Circulars related to this event are archived at https://gcn.gsfc.nasa.gov/other/S190425z.gcn3.

\footnote{205} GCN Circulars Archive: http://gcn.gsfc.nasa.gov/gcn3_archive.html.

\footnote{206} Swift/BAT GRB Catalog: http://swift.gsfc.nasa.gov/results/batgrbcat/.

\footnote{207} Swift GRB Archive: http://swift.gsfc.nasa.gov/archive/grb_table/.

\footnote{208} FERMIGRST—Fermi-GBM Burst Catalog: https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigrst.html.
however, we followed up as many GRBs as we could and we were indeed able to analyze these three cases.

3. Search Methods

We now provide a description of the two targeted search methods used in this paper. These are the same methods applied to GW data coincident with GRBs that occurred during the first (Abbott et al. 2017c) and second (Abbott et al. 2017a, 2019b) Advanced LIGO and Virgo observing runs. In Section 3.1 we summarize the modeled search method that aims at uncovering subthreshold GW signals emitted by BNS and NSBH binaries (PyGRB; Harry & Fairhurst 2011; Williamson et al. 2014). In Section 3.2 we discuss the search for generic GW transients (X-Pipeline; Sutton et al. 2010; Was et al. 2012). Results from these two searches are presented in Section 4.

3.1. Modeled Search for Binary Mergers

This analysis searches for a GW signal compatible with the inspiral of a BNS or NSBH binary—collectively NS binaries—within 6 s of data associated with an observed short GRB. This stretch of data is the on-source window and runs from −5 s to +1 s around the start of the GRB emission (i.e., the GRB trigger time). The surrounding ∼30–90 minutes of data are split into 6 s off-source trials which are also analyzed in order to build a background. Around 30 minutes allows the modeled search to accurately estimate the power spectral density of the available instruments and ensures that it can assess at sub-percent level accuracy the significance of any candidate events found in the on-source window. All the data are processed using PyGRB (Harry & Fairhurst 2011; Williamson et al. 2014), a coherent matched filtering pipeline that is part of the general open-source software PyCBC (Nitz et al. 2020) and has core elements in the LALSuite software library (LIGO Scientific Collaboration 2018). We scan each trial of data and the on-source window in the 30–1000 Hz frequency band using a predefined bank of waveform templates (Owen & Sathya-prakash 1999) created with a hybrid geometric–stochastic method (Capano et al. 2016; Dal Canton & Harry 2017) and using a phenomenological inspiral-merger-ringdown waveform model for non-precessing point-particle binaries (IMRPhenomD; Husa et al. 2016; Khan et al. 2016).210 The waveform template bank includes waveforms corresponding to a range of masses ([1.0, 2.8]M☉ for NSs, [1.0, 25.0]M☉ for BHs) and dimensionless spin magnitudes ([0, 0.05] for NSs, [0, 0.998] for BHs) for aligned-spin, zero-eccentricity BNS or NSBH systems that may produce an electromagnetic counterpart via the tidal disruption of the NS (Pannarale & Ohme 2014). Aside from the updated sensitivity of our detectors, the only difference with respect to the second LIGO–Virgo observing run (Abbott et al. 2019b) is that the generation of the bank has been updated to apply more accurate physics to determine whether an NSBH system could produce an accretion disk from the disruption (Foucart et al. 2018). We only search for circularly polarized GWs, which may be emitted by binaries with inclinations of 0° or 180°: such systems have GW amplitudes that are consistent (Williamson et al. 2014) with those of binary progenitors with inclination angles over the full range of viewing angles that we expect for typical brightness GRBs (<30°; Fong et al. 2015), such as those in our sample.

The strength of any potential signal is ranked via a coherent matched filter signal-to-noise ratio (S/N; Harry & Fairhurst 2011; Williamson et al. 2014) which is re-weighted according to a χ² goodness-of-fit between the template that identified it and the signal itself. The significance of the latter is quantified as the probability of background alone producing such an event. This is evaluated by comparing the re-weighted S/N of the loudest trigger within the 6 s on-source to the distribution of the re-weighted S/Ns of the loudest triggers in the 6 s off-source trials. When data from more than one detector are available, this background S/N distribution is extended by generating additional off-source trials via time slides, that is, by combining data from detectors after introducing time shifts longer than the light-travel time across the network. Specifically, our time shifts are 6 s long, in order to match the width of the on-source window and the off-source trials.

In order to derive the sensitivity of this search to potential GRB sources, simulated signals are injected in software into the off-source data. The 90% exclusion distances, D90, are defined as the distances within which 90% of the injected simulated signals are recovered with a greater ranking statistic than the loudest on-source event. Three different astrophysical populations are considered: BNS binaries with generically oriented—i.e., precessing—spins, aligned-spin NSBH binaries, and NSBH binaries with generically oriented spins. These simulated signals cover a portion of parameter space that extends beyond that covered by the template bank, as they include NS dimensionless spin values up to 0.4 and, for two families of injected signals, admit precession. As stated previously, the templates used to filter the data are produced using IMRPhenomD. In order to factor into the sensitivity assessment any potential loss due to uncertainties in GW signal modeling, the injected signals are not produced with the same model used for the templates. Precessing BNS signals are simulated using the TaylorT2 time-domain, post-Newtonian inspiral approximant (SpinTaylorT2; Sathyaprakash & Dhurandhar 1991; Blanchet et al. 1996; Mikoczi et al. 2005; Arun et al. 2009; Bohé et al. 2013, 2015; Mishra et al. 2016), while NSBH-injected waveforms are generated assuming a point-particle effective-one-body model tuned to numerical simulations which can allow for precession effects from misaligned spins (SEOBNRv3; Pan et al. 2014; Taracchini et al. 2014; Babak et al. 2017). The three populations used to build the injected signals are defined as in the first two LIGO–Virgo observing runs, to allow for direct comparisons (Abbott et al. 2017c, 2019b). NS masses for the injections are taken between 1 M☉ and 3 M☉ from a normal distribution centered at 1.4 M☉ with a standard deviation of 0.2 M☉ (Kiziltan et al. 2013) and 0.4 M☉ for BNS and NSBH systems, respectively. BH masses are taken to be between 3 M☉ and 15 M☉ from a normal distribution centered at 10 M☉ with a standard deviation of 6 M☉. Spins are drawn uniformly in magnitude and, when applicable, with random orientation; the maximum allowed NS spin magnitude is 0.4, from the fastest observed pulsar spin (Hessels et al. 2006), while the maximum BH spin magnitude is set to 0.98, motivated by X-ray binary observations (e.g., Ózel et al. 2010; Kreidberg et al. 2012; Miller & Miller 2014). Injected signals have a range of total inclinations from 0°–30° and 150°–180° while removing any systems which could not feasibly produce a short GRB (Pannarale & Ohme 2014).

3.2. Unmodelled Search for Generic Transients

X-Pipeline looks for excess power that is coherent across the network of GW detectors and consistent with the sky.
localization and time window for each GRB. As in the first two observing runs, we use a search time window that begins 600 s before the GRB trigger time and ends 60 s after it, or at the $T_{90}$ time itself (whichever is larger). This window is long enough to encapsulate the time delay between GW emission from a progenitor and the GRB prompt emission (Koshut et al. 1995; Aloy et al. 2000; MacFadyen et al. 2001; Zhang et al. 2003; Lazzati 2005; Wang & Meszaros 2007; Burlon et al. 2008, 2009; Lazzati et al. 2009; Vedrenne & Atteia 2009). Our frequency range is restricted to the most sensitive band of the GW detectors, namely 20–500 Hz. While gravitational radiation from core-collapse supernovae is expected to contain frequency content above this band (Radice et al. 2019), detection of bursts above a few hundred hertz is not energetically favorable (see, e.g., Figure 4 in Abbott et al. 2019a) and increasing the frequency upper limit also increases the computational cost.

The generic transient search pipeline coherently combines data from all detectors and produces time–frequency maps of this GW data stream. The maps are scanned for clusters of pixels with excess energy, referred to as events. The events obtained this way are first ranked according to a detection statistic based on energy and then subject to coherent consistency tests. These are based on correlations between data in different detectors and reject events associated with noise transients. The surviving event with the largest ranking statistic is taken to be the best candidate for a GW detection. Its significance is evaluated in the same way as in the modeled analysis, but with 660 s long off-source trials. In order to ensure that the significance is assessed at a sub-percent level, we require at least $\sim$1.5 hr of coincident data from at least two detectors around the time of a GRB. Non-Gaussian noise transients, or glitches, are handled as described in Abbott et al. (2019b).

Similarly to the modeled search, we quantify the sensitivity of the generic transient search by injecting simulated signals into off-source data in software and recovering them. Calibration errors are accounted for by jittering the amplitude and arrival time of the injections according to a Gaussian distribution representative of the calibration uncertainties in O3a (Abbott et al. 2017c). We report results obtained for four distinct sets of circular sine-Gaussian (CSG) waveforms, with fixed quality factor $Q = 9$ and with central frequencies of 70, 100, 150, and 300 Hz (see Equation (1) and Section 3.2 of Abbott et al. 2017c). These models are intended to represent the GWs from stellar collapses. In all four cases, we set the total radiated energy to $E_{\text{GW}} = 10^{-2}M_{\odot}c^2$, a choice that is about an order of magnitude higher than the results presented in Abbott et al. (2020c) for the detectability of core-collapse supernovae. As optimistic representatives (Ott & Santamaria 2013) of longer-duration GW signals detectable by the unmodeled search, we use accretion disk instability (ADI) waveforms (van Putten 2001; van Putten et al. 2014). In these ADI models, instabilities form in a magnetically suspended torus around a rapidly spinning BH, causing GWs to be emitted. The model specifics and parameters used to generate the five families of ADI signals that we consider are the same as in Table 1 and Section 3.2 of Abbott et al. (2017c).

4. Results

During O3a we used the generic transient method to follow up a total of 105 GRBs, whereas the modeled search was applied to the 32 GRB triggers classified as short or ambiguous. For all of the most GW-signal-like triggers associated with the examined GRBs, the searches returned no significant probability of incompatibility with background alone ($p$-value). This indicates that no GW signal was uncovered in association with any of these GRBs. This is consistent with the estimated GW–GRB joint detection rate with Fermi-GBM of 0.07–1.80 per year reported in Abbott et al. (2019b) for the 2019–2020 LIGO–Virgo observing run. The most significant events found by the generic transient method and by the modeled search had $p$-values of $5.5 \times 10^{-3}$ (GRB 190804058) and $2.7 \times 10^{-2}$ (GRB 190601325), respectively.

Figures 1 and 2 show the cumulative distributions of $p$-values returned by the modeled search and the generic transient search, respectively. For cases in which no associated on-source trigger survived the analysis cuts of the modeled search, the associated $p$-value ranges between 1—i.e., an upper bound on a probability—and the fraction of background trials for the GRB that also yielded no associated GW trigger. In both figures, the expected background distribution under the no-signal hypothesis is shown by the dashed line, and its $2\sigma$ limits are indicated by the two dotted lines. Both cumulative distributions are within the $2\sigma$ lines and therefore compatible with the no-signal hypothesis. These figures indicate that the lowest $p$-value found by each search is compatible with the no-signal hypothesis.

Having found no GW signal associated with the GRBs followed up by our searches, we consider the set of modeled search results and the set of generic transient search results, collectively. We apply a weighted binomial test described in Abadie et al. (2012) to evaluate how consistent each set of results is collectively with the no-signal hypothesis. This test is conducted using the most significant 5% of $p$-values in the sample weighted by a prior probability of detection estimated.
using the network detector sensitivity at the time and location of each GRB. This final probability of observing this distribution of $p$-values given background alone, i.e., under the no-signal hypothesis, was 0.43 (0.31) for the modeled (generic transient) search method. Therefore, both searches gave no significant evidence for a population of unidentified subthreshold GW signals. For the analyses carried out in the first observing run of Advanced LIGO and Advanced Virgo, the combined $p$-values were 0.57 and 0.75 for the modeled and generic transient search, respectively (Abbott et al. 2017c); in the second observing run of Advanced LIGO and Advanced Virgo, they were 0.30 and 0.75 (Abbott et al. 2019b).

In Figure 3, we show the cumulative 90% exclusion distances for the 32 short and ambiguous GRBs followed up with the modeled search. The lowest exclusion distance values ($\sim$20 Mpc) were obtained for ambiguous GRB 190409901. This is due to the fact that only Virgo data were available for this GRB and that the sky location of this event was in a direction in which Virgo had $\sim$30% sensitivity with respect to an optimal sky location. For each of the three simulated signal classes, we quote the median of the 32 $D_{90}$ results in the top part of Table 1. All three values are 40%–60% times higher than those reported in Abbott et al. (2019b) for the previous LIGO–Virgo observing run. The individual $D_{90}$ values for each class of simulated signals are reported in Table 2. As a term of comparison, during the six month duration of O3a, the Hanford and Livingston Advanced LIGO instruments, and the Virgo interferometer had BNS ranges of 108 Mpc, 135 Mpc, and 45 Mpc, respectively. We also place a 90% confidence level lower limit on the distance for each of the 105 GRBs analyzed by the generic transient search, assuming the various emission models discussed in Section 3.2 (see also Abbott et al. 2017c). Figure 4 shows the distribution of $D_{90}$ values for the ADI model A (van Putten 2001; van Putten et al. 2014) and for a CSG with central frequency of 150 Hz (Abbott et al. 2017c). These limits depend on the sensitivity of the detector network which, in turn, varies over time and with sky location, and have been marginalized over errors introduced by detector calibration. For the ADI and the CSG models mentioned above, as well as for the other seven models used in the generic transient

211 The BNS inspiral range is defined as the distance at which the coalescence of two 1.4 $M_\odot$ NSs can be detected with an S/N of 8, averaged over all directions in the sky, source orientation, and polarization (Finn & Chernoff 1993; Allen et al. 2012; Chen et al. 2021).
| GRB Name | UTC Time | R.A. | Decl. | Satellite | Type | Network | BNS | Generic NSBH | Aligned NSBH | ADI-A | CSG 150 Hz |
|----------|----------|------|-------|-----------|------|---------|-----|--------------|--------------|-------|-------------|
| 190404293 | 07:01:21 | 8° 05' 33" | +55° 25' | Fermi | Long | HIL1 | ... | ... | 35 | 152 |
| 190404500 | 10:47:20 | 23° 46' 21" | +20° 23' | Fermi | Long | HILIV | ... | ... | 2 | 115 |
| 190406465 | 11:09:47 | 19° 05' 21" | +61° 30' | Fermi | Long | HILIV | ... | ... | 69 | 186 |
| 190407575 | 13:48:36 | 6° 02' 07" | -64° 08' | Fermi | Long | HIL1V | ... | ... | 61 | 171 |
| 190407672 | 16:07:26 | 12° 07' 16" | +40° 37' | Fermi | Long | HIL1V | ... | ... | 32 | 49 |
| 190407788 | 18:54:41 | 1° 30' 57" | -7° 57' | Fermi | Ambiguous | LIV | 169 | 311 | 395 | 34 | 54 |
| 190409990 | 21:28:05 | 15°19'55" | -33° 52' | Fermi | Ambiguous | LIV | 19 | 22 | 34 | ... | ... |
| 190411579 | 13:53:58 | 3° 02' 31" | +48° 38' | Fermi | Long | HIL1V | ... | ... | 10 | 108 |
| 190415173 | 04:09:49 | 1° 50' 50" | +17° 26' | Fermi | Long | HILIV | ... | ... | 2 | 5 |
| 190419414 | 09:55:37 | 7° 05' 48" | -40° 08' | Fermi | Long | HIL1V | ... | ... | 34 | 54 |
| 190420981 | 23:32:24 | 21° 17' 09" | -66° 25' | Fermi | Ambiguous | LIV | 175 | 215 | 315 | 35 | 52 |
| 190422284 | 06:48:17 | 20° 26' 38" | -73° 01' | Fermi | Long | HIL1V | ... | ... | 14 | 127 |
| 190422670 | 16:05:04 | 12° 36' 55" | -54° 57' | Fermi | Long | HILIV | ... | ... | 2 | 167 |
| 190425089 | 02:07:43 | 21° 01' 43" | -15° 13' | Fermi | Ambiguous | LIV1(L1H1V1) | 204 | 247 | 440 | 23 | 38 |
| 1904274A | 04:34:15 | 18° 40' 52" | +40° 19' | Swift | Short | LIV | 138 | 199 | 253 | 33 | 92 |
| 190428783 | 18:48:12 | 1° 55' 45" | +15° 51' | Fermi | Long | HILIV | ... | ... | 29 | 38 |
| 190429743 | 17:49:50 | 13° 20' 12" | -7° 60' | Fermi | Long | HILIV | ... | ... | 70 | 126 |
| 190501794 | 19:03:42 | 10° 25' 09" | -22° 00' | Fermi | Long | HIL1V | ... | ... | 18 | 35 |
| 190502168 | 04:01:30 | 6° 16' 43" | +3° 17' | Fermi | Long | HILIV | ... | ... | 34 | 92 |
| 190504415 | 09:57:34 | 4° 41' 57" | -39° 34' | Fermi | Long | HIL1V | ... | ... | 16 | 50 |
| 190504678 | 16:16:28 | 9° 09' 43" | +33° 01' | Fermi | Short | LIV | 93 | 124 | 189 | 17 | 68 |
| 190505051 | 01:14:09 | 22° 21' 33" | +42° 11' | Fermi | Long | HIL1V | ... | ... | 100 | 149 | 206 | 24 | 36 |
| 190507270 | 06:28:23 | 10° 23' 50" | -12° 48' | Fermi | Long | HIL1V | ... | ... | 39 | 111 |
| 190507712 | 17:05:16 | 0°44'53" | -61° 7' | Fermi | Short | V1 | 42 | 58 | 70 | ... | ... |
| 190507970 | 23:16:29 | 19° 11' 16" | -22° 49' | Fermi | Long | HIL1V | ... | ... | 32 | 231 |
| 190508987 | 23:41:24 | 6° 54' 02" | +27° 02' | Fermi | Long | HIL1V | ... | ... | 30 | 178 |
| 190510120 | 02:52:13 | 8° 18' 09" | -53° 04' | Fermi | Long | HIL1V | ... | ... | 8 | 53 |
| 190510430 | 10:19:16 | 6° 32' 31" | +33° 33' | Fermi | Short | HIL1 | 128 | 196 | 253 | 48 | 116 |
| 190511A | 07:14:48 | 8° 25' 46" | -20° 15' | Swift | Short | HIL1V | ... | ... | 50 | 142 |
| 190512A | 14:40:09 | 5° 29' 35" | -7° 35' | Swift | Short | HIL1V | ... | ... | 20 | 56 |
| 190515190 | 04:33:03 | 9° 10' 45" | +29° 17' | Fermi | Short | HIL1V | 122 | 148 | 194 | 22 | 42 |
| 190517813 | 19:30:10 | 18° 00'04" | +25° 46' | Fermi | Long | HILIV | ... | ... | 30 | 74 |
| 190519A | 07:25:39 | 7° 39' 01" | -38° 49' | Swift | Long | HIL1V | ... | ... | 10 | 190 |
| 190525032 | 00:45:47 | 22° 32' 04" | 5° 27' | Fermi | Short | HIL1V | 128 | 248 | 385 | 22 | 165 |
| 190531312 | 07:29:11 | 1° 24' 28" | +16° 21' | Fermi | Short | HIL1V | ... | ... | 21 | 73 |
| 190531568 | 13:38:03 | 18° 16' 40" | 38° 52' | Fermi | Short | HIL1V | 86 | 150 | 187 | 3 | 29 |
| 190601325 | 07:47:24 | 10° 51' 55" | +54° 35' | Fermi | Short | HIL1V | 136 | 169 | 248 | 17 | 34 |

| Table 2 | Information and Limits on Associated GW Emission for Each of the Fermi and Swift GRBs Followed Up during the LIGO-Virgo Run O3a |

**$D_{90}$ (Mpc)**
Table 2 (Continued)

| GRB Name | UTC Time | R.A.  | Decl.  | Satellite | Type   | Network | BNS | Generic NSBH | Aligned NSBH | ADI-A | CSG 150 Hz |
|----------|----------|-------|--------|----------|--------|---------|-----|--------------|-------------|-------|-------------|
| 190707308 | 07:23:01 | 12° 17’ 19” | −9° 31’ | Fermi | Long | HIL1 | ... | ... | ... | ... | 34 | 75 |
| 1907008365 | 08:45:11 | 13° 59’ 24” | −1° 18’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 18 | 58 |
| 190712018 | 00:25:20 | 23°44’41” | −38°35’ | Fermi | Ambiguous | HIL1 | 68 | 204 | 357 | ... | ... | 5 | 12 |
| 190712095 | 02:16:41 | 19° 13’ 33” | 56° 09’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 38 | 159 |
| 190716019 | 00:27:59 | 4° 41’ 40” | 16° 28’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 5 | 12 |
| 190718A | 04:41:15 | 22° 26’ 25” | −41° 11’ | Swift | Long | HIL1/V1 | ... | ... | ... | ... | 12 | 93 |
| 190719A990 | 11:57:51 | 6° 34’ 26” | 6° 42’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 33 | 94 |
| 190719C | 14:58:34 | 16° 00’ 49” | 13° 00’ | Swift | Long | HIL1/V1 | ... | ... | ... | ... | 4 | 157 |
| 190720613 | 14:42:09 | 13° 30’ 52” | 41° 47’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 10 | 38 |
| 190720964 | 23:08:38 | 9° 15’ 28” | −55° 35’ | Fermi | Long | HIL1 | ... | ... | ... | ... | 10 | 34 |
| 190724031 | 00:43:56 | 11°21’24” | 15°9’ | Fermi | Short | HIL1 | 197 | 286 | 329 | ... | ... | ... |
| 190726642 | 15:24:53 | 20° 41’ 02” | 34° 17’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 34 | 85 |
| 190726843 | 20:14:30 | 22° 50’ 43” | −55° 59’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 72 | 180 |
| 190727668 | 16:01:52 | 14° 57’ 57” | 19° 26’ | Fermi | Long | HIL1 | ... | ... | ... | ... | 24 | 109 |
| 190727B | 20:18:17 | 6° 25’ 59” | −13° 16’ | Swift | Long | LIV1 | ... | ... | ... | ... | 34 | 68 |
| 190728271 | 06:30:36 | 23° 46’ 45” | 5° 26’ | Fermi | Short | HIL1/V1 | 160 | 204 | 272 | 32 | 79 |
| 190804058 | 01:23:27 | 7° 12’ 04” | −64° 52’ | Fermi | Ambiguous | HIL1 | 132 | 184 | 240 | 34 | 74 |
| 190805106 | 02:32:30 | 11° 10’ 36” | −23° 46’ | Fermi | Ambiguous | HIL1 | ... | ... | ... | ... | 35 | 121 |
| 190805199 | 04:46:00 | 13° 59’ 00” | 19° 28’ | Fermi | Long | HIL1 | ... | ... | ... | ... | 33 | 75 |
| 190806535 | 12:50:02 | 20° 22’ 14” | 0° 33’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 20 | 52 |
| 190808752 | 18:03:17 | 11° 12’ 12” | 39° 43’ | Fermi | Long | LIV1 | ... | ... | ... | ... | 32 | 62 |
| 190810675 | 16:12:01 | 12° 55’ 07” | −37° 34’ | Fermi | Short | HIL1/V1 | 85 | 159 | 222 | 2 | 50 |
| 190813520 | 12:29:09 | 7° 05’ 31” | −23° 16’ | Fermi | Short | HIL1 | 84 | 121 | 161 | 23 | 56 |
| 190816A | 14:42:24 | 22° 44’ 43” | −29° 45’ | Swift | Long | LIV1/V1 | ... | ... | ... | ... | 34 | 75 |
| 190817953 | 22:52:25 | 18° 20’ 40” | −31° 08’ | Fermi | Ambiguous | HIL1 | 61 | 102 | 109 | 1 | 30 |
| 190822705 | 16:55:29 | 8° 49’ 04” | −8° 05’ | Fermi | Short | LIV1 | 148 | 181 | 278 | 2 | 17 |
| 190824A | 14:46:39 | 14° 21’ 17” | −41° 54’ | Swift | Long | HIL1/V1 | ... | ... | ... | ... | 24 | 160 |
| 190825171 | 04:06:56 | 14° 03’ 26” | −74° 08’ | Fermi | Long | HIL1 | ... | ... | ... | ... | 17 | 38 |
| 190827467 | 11:12:48 | 11° 43’ 14” | 46° 27’ | Fermi | Long | HIL1 | ... | ... | ... | ... | 7 | 26 |
| 190828B | 12:59:59 | 16° 47’ 21” | 27° 17’ | Swift | Long | HIL1/V1 | ... | ... | ... | ... | 22 | 52 |
| 190828F | 19:56:44 | 2° 48’ 10” | −8° 57’ | Swift | Long | LIV1/V1 | ... | ... | ... | ... | 33 | 51 |
| 190830023 | 00:32:48 | 7° 27’ 36” | −23° 46’ | Fermi | Long | HIL1/V1 | ... | ... | ... | ... | 33 | 59 |
| 190830264 | 06:20:46 | 10° 36’ 48” | −54° 43’ | Fermi | Ambiguous | HIL1/V1 | 242 | 331 | 478 | 31 | 45 |

Note: The Satellite column lists the instrument the sky localization of which was used for GW analysis purposes. The Network column lists the GW detector network used in the analysis of each GRB: L1 = LIGO Hanford, L1 = LIGO Livingston, V1 = Virgo. A denotes cases in which T_{90} > 60 s, so the on-source window of the generic transient search was extended to cover the GRB duration. For cases in which the generic transient search (Section 3.2) and the neutron star binary search (Section 3.1) used a different network, we report the network used by the latter in parentheses. Columns 8–12 display the 90% confidence exclusion distances to the GRB (D_{90}) for several emission scenarios: BNS, generic and aligned-spin NSBH, ADI-A, and CSG GW burst at 150 Hz with total radiated energy E_{GW} = 10^{-2} M_{8} c^{2}. The first three are determined with the neutron star binary search, while the last two are calculated with the generic transient search.
Figure 4. Cumulative histograms of the 90% confidence exclusion distances, $D_{90}$, for accretion disk instability (ADI; van Putten 2001; van Putten et al. 2014) signal model A (orange, thin line) and circular sine-Gaussian (CSG) 150 Hz (Abbott et al. 2017c) model (green, thick line). For a given GRB and signal model this is the distance within which 90% of simulated signals inserted into off-source data are successfully recovered with a significance greater than the loudest on-source trigger. The median values for ADI-A and CSG-150 waveforms are 23 Mpc and 73 Mpc, respectively.

method search (see Section 3.2), we provide population median exclusion limits, $D_{90}$, in Table 1. These vary roughly over one order of magnitude, which reflects the wide range of models used in the analysis. We report the $D_{90}$ values found for each GRB in the case of ADI model A simulated signals and CSG simulated signals with central frequency of 150 Hz in Table 2.

4.1. GRB 190610A

For each event in the O3a sample that was localized with an error radius smaller than 0.5°, we searched GLADE (Dálya et al. 2018) for galaxies within 200 Mpc. We then compared the angular separation between each GRB and galaxy, and recorded all separations less than or equal to twice the error radius for each GRB. Of the 141 events in our sample, four had nearby galaxies according to the definition above: GRB 190530430, GRB 190531840, GRB 190610A, and GRB 190731943. Data for our GW follow-up analysis were available only in the case of the short GRB 190610A, first observed by Swift/BAT (Evans et al. 2019) and localized to within a 90% error radius of 1.9° (Lien et al. 2016; Palmer et al. 2019). On the edge of its localization region, there is a nearby galaxy at a luminosity distance of approximately 165 Mpc ($z = 0.037$), as reported in GLADE (see Figure 5).212 The angular separation between the center of the localization region and the nearby galaxy is at the 2.21$\sigma$ level relative to the formal fit error, which is slightly less conservative than the quoted 90% localization derived from the S/N, and is consistent with expectations of angular offsets from a host galaxy at that distance (Fong & Berger 2013).

We did not find any GW signal associated with GRB 190610A in the data available from the two LIGO detectors (Virgo data were not in observing mode at that particular time). Our modeled search described in Section 3.1, which uses an on-source window from $-5$ s to $+1$ s around the GRB trigger time, placed 90% confidence exclusion distances of 63 Mpc, 82 Mpc, and 114 Mpc for BNS binaries with generically oriented spins, NSBH binaries with generically oriented spins, and aligned-spin NSBH binaries (see Section 3.1 for more details on these three populations). In general, a distance of 165 Mpc can be within the reach of our modeled search, but GRB 190610A was in a sky location such that the sensitivity of both detectors was less than 30% of what it would have been in an optimal sky location.

5. Conclusions

We carried out targeted analyses for GWs associated with Fermi and Swift GRBs reported during the O3a LIGO–Virgo observing run. In the case of short and ambiguous GRBs events (see Section 2), we ran a modeled search for NS binary merger signals (Harry & Fairhurst 2011; Williamson et al. 2014), while an unmodeled search for GW transient signals was performed for all GRBs (Sutton et al. 2010; Was et al. 2012). As a result of our analyses, we found no GW signal in association with the GRBs that we followed up. This is consistent with the previously predicted rate of coincident detections of 0.1–1.4 per year for the third observing run of Advanced LIGO and Advanced Virgo (Abbott et al. 2017a). Additionally, by carrying out a weighted binomial test, we found no strong evidence for a population of unidentified subthreshold GW signals in our results. We set lower bounds on the distances to the progenitors of all GRBs we analyzed for a number of emission models. These $D_{90}$ values are reported in Table 2, along with other information about each GRB that we considered; this includes timing, sky location, observing instrument, and GW detectors with available data. The

212 This galaxy can be found in the HyperLeda database (http://leda.univ-lyon1.fr/) under the identifier PGC 1015066 (Makarov et al. 2014), as well as the Sloan Digital Sky Survey under the identifier J030449.65-073956.6 (Alam et al. 2015).
90% confidence level exclusion distances achieved in this run include the largest values published so far for some individual GRBs (see Abbott et al. 2017c, 2019b). Among the GRBs we analyzed is GRB 190610A, the sky localization of which included a nearby galaxy at a luminosity distance of 165 Mpc. We placed 90% confidence level exclusion distances lower than this value for NS binary merger GW signals and are therefore unable to rule out the possibility that GRB 190610A occurred in such galaxy.

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