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Search for Gravitational Waves Associated with Fast Radio Bursts Detected by CHIME/FRB During the LIGO–Virgo Observing Run O3a

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ABSTRACT

We search for gravitational-wave transients associated with fast radio bursts (FRBs) detected by the Canadian Hydrogen Intensity Mapping Experiment Fast Radio Burst Project (CHIME/FRB), during the first part of the third observing run of Advanced LIGO and Advanced Virgo (1 April 2019 15:00 UTC − 1 Oct 2019 15:00 UTC). Triggers from 22 FRBs were analyzed with a search that targets compact binary coalescences with at least one neutron star component. A targeted search for generic gravitational-wave transients was conducted on 40 FRBs. We find no significant evidence for a gravitational-wave association in either search. Given the large uncertainties in the distances of the FRBs inferred from the dispersion measures in our sample, however, this does not conclusively exclude any progenitor models that include emission of a gravitational wave of the types searched for from any of these FRB events. We report 90% confidence lower bounds on the distance to each FRB for a range of gravitational-wave progenitor models. By combining the inferred maximum distance information for each FRB with the sensitivity of the gravitational-wave searches, we set upper limits on the energy emitted through gravitational waves for a range of emission scenarios. We find values of order 10^{51}–10^{57} erg for a range of different emission models with central gravitational wave frequencies in the range 70–3560 Hz. Finally, we also found no significant coincident detection of gravitational waves with the repeater, FRB 20200120E, which is the closest known extragalactic FRB.

1. INTRODUCTION

Fast radio bursts (FRBs) are bright millisecond duration radio pulses that have been observed out to cosmological distances, several with inferred redshifts greater than unity (Lorimer et al. 2007; Petroff et al. 2019; Cordes & Chatterjee 2019). Although intensely studied for more than a decade, the emission mechanisms and progenitor populations of FRBs are still one of the outstanding questions in astronomy.

Some FRBs have been shown to repeat (Amiri et al. 2019a; CHIME/FRB Collaboration et al. 2019; Kumar et al. 2019), and the recent association of a FRB with the Galactic magnetar SGR 1935+2154 proves that magnetars can produce FRBs (CHIME/FRB Collaboration et al. 2020). Alternative progenitors and mechanisms to produce non-repeating FRBs are still credible and have so far not been ruled out (Zhang 2020b). Data currently suggests that both repeating and non-repeating classes of FRBs have Dispersion Measures (DMs), a quantity equal to the integral of the free electron density along the line of sight, and sky locations consistent with being drawn from the same population. However, the two classes have been shown to differ in their intrinsic temporal widths and spectral bandwidths (CHIME/FRB Collaboration et al. 2021). Whether genuine non-repeating sources have a different origin to their repeating cousins is an unresolved question.

The first discovery of an FRB was made over a decade ago by Parkes 64m radio telescope (Lorimer et al. 2007). This burst, FRB 010724 or FRB 20010724A, known as the *Lorimer burst*, first indicated an extragalactic origin for FRBs through its observed DM. This burst had a DM of 375 pc cm^{-3}, far in excess of the likely Galactic DM contribution along the line of sight (of order 45 pc cm^{-3} for this event), supporting an extragalactic origin. The precise localizations of FRB host galaxies have since unambiguously confirmed an extragalactic hypothesis (Chatterjee et al. 2017; Bannister et al. 2019; Li & Zhang 2020; Heintz et al. 2020) and constraints on the progenitor population are starting to be understood (e.g. Bhandari et al. 2020). The inferred cosmological distances for many FRBs have shown that these transients have extreme luminosities by radio standards, of the order $10^{38} - 10^{46}$ erg s^{-1} (Zhang 2018).

Recent studies suggest a volumetric rate of order $3.5^{+5.7}_{-2.4} \times 10^4$ $\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ above 10^{42} erg s^{-1} (Luo et al. 2020). Up to mid-2018, around 70 FRBs had been publicly announced (Petroff et al. 2016), of which around 7% had been shown to repeat. The majority of the de-

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* Deceased, August 2020.

tections during this period had been made by Parkes (27 FRBs at ~ 1.5 GHz; Champion et al. 2016; Thornton et al. 2013) and ASKAP (28 FRBs at central frequencies of ~ 1.3 GHz; Bannister et al. 2017; Shannon et al. 2018). Other detections were contributed by telescopes including UTMOST (Caleb et al. 2017) and the Green Bank Telescope (Masui et al. 2015), each operating around 800 MHz, and Arecibo (Spitler et al. 2014), operating around ~ 1.5 GHz.

The FRB detection rate has greatly increased since the Canadian Hydrogen Intensity Mapping Experiment (CHIME) instrument (Newburgh et al. 2014; Bandura et al. 2014; CHIME/FRB Collaboration 2020, ;see https://chime-experiment.ca/) began its commissioning phase in late 2018, and its first FRB observation run shortly after. The CHIME radio telescope observes in the frequency range $400-800$ MHz and consists of four $20\ \mathrm{m}\times 100\ \mathrm{m}$ cylindrical parabolical reflectors. Its large collecting area and wide field-of-view ($\approx 200\ \mathrm{deg}^2$) make it a valuable survey instrument for radio transients. FRB detection for this instrument has been led by the CHIME/FRB project (CHIME/FRB Collaboration et al. 2018) which published its first sample of 13 FRBs during its early commissioning phase, despite operating at a lower sensitivity and field-of-view than design specifications (Amiri et al. 2019b).

The CHIME/FRB project recently published a catalog of 535 FRBs detected during their first year of operation; this includes 62 bursts from 18 previously identified repeating sources (CHIME/FRB Collaboration et al. 2021). This is the first large collection of FRBs from a homogeneous survey and represents a significant milestone in this area of study. The CHIME/FRB data is supportive of different propagation or emission mechanisms between repeaters and non-repeaters, however, it is still not clear whether all FRBs do repeat (Ravi 2019) and, significantly, the FRB emission mechanism remains unknown. There presently exist many competing FRB emission theories (Platts et al. 2019), some of which predict the accompaniment of a time-varying mass quadrupole moment, and thus, the emission of gravitational waves (GWs).

A number of studies have looked at the possibility of GW emission associated with FRBs indirectly, using radio observations to search for coherent FRB-like emissions associated with short, hard gamma-ray bursts (GRBs) (Anderson et al. 2018; Rowlinson & Anderson 2019; Gourdji et al. 2020; Rowlinson et al. 2020). A radio search for FRB-like signals using early warning GW alerts has also been suggested (James et al. 2019).

The identification of an FRB within the sensitive reach of GW interferometric detectors could provide conclusive proof of an association or constrain the parameters of the emission mechanisms for a given FRB. The increased population of detected FRBs from the CHIME/FRB Project therefore offers a unique chance of achieving this endeavor.

A first search for GW counterparts to transient radio sources was conducted by Abbott et al. (2016). This used a minimally modelled coherent search (`X-Pipeline`) ± 2 min around the detection time of 6 Parkes FRBs using GW data from GEO600 (Grote 2010) and initial Virgo (Accadia et al. 2012). No GW coincidences were found, but this study provided a useful framework for future searches using improved GW sensitivities.

In this paper we present the second targeted GW follow-up of FRBs using bursts detected by CHIME/FRB during the first part of the third observing run of Advanced LIGO and Advanced Virgo (O3a) (Aasi et al. 2015; Acernese et al. 2015), which took place between 1 April 2019 15:00 UTC and 1 October 2019 15:00 UTC. This search uses both a generic GW transient search and a modelled search targeting coalescing binary systems.

The organization of this paper is as follows: in Section 2 we describe the motivation of this study by discussing possible GW counterparts to FRBs. We introduce the CHIME/FRB data sample in Section 3 and in Section 4 discuss the GW search methods employed; this includes an overview of both of the pipelines used in our analysis. Section 5 provides the results of the GW analysis of the FRB sample. In Section 6 we report results of a gravitational wave analysis of the repeater, FRB 20200120E, which is the closest known extragalactic FRB. Finally, in section 7 we summarize the astrophysical implications of our results and discuss future GW searches for FRB counterparts at greater GW sensitivities.

2. PROPOSED GRAVITATIONAL WAVE COUNTERPARTS TO FRBS

This section will review some of the more popular models of non-repeating and repeating FRBs that could provide plausible GW counterparts and could therefore be constrained or confirmed through GW searches. (An online theory catalog tracks new FRB models; see https://frbtheorycat.org).

As the millisecond durations of FRBs indicate compact emission regions, many models of non-repeating FRBs have suggested cataclysmic events, including coalescing compact objects. A number of studies have investigated the possibility of FRB-like emissions from binary neutron star (BNS) coalescence around the time of merger (see review in Platts et al. 2019). During this phase the magnetic fields of the NSs are synchronized to binary rotation and a coherent radiation could be generated due to magnetic braking. The mechanism requires magnetic fields of order 10^{12}–10^{13} Gauss and would produce FRB pulse widths consistent with the timescale of the orbital period of the BNS just prior to coalescence (Totani 2013).

Wang et al. (2016) considered that an FRB could be produced during the final stages of a BNS inspiral through magnetic reconnection due to the interaction of a toroidal magnetic field, produced as the NS magnetospheres approach each other. Dynamic ejecta launched shortly after the final merger would produce significant opacity over a large solid angle, thus screening an FRB-type signal via absorption (Yamasaki et al. 2018). Zhang (2020a) has recently entertained the idea that similar interactions between the two NS magnetospheres could produce repeating FRB-like coherent radio emissions decades or centuries before the final plunge.

Other studies have suggested that BNS mergers could generate prompt coherent radio emission on ms timescales through mechanisms such as excitation of the circumbinary plasma by GWs (Moortgat & Kuijpers 2005), from a dynamically-generated magnetic field after the merger (Pshirkov & Postnov 2010) or from the onset of the collision of a GRB forward shock with the surrounding medium (Usov & Katz 2000; Sagiv & Waxman 2002).

Zhang (2016) postulated that the inspiral of a pair of spinning black holes (BHs) could produce a Poynting flux, if at least one them is charged, by inducing a global magnetic dipole normal to the orbital plane (one of the black holes would require a characteristic charge of order 3.3×10^{21} C $(\mathrm{M}/\mathrm{M}_\odot)$). During the inspiral, as the orbital separation decreases, the magnetic flux of the system would change rapidly to produce particle bunching and thus, emission of coherent curvature radiation. The theory was extended in Zhang (2019) to show that the methodology could also be applied to BNS and neutron star-black hole (NSBH) systems; it was termed the *charged compact binary coalescence* signal. However, Zhang (2019) showed that the relatively small charge sustained by the NSs would mean that the radio signal would be orders of magnitude dimmer than observed FRB events. Additionally, as in the case of BNS mergers, the opacity from dynamic ejecta launched during the merger would negate an FRB-type signal. However, for systems with a mass ratio $m_1/m_2 \gtrsim 5$ (Shibata et al. 2009), this process could produce an FRB as the NS would plunge into the BH with no tidal disruption.

Mergers of significant fractions of BNSs are likely to give rise to millisecond magnetars (Gao et al. 2016; Margalit et al. 2019), although this is highly dependent on the unknown nuclear equation of state (see Sarin & Lasky 2021, for a review). If the remnant NS mass is greater than the maximum non-rotating mass, it can survive for hundreds to thousands of seconds before collapsing to form a BH (Ravi & Lasky 2014). As the magnetic field lines snap as they cross the BH horizon, an outwardly directed magnetic shock would dissipate as a short, intense radio burst (Falcke & Rezzolla 2014; Zhang 2014). This model has been motivated by the observation of relatively long lived X-ray plateaus following short gamma-ray bursts (sGRBs) that exhibit an abrupt decay phase, commonly interpreted as the collapse of the nascent NS to a BH (Troja et al. 2007; Lyons et al. 2010; Rowlinson et al. 2010, 2013). Such collapses are expected to occur $\lesssim 5 \times 10^4$ s after the merger (Ravi & Lasky 2014).

It has been suggested that FRBs could be related to the activity of magnetars or to strong pulses of energetic radio pulsars (Popov & Postnov 2013). Additionally, the energy stored in rotational kinetic energy and the magnetic field of a millisecond pulsar are ample to power a repeating FRB (Metzger et al. 2017). Resonant oscillation modes in the core and crust of magnetars have been suggested to cause quasi-periodic oscillations observed in the X-ray tails of giant flares. If the process by which these FRBs are created also excites non-radial modes in the magnetars, then GWs could simultaneously be produced (e.g. Levin & van Hoven 2011; Quitzow-James et al. 2017). The detection of a repeating FRB-like event associated with the Galactic magnetar SGR 1935+2154 makes this a possible candidate for repeated GW emissions for repeating FRBs.

The stellar oscillation mode that couples strongest to GW emission is the fundamental f-mode. The frequency of this mode depends on the equation of state, however analyzes of the tidal deformability of GW170817 are consistent with NS f-mode frequencies typically being around 2 kHz (Abbott et al. 2017a; Abbott et al. 2017; Wen et al. 2019; Abbott et al. 2018). This is above the most sensitive frequency of the Advanced LIGO/Virgo observatories. While early theoretical studies indicated the GW amplitude could be large enough for f-mode oscillations from Galactic magnetar flares to be observable by Advanced LIGO/Virgo (Ioka 2001; Corsi & Owen 2011), more sophisticated analyzes give much more pessimistic predictions (Levin & van Hoven 2011; Zink et al. 2012). Other modes such as gravity modes (known as g-modes - here the restoring force is buoyancy) and r-modes (where the restoring force is the Coriolis force) emit at frequencies closer to the most sensitive range for Advanced LIGO/Virgo, however these modes couple more weakly to gravitational modes, and are therefore not likely to be detectable in association with an FRB.

3. THE CHIME/FRB SAMPLE

The CHIME/FRB data sample provided for this analysis consists of 338 bursts observed within O3a. Out of this sample, 168 bursts have been published in the first CHIME/FRB catalog (CHIME/FRB Collaboration et al. 2021). Within the sample of 338 bursts, only events overlapping with up-time of at least one of the three GW observatories were considered for analysis. Within this sub-sample, the selection of bursts that were analyzed was based on the inferred distance to each burst. This selection will be described at the end of this section, after the calculation of the inferred distance is described.

The data for each FRB includes localization information, a topocentric arrival time and a measure of the total DM. For each burst, a Transient Name Server (TNS; see https://www.wis-tns.org) designation was also provided. The TNS naming convention takes the form 'FRB YYYYMMDDLLL' with YYYY, MM and DD the year, month and day information in UTC and LLL a string from 'A' to 'Z', then from 'aaa' to 'zzz', indicating reporting order on any given day.

The arrival time at the CHIME instrument's location (topocentric) at 400 MHz was converted to a dedispersed arrival time using the DM value associated with each event. This time was used as the central event time around which each GW search was conducted.

The localization information of each FRB is in the form of up to 5 disjoint error regions of varied morphology centered around the region with the highest SNR; each separate localization "island" has a central value and a 90% confidence uncertainty region. The different approaches to these localization data adopted by the generic transient and modelled search pipelines will be described in Section 4.

To determine a measure of the luminosity distance of each FRB we employ the Macquart relation (Macquart et al. 2020). This relation maps the redshift to the quantity $\mathrm{DM_{IGM}}$, which is the DM contribution from extragalactic gas along the line of sight; this can be obtained after all other contributions are subtracted. Taking into account all contributions to the total DM, the quantity $\mathrm{DM_T}$, a measure of redshift can therefore be determined by solving:

$$\begin{aligned}\mathrm{DM_T}(z) = \mathrm{DM_{MW}} + \mathrm{DM_{halo}} + \mathrm{DM_{IGM}}(z) \\ + \mathrm{DM_{host}}(z)/(1+z)\,,\end{aligned} \tag{1}$$

where $\mathrm{DM_{MW}}$ is the Milky Way contribution to the DM along the line of sight, $\mathrm{DM_{halo}}$ is the contribution from the Milky Way halo and $\mathrm{DM_{host}}$ the contribution from the host galaxy, which is corrected by the cosmic expansion factor. The estimates of z are then converted to a luminosity distance assuming a 'flat-Λ' cosmology with the cosmological parameters $\Omega_\mathrm{m} = 0.31$, $\Omega_\Lambda = 0.69$ and $H_0 = 67.8$ km s^{-1} Mpc^{-1} (Planck Collaboration et al. 2016).

To determine redshift values for each FRB we employ the Bayesian Markov-Chain Monte Carlo (MCMC) sampling framework described in (Bhardwaj et al. 2021a) with a posterior distribution defined by:

$$\mathcal{P}(\hat{\theta}\,|\,\mathrm{DM_{T,O}}) = \frac{\mathcal{L}(\mathrm{DM_{T,O}}\,|\,\hat{\theta}\,)\,\pi(\hat{\theta})}{\mathcal{Z}}\,, \tag{2}$$

where $\mathcal{L}(\mathrm{DM_{T,O}}\,|\,\hat{\theta}\,)$ is the likelihood distribution of the observed quantity $\mathrm{DM_{T,O}}$ given the parameters $\hat{\theta}$, $\pi(\hat{\theta})$ are the prior distributions on $\hat{\theta}$ and $\mathcal{Z}$ is the Bayesian evidence; this latter factor enters Eq. (2) as a normalization factor independent of the model parameters and can be ignored if one is only interested in the posterior distribution rather than model selection. We assume a Gaussian likelihood function provided as:

$$\mathcal{L}(\mathrm{DM_{T,O}}\,|\,\hat{\theta}\,) = \frac{1}{\sqrt{2\pi\sigma^2}}\exp\left[-\frac{(\mathrm{DM_{T,O}} - \mathrm{DM_T}(\hat{\theta}))^2}{2\sigma^2}\right], \tag{3}$$

with σ the uncertainty on $\mathrm{DM_{T,O}}$ for each burst and $\mathrm{DM_T}$ given by Eq. (1) (Rafiei-Ravandi et al. 2021).

For the Milky Way contribution $\mathrm{DM_{MW}}$, there is no consensus between the two popular models of Cordes & Lazio (2002) and Yao et al. (2017). Therefore, we follow Bhardwaj et al. (2021a) and assume a Gaussian prior based around the minimum of $\mathrm{DM_{MW}}$ from these two models along the line of sight; a standard deviation of 20% of this value is also used.

The contribution $\mathrm{DM_{halo}}$ has been estimated in a number of studies but is quite uncertain. For example, Yamasaki & Totani (2020) found values of $\mathrm{DM_{halo}} \sim 30 - 245$ pc cm^{-3} using a two component model. Studies by Dolag et al. (2015) found values between $\mathrm{DM_{halo}} \sim\ 30 - 50$ pc cm^{-3} based on cosmological simulation and Prochaska & Zheng (2019) estimated values between $30 - 80$ pc cm^{-3}. To take account of the large uncertainty in this quantity we follow Bhardwaj et al. (2021a) and assume a Gaussian prior such that at 3σ, $\mathrm{DM_{halo}}$ has a value 0 or 80 pc cm^{-3}.

The prior on $\mathrm{DM_{IGM}}$ assumes the parameterization $\Delta = \mathrm{DM_{IGM}}/\langle\mathrm{DM_{IGM}}\rangle$ with the denominator obtained through the Macquart relation. This takes the form provided in Macquart et al. (2020):

$$P(\Delta) = A\Delta^{-\beta}\exp\left[\frac{-(\Delta^{-\alpha} - C^2)}{2\alpha^2\sigma_\mathrm{DM}^2}\right], \tag{4}$$

with $\sigma_{\rm DM} = 0.2z^{-0.5}$ and $[\alpha, \beta] = 3$; the value of C is determined by requiring that $\langle\Delta\rangle = 1$. The form of this model is motivated by the requirement that the DM distribution approaches a Gaussian at small $\sigma_{\rm DM}$ in accordance with the Gaussianity of large scale structure. It also incorporates a skew at large $\sigma_{\rm DM}$ to reflect the possibility of over-densities along the line of sight.

Finally, for a prior on $\rm DM_{host}$, we adopt a lognormal distribution with median $e^{\mu} = 68.2$ and logarithmic width parameter $\sigma_{\rm host} = 0.88$ as in Macquart et al. (2020).

The quantities outlined above have a large range of uncertainty and there could be additional contributions e.g., circumburst material. As a result, redshift values calculated from DMs are generally taken as upper limits. We perform MCMC sampling using the `emcee` package (Foreman-Mackey et al. 2013) based on an affine-invariant sampling algorithm (Goodman & Weare 2010) using 256 walkers of 20,000 samples. Inferred values of z, and thereby luminosity distance, and their 90% credible intervals are thus determined for each FRB, based on the observed values of $\rm DM_T$, right ascension (RA) and declination (Dec), the estimated $\rm DM_{MW}$ along the line of sight and the priors on other DM contributions described above.

Given the large uncertainties in the distances of FRBs, we based our analysis and results on the 90% credible intervals inferred for the CHIME/FRB sample of bursts. However, for illustration, we show in Fig. 1 the distribution of the median distances of the total sample of 338 FRBs that occurred during O3a. The plot shows that most events seem to occur within 1700 Mpc ($z \sim 0.3$) and 6000 Mpc ($z \sim 0.9$). The closest events in the distribution include a significant number of repeating FRBs. Due to the relatively limited range of the GW detectors, in selecting which bursts to analyze, we first downselected the sample to all bursts from the closest 10% of CHIME/FRB non-repeating bursts that have GW detector network data available for analysis (if the recent CHIME/FRB catalog of 535 bursts is representative of the FRB population, at least around 11% of FRBs repeat). Within this selection, a coherent analysis using modelled waveforms was then conducted on a smaller subset of the closest 22 non-repeating events for which data was available from at least one interferometric GW detector, and a generic transient coherent analysis was conducted on a subset of FRBs for which data was available from at least two interferometric GW detectors. The further downselection to the final set of analyzes reported was based on two considerations. For some events, the systematic noise in the detector was too significant near the time of the burst for one or both of our two searches, and these events were then excluded. Finally, as each search requires significant personpower and computational resources, we performed searches on the remaining subset of events in order of increasing distance, until we reached a point of diminishing returns caused by the reduced overlap between the effective detection range of the GW detection network and the inferred distance to each FRB event. These considerations yielded a sample of 34 non-repeating FRBs that were analyzed by one or both types of analysis. Using the same considerations for selection, we analyzed a total of 11 repeated bursts from the closest 3 repeating sources: FRB 20180916B (7 repeat events during O3A), FRB 20180814A (2 repeat events) and FRB20190303A (2 events). The lower and upper 90% limits of the credible intervals on the luminosity distances to each of the non-repeating FRBs analyzed are included in the tables in Section 5.

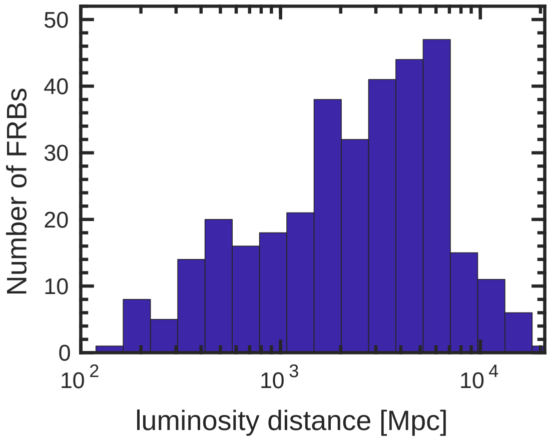

Figure 1. The distribution of inferred median distances for the CHIME/FRB data sample based on the MCMC analysis of Section 3; there is a large uncertainty in these distances, thus this distribution should be taken as only an approximate representation. The distribution peaks between 1700 Mpc ($z \sim 0.3$) and 6000 Mpc ($z \sim 0.9$). The closest non-repeating event analyzed in our sample was FRB 20190425A for which we inferred a median distance of 133 Mpc and a range [13–386] Mpc at 90% confidence; the most distant was FRB 20190601C with a median inferred distance of 914 Mpc within a range [199–1737] Mpc.

4. SEARCH METHODS

Here we will provide a description of the two targeted search methods used in this paper. These are the same methods applied to search for GW events coincident with GRBs that occurred during the first (Abbott et al. 2017b), second (Abbott et al. 2019b) and third (Abbott et al. 2021) Advanced LIGO and Advanced Virgo observing runs. In Section 4.1 we describe the modelled search method that aims to uncover sub-threshold GW signals emitted by BNS and NSBH binaries (`PyGRB`; Harry & Fairhurst 2011; Williamson et al. 2014), highlighting choices in analysis configuration that are unique to the followup of FRB events. In Section 4.2 we discuss the search for generic GW transients (`X-Pipeline`; Sutton et al. 2010; Was et al. 2012).

4.1. *PyGRB- Modelled search for binary mergers*

The modelled search for GWs associated with FRB events makes use of the `PyGRB` data analysis pipeline (Harry & Fairhurst 2011; Williamson et al. 2014), and the search is configured to be similar to the search for GW signals coincident with GRBs in O3a (Abbott et al. 2021). This is a coherent matched-filtering pipeline that compares the GW detector network data with a bank of pre-generated waveforms, including the inspiral of BNS and NSBH binaries. `PyGRB` uses the `PyCBC` (Nitz et al. 2020) open-source framework for distribution of the analysis of the GW data across large computing clusters, and also relies on several elements of the `LALSuite` software library (LIGO Scientific Collaboration 2018).

The `PyGRB` analysis searches the combined detector data in the range 30–1000 Hz. A set of coherent data streams is formed by combining the data from the detectors, using a sample of sky-positions in the region reported for the FRB event that is being studied. These data streams are then compared using matched filtering to the same predefined bank of waveform templates (Owen & Sathyaprakash 1999) used in the search for GWs associated with GRBs events in O3a (Abbott et al. 2021). The bank is created with a hybrid of geometric and stochastic template placement methods across target search space (Harry et al. 2008; Brown et al. 2012; Harry et al. 2014; Capano et al. 2016; Dal Canton & Harry 2017), using a phenomenological inspiral-merger-ringdown waveform model for non-precessing point-particle binaries (`IMRPhenomD`; Husa et al. 2016; Khan et al. 2016). This bank of templates is designed to cover binary masses in the range $[1.0, 2.8]\mathrm{M}_\odot$ for NSs, and $[1.0, 25.0]\mathrm{M}_\odot$ for BHs. The bank also allows for aligned-spin, zero-eccentricity BNS and NSBH, with dimensionless spins in the range $[0, 0.05]$ for NSs and $[0, 0.998]$ for BHs.

Coherent matched filtering can be susceptible to loud transient noise in the detector data and can produce a high signal-to-noise ratio (SNR) (Nitz et al. 2017). To combat this, the analysis performs additional tests on each point of high SNR data, which we also refer to as triggers. These tests can either remove the trigger or re-weight the SNR using a χ^2 test. This latter test determines how well the data agrees with the template over the whole template duration. Such cuts and re-weighting significantly improve the ability of the search to distinguish a GW from many types of transient noise, thus improving the significance of real GW triggers. The final re-weighted SNR of each candidate event is used as the measure of its relative significance, or ranking statistic, within the search.

The `PyGRB` analysis searches for GW inspiral events that merge within 12 s of the de-dispersed event time of each FRB, with an asymmetric *on-source window* starting 10 s before the FRB event and ending 2 s after the event. The search window is chosen to strike a balance between maximizing the possible progenitor models through a wider window or maximizing the sensitivity of the search by using a narrower window. In this search we seek a GW signal with a merger time close to the time of the FRB, assuming the FRB results from the interaction of the two binary components.

The sensitivity of the search is governed by the comparison between the most significant event in the on-source window and the most significant event in equivalent trial searches of 12 s windows in the surrounding data, known as the *off-source trials*. These off-source trials form the background data for the search, and if a sufficient number of background trials are conducted, this allows the search to determine the significance of any candidate events in the on-source window to the level needed to make a confident detection statement by computing a false-alarm probability.

If multiple detectors are available, then additional effective background data can be produced by combining the data from the detectors with an intentional misalignment in time of at least the light-travel time across the network to ensure any detected events cannot possibly be true coherent GW candidates (Williamson et al. 2014). This can be repeated for multiple possible time shifts, and in this search, these time shifts are set to match the on-source window length of 12 s. This produces fewer time shifts than a 6 s on-source window, as used in previous searches for GW associated with GRB events such as Abbott et al. (2021). This again impacts the effective significance of any detected events, because the amount of background data used by the search is limited by the amount of coherently analyzable data for all detectors in the network that surrounds the target time. Thus, a search is only conducted if a minimum of 30 min of data are available.

In the results section, we report the effective range of each search conducted as a 90% exclusion distance, D_{90}. This is calculated by first creating a set of simulated GW signals to inject into the off-source data, then attempting to find these injected signals with the standard search pipeline. The signals are injected with amplitudes appropriate for a distribution of distances between their simulated origin and the detectors, and the D_{90} distance is defined as the distance within which 90% of the injected simulated signals are recovered with a ranking statistic greater than the loudest on-source event.

Mirroring the approach taken in the O3a search for GW events associated with GRB detections (Abbott et al. 2021), the injected signals include BNS systems with dimensionless spins in the range -0.4 to 0.4, taken from observed pulsar spins (Hessels et al. 2006), and are distributed uniformly in spin and with random orientations. Injections also include aligned spin NSBH binaries, and NSBH binaries with generically oriented spins up to 0.98, motivated by X-ray binary observations (e.g., Özel et al. 2010; Kreidberg et al. 2012; Miller & Miller 2014). The simulated signals are intentionally generated using different GW signal models than those used in the matched-filtering template bank, to approximate the target search space difference between the approximate templates used and the true GW signals. In particular, the injected waveforms are identical to those used in the equivalent O3a GRB event follow up analysis (Abbott et al. 2021). Precessing BNS signals are simulated using the TaylorT2 time-domain, post-Newtonian inspiral approximant (`SpinTaylorT2`; Sathyaprakash & Dhurandhar 1991; Blanchet et al. 1996; Bohé et al. 2013; Arun et al. 2009; Mikoczi et al. 2005; Bohé et al. 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). Again, identical to the injections used in Abbott et al. (2021), NS masses for the injections are taken between 1 $M_\odot$ and 3 $M_\odot$ from a normal distribution centered at 1.4 $M_\odot$ with a standard deviation of 0.2 $M_\odot$ Kiziltan et al. (2013) and 0.4 $M_\odot$ for BNS and NSBH systems, respectively. BH masses are taken to be between 3 $M_\odot$ and 25 $M_\odot$ from a normal distribution centered at 10 $M_\odot$ with a standard deviation of 6 $M_\odot$.

Although this `PyGRB` follow up of FRB events mirrors the search conducted for GWs associated with GRB events in O3a (Abbott et al. 2021) where appropriate, there were several differences in the choices of analysis parameters for the FRB analysis. The first major difference has been noted above, wherein a 12 s on-source window is used, which is double that of the GRB analysis. This does reduce the significance of any detected signals, but has the benefit of allowing for more progenitor models where the EM emission occurs further in time from the peak of the GW emission.

Another significant change was the method of determining the area of sky over which to search for the GW signals. The FRB data sample contains multiple localizations for each event, each with their own RA and Dec uncertainties. This effectively creates multiple patches on the sky where the source could potentially reside. The effective GW network localization capability results in 90% credible regions for detections on the order of $\approx 10 - 10000$ deg^2, with an average of order 100 deg^2. In contrast, the multiple O3a FRB sample localizations spanned only order 1 deg^2 in total (Abbott et al. 2020). The sensitivity of the search also did not vary significantly over the sky localizations, and so the final set of sky positions considered by the analysis was one circular patch on the sky with a size large enough to ensure coverage over all possible provided FRB localizations. Within this patch, the sky is sampled by creating a circular grid of sky positions such that the time-delay between grid points is kept below 0.5 s (Williamson et al. 2014). This ensures coverage of the possible sky location of the source. For each sky position, the timestream data from each GW detector is combined with the appropriately different time offsets required to form a coherent streams of data for that point on the grid. These multiple coherent time streams are finally each considered in the search.

4.2. *`X-Pipeline`- Unmodelled search for generic transients*

The search for generic transients is performed with the coherent analysis algorithm `X-Pipeline` (Sutton et al. 2010; Was et al. 2012). This targeted search uses the sky localization and time window for each CHIME/FRB trigger to identify consistent excess power that is coherent across the network of GW detectors. We use different search parameters in our searches for repeating and non-repeating FRB sources.

There are a number of differences between our generic transient search on non-repeated sources and those previously conducted on GRBs (Abbott et al. 2017b, 2019b, 2021). As in GRB searches, the on-source time window is chosen to start 600 s before the trigger, but is extended from 60 s seconds post trigger to 120 s to allow for the possibility of GW emissions delayed relative to the FRB emission. This on-source window is also longer than the ±120 s window employed in the previous FRB search (Abbott et al. 2016). The extended window allows for a greater number of non-Compact Binary Coalescence (CBC) sources than those considered in GRB searches and possible GW emissions from magnetars, given the recent FRB-magnetar association (CHIME/FRB Collaboration et al. 2020).

The broadband search for FRBs with `X-Pipeline` covers the range 32 Hz up to 2 kHz, the upper range being higher than the GRB search (20–500 Hz) in order to include GW emissions from oscillation modes of NSs that are likely to occur above 1 kHz, specifically f-modes (Wen et al. 2019; Ho et al. 2020). We note that above 300 Hz a $\propto f^2$ frequency dependence in energy (see later Eq. (5)) combined with the $\propto f^1$ of the noise power spectral density of the detector increases the GW energy required to enable a confident detection as $\propto f^3$. Although including high frequency data increases the computational cost, including this data allows us to set limits on a wider variety of signal models.

`X-Pipeline` processes the on-source data around each FRB trigger by combining the GW data coherently, taking into account the antenna response and noise level of each detector to generate a series of time–frequency maps. The maps show the temporal evolution of the spectral properties of the signal and allow searches for clusters of pixels with excess energy significantly greater than one would expect from background noise. These clusters are referred to as *events*.

Events are given a ranking statistic based on energy and are subjected to coherent consistency tests based on the signal correlations between data in different detectors. This allows `X-Pipeline` to veto events that have properties similar to the noise background.

The surviving event with the largest ranking statistic is taken to be the best candidate for a GW detection. Its significance is quantified as the probability for the background alone to produce such an event. This is done by comparing the SNR of the trigger within the 720 s on-source to the distribution of the SNRs of the loudest triggers in the off-source trials. The off-source data are set to consist of at least 1.5 hours of coincident data from at least two detectors around the trigger time. This window is small enough to select data where the detectors should be in a similar state of operation as during the on-source interval, and large enough so that through artificial time-shifting, probabilities can be estimated at the sub-percent level.

We quantify the sensitivity of the generic transient search by injecting simulated signals into off-source data and recovering them. We account for calibration errors by jittering the amplitude and arrival time of the injections according to a Gaussian distribution representative of the typical calibration uncertainties expected in O3a. We compute the percentage of injections that have a significance higher than the best event candidate and determine the amplitude at which this percentage is above 90%; this value sets the upper limit.

As discussed in Section 3, localization information for each FRB is in the form of up to 5 non-contiguous or overlapping error regions of varied morphology. Occasionally these islands can be dominated by the uncertainty of a single island. The sky position errors can span a few degrees or more in RA. This could result in a temporal shift causing a GW signal to be rejected by a coherent consistency test (Was et al. 2012). For each island we set up a circular grid around the central location of the island, with overlapping grid points discarded. A coherent data stream is formed from the GW detector data with an appropriate time offset for each point on the grid. These data streams are then analyzed. Grid positions are large enough to cover the error radius and dense enough to ensure a maximum timing delay error, set as 1.25×10^{-4} s, is within 25% of the signal period at our frequency upper limit of 2000 Hz. This is 4 times finer than GRB searches that typically analyze data up to a frequency cutoff of 500 Hz. Using this grid approach, the antenna responses change only slightly over sky position; of order a few percent over a few degrees (Aasi et al. 2014). The responses are known to change rapidly near a null of the response; in such a case they are already negligible.

A particular difference between this search and other searches focused on GRBs is the increased number of simulated waveform types used in this study. Given the uncertainty in plausible GW emissions, we consider a larger range of generic burst scenarios, using an extended set of those used in both GRB and magnetar searches (Abbott et al. 2021, 2019c). Also, as we have no knowledge on whether or not FRBs are beamed along the rotation axis of the progenitor, all of our signal models correspond to elliptical and random polarization.

The waveforms chosen to cover the search parameter space are from 3 families that have different morphological characteristics: binary signals, generic burst-like signals and accretion disk instability (ADI) models. `X-Pipeline` is equally adept at detecting signals whose frequency decreases with time (ADI) and signals whose frequency increases with time (CBC models; Abadie et al. (2012); Abbott et al. (2017b)). This paper reports the results for CBCs when obtained using the dedicated modelled search (described in Section 4.1), so we will limit our discussions here to only the latter two waveform families.

The generic burst-type waveforms are described in Table 1, where we list the most important parameters (see also Abbott et al. 2019a). In all cases, to determine exclusion distances for this model family, we assume an op-

Table 1. The main parameters of the waveform injections used for the generic transient search. Models and their parameters have been chosen to cover as large a parameter space as possible. For all models the central frequencies are shown. We note that WNB models are defined by an additional frequency bandwidth, this parameter is shown in parenthesis. For the SG and WNB waveforms the duration parameter scales the width of the Gaussian envelope; for the DS2P models this parameter defines the decay time constant. An asterisk (*) denotes waveforms used in the repeaters search only; ^{c} denotes waveforms with a circular polarization.

Label	Frequency [Hz]	Duration Parameter [ms]
Sine–Gaussian Chirplets		
SG-A	70	14
SG-B	90	11
SG-C	145	6.9
SG-D	290	3.4
SG-E	650	1.5
SG-F	1100	0.9
SG-G	1600	0.6
SG-H	1995	0.5
SG-I*	2600	0.38
SG-J*	3100	0.32
SG-K*	3560	0.28
SG-L*^{c}	1600	0.6
SG-M*^{c}	1995	0.5
Ringdowns		
DS2P-A	1500	100
DS2P-B	1500	200
White noise bursts		
WNB-A	150 (100–200)	11
WNB-B	150 (100–200)	100
WNB-C	550 (100–1000)	11
WNB-D	550 (100–1000)	100

timistic emission of energy in GWs of $E_{\rm GW} = 10^{-2} {\rm M}_{\odot} {\rm c}^2$ (Abbott et al. 2021). Waveforms in this family aim to capture the general characteristics of a burst of GW energy:

Sine–Gaussian: These signals have been used previously to represent the GWs from stellar collapses. The models are defined in Eq. (1) of Abbott et al. (2017b) with a Q factor of 9 and varying central frequency as shown in Table 1. They can also model f-modes in the core of a canonical NS. We therefore also include them in the search over repeating sources, and include SG waveforms at additional frequencies listed in Table 1. In order to better constrain some models, we also include circularly polarized SG chirplets at the frequencies nearest the f-mode range (1600 Hz and 1995 Hz) in the search over repeated sources.

Ringdowns (DS2P): These signals capture the form of damped sinusoids (DS2P) at a frequency of 1500 Hz and decay constants of 100 ms and 200 ms.

White Noise Bursts (WNB): These signals mimic broad bursts of uncorrelated white noise, time-shaped by a Gaussian envelope. We use two models band-limited within frequencies of 100–200 Hz and 100–1000 Hz, and with time constants of 11 ms and 100 ms.

Following the predictions from oscillation modes for NS starquakes (Wen et al. 2019; Li et al. 2019), the first two waveforms in this family (SG and DS2P) have been used in the search for GWs associated with magnetar bursts (Abbott et al. 2019c).

We also consider a range of Accretion Disk Instability (ADI) models. These are long-lasting waveforms which are modelled to represent the GW emissions from instabilities in a magnetically suspended torus around a rapidly spinning BH. The model specifics and parameters used to generate the five types of ADI signals, designated ADI-A to ADI-E, are the same used in the previous searches (see Table 1 of Abbott et al. 2017b).

The version of `X-Pipeline` used in this analysis has a new feature named autogating. This feature increases the sensitivity of the longer-duration ($\gtrsim$ 10 s) signals, previously limited by loud background noise transients (Abbott et al. 2021). This technique gates the whitened data from a single detector if the average energy over a 1-second window exceeds a user-specified threshold. To minimize the possibility of a loud GW transient be gated, this procedure is canceled if the average energy at the same time in any other detector exceeds the threshold.

4.2.1. *X-pipeline Search on Repeating FRBs*

A subset of 11 of the FRBs that we analyze have been identified to repeat. Repeating FRBs are likely caused by a process distinct from those that produce singular FRBs; most notably they are unlikely to be associated with CBC events. We therefore only run the `X-Pipeline` generic transient search on these events, and we choose the parameters to provide maximal sensitivity to the GW transients that would most probably be produced by flaring magnetars.

This search is similar to that for GW events associated with magnetars during the third observing run of Advanced LIGO and Advanced Virgo (O3) (Abbott et al. in preparation). The frequency band of the search ranges from 50 Hz to 4000 Hz, which encapsulates the NS f-mode frequency band, but excludes the lowest frequencies where nonstationary noise could potentially 'pollute' the search statistics. The search spans 8 s of time centered within one second of the arrival time of the FRB to ensure optimal sensitivity at the event time. Injected waveforms are chosen to reasonably model the f-modes of a canonical NS as described in Kokkotas et al. (2001). This includes a series of SG chirplets with a Q factor of 9 and varying center frequencies as shown in Table 1. We also neglect to use the autogating algorithm for noise transients as described above, as its tendency is also to gate fast injections such as SG. We also inject white noise bursts to estimate sensitivity at broadband frequency ranges.

4.3. *RAVEN Coincident Analysis*

To perform a wider sweep of the O3a data, we also looked for coincidences between these CHIME/FRB events and existing GW candidates using the tools of the Rapid, on-source VOEvent Coincidence Monitor (RAVEN; Urban 2016; Cho 2019) to query the Gravitational-Wave Candidate Event Database GraceDB (Pace et al. 2012). This query to GraceDB tests whether any GW candidates were found by any of the modelled or generic transient low-latency GW search pipelines within a time window around the FRB events. The queries used the same on-source search windows as our modelled and generic transient searches, with [−10 s,+2 s] and [−600 s,+120 s] windows around the FRB triggers, respectively. We then computed the joint false-alarm rate of any coincident GW candidate within these windows using the overall rate of FRB events in the CHIME/FRB sample calculated across the full span of the O3a observing run and the false-alarm rate of the GW candidate.

5. RESULTS OF ANALYSIS

5.1. *Analysis Subsample*

We performed two different searches: for non-repeating FRBs, a `PyGRB` modelled search was completed on a total of 22 FRB events and an `X-Pipeline` search for generic transient signals was completed on a total of 29 non-repeaters and 11 repeating FRBs.

5.2. *The false-alarm probability (p-value) distribution*

The searches conducted for GW counterparts returned no likely GW signals in association with any of the analyzed repeating or non-repeating FRB events.

The most significant events found by the `PyGRB` search and the `X-Pipeline` search had p-values of 3.74×10^{-2} and 1.90×10^{-2}, respectively. For the `X-Pipeline` analysis of the repeating FRBs, the lowest p-value was 1.3×10^{-1}, corresponding to the repeat FRB 20190702B of burst FRB 20190303A, for which we analyzed 2 burst events.

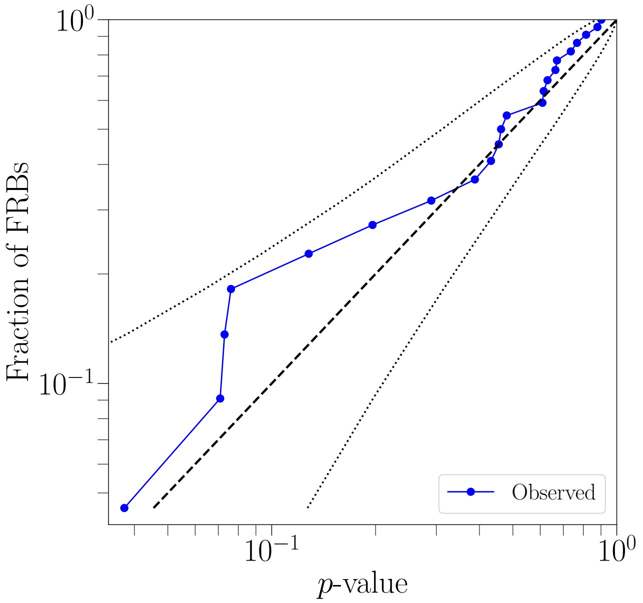

Figure 2. The cumulative distribution of p-values for the loudest on-source events for the modelled search in O3a around CHIME/FRB data. The dashed line indicates an expected uniform distribution of p-values under a no-signal hypothesis, with the corresponding 90% confidence band shown by the dotted lines.

The cumulative p-value distributions from both search methods are shown in Fig. 2 and Fig. 3. In both figures, the dashed lines indicate the expected background distribution under the no-signal hypothesis, and the dotted lines indicate the 90% confidence band around the no-signal hypothesis.

5.3. *Exclusion Distance Results*

Fig. 4 shows the cumulative 90% exclusion distances for the 22 FRBs followed up with the modelled search. The lowest exclusion distances, of order 40 Mpc, were obtained for FRBs that occurred during times in which only Virgo data was available.

For each of the three simulated signal classes considered in the modelled search, we quote the median of the D_{90} results in the top row of Table 2; we see values of the order of 190 Mpc for BNS and around 260 Mpc (350 Mpc) for NSBH with generic (aligned) spins.

Fig. 5 provides the cumulative 90% exclusion distances for 29 non-repeating FRBs considered in the generic transient search. This plot shows three representative burst models; ADI-A, SG-C and a WNB-C; the

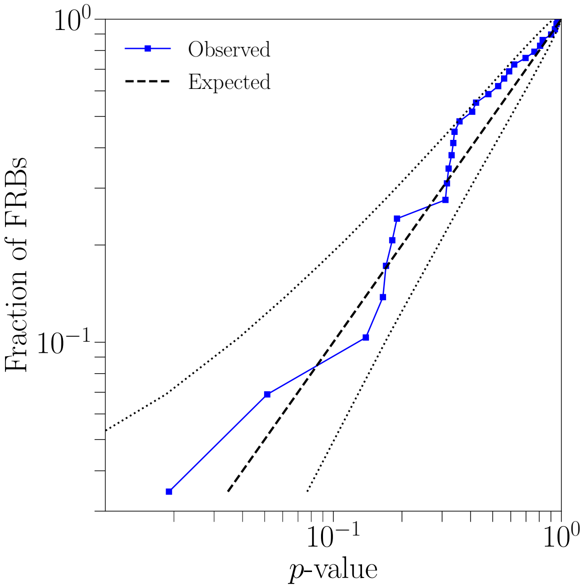

Figure 3. The cumulative distribution of p-values for the loudest events from the generic transient search for transient GWs associated with 29 non-repeating CHIME/FRB bursts. The dashed line represents the expected distribution under the no-signal hypothesis, with the 90% bands shown as dotted lines.

latter two have central frequencies of 145 Hz and 550 Hz respectively. Based on a standard $E_{\rm GW} \sim 10^{-2}{\rm M}_{\odot}{\rm c}^2$ of emitted GW energy, there is a noticeable offset between the SG and the other two GW burst models. For the ADI-A waveform model, this is due to the energy of the former being distributed over a longer signal duration, of order $\sim$ 40 s; for the WNB-C model, this effect is due to a significant portion of its energy content being at higher frequency where detector performance is more comparatively limited.

The lower rows of Table 2 show the median of the D_{90} estimates for all other waveforms considered by the generic transient search. We see that SG models spanning central frequencies 70 Hz to 2000 Hz have corresponding median values of D_{90} in the range 78 Mpc to 0.5 Mpc; the latter models' performance diminished at higher frequency through detector response. This is also clearly evident for the DS2P ringdown models, which are more likely to encounter a transient burst of noise than SG models due to their longer durations. Similarly, the median D_{90} values for the higher frequency WNB models are lower in comparison with the lower frequency models (WNB-A and WNB-B). These median D_{90} values of the 150 Hz and 550 Hz models differ by around a factor of at least 4. Overall, the median D_{90} varies within a range approaching 2 orders of magnitude, reflecting the wide range of models used in the analysis.

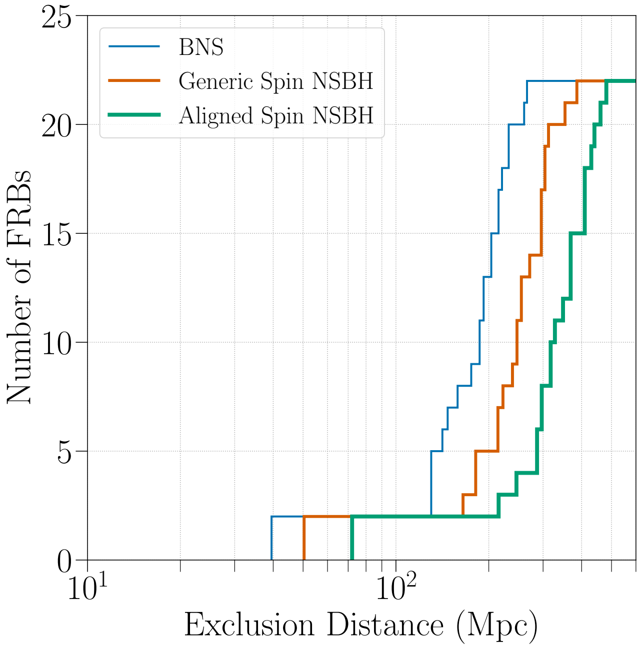

Figure 4. Cumulative histograms of the 90% confidence exclusion distances, D_{90}, for the 22 CHIME/FRB bursts followed up by the modelled search. The blue line shows generically spinning BNS models, the orange line shows generically spinning NSBH models, and the thick green line shows aligned spin NSBH models. We define D_{90} as the distance within which 90% of the simulated GW signals injected into the off-source data were recovered with a significance greater than the most significant on-source trigger.

In comparison with D_{90} values obtained in the O3a GRB paper (Abbott et al. 2021) the values in Table 2 are almost systematically a factor of 2 smaller for the SG and ADI models used in that study. We find that this is a result of the sky locations surveyed by CHIME corresponding with a region of weak sensitivity for the Virgo interferometric detector, due to their relative locations on the surface of the Earth. The average antenna responses for the LIGO Hanford (H1) and LIGO Livingston (L1) detectors are of order 0.72 and 0.65 respectively; the same metric for the V1 instrument is 0.28. This has a severe effect when V1 is one of only two detectors in a network, a situation that has occurred 55% of the time for the generic transient analysis of non-repeating FRBs. Looking ahead, this type of sensitivity bias will be a feature of future searches for CHIME/FRB triggers, as well as surveys by other facilities, depending on their location on the Earth.

In Table 3 we present the exclusion distances achieved for each of the FRBs analyzed in our joint analysis. For the modelled search we quote values from each of the 3 classes of compact binary progenitor models considered. For the generic transient search we present values of D_{90} for a representative sample of SG, ADI, DS2P and WNB models. We also provide information relating to the times and positions of these events as well as values of the DM, and the inferred 90% credible intervals on the luminosity distance. Table 3 allows comparison of the inferred luminosity distances of each FRB with the D_{90} value for different searches.

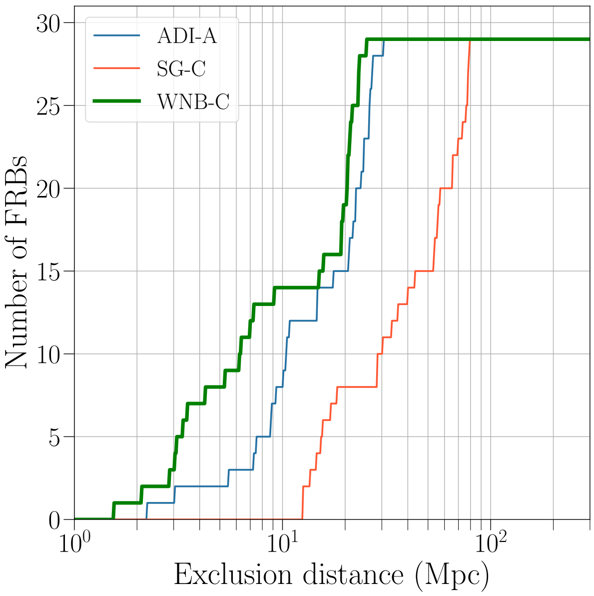

Figure 5. Cumulative histograms of the 90% confidence exclusion distances, D_{90}, for SG model C (orange line), accretion disk instability (ADI) signal model A (blue line) and white noise burst (WNB) model C (green, thick line). The quantity has the same definition as described in Fig. 4.

Table 2. Median values for the 90% confidence level exclusion distances, D_{90}. Modelled search results are shown for three classes of BNS progenitor model, and generic transient search results are shown for models described in Table 1.

Modelled search	BNS	NSBH Generic Spins	NSBH Aligned Spins			
D_{90} [Mpc]	191.9	256.6	345.1			
Unmodelled search	SG A	SG B	SG C	SG D		
D_{90} [Mpc]	77.9	63.3	43.7	24.9		
Unmodelled search	SG E	SG F	SG G	SG H		
D_{90} [Mpc]	6.8	2.3	1.2	0.5		
Unmodelled search	DS2P A	DS2P B	WNB A	WNB B	WNB C	WNB D
D_{90} [Mpc]	0.7	0.7	66.4	71.7	15.2	9.2
Unmodelled search	ADI A	ADI B	ADI C	ADI D	ADI E	
D_{90} [Mpc]	17.6	64.9	23.1	8.4	25.7	

Table 3. Details of the FRB sample and the 90% exclusion distances for each of the events considered in this analysis. The TNS name is provided in the first column. The Network column lists the GW detector network used: H1 = LIGO Hanford, L1 = LIGO Livingston, V1 = Virgo. The total DM for each FRB is listed in the DM column and the 90% credible intervals on the luminosity distance of each burst are provided in columns $D_{\rm L}$-Low and $D_{\rm L}$-High. Where the generic transient search (Section 4.2) and the modelled search (Section 4.1) used a different IFO network, the network used by the generic transient search is shown in parentheses. The last 8 columns show the 90% confidence exclusion distances for each FRB (D_{90}) for the following emission scenarios: BNS, generic and aligned spin NSBH from the modelled search, and from the generic transient search, SG-C, SG-F, ADI-A, DS2P-A and WNB-C; for the latter 5 types of GW bursts we assume a total radiated energy $E_{\rm GW} = 10^{-2}\,{\rm M}_{\odot}{\rm c}^2$.

								D_{90} [Mpc]							
FRB Name	UTC Time	R.A.	Dec.	Network	DM [pc cm^{-3}]	D_L-Low [Mpc]	D_L-High [Mpc]	BNS	Generic NSBH	Aligned NSBH	SG C	SG F	ADI A	DS2P A	WNB C
FRB 20190410A	12:19:41	$17^{\rm h}33^{\rm m}43^{\rm s}$	$-2^{\circ}10'$	L1V1	267.8	60.1	956.6	161.1	187.5	301.4	36.3	1.1	14.8	0.6	6.4
FRB 20190418A	22:34:17	$4^{\rm h}21^{\rm m}07^{\rm s}$	$15^{\circ}27'$	V1	184.5	26.9	605.3	39.5	50.4	72.3	-	-	-	-	-
FRB 20190419B	22:38:24	$17^{\rm h}02^{\rm m}02^{\rm s}$	$86^{\circ}44'$	L1V1	165.2	24.8	575.7	135.0	168.2	247.6	33.7	1.1	10.2	0.5	6.2
FRB 20190423B	13:51:43	$19^{\rm h}54^{\rm m}44^{\rm s}$	$26^{\circ}19'$	H1V1	585.0	57.8	1704.6	187.1	254.5	318.0	12.6	0.3	5.6	0.2	3.1
FRB 20190425A	10:47:49	$17^{\rm h}02^{\rm m}47^{\rm s}$	$21^{\circ}30'$	H1L1V1	128.1	12.6	385.9	236.3	386.8	437.9	66.1	3.2	27.2	0.1	20.6
FRB 20190517B	20:33:37	$4^{\rm h}16^{\rm m}49^{\rm s}$	$73^{\circ}10'$	V1	191.4	19.6	536.3	134.5	227.7	295.7	-	-	-	-	-
FRB 20190517C	22:06:34	$5^{\rm h}50^{\rm m}57^{\rm s}$	$26^{\circ}34'$	L1V1	335.5	44.3	1030.5	-	-	-	40.2	1.3	10.4	0.7	7.4
FRB 20190518D	09:04:35	$12^{\rm h}06^{\rm m}50^{\rm s}$	$89^{\circ}25'$	H1L1	202.5	62.0	852.0	141.9	185.4	222.1	54.3	3.2	20.9	1.0	15.9
FRB 20190531B	08:47:40	$17^{\rm h}31^{\rm m}26^{\rm s}$	$49^{\circ}18'$	L1V1	167.9	37.2	675.5	205.1	311.7	372.9	55.8	3.5	22.8	2.1	19.7
FRB 20190601C	21:13:28	$5^{\rm h}55^{\rm m}06^{\rm s}$	$28^{\circ}28'$	H1L1V1	424.1	198.7	1736.9	-	-	-	65.9	3.2	21.1	1.1	21.2
FRB 20190604G	23:12:19	$8^{\rm h}03^{\rm m}13^{\rm s}$	$59^{\circ}32'$	L1V1	233.0	97.1	1143.0	-	-	-	13.6	0.5	8.8	0.3	1.6
FRB 20190605C	02:20:41	$11^{\rm h}14^{\rm m}04^{\rm s}$	$-5^{\circ}18'$	H1L1V1 (L1V1)	187.2	68.2	893.7	194.9	259.1	374.5	28.7	0.9	14.9	0.6	5.4
FRB 20190606B	22:19:30	$7^{\rm h}14^{\rm m}42^{\rm s}$	$86^{\circ}58'$	H1L1V1	278.0	168.6	1465.7	-	-	-	43.7	2.3	17.6	0.9	15.2
FRB 20190611A	18:52:42	$4^{\rm h}05^{\rm m}12^{\rm s}$	$73^{\circ}37'$	V1	196.2	19.4	554.6	43.4	56.9	72.1	-	-	-	-	-
FRB 20190612B	05:30:37	$14^{\rm h}48^{\rm m}53^{\rm s}$	$4^{\circ}21'$	H1L1	187.1	64.9	922.2	221.1	297.1	412.2	70.4	3.3	26.3	1.1	20.8
FRB 20190613B	18:56:15	$4^{\rm h}23^{\rm m}08^{\rm s}$	$42^{\circ}37'$	H1L1V1	285.1	27.7	780.1	265.3	319.8	465.9	78.3	4.3	27.5	1.5	23.3
FRB 20190616A	05:56:30	$15^{\rm h}34^{\rm m}04^{\rm s}$	$34^{\circ}21'$	H1V1	212.7	107.3	1125.8	-	-	-	17.2	0.6	9.0	0.3	4.3
FRB 20190617A	02:12:33	$11^{\rm h}49^{\rm m}13^{\rm s}$	$83^{\circ}50'$	H1L1V1 (H1V1)	195.8	62.2	872.9	205.3	305.1	416.7	53.9	2.9	22.7	1.4	19.4
FRB 20190618A	11:42:06	$21^{\rm h}24^{\rm m}28^{\rm s}$	$25^{\circ}25'$	H1L1	228.9	78.3	964.0	268.5	359.3	484.7	80.0	4.3	24.9	1.6	25.5
FRB 20190621A	02:21:17	$12^{\rm h}06^{\rm m}36^{\rm s}$	$74^{\circ}43'$	L1V1	199.5	78.0	978.1	152.0	218.1	299.1	15.4	0.4	2.2	0.3	2.9
FRB 20190624B	22:11:00	$20^{\rm h}01^{\rm m}07^{\rm s}$	$73^{\circ}34'$	H1V1	213.9	47.0	822.5	-	-	-	30.5	1.3	7.5	0.5	9.2
FRB 20190710A	22:09:19	$9^{\rm h}26^{\rm m}32^{\rm s}$	$63^{\circ}06'$	H1L1	204.0	89.5	997.6	-	-	-	78.1	4.3	30.9	1.9	23.4
FRB 20190713A	02:19:56	$1^{\rm h}35^{\rm m}49^{\rm s}$	$72^{\circ}53'$	H1V1	335.9	141.1	1436.5	-	-	-	28.8	0.9	10.6	0.4	7.0
FRB 20190718A	01:11:16	$13^{\rm h}04^{\rm m}18^{\rm s}$	$74^{\circ}14'$	H1L1	199.6	71.8	973.4	220.4	300.9	410.3	57.6	3.5	24.7	1.6	20.8
FRB 20190722A	18:30:18	$6^{\rm h}35^{\rm m}11^{\rm s}$	$64^{\circ}17'$	L1V1	252.0	97.8	1129.9	-	-	-	18.4	0.7	10.9	0.4	2.1

								D_{90} [Mpc]							
FRB Name	UTC Time	R.A.	Dec.	Network	DM [pc cm^{-3}]	D_L-Low [Mpc]	D_L-High [Mpc]	BNS	Generic NSBH	Aligned BHNS	SG C	SG F	ADI A	DS2P A	WNB C
FRB 20190812A	04:35:08	$17^{\rm h}53^{\rm m}14^{\rm s}$	$50^\circ48'$	H1L1V1	254.6	186.5	1362.0	-	-	-	79.3	4.1	24.2	1.5	23.5
FRB 20190903A	12:25:19	$3^{\rm h}12^{\rm m}01^{\rm s}$	$21^\circ25'$	L1V1	213.2	66.8	925.4	177.7	258.8	357.4	12.6	0.3	7.3	0.3	3.1
FRB 20190912A	00:50:21	$16^{\rm h}13^{\rm m}58^{\rm s}$	$22^\circ13'$	L1V1	211.8	97.6	1090.5	-	-	-	14.7	0.5	9.4	0.3	3.5
FRB 20190912B	08:51:31	$0^{\rm h}15^{\rm m}57^{\rm s}$	$6^\circ12'$	H1L1	129.2	22.7	485.0	235.7	304.1	440.5	73.8	3.6	26.6	1.1	21.3
FRB 20190912C	09:46:46	$1^{\rm h}13^{\rm m}16^{\rm s}$	$67^\circ08'$	H1	337.8	42.1	1005.9	188.8	241.5	323.2	-	-	-	-	-
FRB 20190913A	15:11:12	$6^{\rm h}40^{\rm m}02^{\rm s}$	$39^\circ39'$	L1	225.9	32.3	714.3	195.1	249.7	332.8	-	-	-	-	-
FRB 20190922A	00:11:04	$16^{\rm h}14^{\rm m}10^{\rm s}$	$68^\circ48'$	H1V1	199.3	66.2	959.6	135.7	217.2	293.1	15.8	0.5	3.1	0.2	3.4
FRB 20190928A	21:32:10	$14^{\rm h}00^{\rm m}25^{\rm s}$	$80^\circ06'$	H1L1V1	143.2	20.5	510.3	215.2	273.7	374.9	56.6	3.0	22.0	1.1	19.4
FRB 20190929B	13:32:01	$6^{\rm h}02^{\rm m}53^{\rm s}$	$11^\circ51'$	H1L1V1	377.0	149.0	1533.6	-	-	-	76.9	3.9	26.3	1.7	21.8

Fig. 6 compares the D_{90} values for the BNS and NSBH (with generic spin) emission models with the 90% credible intervals on D_L inferred by the MCMC analysis. The plot shows the FRB sample in order of increasing distance. No event can be fully excluded from any of the models we have considered for this search, because there is still a sufficient region of space from which the FRB events could have originated that is outside the detection range of the searches performed.

5.4. *RAVEN Analysis Results*

As described in Section 4.3, two RAVEN coincidence searches were completed with differing time windows, [−600 s,+120 s] for the generic transient search and [−10 s,+2 s] for the modelled search. The generic transient search found 8 coincidences and the modelled search found 1 coincidence. However, none of these were of sufficient significance, as determined by the computed joint false-alarm rate from the two samples, to be distinguished from random coincidences. All of the FRBs in these coincidences had distances that were well beyond the values of D_{90} obtained, with the exception being FRB 20190518E, a repeat of burst FRB 20190518A, with 9 episodes occurring during O3a. Of these 9 repeating episodes, 7 were also analyzed using our generic transient search method, as described earlier. Again, none of the repeating episodes returned a significant false-alarm probability, with the minimum p-value across the search of repeating FRB events equal to 1.3×10^{-1}.

5.5. *Upper Limits on GW Energy*

A measure of the inferred distance to a FRB source also allows one to place constraints on the energy carried in a burst of GWs. The GW energy, $E_{\rm GW}$, emitted by an elliptically polarized GW burst signal can be related to the root-sum-square signal amplitude $h_{\rm rss}$ and the central frequency of the source, f_0, through (Sutton 2013):

$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} D_{\rm L}^2 f_0^2 h_{\rm rss}^2\,, \tag{5}$$

where $D_{\rm L}$ is the luminosity distance to the source. As the DMs of FRBs provide a measure of the maximum distance, one can use Eq. (5) to place 90% upper limits on the GW energy emitted by each FRB source, $E_{\rm GW}^{90\%}$. This estimate, calculated using $h_{\rm rss}^{90\%}$, the 90% detection upper limit on the root-sum-squared GW amplitude, is highly dependent on the detector sensitivity and antenna factors at the time of the FRB as well as the central frequency of the simulated waveform injections.

Table 4 and Table 5 provide the upper limits on $E_{\rm GW}^{90\%}$ for SG models and DS2P or WNB GW burst models respectively. These limits assume that the FRB distances are at the lower limits of their inferred distance ranges. Given a large range of models, and since this quantity scales as $h_{\rm rss}^2\ f_0^2$, one would expect the lower frequency models to provide the most constraining limits. For SG models, the most constraining estimate was $2.5\ \times\ 10^{50}$ erg for the 70 Hz SG-A model and for the highest frequency model considered, SG-H at 1995 Hz, the upper limit was $7.9\ \times\ 10^{54}$ erg. These values were obtained for the closest inferred burst in the sample, FRB 20190425A. The same burst yielded upper limit values in the range $4.8 - 470\ \times\ 10^{50}$ erg for the WNB model. The DS2P model gave the best constraints, $5.8 - 6.4\ \times\ 10^{54}$ erg, for FRB 20190531B.

For completeness, in Table 6 and Table 7, we also provide less constraining limits on $E_{\rm GW}^{90\%}$ based on the upper credible intervals on the distance of each FRB.

Table 8 lists the repeating bursts that were analyzed in the generic transient search. The most sensitive counterpart to a repeating FRB was for CHIME/FRB event FRB20190825A. The SG injection centered at 1600 Hz (which most closely models an f-mode) was recovered 90% of the time at $h_{\rm rss} = 2.62\times\ 10^{-22}$. The distance to this event is 148.1 Mpc to 149.9 Mpc. This corresponds to an energy upper limit range of $5.83\ \times\ 10^{55}$ erg to $5.98\ \times\ 10^{55}$ erg.

These estimates are well above predictions of the GW emissions by the NS's fundamental f-mode. For example Corsi & Owen (2011) have suggested $E_{\rm GW} \sim 10^{48} - 10^{49}$ erg in GW energy emitted at around $1-2$ kHz, although predictions in (Levin & van Hoven 2011; Zink et al. 2012) span a much lower range $E_{\rm GW} \sim 10^{28} - 10^{38}$ erg based on studies that suggest lower effective energy conversion to GWs.

6. THE M81 REPEATER FRB 20200120E

A repeater, FRB 20200120E, which was discovered by CHIME/FRB on 20 Jan 2020, overlaps with the second part of the third observing run of Advanced LIGO and Advanced Virgo (O3b). This burst is at 3.6 Mpc, the closest extragalactic FRB so far discovered (Bhardwaj et al. 2021b). This event was shown to be conclusively associated with a globular cluster in the M81 galactic system (Kirsten et al. 2021) which supports the possibility that it was formed from an evolved stellar population such as a compact binary system. Due to the proximity and significance of this burst, we discuss it in this paper, despite it being discovered after O3a.

The burst FRB 20200120E was shown to repeat at least 4 times. Two of the repeats occurred after O3b; another episode, despite being consistent with the localization of the other associated bursts, had no intensity

Table 4. The upper limits on the energy emitted through GWs in erg for the generic transient search using the SG waveforms described in Table 1. The distances represent the lower bounds of 90% credible intervals from the MCMC inference described in Section 3.

FRB	D_{L} [Mpc]	SG A	SG B	SG C	SG D	SG E	SG F	SG G	SG H
FRB 20190410A	60.1	1.5×10^{52}	2.8×10^{52}	4.9×10^{52}	4.1×10^{53}	5.5×10^{54}	5.4×10^{55}	3.0×10^{56}	1.1×10^{57}
FRB 20190419B	24.8	2.6×10^{51}	4.3×10^{51}	9.7×10^{51}	5.9×10^{52}	9.4×10^{53}	8.9×10^{54}	5.0×10^{55}	1.5×10^{58}
FRB 20190423B	57.8	5.9×10^{52}	8.9×10^{52}	3.7×10^{53}	3.7×10^{54}	4.6×10^{55}	5.6×10^{56}	3.4×10^{57}	1.1×10^{58}
FRB 20190425A	12.6	2.5×10^{50}	3.5×10^{50}	6.5×10^{50}	3.4×10^{51}	2.6×10^{52}	2.7×10^{53}	1.6×10^{54}	7.9×10^{54}
FRB 20190517C	44.3	5.8×10^{51}	8.8×10^{51}	2.2×10^{52}	1.3×10^{53}	2.3×10^{54}	2.1×10^{55}	9.8×10^{55}	3.5×10^{56}
FRB 20190518D	62.0	9.5×10^{51}	1.3×10^{52}	2.3×10^{52}	9.5×10^{52}	1.1×10^{54}	6.8×10^{54}	3.6×10^{55}	2.0×10^{56}
FRB 20190531B	37.2	3.2×10^{51}	3.4×10^{51}	7.9×10^{51}	3.3×10^{52}	2.5×10^{53}	2.0×10^{54}	8.1×10^{54}	3.1×10^{55}
FRB 20190601C	198.7	8.6×10^{52}	1.1×10^{53}	1.6×10^{53}	6.3×10^{53}	1.1×10^{55}	6.8×10^{55}	4.8×10^{56}	1.5×10^{57}
FRB 20190604G	97.1	1.1×10^{53}	3.2×10^{53}	9.0×10^{53}	3.7×10^{54}	8.7×10^{55}	7.5×10^{56}	3.2×10^{57}	1.2×10^{58}
FRB 20190605C	68.2	3.0×10^{52}	2.8×10^{52}	1.0×10^{53}	5.2×10^{53}	8.7×10^{54}	9.4×10^{55}	5.2×10^{56}	1.6×10^{57}
FRB 20190606B	168.6	1.7×10^{53}	1.3×10^{53}	2.7×10^{53}	8.2×10^{53}	1.1×10^{55}	9.6×10^{55}	3.6×10^{56}	1.4×10^{57}
FRB 20190612B	64.9	8.2×10^{51}	8.5×10^{51}	1.5×10^{52}	7.3×10^{52}	8.0×10^{53}	7.0×10^{54}	3.7×10^{55}	3.6×10^{56}
FRB 20190613B	27.7	1.2×10^{51}	1.0×10^{51}	2.2×10^{51}	1.3×10^{52}	9.3×10^{52}	7.4×10^{53}	4.2×10^{54}	1.8×10^{55}
FRB 20190616A	107.3	1.9×10^{53}	2.1×10^{53}	6.9×10^{53}	3.1×10^{54}	3.5×10^{55}	5.1×10^{56}	2.8×10^{57}	8.2×10^{57}
FRB 20190617A	62.2	9.5×10^{51}	1.3×10^{52}	2.4×10^{52}	9.2×10^{52}	9.2×10^{53}	8.3×10^{54}	4.2×10^{55}	8.8×10^{55}
FRB 20190618A	78.3	6.0×10^{51}	7.7×10^{51}	1.7×10^{52}	7.0×10^{52}	6.8×10^{53}	5.9×10^{54}	3.0×10^{55}	1.4×10^{56}
FRB 20190621A	78.0	1.1×10^{53}	1.2×10^{53}	4.6×10^{53}	1.5×10^{54}	5.4×10^{55}	6.5×10^{56}	1.7×10^{57}	4.9×10^{57}
FRB 20190624B	47.0	1.3×10^{52}	1.9×10^{52}	4.2×10^{52}	1.7×10^{53}	2.9×10^{54}	2.3×10^{55}	1.5×10^{56}	8.3×10^{56}
FRB 20190710A	89.5	1.1×10^{52}	1.6×10^{52}	2.3×10^{52}	1.0×10^{53}	9.4×10^{53}	7.6×10^{54}	3.3×10^{55}	1.4×10^{56}
FRB 20190713A	141.1	1.2×10^{53}	1.6×10^{53}	4.3×10^{53}	2.3×10^{54}	4.2×10^{55}	4.4×10^{56}	2.2×10^{57}	6.7×10^{57}
FRB 20190718A	71.8	1.1×10^{52}	1.1×10^{52}	2.8×10^{52}	1.1×10^{53}	1.1×10^{54}	7.7×10^{54}	3.1×10^{55}	1.2×10^{56}
FRB 20190722A	97.8	7.0×10^{52}	1.3×10^{53}	5.0×10^{53}	3.3×10^{54}	5.4×10^{55}	4.0×10^{56}	1.6×10^{57}	9.6×10^{57}
FRB 20190812A	186.5	3.7×10^{52}	4.1×10^{52}	9.9×10^{52}	4.3×10^{53}	4.3×10^{54}	3.7×10^{55}	1.6×10^{56}	5.8×10^{56}
FRB 20190903A	66.8	9.0×10^{52}	9.8×10^{52}	5.0×10^{53}	4.4×10^{54}	5.5×10^{55}	7.4×10^{56}	3.4×10^{57}	9.2×10^{57}
FRB 20190912A	97.6	1.2×10^{53}	2.0×10^{53}	7.9×10^{53}	4.6×10^{54}	1.0×10^{56}	8.1×10^{56}	3.8×10^{57}	1.7×10^{58}
FRB 20190912B	22.7	7.1×10^{50}	9.1×10^{50}	1.7×10^{51}	8.1×10^{51}	6.9×10^{52}	7.1×10^{53}	3.9×10^{54}	1.5×10^{55}
FRB 20190922A	66.2	5.1×10^{52}	7.7×10^{52}	3.1×10^{53}	1.5×10^{54}	2.4×10^{55}	2.8×10^{56}	1.5×10^{57}	4.7×10^{57}
FRB 20190928A	20.5	9.9×10^{50}	1.1×10^{51}	2.3×10^{51}	9.2×10^{51}	1.1×10^{53}	8.2×10^{53}	3.7×10^{54}	1.4×10^{55}
FRB 20190929B	149.0	2.9×10^{52}	3.9×10^{52}	6.7×10^{52}	3.4×10^{53}	2.8×10^{54}	2.6×10^{55}	1.2×10^{56}	4.0×10^{56}

data saved. Therefore, we discuss here only the initial burst FRB 20200120E, for which GW data exists.

At the time of FRB 20200120E, only H1 data was available, thus a generic transient search was not conducted. Likewise, since this is a repeating event, it does not pass our criteria for conducting a modelled search. Due to these restrictions, only a RAVEN coincidence search was conducted within a [−6000, +6000] s time window. No coincidences were found with sufficient significance as determined by the coincident false-alarm rate. Given the relative close proximity of this burst, further repeat emissions will be of interest for GW follow-up during the fourth observing run of Advanced LIGO, Advanced Virgo and Kagra (O4) (Abbott et al. 2020).

7. CONCLUSIONS

We performed a targeted search for GWs associated with FRBs detected by the CHIME/FRB project during O3a. As the sources of non-repeating FRBs are currently not known, we ran both a modelled search for BNS and NSBH signals (Harry & Fairhurst 2011; Williamson et al. 2014) and a generic transient search for generic GW transient signals (Sutton et al. 2010; Was et al. 2012).

Our searches found no significant GW event candidates in association with the analyzed FRBs. We set 90% confidence lower bounds on the distances to FRB progenitors for several different emission models. Additionally, we present 90% credible intervals on the lumi-

Table 5. The upper limits on the energy emitted through GWs in erg for the generic transient search using the DS2P and WNB waveforms described in Table 1. The distances represent the lower bounds of 90% credible intervals from the MCMC inference described in Section 3.

FRB	$D_{\rm L}$ [Mpc]	DS2P A	DS2P B	WNB A	WNB B	WNB C	WNB D
FRB 20190410A	60.1	2.0×10^{56}	1.8×10^{56}	1.2×10^{53}	9.5×10^{52}	3.4×10^{54}	1.0×10^{55}
FRB 20190419B	24.8	4.4×10^{55}	3.0×10^{55}	1.6×10^{54}	1.8×10^{52}	6.0×10^{53}	1.7×10^{54}
FRB 20190423B	57.8	2.4×10^{57}	2.6×10^{57}	2.8×10^{53}	3.0×10^{53}	1.4×10^{55}	3.6×10^{55}
FRB 20190425A	12.6	1.7×10^{56}	4.6×10^{54}	4.8×10^{50}	7.9×10^{50}	1.4×10^{52}	4.7×10^{52}
FRB 20190517C	44.3	6.7×10^{55}	5.8×10^{55}	2.4×10^{52}	3.1×10^{52}	1.4×10^{54}	7.3×10^{54}
FRB 20190518D	62.0	6.7×10^{55}	1.1×10^{56}	2.0×10^{52}	2.6×10^{52}	5.8×10^{53}	1.7×10^{54}
FRB 20190531B	37.2	5.8×10^{54}	6.4×10^{54}	5.7×10^{51}	8.6×10^{51}	1.4×10^{53}	5.6×10^{53}
FRB 20190601C	198.7	5.5×10^{56}	8.3×10^{56}	1.2×10^{53}	1.6×10^{53}	3.4×10^{54}	8.6×10^{54}
FRB 20190604G	97.1	1.9×10^{57}	1.6×10^{57}	–	4.9×10^{54}	1.5×10^{56}	3.4×10^{56}
FRB 20190605C	68.2	2.4×10^{56}	1.7×10^{56}	3.5×10^{53}	1.6×10^{53}	6.2×10^{54}	1.8×10^{55}
FRB 20190606B	168.6	5.7×10^{56}	9.9×10^{56}	3.6×10^{53}	2.0×10^{53}	4.7×10^{54}	1.3×10^{55}
FRB 20190612B	64.9	6.2×10^{55}	1.1×10^{58}	1.3×10^{52}	2.1×10^{52}	3.7×10^{53}	1.2×10^{54}
FRB 20190613B	27.7	6.2×10^{54}	1.1×10^{55}	1.6×10^{51}	2.5×10^{51}	5.4×10^{52}	1.6×10^{53}
FRB 20190616A	107.3	2.2×10^{57}	2.7×10^{57}	1.1×10^{54}	7.3×10^{53}	2.4×10^{55}	1.4×10^{56}
FRB 20190617A	62.2	3.6×10^{55}	5.1×10^{55}	3.3×10^{52}	2.7×10^{52}	3.9×10^{53}	1.6×10^{54}
FRB 20190618A	78.3	4.4×10^{55}	7.0×10^{55}	1.0×10^{52}	1.8×10^{52}	3.6×10^{53}	1.2×10^{54}
FRB 20190621A	78.0	1.1×10^{57}	4.8×10^{56}	–	9.3×10^{53}	2.8×10^{55}	5.9×10^{55}
FRB 20190624B	47.0	1.9×10^{56}	3.6×10^{56}	2.8×10^{52}	4.4×10^{52}	1.0×10^{54}	3.7×10^{54}
FRB 20190710A	89.5	3.9×10^{55}	4.3×10^{55}	1.7×10^{52}	2.6×10^{52}	5.6×10^{53}	1.6×10^{54}
FRB 20190713A	141.1	2.3×10^{57}	3.7×10^{57}	3.1×10^{53}	5.0×10^{53}	1.5×10^{55}	4.4×10^{55}
FRB 20190718A	71.8	3.7×10^{55}	6.1×10^{55}	1.7×10^{52}	2.3×10^{52}	4.6×10^{53}	1.4×10^{54}
FRB 20190722A	97.8	1.1×10^{57}	8.0×10^{56}	9.2×10^{55}	2.7×10^{54}	8.2×10^{55}	1.8×10^{56}
FRB 20190812A	186.5	2.7×10^{56}	5.3×10^{56}	8.2×10^{52}	1.1×10^{53}	2.4×10^{54}	7.1×10^{54}
FRB 20190903A	66.8	1.1×10^{57}	7.3×10^{56}	5.0×10^{53}	3.6×10^{53}	1.7×10^{55}	4.5×10^{55}
FRB 20190912A	97.6	2.0×10^{57}	1.5×10^{57}	7.9×10^{53}	6.6×10^{53}	2.9×10^{55}	8.9×10^{55}
FRB 20190912B	22.7	7.6×10^{54}	1.4×10^{55}	1.4×10^{51}	1.7×10^{51}	4.3×10^{52}	1.2×10^{53}
FRB 20190922A	66.2	2.2×10^{57}	3.2×10^{57}	1.5×10^{54}	4.2×10^{53}	1.5×10^{55}	3.9×10^{55}
FRB 20190928A	20.5	6.2×10^{54}	1.1×10^{55}	1.8×10^{51}	2.6×10^{51}	4.3×10^{52}	1.7×10^{53}
FRB 20190929B	149.0	1.4×10^{56}	3.0×10^{56}	6.6×10^{52}	7.3×10^{52}	1.8×10^{54}	4.7×10^{54}

nosity distance, D_L, inferred from the DM measurement of each FRB source.

The D_L information can be used to test models based on the simulated injections used for calculating the D_{90} values of each FRB. However, the significant uncertainties in the relative contributions to the total DM for each FRB produce relatively wide credible intervals for the D_L posteriors. We find no FRB event can be fully excluded from any of the models we have considered due to some posterior support on D_L existing for the FRB outside the detection range of the analyzes performed.

The results however, as illustrated in Fig. 6, indicate that the GW network's detection range is advancing into cosmological volumes where FRB emissions are expected. This is encouraging as we look forward to future GW searches at higher sensitivity. Furthermore, the redshifts obtained from the ongoing efforts to localize host galaxies (there are currently 18 FRBs with an associated host galaxy (see http://frbhosts.org/) could significantly improve the chances of constraining progenitor populations (Heintz et al. 2020; Bhandari et al. 2021).

The distance estimates for each FRB allowed us to place 90% upper limits on the GW energy emitted by each FRB source, $E_{\rm GW}^{90\%}$. For each non-repeating FRB analyzed with a generic transient search, we provided limits on $E_{\rm GW}^{90\%}$ for a range of emission models. Repeating FRBs were also analyzed to determine 90% upper limits on the energy emitted through GWs. For the most sensitive repeating FRB analysis in our sample we

Table 6. As for Table 4 but with distances based on the the upper bounds of 90% credible intervals on the luminosity distance.

FRB	D_{L} [Mpc]	SG A	SG B	SG C	SG D	SG E	SG F	SG G	SG H
FRB 20190410A	956.6	3.9×10^{54}	7.2×10^{54}	1.2×10^{55}	1.0×10^{56}	1.4×10^{57}	1.4×10^{58}	7.5×10^{58}	2.7×10^{59}
FRB 20190419B	575.7	1.4×10^{54}	2.3×10^{54}	5.2×10^{54}	3.2×10^{55}	5.1×10^{56}	4.8×10^{57}	2.7×10^{58}	8.0×10^{60}
FRB 20190423B	1704.6	5.1×10^{55}	7.7×10^{55}	3.2×10^{56}	3.2×10^{57}	4.0×10^{58}	4.9×10^{59}	2.9×10^{60}	9.4×10^{60}
FRB 20190425A	385.9	2.4×10^{53}	3.3×10^{53}	6.1×10^{53}	3.2×10^{54}	2.4×10^{55}	2.5×10^{56}	1.6×10^{57}	7.5×10^{57}
FRB 20190517C	1030.5	3.1×10^{54}	4.7×10^{54}	1.2×10^{55}	6.8×10^{55}	1.2×10^{57}	1.1×10^{58}	5.3×10^{58}	1.9×10^{59}
FRB 20190518D	852.0	1.8×10^{54}	2.4×10^{54}	4.4×10^{54}	1.8×10^{55}	2.0×10^{56}	1.3×10^{57}	6.9×10^{57}	3.8×10^{58}
FRB 20190531B	675.5	1.0×10^{54}	1.1×10^{54}	2.6×10^{54}	1.1×10^{55}	8.2×10^{55}	6.7×10^{56}	2.7×10^{57}	1.0×10^{58}
FRB 20190601C	1736.9	6.6×10^{54}	8.3×10^{54}	1.2×10^{55}	4.8×10^{55}	8.2×10^{56}	5.2×10^{57}	3.6×10^{58}	1.1×10^{59}
FRB 20190604G	1143.0	1.5×10^{55}	4.5×10^{55}	1.3×10^{56}	5.1×10^{56}	1.2×10^{58}	1.0×10^{59}	4.5×10^{59}	1.6×10^{60}
FRB 20190605C	893.7	5.1×10^{54}	4.9×10^{54}	1.7×10^{55}	8.9×10^{55}	1.5×10^{57}	1.6×10^{58}	8.9×10^{58}	2.7×10^{59}
FRB 20190606B	1465.7	1.3×10^{55}	9.6×10^{54}	2.0×10^{55}	6.2×10^{55}	8.3×10^{56}	7.3×10^{57}	2.7×10^{58}	1.0×10^{59}
FRB 20190612B	922.2	1.7×10^{54}	1.7×10^{54}	3.1×10^{54}	1.5×10^{55}	1.6×10^{56}	1.4×10^{57}	7.4×10^{57}	7.3×10^{58}
FRB 20190613B	780.1	9.7×10^{53}	8.2×10^{53}	1.8×10^{54}	1.0×10^{55}	7.4×10^{55}	5.8×10^{56}	3.4×10^{57}	1.4×10^{58}
FRB 20190616A	1125.8	2.1×10^{55}	2.4×10^{55}	7.6×10^{55}	3.4×10^{56}	3.9×10^{57}	5.6×10^{58}	3.1×10^{59}	9.0×10^{59}
FRB 20190617A	872.9	1.9×10^{54}	2.5×10^{54}	4.7×10^{54}	1.8×10^{55}	1.8×10^{56}	1.6×10^{57}	8.2×10^{57}	1.7×10^{58}
FRB 20190618A	964.0	9.1×10^{53}	1.2×10^{54}	2.6×10^{54}	1.1×10^{55}	1.0×10^{56}	9.0×10^{56}	4.5×10^{57}	2.1×10^{58}
FRB 20190621A	978.1	1.7×10^{55}	2.0×10^{55}	7.2×10^{55}	2.3×10^{56}	8.4×10^{57}	1.0×10^{59}	2.6×10^{59}	7.7×10^{59}
FRB 20190624B	822.5	4.0×10^{54}	5.8×10^{54}	1.3×10^{55}	5.1×10^{55}	8.9×10^{56}	7.0×10^{57}	4.6×10^{58}	2.5×10^{59}
FRB 20190710A	997.6	1.4×10^{54}	2.0×10^{54}	2.9×10^{54}	1.2×10^{55}	1.2×10^{56}	9.5×10^{56}	4.1×10^{57}	1.7×10^{58}
FRB 20190713A	1436.5	1.2×10^{55}	1.6×10^{55}	4.4×10^{55}	2.4×10^{56}	4.4×10^{57}	4.6×10^{58}	2.2×10^{59}	6.9×10^{59}
FRB 20190718A	973.4	2.0×10^{54}	2.1×10^{54}	5.1×10^{54}	2.0×10^{55}	1.9×10^{56}	1.4×10^{57}	5.8×10^{57}	2.3×10^{58}
FRB 20190722A	1129.9	9.4×10^{54}	1.7×10^{55}	6.7×10^{55}	4.4×10^{56}	7.2×10^{57}	5.3×10^{58}	2.2×10^{59}	1.3×10^{60}
FRB 20190812A	1362.0	2.0×10^{54}	2.2×10^{54}	5.3×10^{54}	2.3×10^{55}	2.3×10^{56}	2.0×10^{57}	8.7×10^{57}	3.1×10^{58}
FRB 20190903A	925.4	1.7×10^{55}	1.9×10^{55}	9.6×10^{55}	8.4×10^{56}	1.0×10^{58}	1.4×10^{59}	6.5×10^{59}	1.8×10^{60}
FRB 20190912A	1090.5	1.5×10^{55}	2.5×10^{55}	9.9×10^{55}	5.8×10^{56}	1.2×10^{58}	1.0×10^{59}	4.7×10^{59}	2.2×10^{60}
FRB 20190912B	485.0	3.2×10^{53}	4.1×10^{53}	7.7×10^{53}	3.7×10^{54}	3.1×10^{55}	3.3×10^{56}	1.8×10^{57}	6.7×10^{57}
FRB 20190922A	959.6	1.1×10^{55}	1.6×10^{55}	6.6×10^{55}	3.2×10^{56}	5.0×10^{57}	5.9×10^{58}	3.2×10^{59}	9.8×10^{59}
FRB 20190928A	510.3	6.1×10^{53}	6.9×10^{53}	1.5×10^{54}	5.7×10^{54}	6.6×10^{55}	5.1×10^{56}	2.3×10^{57}	8.4×10^{57}
FRB 20190929B	1533.6	3.0×10^{54}	4.1×10^{54}	7.1×10^{54}	3.6×10^{55}	3.0×10^{56}	2.8×10^{57}	1.3×10^{58}	4.2×10^{58}

find an energy upper limit range of 5.83×10^{54} erg to 5.98×10^{55} erg, well above the predictions for GW emissions from the fundamental f-modes of NSs. Based on Equation 5, an FRB event such as that associated with SGR 1935+2154 occurring during O3a would have allowed the search to probe the more optimistic of these estimates allowing limits, $E_{\mathrm{GW}} \sim 10^{47}$ erg, assuming a generic burst waveform emitting at roughly 1 kHz at 10 kpc.

We also analyzed the repeater, FRB 20200120E, discovered on 20 Jan 2020 during O3b. A RAVEN (Urban 2016; Cho 2019) coincidence search for any previously detected compact binary coalescence GW events was conducted within a $[-6000, +6000]$ s time window around the first burst of this repeater. No coincidences were found with sufficient significance to be distinguished from random coincidences, as determined by the computed joint false-alarm rate from the two samples.

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Table 7. As for Table 5 but with distances based on the the upper bounds of 90% credible intervals on the luminosity distance.

FRB	D_{L} [Mpc]	DS2P A	DS2P B	WNB A	WNB B	WNB C	WNB D
FRB 20190410A	956.6	5.0×10^{58}	4.5×10^{58}	3.2×10^{55}	2.4×10^{55}	8.6×10^{56}	2.5×10^{57}
FRB 20190419B	575.7	2.3×10^{58}	1.6×10^{58}	8.4×10^{56}	9.5×10^{54}	3.2×10^{56}	9.0×10^{56}
FRB 20190423B	1704.6	2.1×10^{60}	2.2×10^{60}	2.4×10^{56}	2.6×10^{56}	1.2×10^{58}	3.2×10^{58}
FRB 20190425A	385.9	1.6×10^{59}	4.4×10^{57}	4.5×10^{53}	7.4×10^{53}	1.3×10^{55}	4.4×10^{55}
FRB 20190517C	1030.5	3.6×10^{58}	3.2×10^{58}	1.3×10^{55}	1.7×10^{55}	7.5×10^{56}	4.0×10^{57}
FRB 20190518D	852.0	1.3×10^{58}	2.1×10^{58}	3.7×10^{54}	4.9×10^{54}	1.1×10^{56}	3.2×10^{56}
FRB 20190531B	675.5	1.9×10^{57}	2.1×10^{57}	1.9×10^{54}	2.9×10^{54}	4.5×10^{55}	1.8×10^{56}
FRB 20190601C	1736.9	4.2×10^{58}	6.4×10^{58}	9.4×10^{54}	1.2×10^{55}	2.6×10^{56}	6.6×10^{56}
FRB 20190604G	1143.0	2.6×10^{59}	2.2×10^{59}	–	6.8×10^{56}	2.0×10^{58}	4.7×10^{58}
FRB 20190605C	893.7	4.1×10^{58}	2.9×10^{58}	5.9×10^{55}	2.7×10^{55}	1.1×10^{57}	3.0×10^{57}
FRB 20190606B	1465.7	4.3×10^{58}	7.5×10^{58}	2.7×10^{55}	1.5×10^{55}	3.6×10^{56}	9.7×10^{56}
FRB 20190612B	922.2	1.3×10^{58}	2.2×10^{60}	2.7×10^{54}	4.2×10^{54}	7.5×10^{55}	2.5×10^{56}
FRB 20190613B	780.1	4.9×10^{57}	8.9×10^{57}	1.3×10^{54}	2.0×10^{54}	4.3×10^{55}	1.3×10^{56}
FRB 20190616A	1125.8	2.4×10^{59}	3.0×10^{59}	1.2×10^{56}	8.0×10^{55}	2.6×10^{57}	1.6×10^{58}
FRB 20190617A	872.9	7.1×10^{57}	1.0×10^{58}	6.4×10^{54}	5.3×10^{54}	7.7×10^{55}	3.2×10^{56}
FRB 20190618A	964.0	6.7×10^{57}	1.1×10^{58}	1.5×10^{54}	2.7×10^{54}	5.4×10^{55}	1.8×10^{56}
FRB 20190621A	978.1	1.8×10^{59}	7.6×10^{58}	–	1.5×10^{56}	4.4×10^{57}	9.2×10^{57}
FRB 20190624B	822.5	5.9×10^{58}	1.1×10^{59}	8.5×10^{54}	1.4×10^{55}	3.1×10^{56}	1.1×10^{57}
FRB 20190710A	997.6	4.8×10^{57}	5.4×10^{57}	2.1×10^{54}	3.2×10^{54}	6.9×10^{55}	2.0×10^{56}
FRB 20190713A	1436.5	2.4×10^{59}	3.8×10^{59}	3.2×10^{55}	5.2×10^{55}	1.6×10^{57}	4.5×10^{57}
FRB 20190718A	973.4	6.7×10^{57}	1.1×10^{58}	3.2×10^{54}	4.2×10^{54}	8.4×10^{55}	2.6×10^{56}
FRB 20190722A	1129.9	1.5×10^{59}	1.1×10^{59}	1.2×10^{58}	3.6×10^{56}	1.1×10^{58}	2.3×10^{58}
FRB 20190812A	1362.0	1.4×10^{58}	2.8×10^{58}	4.4×10^{54}	6.1×10^{54}	1.3×10^{56}	3.8×10^{56}
FRB 20190903A	925.4	2.1×10^{59}	1.4×10^{59}	9.6×10^{55}	7.0×10^{55}	3.3×10^{57}	8.6×10^{57}
FRB 20190912A	1090.5	2.5×10^{59}	1.8×10^{59}	9.8×10^{55}	8.2×10^{55}	3.7×10^{57}	1.1×10^{58}
FRB 20190912B	485.0	3.5×10^{57}	6.4×10^{57}	6.5×10^{53}	7.9×10^{53}	2.0×10^{55}	5.3×10^{55}
FRB 20190922A	959.6	4.7×10^{59}	6.7×10^{59}	3.2×10^{56}	8.8×10^{55}	3.1×10^{57}	8.2×10^{57}
FRB 20190928A	510.3	3.8×10^{57}	7.1×10^{57}	1.1×10^{54}	1.6×10^{54}	2.6×10^{55}	1.1×10^{56}
FRB 20190929B	1533.6	1.5×10^{58}	3.1×10^{58}	7.0×10^{54}	7.8×10^{54}	1.9×10^{56}	5.0×10^{56}

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Table 8. Details of the 3 repeating FRBs analyzed in the generic transient search and their various repeating episodes. The TNS name is provided in the first column. The Network column lists the GW detector network used: H1 = LIGO Hanford, L1 = LIGO Livingston, V1 = Virgo. The total DM for each FRB is listed in the DM column and the 90% credible intervals on the luminosity distance are provided in columns D_L-low and D_L-High. 11 total events were analyzed for the three different FRB repeaters considered. For FRB 20190518A and its associated repeats, we list only the distance of Marcote et al. (2020) obtained by galaxy localization.

FRB Name	UTC Time [s]	R.A.	Dec.	Network	DM [pc cm^{-3}]	D_L-Low [Mpc]	D_L-high [Mpc]
FRB20190817A	14:39:52	$4^{\mathrm{h}}21^{\mathrm{m}}08^{\mathrm{s}}$	$73^\circ47'$	H1L1V1	189.5	19.5	539.2
FRB20190929C	11:58:29	$4^{\mathrm{h}}22^{\mathrm{m}}25^{\mathrm{s}}$	$73^\circ40'$	H1L1V1	191.6	20.8	550.1
FRB20190518A	18:13:33	$1^{\mathrm{h}}58^{\mathrm{m}}14^{\mathrm{s}}$	$65^\circ46'$	L1V1	350.5	148.1	149.9
FRB20190518E	18:20:57	$1^{\mathrm{h}}57^{\mathrm{m}}50^{\mathrm{s}}$	$65^\circ43'$	L1V1	350.0	148.1	149.9
FRB20190519A	17:50:16	$1^{\mathrm{h}}43^{\mathrm{m}}44^{\mathrm{s}}$	$65^\circ48'$	H1V1	350.0	148.1	149.9
FRB20190519C	18:10:41	$1^{\mathrm{h}}58^{\mathrm{m}}00^{\mathrm{s}}$	$65^\circ47'$	H1V1	348.8	148.1	149.9
FRB20190809A	12:50:40	$1^{\mathrm{h}}58^{\mathrm{m}}16^{\mathrm{s}}$	$65^\circ43'$	H1L1	356.2	148.1	149.9
FRB20190825A	11:48:18	$1^{\mathrm{h}}58^{\mathrm{m}}07^{\mathrm{s}}$	$65^\circ42'$	H1L1	349.6	148.1	149.9
FRB20190825B	11:51:54	$1^{\mathrm{h}}58^{\mathrm{m}}04^{\mathrm{s}}$	$65^\circ23'$	H1L1	349.9	148.1	149.9
FRB20190421A	08:00:04	$13^{\mathrm{h}}51^{\mathrm{m}}57^{\mathrm{s}}$	$48^\circ10'$	H1L1V1	225.9	125.1	1260.8
FRB20190702B	03:14:36	$13^{\mathrm{h}}52^{\mathrm{m}}25^{\mathrm{s}}$	$48^\circ15'$	L1V1	224.4	125.8	1257.5

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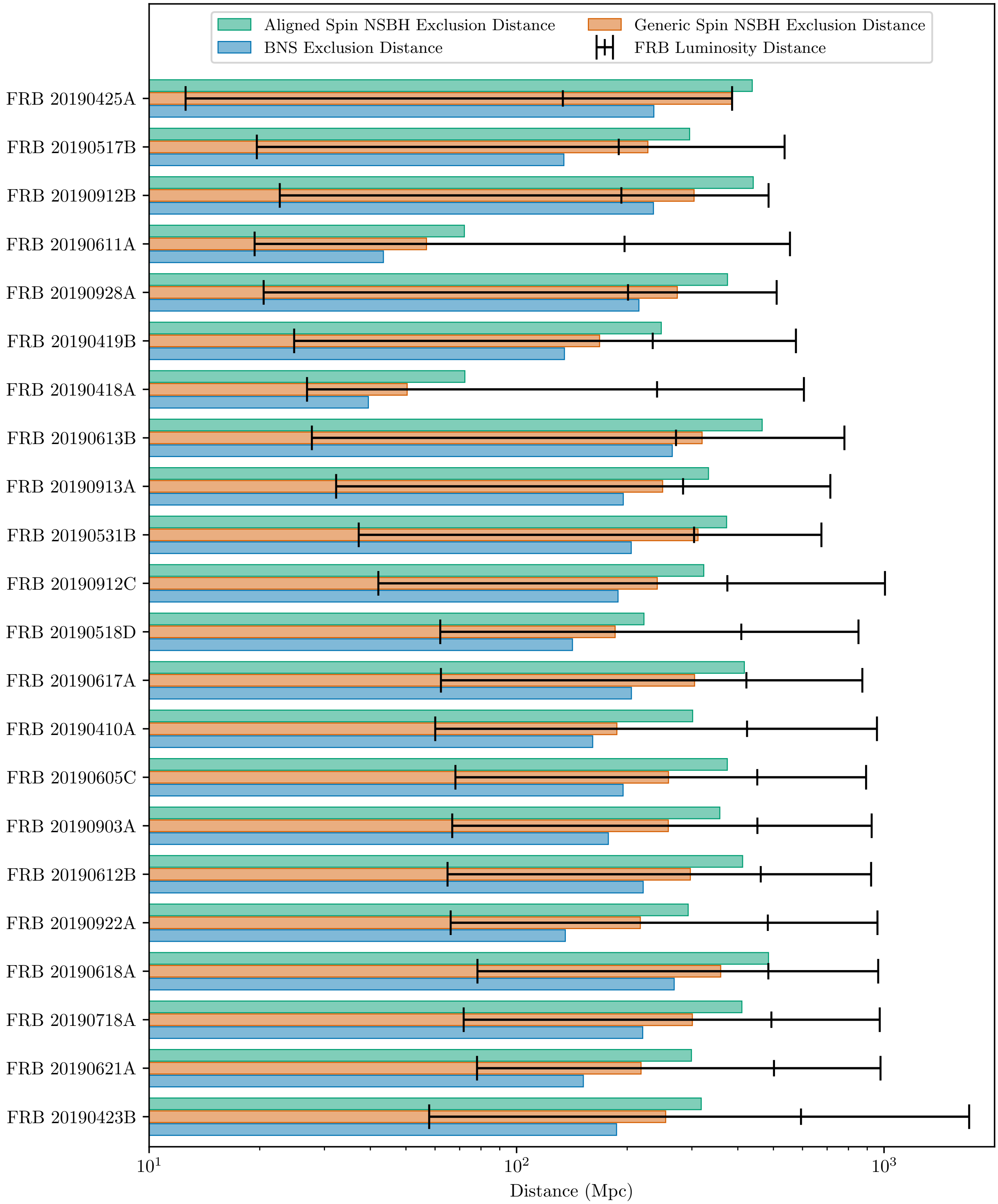

Figure 6. Lower limits on the 90% confidence level exclusion distances for BNS (lower bar), generic spin NSBH (middle bar), and aligned spin NSBH (upper bar) progenitor systems are shown as found by the modelled search. These are compared to the 90% credible intervals (whisker plot) on the D_L posterior determined by the MCMC method for the FRBs considered in this study.

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