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Search for gravitational-wave transients associated with magnetar bursts in Advanced LIGO and Advanced Virgo data from the third observing run

The LIGO Scientific Collaboration, the Virgo Collaboration, and the KAGRA Collaboration

ABSTRACT

Gravitational waves are expected to be produced from neutron star oscillations associated with magnetar giant flares and short bursts. We present the results of a search for short-duration (milliseconds to seconds) and long-duration (~ 100 s) transient gravitational waves from 13 magnetar short bursts observed during Advanced LIGO, Advanced Virgo and KAGRA's third observation run. These 13 bursts come from two magnetars, SGR 1935+2154 and Swift J1818.0−1607. We also include three other electromagnetic burst events detected by Fermi GBM which were identified as likely coming from one or more magnetars, but they have no association with a known magnetar. No magnetar giant flares were detected during the analysis period. We find no evidence of gravitational waves associated with any of these 16 bursts. We place upper bounds on the root-sum-square of the integrated gravitational-wave strain that reach $2.2 \times 10^{-23}\,/\sqrt{\mathrm{Hz}}$ at 100 Hz for the short-duration search and $8.7 \times 10^{-23}\,/\sqrt{\mathrm{Hz}}$ at 450 Hz for the long-duration search, given a detection efficiency of 50%. For a ringdown signal at 1590 Hz targeted by the short-duration search the limit is set to $1.8 \times 10^{-22}\,/\sqrt{\mathrm{Hz}}$. Using the estimated distance to each magnetar, we derive upper bounds on the emitted gravitational-wave energy of 3.2×10^{43} erg (7.3×10^{43} erg) for SGR 1935+2154 and 8.2×10^{42} erg (2.8×10^{43} erg) for Swift J1818.0−1607, for the short-duration (long-duration) search. Assuming isotropic emission of electromagnetic radiation of the burst fluences, we constrain the ratio of gravitational-wave energy to electromagnetic energy for bursts from SGR 1935+2154 with available fluence information. The lowest of these ratios is 3×10^3.

1. INTRODUCTION

Magnetars—highly-magnetized neutron stars—exhibit intermittent bursts of hard X-rays and soft gamma rays with typical peak luminosities $\lesssim 10^{43}\,\mathrm{erg\,s^{-1}}$ (see Kaspi & Beloborodov 2017, for a review). Galactic (Evans et al. 1980; Hurley et al. 1999; Hurley et al. 2005; Mereghetti et al. 2005; Boggs et al. 2007) and extragalactic (Mazets et al. 2008; Abadie et al. 2012; Svinkin et al. 2021; Burns et al. 2021) giant flares have peak luminosities up to five orders of magnitude larger. Although the mechanisms that causes these bursts and giant flares are not well understood, many models predict accompanying gravitational-wave emission from excited core and/or crust oscillations (Ioka 2001; Corsi & Owen 2011; Kashiyama & Ioka 2011; Zink et al. 2012; Ciolfi et al. 2011). This hypothesis is enhanced by the identification of quasi-periodic oscillations (QPOs) in the tails of giant flares (Barat et al. 1983; Israel et al. 2005; Strohmayer & Watts 2005, 2006; Watts & Strohmayer 2006), and possibly fainter bursts (Huppenkothen et al. 2014b,a), which have been attributed to various oscillations of the stellar crust and core (e.g., Duncan 1998; Messios et al. 2001; Piro 2005; Strohmayer & Watts 2006; Glampedakis et al. 2006; Levin 2007; Colaiuda & Kokkotas 2011; Glampedakis & Jones 2014).

Initial estimates for the potential gravitational-wave emission from giant flares were optimistic that the fundamental oscillation mode (f-mode) of magnetars could be excited by the catastrophic rearrangement of the star's interior magnetic field. These f-modes are excited at frequencies between ~ 1 kHz and 3 kHz, and could potentially emit up to $\sim 10^{49}$ erg (Ioka 2001; Corsi & Owen 2011) for ~ 100 ms (Lindblom & Detweiler 1983; McDermott et al. 1988; Wen et al. 2019), making them detectable with Advanced LIGO (Aasi et al. 2015), Advanced Virgo (Acernese et al. 2015), and KAGRA (Akutsu et al. 2019; Akutsu et al. 2021) gravitational-wave observatories (Abbott et al. 2018). Detailed calculations of the rearrangement of the neutron star's magnetic field using analytic calculations (Levin & van Hoven 2011) and numerical-relativity simulations (Ciolfi et al. 2011; Zink et al. 2012; Ciolfi & Rezzolla 2012; Tsokaros et al. 2021) yield more realistic estimates for the gravitational-wave energy emitted in the f-mode during these events. These models suggest gravitational waves associated with Galactic magnetar flares are not observable with the current generation of observatories, but instead require the sensitivity of at least third-generation observatories such as the Einstein Telescope (Punturo et al. 2010) or Cosmic Explorer (Reitze et al. 2019; Evans et al. 2021), or dedicated kilohertz facilities such as the proposed NEMO observatory (Ackley et al. 2020).

Other oscillation modes in the star, which are generally longer-lived and at lower frequencies than the f-mode, may be excited. These include buoyancy modes (g-modes) and Alfvén modes where the magnetic field provides the oscillation restoring force. The latter of these modes has been suggested as potential long-lived gravitational-wave sources from magnetar giant flares (Kashiyama & Ioka 2011; Zink et al. 2012), with the resonant frequency correlated to the initial rise time of the magnetar giant flare (Mazets et al. 2008; Hurley et al. 1999; Hurley et al. 2005). The damping time and mode excitation amplitude of these modes are largely unknown, making them interesting candidates for longer-lived gravitational-wave signals.

Only one Galactic giant flare has been observed coincident with a LIGO-Virgo observing run: the 2004 giant flare from SGR 1806−20. Upper limits on the gravitational-wave energy associated with the burst were determined to be between $\sim 10^{46}$ and 10^{52} erg, depending on the assumed waveform model (Kalmus et al. 2007; Abbott et al. 2008a; Kalmus 2009). A stacked search was performed on a series of bursts from the same magnetar occurring in the same minute of time, reducing the above upper limits to $\sim 10^{45}$ and 10^{50} erg assuming the same f-mode frequency and damping time for each burst (Kalmus et al. 2009; Abbott et al. 2009; Kalmus 2009). Further searches for f-modes on 1279 bursts from six different magnetars yielded upper limits between $\sim 10^{44}$ and 10^{47} erg (Abadie et al. 2011), while the first search for f-modes in the Advanced era of gravitational-wave interferometers yielded comparable upper limits on four bursts from two magnetars (Abbott et al. 2019; Schale 2019). These energy upper limits are in the range of possible gravitational-wave energies given the most optimistic predictions (Ioka 2001; Corsi & Owen 2011).

Longer-duration searches initially targeted the QPO frequencies in the tail of the giant flare of SGR 1806−20, with upper limits of various modes at $\lesssim 10^{46}$ erg (Matone & Márka 2007; Abbott et al. 2007), comparable to the electromagnetic energy emitted from the giant flare. A study was performed on a method to detect gravitational waves targeting repeated QPOs (Murphy et al. 2013). A search for long-duration gravitational waves from four magnetar bursts was performed using LIGO's sixth science run (S6) data (Quitzow-James 2016; Quitzow-James et al. 2017). The best upper limits from magnetar bursts come from recent observations in the Advanced LIGO-Virgo second observing run (O2), with gravitational-wave energies constrained to less than $\sim 10^{44}$ to 10^{48} erg, again depending on signal model, frequency, and damping time (Abbott et al. 2019; Schale 2019). We previously placed limits on gravitational-wave emission from purported extragalactic magnetar giant flares (Abbott et al. 2008b; Abadie et al. 2012)[1], with long-duration searches constraining the gravitational-wave energy emitted to between $\sim 10^{49}$ and 10^{52} erg for four different giant flares (Macquet et al. 2021).

In this Paper, we report on a search for gravitational waves coincident with 13 magnetar short bursts from SGR 1935+2154, Swift J1818.0−1607, and 3 electromagnetic bursts from an unidentified source (or sources) during the LIGO-Virgo-KAGRA third observing run (O3). Targeted gravitational-wave searches associated with magnetar bursts can broadly be split in two categories following theoretical predictions of short-duration and long-duration signals. We describe a short-duration and long-duration search and provide constraints on the gravitational-wave strain and energy for each search. We measure the sensitivity of our search as the threshold of a parameter (integrated root-sum-square strain amplitude or gravitational wave energy) at which 50% of the injections which survive the pipeline cuts are recovered with a greater significance than that of the loudest surviving trigger near the time of the burst. We call these the root-sum-square of the integrated gravitational-wave strain threshold ($h_{\rm rss}^{50\%}$) and gravitational-wave energy threshold ($E_{\rm GW}^{50\%}$) respectively.

2. METHODOLOGY

The O3 observing run extended from April 1, 2019, to March 27, 2020, with 3 gravitational-wave detectors taking data: LIGO Hanford Observatory (LHO), LIGO Livingston Observatory (LLO) and Virgo, all of which had been upgraded so that the binary neutron star inspiral ranges increased by a factor of 1.53 for LLO, 1.64 for LHO and 1.73 for Virgo (Davis et al. 2021) compared to their performance during O2. For each detector, several data quality checks are performed to mitigate terrestrial noise (Davis et al. 2021). In addition, multi-detector analyses are used to mitigate non-astrophysical features present in the data. In January 2020, a new technique was implemented to mitigate the

[1] GRB 070222, included in a search targeting gamma ray bursts (Aasi et al. 2014), was later determined to likely be an extragalactic magnetar giant flare (Burns et al. 2021; Macquet et al. 2021).

impact in LIGO detectors of scattered light, a transient noise coupled with ground motion. Data available for bursts that occurred in February and March show a lower transient noise rate.

The list of magnetar short bursts and giant flares from Hurley (2021) provides the source object and observation time for each burst. In both the long-duration and short-duration searches, we describe the data in which we look for a signal as the *on-source* window, while the time around this composing the background is the *off-source* window. Analysis requirements include at least two gravitational-wave detectors in observation mode, sufficiently good data quality, and sufficient data available in the burst's on-source window. Several bursts did not meet the two-detector criterion (one detector available for 2651, 2658, 2659, and 2667 in Hurley (2021) and none for 2662, 2663, and 2664), had poor data quality (2650 and 2672), or had very little data available in the on-source window (2650). Considering these requirements, 12 magnetar short bursts from known sources and three electromagnetic bursts thought to likely be magnetar short bursts from an unknown source or sources occurred when at least two detectors were in observation mode with sufficiently good data quality and are included in this search. In addition, although burst 2651 occurred when LHO was in observation mode and 87 s before Virgo was in observation mode (LLO was not taking data), data of sufficiently good quality was available for most of the long-duration search on-source window, thus the burst was analyzed by the long-duration search only. Eleven short bursts were from SGR 1935+2154 (Cummings et al. 2014), a magnetar which emitted a fast radio burst in April of 2020 (Kirsten et al. 2020), and two short bursts were from Swift J1818.0−1607, a magnetar discovered in 2020 (Evans et al. 2020). Note that SGR 1935+2154 generated more bursts on November 4, 2019, but only nine can be analyzed as at least two detectors in observing mode are necessary.

The source or sources of the remaining three electromagnetic bursts, detected by Fermi GBM (Meegan et al. 2009), are unknown as they have very poor sky localization. These three electromagnetic bursts were accompanied by a fourth burst which did not meet the two-detector condition necessary for our analysis, but all four of these bursts occurred in a 33 hour window of time between February 3 and February 4, 2020. Because of their temporal proximity, we search for a signal assuming that they were emitted by the same magnetar. Only two known galactic magnetars are in the 3σ error region of all four electromagnetic bursts. To obtain the best constraints, we consider the closest of these two magnetars, 1 RXS J170849 at 3.8 kpc (Durant & van Kerkwijk 2006), as the source of these bursts. The sources, times, active detectors, and the isotropic electromagnetic energy ($E_{\rm EM}^{\rm iso}$) of each burst included in this search are listed in Table 1; fluence information for some of the bursts from SGR 1935+2154 were obtained from Lin et al. (2020) and used to estimate $E_{\rm EM}^{\rm iso}$.

We follow Abbott et al. (2019) to search for short-duration signals (as potentially emitted by f-modes) and long-duration signals (such as might accompany observed QPOs). Each search combines the data from two (or more when available in the case of the short-duration search) detectors into a time-frequency map and then forms groups of pixels, called clusters, to search for gravitational-wave signals. The three electromagnetic bursts without a known source are only analyzed with the short-duration search. The searches are described in the following sections.

2.1. *Short-duration search*

The search for short-duration transient gravitational waves (milliseconds to seconds) is motivated by a potential signal associated with f-mode oscillations in the magnetar's core. Because the frequencies of the expected gravitational-wave signals can be as high as several kilohertz (Wen et al. 2019; Ho et al. 2020), the search ranges in frequency from 50 Hz to 4000 Hz, extending to higher frequencies than the other unmodeled searches (most notably LIGO-Virgo-KAGRA's burst searches associated with gamma-ray bursts (Abbott et al. 2021a,b) and fast radio bursts (Abbott et al. 2022).

Data are searched with X-pipeline, which is an unmodeled, coherent search pipeline (Sutton et al. 2010; Was et al. 2012). The X-pipeline algorithm coherently combines the data from each detector in the network to produce a multi-resolution time-frequency map displaying the energy in each pixel. The brightest 1% of these pixels are then selected, and neighboring bright pixels are combined into clusters, which are then assigned a ranking statistic. A large fraction of background clusters are rejected applying vetos built from the coherent and incoherent power across the detector network. Other details on the parameters of the short-duration search that have been modified are summarized in Appendix A.

The search for short-duration gravitational waves is comprised of two components: an 8 s duration on-source window centered on the magnetar burst time (a *centered on-source* window) so as to optimize sensitivity at the time when gravitational wave emission is most probable, and a 500 s long on-source window beginning just after the centered on-source window (a *delayed on-source* window). The longer delayed on-source window is meant to search for short-

Burst	Source	Date	Time (UTC)	Detectors	$E_{\rm EM}^{\rm iso}$ (erg)	GCN Circulars
2651	SGR 1935+2154	Nov 04, 2019	01:54:37	H V*	-	26169
2652	SGR 1935+2154	Nov 04, 2019	02:53:31	H V	1.4×10^{39}	26163, 26151
2653	SGR 1935+2154	Nov 04, 2019	04:26:55	H L V	1.1×10^{39}	26163
2654	SGR 1935+2154	Nov 04, 2019	06:34:00	H L V	-	26153
2655	SGR 1935+2154	Nov 04, 2019	09:17:53	H L	5.7×10^{39}	26163, 26154
2656	SGR 1935+2154	Nov 04, 2019	10:44:26	H L	2.2×10^{40}	26242, 26163, 26158, 26157
2657	SGR 1935+2154	Nov 04, 2019	12:38:38	H L V	2.7×10^{39}	26163
2660	SGR 1935+2154	Nov 04, 2019	15:36:47	H V	1.2×10^{39}	-
2661	SGR 1935+2154	Nov 04, 2019	20:29:39	H V	1.3×10^{39}	26165, 26166
2665	SGR 1935+2154	Nov 05, 2019	06:11:08	H V	7.8×10^{40}	26242
2668	SGR 1935+2154	Nov 15, 2019	20:48:41	L V	7.7×10^{38}	-
2669	-	Feb 03, 2020	03:17:11	H L V	-	26980
2670	-	Feb 03, 2020	03:44:03	H L V	-	26969, 26980
2671	-	Feb 03, 2020	20:39:37	H L V	-	26980
2673	Swift J1818.0−1607	Feb 28, 2020	22:19:32	L V	-	-
2674	Swift J1818.0−1607	Mar 12, 2020	21:16:47	H L V	-	27373

Table 1. List of magnetar short bursts considered for this search from the interplanetary network master burst list (Hurley 2021), and the available GW detectors: LIGO Hanford Observatory (H), LIGO Livingston Observatory (L), Virgo (V). Three electromagnetic bursts (2669, 2670, 2671) were not identified with a source and are thought to likely come from one or more magnetar(s), as reported in GCN circular 26980 (Lesage et al. 2020) and in the Fermi GBM Meegan et al. (2009) on-board Trigger Catalog, available online†. The isotropic electromagnetic energy ($E_{\rm EM}^{\rm iso}$) is estimated from the fluence given in Lin et al. (2020) considering a distance of 9.0 kpc for SGR 1935+2154 (Zhong et al. 2020), and 3.8 kpc for 1 RXS J170849 (Olausen & Kaspi 2014). Karuppusamy et al. (2020) estimates a distance of 4.8 to 8.1 kpc for Swift J1818.0−1607, and we optimistically perform our analysis assuming a distance of 4.8 kpc.
*Burst 2651 occurred 87 s before Virgo was in observation mode.
†https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermigtrig.html

duration signals emitted during the time following the burst, analogous to the QPOs that have been observed in the giant flares. For both on-source windows, 3 h of data taken symmetrically about the burst time with an extra gap of 16 s before and after the on-source window are used to determine the background significance.

The two short-duration search components are considered independent, and no trials factor will be incurred between the searches. However, since the delayed on-source window is 500 s long and starts just after the end of the centered on-source window, it overlaps with background data for the centered on-source component of the search. This introduces the possibility of there being a signal detected in the delayed on-source window, and this signal being included in the background of the centered on-source window. We mitigate this possibility by examining the results of the delayed on-source search and verifying the absence of such a signal before viewing the results of the centered on-source window. A summary of the main characteristics of both searches is reported in Table 2.

2.2. *Long-duration search*

Following previous searches (Quitzow-James 2016; Quitzow-James et al. 2017; Abbott et al. 2019), the O3 long-duration signal search is carried out with the Stochastic Transient Analysis Multi-detector Pipeline (STAMP) pipeline (Thrane et al. 2011). Signal to noise ratio (SNR) time-frequency maps are built using the cross-power between two detectors. We then use STAMP's seedless clustering algorithm, which generates clusters with quadratic Bézier curves (Thrane & Coughlin 2013), to search for gravitational wave signals. Restricting the variation of the clusters in frequency to a maximum of 10% allows us to target nearly-monochromatic gravitational waves signals potentially emitted from the mechanisms responsible for QPOs while reducing computational resources (Abbott et al. 2019). Clusters are ranked according to their SNR defined as the sum of the pixels' SNR that compose the cluster (Thrane & Coughlin 2013).

The on-source window starts 4 s before the burst time and ends 1600 s after. Several on-source windows had data removed from the analysis, as discussed in Appendix B. The frequency range is 24 Hz – 2500 Hz, limited by seismic noise

Search name	Pipeline	On-source window [s]	On-source interval [s]	Off-source window [s]	Frequency range [Hz]
Centered on-source	X pipeline	8	$[-4, +4]$	10,800	$50 - 4000$
Delayed on-source	X pipeline	500	$[+4, +504]$	10,800	$50 - 4000$
Long-duration	STAMP	1604	$[-4, +1600]$	58,800	$24 - 2500$

Table 2. On-source, off-source and frequency range of searches performed. The on-source interval is centered around the magnetar burst time.

at low frequencies, and going to just above the highest observed QPO in the tail of the 2004 giant flare (Mereghetti et al. 2005). Data from LHO and LLO are used when available, with data from Virgo used for bursts that also have data from either LHO or LLO (see Table 1 for available detectors for each burst).

The background for each burst is estimated using 58,800 s of off-source data with a consistent detector network which is as close as possible to the burst's on-source window while excluding the on-source windows of all of the other bursts. This data is broken up into 36 off-source analysis windows. We combine the data from one detector from each of these analysis windows with the data from the other detector from every other analysis window to create 1260 ($36^2 - 36$) SNR time-frequency maps (which we will refer to as background segments) to calculate a background distribution for each burst.

3. RESULTS

The results of the short-duration and long-duration searches for each burst are presented in the following sections. Clusters found in the on-source windows of the short-duration search are ranked by their p-value, which is the probability of having a cluster as significant or more in the on-source window under the null hypothesis. They are calculated considering the clusters in the background with a ranking statistic larger than the on-source cluster. We characterize the significance of the on-source clusters of the long-duration search with the fraction of background segments (FBS)

$$\mathrm{FBS} = N_{\geq}/N_{\mathrm{Total}} \,, \tag{1}$$

where $N_{\geq}$ is the number of segments in the respective burst's background whose loudest cluster has an SNR greater than or equal to the on-source cluster's SNR, and N_{Total} is the total number of segments in that background. The p-value in the short-duration search is found similarly to Equation 1, but where $N_{\geq}$ and N_{Total} include all clusters in the background with a higher SNR than the on-source cluster rather than merely the loudest cluster from each time segment.

To estimate the search sensitivity for each burst, we inject waveforms in the data and calculate the amplitude for which 50% of the signals have a detection statistic equal to or greater than the respective on-source most significant cluster statistic. These waveforms are phenomenological, and the distinguishability of different source-emmission types has not yet been studied in great detail. We then derive the root-sum-square of the integrated gravitational-wave strain (h_{rss}) and gravitational-wave energy (E_{GW}) for this amplitude at 50% detection efficiency ($h_{\mathrm{rss}}^{50\%}$ and $E_{\mathrm{GW}}^{50\%}$). The definition of h_{rss} is

$$h_{\mathrm{rss}} = \sqrt{\int_{-\infty}^{\infty} |h_+(t)|^2 + |h_\times(t)|^2 \, \mathrm{d}t} \,, \tag{2}$$

where $h_+(t)$ and $h_\times(t)$ are the two signal polarizations. In Appendix C we derive h_{rss} and E_{GW} for different waveforms used in the analysis.

When calculating E_{GW}, we use 9 kpc for SGR 1935+2154 (Zhong et al. 2020). The distance of Swift J1818.0−1607 is estimated to be in the range of 4.8 to 8.1 kpc (Karuppusamy et al. 2020); we calculate E_{GW} with the optimistic closer value of 4.8 kpc. For the magnetar bursts with unknown source(s), we consider 1 RXS J170849 as the source and use 3.8 kpc for the distance (Olausen & Kaspi 2014).

3.1. *Short-duration search results*

Burst	Long-Duration FBS	Centered (8 s) p-value	Delayed (500 s) p-value
2651	9.1×10^{-1}	-	-
2652	2.1×10^{-1}	1.0	4.1×10^{-1}
2653	7.7×10^{-1}	1.8×10^{-2}	3.5×10^{-3}
2654	8.5×10^{-1}	9.9×10^{-2}	6.6×10^{-1}
2655	7.8×10^{-1}	1.0	7.3×10^{-1}
2656	9.7×10^{-1}	8.6×10^{-3}	5.2×10^{-1}
2657	1.6×10^{-1}	6.7×10^{-2}	4.8×10^{-1}
2660	2.2×10^{-2}	4.8×10^{-1}	4.9×10^{-1}
2661	9.0×10^{-1}	1.9×10^{-1}	7.4×10^{-1}
2665	8.2×10^{-1}	-	-
2668	9.9×10^{-1}	1.0	4.3×10^{-1}
2669	-	1.0	6.3×10^{-1}
2670	-	2.9×10^{-1}	7.8×10^{-1}
2671	-	3.4×10^{-1}	-
2673	6.8×10^{-1}	1.0	4.8×10^{-1}
2674	5.9×10^{-1}	1.0	5.0×10^{-2}

Table 3. False alarm statistic for the most significant cluster found for each burst by all searches. FBS is reported for the long-duration search, and the p-value for the short-duration searches. A p-value of 1 indicates that there were no clusters in the on-source window that survived the veto cuts. Table entries of '-' indicate that no value is recorded, because no search was run. Bursts 2669-2671 are from the magnetar with no identified source, and the long-duration search was not conducted on these. Bursts 2651 and 2665 were missing segments of data from the on-source window such that the short-duration searches could not run, and burst 2671 had data missing in the delayed on-source window such that the delayed on-source search could not be run.

All bursts listed in Table 1 have been considered by the short-duration search except bursts 2651 and 2665 because of missing data in the on-source windows. For all the others, the short-duration centered and delayed on-source searches have found clusters whose significance is estimated in terms of their p-value reported in Table 3. The cumulative distribution of these p-values is represented in Figure 1.

In the short-duration searches simulated signals are added into the on-source data and time-frequency maps are processed similarly to the on-source time-frequency maps. The injected signals are chosen such that they adequately model a short-duration transient consistent with a magnetar f-mode signal, and also such that they cover a reasonable range of frequencies outside of the f-mode frequency range. We inject sine-Gaussian waveforms, described in Appendix C, at a range of frequencies between 70 Hz and 3560 Hz, and standardize the damping time to be the inverse of the frequency. We also inject a series of ringdown waveforms characterized by sinusoids with an exponentially decaying amplitude as described in Appendix C, characterized by damping times of 100 ms and 200 ms. Frequencies are between 1500 Hz and 2020 Hz to be consistent with previous searches. We also include a series of white noise burst signals ranging in frequency from 100 Hz to 1000 Hz to probe search sensitivity at lower frequencies. For each injected waveform we give the lowest value of the $h_{\rm rss}^{50\%}$, and the corresponding $E_{\rm GW}^{50\%}$ considering all bursts from SGR 1935+2154, Swift J1818.0−1607, and the unknown source in Table 4, Table 5, and Table 6, respectively. In Table 7 we give the results for two waveforms that best model the f-mode for each burst.

We now discuss the most significant clusters found for bursts 2653 and 2656 by the short-duration search.

Burst 2653: Two significant clusters are detected by the delayed on-source search. The most significant cluster has a p-value of 3.5×10^{-3}, a peak frequency of 97 Hz and duration of 31 ms. This is the outlier displayed in Figure 2. X-pipeline identifies another loud cluster 50 s earlier with the same p-value, a peak frequency at 228 Hz and a duration of 7.8 ms. Given their frequency and duration, each of these clusters is only a couple of cycles long. Both clusters display similar characteristics in the LHO data, appearing in spectrograms as a short-duration and low-frequency spike. In both cases, another high-SNR spike is seen in the data ~ 0.3 s from the time of the cluster as shown on Figure 2. Several other of these high-SNR features are detected on the same day as trigger 2653, and these are also in groups

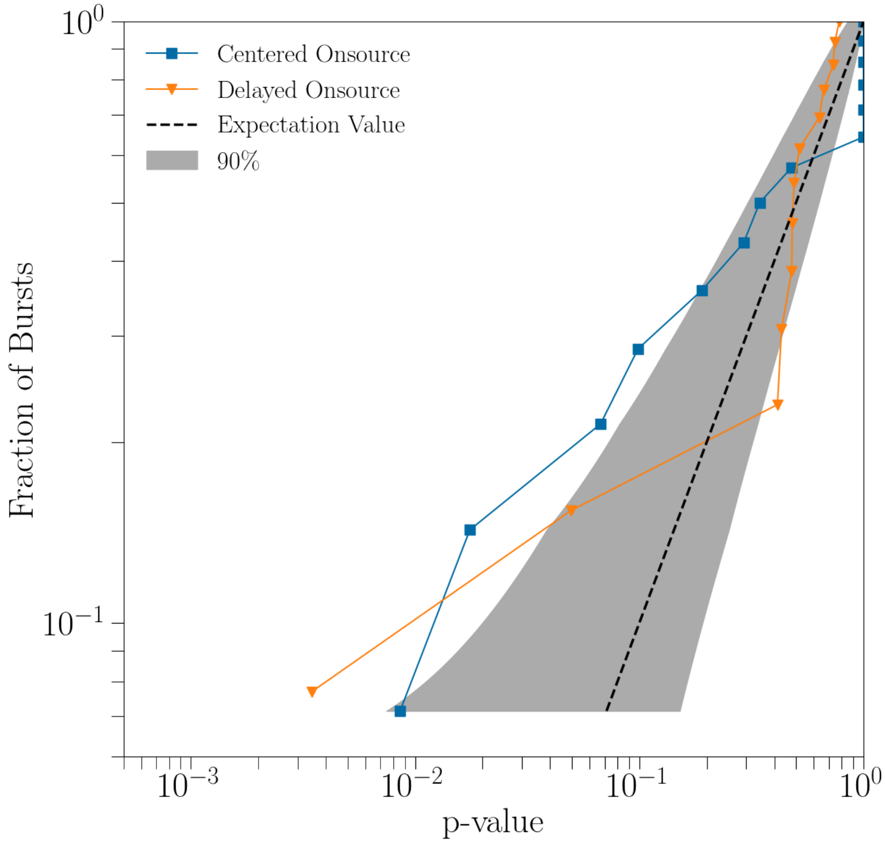


Figure 1. Cumulative distribution of the p-values of the most significant clusters found by the short-duration searches. The expectation value and 90% confidence interval are calculated numerically as in (Abbott et al. 2022); the expectation value is calculated assuming a uniform distribution of p-values (given by the null hypothesis), with each point having a 90% probability of landing in the shaded region. The lowest p-value in the delayed on-source search is 3.5×10^{-3} from burst 2653, and is determined to be most likely an instrumental artifact through arguments invoking both astrophysics and the characteristics of the detector. Several centered on-source search clusters fall outside of the 90% confidence interval, which is not unlikely given how few data points there are, and many of them have properties inconsistent with what one would expect from an astrophysical source. Although the most significant of these, which appears in burst 2656, has p-value 8.6×10^{-3} and a peak frequency (1577 Hz) which is consistent with expectations for an f-mode, we provide arguments for why this is not the case in Sec. 3.1.

of two spaced out by .3 s. While X-pipeline does not reconstruct either of these neighboring spikes in a coherent cluster, their presence at such a constant and short time-separation from the cluster strongly suggests that each of these clusters has a terrestrial origin. While X-pipeline conducts a coherent search, there remains poor coherence across the two detectors network for these clusters. When the energy per time-frequency pixel is standardized to be 1 unit for Gaussian data, this signal was detected with 165.3 units in LHO, and only 6.2 units and 12.8 units of energy in LLO and Virgo respectively. The ratio between the LHO and LLO energies is more than can be accounted for by the ratio of antenna factors squared, which gives a measure of the directional sensitivity (4.8 for LHO - LLO, and 1.3 LHO - Virgo) at the time of the burst. Finally, neither of these clusters is visibly identifiable in LLO nor Virgo time-frequency maps, meaning they are likely instrumental artifacts in LHO only.

Burst 2656: the most significant cluster found by the centered on-source search has a p-value of 8.6×10^{-3}. This cluster is 63 ms long, and its frequency lies in $1560 - 1608$ Hz which matches the expected frequency range of neutron star f-mode oscillations. The cluster appears ~ 3.1 s before the burst time. There are no known physical mechanisms

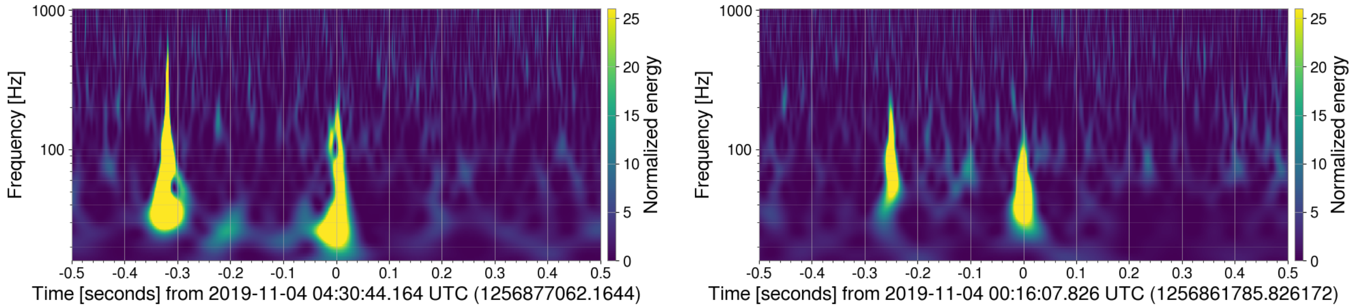


Figure 2. Spectrograms of the LHO data (left) at the time of the most significant cluster found in the on-source window of burst 2653, and an instrumental artifact appearing also in LHO data (right). The time separation between these two events is $\sim 15{,}277\,\mathrm{s}$, which is larger than the size of the background window in our analysis, and therefore the instrumental artifact was not included in the background. These two spectrograms display very similar structure, with a similar double short-duration transients separated in both cases by $\sim 0.3\,\mathrm{s}$. Several instrumental artifacts of this nature were found by Omicron (Robinet et al. 2020) within the day of burst 2653. The second most significant cluster in the same delayed on-source analysis of burst 2653 also has this same double-peaked structure.

to produce gravitational waves so long before the electromagnetic emission; while this does not rule out this cluster being astrophysical, it makes it less plausible.

Unlike the clusters found for burst 2653, this one is only visible in the LLO data spectrogram shown on Figure 3 that also illustrates that no high-SNR glitches are present in the ambient noise at the time of the burst. The data quality monitor tool iDQ (Essick et al. 2020) indicates that the probability of this cluster being an instrumental artifact in LLO is 62%, and 23% in LHO.

The number of analyses in the long duration and the short-duration searches (40 in total across the three on-source windows of the 16 bursts) imply this cluster has a $\approx 29\%$ chance of being background noise. This, and the high probability that the cluster is due to an instrumental artifact, imply it is highly unlikely to be a signal of astrophysical origin. Nevertheless, we can calculate the strain and gravitational-wave energy required for such a signal assuming it is of astrophysical origin. Using the ringdown waveform with 100 ms damping time and 1590 Hz frequency, the h_{rss} and E_{GW} estimated at 50% detection efficiency are $2.2 \times 10^{-22}\,\mathrm{Hz}^{-1/2}$ and $1 \times 10^{47}\,\mathrm{erg}$, respectively. For this burst, this implies the ratio of gravitational-wave to electromagnetic energy is $E_{\mathrm{GW}}^{50\%}/E_{\mathrm{EM}}^{\mathrm{iso}} = 6 \times 10^{6}$. It is difficult to imagine a physical scenario whereby this much more energy is deposited into gravitational rather than electromagnetic waves, adding further weight to the conclusion that this cluster is not of astrophysical origin.

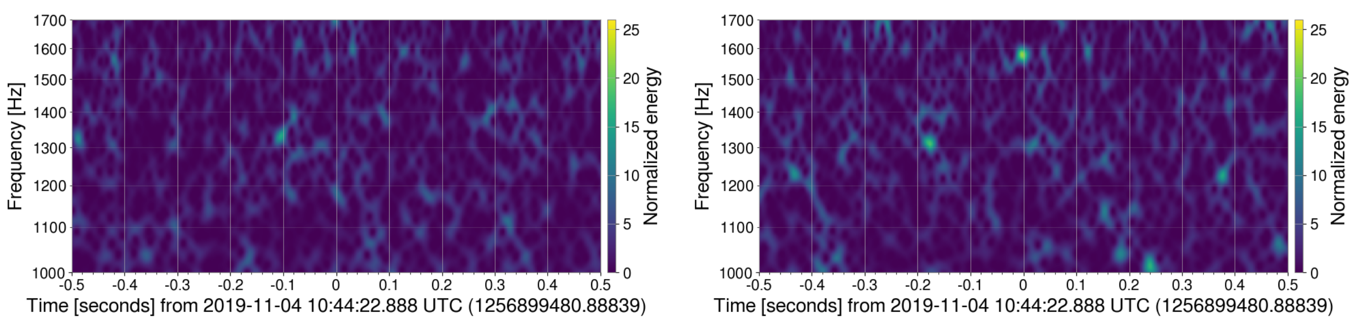


Figure 3. Spectrograms of the LHO (left) and LLO (right) data around the time of the most significant cluster found by the centered-window short-duration search of burst 2656. Even though the cluster is only barely visible in LLO data, these spectrograms show that the ambient noise in each detector is in a normal state around the time of the flare.

Injection Type	Frequency (Hz)	Duration/ τ (ms)	Centered (8 s) Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	Delayed (500 s) Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)
Sine Gaussian	70	14.3	2655	7.3×10^{-23}	3.2×10^{43}	2656	8.5×10^{-23}	4.4×10^{43}
Sine Gaussian	90	11.1	2668	5.8×10^{-23}	3.3×10^{43}	2656	7.4×10^{-23}	5.5×10^{43}
Sine Gaussian	145	6.89	2668	5.7×10^{-23}	8.4×10^{43}	2656	6.6×10^{-23}	1.1×10^{44}
Sine Gaussian	290	3.45	2655	5.8×10^{-23}	3.5×10^{44}	2656	6.7×10^{-23}	4.7×10^{44}
Sine Gaussian	1100	0.909	2655	1.3×10^{-22}	2.6×10^{46}	2656	1.5×10^{-22}	3.4×10^{46}
Sine Gaussian	1600	0.625	2655	1.9×10^{-22}	1.1×10^{47}	2656	2.2×10^{-22}	1.6×10^{47}
Sine Gaussian	2020	0.495	2655	2.4×10^{-22}	3.0×10^{47}	2656	2.9×10^{-22}	4.3×10^{47}
Sine Gaussian	2600	0.385	2655	3.3×10^{-22}	9.2×10^{47}	2656	4.0×10^{-22}	1.3×10^{48}
Sine Gaussian	3100	0.323	2655	4.1×10^{-22}	2.0×10^{48}	2652	5.2×10^{-22}	3.1×10^{48}
Sine Gaussian	3560	0.281	2655	5.1×10^{-22}	4.0×10^{48}	2652	6.2×10^{-22}	6.0×10^{48}
Sine Gaussian*	1600	0.625	2655	1.1×10^{-22}	3.8×10^{46}	2656	1.3×10^{-22}	5.2×10^{46}
Sine Gaussian*	2020	0.495	2655	1.4×10^{-22}	9.6×10^{46}	2656	1.7×10^{-22}	1.4×10^{47}
Ringdown	1590	100	2655	1.9×10^{-22}	1.1×10^{47}	-	-	-
Ringdown	1590	200	2655	1.8×10^{-22}	9.6×10^{46}	-	-	-
Ringdown	1500	100	2668	2.5×10^{-22}	1.8×10^{47}	-	-	-
Ringdown	1500	200	2668	2.3×10^{-22}	1.5×10^{47}	-	-	-
Ringdown	2020	100	2655	2.2×10^{-22}	2.4×10^{47}	-	-	-
Ringdown	2020	200	2655	2.2×10^{-22}	2.3×10^{47}	-	-	-
WNB	100-200	11	2668	3.8×10^{-23}	1.0×10^{44}	2656	4.1×10^{-23}	1.2×10^{44}
WNB	100-200	100	2668	5.3×10^{-23}	2.0×10^{44}	2656	6.1×10^{-23}	2.7×10^{44}
WNB	100-1000	11	2655	6.7×10^{-23}	5.1×10^{45}	2656	7.5×10^{-23}	6.4×10^{45}
WNB	100-1000	100	2655	1.1×10^{-22}	1.5×10^{46}	2656	1.5×10^{-22}	2.4×10^{46}

Table 4. $h_{\rm rss}$ and isotropic energy estimated at 50% detection efficiency for the most sensitive burst from SGR 1935+2154 for each injected waveform in the centered and delayed on-source windows of the short-duration search. All waveforms are elliptically polarized, except those denoted by *, which have circular polarization, and the WNBs, which are unpolarized.

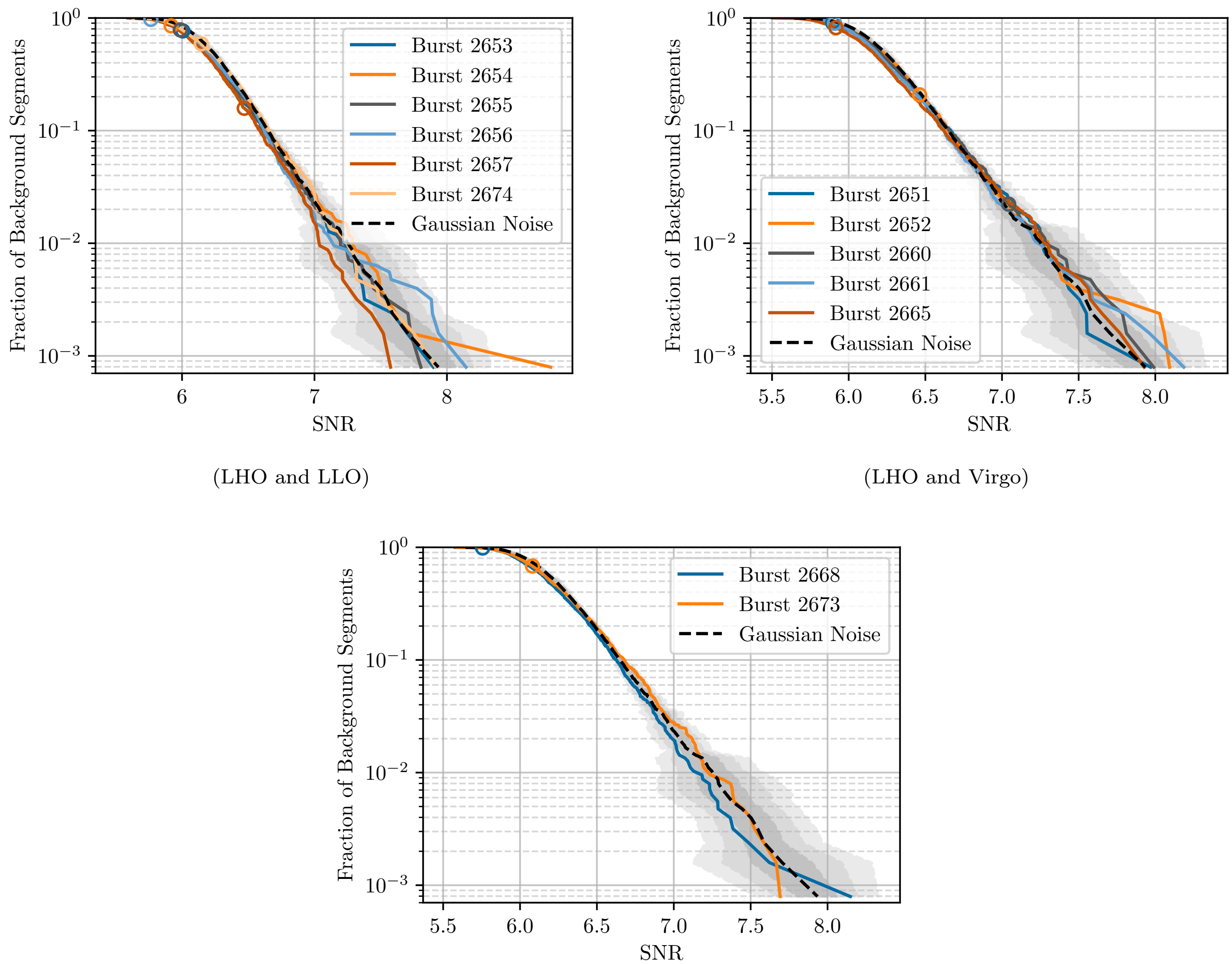
3.2. *Long-duration search results*

All bursts from Table 1 have been analyzed by the long-duration search except the 3 bursts from the unknown source. The on-source window results for each burst are shown in Table 3, which lists the FBS of the most significant cluster for each burst, determined using the background clusters. No interesting cluster has been found as the most significant cluster has an FBS of 0.02. Figure 4 compares the most significant on-source cluster to the corresponding background distribution for each burst.

As in the O2 search (Abbott et al. 2019), two families of waveforms, half sine-Gaussians and exponentially decaying sinusoids (ringdowns), are injected at five frequencies (55 Hz, 150 Hz, 450 Hz, 750 Hz, and 1550 Hz) and two damping times (150 s and 400 s). The most constrictive $h_{\rm rss}^{50\%}$ is provided by burst 2656, identified with SGR 1935+2154, which has the largest sum squared antenna factors. The results for burst 2656 indicate an increase in search sensitivity from O2 to O3 ranging from a factor of ~ 1.2 to ~ 2.0, which follows roughly the detectors' sensitivity increase, although this improvement also depends on additional considerations such as the detector antenna factors at the time of the burst. The half sine-Gaussian $h_{\rm rss}^{50\%}$ for burst 2656 are plotted against the best sensitivity curves of LHO and LLO during O3 (Kissel 2020) in Figure 5, along with $h_{\rm rss}^{50\%}$ from O2 as a comparison. In Table 8 and Table 9 we report $h_{\rm rss}^{50\%}$and $E_{\rm GW}^{50\%}$for bursts 2656 and 2674, which provide the most constrictive values among all bursts emitted by SGR 1935+2154 and Swift J1818.0−1607, respectively.

The optimistic closer distance estimate for Swift J1818.0−1607 of 4.8 kpc (Karuppusamy et al. 2020) is roughly half the distance of SGR 1935+2154, so although $h_{\rm rss}^{50\%}$ results are slightly worse, upper bounds on $E_{\rm GW}^{50\%}$ are 2.6 times better, with the best results from burst 2674 of 2.8×10^{43} erg at 55 Hz. All values of $h_{\rm rss}^{50\%}$ and $E_{\rm GW}^{50\%}$ for bursts 2656 and 2674 are presented in Table 8 and Table 9, respectively.

4. CONCLUSIONS



(LHO and LLO)

(LHO and Virgo)

(LLO and Virgo)

Figure 4. Distributions of background and on-source clusters for each burst analyzed with data from LHO, LLO and Virgo. The background of each burst is displayed along with the SNR of its on-source cluster denoted by a circle. The dashed black line is the mean, and the grey contours are the one, two, and three standard deviations of the distribution of FBS obtained simulating Gaussian noise colored with the aLIGO design sensitivity curve (Barsotti et al. 2018).

In this study, we search for and find no evidence of gravitational waves coincident with 16 bursts (13 magnetar short bursts and three electromagnetic bursts thought to be magnetar short bursts but with no identified source object) during O3. We search for both short-duration signals produced by excited f-modes in the neutron star's core, and for long-duration signals that may be generated from core buoyancy or Alfvén modes. Statistics for both short-duration and long-duration searches are consistent with background noise; when accounting for the number of searches performed over all of the bursts, the most significant cluster found that was not clearly identified as an instrumental artifact has a p-value of 0.00857 and a $\approx 29\%$ chance of being background noise. In order to have a 50% probability of detecting a signal with similar time and frequency properties as those of this cluster with a p-value of 1×10^{-4}, the signal would have to be louder by a factor of approximately 1.2.

See Appendix C for a discussion of the injections and calculations of $h_{\rm rss}^{50\%}$ and $E_{\rm GW}^{50\%}$, and see Abbott et al. (2019) for a discussion of the effects of the polarization on these quantities. For each injected waveform with frequencies in the range of 1500 Hz to 2020 Hz, the lowest recovered $h_{\rm rss}^{50\%}$ from the bursts with known sources found $E_{\rm GW}^{50\%}$ ranging from 1×10^{46} erg to 3×10^{47} erg, two orders of magnitude lower than initial estimates predicted.

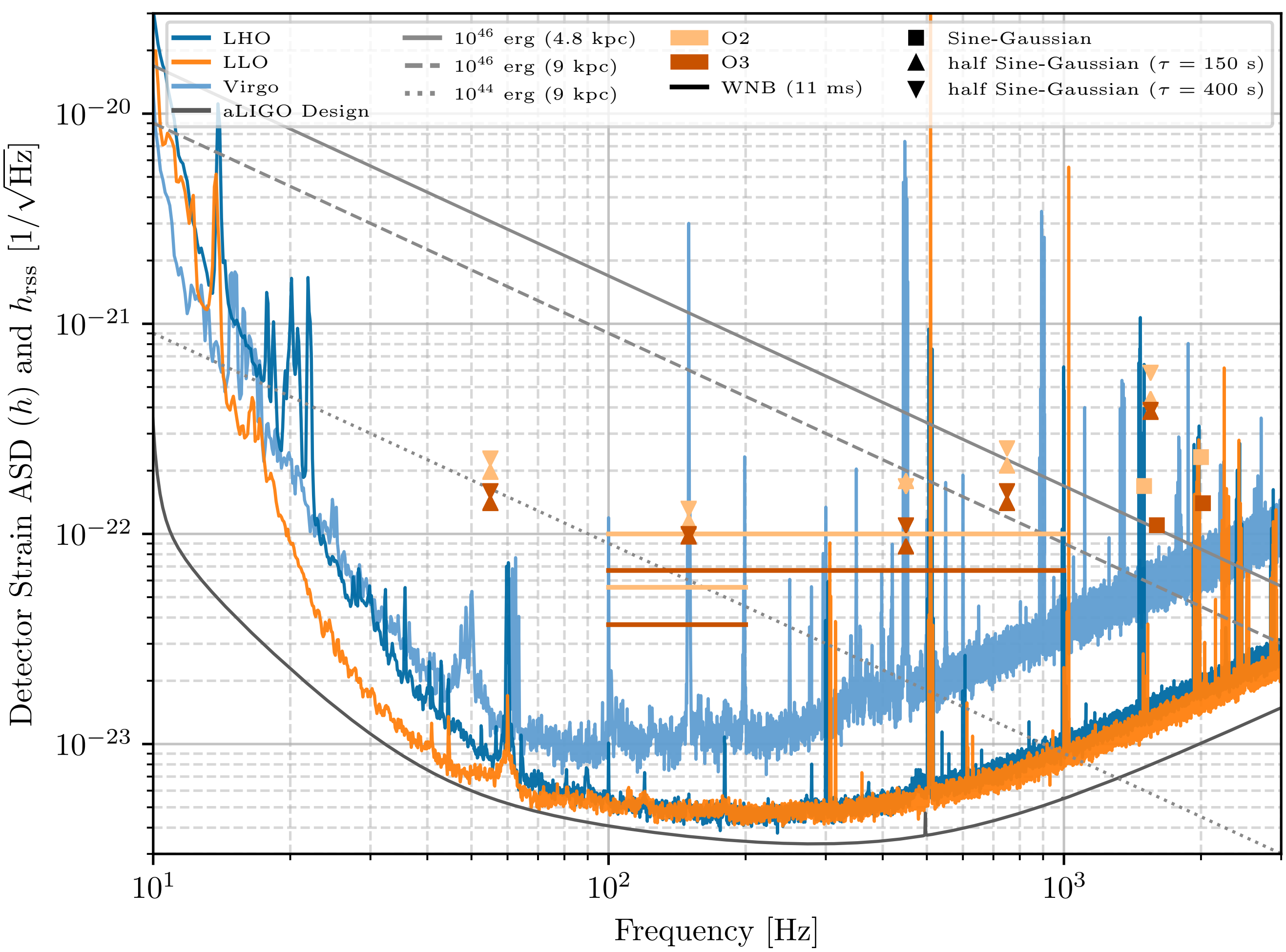


Figure 5. Removed first sentence. The most constrained $h_{\rm rss}^{50\%}$ across all bursts with known sources are displayed and compared to O2 results. The detectors' amplitude strain density curves correspond to the best sensitivity for each detector during O3 (Kissel 2020; Verkindt 2021; Buikema et al. 2020).

In Table 4, Table 5, and Table 6 we report the most constrained $h_{\rm rss}^{50\%}$ values over all bursts for each waveform. The only injected waveforms with exactly the same parameters as the O2 search are the white noise bursts, and we see a factor of improvement in $h_{\rm rss}^{50\%}$ of 1.1 for the 100−200 Hz, 11 ms WNB. To obtain an approximate metric of improvement, we compare injected sine-Gaussian waveforms at 1600 Hz and 2020 Hz from O3 to sine-Gaussian waveforms of 1500 Hz and 2000 Hz in O2 and see factors of improvement of 1.5 and 1.7 in $h_{\rm rss}^{50\%}$, respectively.

The long-duration search sets the lowest thresholds on long-duration gravitational wave emission from magnetar bursts to date. The lowest values of $h_{\rm rss}^{50\%}$ came from SGR 1935+1254, with $h_{\rm rss}^{50\%}$ values as low as $8.7 \times 10^{-23}\,/\sqrt{\rm Hz}$ at 450 Hz ($E_{\rm GW}^{50\%} = 1.9 \times 10^{45}$ erg) for burst 2656. The lowest thresholds of $E_{\rm GW}^{50\%}$ come from Swift J1818.0−1607 because of its closer proximity (4.8 kpc vs 9 kpc), with $E_{\rm GW}^{50\%} = 2.8 \times 10^{43}$ erg at 55 Hz ($h_{\rm rss}^{50\%} = 1.6 \times 10^{-22}\,/\sqrt{\rm Hz}$) for burst 2674.

We also place constraints on the ratio of gravitational-wave energy to electromagnetic energy emitted by SGR 1935+2154 (the only source whose bursts have published electromagnetic energies) using the calculated isotropic electromagnetic energies given in Table 1. The most constraining values of this ratio for both the short-duration and long-duration searches come from burst 2656. For the short-duration search, the most constraining ratio when taking the gravitational-wave energy from the 1590Hz, 100ms ringdown waveform is $E_{\rm GW}^{50\%}/E_{\rm EM}^{\rm iso} = 6.4 \times 10^6$. For the long-duration search, this is $E_{\rm GW}^{50\%}/E_{\rm EM}^{\rm iso} = 3.3 \times 10^3$, which comes from a half sine-Gaussian at 55 Hz with $\tau = 150$ s. These ratios are less constraining than that of SGR 1806−20's 2004 giant flare, $E_{\rm GW}^{50\%}/E_{\rm EM}^{\rm iso} = 9 \times 10^4$ for a 200 ms

Injection Type	Frequency (Hz)	Duration/	Centered (8 s)			Delayed (500 s)		
		τ (ms)	Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)
Sine Gaussian	70	14.3	2674	6.9×10^{-23}	8.2×10^{42}	2673	9.2×10^{-23}	1.4×10^{43}
Sine Gaussian	90	11.1	2674	6.1×10^{-23}	1.1×10^{43}	2673	8.7×10^{-23}	2.1×10^{43}
Sine Gaussian	145	6.89	2674	5.7×10^{-23}	2.4×10^{43}	2674	8.5×10^{-23}	5.4×10^{43}
Sine Gaussian	290	3.45	2674	5.9×10^{-23}	1.0×10^{44}	2674	9.1×10^{-23}	2.4×10^{44}
Sine Gaussian	1100	0.909	2674	1.3×10^{-22}	7.5×10^{45}	2674	2.0×10^{-22}	1.7×10^{46}
Sine Gaussian	1600	0.625	2674	2.0×10^{-22}	3.7×10^{46}	2674	2.9×10^{-22}	7.5×10^{46}
Sine Gaussian	2020	0.495	2674	2.7×10^{-22}	1.0×10^{47}	2674	3.9×10^{-22}	2.1×10^{47}
Sine Gaussian	2600	0.385	2674	3.5×10^{-22}	2.9×10^{47}	2674	4.9×10^{-22}	5.7×10^{47}
Sine Gaussian	3100	0.323	2674	4.4×10^{-22}	6.4×10^{47}	2674	6.1×10^{-22}	1.2×10^{48}
Sine Gaussian	3560	0.281	2674	5.3×10^{-22}	1.2×10^{48}	2674	7.1×10^{-22}	2.2×10^{48}
Sine Gaussian*	1600	0.625	2674	1.2×10^{-22}	1.2×10^{46}	2674	1.7×10^{-22}	2.6×10^{46}
Sine Gaussian*	2020	0.495	2674	1.5×10^{-22}	3.2×10^{46}	2674	2.1×10^{-22}	6.3×10^{46}
Ringdown	1590	100	2674	2.1×10^{-22}	3.8×10^{46}	-	-	-
Ringdown	1590	200	2674	2.1×10^{-22}	4.0×10^{46}	-	-	-
Ringdown	1500	100	2673	2.6×10^{-22}	5.3×10^{46}	-	-	-
Ringdown	1500	200	2673	2.6×10^{-22}	5.3×10^{46}	-	-	-
Ringdown	2020	100	2674	2.6×10^{-22}	9.3×10^{46}	-	-	-
Ringdown	2020	200	2674	2.5×10^{-22}	8.7×10^{46}	-	-	-
WNB	100-200	11	2674	3.7×10^{-23}	2.8×10^{43}	2673	5.6×10^{-23}	6.5×10^{43}
WNB	100-200	100	2674	5.3×10^{-23}	5.7×10^{43}	2673	7.8×10^{-23}	1.2×10^{44}
WNB	100-1000	11	2674	7.0×10^{-23}	1.6×10^{45}	2674	1.0×10^{-22}	3.3×10^{45}
WNB	100-1000	100	2674	1.2×10^{-22}	4.6×10^{45}	2674	1.8×10^{-22}	1.1×10^{46}

Table 5. $h_{\rm rss}$ and isotropic energy estimated at 50% detection efficiency for the most sensitive burst from SGR 1818−1607 for each injected waveform in the centered and delayed on-source windows of the short-duration search. All waveforms are elliptically polarized, except those denoted by *, which have circular polarization, and the WNBs, which are unpolarized.

ringdown waveform at 1590 Hz (Abbott et al. 2008a) and $E_{\rm GW}^{50\%}/E_{\rm EM}^{\rm iso} \approx 5$ for a band surrounding the 92.5 Hz QPO in the giant flare's tail (Abbott et al. 2007, 2008a).

With the current sensitivities of the LIGO and Virgo detectors, we can now probe well below the potential energy budgets available to generate gravitational waves from catastrophic rearrangements of the star's internal magnetic field (Ioka 2001; Corsi & Owen 2011). However, even the most constrained values of $E_{\rm GW}^{50\%}$ provided here are well above the expected gravitational wave energy one would expect from f-mode emission from giant flares (e.g., Levin 2007; Zink et al. 2012; Ciolfi & Rezzolla 2012), let alone the lower-energy bursts being considered here. As gravitational wave observatories continue to improve in sensitivity, and more observatories such as KAGRA (Akutsu et al. 2019) reach comparable sensitivity, searches for gravitational waves from magnetar bursts will eventually probe several orders of magnitude below the electromagnetic energy of giant flares, increasing the probability of a discovery of gravitational waves from magnetar flares.

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Injection Type	Frequency (Hz)	Duration/	Centered (8 s)			Delayed (500 s)		
		τ (ms)	Burst	$h_{\rm rss}^{50\%}$ ($\rm Hz^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	Burst	$h_{\rm rss}^{50\%}$ ($\rm Hz^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)
Sine Gaussian	70	14.3	2669	4.2×10^{-23}	1.9×10^{42}	2669	5.0×10^{-23}	2.7×10^{42}
Sine Gaussian	90	11.1	2669	4.0×10^{-23}	2.8×10^{42}	2669	4.6×10^{-23}	3.8×10^{42}
Sine Gaussian	145	6.89	2669	3.3×10^{-23}	5.1×10^{42}	2669	3.9×10^{-23}	7.0×10^{42}
Sine Gaussian	290	3.45	2669	3.6×10^{-23}	2.4×10^{43}	2669	4.1×10^{-23}	3.1×10^{43}
Sine Gaussian	1100	0.909	2669	7.7×10^{-23}	1.6×10^{45}	2669	8.8×10^{-23}	2.1×10^{45}
Sine Gaussian	1600	0.625	2669	1.1×10^{-22}	7.1×10^{45}	2670	1.3×10^{-22}	9.5×10^{45}
Sine Gaussian	2020	0.495	2669	1.5×10^{-22}	1.9×10^{46}	2669	1.7×10^{-22}	2.5×10^{46}
Sine Gaussian	2600	0.385	2669	2.0×10^{-22}	5.9×10^{46}	2669	2.4×10^{-22}	8.8×10^{46}
Sine Gaussian	3100	0.323	2669	2.5×10^{-22}	1.3×10^{47}	2670	3.0×10^{-22}	1.9×10^{47}
Sine Gaussian	3560	0.281	2669	2.9×10^{-22}	2.3×10^{47}	2670	4.0×10^{-22}	4.5×10^{47}
Sine Gaussian*	1600	0.625	2669	6.2×10^{-23}	2.2×10^{45}	2669	7.7×10^{-23}	3.3×10^{45}
Sine Gaussian*	2020	0.495	2669	8.6×10^{-23}	6.6×10^{45}	2670	9.5×10^{-23}	8.1×10^{45}
Ringdown	1590	100	2670	1.1×10^{-22}	6.8×10^{45}	-	-	-
Ringdown	1590	200	2670	1.1×10^{-22}	7.0×10^{45}	-	-	-
Ringdown	1500	100	2669	1.8×10^{-22}	1.6×10^{46}	-	-	-
Ringdown	1500	200	2671	2.7×10^{-22}	3.6×10^{46}	-	-	-
Ringdown	2020	100	2670	1.3×10^{-22}	1.6×10^{46}	-	-	-
Ringdown	2020	200	2670	1.3×10^{-22}	1.6×10^{46}	-	-	-
WNB	100-200	11	2669	2.2×10^{-23}	6.2×10^{42}	2669	2.5×10^{-23}	8.2×10^{42}
WNB	100-200	100	2669	3.2×10^{-23}	1.3×10^{43}	2670	3.6×10^{-23}	1.7×10^{43}
WNB	100-1000	11	2669	3.9×10^{-23}	3.0×10^{44}	2669	4.6×10^{-23}	4.4×10^{44}
WNB	100-1000	100	2669	7.1×10^{-23}	1.0×10^{45}	2669	8.2×10^{-23}	1.4×10^{45}

Table 6. $h_{\rm rss}$ and isotropic energy estimated at 50% detection efficiency for the most sensitive burst from the unknown source for each injected waveform in the centered and delayed on-source windows of the short-duration search. All waveforms are elliptically polarized, except those denoted by *, which have circular polarization, and the WNBs, which are unpolarized.

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Burst	Source	Ringdown			Sine Gaussian		
		$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	$\frac{E_{\rm GW}^{50\%}}{E_{\rm EM}^{\rm iso}}$	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	$\frac{E_{\rm GW}^{50\%}}{E_{\rm EM}^{\rm iso}}$
2652	SGR 1935+2154	3.2×10^{-22}	3.2×10^{47}	2.2×10^{8}	3.2×10^{-22}	3.2×10^{47}	2.2×10^{8}
2653	SGR 1935+2154	2.6×10^{-22}	2.2×10^{47}	1.9×10^{8}	2.6×10^{-22}	2.2×10^{47}	1.9×10^{8}
2654	SGR 1935+2154	5.0×10^{-22}	7.8×10^{47}	-	5.2×10^{-22}	8.6×10^{47}	-
2655	SGR 1935+2154	1.9×10^{-22}	1.1×10^{47}	1.9×10^{7}	1.9×10^{-22}	1.1×10^{47}	2.0×10^{7}
2656	SGR 1935+2154	2.1×10^{-22}	1.4×10^{47}	6.4×10^{6}	2.1×10^{-22}	1.4×10^{47}	6.5×10^{6}
2657	SGR 1935+2154	2.4×10^{-22}	1.8×10^{47}	6.6×10^{7}	2.6×10^{-22}	2.1×10^{47}	7.8×10^{7}
2660	SGR 1935+2154	3.4×10^{-22}	3.6×10^{47}	3.0×10^{8}	3.5×10^{-22}	3.9×10^{47}	3.3×10^{8}
2661	SGR 1935+2154	3.2×10^{-22}	3.2×10^{47}	2.4×10^{8}	3.4×10^{-22}	3.6×10^{47}	2.7×10^{8}
2668	SGR 1935+2154	2.1×10^{-22}	1.4×10^{47}	1.8×10^{8}	2.1×10^{-22}	1.4×10^{47}	1.9×10^{8}
2669	unknown	1.1×10^{-22}	7.3×10^{45}	-	1.1×10^{-22}	7.1×10^{45}	-
2670	unknown	1.1×10^{-22}	6.8×10^{45}	-	1.2×10^{-22}	8.0×10^{45}	-
2671	unknown	2.0×10^{-22}	2.2×10^{46}	-	2.1×10^{-22}	2.5×10^{46}	-
2673	Swift J1818−1607	2.7×10^{-22}	6.6×10^{46}	-	2.7×10^{-22}	6.6×10^{46}	-
2674	Swift J1818−1607	2.1×10^{-22}	3.8×10^{46}	-	2.0×10^{-22}	3.7×10^{46}	-

Table 7. Values of $h_{\rm rss}^{50\%}$ and $E_{\rm GW}^{50\%}$ for the centered on-source short-duration search. We present these values for the elliptically polarized 1600Hz Sine Gaussian waveform, and 100ms ringdown waveform at central frequency 1590Hz. These are the specific waveforms of each type that best model the gravitational wave one would expect in conjuncture with an f-mode. The burst numbers are consistent with those used in the catalogue: http://www.ssl.berkeley.edu/ipn3/sgrlist.txt.

Frequency (Hz)	τ (s)	Half Sine-Gaussian			Ringdown		
		Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)
55	150	2656	1.4×10^{-22}	7.3×10^{43}	2656	1.4×10^{-22}	7.8×10^{43}
-	400	2656	1.6×10^{-22}	9.3×10^{43}	2656	1.7×10^{-22}	1.0×10^{44}
150	150	2656	9.7×10^{-23}	2.6×10^{44}	2656	1.0×10^{-22}	2.9×10^{44}
-	400	2656	1.0×10^{-22}	2.9×10^{44}	2656	1.1×10^{-22}	3.3×10^{44}
450	150	2656	8.7×10^{-23}	1.9×10^{45}	2656	9.3×10^{-23}	2.1×10^{45}
-	400	2656	1.1×10^{-22}	3.1×10^{45}	2656	1.2×10^{-22}	3.5×10^{45}
750	150	2656	1.4×10^{-22}	1.4×10^{46}	2656	1.5×10^{-22}	1.7×10^{46}
-	400	2656	1.6×10^{-22}	1.7×10^{46}	2656	1.7×10^{-22}	1.9×10^{46}
1550	150	2656	3.8×10^{-22}	4.2×10^{47}	2656	3.8×10^{-22}	4.2×10^{47}
-	400	2656	3.9×10^{-22}	4.4×10^{47}	2656	4.1×10^{-22}	5.0×10^{47}

Table 8. Values for the $h_{\rm rss}^{50\%}$ and $E_{\rm GW}^{50\%}$ for half sine-Gaussian and ringdown waveforms for the most sensitive burst from SGR 1935+2154 for the long-duration search.

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Frequency (Hz)	τ (s)	Half Sine-Gaussian			Ringdown		
		Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)	Burst	$h_{\rm rss}^{50\%}$ (Hz$^{-1/2}$)	$E_{\rm GW}^{50\%}$ (erg)
55	150	2674	1.6×10^{-22}	2.8×10^{43}	2674	1.7×10^{-22}	3.1×10^{43}
-	400	2673	1.9×10^{-22}	3.7×10^{43}	2673	2.0×10^{-22}	4.1×10^{43}
150	150	2674	1.3×10^{-22}	1.3×10^{44}	2674	1.4×10^{-22}	1.5×10^{44}
-	400	2674	1.4×10^{-22}	1.5×10^{44}	2674	1.4×10^{-22}	1.6×10^{44}
450	150	2674	1.2×10^{-22}	1.1×10^{45}	2674	1.3×10^{-22}	1.2×10^{45}
-	400	2674	1.5×10^{-22}	1.6×10^{45}	2674	1.6×10^{-22}	1.8×10^{45}
750	150	2674	2.0×10^{-22}	8.1×10^{45}	2674	2.2×10^{-22}	9.6×10^{45}
-	400	2674	2.2×10^{-22}	9.9×10^{45}	2674	2.4×10^{-22}	1.1×10^{46}
1550	150	2674	5.7×10^{-22}	2.7×10^{47}	2674	5.6×10^{-22}	2.6×10^{47}
-	400	2674	4.9×10^{-22}	2.0×10^{47}	2674	5.0×10^{-22}	2.1×10^{47}

Table 9. Values for the $h_{\rm rss}^{50\%}$ and $E_{\rm GW}^{50\%}$ for half sine-Gaussian and ringdown waveforms for the most sensitive burst from Swift J1818.0−1607 for the long-duration search.

APPENDIX

A. MODIFICATIONS TO THE PARAMETERS OF THE SHORT-DURATION SEARCH

It should be noted that the burst times are distributed such that the standard 3 h symmetric background in the short-duration searches would in some cases include the time of the previous or subsequent burst. We mitigate this by either reducing the background length or adjusting the background asymmetry factor (the fraction of background time before the burst) to optimize the amount of background data that could be used for each burst. Full details of these modifications are provided in Table 10.

In addition to modifying the length and background asymmetry factor of the background to exclude neighboring bursts, there are also modifications to the search that we do in order to increase the sensitivity of each burst. These include vetoing events in specific frequency bands that display high non-Gaussianity and introducing an error region of the source to adjust for the motion of the Earth during the on-source window. A full list of these changes is given in Table 10.

B. DATA REMOVED FROM LONG-DURATION SEARCH WINDOWS

Data is required both before and after each pixel in the long-duration time-frequency map to estimate the pixel background (see Thrane et al. (2011) for details). In this search, we used 18 s of data before and after each pixel, as was done in Quitzow-James (2016); Quitzow-James et al. (2017); Abbott et al. (2019). Thus, any data removed from the long-duration on-source window includes up to an additional 36 s, with 18 s both before and after the interval to be removed (we also note that 1640 s of data are required for the full 1604 s long-duration on-source window).

Two on-source windows were missing data. One was the on-source window of burst 2651, which starts 87 s after the burst; since the on-source window starts 4 s before the burst and 18 s is needed to estimate the pixel background, the time-frequency map starts 109 s after the start of the on-source window (105 s after the burst). Data is available for the first 1121 s of the on-source window of burst 2665, leading to the time-frequency map ending after 1103 s. The on-source windows for bursts 2652, 2660 and 2665 each had 8 s of data removed due to data quality issues, leading to gaps of 44 s in the time-frequency maps. As was done in previous searches (including the O2 search (Abbott et al. 2019)), noisy spectral lines, such as 60Hz power line harmonics, were identified and removed from the time-frequency maps for each detector pair. Of special note, 55 Hz and 150 Hz were removed for the LHO/Virgo detector pair and 150 Hz for LLO/Virgo; thus, these detector pairs were not sensitive to injected waveforms in these respective frequencies. The Bezier curves for the clusters were generated identically to the other windows, with the missing times (and data removed due to noisy lines) not included in the calculation of the cluster SNR. The background segments were treated identically to their respective on-source windows.

Burst	Parameters of delayed on-source search	Parameters of centered on-source search
2652	Background Asymmetry Factor = .3726 Background length = 8090s Frequency Range = 300Hz to 4000Hz	Background Asymmetry Factor = .3858 Background length = 9056s
2653	Background Asymmetry Factor = .4711 Background length = 10790s Frequency Range = 65Hz to 4000 Hz Error Region = 1 deg.	
2655	Background Asymmetry Factor = 0.5677 Background length = 10790s	Background Asymmetry Factor = .5225 Background length = 10790s
2656	Background Asymmetry Factor = 0.4331 Background length = 10790s	Background Asymmetry Factor = .4775 Background length = 10790s
2660	Background Asymmetry Factor = 0.3421 Background length = 10790s	Background Asymmetry Factor = .3403 Background length = 10790s
2661	Error Region = 1 deg.	
2668	Error Region = 1 deg.	Frequency Range = 85 - 4000Hz
2669	Background Asymmetry Factor = 0.8993 Background length = 10790s	Background Asymmetry Factor = .854 Background length = 10790s
2670	Background Asymmetry Factor = 0.1015 Background length = 10790s	Background Asymmetry Factor = .1459 Background length = 10790s
2671		Background length = 10790s
2673	Frequency Range = 60Hz to 4000Hz Error Region = 1 deg.	

Table 10. Parameters used in the centered on-source and delayed on-source short-duration searches. When no value is specified, the search was run with the default parameters, including frequency ranging from 50-4000 Hz, a symmetric background window 10800s in length, and 0 degree error region. The background asymmetry factor is defined as the fraction of the background time before the burst time, with 0.5 corresponding to a symmetric background. The error region is defined as the 1σ uncertainty in the sky position of the source. Using a non-zero error region on a point source can sometimes increase the search sensitivity because it counters the effects of the earth's rotation during the on-source window.

C. INJECTED WAVEFORMS AND THRESHOLD CALCULATIONS

For both short-duration and long-duration searches we consider sine-Gaussian and ringdown waveforms whose polarizations are given respectively by

$$\begin{bmatrix} h_{+}^{\rm SG}(t) \\ h_{\times}^{\rm SG}(t) \end{bmatrix} = \frac{h_0}{\sqrt{2}} \begin{bmatrix} \frac{1+\cos^2\iota}{2} \times \cos(2\pi f_0 t) \\ \cos\iota \times \sin(2\pi f_0 t) \end{bmatrix} e^{-\frac{t^2}{\tau^2}} \tag{C1}$$

and

$$\begin{bmatrix} h_{+}^{\rm RD}(t) \\ h_{\times}^{\rm RD}(t) \end{bmatrix} = \frac{h_0}{\sqrt{2}} \begin{bmatrix} \frac{1+\cos^2\iota}{2} \times \cos(2\pi f_0 t) \\ \cos\iota \times \sin(2\pi f_0 t) \end{bmatrix} e^{-\frac{t}{\tau}} \qquad \text{for t} > 0 \tag{C2}$$

where ι is the inclination angle and τ is the damping time. An injection is circularly polarized in the case where $\iota = 0$, and elliptically polarized when ι is uniformly injected between -1 and 1.

All waveforms in the long-duration search (half sine-Gaussians and ringdowns) have circular polarization. For the short-duration search, the ringdown and most of the sine-Gaussian waveforms are elliptically polarized, and we calculate the threshold values of $E_{\rm GW}^{50\%}$ from the corresponding $h_{\rm rss}^{50\%}$ using the rotating system emission formula in the narrow-band approximation given by equation 17 of (Sutton 2013):

$$E_{GW} \approx \frac{2}{5}\frac{c^3\pi^2}{G}d^2 f_0^2 h_{\rm rss}^2 \ , \tag{C3}$$

where d is the distance to the source and f_0 is the central frequency. We note that Equation 17 of (Sutton 2013) defines hrss as that for an optimally oriented source ($\iota = 0$); the short-duration search uses this same convention when reporting the $h_{\rm rss}^{50\%}$ values given in Tables 4-7.

We calculate the $E_{\rm GW}^{50\%}$ of the white noise burst waveforms using equation 11 of (Sutton 2013) for isotropic emission, with correction factors to account for our waveforms being broadband. Specifically, we use:

$$E_{GW} = 1.0370 \times \frac{c^3\pi^2}{G}d^2 f_0^2 h_{\rm rss}^2 \tag{C4}$$

for white noise bursts with a frequency range from 100-200 Hz, and

$$E_{GW} = 1.2231 \times \frac{c^3\pi^2}{G}d^2 f_0^2 h_{\rm rss}^2 \tag{C5}$$

for white noise bursts with a frequency range of 100-1000 Hz.

The $h_{\rm rss}$ of a sine-Gaussian waveform derived from equation (2) is (Quitzow-James 2016):

$$h_{\rm rss}^{\rm SG} = h_0 \tau^{1/2} \frac{\pi^{1/4}}{2\left(2^{1/4}\right)} \sqrt{\left(\frac{(1+\cos^2\iota)^2}{4} + \cos^2\iota\right) + \left(\frac{(1+\cos^2\iota)^2}{4} - \cos^2\iota\right) \mathrm{e}^{-2\pi^2 f_0^2 \tau^2}} \ , \tag{C6}$$

The $h_{\rm rss}$ of a sine-Gaussian when the inclination angle $\iota = 0$ is:

$$h_{{\rm rss},\iota=0}^{\rm SG} = h_0 \sqrt{\tau} \frac{\pi^{1/4}}{2^{3/4}} \ . \tag{C7}$$

The $E_{\rm GW}$ of a sine-Gaussian waveform is (Quitzow-James 2016):

$$E_{\rm GW}^{\rm SG} = \frac{c^3 \pi^{5/2}}{5\sqrt{2}\, G} {h_0}^2 d^2 {f_0}^2 \tau \left[1 + \frac{1}{4\pi^2 f_0^2 \tau^2}\left(1 + \frac{1}{6}\mathrm{e}^{-2\pi^2 f_0^2 \tau^2}\right)\right] \ . \tag{C8}$$

For $Q = \sqrt{2}\pi f_0 \tau \gg 1$, this can be approximated as (Quitzow-James 2016):

$$E_{\rm GW}^{\rm SG} \approx \frac{c^3 \pi^{5/2}}{5\sqrt{2}\, G} {h_0}^2 d^2 {f_0}^2 \tau \ . \tag{C9}$$

The $E_{\rm GW}$ of a half sine-Gaussian is half of the $E_{\rm GW}$ of a sine-Gaussian, and the $h_{\rm rss}$ of a half sine-Gaussian is the $h_{\rm rss}$ of a sine-Gaussian divided by $\sqrt{2}$. The $h_{\rm rss}$ of a half sine-Gaussian with $\iota = 0$ is (Quitzow-James 2016):

$$h_{{\rm rss},\iota=0}^{\rm hSG} = \frac{h_{{\rm rss},\iota=0}^{\rm SG}}{\sqrt{2}} = h_0 \sqrt{\tau} \frac{\pi^{1/4}}{2^{5/4}} \ . \tag{C10}$$

The $E_{\rm GW}$ of a half sine-Gaussian waveform with $Q = \sqrt{2}\pi f_0 \tau \gg 1$ can be approximated as (Quitzow-James 2016):

$$E_{\rm GW}^{\rm hSG} \approx \frac{c^3 \pi^{5/2}}{10\sqrt{2}\, G} {h_0}^2 d^2 {f_0}^2 \tau \ . \tag{C11}$$

The $h_{\rm rss}$ of a ringdown waveform can be derived from (2):

$$h_{\rm rss}^{\rm ringdown} = \frac{h_0}{2}\sqrt{\frac{\tau}{2}} \left[\left(\frac{(1+\cos^2\iota)^2}{4} + \cos^2\iota\right) + \frac{1}{1+4\pi^2 f_0^2 \tau^2}\left(\frac{(1+\cos^2\iota)^2}{4} - \cos^2\iota\right)\right]^{1/2} \ . \tag{C12}$$

For $\iota = 0$ this becomes:

$$h_{{\rm rss},\iota=0}^{\rm ringdown} = \frac{h_0}{2}\sqrt{\tau} \ . \tag{C13}$$

And $E_{\rm GW}$ can be calculated to be:

$$E_{\rm GW}^{\rm ringdown} = \frac{c^3}{40G} h_0^2 d^2 \left(\frac{1+4\pi^2 f_0^2 \tau^2}{\tau}\right) \left(1 + \left(\frac{1}{6}\right) \frac{1}{1+4\pi^2 f_0^2 \tau^2}\right) . \tag{C14}$$

For $Q = \sqrt{2}\pi f_0 \tau \gg 1$:

$$E_{\rm GW}^{\rm ringdown} \approx \frac{\pi^2 c^3}{10G} d^2 f_0^2 h_0^2 \tau . \tag{C15}$$

It is important to note that the short-duration ringdown waveforms include a *ringup* right before the injection time for the purpose of avoiding a discontinuous jump in the signal. This ringup has a rise time that is $\frac{1}{10}$ of the ringdown damping time. When including this ringup, the $h_{\rm rss}$ of the total waveform is the $h_{\rm rss}$ of the ringup and ringdown added in quadrature while the $E_{\rm GW}$ of the ringup and ringdown are add linearly. This gives:

$$h_{{\rm rss},\iota=0}^{\rm ringup+ringdown} = \frac{h_0}{2}\sqrt{\tau + \tau\frac{1}{10}} = \frac{h_0}{2}\sqrt{\tau\frac{11}{10}} , \tag{C16}$$

and (for $\sqrt{2}\pi f_0 \tau \gg 1$):

$$E_{\rm GW}^{\rm ringup+ringdown} \approx \frac{\pi^2 c^3}{10G} d^2 f_0^2 h_0^2 \tau (11/10) . \tag{C17}$$

REFERENCES

Aasi, J., Abbott, B. P., Abbott, R., et al. 2015, Classical and Quantum Gravity, 32, 074001, doi: 10.1088/0264-9381/32/7/074001

Aasi, J., et al. 2014, Phys. Rev. Lett., 113, 011102, doi: 10.1103/PhysRevLett.113.011102

Abadie, J., et al. 2011, The Astrophysical Journal, 734, L35, doi: 10.1088/2041-8205/734/2/l35

—. 2012, The Astrophysical Journal, 755, 2, doi: 10.1088/0004-637x/755/1/2

Abbott, B. P., et al. 2007, Phys. Rev. D, 76, 062003, doi: 10.1103/PhysRevD.76.062003

—. 2008a, Phys. Rev. Lett., 101, 211102, doi: 10.1103/PhysRevLett.101.211102

—. 2008b, The Astrophysical Journal, 681, 1419, doi: 10.1086/587954

—. 2009, The Astrophysical Journal, 701, L68, doi: 10.1088/0004-637x/701/2/l68

—. 2018, Living Rev. Rel., 21, 3, doi: 10.1007/s41114-020-00026-9

—. 2019, ApJ, 874, 163, doi: 10.3847/1538-4357/ab0e15

Abbott, R., et al. 2021a, ApJ, 915, 86, doi: 10.3847/1538-4357/abee15

—. 2021b, doi: 10.48550/ARXIV.2111.03608

—. 2022, doi: 10.48550/ARXIV.2203.12038

Acernese, F., Agathos, M., Agatsuma, K., et al. 2015, Classical and Quantum Gravity, 32, 024001, doi: 10.1088/0264-9381/32/2/024001

Ackley, K., Adya, V. B., Agrawal, P., et al. 2020, PASA, 37, e047, doi: 10.1017/pasa.2020.39

Akutsu, T., Ando, M., Arai, K., et al. 2019, Nature Astronomy, 3, 35, doi: 10.1038/s41550-018-0658-y

Akutsu, T., Ando, M., Arai, K., et al. 2021, Progress of Theoretical and Experimental Physics, 2021, doi: 10.1093/ptep/ptab018

Barat, C., Hayles, R. I., Hurley, K., et al. 1983, A&A, 126, 400

Barsotti, L., Gras, S., Evans, M., & Fritschel, P. 2018, Updated Advanced LIGO sensitivity design curve. https://dcc.ligo.org/LIGO-T1800044/public

Boggs, S. E., Zoglauer, A., Bellm, E., et al. 2007, ApJ, 661, 458, doi: 10.1086/516732

Buikema, A., Cahillane, C., Mansell, G. L., et al. 2020, Phys. Rev. D, 102, 062003, doi: 10.1103/PhysRevD.102.062003

Burns, E., Svinkin, D., Hurley, K., et al. 2021, The Astrophysical Journal Letters, 907, L28, doi: 10.3847/2041-8213/abd8c8

Ciolfi, R., Lander, S. K., Manca, G. M., & Rezzolla, L. 2011, ApJL, 736, L6, doi: 10.1088/2041-8205/736/1/L6

Ciolfi, R., & Rezzolla, L. 2012, ApJ, 760, 1, doi: 10.1088/0004-637X/760/1/1

Colaiuda, A., & Kokkotas, K. D. 2011, MNRAS, 414, 3014, doi: 10.1111/j.1365-2966.2011.18602.x

Corsi, A., & Owen, B. J. 2011, Physical Review D, 83, doi: 10.1103/physrevd.83.104014

Cummings, J., Barthelmy, S., Chester, M., & Page, K. 2014, The Astronomer's Telegram, 6294, 1

Davis, D., et al. 2021, Classical and Quantum Gravity, 38, 135014, doi: 10.1088/1361-6382/abfd85

Duncan, R. C. 1998, ApJL, 498, L45, doi: 10.1086/311303

Durant, M., & van Kerkwijk, M. H. 2006, The Astrophysical Journal, 650, 1070–1081, doi: 10.1086/506380

Essick, R., Godwin, P., Hanna, C., Blackburn, L., & Katsavounidis, E. 2020, Machine Learning: Science and Technology, 2, 015004

Evans, M., et al. 2021. https://arxiv.org/abs/2109.09882

Evans, P., Gropp, J., Kennea, J., et al. 2020, GRB Coordinates Network, 27373, 1

Evans, W. D., Klebesadel, R. W., Laros, J. G., et al. 1980, ApJL, 237, L7, doi: 10.1086/183222

Glampedakis, K., & Jones, D. I. 2014, MNRAS, 439, 1522, doi: 10.1093/mnras/stu017

Glampedakis, K., Samuelsson, L., & Andersson, N. 2006, MNRAS, 371, L74, doi: 10.1111/j.1745-3933.2006.00211.x

Ho, W. C. G., Jones, D. I., Andersson, N., & Espinoza, C. M. 2020, Phys. Rev. D, 101, 103009, doi: 10.1103/PhysRevD.101.103009

Huppenkothen, D., Heil, L. M., Watts, A. L., & Göğüş, E. 2014a, ApJ, 795, 114, doi: 10.1088/0004-637X/795/2/114

Huppenkothen, D., D'Angelo, C., Watts, A. L., et al. 2014b, ApJ, 787, 128, doi: 10.1088/0004-637X/787/2/128

Hurley, K. 2021, SGR Burst List. http://www.ssl.berkeley.edu/ipn3/sgrlist.txt

Hurley, K., Cline, T., Mazets, E., et al. 1999, Nature, 397, 41, doi: 10.1038/16199

Hurley, K., Boggs, S. E., Smith, D. M., et al. 2005, Nature, 434, 1098, doi: 10.1038/nature03519

Ioka, K. 2001, Monthly Notices of the Royal Astronomical Society, 327, 639–662, doi: 10.1046/j.1365-8711.2001.04756.x

Israel, G. L., Belloni, T., Stella, L., et al. 2005, ApJL, 628, L53, doi: 10.1086/432615

Kalmus, P. 2009, PhD thesis. https://arxiv.org/abs/0904.4394

Kalmus, P., Cannon, K. C., Márka, S., & Owen, B. J. 2009, Phys. Rev. D, 80, 042001, doi: 10.1103/PhysRevD.80.042001

Kalmus, P., Khan, R., Matone, L., & Márka, S. 2007, Classical and Quantum Gravity, 24, S659, doi: 10.1088/0264-9381/24/19/s28

Karuppusamy, R., et al. 2020, Detection of pulsed radio emission from new magnetar Swift J1818.0-1607. https://www.astronomerstelegram.org/?read=13553

Kashiyama, K., & Ioka, K. 2011, Phys. Rev. D, 83, 081302, doi: 10.1103/PhysRevD.83.081302

Kaspi, V. M., & Beloborodov, A. M. 2017, Annual Review of Astronomy and Astrophysics, 55, 261–301, doi: 10.1146/annurev-astro-081915-023329

Kirsten, F., Snelders, M. P., Jenkins, M., et al. 2020, Nature Astronomy, 5, 414, doi: 10.1038/s41550-020-01246-3

Kissel, J. 2020, aLIGO, CAL, Official Advanced LIGO Sensitivity Plots. https://dcc.ligo.org/LIGO-G1500623/public

Lesage, S., et al. 2020, GCN Circular 26980. https://gcn.gsfc.nasa.gov/gcn/gcn3/26980.gcn3

Levin, Y. 2007, MNRAS, 377, 159, doi: 10.1111/j.1365-2966.2007.11582.x

Levin, Y., & van Hoven, M. 2011, Monthly Notices of the Royal Astronomical Society, 418, 659–663, doi: 10.1111/j.1365-2966.2011.19515.x

Lin, L., Göğüş, E., Roberts, O. J., et al. 2020, The Astrophysical Journal Letters, 902, L43

Lindblom, L., & Detweiler, S. L. 1983, ApJS, 53, 73, doi: 10.1086/190884

Macquet, A., Bizouard, M. A., Burns, E., et al. 2021, ApJ, 918, 80, doi: 10.3847/1538-4357/ac0efd

Matone, L., & Márka, S. 2007, Classical and Quantum Gravity, 24, S649, doi: 10.1088/0264-9381/24/19/s27

Mazets, E. P., Aptekar, R. L., Cline, T. L., et al. 2008, ApJ, 680, 545, doi: 10.1086/587955

McDermott, P. N., van Horn, H. M., & Hansen, C. J. 1988, ApJ, 325, 725, doi: 10.1086/166044

Meegan, C., et al. 2009, ApJ, 702. https://iopscience.iop.org/article/10.1088/0004-637X/702/1/791/meta

Mereghetti, S., Götz, D., von Kienlin, A., et al. 2005, ApJL, 624, L105, doi: 10.1086/430669

Messios, N., Papadopoulos, D. B., & Stergioulas, N. 2001, MNRAS, 328, 1161, doi: 10.1046/j.1365-8711.2001.04645.x

Murphy, D., Tse, M., Raffai, P., et al. 2013, Phys. Rev. D, 87, 103008, doi: 10.1103/PhysRevD.87.103008

Olausen, S. A., & Kaspi, V. M. 2014, The Astrophysical Journal Supplement Series, 212, 6, doi: 10.1088/0067-0049/212/1/6

Piro, A. L. 2005, ApJL, 634, L153, doi: 10.1086/499049

Punturo, M., Abernathy, M., Acernese, F., et al. 2010, Classical Q. Gravity, 27, 194002, doi: 10.1088/0264-9381/27/19/194002

Quitzow-James, R. 2016, PhD thesis. https://dcc.ligo.org/LIGO-P1600095

Quitzow-James, R., et al. 2017, Classical and Quantum Gravity, 34, 164002, doi: 10.1088/1361-6382/aa7d5b

Reitze, D., et al. 2019, Bull. Am. Astron. Soc., 51, 035. https://arxiv.org/abs/1907.04833

Robinet, F., Arnaud, N., Leroy, N., et al. 2020, SoftwareX, 12, 100620

Schale, P. 2019, PhD thesis. https://scholarsbank.uoregon.edu/xmlui/handle/1794/24835

Strohmayer, T. E., & Watts, A. L. 2005, ApJL, 632, L111, doi: 10.1086/497911

—. 2006, ApJ, 653, 593, doi: 10.1086/508703

Sutton, P. J. 2013, A Rule of Thumb for the Detectability of Gravitational-Wave Bursts, arXiv, doi: 10.48550/ARXIV.1304.0210

Sutton, P. J., Jones, G., Chatterji, S., et al. 2010, New Journal of Physics, 12, 053034, doi: 10.1088/1367-2630/12/5/053034

Svinkin, D., Frederiks, D., Hurley, K., et al. 2021, Nature, 589, 211, doi: 10.1038/s41586-020-03076-9

Thrane, E., & Coughlin, M. 2013, Phys. Rev. D, 88, 083010, doi: 10.1103/PhysRevD.88.083010

Thrane, E., Kandhasamy, S., Ott, C. D., et al. 2011, Phys. Rev. D, 83, 083004, doi: 10.1103/PhysRevD.83.083004

Tsokaros, A., Ruiz, M., Shapiro, S. L., & Uryū, K. 2021, Magnetohydrodynamic simulations of self-consistent rotating neutron stars with mixed poloidal and toroidal magnetic fields. https://arxiv.org/abs/2111.00013

Verkindt, D. 2021, Sensitivity curves and BNS range for Virgo in O2 and O3. https://tds.virgo-gw.eu/?content=3&r=19594

Was, M., Sutton, P. J., Jones, G., & Leonor, I. 2012, Phys. Rev. D, 86, 022003, doi: 10.1103/PhysRevD.86.022003

Watts, A. L., & Strohmayer, T. E. 2006, ApJL, 637, L117, doi: 10.1086/500735

Wen, D.-H., Li, B.-A., Chen, H.-Y., & Zhang, N.-B. 2019, Physical Review C, 99, doi: 10.1103/physrevc.99.045806

Wen, D.-H., Li, B.-A., Chen, H.-Y., & Zhang, N.-B. 2019, Phys. Rev. C, 99, 045806, doi: 10.1103/PhysRevC.99.045806

Zhong, S.-Q., Dai, Z.-G., Zhang, H.-M., & Deng, C.-M. 2020, The Astrophysical Journal, 898, L5, doi: 10.3847/2041-8213/aba262

Zink, B., Lasky, P. D., & Kokkotas, K. D. 2012, Phys. Rev. D, 85, 024030, doi: 10.1103/PhysRevD.85.024030

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