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A search using GEO600 for gravitational waves coincident with fast radio bursts from SGR 1935+2154

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

ABSTRACT

The magnetar SGR 1935+2154 is the only known Galactic source of fast radio bursts (FRBs). FRBs from SGR 1935+2154 were first detected by CHIME/FRB and STARE2 in 2020 April, after the conclusion of the LIGO, Virgo, and KAGRA Collaborations' O3 observing run. Here we analyze four periods of gravitational wave (GW) data from the GEO600 detector coincident with four periods of FRB activity detected by CHIME/FRB, as well as X-ray glitches and X-ray bursts detected by NICER and NuSTAR close to the time of one of the FRBs. We do not detect any significant GW emission from any of the events. Instead, using a short-duration GW search (for bursts ≤ 1 s) we derive 50% (90%) upper limits of 10^{48} (10^{49}) erg for GWs at 300 Hz and 10^{49} (10^{50}) erg at 2 kHz, and constrain the GW-to-radio energy ratio to $\leq 10^{14} - 10^{16}$. We also derive upper limits from a long-duration search for bursts with durations between 1 and 10 s. These represent the strictest upper limits on concurrent GW emission from FRBs.

Keywords: gravitational waves—fast radio bursts—multi-messenger astronomy—magnetars—neutron stars

1. INTRODUCTION

Fast radio bursts (FRBs) are a class of extremely energetic radio transients which are theorized to be associated with neutron stars (Platts et al. 2019; Petroff et al. 2019; Bailes 2022; Zhang 2023). To date, thousands of FRBs have been detected. The majority of these have been discovered using the Canadian Hydrogen Intensity Mapping Experiment (CHIME) telescope (Amiri et al. 2022) by the CHIME/FRB Collaboration (CHIME/FRB) (CHIME/FRB Collaboration et al. 2018)[1]. Though the origins of FRBs remain unknown, their dispersion measure (DM) as observed by radio telescopes localizes them to extragalactic (and even cosmological) distances (Thornton et al. 2013; Cordes & Chatterjee 2019).

The notable exceptions to this extragalactic consensus are the FRBs associated with FRB 20200428A. First detected in 2020 April by CHIME/FRB and the Survey for Transient Astronomical Radio Emission 2 (STARE2) (Bochenek et al. 2020a), FRB 20200428A was quickly found to be associated with the Galactic magnetar SGR 1935+2154, which was undergoing an unusual period of flaring X-ray activity at that time (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020b; Barthelmy et al. 2020; Palmer & BAT Team 2020). Simultaneous X-ray observations from Konus-Wind (Frederiks et al. 2022), INTEGRAL (Mereghetti et al. 2020), AGILE (Tavani et al. 2020), and Insight-HXMT (Li et al. 2022) led to the first coincident observation of both radio emission and X-rays from an FRB source. FRBs from SGR 1935+2154 were also observed during three other epochs by CHIME/FRB and others, on 2020 October 08, 2022 October 14, and 2022 December 01.[2] Additionally, X-ray glitches and bursts from SGR 1935+2154 were observed by NICER and NuSTAR during the nine hours surrounding the 2022 October 14

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[1] https://www.chime-frb.ca/voevents

[2] We note that the classification of these radio bursts as FRBs remains unclear: the SGR 1935+2154 radio bursts are a few orders of magnitude less luminous than typical extragalactic FRBs, but are still brighter than most giant radio pulses (Giri et al. 2023). Bochenek et al. (2020a) name them as FRBs while Giri et al. (2023) call them FRB-like. Here, we describe them as FRBs.

FRB (Hu et al. 2024). The connection between these X-ray bursts and FRBs, even from the same magnetar, is not well understood—indeed, radio emission with no coincident X-rays has been detected from SGR 1935+2154 (Zhu et al. 2023) and vice versa (Younes et al. 2017).

The compact object nature of these powerful transients suggests that gravitational waves (GWs) could also be emitted by the same mechanisms that produce FRBs. The detection of GWs from an FRB source (or lack thereof) could help to elucidate the mechanisms behind FRBs (Zhang 2023), and potentially expand the realm of detected GWs beyond those with compact binary coalescence (CBC) origins.

Previous works by the LIGO, Virgo, and KAGRA Collaborations (LVK) have searched for GW emission coincident with FRBs (Abbott et al. 2016, 2023), as well as for GWs from magnetar bursts (Abbott et al. 2019a,b; Macquet et al. 2021; Abbott et al. 2024) and pulsar glitches (Abadie et al. 2011; Keitel et al. 2019; Abbott et al. 2022) using the Advanced LIGO and Advanced Virgo GW observatories (Aasi et al. 2015; Acernese et al. 2014). While no detections were found in these studies, the searches have established upper limits on GW energy that may have been emitted in association with these events. In particular, Abbott et al. (2023) performed a search for GW emission coincident with FRBs from CHIME/FRB during the O3a LIGO–Virgo observing run, with searches targeted at GWs from CBCs as well as generic GW transients, setting an upper limit of $10^{51}-10^{57}$ erg of GW energy within 70-3560 Hz. In addition, Abbott et al. (2024) placed upper limits on GW energy ($\sim 10^{43}$ erg) coincident with 11 X-ray and soft gamma-ray magnetar bursts from SGR 1935+2154.

SGR 1935+2154, as the first (and at the time of writing, only) FRB source to be confidently associated with a specific neutron star progenitor, presents a unique opportunity to search for GWs when the source is localized to a particular compact object. Additionally, at $\sim$ 6.6 kpc (Zhou et al. 2020), it is more than two orders of magnitude nearer to Earth than the next closest FRB, which has been localized to the nearby galaxy M81, 3.6 Mpc away (Bhardwaj et al. 2021; Kirsten et al. 2022).

The four periods of FRB activity from SGR 1935+2154 fell in between the O3 and O4 observing runs of the LVK, when the LIGO and Virgo detectors were offline[3]. Fortunately, GEO600 (Grote et al. 2004; Lueck et al. 2010; Affeldt et al. 2014; Dooley et al. 2016), a GW detector in Hannover, Germany that is operated by members of the LIGO Scientific Collaboration, was observing in Astrowatch mode (Grote & the LIGO Scientific Collaboration 2010) and collecting GW data during all four periods. The CHIME/FRB events for three of the four periods occurred when GEO600 was in observing mode, while the fourth FRB occurred within minutes of when GEO600 was observing (see Sec. 3).

In this paper, we analyze GEO600 data to search for GW emission coincident with the four FRBs observed by CHIME/FRB from SGR 1935+2154. We conduct two searches for unmodeled GW transients: one targeted at short-duration bursts with $\mathcal{O}$(second) durations, and another aimed at long-duration bursts lasting from 1 to 10 seconds. Due to SGR 1935+2154's proximity, the results constitute the most sensitive searches for GWs from FRB sources to date, despite GEO600's lower sensitivity compared to LIGO and Virgo (see Fig. 1). We also search for GWs coincident with the two X-ray glitches and the X-ray burst peak observed by NICER and NuSTAR in the hours around the FRB on 2022 October 14 (Hu et al. 2024). The paper is organized as follows: in Sec. 2, we describe the electromagnetic (EM) observations of FRBs from SGR 1935+2154. Section 3 details our short- and long-duration searches for GWs, with results presented in Sec. 4. We discuss the implications of these findings and conclude in Sec. 5.

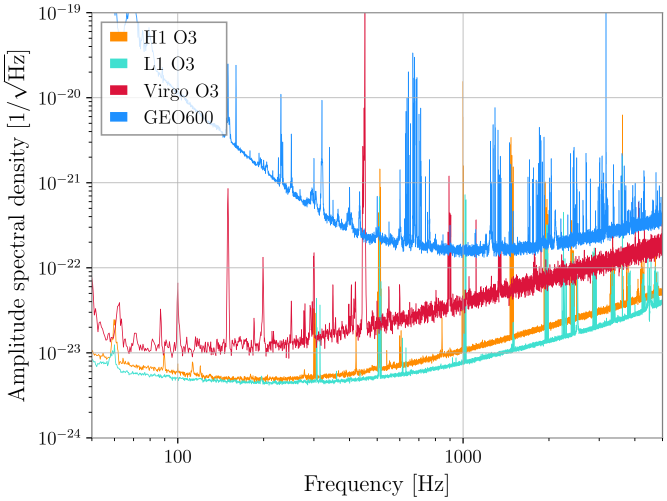

Figure 1. Amplitude spectral density of GEO600 on 2020 April 28 compared to those of LIGO Hanford, LIGO Livingston, and Virgo during O3 (Abbott et al. 2020). While at low frequencies GEO600's sensitivity is substantially diminished compared to that of the larger detectors, the gap narrows at frequencies around 2 kHz, near the expected neutron star f-mode frequency.

2. FAST RADIO BURSTS FROM SGR 1935+2154

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[3] https://observing.docs.ligo.org/plan/

The magnetar SGR 1935+2154 was discovered by Swift in 2014 (Stamatikos et al. 2014; Lien et al. 2014). Since then, it has been highly active, with periods of intense emission in the X-ray and radio (Israel et al. 2016; Younes et al. 2017).

On 2020 April 27, Swift observed multiple X-ray bursts from SGR 1935+2154, suggesting that the magnetar had entered a period of high activity (Barthelmy et al. 2020). Less than 24 hours later, CHIME/FRB and STARE2 detected an FRB from the location of SGR 1935+2154 (CHIME/FRB Collaboration et al. 2020; Bochenek et al. 2020b). Konus-Wind (Frederiks et al. 2022), INTEGRAL (Mereghetti et al. 2020), AGILE (Tavani et al. 2020), and Insight-HXMT (Li et al. 2022) observed hard X-rays arriving at the same time, serving as the first ever observation of simultaneous radio and X-ray emission from an FRB source. Follow-up radio observations during the same active period by the Five-hundred-meter Aperture Spherical radio Telescope (FAST) (Zhang et al. 2020) and radio telescopes from the European VLBI Network (EVN) (Kirsten et al. 2021) identified additional radio bursts from SGR 1935+2154, though at lower energies. At higher energies, no gamma-ray emission has been observed from this source (Abdalla et al. 2021; Principe et al. 2023).

Since 2020 April, SGR 1935+2154 has had multiple periods of high activity leading to the emission of FRBs. On 2020 October 08, CHIME/FRB observed three FRBs from SGR 1935+2154 arriving within a few seconds (Good & CHIME/FRB Collaboration 2020; Pleunis & CHIME/FRB Collaboration 2020; Giri et al. 2023). CHIME/FRB and the Green Bank Telescope (GBT) observed FRBs again two years later on 2022 October 14, with a CHIME/FRB event surrounded by five GBT FRBs within 1.5 seconds (Dong & CHIME/FRB Collaboration 2022; Maan et al. 2022; Giri et al. 2023). During the days around the FRBs on 2022 October 14, SGR 1935+2154 was undergoing a period of intense X-ray burst activity. This burst storm began on October 10 (Mereghetti et al. 2022; Palmer 2022) and was monitored by various telescopes such as NICER, NuSTAR, and XMM-Newton (see, e.g., Hu et al. (2024); Ibrahim et al. (2024)), which detected hundreds of milliseconds- to seconds-long bursts of high energy photons. The X-ray burst rate peaked during a flare 2.5 hr (±1 min) before the FRB and then steadily decreased over the next hours (Hu et al. 2024). In addition, the high-cadence monitoring observations allowed accurate measurements of the spin rate of SGR 1935+2154 (nominally 0.308 Hz; Israel et al. (2016)). The evolution of the spin rate showed that SGR 1935+2154 underwent a spin-up glitch about 4.4 hr (±30 min) before the FRB and another spin-up glitch about 4.4 hr (±30 min) after the FRB, while the magnetar's spin-down rate between these two glitches was about one hundred times higher than its normal rate (Hu et al. 2024). X-ray bursts were also detected by GECAM and HEBS (Wang et al. 2022) and Konus-Wind (Frederiks et al. 2022) arriving within the expected FRB dispersion time. In addition to the NICER and NuSTAR observations mentioned above (Enoto et al. 2022), Insight-HXMT (Li et al. 2022) also observed X-rays from SGR 1935+2154 during this active period, though at the time of the FRB, all three were occulted by the Earth. Finally, a fourth FRB was detected by CHIME/FRB on 2022 December 01 (Pearlman & CHIME/FRB Collaboration 2022; Giri et al. 2023), accompanied by a faint hard X-ray signal detected by Fermi-GBM (Younes et al. 2022).

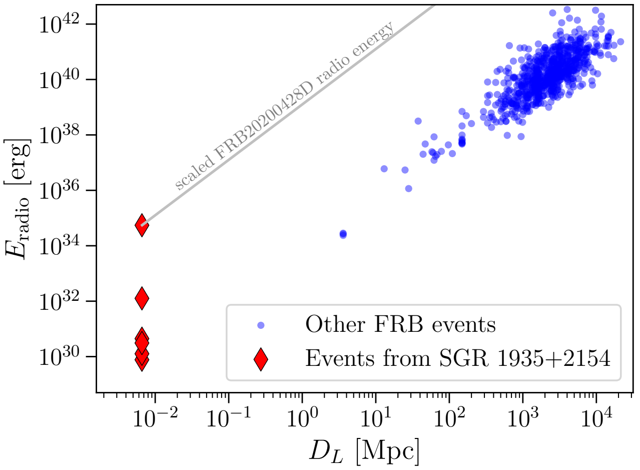

Figure 2. Radio energy versus luminosity distance for the SGR 1935+2154 FRBs investigated in this work (dark orange, Giri et al. (2023)) and for 749 other public FRBs published by CHIME/FRB and others (Petroff et al. 2016; Rajwade et al. 2020; CHIME/FRB Collaboration et al. 2021) (blue). The FRB sample and the calculation of distances and radio energies is described in Principe et al. (2023) (with the exception of the FRBs studied in Abbott et al. (2023), for which we use the lower bound 90% distances from that analysis). Note that the radio energies from CHIME/FRB (derived from fluxes and fluences) should be interpreted as lower limits (CHIME/FRB Collaboration et al. 2021; Andersen et al. 2023). We show the radio energy of the most luminous SGR 1935+2154 FRB, FRB20200428D, scaled to larger distances.

Most estimates and methods place the distance to SGR 1935+2154 between 1.5 and 15 kpc (Park et al. 2013; Pavlovic et al. 2014; Surnis et al. 2016; Kothes et al. 2018; Ranasinghe et al. 2018; Zhong et al. 2020; Zhou et al. 2020; Bailes et al. 2021). We adopt the determination by Zhou et al. (2020) of 6.6 ± 0.7 kpc, falling near the mean of the measurements.

These SGR 1935+2154 FRBs are not quite like the rest of the population of FRBs, as mentioned in Sec. 1. As shown in Nimmo et al. (2022), they exhibit characteristics very similar to the extragalactic FRBs, but are a few orders of magnitude less luminous. Whether the SGR 1935+2154 FRBs are in the tail of the same population or truly occupy a different part of the phase space remains an open question. For example, while the 2020 April FRB from SGR 1935+2154 was several orders of magnitude less energetic than most FRBs, it was three orders of magnitude brighter than the next brightest previously observed radio flare from a magnetar (CHIME/FRB Collaboration et al. 2020). Figure 2 shows the radio energy as a function of distance for the FRBs from SGR 1935+2154, alongside a sample of 749 FRBs from CHIME/FRB[4] (CHIME/FRB Collaboration et al. 2021), the FRBCAT (Petroff et al. 2016), and the 76 m Lovell telescope (Rajwade et al. 2020) as collected and described in Principe et al. (2023). This could suggest that the emission mechanism which produces FRBs from SGR 1935+2154 may be different from that which results in FRBs from cosmological distances. Despite this reduced brightness compared to the typical FRB population, SGR 1935+2154's proximity as the only known Galactic FRB source means that it presents the most promising opportunity to date for multi-wavelength and multi-messenger studies of FRB emitters.

2.1. *Models for coincident GW-FRB emission*

Magnetars have long been theorized to be progenitors of FRBs (Platts et al. 2019). The detection of FRBs from SGR 1935+2154, a well-studied magnetar, has now confirmed this association for at least some FRBs, though the exact emission mechanism remains unclear (Lyubarsky 2021; Zhang 2023).

Most models which predict GW emission from FRB progenitors assume a CBC association, such as during or after the final stages of the CBC inspiral (Wang et al. 2016; Yamasaki et al. 2018), long before the CBC merger through interactions of magnetospheres (Zhang 2020), or other interactions of compact binaries with their environments (see Platts et al. (2019) for a review of FRB theory). Prior studies such as Abbott et al. (2023) have searched for GWs from these sources using targeted matched-filter analyses, aimed at CBC sources. Since SGR 1935+2154 is not in a compact binary (Chrimes et al. 2022) and has exhibited multiple periods of FRB activity, we do not expect CBC-like GW emission from this source. Instead, as a magnetar, we can focus on only a few possible emission mechanisms for GWs coincident with FRBs.

Since at least some FRBs originate from magnetars, theories have drawn connections between them and magnetar giant flares (Tendulkar et al. 2016; Margalit et al. 2020; Cehula et al. 2024), which are are thought to be powered by magnetic activity near the surface of a neutron star (Thompson & Duncan 1996; Gaensler et al. 2005). These giant flares are rare but so energetic that GW emission may be detectable (Ioka 2001; Corsi & Owen 2011). Quasi-periodic oscillations in the X-ray tails of giant flares may also create GWs (Levin & van Hoven 2011; Quitzow-James et al. 2017). While no giant flares from SGR 1935+2154 were detected during its periods of FRB activity, the coincident X-ray activity suggests a potential link in the provenance of the high-energy EM emission.

Crustal f-modes are a possible source of transient GWs from isolated neutron stars (Glampedakis & Gualtieri 2018; Ho et al. 2020). These typically fall at around 2 kHz (Andersson & Kokkotas 1996), near the frequencies where GEO600 is most sensitive (see Fig. 1).

Moreover, neutron star glitches, such as those from SGR 1935+2154 in 2022 October investigated in this work, may emit GWs potentially observable by current GW detectors (Prix et al. 2011; Warszawski & Melatos 2012; Melatos et al. 2015). Previous limits were derived for the Vela pulsar (located at 290 pc; Dodson et al. (2003)) glitch in 2006, providing limits on the emitted GW energy of the order of 10^{45} erg (Abadie et al. 2011).

3. SEARCH FOR GRAVITATIONAL WAVES

Using data from GEO600 we search for generic GW transients from SGR 1935+2154 around the times of four FRBs detected by CHIME/FRB. GEO600 is a dual-recycled Michelson interferometer with folded arms and takes astrophysical observations in the 40 Hz - 6 kHz frequency band when operating in Astrowatch mode (Grote & the LIGO Scientific Collaboration 2010). Over the past two decades, it has pioneered several key technologies for GW detectors (Affeldt et al. 2014; Lough et al. 2021). GEO600 has lower sensitivity compared to the Advanced LIGO & Advanced Virgo detectors ($\sim 10^{-22}/\sqrt{\mathrm{Hz}}$ at 1 kHz, see Fig. 1), but has strengths in uptime. It continued taking observations during the initial period of the COVID-19 pandemic and subsequent LIGO and Virgo upgrades throughout 2020-2022, during which CHIME/FRB observed these FRBs from SGR 1935+2154.

Given the unknown nature of the emission mechanism of the FRBs, we search for generic transient gravitational-wave signals present in the GEO600 data using two un-

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[4] https://www.chime-frb.ca/repeaters

modeled burst searches: `PySTAMP` (Macquet et al. 2021), targeted at long-duration bursts with lengths from 1-10 s, and `X-Pipeline` (Sutton et al. 2010; Was et al. 2012), for short-duration bursts lasting less than 1 s. Previous searches for GWs coincident with FRBs, such as the ones presented in Abbott et al. (2023), also considered a possible CBC origin for the GW emission; the non-compact binary nature of SGR 1935+2154 precludes the use of CBC matched-filter searches. Given that SGR 1935+2154 is a magnetar, we follow the previous GW magnetar study presented in Abbott et al. (2024) and employ `PySTAMP` to perform a long-duration search, which has not previously been used for GW FRB analyses. Additionally, prior searches have typically been restricted to coincidences with FRBs where data from at least two GW detectors is available. For these FRBs from SGR 1935+2154, only GEO600 was observing, so we employ a single-detector search. This limits our ability to veto candidates based on coherence between detectors and the amount of background that can be estimated, reducing the search sensitivity, but given the extraordinary nature of these FRBs, we determined that a single-detector search in GEO600 data was warranted.

For the 2020 April 28, 2020 October 08, and 2022 October 14 FRBs, we perform a search within an "on-source" time window starting at 1200 s before the infinite-frequency arrival time (i.e., the time accounting for the frequency-dependent delay introduced by the dispersion measure) of the FRB, t_0, and ending 120 s after. On 2020 October 08, three bursts were detected by CHIME/FRB within 3 s; we use the first time, corresponding to the FRB with the highest fluence on that day, as our t_0. The FRB on 2022 December 01 occurred during a time when GEO600 was not taking data, having exited observing mode approximately six minutes before the FRB, at 22:01:09 UTC. GEO600 returned to observing mode 23 minutes later, at 22:23:59 UTC. To be consistent with the on-source window for the other FRBs, we analyze the 800 s period of data beginning 1200 s before the FRB and ending shortly before GEO600 exited observing mode. Due to the large uncertainties in FRB–GW models (as described above in Sec. 2.1), we use a wide extended on-source window of $[-1200, 120]$ s. This allows us to probe a broad parameter space while keeping the detector behavior relatively stationary. We also employ a compact $[-4, 4]$ s search window in the short-duration search to probe the time immediately surrounding the FRB with higher sensitivity. In addition, we search for emission around the time of three X-ray events detected by NuSTAR and NICER on 2022 October 14. These events consisted of a spin-up glitch, a peak in the X-ray burst emission, and another spin-up glitch. Since the uncertainty in their times is greater than a minute, we only perform an extended-window search, targeting a symmetric $[-1000, 1000]$ s window, subject to data availability. Table 1 summarizes the times and windows for which we perform searches.

We restrict our search to frequencies from 300 Hz to 4096 Hz, with the lower cutoff set by the low frequency sensitivity of GEO600 and the upper cutoff aiming to capture neutron star crustal f-modes, which are predicted to fall at approximately 2 kHz (Andersson & Kokkotas 1996).

3.1. *Simulated waveforms to quantify sensitivity*

We measure the sensitivity of our search by inserting simulated waveforms ("injections") into the off-source data and quantifying the pipeline's ability to recover them. For the short-duration `X-Pipeline` search, these injections are largely the same as those used in Abbott et al. (2023). The waveforms include Sine-Gaussians and damped sinusoids and are summarized in Table 2. We briefly describe each waveform family below:

- **Sine-Gaussians:** The majority of the simulated waveforms we use are Sine-Gaussians, which can model starquakes and certain neutron-star f-modes. They are described in Eq. 1 of Abbott et al. (2017). Most of these injections are performed with inclinations chosen randomly, but we also employ some optimally inclined (circular polarization only, emitted face-on to the observer) waveforms near the expected f-modes at ~2000 Hz to better constrain our sensitivity to these models. In all the injected waveforms, we use a quality factor $Q = 9$ following Abbott et al. (2021, 2023), with central frequencies f_0 spanning from 300 Hz to 3560 Hz, as shown in Table 2.

- **Damped sinusoids:** We also use damped sinusoids to characterize any ringdown behavior in the magnetar. The waveform is described in Eq. C12 of Abbott et al. (2024). These are placed at two frequencies, 1590 Hz and 2020 Hz, to represent plausible f-mode signals. For each frequency, we use two damping timescales to probe a larger parameter space.

The waveforms used by the long-duration `PySTAMP` analysis are also Sine-Gaussians, but with a duration parameter of 10 s. They are also described in Table 2.

3.2. *Long-duration search with `PySTAMP`*

We use `PySTAMP` (Macquet et al. 2021) to target GW signals with durations longer than 1 s around the three FRBs with coincident GEO600 data. The background

Table 1. Table of FRB and X-ray events for which we perform GW searches. The long-duration `PySTAMP` search is performed with one time window, while the short-duration `X-Pipeline` search is performed with both a compact window and an extended window, where data availability and timing uncertainties permit. A dash (-) indicates that no search was performed, while an asterisk (*) denotes search windows which were necessarily truncated due to data availability.

FRB/X-ray event	Time (UTC)	Window for long-duration search (s)	Compact window for short-duration search (s)	Extended window for short-duration search (s)
2020 April 28	14:34:24	$[-1200, 120]$	$[-4, 4]$	$[-1200, 120]$
2020 October 08	02:23:33	$[-1200, 120]$	$[-4, 4]$	$[-1200, 120]$
2022 October 14 X-ray glitch 1	15:07:12	-	-	$[-480, -240]$*
2022 October 14 X-ray burst peak	16:55:12	-	-	$[-1000, 1000]$
2022 October 14	19:21:39	$[-687, 120]$*	$[-4, 4]$	$[-600, 120]$*
2022 October 14 X-ray glitch 2	23:45:36	-	-	$[-500, 500]$*
2022 December 01	22:06:59	-	-	$[-1200, -400]$*

distribution and the detection efficiency of the search are characterized using an off-source window that consists of $\sim$ 12 hr of data centered on the event time, excluding the on-source window described above. The workflow of the pipeline is as follows. The data are first down-sampled from 16384 Hz to 8192 Hz, then high-pass filtered with a frequency cutoff of 40 Hz to remove potential spectral leakage from lower frequencies. After these pre-processing steps, the resulting time series are split into 1 s Hann-windowed segments with 50% overlap. The fast Fourier transform is computed over each segment to build a time-frequency map (tf-map) with a resolution of 1 s $\times$1 Hz. For each frequency bin, the power spectral density (PSD) is estimated by taking the median of the squared modulus of the Fourier transform over 1320 s of adjacent data (similar to Welch's method but using the median instead of the mean), and a signal-to-noise ratio (S/N) tf-map is built by dividing the value of the Fourier transform in each pixel by the square root of the PSD. To identify candidate GW events, a pattern recognition algorithm is run over the tf-map. We use the `burstegard` algorithm (Prestegard 2016) which identifies clusters of neighbouring pixels whose S/N is above a threshold of 2.5. Clusters consisting of 5 or more pixels are saved as candidate GW events. Each cluster is then assessed a ranking statistic Λ that is the sum of the S/N of each of its pixels divided by the square root of the total number of pixels.

Clusters found in the off-source window form the background of the search, and are used to estimate the false-alarm rate (FAR) of clusters found in the on-source window as a function of the ranking statistic Λ. `PySTAMP` is primarily intended to work on cross-correlated data from a pair of independent detectors, which allows for the simulation of an extended amount of background by shifting the time series of one detector with respect to the other. Such a method cannot be applied here in the single-detector GEO600 search. Hence, the background lifetime is limited to the duration of the off-source window, so the FAR of each cluster can only be estimated down to a minimum of $\sim$ 1 per 12 hours (2.3×10^{-5} Hz). See Sec. 5 for further discussion of the limited FAR.

Noise from GW detectors typically features narrowband spectral artifacts which appear as horizontal lines in a time-frequency representation. Because the PSD is estimated for each frequency bin by taking the median over neighbouring time segments, most of these lines are correctly factored into the PSD and do not generate high S/N pixels. However, we observe an excess of clusters in the off-source window around some specific frequencies, likely due to fluctuations of spectral lines around their central values. We therefore remove clusters for a narrow range of frequencies corresponding to known GEO600 spectral lines. In order to reject short, broadband noise transients (known as glitches), we also remove clusters for which more than 30% of the total energy is contained within a single 1 s time segment.

3.3. *Short-duration search with `X-Pipeline`*

We perform a search for short-duration unmodeled GW transients using `X-Pipeline` (Sutton et al. 2010; Was et al. 2012). While typically run as a coherent search across multiple detectors (such as in previous searches for GWs from FRBs (Abbott et al. 2023), gamma ray bursts (GRBs) (Abbott et al. 2021, 2022), and magnetars (Abbott et al. 2024)), we use `X-Pipeline` in a single-detector mode since GEO600 was the only GW detector collecting data at the time of the FRBs. `X-Pipeline` splits the PSD-whitened data into 64 s segments, then applies a Fourier-transform to produce time-frequency maps. The time-frequency pixels with amplitudes in the highest 1% that neighbor each other are clustered into candidate detection events. Each event is then

Table 2. Parameters for waveforms injected into off-source data for recovery to quantify each search's sensitivity. For the generic short-duration transient search `X-Pipeline`, we follow the labeling convention in Abbott et al. (2023) for each waveform, where "SG" waveforms are sine-Gaussians and "DS2P" (damped sinusoid 2 polarizations) waveforms represent ringdowns. There are few enough long-duration waveforms that we did not assign labels to them. The duration parameter scales the width of the Gaussian envelope for the sine-Gaussian chirplets, and describes the damping time of the damped sinusoids used as ringdown waveforms. The ^{c} superscript denotes waveforms with circular polarizations.

Label	Frequency f_0 [Hz]	Duration Parameter [ms]
Short-duration Sine–Gaussian Chirplets		
SG-D	300	3.3
SG-E	500	0.20
SG-F	1100	0.91
SG-G	1600	0.63
SG-H	1995	0.50
SG-I	2600	0.38
SG-J	3100	0.32
SG-K	3560	0.28
SG-L^c	1600	0.63
SG-M^c	1995	0.50
Short-duration Ringdowns		
DS2P-A	1590	100
DS2P-B	1590	200
DS2P-C	2020	100
DS2P-D	2020	200
Long-duration Sine–Gaussian Chirplets		
-	520	10^4
-	1020	10^4
-	1520	10^4
-	2020	10^4

assigned a ranking statistic based on the summed energy contained in the pixels. To determine the significance of these candidate events, we compare them against a distribution of background energies empirically measured in an identical manner from an "off-source" period. This is chosen to fall around (but not including) the time of the on-source data, and to be long enough to allow for meaningful significances to be calculated but not so long that the detector's behavior is nonstationary. We employ a 24-hour off-source window, symmetric about each event's time.

When `X-Pipeline` is run on data from multiple detectors as is typical, vetoes of problematic event candidates can be applied by utilizing the presumed coherence of any real GW event across detectors. This is unfortunately not an option in a single-detector search such as this, meaning that the search becomes more vulnerable to background noise. To improve the sensitivity of our search, we apply frequency-domain vetoes based on the distribution of time-frequency candidate events in the off-source window, for each FRB search. We veto narrow frequency bands ($\sim$ 10 Hz bandwidth) where there is considerable excess noise; most of these vetoes corresponded to known spectral lines from the GEO600 detector.

4. SEARCH RESULTS AND LIMITS ON COINCIDENT EMISSION

In this section, we present the results of the long- and short-duration searches described above (see Table 1 for a summary).

We do not find any candidate GW events in either the long-duration or short-duration compact-window searches, for any of the FRBs. For the long-duration `PySTAMP` search, no triggers survive the cuts described in Sec. 3.2 for the 2020 April and 2022 October FRBs. Five triggers survive for the 2020 October FRB, but the loudest trigger has a FAR of $\sim$ 1 per 1000 s with a p-value of 0.76 and is thus not significant. In the short-duration `X-Pipeline` case, only the 2020 April, 2020 October, and 2022 October FRBs compact-window searches had enough background to be considered useful for GW searches, as described above. The only surviving trigger from these three searches is from the 2022 October FRB and has a p-value of 0.53, and thus is also not significant.

For the short-duration extended-window searches, long off-source windows are required to estimate the background, and the single-detector nature of this search prevents the use of "time-slides" between multiple detectors to artificially generate background. These limitations mean that for the extended-window short-duration searches, there are sometimes as few as six off-source background trials, limiting any potential detection's maximum significance to a p-value of $1/6 \approx 0.17$—insufficient for any meaningful statement about the astrophysical nature of any outlier in the data. Thus, instead of reporting potential GW candidates from the extended-window searches with inconsequential statements about significance, we decided to use the searches only to determine the loudest trigger within the on-source window for a given waveform model, thereby setting an upper limit on the corresponding GW energy. This is the "loudest event statistic" (Biswas et al. 2009, 2013).

For all searches and windows (listed in Table 1), we estimate the root-sum-square signal amplitude of the

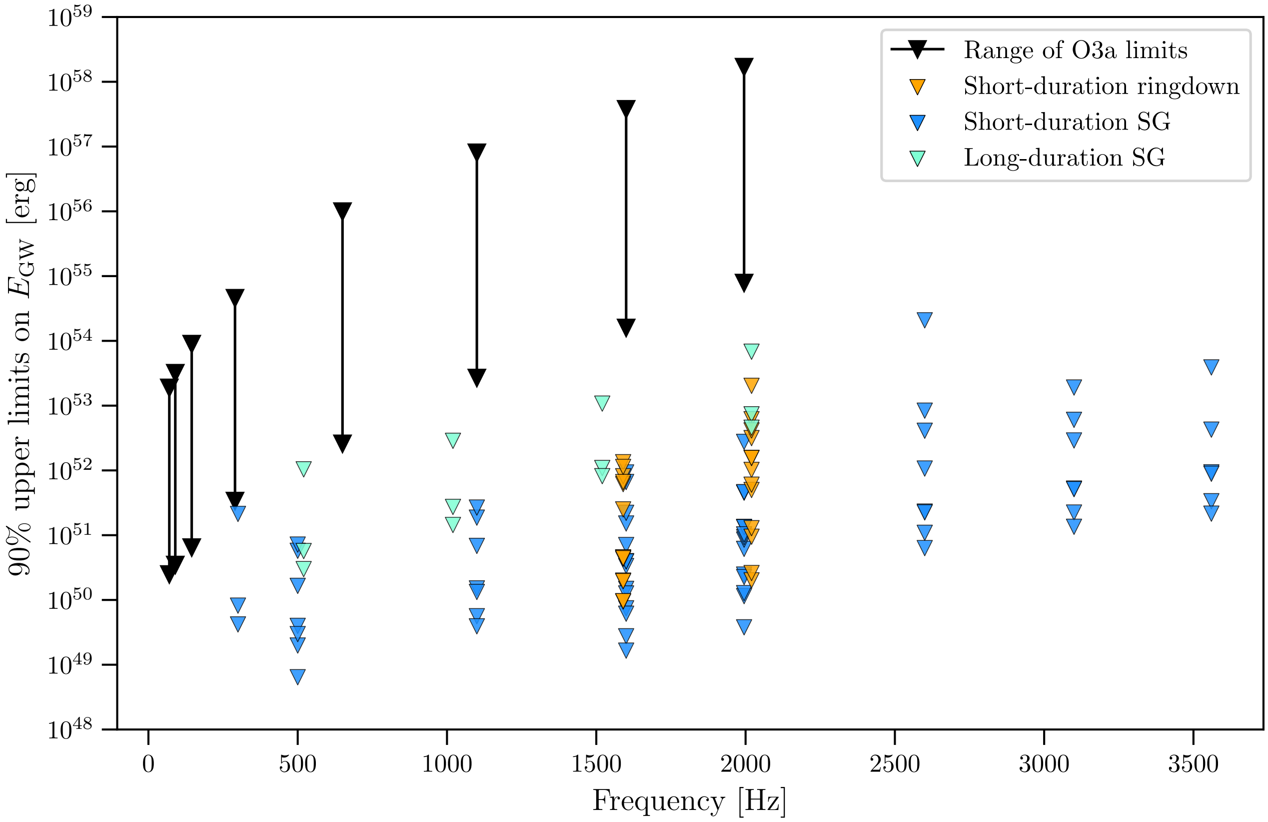

Figure 3. 90% upper limits on the emitted GW energy from SGR 1935+2154 coincident with FRBs, alongside GW energy limits from FRBs during the O3a observing run as reported in Abbott et al. (2023). We plot the short-duration ringdown (orange) and Sine-Gaussian (SG; blue) waveforms from Table 5, and the long-duration SG waveforms (aquamarine) from Table 3. The previous range of 90% limits from Abbott et al. (2023), based on the lower bounds of the 90% credible distance as reported in their Table A1, are plotted in vertical black lines. These are for a short-duration search; Abbott et al. (2023) did not perform a long-duration analysis.

Table 3. 50% and 90% upper limits on GW emission energy in ergs from the long-duration `PySTAMP` search. Each frequency corresponds to the central frequency f_0 of a Sine-Gaussian waveform with duration parameter equal to 10 s.

Event	520 Hz		1020 Hz		1520 Hz		2020 Hz	
	50%	90%	50%	90%	50%	90%	50%	90%
2020 April 28	2.0×10^{50}	5.7×10^{50}	7.4×10^{50}	2.7×10^{51}	3.3×10^{51}	1.1×10^{52}	2.3×10^{52}	7.3×10^{52}
2020 October 08	1.6×10^{51}	1.0×10^{52}	4.4×10^{51}	2.9×10^{52}	1.7×10^{52}	1.1×10^{53}	1.1×10^{53}	6.8×10^{53}
2022 October 14	8.6×10^{49}	3.0×10^{50}	4.3×10^{50}	1.4×10^{51}	2.4×10^{51}	8.1×10^{51}	1.5×10^{52}	4.6×10^{52}

GW strain $h_{\rm rss}$ (see Eqs. 3 and 4 of Sutton (2013)) at 50% and 90% detection efficiency to set upper limits on the GW energy emitted. To convert the $h_{\rm rss}$ values for each injection type that are output by the search pipelines to energy, we use (following Sutton (2013))

$$E_{\rm GW} = \frac{2}{5}\frac{\pi^2 c^3}{G} D_L^2 f_0^2 h_{\rm rss}^2, \tag{1}$$

with f_0 describing the central frequency of each injection and D_L set to the 6.6 kpc distance of SGR 1935+2154 (Zhou et al. 2020). The results of the long-duration search are shown in Tab. 3. The 50% and 90% limits from the short-duration analysis are shown in Tab. 4 and Tab. 5 respectively. We show in Fig. 3 our 90% upper limits from both the long- and short-duration analyses as a function of frequency, corresponding to the upper limits at which 90% of the injected signals were recovered. To be explicit, the $X\%$ $h_{\rm rss}$ value for a given waveform model (and corresponding GW energy) is calculated by finding the $h_{\rm rss}$ at which $X\%$ of the injected waveforms are recovered (i.e., found with a significance higher than the loudest non-injection event in the window).

Table 4. 50% upper limits on GW emission energy in ergs from the short-duration `X-Pipeline` search. Each injection waveform is defined as in Table 2. Dashes indicate that no limit was obtainable for this set of injections due to insufficient background or poor data quality.

Event Date	Window	SG-D 300 Hz	SG-E 500 Hz	SG-F 1100 Hz	SG-G 1600 Hz	SG-H 1995 Hz	SG-I 2600 Hz	SG-J 3100 Hz
2020 April 28	Compact	7.1×10^{48}	3.4×10^{48}	1.1×10^{49}	2.9×10^{49}	8.3×10^{49}	1.6×10^{50}	3.2×10^{50}
2020 April 28	Extended	2.0×10^{49}	9.2×10^{48}	3.0×10^{49}	7.9×10^{49}	2.1×10^{50}	4.2×10^{50}	8.3×10^{50}
2020 October 08	Compact	5.8×10^{49}	1.7×10^{49}	3.6×10^{49}	9.1×10^{49}	2.3×10^{50}	5.4×10^{50}	1.1×10^{51}
2020 October 08	Extended	1.7×10^{51}	3.4×10^{50}	7.6×10^{50}	1.8×10^{51}	4.4×10^{51}	8.9×10^{51}	1.7×10^{52}
2022 October 14 glitch 1	Extended	-	8.2×10^{49}	3.3×10^{50}	1.0×10^{51}	2.6×10^{51}	6.5×10^{51}	1.4×10^{52}
2022 October 14 X-ray peak	Extended	-	3.8×10^{49}	1.6×10^{50}	5.1×10^{50}	1.2×10^{51}	3.0×10^{51}	6.6×10^{51}
2022 October 14	Compact	-	1.3×10^{48}	6.4×10^{48}	2.0×10^{49}	4.4×10^{49}	1.2×10^{50}	2.6×10^{50}
2022 October 14	Extended	-	7.1×10^{48}	3.3×10^{49}	1.0×10^{50}	2.3×10^{50}	5.7×10^{50}	1.2×10^{51}
2022 October 14 glitch 2	Extended	4.8×10^{50}	1.6×10^{50}	7.4×10^{50}	2.5×10^{51}	6.8×10^{51}	2.0×10^{52}	4.5×10^{52}
2022 December 1	Extended	9.4×10^{49}	3.4×10^{49}	9.3×10^{49}	2.7×10^{50}	7.4×10^{50}	1.7×10^{51}	3.1×10^{51}
Event Date	Window	SG-K 3560 Hz	SG-L 1600 Hz	SG-M 1995 Hz	DS2P-A 1590 Hz	DS2P-B 1590 Hz	DS2P-C 2020 Hz	DS2P-D 2020 Hz
2020 April 28	Compact	5.8×10^{50}	1.0×10^{49}	2.4×10^{49}	2.5×10^{49}	2.9×10^{49}	1.6×10^{50}	2.3×10^{50}
2020 April 28	Extended	1.5×10^{51}	2.5×10^{49}	6.0×10^{49}	7.8×10^{49}	7.5×10^{49}	3.6×10^{50}	6.6×10^{50}
2020 October 08	Compact	2.0×10^{51}	2.8×10^{49}	7.1×10^{49}	8.9×10^{49}	8.7×10^{49}	3.2×10^{50}	3.4×10^{50}
2020 October 08	Extended	3.5×10^{52}	4.7×10^{50}	1.0×10^{51}	1.8×10^{51}	2.0×10^{51}	6.7×10^{51}	6.7×10^{51}
2022 October 14 glitch 1	Extended	2.2×10^{52}	3.2×10^{50}	9.1×10^{50}	1.1×10^{51}	1.2×10^{51}	3.0×10^{51}	2.9×10^{51}
2022 October 14 X-ray peak	Extended	1.0×10^{52}	1.6×10^{50}	4.3×10^{50}	5.7×10^{50}	5.6×10^{50}	1.4×10^{51}	1.4×10^{51}
2022 October 14	Compact	4.3×10^{50}	6.3×10^{48}	1.6×10^{49}	1.7×10^{49}	1.7×10^{49}	4.1×10^{49}	4.7×10^{49}
2022 October 14	Extended	2.0×10^{51}	3.1×10^{49}	8.0×10^{49}	9.9×10^{49}	9.6×10^{49}	2.5×10^{50}	2.6×10^{50}
2022 October 14 glitch 2	Extended	1.0×10^{53}	8.8×10^{50}	2.2×10^{51}	2.8×10^{51}	2.7×10^{51}	8.8×10^{51}	8.9×10^{51}
2022 December 1	Extended	5.9×10^{51}	7.9×10^{49}	1.9×10^{50}	2.4×10^{50}	2.5×10^{50}	7.9×10^{50}	8.1×10^{50}

For some injections in the short-duration search (mostly those at lower frequencies such as SG-D with $f_0 = 300$ Hz), limits could not be established since noise in the detector prevented sufficient recovery of the injected signals. Limited data availability and poor data quality around the time of the 2020 October 08 event meant that no injection reached 90% recovery, leading to the lack of 90% limits.

The non-detection of GW emission from our analyzed FRBs implies that the GW-to-radio energy ratio must be less than $E_{\rm GW}/E_{\rm radio} \sim 8 \times 10^{14}$ at the 90% level, for a time window from [-4, 4] s at a GW frequency of approximately 300 Hz. At the ~ 2 kHz frequencies close to the neutron star f-mode, $E_{\rm GW}/E_{\rm radio} \lesssim 1.7 \times 10^{16}$ at the 90% level. The GW and radio energies for our analyzed FRBs are shown in Fig. 4, alongside the same quantities for FRBs from O3a analyzed in Abbott et al. (2023).

5. DISCUSSION AND CONCLUSION

The previous best limits on coincident GW emission with FRBs were set by Abbott et al. (2023) using extragalactic FRBs observed during the O3a LVK observing run, using SG waveforms and `X-Pipeline`. Fig. 3 shows the 90% upper limits on the GW energy during our analyzed FRBs from SGR 1935+2154, compared previous limits presented as a range spanning the best and worst 90% limits from Abbott et al. (2023). In the short-duration search at approximately 300 Hz, the best previous 90% upper limit on GW energy was set at 3.4×10^{51} erg; at approximately 2 kHz, the best previous 90% upper limit was 7.9×10^{54} erg. We improve on the 300 Hz constraint by about two orders of magnitude, and the 2 kHz constraint by over four orders of magnitude. No previous long-duration searches around FRB events have been performed, so the long-duration search results presented here represent the first constraints on such emission. Studies have found that magnetar flares can emit up to $10^{48} - 10^{49}$ erg in GW energy near the f-mode for ~ 200 ms (Ioka 2001; Corsi & Owen 2011)—a regime that is probed by our most stringent 50% short-duration constraints at approximately 2 kHz (see SG-H waveform in Table 4). We also slightly improve the upper limit on $E_{\rm GW}/E_{\rm radio}$, as shown in Fig. 4.

We note that our results are not the most constraining limits on GW emission from the magnetar SGR 1935+2154, which are reported in Abbott et al. (2024) in a search for GW emission around times of

Table 5. Same as Table 4 but with 90% upper limits. For some injections (marked by a dash), fewer than 90% of the injections are recovered, preventing the calculation of 90% limits.

Event Date	Window	SG-D 300 Hz	SG-E 500 Hz	SG-F 1100 Hz	SG-G 1600 Hz	SG-H 1995 Hz	SG-I 2600 Hz	SG-J 3100 Hz
2020 April 28	Compact	4.2×10^{49}	2.0×10^{49}	5.6×10^{49}	1.5×10^{50}	9.3×10^{50}	1.1×10^{51}	2.2×10^{51}
2020 April 28	Extended	8.2×10^{49}	4.0×10^{49}	1.5×10^{50}	4.0×10^{50}	1.3×10^{51}	2.3×10^{51}	5.2×10^{51}
2020 October 08	Compact	-	-	-	-	-	-	-
2020 October 08	Extended	-	-	-	-	-	-	-
2022 October 14 glitch 1	Extended	-	5.7×10^{50}	1.9×10^{51}	6.6×10^{51}	-	4.1×10^{52}	-
2022 October 14 X-ray peak	Extended	-	1.6×10^{50}	6.8×10^{50}	2.2×10^{51}	4.6×10^{51}	1.1×10^{52}	2.9×10^{52}
2022 October 14	Compact	-	6.4×10^{48}	3.9×10^{49}	1.3×10^{50}	2.3×10^{50}	6.3×10^{50}	1.3×10^{51}
2022 October 14	Extended	-	3.0×10^{49}	1.3×10^{50}	3.9×10^{50}	1.0×10^{51}	2.2×10^{51}	5.1×10^{51}
2022 October 14 glitch 2	Extended	2.1×10^{51}	7.2×10^{50}	2.7×10^{51}	9.3×10^{51}	2.8×10^{52}	8.4×10^{52}	1.9×10^{53}
2022 December 1	Extended	-	-	-	-	-	2.1×10^{54}	6.0×10^{52}

Event Date	Window	SG-K 3560 Hz	SG-L 1600 Hz	SG-M 1995 Hz	DS2P-A 1590 Hz	DS2P-B 1590 Hz	DS2P-C 2020 Hz	DS2P-D 2020 Hz
2020 April 28	Compact	3.3×10^{51}	2.7×10^{49}	1.1×10^{50}	2.0×10^{50}	1.9×10^{50}	1.0×10^{52}	-
2020 April 28	Extended	9.3×10^{51}	7.4×10^{49}	2.5×10^{50}	4.5×10^{50}	4.3×10^{50}	-	-
2020 October 08	Compact	-	-	-	-	-	-	-
2020 October 08	Extended	-	-	-	-	-	-	-
2022 October 14 glitch 1	Extended	-	7.0×10^{50}	1.3×10^{51}	6.1×10^{51}	8.1×10^{51}	1.6×10^{52}	1.6×10^{52}
2022 October 14 X-ray peak	Extended	4.3×10^{52}	3.3×10^{50}	6.1×10^{50}	-	2.5×10^{51}	5.0×10^{51}	6.0×10^{51}
2022 October 14	Compact	2.1×10^{51}	1.6×10^{49}	3.8×10^{49}	9.5×10^{49}	9.6×10^{49}	2.0×10^{50}	2.6×10^{50}
2022 October 14	Extended	8.9×10^{51}	6.1×10^{49}	1.3×10^{50}	4.5×10^{50}	4.4×10^{50}	9.5×10^{50}	1.3×10^{51}
2022 October 14 glitch 2	Extended	3.9×10^{53}	1.5×10^{51}	4.5×10^{51}	1.3×10^{52}	1.1×10^{52}	3.2×10^{52}	4.1×10^{52}
2022 December 01	Extended	-	-	8.5×10^{50}	-	6.6×10^{51}	6.2×10^{52}	2.0×10^{53}

magnetar X-ray and gamma-ray flares. The relationship between these magnetar bursts and FRBs is poorly understood, but are likely to be caused by different physical processes, even if the underlying magnetar behavior may be related (Tsuzuki et al. 2024). Hence, both GW limits are complementary and can help to better understand the emission mechanisms at play. Considering the X-ray spin-up glitches, our best limits on the emitted GW energy ($\sim 10^{51}$ erg at 300 Hz) are still far from the X-ray measured changes in rotational energy ($\sim 10^{42}$ erg from Hu et al. (2024)).

Since $E_{\rm GW} \propto D_L^2$ in Eq. 1, our constraints are heavily dependent on the distance to SGR 1935+2154. As mentioned in Sec. 2, estimates for SGR 1935+2154's distance vary by almost an order of magnitude. If its true distance is as close as the 1.5 kpc measured by Bailes et al. (2021), our energy constraints would improve by a factor of almost 20. On the other hand, if SGR 1935+2154 is at almost 15 kpc, as suggested by Surnis et al. (2016), our constraints would worsen by a factor of 5.

As a single-detector search, the number of possible background trials (and thus the assessment of GW candidates via p-value or FAR) is limited by the time in which the detector behavior remains similar to that of the on-source window. For example, the minimum FAR for the long-duration `PySTAMP` search was limited to $\sim$ 1 per 12 hours. Since we do not recover any candidates in the on-source windows which appear to differentiate themselves from the background, we did not have to assess any candidate's significance beyond 1 per 12 hours, meaning that this limitation did not affect our results. However, future single-detector searches may encounter the problem where a candidate in the on-source window is unlike anything found in the background trials, complicating an accurate assessment of its significance. Some GW CBC searches have implemented techniques to improve single-detector significance estimation (Sachdev et al. 2019; Cabourn Davies & Harry 2022); unmodeled searches like `PySTAMP` and `X-Pipeline` may also benefit from such enhancements.

At the time of writing, no FRBs have been detected from SGR 1935+2154 since 2022. The O4 observing run of the LVK, with participation from the LIGO, Virgo, and KAGRA detectors will continue until mid-2025. Given the increased sensitivity of these detectors compared to GEO600, any SGR 1935+2154 FRB during the remainder of O4 could provide another opportunity to probe the GW–FRB connection.

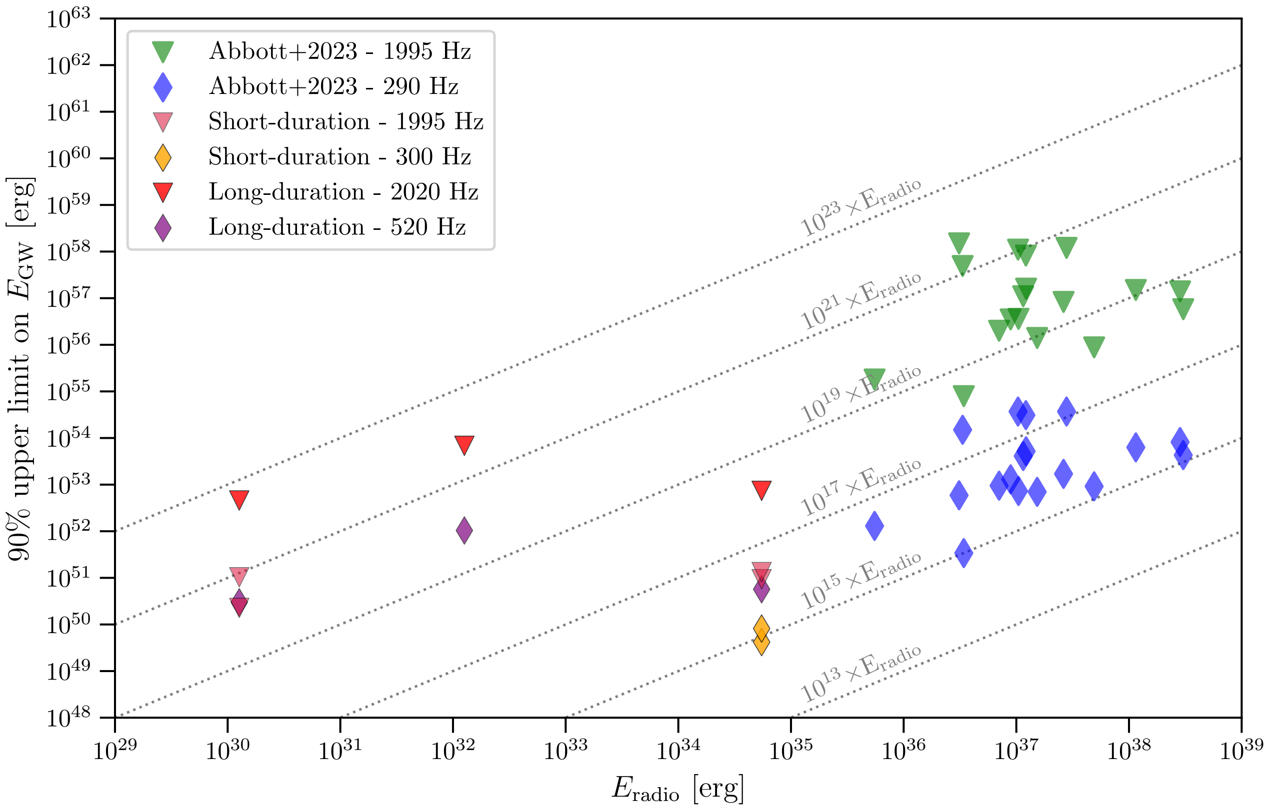

Figure 4. 90% upper limits on the emitted GW energy from FRBs as a function of the FRB's radio energy. In the pink, orange, red, and purple, we show limits from FRBs emitted by SGR 1935+2154, for both our short- and long-duration searches. We plot limits for the Sine-Gaussian model at 300 Hz (SG-D) and 1995 Hz (SG-H) for the short-duration search and at 520 Hz and 2020 Hz for the long-duration search. In the blue and green markers, we show the upper limits on GW energy and the corresponding radio energy for FRBs analyzed in Abbott et al. (2023), at 290 Hz and 1995 Hz, for events with radio flux/fluence information from CHIME/FRB Collaboration et al. (2021) allowing for radio energy reconstruction. The estimated radio energies are calculated as described in Principe et al. (2023), scaled to the lower bound 90% distances as reported in Abbott et al. (2023). Note that the radio energies (derived from fluxes and fluences) should be interpreted as lower limits (CHIME/FRB Collaboration et al. 2021; Andersen et al. 2023). We also plot dotted lines representing different ratios of $E_{\rm GW}$ to $E_{\rm radio}$, showing a slight improvement in $E_{\rm GW}/E_{\rm radio}$ compared to the Abbott et al. (2023) results.

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The gravitational-wave data analyzed in this paper is available on the Gravitational Wave Open Science Center at LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration (2024a). The scripts and data used to produce the figures in this paper are available at LIGO Scientific Collaboration, Virgo Collaboration and KAGRA Collaboration (2024b).

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Facilities: GEO600, CHIME, NICER, NuSTAR

Software: `astropy` (Robitaille et al. 2013), `gwpy` (Macleod et al. 2021), `LVK Algorithm Library Suite` (LIGO Scientific, Virgo, and KAGRA Collaboration 2018). `matplotlib` (Hunter 2007), `numpy` (Harris et al. 2020), `pandas` (pandas development team 2020; McKinney 2010)

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