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Search for Coincident Gravitational Waves and Long Gamma-Ray Bursts from 4-OGC and the Fermi-GBM/Swift-BAT Catalog

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Abstract

The recent discovery of a kilonova associated with an apparent long-duration gamma-ray burst has challenged the typical classification that long gamma-ray bursts originate from the core collapse of massive stars and short gamma-ray bursts are from compact binary coalescence. The kilonova indicates a neutron star merger origin and suggests the viability of gravitational-wave and long gamma-ray burst multimessenger astronomy. Gravitational waves play a crucial role by providing independent information for the source properties. This work revisits the archival 2015–2020 LIGO/Virgo gravitational-wave candidates from the 4-OGC catalog that are consistent with a binary neutron star or neutron star–black hole merger and the long-duration gamma-ray bursts from the Fermi-GBM and Swift-BAT catalogs. We search for spatial and temporal coincidence with up to a 10 s time lag between gravitational-wave candidates and the onset of long-duration gamma-ray bursts. The most significant candidate association has only a false-alarm rate of once every 2 yr; given the LIGO/Virgo observational period, this is consistent with a null result. We report an exclusion distance for each search candidate for a fiducial gravitational-wave signal with conservative viewing angle assumptions.

Unified Astronomy Thesaurus concepts: Gravitational wave astronomy (675); Gamma-ray bursts (629)

1. Introduction

The direct detection of a gravitational wave (GW) from the binary neutron star merger GW170817 together with an electromagnetic counterpart began a new era of multimessenger astronomy (Abbott et al. 2017a, 2017b, 2017c). The initial report of the GW by Advanced LIGO (Aasi et al. 2015) and Virgo (Acernese et al. 2015) and the short gamma-ray burst (GRB) GRB 170817A (Goldstein et al. 2017) by the Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009) triggered an extensive campaign of follow-up observations across the electromagnetic (EM) spectrum (e.g., Savchenko et al. 2017; Cowperthwaite et al. 2017; Haggard et al. 2017). This multimessenger event provided a great wealth of knowledge for astrophysics and fundamental physics. For example, the speed of GW propagation was constrained to deviate by no more than a factor of $[-3 \times 10^{-15}, 7 \times 10^{-16}]$ from the speed of light (Abbott et al. 2017b, 2019a). Besides, direct measurement of the Hubble constant was found to be $H_0 = 70.0^{+12.0}_{-8.0}$ km s^{-1} Mpc^{-1} within the 68% credible interval (Abbott et al. 2017d; see also, e.g., Guidorzi et al. 2017; Hotokezaka et al. 2019 for later improvements). It also confirmed the long-held hypothesis that short-duration GRBs originate from the merger of compact objects involving neutron stars (Paczynski 1986; Goodman 1986; Eichler et al. 1989; Narayan et al. 1992), and provided the first confirmation for a kilonova associated with a neutron star merger and r-process nucleosynthesis (e.g., Abbott et al. 2017e).

The correlation analysis of signals from different observations underlies GW/EM multimessenger astronomy. Since the beginning of the third observational run in 2019 April, LIGO/Virgo have released real-time public trigger alerts (Abbott et al. 2021a), enabling swift follow-up observation of EM-band or neutrino signals. Later, archival GW/EM searches were performed to dig deeper for associated signals missed by the low-latency searches. For instance, Abbott et al. (2017f, 2019b, 2021b, 2022) and Nitz et al. (2019) have studied temporal and spatial coincidence between GW and GRB using archival LIGO/Virgo data and Fermi-GBM/Swift-Burst Alert Telescope (BAT; Gehrels et al. 2004; Barthelmy et al. 2005; Meegan et al. 2009) data. The LIGO Scientific Collaboration et al. (2022) and Wang & Nitz (2022) have searched for GWs coincident with observations from the fast radio burst catalog released by the CHIME collaboration (Amiri et al. 2018, 2021).

Conventionally, GRBs are separated into two classes based on their duration and spectral characteristics, i.e., short-duration hard spectral and long-duration soft spectral (Dezalay et al. 1992; Kouveliotou et al. 1993). As confirmed by GW170817, short GRBs are known to originate from neutron star mergers, while many long GRBs are generated by the core collapse of massive stars as determined by the co-observation of supernovae (Galama et al. 1998; Stanek et al. 2003; Hjorth et al. 2003). Based on this knowledge, previous searches (Abbott et al. 2017f, 2019b; Nitz et al. 2019; Abbott et al. 2021b, 2022) for GW/GRB coincidences have only targeted short GRBs with a template-based match-filtering method to look for associated GW signals from compact binary coalescence. The GW candidates potentially associated with long GRBs were analyzed with a template-free generic search, with the aim to detect GWs from asymmetric core-collapse massive stars.

However, the separation of GRBs based on their observed light-curve duration is not precise (Gal-Yam et al. 2006; Gehrels et al. 2006; Ahumada et al. 2021; Zhang et al. 2021). In particular, Rastinejad et al. (2022) recently reported a kilonova located at 350 Mpc associated with GRB 211211A, an apparent long-duration GRB with $T_{90} = 51.37$s given by Swift/BAT (2018), challenging the previous paradigm for GRB classification and progenitor. Additional interesting features were reported, including a quasiperiodic oscillated precursor that occurred ∼1 s prior to the main emission (Xiao et al. 2022), and a high-energy (>100 MeV) gamma-ray afterglow lasting $\sim 2 \times 10^4$ s that occurred ∼1000 s after the burst (Mei et al. 2022; Zhang et al. 2022). Several models have been proposed to explain the emission mechanism of GRB 211211A; for instance, fast-cooling synchrotron radiation after a binary neutron star merger (Gompertz et al. 2022), magnetic barrier effect involving a magnetar progenitor (Gao et al. 2022), a neutron star–white dwarf merger (Yang et al. 2022), or thermal emission from heated dust as an alternative scenario to kilonova (Waxman et al. 2022). The associated kilonova clearly indicates the progenitor of GRB 211211A is a binary merger with at least one neutron star, suggesting the prospect of detecting a GW signal from events of this kind (however, see Waxman et al. 2022 for an alternative explanation). GW observation provides unique information about the source's mass and spin (Veitch et al. 2015), which may help disentangle different models (Gao et al. 2022; Gompertz et al. 2022; Waxman et al. 2022; Yang et al. 2022). Unfortunately, none of the GW detectors were in observation mode at the time of the GRB 211211A.

Nevertheless, we revisit the archival GW data from LIGO/Virgo and long-GRB candidates from the Fermi-GBM and Swift-BAT observation motivated by the kilonova/GRB 211211A association. We focus on GW candidates, both significant and subthreshold, that are consistent with mergers involving at least one neutron star and study their temporal and spatial coincidence with confident long-GRB observations recorded by Fermi-GBM and Swift-BAT.

2. Candidate Selection and Ranking Statistic

This section describes the selection of GW and long-GRB candidates, and our algorithm to rank the GW/long-GRB temporal and spatial coincidence.

Advanced LIGO and Virgo have completed three observational runs from 2015 to 2020 and released around 90 GW events in the Gravitational Wave Transient Catalog (Abbott et al. 2021c). Additional detections were reported by independent groups (Nitz et al. 2021; Olsen et al. 2022). This work utilizes the GW search results from the fourth Open Gravitational-wave Catalog (4-OGC; Nitz et al. 2021). 4-OGC has searched for the entire three observation runs of Advanced LIGO/Virgo using the `PyCBC` toolkit (Nitz et al. 2018) and detected 94 confident GW events from compact binary coalescences. The subthreshold triggers' search results are also publicly released (Nitz et al. 2021).

To select potential GW signals comprising at least one neutron star, we choose those confident and subthreshold candidates in 4-OGC where the secondary mass m_2 (the mass of the lighter component of the binary) of the associated gravitational-wave template is within [1, 3] $M_\odot$. Given the observation of low-spin neutron star–black hole mergers (Abbott et al. 2021d), we also extend the mass range up to total mass $m_1 + m_2$ of 10 $M_\odot$. Since we primarily target EM counterpart from binary neutron star mergers, we constrain the effective spin $\chi_{\rm eff}$ in [−0.2, 0.2]. Effective spin is the primary spin parameter characterizing the GW signal (Ajith et al. 2011) and is defined as

$$\chi_{\rm eff} = \frac{m_1\chi_1 + m_2\chi_2}{m_1 + m_2}, \quad (1)$$

where $\chi_{1/2}$ is the dimensionless component spin aligned with the orbital angular momentum direction. We limit $\chi_{\rm eff}$ because observations show that galactic binary neutron stars would have small spin ($\chi_{\rm eff} \lesssim 0.05$) at merger (Zhu et al. 2018); the binary neutron star events GW170817 and GW190425 are consistent with zero spin (Abbott et al. 2019c, 2020). Also, note that [1, 2] $M_\odot$ is considered the binary neutron star search region in 4-OGC, and $\chi_{\rm eff}$ in the search template is constrained to [−0.05, 0.05]. While we expect high-spin black hole–neutron star mergers to experience greater disruption (Foucart et al. 2018; Capano et al. 2020), our candidate population may have significant observational biases if the spin axis is misaligned with the orbital axis (Dhurkunde & Nitz 2022), which can be improved in future GW searches by accounting for spin precession. We also expect that for neutron star–black hole mergers with a mass ratio greater than ∼10:1 there is not likely to be sufficient mass ejecta to produce a GRB (Foucart et al. 2018; Capano et al. 2020).

We further require the candidates to trigger at least two GW detectors, i.e., no single detector triggers are considered (Nitz et al. 2020). Single detector triggers have less precise sky localization, typically with uncertainty up to tens of thousands of square degrees. Two or three detector detections, on the other hand, can pinpoint the source to within tens of square degrees in the most precise cases, thereby significantly reducing background noise contamination. Furthermore, quantitative estimates indicate that only 6% of horizon volume-time will be lost during the first three observation runs of LIGO/Virgo if single detector observations are excluded. Consequently, we do not consider single detector triggers in light of the aforementioned factors. The 4-OGC catalog assigns a search ranking statistic, $\lambda_{\rm gw}$, to each GW trigger, which is the natural logarithm of the ratio of rate densities for signal and noise hypothesis (Nitz et al. 2017; Davies et al. 2020). We only consider those triggers with $\lambda_{\rm gw} \geqslant 0$. These choices resulted in $\sim 5 \times 10^5$ triggers from the three observational runs in 2015–2022.

For each GW candidate, we use `PyCBC Inference` (Biwer et al. 2019) to estimate the Bayesian posterior of the sky localization. To save the computation resources, we fix the mass and spin parameters to be those reported by 4-OGC (Nitz et al. 2021) from the PyCBC search. We do not expect this procedure would significantly bias the sky position estimation because of the decoupling of intrinsic parameters (the source parameters independent of the observer orientation) and extrinsic parameters (the source parameters dependent on the observer orientation) (Singer & Price 2016). Therefore, the variables to be estimated include the luminosity distance, R.A., decl., polarization angle, inclination angle between the source orbital angular momentum and the line of sight of observatories, and the phase and time of coalescence. The posterior is numerically estimated using the dynamical nested sampler *dynesty* (Speagle 2020) using the standard GW likelihood (Finn 1992) assuming stationary and Gaussian noise.

For long GRBs, we select those from the Fermi-GBM and Swift-BAT, with $T_{90} - \delta T_{90} > 4$ s, where T_{90} and δT_{90} are the time duration containing 90% of the burst fluence and its associated error, respectively. The sky maps of these long GRBs are released by Fermi-GBM and Swift-BAT, respectively (Gehrels et al. 2004; Meegan et al. 2009).

We describe the algorithm to quantify the temporal and spatial coincidence of GWs and long GRBs. The time lag between the GW signal and long GRBs is allowed to be within [0, 10] s. We select the search window based on the expected delay time between the GW signal and the emission of the GRB. For GRB 170817A, such delay time, $\Delta t_{\mathrm{GW-GRB}}$, is $\sim$1.7 s, which coincides with the burst duration of $T_{90} \sim 2$ s (Zhang et al. 2018). The coincidence can be explained by a magnetized jet dissipating in an optically thin region in a large emission radius (Zhang et al. 2018). Assuming such a model can also be applied to the recently discovered merger-type long-duration GRB 211211A (Yang et al. 2022), we applied our search window to 10 s in accordance with the duration of the main peak of GRB 211211A. GW/long-GRB pairs that meet this condition are considered temporally associated. We further compute the sky overlap probability for the associated pairs using the posterior overlap integral following Equation (11) in Ashton et al. (2018) as

$$\mathcal{B}_{\mathrm{overlap}} = \int \frac{P(\vec{\theta}|d_{\mathrm{GW}}, \mathcal{H}) P(\vec{\theta}|d_{\mathrm{GRB}}, \mathcal{H})}{P(\vec{\theta}|\mathcal{H})} d\vec{\theta}, \quad (2)$$

where $\vec{\theta}$ is the sky localization (R.A. and decl.), $P(\vec{\theta}|d_{\mathrm{GW}}, \mathcal{H})$ and $P(\vec{\theta}|d_{\mathrm{GRB}}, \mathcal{H})$ are the sky location posterior estimated by GW and GRB data, respectively, and $P(\vec{\theta}|\mathcal{H})$ is the prior that we choose to be isotropic. $\mathcal{H}$ is the underlying hypothesis characterizing the GW and GRB data analysis.

Given the search ranking statistic λ_{gw} from PyCBC, we design the following ranking statistic for GW/long-GRB association:

$$\lambda_{\mathrm{gw+lgrb}} = \lambda_{\mathrm{gw}} + \ln \mathcal{B}_{\mathrm{overlap}}. \quad (3)$$

To measure the statistical significance for a specific associate GW/long-GRB pair, we time shift the GRB data with respect to GW data with a time stride larger than 10 s (we use 200 s) and calculate the ranking statistics of the new associated pairs. Any coincidence obtained after the time shifting is nonastrophysical and thus considered as the background distribution from the null hypothesis that GW and GRB candidates are only chance associations. Performing the time shifting multiple times, we effectively created a background observation of $\sim$1000 yr. The false-alarm rate for a foreground association is quantified by the rate of background signals with an equal or more significant ranking statistic. Following the conventions in the literature (e.g., Abbott et al. 2016), we consider GW candidate events that have a false-alarm rate less than 1 in 100 yr to be a confident detection.

3. Search Results and Implications

As described, we target the long-GRB signals that occurred at most 10 s after a GW candidate and rank their spatial overlap and statistical significance. The complete search results are illustrated in Figure 1 for the cumulative number of candidates and the inverse false-alarm rate from search and expected from noise background, and Table 1 for more detailed source information for the associated pairs.

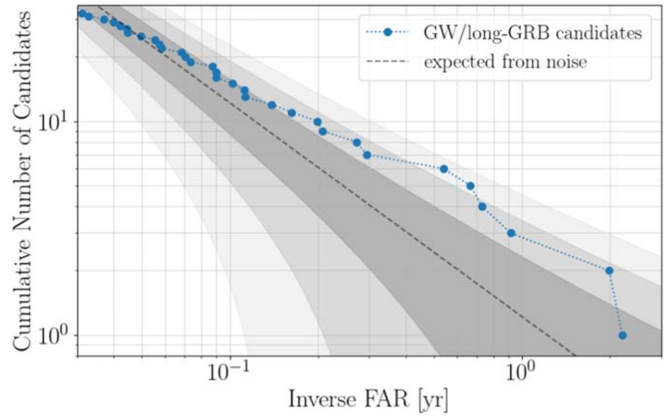

Figure 1. Cumulative number of GW/long-GRB association candidates vs. the inverse false-alarm rate. The dashed line and shading show the expected results from background noise fluctuation and 1σ, 2σ, and 3σ uncertainty from a Poisson process. The most significant associated pair 200205_201716/GRB 200205845 has a ranking statistic $\lambda_{\mathrm{gw+grb}} = 5.53$, which corresponds to a false-alarm rate of 1 in 2.2 yr.

There are 32 associated GW/long-GRB candidates from 2015 to 2020 when the GW and GRB detectors were both in observation mode. The most significant candidate is from the GW candidate 200205_201716 and the long-duration GRB 200205845, which occurs 6.7 s after the GW coalescence time. The sky overlap integral is $\ln \mathcal{B}_{\mathrm{overlap}} = 1.35$ and visualized in Figure 2. The false-alarm rate is once every 2.2 yr, which is consistent with the null hypothesis given that the total observation time of LIGO/Virgo is 443 days with at least two detectors running (Nitz et al. 2021). Since none of the search candidates meet the criteria that the false-alarm rate is lower than 1-in-100 yr, we conclude no statistically significant GW/long-GRB associations are found in our search.

We further retrieved any follow-up observations for the top five long-GRB candidates in Table 1 and noticed Swift/UVOT had detected an afterglow 109 s after the trigger time of GRB 170330A (Swift/UVOT team 2017), the second top in our search results. We are unaware of any additional follow-up observations associated with these long GRBs. In addition, a visual inspection of the light curves of the GRBs in Table 1 shows that GRB 170626A seems the only event that resembles the morphology of the light curve of GRB 211211A, i.e., with the main emission phase followed by some extended emission. Unfortunately, no firm conclusions can be drawn due to the lack of information, such as the GRB's host galaxy (thus, the redshift). Nevertheless, future improvements along this line can incorporate the GRB light-curve properties into the ranking statistic as our knowledge evolves for long GRBs as the result of compact binary mergers.

Given the nondetection, we define an effective exclusion distance d_{ex} for each GW/long-GRB pair as the distance at which a 1.4–1.4 $M_{\odot}$ (source frame mass) binary neutron star merger would have a signal-to-noise ratio (S/N) of 8 at the GW trigger time while conservatively assuming the viewing angle is 30°. An S/N of 8 is a conservative detection criterion for coincident gravitational-wave candidates. We marginalize the assumed source's location over the sky map given by Fermi-GBM/Swift-BAT and over the gravitational-wave polarization angle, assuming a uniform [0, 2π] interval. The physical

Table 1
Complete List of the Search Results

	GW Candidate	$\mathcal{M}_c/M_\odot$	Long GRB	$t_{\rm GRB}$	$\lambda_{\rm gw}$	$\lambda_{\rm gw+grb}$	IFAR/yr	GWobs	$d_{\rm ex}$/Mpc
1	200205_201716	1.01	GRB 200205845	2020-02-05 20:17:23.32	4.2	5.5	2.20	HL	281
2	170330_222948	1.05	GRB 170330A	2017-03-30 22:29:51.34	6.9	6.7	1.99	HL	191
3	191213_060532	1.01	GRB 191213254	2019-12-13 06:05:33.02	4.1	4.1	0.91	HLV	286
4	151001_082025	1.12	GRB 151001348	2015-10-01 08:20:35.16	3.2	5.2	0.73	HL	156
5	190404_070114	1.03	GRB 190404293	2019-04-04 07:01:21.92	1.7	3.9	0.67	HLV	341
6	191110_140525	1.20	GRB 191110587	2019-11-10 14:05:34.99	0.3	3.2	0.54	HLV	231
7	191213_040623	1.53	GRB 191213A	2019-12-13 04:06:23.92	2.7	1.8	0.29	HLV	363
8	190701_094513	1.03	GRB 190701A	2019-07-01 09:45:20.83	3.4	1.9	0.27	HLV	295
9	170723_161524	0.97	GRB 170723677	2017-07-23 16:15:27.85	1.8	2.2	0.21	HL	176
10	170409_024157	0.88	GRB 170409112	2017-04-09 02:42:00.49	1.9	2.1	0.20	HL	194
11	190613_040717	1.19	GRB 190613A	2019-06-13 04:07:18.31	1.7	0.6	0.16	HLV	343
12	200216_090724	0.88	GRB 200216380	2020-02-16 09:07:25.03	0.6	−0.0	0.14	HLV	274
13	190827_111245	1.57	GRB 190827467	2019-08-27 11:12:48.54	1.3	−0.5	0.11	HL	76
14	190508_234118	1.24	GRB 190508987	2019-05-08 23:41:24.14	0.6	−0.5	0.11	HLV	389
15	190628_123052	1.55	GRB 190628521	2019-06-28 12:30:55.31	0.4	−0.8	0.10	HL	313
16	170402_065048	2.42	GRB 170402285	2017-04-02 06:50:54.39	1.1	−0.7	0.09	HL	184
17	190726_152445	0.87	GRB 190726642	2019-07-26 15:24:53.60	0.7	−1.3	0.09	HLV	183
18	151029_074936	1.40	GRB 151029A	2015-10-29 07:49:38.96	4.2	−0.5	0.09	HL	65
19	191119_061605	1.27	GRB 191119261	2019-11-19 06:16:07.17	5.1	−2.4	0.07	HL	192
20	170424_101224	1.03	GRB 170424425	2017-04-24 10:12:30.75	1.7	−1.7	0.07	HL	129
21	190623_110326	1.46	GRB 190623461	2019-06-23 11:03:27.09	0.7	−2.7	0.07	HLV	238
22	170626_093721	1.17	GRB 170626A	2017-06-26 09:37:23.12	0.4	−2.6	0.06	HL	137
23	200317_004025	0.91	GRB 200317028	2020-03-17 00:40:30.48	0.6	−4.4	0.06	HLV	131
24	200117_122400	1.05	GRB 200117517	2020-01-17 12:24:06.53	2.9	−4.9	0.06	HLV	213
25	190919_181958	1.34	GRB 190919764	2019-09-19 18:20:02.65	0.7	−6.7	0.05	HLV	394
26	190805_044554	1.84	GRB 190805199	2019-08-05 04:46:00.97	3.2	−10.8	0.04	HLV	204
27	190422_160459	2.95	GRB 190422670	2019-04-22 16:05:04.52	4.2	−11.1	0.04	HLV	370
28	170825_120003	1.12	GRB 170825500	2017-08-25 12:00:05.99	0.2	−6.7	0.04	HLV	186
29	170323_012316	2.04	GRB 170323058	2017-03-23 01:23:23.26	4.6	−9.5	0.04	HL	121
30	190824_144634	1.19	GRB 190824A	2019-08-24 14:46:39.57	0.8	-inf	0.04	HLV	292
31	151027_224040	1.90	GRB 151027B	2015-10-27 22:40:40.66	7.4	-inf	0.03	HL	182
32	170629_125329	2.17	GRB 170629A	2017-06-29 12:53:33.15	3.6	-inf	0.03	HL	195

Note. We list the name of the GW candidates, their chirp mass $\mathcal{M}_c = (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$, the name of the long-GRB candidates, their trigger time in coordinated universal time (UTC), the GW search statistic $\lambda_{\rm gw}$, the ranking statistic of GW/long-GRB association $\lambda_{\rm gw+grb}$, the inverse false-alarm rate (IFAR), the GW observatories that record the data (H, L, and V stand for LIGO Hanford, LIGO Livingston, and Virgo, respectively) and the exclusion distance $d_{\rm ex}$. The nomenclature of GW candidates is in the form of YYMMDD_HHMMSS, which is the coalescence time in UTC.

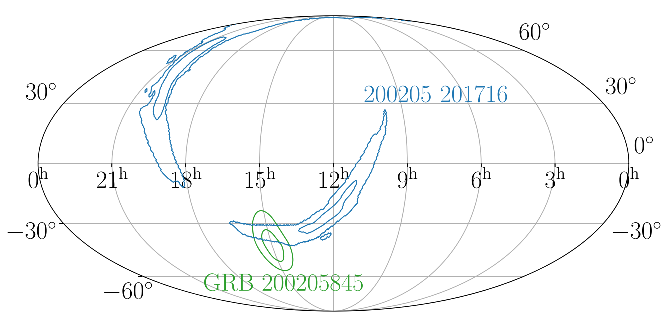

Figure 2. The posterior distribution of sky location for 200205_201716 from Bayesian inference and GRB 200205845 from the Fermi-GBM burst catalog. The inner and outer contours correspond to 50% and 90% credible intervals, respectively. The sky map overlap integral is $\ln B_{\rm overlap} = 1.35$.

meaning of $d_{\rm ex}$ is the critical distance at which a source would have been conservatively detected, assuming it is indeed from a 1.4–1.4 $M_\odot$ binary neutron star merger with a sky map inferred from Fermi-GBM/Swift-BAT. For other component mass and inclination viewing angle assumptions, one can straightforwardly rescale $d_{\rm ex}$. The exclusion distance for all the GW/long-GRB search candidates is presented in the last column of Table 1. A number of the GRBs in Table 1 were observed by Swift-BAT, which enabled us to further confirm the null results by examining the Swift-BAT catalog, which showed that none of those bursts are associated with any nearby galaxies within the $d_{\rm ex}$ reported in Table 1.

4. Discussion and Conclusion

Inspired by the discovery of a kilonova located at 350 Mpc associated with a long-GRB event (Rastinejad et al. 2022), this work performs the first multimessenger search for GW from binary neutron star or neutron star–black hole mergers and potentially associated long-GRB signals. We set a 10 s time lag window for a long GRB compared to a GW candidate and rank their correlation by their spatial overlap and the confidence of GWs as real signals. We present the complete search results in Figure 1 and Table 1, and do not find statistically significant associated pairs and thus conclude no detection. With the null results, we report the exclusion distance as a threshold for the GW/GRB candidates, closer than that any 1.4–1.4 $M_\odot$ binary neutron star mergers with an inclination angle of 30° should have been detected through GW signals.

The observation reported by Rastinejad et al. (2022) opens up a promising future for a new type of GW multimessenger astronomy (also see Gottlieb et al. 2022). Richer structures of the burst, such as a precursor (Xiao et al. 2022) and an afterglow (Mei et al. 2022; Zhang et al. 2022), are reported. GW observation can provide irreplaceable information for the source properties of compact objects, including their mass, spin, tidal deformability, luminosity distance, and inclination angle, which is crucial to distinguish different scenarios between binary neutron stars and neutron star–black hole mergers (e.g., Gao et al. 2022; Gompertz et al. 2022; Yang et al. 2022). Even with nondetection, GW can constrain the exclusion distance and provide evidence for alternative explanations for the engine of GRB 211211A, such as neutron star–white dwarf mergers (Yang et al. 2022). The next observation run of LIGO/Virgo/KAGRA is scheduled to start in 2023 March with further improved horizon distance. Future (non)detections will shed more light on the source property mystery of the GRB 211211A-like events.

We release all the data and scripts necessary to reproduce this work in Wang (2022).

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