The possible electromagnetic counterparts of the first high-probability NSBH merger LIGO/Virgo S190814bv

Hao Wei¹,4 and Minzi Feng²,3

¹ School of Physics, Beijing Institute of Technology, Beijing 100081, China
² Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
³ University of Chinese Academy of Sciences, Beijing 100049, China

E-mail: haowei@bit.edu.cn

Received 4 February 2020, revised 8 March 2020
Accepted for publication 10 March 2020
Published 18 May 2020

Abstract

LIGO/Virgo S190814bv is the first high-probability neutron star–black hole (NSBH) merger candidate, whose gravitational waves (GWs) triggered LIGO/Virgo detectors at 21:10:39.012957 UT, 14 August 2019. It has a probability >99% of being an NSBH merger, with a low false alarm rate (FAR) of one per 1.559e+25 years. For an NSBH merger, electromagnetic counterparts (especially short gamma-ray bursts (GRBs)) are generally expected. However, no electromagnetic counterpart has been found in the extensive follow-up observing campaign. In the present work, we propose a novel explanation for this null result. In our scenario, LIGO/Virgo S190814bv is just a GW mirror image of the real NSBH merger which should have been detected before 14 September 2015, but at that time we had no ability to detect its GW signals. The electromagnetic counterparts associated with the real NSBH merger should be found in the archive data before 14 September 2015. In this work, we indeed find nine short GRBs that are possibly electromagnetic counterparts.

Keywords: gravitational wave, electromagnetic counterpart, gamma-ray burst, neutron star, black hole, mirror image

1. Introduction

The first direct detection of the gravitational wave (GW) event on 14 September 2015 [1, 2] opened a new window in physics and astronomy. Since the first GW event, GW150914, one can study the Universe by using GWs, in addition to the traditional means mainly based on electromagnetic radiations. In the case of binary black hole (BBH) merger (like GW150914), only GWs are expected. However, if at least one of the binary compact objects is a neutron star, electromagnetic radiation will be also expected in addition to GWs. In fact, the first detection of binary neutron star (BNS) merger GW170817 [3–6] began a new era of multi-messenger astronomy. Through GWs, LIGO/Virgo detected the BNS merger GW170817 at 12:41:04 UTC, 17 August 2017 [3, 6]. Only ~1.7s later, the Fermi Gamma-ray Burst Monitor (GBM) independently detected a short gamma-ray burst GRB170817A [4, 5, 7]. Then, an extensive observing campaign [8] was launched across the electromagnetic spectrum leading to the discovery of a bright optical transient (SSS17a or AT 2017gfo) in NGC 4993 [4]. Such an extensive observing campaign [8] covering GW, gamma-ray, x-ray, radio, ultraviolet, optical, near-infrared, infrared, neutrino observations and so on is very impressive in scientific history.

It is natural to expect another one. During the first observing run (O1, from 12 September 2015 to 19 January 2016) of LIGO/Virgo, GWs from three BBH mergers were detected; and during the second observing run (O2, from 30 November 2016 to 25 August 2017), GWs from seven BBH mergers and one BNS merger (GW170817) were detected [9, 10]. Unfortunately, no further BNS mergers besides GW170817 were detected, and also no neutron star–black hole (NSBH) mergers were detected [9, 10].

⁴ Author to whom any correspondence should be addressed.
LIGO/Virgo began the third observing run (O3) on 1 April 2019 and it is scheduled to end on 30 April 2020, and the KAGRA detector may join the later part of the O3 run as commissioning progress permits [11, 12]. The official candidate event database is GracDB [13]. Thirty-six GW detection candidates were found as of 1 December 2019 [14]. Among them, LIGO/Virgo S190814bv is the first high-probability NSBH merger candidate [15–17], whose GWs triggered LIGO/Virgo detectors at 21:10:39.012957 UT, 14 August 2019 [16]. It has a probability >99% of being an NSBH merger, with a low false alarm rate (FAR) of one per 1.559e+25 years, at a distance of 267 ± 52 Mpc [15–17]. Unlike most GW events, S190814bv was well localized to a small area of 23 (5) deg² at 90% (50%) confidence [15, 17], mainly thanks to its favorable location in the sky with respect to the antenna pattern of the three LIGO/Virgo GW detectors [18]; it was detected by all three instruments: H1, L1 and V1 [15]. The classification ‘NSBH’ means that the lighter component has a mass <3 $M_\odot$ and the heavier component has a mass >5 $M_\odot$ [18–20]. According to the physical upper limit for neutron star mass [21] (see also e.g. [22, 23]), it is commonly believed that the lighter one with a mass <3 $M_\odot$ is probably a neutron star, while the heavier one with a mass >5 $M_\odot$ is probably a black hole.

For a long time, NSBH mergers were theorized as potential sites of $r$-process nucleosynthesis [24], leading to GWs detectable by laser interferometers like LIGO/Virgo [25], associated with the possible electromagnetic counterparts including short gamma-ray bursts (GRBs), optical and radio afterglows, as well as day-long optical transients (kilonovae) [26]. In particular, short GRBs are promising and have long been suspected on theoretical grounds to arise from NSBH or BNS mergers [27].

Therefore, another extensive follow-up observing campaign [17] began immediately after the public alert of LIGO/Virgo S190814bv. Unfortunately, no evidence for a coincident short GRB was found [17], and optical, near-infrared and radio observations found numerous candidate counterparts but they were quickly ruled out [17–20]. As of 1 December 2019, no electromagnetic counterpart of LIGO/Virgo S190814bv has been found [15, 17]. This extensive observing campaign ended with nothing.

How to understand this null result? At first, there exists the possibility that LIGO/Virgo S190814bv might be classified as ‘MassGap’ instead of NSBH, with a low probability <1% [15, 16]. A MassGap system refers to a binary where the lighter companion has a mass 3 $M_\odot$ < $M$ < 5 $M_\odot$, and no material is expected to be ejected, so that the merger is unlikely to produce electromagnetic emission [18, 19]. On the other hand, the actual upper limit for neutron star mass is not well constrained in fact and hence S190814bv might actually be a BBH merger [18–20], while the lighter component could be a low-mass black hole (e.g. a primordial black hole). For a BBH merger, no electromagnetic counterpart is expected. Another possibility is that the tidal breakup of the neutron star near the black hole [24, 27] has not happened, and the black hole could have swallowed the neutron star in one clean gulp with little left to see [28]. However, all the above explanations have their own difficulties. The probability of the first one is low, namely <1% [15, 16]. The second one will impact the neutron star and black hole theories about the upper limit for neutron star mass and the lower limit for black hole mass (as well as the primordial black hole theory if it is invoked). The third one will impact the NSBH merger theory [24, 27]. By now, the parameters of the binary LIGO/Virgo S190814bv (e.g. mass and spin) are not publicly available and hence the status is still unclear.

While the BNS merger GW170817 opened a new era of multi-messenger astronomy, could the high-probability NSBH merger candidate S190814bv be a stage for crazy ideas? In the present work, we try to propose a novel explanation. In our scenario, LIGO/Virgo S190814bv corresponds to a real NSBH merger associated with electromagnetic counterparts. However, the GW event LIGO/Virgo S190814bv detected on 14 August 2019 is not the NSBH merger itself. The real NSBH merger associated with electromagnetic counterparts should be detected many years before 14 September 2015, but at that time we had no ability to detect its GW signals, while its electromagnetic counterparts might be recorded in the archive data. LIGO/Virgo S190814bv is just a mirror image of this real NSBH merger and we saw this mirror image many years later through GWs. However, the mirror-imaging mechanism only works for GWs, not for electromagnetic signals. Therefore, we cannot find the electromagnetic counterparts while we detected GWs of LIGO/Virgo S190814bv on 14 August 2019. In fact, the corresponding electromagnetic counterparts should be found in the archive data before 14 September 2015.

In section 2, we will discuss the mirror-imaging mechanism for GWs in detail. In section 3, we will discuss the method to find the electromagnetic counterparts in the archive data before 14 September 2015. Then, in the archive data we indeed find several short GRBs probably associated with LIGO/Virgo S190814bv. In section 4, a brief summary will be given.

2. A mirror-imaging mechanism for GWs

Recently, a novel mirror-imaging mechanism for GWs was proposed in [29]. This mirror-imaging mechanism is related to superconductivity. In [30–33], superconducting film was predicted to be a highly reflective mirror for GWs (see also e.g. [34–36]). Following [30–36], let us try to give a perceptive picture for this GW mirror reflection. As a ripple in spacetime, the effect of a passing GW is mainly to make the particles follow the distortion in spacetime and then float (freely fall). In the superconductor, according to the well-known Bardeen–Cooper–Schrieffer (BCS) theory of superconductivity, negatively charged Cooper pairs will be formed. The Cooper pairs in the BCS ground state are in an exactly zero-momentum eigenstate and hence their positions are completely uncertain, namely their trajectories are completely delocalized, due to the Heisenberg uncertainty relation for momentum and position. This quantum delocalization of Cooper pairs is protected from the localizing effect of...
decoherence by the BCS energy gap. Thus, Cooper pairs cannot undergo free fall along with the positively charged ions and normal electrons. In the presence of a GW, Cooper pairs of a superconductor undergo non-geodesic motion relative to the geodesic motion of its ionic lattice. So, Cooper pairs cannot respond at all to the passage of a GW, in contrast to the positive ions. This non-geodesic motion leads to the existence of mass and charge supercurrents inside the superconducting film. The generation of supercurrents by a GW has an important consequence, namely the electrical polarization of the superconductor. The resulting separation of oppositely signed charges leads to a huge Coulomb force that strongly opposes the tidal force of the incoming GW. Thus, this incoming GW is expelled and then reflected. Such an effect in a superconductor was called the ‘Heisenberg–Coulomb effect’. We refer to [30–36] for technical details.

Due to historical reasons, GWs at microwave frequencies were mainly considered in [30–36], far before the first direct GW detection by LIGO. However, the arguments in [30–36] are also applicable for GWs at much lower frequencies (e.g. 1 Hz to 100 Hz GWs detectable for LIGO/Virgo). In fact, it was argued that for the incident GWs at angular frequencies \( \omega \ll 10^{16}\text{rad s}^{-1} \) (equivalently \( f \ll 10^{15}\text{Hz} \)), the reflectivity \( R_G \) is extremely close to 100% [30–33]. Thus, the mirror reflection of GWs from superconducting film is possible. Unfortunately, this type of experiment on Earth for laboratory-scale superconducting mirrors of GWs is in fact very difficult to achieve.

In [29], it was proposed that the GW mirror reflection might happen in the sky. As is well known, neutron stars exhibit superconductivity and superfluidity (see e.g. [37–41]). They could play the role of plane mirrors (superconducting films) for GWs in the Universe. In [29], it was predicted that there are two types of GW mirror-imaging phenomena caused by the neutron star located in Milky Way or the same host galaxy of the GW source, which might be detected within a life period of man (namely the time delay \( \Delta t \) can be a few years to a few tens of years). To be self-contained, we reproduce the plots (2a), (3a) and (3b) of [29] as the plots (I), (II) and (III) in figure 1 (not to scale). The observer O on Earth firstly detects a GW signal from the GW source S directly and, after a time delay \( \Delta t = (d_{\text{SN}} + d_{\text{ON}} - d_{\text{OS}}) / c \), the observer O will detect a secondary GW signal from the mirror image \( S' \). The neutron star N plays the role of mirror for GWs. \( c \) is the speed of light. Note that the luminosity distance of GW source \( d_{\text{OS}} \) is usually huge (\( O(10^7) \text{Mpc} \) or larger). In case (I), the neutron star N can be located in the same host galaxy of O (namely Milky Way), with luminosity distance \( d_{\text{ON}} \ll d_{\text{SN}} \), and hence \( c \Delta t \approx (1 - \cos \theta) d_{\text{SN}} \).

3. The possible electromagnetic counterparts

Let us consider the high-probability NSBH merger candidate LIGO/Virgo S190814bv in light of the mirror-imaging mechanism for GWs mentioned above. It is possible that the corresponding NSBH merger ‘S’ associated with electromagnetic counterparts is real, but its GW and electromagnetic signals arrived at Earth many years before 14 September 2015. At that time we had no ability to detect its GW signals, while...
its electromagnetic counterparts might be recorded in the archive data. LIGO/Virgo S190814bv is nothing but the mirror image ‘S’. The structure of a neutron star is complicated [37, 38]. When the GWs and electromagnetic radiations from the NSBH merger ‘S’ arrive at the non-superconducting surface of the neutron star, most of the electromagnetic radiations are absorbed, while the surface of the neutron star is almost transparent to GWs. Then, the incident GWs will be reflected by the inner superconducting structure of the neutron star (which can be safely regarded as a plane mirror (superconducting film) for GWs, due to the huge luminosity distance of the GW source and the small size of the neutron star). So, only the reflected GWs can be detected after a time delay $\Delta t$, but no electromagnetic counterparts can be found at the same time. This is the very case of LIGO/Virgo S190814bv.

If the real NSBH merger corresponding to LIGO/Virgo S190814bv and its electromagnetic counterparts does not happen before 14 September 2015, according to the mirror-imaging mechanism mentioned above, LIGO/Virgo should detect another GW signal with almost same intensity and wave form of LIGO/Virgo S190814bv between 14 September 2015 and 14 August 2019. However, this did not happen. So, we must assume that the real NSBH merger and its electromagnetic counterparts can only be found before 14 September 2015 (the day when LIGO directly detected the first GW signal).

As the next step, it is natural to find the possible electromagnetic counterparts associated with the real NSBH merger ‘S’ in the archive data before 14 September 2015. The key is to find the neutron star ‘N’ as the mirror for GWs at first. As mentioned above, there are two types of location of the neutron star ‘N’ as the mirror for GWs. So, we consider case (I) and cases (II), (III) in the following two subsections, respectively.

### 3.1. Case (I)

Since almost all known neutron stars are located in Milky Way and the nearby Magellanic Clouds, we firstly consider case (I) of figure 1 (i.e. the case (2a) of [29]), namely the neutron star ‘N’ is located in Milky Way (and Magellanic Clouds). From the left panel of figure 1, it is easy to see that the neutron star ‘N’ as the mirror for GWs is in the same direction of the image ‘S’ (namely LIGO/Virgo S190814bv) in this case. To our best knowledge, there are about 3000 known neutron stars by now [43]. It is easy to understand that most of the known neutron stars are pulsars. As of 1 December 2019, the ATNF Pulsar Catalogue [44, 45] (version 1.62) archived 2801 known pulsars. It is convenient to search the known pulsars in the ATNF Pulsar Catalogue [45]. Since LIGO/Virgo S190814bv was well localized to a small area of 23 deg$^2$ at 90% confidence [15, 17] centered on right ascension (J2000) RA = 00:50:37.5 (hms) and declination (J2000) DEC = –25:16:57.371 (dms) [20], we search the known pulsars in the ATNF Pulsar Catalogue [45] with this center (RA, DEC) and a radius of 3 degrees. There is only one known pulsar J0038$-$2501 in this area (actually it is also the unique known pulsar even searching with a larger radius of 8 degrees) as of 1 December 2019. The unique known pulsar J0038$-$2501 in this direction was discovered by the Green Bank North Celestial Cap (GBNCC) Pulsar Survey recently, and its detailed information can be found in [46]. Its distance is given by [46]

$$d_{ON} = 320 \text{ pc} \quad \text{or} \quad d_{ON} = 600 \text{ pc},$$

(1)

according to NE2001 [47] or YMW16 [48] models, respectively. Note that 1 pc = 3.261563777 light years. We will equally use these two distances in this work. Its direction in the sky reads [46]

$$\begin{align*}
\text{RA} &= 00:38:10.264 \quad (\text{J2000, hms}) \\
\text{DEC} &= -25:01:30.73 \quad (\text{J2000, dms}),
\end{align*}$$

(2)

which is slightly outside the 90% area of LIGO/Virgo S190814bv, but still inside the 2$\sigma$ area. There are three possibilities: (1) Pulsar J0038$-$2501 might not be the one we want and there might be another unknown neutron star in this direction as the mirror for GWs. (2) The true position of LIGO/Virgo S190814bv might be slightly outside the 90% area given by [15, 17] due to measurement error. (3) The mirror image ‘S’ (i.e. LIGO/Virgo S190814bv) might slightly deviate from the direction of the GW mirror (i.e. the neutron star J0038$-$2501) due to the spherical shape of the neutron star (namely it is not a perfectly flat mirror). Taking the last two arguments into account, we adopt the pulsar J0038$-$2501 as the right mirror for GWs in this work.

Then, let us try to find the possible electromagnetic counterparts associated with the real NSBH merger ‘S’ in the archive data before 14 September 2015. As mentioned above, short GRBs are the most promising electromagnetic counterparts associated with an NSBH merger. Fortunately, the first GRB was observed by the US’ military satellites in the late 1960s (the discovery was declassified and published in the early 1970s) [49] and hence there are rich archive data of GRBs which can be traced back to the early 1970s. Usually, the value of $T_90$ (the duration, in seconds, during which 90% of the burst fluence was accumulated) separating short and long GRBs is 2s [27]. A short GRB has a short duration $T_90 < 2s$.

So, we focus on the archive data of GRBs in this work. For a given GRB, its name is usually the date it was detected and its trigger time is also recorded (for a few of GRBs their trigger times are absent and then we can set them to be 00:00:00.000 UT for convenience). Thus, we can get the time delay $\Delta t$ between this GRB and LIGO/Virgo S190814bv triggered at 21:10:39.012957 UT, 14 August 2019 [15, 17]. Also, the position (RA, DEC) in the sky of this GRB is known, with an error radius. Thus, by using e.g. Astropy [50, 51], we can also get the separate angle $\theta$ between this GRB and the GW mirror (namely the neutron star J0038$-$2501) whose position in the sky is given by equation (2). As mentioned above (see also [29]), from the left panel of figure 1, if this GRB is associated with the real NSBH merger ‘S’, we have a simple relation

$$c\Delta t \simeq (1 - \cos \theta) d_{ON},$$

(3)
due to the huge distance $d_{OS} \gg d_{ON}$. The distance of the GW mirror (i.e. the neutron star J0038−2501) is already given by equation (1). Obviously, it is convenient to use $d_{ON}$ and $\Delta t$ in units of light years and years, respectively. Note that in equation (3), we do not need to know the distance or the redshift of the given GRB. This is a great advantage in fact. We can check the relation in equation (3) to see whether a given GRB is indeed associated with the real NSBH merger ‘S’. However, the position (RA, DEC) in the sky of the given GRB is not exactly measured and its 1$\sigma$ uncertainty in the position is usually characterized by an error radius (which is also given in the GRB data usually). So, we introduce a new quantity to describe the deviation between the central position of this GRB and the real NSBH merger ‘S’, namely

$$\Delta \theta \equiv | \arccos(1 - c\Delta t/d_{ON}) - \theta |,$$

(4)

where |x| denotes the absolute value of any x. Obviously, $\Delta \theta \approx 0$ for the GRB associated with the real NSBH merger ‘S’. Due to the uncertainty in the position of GRB, if $\Delta \theta$ is less than the corresponding error radius, this GRB is a possible electromagnetic counterpart associated with the real NSBH merger ‘S’. In other words, this GRB can satisfy the relation in equation (3) within its 1$\sigma$ uncertainty area in the position. Of course, we should calculate two $\Delta \theta$ for the two distances $d_{ON}$ of the GW mirror (namely the neutron star J0038−2501) in equation (1) derived from the NE2001 and YMW16 models, respectively.

Clearly, it is not necessary to scan every GRB detected before 14 September 2015 in the whole sky. Noting equation (3), for a separate angle $\theta > 25^\circ$ and $d_{ON} > 1000$ light years, the time delay $\Delta t > 93.7$ years, far beyond the time when the first GRB was detected in the late 1960s. Therefore, it is enough to scan the GRBs detected before 14 September 2015 in a smaller area centered around the neutron star J0038−2501, namely

$$22 \, h < \text{RA} < 03 \, h \quad \text{and} \quad -50 \, \text{deg} < \text{DEC} < 0 \, \text{deg} \quad (5)$$

Most GRBs were detected by the telescopes Fermi, Swift, INTEGRAL, BATSE, AGILE, HETE, Konus-Wind, Beppo-SAX, MAXI, IPN and so on. Let us consider the Fermi GBM GRBs [52, 53] at first. The well-known Fermi Gamma-ray Space Telescope was launched on 11 June 2008. In fact, the first electromagnetic signal of the well-known BNS merger GW170817 was detected by Fermi GBM [4, 5, 7] and it sent the first GCN circular of GW170817 before LIGO/Virgo [8]. As of 1 December 2019, Fermi GBM detected 2695 GRBs [54]. It is easy to find all Fermi GBM GRBs in the area defined by equation (5) before 14 September 2015 by using the online query form [54] (see also [55]). There are 143 short and long GRBs on hand. Then, we calculate the corresponding $\Delta t$, $\theta$ and $\Delta \theta$ for these 143 GRBs. Finally, we find nine short GRBs (namely $T_{90} < 2s$ by taking its error into account) which can satisfy the relation in equation (3) within its 1$\sigma$ uncertainty area in the position (namely $\Delta \theta < $ error radius) and we present them in table 1. In these nine short GRBs, GRB120314A412 can only be a possible electromagnetic counterpart for the NE2001 case but not for the YMW16 case, while the other eight short GRBs can be the possible electromagnetic counterparts for both the NE2001 and YMW16 cases. Note that a (too) large error radius means that the localization of the GRB is not well determined. So, we classify the last five short GRBs as ‘Silver’ candidates because of their large error radii and/or large $\Delta \theta$, and classify the first four short GRBs as ‘Gold’ candidates. It is worth noting that such a classification is subtle/subjective and just for reference. In principle, all these nine short GRBs could be the possible electromagnetic counterparts associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv.

Next, we turn to the well-known Swift Gamma-Ray Burst Mission (renamed the Neil Gehrels Swift Observatory on 10 January 2018) [56–58], which was launched on 20 November 2004. Actually, in the extensive follow-up observing campaign of the well-known BNS merger GW170817 [8], Swift caught the first UV light from GW170817 [59]. It has found 1332

| GRB name | GRB name | RA (J2000, hms) | DEC (J2000, dms) | Error radius (deg) | $T_{90}$ (s) | $\Delta t$ (year) | $\theta$ (deg) | $\Delta \theta$ (NE2001) (deg) | $\Delta \theta$ (YMW16) (deg) | Candidate |
|----------|----------|----------------|-----------------|-------------------|------------|-----------------|------------|------------------|------------------|-----------|
| GRB10010707 | GRB10010707A | 00:25:14.4 | −21:14:24 | 5.97 | 0.576 ± 0.465 | 9.601 | 4.813 | 2.965 | 0.865 | Gold |
| GRB14112208 | GRB14112208B | 00:38:50.4 | −20:01:12 | 10.90 | 1.280 ± 0.945 | 4.728 | 5.008 | 0.448 | 1.024 | Gold |
| GRB10121474 | GRB101214A4 | 00:24:56.5 | −28:16:12 | 5.56 | 2.240 ± 2.084 | 8.666 | 8.549 | 1.160 | 3.155 | Gold |
| GRB09010832 | GRB090108B | 00:01:36.0 | −32:54:00 | 8.30 | 0.192 ± 0.143 | 10.597 | 11.215 | 3.043 | 5.250 | Gold |
| GRB08121317 | GRB081213B | 00:51:36.0 | −33:54:00 | 13.20 | 0.256 ± 0.286 | 10.669 | 9.342 | 1.143 | 3.356 | Silver |
| GRB12052413 | GRB120524A | 23:52:36.0 | −15:36:36 | 10.45 | 0.704 ± 0.466 | 7.224 | 14.226 | 7.481 | 9.301 | Silver |
| GRB120314 | GRB120314A | 01:11:33.6 | −48:43:48 | 17.82 | 1.280 ± 1.086 | 7.418 | 24.592 | 17.756 | 19.601 | Silver |
| GRB12092675 | GRB12092675B | 01:38:26.4 | −45:34:48 | 21.32 | 3.072 ± 2.064 | 6.881 | 23.860 | 17.278 | 19.054 | Silver |
| GRB14010987 | GRB14010987B | 01:36:21.6 | −25:03:00 | 37.45 | 3.328 ± 2.560 | 5.593 | 13.174 | 7.239 | 8.841 | Silver |
GRBs as of 1 December 2019 [56]. The error radii of Swift GRBs are commonly a few arcmins. There are 73 Swift short and long GRBs in the area defined by equation (5) before 14 September 2015 [56]. Unfortunately, all these 73 GRBs are not electromagnetic counterparts associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv because their Δθ are all larger than the corresponding error radii in the position.

Obviously, it is not convenient to check every telescope for GRBs one by one (with the exception of telescopes like Fermi and Swift which have their own remarkable GRB databases). Fortunately and gratefully, there are several online GRB databases created and maintained by volunteers, such as GRBOX [60], Jochen Greiner’s GRB table [61], GRBlog [62] and so on. Some of them have been discontinued, but some are still live. They usually collect the GRB information from GCN circulars and hence they contain numerous GRBs from various telescopes, but the GRB parameters are preliminary and final results should be found in the published GRB Catalog of the corresponding telescope. On the other hand, they might also miss some GRBs which have not been reported in GCN. In this work, we chose to use GRBOX [60], since it has a user-friendly interface and we only need GRBs before 14 September 2015. In GRBOX [60], it is easy to get 149 short and long GRBs in the area defined by equation (5) before 14 September 2015, while we have excluded 29 GRBs without RA and DEC from the original 178 GRBs. Note that the pre-1990 GRBs (including four GRBs in the 1970s) have coordinates reported in B1950, and we have transformed them into J2000 by using the NED Coordinate Transformation [63]. Again, we calculate the corresponding Δt, θ and Δθ for these 149 GRBs. Since T90 in GRBOX is given without error information, we relax it to T90 < 5 s for the possible short GRBs and also take GRBs whose T90 are not available into account. So, we find four GRBs with T90 < 5 s (or n/a) and error radius > Δθ. They are presented in table 2. As mentioned above, they were collected from GCN circulars and hence their GRB parameters are preliminary. We should check them in the published GRB Catalog of the corresponding telescope. In fact, GRB100415A was found by MAXI [64]. We check GRB100415A in [64] and find that its T90 ≥ T90 = 23.4 s. So, it should be excluded because it is, in fact, a long GRB. Similarly, GRB090426B is actually the Fermi GBM GRB090426066, whose final T90 = 16.128 ± 5.152 s [53] and should also be excluded since it is a long GRB instead. On the other hand, GRB090108B and GRB081213 are also Fermi GBM GRBs [53], which are indeed short GRBs probably associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv, as shown in table 1 (and the results of these two GRBs in table 1 should prevail).

### 3.2. Cases (II) and (III)

Here, we turn to cases (II) and (III), in which the neutron star ‘N’ as the mirror for GWs is located in the same host galaxy of the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv, as shown in the middle and right panels of figure 1. In these cases, the neutron star ‘N’ is certainly unknown. Only the GW mirror image ‘S’ is known, namely LIGO/Virgo S190814bv at a distance of 267 ± 52 Mpc [15–17]. It was well localized to a small area of 23 deg² at 90% confidence [15, 17] centered on [20]

\[
\text{RA} = 00:50:37.5 \quad \text{(J2000, hrs)} \quad \text{and} \quad \text{DEC} = -25:16:57.371 \quad \text{(J2000, dms)}.
\]

As mentioned above, the time delay \(\Delta t \simeq (1 - \cos \phi)\Delta t_{SN}\) and \(\Delta \theta \simeq (1 + \cos \psi)\Delta \theta_{SN}\) in cases (II) and (III), respectively. The separate angle θ between the real NSBH merger ‘S’ and the GW mirror image ‘S’ (namely LIGO/Virgo S190814bv) must be very close to 0 due to the huge distance \(d_{OS} \simeq d_{OS} = 267 \pm 52 \text{ Mpc}\). In fact, \(\theta\) is on the order of \(\Delta \theta_{SN}/d_{OS} \sim \Delta \theta_{SN}/d_{OS} \sim 10^{-8}\) or \(10^{-7}\). So, if a GRB is associated with the real NSBH merger ‘S’, the separate angle \(\theta\) between this GRB and LIGO/Virgo S190814bv should be \(\theta \to 0\). However, as mentioned above, the position (RA, DEC) in the sky of a given GRB is not measured exactly and its 1σ uncertainty in the position is usually characterized by an error radius. On the other hand, the position of LIGO/Virgo S190814bv has also not been exactly measured in fact. Its true position in the sky is somewhere in an area of 23 deg² at 90% confidence [15, 17] centered on equation (6), as mentioned above. So, if the 1σ uncertainty area in the position of a given GRB overlaps with the one of LIGO/Virgo S190814bv, this GRB might be associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv.

In this case, the separate angle \(\theta\) between the central positions of this GRB and LIGO/Virgo S190814bv can be not close to 0. For convenience, the 90% uncertainty area in position of LIGO/Virgo S190814bv can be conservatively approximated to an area centered on equation (6) with an error radius \(\sim 2.5\) deg. Therefore, if the separate angle \(\theta\) is less than the corresponding error radius of a given GRB plus 2.5 deg, this

| GRB name | \(T_{90}\) (ymmddx) | RA (J2000, deg) | DEC (J2000, deg) | Error radius (deg) | \(\Delta t\) (year) | \(\theta\) (deg) | \(\Delta \theta\) (NE2001) (deg) | \(\Delta \theta\) (YMW16) (deg) |
|----------|---------------------|-----------------|-----------------|-------------------|-----------------|--------------|----------------|------------------------|
| 090108B  | 0.8                 | 3.75            | -32.2           | 6.4               | 10.597          | 8.790        | 0.619           | 2.825                  |
| 081213   | n/a                 | 25.5            | -35.3           | 12.5              | 10.669          | 17.163       | 8.964           | 11.178                 |
| 100415A  | n/a                 | 7.7             | -16.46          | ~2                | 9.333           | 8.736        | 1.069           | 3.139                  |
| 090426B  | 3.8                 | 17.5            | -19.2           | 18.1              | 10.302          | 9.391        | 1.334           | 3.510                  |

Table 2. The GRBOX GRBs in the area defined by equation (5) before 14 September 2015, with \(T_{90} < 5 \text{ s (or n/a)}\) and error radius > Δθ. These results are for case (I). See the text for details.
GRB might be associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv.

Similar to section 3.1, it is not necessary to scan all GRBs in the whole sky. Instead, it is enough to scan the GRBs detected before 14 September 2015 in a smaller area defined by equation (5). We consider the Fermi GBM GRBs [52, 53] at first, and present the results in table 3. There are five short GRBs associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv for cases (II) and (III). Note that a (too) large error radius means that the localization of the GRB is not well determined. So, we classify the last three short GRBs as ‘Silver’ candidates because of their large error radii and/or large $\theta$, and classify the first two short GRBs as ‘Gold’ candidates. It is worth noting that these five short GRBs are also included in table 1. That is, they are the possible electromagnetic counterparts associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv in all cases (I), (II) and (III).

Next, we turn to other GRB databases. Let us consider the Swift GRBs [56]. Unfortunately, none of them could be the electromagnetic counterparts associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv. Similar to section 3.1, we also consider the GRBox GRBs [60] and find only two GRBs (GRB090426B and GRB081213) that might be the electromagnetic counterparts for cases (II) and (III). However, as mentioned at the end of section 3.1, GRB090426B is in fact a long GRB and it should be excluded. So, only GRB081213 is the possible electromagnetic counterpart associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv for cases (II) and (III). Noting that GRB081213 has also been presented in table 3, we do not show it again.

4. Summary

LIGO/Virgo S190814bv is the first high-probability NSBH merger candidate, whose GWs triggered LIGO/Virgo detectors at 21:10:39.012957 UT, 14 August 2019 [15–17]. It has a probability >99% of being an NSBH merger, with a low false alarm rate (FAR) of one per 1.559e+25 years. For an NSBH merger, electromagnetic counterparts (especially short GRBs) are generally expected. However, no electromagnetic counterpart has been found in the extensive follow-up observing campaign [17]. In the present work, we propose a novel explanation to this null result. In our scenario, LIGO/Virgo S190814bv is just a GW mirror image of the real NSBH merger which could have been detected many years before 14 September 2015, but at that time we had no ability to detect its GW signals. The electromagnetic counterparts associated with the real NSBH merger ‘S’ corresponding to LIGO/Virgo S190814bv should be found in the archive data before 14 September 2015. In this work, we indeed find nine short GRBs as the possible electromagnetic counterparts. The names of all nine short GRBs can be found in table 1 (note that the names of five short GRBs in table 3 are also included in table 1).

Acknowledgments

We thank the anonymous referee for quite useful comments and suggestions, which helped us to improve this work. We are grateful to Profs. Rong-Gen Cai, Shuang Nan Zhang, Bobing Wu, Jian-Min Wang, Zong-Kuan Guo, Zhoujian Cao, Wen Zhao, Bin Hu, Hongsheng Zhang, Yi Zhang and Lijun Gou for helpful discussions. We also thank Da-Chun Qiang, Zhong-Xi Yu, Hua-Kai Deng and Shu-Ling Li for kind help and discussions. This work was supported in part by NSFC under Grants No. 11975046 and No. 11575022.

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